

FOREWORD

This Report of the Design Specification for the DIAMOND Synchrotron Light Source was first produced at the completion of the Design Specification Phase in March 2002. It was presented to the DIAMOND Technical Advisory Committee at a meeting in April 02 and both then and subsequently a number of comments and corrections were made. All these have now been incorporated in this, the final version of the Report.

Since March 02 the DIAMOND design has continued to be refined in detail as the Procurement Phase makes progress. However, such refinements have not been included in this final version which remains essentially a statement of the design as it existed in March 02. For historical accuracy the publication date on this final version is shown as June 02.

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A.1 Introduction

1.1 INTRODUCTION

This report is a detailed technical description of the design specification for the DIAMOND synchrotron light source facility. The concept for such a facility has been under consideration for about 10 years following a recommendation of the review of UK synchrotron radiation science made under the chairmanship of Professor M M Woolfson FRS [1]. Subsequently, feasibility studies were carried out by staff at the Daresbury Laboratory over a number of years which culminated in the production of the DIAMOND “Red Book” in May 1997 [2].

The status of the project was significantly moved forward in 1998 when it was announced, by the Wellcome Trust in July and by the UK Government Minister for Science in October, that financial support would be made available. In August 1999 the French Government decided to co-operate with the existing partners, the UK Government and the Wellcome Trust, in the construction of a third generation light source facility. In March 2000 the decision was taken to site the DIAMOND facility at the CLRC Rutherford Appleton Laboratory and to form between the partners a Joint Venture Company to undertake construction of the facility.

During the second half of 2000 widespread consultation with the User Community took place in conjunction with continuing feasibility design by CLRC staff which resulted in agreement on the main technical parameters of the DIAMOND facility. From November 2000 to March 2002 a detailed design specification was made by CLRC with funding provided by the UK Government Office of Science and Technology. This DIAMOND “Green Book” is the technical summary of that work.

1.2 DESIGN EVOLUTION

The initial design for the DIAMOND 3 GeV storage ring was based on the preferences, as then stated, of the user community for a moderate brightness source of X-rays which was complementary to the ESRF in Grenoble. That design would have catered for about 10 insertion devices of length up to 4.5 m, with an additional capacity for 2 very long devices, such as FELs or long period undulators, up to 18 m. The racetrack storage ring structure consisted of 16 cells of the double bend achromat (DBA) type, which was by then well established as a suitable choice for third generation synchrotron light sources. With a total circumference of almost 350 m, this design delivered the required medium source brightness from an electron beam emittance of 14 nm-rad. (The source brightness increases as the emittance reduces. The original design emittance of the ESRF was 7 nm-rad.)

PART A: GENERAL

By 1998 the anticipations for very long undulators and FELs in high energy storage rings were fading and, more importantly, the advantages of high brightness source properties in the medium X-ray region were beginning to be emphasised. This led to pressure to improve the brightness of the DIAMOND design and the lengths of the very long straights were also reassessed. An additional motivation for the latter resulted from analyses of the electron beam nonlinear dynamics behaviour of the storage ring, which was proving to be inadequate due to the low symmetry (2 fold) of its structure.

A further important realisation was that because a third generation source relies mainly on its insertion devices for the premium beamlines, with 16 cells the capacity of the DIAMOND facility appeared limited for a major national facility with a projected lifetime of 20 to 30 years. Therefore in 1998/9 the design was increased to 20 cells with higher symmetry (5 fold), the very long straights reduced in length and a higher source brightness. By mid-1999 a dramatically improved brightness had been achieved (5 nm-rad emittance) with much improved electron beam dynamics.

The prospect of participation of the French in August 1999 prompted further consideration of the facility capacity and it was realised that an increased complement of insertion device straights would be needed for them. A study of a 24 cell 6 fold symmetric structure showed further desirable increases in brightness, as expected, with an electron beam emittance of between 2 or 3 nm-rad readily achievable; this improvement follows from a known rapid scaling with cell number.

The DIAMOND Technical Advisory Committee (TAC) and Scientific Advisory Committee (SAC), which were established in Autumn 2000, have made important contributions to the evolution of the DIAMOND specification. As a result of their advice the standard straights for insertion devices have been increased in length to 5 m and a substantial amount of work has been done to optimise the dynamic beam behaviour to achieve long stored beam lifetime.

The design of the DIAMOND storage ring has now been refined such that the facility can expect to provide a world leading performance for a medium energy third generation synchrotron light source for the foreseeable future. The 24 cell, 6 fold structure has been shown to generate an electron beam of extremely high brightness (emittance 2.7 nm-rad) with excellent dynamic properties which will permit long beam lifetimes (10–20 hrs). The circumference of 560 m will accommodate 18 insertion devices up to 5 m long with an additional 4 up to 8m. A further 20 beams of somewhat lower brightness will be able to be exploited (finances permitting) using the storage ring dipole magnets as sources. Furthermore the engineering feasibility of all engineering systems has been verified.

1.3 INITIAL BEAMLINES AND INSERTION DEVICES

The DIAMOND project includes not only the basic facility but also the first 7 beamlines and their associated experimental equipment which will come into

A.1 INTRODUCTION

immediate use for research at the completion of the construction project. These are usually referred to as the “day-one” beamlines. These beamlines have been selected through peer review after an initial call to the user community for proposals, which produced an enthusiastic response of more than 20 suggestions. The results of the selection can be seen in Part B of this report where the individual day-one beamlines are described.

The day-one beamlines do not, of course, fill up the capacity of the facility. The intention will be to install additional beamlines and their experimental equipment on a rolling programme, probably by an annual process. Because of the long timescale which is required to specify, design, install and commission a new beamline the process has already been initiated for the next beamlines to be installed after the first year of facility operation. However, those beamlines are not included in the scope of this report.

Each of the day-one beamlines will be served by a specific insertion device optimised to deliver the photon beam characteristics needed for the chosen scientific applications. Since the beamline selection was only finalised within the last 6 months of the design specification period, the majority of the design work on insertion devices, described in chapter B 2, has been of a generic nature. Nevertheless from the outline specifications of the initial insertion devices it is now possible to calculate the photon beam outputs which will be available, and these are shown in chapter A 2.

1.4 DIAMOND JOINT VENTURE COMPANY

The work described in this report has been carried out by CLRC staff and the user community under the direction of the interim DIAMOND Board of Directors acting through the interim Project Office. The DIAMOND Joint Venture Company is due to be formed in April 2002 and will subsequently take ultimate responsibility for all aspects of the project. However there will be a need for project continuity, not least to progress those remaining detailed design issues and to provide well informed advice to the procurement process.

In carrying out the work described in this report it has been essential to effective progress to make important key assumptions; for example, that the booster synchrotron will be procured by a turn-key contract. Following the formation of the Joint Venture Company it is likely that all these assumptions will be revisited. Therefore it needs to be stated that this design specification report represents a current view of the design and that in the future there may be changes as the procurement philosophy and project plan becomes clarified.

1.5 ACKNOWLEDGEMENTS

Many individuals within CLRC and in the user community have contributed to the DIAMOND Design Specification, both in the period since November 2000 and in the key parameter definition phase before that. The exciting performance which the

PART A: GENERAL

DIAMOND design offers is undoubtedly due to the enthusiasm, motivation and skilful creativity which has been applied in this work.

It is not possible to acknowledge individually the large number of persons contributing to the DIAMOND design, but it is useful to indicate those who have taken the main responsibilities in carrying out the work reported here. They are:-

Interim Board of Directors	Chris Henshall (prev Martin Earwicker) (OST); Michael Morgan (Wellcome Trust), Gerhard Materlik
Interim Project Office	Ian Gibson (prev David Hull) (OST); Trefor Edwards
Interim Science Directors	Colin Norris (Leicester Univ); Chris Dobson (Cambridge Univ)
CLRC Project Manager	Vic Suller
Key Parameter and Accelerator Definition	Mike Poole
Accelerator Physics	Susan Smith
Beamlines	Colin Nave
Insertion Devices	Jim Clarke
Magnets	Neil Marks
Radio Frequency and Diagnostics	Mike Dykes
Vacuum Systems	Ron Reid
Controls	Mark Heron
Radiation Safety and Shielding	Roy Ryder
Buildings and Civil Engineering	Rick Mason
Professional Engineering Design	Jim Kay
Safety Management	Paul Quinn
Power Converters	Steve Griffiths

REFERENCES

- [1] M M Woolfson (Chairman), Report of the Review of Synchrotron Radiation Science June 1993, SERC Daresbury Laboratory, Warrington WA4 4AD, UK.
- [2] DIAMOND Synchrotron Light Source, Report of a Feasibility Study, May 1997; CLRC Daresbury Laboratory, Warrington WA4 4AD, UK.

A.2 Facility Specifications and Outputs

2.1 INTRODUCTION

This chapter summarises the main, user defined, specifications of the DIAMOND source and provides details of the calculated photon beam performances. All this data is repeated elsewhere in this report, but the compilation in this chapter is intended to be a concise presentation for synchrotron light users and others who are not accelerator specialists.

The photon outputs are shown for the specific insertion devices required by the day-one beamlines. These are, however, not fully representative of the facility capabilities and to cover that fact some additional, generic, insertion devices are included.

2.2 TABLE OF PRINCIPAL FACILITY PARAMETERS

Table 2.2-1 Principal DIAMOND Parameters

Energy	3 GeV
Circumference	561.6 m
Lattice	24 x DBA, 6 fold symmetry
Max length for IDs	18 x 5 m; 4 x 8 m
Injection energy	3 GeV
Beam current	300 mA
Lifetime	10-20 hrs
Emittance; horiz, vert	2.7, 0.03 nm-rad
Bunch length (fwhm)	25.6 pS
Source sizes (fwhm)	
5 m straight, h x v	290 μm x 15 μm
8 m straight, h x v	421 μm x 30 μm
dipole magnet, h x v	127 μm x 56 μm

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2.3 TABLE OF INSERTION DEVICE PARAMETERS

Table 2.3-1 Table of Day-one Insertion Devices

Name	Beamline	Technology	B _{Max} (T)	K _{Max}	Period (mm)	N _{Periods}	Length (m)
MPW60	VHE	SC MPW	3.5	19.6	60	16	1.0
U33	Materials	Und	0.54	1.66	33	149	5.0
U23 IV a	PX	In Vac Und	0.70	1.49	23	85	2.0
U23 IV b	PX	In Vac Und	0.70	1.49	23	85	2.0
U23 IV c	PX	In Vac Und	0.70	1.49	23	85	2.0
U27 IV	XAS	In Vac Und	0.80	2.02	27	72	2.0
HU64	SXR	Helical Und	0.57	3.4	64	75	5.0
U27	NCD	Und	0.70	1.76	27	72	2.0

Table 2.3-2 Table of Generic MPWs

Technology	B _{Max} (T)	K _{Max}	Period (mm)	N _{Periods}	Length (m)	Magnet Gap (mm)
PM	1.6	14.9	100	50	5.0	15.0
PM	2.5	28.0	120	16	2.0	10.0

Table 2.3-3 Table of Generic Undulators

Name	B _{Max} (T)	K _{Max}	Period (mm)	N _{Periods}	Length (m)	Magnet Gap (mm)
U24	0.60	1.36	24	82	2	10
U36	0.60	2.03	36	137	5	15
U48	0.84	3.76	48	103	5	15
U80	0.67	5.00	80	62	5	15
U200	0.27	5.00	200	39	8	20

2.4 PLOT OF FLUX OUTPUTS

The photon flux spectra generated by different DIAMOND sources are shown in Figure 2.4-1. The plotted data assume horizontal collection angles of 1 mrad for the multipole wiggler and 5 mrad for the dipole magnet. The flux from the dipole magnets is seen to be useful to beyond 20 keV.

A.2 FACILITY SPECIFICATIONS AND OUTPUTS

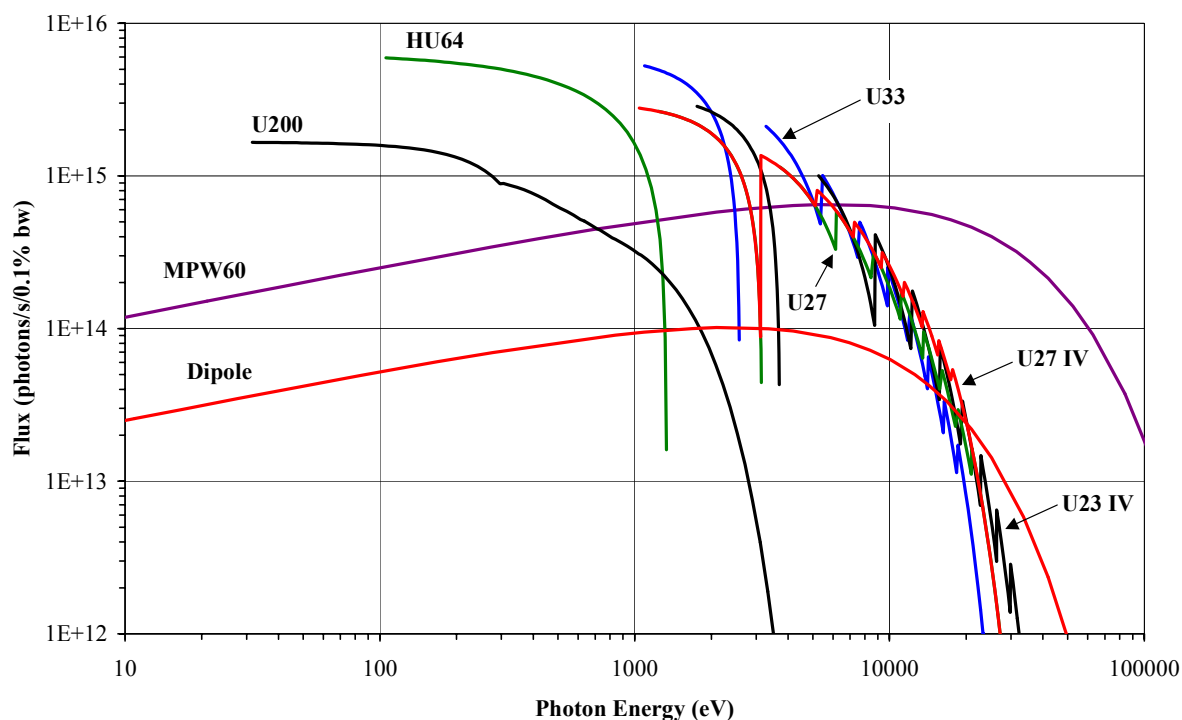


Figure 2.4-1 Flux outputs for the first DIAMOND insertion devices; the dipoles and an example 200 mm period undulator. A horizontal collection angle of 5 mrad has been assumed for the dipole and 1 mrad for the MPW.

2.5 PLOT OF BRIGHTNESS

Photon beam brightness outputs from the insertion devices listed in Table 2.3-1 are shown in Figure 2.5-1. This plot demonstrates the very high brightness which will be available from DIAMOND over the photon energy range 30 eV to 20 keV. This, in particular, will make DIAMOND an excellent source for the technique of Protein Crystallography as it encompasses the important photon energy of 12.7 keV.

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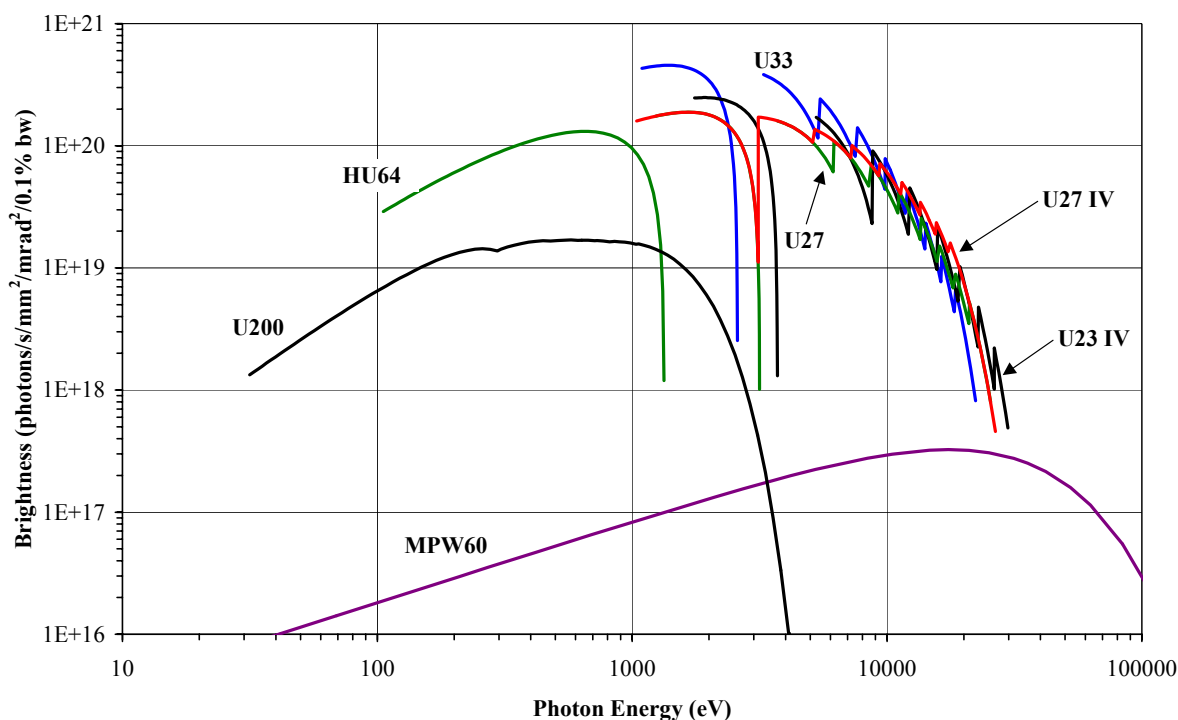


Figure 2.5-1 Brightness outputs for the first DIAMOND insertion devices and an example 200 mm period undulator.

2.6 OTHER PHOTON OUTPUTS

Strong interest has been expressed by the user community in using the low energy photon output produced by DIAMOND because of the superior beam source stability which can be anticipated. Two principal spectral regions have been identified:-

- Infra Red (IR) from about 100 to 2.5 microns;
- Circular Dichroism (CD) from 3 to 10 eV.

At these low photon energies the natural emission angles for synchrotron light are large so that it is essential to collect large horizontal and vertical beam angles to provide sufficient flux. Whilst DIAMOND will not be equipped on day-one with special large angle ports, design work has established that the following collection angles can be retrofitted if it is decided to build beamlines for the above mentioned scientific techniques. The acceptance angles for them are as follows:-

- IR: 35 mrad horizontal x 30 mrad vertical
- CD: 35 mrad horizontal x 8 mrad vertical

For these angles the fluxes which can be collected are shown in Table 2.6-1

A.2 FACILITY SPECIFICATIONS AND OUTPUTS

Table 2.6-1 Flux available for CD and IR beamlines

Photon	Flux (photons/s/0.1% bw)
IR	
100 microns	1.58E13
2.5 microns	6.50E13
CD	
3 eV	1.18E14
10 eV	1.75E14

2.7 PLOT OF ELECTRON BEAM SIZES

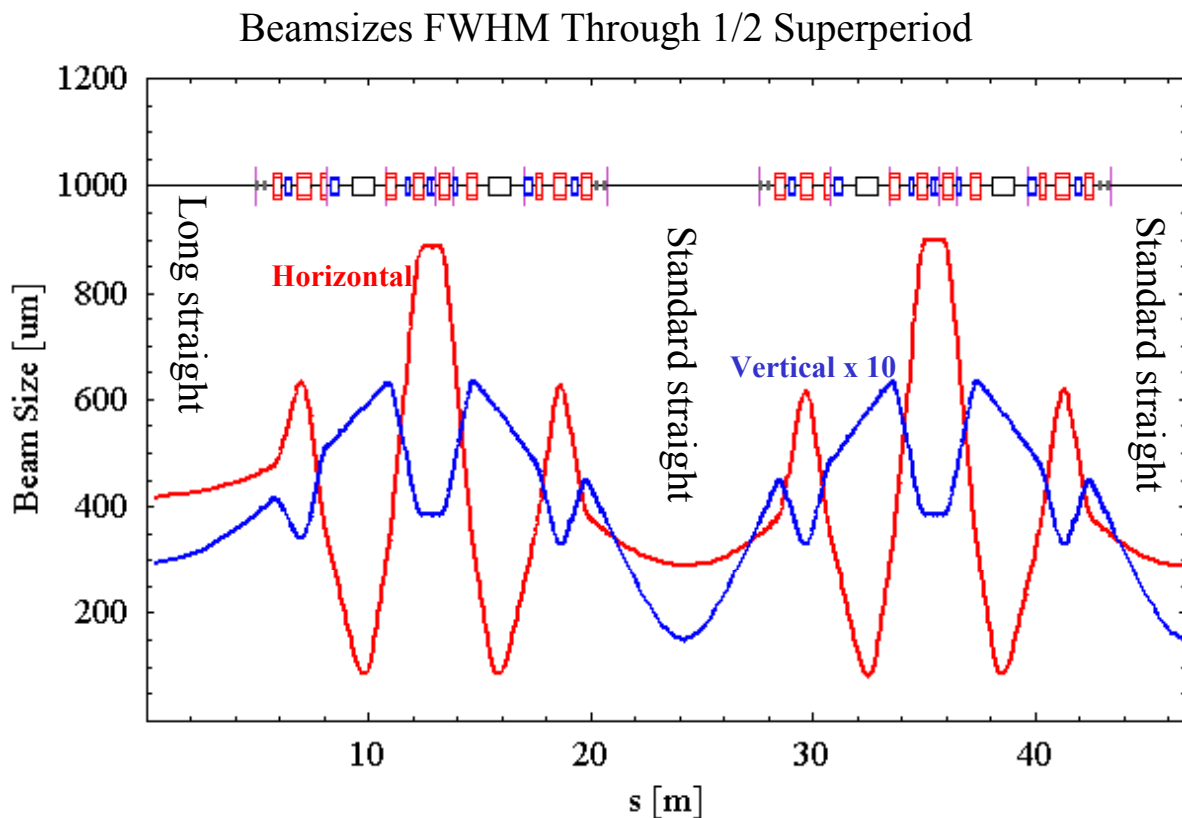


Figure 2.7-1 Full width half maximum beam sizes in the horizontal and vertical planes around a representative section of the storage ring.

The electron beam size varies in a repetitive manner around the circumference of the storage ring due to the periodicity of the 24 cell structure. This is shown in Figure 2.7-2 for adjoining cells containing a 5 m straight and an 8 m straight. The beam sizes in all other positions may be inferred from this figure. In the future, after the facility

PART A: GENERAL

has been in operation and its behaviour fully investigated, the flexibility of the design could allow for adjustment of the beam sizes in different straight sections to meet the requirements of specific beamlines.

A.3 Resources

This chapter has been left blank intentionally in this issue.

A.4 Timescales

4.1 INTRODUCTION

A detailed planning exercise has been undertaken involving all the respective technical sections involved in the Diamond project. The first part of the process was to construct a detailed Work Breakdown Structure (WBS) which describes the project in terms of the key systems, sub-systems and packages of work that make up the whole project. An important part of developing the WBS is to identify persons responsible for a specific system and sub-system. Once the project was described in detail at level 4 in the WBS, a task template was developed describing the standardised process by which each work package would be delivered.

This template includes the design, procurement, processing, installation and commissioning phases with milestones applied at appropriate points. By adopting a template, this ensured that the terminology used by each technical system is consistent and also that milestones are applied at the same points for each work package. These tasks are applied at level 5 in the overall schedule. Although each technical system has developed a detailed plan below level 5, in planning such a major project as Diamond it is an unwieldy task trying to knit very detailed plans together and produce high level reports. Thus a further advantage of the template approach is to gain summary information from each technical system for inclusion in the high level plan, but ascribe responsibility for the detailed planning to the technical area.

As the schedule stands at the moment, it represents a detailed view of the tasks involved, their realistic timescales and a logic that inter-relates them. The next stage is to apply resources to each task and then by analysing resources in total, a staffing plan and budget can be generated. Some durations will have to be extended through the process of 'staff levelling' but all reasonable attempts will be made to absorb this and not push the end date out further.

4.2 TIMESCALES

On first combining the schedules for each sub-system and applying logic to network them together, the completion date was found to be in late 2007. By a process of identifying the critical path and refining the logic and timescales associated with tasks on the critical path, the completion date predicted is now November 2006. As the timescale was compressed, many and different logic streams began to vie for the critical path and this gives confidence that a limit of a practically achievable date has been reached.

PART A: GENERAL

The full schedule contains 2400 task lines and would occupy 100 pages if printed here. A milestone schedule has been included occupying some 30 pages. As can be seen, the milestones can be used to track the logical progress of each sub-system through the course of the whole plan and also the extent of the WBS can be seen in the identification of each major system and sub-systems.

4.3 CRITICAL PATH

The critical path as shown hinges around a target building availability of August 2004 (Task ID5). Once this access to the building and accelerator tunnels is available, then the schedule is driven by the time needed to install pre-assembled girders, connect the whole vacuum system together and pump down before commissioning the storage ring with beam. Once beam is circulating and synchrotron light is produced, the final stage of commissioning the beamlines with beam can be carried out. In parallel with assembling girders, the schedule currently shows a parallel critical path through the installation and commissioning of the cryogenic RF system for the storage ring.

For the 2 years before the building is available, the critical path follows the design and procurement of essential components to be mounted on the pre-assembled girders. In the case shown, this includes the storage ring quadrupoles and dipoles. However, the project team fully appreciates that just because certain components are identified on the critical path, this is no cause for complacency as many other systems and components are just off the critical path.

4.4 CONCLUSIONS

The schedule as shown indicates a project completion of November 2006. However, this plan is a living document and all the durations are based on a reasonable view of time needed for design, supplier leadtimes and time needed for installation and commissioning. These will change as firm quotes from industry are obtained and as the reality of applying staff resources unfolds.

The critical path follows the design and procurement of components required to be mounted on the storage ring girders and then once the building is made available in August 2004, the installation of the girders in the storage ring tunnel and the commissioning of the storage ring and beamlines.

A.5 General Diagrams

5.1 TOWARDS A FULL COMPLEMENT OF BEAMLINES

A major contribution has been made by the design team in support of the Science Directors in proposing the position of the first 7 beamlines, and also for those beamlines that are planned in the subsequent 4 years of operation and development.

Account has been taken of the requirements for building design, RF cryogenics and power supplies, storage ring diagnostics, injection, the position of long beamlines that extend out onto the RAL site, shield wall thickness and the geometry of the 6 fold lattice that results in a variation in beamline length available.

The results of the Science Directors' deliberations are published in DM-SAC-TN-010 and the 'Straw Plan' from that document is reproduced below.

Diamond Straw Plan

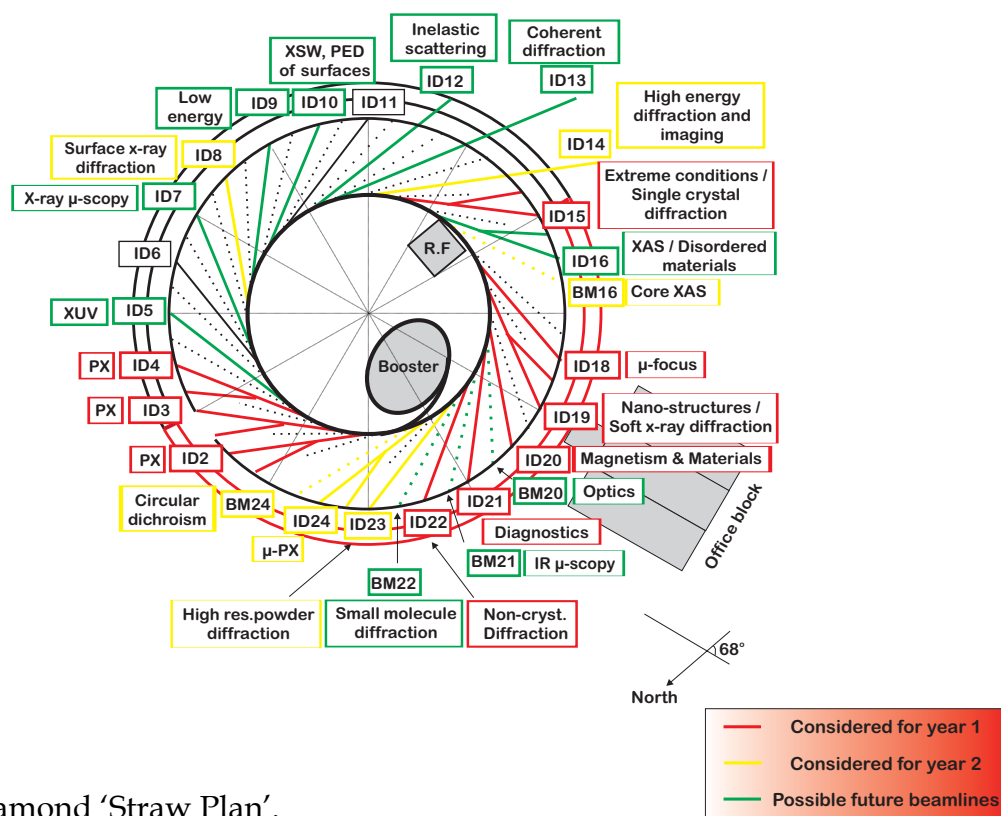


Figure 5.1-1 Diamond 'Straw Plan'.

The achromat layout, a cross-section through the Experimental Hall and the overall plan view of the DIAMOND facility are shown below.

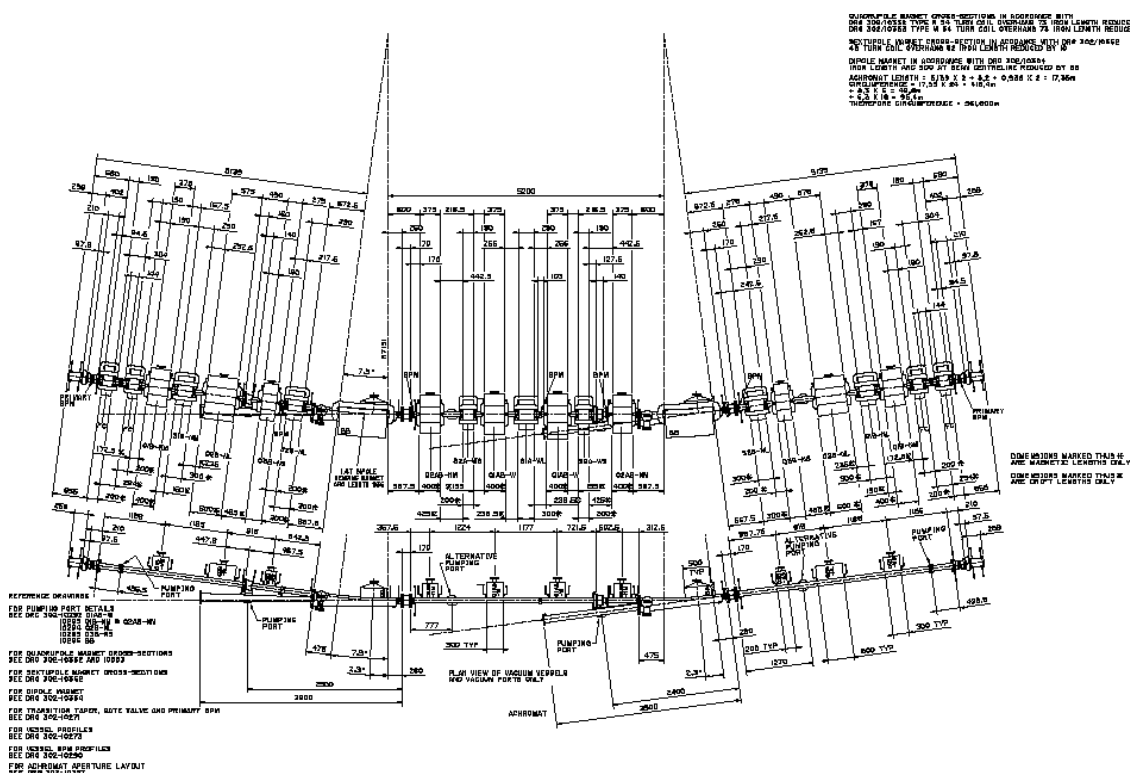


Figure 5.1-2 Achromat Layout

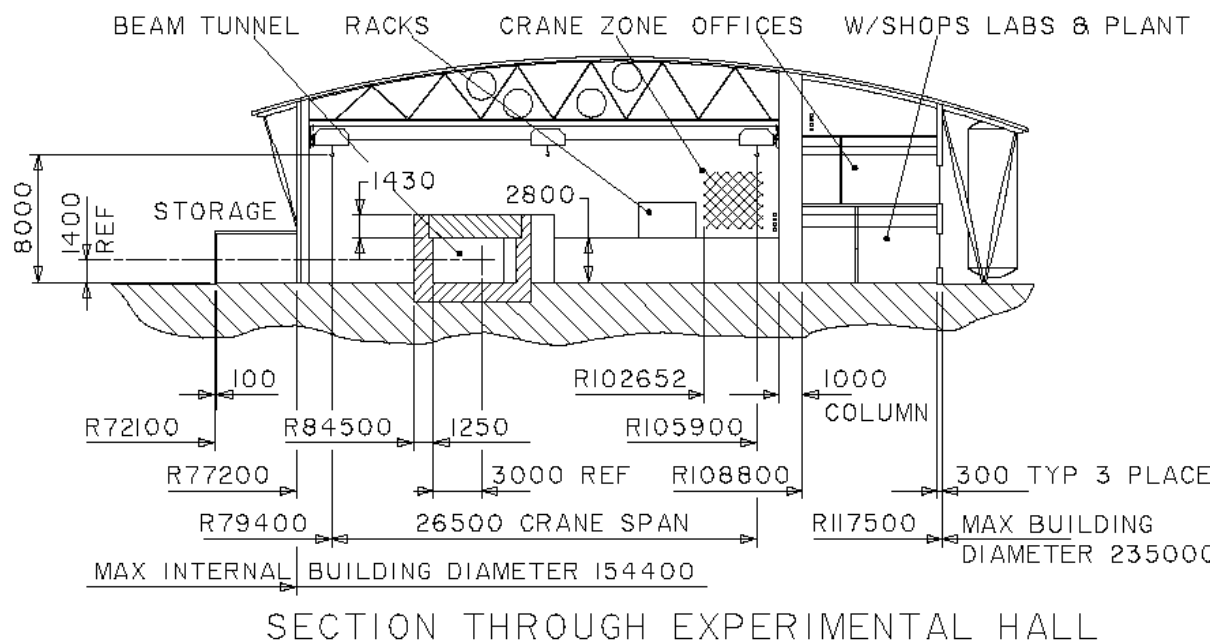


Figure 5.1-3 Cross Section through Experimental Hall.

A.5 GENERAL DIAGRAMS

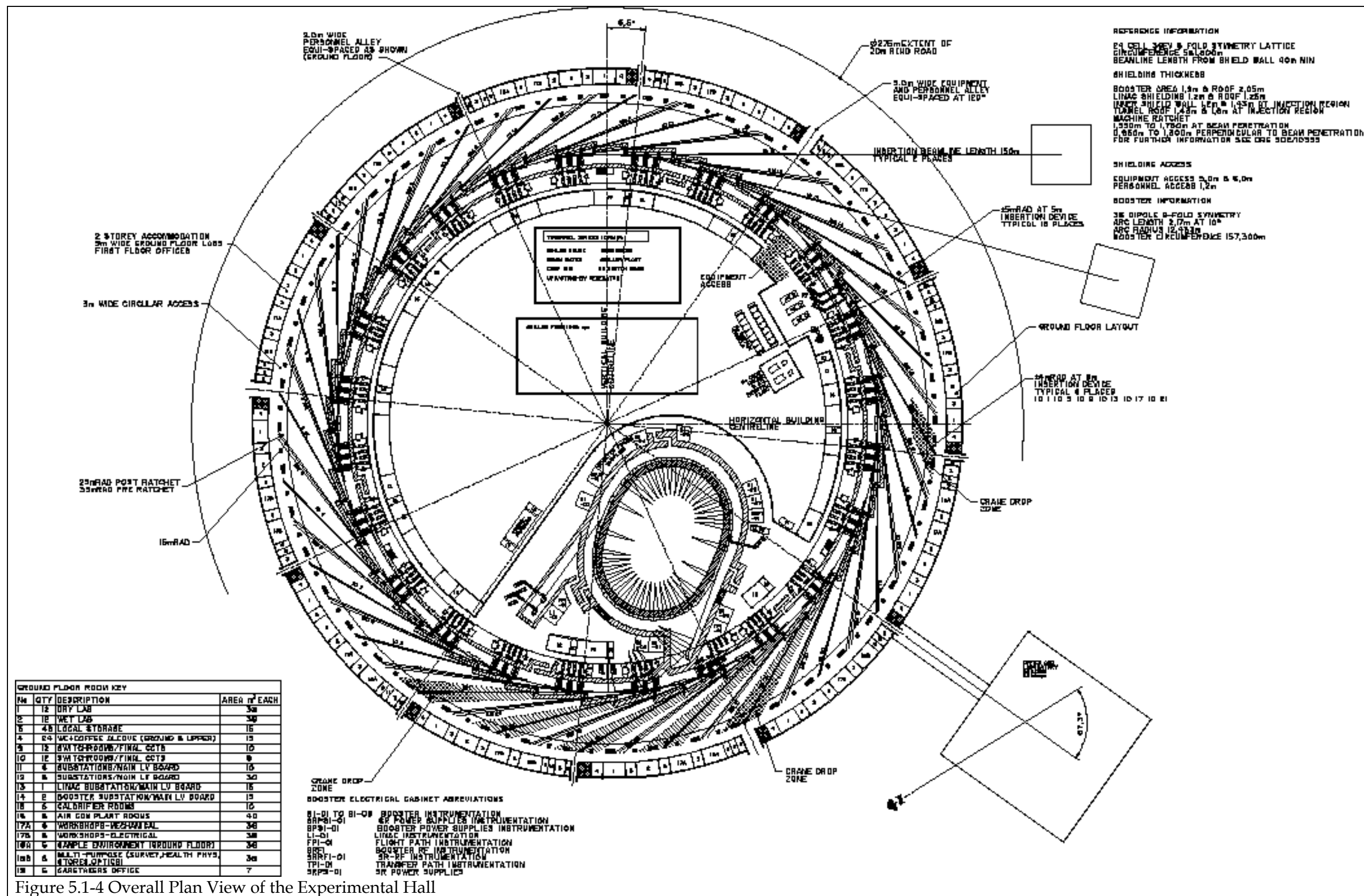


Figure 5.1-4 Overall Plan View of the Experimental Hall

B.1 Beamline Specifications

1.1 INTRODUCTION

This part of the Green Book covers the experimental facilities planned in the first phase of Diamond. These are the beamlines and associated facilities known as the day-one beamlines, which are planned to come into use for research at the formal start of the operation of the DIAMOND facility.

1.2 DAY-ONE BEAMLINES

The DIAMOND project was specified to include an initial complement of 7 beamlines with insertion devices as their source points, and all staff and cost estimates have been based on that specification. For some time the precise specification of the 7 beamlines was not made, to allow a close consultation with the user community so that the scientific uses would be optimum at the time the beamlines came into active use. That consultation has now been completed and an initial suite of beamlines selected.

1.3 SELECTION PROCESS

Broad consultation with the user community was initiated in 2000 by the interim Science Directors, using a web-based process and also discussions with the User Forum and SR staff at Daresbury Laboratory. Distilling the expressions of interest produced 22 possible generic beamlines that were publicised, of which 8 were highlighted to receive detailed consideration by six working groups (three of the lines were assumed to be for PX). During 2001 these working groups then developed the scientific and business cases, in consultation with the wider user communities. Daresbury staff played an important role on each group.

The six cases were then sent to independent international referees for comment and an open meeting was held in September 2001 at Daresbury Laboratory at which each of the candidate beamlines was presented. The Science Advisory Committee then examined the detailed cases, including all comments and presentations, and prioritised the 7 day-one beamlines for recommendation to the interim Board of Directors; however the omitted line was also strongly supported by the SAC for inclusion in the next phase of beamlines to be installed on DIAMOND. The Board confirmed the three PX lines but deferred final decision on the others: as a result design work has continued on all beamlines.

PART B: SCIENCE EXPLOITATION

1.4 SELECTED BEAMLINES

The day-one beamlines prioritised by the SAC are as follows. The numbers allocated to each beamline derive from the original list publicised to the community.

1.4.1 Day-one beamlines

- Beamline 1: A very high energy beamline for materials in extreme conditions,
- Beamline 6: A diffraction beamline for studying materials,
- Beamlines 8, 9, & 10: Three beamlines for macromolecular structures,
- Beamline 13: A microfocus spectroscopy beamline,
- Beamline 14: A soft X-ray beamline for studying nanostructures.

1.4.2 Recommended for the following phase

- Beamline 11: A non-crystalline diffraction beamline for physical and life sciences.

1.4.3 Working groups

A series of working groups has been established to develop the designs of these beamlines and associated facilities with representatives from academia, the funding councils and SRS facility groups. The work of these groups is reported here in Part B.

The beamline descriptions have been updated with the technical work that has been carried out since the original beamline proposals were submitted to the approval process. No attempt has been made to get a uniform presentation for each beamline as they are all at different stages in the requirement and specification process, with the exact scientific use of some beamlines only just decided. However, the descriptions given in Part B should be a good starting point for the more detailed beamline technical designs, which will be led by the principal beamline scientists.

During the initial specification of the experimental facilities it became apparent that there were many common issues. It should be possible to achieve the required specification with a limited number of insertion device types and a chapter is included here on insertion device design. The details (e.g. length, magnetic field, periodicity) of each insertion device will be matched as far as possible to the individual requirements for each beamline. A proper understanding of the effects of errors in the insertion device is required in order to achieve this and this aspect is also covered. The design of the beamline front ends needs to be properly informed about the scientific requirements. However, it is intended to standardise as much as possible on the front end designs and a separate chapter on this subject is included. A number of other common issues are gathered together in a separate chapter. This includes sections on beamline optics, test and development facilities, stability considerations and experimental controls and data handling. Some of these areas are crucial to the success of the facility. It is expected that many of these generic topics will expand

B.1 BEAMLINE SPECIFICATIONS

significantly, while keeping a strong link to the requirements and design of individual experimental facilities.

B.2 Insertion Devices

2.1 INTRODUCTION

DIAMOND is a 3rd generation synchrotron light source that is optimised for the use of Insertion Devices (IDs). Located in the field free spaces of the long straights these IDs will be the primary photon sources for the scientific research programme and the detailed specification and design of each one will be strongly related to its scientific application. At the time this study started, none of the beamlines had been decided in any detail and so it was reasonable to only study generic IDs, which were representative of feasible devices in DIAMOND. Details will be given in this Chapter of these 'generic' studies and also output curves for possible DIAMOND IDs. Towards the end of the design study eight beamlines were allocated to be the first complement of beamlines on DIAMOND (the so-called 'Day 1' beamlines). The requirements for each of these eight beamlines will be discussed and the appropriate ID selected.

There will be two types of ID installed in DIAMOND, undulators and multipole wigglers (MPWs). Both are periodic magnets that will provide intense sources of synchrotron radiation. The undulator is an interference device that provides photons at discrete harmonics and the MPW is essentially a series of alternating bending magnets that provides radiation with the same characteristics as bending magnet radiation but enhanced linearly by the number of poles in the device. Both types of magnet have great potential in DIAMOND.

2.1.1 Electron Beam Properties

The storage ring parameters which are relevant to the computation of the ID radiation are given in Table 2.1-1. The source dimensions for the dipole and the centre of the insertion device straights are given in Table 2.1-2. Note that the dipole beam dimensions correspond to a source point approximately 10 cm from the upstream end of the dipole prior to the insertion device straight.

PART B: SCIENCE EXPLOITATION

Table 2.1-1 Machine parameters used for the synchrotron radiation calculations.

Energy (GeV)	3.0
Beam Current (mA)	300
Electron Beam Emittance (nm rad)	2.7
Assumed Emittance Coupling (%)	1.0
Energy Spread	0.00096
Straight Section Lengths Available for IDs (m)	18 x 5.0 3 x 8.0
Dipole Field (T)	1.4
Standard Dipole Beamline Apertures (mrad)	20.0 x 3.0 (H x V)
Special Dipole Beamline Aperture for CD (mrad)	35.0 x 8.0 (H x V)
Special Dipole Beamline Aperture for Infra-Red (mrad)	35.0 x 30.0 (H x V)
5m Insertion Device Straight Beamline Apertures (mrad)	10.0 x 1.0 (H x V)
8m Insertion Device Straight Beamline Apertures (mrad)	8.0 x 0.9 (H x V)
Vertical Beam Stay Clear over central 2m of 5m Straight (mm)	7.0
Vertical Beam Stay Clear over Full 5m of 5m Straight (mm)	12.0
Vertical Beam Stay Clear over Full 8m of 8m Straight (mm)	17.0

Table 2.1-2 Electron beam (rms) dimensions at the possible source points.

	σ_x (μm)	σ_y (μm)	$\sigma_{x'}$ (μrad)	$\sigma_{y'}$ (μrad)
Dipole	53.7	23.7	81.4	2.6
Centre of 5m Straight	122.9	6.4	24.2	4.2
Centre of 8m Straight	178.4	12.6	16.5	2.2

2.1.2 Possible Straight Layouts

There are 2 types of straight in the DIAMOND storage ring, one of 5 m and one of 8 m. Both are sufficiently long that more than one ID can easily be put into each straight. For instance, in the 5 m straight two IDs could be installed with a small deflection magnet between so that the two sources of radiation can be separated by an angle (probably of the order of 1 mrad). Such an arrangement could be used to provide two independent experimental stations or perhaps two light sources for one experiment, maybe with different polarization orientations. Of course, there is even more flexibility in the 8 m straight for multiple insertion devices.

Since the beta functions are symmetric in the straight sections, with a minimum in the centre, if a small magnet gap ID is required then it must be installed in the centre of the straight to maintain the best possible lifetime. For instance, in the 5 m straights an ID that only uses the central 2 m has a vertical beam stay clear of 7 mm, whereas an ID that is installed at the end of the straight would need a vertical beam stay clear of 12 mm. This is particularly important for undulators which want to reach photon energies beyond about 10 keV.

2.2 MULTIPOLE WIGGLER SOURCES

Multipole wigglers (MPWs) are extremely useful sources of radiation on DIAMOND, especially above about 20 keV, when compared with the alternative undulator sources. They will provide high flux levels over a wide energy range and with a smooth spectrum. Traditionally MPWs have been made from permanent magnets but there has recently been a renewed interest in superconducting devices [1, 2]. We have modelled a generic superconducting MPW for DIAMOND to examine the advantages that such a device might have over a permanent magnet solution.

2.2.1 Generic Superconducting MPW Design

A superconducting MPW has been modelled using the RADIA magnet design software [3]. The design is based upon one proposed for the MAX II storage ring [1] which consists of the basic building block of a superconducting coil wound around an iron pole with an iron return yoke. A view of the modelled structure, which consisted of 7 full strength poles and 2 lower field end poles, is given in Figure 2.2-1 and an example field along the electron axis is plotted in Figure 2.2-2 [4]. The dimensions of the MPW were altered whilst maintaining the same proportions to see how the peak field altered as a function of period. The result is given in Figure 2.2-3.

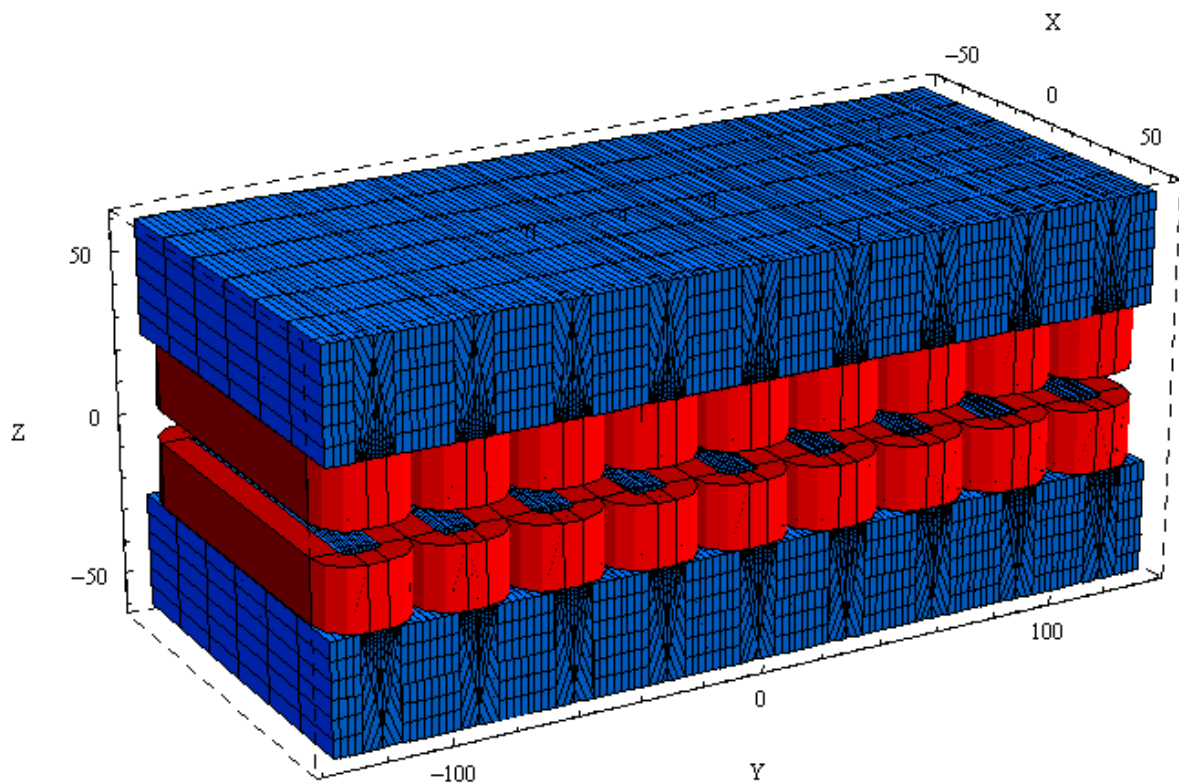


Figure 2.2-1 View of the superconducting MPW magnet model. The dimensions are given in mm.

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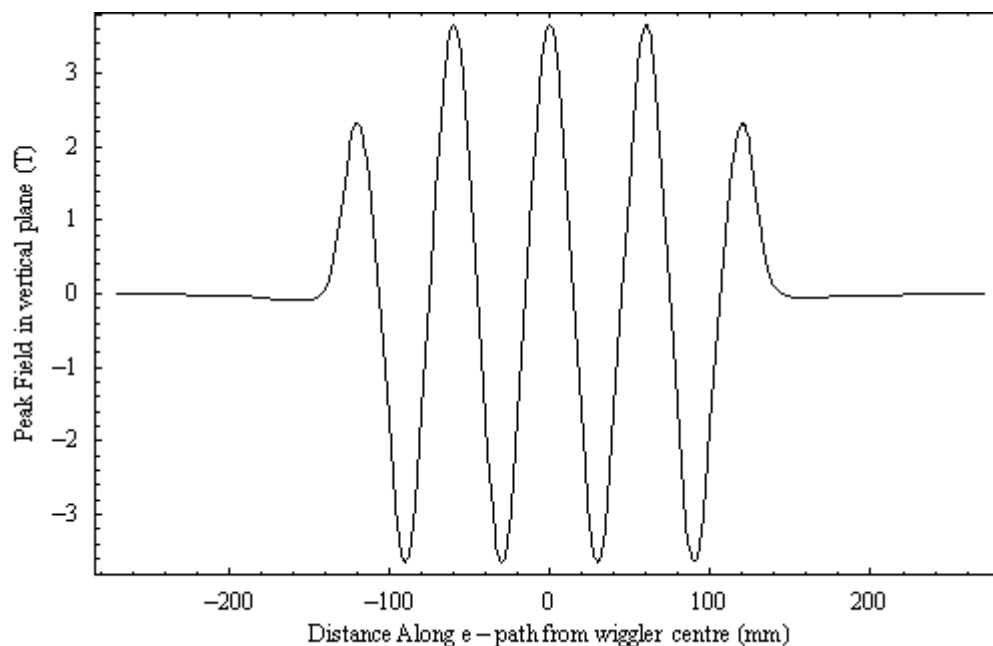


Figure 2.2-2 Example magnetic field profile along the electron beam axis.

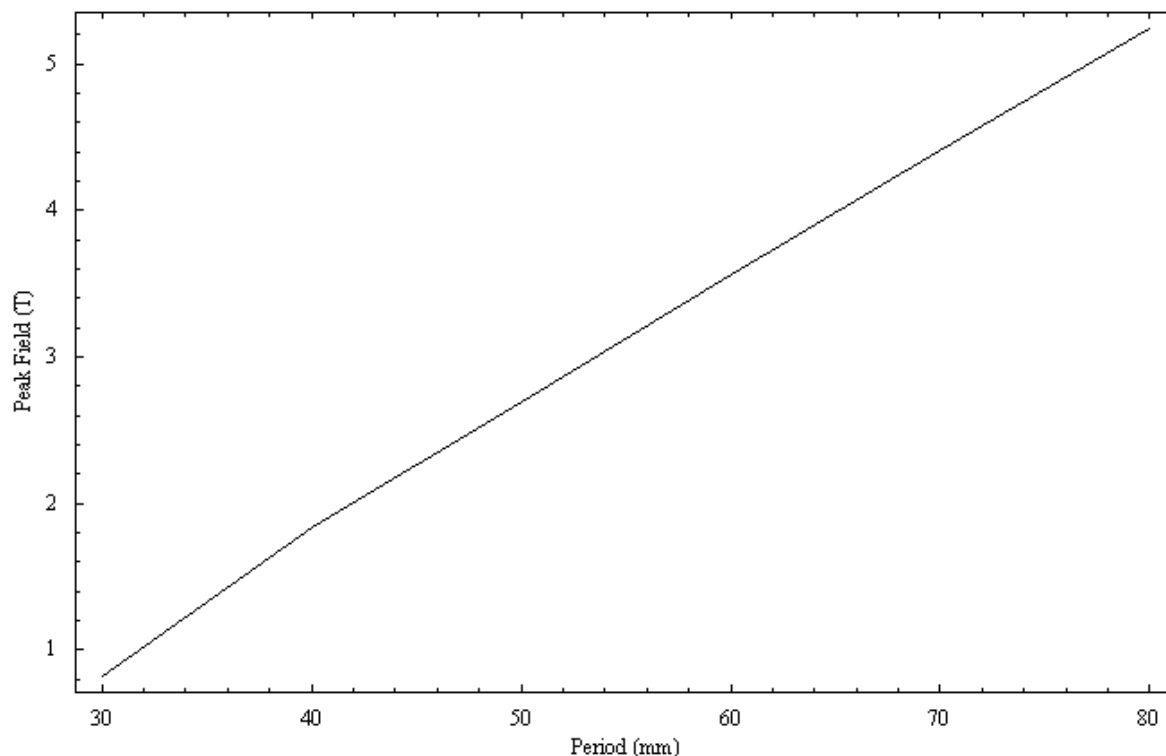


Figure 2.2-3 Variation in peak field for a range of periods between 30 and 80 mm.

2.2.2 SR Output from Potential MPWs

To calculate the possible peak magnetic fields that can be generated by a permanent magnet MPW it is usual to use the empirical equation [5]

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$$B_0 = 3.44 * \exp\left(-\frac{g}{\lambda}\left(5.08 - 1.54 \frac{g}{\lambda}\right)\right)$$

where g is the magnet gap and λ is the magnet period. However, this equation is only valid over the range $0.07 < g/\lambda < 0.7$ which corresponds to a peak field of only about 2.4 T. Recently, stronger magnet materials and more highly optimised designs have been used to generate fields as high as 3 T with permanent magnets [6]. A magnet model which has been developed for the design of a 2.4 T permanent magnet MPW for the SRS [7] has been used to generate a new equation which covers a higher magnetic field range with realistic gap and period values. The new equation, which is valid over the range $0.04 < g/\lambda < 0.2$, is given by [8]

$$B_0 = 4.3 * \exp\left(-6.45 \frac{g}{\lambda} + \left(\frac{g}{\lambda}\right)^2\right)$$

and this now reaches a peak field of about 3.3 T.

Three example MPWs are presented in Table 2.2-1. The first is a moderate field permanent magnet, the second is a high field permanent magnet and the third is a high field superconducting magnet. The lengths of these devices reduces as the field increases in an attempt to keep the total power produced by these magnets roughly constant. More comments on the power levels will be made in section 2.2.3. The flux and brightness for these three MPWs is given in Figure 2.2-4 and Figure 2.2-5.

Table 2.2-1 Possible MPWs for the DIAMOND storage ring.

Technology	B _{Max} (T)	K _{Max}	Period (mm)	N _{Periods}	Length (m)	Magnet Gap (mm)
PM	1.6	14.9	100	50	5.0	15.0
PM	2.5	28.0	120	16	2.0	10.0
SC	3.5	19.6	60	16	1.0	10.0

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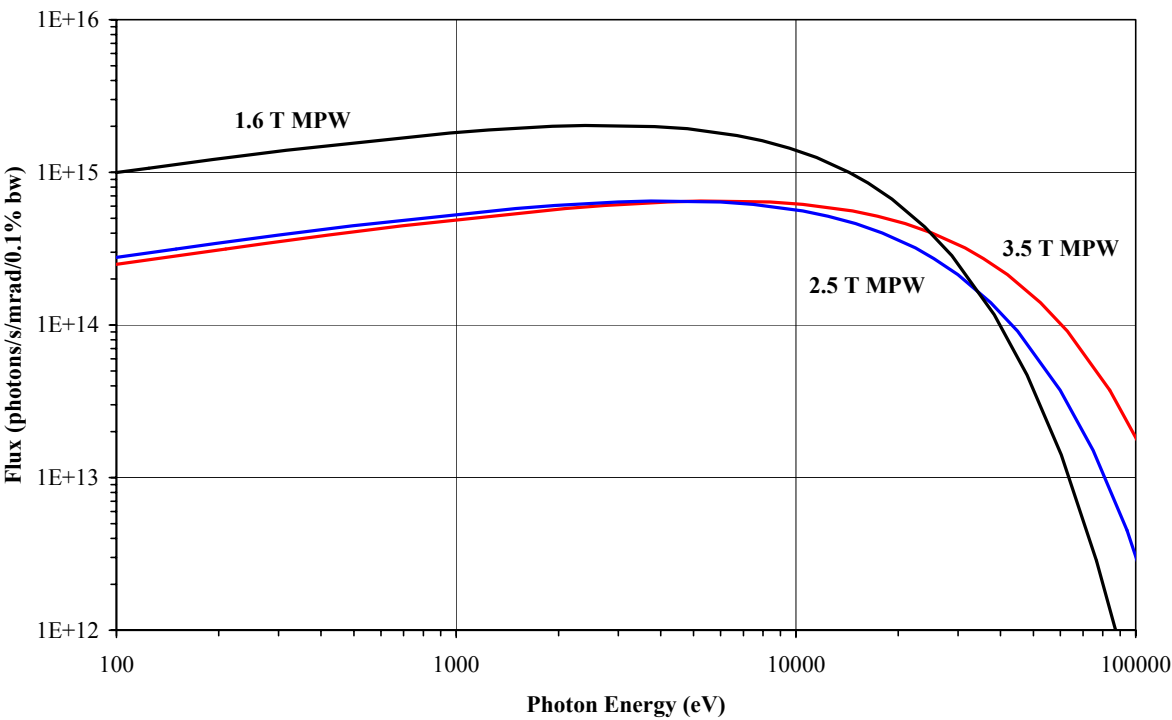


Figure 2.2-4 Spectral flux for the three MPWs of Table 2.2-1.

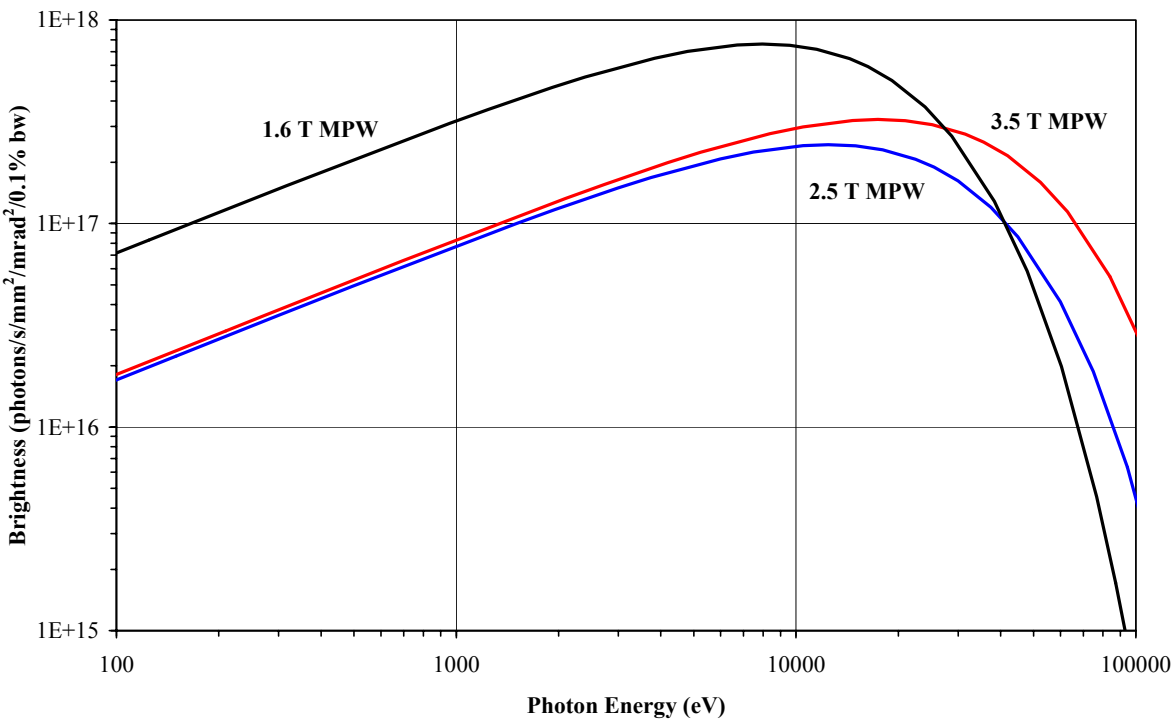


Figure 2.2-5 Spectral brightness for the three MPWs of Table 2.2-1 installed in a 5 m straight.

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2.2.3 Power and Power Density from MPWs

The total power and power densities from MPWs on DIAMOND is cause for some concern. In principal, enormous power levels can be generated but they are not feasible at present in terms of the beamline front end handling such large power levels and also the beamline optics becoming damaged or distorted. The lengths of the MPWs presented in Table 2.2-1 were deliberately altered to keep the total power levels to feasible values. One issue which must be remembered is that although DIAMOND will initially run at 300 mA it may be upgraded in the future to 500 mA. The power output from the three example MPWs is tabulated in Table 2.2-2 and shown as a function of horizontal and vertical angle in Figure 2.2-6 and Figure 2.2-7.

Table 2.2-2 Total power, on axis power density and full horizontal fan width for three example MPWs with a beam current of 300 mA.

B_{Max} (T)	Length (m)	Total Power (kW)	Power Density (kW/mrad ²)	Fan Width (mrad)
1.6	5.0	21.9	21.1	5.1
2.5	2.0	21.4	11.0	9.5
3.5	1.0	20.9	15.4	6.7

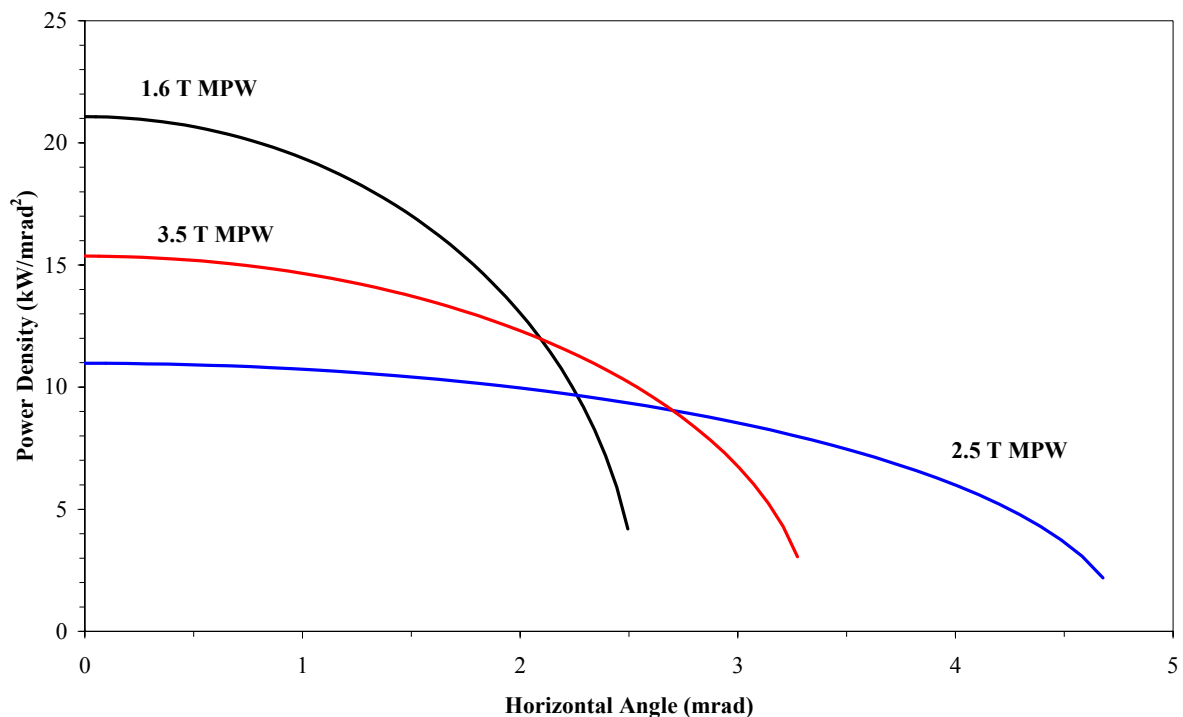


Figure 2.2-6 Power density as a function of horizontal angle for the three example MPWs (the vertical angle is zero). A beam current of 300 mA has been assumed.

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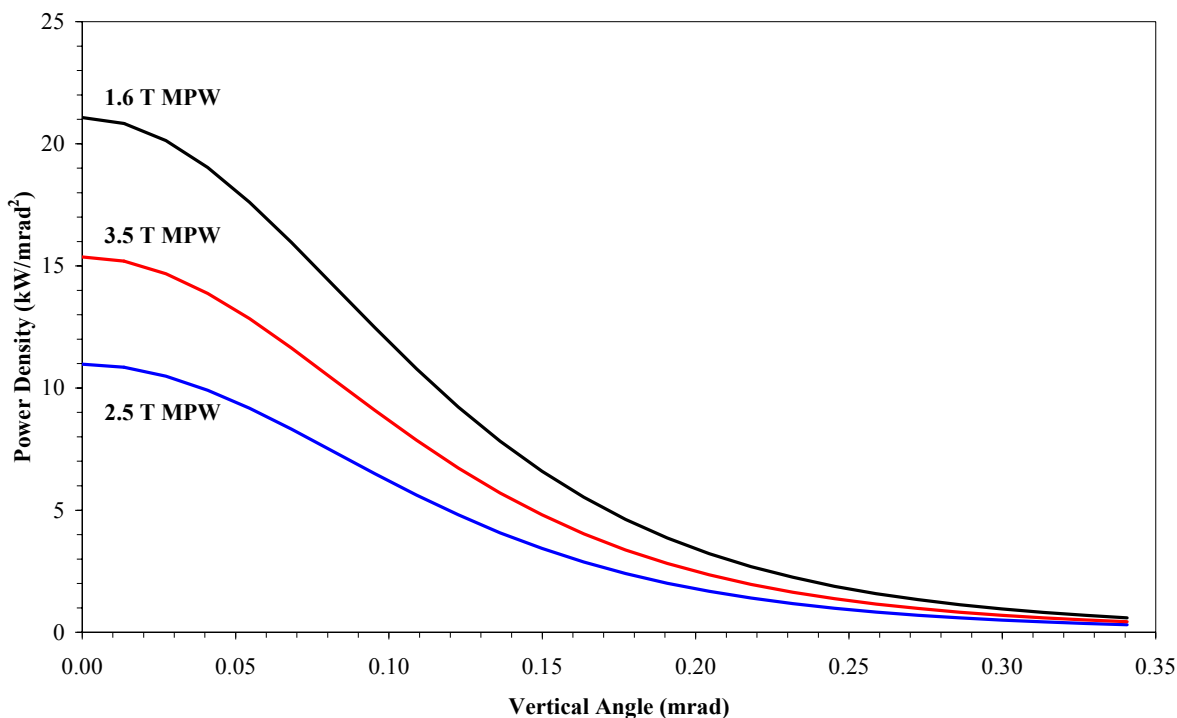


Figure 2.2-7 Power density as a function of vertical angle for the three example MPWs (the horizontal angle is zero). A beam current of 300 mA has been assumed.

2.2.4 The Cross-over Between Undulators and MPWs

It is not always obvious whether a MPW should be used as the light source for a beamline or an undulator. In DIAMOND at photon energies in the range ~ 100 eV to ~ 10 keV an undulator generally outperforms a MPW. However, beamlines which demand higher energies than this will seriously consider using a MPW. An example comparison between a MPW and an undulator is given in Figure 2.2-8 where the flux emitted by the MPW into a small, $100 \mu\text{rad} \times 25 \mu\text{rad}$ aperture has been calculated. This aperture is approximately equivalent to the central cone size of the undulator. Therefore if the aperture were to be increased then the MPW would provide greater flux whereas the undulator curve would not change. From this graph it appears that the cross-over between undulators and MPWs is at approximately 25 keV. However, the undulator flux shown is for an ideal device with no degradation included due to magnet errors or electron beam effects. Of course, the choice between an undulator and a MPW depends upon far more than just flux arguments but it is useful to have an idea of the relative photon outputs of each device.

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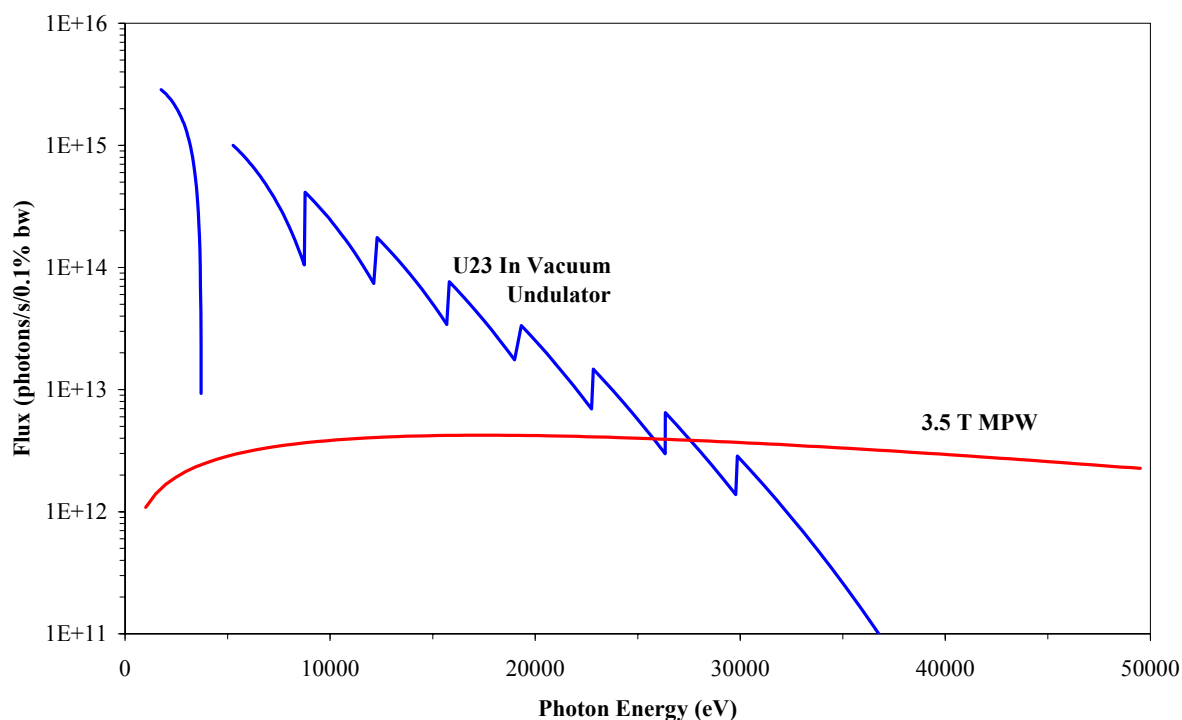


Figure 2.2-8 Photon flux in the central cone of a representative undulator and integrated over a $100\ \mu\text{rad} \times 25\ \mu\text{rad}$ aperture for a MPW.

2.3 DIPOLE RADIATION

Although the primary source of synchrotron radiation from DIAMOND will be the insertion devices, the dipoles will also provide extremely useful radiation. Not all of the dipoles can be used for beamlines because of the floor space limitations in the experimental hall. However, every dipole prior to an ID straight will be available for future beamlines potentially providing 24 extra sources of extremely powerful light. The parameters that are needed for the calculation of the dipole radiation are given in Table 2.1-1 and Table 2.1-2.

The standard dipole front end will allow $20 \times 3\ \text{mrad}$ (horizontal $\times$ vertical) of light to pass through to the beamline. This will be suitable for beamlines that require photon energies above about 100 eV but beamlines which want to use lower energies than this, for infra-red experiments for example, will use a special dipole chamber design that provides a greater aperture to be accepted, especially in the vertical plane.

2.3.1 SR Output from Dipoles

The flux and brightness for the DIAMOND dipole is given in Figure 2.3-1 and Figure 2.3-2. A summary of the relevant dipole parameters are given in Table 2.3-1. Note that the standard dipole takes radiation from between 5 and 25 mrad from the entrance to the dipole.

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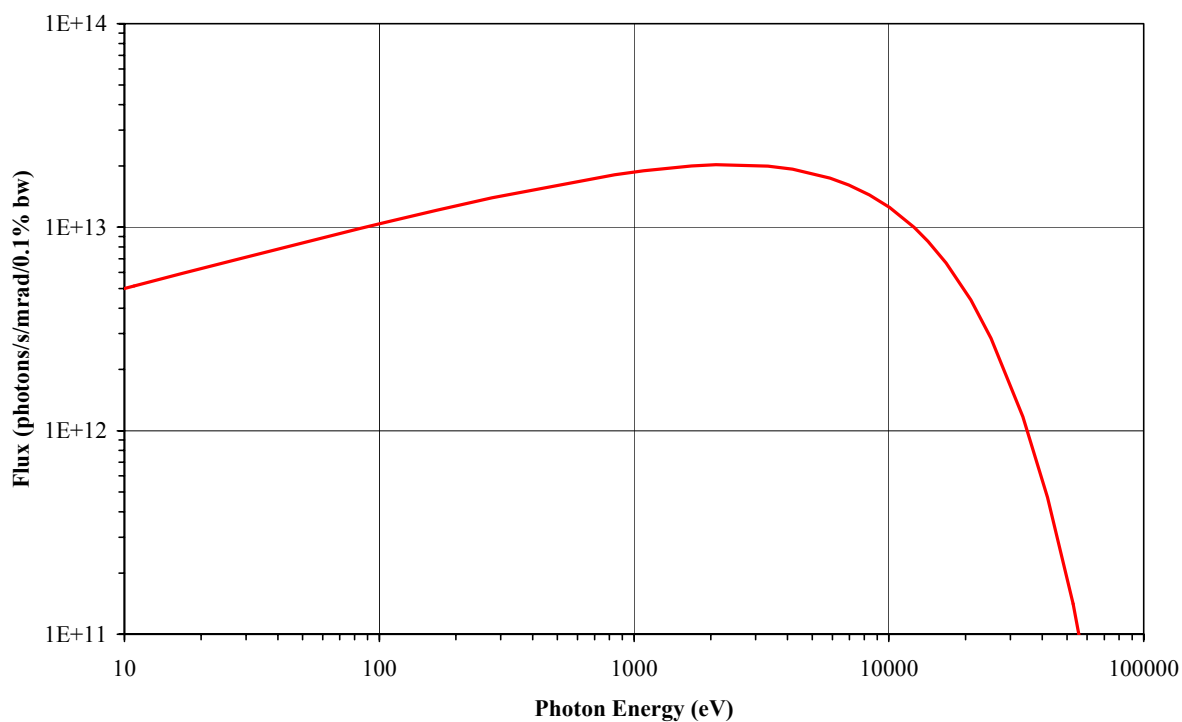


Figure 2.3-1 Spectral flux for the dipole per horizontal mrad.

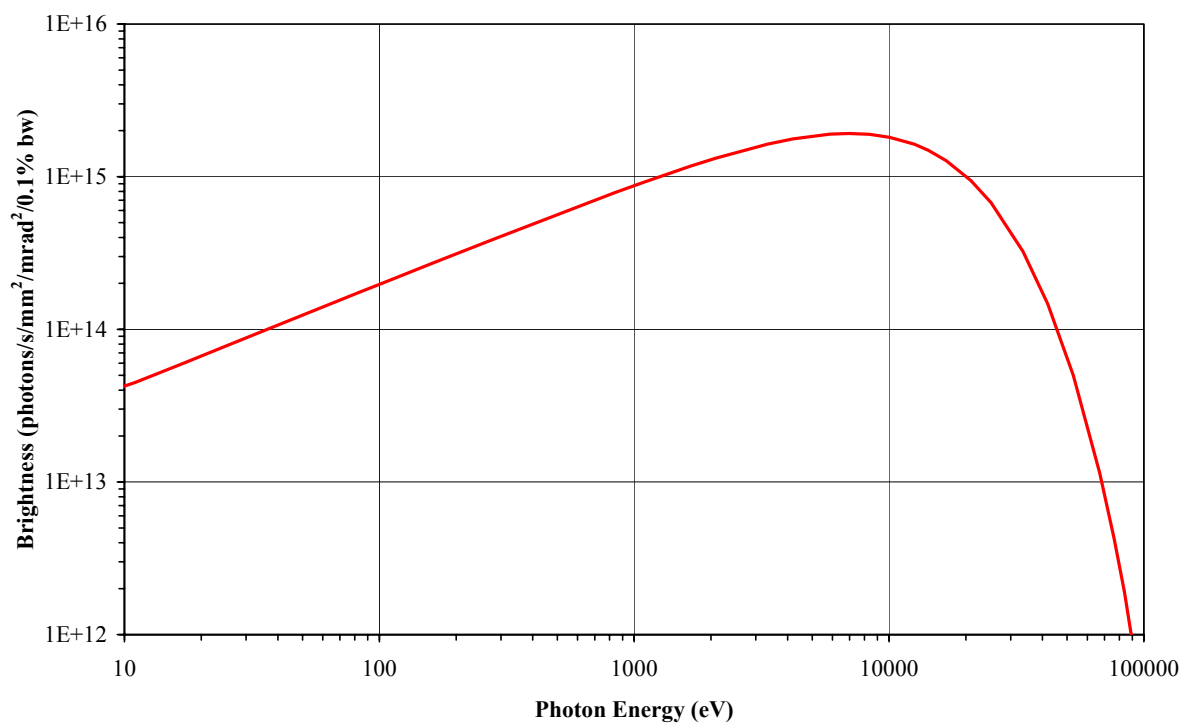


Figure 2.3-2 Spectral brightness for the dipole.

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Table 2.3-1 Synchrotron radiation related parameters for the dipole for a 300 mA beam current.

Dipole Field (T)	1.4
Bending Radius (m)	7.148
Number of Dipoles	48
Critical Energy (keV)	8.39
Dipole Power per Horiz Angle (W/mrad)	47.9
On Axis Power Density (W/mrad ²)	184.4

2.3.2 Edge Radiation from the Dipoles

The synchrotron radiation that is generated at the longitudinal ends of a dipole has different properties from that which is produced in a uniform field. This so-called edge radiation is created in a boundary region where the electron acceleration is changing between zero and uniform. At long wavelengths the synchrotron radiation properties can be significantly altered and this is why it is of particular interest to infrared (IR) users of synchrotron light sources [9, 10]. In particular, the brightness of the IR radiation is enhanced which can be beneficial for some experiments. A brief study has been made of the edge radiation produced by the DIAMOND dipoles.

The dipole magnetic field has been assumed to rise from zero to 1.4 T over a distance of 10 cm and the two dipoles in the achromat to be separated by 6 m. The IR synchrotron radiation has been calculated with such a dipole model using SRW [11] which correctly calculates near field effects which are important in this case. It is important that both dipoles in the achromat are included because the observer will generally see the falling edge of one and the rising edge of the other. Interference effects occur between these two sources and they have also been included in the calculations.

The flux density observed 1.5 m from the edge of a dipole at a wavelength of 10 μm is plotted in Figure 2.3-3. When the upstream dipole is included in the model the flux density graph alters because of interference effects (Figure 2.3-4).

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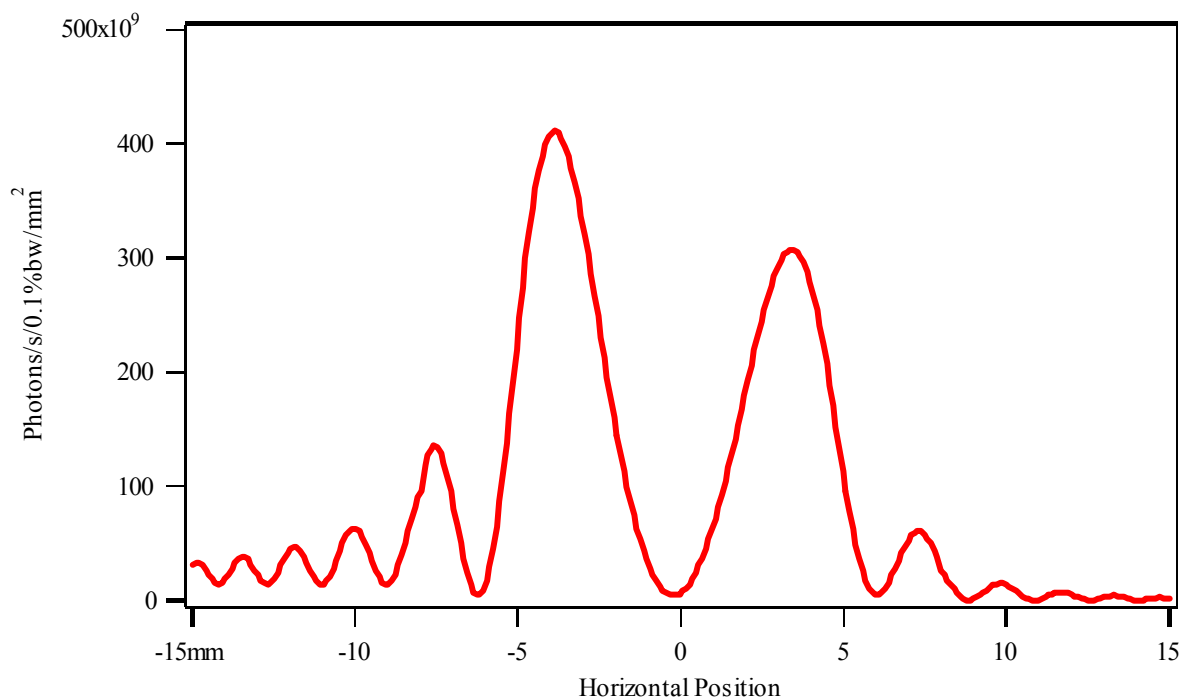


Figure 2.3-3 Flux density at 10 μm produced by a single dipole observed 1.5 m from the dipole edge.

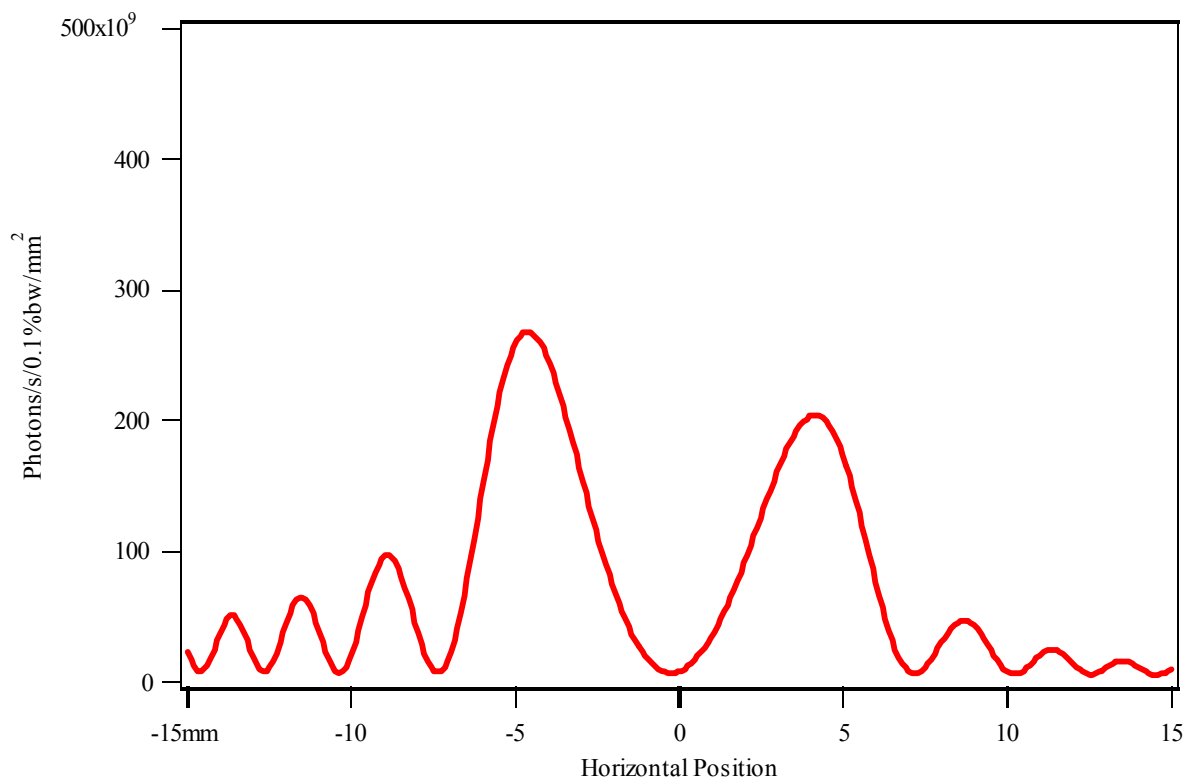


Figure 2.3-4 Flux density at 10 μm produced by two dipoles separated by 6 m observed 1.5 m from the downstream dipole edge.

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There is also considerable structure in the edge radiation in the vertical plane. The flux density produced on the achromat straight axis is compared with that produced by a uniform dipole field in Figure 2.3-5. In fact the edge radiation is largely emitted into a hollow cone of radius $\sim 1/\gamma$ as can be seen in the image plot of Figure 2.3-6. A comparison of the total flux emitted into different angular acceptances has been made for 10 μm radiation (Figure 2.3-7 and Figure 2.3-8). It can be seen that the edge radiation gives significantly higher flux into the smaller apertures but as the apertures increase the difference reduces. The aperture that is presently being assumed for the exploitation of IR on DIAMOND is 35×30 mrad (H $\times$ V).

Apart from the increased brightness of the IR radiation, another advantage of edge radiation is that the heat loads on the optics due to high energy radiation are reduced. However, the polarization properties are not so favourable and the oscillating intensity profile could also be a problem. It must also be remembered that all magnet 'edges' can generate this radiation so other magnets in the achromat straight (quadrupoles, corrector dipoles and sextupoles) will contribute to some extent to the radiation observed.

A workshop was held in September 2000 that considered the use of IR on DIAMOND [12]. The use of edge radiation was discussed but it was decided that the radiation from a standard uniform bending magnet was the preferred option at that time.

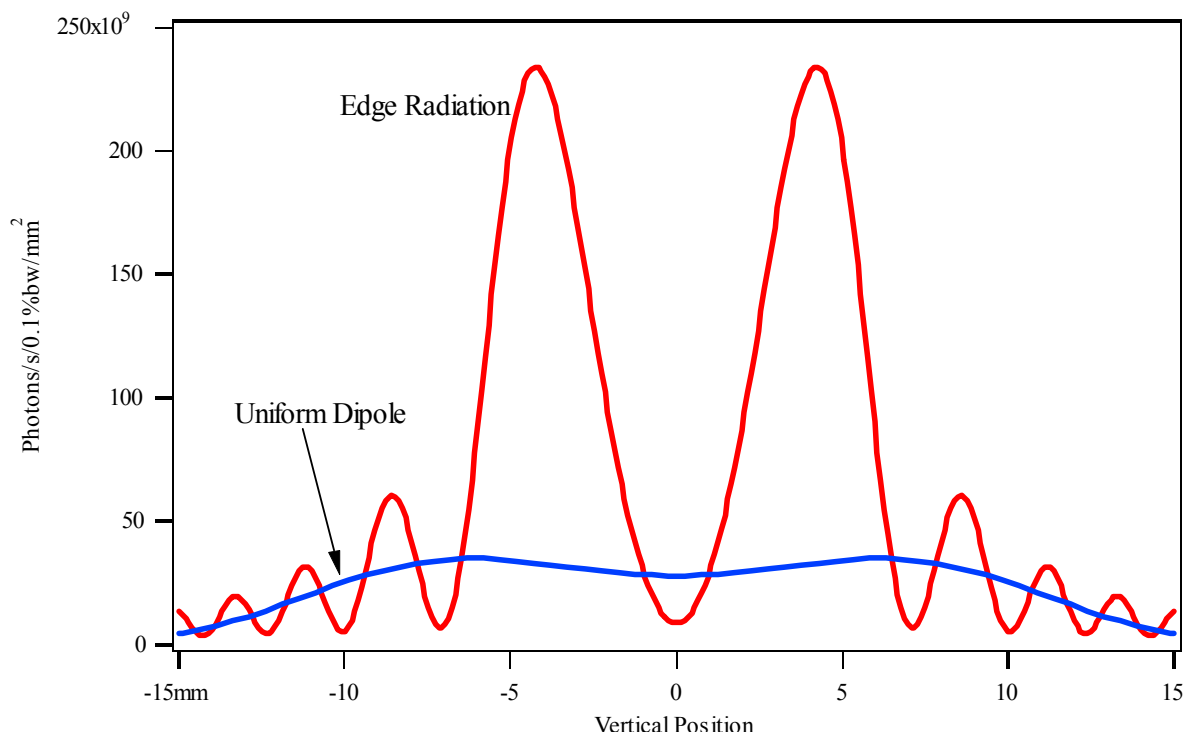


Figure 2.3-5 On axis flux density at 10 μm in the vertical plane for two dipole edges compared with that produced by a standard uniform dipole field, observed 1.5 m from the downstream dipole edge.

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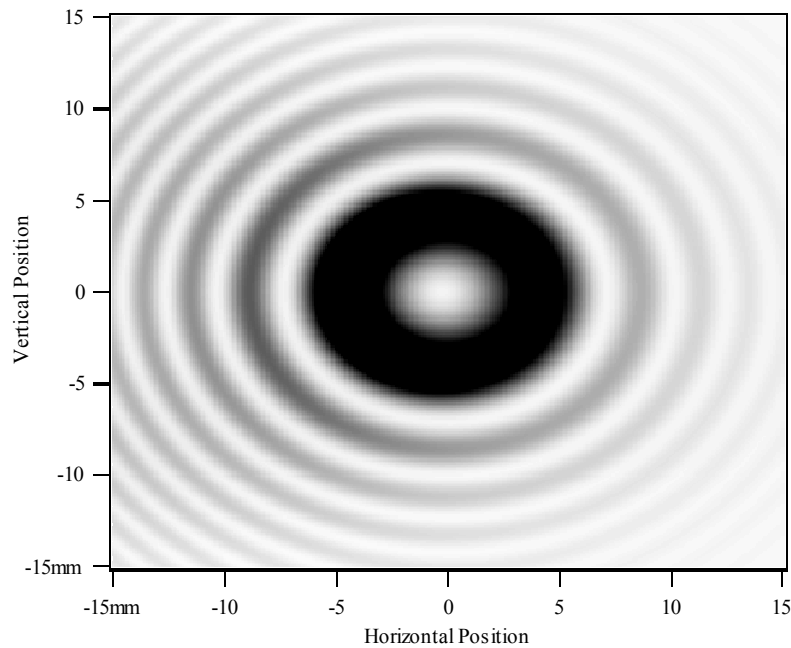


Figure 2.3-6 Flux density image at 10 μm of edge radiation from two dipoles separated by 6 m.

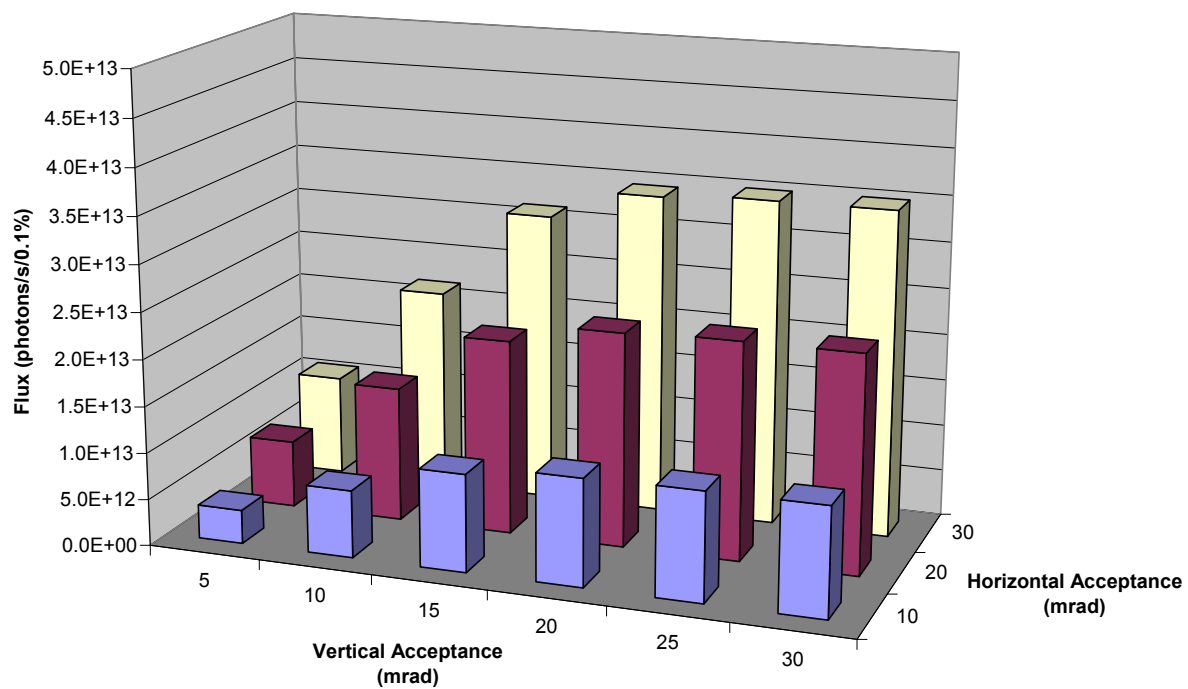


Figure 2.3-7 Integrated flux at 10 μm wavelength for a uniform dipole as a function of horizontal and vertical aperture.

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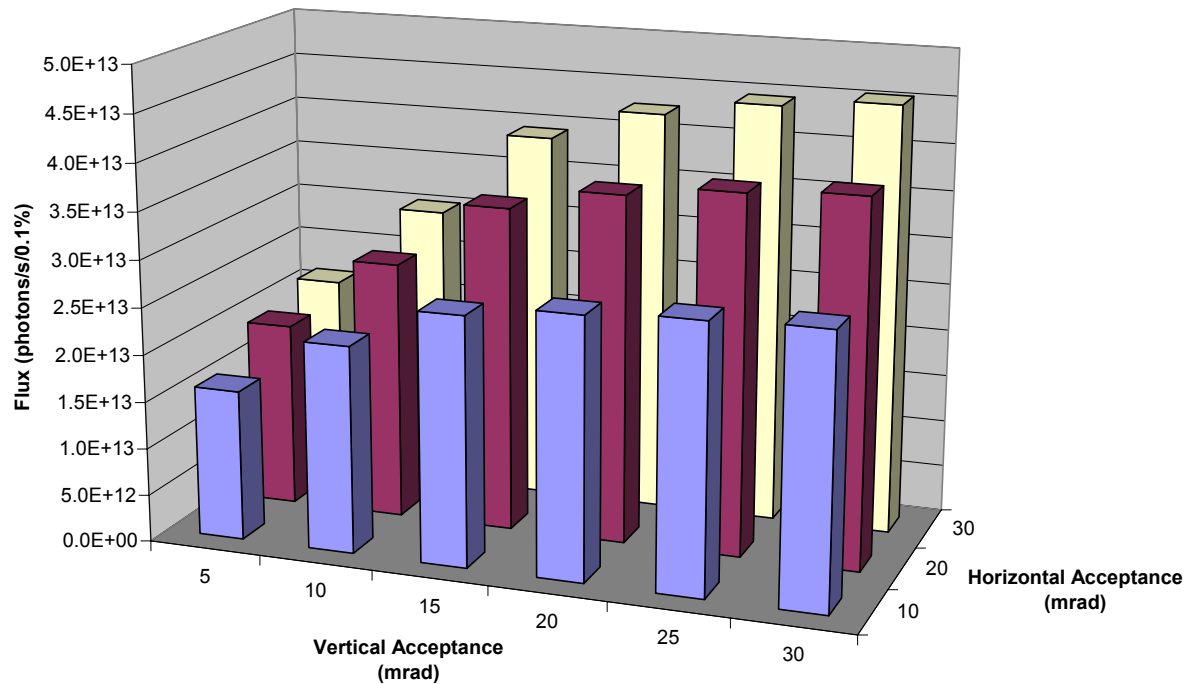


Figure 2.3-8 Integrated flux at 10 μm wavelength for edge radiation as a function of horizontal and vertical aperture.

2.4 UNDULATOR SOURCES

Undulators will be the primary source of radiation for the majority of the insertion device based beamlines. They will provide extremely bright light over the photon energy range of approximately ~ 100 eV to ~ 10 keV. The undulators will be predominantly permanent magnet based devices and so a generic design of a possible device has been carried out during the design study.

One of the key photon energy regions for DIAMOND is between about 5 and 20 keV. The preferred ID for this region is the undulator because of the higher brightness of the source and the lower overall power levels compared with MPWs. However, for DIAMOND to reach beyond about 15 keV necessitates the use of high harmonics in the undulator spectrum ($\sim 7^{\text{th}}$ to 15^{th} harmonic). It is well known that undulator technology has improved significantly over recent years with the extensive development of block sorting and magnet shimming to such an extent that higher harmonics are observable. However, it is unusual for a light source to be designed to rely on these higher harmonics in order to meet the needs of the beamlines. To understand the practical implications of exploiting harmonics well beyond the 5^{th} a study has been carried out to calculate the spectral output for undulators with realistic errors and then to pass this output into an optical ray tracing code to assess how it interacts with the beamline design.

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2.4.2 SR Output from Potential Undulators

Five undulators have been selected as example devices that between them cover the photon energy range between about 30 eV and 20 keV. The main parameters for these undulators are given in Table 2.4-1. Note that the 80 and 200 mm period devices have had their K values restricted to a maximum of 5 to limit the power generated by them. Also the 200 mm period device has been modelled in an 8 m straight so that the number of periods is kept high. The flux and brightness for all of these undulators is plotted in Figure 2.4-3 and Figure 2.4-4. Brightness levels beyond 10^{19} are achieved over the range 100 eV to 15 keV and levels well beyond 10^{20} are reached over a more restricted range.

Table 2.4-1 Possible undulators for the DIAMOND storage ring.

Name	B _{Max} (T)	K _{Max}	Period (mm)	N _{Periods}	Length (m)	Magnet Gap (mm)
U24	0.60	1.36	24	82	2	10
U36	0.60	2.03	36	137	5	15
U48	0.84	3.76	48	103	5	15
U80	0.67	5.00	80	62	5	15
U200	0.27	5.00	200	39	8	20

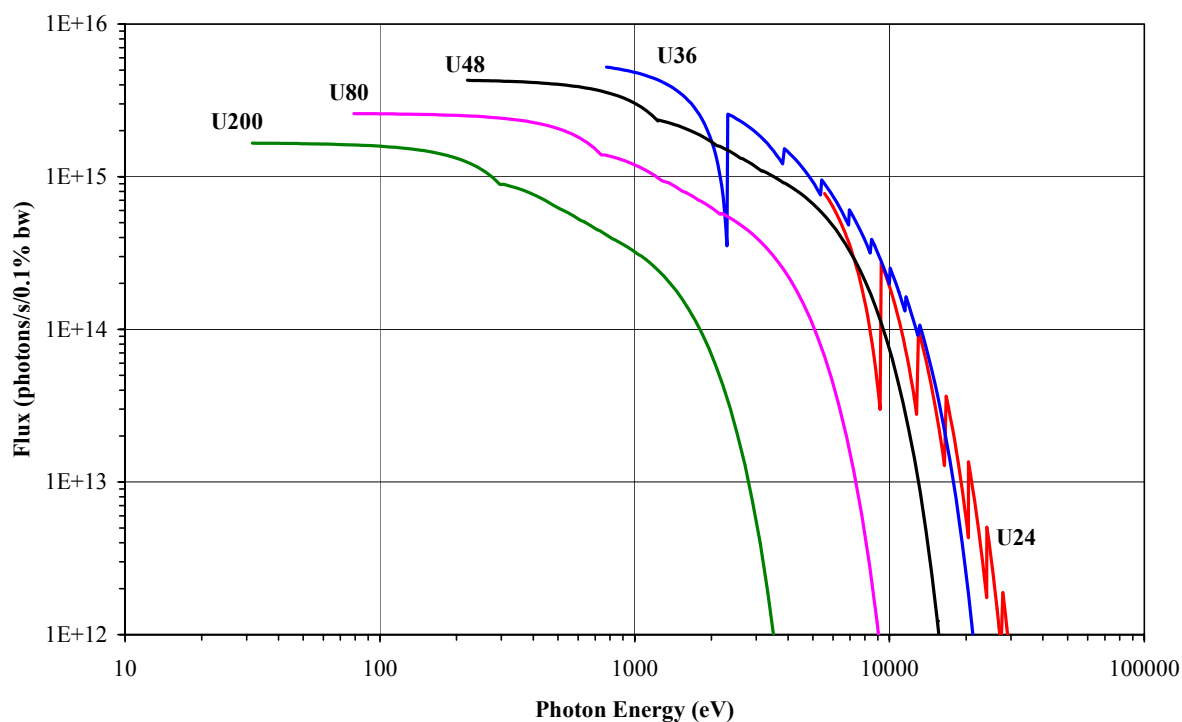


Figure 2.4-3 Spectral flux for the 5 undulators of Table 2.4-1.

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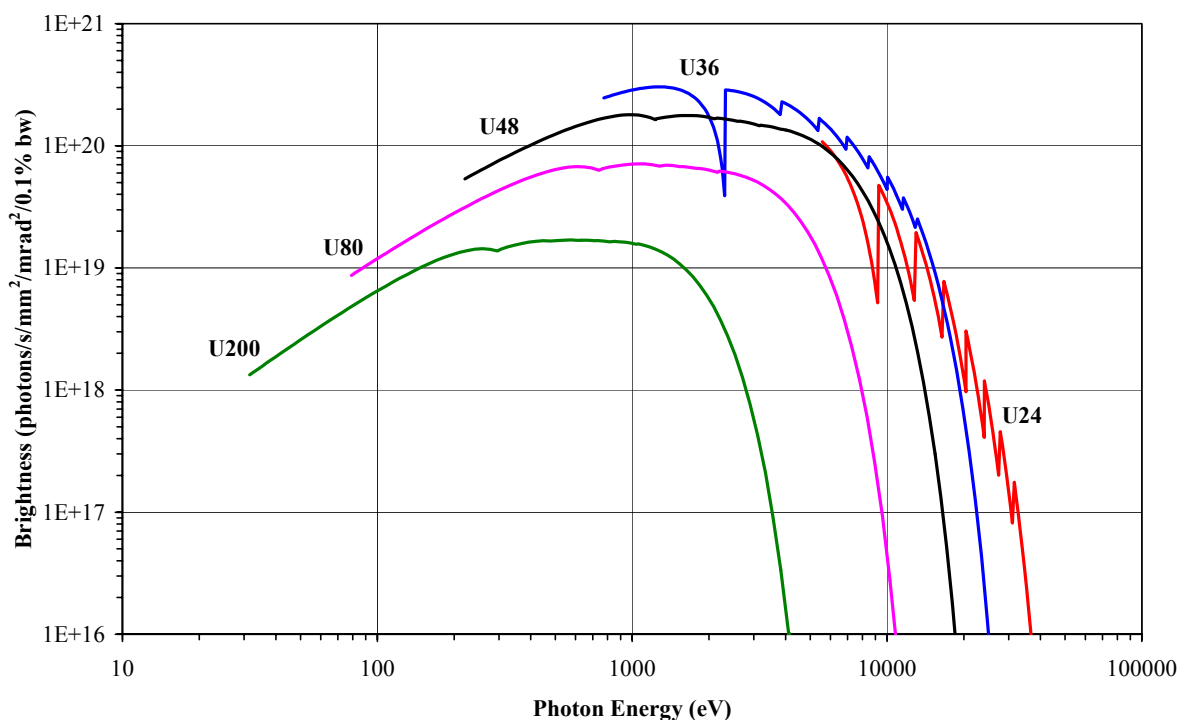


Figure 2.4-4 Spectral brightness for the 5 undulators of Table 2.4-1.

2.4.3 Undulators for Variable Polarization

A rapid area of growth in the field of IDs in recent years has been the development of variable polarization undulators. The use of variable polarization has been an area of considerable interest for many members of the UK SR user community and it is likely that several of these devices will eventually be installed in DIAMOND. Since these are intrinsically more complicated IDs than standard planar undulators it was decided that it would be useful to develop a flexible generic design to assess the potential of such a device.

There are several possible insertion device sources of variable polarization. A planar helical type of undulator, of which there are several variations [14], has been studied as these matched the initial specification for potential beamlines put forward by the user community. The most common planar helical design is the APPLE-2 variation developed in Japan [15] and so this was selected for the generic ID design.

The undulator consists of four conventional arrays of permanent magnet (Figure 2.4-5), two below the beam and two above. The relative strengths of the horizontal and vertical magnetic fields are varied by sliding the arrays with respect to each other. The upper right and lower left arrays move together with respect to the other two. The vertical magnetic gap is also varied as in a conventional undulator to tune the device to the required photon energy.

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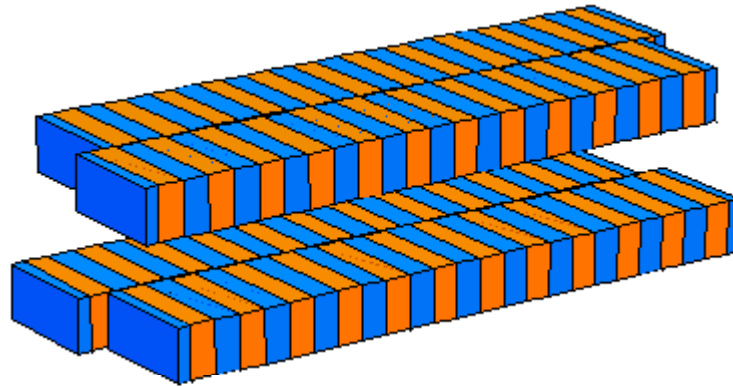


Figure 2.4-5 Schematic view of APPLE undulator arrays. Different colours are used to highlight the individual permanent magnet blocks.

The magnet design software RADIA [3] has been used to calculate the magnetic fields that can be generated by such an undulator. Some basic assumptions have been made so that fair comparisons can be made. Firstly, each array is assumed to have four blocks per period with the height of each block being half the period. The horizontal gap between the arrays that slide with respect to one another has been fixed at 1 mm. A remanent field of 1.25 T for the permanent magnet material has also been assumed. Using these basic assumptions the period has been varied and the magnetic field for the circular polarization mode ($B_{x_{\text{peak}}} = B_{y_{\text{peak}}}$) calculated. The results are shown in Figure 2.4-6 along with the corresponding photon energy for the circular polarization mode.

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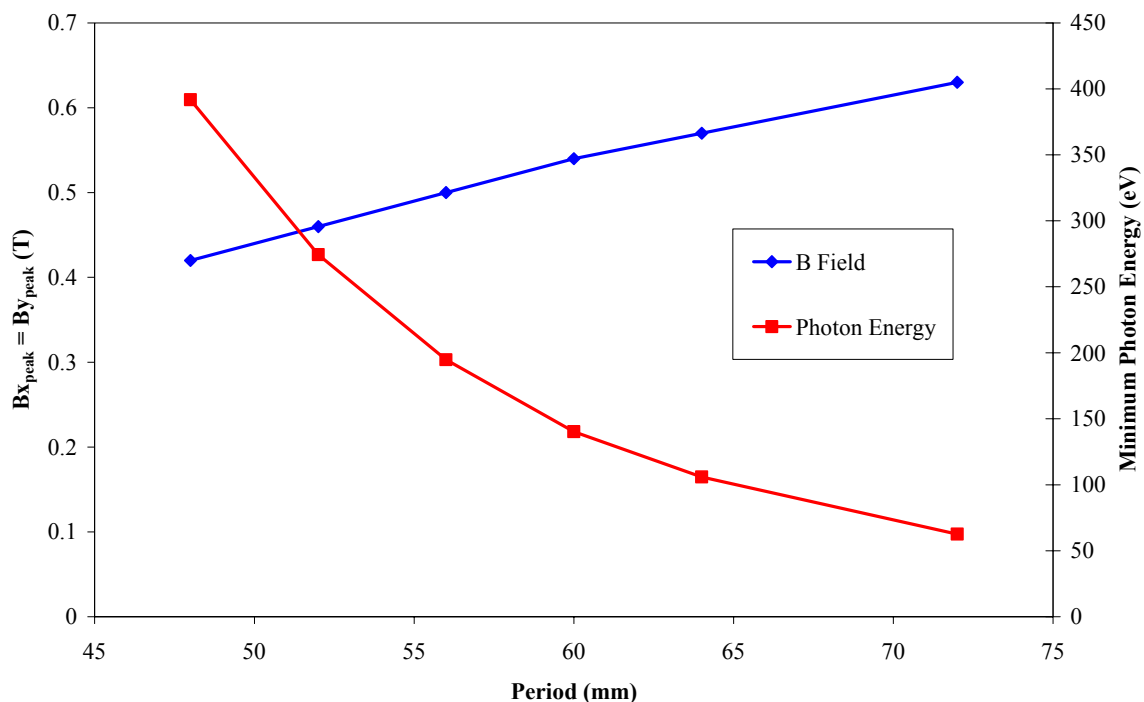


Figure 2.4-6 Magnetic field calculated for the circular polarization condition as a function of undulator period and the corresponding photon energy.

A period of 60 mm was chosen for further study and Figure 2.4-7 shows the calculated magnetic fields on axis for the undulator in the circular polarization mode. A simple half length block end termination was assumed for this model. Figure 2.4-8 shows the trajectory of a 3 GeV electron starting outside the undulator and initially travelling along the axis.

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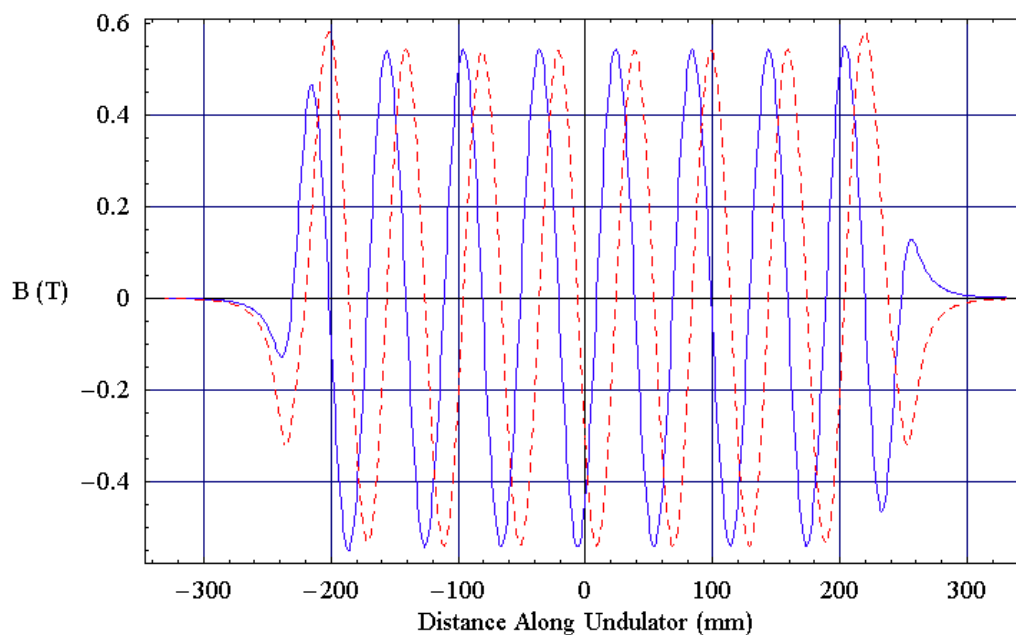


Figure 2.4-7 The calculated magnetic fields on axis for a seven period model of the undulator in the circular polarization mode. The solid line is the horizontal field and the dashed line is the vertical field.

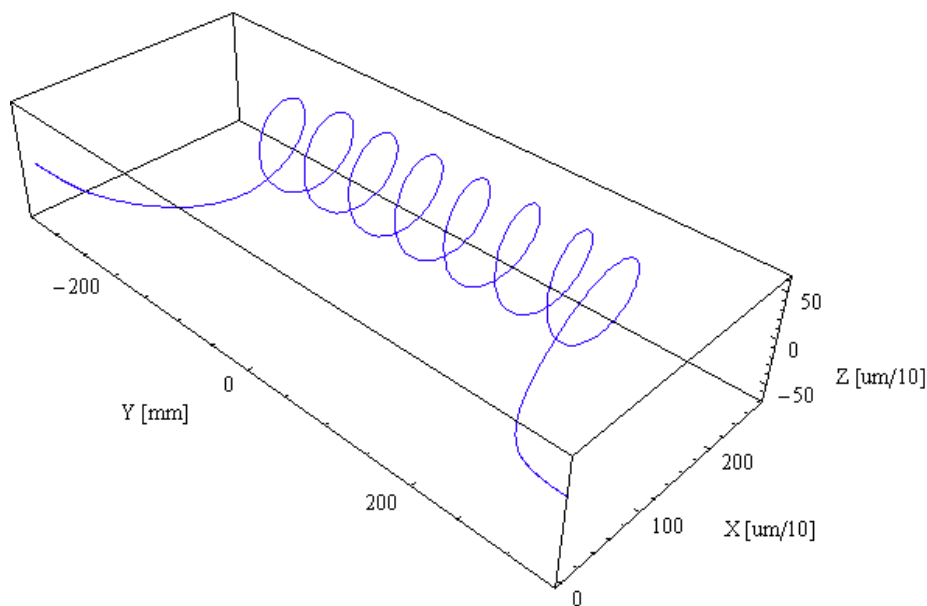


Figure 2.4-8 Electron trajectory along the undulator in circular polarization mode. The X and Z axes are in units of $0.1 \mu\text{m}$.

In order to specify the mechanical system for the undulator it is useful to understand the changes that are required to the gap for a particular photon energy change. The magnet model has been used to calculate how the magnetic field and hence the photon energy in the circular polarization condition varies with magnet gap (Figure

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2.4-9). One of the features of the APPLE 2 type undulators is that the array phase needs to be adjusted during gap scanning to maintain circular polarization. The data for the phase setting is also presented in Figure 2.4-9. We can look at the gradient of these curves to get an idea of the mechanical movements required during gap scanning. The steepest gradient for the photon energy change for this particular device is at the larger gaps where it varies by about 45 eV/mm. The phase has the largest gradient at the smaller gaps and here it reaches about 0.2 mm/mm. In other words, scanning in discrete 0.25 eV steps would require a gap change of the order of 5 μm and an array phase change of the order of 1 μm .

At minimum gap the array phase needs to change from 17.7 mm to -17.7 mm in order to switch between left and right circular polarization. This mechanical movement of more than 35 mm with high precision under variable forces is likely to take of the order of 30 seconds to complete.

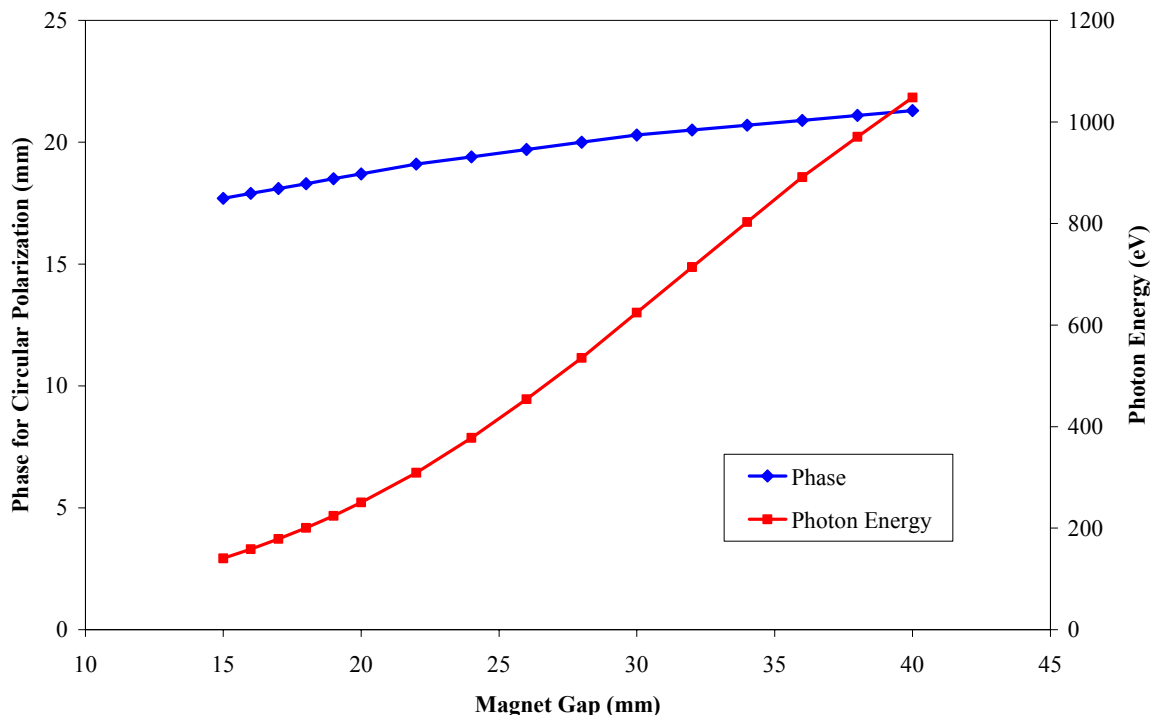


Figure 2.4-9 Array phase and photon energy against magnet gap for the circular polarization mode of the 60 mm period helical undulator.

A feasible magnetic design for a variable polarization undulator has been demonstrated and software models generated that will simplify future designs. However, several areas of the design will need to be studied in more detail, especially the exact magnet block dimensions and the mechanical support structure. The generation of arbitrary linear polarization is also possible with the APPLE 2 device if the two diagonally opposite arrays are moved in antiphase rather than phase and the implications of this possibility will also need to be assessed.

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2.4.4 In-Vacuum Undulators

As the scientific case for DIAMOND has developed it has become clearer that high brightness up to about 20 keV would be advantageous. To reach these high energies with an undulator on a 3 GeV storage ring necessitates the use of high harmonics and short periods. It is also an advantage if the undulator is placed inside the vacuum system so that the magnet gap between the arrays can be smaller. International experience with in-vacuum undulators has grown significantly over the past 5 years, particularly at SPring-8 in Japan and more latterly at ESRF in Europe. These devices are more complex than standard devices and the addition of moving components into the machine vacuum is not without risk but experience has generally been very good. One drawback of in-vacuum devices is the need to bake all of the components which are used, including the permanent magnet blocks. This restricts the magnet materials that can be used somewhat since the highest remanent field materials can not be raised to the temperature required for vacuum baking. One other concern, which does not just apply to in-vacuum devices, is that of radiation damage. It is thought that materials inside the vacuum system are more susceptible to radiation damage because they do not have the benefit of the protection offered by a narrow gap vacuum vessel. Choosing a magnet material which has good resistance to radiation damage restricts the choice of material even further. In this design study a grade of $\text{Sm}_2\text{Co}_{17}$ has been assumed for in-vacuum undulator designs which has a remanent field of 1.05 T. For IDs which will not be in the vacuum system a remanent field of 1.3 T has been assumed using NdFeB. This difference in materials does reduce the attractiveness of in-vacuum devices at face value although they do still outperform out of vacuum devices when the magnet gaps assumed are 10 mm out of vacuum and 7 mm in-vacuum. One of the advantages of the in-vacuum device is that if the storage ring lifetime is good then the magnet gap will be able to be reduced further in the future without the need or risk of replacing the ID vacuum vessel. A further advantage is that the ID can be installed into the ring with the gap fully open before commissioning starts so that commissioning of the electron beam is not restricted. This replaces the need to either commission the ring with narrow gap vessels in many places or to replace larger bore vessels as soon as possible once the electron beam orbit has been understood.

2.4.5 Power and Power Density from Undulators

Although the total power from an undulator is much less than that from a MPW, the power densities can be similar or higher. Handling very high power densities will require careful engineering design and will also be a major consideration in the beamline optics layout. The total power and power density on axis for the 5 example undulators of Table 2.4-1 is given in Table 2.4-2.

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Table 2.4-2 Total power and on axis power density for example undulators.

Name	K_{Max}	Length (m)	Total Power (kW)	Power Density (kW/mrad ²)
U24	1.36	2	1.2	12.7
U36	2.03	5	3.1	21.5
U48	3.76	5	6.0	23.0
U80	5.00	5	3.8	11.0
U200	5.00	8	1.0	2.8

The power density as a function of angle for the U36 example is plotted in Figure 2.4-10 and Figure 2.4-11.

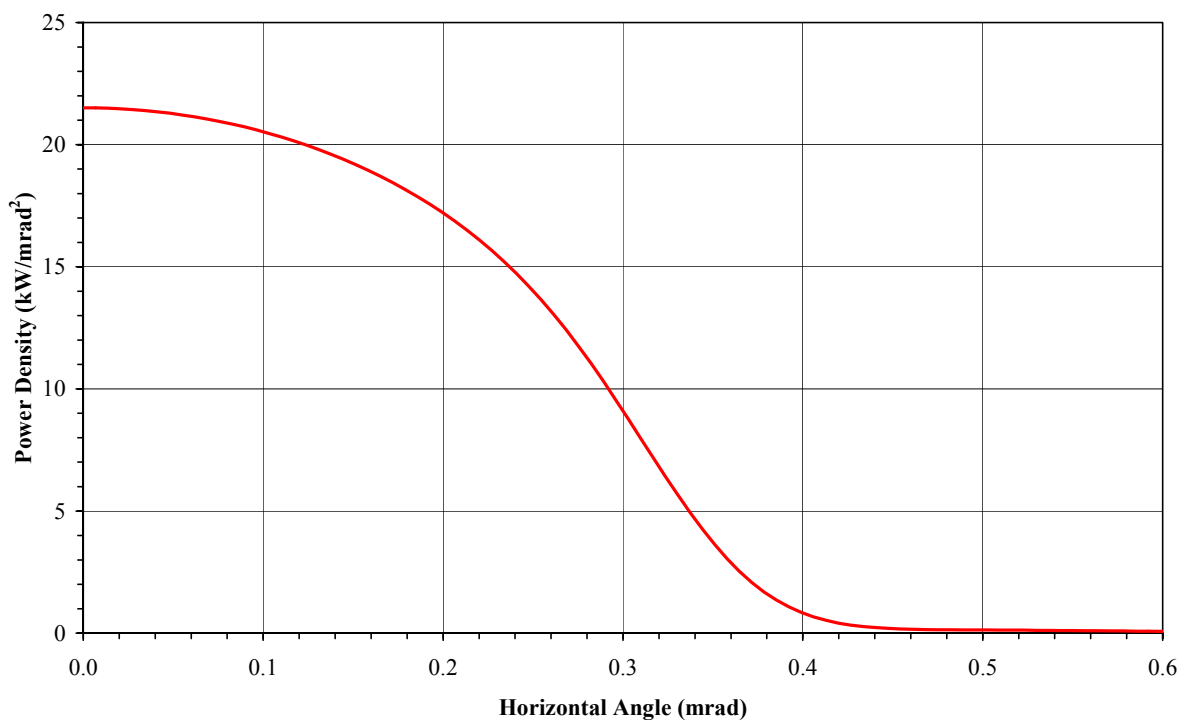


Figure 2.4-10 Power density for U36 as a function of horizontal angle (the vertical angle is zero).

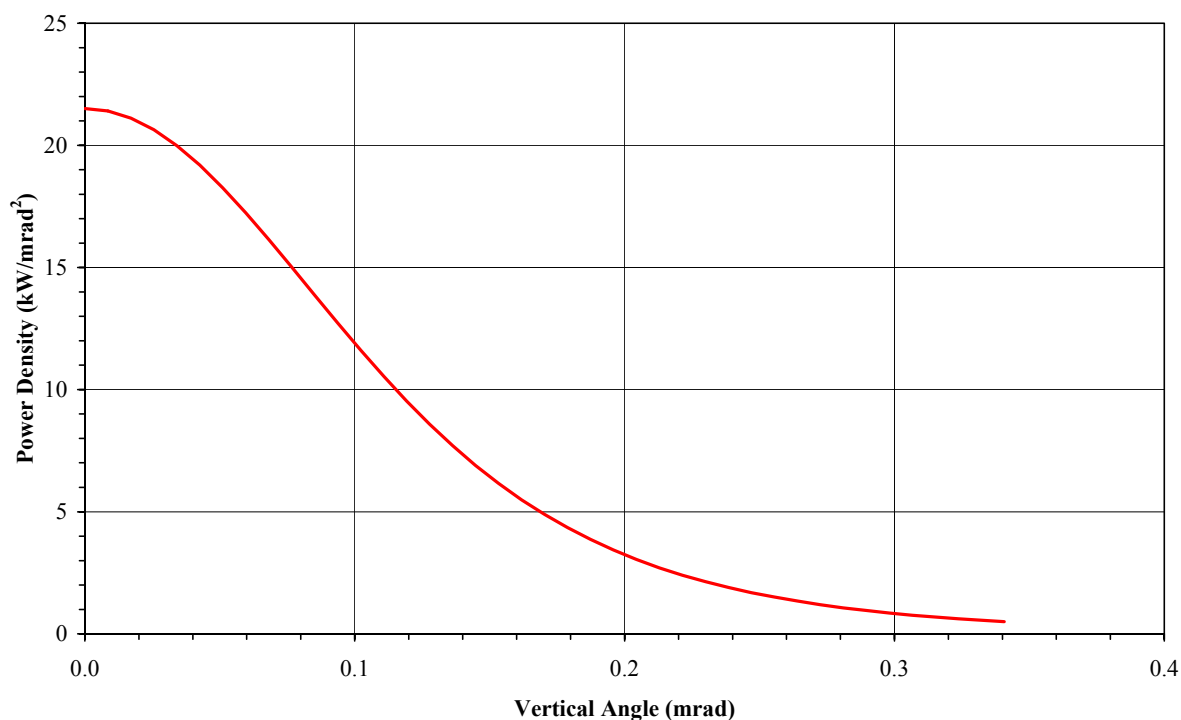


Figure 2.4-11 Power density for U36 as a function of vertical angle (the horizontal angle is zero).

2.4.6 The Effect of Errors and Imperfections in the Undulators

Generation of undulator radiation in the 10 to 20 keV photon energy range with DIAMOND is only possible with short periods, small magnet gaps and the utilisation of the higher harmonics. It is worth remembering that the 6 GeV ESRF was designed for the generation of undulator radiation at up to 14.4 keV [16]. Such radiation is now expected of storage rings with electrons of 3 GeV or less, typically this requires periods of the order of 20 mm and magnet gaps less than 10 mm.

It is well known that higher harmonic radiation from undulators is more susceptible to effects caused by non-ideal undulators. Much effort has been made over the past decade to improve the quality of undulator magnetic fields by block sorting and various shimming techniques. The results have been very good and rms phase errors in planar undulators below 5 degrees are now achieved routinely.

For the DIAMOND project we have studied a pure permanent magnet hard x-ray undulator design with realistic mechanical and magnetic errors included to assess the contribution each error makes to the overall spectral degradation. A typical angular acceptance for protein crystallography has been assumed and the photon flux through this aperture used as the figure of merit for each set of errors. No block sorting or shimming was applied to any model so the results are somewhat pessimistic in this respect.

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The pure permanent magnet undulator model described in section 2.4.1 was modified for this study. The model was created so that random errors in several parts of the device could be included. In particular, all block dimensions could have errors included to simulate manufacturing tolerances and the magnetization direction of each block could also have an error term applied.

For each particular error value studied, 50 random magnet models were generated and the on-axis magnetic field examined. The phase error for each model was calculated and then the average for each particular type of error determined [17]. From the results it was clear that the largest phase errors were generated when errors in the magnet block lengths were considered. This was expected because this error had the largest effect on the periodicity of the magnetic field.

A typical permanent magnet block dimensional tolerance of 50 μm in all three axes was also investigated with the model to see if such tolerances were either sufficient or over-specified. The phase error found for each of the 50 random models generated is given as a histogram in Figure 2.4-12. The average phase error was found to be 7.9 degrees. This implies that a 50 μm tolerance is sensible for generating undulators with phase errors of only a few degrees after sorting and shimming.

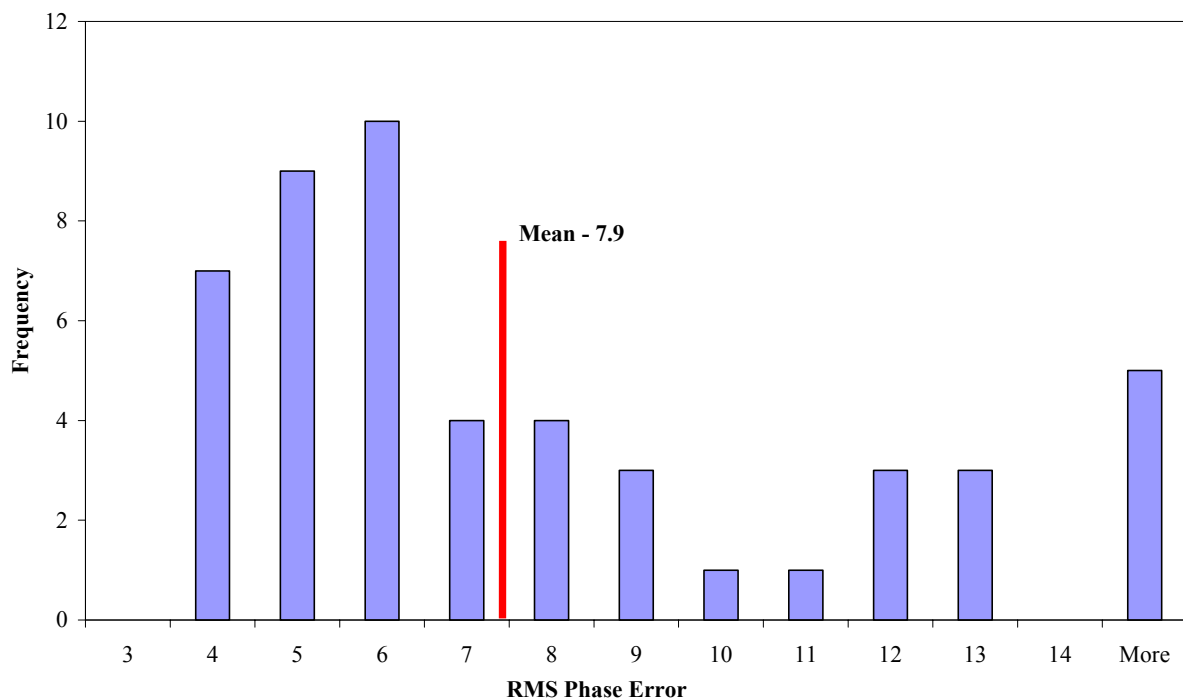


Figure 2.4-12 Phase error frequency plot for 50 sets of random dimensional errors with a maximum error of $\pm 50 \mu\text{m}$ in each dimension. No block sorting and shimming has been applied.

It is common in the synchrotron light community to either quote flux or brightness for undulators and wigglers. Although this is helpful when comparing different light sources it is not the most useful figure when particular experiments or beamlines are

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being planned. The most useful figure of merit will vary between experimental techniques and even between different experiments on the same beamline. The figure of merit which we have considered here is the actual number of photons in a particular bandwidth which will travel through a defined angular acceptance. For this exercise we chose an angular acceptance that was applicable to protein crystallography experiments. In particular a full angular acceptance of $100\text{ }\mu\text{rad}$ horizontally by $25\text{ }\mu\text{rad}$ vertically has been used throughout.

For each set of errors an example magnetic field was chosen (from the 50 data sets available) that had a phase error equal to the average value for that particular error type. This magnetic field was used to calculate the total flux passing through an angular acceptance of $100\text{ }\mu\text{rad}$ horizontally by $25\text{ }\mu\text{rad}$ vertically. The calculation was carried out using B2E [18], with standard DIAMOND values for emittance and energy spread. The flux at several (odd) harmonics was recorded and the results for different block length errors is given in Figure 2.4-13. Harmonics 5, 7 and 9 are required for protein crystallography and as expected the effect of the magnetic imperfection increases with harmonic number. It was also clear that the largest effects were produced by the block length errors, confirming that the magnet phase error is indeed the correct parameter to be minimising when designing, measuring and shimming undulators.

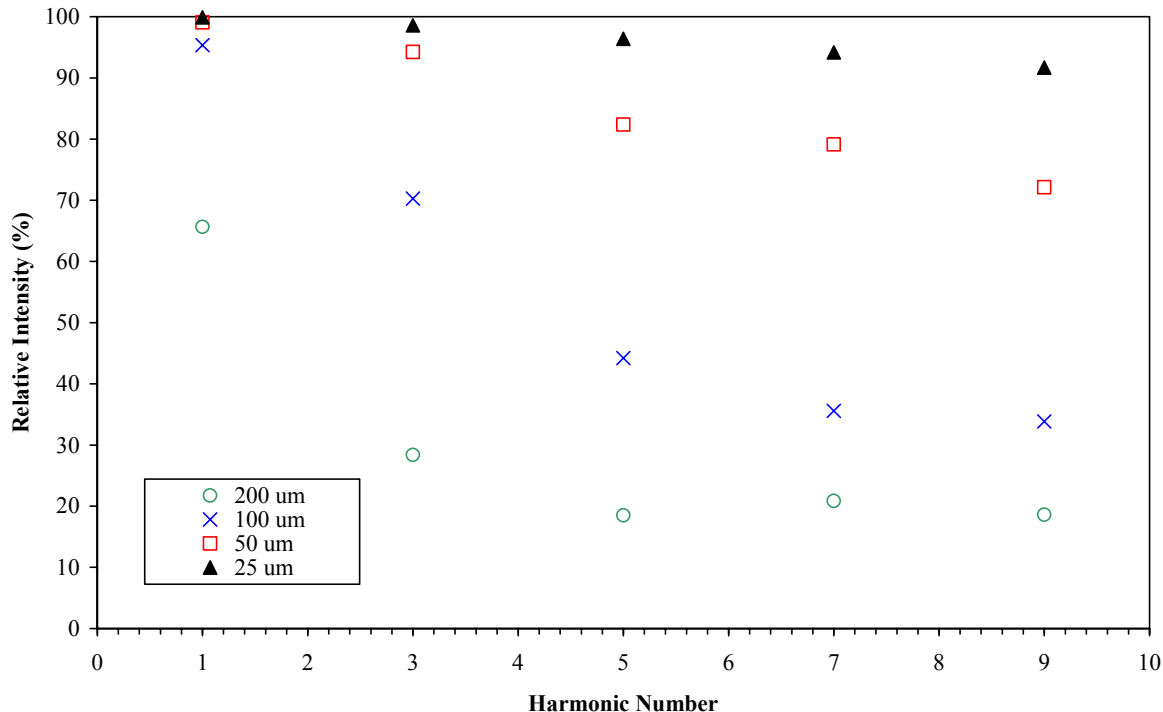


Figure 2.4-13 Relative photon flux through a $100\text{ }\mu\text{rad}$ by $25\text{ }\mu\text{rad}$ aperture for U24 at minimum gap ($K = 1.36$) as a function of different undulator harmonics for alternative random errors in the block length.

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For further calculations that have been performed during the ID selection process for the first beamlines we have assumed a phase error of 3 degrees can be achieved. This is certainly achieved routinely at light source laboratories and is often less than this. Using a magnet model that gives a 3 degree phase error we calculated the flux into a $100 \times 25 \mu\text{rad}$ aperture (Figure 2.4-14). Also shown in the figure is the flux into the same aperture for an ideal undulator and, for comparison, the flux into the central cone. It is clear that the aperture is slightly smaller than the central cone (most of the flux is lost on the vertical aperture in fact) and also that the effect of the phase error is larger at the higher harmonics, as expected. The loss in flux on the 3rd harmonic is about a factor of 2 and on the 15th is about a factor of 6.

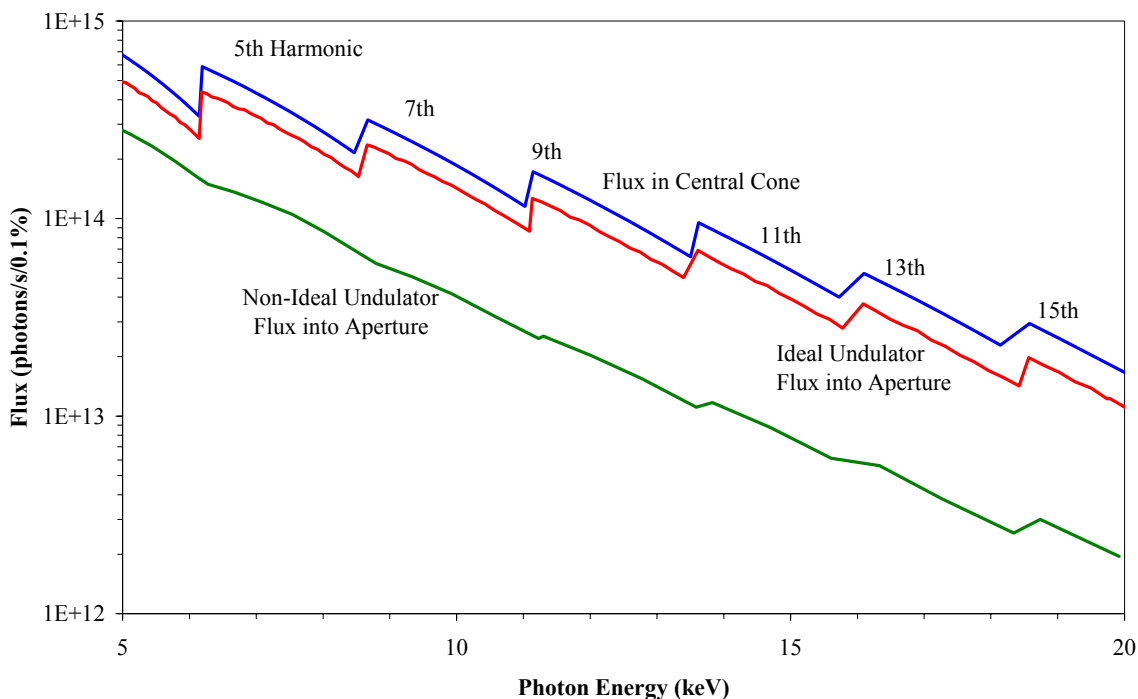


Figure 2.4-14 Photon flux as a function of photon energy for a 27 mm period undulator with a 10 mm magnet gap. The non-ideal undulator had a 3 degree phase error.

In conclusion, our studies have shown that if a number of realistic engineering and magnetic tolerances are assumed then high photon fluxes can still be achieved with short period, small gap undulators. A loss in intensity of the order observed is certainly tolerable and the use of block sorting and shimming as well as careful mechanical design should further improve this situation.

2.4.7 Ray Tracing of Undulator Beamlines

The geometric ray tracing code SHADOW from CNTech at the University of Wisconsin [19] is heavily used by the SR community for modelling beamlines. It has a built-in undulator model, but only for ideal planar undulators. The effects of

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deviation from ideal undulators, for example magnetic field errors, as well as electron energy spread, become more important at the higher undulator harmonics which are proposed for several of the beamlines on DIAMOND. A small project was established to allow ray tracing to be carried out using SHADOW on realistic non-ideal undulators. Helical undulators required to produce circularly polarised light have also been incorporated.

The code SRW [11], provides the necessary flexibility in the description of the undulator magnetic field, which can either be generated from ideal sinusoidal fields or can be input from a data file (real magnet measurement results for example). The SRW_SHADE interface, written at Daresbury Laboratory and outlined here, converts the output from SRW into suitable input for SHADOW.

The output from SRW is the complex electric field, for s and p polarisations, at a mesh of points downstream from the undulator. The begin.dat files required for SHADOW contain a description of a set of rays - position, angle, wavenumber and information on the electric field vector. The number of rays of a given description is proportional to the intensity at that wavelength, angle and position, and is obtained from the SRW intensities using cumulative density functions, as in SHADOW.

In order to extract the angle information required for ray tracing, it has to be assumed that all the radiation is emitted (or appears to be emitted) from the centre of the undulator. For some types of devices, this may be a limitation, and the effect can be checked by running SRW with the mesh at different distances from the undulator. Because of this approximation, it is best to run SRW with zero emittance and to add the effect of non-zero beam sizes in the interface code. Ideally, one should not use geometric ray tracing, but should propagate the electric field down the beamline. This is possible with SRW but transfer functions across the optical elements are required and it is very memory intensive. The SRW_SHADE code provides an alternative method.

As an example, outputs from an ideal (sinusoidal) and a non-ideal (random magnet errors included) undulator were traced through a simple X-ray beamline consisting of a defining aperture (100 μ rad horizontal by 25 μ rad vertical), a double crystal monochromator and a 1:1 post-focusing toroidal mirror. The undulator was a 2 m long, 28 mm period device with a K-value of about 0.54, yielding 3rd harmonic radiation at about 8 keV. The magnetic field for the non-ideal undulator had random errors leading to a phase error of 3 degrees, and was read in as a set of field values along the device.

The scatter plot at the focal point for the non-ideal undulator is shown in Figure 2.4-15. The rays have been coloured by the intensity, so that only the rays with a significant intensity are seen on the plot. The histogram in the top right hand corner of the figure shows the number of rays and the colour associated with each intensity bin. Out of 15,000 source rays, 3298 were lost at the aperture, and the final intensity is the equivalent of 4428 rays. The plot looks very similar for the ideal undulator source,

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except that only 1507 rays were lost at the aperture, leading to a final intensity of the equivalent of 5131 rays. As both sources were 100 by 25 μ rads in extent, the difference is in the methodology between using SHADOW (which assumes an ideal undulator) and SRW (which takes account of field errors) to generate the source. However, the source peak intensities were also similar and hence the conclusion is that for this example, the intensity at the sample would not be significantly altered by magnetic field errors of this magnitude.

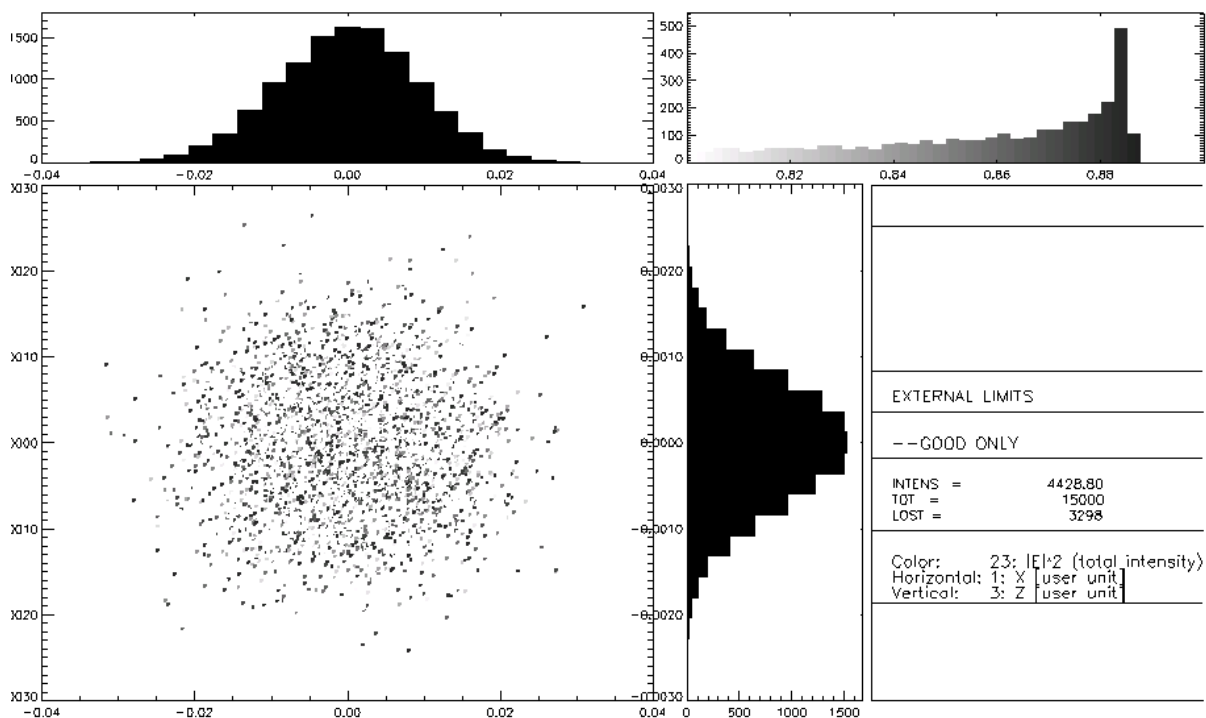


Figure 2.4-15 A scatter plot at the focal point of the modelled beamline for the non-ideal undulator case. The x and y units are in cm.

Figure 2.4-16 shows the scatter plot of the energy against vertical angle at the sample, coloured again with the intensity - in this case all of the rays, even with very small intensity, are plotted. The histogram in the top right hand corner of the figure illustrates the range of intensities over which the rays are coloured.

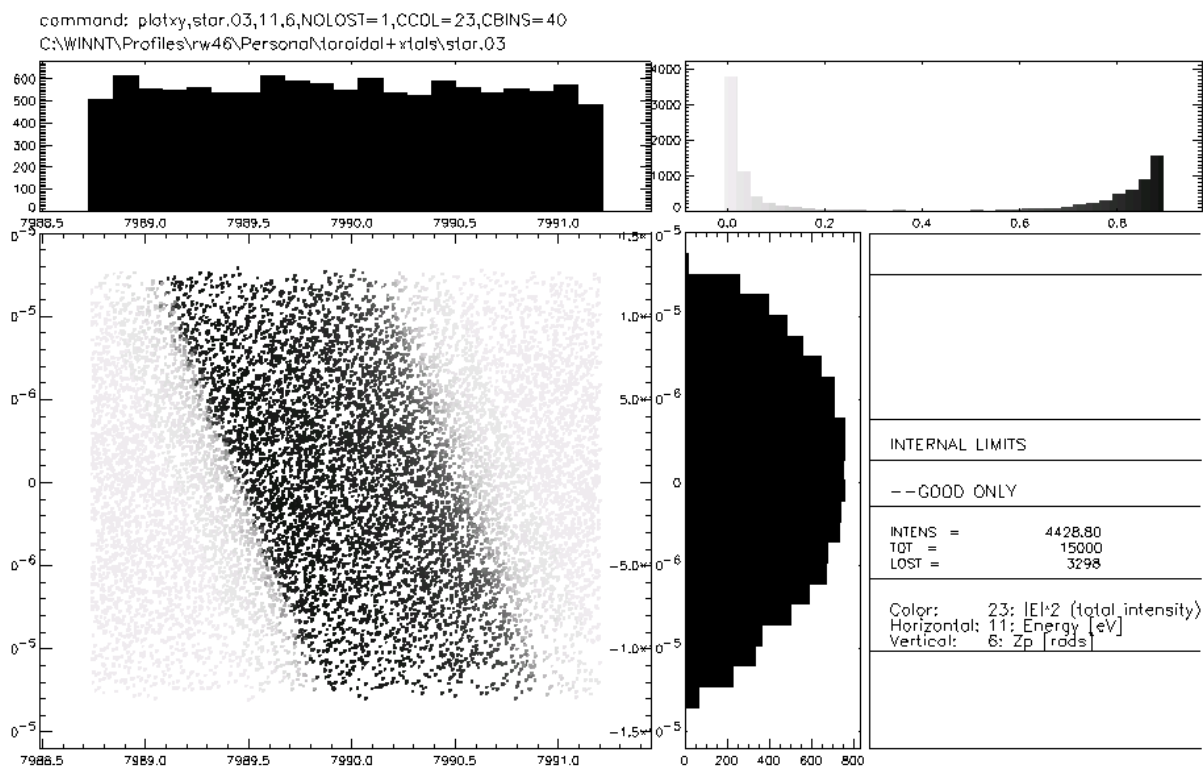


Figure 2.4-16 A scatter plot of the photon energy (eV) against vertical angle (radians) at the sample.

2.4.8 Requirements for Undulator Beam Divergence

The requirements for X-ray beam divergence on crystal diffraction beamlines depends on a number of factors, such as sample quality and size, and the geometry and resolution of the detector system. Focusing optics typically employ ~2:1 focusing in order to demagnify the source (mainly horizontally) and reduce the effects of mirror slope-errors (mainly vertically), while limiting the vertical beam divergence at the sample, which increases with the demagnification factor. In addition to the effects of beam divergence at the sample, the diffraction resolution is further degraded by the monochromator bandwidth, which in turn depends on both the ‘Darwin width’ of the monochromator crystal and the vertical divergence of the beam at the monochromator. The latter can be reduced by the use of a pre-monochromator collimating mirror. Even with realistic mirror slope errors (~ 5 μ rad rms), such a scheme offers a clear advantage in terms of restricting the monochromator bandwidth. The price to pay, however, is an increase in complexity, and a potential deterioration in the focus arising from extra slope errors. There is clearly advantage in avoiding a collimating mirror if possible.

In Table 2.4-3, we consider the effects of vertical beam divergence on the monochromator bandwidth, compared with the intrinsic resonance widths at the Cu and Se K edges, assuming a Si 111 monochromator. The results indicate that, with vertical divergences reduced to below 25 μ rad, resolution gains are modest. If the

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divergence of the incident beam does not exceed 25 μrad then the disadvantages of a collimating mirror probably out-weigh the advantages. Furthermore, as this figure is very close to the predicted value for DIAMOND undulators, we have chosen 25 μrad as an acceptable vertical aperture for flux calculations.

The horizontal divergence requirements are harder to quantify, since this does not significantly affect the bandwidth. We have chosen a working value of 100 μrad , which is close to the limit due to the electron beam divergence.

Table 2.4-3 Comparison between the natural lifetime widths (Γ) for Cu and Se K-edge resonances, and the energy bandwidths from a Si 111 monochromator with various vertical beam divergences.

Edge	Energy (eV)	Γ (eV)	Darwin width (μrad)	Bandwidth (eV)			
				0 μrad	15 μrad	25 μrad	50 μrad
Cu K	8979	1.55	30.4	1.21	1.35	1.57	2.33
Se K	12658	2.33	21.0	1.68	2.07	2.61	4.34

2.5 ENGINEERING OF THE INSERTION DEVICES

Since there are a significant number of insertion devices required for DIAMOND, the mechanical structure of the devices will be standardised as far as possible to reduce costs and simplify maintenance. The available space in the standard storage ring straight sections for each ID is 5 m. To reduce the forces on the magnet structure, ease magnetic testing, handling and provide flexibility it is proposed to construct each full length ID from 2 or 3 standard modules.

A significant amount of finite element analysis has been carried out to see if it is feasible to have a single support structure design with four alternative magnet array lengths; 1.5 m, 2.0 m, 2.3 m and 2.5 m. These lengths have been selected to offer flexibility for the straight sections as required by DIAMOND. The study has looked at alternative positions for the two mounting points for each array. The positions chosen have been at or near to the Airy points for each configuration [20]. The results have been encouraging with maximum deflections of less than 100 μm per array being calculated for a 50 kN/m load which is approximately equivalent to a 2 T MPW. A significant contribution to this deflection has been the dishing of the magnet beam due to its box type construction (Figure 2.5-1). This dishing has been reduced by increasing the number of transverse bulkheads [21] and also by the addition of a third axial member [22] (Figure 2.5-2).

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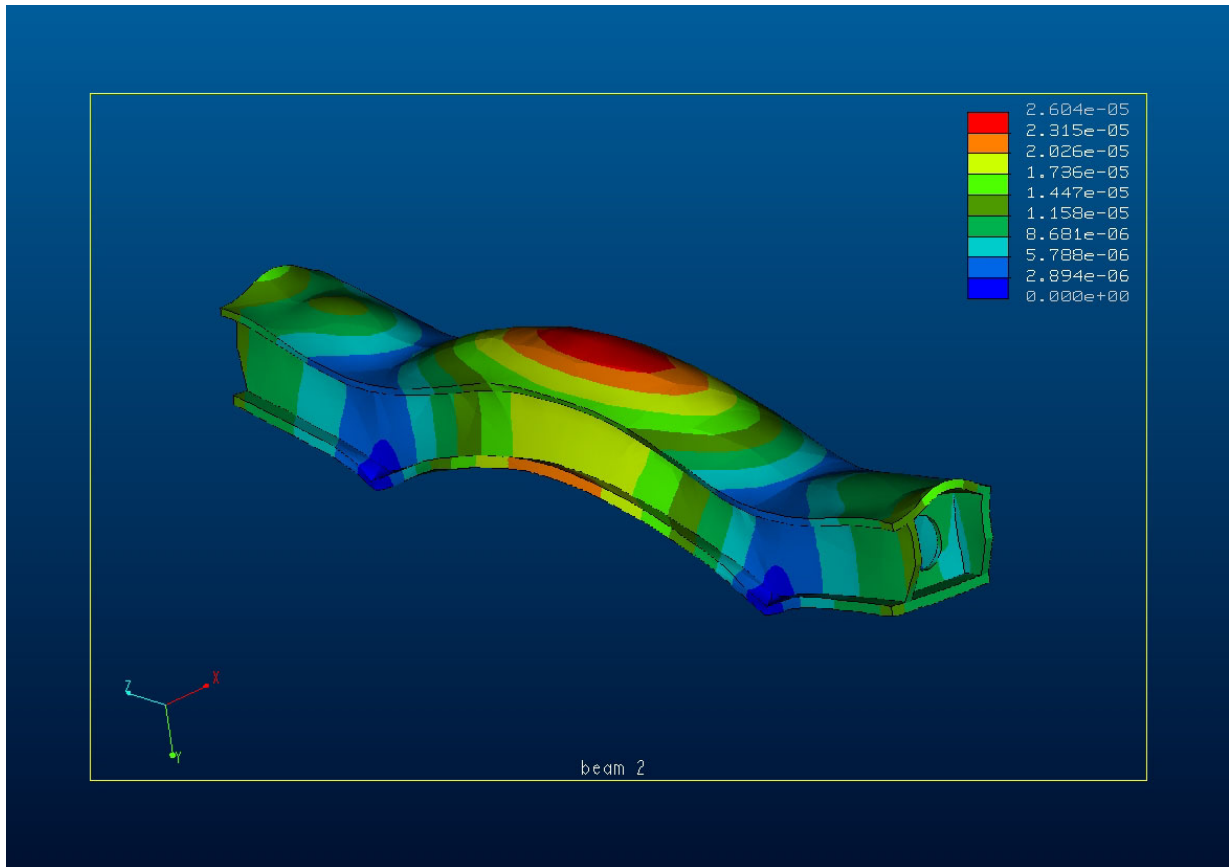


Figure 2.5-1 Example finite element analysis plot showing dishing effect on top surface of magnet array beam.

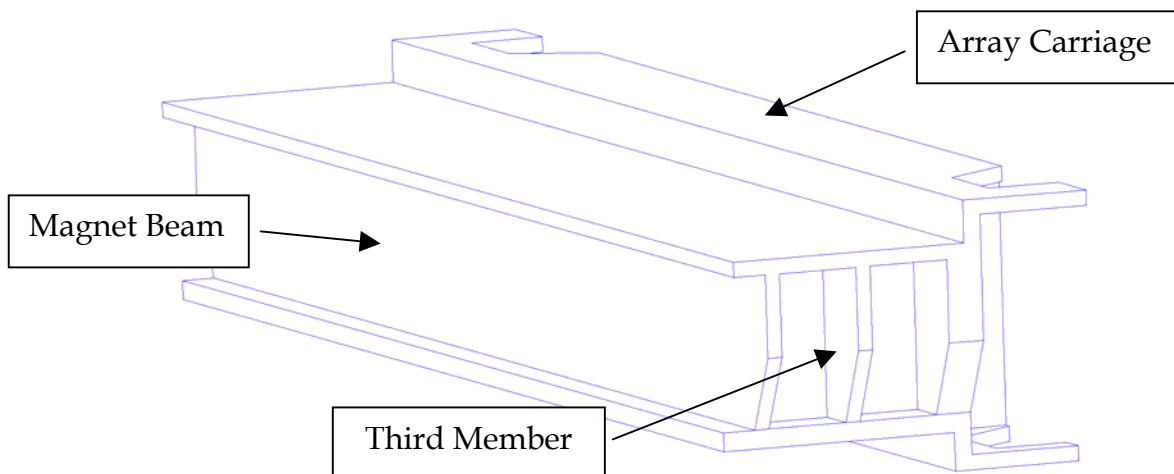


Figure 2.5-2 Revised magnet array beam with additional axial member.

The current design is a 1.5 m wide support structure with the two mounting points being approximately 1.3 m apart. Figure 2.5-3 shows the current conceptual design, this concept satisfies the required working parameters of maintaining the longitudinal flatness and parallelism of opposed faces to better than 50 μm over the whole length

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and relative to the horizontal centreline and the transverse parallelism to be less than $20\text{ }\mu\text{m}$ relative to the horizontal centreline and measured across the central 100 mm . It is based on an “A” frame construction, fabricated from standard structural steel sections, therefore minimising material and fabrication costs. Finite element analysis results indicate that the peak deflection for the top and bottom arrays will be less than 45 and $20\text{ }\mu\text{m}$ respectively for a 50 kN/m load. Also the transverse skew across the central 100 mm is predicted to be $12\text{ }\mu\text{m}$ for the top beam and $6\text{ }\mu\text{m}$ for the bottom beam. The displacements experienced by the support structure are highlighted in Figure 2.5-4. Note that only one Belville spring support has been included in the model to simplify the analysis.

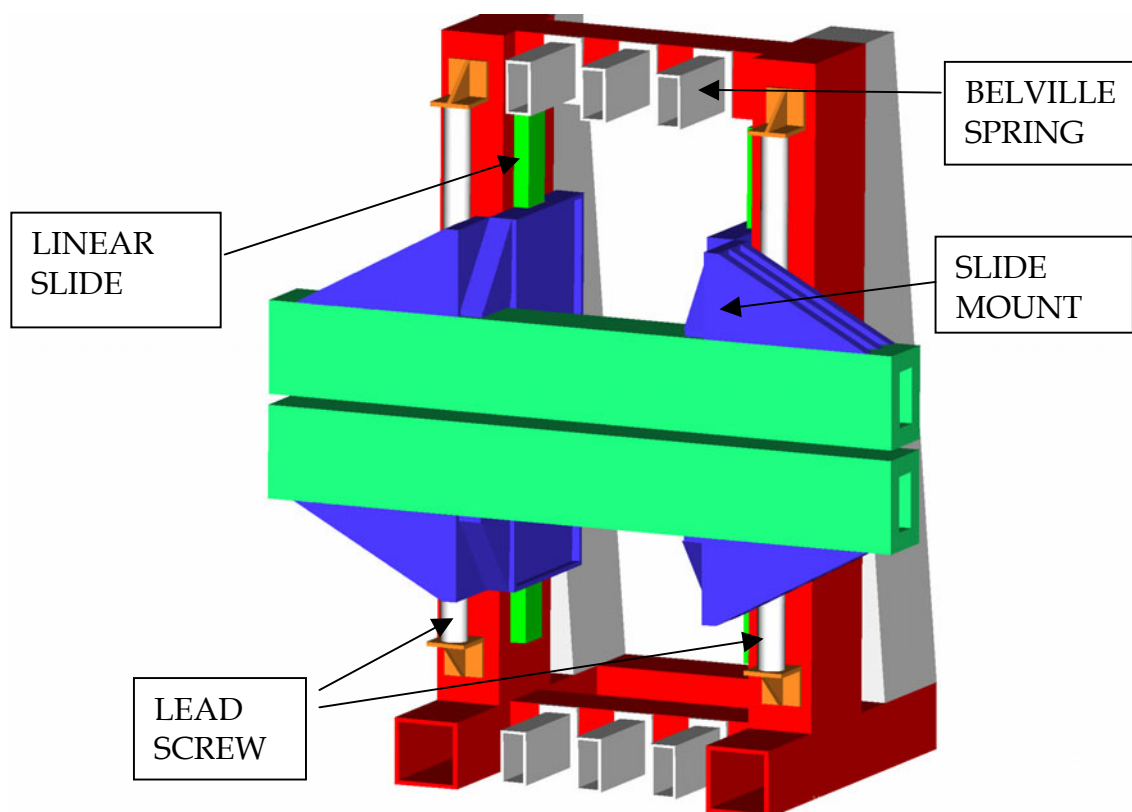


Figure 2.5-3 The current standard ID support structure concept.

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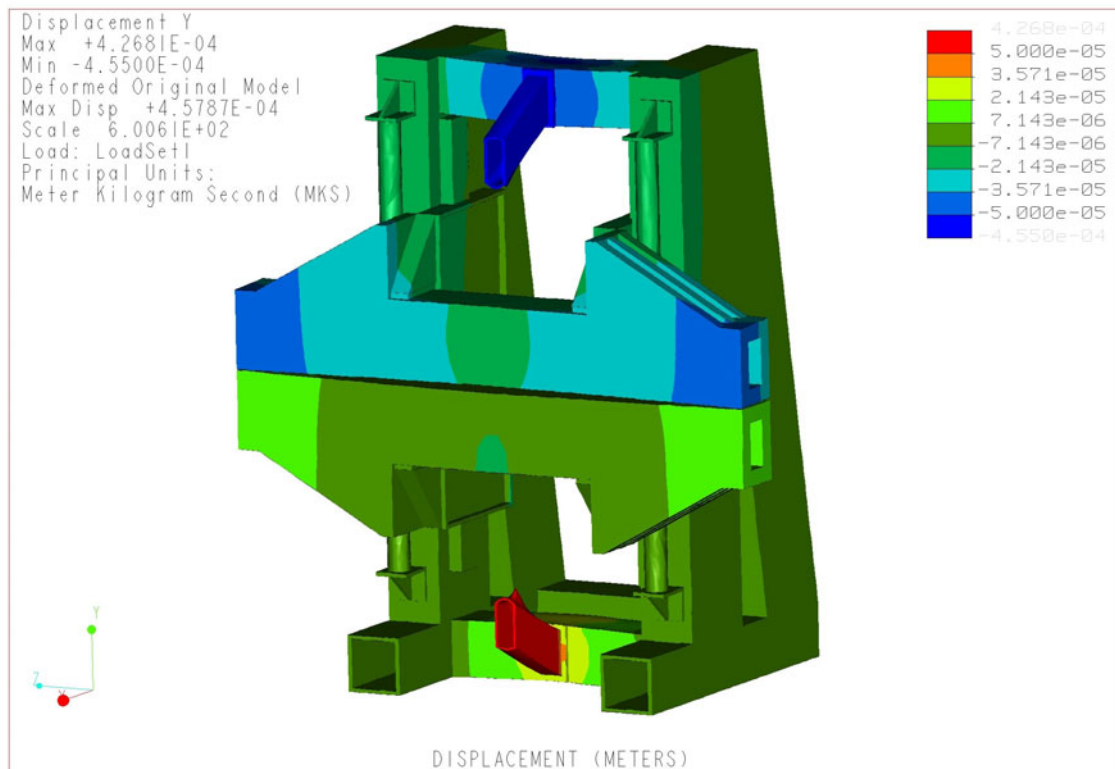


Figure 2.5-4 Finite element analysis results showing the displacement of the support structure.

The basic “A” frame is designed to support the four sizes of magnet array carriages, by means of a unique slide mount, being the only non-generic component for the insertion device. The magnet beams are mounted on high load bearing precision linear slides; two precision ground lead screws provide the jaw action of the magnet array carriages. To aid the smooth movement and reduce some of the large forces on the lead screws, slides and gearbox, produced by the attractive force of the magnet array carriages, spring compensation is offered to both beams. This is currently set to one quarter of the maximum magnetic force (based on previous successful implementation at the SRS). The standard design will include, one or two AC brushless motors coupled via a low backlash gearbox to the two lead screws, providing vertical gap control of the magnet array carriages. Two optical linear encoders mounted directly on the magnet array carriages will measure the magnet gap to 5 μm accuracy and 1 μm resolution. Tilt sensors mounted on the magnet array carriage, in conjunction with slip disks, will provide mechanical adjustment to the parallelism of the magnet array carriages. Figure 2.5-5 gives some overall dimensions for the present support structure design.

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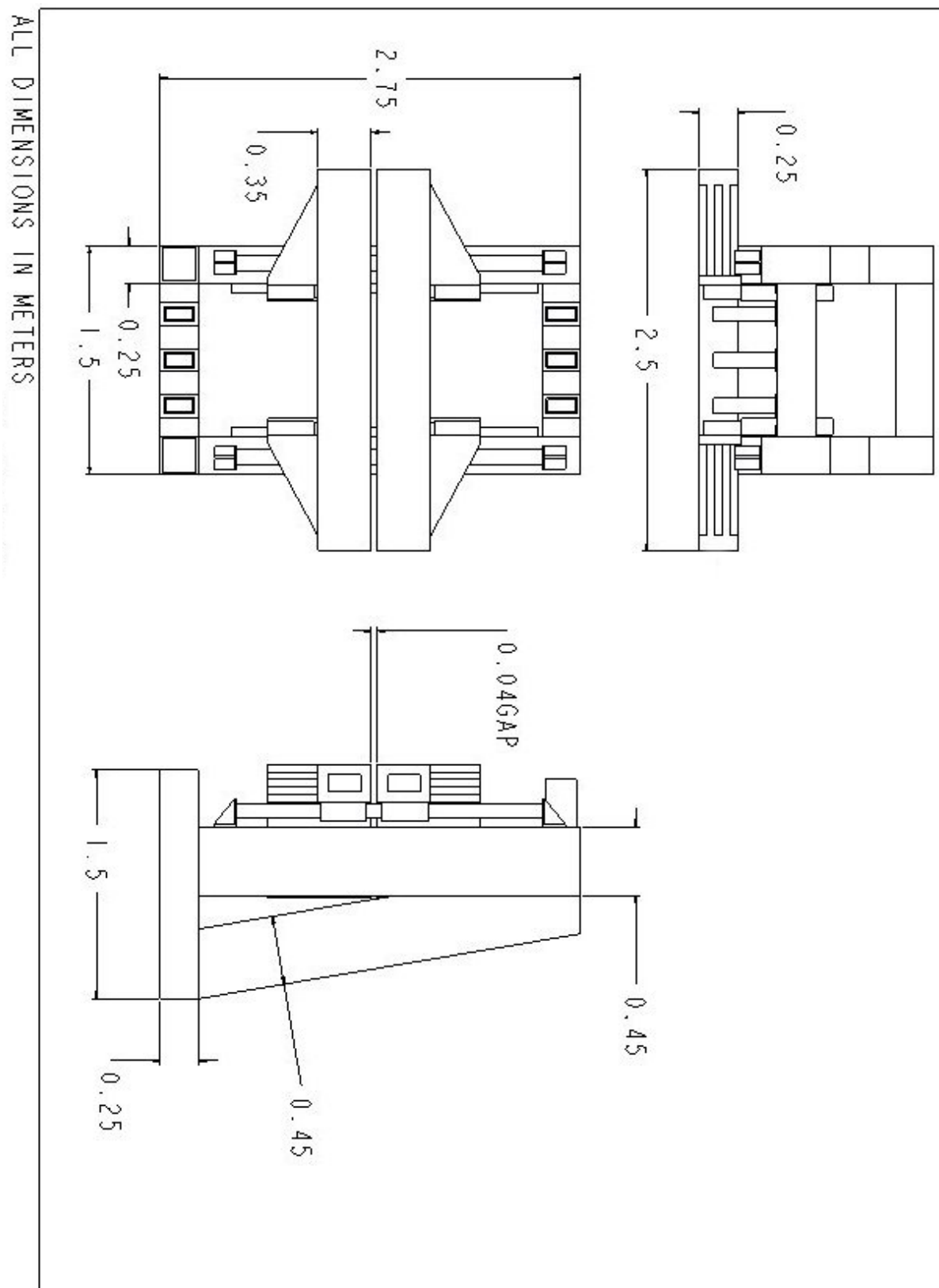


Figure 2.5-5 Some basic dimensions for the support structure.

2.6 SELECTION OF THE FIRST INSERTION DEVICES

Eight beamlines have been selected for 'Day 1' operation on DIAMOND (funds permitting) and insertion devices have been matched to the requirements of each of these. Each ID has been optimised to meet the requirements put forward by each individual Beamline Working Party.

2.6.1 Very High Energy Beamline

(a) Insertion Device Requirements

This is a very high energy beamline to support research into materials under extreme conditions. The beamline proposal [23] contains an outline insertion device requirement and this has been refined at a meeting of the Beamline Working Group [24].

The beamline will consist of two experimental areas. The first experimental area requires high flux over 20 to 100 keV, maximised over 40 to 80 keV, if possible. The experimental area will accept 1 mrad horizontally and all the flux vertically (this will be less than 1 mrad). It is expected that the defining aperture will be ± 0.5 mrad horizontally about the axis of the insertion device. The second experimental area is expected to cover the horizontal acceptance between +1 and +2 mrad (taking a horizontal fan of 1 mrad in total) and all the flux vertically (this will be less than 1 mrad). This experiment will cover the photon energy range between 20 and 40 keV.

The total power produced by the insertion device is a concern. Until detailed front end design and optics design has been carried out it was decided to limit the power produced by the insertion device to a total of 20 kW at 300 mA of beam current.

(b) Selection of the Insertion Device

To reach up to 100 keV, with a horizontal fan of at least ± 2 mrad is only possible with either an MPW or a wavelength shifter. It is easy to show that a wavelength shifter offers no advantage in terms of flux over this photon energy range as well as greater detrimental effects on the electron beam emittance and so the ID selection for this beamline has concentrated on MPWs.

The photon flux over the energy range 20 to 100 keV has been calculated for superconducting MPWs with a peak magnetic field between 3.0 and 3.5 T. The period of each MPW has been chosen with reference to the magnet model developed in section 2.2.1. The flux for 20 keV and 100 keV is shown in Figure 2.6-1 and Figure 2.6-2, and a comparison of flux levels for specific photon energies and magnetic field values is given in Table 2.6-1. Note that the step changes in the flux graphs occur when the number of periods changes by 1. The length of each MPW has been limited so that the total power output from each does not exceed 20 kW.

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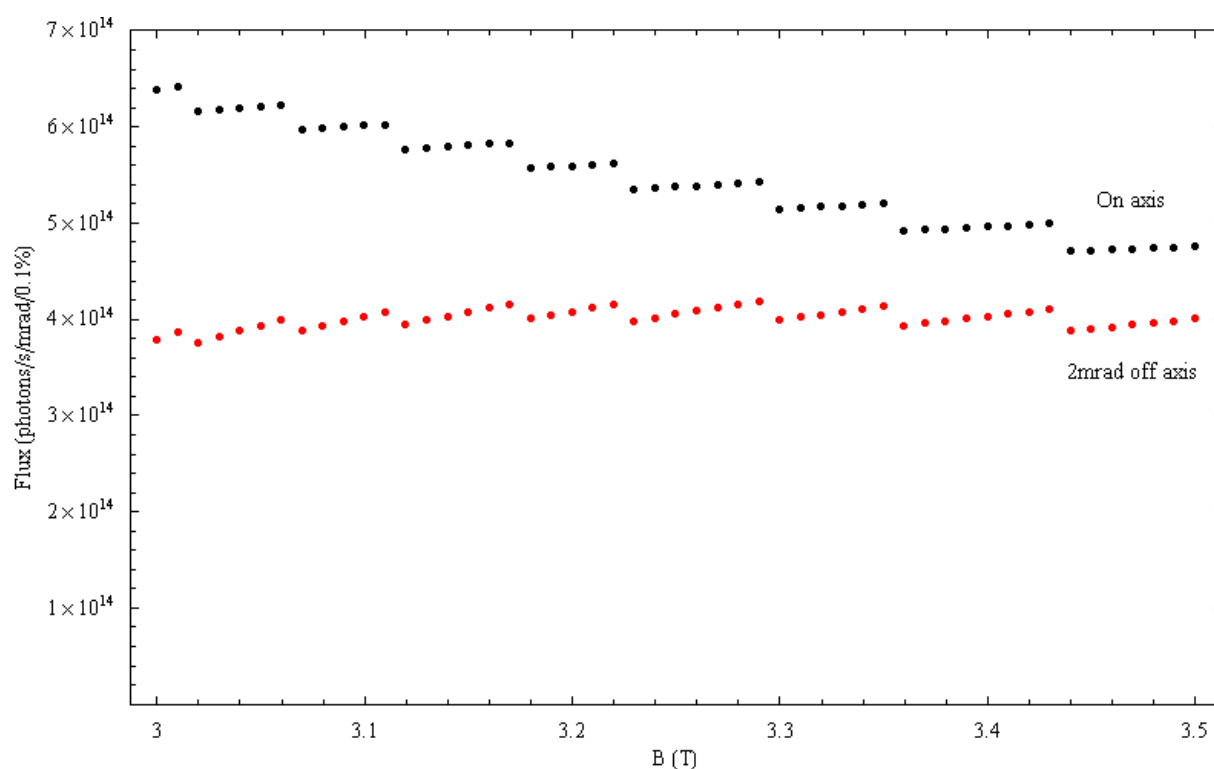


Figure 2.6-1 The photon flux on axis and 2 mrad off-axis as a function of peak field strength at 20 keV.

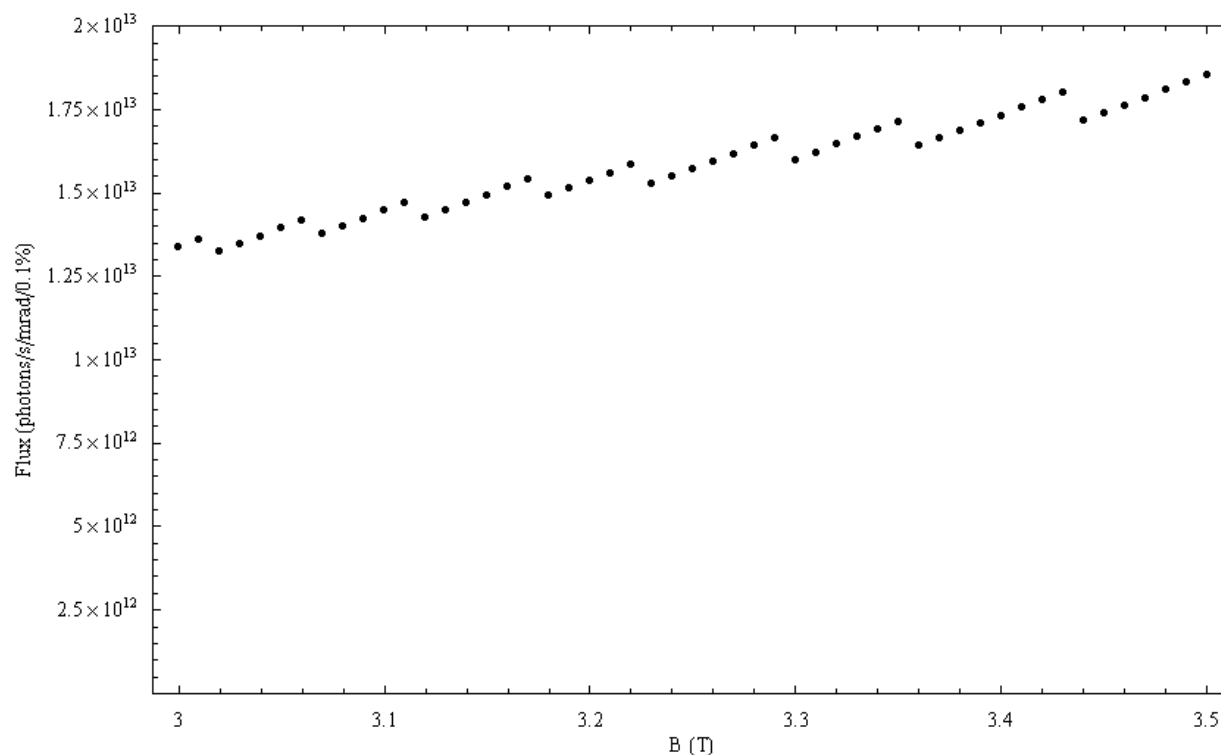


Figure 2.6-2 The photon flux on axis as a function of peak field strength at 100 keV.

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Table 2.6-1 On axis flux (photons/s/mrad/0.1%) comparison for different superconducting (SC) or permanent magnet (PM) MPWs.

Technology	Peak Field (T)	N _{Poles}	Flux at 20keV	Flux at 40keV	Flux at 80keV	Flux at 100keV
SC	3.0	48	6.4E+14	2.7E+14	3.7E+13	1.3E+13
SC	3.1	44	6.0E+14	2.6E+14	3.9E+13	1.4E+13
SC	3.2	40	5.6E+14	2.5E+14	4.0E+13	1.5E+13
SC	3.3	36	5.1E+14	2.4E+14	4.0E+13	1.6E+13
SC	3.4	34	5.0E+14	2.3E+14	4.2E+13	1.7E+13
SC	3.5	32	4.8E+14	2.3E+14	4.4E+13	1.9E+13
PM	3.0	14	1.9E+14	7.7E+13	1.1E+13	3.9E+12

Although the 3 T SC MPW provides greater flux at the lower end of the photon energy range, the 3.5 T SC MPW is the preferred ID for this beamline because it is felt that the high energy end of the beamline has greater priority and also because the lower energy photons have a flatter profile with horizontal angle for the second (off axis) experimental area. A summary of the selected ID for this beamline is given in Table 2.6-2 and the on axis flux is plotted in Figure 2.6-3. The relative flux as a function of horizontal angle for 20 and 100 keV is given in Figure 2.6-4.

Table 2.6-2 Summary of the parameters of the insertion device for the very high energy beamline.

Type of Insertion Device	Multipole Wiggler
Magnet Technology	Superconducting
Peak Field (T)	3.5
Magnet Period (mm)	60
Number of Periods	16
K _{Max}	19.6
Nominal Magnet Gap (mm)	10
Nominal Length (m)	1.0
Total Power at 300 mA (kW)	20.1
On Axis Power Density at 300 mA (kW/mrad ²)	14.8

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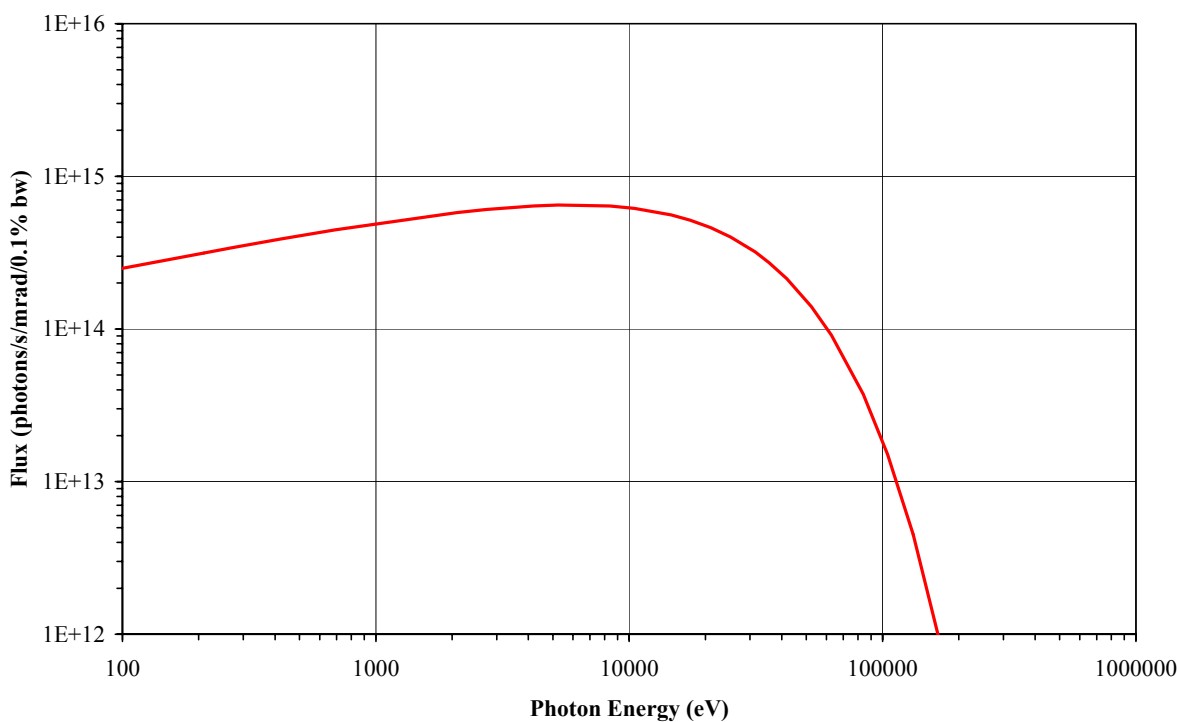


Figure 2.6-3 The on axis spectral flux for the 3.5 T SC MPW.

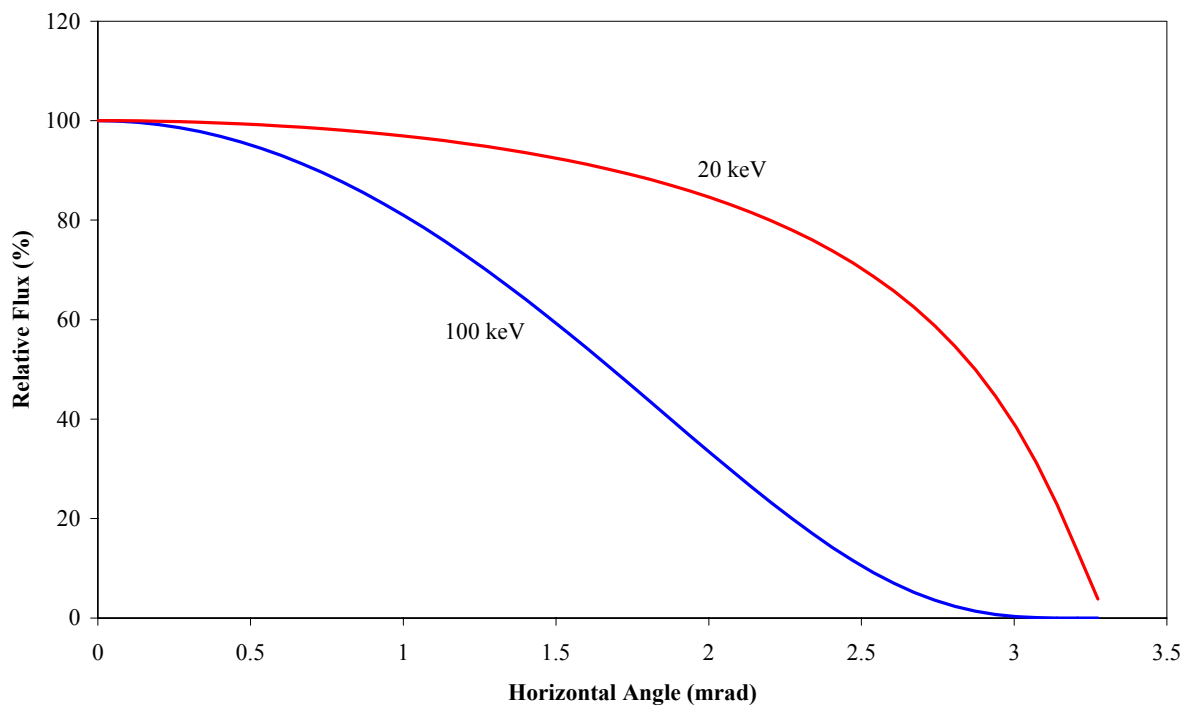


Figure 2.6-4 The relative spectral flux as a function of horizontal angle for the 3.5 T SC MPW.

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2.6.2 Materials Beamline

(a) Insertion Device Requirements

This beamline will be a high resolution diffraction beamline for the study of materials and magnetism. The beamline proposal [23] contains an outline insertion device specification and this has been refined at a meeting of the Beamline Working Group [25].

The flux generated by the insertion device and transmitted through the 100 μ rad horizontal $\times$ 25 μ rad vertical beamline aperture should be maximised over the beamline photon energy range of the beamline, which is between 3.4 and 20 keV. The spectral coverage of the insertion device should be continuous over this energy range.

Low divergence of the beam in both planes is essential and this implies the use of an undulator rather than a multipole wiggler (see section 2.2.4). Small divergence, especially in the vertical plane, is very important and it would be beneficial if the vertical divergence was less than the Darwin Widths of the potential monochromator crystals (see section 2.4.8). Tapering of the undulator to broaden the harmonic widths at the expense of flux is not required.

(b) Selection of the Insertion Device

Three types of undulator have been compared; a 5 m device with a 15 mm magnet gap, a 2 m device with a 10 mm magnet gap and a 2 m in-vacuum (IV) device with 7 mm magnet gap. A direct comparison between the optimum of each type of undulator is given in Figure 2.6-5. The flux into the beamline aperture for undulators with ~ 3 degree phase errors has been calculated and the results given in Table 2.6-3. The theoretical vertical divergence of the radiation for different photon energies and undulator lengths is given in Table 2.6-4.

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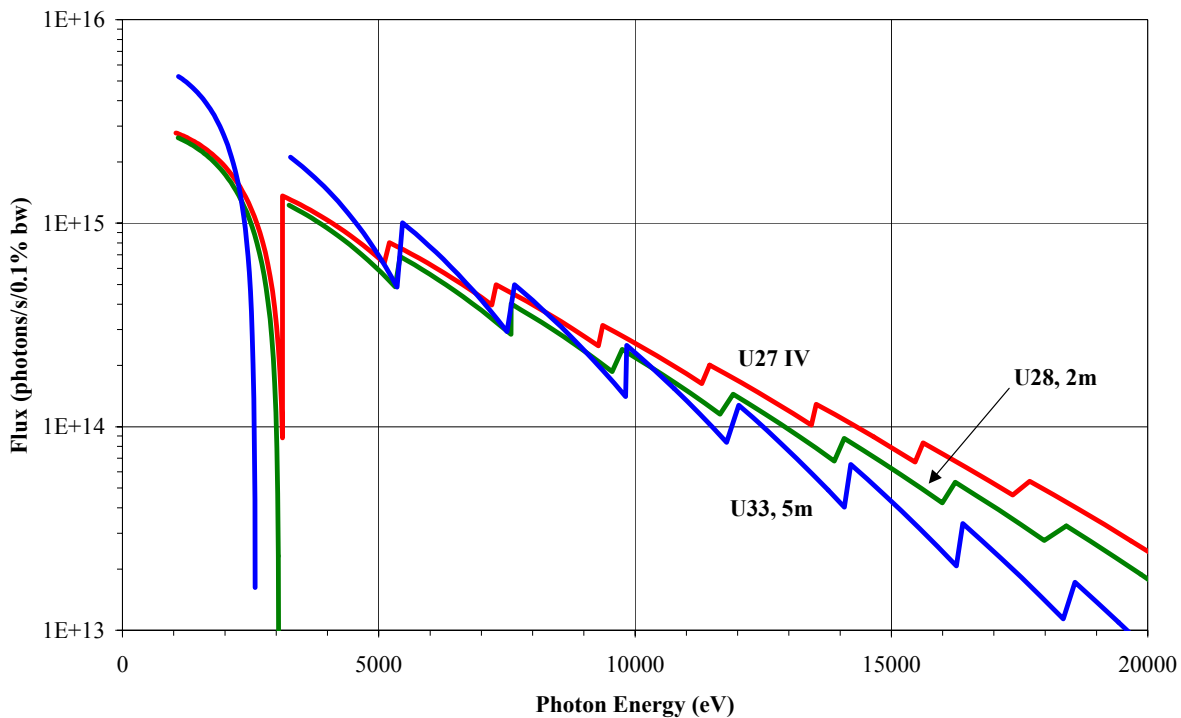


Figure 2.6-5 Spectral flux comparison between a 27 mm period in-vacuum undulator, a 28 mm period, 2 m out of vacuum undulator and a 33 mm period, 5 m out of vacuum undulator.

Table 2.6-3 Estimated spectral flux (photons/s/0.1%) at particular photon energies for realistic undulator models with ~ 3 degree phase error and the total power emitted by each undulator into the $100 \mu\text{rad}$ horizontal $\times$ $25 \mu\text{rad}$ vertical beamline aperture.

Name	Magnet Gap (mm)	3.4 keV	6 keV	13 keV	20 keV	Power in Aperture (W)
U27 IV	7	4.8E+14	1.8E+14	1.5E+13	2.2E+12	35.7
U28	10	4.4E+14	1.6E+14	1.1E+13	1.6E+12	31.3
U33	15	9.5E+14	2.8E+14	1.1E+13	9.0E+11	50.0

Table 2.6-4 Theoretical divergence (full width at half maximum) of the radiation for different photon energies and undulator lengths assuming an electron beam divergence of $4.2 \mu\text{rad}$.

Photon Energy (keV)	Divergence for 2 m Undulator (μrad)	Divergence for 5 m Undulator (μrad)
3.4 keV	24.6	17.3
6 keV	19.6	14.6
13 keV	15.2	12.3
20 keV	13.6	11.5

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The lower divergence with the longer ID is significant and this is considered to be sufficiently attractive when compared to the rather marginal flux differences between the three ID types to tip the balance in favour of the U33, 5 m undulator. The predicted divergence levels have not yet been checked for the realistic undulator model and this will need to happen in the next three months to confirm this choice of ID. A summary of the parameters for the selected undulator is given in Table 2.6-5.

Table 2.6-5 Summary of the parameters of the insertion device for the Materials Beamline.

Type of Insertion Device	Undulator
Magnet Technology	Permanent Magnet
Peak Field (T)	0.54
Magnet Period (mm)	33
Number of Periods	149
K_{Max}	1.66
Nominal Magnet Gap (mm)	15
Nominal Length (m)	5.0
Total Power at 300 mA (kW)	2.5
On Axis Power Density at 300 mA (kW/mrad ²)	21.0

2.6.3 Macromolecular Beamlines

(a) Insertion Device Requirements

Three beamlines will be dedicated to protein crystallography. The beamline proposal [23] contains an outline insertion device specification, which is the same for each of the beamlines, and this has been refined at a meeting of the Beamline Working Group [26].

The flux generated by the insertion device and transmitted through the 100 μ rad horizontal $\times$ 25 μ rad vertical beamline aperture should be maximised over the photon energy range of the beamline, which extends from 5 to 25 keV. The spectral coverage of the insertion device should be continuous over this photon energy range. Also, specific key photon energies that correspond to particular element edges are contained within the beamline energy range and the flux should be maximised at these values as far as possible. The three most important edges are Se K (12.658 keV), Hg L₃ (12.284 keV) and Pt L₃ (11.564 keV).

At least one of the three beamlines is likely to include a side-station as some point in the future. This will operate at one or two fixed photon energies. This is likely to be served by a separate insertion device in a chicane arrangement.

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(b) Selection of the Insertion Device

Given the small sample size that is now routinely used during protein crystallography experiments and the correspondingly small beamline aperture, the ID of choice for these beamlines is an undulator. A MPW will cover the photon energy range required but the undulator should outperform it as shown earlier in Figure 2.2-8.

Three types of undulator have been compared; a 5 m device with a 15 mm magnet gap, a 2 m device with a 10 mm magnet gap and a 2 m in-vacuum (IV) device with 7 mm magnet gap. The longer device with the larger gap was discarded because of its poor performance beyond about 20 keV. A direct comparison between the optimum of each type of 2 m undulator is given in Figure 2.6-6.

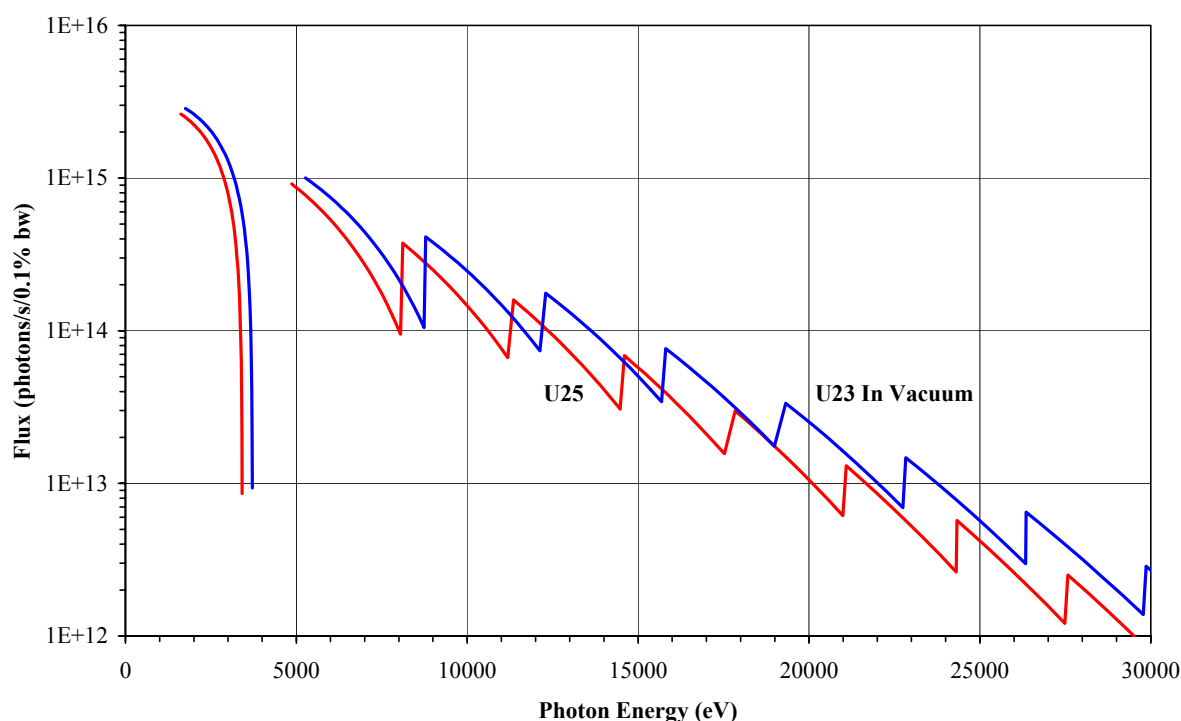


Figure 2.6-6 Spectral flux comparison between a 23 mm period in-vacuum undulator and a 25 mm period out of vacuum undulator.

The flux into the beamline aperture for undulators with ~ 3 degree phase errors has been calculated and the results given in Table 2.6-6. The advantage of the in-vacuum undulator is significant and therefore the U23 IV undulator has been selected for two out of the three beamlines. The third beamline will also be an in-vacuum undulator of the same length but it may opt for a shorter period to enhance the higher energy radiation at the expense of tunability. Then, if DIAMOND performs beyond the present specification and allows the 7 mm minimum gap to be reduced further during operations a shorter period device would have significant advantage. This is a somewhat risky approach but can be justified for a user community which has three very similar beamlines. A summary of the selected ID for two of the three beamlines is

B.2 INSERTION DEVICES

given in Table 2.6-7. The period of the third ID will be selected in the next three months.

Table 2.6-6 Estimated spectral flux (photons/s/0.1%) at key photon energies for realistic undulator models with ~3 degree phase error.

Name	Magnet Gap (mm)	7.1 keV	11.6 keV	12.3 keV	12.7 keV	13.5 keV
U23 IV	7	1.6E+14	2.9E+13	3.5E+13	2.9E+13	2.1E+13
U25	10	9.5E+13	2.9E+13	2.1E+13	1.7E+13	1.1E+13

Table 2.6-7 Summary of the parameters of the insertion device for the protein crystallography beamlines.

Type of Insertion Device	Undulator
Magnet Technology	In-Vacuum Permanent Magnet
Peak Field (T)	0.70
Magnet Period (mm)	23
Number of Periods	85
K_{Max}	1.49
Nominal Magnet Gap (mm)	7
Nominal Length (m)	2.0
Total Power at 300 mA (kW)	1.7
On Axis Power Density at 300 mA (kW/mrad ²)	15.6

2.6.4 Microfocus XAS Beamline

(a) Insertion Device Requirements

This beamline will be a medium energy microfocus beamline for X-ray spectroscopy. The beamline proposal [23] contains an outline insertion device specification and this has been refined at a meeting of the Beamline Working Group [27]. An undulator is proposed because high flux levels are required in a small phase space area with minimal power being absorbed by the beamline elements.

The flux generated by the undulator in the central cone should be maximised over the beamline photon energy range of the beamline, which is between 1.5 and 20 keV. The spectral coverage of the insertion device should be continuous over this energy range.

Tapering of the undulator to broaden the harmonic widths at the expense of flux is required. Scans are likely to cover 1000 eV so as broad a harmonic as is practically possible would be useful, especially during early commissioning of the beamline.

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(b) Selection of the Insertion Device

Three types of undulator have been compared; a 5 m device with a 15 mm magnet gap, a 2 m device with a 10 mm magnet gap and a 2 m in-vacuum (IV) device with 7 mm magnet gap. The longer device with the larger gap was discarded because the consequence of providing continuous radiation from 2 keV upwards is that the flux at 20 keV is not competitive. A direct comparison between the optimum of each type of 2 m undulator is given in Figure 2.6-7.

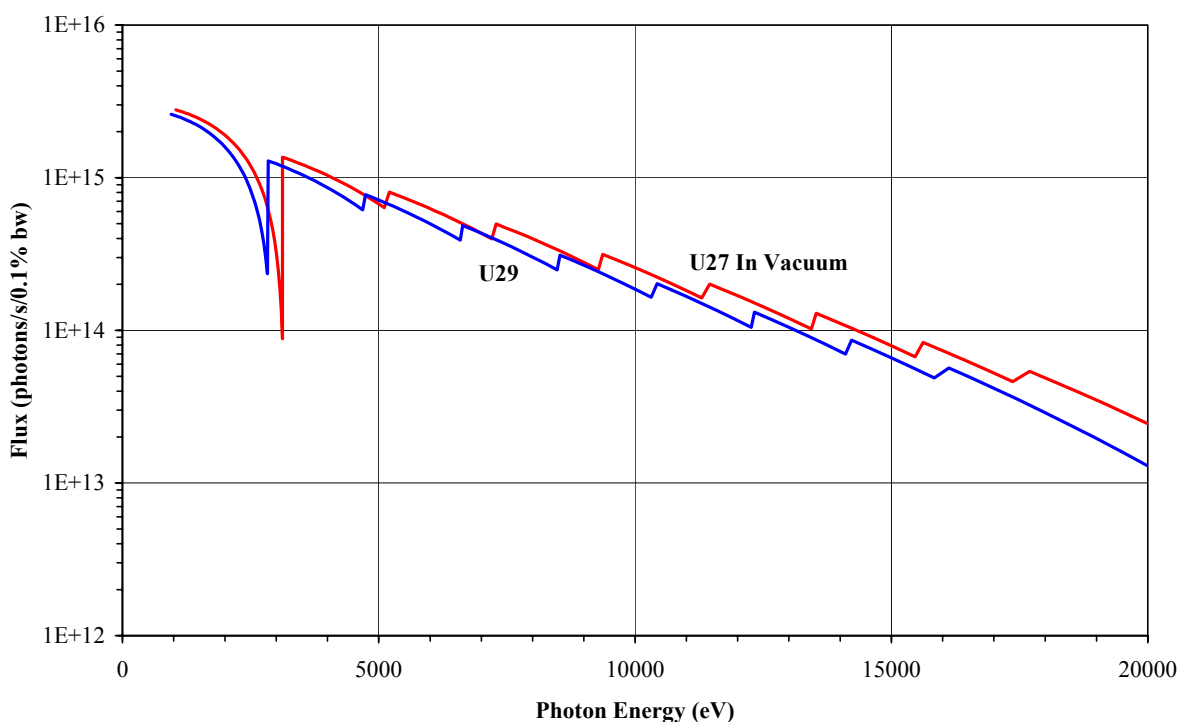


Figure 2.6-7 Spectral flux comparison between a 27 mm period in-vacuum undulator and a 29 mm period out of vacuum undulator.

The flux into the beamline aperture for undulators with ~ 3 degree phase errors has been calculated and the results given in Table 2.6-8. The advantage of the in-vacuum undulator is significant and therefore the U27 IV undulator has been selected for this beamline. A summary of the selected ID for this beamline is given in Table 2.6-9.

Table 2.6-8 Estimated spectral flux (photons/s/0.1%) at particular photon energies for realistic undulator models with ~ 3 degree phase error.

Name	Magnet Gap (mm)	2keV	7keV	12keV	20keV
U27 IV	7	7.6E+14	1.3E+14	2.0E+13	2.1E+12
U29	10	6.3E+14	9.4E+13	1.4E+13	1.2E+12

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Table 2.6-9 Summary of the parameters of the insertion device for the Microfocus XAS Beamline.

Type of Insertion Device	Undulator
Magnet Technology	In-Vacuum Permanent Magnet
Peak Field (T)	0.80
Magnet Period (mm)	27
Number of Periods	72
K_{Max}	2.02
Nominal Magnet Gap (mm)	7
Nominal Length (m)	2.0
Total Power at 300 mA (kW)	2.2
On Axis Power Density at 300 mA (kW/mrad ²)	15.3

2.6.5 SXR for Nanostructures Beamline

(a) Insertion Device Requirements

This beamline will be a soft X-ray beamline dedicated to the study of nanostructures. The beamline proposal [23] contains an outline insertion device specification and this has been refined at a meeting of the Beamline Working Group [28].

An insertion device is required that can provide variable polarization and high flux over the prime energy range of the beamline which is between 200 eV and 1300 eV. In particular, left and right circular, linear horizontal and vertical are required to be available. Arbitrary, selectable linear polarization is also required. The photon energy range in linear polarisation mode will be much wider and this will determine the operating range of the beamline, this operating range must provide continuous cover between 80 and 1500 eV.

In each chosen polarization state, the light should be at least 95% polarized in the selected mode in the central cone of the undulator. The speed with which the polarization can be switched between, say, left and right circular is likely to be slow (several seconds) because of mechanical movements and this is understood. However, every effort should be made to make this switching time as fast as possible. The concept of two undulators separated in the beamline by an angle or position offset has been rejected.

(b) Selection of the Insertion Device

An APPLE 2 device (see section 2.4.3) has been assumed for this beamline as it matches the ID requirements well. This is a somewhat self-fulfilling prophesy because the ID requirements were written with this type of ID in mind. Alternative helical undulators may be studied over the next three months if significant advantages over the APPLE 2 can be perceived.

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Once the decision for the APPLE 2 technology is made the choice of period is quite straightforward. In fact, the requirement for horizontal polarization down to 80 eV is the limiting factor and this requires a period of 64 mm for a 5 m device with a 15 mm gap. The flux and brightness for this undulator is given in Figure 2.6-8 and Figure 2.6-9. A summary of the ID parameters is given in Table 2.6-10.

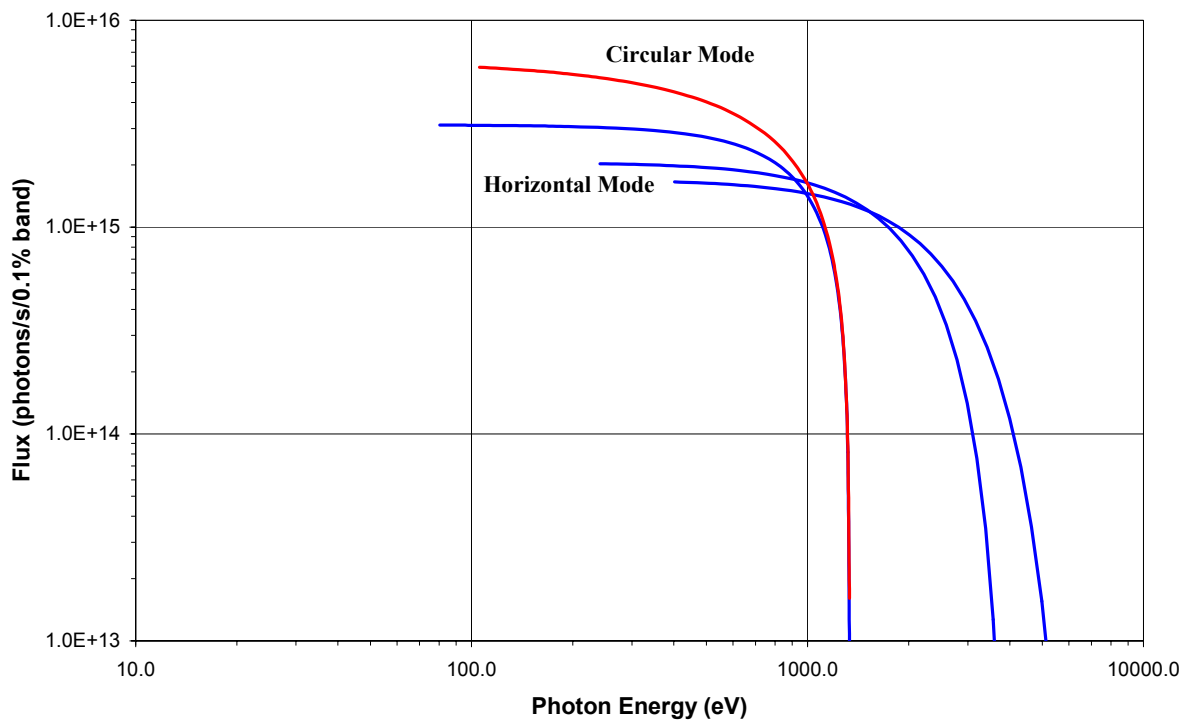


Figure 2.6-8 Spectral flux for 64 mm period APPLE 2 helical undulator.

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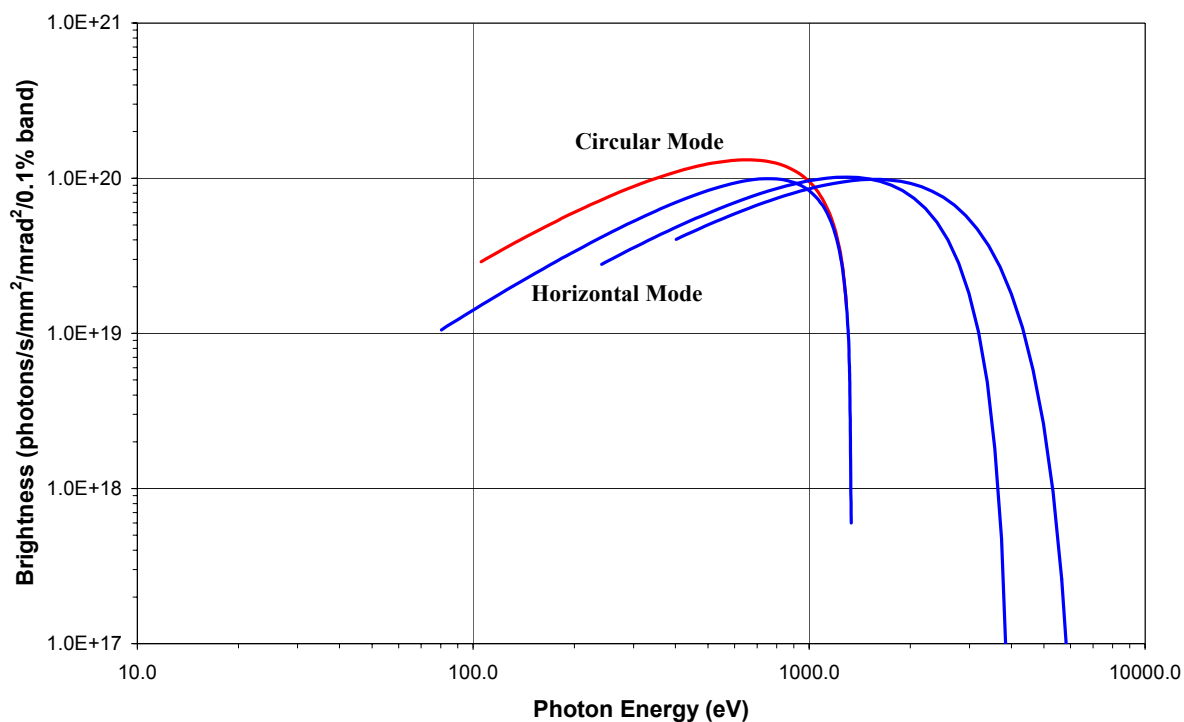


Figure 2.6-9 Spectral brightness for 64 mm period APPLE 2 helical undulator.

Table 2.6-10 Summary of the parameters of the insertion device for the SXR for Nanostructures Beamline.

Type of Insertion Device	Helical Undulator
Magnet Technology	Permanent Magnet APPLE 2
Magnet Period (mm)	64
Number of Periods	75
Nominal Magnet Gap (mm)	15
Nominal Length (m)	5.0
Peak Field in Horizontal Mode (T)	0.94
Peak Field in Vertical Mode (T)	0.72
Peak Field in Circular Mode (T)	0.57
K_{Max} in Horizontal Mode	5.6
K_{Max} in Vertical Mode	4.3
K_{Max} in Circular Mode	3.4
Minimum Photon Energy in Horizontal Mode (eV)	80
Minimum Photon Energy in Vertical Mode (eV)	130
Operating Range in Circular Mode (eV)	106 to 1300

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2.6.6 Non-Crystalline Diffraction Beamline

(a) Insertion Device Requirements

This beamline will be dedicated to non-crystalline diffraction. The beamline proposal [23] contains an outline insertion device specification and this has been refined at a meeting of the Beamline Working Group [29].

The flux generated by the insertion device and transmitted through the 100 μ rad horizontal $\times$ 25 μ rad vertical beamline aperture should be continuous over the photon energy range of the beamline which is between 6.5 and 20 keV. The beamline should also be able to operate at one key photon energy that does not fall within the photon energy range, this corresponds to the Calcium K edge (4.04 keV).

Low divergence of the beam in both planes is necessary in order to minimise the smearing at the detector and this implies the use of an undulator rather than a multipole wiggler. Tapering of the undulator to broaden the harmonic widths at the expense of flux is not required.

(b) Selection of the Insertion Device

Three types of undulator have been compared; a 5 m device with a 15 mm magnet gap, a 2 m device with a 10 mm magnet gap and a 2 m in-vacuum (IV) device with 7 mm magnet gap. A direct comparison between the optimum of each type of undulator is given in Figure 2.6-10.

B.2 INSERTION DEVICES

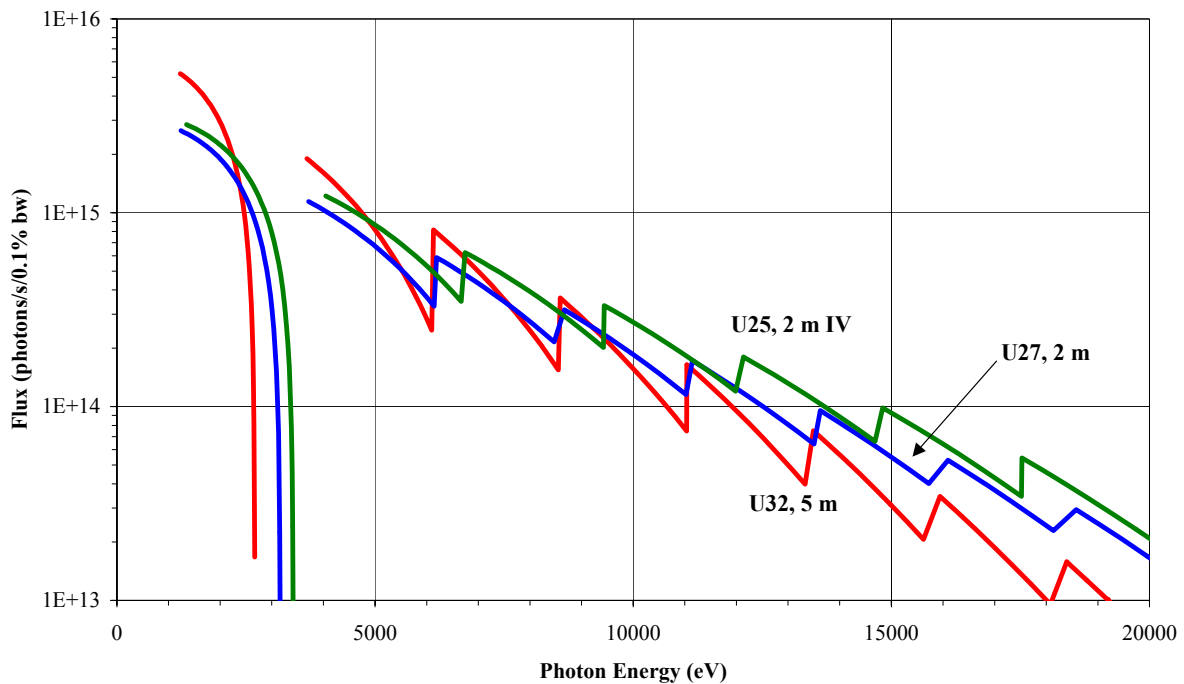


Figure 2.6-10 Spectral flux comparison between a 25 mm period in-vacuum undulator, a 27 mm period 2 m out of vacuum undulator and a 32 mm period 5 m out of vacuum undulator.

The flux into the beamline aperture for undulators with ~ 3 degree phase errors has been calculated and the results given in Table 2.6-11. The 5 m, 15 mm gap device is rejected because of the relatively poor performance at the high photon energy end. Also the advantage of the in-vacuum undulator is not considered significant in this case when compared to the increased cost and risk to the storage ring vacuum and therefore the U27 undulator has been selected for this beamline. A summary of the selected ID for this beamline is given in Table 2.6-12.

Table 2.6-11 Estimated spectral flux (photons/s/0.1%) at particular photon energies for realistic undulator models with ~ 3 degree phase error.

Name	Magnet Gap (mm)	4 keV	6.5 keV	12 keV	20 keV
U25 IV	7	4.6E+14	1.5E+14	2.4E+13	2.3E+12
U27	10	4.0E+14	1.5E+14	2.0E+13	1.7E+12
U32	15	7.6E+14	2.4E+14	1.9E+13	7.7E+11

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Table 2.6-12 Summary of the parameters of the insertion device for the Non-Crystalline Diffraction Beamline.

Type of Insertion Device	Undulator
Magnet Technology	Permanent Magnet
Peak Field (T)	0.70
Magnet Period (mm)	27
Number of Periods	72
K_{Max}	1.76
Nominal Magnet Gap (mm)	10
Nominal Length (m)	2.0
Total Power at 300 mA (kW)	1.7
On Axis Power Density at 300 mA (kW/mrad ²)	13.4

2.6.7 Summary of the First Insertion Devices

Table 2.6-13 summarises the proposed first eight insertion devices for 'Day 1' operation on DIAMOND. The flux and brightness for all of these devices is given in Figure 2.6-11 and Figure 2.6-12.

Table 2.6-13 Summary of the parameters of the first insertion devices for DIAMOND.

Name	Beamline	Technology	B_{Max} (T)	K_{Max}	Period (mm)	N_{Periods}	Length (m)
MPW60	VHE	SC MPW	3.5	19.6	60	16	1.0
U33	Materials	Und	0.54	1.66	33	149	5.0
U23 IV a	PX	IV Und	0.70	1.49	23	85	2.0
U23 IV b	PX	IV Und	0.70	1.49	23	85	2.0
U23 IV c	PX	IV Und	0.70	1.49	23	85	2.0
U27 IV	XAS	IV Und	0.80	2.02	27	72	2.0
HU64	SXR	Helical Und	0.57	3.4	64	75	5.0
U27	NCD	Und	0.70	1.76	27	72	2.0

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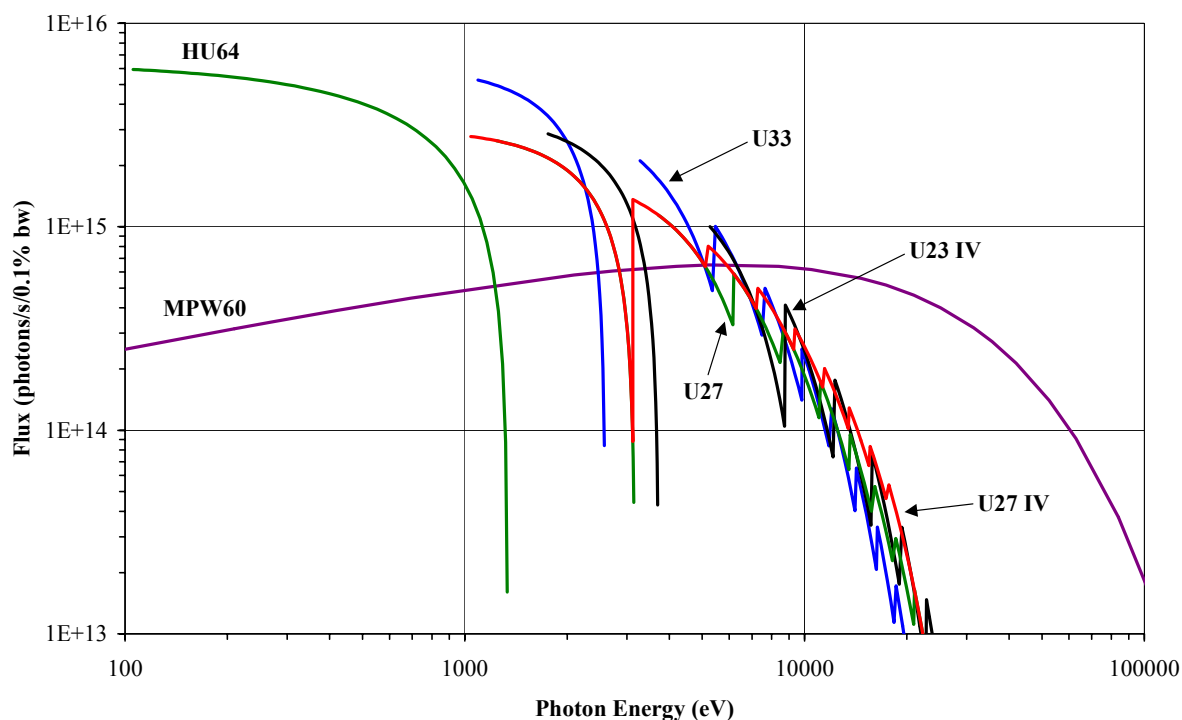


Figure 2.6-11 The spectral flux for the first insertion devices for DIAMOND. The MPW flux is for one horizontal mrad.

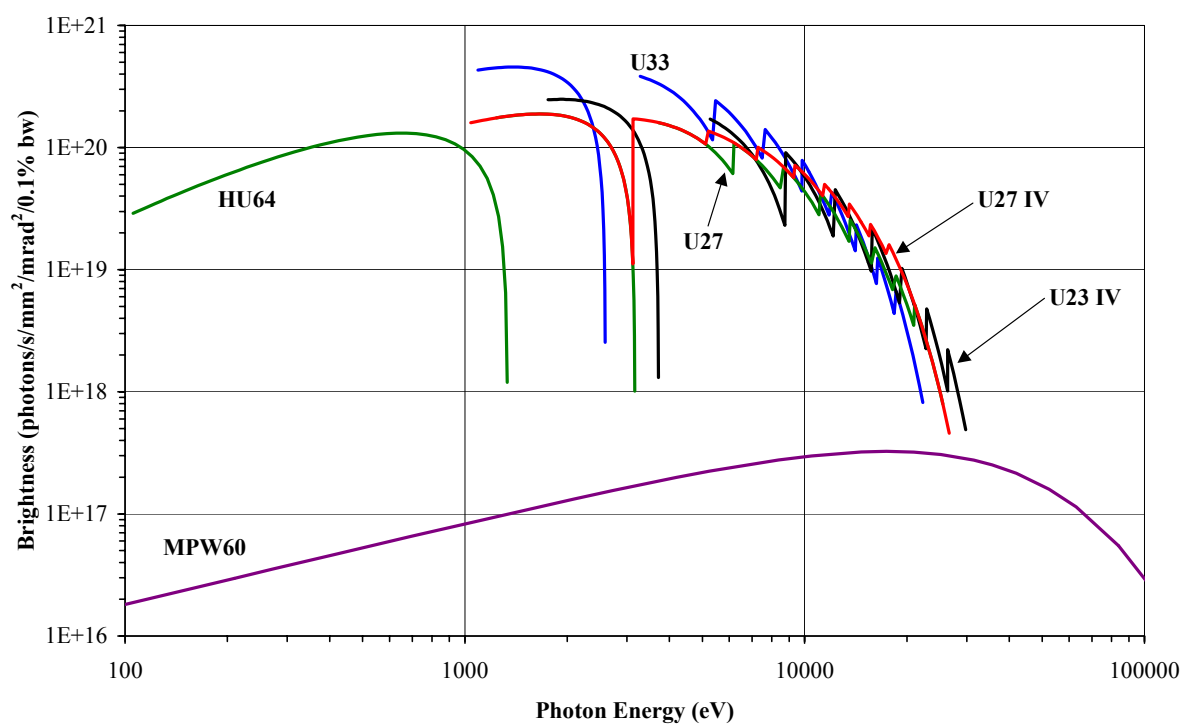


Figure 2.6-12 The spectral brightness for the first insertion devices for DIAMOND.

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B.2 INSERTION DEVICES

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[25] Beamline 6 Working Group Meeting held at DL on 29th January 2002.

[26] PX Working Group Meeting held at RAL on 28th November 2001.

[27] Beamline 13 Working Group Meeting held at DL on 27th February 2002.

[28] Beamline 14 Working Group Meeting held at DL on 22nd February 2002.

[29] Beamline 11 Working Group Meeting held at DL on 25th January 2002.

B.3 Front-Ends

3.1 INTRODUCTION

The aim of this section is to describe in general terms the front-ends of DIAMOND. The specification will look at the different issues that affect the front-end and cover the major design problems to be solved. The document will define a typical overall layout of the front-end and the design philosophies to be used. The result will be a document that can be used in discussion with suppliers or can be expanded to provide tight specifications for individual components.

On DIAMOND's storage ring there are 48 dipole magnets, 18 x 5m 'straights', and 6 x 8m 'straights'. The front-ends are the section of the synchrotron that runs between the storage ring and the shield wall (see Figure 3.1-1). The front-ends in effect connect the storage ring to the beamlines. There is provision for 48 front-ends. 24 front-ends will be used for synchrotron radiation created from dipoles (BM front-ends) and 22 will be used for synchrotron radiation created from the insertion devices in the 'straights' (ID front-ends). There will be special arrangements in 'straights' 1 and 17 which are used for injection and RF.

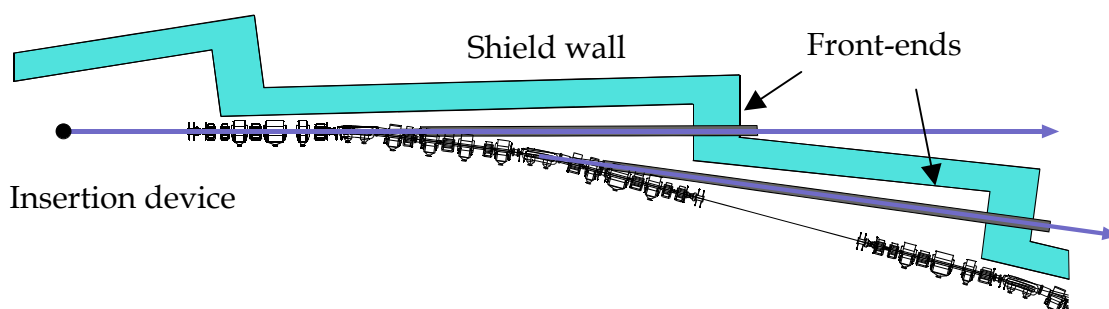


Figure 3.1-1 Front-end position

The front-ends then, interact with the beamlines, the storage ring, and insertion device radiation and are affected by the design of all these sections. Other factors also affect the design, issues that are common to the whole machine, for example the quality of the services within the building. In section 3.2 these outside factors are looked at and described in detail.

After establishing design constraints common throughout the whole machine, we can look at ones more specific to the front-ends. A major factor that affects the design is the location within the building of the front-ends. The physical constraints so to speak.

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In section 3.3 the space constraints of the front-end and the required beam apertures through the front-end are given.

Section 3.4 looks more specifically at the functions to be carried out by the front-ends. It looks individually at the components used to carry out these functions and discusses issues particular to each component. This leads on to section 3.5, which looks at design issues that apply to the front-end as a whole. Section 3.6, looks at the proposed layout of the standard insertion device front-end with respect to the issues raised in section's 3.4 and 3.5 and goes through the design rationale of the solution proposed.

Section 3.7 lists some of the front-ends on the ESRF and other machines so that a comparison may be made between the front-end in section 3.6 and other 3rd generation front-ends.

Finally, section 3.8 goes on to look at the procurement method for the front-ends.

3.2 GENERAL SPECIFICATIONS

This section describes services required and other information that will be required in order to design the front-ends.

3.2.1 MACHINE SPECIFICATIONS

(a) AIR SERVICE

Level of Lubrication:	Oil free air
Level of filtration:	10 micron minimum
Pressure:	9 bar

All solenoids for pneumatic equipment must be compatible with oil-free air.

(b) WATER SERVICE

There are to be two water supplies. The demineralised supply is used to provide water to the magnets on the storage ring, as well as general cooling on the front-ends and beamlines. Aluminium components will not be connected to this circuit and will have a local system connected through a heat exchanger.

Demineralised water system

Inlet Pressure:	10 bar
Water inlet temperature:	22°C
Electrical isolation:	0.1 mS/m or Grade 2 BS ISO 3696:1995
Oxygen level:	To be de-oxygenated

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Wetted surfaces: Oxygen free Copper or stainless steel

All solders to be demineralised water compatible. No joints allowable inside vacuum.

Non-demineralised cooling water supply

Inlet Pressure:	10 bar
Water inlet temperature:	22°C
Water quality	Bio-inhibited water.
Wetted surfaces:	Aluminium.

No joints are permissible inside vacuum.

(c) ELECTRICITY SERVICE

Three phase Voltage:	400V
Single phase Voltage:	230V
Frequency:	50Hz
Control Voltage:	24Vdc

All equipment supplied must be CE marked and conform to BS 7671:1992 and the Electricity at Work Regulations and where appropriate must comply with The Low Voltage Directive (73/23/EC). Wire/cabling sizes and colours are to meet the requirements of the current edition of the IEE Regulations and must comply with the EMC regulations for emission of noise in sensitive environments.

(d) SERVICE ACCESS

The main service routes through the shield wall to the front-ends are shown in Figure 3.2-1.

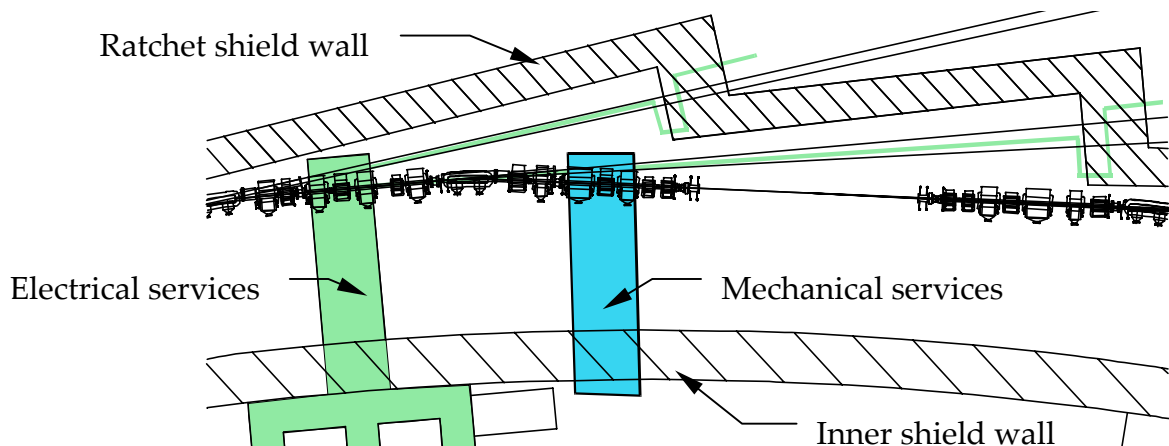


Figure 3.2-1 Service routing

The main services will come through the inner shield wall although there is also limited access for cables through the ratchet shield wall.

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(e) ELECTRON BEAM

Beam energy actual:	3	GeV
Beam current initial:	300	mA
Total Dipole Power Initial:	300	kW
Total Dipole Power Initial Design:	330	kW (design)
Single Dipole Power Initial:	6.3	kW
Single Dipole Power Initial Design:	7	kW (design)
Beam Current Future:	500	mA
Total Dipole Power Future:	500	kW
Total Dipole Power Future Design:	550	kW (design)
Single Dipole Power Future:	10.5	kW
Single Dipole Power Future Design:	11.6	kW (design)

Beam Current Future is an upgrade route for DIAMOND. Beam Current Initial is the initial current that will be run on DIAMOND. The difference in cost between the two options will determine if the front-end components will be designed to the Beam Current Initial figures or the Beam Current Future.

(f) STANDARD BM RADIATION SOURCE APERTURES

Dipole Vertical aperture	3	mrads (+1.5 to -1.5 mrads)
Dipole Horizontal aperture	20	mrads (+5 to +25 mrads)
Single Dipole Power Initial	48	W/mrad
Single Dipole Power Initial (+10%)	52.8	W/mrad (design)
Single Dipole Power Future	80	W/mrad
Single Dipole Power Future (+10%)	88	W/mrad (design)
B – Field	1.4	T
Bend radius	7.1429	m

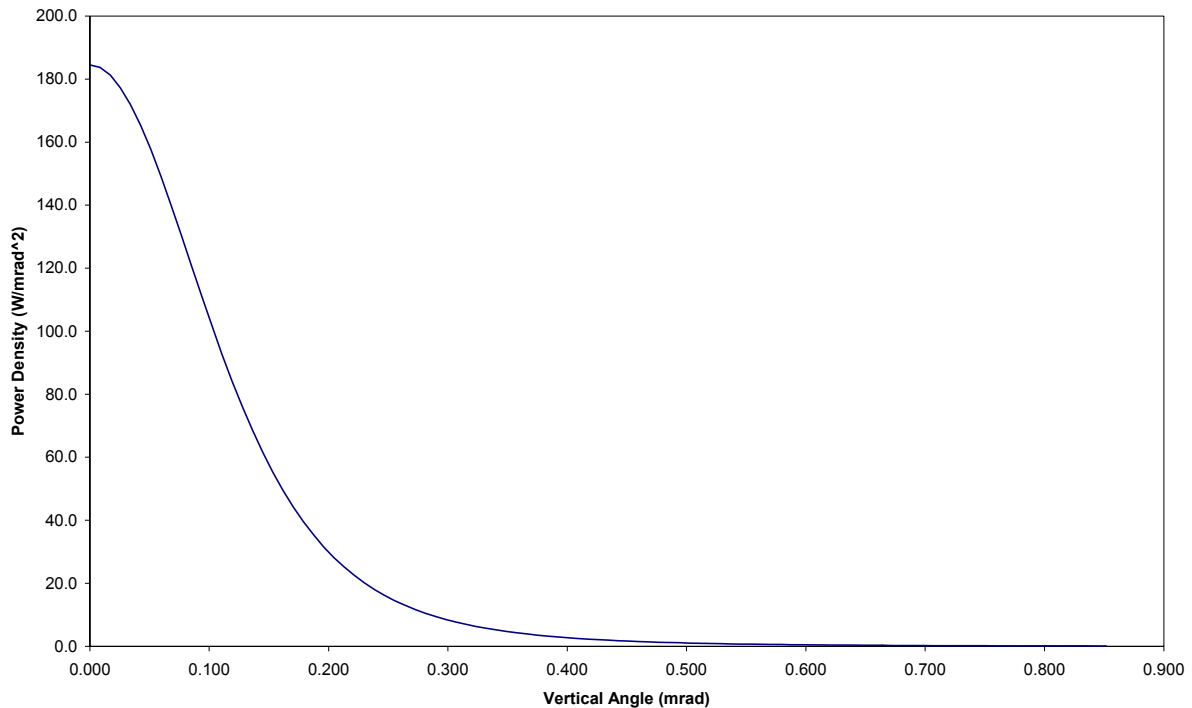


Figure 3.2-2 Dipole Power Density Graph Initial:

(g) SPECIAL BM RADIATION SOURCE APERTURES

CD BM Radiation Source Apertures

Dipole Vertical aperture	8	mrads (+4 to -4 mrads)
Dipole Horizontal aperture	35	mrads (0 to +35 mrads)
Single Dipole Power Initial	48	W/mrad
Single Dipole Power Initial (+10%)	52.8	W/mrad (design)

Single Dipole Power Future	80	W/mrad
Single Dipole Power Future (+10%)	88	W/mrad (design)

IR BM Radiation Source Apertures

Dipole Vertical aperture	30	mrads (+15 to -15 mrads)
Dipole Horizontal aperture	35	mrads (0 to +35 mrads)
Single Dipole Power Initial	48	W/mrad
Single Dipole Power Initial (+10%)	52.8	W/mrad (design)

Single Dipole Power Future	80	W/mrad
Single Dipole Power Future (+10%)	88	W/mrad (design)

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(h) STANDARD 5m STRAIGHT ID RADIATION SOURCE APERTURES

Undulators

Undulator Vertical aperture	1	mrad (+0.5 to -0.5 mrads)
Undulator Horizontal aperture	1	mrad (+0.5 to -0.5 mrads)

A typical Undulator output is between 1 and 6kW at 300mA
A typical Undulator output is between 2 and 10kW at 500mA
A typical max power density for an undulator is 22kW/mrad².

Wavelength Shifter

Wavelength Shifters Vertical aperture	1	mrad (±0.5 mrads)
Wavelength Shifters Horizontal aperture	10	mrads (±5 mrads)

A typical Wavelength Shifters output is 8kW at 300mA
A Typical Wavelength Shifters output is 14kW at 500mA

Superconducting Multipole Wigglers

Multipole Wiggler Vertical aperture	1	mrad (±0.5 mrads)
Multipole Wiggler Horizontal aperture	10	mrads (±5 mrads)
B-Field	3.5	T
No. of periods	24	
Period length	60	mm

Typical Superconducting Wiggler output is 31kW at 300mA

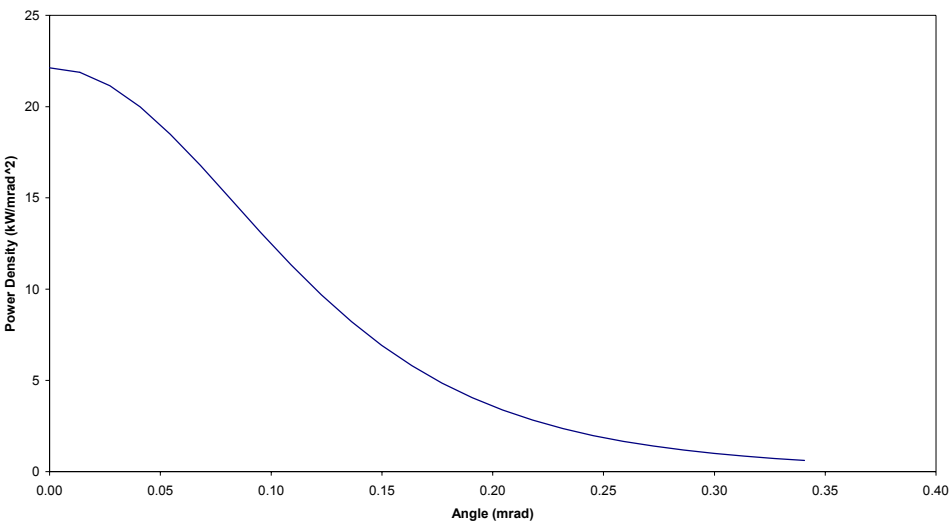


Figure 3.2-3 Power density on vertical axis

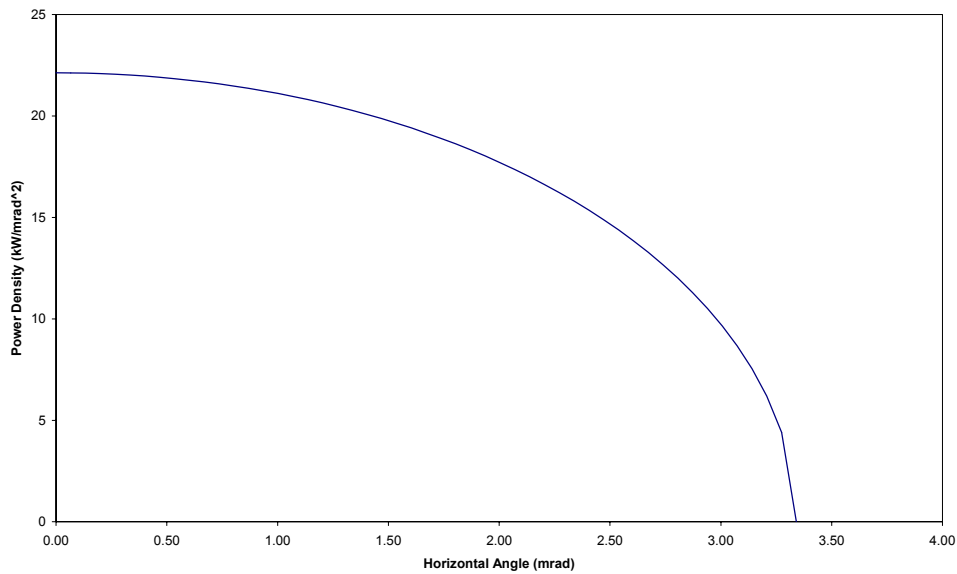


Figure 3.2-4 Power density on horizontal axis

Permanent Magnet Multipole Wigglers

Multipole Wiggler Vertical aperture	1	mrad (± 0.5 mrad)
Multipole Wiggler Horizontal aperture	10	mrads (± 5 mrad)
B-Field	2.25	T
No. of periods	24	
Period length	200	mm

Typical Wiggler output is 43kW at 300mA

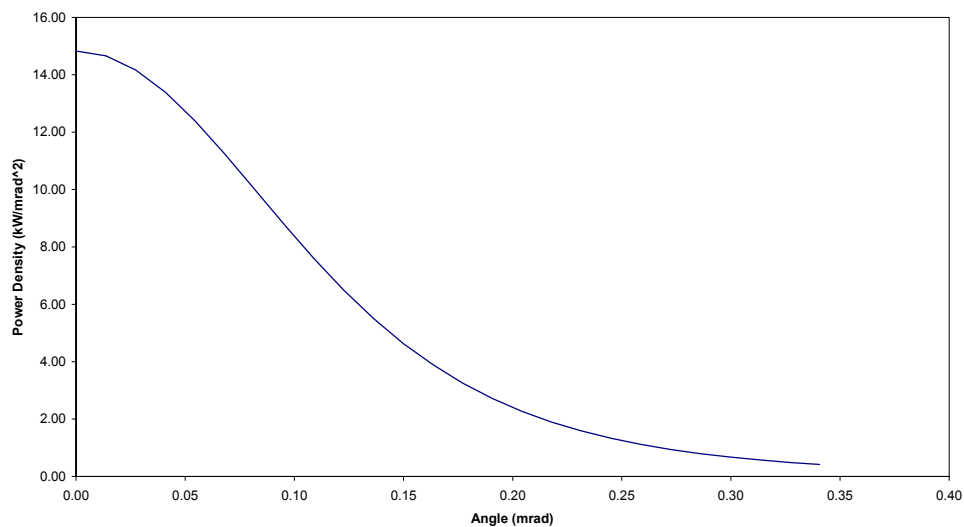


Figure 3.2-5 Power density on vertical axis

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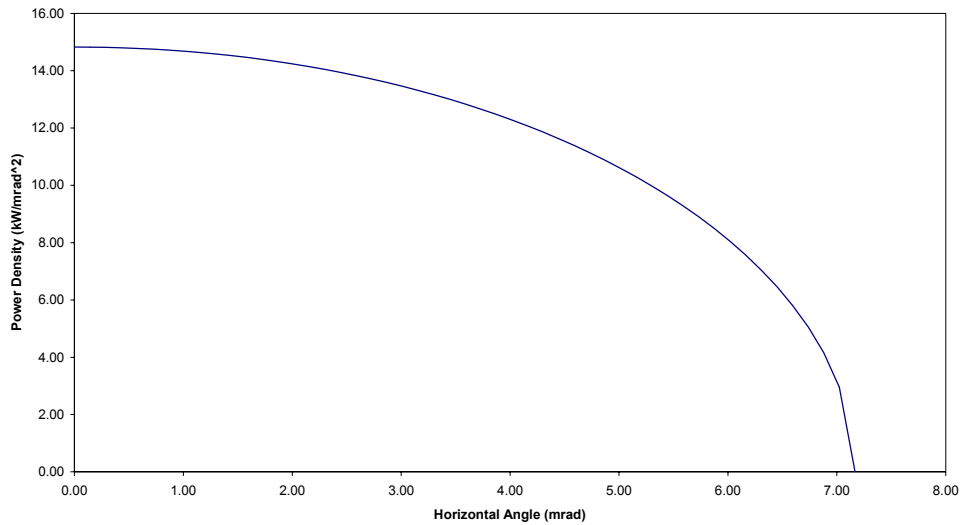


Figure 3.2-6 Power density on horizontal axis

(i) VACUUM LEVELS

Static pressure in storage ring and front-ends: (To be achieved after 100Ahr of beam conditioning.)	10^{-10}	mbar
Dynamic vacuum level in storage ring and front-ends:	$<10^{-9}$	mbar

(j) BEAM HEIGHT

Height of electron beam above floor:	1400	mm

3.3 FRONT-END SPACE CONSTRAINTS

There are two basic space constraints on the footprint of the front-end: the ratchet shield wall and the acromat. This is true for all types of front-ends. This section will look at a number of different front-end types, all of which have to fit into one of two positions: BM front-ends, or ID front-ends.

3.3.1 BM FRONT-ENDS

Each of the bending magnets on DIAMOND produces 131mrads of synchrotron radiation. 35mrads of radiation go into the entrance of every BM front-end via the connection flange on the storage ring. There are two different types of BM front-ends. Standard BM front-ends and Special BM front-ends. The majority of the front-ends will be Standard BM front-ends; these then should be a standard design. The Special BM front-ends have to be individually designed for each beamline and so will only be introduced in this specification.

(a) STANDARD BM FRONT-ENDS

Standard front-ends require the delivery of 20mrads of uncollimated synchrotron radiation up to the shield wall. There is the possibility of passing this 20mrads of radiation through the shield wall to the optics and experimental areas.

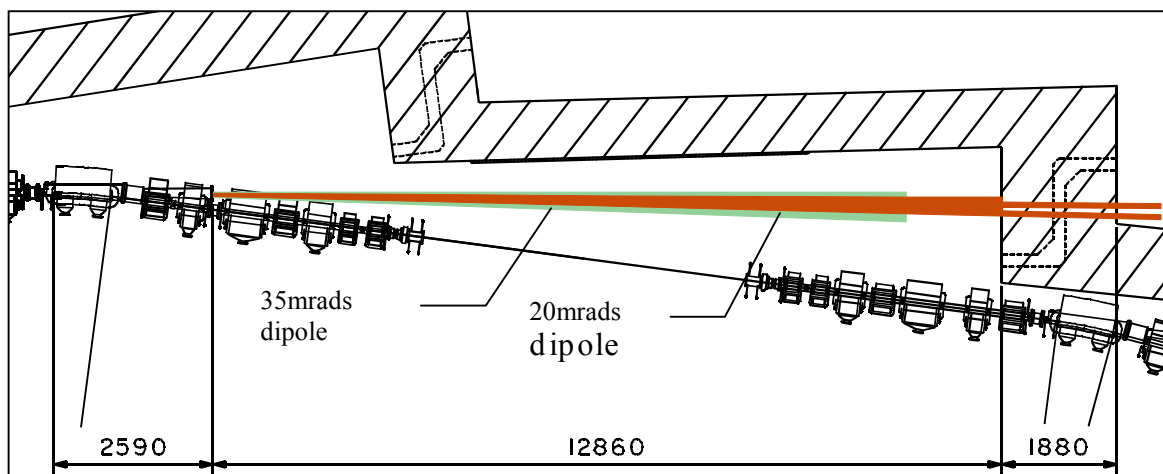


Figure 3.3-1 Space constraints of Standard Bending Magnet (Dipole) front-ends

Although the standard BM front-end only passes 20mrads of radiation, 35mrads enter the front end and so 15mrads must be absorbed. The first 5mrads that enter are poor quality due to end effects from the dipole magnet and must be absorbed. The next 20mrads of synchrotron radiation are suitable for the standard BM front-ends and can be used in experiments. The final 10mrads do not fit through the shield wall thus must be removed. This is shown in Figure 3.3-1.

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(b) SPECIAL BM FRONT-ENDS

The special BM front-ends are those that will have no standard design. These include front-ends for CD and IR beamlines. CD front-ends require 35mrad horizontal by 8mrad vertical of BM radiation. This has to be extracted through the front-end. IR Front-ends require 35mrad horizontal by 30mrad vertical, this is taken out in a specially constructed dipole chamber.

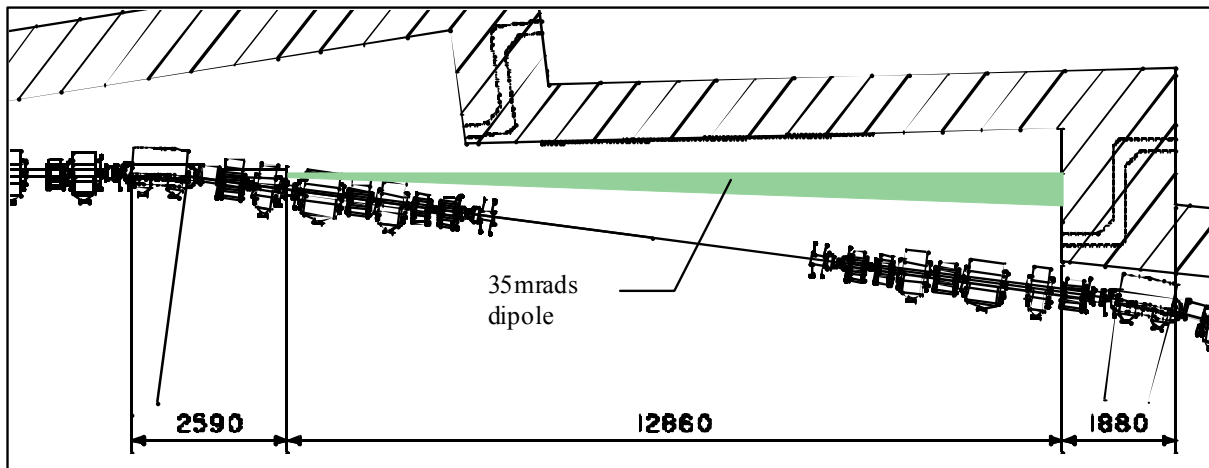


Figure 3.3-2 Space constraints of Special Bending Magnet (Dipole) front-ends.

Figure 3.3-2 shows that it would be possible to have 35mrad horizontally of radiation up to the shield wall. Due to shielding constraints only the first 25mrad could pass through the shield wall. It is much more likely that the 35mrad would be collimated or focussed at an earlier stage to allow more beam through the shield wall while reducing the size of the optical elements required.

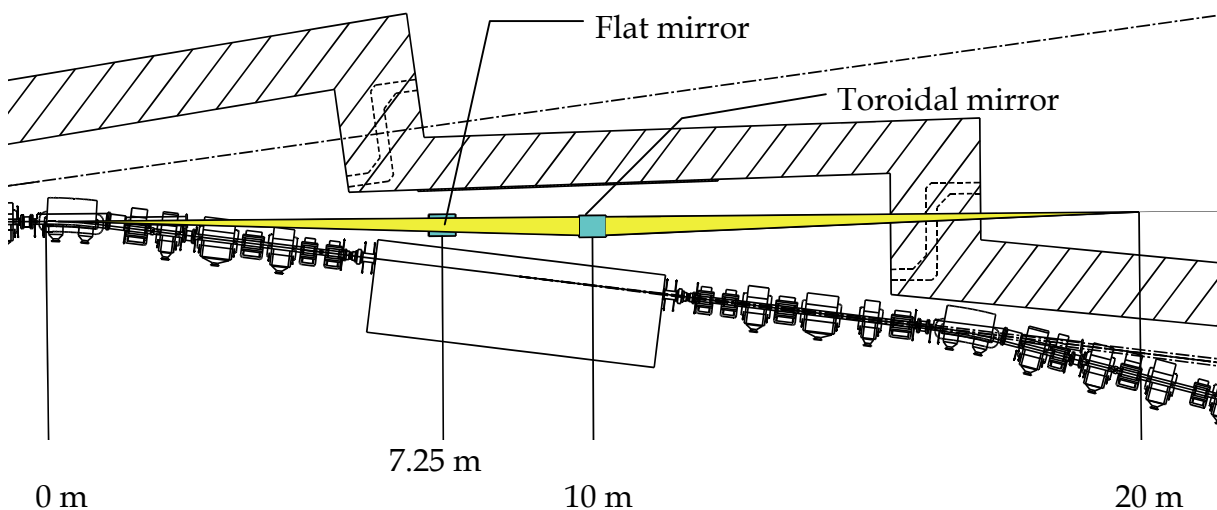


Figure 3.3-3 Example CD schematic plan

B.3 FRONT-ENDS

Figure 3.3-3 shows a plan view of an example CD line that could fit within the imposed space constraints. It consists of: a plain mirror and a toroidal mirror. The plain mirror is at a 10° angle vertically (400mm wide [across the beam] by 500mm long [along the beam]) and deflects the beam vertically by 20° and is placed at 7.25m from the source. The toroidal mirror, placed 10m from the source is at a -10° angle vertically (400mm by 500mm) it deflects the beam back to horizontal and provides 1:1 focussing. This gives a focus at 20m from tp. Provision is to be made for a toroidal grating of similar size to mirror 2 placed beside mirror 2 and able to slide into place to replace mirror 2. The mirror is to be used for dispersive CD and the grating for monochromatic CD.

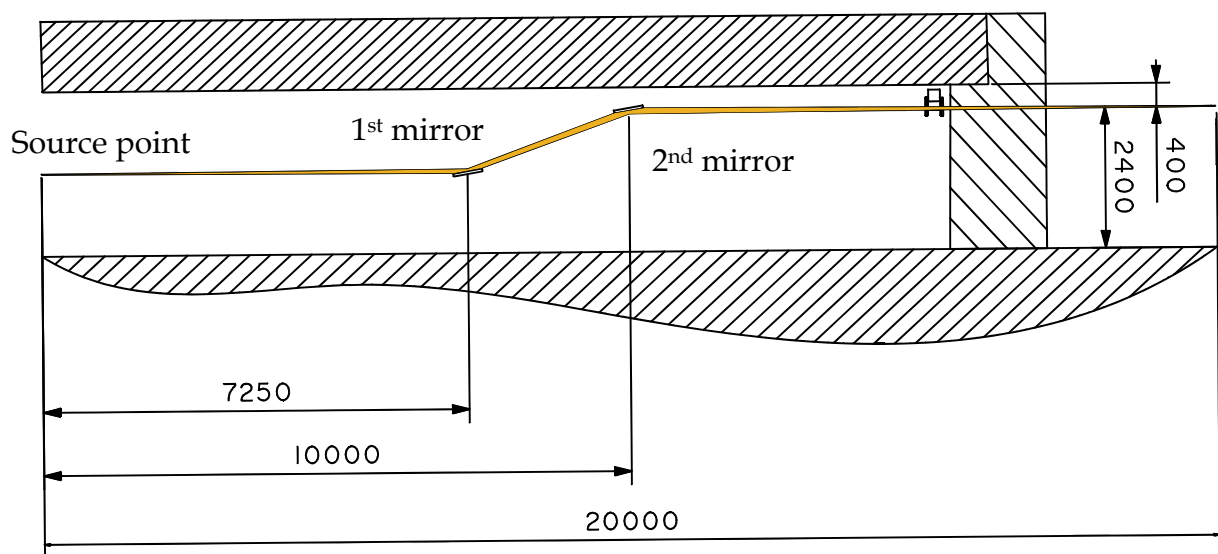


Figure 3.3-4 Example CD schematic elevation

Figure 3.3-4 Shows the beam height in order to show how much room there is between the beam and tunnel roof. This may affect the design of some of the components forcing them to become more compact.

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IR Beamline

IR front-ends require 35mrad horizontal by 30mrad vertical of dipole radiation. This necessitates a mirror in the dipole vessel that will extract the radiation vertically and collimates or focuses it at an early stage.

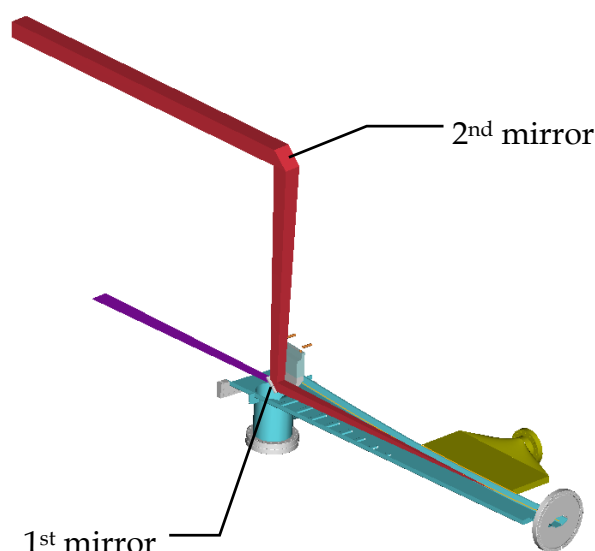


Figure 3.3-5 Example IR beamline schematic

Figure 3.3-5 shows a mirror arrangement that would be positioned within a specially designed dipole vessel. The 1st mirror is a flat mirror with a slit in the middle to let the x-rays continue on while deflecting the longer wavelength beam upwards. The 2nd mirror is a toroidal mirror that collimates or focuses the diverging beam, whilst bringing the beam back to the horizontal.

3.3.2 ID FRONT-ENDS

Each ID front-end has an aperture of 10mrad from the front flange on the crotch vessel. This 10mrad will contain both synchrotron radiation from IDs in the 'straights' and some unwanted BM radiation from the dipoles. Only the ID radiation is desired, however, and so as much as possible of the BM synchrotron radiation is absorbed. The space constraints for all ID front-ends are the same for both the 8m and 5m 'straights'. Many different types of insertion device can be fitted into a 'straight'; these are listed as follows:

- Undulators
- Wigglers
- Wavelength shifters
- Combinations

B.3 FRONT-ENDS

It is proposed to design a Standard ID front-end that will cater for as many cases as possible, though special designs will be used when the standard design is not practical.

(a) STANDARD ID FRONT-ENDS

It is proposed to have a standard front-end layout that can cater for single Undulators, single Wigglers, single wavelength shifters and multiple co-linear Undulators. This is to be achieved by allowing 10mrads of radiation to pass through to the shield wall in every standard ID front-end (See Figure 3.3-6). A further advantage of this is that if a single Undulator beamline is altered to a multiple Undulator beamline in the future, it may be possible to have the same front-end.

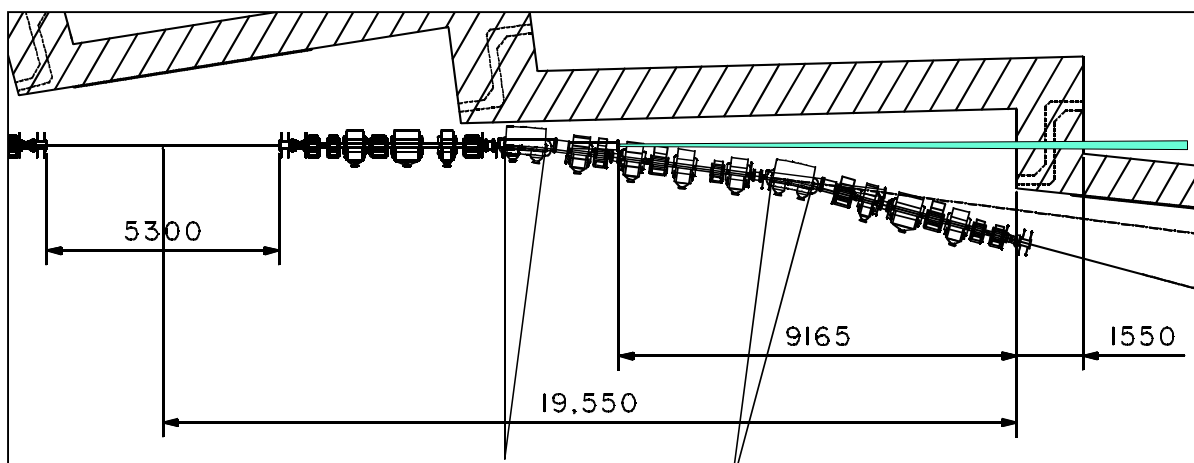


Figure 3.3-6 Space constraints of Insertion Device front-ends

Figure 3.3-6 shows a space acceptable for a front-end from a 5m straight. It is similar for an 8m straight.

(b) SPECIAL ID FRONT-ENDS

Special ID Front-ends are those where there are multiple insertion devices in a 'straight' that are not co-linear. A number of possibilities are available: Multiple Undulators, combination of Undulator and Wiggler, combination of Undulator and Wavelength shifter and further possibilities that may be developed in the future. The combination of insertion devices required depends upon the experiment being carried out. This cannot be foreseen and thus the front-ends may not be of a standard design for these cases.

The term Multiple Undulators is used when there is more than 1 Undulator in a straight. A maximum of 3 Undulators could be positioned in a 5m straight. Individually these would be less powerful than a single 5m Undulator would, as the power output is linear to Undulator length. The advantage of using multiple Undulators is that a number of beams could be obtained from the same front-end. The

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multiple beams can be split into three groups: Co-linear multiple beams, Parallel and offset multiple beams, and Angular offset multiple beams.

‘Co-linear multiple beams’ is a combination consisting of multiple beams travelling down the same centre line, these can be treated similar to a single Undulator and thus come under the Standard ID front-end.

‘Parallel and offset beams’ describes the situation of multiple beams travelling parallel to each other but offset by a small distance (1mm or so). The beams are so close to each other that this situation can be treated similar to a single Undulator design.

‘Angular offset multiple beams’ describes the situation of multiple beams diverging from one another. For example, it is proposed that 3 Undulators could be positioned in the same straight, and between the insertion devices dipoles would be placed. This diverts the electron beam so that it takes an angled path through the insertion device thus producing angular offset beams as shown in Figure 3.3-7.

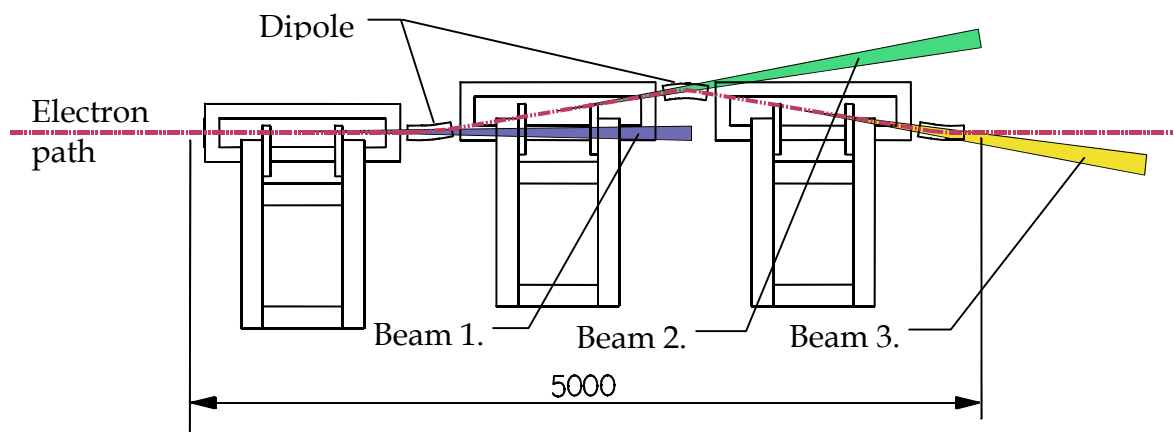


Figure 3.3-7 Angular offset beam production

It should be noted that the angles are exaggerated for clarity.

In order for three beams to pass through the same front-end, the front-end has to have a 10mrads H x 1mrad V aperture (see Figure 3.3-8). This allows three beams spaced as follows: one down the centre and the others at 4mrads to either side. This is the same aperture size as for a wiggler and so 10mrads H x 1mrad V will be the standard aperture size for both undulator and wiggler front-ends.

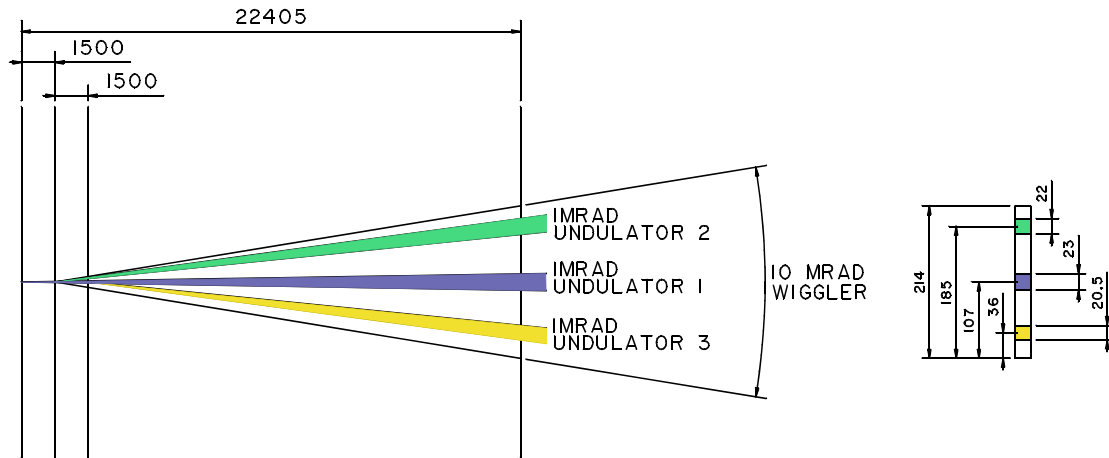


Figure 3.3-8 Undulator beam layout

When an Undulator and Wiggler or wavelength shifter are positioned together in the same straight, the front-end will have to be designed around the exact positioning of the ID beams. This can vary over a large range and so unless the devices are co-linear, there will be no standard design for these cases.

3.4 FRONT-END FUNCTIONS

This section will look at the different functions carried out by the front-end, the components that carry out these functions, and the issues that will need to be taken into account when designing these components.

The main functions that will be looked at in this section are:

- 3.4.1 Beam Quality
- 3.4.2 Beam Diagnostics
- 3.4.3 Defining the beam
- 3.4.4 Optics heat loading
- 3.4.5 Achieving and protecting vacuum
- 3.4.6 Radiation Safety and Operations

3.4.1 BEAM QUALITY

It is essential that beam quality be preserved through the front-ends. This involves preserving the beams' coherence and its polarisation. As far as the front-end design is concerned, this means interfering with the beam as little as possible.

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3.4.2 BEAM DIAGNOSTICS

The primary purpose of beam diagnostics is to monitor the beam position and to provide the required information to the global feedback system to stabilise the beam.

The DIAMOND synchrotron radiation source is being designed as a 'low emittance high brightness' source. In order for the experiments to take advantage of the small source size, it will be necessary for the positional and angular stability of the source to be maintained to a sufficient extent that the beamline optics can deliver a stable photon beam to the sample. Beamline optics will produce an image of the source at the sample (or detector) position. Defining the required stability of this image as 10% of the image dimension leads to a required source stability of 10% of the source size. Single photon beam monitors in a beamline allow the photon beam to be measured at a given point along the beamline. Two such monitors are required to establish the position and angle of the photon beam thereby establishing the source position.

The current FWHM predicted source sizes for DIAMOND are (see table A2 3.4-1)

ID straight 5 m	15	290 microns (v x h)
ID straight 8 m	30	421 microns (v x h)
Bending Magnet	56	127 microns (v x h)

Beamline optics contain both focussing and monochromating elements which may be combined into a single optical element or distributed over several elements. The wavelength (or energy) resolution of the monochromator depends on the angular range of the light accepted, hence angular movements will degrade this resolution. Angular movements also result in changes of the position of the photon beam.

Changes in the source position will be reflected by the optical elements and result in a changed focal spot position. The extent of this movement depends on the magnification factor of the optical arrangement. This is true for vertical and horizontal movements for both undulator and wide fan (bending magnets, multipole wigglers and wavelength shifter) sources leading to similar stability requirements irrespective of the source type.

Typical ID beamline layouts will have optical elements at around 25 metres and the focus at 50 metres. In a bending magnet beamline optical elements can be at around 20 metres. The front-end will allow space for beam position monitors in the region 10 to 15 metres for ID beamlines and 5 to 10 metres for bending magnet beamlines.

Simple geometrical considerations imply, for an ID beamline, ± 0.3 micron vertical positioning of the beam will be required at monitors at both 10 and 15 metres to give the required 10% source stability. Horizontally 3 microns will be adequate. For a bending magnet with monitors at 5 and 10 metres 1.25 microns vertical positioning is required and again 3 microns horizontally. These requirements have implications for the stability and vibration isolation of the position of the photon monitors, optical elements and sample position.

B.3 FRONT-ENDS

Consideration will have to be given to minimising the vibration of the floor and the support columns of the PBPMS and to minimising the drift and thermal movement of the systems if the required accuracy is to be achieved. The mechanical design and accuracy of encoders, motors and electronics need to be consistent with the required sub-micron resolution.

The two devices that define the path of the photon beam need not be identical (e.g. two tungsten vane monitors, or a pinhole and an imaging screen). The most appropriate system should be chosen to match the source properties being monitored. A study into the present state of photon beam position monitors is underway and will report shortly.

Whatever the exact nature of the photon beam position monitoring system chosen, the above requirements imply that that space be provided in the front ends for these devices. This is shown in the schematic diagrams. This also implies that there are no optical elements between the photon beam position monitors and the source.

If the PBPM are to be included in the fast feedback, thought has to be given to the placement and interlock arrangements of valves, absorbers etc. As far as possible these devices should be placed downstream to avoid interruption of the feedback due to port crashes caused by whatever reason. The upstream valves (if any) should be operated manually or triggered only by vacuum problems. They should also provide a trigger to the feedback system so it can take the PBPM out of the servo loop before the valve actually closes.

Photo-emission based monitors are excellent for vertical diagnostics of the photon beams. Typical systematic intrinsic and extrinsic effects that can lead to errors are (not exhaustive):

1. Intrinsic effects :Stray radiation on the blades
 - Blade misalignment
 - Electronics thermal drift
 - Gap dependent effects
2. Extrinsic effects :Magnet power supply noise/ripple
 - Mechanical vibration
 - Thermal effects
 - Insertion device gap changes
 - Ground motion

Each effect will have its own noise spectrum which will contribute to the overall performance of the system.

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Despite the above, resolutions that can typically be achieved are 1 μm at 100 Hz and 0.1 μm at 1 Hz. PBPMs included in the fast feedback system, which will be operating at several kHz update rate, will require careful optimization.

In general with photo-emission based monitors, there is a problem with dipole radiation contaminating ID radiation. Proper consideration of this effect is required before producing a detailed design for the PBPMs.

There may be more than one ID operating in each straight. Depending on detailed design and source specifications it may or may not be possible to supply independent beam diagnostics for each ID.

3.4.3 DEFINING THE BEAM

There are two main types of aperture proposed for experiments. The BM (standard) aperture which defines a “low power density” beam of 20mrads $\times$ 3mrads, and the ID beam aperture which defines a “high power density” beam within a 10mrads $\times$ 1mrad aperture. These beams are the outputs of the front-ends. The input to the front end is the crotch vessel aperture. The crotch vessel aperture for a BM front-end is 35mrads $\times$ 8mrads of BM radiation. The crotch vessel aperture of an ID front-end is 10mrads $\times$ 8mrads of BM radiation.

Several different components are used to define the beam along the length of the front-end. These will be described as follows:

- (a) Absorbers
- (b) Cooled fingers
- (c) Defining apertures
- (d) Slots

(a) ABSORBERS

The absorber is a cooled plate that may be dropped into the path of the photon beam. This is done in order to stop the photon beam from reaching the sample, thus allowing work to be done in the sample area. The design of absorber is set by the heat loading and heat profile it has to absorb. The heat loading depends on the beam type.

Further work needs to be done to assess the number of absorber designs required on the ID front-ends. The ESRF absorber design described in ‘Design and Performance of ESRF high power Undulator front-end components’ by Jean Biasci, Bernard Plan and Lin Zhang will form the basis of this work.

(b) COOLED FINGERS

When an experiment that is taking place over a long period of time only requires a set percentage of the maximum aperture size of the photon beam, cooled fingers can be

B.3 FRONT-ENDS

used to remove the rest of the aperture. These are not adjustable, however, and once an aperture has been selected, it cannot be changed without installing a different finger.

These can also be used for instance when absorbing the BM radiation from the ID front-end. The position of the fingers within the front-end (and therefore the heat loading on them) is dependent upon the layout of the other components. After a beam line concept has been decided, it will be necessary to do further work on the design of the fingers. For instance, the fingers may have to be angled to the photon beam to decrease the maximum thermal loading on them.

(c) DEFINING APERTURE

When the beam enters the front-end it is larger than that required out the exit. The component that resizes the beam is called a defining aperture. Effectively this cooled fixed picture frame sizes the beam vertically and horizontally simultaneously. This defines a maximum beam aperture very accurately.

A design similar to that used on the ESRF could be used for the BM front-ends and for the single Undulator and Wiggler front-ends. The multiple Undulator lines need further work.

An option is to split the defining aperture into two halves vertical, and horizontal. This would allow a design similar to the slits to be used and would allow a variable aperture size. The ESRF are looking at such a design for their own use. It should be possible to have a standard range of these variable defining apertures in the beginning, although more options could be derived depending on the position, size, and number of Insertion devices to be used.

The ESRF experience is that in order to reduce heat loading on any single defining aperture or slit assembly it is best to split the heat loading between a number of similar components.

(d) SLITS

Sometimes photon beams of varying power levels are required for an experiment. In this case, moving slits can be used to absorb some of the energy in the beam. This gives the user a useful tool for controlling power.

Further work needs to be done on the design of these slits, in principle they could be similar to the design discussed for the defining aperture.

The slits would be used to help spread the heat load from the defining aperture in such a way that the defining aperture would take half the loading and the slits half the loading.

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Special attention needs to be paid to the multiple Undulator front-ends. This will require careful modelling and again may need to be designed according to size, position and number of Undulators.

3.4.4 PROVISION FOR FRONT-END OPTICS

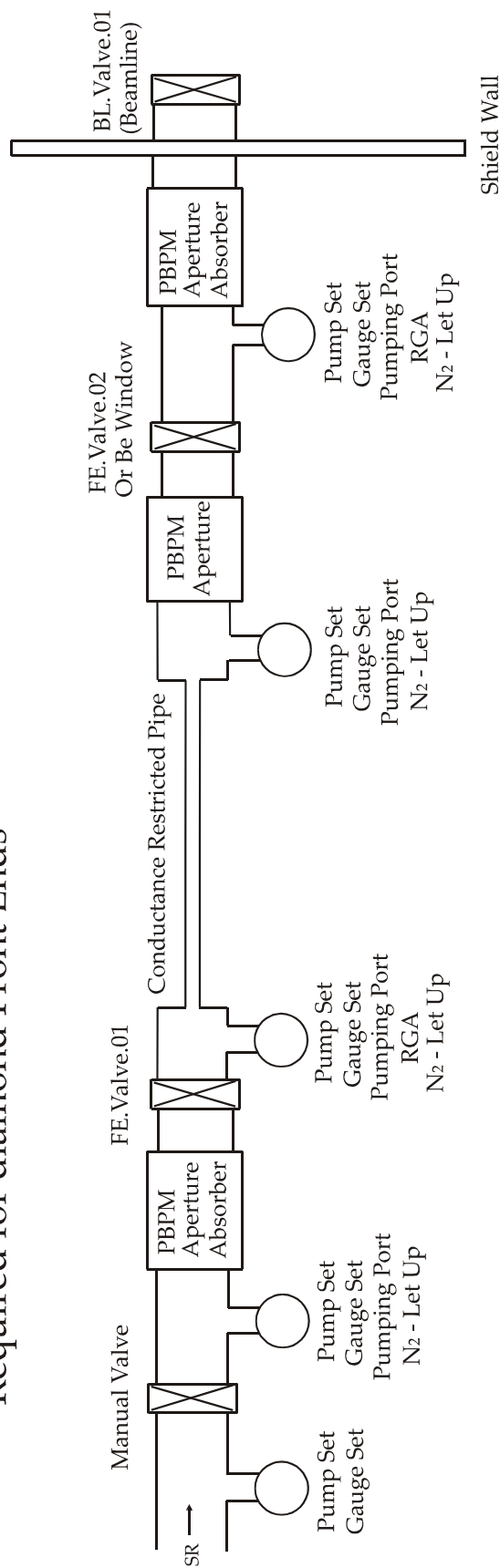
Optics and filters are used to filter out the longer wavelengths from the photon beam before it reaches any delicate components. This works as when the longer wavelengths are removed a lot of power is removed with them. However, the filters in themselves are quite delicate and have maximum power loadings. This means that there is a limit to how close they can be positioned to the insertion device. Provision should be made for an optic that can be lifted in and out of the radiation beam.

3.4.5 ACHIEVING AND PROTECTING VACUUM

Much of the information contained in section E5 (Vacuum) of this document is applicable to the front-end design and reference should be made to it for design details.

The front-ends are coupled directly to the storage ring which is necessary to allow synchrotron radiation to pass down the front-ends and on into the experimental stations. Because of this direct coupling, it is essential that the front-end vacuum system does not compromise the operation of the storage ring. Therefore, a similar approach is made in designing the vacuum system for the front-ends as is used for the storage ring. See references[1];[2];[3].

Schematic Layout of Vacuum Equipment Required for diamond Front Ends



Notes:

Manual Valve = All Metal, Manually Operated Gate Valve with valve protection switches incorporated into the control system.

(The inclusion of this manual valve has not yet been agreed by the storage ring design group)

Pump Set = Not yet defined but large ion pump with integral TSP can be assumed as minimum requirement.

Gauge Set = A combination of inverted magnetron cold cathode and pirani gauge.

Pumping Port = A right angle all metal valve with DL type 5 CF flanges, connected by manifold into Rough Pumping Station..

RGA = Residual Gas Analyser for partial pressure analysis.

N₂-Let Up = All metal valve connected into a dry nitrogen system for letting up the vacuum system to atmospheric pressure.

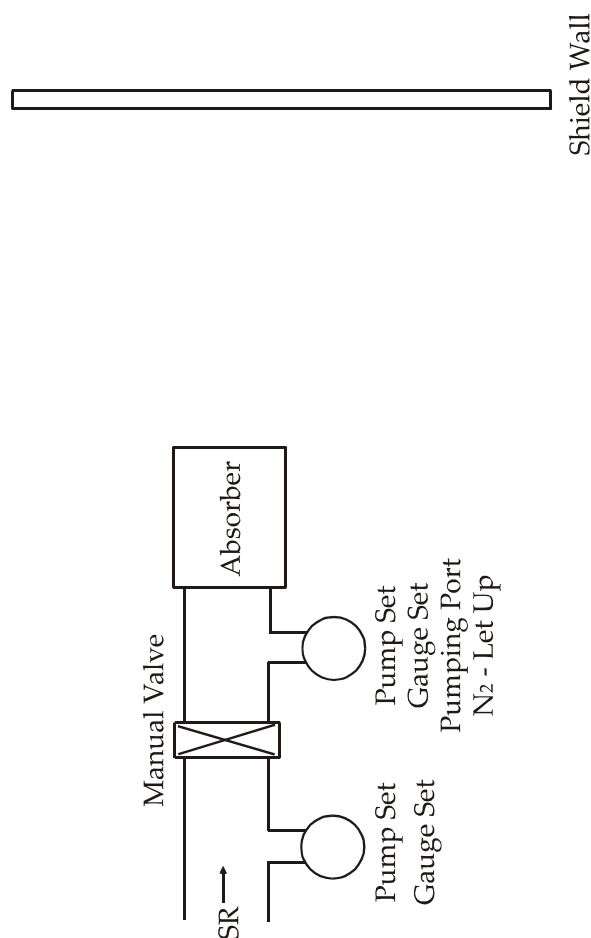
FE Valve.01 = All metal gate valve - pneumatic operation

FE Valve.02 or Be Window = In this position either an all metal gate valve (pneumatic operation) will be required or a Beryllium Window.

BL Valve.01 (Beamline) = This will be the first beamline vacuum gate valve, it may need to be all metal but will probably be viton sealed - Pneumatic operation

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Schematic Layout of Vacuum Equipment Required for unused Front Ends



Notes:

- Manual Valve = All Metal, Manually Operated Gate Valve with valve protection switches incorporated into the control system.
(The inclusion of this manual valve has not yet been agreed by the storage ring design group)
- Pump Set = Not yet defined but large ion pump with integral TSP can be assumed as minimum requirement.
- Gauge Set = A combination of inverted magnetron cold cathode and pirani gauge.
- Pumping Port = A right angle all metal valve with DL type 5 CF flanges, connected by manifold into Rough Pumping Station..
- N2 Let-up = All metal valve connected into a dry nitrogen system for letting up the vacuum system to atmospheric pressure.

B.3 FRONT-ENDS

The vacuum levels in the front-end are set to have no deleterious effect on the storage ring vacuum while maintaining effective transfer of synchrotron radiation. This specification requires that the following total pressures be met:

$$P_{\text{with SR}} < 1 \times 10^{-9} \text{ mbar}$$

$$P_{\text{without SR}} \leq 1 \times 10^{-10} \text{ mbar}$$

To achieve these vacuum levels in the front-end it will be necessary first to rough down the system using an installed network of vacuum pipes that couple into rough pumping stations. The rough pumping stations could be those installed on the storage ring (fixed stations) or could be mobile roughing stations located outside the shield wall (See reports: VAC-SR-rpt-004 and 005). It is likely that the former scenario will be adopted, as this will be the cheapest option, the simplest to implement and allow greater control thus reducing the possibility of contamination. Written instructions will be in place to define the pump down process and suitable control interlocks will be installed to prevent vacuum failure. When appropriate, the main system pumps will be used to bring the total pressure down to the desired levels. It is likely that these main pumps will be a combination of Ion Pumps and Titanium Sublimation or Non-Evaporable Getter pumps.

It will be necessary to carry out a review of available ion pump designs before selecting those most suitable for the diamond front-ends. It is likely that some form of differential diode (noble diode) ion pump will be used. It may also be possible to include in-line ion pumps in some pump locations if there is a clear benefit to the project. This will be assessed in the ion pump review that will be carried out in the next phase of the diamond project.

The main contribution to the gas load in the front-ends will be from synchrotron radiation that strikes components such as absorbers, moving slits, and defining apertures. When designing these components it will be necessary to pay particular attention to their vacuum performance. It is likely that the main system pumps will be located as close to these components as possible to be able to deal with the gas load effectively.

The vacuum level will be measured using a combination of inverted magnetron cold cathode gauges and Pirani gauges in the same way as for the storage ring. If the total pressure is above a set limit then the beamline front-end isolation valve will be closed automatically to protect the storage ring vacuum. It is expected that the storage ring vacuum will be protected from any sudden inrush of gas, caused by catastrophic component failures on the front-ends, by installing suitable differential pumping, fast closing gate valves and a conductance restricted vacuum pipe.

A partial pressure gauge will also be installed in the first part of the front-end to monitor the particular gas species present in the vacuum system so that the status of

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the vacuum system can be better understood. If a high concentration of high mass gas species is present, then indications of serious beam mis-steer or a serious vacuum leak is identified in a front-end, and the isolation protection valve will be closed. The front-end control system will automatically provide some of this protection by direct communication with the RGA.

A series of isolation gate valves will be present in the front-ends to provide adequate protection to the storage ring vacuum system as well as simplifying operations and maintenance programmes. Because of the vacuum levels required and the presence of high levels of electromagnetic radiation, these isolation valves will be of an All-Metal design. In some front-end designs, it is likely that some of the isolation gate valves will be replaced with Beryllium windows.

All vacuum components will be specified to handle a bakeout of up to 250°C. The components will be pre-conditioned before installation and will need to meet strict vacuum criteria before acceptance. The acceptance criteria for these components will be determined at a later date. After installation, it may be necessary to carry out an in-situ bake before the front-end can be operated. At this stage of the design, it is necessary to assume that a bakeout system will be installed. A final decision on bakeout will be taken after a detailed calculation of the front-end vacuum system has been carried out.

When it is necessary to make a vacuum intervention, the rough pumping stations will be used to control the let up to atmospheric pressure with the permanently installed dry nitrogen gas supply.

The final component of the front-ends is the first beamline isolation gate valve. It is likely that this valve will be subjected to a sufficiently reduced synchrotron radiation level to facilitate a significantly cheaper design of gate valve – viton sealed rather than metal. However, if there is no Beryllium window in the front end then all components up to and including this valve will have to be all metal.

3.4.6 RADIATION, SAFETY AND OPERATIONS

The operation of the storage ring and beamlines will create significant radiation problems. Control measures must be applied to ensure that the health and safety of all personnel is guaranteed at all times.

(a) BREMSSTRAHLUNG

High energy electrons lost from the electron beam will interact with any material or component that they strike by releasing energy in the form of gamma radiation. High energy electrons can also interact through the bremsstrahlung effect producing high energy photons. These photons will subsequently interact with material through pair production resulting in the creation of a positron and an electron. The positron will annihilate causing more photons and the electron, if having sufficient energy will again interact through the bremsstrahlung effect. The number of particles will increase whilst the mean energy of the particles decreases. This is the electromagnetic cascade. Eventually, the mean energy decreases so that other reactions can occur. The cascade is then progressively attenuated. The photon (gamma) dose rate is extremely high at small angles to the electron beam and is less at wide angles. Gamma radiation is attenuated efficiently by dense or high z materials such as lead or concrete.

(b) GAS BREMSSTRAHLUNG

A particular form of bremsstrahlung is 'gas' bremsstrahlung. This is produced when electrons interact with the residual gas molecules within the vacuum chamber. This radiation is experienced as a narrow beam of energetic photon radiation that passes down the beamline.

(c) NEUTRON RADIATION

Some of the bremsstrahlung photons will create high energy neutrons by the giant resonance, pseudo-deuteron and photon-pion reactions. The neutron dose rate is much less than the photon, but the neutrons are more difficult to attenuate. Concrete is a cheap shield hydrogenous material that attenuates neutrons in the MeV energy range efficiently. Higher energy neutrons may need denser materials such as barytes concrete, iron or lead.

(d) SYNCHROTRON RADIATION

The synchrotron radiation that passes down the beamlines is electro-magnetic radiation which spans the spectrum from infrared to ultraviolet and x-rays. The x-rays have energies up to around 100keV in shielding terms. The dose rate in the beam and the dose rate scattered from beam shutters, collimators, apertures, etc. is highly dangerous to people.

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(e) SHIELD WALL

The accelerator and beamline front ends will be located in a shielded tunnel (see Figure 3.4-1 Shield wall). The Operations Team will ensure that no one will be present in the tunnel by means of a search and interlock procedure. People will enter the tunnel through labyrinths. All cables and services will enter the tunnel through shielded ducts.

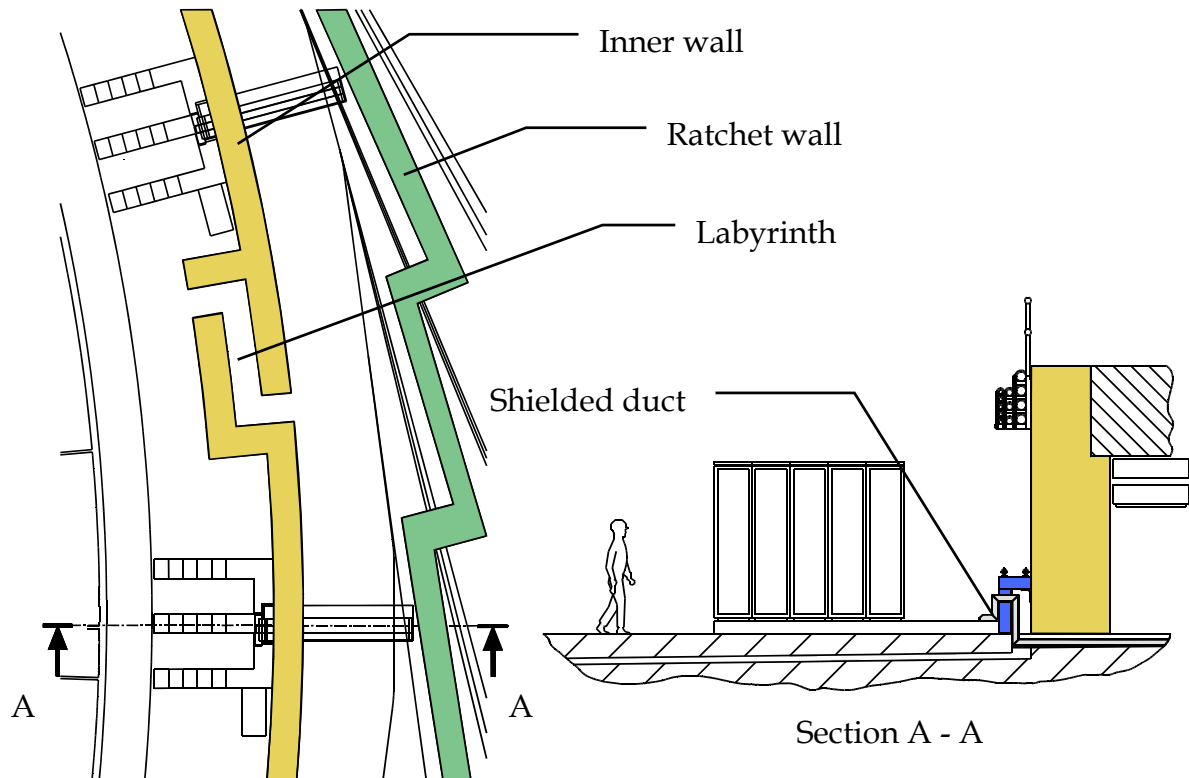


Figure 3.4-1 Shield wall

The wall has to be thick enough to absorb all the radiation from the synchrotron. If any part of the wall is to be made of blocks, special care must be taken to ensure that no radiation can escape through the cracks between the blocks.

(f) SHUTTERS

A port shutter will close off each beamline during normal injection of the Ring. Eventually, it might be possible, in the right circumstances, to use top-up injection with the port shutter open. Extra shielding will be positioned to prevent any cross over radiation penetrating down the beamline. Beamline shutters will allow access into the optics and experimental hutches. All shutters must be designed according to the requirements of the defined standard[4].

B.3 FRONT-ENDS

The Front-end design group has debated the number of Hutch Shutters required for each beamline.

The issue is whether it is necessary to operate with a Port Shutter, Optics Hutch Shutter and Experimental Hutch Shutter. The other option would be to use the Port Shutter to perform the function of the Optics Hutch Shutter as well as its own function and operate with the Port Shutter and Experimental Hutch Shutter only.

By using 'available' health & safety, maintenance, reliability and financial information an attempt has been made to determine the necessity of the Optics Hutch Shutter to perform a specific function, and the impact or consequences of excluding it from the Diamond design. Consideration of other synchrotron light sources has been included in the discussions and it is understood that although the APS and SRS use a Port Shutter, Optics and Experimental Hutch Shutters the ESRF use a Port Shutter and Experimental Hutch Shutter only.

It is the opinion of the group that, because of the implications of this decision on other departments, the discussion should be introduced to a wider audience of participants. This audience would include the JVC Technical Director and Beamline Scientists, to enable the discussion to be brought to a satisfactory conclusion.

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(g) ACCESS TO FRONT-ENDS

Access to the front-ends can only be permitted when the electron beam is stopped. Entry routes into the shield wall will be interlocked so that when the synchrotron is producing radiation it will not be possible to enter. Refer to machine safety document.

When the radiation is stopped normal access to the front-ends will be via a set of ladders that will go over the storage ring similar in principle to that on the current SRS. The ladders will be attached to the floor separate from the girder.

In order to ensure that it is not possible to be trapped within the shield wall when the machine is operating a search within the shield walls must be carried out before the machine can be activated. For safety reasons there will be a button at each of the front-ends. Before the machine can be started this button must be depressed. (Refer to machine safety document). There is to be one ladder per front-end to provide access as shown in Figure 3.4-2.

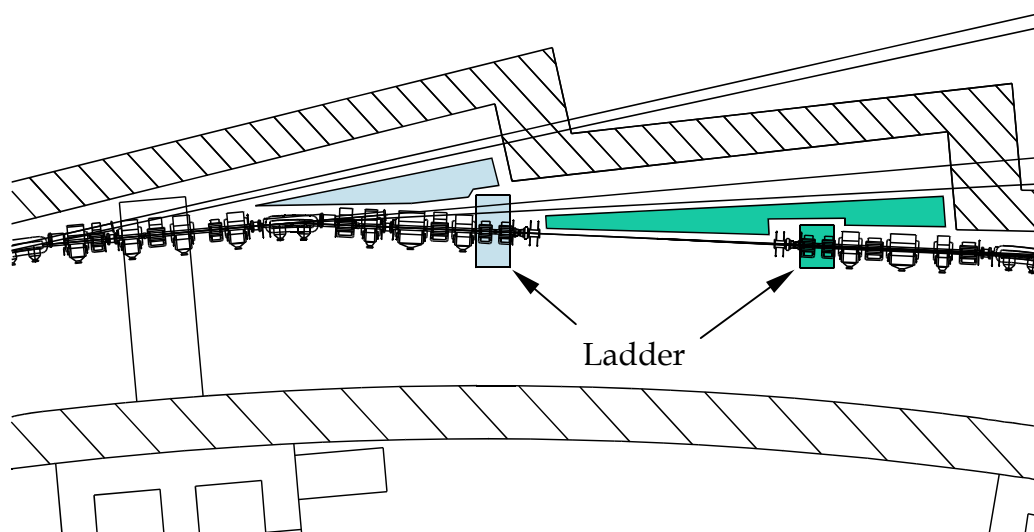


Figure 3.4-2 Plan view of Front-end access

A second method of access for maintenance and installation is via removal of the roof. This will be required when larger components (such as the vacuum chamber) have to be extracted or installed as a crane can be used to aid with lifting.

3.5 FRONT-END DESIGN CONSTRAINTS

This section looks at issues that are common to all of the components in the front-end.

3.5.1 MODULARITY

There are two standard front-end types: BM front-ends and ID front-ends.

Due to the fact that there will only be one front-end per dipole, it should be possible to include a degree of modularity in the design. This would reduce the design time required, and because of economies of scale will reduce the individual cost.

There are 2 main types of beamline: BM beamlines, and ID beamlines. ID beamlines can further be split into single Undulators, Wigglers, and Wavelength Shifters.

BM beamlines require a 20mrads spread of radiation to be carried to the shield wall. This will be split into smaller arcs before passing through the shield wall. It should be possible to have common components as far as the beam splitter. Thus most of the components for all BM front-ends should be identical, those that are not identical should be modular so that they can easily be changed to suit different beam splits.

ID beamlines are more complex due to the different types of ID device that can be installed. Undulators require only 1mrad of vertical and horizontal radiation, Wigglers, and Wavelength shifters require 10mrads horizontal and 1mrad vertical. It is proposed that in order to leave open the possibility of upgrading single Undulator lines all ID front-ends are to give 10mrads horizontal by 1mrad vertical.

The main difference between Undulator, Wigglers, and Wavelength shifters is power distribution. A wavelength shifter gives a broad band of energy with a 'moderate' overall power distribution and 'low' peak power. A Wiggler gives a broad band of energy with a 'high' overall energy level but 'low' peak power. An Undulator gives a 'low' overall energy level but a 'high' peak power. The arrangement of components in the two lines should be similar, where possible components should be designed for use in either line. Other components such as the defining apertures, absorbers, and slots may be designed in such a way that only a small part of them has to be replaced in order to accommodate the different beams. Other components such as the PBPM may need to be completely different.

The ID front-ends then should all have a similar layout. Some of the components that carry out similar functions may have to be different, however, in order to cope with the differing beam types. These different components may have to be unique depending on the beamline. In this case, a modular design of components should be pursued so that they are easy to remove or replace. For instance all apertures could be fixed at 1m long, thus allowing different apertures to be slotted into position if different beam shapes are required.

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3.5.2 RADIATION

All of the components within the front-end will be subject to x-rays of varying powers. Electrical components should be placed as far away from the vacuum vessel as possible. If possible, rubber hoses or cables should not cross beam height close to the storage ring or beamline vacuum vessel as they can be embrittled by the synchrotron radiation.

3.5.3 ALIGNMENT

The components must be very accurately aligned to each other, to the storage ring and to the beam lines. In order to achieve this, two fiducial points must be accurately positioned on each component. See the alignment document.

Each component should be capable of being adjusted without affecting the position of the others.

In order to align the front-ends with the beamlines without removing the tunnel roof, survey holes will be located 2.4m from the floor level, and on beam centre horizontally.

3.5.4 HEAT LOADING

The components subjected to intense heat loading must be carefully modelled to ensure problem free operation. Care should also be taken to ensure that no component could be damaged due to beam mis-steers.

3.5.5 BAKE-OUT

Provision must be made to bakeout all the vacuum components to 250°C in situ. A final decision on whether to use in-situ bakeout for the front-ends will be taken after a detailed calculation of the front-end vacuum system has been carried out. However all vacuum components will be baked during pre-conditioning and it is anticipated that sections of front-end components will be built up off line and baked as assemblies.

3.5.6 VACUUM

Much of the information contained in section E5 (Vacuum) of this document provides details of design constraints for example material choice and specification.

Detailed quality assurance documentation for the diamond vacuum system will be written covering aspects such as cleaning, material handling and specification as well as manufacturing guidelines. To achieve the necessary vacuum levels for the project it will be essential that the quality assurance documentation is adhered to and so will need to be policed rigorously. This documentation will need to be written early in the next phase of the diamond project.

B.3 FRONT-ENDS

These documents will be required for all the diamond facility vacuum systems including the front-ends. It is likely that existing CLRC specifications will form the basis of these quality assurance documents. Typical examples include:

- General manufacturing specification[5].
- Cleaning specification[6].
- Leak testing specification LT/02/88/A.

For bakeout considerations see section 3.5.5 of this document.

The levels of synchrotron radiation gas desorption will have a major influence on the design of the vacuum system (including chambers and pipes). It will be necessary to carry out detailed calculations of gas desorption before the design can be finalised.

3.5.7 TEST AND ASSEMBLY

The front-end should be designed in such a manner that it can be assembled and tested off the synchrotron and then lowered into position with the minimum of installation time. All systems including water, electrical and vacuum integrity should be tested before the front-end is lowered into position to ensure a short shutdown period.

3.5.8 VIBRATION

Each component must be checked to ensure that when it is operated it does not cause vibration in any of the adjoining components. Attention must be paid during detailed design to reduce the production and transmission of vibration to the ground and neighbouring sensitive components.

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3.6 FRONT-END COMPONENT LAYOUT

The previous sections have defined the functions of the front-end components. They have also looked at any limitations on the arrangement of these components. This section will first look at a block diagram of these components that meet the set criteria and then will examine the physical constraints.

3.6.1 UNUSED FRONT-ENDS

Before front-ends are installed, an assembly of parts is required to absorb the radiation produced from the dipole magnets. This will be done as shown below. A decision on whether to install this isolation valve will be taken following detailed development of the operational philosophy of the front-end early in the next phase of the design study.

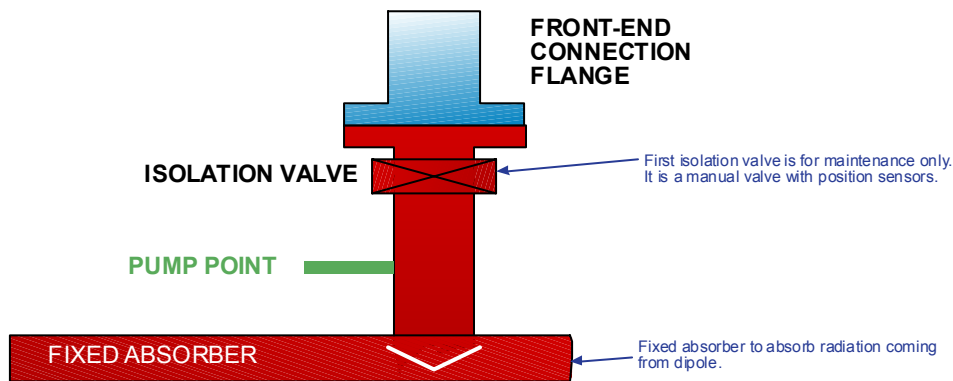


Figure 3.6-1 Dipole absorber assembly for unused front ends

B.3 FRONT-ENDS

3.6.2 STANDARD ID FRONT-END BLOCK DIAGRAM (UNDULATOR)

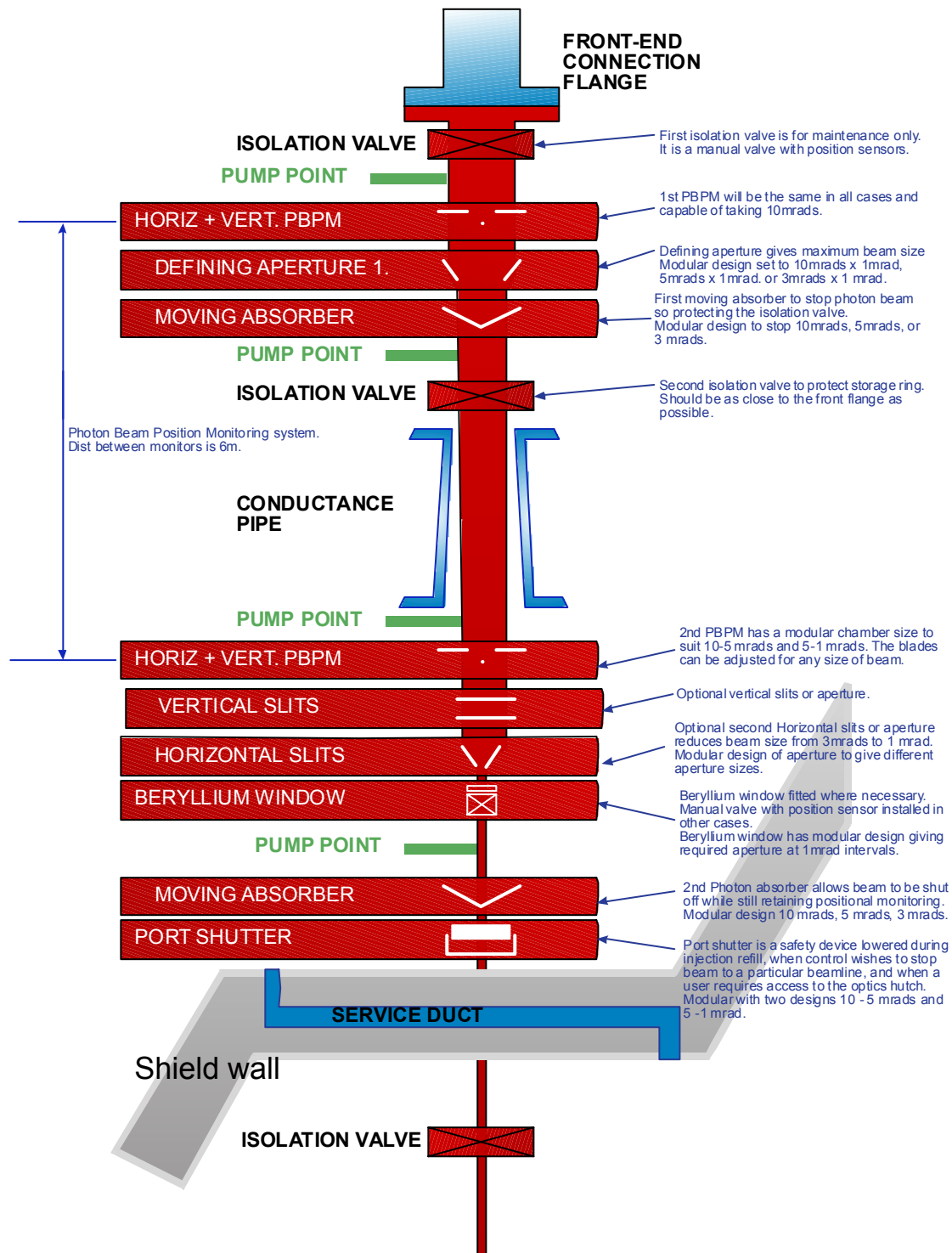


Figure 3.6-2 Standard front-end block diagram (undulator)

See section 3.6.7 for an explanation of design rationale.

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3.6.3 STANDARD ID FRONT-END BLOCK DIAGRAM (W/S AND MPW)

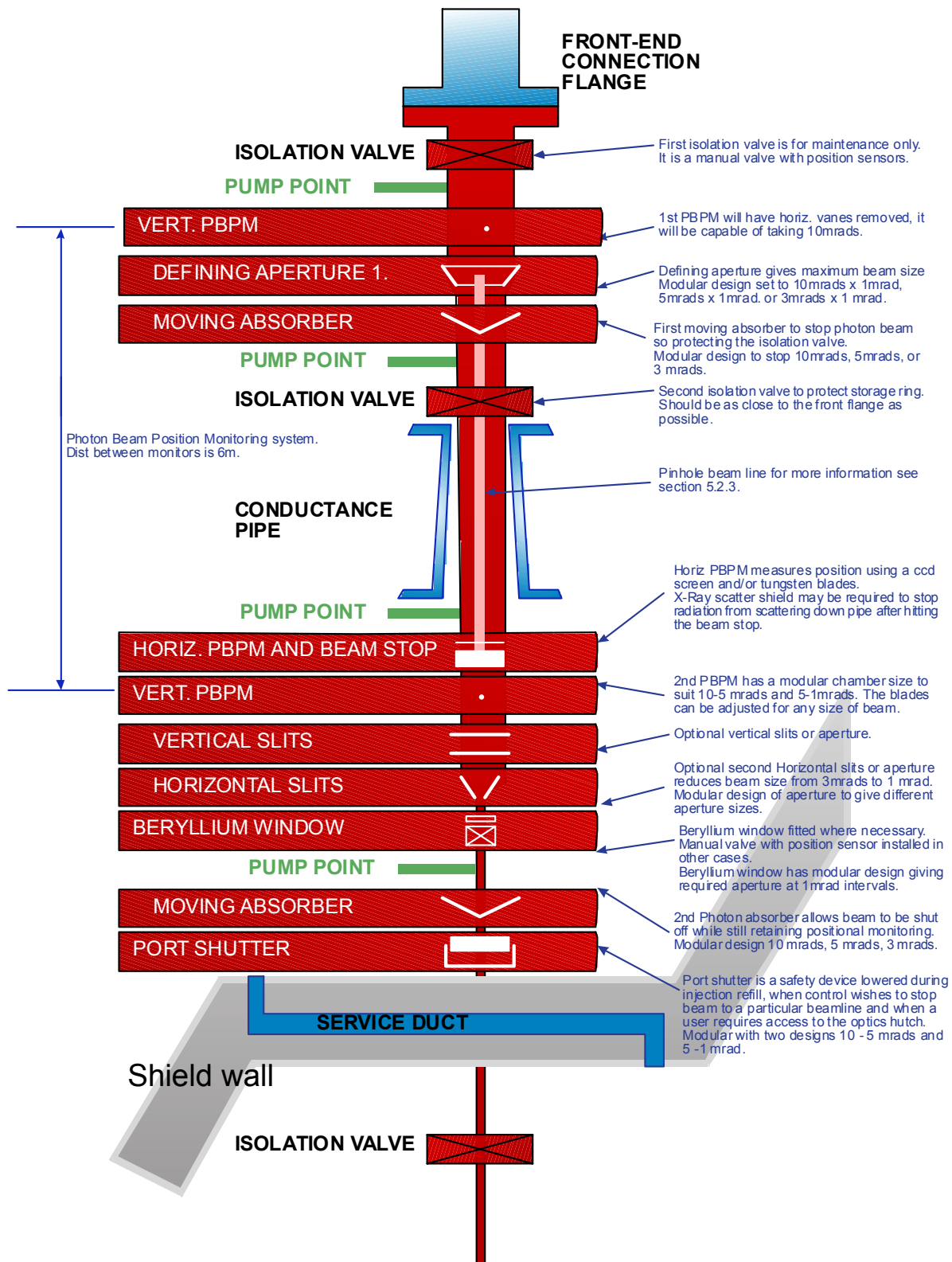


Figure 3.6-3 Standard ID front-end block diagrams (W/S and MPW)

See section 3.6.7 for an explanation of design rationale.

3.6.4 STANDARD BM FRONT-END BLOCK DIAGRAM

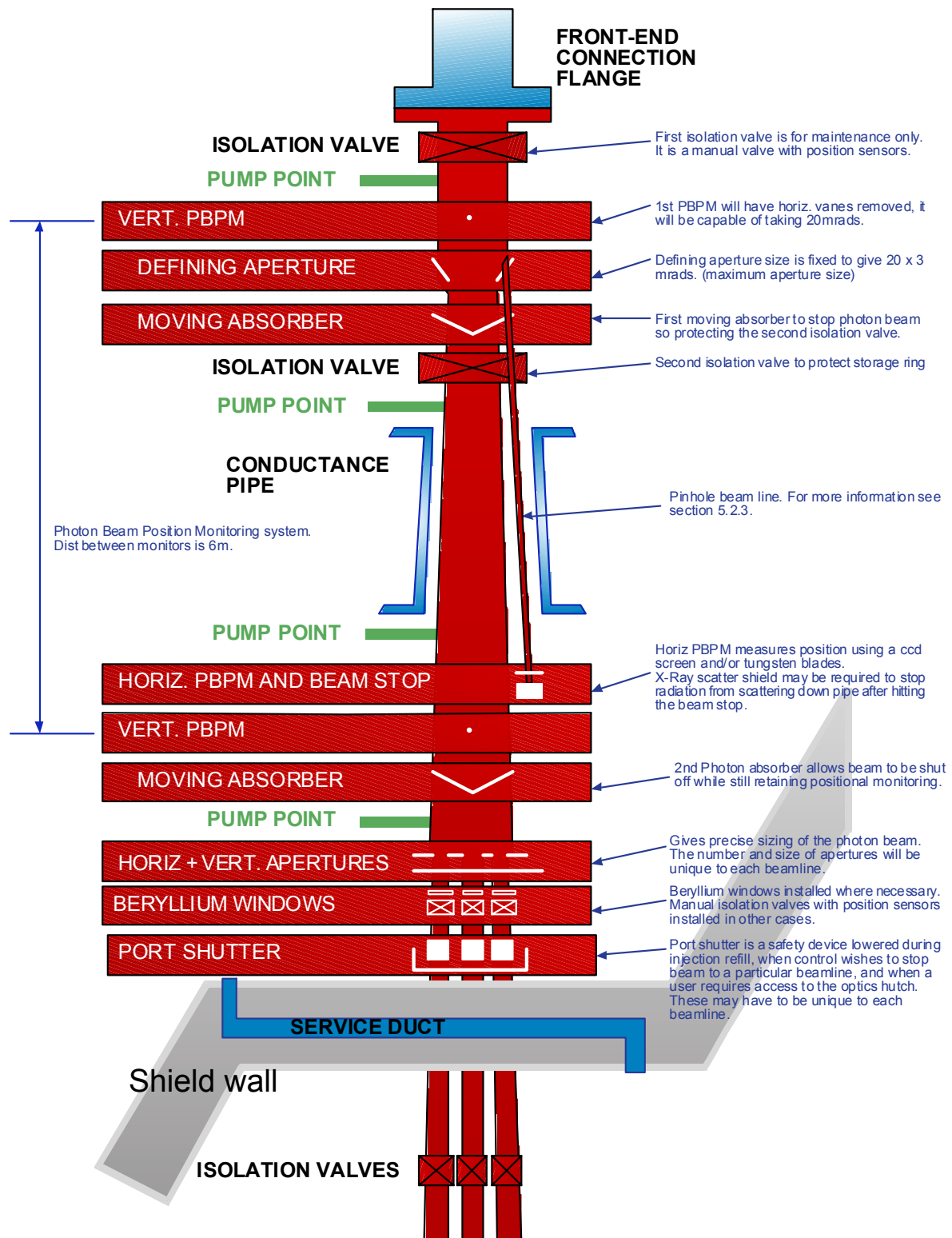
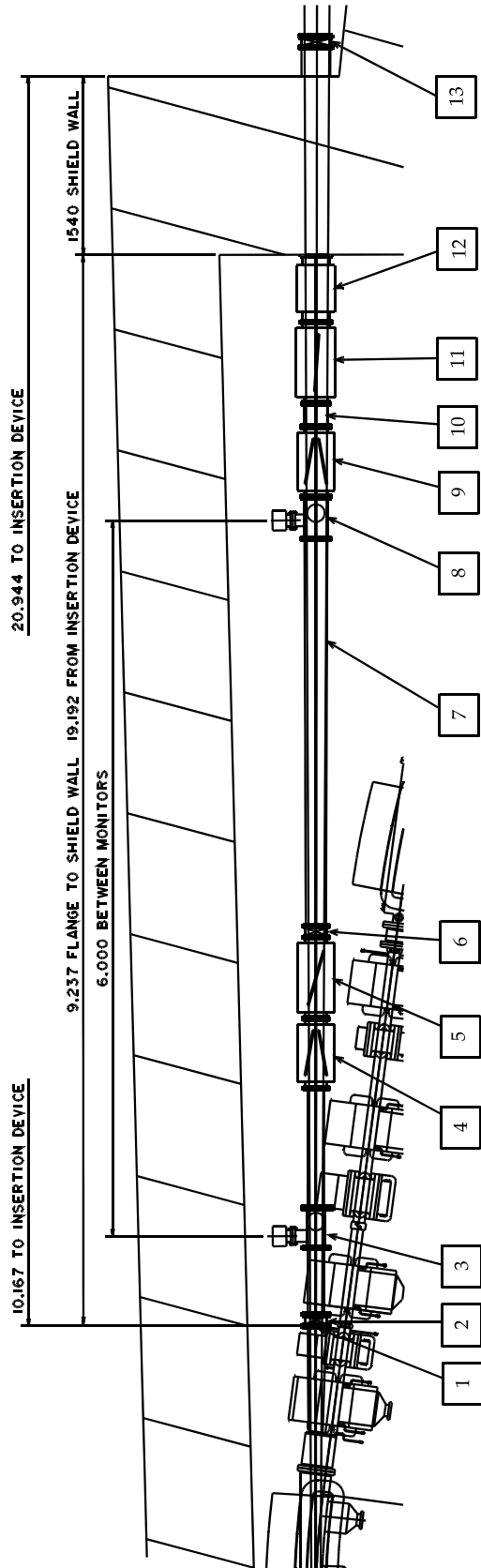


Figure 3.6-4 Standard BM front-end block-diagram

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3.6.5 PHYSICAL STANDARD ID FRONT-END LAYOUT



3.6.6 STANDARD ID FRONT-END PARTS LIST

The following table lists the front-end components with their distance to the insertion device (5m straight)

No.	Item	Dist X	No.	Item	Dist X
1.	Front Flange	10.169m	8.	Horiz + Vert PBPM	17m
2.	Isolation Valve	10.2m	9.	Horiz + Vert slits/apertures	17.8m
3.	Horiz + Vert PBPM	11m	10.	Beryllium window (option)	18m
4.	Defining aperture	12.6m	11.	Absorber	18.5m
5.	Absorber	13.2m	12.	Port shutter	19.2m
6.	Isolation valve	13.6m	13.	Isolation valve	21.3m
7.	Conductance pipe	14m			

3.6.7 ID FRONT-END DESIGN RATIONALE

This section will look at the proposed design and explain its features. It will start at the downstream side of the front-end and work upstream explaining each component in turn.

(a) 1ST ISOLATION VALVE

This valve is not included in the cost breakdown but is included here as a recommendation to improve the operational ease of front-end maintenance and to allow the installation of the initial front ends without storage ring venting. If agreed, the valve could be fitted at all ports to allow the installation of future front ends without storage ring venting. A manually operated all metal gate valve is proposed although the cost/benefits of pneumatic operation need to be considered in detail. The valve will require special position indicators to be fitted similar to those used on personnel safety valves. This is to ensure that the valve cannot be closed by accident during operations. The facility control system will generate the necessary interlocks. A decision on whether to install this isolation valve will be taken following detailed development of the operational philosophy of the front-end early in the next phase of the design study.

(b) 1ST PBPM

The second component then is a PBPM. The two PBPM's need to be as far apart as possible and this is achieved by positioning the first one close to the front flange. This is similar to the approach taken by the ESRF.

To cope with the different beam sizes and types it may be necessary to motorise the blades so that they can be moved close together to measure Undulator beams and far apart to measure MPW beams. This would allow easier alteration of beamlines. It is also possible to have a non-motorised blade that has to be changed manually after venting up a section of the front-end.

The two devices that define the path of the photon beam need not be identical (e.g. two tungsten vane monitors, or a pinhole and an imaging screen). The most appropriate system should be chosen to match the source properties being monitored.

However, it would be convenient to use as small a group of device types as possible.

(c) DEFINING APERTURE

The defining aperture is positioned next in order to keep the size of the vacuum chambers as small as possible. This may define the horizontal aperture separately from the vertical one and so effectively become slits. This would allow a standard

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design that could also be used for the slits further upstream. It is envisaged to fix standard horizontal aperture sizes; say 10mrads, 5mrads and 3mrads. This would mean that components downstream of the aperture would be no larger than necessary.

A further advantage of defining the horizontal aperture separately from the vertical one is that it may be practical to design a “Christmas tree”. This would allow one design of aperture to cater for all three aperture sizes simply by moving the horizontal aperture in the vertical plane.

With the Wigglers and wavelength shifters a pinhole may need to be positioned in the defining aperture in order to create the monitoring beam. This could be done by drilling a 2 or 3mm diameter hole in the defining aperture and positioning a thin tungsten plate with a 50micron hole further downstream to filter out the excess beam.

(d) 1ST ABSORBER

The absorber comes next. The ESRF design of absorber is unconventional but appears very good. There is no possibility of a water leak inside the vacuum and it is more efficient than the standard design. It is proposed to have 3 different heads on the absorber to cope with a 10mrads, 5mrads or 3mrads beam from the defining aperture. The design would allow utilisation of the same framework and adjustment mechanism on every option with different heads to suit the 3 power loadings. This is as close to the storage ring as practical to give the isolation valve as much time as possible to close.

The absorber comes after the defining aperture in order to reduce the heat loading on this component so making it easier to design.

(e) 2ND ISOLATION VALVE

The second isolation valve is used to provide protection to the storage ring vacuum system and the front-end vacuum system in the event of a failure of either of the two systems. The 1st absorber protects this valve from synchrotron radiation. The total pressure and partial pressure measuring systems will provide interlocks to facilitate the opening/closing of this valve.

(f) CONDUCTANCE PIPE

The conductance-restricting pipe forms part of the vacuum protection system. It will be designed to have the smallest internal dimensions that will allow a beam of 10 mrads of synchrotron radiation through. It is envisaged that IR and CD beamlines will be added to the diamond project at some stage. These beamlines require optics to be located in the front-end and will preclude the use of a conductance-restricting pipe. These front-ends will be considered as specials and will be the subject of individual front-end design.

B.3 FRONT-ENDS

(g) 2ND PBPM

The second photon absorber is positioned next. This is before the second absorber the idea is that the location of the beam is known before it is allowed to enter the optics hutch. It is positioned before the slots in order to eliminate any possibility of shadowing.

It would be envisaged to provide a 10-5mrads PBPM design and a 5-0.2mrads PBPM design in order to reduce the size and cost of the components. These two designs would use the same blades and mechanisms, just have different casing sizes. The design and type of PBPM has yet to be fixed, but one can envisage a modular system with two designs (one for 10mrads of horizontal beam and one for ca. 1mrads of horizontal beam).

(h) HORIZ. + VERT. SLITS

The horizontal and vertical slits come next. These could either be of fixed size, so becoming a second defining aperture or a “Christmas tree” design could again be used allowing for an adjustable beam width of say 3mrads, 2mrads or 1mrads. If a fixed size was used this would be unique to every experiment. For instance if 1mrads was required the beam would initially be reduced to 3mrads by the defining aperture and then to 1mrads in this later section. If 4mrads were required the beam would initially be reduced to 5mrads in the defining aperture and then to 4mrads in this later section. The component could be tabled meaning that no extra design time would be required after the initial design.

(i) BERYLLIUM WINDOW OR 3RD ISOLATION VALVE

The beryllium window is fitted after the PBPM so that it does not affect the accuracy of beam positioning. Alternatively, a diamond or CVD coated window could be used with the possibility that the window could be motorised. For front-end designs that don't require a window, a 3rd Isolation valve will be installed. The criteria for the 2nd Isolation valve apply. The purpose of the valve would be to provide isolation between different parts of the vacuum system for added protection and for ease of maintenance and operation. If a beryllium window is fitted onto a beamline that utilises the coherence of the source, then it will have to be highly polished.

(j) 2ND ABSORBER

The second absorber will be identical in principle to the first although dimensions may be different to allow for larger size of beam at this point.

(k) PORT SHUTTER

The port shutter prevents radiation from passing down the beamline during injection, and when the optics hutch has not been searched and interlocked. It should be designed to comply with the standard [7]. The ESRF design and new SRS design

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should be considered for this application. It is recommended that 2 sizes be catered for 10mrads and 5mrads. The 5mrads design will be comparable to the ESRF but the 10mrad design will be much larger. For safety reasons, a dual control system will need to be looked at.

(l) 4TH ISOLATION VALVE

The last component is an isolation valve located after the shield wall. This valve provides front-end/beamline isolation for protection to each vacuum system and for satisfactory operation of both vacuum systems. This valve will be a gate valve but may not need to be all metal, this will be determined after the completion of the detailed front-end vacuum system calculations. If there is no beryllium window in the beamline then it is likely that this valve will need to be all metal.

(m) BEAM SIZES

It should be noted that 10mrads was chosen as it is the maximum beam size, 5mrads as this is similar to the ESRF maximum beam size, 3mrads as this would suit an Undulator and spread the heat loading better. There may be more optimal sizes, which will be obtained after thermal simulation.

3.6.8 STANDARD ID FRONT-END SPECIAL OPERATIONS

(a) VACUUM FAILURE ON BEAMLINE

The control system will close the 1st absorber and all the isolation valves.

(b) VACUUM FAILURE ON STORAGE RING

Electron beam is stopped and all the isolation valves close.

(c) VACUUM FAILURE ON FRONT-END

The control system will close the 1st absorber as well as all the isolation valves.

(d) BEAMLINE SHUT DOWN FOR MAINTENANCE

Electron beam is stopped and all isolation valves close.

The 1st isolation valve can be closed manually to isolate the front-end from the storage ring.

Any component in the front-end can be worked on without having to bring the storage ring up to atmosphere.

(e) USER STOPS THE PHOTON BEAM

Second absorber closes allowing the beam position to be constantly monitored by the 1st and 2nd PBPM. Station shutter in the optics hutch drops into position.

(f) CONTROL STOPS THE PHOTON BEAM

2nd absorber closes allowing the beam position to be constantly monitored by the 1st and 2nd PBPMs. Port shutter drops into position.

This turns both control circuit and user circuit red

(g) USER STARTS THE PHOTON BEAM

Beam position constantly monitored. So Port shutter (providing the control circuit is green) is removed then 2nd absorber. If Port shutter cannot be opened, control has closed the shutter

(h) CONTROL STARTS THE PHOTON BEAM

Control turns control circuit green. This allows the user to turn the user circuit green and thus a User start beam can then proceed.

3.7 SIMILAR FRONT-ENDS

This section will look at front-ends constructed to do similar jobs to the front-ends on DIAMOND but on other machines.

3.7.1 BEAMLINE 6 AND 10 SRS

Beamlines 6 and 10 on the SRS are very similar to each other. They both have Multipole Wigglers for sources and they both contain similar components in a similar order. Below are listed the components of the front-ends for beamlines 6 and 10 in order from the storage ring to the beamline.

- Cooled absorber
- Defining aperture
- Isolation valve
- Pumping and Instrumentation point
- PBPM
- Port shutter

3.7.2 BEAMLINE 14 SRS

Beamline 14 is slightly different from 6 and 10. It has a 2 Tesla Multipole Wiggler as an insertion device. This beamline intersects the transfer path into the storage ring. Below are listed the components on this front-end in order from the storage ring to the beamline.

- Cooled absorber
- Defining aperture
- Isolation valve

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Pumping and instrumentation point
 Beamtube (1.65m long)
 Finger absorber
 Fixed mask with pumping
 PBPM
 Finger absorber
 Fixed mask
 Pumping port
 Beryllium window
 (Transfer path intersects at this point)
 Beryllium window
 Port shutter
 Station shutter

3.7.3 BEAMLINE 16 SRS

Beamline 16 is different in that it uses a cryogenic wiggler for its insertion device. Below are listed the components on this front-end in order from the storage ring to the beamline.

Cooled absorber
 Defining aperture
 Isolation valve
 Pumping and instrumentation point
 Beryllium window
 PBPM vessel
 Kratky aperture
 Isolation valve
 Port shutter
 Station shutter

3.7.4 ESRF STANDARD ID FRONT-END ASSEMBLY

The ESRF break up a front-end into 3 parts. Module 1 is closest to the storage ring, Module 2 is closest to the shield wall, and the transition module lies between the two. Listed below are the components in the module 1 ID standard assembly starting from the storage ring side.

Isolation valve
 X-BPM sensor
 Pumping tee
 Fixed absorber assembly (270mm flange to flange)
 Moveable absorber assembly (800mm flange to flange)
 Isolation valve
 Fast closing shutter

Continuing with the transition module

Approx. 3m of pipe
Acoustic delay chamber (2.4m long)

Continuing with module 2

Absorber
X-BPM sensor (14m from 1st)
Slit filter (800mm flange to flange)
Beryllium window
X-BPM sensor (2m from 2nd)
Port shutter

3.7.5 ESRF HIGH POWER STANDARD ID FRONT-END ASSEMBLY

Listed below are the components in Module 1 High Power ID Standard assembly starting from the storage ring side

Isolation valve
X-BPM sensor
Pumping tee
Fixed absorber assembly (270mm flange to flange)
Mask dia 8mm (265mm flange to flange)
Isolation valve.
Defining aperture
Absorber
Valve
Fast acting valve

Continuing the transition module

Pumping chamber
Straight chamber (2.6m flange to flange)
Acoustic delay chamber (2.4m flange to flange)

As shown in the general layout this line has the standard module 2 assembly. There is also a second option as listed below :-

Starcell pump (in-line Ion pump)
Vertical slit (270mm flange to flange)

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- Isolation valve
- Pumping tee
- Horizontal slit (270mm flange to flange)
- Cooled window
- X-BPM Sensor (11m from 1st)
- Port shutter (510mm flange to flange)

3.8 FRONT-END PROCUREMENT

It is likely that the front-end will be broken down into sub-sections with a high level specification pulling all the component specifications together.

Sub-sections would include:

- PBPM's
- Absorber assembly
- Defining Aperture and slits assemblies
- Port shutter assembly

These would be tied together with a high level specification detailing:

- Physical layout of front-end
- Max. Size flange-flange of each component
- Construction standards
- Quality assurance requirements
- Deliverables
- Numbering systems to be used
- CAD Drawing standards
- Time schedule
- IPR and Confidentiality agreements.

REFERENCES

- [1] DIAMOND internal report: VAC-SR-rpt-006
- [2] DIAMOND internal report: VAC-SR-rpt-008
- [3] DIAMOND internal report: VAC-XX-rpt-010
- [4] HPR91/178, rev 2002
- [5] Daresbury Laboratory internal report: DL/UHV/01/90
- [6] Daresbury Laboratory internal report: CS/05/95
- [7] HPR91/178, rev 2002

B.4 Very High Energy Beamline

4.1 INTRODUCTION

The study of materials held at high pressures and temperatures (high P, high T) is a rapidly expanding field impacting fundamental physics and chemistry, earth and planetary science, bio-molecular science, and research into processes to deliver novel materials. UK scientists require regular and easy access to dedicated facilities to maintain a very strong, internationally recognised position.

Samples will be taken routinely to extreme pressures and temperatures, often in chemically corrosive environments, requiring specially engineered thick-walled pressure vessels, experimental containers, and diamond anvil cells. Intense, very high-energy X-rays are essential for penetrating these sample environments.

4.2 SCIENTIFIC CASE

Over the past decade, a series of technical and scientific breakthroughs have led to ground-breaking experiments revealing new phenomena that are revolutionising physical science. The potential impact of this area extends from the discovery of new insights into physical processes and orders of magnitude improvements in our understanding of planetary interiors to the development of energy efficient routes for the production of materials and the biophysics-chemistry interface.

Advances in diamond anvil cell (DAC) and multi-anvil device technology now permit precise control and manipulation of the pressure variable for probing materials into the megabar regime where material densities are increased up to tenfold and electron configurations are significantly perturbed. These can be used in conjunction with sample heating (to $T \sim 3000\text{--}5000$ K using IR lasers and resistive methods) and cryogenic cooling, with high applied fields, chemical potentials or non-uniform stress states, to investigate the properties of matter under a wide range of extreme conditions.

Synchrotron diffraction experiments are fundamental to structural studies of materials under extreme conditions. The high brightness of a 3rd-generation source will allow collimation of the incident radiation to a few μm and penetration by high energy (20–100 keV) X-rays of the necessarily thick walls of sample containers. Efficient recording of the diffraction which emerges from very small exit windows will be effected by (and improved by advances in) energy resolving and two-dimensional X-ray detectors.

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The ESRF (and other synchrotron facilities world-wide) will have unique capabilities and complementary techniques, but the limited access cannot possibly support the existing UK activity or allow for the expected increase in demand. This extreme conditions beamline will provide a dedicated facility designed by and for the UK user network. With user groups present at the facility in periods between scheduled beam time to construct, design and maintain experiments, and to conduct research in off-line laboratories, a strong community will develop. The combination of good access and proximity to home laboratories is expected to promote long term programmes in the following areas of extreme conditions research.

4.2.1 New physics

Recent experimental results have challenged theories in solid state physics. Future experiments will be performed specifically to provide a testing ground for problems that are not yet tractable, e.g. the effects of pressure on superconductivity, where high pressure increases T_c for compound superconductors. Light elements such as O, N and S are also joining the superconducting elements. New complex structures and physical behaviour are being discovered under high P, such as magnetic phases of highly correlated systems. New metal phases are appearing in the "intermediate" pressure range where Ba develops an "alloy" structure with incommensurate sublattices. Understanding these sublattices, and the passage from single crystalline to powder behaviour in materials, presents new challenges to experimental diffraction physics and crystallography.

New phenomena are being observed in liquid-liquid phase transitions driven not by composition but by density and entropy. Recent examples include first order liquid-liquid transitions in phosphorous, and structure changes in liquid Se and S. Studies must now be extended to other elements and compounds. Viscosities of some network liquids are found to decrease with increasing pressure: transmission radiography will be used to extend studies into the 20-30 GPa range.

4.2.2 Stress-strain relationships and mechanical relaxation

Experiments are being designed to probe materials properties to follow their time-temperature evolution under particular stress-strain environments. These have enormous applications in geoscience and to ceramics and composites. It will be possible to extract details of strain relaxation and/or recrystallisation in strained crystals. Powdered samples are pressed under non-hydrostatic conditions: diffraction peak broadening (or d_{hkl} variability) will be used to determine the strain tensor in minerals, rocks, ceramics, metals and composites.

4.2.3 Solid state chemistry and materials science

Solid state chemistry is only just beginning to be explored under extreme conditions revealing new polymeric and framework forms of CO_2 and N_2 , layered forms of C_3N_4 , new dense nitrides, low-dimensional silicides and icosahedral borides. *In situ* time-resolved diffraction studies of self-propagating high temperature synthesis reactions

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(including under high magnetic and electric fields) is a new area currently being developed for solid state/materials chemistry.

Most solid state compounds and/or materials are prepared at atmospheric pressure and moderate to high temperature. Extreme conditions experiments will result in new solid state chemistry and will be combined with theory to predict new materials and their properties. Decompression pathways will be established to recover new dense materials to ambient conditions. Discovery of unusual properties can be expected to drive the development of technological materials of relevance to communities interested in new “superhard”, electronic or magnetic materials.

4.2.4 *In situ* kinetics studies and catalysis

Determination of structure and bonding in new materials synthesised under extreme conditions generally requires a detailed knowledge of the evolution and kinetics of compounds to effect the transfer to a viable and efficient commercial process. Having contributed significantly to the development and use of *in situ* diffraction (and spectroscopy) for this type of application, the UK community will be looking to extend the range and speed of current capabilities.

In situ catalytic experiments will continue to be of strong interest to industrial chemists, and reaction chemistry under hydrothermal, ammonothermal reactor conditions is a vital area to be developed that will lead to new high throughput synthesis and new catalytic pathways.

4.2.5 Earth and planetary science

UK researchers are world leading in developing understanding of the geophysics, mineralogy and petrology of the deep Earth and other planets. There is a need for both steady state and *in situ* reaction studies under extreme conditions to explore changes in rocks and mineral structure, melting, and deformation. The techniques used will also have applications in studies of polar ice environments, bio-materials, and rheology of composite materials (of relevance to ceramics engineers).

Earth science research will impact our understanding of the core-mantle boundary, known as the most chemically reactive region of the planet, by studying chemical reactions between Fe-based metals and silicates. Dehydration of subducting slab materials will be studied *in situ*. The role of the fluid phase in deep Earth geochemistry will be studied by time resolved diffraction experiments. These will be complemented by theoretical studies of mineral behaviour. Studies of the interaction between minerals and fluids will examine the interface during hydrothermal materials synthesis.

The structure, phase relations and chemistry of C-O-H-N materials will be explored to determine the mineralogy and petrology of giant planets and deep polar ices, and light element compounds (H₂O ion-conducting fluorite; CO₂ cristobalite/tridymite; N₂ polymers) will feed into materials science research.

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4.2.6 Biomaterials and organic synthesis

High pressures and temperatures ($T \sim 300\text{--}600\text{ K}$; $0.1\text{--}1\text{ kbar}$) are becoming important in pharmaceutical/biotechnology materials design and in "origins of life" research. Medium resolution structure determination of proteins and other biomolecules at these "extreme" conditions is essential. These studies will also help in understanding the effects of pressure in processing foodstuffs.

X-ray tomography of recovered ocean-bed synthesis environments ("black smoker" towers) will elucidate conditions necessary for organosynthesis at the biogeochemistry interface in the context of studying deep sea origins of life. Studies will be linked to *in situ* experiments in hydrothermal cells and catalytic convertors, as the interface between organometallic and biomolecular chemistry and materials synthesis/catalysis is explored.

4.3 BEAMLINE REQUIREMENTS

The wide range of interests to be served by this beamline makes it very difficult to simplify the requirements without compromising the quality of the science produced. To begin with, the research programme outlined above (and represented in over 60 letters of support received from research groups in the UK) requires high-intensity X-rays over an energy range of $20\text{--}100\text{ keV}$ for diffraction and transmission measurements on materials held under extreme conditions deep within sample cells, containers and other apparatus.

Angle dispersive diffraction (ADX) techniques give the highest resolution ($\Delta d/d \sim 0.001$) as well as the quantitative intensity information necessary to determine reliable structures of the materials being studied. Energy-dispersive diffraction (EDX) has the advantage of quickly accessing a large range of reciprocal space with minimal requirements for the angle of diffraction. The detector only receives signals from a small volume (defined by the overlap of finely collimated incident and scattered beams), thus providing high spatial resolution even when the samples are large and containers have thick walls. The time resolution is essential for chemical synthesis/kinetics studies and laser-heating experiments. Clearly, both ADX and EDX will be required on this beamline.

Multi-anvil and hydrothermal experiments both require larger sample volumes contained within thicker cell assemblies but the former requires either a monochromatic or a white beam and the latter requires white beam only (to 100 keV or more). DAC experiments are carried out on minute samples or sample areas ($1\text{--}10\text{ }\mu\text{m}$ in dimension) and require tightly collimated beams (using slits or focusing). The radiation must pass through diamond windows (of up to 5 mm thickness), and Be, B_4C or other materials. High energy monochromatic or white beam radiation extending to 80 keV is required.

Four classes of experiment can be defined:

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- 1) white beam (W1) : high P-high T experiments with DACs and laser-heating
- 2) white beam (W2) : hydrothermal cells, autoclaves and reactors for *in situ* chemistry, catalysis, synthesis, and kinetics measurements
- 3) monochromatic beam (M1) : DAC experiments with two-dimensional detector (image-plates or CCD), mainly for powder studies, but also to explore the passage between powders and single crystals
- 4) monochromatic beam (M2) : a diffractometer for studying single crystals held at high P, at high or low T, grown *in situ* in either a larger volume cell (such as a Paris-Edinburgh cell) or a DAC, to extend precise single crystal methods into the megabar regime.

Many high P-high T experiments should combine simultaneous measurement of e.g. conductivity, impedance, viscosity, density, and other properties to maximise the information obtained, to compare with theory and other published results, and to advance the development of new materials for specific applications. On-line luminescence spectroscopy will be essential for pressure calibration and extensive off-line support laboratories will ensure the best use of beamtime and promote research programmes.

4.4 OUTLINE BEAMLINE SPECIFICATION

This exciting yet ambitious project has stimulated a great deal of debate in which many aspects had to be taken into account. A significant number of facilities were demanded by the community, but it was important to take a realistic view of the potential costs and the space likely to be available. The fundamental requirement of high energy X-rays dictated the need for a high magnetic field insertion device and the impact of this on the machine (increased emittance, input power demanded from the RF system, output power loading on the beamline front-end etc.) and the potential degradation of performance for other beamlines had to be considered. The projected demand for this energy range for all applications was also a relevant factor. There remain several unanswered questions that require further investigation (see 4.4.3) preventing a firm specification being reached at this stage: ongoing discussions and feasibility studies will lead to a more detailed definition in due course.

4.4.1 The source

Output from diamond undulators will (practically) have a maximum photon energy ~25 keV which is clearly not well matched to the primary requirements of the science to be undertaken on this beamline. A high field wiggler however, would produce significant intensity up to and above 100 keV albeit at lower brightness. Focusing might then be desirable in monochromatic studies to concentrate the more divergent radiation onto the small sample sizes, in which case the flux requirement on this beamline will be at least 10^{14} photons/s/mm²/0.1% band width over the range 20-80keV.

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A range of devices (2.5T to 3.5T permanent magnet, 2.5T to 3.5T superconducting magnets) have been examined: one that appears to be capable of delivering 20-100keV radiation, and having on- and off-axis intensities in the desired range, is a 32-pole 3.5T superconducting multipole wiggler (MPW). The estimated performance is shown in the plots in Figure 4.4-1 and Figure 4.4-2, and summarised in table 4.4-1.

Table 4.4-2 3.5Tesla Multipole Wiggler parameters

Type of Insertion Device	Multipole Wiggler
Magnet Technology	Superconducting
Peak Field (T)	3.5
Magnet Period (mm)	60
Number of Periods	16
K_{Max}	19.6
Nominal Magnet Gap (mm)	10
Nominal Length (m)	1.0
Total Power at 300 mA (kW)	20.1
On Axis Power Density at 300 mA (kW/mrad ²)	14.8

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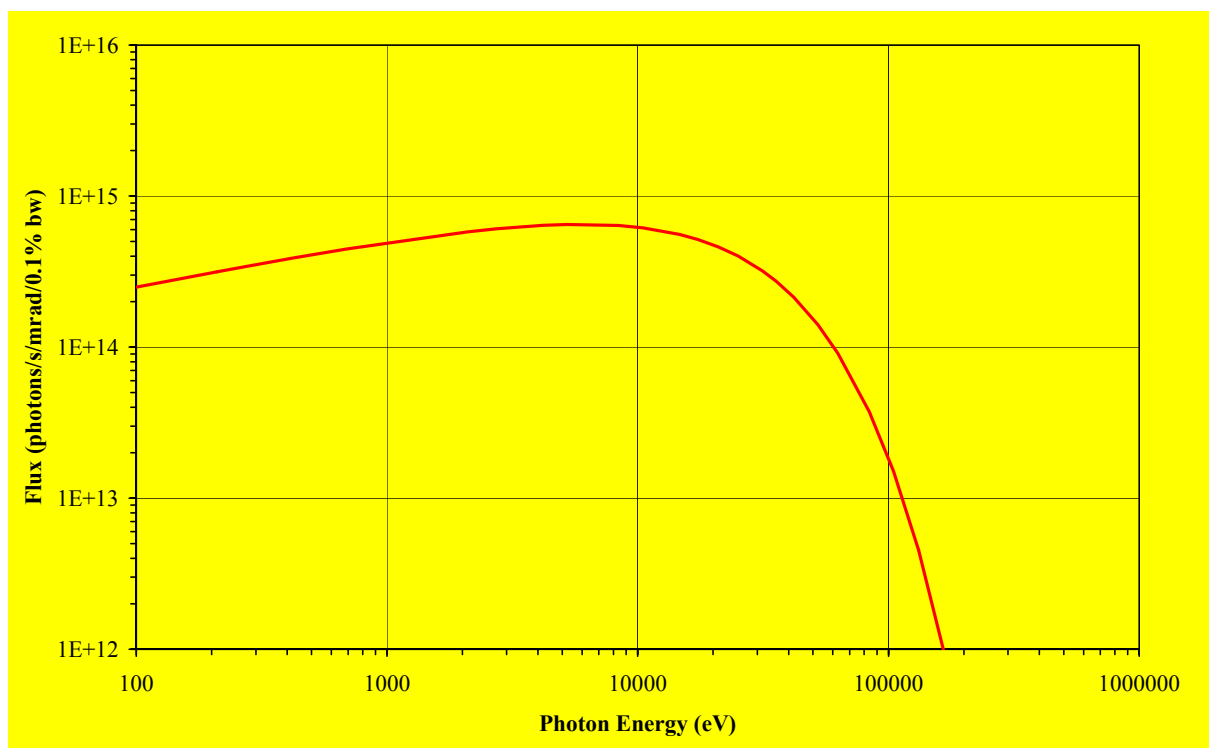


Figure 4.4-1 3.5 Tesla Multipole Wiggler Flux

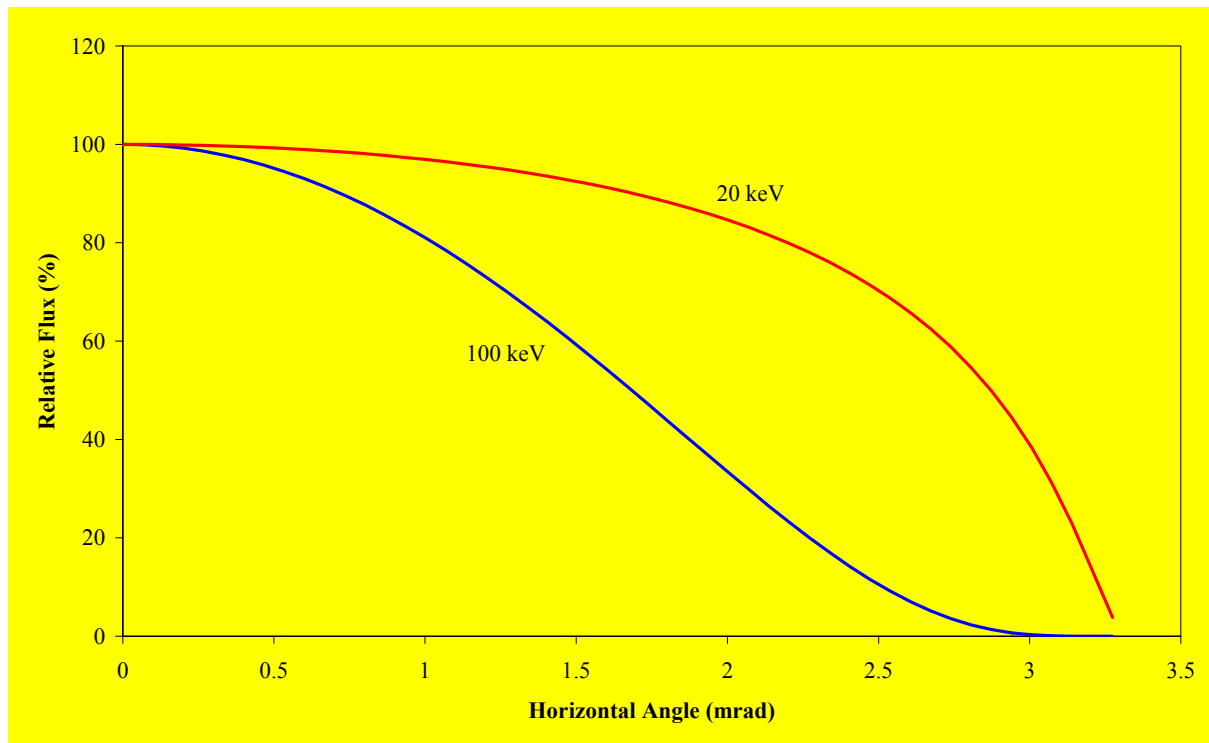


Figure 4.4-2 3.5 Tesla Multipole Wiggler Relative Flux at 20keV and 100keV as a function of horizontal angle.

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4.4.2 The beamline layout

Once again, it is not possible to show a definitive beamline layout at this stage as several crucial issues still have to be resolved, though the intention is to build a beamline that will deliver (on-axis) a white beam up to 100keV (and even beyond) for one group of experiments and (off-axis) monochromatic radiation in the photon energy range 20-100 keV to the other group.

The radiation fan from the MPW defines the axis of the beamline. The central 1mRad of the fan (i.e. ± 0.5 mRad) would serve the white beam experiments and a portion from the 1 to 2 mRad position would be taken for the monochromatic experiments. Whereas the multiple sources are simply additive for the centre of the fan, the off-axis branch would effectively experience a wider source because of the oblique projection of the multiple poles of the magnet (see Figure 4.4-3).

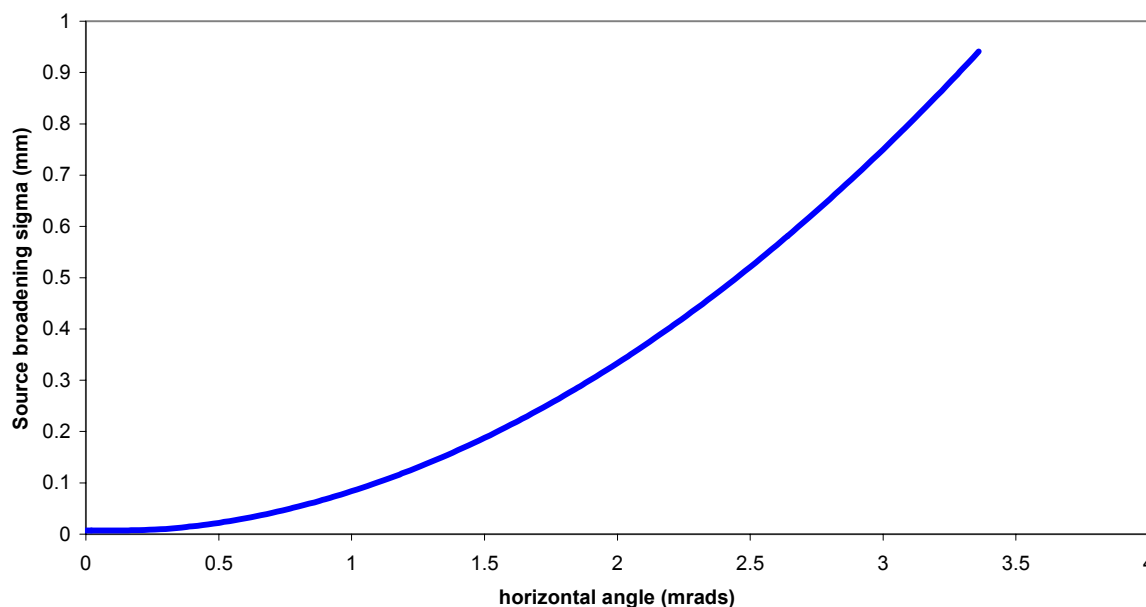


Figure 4.4-3 Broadening of the source (sigma) as a function of horizontal angle for a 1m long source.

A possible layout to support the experiments is shown in the Figure 4.4-4.

B.4 VERY HIGH ENERGY BEAMLINE

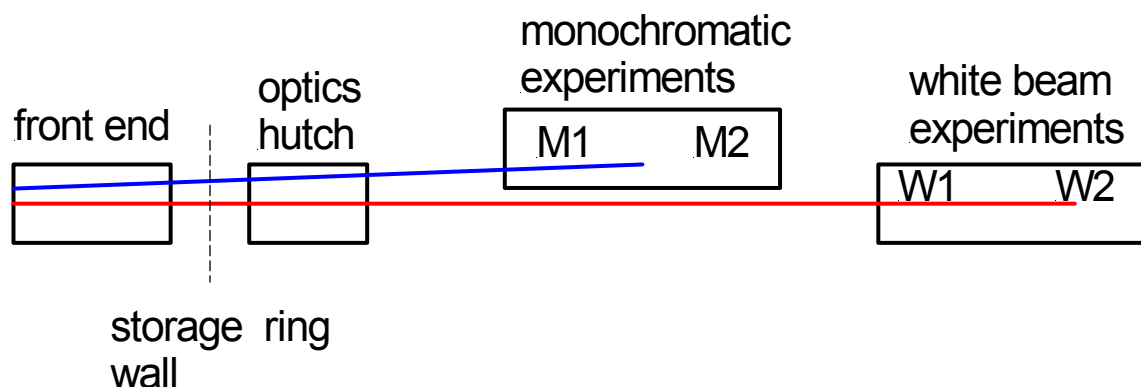


Figure 4.4-4 Schematic Beamline Layout

Grouping into two radiation enclosures would allow two experiments to be conducted simultaneously though each of these would preclude operation of the other experiment in that enclosure. This would maximise user access so maintaining the principal advantage over the ESRF. Experiments W1 and W2 (the high P-high T laser-heated DAC work and the hydrothermal/time resolved experiments) would occupy the 'white beam' enclosure. Experiments M1 and M2 (the studies with DACs and the single crystal diffractometer) would be mounted together in a second enclosure taking (focused) monochromatic radiation. Ideally, to maximise use of space, all X-ray optics and primary beam definition slits would be accommodated in a single enclosure next to the storage ring wall, which would reduce not only the costs but also the background scatter (noise) for the experiments.

4.4.3 Further specification work

(a) Source

The precise design (field strength, number and length of poles etc.) of the multipole wiggler will need to be finalised to match the on- and off-axis wavelength distribution to the experimental requirements as far as possible.

(b) Optics

Currently, it is unclear how best to focus the high energy radiation for these experiments. Above 25keV, incident angles on monochromators become extremely small (corresponding beam 'footprints' are extremely long), and mirrors become far less effective at these energies. The power loading from a 3.5T multipole wiggler would be approximately 20 W/mm² probably requiring liquid nitrogen cooling for Bragg-reflecting Si monochromators. Diamond has better thermal properties than silicon and is a possible alternative material for monochromators under these circumstances (see 10.2).

Focusing might be achieved in several ways. Sagittally-bent Bragg crystals can be used up to about 50 or 60 keV but anticlastic bending gives a progressively worse

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focus even when ribs are incorporated to reduce this. Asymmetrically-cut meridionally-bent crystals (often triangular in shape) can be used to good effect but give a sideways deflection to the beam requiring either a second reflection to bring the beam parallel again or the end station experiment to be motorised to follow the beam movements when the energy/wavelength is changed.

Recently, it has been demonstrated that bent Laue monochromators can be used for focusing. This transmission geometry has the advantage of reduced heat load and, potentially, a high energy capability. Using two crystals, a constant off-set can be maintained between the incident and monochromatic beams to avoid having to realign the experiment. In bending crystals to focus the beam, the natural reflecting range (bandwidth) is broadened which can be better matched to both the horizontal beam divergence and the reflecting range of crystalline powder or imperfect crystal samples resulting in improved incident and diffracted intensities. Clearly, work should be done on investigating the use of bent monochromators to focus the beam and tailor the bandwidth. In particular, Bent Laue arrangements, and Laue-Bragg combinations should be explored.

(c) Detectors

For EDX experiments, high count rate capability will be required giving good signal to background and fast time resolution (~ 10 ns) to follow changes during laser heating and kinetics measurements. Use of multi-element detectors will allow a broader range of reciprocal space to be examined.

ADX work will require a range of robust area detectors which might be image-plates or tiled CCD devices. All the experiments require installation of the highest efficiency detectors and should exploit advances that will undoubtedly be made before the beamline becomes operational. New materials are already being studied which would significantly enhance detector efficiency at high energies.

4.5 SAMPLE ENVIRONMENTS

A range of DACs are currently available for both white beam and monochromatic work, and these are continually being extended to higher pressures and to accommodate laser heating and a range of parallel measurements to monitor physical properties. Because of the world-wide activity in this area, further advances can be expected without specific development for this beamline, though the community will undoubtedly wish to experiment and build cells with new features. Similarly, multi-anvil and opposed anvil cells will be further developed for larger sample volumes.

Sample cells and reaction vessels are already available for studying reaction kinetics, looking at intercalation processes, creating hydrothermal environments etc. with heating, cooling, stirring and so on controllable through a computer interface. Time resolved experiments will be applied to ever more complex systems and it is this type

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of sample environment that will need to be developed as the boundaries of extreme conditions are stretched in many directions.

4.6 OFF-LINE SUPPORT LABORATORIES

The beamline will require extensive support facilities to characterise and prepare samples and cells for experiments. These will form an integral part of the research programme for many visiting groups and will help to strengthen collaborations within the community.

Besides the usual features of a well-found laboratory (e.g. bench space, sinks, fume hoods, chemicals, storage space etc.), the labs should include microscopes, spectrometers, and wet/dry chemistry for materials synthesis. Specialised equipment will also be required for sample handling and loading (controlled atmosphere glove boxes, Schlenck line, vacuum pumps), micro-machining cells and gasket materials, cell calibration and testing, gas loading under pressure, and characterisation measurements (e.g. off-line X-ray powder diffraction, magnetic and electrical properties determination).

B.5 Materials Beamline

5.1 INTRODUCTION

This chapter describes the current state of the evolving design for the Diamond Material Beamline. The Materials beam line is optimised to combine high flux and high resolution over a wide and continuously tuneable energy range, for diffraction and scattering experiments. The brightness of Diamond undulators will provide a beamline performance comparable to, and in some important aspects better than, insertion-device beamlines in existing third-generation synchrotron sources such as the ESRF.

The design team has not so far taken all topics to an equivalent level so that it will be seen that the treatment varies considerably in detail between them. Nevertheless the design concept presented has had its basic feasibility established and this has allowed the specification of all major technical systems to be defined with some confidence.

5.2 SCIENTIFIC CASE SUMMARY

A versatile high flux/high resolution diffraction facility will be fully optimised for a wide range of science programmes which fall broadly under the heading of Materials. The high flux on this beamline will be essential for two key categories of study: Measurements on very small samples volumes, including artificial nanostructures, thin films and surfaces, and measurements of very weak, but increasingly important, scattering processes such as diffraction from magnetic, charge and orbital ordering.

5.1.1 Applications in Hard Condensed Matter

The strongest theme for the Materials beamline is hard condensed matter science and technology, with studies of magnetic materials expected to play a prominent role. In fact, some of the materials that are currently exciting much interest in their fundamental physical properties, such as thin films and multilayers exhibiting perpendicular magnetic anisotropy and giant magnetoresistance, are expected to form the basis of a multi-billion dollar magnetic recording industry over the next few years. X-ray studies of such materials, mainly at overseas third-generation light sources, are already probing the basic physics of the materials and correlating it to structural properties such as microstructure and strain. The current trend, and possibly future technology, is towards patterned media and heterostructures, and the demands for flux, resolution and coherence will push beamline requirements to the limits.

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Polarisation analysis and polarisation-dependent scattering are emerging as important techniques for extracting the full information from (mainly weak) polarisation-dependent scattering cross-sections. It has played a major role in recent studies of the nature of fractional-integer Bragg reflections from transition metal oxide crystals. Future measurements should address the controversy over the ordering mechanisms, explore behaviour under the influence of high magnetic fields, and allow studies of MBE films.

The ultra high resolution capability and high coherence of the beamline in non-focusing mode will play a major role in elucidating the structural properties of high quality crystals and nanostructures. These include, for example, the relationship between structure (notably strain) and electronic properties of quantum wires and dots, high resolution diffraction and coherent imaging of ferroelectric optical devices, studies of strain in CVD crystallites, and multiple diffraction (Renninger scans) on semiconductor and possibly protein crystals.

5.1.2 Applications in Soft Condensed Matter

A fundamental understanding of the influence of free surfaces and buried interfaces on the properties of thin polymer films is important in many applications, including coatings, adhesion and the electronic behaviour at interfaces in polymer-based optoelectronic devices. Both the free surface and the buried interface may differently affect properties such as the chain conformation, the composition of mixed systems and chain dynamics, while a combination of surface and finite size effects may also influence the character and temperature of the crystallisation and glass transitions. In contrast to the extensive data available for semiconductors and other inorganic materials, indicating pronounced differences in the state of order between surfaces and bulk, very little information is available about the surface structure of polymers. Grazing incidence diffraction with synchrotron radiation is an ideal tool for such studies since the penetration depth is of the order of the molecular dimensions at the surface and the surface and bulk structure can be compared by adjustment of the incident angle. The scattering is weak from a molecular monolayer and the beam cross-section is small so the high brightness of the Diamond source will greatly benefit this relatively new area of research.

Semiconducting polymers for electronic devices are a big growth area both scientifically and commercially. Here polymers are used in thin films, often in multilayer structures. Since the device performance depends very largely on its interfacial properties, and as we know that electronic properties of polymers are strongly coupled to their chain conformations, we can anticipate that an understanding of the factors controlling chain ordering near surfaces and interfaces will be crucial to optimising device performance. Structural studies of in-situ processing of semiconducting polymer films is likely to be an important growth area for the coming decade.

5.2 OUTLINE TECHNICAL SPECIFICATION

The requirements for a Materials beamline are to some extent unpredictable, emphasising the need for a highly flexible beamline and end-station. It is clear from recent and planned experiments that the beamline will require a low-divergence undulator radiation source, and that the energy range must be continuously tuneable from 3.4 keV (just below the uranium M-edges) to a less well defined upper limit of the order 20 keV. The requirements for small focal spots (small samples, grazing incidence, etc) on one hand, and very high resolution diffraction and coherence on the other hand, necessitates the use of easily removable focusing optics. Furthermore, the optimum monochromator bandwidth will also vary from experiment to experiment, and in order to optimally match the beam parameters to the sample quality, the monochromator should contain a set of remotely interchangeable crystals, including an option for 'pink' undulator radiation.

Many experiments will require tuneable incident beam polarization (circular, linear and elliptical) and so in addition to the basic beamline optics a diamond crystal phase retarder will select the required polarisation state. Similarly, microfocusing optics may be installed for experiments needing micron beam sizes, although the specific requirements will depend on the facilities available on other Diamond beamlines.

The experimental hutch will contain a large, general-purpose optics table, a multi-axis high-resolution diffractometer, and a heavy-duty horizontally-deflecting diffractometer.

5.2.1 The source

The beamline specification requires a low-divergence (undulator) source, continuously tuneable from 3.4 keV to ~20 keV (an approximate anticipated distribution of photon energies is illustrated below in Figure 5.2-1).

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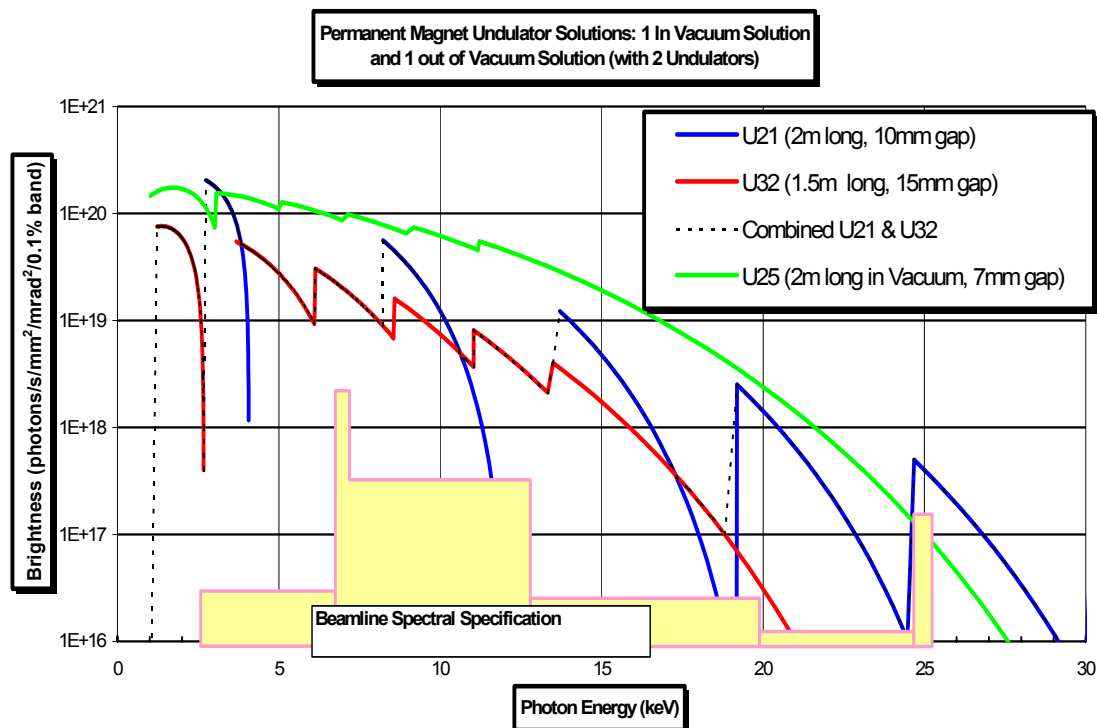


Figure 5.2-1 The anticipated demand for various energy ranges (histogram) compared with some calculated undulator tuning curves.

The device expected to best satisfies the above criteria is a 5 m long 33 mm period period (U33). The flux spectrum for the U33 is shown below in Figure 5.2-2.

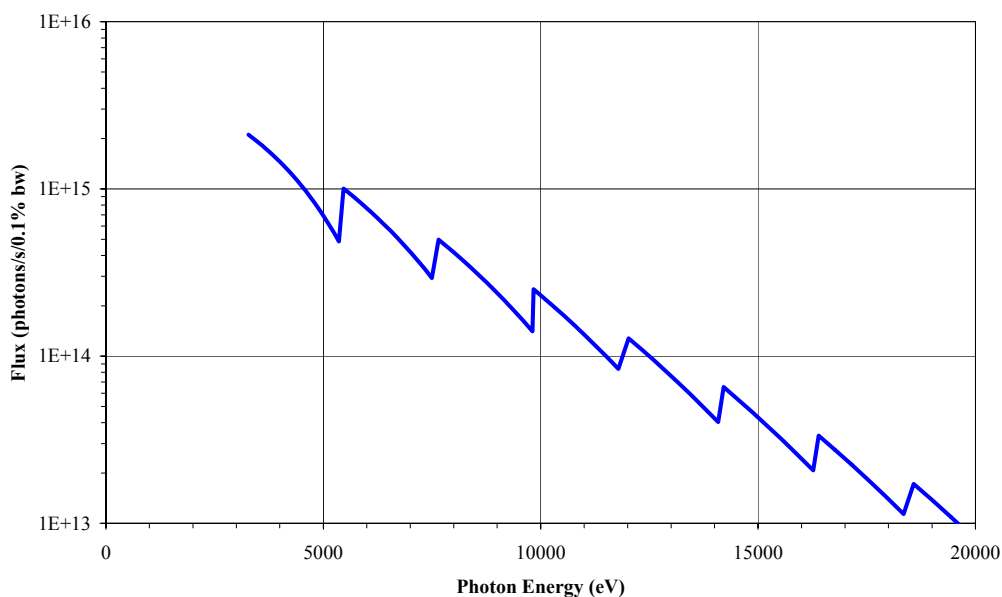


Figure 5.2-2 Tuning curve showing calculated flux for a U33, 5m undulator.

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An estimate of the performance of such a facility is given below. These performance figures need to be verified during the feasibility stage.

Table 5.2-1 Expected performance figures for the beamline.

Beam at Source	
$\sigma_{x,y}$ [mm]	0.12, 0.006
$\sigma_{x,y}$ [mrad]	0.024, 0.004
Flux in to 0.1X0.025 mrad aperture (10 ⁻³ bandpass)	10 ¹⁴
Collection efficiency	0.8
Beam at Experiment	
Focal Spot Size (fwhm h,v) / mm (2:1 focusing)	0.5, 0.1
Divergence (fwhm h,v) / mrad (2:1 focusing)	0.2, 0.05
Focal Spot Size (fwhm h,v) / mm (no focusing)	5, 1
Divergence (fwhm h,v) / mrad (no focusing)	0.1, 0.025

5.2.2 Optics

The optics layout for this beamline has evolved considerably over time, and is likely to continue to do so. The main requirements that govern the choices for beamline optics are:

- Energy range 3.4 keV~20 keV
- Focussed beam option (focal spot ~0.1 x 0.5 mm (V,H))
- Unfocused, low divergence, high coherence option
- Selectable bandwidth (remotely interchangeable monochromators), to cover bandwidths from 10⁻² to 10⁻⁵, with an emphasis on 10⁻⁴ range.

In addition to the above points, the beamline requires a phase-retarder for variable polarization, a microfocus provision, and, if possible, remotely-selectable 'pink' beam option, for which the monochromators would be removed.

A key design decision for the beamline optics concerns the requirement for a pre-monochromator collimating mirror. The current optical layout (see Figure 5.2-3) is based on the assumption that such a mirror is not required, since the vertical beam divergence is very close to the Si 111 Darwin width (see Figure 5.2-5). (The effects of beam aperture on photon bandwidth is discussed in chapter B 10). Since the extra mirror will add to the complexity, cost and optical aberration in the beamline, it is unlikely that the inclusion of such a device will be beneficial. This assumption will be confirmed or rejected following future detailed undulator and ray-tracing calculations.

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Experimental hutch

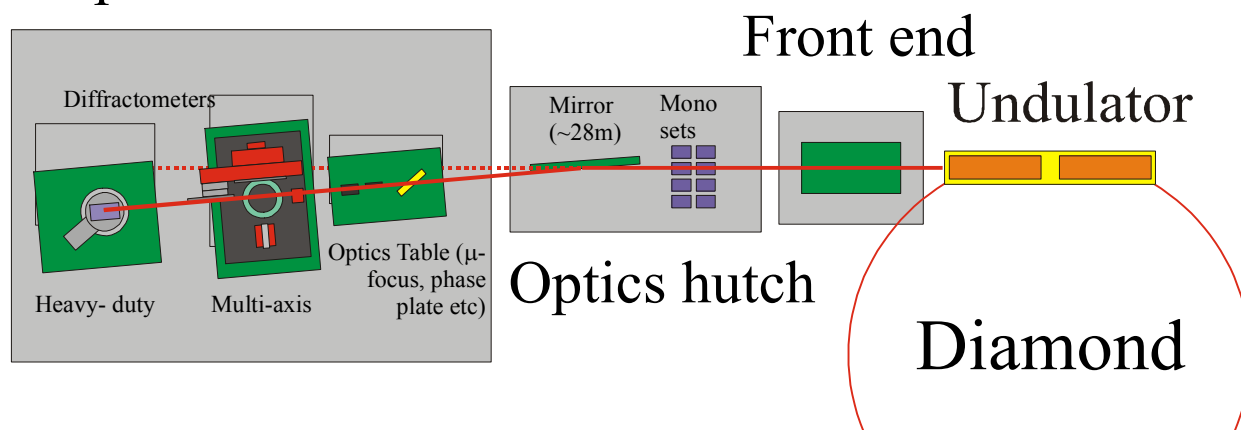


Figure 5.2-3. A schematic layout of the beamline and optics, showing horizontally-deflecting focusing and positions for unfocused mode.

Preliminary ray-tracing results (Figure 5.2-4, below) indicate that degradation of the focal spot size is completely dominated by shape errors in optical components, principally mirror slope errors, but potentially also from monochromator ‘heat bumps’. The latter have yet to be modelled, but an overview of the issues regarding monochromator heat-loads is given in chapter B 10. The effects of mirror slope errors can be halved by adopting a shorter focal length (i.e., 2:1 rather than 1:1), which also demagnifies the source, albeit at the expense of divergence, which increases by the same factor (divergence figures for focused and unfocused modes are given in Table 5.2-1

A novel variation on traditional optical design that is currently being investigated is the possibility of adopting a horizontally-deflecting toroidal mirror (Figure 5.2-4 (D)). This has the advantage that the slope errors then mainly spread the beam along its largest (horizontal) direction, rather than its smallest (vertical) direction. The larger horizontal beam size means that the beam footprint just fits on a standard 1m long mirror. This and other technical issues need addressing before such a design is finally adopted, but preliminary modelling gives very favourable results.

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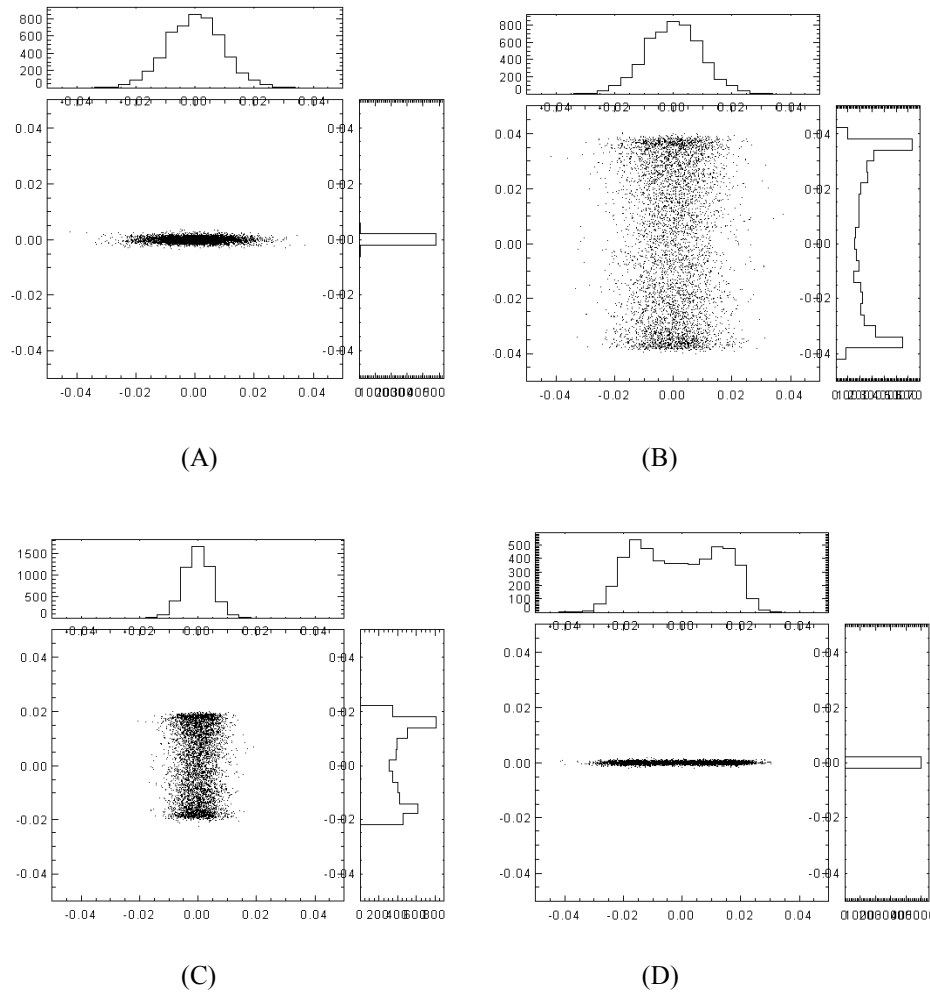


Figure 5.2-4 . Ray tracing results (1mm x 1mm plots); (A) 1:1 focusing with ideal toroidal mirror; (B) 1:1 focusing with 5 μ rad rms slope error (sinusoidal); (C) 2:1 focusing with 5 μ rad rms slope error; (D) focusing with 5 μ rad rms slope error, horizontally deflecting mirror.

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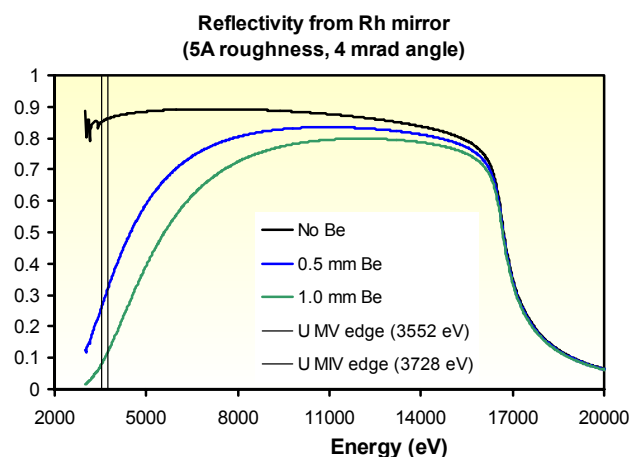


Figure 5.2-5 The energy spectrum from a Rh-coated mirror at 4 mrad, including attenuation from beryllium windows.

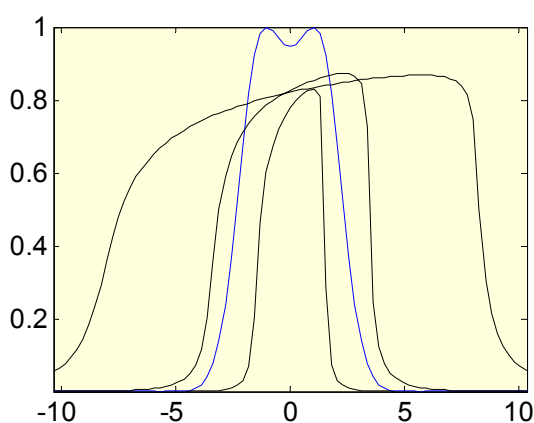


Figure 5.2-6 A simulation of the vertical angular distribution of radiation from an ideal 80-period U25 (5th harmonic, 9.8 keV – blue curve), compared with rocking-curves for Ge 111, Si 111 and Si 311 monochromators.

The horizontal geometry is also potentially simpler for rapid changing between focusing and non-focusing modes, as the beamline components and diffractometers then translate horizontally, rather than vertically. Similarly, a small horizontal movement, combined with changes to the mirror radius, will allow the focal distance to be selected as appropriate for each experiment.

The monochromator vessel is expected to house a set of remotely interchangeable monochromators with common goniometry and cryogenic cooling. Although the total power on the monochromator is expected to be modest (less than 50 W) compared with multipole wiggler beamlines, a thermally-induced gradient change (heat bump) of less than one arc second can cause a substantial deterioration of the focal spot. Detailed modelling of this effect will therefore be required. As the monochromator is expected to be the first optical element, and will be wider than conventional designs,

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the issue of available space on the shield-wall side of the optics hutch will require detailed examination.

While the optimum position of the phase-retarding optics (based on a set of high-quality diamond crystals) is before the focusing mirror, where the divergences is lowest, it is likely to be much simpler in practice to position the device on the hutch optics table. Future detailed studies of the feasibility of various optical layouts will be required to confirm this and a number of other assumptions.

Options for microfocusing have not been considered in detail for this beamline, except that it is expected that any such device will be mounted on the rigid hutch optics table. A general survey of potential technologies is summarised in chapter B 10.

The key aspects of the optical layout that have been identified as requiring further detailed study include:

- Specification, divergences and heat load of the chosen undulator

Which has important implications for:

- Confirmation that a collimating mirror is not required
- Modelling of the monochromator 'heat bump'
- Viability of adopting a horizontally-deflecting mirror

5.2.3 Diffractometers

Two diffractometers are proposed for this beamline: (1) a large, multi-axis high-resolution, general-purpose instrument that is capable of supporting modest sample loads (small magnets, 10K cryostat etc), and both polarization and high-resolution analyser stages, and (2) a simpler, heavy-duty (possibly horizontally scattering) instrument, capable of supporting much larger sample stages, including 1K cryostat stage and a superconducting magnet. Both instruments will support a range of detector systems, including a solid-state detector and 2D pixel array. The instruments will have built-in optical alignment systems and will be fully remotely controllable (i.e. no manual adjustments during normal operation). Both diffractometers will share a common optical mounting system with removable beamline components. Short air paths or helium/vacuum tubes will be available to transport the beam to the sample position.

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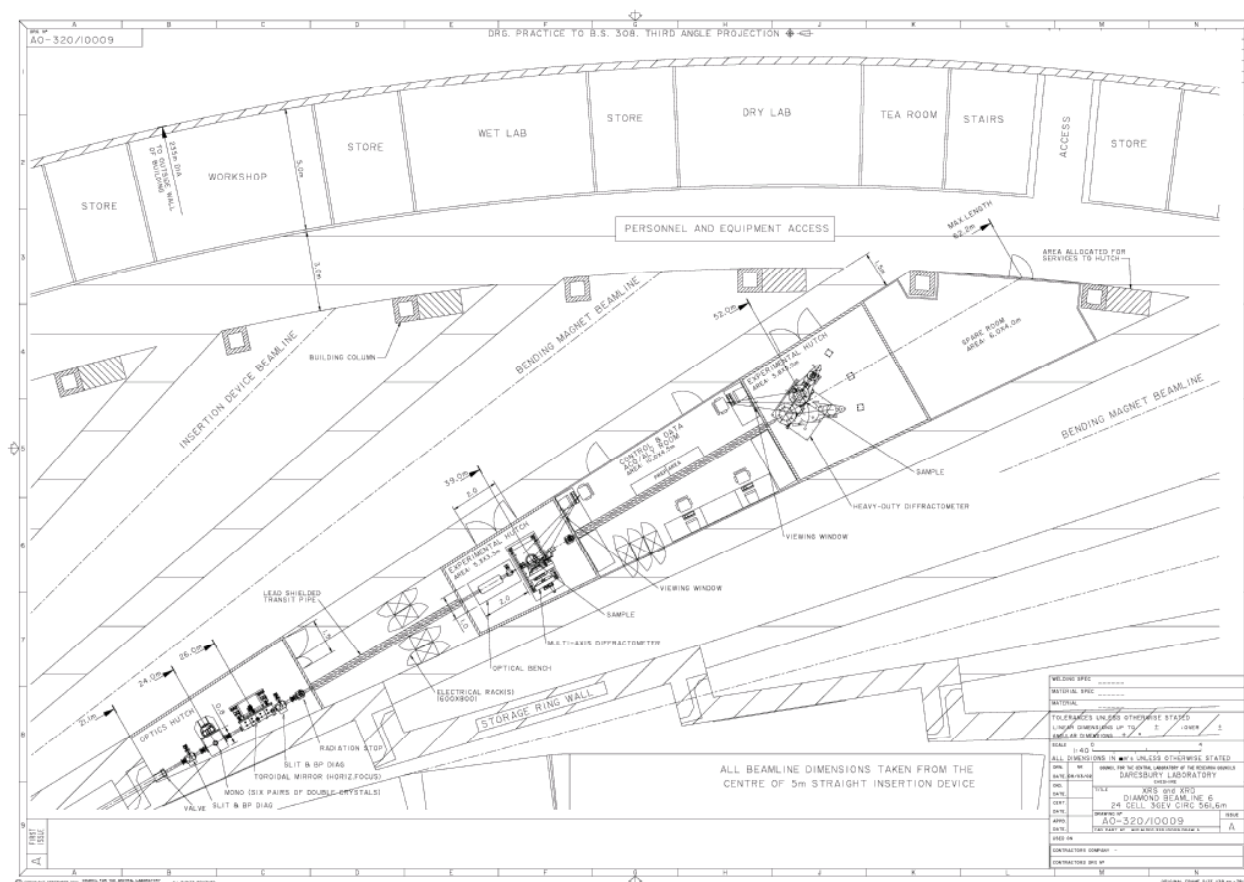


Figure 5.2-7 A plan of the proposed beamline layout.

The diffractometers, and hutch optics table, will be remotely positionable to aid alignment and to select between focused and unfocused modes, although it has not yet been decided whether the three components will share a common support.

5.2.4 Data Acquisition Software

The versatile nature of the beamline necessitates the use of similarly flexible data acquisition software. The most important requirement is for a general-purpose user-configurable command-line interpreter, with a powerful but simple programming language. Limited use of GUI controls could be an advantage, but are not essential. The programming language must be powerful enough to allow complex structures and mathematical operations, such as vector/matrix calculations for reciprocal space positioning and unit cell refinement. The language must also be simple enough to allow inexperienced users to write data collection macros with a minimum of training. It should include all the desirable features of existing systems (PINCER/CLAM, SPEC etc) while providing a greatly enhanced programming language, access to external processes (including beamline and machine parameters), and a flexible data file format.

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The adopted data acquisition software must allow users to rapidly incorporate their own equipment (with any standard interface) into the experimental control, without requiring effort from a software engineer.

5.2.5 Offline Laboratory Provision

Off-line laboratory requirements are mainly of standard laboratory equipment such as glassware, fume cupboards, scales, microscopes, desiccators, ultrasonic bath and a press. Equipment for melting samples under vacuum/gaseous environments will be required, as will access to crystal cutting (including diamond saws and a spark cutter) and polishing equipment.

B.6 Macromolecular Beamlines

6.1 INTRODUCTION

It is proposed to establish three diffraction beamlines using undulator sources on Diamond for the determination of the atomic structures of macromolecules.

The ultimate goal of modern biology is to provide an understanding, at a molecular level, of the myriad of processes that take place within living organisms. Fundamental to this understanding is knowledge of the three-dimensional structures of the molecules themselves, because of the causal link between structure and function. Structural biology is currently undergoing a revolution in terms of both the number and the complexity of the biological macromolecules for which structural information is becoming available at atomic resolution.

6.2 SCIENCE CASE

UK research groups are actively leading structural work across a very broad spectrum of scientific areas. Some of their activities are described briefly below in terms of a number of broad identified themes, although these are necessarily far from being all-inclusive.

6.2.1 Macromolecular assemblies

Large macromolecular complexes carry out many cellular functions. Examples include: (a) the ribosome, which decodes the genetic information in messenger RNA and synthesises proteins, (b) ATP synthase, which synthesises ATP using energy derived from a transmembrane proton gradient, and (c) the spliceosome, which excises introns from eukaryotic pre-mRNA. Detailed atomic structures on parts or all of these systems has been obtained by crystallographic methods, although in all cases further work is required to obtain a complete picture of their respective activities. A further example is Blue Tongue Virus, a transcriptionally active assembly of over 1000 protein components. Other viruses, including hepatitis B virus and an enveloped phage virus are being actively studied.

Signal Transduction

The activity of many cellular processes is regulated by protein phosphorylation in response to the binding of extra cellular ligands to their cognate receptors. Structural studies of the numerous components of these signal transduction pathways is a major activity amongst UK research groups, including studies of the membrane bound receptors (rhodopsin), protein kinases and phosphatases and complexes with their

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binding partners. The structures of complexes of these proteins with their target enzymes, with guanine exchange factors, GTPase activating proteins and proteins that promote cross talk between pathways, are providing valuable insights into the mechanisms of these complex pathways.

Cell cycle progression

Equally important in maintaining cellular function is the regulation of progression through the cell cycle, from DNA synthesis (S phase) to mitosis (M phase) via the intervening gap phases (G1 and G2). The anaphase promoting complex contributes to this regulation by the ubiquitination of specific proteins. Retinoblastoma (Rb) tumour suppressor protein acts by regulating transcription factors that control the G1 to S cell cycle transition. Mutations in Rb are associated with many human cancers. Phosphorylation by cyclin-dependent protein kinases also plays a critical role in ordering cell cycle events. Multi-protein complexes are frequently involved in regulation.

Protein-nucleic acid complexes

Protein-nucleic acid interactions (involving both DNA and RNA) represent another important focus. This includes nuclear hormone receptors and a large number of transcription factors which control gene expression at the level of transcription, in the former case in response to the presence of specific ligands such as oestrogen. DNA repair enzymes are essential for the maintenance of chromosome integrity, and there are several distinct families of enzymes that target specific types of DNA damage. The machinery associated with DNA replication and homologous recombination, including polymerases, helicases, resolvases and replicases are also targets for structural work.

Enzymes

In many cases, work is targeted on enzymes that belong to essential biosynthetic pathways that are unique to pathogenic bacteria or parasites. The enzymes in these pathways form attractive targets for the development of novel antimicrobial or antiparasitic agents (new antibiotics) in the treatment of human disease.

Immune system

Proteins involved in inflammatory and immune responses, including superantigens, auto-antibodies (responsible for rheumatoid arthritis), and immunoglobulin E and its receptor (which play a key role in all allergic diseases) are important biological and medical targets for X-ray crystallographic analysis.

Membrane proteins

There are considerable difficulties in the over-expression of membrane proteins that are present in low natural abundance, and additional problems of crystallisation. As a

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result, progress in the structure determination of this class of proteins has been quite slow, and a relatively small number of groups are active in this area. However, membrane proteins are estimated to represent up to 30% of the gene products of a typical genome, and they are of considerable interest to the pharmaceutical industry (almost 50% of drug compounds in clinical use are targeted at membrane proteins). Consequently, structural studies of membrane proteins will become increasingly important in the next decade.

Rational drug design

A growing number of pharmaceutical companies are making increasing use of macromolecular crystallography. Improvements in the speed of data collection and structure solution mean that it is now possible to obtain structural information on a timescale that allows chemists and structural biologists to work together in the development of lead compounds into drug candidates. There are several examples of drugs developed in this way that are already in use and many others are at the stage of clinical trials.

6.2.2 Genomic Studies

The recent elucidation of the sequence of the human genome, together with genome sequences for an increasing number of less complex organisms, has profound implications for structural biology. Special initiatives to exploit genomic information are already underway in the United States, funded by the National Institute of General Medical Sciences, in Japan at the RIKEN Centre, and in Germany (Berlin) and several centres in France. The Medical Research Council has recently funded a protein production facility for structural and functional genomics in Oxford, and the possibility of setting up an industrial consortium is under discussion.

6.3 BEAMLINE REQUIREMENTS

Requirements for UK Health and Life Sciences were defined at a workshop held at MRC Head Office in May 1999, attended by scientists, industrial representatives, synchrotron scientists from UK and abroad and funding agencies. The workshop based its proposals on almost 100 responses to a detailed questionnaire circulated to the UK community. Taking into account the current level of synchrotron usage, the anticipated expansion of the community, and the expected performance of the Diamond PX beamlines, it was concluded that five beamlines dedicated to macromolecular crystallography would be required. Furthermore, this requirement was likely to increase significantly in the event that a major initiative in structural genomics was undertaken in the UK. It was felt to be of crucial importance that three PX beamlines are available from Day 1 operation of Diamond.

Because of the increasing importance of anomalous dispersion measurements in structure solution, all three beamlines should be rapidly tuneable over a minimum wavelength range of 0.7-1.3Å. In order to access additional absorption edges, there

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should be the capability of extending this range down to 0.5Å and up to 3.5Å over the three beamlines as a group.

It was viewed as essential that the beamlines are designed to deal with very small samples, both with regard to visualisation and in terms of mechanical stability and reproducibility.

Robotic systems for automated sampling handling and crystal centring, and software which will allow automated data collection and processing are essential to achieve the highest possible productivity from the beamlines. An interest was also expressed in remote monitoring, or even remote operation, though at the time this was not being carried out at any facility.

Support facilities to allow sample storage, inspection and manipulation are absolutely necessary for each beamline. This includes provision of basic equipment (microscopes, pipettes, dewars, glassware) as well as working space.

Category III contained beamlines would allow studies on many important human pathogens. This is already available at the APS and would be a major advance for Europe. Such studies could revolutionize our ability to design new chemical therapies and vaccines. Given the groundwork that has been performed on other viruses of comparable complexity, this is a realistic goal. The JIF funded Facility for the Evaluation of Infectious Particles in Oxford (which provides a suite of contained laboratories) would be available to provide a staging post and a crystallization laboratory to support such activities. It is possible that in the future a much broader range of genetically engineered material may be classified as hazardous and so building in such capability to all beamlines might be both cost effective and prescient. All three beamlines should be designed to include this; it should be available for one beamline on day one.

6.4 BEAMLINE SPECIFICATION

The schematic diagram shown below (Figure 6.4-1) illustrates a possible optical layout for a protein crystallography beamline built to meet the specification outlined above.

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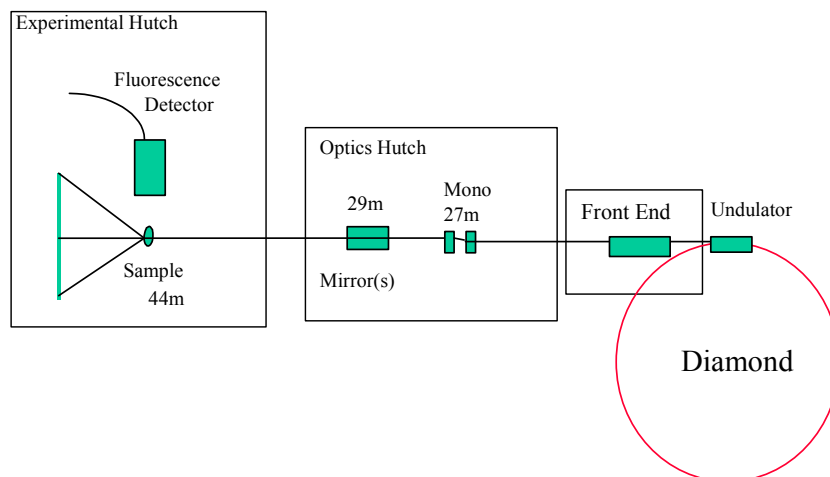


Figure 6.4-1 Possible optical layout for a protein crystallography beamline

Table 6.4-1 Expected performance figures for the beamline.

Beam at Source	
$\sigma_{x,y}$ [mm]	0.123, 0.006
$\sigma'_{x,y}$ [mrad]	0.024, 0.004
Flux in to 0.1 X 0.025 mrad aperture (10^{-3} bandpass)	3×10^{13}
Collection efficiency	0.7
Beam at Experiment	
Focal Spot Size (FWHM h,v) / mm	0.15, 0.05
Divergence (h,v) / mrad	0.2, 0.014
Flux at 0.98Å / ps ⁻¹	2×10^{12}

6.4.1 Choice of Insertion Device

There are now several examples of successful protein crystallography beamlines operating on undulators (e.g. ID14, ID29 ESRF; SBC-CAT, APS). However it should be noted that all of these are on higher energy machines than Diamond (ESRF at 6 GeV and APS at 7 GeV). This means that even with undulator gaps of 10mm or more, it is possible to operate at lower harmonics. The requirement that the protein crystallography beamlines operate at energies of up to 24keV (0.5Å) means that undulator operation at higher harmonics will be required, independent of the type of undulator used.

Calculations have been carried out to determine the undulator optimally suited for protein crystallography. Aspects taken into account were issues such as minimum operational gap (and the effect on lifetime) and the length of undulator possible in a straight. Both in-vacuum and ex-vacuum undulators were considered and the output examined at key wavelengths of interest for protein crystallographers.

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The result of these calculations was that an in-vacuum undulator of period 23mm and operational gap of 7mm was proposed for the protein crystallography beamlines on diamond. This was taken on board for 2 of three beamlines. However it has been suggested that for one of the three beamlines an alternative undulator be chosen which is optimised for a narrower gap. It is hoped that this beamline would allow data to be collected on projects that provide a real technical challenge to the beamline such as experiments on weakly diffracting virus crystals.

The aperture at the undulator required for the protein crystallography beamlines was set to be $100\mu\text{rad} \times 25\mu\text{rad}$. The effect of errors on the output of undulator was also taken into account – factors such as the energy spread of the electron beam and the phase error on the magnet itself. If one also includes the efficiency of the optics and the bandpass of the monochromator then at $1\text{\AA}$ the flux at the sample is expected to be 2×10^{12} photons/s. The flux over the wavelengths of interest for protein crystallography is shown below.

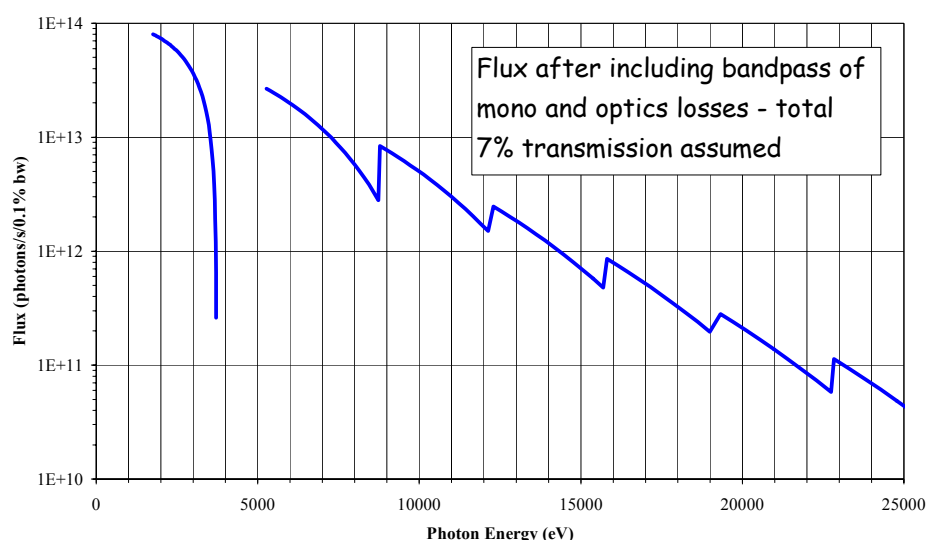


Figure 6.4-2 Flux over the wavelengths of interest for protein crystallography .

In order to accommodate a side station it is planned to use a second undulator positioned at the end of the straight with a small “bending magnet” placed between the main and second undulator to provide about 1mrad gap between the two beamlines. The second undulator would be one external to the machine vacuum chamber. One possible option would be a 0.8m U26 operating with a 15mm gap. However investigations need to be done to determine whether this undulator will be of greater benefit than a bending magnet beamline.

6.4.2 Design Issues

Associated with these beamlines are several design issues that need to be investigated in due course. These principally concern the use of undulators on Diamond and what

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precise optical components are required for the beamline to meet the required specification. Due to machine energy spread and errors in the undulators, the characteristics of the radiation, in position-angle-wavelength space, are likely to be complex at the higher harmonics. This has yet to be analysed but it is likely that the radiation at these higher energies will have a significantly higher divergence compared with that given by an ideal undulator. At present, it is assumed that a collimating mirror will not be needed to provide a low wavelength bandpass at these higher harmonics but this option will be considered in full during the more detailed specification stage.

The outline specification states that all the protein crystallography beamlines should cover the wavelength range $0.7\text{\AA}$ – $1.3\text{\AA}$ with the additional capability of operation between $0.5\text{\AA}$ and $3.5\text{\AA}$ on some facilities. Therefore each beamline should be designed to provide optimum performance at $1\text{\AA}$ wavelength and with useful radiation up to $1.3\text{\AA}$ and down to $0.7\text{\AA}$. If it emerged that an undulator optimised for performance at $1\text{\AA}$ had significant gaps in the tuning range between $1.3\text{\AA}$ and $3.5\text{\AA}$, then the option of a second insertion device, optimised for longer wavelengths, would be considered for one of the beamlines.

Investigations will also be made into beamline performance at wavelengths in the range $0.5\text{\AA}$ - $0.7\text{\AA}$. If this extension to higher energies (lower wavelengths) does cause significant problems, then it is possible that this aspect of the beamline specification will be relaxed to $0.7\text{\AA}$.

Focusing of the undulator beam can be achieved in several ways

- A single toroidal mirror to focus horizontally and vertically
- A sagittal bent monochromator to focus horizontally followed by a mirror bent to a large radius to focus vertically
- Two orthogonal mirrors to provide separate focusing in the horizontal and vertical directions (Kirkpatrick-Baez arrangement).

All of these arrangements have been successfully used on undulator sources. The final choice of systems depends on factors such as cost and any requirement for flexibility in focusing. A full assessment of these options will be done in the next (feasibility) stage. The protein crystallography beamline working group felt that the requirement for small ($10\mu\text{m}$) beams could be met by slitting down the beam dimensions and that microfocussing was probably unnecessary and possibly more problematic. This issue will be further investigated in due course.

A double crystal monochromator is placed upstream of the focusing mirror. If the divergence of the undulator beam is low (assuming issues stated above prove to be negligible) it is not necessary to have a pre-mirror to provide angular collimation at

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the monochromator (and therefore a small wavelength spread). Liquid nitrogen cooling for the monochromator is planned as it has been shown elsewhere that this is an efficient method of cooling silicon crystals. The heat load on any mirror placed after the monochromator will be low, so thermal distortion of the mirror surface should not be a problem.

The demand for access to protein crystallography beamlines is expected to exceed the capacity of three beamlines. To anticipate future expansions in the floor layout and avoid retrofitting a new front end the feasibility of putting an additional fixed wavelength station onto the side of each beamline will be investigated in the detailed design.

6.4.3 Further specification work

In preparation of a detailed, the following issues need to be resolved.

- Parameters of the insertion device or devices to match the experimental requirements, including possible use of in vacuum undulators.
- Need or otherwise for pre-collimating mirror
- Choice of focussing option and final focussed beams size
- Requirements to accommodate a side station

6.5 BEAMLINE LAYOUT

Figure 6.5-1 shows a possible layout for a main undulator beamline indicating that it is possible to fit the beamline into the constraints imposed by the building.

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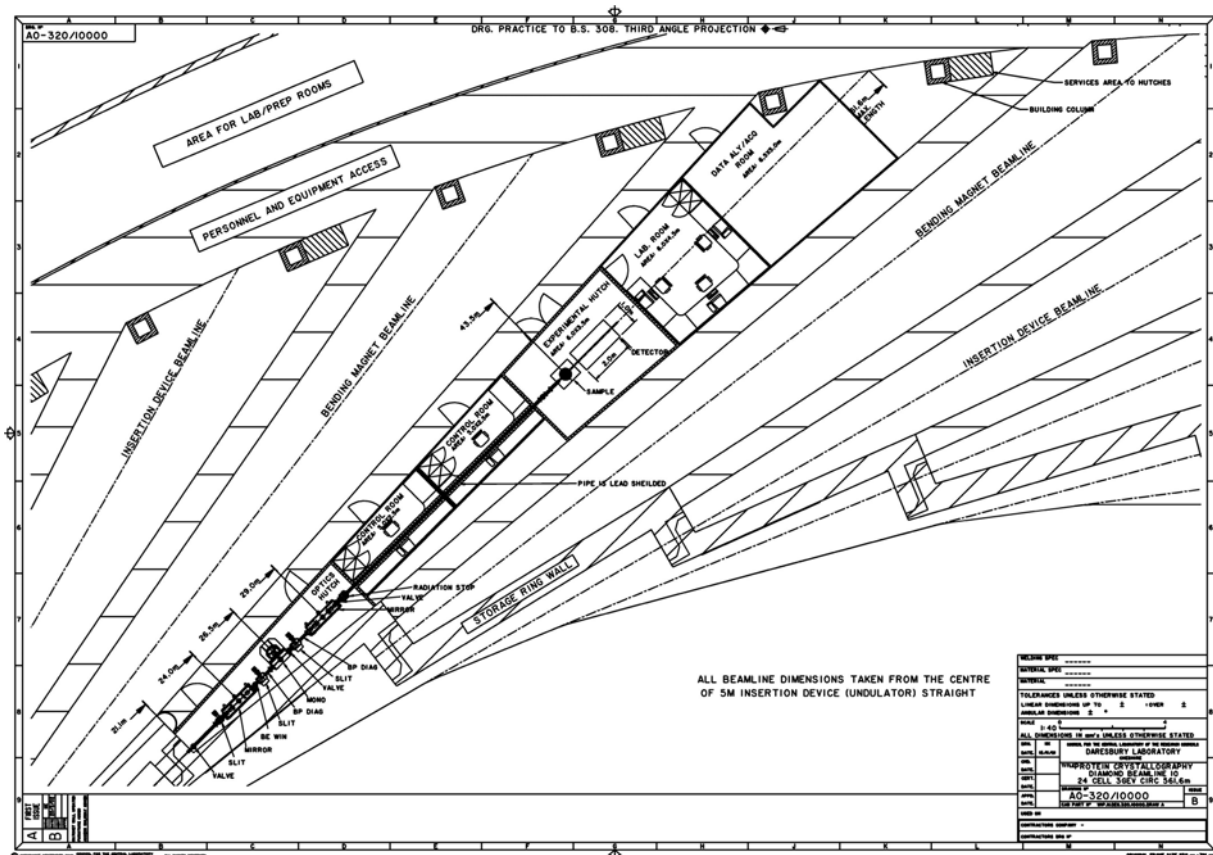


Figure 6.5-1 A possible layout for a main undulator beamline.

The plan to incorporate Category 3 Biological Containment on the beamlines will affect the layout of the beamlines as both robing rooms and laboratories will be required in addition to the usual control cabins. An off-line laboratory will also be required for each beamline in the area on the other side of the walkway. This off-line facility will be equipped to allow standard sample preparation to take place away from the beamline. It is expected that there will also be laboratories available remote from the beamline in Research Council funded “Research Hotels” though the mechanism for user access (if any) has yet to be discussed.

The side station could be accommodated however it would involve encroaching onto the end portion of the adjacent bending magnet space. Figure 6.5-2 shows a possible layout for a side station and indicates how it would lie with respect to the main beamline.

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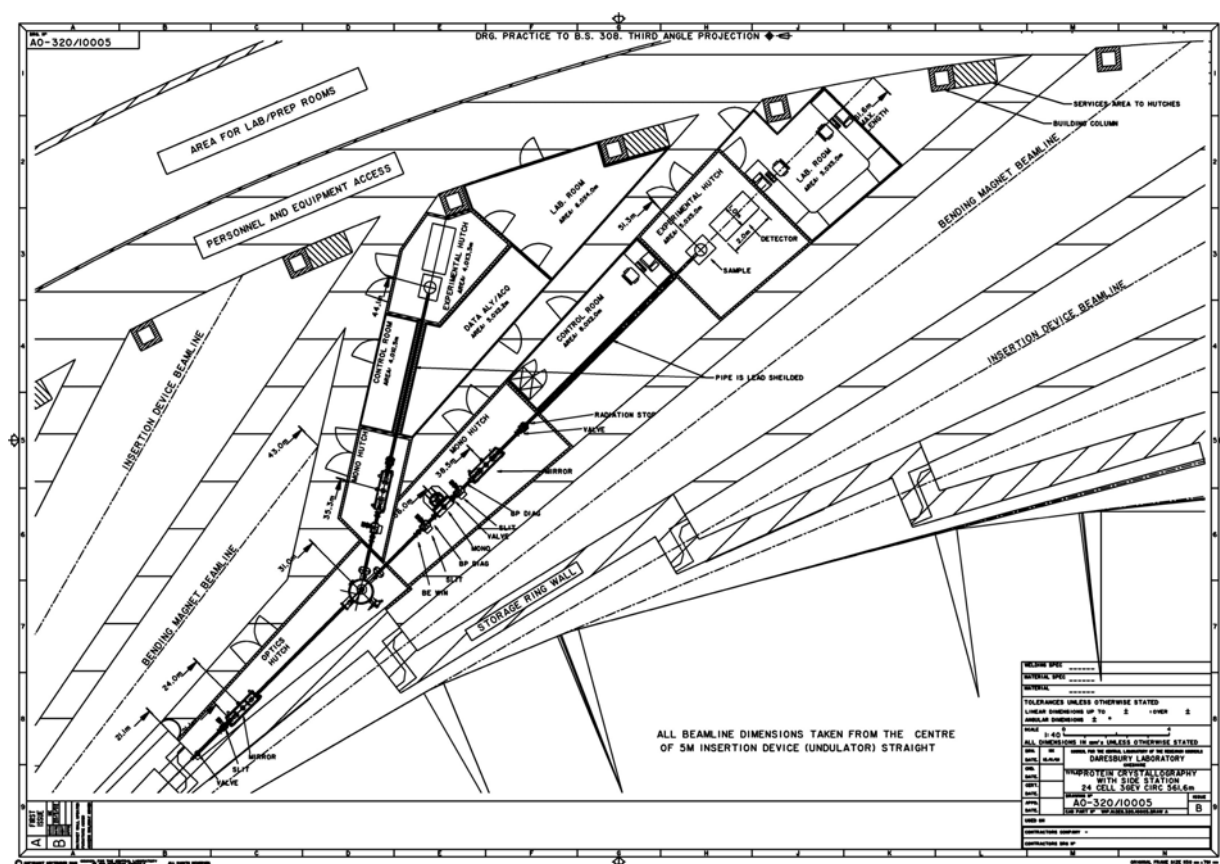


Figure 6.5-2 Possible layout for a side station.

B.7 Microfocus XAS Beamline

7.1 INTRODUCTION

This chapter explains the basic design for a microfocus X-ray Absorption Spectroscopy (XAS) beamline on DIAMOND. The outstanding characteristic of a third generation synchrotron light source is the extreme brightness of the light that it produces which makes it possible to produce micron-sized x-ray beams as a matter of routine. Whilst these have been exploited extensively for diffraction, exploitation of these beams for spectroscopy is still challenging. The key objective for this beamline is to produce a beamline dedicated to the production of micron or even sub-micron microfocus x-ray beams with an emphasis upon spectroscopy i.e. XANES and EXAFS. In addition the beamline will be equipped for the use of combined techniques e.g. microdiffraction and complementary optical imaging facilities. It is clear that only an undulator will have the necessary qualities in order to deliver high photon fluxes into the smallest focal spot, although there are key technical challenges to be overcome as gap scanning will be required. The working group has not taken all topics to an equivalent level, so this report mainly concentrates on the specification of the insertion device, but it is clear that in order to have confidence in the ID specification an outline of the optical components is required and this is included here as a preliminary specification.

7.2 SCIENTIFIC CASE SUMMARY

Early work with XAS tended to concentrate upon pure or ideal systems, but as the technique has developed there has been a strong trend towards the study of systems under their normal working conditions. In addition the impetus for studies of typical or real rather than model samples adds complexity to the problem. This complexity may be resolved in three dimensions: compositional, temporal and spatial.

The SRS has pioneered the application of synchrotron radiation using combined x-ray spectroscopy and structural techniques to study complex materials under realistic conditions as they evolve in time. Outstanding results have been obtained in the fields of catalysis, polymers and amorphous solids. However spatial complexity eludes study at a second-generation source. As a consequence there are many important areas of scientific activity for which spatial complexity is intrinsic that are currently denied the benefits of Synchrotron radiation. A versatile microfocus x-ray beamline will have a very wide appeal.

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7.2.1 Applications in Earth sciences

In *Earth Sciences* the applications range from geochemistry, mining, study of fluid inclusions in rocks, to the use of speciation as indicators of climate change. *Extraterrestrial Geology* will require sub-micron x-ray mapping for the study of minute and immensely precious minerals returned in separate Martian and cometary return missions from 2007/8. The opportunities for *Environmental Science* are numerous, and include such diverse topics as: bioremediation of heavy metals, tracing the routes of pollutants in the natural environment, and the containment of radioactive waste. X-ray microprobes are already being shown to be very valuable in archaeometry.

7.2.2 Applications in the physical sciences

The potential of microfocus x-ray spectroscopy is largely unexplored for most of the *Physical Sciences*. It is clear that sub-micron beams will open up the study of transient intermediates and give fundamental insights into a wide range of important chemical reactions and ultra-dilute systems. The study of reactions at solid interfaces (high temperature fuel cells) and solid/liquid interfaces (hydrothermal synthesis of materials) should be greatly enhanced. Important applications are envisaged for ceramic and composite materials where the relationship between materials failure and spatial heterogeneity may be investigated. This should lead to the development of improved materials. In the same way new insights into corrosion in hostile high temperature environments will be achievable. The spot size of microfocused beams is approaching the point where useful application in the field of nanotechnology can be imagined for the investigation of self assembled complex heterostructures.

Construction of a beamline for microfocus x-ray spectroscopy will have a synergetic effect upon the other beamlines planned for Diamond, since the technology developed for x-ray focusing and detection will find widespread applicability. Furthermore developments in secondary spectroscopy will nurture the application of fundamental solid-state physics to chemistry and the construction of novel materials for device fabrication.

7.2.3 Competing Facilities

Development of microfocus beamlines is a source of intense competition between synchrotron facilities world-wide and the demand for these facilities from users outstrips the supply by a factor of five. Thus the fraction of users world-wide who have access to these facilities is very small. Furthermore there are very few groups in the UK who have had any access to or experience of this technology. Looking at the growth rate of these facilities against the increasing demand, it is clear that the competition for access will be just as great in five years time as it is today. DIAMOND has to be competitive in this area since the production of microfocus beams is fundamental to operation of third generation synchrotrons.

For further details on the above applications see the proposal for DIAMOND beamline 13, see reference [1].

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7.3 OUTLINE TECHNICAL SPECIFICATION

The wide ranging scientific needs require the energy range to be maximised in order to cover as many absorption edges as possible ideally (1.5 - 20keV). It is also clear that in order to collect EXAFS data gap scanning is required and an undulator specified which does not have any spectral gaps in its tuning curve.

7.3.1 The source

The initial specification of photon energy range was loosely defined as 2-13 keV, but ideally 20keV, with the boundary to be defined in the design study. With regard to the expressions of interest from the user community and from the working group discussions it was clear that there is sufficient interest in reaching the Si and Al K edges, thus the minimum energy range was lowered to 1.5keV as this did not significantly impact on the undulator design. There is also significant requirement for the high energy x-rays to study for example Sr K and U L edges, so the working party were keen to ensure the high energy cutoff was 18-20 keV. This requires using higher harmonics on the undulator which is a technical challenge, and it was also recognised that the higher the energy cutoff prescribed, the more inefficient the optics become as they will not be able to collect the whole radiation fan. The final high energy cutoff is thus still dependent on the optical design study. It was also clear from the letters of support that the prime energy range was 5-12 keV and some loss of efficiency would be acceptable outside this energy range.

A number of options were considered for the insertion device, but the recommended solution is a 2m long U27 in-vacuum undulator with a minimum gap of 7mm and a maximum K value of 2.0. A period of just less than 30mm is required in order to ensure overlap of successive harmonics. Central cone calculations of the flux output of this undulator is shown in Figure 7.3-1 and requires an acceptance aperture of approximately 100 μ rad x 40 μ rad (HxV). The decision to choose an in-vacuum undulator as opposed to an ex-vacuum was not straightforward as the gains in tuning range by having an allowed minimum gap of 7mm as opposed to 10mm ex-vacuum are somewhat compromised by the lower magnetic field of an in-vacuum undulator. However the working party felt that an in-vacuum undulator offers the possibility of closing the gap even more in the future when operation of the DIAMOND machine has matured and thus offers better 'future-proofing' than an ex-vacuum device.

It is also important that the device can be tapered as this will broaden the harmonic width of the undulator flux, albeit at the expense of reduced flux. The gain in harmonic width is only likely to be at most to 200eV, but will be a useful tool enabling XANES scans to be easily obtained in early days of DIAMOND operations. Figure 7.3-2 shows the effect of a taper on a 2m long U24 undulator, the effect of tapering on the U27 will be similar.

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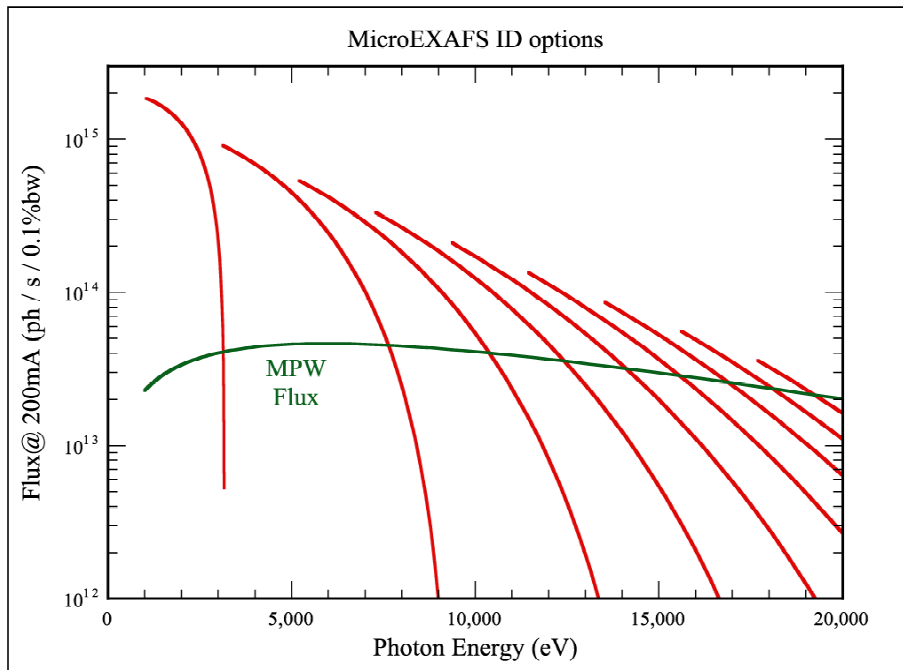


Figure 7.3-1 Flux outputs into central cone (approx. $100\mu\text{rad} \times 40\mu\text{rad}$ (HxV)) for a U27 in-vacuum undulator and for a 45pole 1.6T MPW into a $100\mu\text{rad} \times 300\mu\text{rad}$ (HxV) aperture.

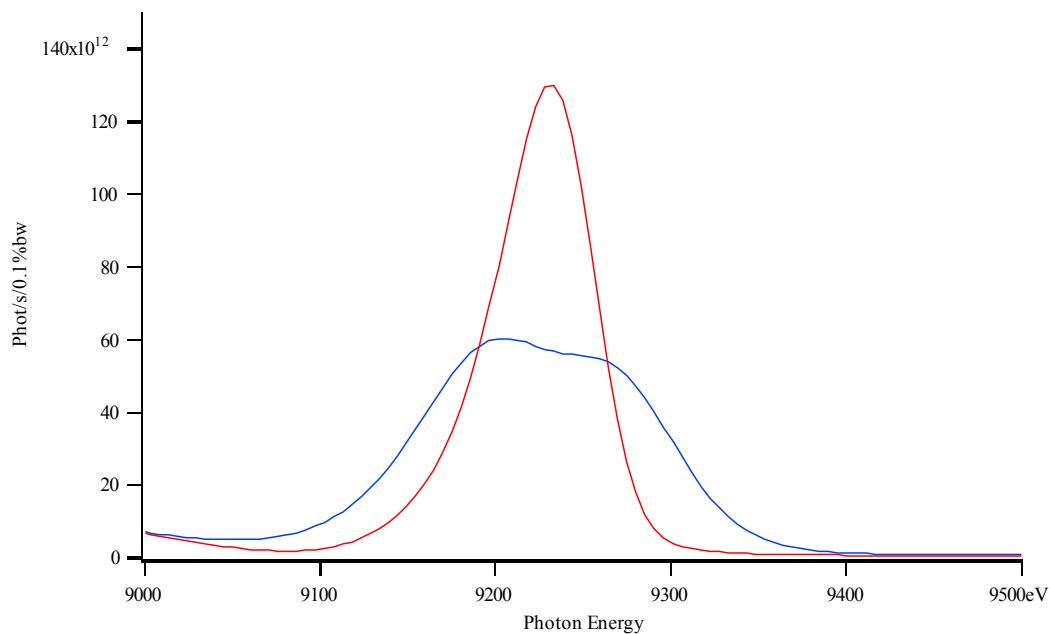


Figure 7.3-2 The effect of tapering an undulator on the spectral output. Shown here is the 5th harmonic of a 2m long U24 device at $K=1.36$.

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In a referee's report and discussion with the SAC [2] it was suggested that due to current difficulties in gap scanning of an undulator at other 3rd generation facilities, that an MPW should be considered as a short term start-up insertion device. Microfocus is a high brightness demanding application and the choice of a MPW requires strong justification. For EXAFS the advantage of the MPW is clear in that it already provides a continuous spectral output. Figure 7.1 also shows the predicted flux output for a 1.6T, 45 pole MPW having a K value of 15 into an on-axis aperture of 100 μ rad x 300 μ rad (H x V). This aperture has been selected it be comparable to the central cone dimensions of the undulator. The MPW has a broader vertical emission than the undulator and the relatively low demagnification in the vertical means that much of the emission in the vertical can be utilised. However it should be realised that not all of the horizontal source can be utilised in delivering 1 micron focal spot from either ID. This is a particular penalty for the MPW as the numerous discrete sources inherent will lead to an effective increase in photon source size and thus to attain a micron resolution a reduced flux will be available at the focus. A horizontal electron beam deflection of $\pm 160\mu$ m between poles indicates at least a 50% increase in horizontal source size and an overall horizontal demagnification of 300:1 rather than 200:1 required (see section on Optics later). Therefore at 10keV the limited divergence that can be accepted will reduce the available flux from an MPW by factor of 80% from that shown in figure 7.1 (90% at 20keV). For the undulator the corresponding optics constraints will reduce usable flux by 60% at 10keV (80% at 20keV). The full impact of the many discrete sources in the MPW on the optics has yet to be investigated in detail, but will reduce its efficiency even more. Because of the extended nature of this source most of these will be focused before or after the sample plane adding to degradation of the spatial resolution. Account also needs to be taken of the unfocused electron beam size away from the centre of the ID straight. Whilst the merits of the MPW can be seen in the early days, it is clearly an expensive route to follow if the MPW then becomes redundant after a period of operation. Additionally the optical constraints in focusing to the desired level dictate that only a narrow cone of on-axis x-rays can be utilised, requiring the use of cooled apertures to absorb 99.5% of the total emitted power (approximately 13kW for the MPW outlined here at 200mA stored current).

7.3.2 Optics

(a) Primary Optics

The referees helpfully raised the issue of whether the source should be directly imaged on to the sample, or whether a preliminary focus onto a set of slits which then act as a secondary source. The advantage of the former is simplicity and the long distance between source and optic enables a high demagnification ratio to be achieved whilst retaining a good working distance. However the necessarily long source distances for direct imaging dictates the need for long mirrors. Use of refocusing optics will offer a resilience to source instabilities and flexibility to the end user in that simply opening and closing slits will change the focus spot. This is at the expense of

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some increase in optical complexity and an increase in beamline length. It is the preferred option here, but the decision should be confirmed in the detailed optical design.

(b) Monochromator

No work has yet been undertaken to determine the monochromator, although with such a large energy range it is likely that a number of crystal sets will be required. Harmonic rejection and the preference for a fixed exit height design will also need to be carefully considered. In this regard the optic layout remains unchanged from the schematic originally proposed and reproduced below in Figure 7.3-3.

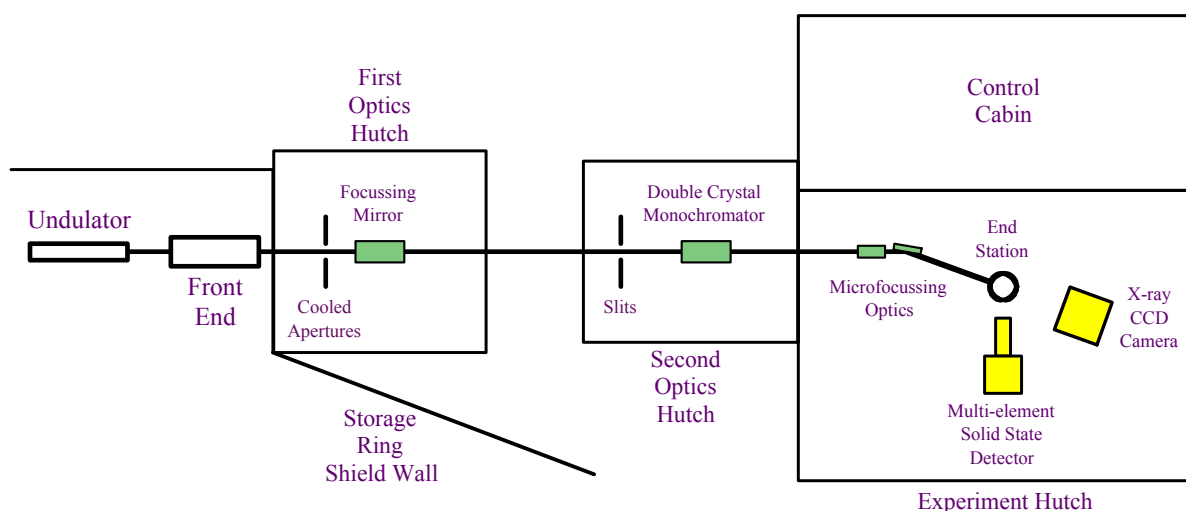


Figure 7.3-3 Schematic of possible layout for an undulator based x-ray spectroscopy microprobe

(c) Microfocus options

A full assessment of the microfocusing options will be taken in the design phase, but it is clear that the Kirkpatrick-Baez (KB) mirror pair arrangement offers the greatest flexibility for EXAFS measurements. They are non-chromatic devices and so are ideal for an energy scanning application such as EXAFS, in addition they will operate over the full energy range specified for this beamline. This means that a single set of optics can be used for all experiments leading to a relative ease of use. The mirror combination allows for independent focusing with separate demagnification ratios in horizontal and vertical directions. Given the highly elliptical source from a storage ring this is a positive asset in generating a more symmetric focal image giving similar horizontal and vertical resolutions.

In order to utilise fully the undulator source size to produce a micron image size requires a horizontal demagnification of approximately 250:1 and a vertical

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demagnification of 20:1. Table 7.3-1 lists the electron beam sizes in the insertion device straight, the predicted photon source size at 10keV for a 2m long U27 undulator and the corresponding photon beam parameters at the focus for these demagnifications. Using KB mirrors at a grazing incidence of 3mrad (half the critical angle for Rh coated optics at 10keV) allows the full vertical beam to be utilised and in the horizontal 20% of the full divergence. It is assumed here that the optical components will be specified for the beamline to deliver maximum throughput in the core energy range; this will be at the expense of performance at the extreme limits of the range (at 20keV the critical angle for reflection off a Rh mirror drops to 3mrad). Optimising at the limits, especially the high energy end, will involve some sacrifice of performance in the core range. In the detailed design stage this issue will be more carefully investigated to produce the best solution.

Table 7.3-1 Electron beam source parameters, the predicted photon source parameters for the U27 undulator at 10keV and photon beam source parameters at the focus assuming 250:1 (H) and 20:1 (V) demagnifications.

	e ⁻ Beam	Photon Source (10keV)	At Focus (FWHM)
σ_x	122.9 μm	122.9 μm	0.49 μm (1.16 μm)
σ_y	6.4 μm	6.8 μm	0.34 μm (0.80 μm)
$\sigma_{x'}$	24.2 μrad	26.3 μrad	6.58 mrad
$\sigma_{y'}$	4.2 μrad	11.1 μrad	0.22 mrad

The preferred optical layout is shown in schematic in Figure 7.3-4 and utilises a two stage optical demagnification with overall ratios of 100:1 and 20:1. Distances from source point shown are illustrative only. It is expected that these will vary in the detailed optical design stage to take account of other issues, such as the positioning of the storage ring shield wall. Such variations will not significantly alter the concepts or overall performance outlined here. Reducing the overall horizontal demagnification enables more of the horizontal divergence to be accepted, the fraction of the total rising to better than 40% at 10keV. Although this increase is offset by a corresponding decrease in source size acceptance if a 1 micron spot size is required, some flexibility is introduced into the optical system as it allows the user to trade off focal size with flux during an experiment. A reduced horizontal demagnification will also lead to an increase in the available working distance between M2 and the sample. The detailed optical design phase will investigate the optimum overall demagnifications that should be used.

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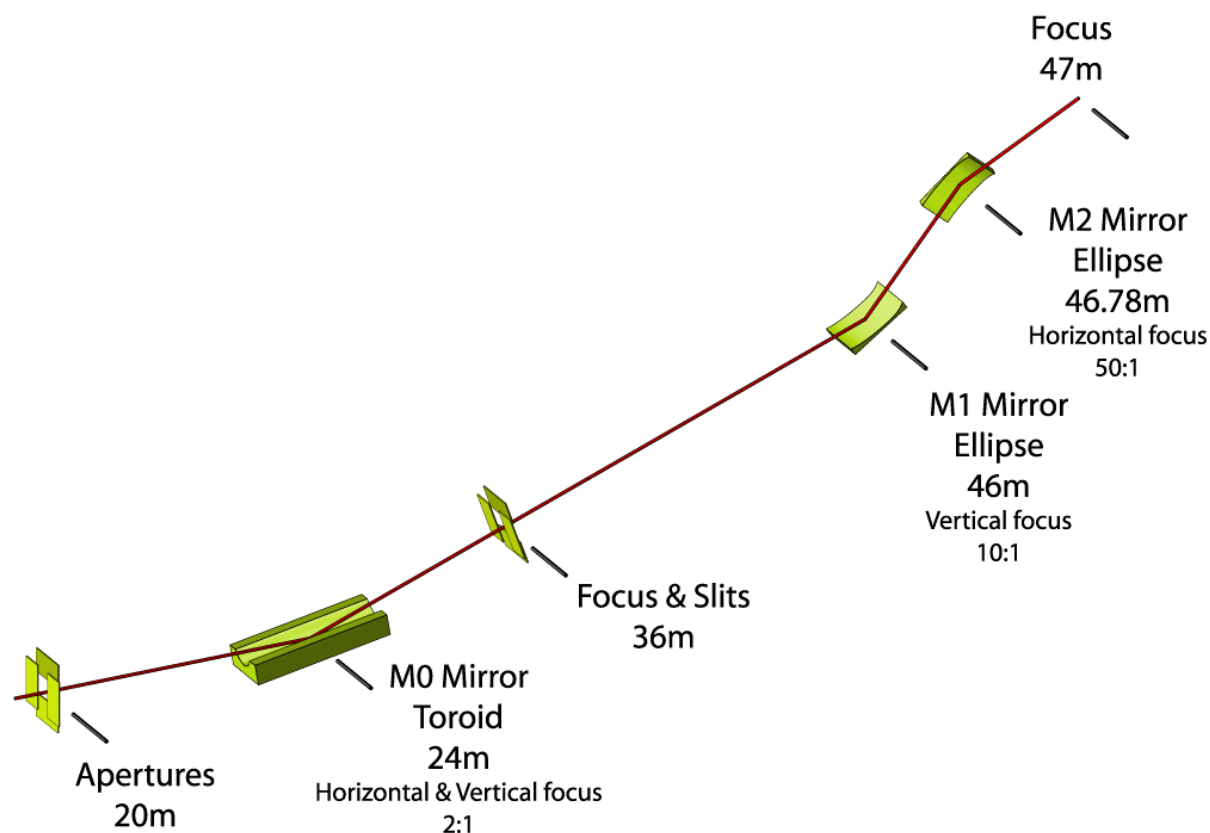


Figure 7.3-4 Schematic of the basic optical layout. Distances quoted are from source point and are for illustrative purposes only. Not shown is the position of the monochromator, ideally situated just upstream of M1.

A set of cooled apertures at the front of the beamline define the beam to the limits of the central undulator emission cone and absorb excess power radiated off axis. A cooled toroidal mirror (M0) provides a focus on a set of slits which then forms a secondary source for imaging by the KB mirrors. The 2:1 demagnification of the toroid keeps the overall length of the beamline down and as M0 will be underfilled by the narrow undulator output cone, generates a well behaved focus at the slits. A KB mirror pair provides the microfocused beam with a focal spot size determined by the apertures set at the slits. A flat crystal bragg monochromator (not shown) will be accommodated in the region between the slits and the KB mirror pair. It should be situated as close to the mirror pair as practicable in order to minimise any beam movements induced during energy scanning and servoing. Further it is recommended that it be preceded by a vertically collimating mirror to maximise the energy resolution of the monochromator, the profile of the first KB mirror then being adjusted to refocus vertically parallel light.

B.7 MICROFOCUS XAS BEAMLINE

The slits will enable the user to easily alter the image size on the sample in order to suit the particular experimental requirements. Careful optical design will ensure that this beamline design remains as efficient as one imaging the full source size when operating at its ultimate spatial resolution, but will enable the benefit of flux gain at lower resolutions. Further advantages inherent in this scheme are a degree of tolerance to electron beam movements and a sharpening of the image for small spot sizes. The undulator source is quasi-gaussian in cross section and if imaged directly will produce a focal image with tails. Re-imaging the beam through a set of slits allows the removal of the tails providing a much tighter image and minimising contamination of the resulting recorded spectra with structural information from outlying regions.

The use of KB mirror pairs is presented here as a robust and easy to use solution that will be applicable to the majority of the anticipated user community over the full energy range of the instrument. Nevertheless it is recognised that this solution will not necessarily be optimal for all requirements and that this microfocus beamline will become a UK centre for development of a range of x-ray microprobe techniques. At present zone plate technology is undergoing rapid advancement in the 2–12keV energy range. As they are already capable of significantly sub-micron images, albeit at the expense of a chromatic focal length, they will be considered for some options such as phase contrast imaging, elemental mapping and XANES. Other advances which this beamline needs to consider for future development include depth-graded multilayers and advanced grazing-incidence reflection systems, such as microstructured optical arrays (MOA's). A considerable degree of development will be needed to make these techniques competitive with zone plate technology, but this will be necessary to ensure continued competitiveness of UK effort in this area.

(d) Detectors

Two main detectors have been bid for, although the detailed specifications will be drawn up as the optics design progresses. Clearly a multi-element compact tessellated solid state detector is required for spectroscopy measurements. Fast electronics and careful consideration to the likely throughput are required in order to for the detector not to be the bottleneck that is often the case on 3rd generation sources. The ability to collect XRD data, either as an integral combined experiment with spectroscopy, or as a fingerprint to ensure the correct part of the specimen is being examined is a vital part of the beamline capability. It is likely that a pixel detector or CCD will be employed here which will also be used in an imaging capability.

7.3.3 Data Acquisition Software

It is vital that the specification of flexible and easy to use software is considered in the overall beamline design. This dictates the requirement for a good GUI system together with scripting control of the data acquisition programmes. The need for undulator gap scanning in EXAFS measurements will require the data acquisition system to seamlessly integrate direct control of the undulator gap with the monochromator.

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Specification for doing this will include QEXAFS capability. The ability to link into other equipment e.g. a PC controlling the sample environment or measuring optical spectra is essential.

7.3.4 Sample Environments

An ability to be able to perform combined XRD experiments should be included as many natural and materials samples will also exhibit crystalline structure on the micron scale which is intimately linked to the chemical variations being examined. One of the most time consuming aspects of microfocus studies is a frequent requirement to characterise relatively large areas of sample to determine the exact locations of particular interest. Crystalline and powder diffraction patterns can be collected relatively quickly whilst rastering samples in order to find localised structural variations and quantify their uniqueness. A combined capability offers the scope for increasing both the throughput and the diversity of experiments.

In-situ cells offering temperature control, sample dosing *etc.* for measuring samples in real chemical environments.

Advanced sample reference mount for rapid alignment of samples on stage. The area of interest on a sample to be defined off-line in an optical microscope or SEM, the co-ordinates stored and then the sample transferred in its mount to sample stage which can then be driven to the same co-ordinates.

7.3.5 Offline laboratory provision

A laboratory infrastructure is required that is compatible with the wide range of activities proposed for the beamline. A review of the activities shows that the following facilities will be required.

A *sample preparation area* is required that is clean (HEPA filtered air). This area would be linked to a *characterisation laboratory* equipped with optical (FTIR and Raman) and electron (SEM) microscopes. These microscopes will be equipped with repositionable stages so that regions of interest identified by these probes may be investigated on the x-ray microprobe without substantial realignment.

A *chemistry laboratory* is essential. This laboratory would contain a glovebox for air sensitive operations, and at least one fume cupboard. Sufficient space should be allocated for routine wet and dry sample manipulations.

REFERENCES

- [1] <http://www.diamond.ac.uk/Publications/188/DM-WG-PP-005.doc>
- [2] <http://www.diamond.ac.uk/Publications/157/DM-SAC-MN-006.doc>

B.8 SXR for Nanostructures Beamline

8.1 INTRODUCTION

A micro-focusing soft X-ray beam line providing radiation of variable circular and linear polarisation will be one of the first phase of beamlines on Diamond. It will be optimised for X-ray photoelectron microscopy (XPEEM) measurements of the morphology, chemical and magnetic state of nanostructures. A branch line may be included equipped with a diffractometer for x-ray magnetic scattering (SoXMaS) measurements of (anti)ferromagnetic lattices, magnetic roughness versus chemical roughness, relative spin orientations, non-collinear moments, and magnetic domain structures.

8.2 SCIENTIFIC CASE

Nanotechnology is a key Foresight area that is supported by the EPSRC Chemistry, Physics and Materials Programmes and by the NERC, BBSRC and MRC. The ability to manufacture and probe systems at the nanometre length scale will address fundamental questions such as behaviour at the quantum/classical boundary and macroscopic quantum effects. These are important for long-term applications such as quantum computing and data storage. Many existing limits on the performance of industrial materials can be overcome by using nanostructured assemblies, for example, thin films made from pre-formed mass-selected nanoclusters that can be deposited in conjunction with a matrix. The field is developing rapidly and encompassing emerging technologies such as heterogeneous chiral catalysis and sensors for genomics and proteomics research. New facilities are needed to support the UK research programme and encourage future technological advance.

The UK nanoscience/nanotechnology community is very active and is becoming increasingly co-ordinated with research council support of individual programmes and networks. In several areas it holds a world-leading position. The ultimate goal of nanoscience is to understand in detail, the chemical, electronic and magnetic state of individual nanostructures with a known and controlled morphology. Achieving this will enable the construction of nanoscale devices and a bottom up approach to designing new materials with engineered properties.

Laboratory-based imaging techniques such as STM, AFM and TEM are capable of resolving nanostructures but, apart from a limited capacity with STM, are unable to provide spectroscopic information. For magnetic imaging, MFM has provided a powerful tool but is limited to ferromagnetic systems and to imaging fringing fields that emerge perpendicular to the sample surface. An SR XPEEM will link structure to

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function by providing spectroscopic data on a length scale <10 nm. The well-defined and variable polarisation state of the SR will provide, via dichroism, a contrast mechanism for imaging different magnetisations in ferromagnetic and antiferromagnetic nanostructures. The comprehensive instrument to be built combines micro-focus, variable linear or circular polarisation and XPEEM. It will exploit the brightest region in the spectrum from diamond and will be more versatile than any other existing SR facility. The UK community has no access to a high-resolution XPEEM facility at the SRS or the ESRF. The consultation exercise identified 26 groups who would use the instrument immediately.

8.3 INSERTION DEVICE

8.3.1 Requirements

An undulator giving left or right circular polarisation and arbitrary linear polarisation is required. This is likely to be a Sasaki type (APPLE II) planar helical undulator with the phasing arrays decoupled to allow an arbitrary angle of linear polarisation to be selected.

An alternative would be the Spring-8 type of planar helical undulator, since this has the advantage that it is not necessary to tune the phase of the undulator as the gap is varied to maintain the maximum degree of polarisation. This could be important if the phase of the Sasaki type needs to be adjusted continuously during photon energy scanning in order to maintain satisfactory polarisation, leading to excessive dead-time and/or very high mechanical tolerance on the phasing arrays.

Other designs of undulator should not be ruled out at this stage.

An important limitation of a helical undulator is that only the first harmonic is usable in circular polarisation mode. The tuning range of this harmonic, and hence the period of the undulator, needs to be carefully chosen to match the needs of the experiment. This then impacts on the minimum energy achievable in linear horizontal polarisation mode.

The original requirement was for linear horizontal polarisation down to 80 eV (to cover Si L-edges) and all polarisations available in a prime energy range of 200 to 950 eV (covering C, N and O K-edges and transition element L-edges). A minimum magnetic gap of 15 mm with remanent field of 1.25 T leads to a period of 64 mm to satisfy these requirements, largely due to the need to reach 80 eV. The limit of the first harmonic in circular polarisation would be c. 1000 eV.

The most recent working party meeting for this beamline (February 2002) raised concerns over not being able to reach c. 1300 eV in circular polarisation to cover important rare earth element M-edges. To achieve 1300 eV in circular polarisation (i.e. with first harmonic) will require reducing the undulator period and so increase the minimum energy the undulator can achieve. The exact cut-off has not been

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determined, but the ability to cover Si L-edges will certainly be lost. Exact calculation is required to see if the C K-edge can still be covered. The alternative is to keep the 64 mm period and to use elliptical polarisation with 3rd harmonic to reach to 1300 eV. Detailed calculation is needed to see if this will give adequate flux and polarisation.

A further concern is that at 80 eV, the undulator will be operating with a high deflection parameter $K = 5.6$, and so the first optical element will have to handle a very high power loading.

It is acknowledged that polarisation switching with a mechanical undulator will be slow e.g. 30 s to change from left to right circular polarisation. Faster switching could be achieved by using two shorter undulators, each tuned to the opposite helicity, and giving physically separated beams through the monochromator. Polarisation switching is then achieved by mechanically chopping between the two beams.

This is the approach adopted by the SLS Surfaces / Interfaces Microscopy beamline. The disadvantage is that it is not possible to focus both beams to micron sized spots at the same position in space. The sample is thus placed off the focus where both beams overlap giving a 20 (h) by 40 (v) micron spot. The other disadvantage is that the flux into each polarisation is half that from the single long undulator.

The consensus of the working party was to accept the slow switching in order to give the smallest beam spot at the sample, maximum insertion device length, and hence maximum flux density.

8.3.2 Issues to be resolved

- Exact choice of undulator design
- Exact tuning range of first harmonic in circular polarisation mode
- Viability of using elliptical polarisation to allow use of higher harmonics and hence wider tuning range for pseudo-circular polarisation.
- Minimum photon energy achievable in linear horizontal polarisation
- Compromise between high energy (1300 eV) coverage with circular polarisation and any low energy (80 eV) coverage.
- Minimum gap increment and phase increment required during photon energy tuning (and consequent mechanical tolerance)

8.4 BEAMLINE

The major design goal for the beamline is to deliver the highest possible flux density at the PEEM end-station. In the range 200 to 950 eV, a flux of c. 5×10^{13} photons per second in a bandwidth of 0.25 eV in a spot size of 1 by 2 μm FWHM is the indicative

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performance required. A smaller bandwidth of 0.1 eV would be preferable if achievable.

The beamline will therefore have to achieve a very high efficiency with moderate to very good resolution and high horizontal and vertical demagnification of the source to the sample.

The requirements for the SoXMaS branchline are somewhat different. Here, a collimated beam with small physical dimensions are required to give maximum flux on small samples at grazing angles of incidence without loss of angular resolution.

Detailed optical design will not commence until the Principal Beamline Scientist is appointed, so it is not possible to say to what extent these criteria can be achieved. The following section gives some points that must be considered in the design.

8.4.1 Optical design considerations for PEEM beamline

For maximum flux, the beamline should produce a monochromatic (within the bandwidth required by the experiment) image of the entire source at the sample. However, the effective source size and divergence will be increased from the electron beam size and divergence by diffraction across the entire operating range of the beamline. The effect is a function of energy and is particularly severe below 500 eV.

Thus, at lower photon energies, higher demagnification is required and is harder to achieve to give the required spot size at the sample.

More importantly, this also means a beamline with fixed overall demagnification will not be able to produce a fixed-sized monochromatic image of the entire source at the sample for all energies. From a practical point of view, this is likely to mean that not all the source is imaged at low energies and so there will be a loss in throughput. Since the variation in effective total vertical source size is a factor of 3 from 100 eV to 1500 eV, this will be a significant loss.

(a) Preoptics

The first optical stage of the beamline will be to produce a demagnified image of the source on the entrance slit of the monochromator. An entrance slitted type of monochromator will be necessary to ensure the energy calibration is not affected by beam movements in the storage ring; energy calibration changes are a significant source of noise in dichroism measurements.

This pre-optical system could be a single mirror, probably focusing in the vertical only. Sagittal focusing will help to reduce the effect of slope errors (thermally induced or inherent in the mirror) on the image. Even so, the mirror is likely to have to be internally cooled to cope with the power loading. If the power from the undulator is too high at minimum gap, a two-mirror system could be used with the first mirror

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removing the bulk of the power. However, the extra reflection will reduce the beamline efficiency.

(b) Entrance and exit slits

The demagnification of the pre-optics will determine the demagnification of the rest of the beamline. The entrance slit size will ideally accept the entire demagnified source to give maximum throughput. The entrance slit will then be imaged in the vertical (dispersive) direction to the monochromator exit slit, and this image will then be demagnified to c. 1 μm at the sample.

The monochromator slits thus not only perform the usual functions of defining bandpass and geometrical throughput, but also act as intermediate vertical image points that must be demagnified to the sample. The slits must therefore simultaneously satisfy all the following conditions.

- The entrance slit must be large enough to accept a large fraction of the vertically demagnified source.
- The entrance slit must be small enough to give the required energy calibration stability i.e. insensitivity to beam movements.
- The exit slit must be small enough to provide a realistic source size for the final vertical demagnification to the sample.
- The exit slit must transmit as large a fraction of the monochromatic image as possible (i.e. the entrance and exit slits must be conjugates). This also determines the (de)magnification of the monochromator.
- The entrance and exit slits must give a source size limited resolution and bandpass that are suitable for the experiment.

Thus we see that we lose the usual flexibility of being able to degrade bandpass in order to improve flux by opening up the slit(s). Increasing the exit slit size will only serve to increase the beam spot at the sample, without increasing the flux density. Increasing the entrance slit should have no effect as it should be set to accept (almost) the entire source anyway.

(c) Monochromator

The monochromator itself will need to be of a fixed-focus design in order to produce an in-focus monochromatic image at the exit slit, which must be fixed in space as it acts as the source point for the final vertically micro-focusing mirror. The monochromator will thus be either a variable included angle plane grating design, a variable included angle spherical grating design, or a varied-line-spacing (VLS) grating design.

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The final choice will take into account the overall efficiency, the number of gratings required to cover the operating range, and how well the required resolution can be achieved with the slit sizes determined from the imaging point of view. Other factors such as higher order rejection must also be considered.

(d) Microfocusing optics

The final optical stage of the beamline will produce the micron size beam spot at the sample. This will almost certainly be achieved by using a pair of plane elliptical mirrors in a Kirkpatrick-Baez arrangement, giving a separation of vertical and horizontal focusing and thus removing the need for the monochromator to produce a stigmatic image. Such mirrors can also be produced effectively by bending high quality optical flats, allowing a degree of adaptability.

With micro-focusing mirrors, the maximum demagnification that can be achieved is limited by aberrations, critical angle effects, and the need to have reasonable working distances, i.e. the distance between mirror and image must be large enough to install the vacuum equipment without making the source distance excessively large.

In practice, the latter point is often the most important. If the source distance is too large, the system may not fit in the space available or the large footprint on the mirror will cause excessive aberrations.

Since the electron beam is much larger in the horizontal than the vertical, the overall beamline demagnification must be much greater in the horizontal. This difference is greatly reduced at low energies by diffraction limiting of the vertical source size. But, it will still be necessary to demagnify the beam horizontally in two stages in order to give the required micron sized beam spot with a usable image distance.

Therefore, there will be an additional horizontally focusing mirror that will probably produce an image somewhere near the monochromator exit slit. The exact position and nature of this mirror will be determined in the detailed design.

8.4.2 Optical design considerations for SoXMaS branch beamline

The SoXMaS branch line will require the addition of an insertable horizontally deflecting mirror to deflect the beam past the PEEM end station. This will need to be after the exit slit of the monochromator, since otherwise the resolution and energy calibration could be severely affected by alignment changes each time the mirror is inserted.

The SoXMaS mirror system will also have to recondition the beam to produce a beam of small physical dimensions (say 1 mm horizontal by 0.1 mm vertical) at the diffractometer axis with low divergence (say 1.5 mrad horizontal by 0.2 mrad vertical). Since the horizontal divergence after the exit slit is likely to be large due to the first stage of horizontal demagnification for the PEEM beamline, this could be challenging to achieve.

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A possible solution could be to have the horizontally deflecting mirror close to the first horizontal focus and collimate the light horizontally. A second mirror could then vertically focus from the exit slit to the diffractometer with about unity or slightly greater magnification. If this second mirror were to sagittally focus, it would also give greater horizontal separation from the PEEM end station. However, if the beam from the exit slit is not horizontal, this will leave the beam at an angle to the vertical through the diffractometer, which is far from ideal.

The optical system for the SoXMaS branchline cannot be considered in detail until a working system for the main PEEM beamline has been developed.

8.5 ENDSTATIONS

8.5.1 PEEM endstation

- Commercial XPEEM with 10 nm spatial resolution and Omega energy filter.
- The XPEEM will be upgradeable to 2 nm resolution by addition of an aberration correction system.
- UHV sample chamber
- Liquid helium sample cooling to at least 40 K (likely to be limited by the difficulties in thermally shielding from close proximity PEEM)
- Sample heating to 800 K
- Adjoining sample preparation chamber with fast entry load lock
- *In situ* STM analysis (in preparation chamber)
- *In situ* magnetisation to 1 T (in preparation chamber)

8.5.2 SoXMaS Endstation

- Four-circle UHV diffractometer with
 - Liquid helium cooling to c.40 K (limited by thermal shielding)
 - *In situ* magnetisation to 1 T

B.9 A Non-Crystalline Diffraction Beamline

9.1 INTRODUCTION

This chapter explains the basic design for a Non-Crystalline Diffraction (NCD) beamline on DIAMOND. The requirements to meet the scientific and technological challenges of the next decade are for a high resolution, high brightness beamline. Only an undulator insertion device will meet the stringent demands of the scientific community taking into account wavelength range, small angle resolution and the ability to microfocus the beam. The BL11 working group has not taken all topics to an equivalent level so that it will be seen that the treatment varies considerably in detail between them. Nevertheless the specification of the undulator has been established and this allows the outline specification of the other components to be identified.

9.2 SCIENTIFIC CASE SUMMAY

NCD provides essential information on the structure and dynamics of molecular assemblies in low ordered environments. These are characteristic of living organisms and many complex materials such as polymers and colloids. The NCD beamline will bridge the gap between optical and high-resolution x-ray diffraction and will supply crucial complementary structural information.

9.2.1 Applications in life sciences

The timescale of biomolecular reorganisation can range from the femtosecond to second time scale. At present most NCD experiments operate in the millisecond to second timescale. Access to shorter time scales is essential to understand processes such as early folding events in proteins, the interaction and complex formation of biological molecules, and, the switching of quaternary structure organisation. Studies in solution as well as in the semi-ordered (fibre) state will provide static (conformation and shape) and dynamic (kinetics) information from the molecular to cellular level. Specific examples include conformational studies on multi-domain proteins and their interactions, trans-membrane signal transduction and the related problem of membrane lipid homeostasis, protein folding and misfolding (the latter is known to be firmly connected with a series of diseases), kinesin-microtubule interactions, the molecular basis of muscle contraction, connective tissue structure and organisation and dynamics of nucleic acid conformation.

In the food and pharmaceutical/medical sectors, non-crystalline diffraction studies are vital to understanding activities such as protein denaturation, emulsification and phase separation, binding and unbinding, and the control of interfaces. The technique

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will play a crucial role in advancing our knowledge of macromolecular structure into function, and in aiding the industrial development of biomaterials, biosensors and other devices.

9.2.2 Applications in materials science

In terms of wealth creation each of the disparate chemical, metal, polymer, liquid crystal, food, pharmaceutical, surfactant, ceramic and glass industries sees the need for replacing craft skill with scientific understanding to reduce the risk associated with technological change. NCD has a significant role to play in creating this understanding in the microstructure-processing-properties loop therefore contributing to the continuing success of UK science and industry. The possibility of investigating materials under extreme environments, mimicking industrial processes (e.g. high pressure, temperature, and or rheology), whilst simultaneously recording X-ray measurements in both small and wide angle X-ray scattering opens up new avenues for addressing questions regarding phase-space and the relationship between microscopic structure and macroscopic properties.

For more details on the above applications see the proposal for Diamond Beamline 11, see reference [1].

9.3 OUTLINE TECHNICAL SPECIFICATION

The needs of the community, with wide research interests from the study of biological samples to materials processes, require a dedicated non-crystalline diffraction beamline accepting radiation from an undulator source. Low divergence is necessary in order to minimise the smearing at the detector and to extract the maximum information from quasi-crystalline systems.

Microfocus will be required to illuminate very small samples, while minimising the scattering from the surrounding substratum. It should allow textures to be distinguished within a material on the micron scale. The end station should have a modular design to give the maximum flexibility.

9.3.1 The source

The specification states that beamline 11 should cover the energy range 4-20 keV, be continuously tuneable and be optimised for 8-12 keV. An out of vacuum U27 undulator working with a minimum gap of 10 mm can supply this. A plot of the flux for an idealised undulator with this specification is shown in Figure 9.3-1.

B.9 A NON-CRYSTALLINE DIFFRACTION BEAMLINE

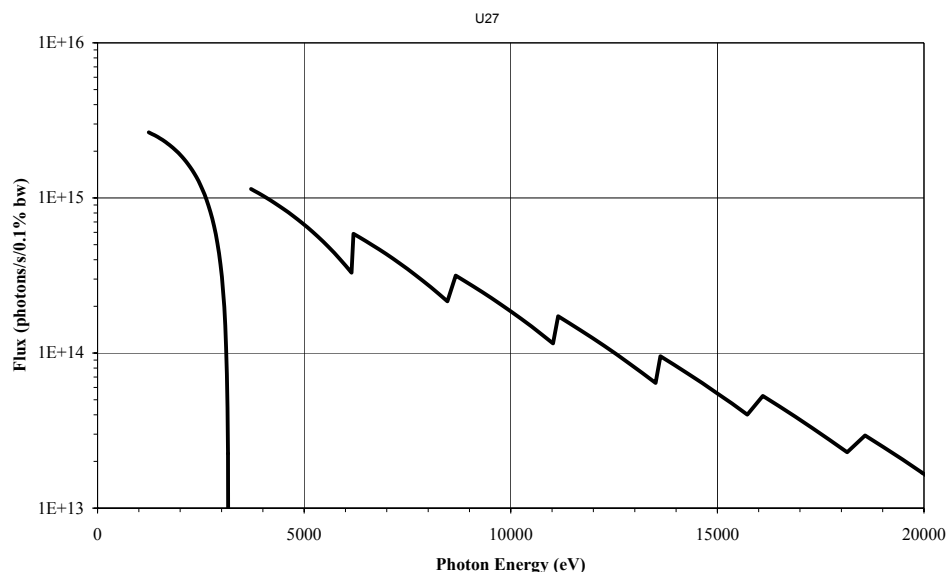


Figure 9.3-1 Idealised flux output from an undulator with a 27mm period with DIAMOND operating at 3 GeV and 300 mA.

Taking account of characteristics of a non-ideal undulator the flux output scaled through a $100 \times 25 \mu\text{rad}$ aperture at following energies is calculated as 4 keV 4×10^{14} , 6.5 keV 1.5×10^{14} , 12 keV 2×10^{13} , 20 keV 1.7×10^{12} . The non-idealised scenario is a pessimistic estimate of the productivity of the insertion device.

There is a requirement for stable beam position of the order of 1% RMS on 5s timescale and at least 3% RMS on 1hr timescale.

Note: Although the referees cautioned as to the technical challenges of the use of such low energies the capability to go to 4keV has been retained in order to fulfil the requirements of the biology and food science communities e.g. Ca edge at 4.0381keV. Figure 9.3-2 below provides an estimate of the likely energy demand likely on beamline 11 on day 1 of operation. This was arrived at after consulting the contributors to the beamline 11 scientific case.

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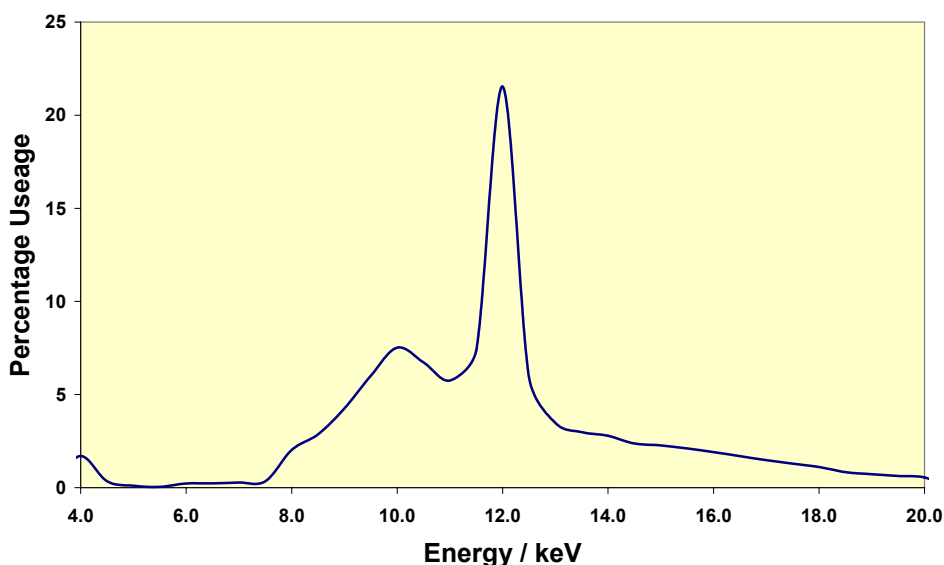


Figure 9.3-2 Expected Energy Demand for BL11

9.3.2 Optics

The option to employ 2 crystal sets has been retained in order to select the bandpass by choosing multilayer (bandpass 10^{-2}) or Si (111) crystal set (bandpass 10^{-4}). The necessity for these will be investigated during the design phase.

Table 9.3-1 Monochromator Options

Options	Pros	Cons
1) Si (111) (bandpass ca. 10^{-4})	Common component used elsewhere. Good resolution and matches the assumed divergence from the undulator.	
2) Multilayer (bandpass ca. 10^{-2})	Most flux onto sample.	Poor resolution w.r.t. other options. Possibly not good enough for length scale range envisaged. But may be fine for many biological solution scattering experiments where flux onto the sample is important. However radiation damage may be an issue.
3) Diamond (bandpass ca. 5×10^{-5})	Best resolution. Easy to cool.	Might not be necessary. Difficult to get perfect diamond crystals due to impurities.

B.9 A NON-CRYSTALLINE DIFFRACTION BEAMLINE

Focusing of the undulator beam can be achieved in several ways

Table 9.3-2 Optics combination options

Option	Pros	Cons
1) Double Crystal Monochromator, Toroidal Mirror	Simple monochromator design.	Fixed focus point from the toroidal mirror – no flexibility to compromise between SAXS and WAXS focus. This may not be an issue.
2) Collimating Mirror, Double Crystal Monochromator, Toroidal Mirror	As above with added help of collimating beam before focusing. A requirement if microfocusing optics are added or if very small beams are produced by slit collimation.	Fixed focus point from the toroidal mirror – no flexibility to compromise between SAXS and WAXS focus. This may not be an issue.
3) Collimating Mirror, Sagittally Focussing Double Crystal Monochromator, Vertically Focusing Mirror	Flexible station thanks to good application of focusing components.	Complicated mono. Although used at a number of beamlines none have proved easy to use or maintain. Also unproven for SAXS applications
4) Same as 1) and 2) except Toroidal Mirror replace by two orthogonal mirrors to provide separate focusing in the horizontal and vertical directions (Kirkpatrick-Baez arrangement)	Would allow “flexible focusing” – fibres held vertically might want horizontal focus at sample and vertical focus at detector.	Little to compare with for SAXS experiments

(a) Microfocus Options

Micro-focus beam options can be provided in a variety of ways including

- Collimation and use of slits
- Use of tapered optic
- Use of wave guides
- Two orthogonal mirrors to provide separate focusing in the horizontal and vertical directions (Kirkpatrick-Baez arrangement).

Most of these arrangements have been successfully used on undulator sources. The final choice of systems depends on factors such as cost and any requirement for flexibility in focusing and acceptable divergences. A full assessment of these options will be done in the feasibility stage. The requirement for a micro beam can be met either through a micro-focussing stage or through slitting down on the normal focussed beam. These options will be investigated in the design phase. More details on microfocus options can be found in Section B 10.4 of this report.

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9.3.3 The camera

The camera should be designed to observe spacings of 5000 Å to 1 Å as requested by the beamline 11 working group.

Different detectors will be needed to cover the range of experiments. The measurement of dynamical effects in muscles demands fast area detectors with large data storage; a fast linear one-dimensional detector for time-resolved powder SAXS/WAXS studies would be needed for materials processing. Oriented materials would require an area detector for WAXS. These detectors may be based on developments to the current RAPID technology.

The space around the sample must be sufficient and flexible enough to take a variety of environments both in size and complexity. For a detailed list see sample environment section (9.5)

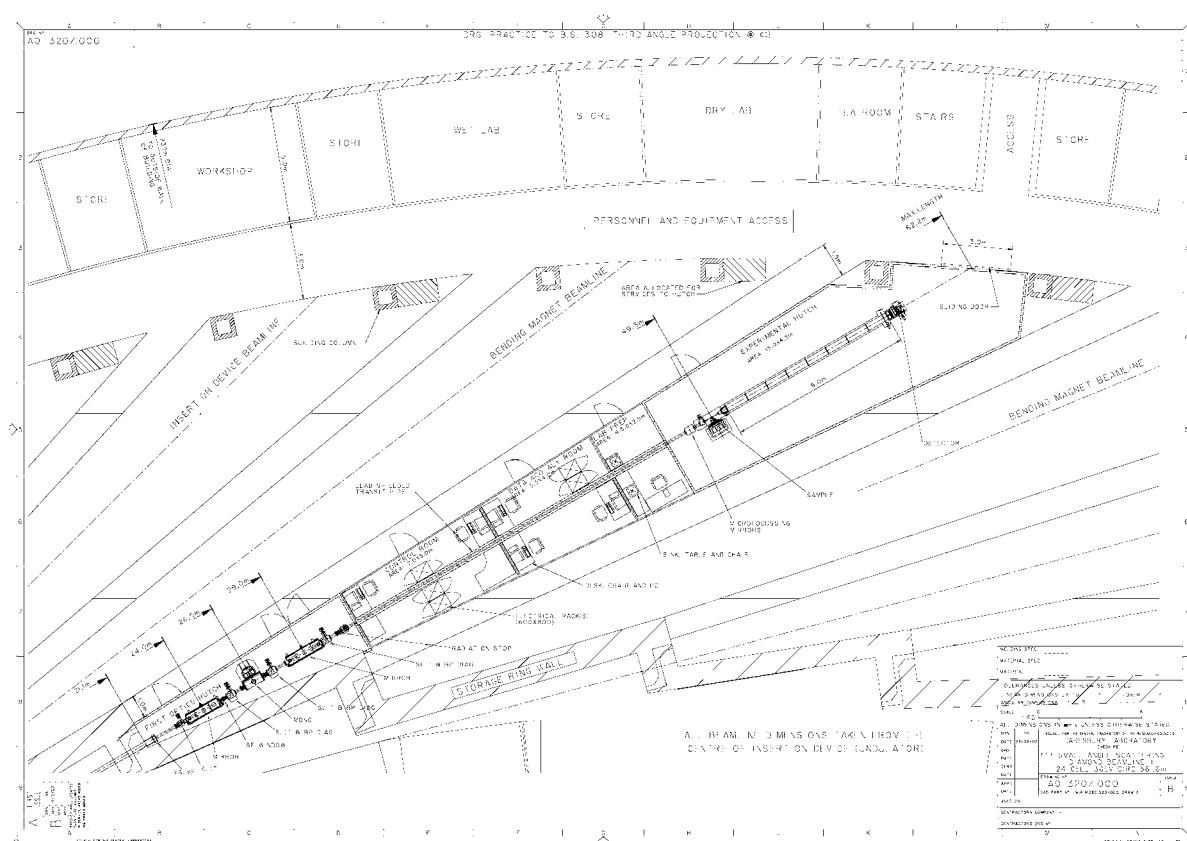


Figure 9.3-3 Schematic Layout of Beamline 11

The schematic diagram shown above illustrates a possible optical layout for a non-crystalline diffraction beamline built to meet the specification outlined earlier. Also included are workspace areas however these have yet to be optimised.

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9.3.4 Further specification work

Before a detailed design can progress, the following issues need to be resolved.

- Confirmation of the range of bandpass required
- Confirm the need for a collimating mirror
- Choice of focussing option and final focussed beams size
- Choice of micro-focus option
- Detector choices

9.4 DATA ACQUISITION SOFTWARE

The user community needs flexible, easy to use software, which can incorporate their own sample environments simply. The software should have an intuitive “look and feel” and to be able to deal with new and experienced users. To achieve this requires a GUI based system together with scripting control of the data acquisition and beamline. It is proposed that provision be made to incorporate LABview control into the data acquisition software capabilities. This is covered in more detail in the Data Acquisition Software section of Chapter 10 of the Green Book.

9.5 SAMPLE ENVIRONMENT

The beamline should be capable of allowing access for large simulations of industrial processes as well as fine manipulation of biological materials. Therefore space around the sample position, including height is important.

Good sample alignment facilities are necessary via simple transmission scanning and sample viewing techniques. Frame grabbing viewer or continual video monitoring of sample environment with close alignment of lens axis to beam path so that sample rather than holder can be monitored.

Examples of sample manipulation include mechanical testing over a wide range of forces 1N-1000N, temperature control from 77K to 1500K. Other requirements include injection system and buffer circulating system for changing solutions that samples are bathed in.

Automated sample changer where multiple samples require relatively little manipulation.

Other online sample environments should include: Linkam single pan DSC with Liquid Nitrogen attachment, Polarising transmission microscope, Linkam Capillary heater, Minimat/Instron materials tester, Bohlin couette /cone and plate rheometer adapted for X-rays, Linkam Shear Cell for X-ray applications and Raman HoloProbe,

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Stopped-Flow and Quenched-Flow. These can be considered as examples only of the type of equipment that should be generally available.

9.6 OFFLINE LABORATORY PROVISION

These facilities should be capable of providing standard manipulations/preparations required in the course of beamline experiments. Ideally they should be placed close to the beamline, well equipped and regulated. These facilities should also be capable of providing the basic infrastructure needed for in-house research in the field of chemistry/materials & life sciences. The following facilities should be locally available to the beamline; glovebox, fume cupboards and bench-top space, pH-meter, deionized and ultrapure water, stirrers, balances, an extensive stock of glassware, refrigerator/freezer, ice-machine, furnaces, ultrasonic bath, frequently, used solvents/chemicals/ consumables, solvent disposal, sharps disposal, 4 hotplate stirrer, Liquid Nitrogen dewar, 6 port peristaltic pump, Consumables to allow all common manipulations. Washing and cleaning room facilities should also be available.

The Beamline 11 Working Group identified the following general laboratory equipment that the DIAMOND facility should provide:

FT-IR and a UV/VIS spectrometer, Electrophoresis equipment for Nucleic acids DNA & RNA and Proteins, FPLC, HPLC, Conventional ion-exchange, gel-filtration, fraction collectors, Eppendorf-type bench top centrifuges, Refrigerated preparative-Sorvall and Kontron, Ultracentrifuges-Beckman L5-65, Centrikon T-1065 and T-1080, Freeze-drier, SpeedVac concentrators (x2), Gene Manipulation, DNA sequencing, UV-Visible Spectrophotometers, Electron Microscope, Jeol. Negative staining and shadowing, Light Scattering Apparatus, P2 Facilities, The NIKON inverted microscope, Safety Level 1 GMO containment, Autoclave for sterilisation, Sealed floor.

REFERENCES

[1] <http://www.diamond.ac.uk/Publications/188/DM-WG-PP-004.doc>

B.10 General Beamline and Experimental Issues

10.1 INTRODUCTION

This chapter covers various design issues, common to many of the beamlines on DIAMOND, which are not treated elsewhere. These issues were identified during the early specification stages of the first phase beamlines and are collected here for reference during the more detailed design of all beamlines.

10.2 HIGH POWER OPTICS

With the advent of third generation synchrotrons there has been increased activity in designing optical elements that can deal with the high power of the x-ray beams. High power loads absorbed in optical components cause temperature gradients, which then cause, through thermal expansion, strain in the optical component. This strain shows up as a distortion of the reflecting surface of a mirror, resulting in degradation of the focusing performance; or deformation of the crystal lattice in a crystal monochromator resulting in poorer energy resolution, deviation and defocusing of the beam or loss of intensity. The problem is most severe for monochromator crystals that receive the white beam. With monochromators, the incident angle is relatively large and the power density can be high. Mirrors operating in the x-ray range on the other hand operate at glancing incidence angles (of order milli-radians) and the incident power is spread out over a large surface area. In addition, only x-rays that have energy above the critical energy for reflection from the mirror are absorbed in the mirror therefore most of the incident power is passed on to the next optical element.

10.2.1 Heat loading on monochromators

Various strategies have been devised for coping with high heat load in crystal monochromators. Cooling schemes must remove the heat from the crystal efficiently but the main aim is not to minimise the temperature of the crystal but to reduce the strain field in the diffracting region, which is caused by temperature gradients. The performance may be characterised by measuring the rocking curve width of a Bragg reflection and comparing with the theoretical Darwin width from dynamical diffraction theory. The effect of heating may be quantified as the measured broadening of the rocking curve due to the heating. However, even when the theoretical rocking curve width is measured, there may be effects on the focusing properties of the beam line due to the strain. The performance of crystals under high

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heat loads may be modelled using FEA (finite element analysis) and the theory of dynamical diffraction in deformed crystals.

The strategies for undulators and wigglers are different because of differences in beam size, power density and total power load. In the case of undulators, thin silicon or diamond crystals in Laue geometry are commonly used. The low x-ray absorption of diamond compared to silicon reduces the power loading considerably and the higher thermal conductivity of diamond improves heat flow and reduces temperature gradients. However, the energy bandpass of diamond is lower than silicon making the intensity correspondingly lower. The small size of diamond crystals makes them most suitable for use with the small undulator beams but it is not possible to use diamond to make curved crystal focusing monochromators. Cryogenic cooling has been extensively used with the advantage of the zero expansion coefficient of silicon at about 125K, and germanium at about 50K, and also the enhanced thermal conductivity of silicon and germanium at cryogenic temperatures. This minimises the effects of strain and heat bumps [1]. In the case of wigglers, the power density may be lower but the total power is higher than from undulators making cryogenic solutions less effective. Water with its high heat capacity is most effective at removing large amounts of power and water cooling is also cheap to implement, but can really only cope with the power loading from 2nd generation synchrotrons. Less work has been done on developing cooling systems which can cope with the colossal heat load of a multi-pole wiggler on a 3rd generation synchrotron and in this area DIAMOND will have to foster some of its own developments.

Table 10.2-1 Comparison of power from various synchrotron radiation sources

Source	ID	Power
SRS	MPW6	270W on station 6.2, 1.2W/mm ²
NSLS	X25	300W [2]
APS	Wiggler A	7.4kW, 81W/mm ² at 30m[3]
APS	Undulator A	3.8kW, 150W/mm ² at 30m[3]
CHESS	F2 Wiggler	10kW in 4mrads, 30 W/mm ² at 21m (projected to double when beam current is increased to 300mA)[4,5]
DIAMOND	3.5 T MPW, 1.0 m, 60 mm period	20kW total, 15kW/mrad ² =24 W/mm ² at 25m
ESRF	ID11 Wiggler	20kW, but limited to 1kW on mono by attenuators, optics and ID gap

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Table 10.2-2 Technologies for coping with high heat loading of monochromators

Technology	Power density	Total power	
Liquid nitrogen cooling	High 100+W/mm ²	Moderate 1kW	Low heat capacity of liquid nitrogen limits the total power [6].
Water cooling	medium	High	Cheaper to implement. Standard for lower power applications. Suitable for dipole beamlines on DIAMOND. Mini-channel, micro-channel or pin post technology [4,6].
Laue crystals			Good at high energies because absorbed power decreases with energy. A pre filter can be used to absorb low energy radiation. Can only be cooled along their edges. Diamond crystals for undulator beams.
Liquid metal cooling	medium	medium	[4]
Active optics	medium	medium	Allows compensation of heat bump[7]

10.2.2 Other beamline components

Other beamline components are affected by heat loading from the x-ray beam. In particular, the effect of heating and cooling methods for beryllium windows, x-ray absorbers, x-ray filters, x-ray shutters, and apertures should be considered. Again, FEA can be used to model heating effects and the effectiveness of cooling. In extreme cases, heat gradients can cause fracture of beryllium windows.

In the case of beryllium windows, increasing the window thickness improves the strength and the heat conduction of the window but leads to greater power absorption. Since the purpose of the beryllium window is to isolate the vacuum in two sections and let through the x-ray beam, the window can only be cooled by water around its edges. The higher power density from an undulator compared to a wiggler is compensated by the beryllium window being smaller. The power loading on the window may be reduced by a pre-filter.

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Filters can be used to preferentially absorb lower energy radiation from the x-ray beam and prevent it reaching components and optics further along the beamline. In the case of beryllium windows [8] and Laue monochromator crystals the filter removes lower energies, leaving higher energy radiation which is less strongly absorbed and can pass straight through without heating. Filtering of the radiation may be essential for third generator undulators windows [9].

10.2.3 Conclusions

The power loading on DIAMOND will be comparable to many existing beamlines on other 3rd generation synchrotrons and it is likely that with some development similar technology can be used to cope with the heating.

10.3 FOCUSING > 25KEV

10.3.1 Introduction

Photons energies in the range up to 100keV are now used world wide for x-ray diffraction studies. The use of high energies has several advantages.

1. Reduction in x-ray absorption. Increased penetration through vessel walls allowing materials in thicker containment vessels to be studied and greater penetration depth in the sample themselves allowing the x-rays to probe inside large and more absorbing samples
2. Accessing high energy absorption edges.
3. Compression of reciprocal space in angle. At higher energy, the diffraction peaks are compressed into the forward direction (lower Bragg angle). This may allow a more complete pattern to be obtained when there are restrictions on the scattering angle due to sample containment.
4. Reduction in extinction. At high energy primary extinction of the x-rays is reduced allowing more accurate measurements of scattering power.

There are however, disadvantages to using higher energies that should be balanced against the advantages.

1. Difficulty of focusing high energy x-rays. Many focusing schemes that are standard and work well at lower x-ray energies cannot be used at higher energy. The available x-ray intensity will be correspondingly lower.
2. Flux and brilliance from undulators and wigglers drops off at the high energy end of their spectra.
3. Reduction in the core hole lifetime at higher energies resulting in worse energy resolution for spectroscopy.

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4. In diffraction experiments, compression of reciprocal space at higher energy results in lower resolution between diffraction orders. The angular collimation of the detector arm has to be correspondingly better to achieve the same reciprocal space resolution, leading to a loss of intensity. The diffraction peaks are more sensitive to the azimuthal resolution.
5. Increased problems due to background scattering. At higher x-ray energy, Compton scattering becomes more significant and causes an unwanted background.
6. For diffraction from a small crystal in the absence of x-ray absorption, the scattered intensity decreases with energy in proportion to E^{-3} [10].

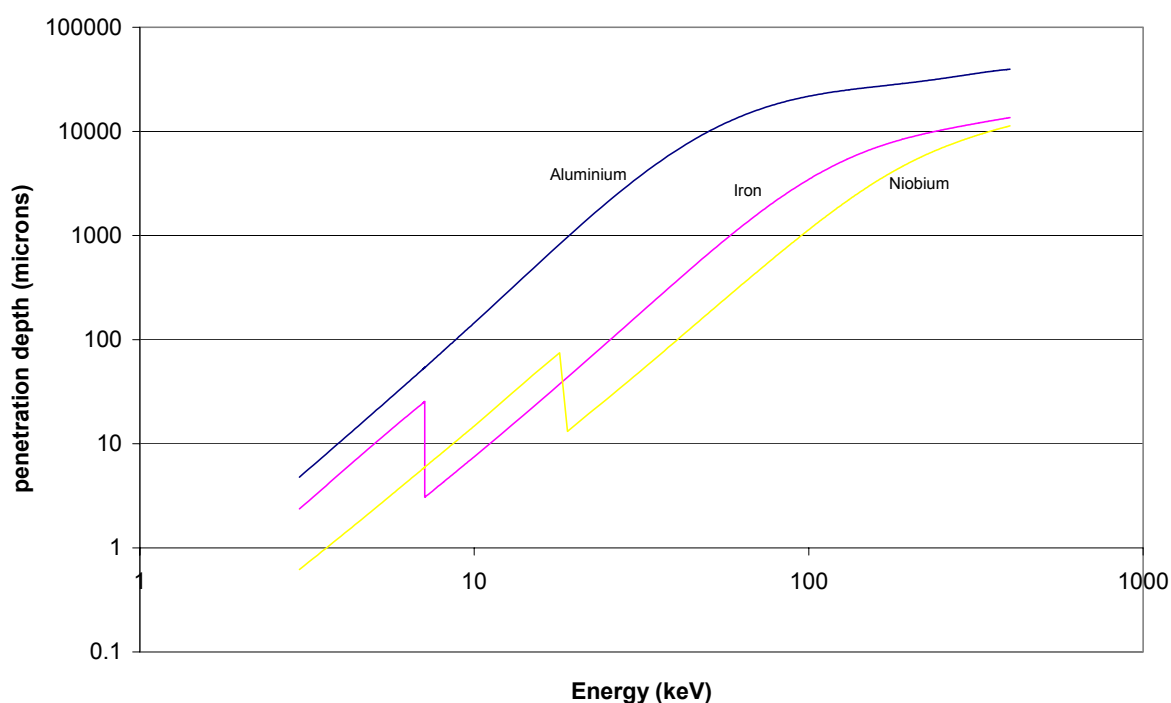


Figure 10.3-1 Absorption of x-rays

All these considerations affect the chosen optimum energy for a measurement.

10.3.2 Insertion devices for high energies

At third generation synchrotron sources (ESRF, APS, SPRING8), undulators are now used for energies up to about 100keV [11]. This has become possible with the advent of new in-vacuum undulators which have higher fields and shorter periods than the ex-vacuum devices. Undulators have the advantage that over their operating range, they are brighter sources of radiation than MPWs, wavelength shifters or bending magnets. For a given useful photon flux, they give the smallest power loading on the optics.

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On DIAMOND, the machine energy is 3GeV compared to 6GeV, 7GeV and 8GeV respectively for ESRF, APS and SPRING8. This means that in terms of brightness, the cross over point between undulators and MPWs as sources of x-rays is about 25keV. On DIAMOND therefore, MPWs must be used to cover the high-energy range 25-100keV.

10.3.3 Comparison between the high-energy performance of DIAMOND and other third generation synchrotrons.

It is important to distinguish between synchrotrons that can use undulators to cover the energy range (e.g. ESRF, APS, SPRING8) and other machines. The former machines have high electron beam energy (6GeV and above) and small electron beam emittance so that small gap undulators can be used to generate x-rays up to 100keV. The remaining synchrotrons either have too low electron beam energy (e.g. DIAMOND, Soleil, SLS) and so undulators can only be used for lower energies or the emittance is too poor (e.g. DESY, CHESS) for undulators to be used. Undulator radiation is typically emitted into a solid angle of order $100\mu\text{-rads}$ wide and $25\mu\text{rads}$ high where as for wiggler radiation, the fan may be several milli-radians wide and several tenths of a milli-radians high. Although the x-ray flux may be comparable from a wiggler and from an undulator, in the case of the wiggler, the flux is spread out into a larger solid angle fan. The (unfocused) flux density from a DIAMOND MPW is expected to be smaller than from an undulator at a third generation source by a factor 100 to 1000. Focusing of the x-rays would allow this difference to be reduced. The aim of focusing is to maximise the x-ray flux into a certain size aperture at the sample. This should be distinguished from microfocusing where the aim is to produce a small x-ray probe.

10.3.4 Scientific requirements

The scientific requirements of an experiment will dictate the beam line optics. Experiments that require small x-ray beam sizes at the sample ($\ll 1\text{mm}$) and do not require low beam divergence ($\ll 1\text{mrad}$) can benefit most from focusing. Such experiments would include for example x-ray spectroscopy of small samples and x-ray diffraction from small samples where the diffraction peaks are relatively broad. The focusing technology may also determine the energy band pass of the radiation. In the case of spectroscopy, a band pass of 10^{-4} may be required but for diffraction experiments, a band pass of 10^{-3} may be acceptable. It should also be noted that at high energy, the Darwin width of crystals becomes very small and the energy band width may become dominated by the angular spread of the x-rays hitting the monochromator when a large fan is collected. It is therefore important that the wavelength dispersion is compensated by the monochromator.

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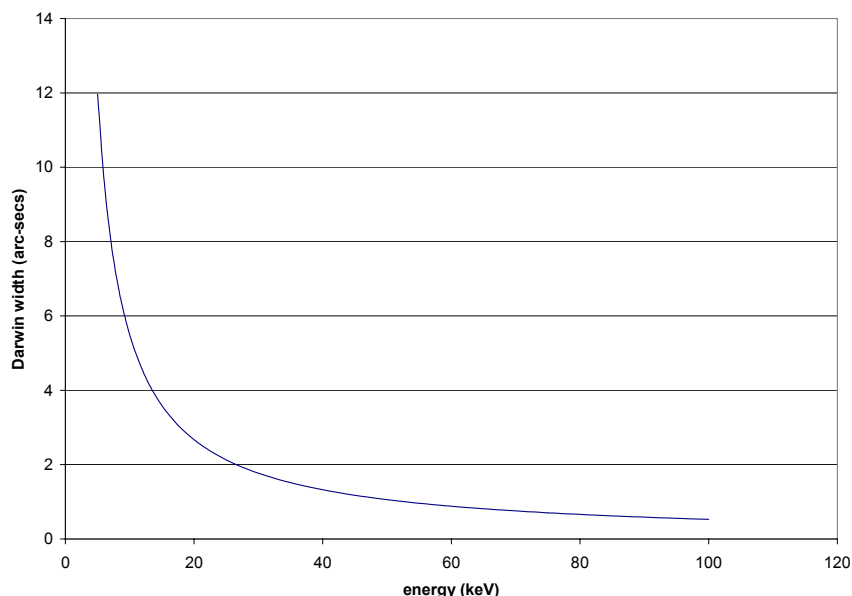


Figure 10.3-2 Darwin width of silicon 111 reflection. At high energy the angular divergence of the radiation may be larger than the Darwin width of the reflection and therefore may dominate the energy resolution.

10.3.5 Current focusing technologies

(a) Mirrors

At low energies, mirrors typically coated with rhodium are commonly used as focusing elements. Slope errors of less than 1 arc second mean that a spot size in the deflection plane of less than 100μ is achievable. At higher energies the mirror must be operated at a lower reflection angle and so a smaller fan of radiation is collected.

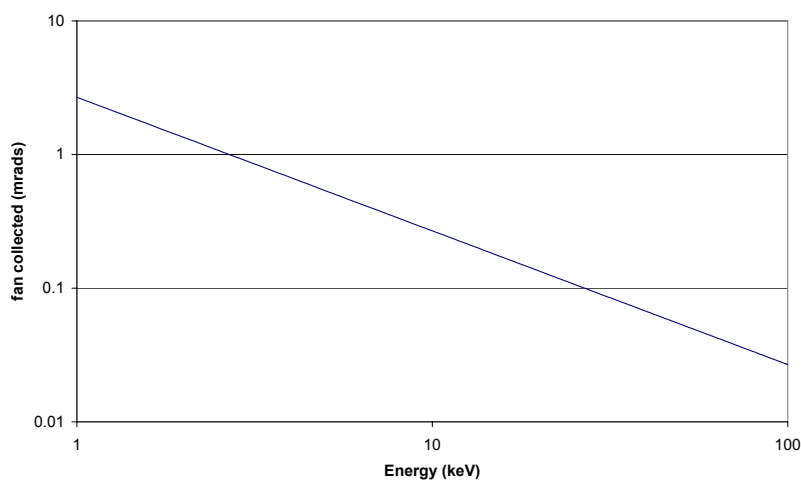


Figure 10.3-3 Collected fan of radiation for a 1m long mirror at 25m from the source as a function of the cut off energy of the mirror. At high energy, the mirror collects a smaller fan.

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(b) Bragg crystals

Perfect crystal Bragg optics are used as simultaneous focusing elements and monochromators. Longitudinal focusing (where the focusing and deflection occur in the same plane) can be done by single bounce bent crystals.

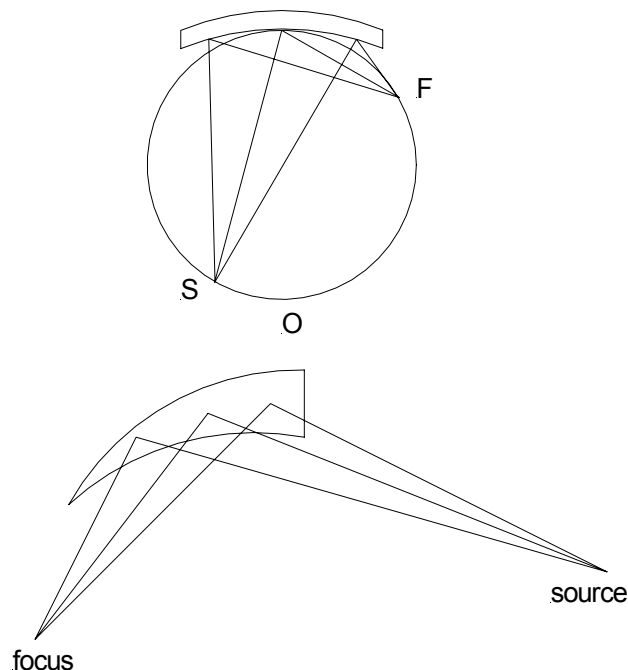
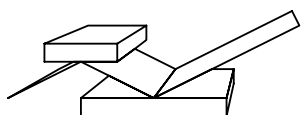


Figure 10.3-4 Arrangement for focusing by a bent Bragg crystal in Johann geometry.

Sagittal focusing (where focusing is in the orthogonal plane to the deflection) may be done by sagittally bent crystals. In this case a double crystal arrangement may be used as the Bragg angle is relatively unaffected by the bending.

1. Plane crystals - no focusing



2. Sagittal mono - horizontal focusing

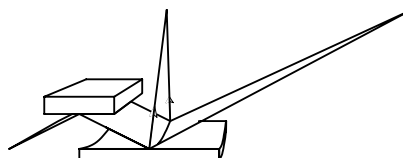


Figure 10.3-5 Double bounce vertically deflecting Bragg monochromators for constant beam offset. 1. Plane crystals. 2. Sagittally bent second crystal for horizontal focusing of the x-rays.

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(c) Laue crystals

At high energies, the Bragg angle becomes small. With Bragg crystals, this requires long crystals. With Laue crystals, the beam passes almost normal to the surface and small crystals can be used. With almost normal incidence, with a sufficiently thin crystal, the power absorbed in the crystal can be significantly reduced.

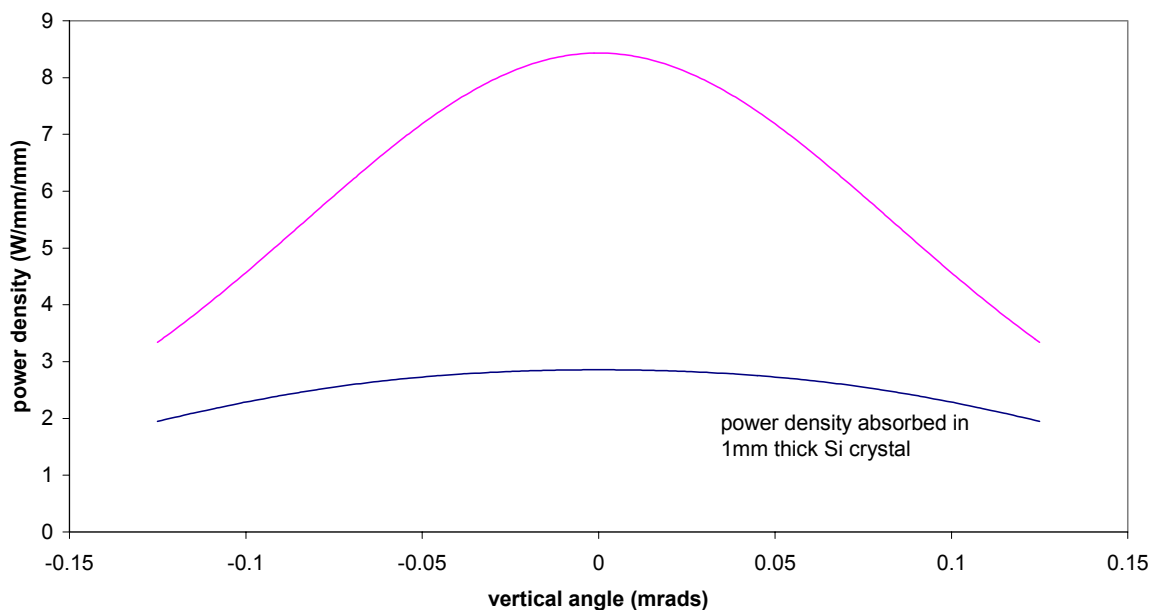


Figure 10.3-6 Power incident and absorbed in a 1mm thick silicon crystal at 40m from a DIAMOND 3.5T MPW.

In addition, if only high energy radiation is required a pre-absorber can be used to reduce the power further. Laue crystals also give the possibility of broadening the band-pass.

Longitudinal focusing with Laue crystals has been used at the ESRF [12]. In this scheme, a Laue-Laue geometry and a Laue-Bragg geometry have been tested for focusing the beam horizontally. In addition, this was combined with a multilayer for vertical focusing [13].

Sagittal focusing has been developed at Brookhaven [14], [15]. A symmetrically cut sagittally bent Laue crystal will not focus but if the crystal is cut asymmetrically then for deflection in the vertical plane, horizontal focusing will be achieved. A double crystal arrangement allows fixed beam offset and tuneability. The thickness, degree of asymmetry, bending radius and the reflection are chosen to optimize the energy spread and integrated reflectivity for a given source and focus distance and x-ray energy. It is suggested that anti-clastic curvature of the crystal can be used to reduce the energy dispersion in the vertical direction or to do vertical focusing.

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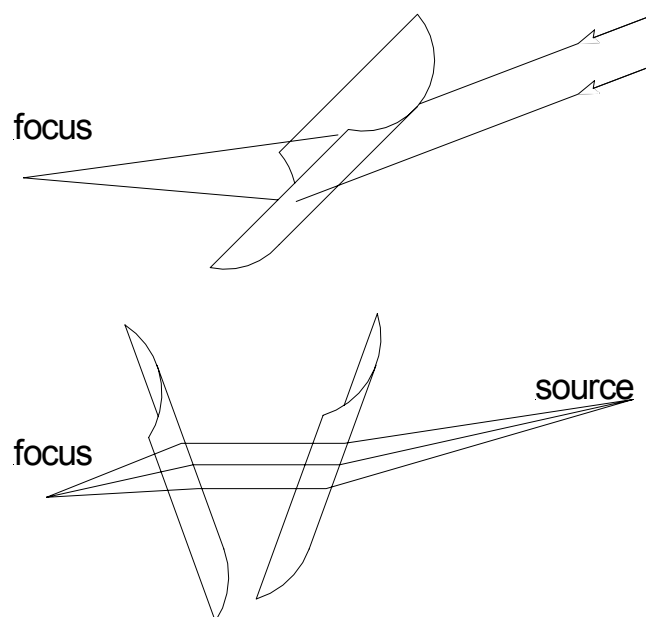


Figure 10.3-7 Saggital focusing by Laue crystals. Top – single bounce. Bottom – double bounce for constant height offset when the energy is tuned.

Table 10.3-1 Summary of Focusing Technologies

Technology	Energy range	Comment
Mirrors	<40keV	Limited by reduction in critical angle with cut off energy.
multilayers	Up to 120keV	Broad band pass. May be used in conjunction with focusing monochromator for vertical focusing. Presently limited in length. May be used for micro fluorescence type applications[16]
Bragg longitudinally bent perfect crystal optics	Up to 60keV	Used for horizontal focusing. Single bounce monochromator so fixed energy operation. At high energy, Bragg angle becomes small so crystals must be long e.g.[17].
Bragg sagittally bent crystals.	Up to 100keV	Used for horizontal focusing in a double bounce arrangement. The energy is tuneable. At high energy, high order reflections must be used otherwise the Bragg angle is small and the required bending radius is too small [18]
Laue longitudinally bent crystals	Up to 200keV?	Double crystals design possible to reduce poychromatic divergence[19].
Laue sagittally bent crystals	20keV to 200keV?	Broadening of band pass. Anticlastic curvature can be used to eliminate wavelength dispersion or to do focusing in vertical direction. Low energy limit determined by absorption. Double bounce arrangement allows a fixed offset geometry for energy tunability. [14,15]

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10.4 MICRO-FOCUS

DIAMOND will be a high brightness synchrotron source and as such will be ideally specified for conducting research across all disciplines at microscopic scale lengths. All the first suite of beamlines proposed for DIAMOND, described in the rest of this chapter, have some requirement for a micro-focus capability. This section collates their specifications and outlines some of the techniques currently in development worldwide which could be applied. X-ray microscopy is a rapidly developing field at present and it is expected that the technology for producing and manipulating micro X-ray beams will evolve substantially in the next decade, therefore the solutions employed by these beamlines may well differ from what is covered here.

This section only deals with microfocusing of X-rays below about 20keV. At higher energies the very small critical angle for grazing incidence reflections and the highly penetrating nature of hard X-ray photons produce special problems in focusing which are covered in a separate section.

10.4.1 Beamline Specifications

(a) Protein Crystallography

Monochromatic radiation from an undulator :

- wavelength range $0.7\text{\AA} - 1.3\text{\AA}$ (17.7 – 9.5keV)
- bandpass ($\Delta E/E$) 10^{-4}
- convergence Up to 0.2mrad (2mrad)
- energy stability 0.25eV
- beam size at sample $100\mu\text{m}$ (5 – $100\mu\text{m}$)
- positional stability 1% RMS on 5s timescale
- 3% RMS on 1hr timescale
- flux 10^{12}ph/s in $100\mu\text{m} \times 100\mu\text{m}$ ($30\mu\text{m} \times 30\mu\text{m}$) @ $1\text{\AA}$ (12.4keV)

Figures quoted are for the three phase one beamlines, with (*in brackets*) those for a proposed phase two, microfocus PX station.

(b) Crystalline diffraction

Although micro-focusing is not a core component of this beamline proposal, the possibility has been raised.

- energy range 3.5 – 15keV
- convergence Not stated, but demand will be for as low as possible
- beam size at sample $\sim 10\mu\text{m}$

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(c) Non-Crystalline Diffraction

- energy range 4 – 20keV, core range of 8.5 – 12keV
- convergence As low as possible
- beam size at sample 5 – 10 μ m, possibly down to 1 μ m

(d) MicroEXAFS

The primary goal of this beamline is to conduct microfocus EXAFS

- energy range 2 – 20keV, core range of 5 – 15keV
- bandpass ($\Delta E/E$) 10^{-4}
- convergence Not a primary issue
- beam size at sample 1 μ m

Additionally this beamline is required to maintain good focus whilst energy scanning by up to 1keV. This makes the use of optics with fixed, *i.e.* energy independent, focal lengths as the preferred solution.

(e) XPEEM

- energy range 500 – 1500eV
- bandpass ($\Delta E/E$) 10^{-4}
- convergence Not a primary issue
- beam size at sample 1 μ m $\times$ 2 μ m

The specification for this beamline is to provide a high flux density in a small area and so the shape of the focus is less critical than in other applications (*e.g.* microEXAFS). This beamline also requires that focus conditions be maintained whilst energy scanning.

10.4.2 Issues

The microfocusing of X-ray beams is a brightness limited process. To efficiently produce small focal spots means ideally utilising photons from the full source cross-section and from the entire source emission cone. There are practical limits to the maximum optical demagnification that can be applied of the source onto the sample, this places limits on the maximum source size that can be utilised. Additionally, the beam convergence will be amplified by approximately the same magnification ratios giving a larger beam convergence at the image point than produced by the source. Again there are limits to the maximum convergence angles that can be utilised because of either optical or experimental considerations. Optically the focal cone size is determined by the critical angle of reflection of optical components, this is smaller at higher energies, for example a rhodium coated mirror will have a critical angle of 6mrad at 10keV, but only 3mrad at 20keV. Experimentally the acceptable divergence at the sample may be limited for diffraction measurements by the need to resolve fine detail in diffraction patterns.

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A high brightness source, whereby a small source emits a high flux into a narrow emission cone, such as obtained from DIAMOND undulators, is therefore required if maximum use is to be made of the high flux in a limited phase space at the sample.

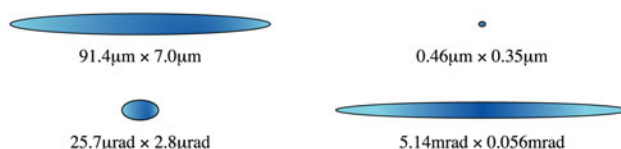


Figure 10.4-1 Transformation of photon beam phase space at source to the sample

Figure 10.4-1 shows how the photon beam phase space at source is transformed into phase space at the sample in order to obtain an approximately micron sized focus. It shows how the phase space of beam size and divergence is transformed by demagnifying optics. The figures quoted for the source (left) are electron beam parameters, the photon beam from an undulator will have slightly larger values. Figures quoted are r.m.s. values. Demagnification values of 200:1 (H) and 20:1 (V) have been assumed to give an image (right) with a fwhm size of approximately $1\mu\text{m} \times 1\mu\text{m}$.

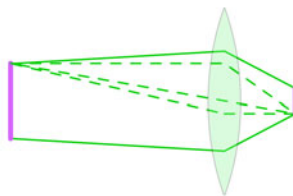


Figure 10.4-2 Photon phase space transformed by a single, simple lens system.

Figure 10.4-2 illustrates how the photon phase space is transformed by a single, simple lens system. It illustrates the principle by which the photon beam phase space is transformed by a single, simple demagnifying optic. It therefore follows that to focus the entire photon source to a micron sized spot at 10keV with a rhodium mirror will restrict the usable cone angle to less than that emitted by the source. This in turn will reduce the flux output that can be transferred to the sample. At 20keV, the smaller critical angle will reduce the usable cone angle further.

Beamline stability is clearly important for microfocus applications. It is common practise to employ compact microfocus optics stages and to mount them on the same optical bench as the sample stage. From the above optical considerations it can be seen that there will be some optical losses involved in utilising even the extremely bright beams available from DIAMOND. It is therefore recommended that the detailed optical design of the beamlines accommodate this optical loss by overfilling the

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microfocus optics, so that instabilities between source and sample do not lead to beam movement across the sample.

Another consideration which needs careful examination in detailed beamline design is the extended nature of the photon source. If long IDs are used, particularly MPWs, then the length of the source will lead to a range of image distances in the optical focusing. This will have the effect of defocusing the image as one end of the source will be focused before the sample with the other end focusing after the sample. This mis-focusing will be worsened as the electron beam size and hence photon source size will be larger further away from the centre of the ID length. These effects also caution against the use of multiple IDs in a single straight for microfocusing applications, although with care the resulting separation of focal planes can be utilised for some beamline applications, for example allowing rapid polarisation switching at SLS [20].

It is expected that the diversity of experiments that will be required on each of the beamlines will call for some flexibility of approach. Therefore several microfocus options may be required to be fitted to individual beamlines. The choice of which is the best option needs ideally to be considered on a per experiment basis. Each technique cited here will have a range of possible implementations, indicating that for a particular application the choice of optical method is not necessarily automatic. Best performance will be achieved with microfocus optics designed for specific experimental requirements on a particular beamline as these will generate a unique specification. To yield ultimate performance requires a solid understanding of the optics and the ability to easily measure and interpret the output of the microfocus optical stage. This is particularly important if an interchange of microfocus optics is envisaged. If the use of microfocus optics on a beamline is foreseen at the design stage, then the optical design of the beamline should be conducted with that in mind.

There are two main experimental reasons for requiring microfocus x-ray beams. For the study of very small samples (*e.g.* small protein crystals) the concern is to increase the flux density on the sample. For the investigation of spatial variations in complex intergrown specimens the concern is to obtain good spatial resolution. In the former case one is less concerned about the shape and size of the focus, in the latter one is using the microfocused beam to resolve detail within the sample and a clean, well formed focus is important. The PX and XPEEM beamlines will fall into the former category, the EXAFS and the other diffraction beamlines will fall into the latter.

10.4.3 Microfocus techniques

This section covers a number of microfocus techniques commonly employed at other 3rd generation synchrotrons. This is a rapidly developing field and much can be expected to change in the interval leading up to commissioning of the first suite of DIAMOND beamlines and beyond. Therefore inclusion is also made of a new technique currently being developed for non-synchrotron applications to indicate the diversity of this field and the need to look outside the synchrotron community for relevant technologies.

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Some review articles have already been written on this subject [21], [22] however, they can rapidly become out of date due to the speed at which developments take place in this field.

(a) Fresnel Zone Plates

Fresnel zone plates for soft X-ray use ($<1\text{keV}$) have been in development for more than a decade and are in use in soft X-ray microscope beamlines at many sources including ALS [23], NSLS [24], BESSY2 [25], [26], Elettra [27], SRRC(Taiwan) [28] and PLS (Korea) [29]. In these applications focal spot sizes of 50nm are routine and 25nm has been reported [30]. The resolution limit is determined by the size and accuracy of manufacture of the outer ring in their structure. Modern fabrication techniques can now produce soft x-ray zone plates up to 0.5mm in diameter. They require to be illuminated by coherent radiation and so their efficiency in photon collection is determined by the coherent fraction of the photon beam factored with their transmission. Because of the diffractive nature of zone plates, they have a focal length which is wavelength dependant and thus require longitudinal motion in the sample – zone plate separation during energy scanning. This complicates matters for EXAFS type measurements, although various solutions are in operation in the soft X-ray regime at different sources.

Zone plates are also being manufactured for hard x-ray use and have been employed at Spring8 [31], [32], ESRF [33], APS and ALS in the 5 to 25keV energy range. At these energies the zone plate ring structure becomes non-opaque to the x-ray beam and so it is possible to build phase diffracting devices. These improve the transmission properties, with values of 40% and better having been reported [34] as opposed to the few percent typical for sub-keV energies. The thicker patterns required however limit the ultimate spatial resolution that can be achieved to 150–500nm. To utilise a wide energy range will require the use of several zone plates of different fabrication. Some means of interchanging and aligning these – either manually or remotely – needs to be included in the experiment design.

The focal spot size of soft X-ray zone plates is over specified for the XPEEM beamline, however in the harder X-ray range phase zone plates may find application, particularly for the X-ray diffraction beamlines where continual energy tuning is not required.

(b) Kirkpatrick Baez Mirrors

Kirkpatrick Baez mirrors use a pair of elliptically shaped mirrors mounted orthogonally to provide independent horizontal and vertical focusing. For small (up to typically 20cm) mirror flats it is relatively easy to form an elliptical shape by simple bending [35] and using two mirrors enables different demagnification ratios to be employed in horizontal and vertical directions. This is useful in transforming the elliptical source shape into a more circular image at the sample.

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Kirkpatrick Baez mirror pairs are commonly employed for medium energy X-ray focusing from a few keV up to 30keV and are in use at a number of sources including ALS [36], ESRF [37] and APS [38]. The upper limit is set by the extremely small critical angle for reflection at hard X-ray energies, although this can be improved by multilayer coating at the expense of introducing chromatic properties. Achievable focal spot sizes are typically a few micron to less than 1 micron.

Unless coated with multilayers to extend their energy range, they are polychromatic devices with focal lengths determined by their shape and angle of incidence and so would form a good choice for the XPEEM and MicroEXAFS beamlines.

(c) Schwartzchild objectives

Schwartzchild objectives use a pair of concentric spherical mirrors in a near normal incidence geometry. This gives a large aperture, but limits them to low energy use up to a maximum of a few hundred eV. This can be increased within the sub-keV region by use of multilayer coatings, but again this is at the expense of the introduction of chromaticity into the optics. Correspondingly they have found limited applications in X-ray focusing on synchrotrons although some examples do exist [39]. They are therefore not suited to the initial suite of beamlines proposed for DIAMOND, although they may find application in subsequent beamlines.

(d) Compound Refractive Lenses

The refraction of X-rays by normal density matter is very close to unity, therefore at first glance refraction, rather than reflection, is not an attractive proposition for the focusing of X-rays. However for low Z materials the transmission of X-rays in the mid to hard energy range is good and so it becomes practicable to build focusing devices using a series of refractive lenses.

Compound refractive lenses (CRL) are being developed principally at ESRF [40] and Spring8 [41] for use in the 2–60keV energy range. Fabrication is normally by stamping the required profile into a series of discs (typically 50–100) of a low Z material such as Al or Be, although CRLs have also been made from a string of air bubbles in epoxy. However, the optical efficiency of lenses constructed by the latter method is less. The lens assemblies can be compact, the ESRF unit measures $70 \times 40 \times 30$ mm although the aperture is small – of the order of 0.5mm, yielding a low numeric aperture. CRLs are capable of focusing to less than a micron and flux densities of 10^{10} ph / s / μm^2 have been recorded at ESRF, equating to a flux density gain of 10^3 . Focal lengths in the metre range can be realised. However CRLs are chromatic devices with a focal length that scales with the square of the wavelength, thus limiting their usefulness in energy scanning experiments such as EXAFS. Also to cover a wide energy range (many keV) a number of lens assemblies made from different materials will be necessary.

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(e) Capillaries

Fabricated from fine glass tubes drawn to a taper with a conical or ellipsoidal inner surface, they operate by internally reflecting the x-ray beam and directing it to a focus upon exit from the capillary. They are available commercially and can be found in use at ESRF (ID13), APS (PNC-CAT) and CHESS. Due to their narrow diameter and long aspect ratio, direct metrology of their optical surfaces is not practicable, however it has proved possible to indirectly determine the roughness and approximate shape of their internal reflecting surfaces through study of the focal pattern. Their manufacture is acknowledged to be as much an art as a science which has limited systematic analysis of their performance. Although 50nm resolution has been achieved using these devices [42], 1 to 10 micron resolution is more routine. Entrance sizes can be of the order of millimetres which is reasonably matched to the beam sizes available from modern 3rd generation synchrotrons. The ESRF has quoted flux densities as high as 10^{10} ph / s / μm^2 / 2×10^{-4} bw at 13keV for single capillary focusing.

For optimum performance, care has to be taken in both manufacture and alignment to minimise the number of internal reflections taking place. Not only will excessive reflections reduce the overall efficiency of the capillary in transmitting X-rays, but the resulting increase in beam divergence from the capillary exit dictates a short working distance to the sample of 10 to 100 beam diameters. Furthermore distortions can become evident in the focal image under misalignment. Development of capillaries with a parabolic internal profile is taking place to provide devices having only a single reflection, however the resolution currently achievable is restricted to the order of 20–30 μm [43].

Bundling many capillaries together before drawing allows the construction of multicapillary arrays having a larger numeric aperture than a single capillary. The drawing process naturally produces a semi-parabolic shape to the capillaries although variations between the capillaries limit the ultimate spatial resolution that can be realised.

As capillaries use grazing incidence reflection they are polychromatic which is an advantage for energy scanning applications such as EXAFS. The sharpness of the focus is subject to the properties of the capillary and it's alignment, so they may not be an ideal optic for imaging applications and better suited to studies of small homogeneous samples. Capillaries have a fixed focal length, but it is small and usually less than 1mm. Mounting of capillaries can be very simple, PNC-CAT using a flat metal plate with a machined groove in it in which rests the capillary. Alignment is more complex.

(f) Waveguides

One dimensional focusing devices operating at harder X-ray energies, they comprise a thin layer (typically 100nm) of an optically transparent low Z material such as carbon sandwiched between two layers of a heavier Z material *e.g.* chromium and laid on a

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quartz substrate [44]. X-rays entering through the top high Z layer at shallow angles are trapped by internal reflection within the middle low Z layer.

If the waveguide is sufficiently long, a relatively large beam can be compressed into a size equal to the thickness of the mid-layer, yielding flux density gains of the order of 100. Apart from the obvious one dimensional nature of the focusing, the primary disadvantage of these devices is that the maximum flux gain is achieved at the exit of the waveguide leading to a working distance of zero. Their main application so far has been in projection imaging of samples exhibiting a one dimensional nature, *e.g.* semi-conductor interconnects [45]. In this case spatial information was provided in the dispersive direction with diffraction information being recorded in the orthogonal, non-dispersive dimension. Operational range is currently 10–20keV and divergence angles of the emitted X-ray beam is set by the critical angle of internal reflection, 1mrad having been reported at 13keV [46]. Currently activity is taking place at Elettra and ESRF in developing this technology. Usage on DIAMOND beamlines is expected to be centred on diffraction and phase contrast imaging applications.

(g) MicroChannel Plate Objectives

Microchannel plates (MCPs) have been primarily developed for electron multiplication and imaging. They comprise many fine drawn glass tubes down to a diameter of a few microns, bonded together into a plate. Conventionally the pores have been circular and hexagonally close packed in the plate. Recently square section pores have been fabricated and internally metal coated to improve their x-ray reflectivity. Work is progressing to mould the plates over rounded formers so that the pores are aligned to direct reflected x-rays to a focus. In this respect they are closely related to multicapillary arrays. The lead for this development comes from X-ray astronomy and is being exploited in the Lobster telescope package proposed for the International Space Station [46], a scheme for an X-ray imaging device based on the construction of a lobster eye. MCP optics will be short in length, but can have a large numeric aperture. One disadvantage of the technique at present is the tendency of the optic to produce a cruciform focal image.

MCP optics are in the early stages of development and the application to synchrotron use has yet to be explored, but in the time scale for realising beamlines on DIAMOND may provide a possible option.

10.5 DIAMOND BEAMLINE CONTROLS, DATA ACQUISITION AND DATA HANDLING

10.5.1 Introduction

This chapter proposes a technical solution to DIAMOND's general beam-line and experimental control requirements and outlines the work required to deliver this. It

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has been produced following a number of meetings, discussions and visits, most notably ...

- DIAMOND Beam Line Controls and Data Handling meetings
- Individual DIAMOND beamline working group meetings
- Discussions at user meetings (e.g. CCP13 ...)
- Visits to ALS and SSRL (April 2001), SLS (Feb 2002) and ESRF (various dates)

As its starting point the paper takes as fact that the accelerator and low-level beam-line controls systems will use EPICS (see section D2), where “beamline” is taken to mean the slits, mirrors and monochromator.

The document examines the seamless integration of the whole “pipeline” from insertion device/bending magnet, through the beamline, experiment and data analysis (i.e. “from source to science”), solutions are proposed and issues raised. Such an integrated approach provides great benefits for standardisation, automation and making the most of new opportunities such as e-Science and the GRID.

Finally, the technologies and infrastructure required to support data acquisition, analysis and handling are also considered.

10.5.2 Beamline and Experimental Control

(a) Requirements

Experimental control has different requirements to machine control. The machine is designed as a single entity since all components have to work together in order to achieve pre-defined beam characteristics at each port. Generally, once running, changes will be minimal with any large modifications (e.g. upgrade of an insertion device) having to be planned on a long time-scale and occur relatively infrequently. Experiment control, and to a lesser extent beam-line control, is likely to be more diverse and will change on a much more regular basis. Reasons for this are as follows.

- Different science areas have different requirements e.g. routine measurements vs dynamic experiments – beam-lines and experiments may change to accommodate a change of use.
- Experiments may transfer from other facilities (and vice-versa).
- Beam-lines and experiments may be designed and built by external agencies (either academic or commercial) e.g. the CATs at APS and CRGs at ESRF.
- Users are likely to want to bring their own equipment and add-ons.
- New technologies need to be accommodated to maintain state-of-the-art science.

The need to accommodate external equipment controlled by RS232 and GPIB and third-party software (e.g. such as LabView) points to a need to have a flexible framework, which will allow quick and easy integration of such tools. This kit may be

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custom made or commercial so the provision of standard interfaces cannot be taken for granted, indeed we are highly unlikely to be able to enforce the provision of EPICS on all suppliers. In fact, SLS has found this to be impossible and use CORBA to integrate their MAR CCD cameras on PX stations.

A flexible framework is also required to allow future technologies to be incorporated without significant effort. This is essential if the facility is to stay at the leading edge.

(b) Hardware

DIAMOND machine controls will use VME64X-based hardware with EPICS running under VxWorks (see section D2). This is the scenario that has been adopted at SLS for the machine, beamlines and experiments. The availability of EPICS IOC's running under other operating systems, most notably, GNU/LINUX, Solaris and NT means that the solutions for beamlines can be more flexible and allow the utilisation of a wider range of hardware, especially when a real-time environment is not necessary. While the availability of drivers for these operating systems is very low at present, it is likely that the community will exploit this area as these solutions become more popular. In some cases, it may not be appropriate to provide an EPICS system and in these circumstances, such solutions can be accommodated much more readily using the software framework.

(c) EPICS

EPICS is an established technology which is widely used for machine and instrument control. There is a broad range of support available from both commercial companies, the large number of facilities that use EPICS (APS, SLS etc.) and a strong user community.

However, when it comes to experimental control, the case is not so clear-cut. From our visit to SLS, it is clear that EPICS can provide basic data acquisition facilities, and is ideal for beamline set-up and commissioning. Other facilities often do not universally extend EPICS to experimental control and data acquisition areas, (e.g. the use of MX and SCIPe at APS) or have to provide interfaces to other software systems to provide the level of functionality that is required. Furthermore, at present EPICS has a buffer size of 16Kbytes, which would severely limit experiments requiring image readout e.g. CCD's and gas filled detectors. This is currently under review.

It is generally agreed that EPICS has a large learning curve and requires a significant infrastructure to support it, compared to writing a simple VisualBasic acquisition program. While this will not be too much of a problem in-house, it would impact on external groups producing experiments for use on the facility. The provision of significant in-house support and the introduction of EPICS soft channels (allowing users to create virtual and simulation instruments) can go some way to alleviating this problem, it still represents a major issue.

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Although EPICS is proven and reliable it is not object-oriented (though object-oriented channel access clients are available) which means that EPICS-based systems that need to integrate with modern software systems require CORBA, CDEV or Java CDEV (all of which are used at the SLS). Thus EPICS by itself is not suitable for heterogeneous multi-platform “plug-and-play” software systems and, thus indicates the need for a framework which can integrate EPICS with other control systems.

Data acquisition software specification must be user driven, and has to be quickly and easily adaptable (usually achieved through the provision of scripting – for experiments) and have a consistent and intuitive user interface (e.g. the pressure from users for Blu-Ice, a GUI for PX measurements developed at Stanford).

Finally, a careful analysis of the security regime is required to enable a separation of machine and user-controllable components, the former has been dealt with in chapter D10.

(d) The Object-Oriented Solution for Control

From past experience we have seen how the software needs to evolve with changes in the source, the science, the instrumentation and computing, hardware and software technologies available to the programmer.

The experience gained has led to a new object-oriented approach to experimental control and data acquisition which gives the programmer flexibility to accommodate, not only current and legacy systems, but also adapt to new technologies and instrumentation. However, it should be noted that this technology can impact performance and the level of the interface between the object-orientated layer and the device control software needs to be appropriate.

This approach has enabled the provision of generic control objects with defined interfaces to the specific hardware. Details of specific implementation can then be hidden behind those interfaces. These interfaces provide a “plug-and-play” framework, which makes the changing of any one component a simple matter of re-configuration (e.g. via XML). Highly intuitive and visual displays to control complex experiments can be developed through the use of this framework, and provides for generic scans with plug-and-play virtual instruments which allow users to rapidly integrate new equipment. Finally, scripting capability is available to allow rapid experimental reconfiguration.

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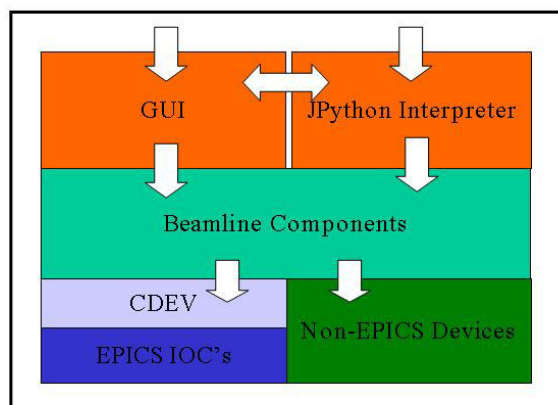


Figure 10.5-1 Framework of the Object-Oriented Solution for Control.

Currently, this framework is based on Java, CORBA and Python technologies. Any or all of these could be replaced should better technologies come along, but this would not be a minor undertaking. Where desirable, existing user-friendly client applications can be bridged to the standard framework based on alternative technologies such as Microsoft VisualBasic, C#, COM, .NET etc. Existing elements of control software (e.g. EPICS) just need software wrappers to integrate them into the framework and, similarly, any future technologies can be incorporated in the same manner. Therefore benefit from standardisation on EPICS where necessary but are not bound to it. The packaging of machine control software has the advantage that well-defined machine interfaces can be presented which enhance the machine's safety and security e.g. for the control of insertion devices.

This flexibility accommodates EPICS on both the beam-line and experiment as appropriate e.g., a monochromator implemented within the framework may be provided with wrapped EPICS motor drivers, or alternatively an EPICS monochromator could be wrapped to provide the generic interface. The programmer has a variety of options available. The choice of EPICS to control beamline elements is largely a matter of the integration required with the machine. For example, it would be sensible to use EPICS to control a monochromator that needed to work in conjunction with the insertion device since a tight integration with the machine is required. However, EPICS may not be the appropriate tool where beamline elements change frequently (e.g. experimental groups bringing their own instruments).

The standard DL Data Acquisition Framework software is currently being developed and deployed on MPW 6.2 and PX stations and is the result of collaboration between programmers from several of the SR facility groups. Interest in this work has been shown by ESRF and SSRL amongst others and the general approach is seen by us as the basis for a new generation of data acquisition software.

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Such a framework offers considerable added value ...

- Accommodates experimental evolution
- Provides simple and consistent user interfaces.
- Allows ease of configuration and experimental software design
- Integrates legacy hardware and is adaptable to new requirements.
- Hides implementation details from the user but will allow direct access to hardware for experts.
- Has the capability of providing a separate security layer (authentication, access control) above hardware control systems and allows easier machine protection.
- Integration of lower level EPICS control.
- Enables solutions for key user requirements
 - Experimental modification via scripting
 - Remote access
 - Automation
 - Integration of users equipment
 - Implementation of multiple techniques
 - Integration with data handling and the GRID

(e) Proposals

EPICS currently offers advantages for rapid delivery and commissioning of beamlines and experiments. This is enhanced because of the wide availability of software and support for SR applications. However, there remains considerable work to provide flexible, efficient and user-friendly experimental software. These deficiencies can be addressed by the object-oriented framework being developed at DL. Such a solution will provide the adaptability required enabling a quick response to user demand and changing technology.

It is inevitable that there will be significant changes in technology over the 5-6 years development period. Systems will become more distributed and web and GRID technologies will become more pervasive. This means that it is essential that the solution is not cast in stone until a feasibility study has been conducted which takes into account user requirements and technological developments.

Nevertheless it should be borne in mind that other developments in this area may result in better solutions to these problems and these should be monitored and tracked.

It is vital to organise the development team to manage the data acquisition software appropriately. From experience it is clear that a single coherent group is required for successful delivery of EPICS systems across the machine and beamline since this allows the EPICS overhead to be dealt with successfully and also promotes a consistent approach. It is similarly crucial to ensure any team has people dedicated to the data acquisition and analysis framework from the beginning. However, it is expected that, as the project progresses, effort will move from machine controls to

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new beamlines and experiments. There will still be effort required to maintain and develop the basic toolkits that are used.

It is suggested that a single group should provide the delivery of DIAMOND machine and beamline controls. EPICS for hardware control should be used where appropriate. Part of the group should be responsible for delivering the object-orientated data acquisition framework so users can take advantage of easy-to-use flexible data acquisition software from the earliest opportunity and also to allow the integration of any non-EPICS hardware.

10.5.3 Data Handling and Acquisition

(a) Automation and Remote Control

Automation, feedback and real time analysis of data will become increasingly important as it can provide considerable benefits to the quality of science and the productivity of the facility. In addition, the ability to remotely access and control experiments and collaborate on-line with remote users can also provide significant benefits.

The object-oriented approach to data acquisition, described in 2.4, enables such technologies to be easily provided.

However, it should be noted that relevant safety and security issues must be taken into account and this represents a significant challenge.

(b) Data Storage and Archiving

A major issue to be addressed is that of data storage – both locally on the beamline and for the facility as a whole. Network bandwidth constraints may mean that significant amounts of storage have to be provided local to the experiment in order to maximise throughput. The amount of storage will depend on the data rate from the experiment and the time available to transfer the data to alternate storage. Such requirements will obviously vary between stations.

The storage requirements for the facility as a whole will depend on the stance taken with data storage and archiving. The drive to GRID enable facilities dictates that the facility will act as a custodian for all data produced by it. This will have significant implications for costs since large, reliable, data storage and archiving systems are expensive – both in capital costs and ongoing support and maintenance.

The GRID technology that will enable this (the “CLRC Data Portal”) is still under development but should deliver within the timescale of the DIAMOND project.

(c) Data Analysis

Consideration is required as to whether users will be fully responsible for analysing their data or whether some on-site expertise (and hence facilities) are to be provided.

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Inevitably, there will be cases where it is sensible to provide pooled resources (especially for “measurements” provided as part of a service) and where primary “on-line” analysis (e.g. visualisation, data-reduction etc) is required to allow the experiment to proceed efficiently. The costs and requirements of this need to be factored in.

Feedback from on-line data analysis will become increasingly important for automation.

If such facilities are provided, then consideration is needed as to whether they should be made available “off-line” or, indeed, from off-site.

The GRID may be able to provide solutions for some of data analysis needs by providing access to distributed applications, data and compute resources.

(d) The GRID

Considerable R&D is being put into GRID projects, many of which will benefit to the DIAMOND project. Indeed the 2000 Spending Review expects such technologies to be applied to DIAMOND. It is clear that the project’s requirements in this area need to be quickly and clearly defined so that such R&D can be directed to addressing these and produce working solutions in appropriate timescales.

10.5.4 Infrastructure

While beamline controls, experiments and data handling can be considered in isolation, it is clear that a considerable support infrastructure is required in order to ensure that these are deliverable.

Most importantly, a network infrastructure must be provided with sufficient bandwidth to handle the data flows that will be generated by experiments and also to support GRID technologies. The infrastructure must be totally reliable (to support 24x7 operation) and secure (through careful provision of firewalls, monitoring, private networks etc.). Name services are required to advertise available resources on the network.

A security infrastructure needs to be put in place to protect computing resources and data (some of which will be commercially sensitive). This will require authorisation servers, monitoring and support.

Central computational resources (e.g. compute clusters) will be required for data analysis.

Finally, data storage, archiving and backup services need to be provided and managed.

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Many of these services should be provided by the evolving GRID infrastructure. However, it is not clear whether dedicated DIAMOND resources should be provided or whether reliance should be placed on a (yet to be provided) CLRC GRID infrastructure.

Other computing resources will be needed to manage the facility and its users and provide information systems (e.g. web servers, intranet etc.). Inevitably, these will require a central database which should also be used to keep track of, catalogue and store data produced on the facility. This database should be available from the earliest stages of the project so that it can be used to store all project-related data – e.g. wiring diagrams.

All these diverse systems will require a significant amount of on-going management and support and the provision of a helpdesk facility should be high priority.

10.5.5 Other Issues

Delivery of such technologies for the DIAMOND project will require significant effort. It cannot be achieved without sufficient resources and hence a feasibility study would be required to assess the experimental requirements and effort required

Further fact-finding is also required to ensure that latest thinking is incorporated and also to investigate the possibility of collaborating on such developments with other facilities.

This work has to be started as soon as possible. Too often, data acquisition is seen as a “last minute” bolt-on extra, when, in reality, it is key to getting high-quality science out of the facility.

10.6 STABILITY REQUIREMENTS

10.6.1 Introduction

In order to exploit the full characteristics of a 3rd generation storage ring, the beamlines and experimental facilities need to have a stability that is matched to the emittance of the photon beam. The source of the photon beam is of course the accelerator itself so the beamline components and the accelerator have to remain stable with respect to each other. Fortunately it is possible to realign optical components to compensate for a slow change in the beam position produced by instabilities in the optical components or the source. However more rapid instabilities and vibration are very difficult to cope with. This section describes the stability requirements and discusses ways of coping with instabilities. The aim is to inform the stability specifications for the building, machine and beamlines.

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10.6.2 Temperature stability.

Thermal expansion of elements in the beamline can introduce movement of the optics and therefore the beam. As an example, experience at the micro-EXAFS beamline at ALS has indicated that temperature swings in an experiment hutch due to temperature differentials between the hutch and outside can introduce offsets into micron scale alignment within the experiment. These swings result from an approximate 5 degC differential and with the hutch door open for 20-30 minutes during sample changeover / alignment. The environment around the beamline will have to be kept at a constant temperature. The most efficient way of achieving this will be to enclose the components inside an air-conditioned hutch or cabin. In many cases, this will be the radiation hutch itself. The hutch could be accessed from another enclosure (typically the control area) which is also air-conditioned to minimise temperature variation when the door is opened. Although there will be a large amount of power incident on the optical elements, all components will be water cooled, including in some cases, the vacuum vessels.

Use of enclosures as above will mean that the requirement for temperature stability in the experimental area of the building itself can be relaxed. There is no need to have the same temperature at different levels in the experimental area and some seasonal variation can be tolerated. The following specification should meet the experimental requirements.

Experimental hall temperature to be ± 1 degreeC per day within a band 5 degrees apart (20-25 suggested) with a slope of change in the mean of no more than 1 degree/month. This specification to be achieved in the 4m stratum closest to the hall floor.

10.6.3 Positional stability.

(a) Translating photon source size in to stability requirements

The minimum vertical source size of DIAMOND is approximately $8\mu\text{m}$ sigma. This will subtend an angle of $0.3\mu\text{rad}$ at a mirror placed 25m away from the source. At present, mirrors with a slope error as low as $1\mu\text{rad}$ can be made although it is hoped that this figure will improve by the time DIAMOND is operational. In order to match these figures sub-microradian stability of the optical system is required during an experiment. This can be translated in to a required specification of less than 0.5 micron per metre (i.e. $0.5\mu\text{rad}$). The floor slab has to have this stability.

(b) Construction of a beamline

In principle a beamline could be built with all optical components and on a long rigid girder. The components would be capable of being aligned on the girder to define the optical axis. The girder could then be realigned at regular intervals to accommodate any movement. In practice, most beamlines are built with the major optical

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components (and photon beam monitors) separately attached to the floor. This minimises vibration by isolating the optical components from the operation of valves, shutters and motors. In some cases, the components have even been placed on piles separate from the experimental floor. However this is impractical for DIAMOND as the position of the optical components is not yet known. The conclusion is that the stability of the experimental floor is a key factor in the stability of the photon beam. The stability of the floor can be divided into 3 components, defined here as long term, short term and vibration.

(c) Long term stability

(d) It is recognised that the floor will settle during the first few years of the operation of the synchrotron. Beamlines will have to be realigned at regular intervals to accommodate this. This could be achieved by a hydrostatic levelling system, similar to that proposed for the accelerator. The system should be made as automatic as possible so that sub mm adjustments could be carried out within a few minutes. Total movements of up to 20mm over the length of a beamline could be allowed for using this system. Connections to the machine hydrostatic levelling system should be made available outside the shield wall for beamline use, as at the SLS. The ability to re-survey the beamline with reference to the machine is an additional requirement. This may for example require removable plugs in the ratchet shield wall to give a line of sight in to the machine.

(e) Short term stability

During an experiment, people and equipment will be moving around the experimental floor. A typical fork-lift truck with its load could weigh 3000kg. Groups of people weighing up to 1000 kg (in total) will often tour the experimental area.

These would create essentially a point load on the floor. The resultant movement in the floor will need to be kept within less than 0.5 microns per metre if the position of the photon beam is to be kept stable.

Unless the floor can be made very stable, consideration might therefore have to be given to minimising movement of heavy equipment during operation of the synchrotron. The balance between use of the overhead crane and fork-lift trucks is another consideration. Although the crane will presumably be isolated from the experimental floor, movement will nevertheless result when the load is placed on the floor. SLS and ESRF have building supports isolated from the main experimental floor, their respective cranes use these supports. Also the outer walkway of these sources is vibrationally isolated from the main floor. The recommendation of the beamline layout working party is for a similar arrangement.

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(f) Vibration

Vacuum pumps, valves, motors, shutters and other equipment are potential sources of vibration within a beamline. The floor could transmit this vibration to the optical components. The angular movement would need to be kept within $0.5\mu\text{rad}$.

A policy of vibration isolation of all mechanical pumps etc from both floor and beamline should be adopted. For modest vacuum requirements, it may be sensible to consider remote pumps with vacuum lines feeding the various beamlines.

Sub micron focal spots are envisaged on DIAMOND. These will normally be achieved by mounting demagnifying optics on the same rigid optical bench as the sample. By coupling the movement of the microfocusing optics and sample in this way, some of the effects of vibration can be minimised.

Although it will be difficult to correct for vibration which occurs during an experiment it may be worth fitting vibration monitors to key components and storing the data from them. These could be referred to when problems occur with experimental data, with perhaps an automatic warning issued. In addition, monitors of this type would be a valuable diagnostic aid in identifying the cause of the vibration.

10.6.4 Conclusions

It is obvious that obtaining a stable photon beam will be a very challenging task. Short term instabilities and vibration will be very difficult to cope with and will have a detrimental effect on many experiments. Significant measures should therefore be adopted to minimise these causes of instability. At the same time, effort should go in to developing automatic feedback and alignment systems to cope with longer term instabilities.

10.7 INSTRUMENT TEST FACILITIES

Successful exploitation of the intense, brilliant, coherent photon beams from DIAMOND will depend on the performance of the state of the art beamlines and experiment systems currently in the conceptual and design phases.

Seven of these beamlines are already approved and around 2 to 4 more will be approved each year. Over the lifetime of the project, more than 40 beamlines are anticipated. All of these will require the highest performance optics and detectors, from current state of the art and beyond.

To ensure rapid and successful operation of these complex instruments, test facilities will be essential. The major areas to cover include tests of conformance of optics with specification and performance tests on detector systems. Current SR demand on optical quality is at the limit of manufacturing ability.

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The facilities required include

- an optics metrology laboratory,
- crystal cutting and test equipment,
- SR beamline test facilities covering the full range of photon energies to be exploited by DIAMOND
- beamline diagnostics support laboratory

Following the build-up phase where the rate of new system installation will reduce considerably, these facilities would support on-going technical developments.

In addition, the test beamline(s) will be invaluable for new technique development and exploratory experiment trials.

10.7.1 Speculative Design Concepts

The beam-lines considered are a medium energy insertion device beamline, 4 to >25keV and a bending magnet beam-line to cover the energy range from 100 eV to several keV. The facility will require a suite of optics and detector test apparatus, which can be flexibly configured to perform a wide range of tests such as:

- Micro-focussing performance of mirror and crystal systems
- Cooling effectiveness for high heat load
- Reflectivity for mirrors, multi-layers and diffraction gratings
- Imaging detector performance
- High count rate detector performance
- Coherence properties of beamline components such as slits, grids, foils, mirrors etc.

Location of these beamlines in a dedicated wedge close to (or incorporating) the accelerator diagnostic insertion device line and light monitor will give an operational advantage. Detailed understanding of the source parameters is essential for both accelerator operations and interpretation of test results.

The facility would also include off-line test laboratories for crystal cutting and tests, optics metrology and diagnostic equipment for beamline performance measurement.

Speculative design concepts are outlined in the following tables.

B.10 GENERAL BEAMLINE AND EXPERIMENTAL ISSUES

(a) Medium X-ray beamline

Table 10.7-1 General Medium X-ray beamline specification

Source:	undulator or MPW, exchangeable design, one module long (2m)
Optics:	monochromatic and white beam energy range 4->25keV resolution 1×10^{-3}
Hutches	30m hutch for sagittal monochromators, high heat load tests, with optics table 60m hutch for focus measurement, optics characterisation, detector test; with optics table, diffractometer, double crystal camera

(b) Soft X-ray beamline

Table 10.7-2 General Soft X-ray beamline specification

Source:	Bending magnet
Optics:	Variable included angle diffraction grating Energy range <100 eV to >2 keV Resolution 1×10^{-4}
endstation	Reflectometer/diffractometer Designed to accept a range of optics and detector vessels for test

Ideally, the facility would also include an SXR undulator beamline, used to develop polarised insertion device sources and polarimetry along with SXR optics and detector tests.

PART B: SCIENCE EXPLOITATION

(c) Optics Laboratory

Table 10.7-3 General Optics Laboratory specification

metrology	Long trace profiler for optics up to 1.5m General purpose interferometer PSI microscope (Micromap, Zygo, Veeco) Atomic force microscope Optical microscope
Diagnostics (for loan to science beamlines)	Calibrated flux measurement diodes Photon beam spot cameras Infra red camera (surface temperature measurement) Wavefront sensors Polarimeters
Optics preparation	Crystal cutting Crystal test facility Ozone cleaning lamps

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C.1 General Buildings and Site Issues

1.1 LOCATION

Diamond is to be located at the Rutherford Appleton Laboratory (RAL), Chilton, Oxfordshire. The facility will utilise two parcels of land. The first is on the eastern boundary of the RAL site, where the buildings will be situated, and the second to the south of the site, where some displaced facilities will be relocated and up to 100,000m³ of soil excavated from the east site will be deposited and landscaped.

The eastern site will be constrained to the north by Fermi Avenue, the incoming road to the Harwell Campus; to the east and south by a new access road serving RAL's southern car park; and to the west by RAL's existing buildings. There is also a proposed housing development to the south-east.

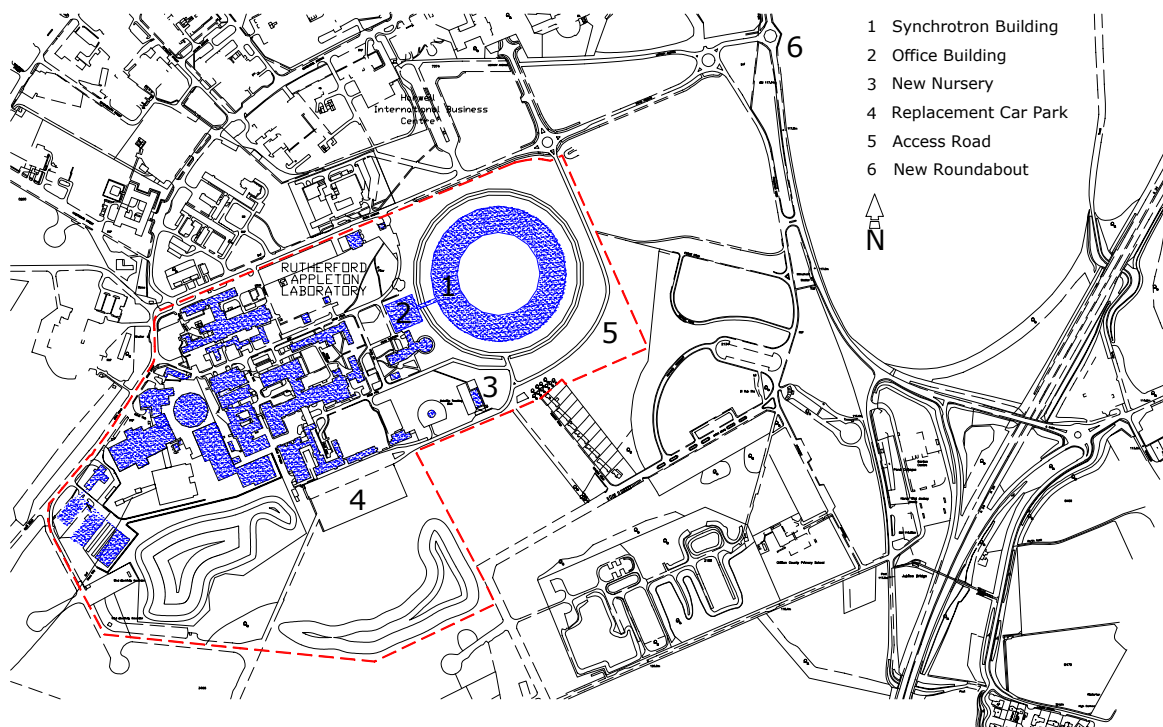


Figure 1.1-1 Site Plan

PART C: BUILDING

1.2 DISPLACED FACILITIES

Siting the Diamond buildings in the location described will require the relocation of the existing children's nursery and relocation of RAL's eastern car park. Both of these are to be carried out as separate projects, as too is the new access road bounding the east and southern edge of the site. As part of a planning permission requirement there will also need to be a new roundabout installed on the main A4185 road at the junction of Fermi Avenue.

1.3 GEOLOGY

A series of site investigations[1] [2] [3] have been carried out to confirm the geology beneath the proposed building site. These have included boreholes to depths of 40m, trial pits up to 3m deep, plate load tests, cross hole seismic surveys and contamination testing. The site falls approximately 3m from west to east. The ground structure is clay overlying structureless chalk over medium density chalk. The depth of clay varies between 1m and 5m, and depth to the medium density chalk is between 7m and 12m. The depth of the clay layer was unexpected and this precludes founding directly on a chalk layer.

The water table varies seasonally between 10m and 18m below ground level. It is believed that groundwater under the campus is funnelled under the proposed site from west to east.

Typical characteristics for the soil materials are shown in Table 1.3-1

Table 1.3-1 Soil Characteristics

GEOTECHNICAL PARAMETERS				
	Poisson's		Young's Modulus (Mpa)	
	V Undrained	v Drained	Eu Undrained	E Drained
Head and reworked chalk	0.5	0.3	6.75 to 21.6	5.4 to 16.2
Structureless chalk	0.3	0.24	100 to 200	60 to 250
Structured Chalk	0.3	0.24	437.5 to 562.5	350 to 450

Analysis of data continues in order to determine the most appropriate foundations for the Diamond buildings.

C.1: GENERAL BUILDINGS AND SITE ISSUES

Description of Strata		Depth m below G.L.
Topsoil		0.35m
Firm pale brown and cream slightly gravelly CLAY. Gravel is fine to medium of subrounded to angular flint. Sand is fine.		2.4m
Structureless CHALK composed of firm cream silt and sand sized comminuted chalk with some gravel. Gravel is angular fine to medium of flint. (Grade VI , DM) From 4.3m becomes less gravelly.		7.0m
Moderately weak low density cream occasionally brown staining CHALK with occasional gravel and rare bioclastic material (Grade II)		9.0m
Weak medium density grey CHALK, closely fractured. Fractures clean and tight (Grade III)		thus onwards water table at 18m

Figure 1.3-1 Typical Borehole Log

Contamination levels are low and it is not anticipated that spoil will be defined as contaminated waste or need to be dealt with in any special way.

PART C: BUILDING

1.4 ARCHAEOLOGY

Historical records show that there is little expectation of finding anything beneath the site of any serious archaeological interest. The site was an airfield during WWII and old runways exist on the site. There may also be the remains of an old roadway called the Thorningdown Road which ran through the site pre WWII from the east to the Golden Mile to the west of the Harwell Campus. An archaeological excavation will be carried out prior to construction starting.

1.5 PLANNING PERMISSION

An outline Planning Application was submitted in May 2001. It went before the Vale of White Horse Planning Committee in December where they determined to approve the application subject to conditions yet to be stated; signing of a Section 106 agreement regarding traffic issues; and because the application was a “departure” from the local plan giving the Secretary of State the opportunity to call in the application for review.

The application has not been called in and therefore Planning approval will be given as soon as the S106 has been resolved.

Detailed Planning Application will be made during the detailed design phase.

1.6 LAND OWNERSHIP

Part of the land is owned by CCLRC and the remainder by UKAEA , both public bodies.

The UKAEA land will be leased to CCLRC who will then sub-lease part of the land to the company set up to build and operate Diamond.

1.7 VIBRATION

Ground vibration measurements have been made at a number of locations on site. These have shown that the site is relatively “quiet” and on a par with other synchrotron sites around the world. Mechanical and electrical plant in the facility will be designed such that they do not transmit vibration to the ground. There will be isolation joints between foundation slabs and bases to avoid transfer of any vibration that does arise.

C.1: GENERAL BUILDINGS AND SITE ISSUES

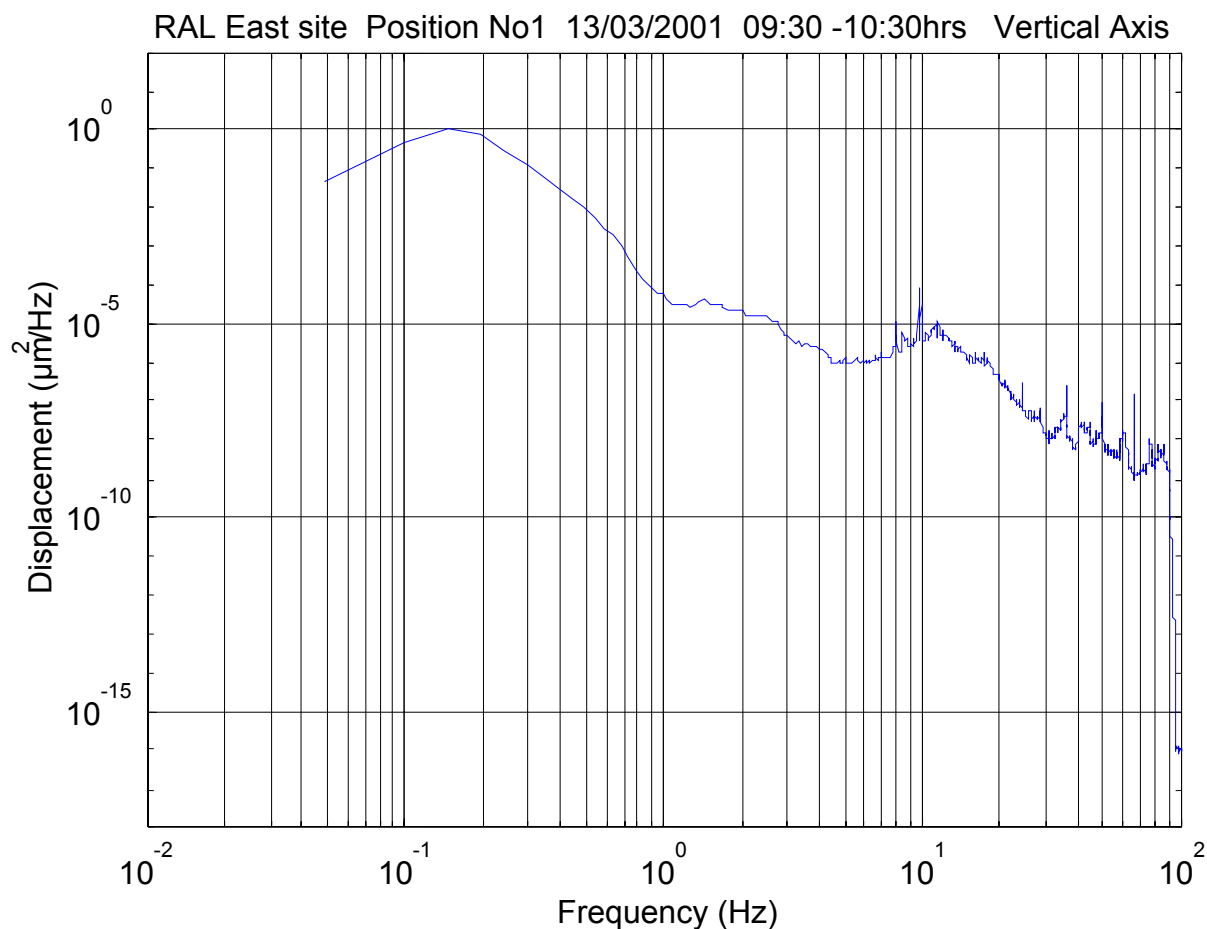


Figure 1.7-1 Vibration Measurements Graph

1.8 BUILDING GROUP

The Diamond facility consists of:

- The **Main Building** containing the synchrotron machine. This also includes a **Services Building**
- An **Office Block** adjacent to the main building to house operations staff.
- **External Works** including roads, car parks, fencing and landscaping.

PART C: BUILDING

1.9 ENVIRONMENTAL ISSUES

An Environmental Impact Assessment[4] and a Traffic Impact Assessment[5] have been carried out as part of the Planning process. These have shown that the project has only slight impact on:

- Visual environment
- Ecology
- Traffic
- Noise
- Air Quality

Impact during construction is greater than during operation. A routeing agreement will be required for construction traffic and mitigation measures will need to be put in place to minimise noise and dust impacts , particularly on local residents.

The buildings will be designed to reduce impacts on the environment and consideration given to sustainable construction principles.

1.10 GENERAL BUILDING REQUIREMENTS

1.10.1 Quality

The whole facility will be designed and built to a good standard appropriate to its status as a world class facility and its location at the front of the RAL site.

1.10.2 Extendibility

The initial facility will not provide the fully functional accommodation that will be required when all beamlines are populated. The buildings will therefore be designed for ease of future modification and extension with sufficient capacity in the services to support the fully populated facility. Space around the Main building is incorporated in the design for future extensions and space is allocated for at least two long beamlines.

1.10.3 Maintenance

Where possible the facility will be designed for low maintenance and, particularly in the Main building, the plant will be specified for high reliability.

C.1: GENERAL BUILDINGS AND SITE ISSUES

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C.2 Main Building

2.1 GENERAL

2.1.1 Layout

The Main Building will be annular in plan form to follow the geometry of the synchrotron machine with an enclosure over the linac and booster in the open area at the centre. The Services building will also be located within the courtyard together with much of the outdoor plant such as air blast coolers for the chilled water system. The accommodation will consist of:

- Linac and booster area
- Inner peripheral ground floor accommodation housing technical and plant areas
- Experimental hall housing the storage ring and beamlines
- Outer peripheral ground floor accommodation for laboratories, workshops, stores, etc.
- Outer peripheral first floor accommodation housing mainly offices, meeting rooms, etc.

Distance between outside wall and perimeter road will be 20m

The dimensions of the building are determined by the shielding to the storage ring and the required length of the beamlines. The dimensions set are:

- Diameter to outside face of inner wall of storage ring 169.26m with 7m clear to building structure
- Diameter to walkway at end of beamlines 217.60m
- Approximately 8m deep outer peripheral accommodation with 3m walkway at ground floor and 1.5m at first floor.
- Approximate building diameter 235m
- Crane hook height 3.79m clear of storage ring shield roof

The building will be divided into 12 sectors with 2 storage ring cells per sector.

PART C: BUILDING

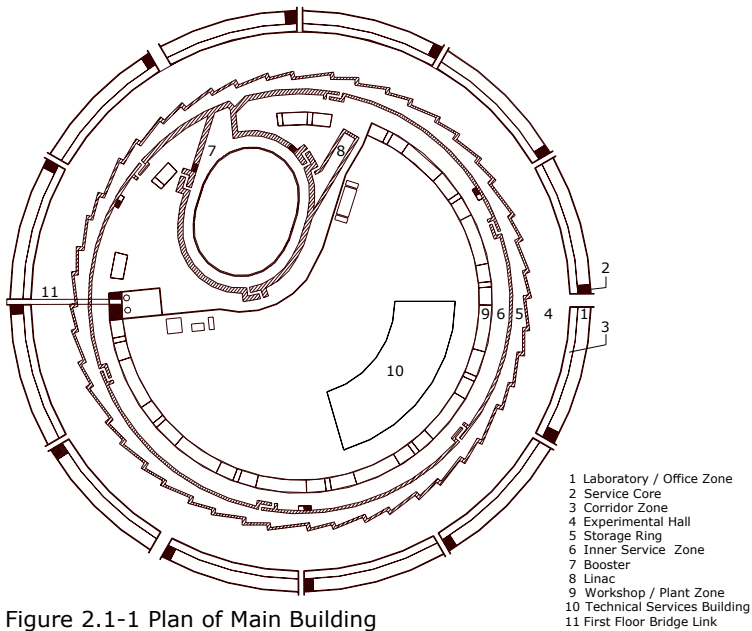


Figure 2.1-1 Plan of Main Building

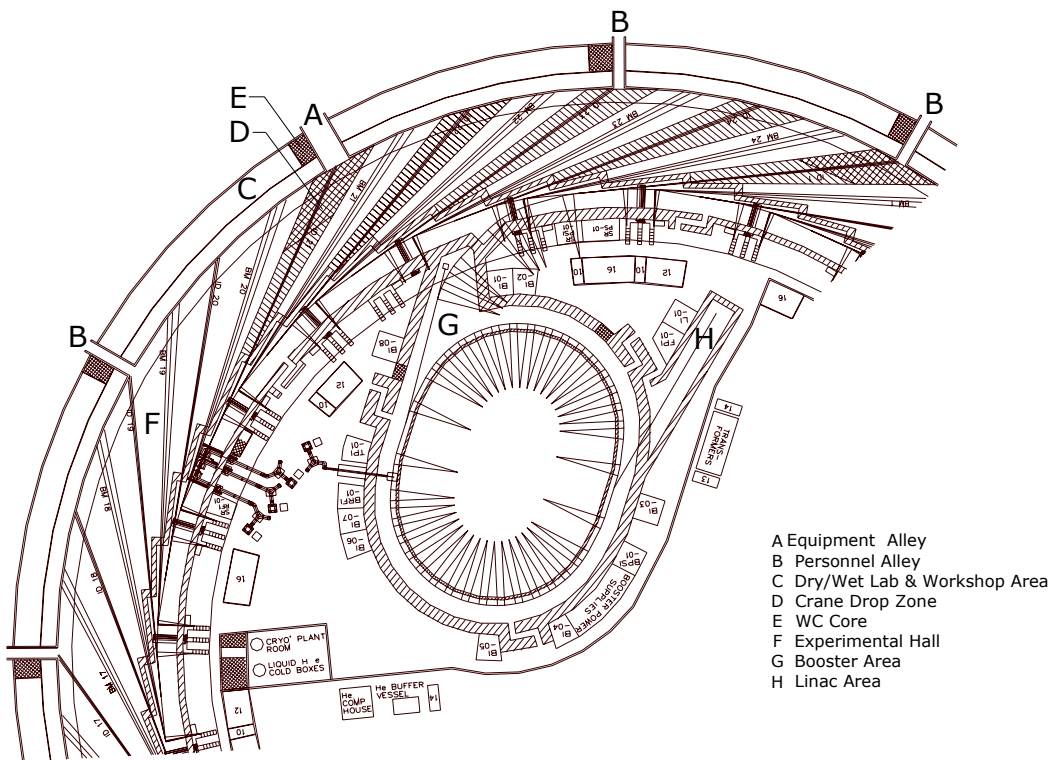
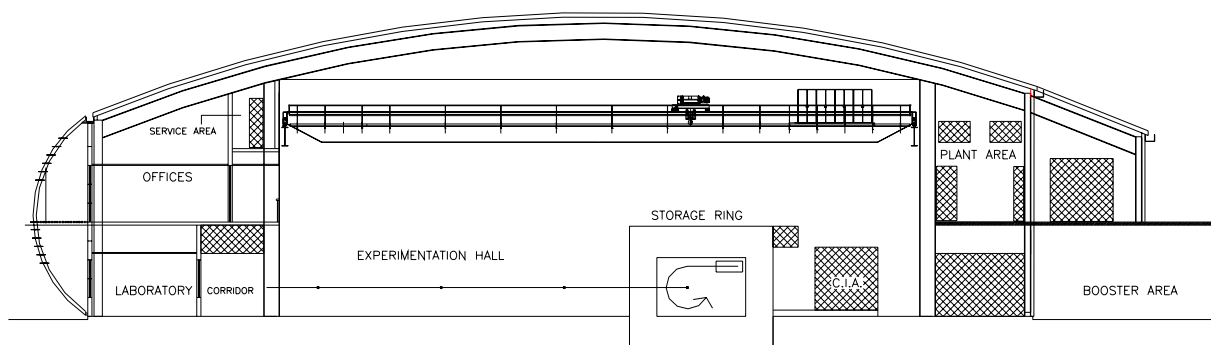
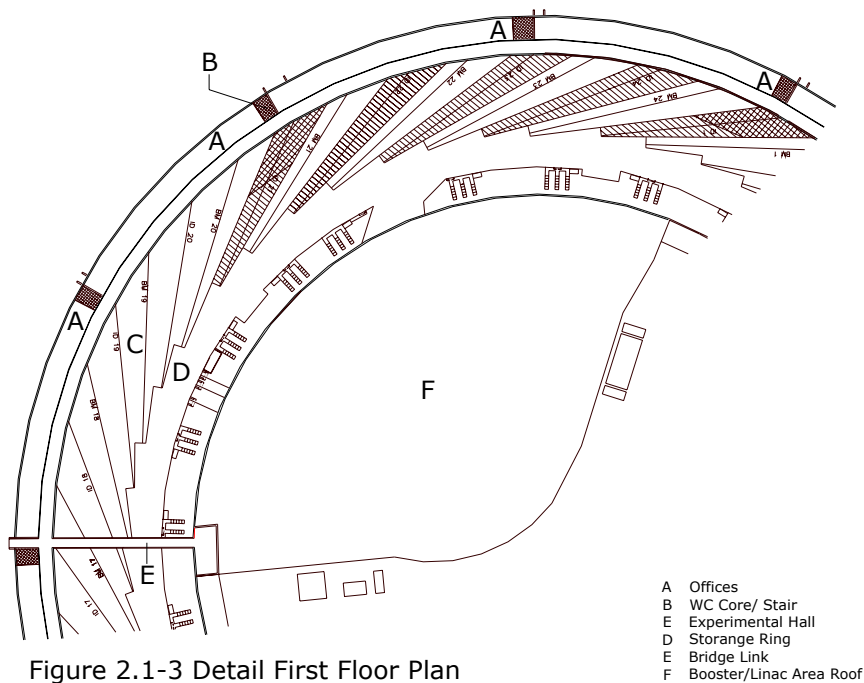


Figure 2.1-2 Detail Plan of Ground Floor

C.2: MAIN BUILDING



PART C: BUILDING

2.1.2 Materials

Materials will be considered in detail in the detailed design stage. However these will be selected taking into consideration Planning requirements, environmental impact, maintainability, sustainability, cost and availability. The likely materials are :

- Concrete foundations
- Steel frame structure
- Concrete upper floors
- Metal cladding
- Aluminium Double Glazed windows and doors
- Concrete block and metal internal partitions.

2.1.3 Drainage

The building will be provided with local rainwater, foul and trade waste drainage systems. Because of the formation level of the building these will probably feed into holding tanks before being pumped into the RAL site drainage systems.

2.1.4 Foundations

Parts of the building are particularly sensitive to movement. The most sensitive are the storage ring and experimental hall floor beneath the beamlines. The stability requirements for these areas are set out below:

Deflections:

Max static displacement at Beamline from 500kg load 2m away --- 1 μm
 Max dynamic displacement at Beamline from 100kg load 2m away --- <1 μm
 peak to peak

Max vibration acceptable at beamlines , linac, booster and storage ring--1 μm peak to peak vertical 4 μm peak to peak horizontal. Most susceptible frequencies 1 Hz to 50 Hz.

Settlements:

Long term	100 μm over 10m per year maximum differential movement of Storage Ring, Booster and Linac floor (250 μm for Experimental Hall)
Diurnal	10 μm over 10m per day across Storage Ring, Booster, Linac and Hall
Short term	1 μm over 10m per hour

C.2: MAIN BUILDING

The detailed design stage will establish the foundations needed to meet this specification. It is unlikely that the specification can be met with a normal slab construction founded on the clay because of the magnitude of settlement. Total differential consolidation settlements are expected to exceed 4mm and residual creep 0.5mm.. Methods being considered to meet the requirements are:

Concrete piled storage ring

Concrete piled or thicker flat slab experimental hall

Piled building frame supports

The method chosen will determine the level at which the ground floor will be founded and the quantity of soil to be excavated.

2.1.5 Temperature control

The experimental hall will be air conditioned to maintain close environmental tolerances because of the sensitivity of beamline equipment. Care therefore needs to be taken in excluding external sources of heat. Direct light into the experimental hall will be minimised although opportunities will be taken to utilise reflected or borrowed light to provide a comfortable environment for staff. External fabric of the building will be chosen to have high thermal insulation to reduce solar gain through the fabric.

The experimental hall air temperature up to 4m above ground floor level will be controlled to +/- 1°C in any 24 hours. This will vary by up to 5°C seasonally but the rate of change shall be no more than 1°C/month.

Temperatures within the storage ring and booster areas will be controlled within +/- 0.5°C. See 2.3.5.

2.1.6 Access

There will be only one external entrance to the facility per sector and additional emergency exits as required by fire regulations. Main entrance to the building will be via a bridge from the office block entering the main building at first floor level.

There will be one vehicle access door approximately 4x4m and designated drop off points within the experimental hall for the crane.

Access for pedestrians across the hall will be via a bridge spanning the width of the hall. The bridge will be demountable to enable the building of beamlines and removal of the storage ring roof. Additional staircases will be provided to give access over the storage ring.

PART C: BUILDING

Access for equipment across the hall will be via the overhead cranes. All equipment required to be transported across the storage ring roof will be designed within the 15T capacity of the crane and within the crane hook clearance dimension of 4m.

2.1.7 Fire Engineering

The size of the experimental hall means that it will fall outside the fire and escape requirements of the Building Regulations. Fire engineering solutions will therefore have to be developed in association with Building Control Officers, the HSE and the County Fire Officer. Solutions may involve additional exit doors, enclosure of the access bridge, secondary staircases across the storage ring, smoke control features and fire fighting equipment.

2.1.8 Noise

The building and the plant within it will be designed to minimise the noise levels within the experimental area and peripheral accommodation to provide a comfortable environment. Target levels will be NR45 in the Experimental Hall and NR35 in the peripheral accommodation.

Plant noise from the facility will also be kept to a minimum for environmental reasons.

2.1.9 Initial Facility

As part of previous cost cutting the initial facility will cater only for the first two years of beamlines. This means that:

- All early beamlines will be in one half of the building
- Peripheral accommodation in this half will be partially fitted out
- The other half of the peripheral accommodation will be shell only, with primary services circuits only.

2.2 ELECTRICAL SERVICES

2.2.1 Power supplies

Two separate 11kV supplies will run from the existing RAL main sub-station on Fermi Avenue to provide an estimated 16MVA maximum load. These will be terminated in a dedicated switchroom in the Services Building at the centre of the Main Building. From here supplies will be distributed at 11 kV via:

- Ring circuits to 7 distributed sub-stations to feed machine supplies
- Ring circuits to 14 distributed sub-stations to feed general building supplies

C.2: MAIN BUILDING

- One radial feed to the office block sub-station.

From the machine supply sub-stations, 400V supplies will feed distribution boards at the linac, booster, storage ring and RF supply points.

The general building supplies will also be distributed to local boards at 400V.

Any power factor correction required is anticipated to take place at the 400V boards.

2.2.2 Back-up Power

Back-up power will be provided for the following:

- Extract systems for COSHH, vacuum exhaust scrubbers, cryogenic systems in the Services Building; 5 minutes UPS with autostart generator.
- Guaranteed compressed air system backed by generator only
- Computers, supervisory equipment, local lighting and small power in the main control room, control system computer room, and machine physics room. On-line UPS's to be rated at 5 minutes, with auto start generator.
- Control system computers and instrumentation at Linac, Booster and Storage Ring control areas. On-line UPS's rated at 5 minutes providing surge protection and clean supplies.

Beamlines constructors will provide any UPS supplies that are required on beamlines.

2.2.3 Data Systems (including telephones)

New data and telephone systems will interface with existing systems within the RAL site. The system within the building will consist of a shared structured cabling network fed from data closets with a distance of no more than 90m from closet to outlet. There will be three independent routes to connect to the outside network.

Containment and cabling to be provided but active equipment and telephones are excluded from the building provision.

Containment for the 'Personal Safety' cabling is to be provided as well as containment for machine controls/data cabling.

2.2.4 Fire Detection and Alarm Systems

The requirements of the fire detection and alarm system are to be agreed with the Local Authority and the HSE during the detailed design stage. However it is expected that the building fire and escape system will have the following features:

PART C: BUILDING

- An addressable analogue detection and fire alarm system with the facility for zonal evacuation.
- Generally manual break glass alarm points throughout the building
- Automatic detection where required by the Authorities probably by optical smoke and rate of rise detectors
- Automatic closure of defined fire doors on actuation of the alarm system
- Alarm panels at the main entrance and repeater panels in the control room
- Interfaces from the panels to automatically call out the emergency services
- Traditional detectors circuits in high voltage or high radiation areas

2.2.5 Public Address

Public address systems will be provided in the following areas:

Linac

Booster

Storage Ring

Experimental Hall (4 zones)

Peripheral Accommodation (4 zones)

The operation will be from either the control room or main reception area via microphone and recorded message.

2.2.6 Closed Circuit Television

Two systems of closed circuit television are anticipated providing access safety to the linac, booster and storage ring areas, and a general building system to limit access to persons authorised to be in particular areas. Cameras and equipment will be suitable for the application used. Monitors and recording equipment will be located in the control room. The system will not have back-up supply.

2.2.7 Information Display Systems

Information display monitors will be located at strategic points around the building. These will be operated from the control room and will display both text and graphical information. Messages will be in different languages with provision for on-line or recorded messaging.

This system will not have UPS back-up.

C.2: MAIN BUILDING

2.2.8 Building Management System

There will be a BMS system for the building. This will be either compatible with and linked to the existing RAL system or a remote satellite station is to be provided. The RAL system is based at Building R18. The BMS main station will have UPS and generator back-up. The outstations will operate off local distribution boards and will have battery back-up. Connection to the RAL site BMS system will be via two independent underground routes.

2.2.9 Internal Lighting

Lighting within the building will be to normal office levels with the following exceptions:

- Control Room and Machine Physics room to have dimmable Cat 2 high frequency fittings with 50% supplied on UPS.
- Low occupancy areas (e.g. Plant Rooms) to have bare switch start fluorescent fittings , 350 lux
- Experimental Hall, Linac , Booster to have SON comfort lamps controllable in sectors from the control room variable up to 400lux.
- Storage ring , linac and booster tunnels to have dual lighting system , white and poison blue; facilities to allow future control from the control room to be provided.
- Emergency lights throughout the facility to be 3 hour rated generally non-maintained.

2.2.10 Lightning Protection

Lightning protection will be provided to BS6651 and BS EN61024

2.2.11 Emergency Klaxons

To meet campus requirements the existing RAL emergency klaxon system will be extended to include the building. Coverage will be required both outside and inside the building.

2.2.12 Supplies to beamlines

The following provisions will be made available at each beamline:

- Three phase 6kW 30A distribution board with supply cable rated at 100amp.
- Single phase 4kW 20A lighting distribution board

PART C: BUILDING

- In each quadrant of the building one beamline can be provided with an additional 100 kw supply
- Fire alarm zone interface box
- Containment for 24 data/telephone points back to the nearest data closet
- Earth stud on nearest substation building column

Each beamline will be responsible for funding its own main power cable and board once its maximum electrical load is known. It will also provide its own transformer and UPS to provide 110v and clean supplies.

2.3 MECHANICAL SERVICES

2.3.1 Cooling Water

Cooling Water will be required for air conditioning, magnet and equipment cooling.

Table 2.3.1 gives heat to air and heat to water loads for the magnets and equipment in the Linac, Booster and Storage Ring and other areas.

To deal with these loads chilled water will be produced by means of water chillers, water-cooled condensers and air blast water coolers. Primary chilled water circuits will supply the air conditioning systems in the Experimental Hall, linac, booster and storage ring areas, the heat exchangers in the secondary circuits and valved off supplies to beamlines. The total capacity of the cooling system will be approximately 10MW.

For the magnets and machine equipment the secondary circuits will have water treatment, filtration , mixing valves and pump sets to achieve required pressure, temperature, flow and water quality. Conductivity of demin water will not exceed 0.1 $\mu\text{S}/\text{cm}$ with 10 μm filtration. Circuits will have de-oxygenation to reduce copper corrosion. Circuits will terminate at a console adjacent to each magnet cell suitably valved off and with temperature, pressure and flow meters. The flow and return limits will vary between supplies but with a rate of change of water temperature not exceeding 0.05°C.

Each beamline will be provided with “beam stop” raw cooling water capacity of 100kW with a total provision for all beamlines of 1MW.

In addition to chilled raw water circuits for beamline air conditioning and secondary cooling circuits, at say 25kW/beamline there will also be circuits for cooling applications such as vacuum pump systems. An allowance of 10kW per beamline will be made with flow and return limits of 22-27°C.

C.2: MAIN BUILDING

2.3.2 Heating Systems

A heating system will be required to provide heating via air conditioning in the experimental hall and via LPHW to radiators in the peripheral accommodation. This will probably be provided by a steam-raising boiler although CHP alternatives will be considered at detailed design stage. The anticipated capacity of the system is 4MW. The system will be designed allowing for an external temperature of -4°C and with 100% saturation.

2.3.3 Compressed Air

Compressed air circuits will be provided to serve:

- Linac, Booster, Storage Ring (to outside of shielding)
- Outer Perimeter of Experimental Hall
- End of beamlines

Capacity will be not less than 175l/s FAD at 9 bar. Compressors will be oil-free, with integral drier to 3°C dew point, and filtration to 0.5µm. Air receivers will have 6 minutes capacity.

There will be a guaranteed system for control pneumatics, safety interlocks, shut-down valves etc. Compressor capacity will be not less than 55l/s FAD at 8 bar.

2.3.4 Nitrogen Distribution

There will be both Nitrogen Gas (N₂) and Liquid Nitrogen (LN₂) distribution systems within the building. These will be supplied by high integrity stainless steel and super-insulated vacuum line from four 120m³ rented storage dewars distributed around the outside of the building. The LN₂ and N₂ distribution will be around the outer wall of the experimental area with valved tees at suitable intervals to serve beamlines. There will also be an N₂ ring main within the storage ring, with valved tees to each cell and extensions to beamline front ends, and ring mains in the linac and booster ring with valved tees at each vacuum roughing pump connection. The rented Dewar system will include heat exchangers for production of N₂.

2.3.5 Air Conditioning and Ventilation

Air conditioning and mechanical ventilation will be provided to areas of the Main Building as follows:

(a) Experimental Hall

Controlled to 4m above floor level to approximately 22°C +/-1°C movement in any 24 hours. The temperature will be allowed to change slowly with no more than a 1°C

PART C: BUILDING

movement per month. There will be no humidity control but there will be filtration to computer room standards.

(b) Storage Ring, Booster and Linac

These areas will be controlled all year round to $22^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$. The rate of temperature change will not exceed $0.05^{\circ}\text{C}/\text{hour}$. There will be no humidity control but there will be filtration to computer room standards.

(c) Control Room

Controlled to $21^{\circ}\text{C} \pm 1^{\circ}\text{C}$ with no humidity control but with filtration to computer room standards.

(d) Fresh Air

Fresh air will be provided as required with consideration given to areas where gases and cryogenic liquids are present. Oxygen depletion detection systems will be considered in the detailed design stage.

(e) Perimeter Accommodation

Where possible these areas will be ventilated naturally with the exception of kitchens, toilets and local computer rooms.

2.3.6 Vacuum and COSHH Exhaust Systems

These will be twin systems providing an air exhaust service from the beamlines and laboratories and to remove exhaust air from vacuum pumps and COSHH enclosures. Each system will operate at approximate 250 Pascals gauge, with suitable fan and damper controls to maintain the negative pressure and to provide the required terminal velocity at the stack.

2.3.7 Cranes and Lifts

The experimental hall will have three 12 Tonne, two speed, annular overhead cranes. These will provide a minimum hook height above storage ring roof of 3.79m. They will be radio controlled but with availability of pendant control. It will be possible to operate more than one crane in any section.

There will be a minimum of four hydraulically actuated 2 tonne goods/passenger lifts in the experimental area to serve the perimeter accommodation and the booster area.

2.3.8 Water Supplies

The following water supplies will be provided:

- Ring main for fire hydrants around the outside of the building

C.2: MAIN BUILDING

- Cold water main distribution around the outer walls of the experimental hall to provide connections to Beamlines and peripheral laboratories and toilets etc.
- Cold water mains to the services building to provide make-up water to boilers etc.
- Domestic Hot water from local water heaters in kitchens and toilets.

2.3.9 Helium Gas Distribution

A helium gas system will be provided to the:

- Storage Ring 3 valved tees per cell
- Booster 12 valved tees
- Linac 2 valved tees

These systems will be provided from local bottle racks and operate at 3barg.

2.3.10 Fire-Fighting Systems

Fire fighting systems will be required as requested by the Authorities. These may include sprinkler systems to certain laboratories together with fire hose reel stations. The cold water system will be sized accordingly to serve these. There will be manual fire extinguishers at intervals requested by the Authorities. There may also be a requirement for smoke extract systems.

2.3.11 Building Energy Management Systems

Monitoring and control of all services in the building will be achieved via outstations and centralised BEMS in the Services Building.

2.3.12 Trade Waste Drainage System

Trade waste drainage from the beamlines will be achieved by one of three methods:

- Vacuum drainage with suitable vacuum pumps and collection vessels around the experimental hall and then connection by gravity to an underground system.
- Macerator and pumped system from the beamline feeding into a gravity system
- By a gravity feed through the storage ring to a storage system from where waste will be pumped.

C.3 Office Block

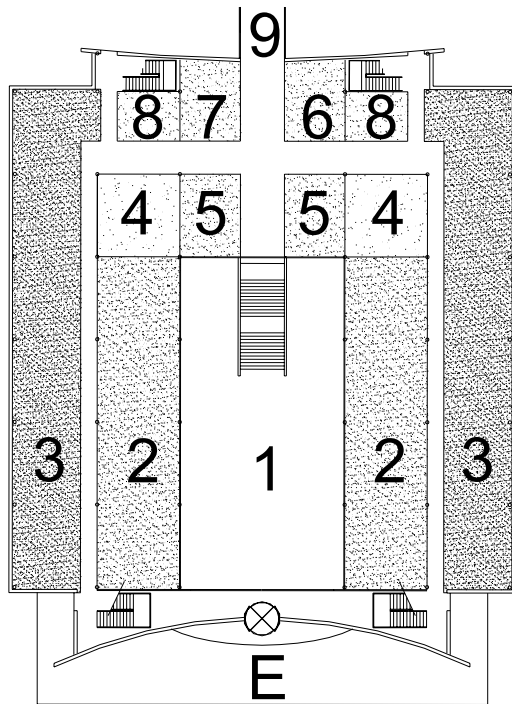
3.1 GENERAL

The facility will be provided with a separate Office Block for the first year of operations. This will have three storeys with approximately 5000m² gross floor area. There will be an additional reception/atrium area. It will be linked via a glazed bridge to the first floor of the Main Building. The building will house Operational, Scientific and Administration staff in a mixture of open-plan and cellular accommodation.

3.2 STRUCTURE

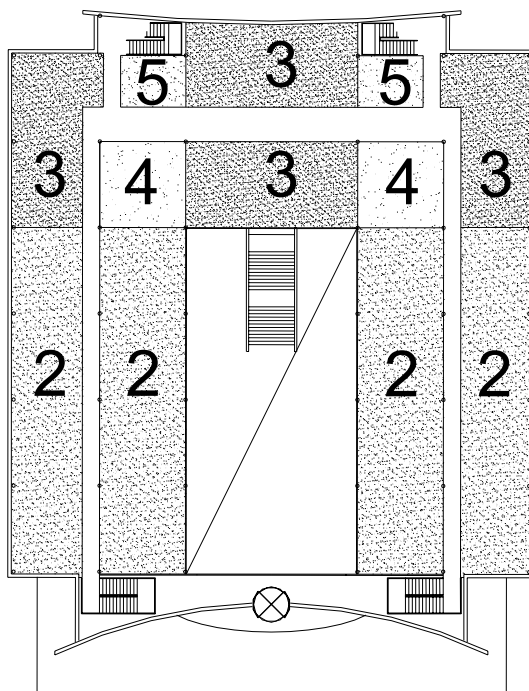
The building will have a framed structure for flexibility of use. Colour and nature of cladding materials will be partially dictated by the Planning Authorities at detailed Planning stage. Selection of materials will be aimed at minimising maintenance costs and promoting sustainability, whilst producing a “statement” building worthy of a world class facility.

PART C: BUILDING



- E Entrance
- 1 Atrium
- 2 Open plan office
- 3 Cellular offices
- 4 Services core
- 5 Meeting room
- 6 Coffee Lounge
- 7 Rest area
- 8 Meeting room
- 9 Link to synchrotron building

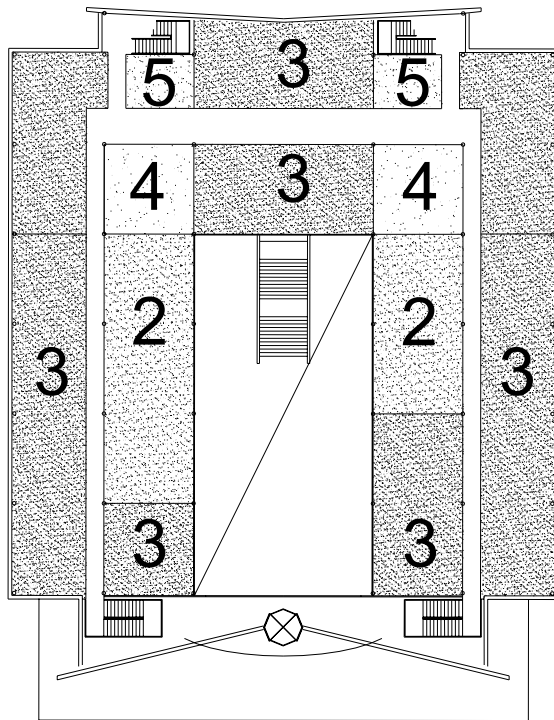
Ground Floor



- 2 Open plan office
- 3 Cellular offices
- 4 Services core
- 5 Meeting room

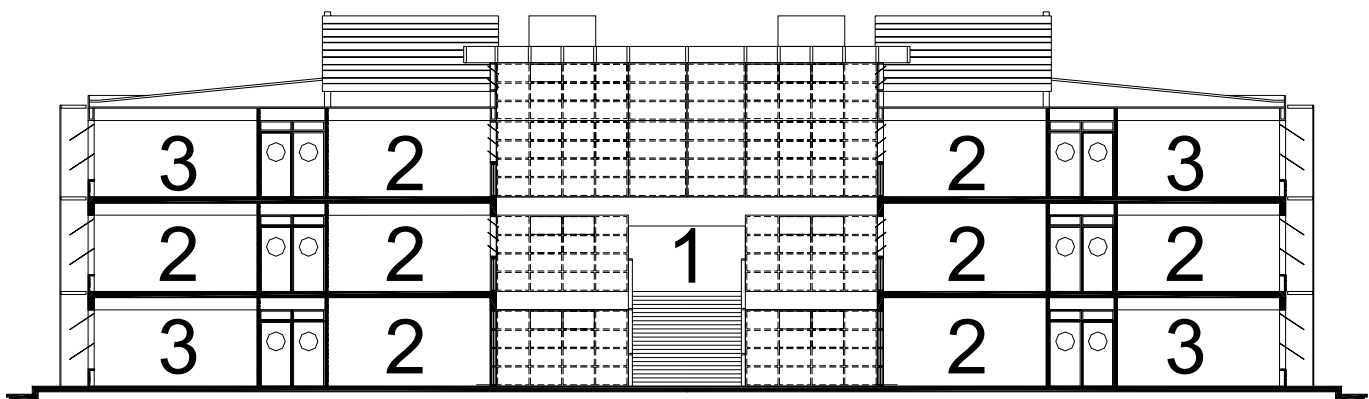
First Floor

C.3: OFFICE BLOCK



- 2 Open plan office
- 3 Cellular offices
- 4 Services core
- 5 Meeting room

Second Floor



Cross Section

- 1 Atrium
- 2 Open plan office
- 3 Cellular offices

PART C: BUILDING

3.3 ACCOMMODATION

The accommodation will be approximately as in table 3.3-1.

Diamond - Office Building Area Schedule*

Ground Floor

	Area in Sq. Mt.	
Atrium		
Reception / Waiting / Coffee Lounge	70	
General Area		
Computer room / Data storage	80	
Library	20	
Meeting room 1	60	
Meeting room 2	20	
Equipment room	15	
Kitchen	10	
First aid room	10	
CEO's Office		
Offices	27	
Science Division		
Cellular office	94	
Open plan office	340	
Laboratory	175	
Technical Division		
Cellular office	54	
Open plan office	180	
Laboratory	120	
Workshop	80	
Total	1355	1355

C.3: OFFICE BLOCK

First Floor**Technical Division**

Cellular office A	25
Open plan office A	50
Cellular office B	257
Open plan office B	500
Drawing office	100
Print room	60
Store rooms	60
Laboratory	130

General

Meeting room 1	40
Meeting room 2	20
Equipment room	15
Kitchen / Lounge	20

Total	1277	1277

Second Floor**CEO's Office**

Cellular office	70

Admin & Finance Division

Cellular	83
Open plan office	170
Meeting rooms	30
Store room	13

Science Division

Cellular office	725
Open plan office	128

General

Meeting room	30
Equipment room	15
Kitchen / Lounge	20

Total	1284	1284

Total for Building	3916

*Excludes area for Services and Circulation

Table 3.3-1 Breakdown of Office Building accommodation requirements by area.

PART C: BUILDING

3.4 SERVICES

Services that will be provided will include:

- Small power
- Lighting
- Air conditioning to laboratories and computer rooms
- Tannoy system
- Information monitors
- Telephone and data systems
- Fire alarm systems
- LPHW heating system
- Security systems
- Goods/Passenger lift

Except as stated above ventilation of the building will, where possible, be via natural means but solar shading will be provided to windows to reduce solar gain.

C.4 External works

4.1 DRAINAGE

There will be three drainage systems serving the buildings:

- Trade Waste
- Foul
- Storm water

Trade waste drainage will be directed to holding tanks adjacent to the Main Building. After testing the waste will flow into the foul system. Because the formation level of the Main Building is likely to be below current ground level, the foul drainage is likely to flow into holding tanks before pumping into the RAL foul drainage system. All pumped systems will have back-up pumps and alarms.

The storm water will be dealt with in a mixture of ways:

- Directly into the RAL system
- Soakaways
- Balancing ponds before pumping to the existing systems.

Oil interceptors will be provided on road drainage systems.

4.2 CAR PARKS AND ROADS

Approximately 150 car parking spaces will be provided for the first year of operation around the outside of the main building. These will be adjacent to the perimeter road which will be a distance of 20m from the building to allow for expansion. The perimeter road will be designed to domestic standards. The roads and car park will have suitable low pollution lighting to the approval of the Planning Authority. Some CCTV security measures will also be provided.

4.3 LANDSCAPING

The area around the buildings will be suitably landscaped to the approval of the Local Authority. This will include earth mounding to create visual screening as well as soft

PART C: BUILDING

and hard landscaping. Balancing ponds for drainage will be used to enhance the landscaping scheme.

Security fencing for the facility will be linked into the existing RAL boundary fence and will extend the laboratory boundary. The Diamond facility will therefore be an integral part of the RAL site.

D.1 Site Services

1.1 MAINS ELECTRICITY

Power for the facility will be provided via the RAL main substation which is fed from two 30MVA 132kV/11kV transformers. Two new feeds will be run from the RAL main sub-station to the Diamond site and it is planned that either feed will be capable of meeting Diamond's load.

1.1.1 Back up Power

Limited back-up power (generator and uninterruptible power supplies) will be provided for building services plant; see Section 2.2.2 for further details.

1.1.2 Harmonic Suppression

Harmonic suppression techniques will be employed with the view of satisfying Electricity Association Engineering Recommendations G5/4 February 2001.

The techniques to be considered embrace:

- Vectored 11kV/400v transformers
- Active filters
- Passive filters

1.1.3 Power Factor Correction

An assessment of the anticipated power factor for the facility will be undertaken and appropriate correction measures will be provided in accordance with Value Engineering considerations and RAL's present charging structure for electricity.

As a precautionary measure space, and if appropriate, switches will be provided so that further power factor correction equipment can be added if future tariff charges justify same.

1.1.4 Earthing

It is envisaged the 11kV/400v networks earthing systems will be interconnected to provide a "mesh network" and comply with BS 7430 and The Electrical Supply Regulations of 1988.

The following items will be bonded to the earthing network:

PART D: INFRASTRUCTURE

- Building structure
- Mechanical services entering/leaving the facility
- Lightning protection system
- All trays/trunking/ distribution boards/ cable armouring

1.2 MAINS GAS

Supplies for the facility's gas fired boiler will be taken from the main gas infrastructure supplying the RAL site etc. It has been established by consultation with the Gas Shipper to the site that there is adequate capacity on this system.

1.3 WATER

The water supply for the RAL site is provided by Thames Water. The supply for the Diamond facility will be taken from the RAL system. Whilst the capacity of the system is adequate the pressure is approximately 2.1 bar and additional local pumping may be required to boost the pressure .

1.4 DRAINAGE

The RAL site foul and storm water drainage systems are extensive and are considered to be adequate to accept the volumes expected to be produced by the facility. Exact connection details and capacity checks will be carried out during the detailed design phase.

D.2 Controls

2.1 INTRODUCTION

This section outlines the control system for the DIAMOND project. The choice of control system toolkit is presented and a description of the chosen solution. The requirements for the control system are considered in the generic sense, for overall functionality, the applications and the underlying hardware interfaces. For each of these, the design is not sufficiently well advanced to define detailed specifications but in each case general requirements and likely solutions are presented.

2.2 SCOPE OF DIAMOND CONTROL SYSTEM

The DIAMOND control system will be a site-wide monitoring and control system for the accelerators, beamlines and conventional facilities. The control system will extend from the interface of the equipment being controlled through to the operator. It will include all hardware and software between these bounds: computer systems, networking, hardware interfaces and programmable logic controllers.

The control system will not include any control or data acquisition for the experimental stations, which is addressed in Part B subsection 10.5. It further will not include the personnel protection system, which is a separate system that will be monitored by the control system and is addressed in Part D section 5

2.3 REQUIREMENTS

2.3.1 Control System User requirements

The control system must support several user groups, each with varying requirements.

(a) Operators

The accelerator operators are the principal users of the control system. The control system must be a complete and consistent interface to perform any function on the accelerator complex. All data and interfaces must be consistent in how data is presented and how equipment is seen to behave. The operation of the accelerators requires real-time control and monitoring of the equipment, archiving, alarm handling, sequencing, backup and restore for routine operation. Alarm and error messages should be supported by information regarding recommended courses of action. The Control System should allow the automation of onerous plant operating

PART D: INFRASTRUCTURE

tasks. The Control System should provide applications which encourage and facilitate the keeping and passing of operation logs, particularly from shift to shift.

(b) Accelerator Physicists

The accelerator physicists requirements of the control system include all the routine operations of the control system together with the ability to integrate programs developed to support particular experiments. Functionality is required to allow easy acquisition of data produced as part of an experiment, and to provide the ability to switch between the accelerator and an accelerator model. Data retrieved from the control system must be acquired with sufficient time accuracy to enable accurate correlation.

(c) Technical Groups

The technical groups require diagnostics to enable maintenance such as calibration and fault finding. Access to the control system is required in the Main Control Room, local to the equipment and potentially in the offices, laboratories and off-site. Applications must provide all diagnostic information necessary to assist in commissioning and debugging of equipment. They must provide useful fault diagnosis facilities to assist with plant equipment maintenance and maintenance of the Control System itself (both hardware and software). An easy interface to databases of equipment properties, manufacturers, documentation, cabling data and fault histories is required, as well as access to information clearly identifying the geographical location of equipment and a system of fault prediction facilities to allow for scheduled maintenance of components likely to fail.

(d) Experimenters

The end users of the experimental station require a straightforward graphical interface to the control system. They also require good integration of control system parameters with the experimental control and data acquisition systems. This is particularly necessary in the case of synchronising scanning of a sample with changing a parameter on an insertion device in the storage ring e.g. the gap of an undulator. Experimenters require clear information on light source status and performance, timing signals and may require remote (i.e. off-site) access to experiments and beamlines.

(e) Control System Engineers

Control system engineers require current and archived data on the status and behaviour of the entire control system. Information required includes CPU loading, network loading, application monitoring (for frozen/crashed applications), connectivity status and reports of any control system faults.

(f) Facility Managers

The Control System should be capable of producing operating reports and statistics in a form which can then be imported into software applications (i.e. spreadsheets, web-based tools etc.) used by management.

Information required could include number of hours of beamtime supplied to users and unplanned beam dump statistics – how often these events occur, time taken to restore beam, reason for beam dump, and signs of common modes of failure.

(g) Staff and Public

A wide range of other groups will require information from the control system. These include technical and scientific groups on- and off-site. These groups should be served through a web service as the user interface.

2.3.2 System requirements

(a) Architecture

The control system will adopt the standard two-layer client server architecture, to ensure scalability and avoid performance limitations. It should use a proven tool kit with well-defined interfaces at both the server and client to enable integration and development. It should enable the use of hardware and software already developed for specific light source requirements.

(b) Network

The connection of the control system layers should use standard network components. These should be in a redundant configuration and include provision for network evolution, i.e. the development to Gbit standards.

(c) Operator Interface

The operator interface will be either workstations or PCs running Unix or NT as these are the established standards. The control system should seamlessly integrate with office systems through a gateway process to maintain security.

(d) Equipment Interface

The equipment interface will provide the physical connection to the equipment being controlled through a variety of interfaces. The preferred standard will be VME because of physical and electrical performance. The PC architecture is particularly discouraged as the equipment interface; however, Compact PCI may be an acceptable alternative to VME.

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(e) Database

The control system must include a relational database as a central repository for all configuration information. This should include all static information about accelerator components such as coefficients to calculate field magnetic strength from current. Consideration should be given to extending the database to include all technical information to enable subsequent support and maintenance. At the application level, there should be a unified and seamless interface to both the static and dynamic data.

2.3.3 General requirements

(a) Performance

The update rate of channels should be at least 10Hz to enable analogue style control for all parameters. On display screens, an update of 1000 channels per second should be achieved. The update of channels should be on data change outside bounds to manage the use of network bandwidth. The loading of control panels or applications should take less than 1 second to impose no significant delay in carrying out a control operation.

(b) Reliability

The control system should be designed as a high reliability system to have greater than 99% availability for 24x7x52 operation enabling facility operation for in excess of 6000 hours per year. This requires a long MTBF and a MTTR. These call for systems to be modular in design and distributed. Single point failure systems with long time to repair such as servers and network infrastructure will be required to be in a redundant configuration.

(c) Scalability

The control system must be scaleable. As the control system expands with the build-up of the accelerators and during the life of the facility this must not impact on the performance.

(d) Openness

The control system should use open standards and an open architecture. The life expectancy of an accelerator complex means that the control system will have to evolve to incorporate upgrades and new technology. The control system must enable seamless integration of systems at both the server and client side through well-defined APIs.

(e) Security

The control system must incorporate security to manage the access requirements of the different classes of user. It must also include security and tools to manage security of the computers and networks systems used.

(f) Integrated

The applications that comprise the DIAMOND Control System should have a consistent “look and feel”. Related functions should be linked to reduce the number of mouse clicks a user has to perform. For example, trends should be accessed by clicking on a process value hotspot displayed on a plant synoptic value.

(g) Seamless

The source of the data should be hidden from the users. For example, it should be possible to display data from the Control System, from the associated Relational Database and from an Accelerator Model on one full-screen synoptic.

(h) Ease Of Use

All Control System facilities which need to be accessed directly should be accessible via menus, where the menu titles give a clear indication of the facility being called up. It should never be necessary for a user to have to remember the name of a program or of data files in order to use the system.

Comprehensive online help facilities should be designed into the system, and these should be context-sensitive so that the operator does not have to navigate through a large selection of Help information.

(i) Ergonomics and Consistency Of Operation

Conscientious attention to common-sense ergonomics during application development will clearly pay dividends for long-term ease of use and minimise familiarisation and training costs for new users.

Production of a concise Style Guide document at an early stage in the development cycle of the project will provide a good ethos for addressing these issues.

(j) Upgradability and Flexibility

Control System applications must be designed, where possible, to enable future upgrades to be incorporated economically.

Wherever possible, application programs should be provided with command-line options, so that the functionality on offer can be increased by simply running the program with a different set of command line options.

2.4 TOOL KIT

2.4.1 Choice of Tool kit

Four options for a control system tool kit were reviewed [1]; EPICS [2], TANGO [3], a commercial SCADA system [4] and a development on the existing SRS control system

PART D: INFRASTRUCTURE

[5]. The conclusion from this was that any of the options could be made to work, but with varying levels of functionality, support and cost. However, EPICS had advantages over the other options in three key areas; user base in the accelerator community, functionality for accelerator-related systems and support for the required hardware interfaces.

2.4.2 The EPICS Tool Kit

EPICS came out of a collaboration of control groups, across a number of research organisations, to produce a tool kit to build distributed control systems. The resultant tool kit is such that it reduces software development and maintenance cost by providing: configuration tools in place of programming, a large user base of proven software, a modular design that is expandable and well defined interfaces for extension at all levels.

World-wide, EPICS has a very large user base, on a variety of accelerators, detector systems, astronomical projects and industrial processes. In Europe it has recently been applied as the control system on both the BESSY II light source and the Swiss Light Source together with other smaller projects. In the USA, EPICS has been used on the APS light source, a number of small accelerator projects and is being applied to the Spallation Neutron Source.

The use of EPICS on a diverse range of projects means that there is a large base of drivers and hardware support already available. The existence of these makes interfacing of the underlying systems less dependent on software development.

The EPICS tool kit is supported through the collaboration with software distribution and documented through the web. There are EPICS training courses run each year by LANL, and two EPICS workshops rotating through America, Europe and Asia each year; a number of individuals and companies are also available to provide support and training. In the UK commercial support is available from at least two companies.

2.4.3 Structure of an EPICS Control System

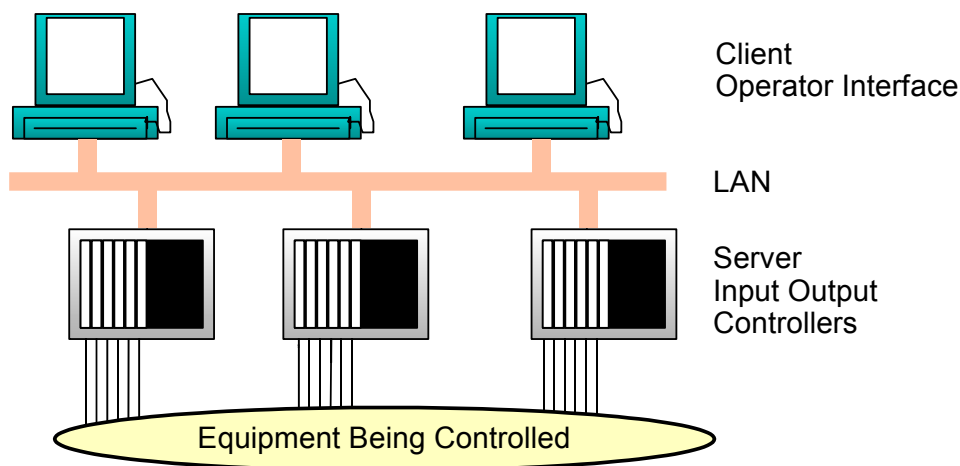


Figure 2.4-1 EPICS Model

EPICS embodies the standard client server model, Figure 2.4-1, for a distributed control system. The user consoles are one class of client that receives and processes information. The servers are the source of information and in the general case interface to the equipment being controlled. The clients and servers are physically connected using network technology and communicate with the EPICS protocol Channel Access.

2.4.4 EPICS Servers

The physical realisation of EPICS servers is typically as multiple embedded VME systems, which are called IOCs, Figure 2.4-2. These interface to the equipment being controlled, for which EPICS supports a large range of physical interface standards, protocols and devices. IOCs also support the use of an event timing signal, to time-stamp transactions and enable synchronous acquisition or control across multiple IOCs.

PART D: INFRASTRUCTURE

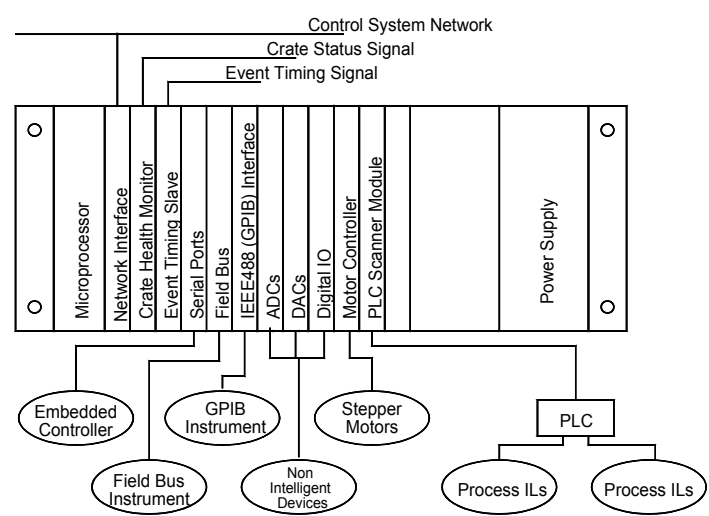


Figure 2.4-2 Example EPICS IOC

2.4.5 Server Side Processing

Within the IOC, the CA server communicates with the Process Database which uses the Record Support, Device Support and Driver Support layers to interface to the plant, fig 2.4-3. The communication from then EPICS client, over CA to the database, can be by synchronous call and reply or by the client establishing a monitor whereby the server asynchronously serves the data. The update of monitors can be on a periodic basis, on change of data or external event.

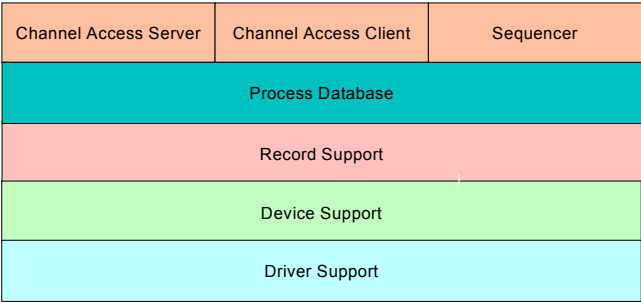


Figure 2.4-3 EPICS IOC data model

The process database is a memory resident database that defines the functionality of the IOC. The database uses the Record Support layer to perform the processing necessary to access IO, perform data conversion, alarm checking, and to update monitors. The IO operations are carried out through the Device Support layer, which handles equipment specific protocols and the Driver Support layer for the hardware interfaces. The structure provides support for interfacing to embedded controllers, field buses, IEEE488 (GPIB), DACs, ADCs, Digital IO, stepper motors, PLCs, power supplies and a range of instrumentation.

Within the IOC there is also a CA client to facilitate IOC-to-IOC communication. This is realised by linking process information from one process database to a process database on another IOC.

An IOC also contains a Sequencer to perform Finite State Machine control on the process database. The sequencer logic is defined as SNL, which is compiled to C code, then to an executable to run on the IOC. This allows for easy production on complex sequences, such as switching through the steps in bringing on a piece of equipment.

A standalone version of the CA server is available, which can be integrated into other systems without the process database and support layers. This facilitates integration of self-contained systems into EPICS, one example being the integration of LabView systems.

2.4.6 EPICS Clients

The client side of EPICS is realised on either Unix workstations or PCs running Windows and is called the OPI.

2.4.7 Client Structure

In the standard EPICS model the OPI application programs interfaced directly to the CA client. This has limitations in that it only provides access to the dynamic control data through the CA API and so limits seamless integration of data from other sources e.g. RDB. A solution to resolve this is presented in section 2.6.8 Application Programming Interface. The EPICS toolkit provides a suite of applications for the OPI. The core tools are: a synoptic user interface for control and monitoring (MEDM), an Alarm Handler, an Archiver for recording and retrieving the historical state of the control system, a backup and restore facility to take snap shots of parameter settings, a knob manager to provide attachment of physical knobs to parameters and a parameter plotting tool.

There is support within EPICS for the scripting languages Tcl/Tk, Perl and Python, Mathematica modelling package, Wingz spreadsheet, IDL graphical visualisation, LabView and Java. Data can be further served up on to web pages through a CGI server.

2.4.8 EPICS Tools

The functionality of a control system built with EPICS is defined in three places; the Operator Interface, the Process Database and the Sequencer logic. EPICS provides a number of tools to develop each of these which do not require software development. The Operator Interface applications can be produced by a number of interface-generating tools, one of which is MEDM. These tools allow for control objects to be placed on pages and animated with a connection to the control parameters. There are both text and graphical tools to produce the Process Database, which involves selecting records and drivers, and linking them to process data and alarms. The

PART D: INFRASTRUCTURE

Sequencer logic is produced from SNL, which can be defined as text or more recently in a graphical form.

2.5 DEVELOPMENT ENVIRONMENT AND TOOLS

2.5.1 Distributed development

Each developer will work on either on a local Solaris workstation or Linux PC. These will be networked to a development file server providing read-access to all the necessary development tools and applications (VxWorks, EPICS base and extensions, configuration, database files etc.) see Figure 2.5-1

Modifications will only be made to local copies of applications, which will then be checked in to a branch of the CVS repository to enable any changes to be backtracked. When the application has been fully tested and is stable, this branch will become the main development branch for the control system.

A central boot server will be used to provide all the necessary files required by the local IOCs for booting. These files will be generated from the CVS repository. This will ensure that all IOCs are running a consistent and stable version of the control system. The contents of the central boot server will be mirrored on boot servers located at each of the CIAs, which will provide local booting of the IOCs in that CIA

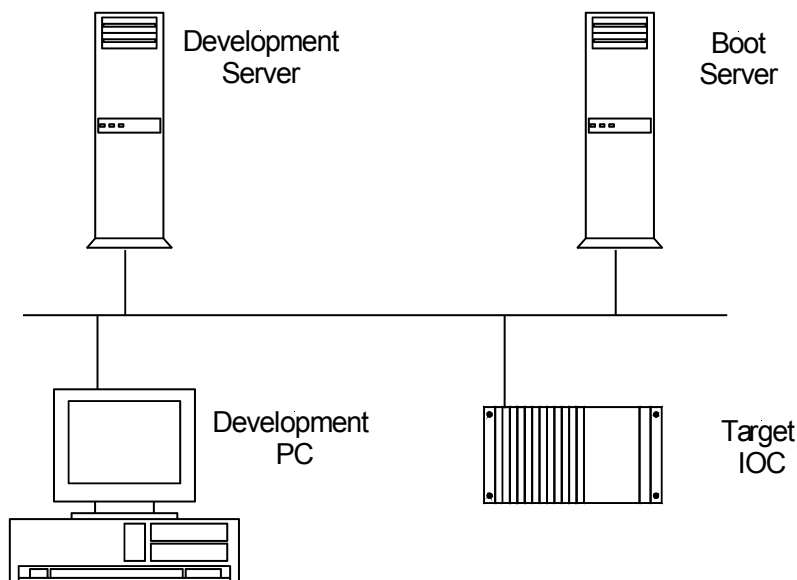


Figure 2.5-1 Distributed development structure

2.5.2 File Management with CVS

CVS [6] is a version control system for keeping track of all modifications to project source code files. CVS is widely used in both open source and proprietary software development projects, and is generally considered to be the best freely available, full-

D.2 CONTROLS

featured version control tool. Two features make CVS particularly suited to collaborative development across any network including the Internet:

- CVS allows multiple developers to edit their own working copies of files simultaneously, then deals with combining all the changes and notifying developers when there are conflicts.
- Remote access to source code file repositories. Developers who are project members can obtain and modify project files from virtually anywhere.

CVS is a client-server system. The CVS repository is maintained on a server; clients run on users' machines and connect to the server via the network (or Internet). Clients are available for nearly all platforms including, Unix, Windows, Macintosh, and any Java-based platform.

CVS allows project members to:

- Check out source files and directories
- View differences between versions of files
- View change log history and comments
- Commit changes made in their local copies of the source files to the main source code repository
- Update their local project files when they want to remain in sync with changes committed by other project members.

CVS has proven very beneficial to many other accelerator projects in the world, and there is a very large CVS knowledge base within the EPICS community .

2.5.3 Application Development

Most application requirements can be met through the standard tools as discussed in section 2.6. Where more intelligence is required at the application level there are EPICS interfaces to all the popular programming languages. The preferred solution will be to use C/C++, Java or scripting languages to minimise the number of supported languages.

(a) C/C++

C and C++ are high-level programming languages which have, for some time, been the de facto standard for portable open systems solutions on Unix/Linux platforms, with C++ usage increasing due to the popularity of Object-Oriented design and programming. Both languages have been widely used both for the EPICS baseline product and for driver software and other applications built on top of the baseline. For the DIAMOND Control System, the emphasis will be on re-use of existing software; it is not anticipated that the project will involve large-scale production of new C/C++ code.

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(b) Tcl/Tk

Tcl is a widely-used open source scripting language. It has a simple and programmable syntax and can be either used as a standalone application or embedded in application programs. Tk is a graphical user interface toolkit that can be used for rapid development of powerful GUIs. Tcl and Tk are highly portable, running on essentially all flavours of Unix, (Linux Solaris, IRIX, AIX, *BSD*, and so on) Windows, Macintosh, and more.

Tcl/Tk is well supported and extensively used on many EPICS-based projects, particularly for GUI development.

(c) Java

Java is an object-oriented interpretative programming language with a built-in API that can handle graphics and user interfaces. Java can be used to create standalone applications. However, a more important use is in the development of applets, programs which can be embedded in a Web page. The growth of the Internet, together with Java's hardware independence, has made the language essential for web-based developments.

Currently, Java performance issues mean its usage will only be considered for applications where response time is unimportant. Generally, though, Java solutions providers are seeking to improve performance with developments such as Just In Time compilers and Java processors. If these developments yield effective performance improvements during the development phase of the DIAMOND project, then the importance of Java on the project will increase.

2.5.4 Server Development

Development of EPICS at the server level is required potentially in three places, namely record and device support, database and state notation language.

(a) Record and Device support

While there is extensive record and device support available for EPICS, addition of unsupported hardware will necessitate the developed of Device and possibly Record support layers. The EPICS toolkit provides well-defined interfaces to each of these layers and examples to aid development. Device development is carried out in C within the standard EPICS development environment.

Building and developing EPICS requires the VxWorks [7] development environment. This is currently only available for Windows or Solaris. However, given that the development environment is based on the GNU tool chain it should be possible to run these tools on Linux, making this an alternative to Solaris. The preference will be to standardise on one operating system for development, possibly Linux.

(b) Database Configuration Tools

There are several DCT's available. These DCT's allow designers to create EPICS databases by implementing them visually with a 'block diagram and link wire' approach, similar to that used in electronic schematic design packages. Two of these are being evaluated for the DIAMOND Control System, CapFast [8] and VisualDCT [9].

The database development cycle will involve importing the EPICS runtime database into the central relational database (see section 2.10) to have a single repository of all control system information.

CapFast is probably the most frequently used EPICS database configuration tool currently in use. It was originally created for electronic circuit design and adapted to EPICS. The EPICS library contains all the standard records and these are represented as graphical symbols and connected via lines. The rest of the properties of each symbol (fields of the record) are edited in a properties window.

One of CapFast's strongest features is the ability to create database templates that can accept field substitutions when instantiated in a database design.

The schematics created with the EPICS library are translated from an intermediate file into the EPICS database format with a build script and schematic compiler tool. This build process is not reversible; i.e. you cannot convert a database file back into a schematic diagram. This has the limitation that any minor changes to the database have to be entered at the schematic level and then the database rebuilt. Any manual changes to the database file will not be reflected in the schematic diagram.

CapFast may be used to create EPICS databases initially, while the newer VisualDCT package is developed, but is unlikely to be used in the long term.

VisualDCT is an EPICS database configuration tool written in Java and can therefore run under any operating system that can support a Java Runtime Environment. It was developed to provide features missing in existing configuration tools and to make databases easier to understand and implement.

VisualDCT has a powerful DB parser, which allows existing DB and DBD files to be imported with ease. The parser detects syntax errors in databases, as well as defective visual composition data or its absence. Faults in DB files are safely handled and do not raise any critical errors. VisualDCT automatically lays out all objects that have no visual composition data and saves all visual data as comments to maintain backward compatibility. The output from VisualDCT is also a DB file, with all comments and record order preserved.

VisualDCT can be considered as a rapid database development tool - intuitive database construction can be done quickly and with little effort. Visualisation of the databases makes them easier to understand, as errors are much simpler to find (e.g.

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broken links are indicated by a red cross) and the hierarchical views simplify the design by splitting databases into logical blocks.

VisualDCT provides many now ‘standard’ features such as clipboard and undo support. Much effort has been given to synchronisation between the database and its visualisation. Every change done visually is immediately reflected in the database and vice versa; all actions, such as moving, renaming and deletion of records, which can affect database links are automatically fixed and updated by VisualDCT in real-time.

VisualDCT does have some deficiencies; some of the more advanced features that other DCT’s have, such as the ability to create database templates and perform field substitutions, are not present. However, VisualDCT is under development and its shortfalls are to be corrected very soon. With these shortfalls in mind, the ease of new database creation, existing database manipulation and cross platform support, Visual DCT is the preferred choice for EPICS database configuration tool.

Visual DCT has been written within the EPICS community specifically to support EPICS, and is available free to EPICS database developers. However, the developments of VisualDCT to add some of the missing functionality will have to be funded.

(c) State Notation Language / Sequencer Tools

The sequencer is a tool within EPICS that allows the implementation and control of (one or more) state machines on the IOC. The state machines are created using EPICS SNL. SNL has a C-like syntax that has constructs for building state machines. Once the SNL source code has been written, a SNC pre-processes it into ‘C’ code and then compiles it to create an object file which the sequencer can run in the IOC.

VisualSNL [10] is a graphical tool used to generate EPICS SNL code. VisualSNL enables non-programmers to build state machines and enables programmers to avoid having to learn yet another language, as well as providing better documentation.

The user creates, on screen, a state transition diagram, and can add, delete, move, and edit states as well as defining transitions between states. New features are being implemented, including the ability to read an existing SNL file.

VisualSNL is written in Java and can therefore run on any operating system that supports a Java Runtime Environment.

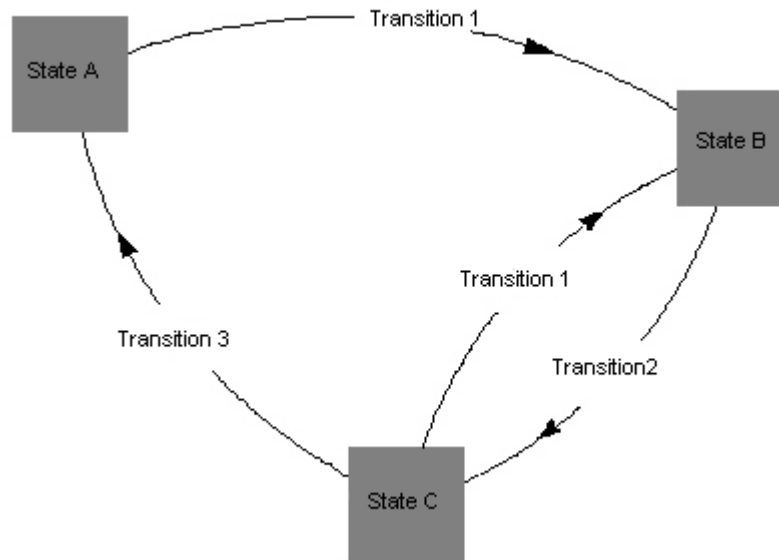


Figure 2.5-2 Example of a state machine in VisualSNL

2.6 USER INTERFACE

2.6.1 Operating Modes

During normal operations, the DIAMOND control system could be regarded as having one of three possible modes. A number of application requirements can be derived by considering these modes.

(a) Storage Ring Fill

The Control System usage reaches a peak during this state. All facilities of the system are in use. Therefore, this is where any performance implications will become critical. No individual application must make excessive demands on system or network resources.

The Control System must provide the operators with a means of consistently managing the fill process, and consistently diagnosing and handling any problems that prevent the storage ring from being filled. The SRS Sequence Manager application successfully achieves this and would provide a good basis for a similar application on the DIAMOND Control System.

(b) Steady State (including Top-up)

Routine adjustments and checks will be carried out. Some of these will be in response to requests from beamline users.

There is, in general, no need for rapid operator intervention.

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Monitoring of trends may highlight certain actions being required, for example in the vacuum system. In general, though, if an event occurs that will cause the beam to dump, the time between the event and the beam dump is so short (of the order of microseconds) that there is no chance of an operator taking remedial action to prevent the beam dump.

(c) Unplanned Beam Dump

The critical application requirement after an unplanned beam dump is to provide control room staff with sufficient diagnostic information to allow identification of remedial action as quickly as possible.

The diagnostic applications must be easy to navigate, and must retrieve the data quickly. The amount of pre-dump data and the frequency at which it has been collected and stored must be sufficient to ensure quick and correct diagnosis of the problem. As a further development, beam dump trip information could be saved for long-term archiving along with operator comments on how the problem was fixed. This information could be saved as one data “package” accessible online, so that control room staff could look for similarities with past beam dumps. This information could also be a useful tool enabling management to identify common failure modes during DIAMOND operations.

2.6.2 Console Applications

The EPICS software package offers comprehensive operator display applications including :

- Tcl/Tk toolkit interface
- Motif Editor and Display Manager (MEDM).
- Extensible Display Manager (EDM).
- Array Display Tool (ADT)
- Parameter Display Page (DP)
- Knob Manager (KM).

These applications will be used to supply operator display facilities which will include.

(a) Operator Menu Bar

This will provide rapid single-click access to all key operator facilities.

(b) Plant synoptics

These full-screen plant schematic diagrams will provide operators with an at-a-glance indication of plant conditions. Each process value displayed on a synoptic will constitute a “hotspot”; clicking on a hotspot will produce a pull-down menu providing access to further information and control actions relevant to that process value. Typically, a text description of the signal, the units of measurement, alarm limits, maximum and minimum, trend, alarm history, wiring information, operator comment and web access to online help might be provided). By this means, plant synoptics will act as the launch platforms which allow operators to access a wide variety of data in a seamless manner.

Ease of navigation will be considered during the detailed design stage for plant synoptics. An overall Synoptic Menu will be provided, which lists all synoptics grouped by functional area, presenting a clear hierarchy. In addition, where appropriate, plant synoptics will contain links to other associated synoptics. The design aim will be that operators should be able to navigate around the hierarchy without the constant need to return to the Synoptic Menu.

Plant synoptics will be designed to have a simple, uncluttered appearance so as not to present more information to the operator than can reasonably be taken in.

(c) Control panels

Usually sized smaller than full-screen, these will be available with a wide variety of control widgets (radio buttons, slider bars, data entry fields with data validity checking etc.) to allow users to apply control actions to the plant.

Control panels can be configured such that a single slider bar is used to control simultaneously a number of control outputs. Mathematical functions are available to define how these combined control outputs operate in relation to one other.

(d) User-configurable tabular displays

Operators will be able to configure their own sets of tabular displays showing closely-related accelerator parameters. Facilities will be provided to save these user-configured displays with a user-chosen name, and to recall the display from a list presented in a pull-down menu.

(e) System Status schematics

These schematics will show the status of IOC's, operator monitors, printers etc. They will also display the health of key applications – so that, for example, operators are made aware quickly if alarm processing stops due to an alarm server program crash.

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(f) Operator Comments facility

This will allow operators to enter lines of text comment for any plant input – to record, for example, when an input is not reading correctly due to a known fault. The presence of an operator comment for a process variable will be clearly indicated on any synoptic which displays that process variable. Individual comments will be easily readable via a suitable control panel, and it will also be possible to collate lists of comments (e.g. all operator comments entered during a shift).

(g) Signal Information Panel

Only a subset of the process variables will be displayed on plant synoptics. However, operators require rapid access to information about any process variable and the Signal Information Panel satisfies this requirement. The panel will provide a Search section and a Display section. The Search section will enable the user to carry out a name search on the relational database, using a name mask to search for either a EPICS database record name or an EPICS record descriptor. Clicking on one of the returned search results will enable the user to request further information (e.g. trend, alarm history, operator comment etc.).

(h) Message Logging

The CMLOG package available with EPICS will be used to provide a distributed message logging system. This package can be used by any application or system that needs to log messages to centralised log files and display distributed messages to users. The CMLOG package supports C++, C and CDEV application interfaces for logging messages and has C++ application interfaces for searching/retrieving messages from a dedicated logging server. Applications may send a selection rule to the server to select a subset of log messages for viewing – these rules can be in a form similar to C logic syntax or in a form similar to SQL.

A sample Message Log Browser (an X-Windows Motif application) is included with the CMLOG package. An additional browser will be developed using the supplied application interfaces once detailed requirements are established during the detailed design phase of the project.

2.6.3 Alarm Handling

The EPICS Alarm Handler package will be used to provide the following facilities:

(a) Alarm List

An Alarm List allows the users to view and manipulate current plant alarms. The Alarm List will incorporate the following facilities :

- Indication of alarm acknowledgement state.

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- Alarm message which includes EPICS record name, descriptive text, alarm value and date/time of alarm generation.
- Removal of acknowledged alarms from the Alarm List when they are no longer in the alarm state.
- Access to a menu-based set of facilities from each alarm in the Alarm list. The menu would give access to further information about the alarmed signal, including :
 - Trend
 - Alarm History
 - Access to a synoptic which includes the alarmed signal.
 - Web access – e.g. a link to a text page with more details about the alarm condition and possible corrective action
- Operator-selectable alarm inhibition to prevent use of the Alarm List from being disrupted by non-genuine alarms (e.g. “flickering” alarms being generated by a faulty switch). The names and descriptions of inhibited signals will be viewable on a separate list, from where it will be possible to de-inhibit each signal.
- Association of each alarm with a plant area, along with the ability to display only alarms for a particular plant area.
- Colour indication of alarm severity.

(b) Alarm Logging

All alarm messages will be logged to text file for interrogation and archiving purposes. An Alarm Log Viewer will be available, with various filtering options such as date/time, alarm severity, input name etc.

(c) Audible/visible alarms

Provision will be made for audible alarm tones, driven from software using wav files. A separate alarm tone will be available for each alarm severity.

(d) Alarm Banner

An alarm banner window will be available to display the latest n (where n is configurable) alarms in a dedicated window at the top or bottom of the screen. Alarms can be acknowledged via the banner without having to call up the main Alarm List.

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2.6.4 Archiving

The EPICS software toolkit offers comprehensive short, medium and long-term data collection, archiving and retrieval through the EPICS Channel Archiver package. This package will be used to provide the following facilities.

(a) Long-term archiving

The archiver provides support for:

- Data retrievable in tabular and trend form.
- A data quality indicator associated with each item of data.
- Data compression to minimise the size of archive files.
- Dumping of data to removable storage media, for long-term storage.
- Loading of archive data from removable storage media for data analysis.
- Timely warning to operators when archive data collection is compromised by a “disk full” condition on the archive server.
- Variable data collection intervals for archiving.
- A mechanism for easily configuring large numbers of process variables for archiving (e.g. by use of name masks).
- Facilities for collecting data in user-definable data sets, where data sets can include files as well as process variable data.

(b) Historical Data Collection

This provides for short to medium-term data collection offering the following features :

- Data retrievable in tabular form and trend form.
- Data quality indicator associated with all data.
- Variable data collection intervals.
- Mathematical functions (e.g. averaging, MIN-MAX etc) applicable to historical data.

(c) Data Retrieval and Data Management Tools.

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A wide variety of data retrieval and data management tools are available as standard with the Channel Archiver package, including :

- Retrieval via scripting tools, provided by the Channel Archiver Scripting Interface. TCL, Python or Perl can be used to develop automation of archive handling.
- Retrieval via native tools, with Xarr/Striptool for UNIX-based systems and WinBrowser for Win32 systems. WinBrowser also provides data export in spreadsheet format or in a format suitable for the Matlab data analysis and modelling package.
- Retrieval via a web server plugin, offered by the CGIExport client, which allows users to browse the archive via any web browser. File download in spreadsheet or Matlab format is supported by this plugin.
- Command-line tools provided by the ArchiveExport/ArchiveManager component, providing commands to manage archives and to export data to a spreadsheet, to Matlab or to the GnuPlot plotting utility program.
- The Archive Engine component of the Channel Archiver package includes a built-in Web server. By using this feature, current operational parameters can be viewed and interactive configuration can be carried out via any Web browser.

2.6.5 Sequence Manager

A sequence manager tool will be needed to automate many of the routine, high-level tasks encountered when operating a light source. These tasks include refilling the storage ring, switching the injector system on and off, opening and closing valves on beamlines etc.

The sequence manager tool should include the following functionality:

- Simple graphical user interface
- Ability to select and execute a pre-defined sequence
- Each stage of the sequence should only be available for execution if all previous stages in the execution flow have been successfully completed.
- Comprehensive reporting of any errors or anomalies that occurred during each step of the sequence.

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- Each stage in the sequence should contain a clear description of its purpose and operation that can be displayed to the operator.
- The operator must be able to make decisions at key points within the sequence to alter the execution flow.
- The sequences will be written in a simple, interpreted language or script (for example Tcl) so that operators, accelerator physicists and technical specialists can write and maintain the sequences.

At present, such an application does not appear to be available within the EPICS community.

2.6.6 Plotting

The StripTool program will be used for displaying trends of current and archived data. The key features of the StripTool program are :

- A StripTool chart displaying recent live data can be scrolled back to view archive data.
- Data acquisition via both Channel Access and CDEV, thereby allowing trending of both EPICS and non-EPICS data on the same axes.
- Ability to drag signals from synoptic diagram (drawn using MEDM) into a graph window.
- Flexible configuration options, including logarithmic and linear transformations, sampling rate, graph refresh rate, plot colours, grid lines, graph legend colouring, and plot line width. The trend can also be easily reconfigured to make one or more plot curves invisible without removing the plot configuration information for that curve.
- Trends can be printed and trend data saved to file.
- Trends are customisable via X resources, giving access to a wider set of configuration options than those offered by the standard StripTool configuration facilities.

2.6.7 Physics Model

A physics modelling system will be needed to provide an interface between the control system and standard codes such as MAD or RING. These codes can mathematically model the behaviour of various accelerator systems. They can be used

to aid understanding of the machine, as well as being a vital tool for optimising and operating a complex accelerator.

The system should be capable of operating in online and predictive modes.

(a) Online mode

Real-time magnet and RF data will be passed to the modelling system. Computed values of Twiss parameters, Q values, chromaticity, momentum compaction factor etc. will be made available to the rest of the control system or to specialised Accelerator Physics applications.

(b) Predictive mode

In this mode offline magnet and RF values are supplied to the modelling system rather than real-time data. This will allow predictive and “look-and-see” experiments to be performed using the machine model to predict the behaviour of the accelerator.

The interface between machine model and the rest of the control system can be achieved by implementing a CDEV service to translate CDEV requests into native machine model commands. This approach allows for easy integration with standard application such as MEDM, ALH etc.

2.6.8 Application Programming Interface

(a) Common Device interface

The CDEV application development framework [11] will be used to provide a single, consistent API to Channel Access, to the Physics Model and to Relational Databases through an ODBC or JDBC layer. This approach greatly simplifies application level programming as it allows database entries to be accessed in exactly the same way as standard channel access devices.

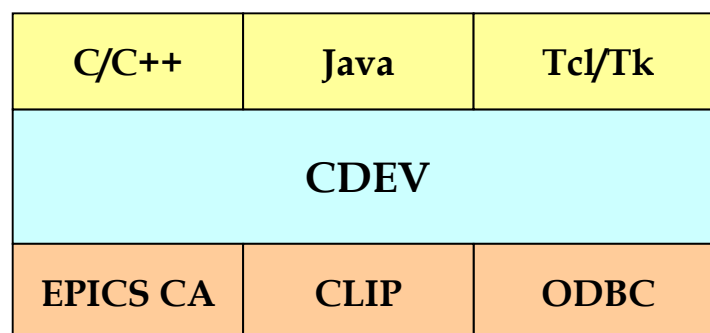


Figure 2.6-1 Application interface

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CDEV is implemented both as a set of C++ classes as well as Java classes. There is also an interface to the Tcl/Tk scripting language.

The standard CDEV distribution includes service layers to implement EPICS CA and CLIP [12]. CLIP provides a generic interface to other CDEV applications. It can be used to communicate between CDEV clients and a CDEV gateway [13] system that fully implements all the required services. This approach allows full multi-language support without having to write every service in both C++ and Java.

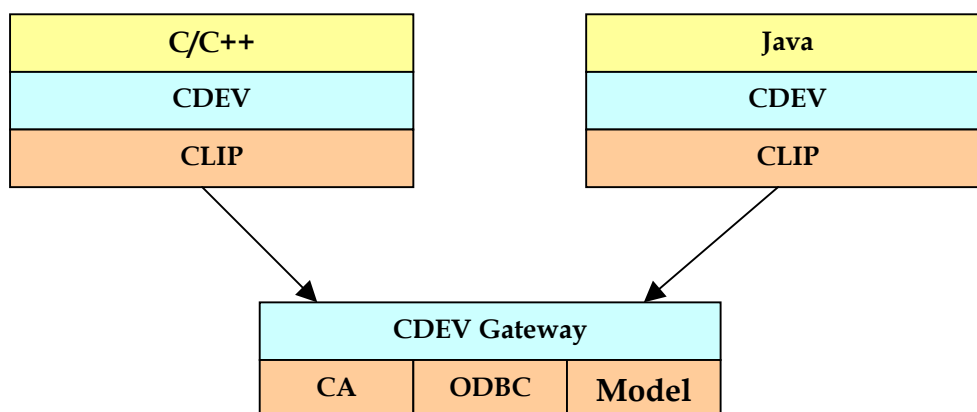


Figure 2.6-2 Application interface using CLIP

CDEV has an object-oriented view of devices. It allows a hierarchy to be created with inheritance of properties. CDEV device names are defined in an ASCII text file containing DDL.

(b) Self Describing Data Sets

SDDS [14] is a way of storing and working with data that was developed at the APS for use in the simulation and operation of accelerators. The basic approach behind SDDS is: define a standard file protocol and then design all programs to work with such files. Since SDDS is very generic in nature, it can be used for processing and displaying data from essentially any source. Parts of SDDS are linked to EPICS.

SDDS is already in use at a number of EPICS sites. In conjunction with the Tcl/Tk scripting language, it has been used to develop GUIs for configuration of the accelerators; data collection, analysis and display; experiment execution; and feedback processes, amongst others. SDDS has also been used for pre- and post-processing of data for accelerator simulations.

(c) Experiment and Data Acquisition Interface

Experiment and data acquisition systems will require a clearly-defined interface to EPICS; for wavelength selection from insertion devices, for example. Such interfaces will be achieved using middleware appropriate for distributed heterogeneous systems, (CORBA being an example); interface specification will be determined during the detail design stage of the project.

(d) External Access

General utilities and EPICS components which will be used to provide external access to Control System data include the following :

- HummingBird Exceed will be used to provide trusted users (e.g. Control System support engineers) with an X-Windows interface for off-site access to the Control System.
- SDDS, in conjunction with Tcl/Tk, will be used to develop graphical user interfaces and for pre- and post-processing of data for accelerator simulations. Security issues can be addressed by making SDDS-compliant data files available for external access via anonymous ftp.
- ActiveXCA provides an ActiveX control interface, allowing any application which is an ActiveX container access to EPICS data. Examples of ActiveX containers include Excel spreadsheets, Internet Explorer and Delphi.
- The CGIExport plugin for web servers will be used to provide web access to EPICS ChannelArchiver data. CGIExport allows the user to browse archived channel names, view online plots. Additionally, there are valuable download features; selected data can be downloaded in spreadsheet format or in a format suitable for Matlab.

Currently, the performance offered by Java is not sufficient to allow generic Control System operator/user interface facilities to be provided for users both inside and outside the Control System LAN. However, improvements in Java performance (such as developments in Just In Time compilers) during the development cycle of the project may make this a viable proposition.

2.7 INTERFACE LAYER

2.7.1 Control System Interface

All the interfaces to the control system will be through the IOCs. Most connections will be directly to an IOC, but signals, which provide interlocking functionality, will be connected to a PLC sub-system. The PLC will manage the protection and the state of the signals will be read from the PLC over a field bus.

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2.7.2 Choice of interface hardware

Several possible hardware standards could be used at the interface level for the IOCs, including VME, Compact PCI and industrial PCs. All of these are compatible with EPICS and supported by the VxWorks [15] operating system. Of these standards only VME is likely to be maintainable throughout the life cycle of the DIAMOND project. VME provides the greatest flexibility in term of available interfaces and mechanical forms. It is clear that VME would have to be used in some of the interface requirement, possibly on the beam position feedback system. For these reasons the interface layer has been standardised on VME and in particular the VME64x variant.

2.7.3 Choice of Processor Board

The processor used in the IOCs will be a Power PC VME board chosen from the then-current range of the market-leading manufacturer in the area. Reliability of the processor board, robustness of the board support pack and life cycle are crucial to initial availability of the DIAMOND control system and long term reliability.

Initial work has used a PPC processor board based on the MPC604 processor, which is current today. According to the road map provided by Motorola this will not be current in 2006, but processor boards now being introduced based on the MPC7400 processor will be and these are the likely choice for the DIAMOND control system

2.7.4 IOCs Physical

Each IOC will consist of a VME64x crate containing a number of various IO boards depending on the equipment being interfaced. The VME64x extensions provide a number of advantages over VME32, including improved electrical interface, geographical addressing and hot-swap capability. Extra connectors provide a large number of spare pins, so IO signals will be brought through the P0 and P2 connectors on the VME64x backplane.

In a typical IOC the processor board will reside in the first slot. This will act as the VME bus controller and host the EPICS server software. It will have a connection to the controls network and a serial port for the system console.

An event receiver module will occupy the third slot. This enables the IOC to use an event timing signal, to time stamp transactions and to synchronise acquisition or control with other IOCs.

The second slot of the IOC should remain unoccupied so that a VME bus analyser can be plugged in for debugging or performance analysis. The remaining slots will be available for IO boards, which will depend on the equipment being interfaced to a particular IOC.

2.7.5 Choice of IO interface

Many of the IO signals will be handled by IP cards. These will reside on VME64x IP carrier boards, which can accommodate up to 4 IP cards and occupy 1 VME slot. The I/O will be performed using a variety of IP modules. The cabling to the carrier boards will be via a transition module in the back of the VME64x crate. The transition modules will connect to DIN rail mounted interfaces in the racks, where the plant wiring will be terminated. This is shown in Figure 2.7-1.

A number of accelerator and HEP experiments make extensive use of IP modules. This has led to there being very good device support from EPICS. Because the IP is an open standard, there are many companies [16][17][18] with specialist knowledge in these areas, providing IP modules for just about any I/O interface.

Due to the size of the IP modules signal conditioning and isolation will be provided

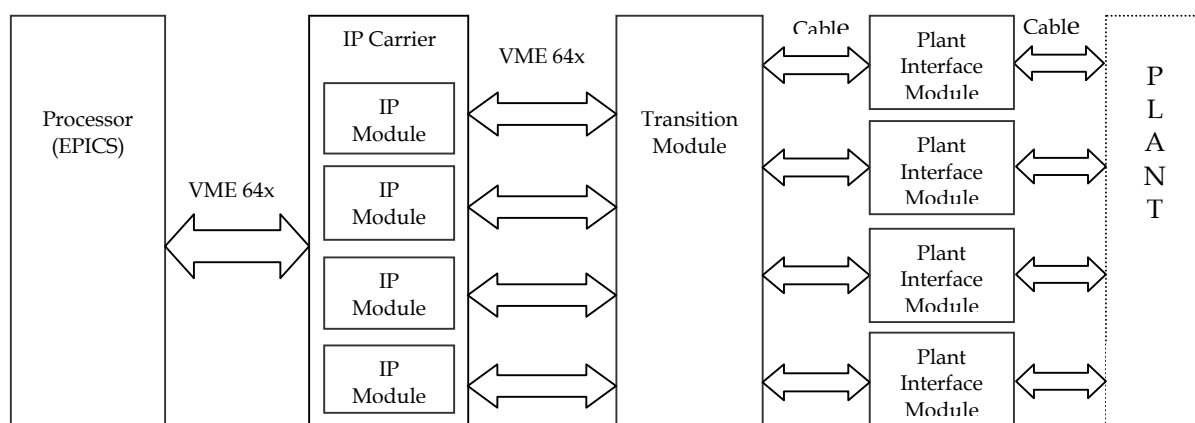


Figure 2.7-1 Block Diagram of IO using IP Modules

on the transition modules. This maintains the modularity of the IP carrier and modules, reducing system cost and component count. However, as isolation and conditioning are specific to I/O types, the IP modules and transition modules must be carefully matched, restricting system modularity. This ensures that for a signal fault the IP Carrier and modules are protected, though the fault is dealt with inside the IOC hardware.

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The I/O requirements for DIAMOND will be met as follows:

(a) Analogue

DAC and ADC IP modules are available from many manufacturers, covering all conversion rates and bit counts that will be required. There are also several manufacturers that supply DACs and ADCs with past conversion memories, of varying sizes, which would allow for the retrieval of post mortem data.

(b) Digital

Digital I/O IP modules are available from many manufacturers, both as exclusively input modules, exclusively output modules and as mixed I/O. There are options for various input and output voltage levels, including various logic levels and relay driven.

(c) Serial

Serial IP modules are available from many manufacturers covering a variety of standards, such as RS232, RS422, RS485, etc.

(d) Field Bus

The DIAMOND control system has the potential requirement to support several field bus protocols. There are IP modules available to support most field buses including Profibus, CAN bus and GPIB. The newer field buses operate over networking protocols so require a network connection. Some Power PC processor boards have a secondary network connection that would enable the network field bus to be physically separate from the controls network.

(e) Motion Control

There are several systems that require the use of motors (usually stepper motors). Several IP module manufacturers make IP modules that specialise in motion and motor control. Some stepper motor manufacturers also supply their motors with serial interfaces. Direct VME64x motion controllers are also available.

(f) Specialist

There are parts of the DIAMOND control system, which will require specialist I/O interfaces, such as potentially magnet power supplies. Some of these interfaces are available in a VME standard, which allows them to be controlled directly from the IOC. However, there are also specialist IP modules available with a multitude of functionality, including from DSPs and FPGAs that will allow the creation of specialist interfaces.

2.7.6 Hot-Swap

The use of VME64x enables Hot-swap functionality which is the ability to unplug a board from a correctly configured and running IOC, replace a defective component, say an IP card, on the board and replace it into the running system. The system will recognise that the board has been removed and replaced and resume normal operation.

Hot-swap capability facilitates increasing overall system uptime, thereby maintaining a high overall MTBF, especially in large installations.

(a) Hot-swap Physical

Electrical protection is taken care of by the VME64x standard. This ensures that boards can be safely removed and inserted into VME crates while the power remains on. Both the crate and the board must comply with the standard. The use of VME64x compliant IP carrier boards will mean that any IP cards can be hot-swapped.

All I/O should be brought through the VME backplane rather than the front panels, to permit access to the boards, and simplify their removal and replacement.

(b) Hot-swap Software

The software must be able to respond robustly to the removal of one or more VME boards and their replacement with functionally equivalent hardware in the same slots. Device drivers will:

- Detect the removal of a card, either by polling or handling an interrupt,
- Trap bus errors caused by attempting to access missing hardware,
- Detect the reinsertion of the board and perform any necessary re-initialisation.

The software will not be required to handle situations where new VME cards are introduced, or cards are moved from one slot to another. In these cases the system will need to be reconfigured, which typically requires at least a re-boot of the IOC.

2.7.7 PLCs

PLCs will be used to perform subsystems control requiring complex logic, such as interlocking and vacuum valve control. Removing the protection logic from the IOC simplifies the design by removing the need for watchdog timers to protect against software failure. It further provides operational flexibility by allowing the plant to remain functional while the IOC is rebooted. This works by holding analogue and digital outputs at their present state and monitoring for fault conditions during reboot.

Communications between the IOC and PLC will be via a field bus. The choice of PLC and field bus will be settled during the detail design phase. PLCs are widely used in

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other accelerator facilities and there is a large EPICS support for many different field buses and PLC makes.

2.7.8 Interface Requirements of Underlying System

Following from initial discussions with the technical group an assessment has been made of the equipment interfaces required. From experience on the SRS and other light sources, the likely interfaces have been considered for each piece of equipment. The numbers and types of interfaces must be considered a baseline guide as inevitably, as designs for the underlying systems evolve, further equipment that requires controlling or monitoring will be identified and the requirement will tend to grow.

Table 2.7-1 shows the control system interface requirement broken down into each of the underlying subsystems and its likely interface. The table columns are as follows:

- System : The DIAMOND subsystem
- No. Sys: the number of subsystems needed to support DIAMOND
- Equipment: The equipment required to support the subsystem
- Per Sys: The numbers of equipment in the subsystem
- Add: The number of addition I/O required by the subsystem
- Total: The total amount of I/O lines needed for the subsystem
- IF Type: I/O the interface types required for the equipment in the subsystem

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Table 2.7-1 Interface number and types for the technical systems

System	No. Sys	Equipment	Per Sys	Add	Total	Possible IF
SR Arc Vacuum	24	Ion Pump	14		336	S
	24	TSP Pump	2		48	S or D
	24	Neg Pump	4		96	S or D
	24	Pirg	4		96	S
	24	IMG	4		96	
	24	Valve	2	1	49	D via PLC
SR Straight Vacuum	24	Ion Pump	2	1	49	S
	24	TSP or Neg Pump	2	1	49	S or D
	24	Pirg	1	3	27	S
	24	IMG	1	3	27	S
SR Roughing Vacuum	24	Turbo Pump	3		72	D Via PLC
	24	Pirg	2		48	S
	24	IMG	2		48	S
	24	Valve	4		96	D via PLC
SR Magnet	1	Dipole	1		1	A,S
	24	Global IL	1		24	BP
	24	Quad	10		240	A,S
	24	Sext	7		168	A,S
	24	Multipoles on Sext	35		840	A,D
	24	Fast Correction	8		192	A,D
	24	Water Flow Meters	5		120	A
SR Vessel Protection	24	Vessel Protection Module	1		24	BP
	24	Global Il Module	1		24	BP
	24	Beam Loss Monitor	20		480	C
	24	Water Flows	5		120	A
	24	Temp Transducers	24		576	A
Insertion Devices PM	7	Motor Drive	1		7	S
	7	Trim PSU	1		7	A,D
Insertion Devices SC	1	Main PSU	1		1	S
	1	Trim PSU	1		1	S
	1	Quench protection	1		1	A,D
	1	Cryogenic Plant	1		1	SI
Front End Vacuum	24	Ion Pump	4		96	S
	24	TSP or Neg Pump	4		96	S or D
	24	Pirg	4		96	S
	24	IMG	4		96	A,S
	24	Valve	3		72	D
	24	Water Flows	5		120	A
	24	Radiation Shutter	2		48	D via PLC
SR Diagnostics	24	EBPM I Tech	2		48	BP

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System	No. Sys	Equipment	Per Sys	Add	Total	Possible IF
	24	EBPM Bego Arc	5		120	A,D
	8	EBPM Bego Straight	2		16	A,D
	24	Photon BPM	2		48	A,S
	2	Total Current Monitor	1		2	A
	1	Screen and Camera	1		1	S,V
	1	Tune Measurement	1		1	G
	1	Charge per bunch	1		1	BP
	1	Streak Camera	1		1	SI
	2	Jaws	1		2	S
SR RF	3	Amplifiers Fundamental	1		3	A,D,S
	3	Cavities Fundamental	1		3	A,D,S
	1	Low Level RF	1		1	BP
	1	DC Supply	3		3	A,D,S
	1	Cryogenic Plant	1		1	SI or O
	1	Harmonic Cavities	1		1	A,D,S
SR Personnel Safety	1	Safety System Interface	4		4	BP
SR Radiation Monitors	1	Monitors	48		48	A,S
SR Traverse Feedback	1	Pick up	1		1	A
	1	Signal processing	1		1	BP
	1	Amplifier	1		1	A,D
	1	Kicker	1		1	A,D
Linac Diagnostics	1	FCM	1		1	A,D
	1	BPM	1		1	A,D
	1	Fast Charge Monitor	1		1	A,D
Linac Vacuum	1	Ion Pump	3		3	S
	1	Pirg	2		2	S
	1	IMG	2		2	A,S
	1	Valve	2		2	D
	1	Radiation Shutter	1		1	D
Linac RF	1	PSU	1		1	A,D,S
	1	RF Amplifier	1		1	A,D,S
Linac and Flight Path Personnel Safety	1	Safety System Interface	1		1	BP
Linac Radiation Monitors	1	Monitors	5		5	A,S
Flight Path Diag	1	Screen and Camera	2		2	S,V
	1	Faraday Cup	2		2	A
	1	FCM	1			
	1	Electron BPM	1		1	A,D or BP
	1	Emittance Measurement	1		1	SI

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System	No. Sys	Equipment	Per Sys	Add	Total	Possible IF
Flight Path Vacuum	1	Ion Pump	6		6	S
	1	Pirg	1		1	S
	1	IMG	2		2	A,S
	1	Valve	1		1	D
	1	Radiation Shutter	1		1	D
Flight Path Magnet	1	Dipole	2		2	A,S
	1	Quad	4		4	A,S
	1	Corrector	8		8	A,D
Transfer Path Diagnostic	1	Screen and Camera	2		2	S,V
	1	Faraday Cup	2		2	A
	1	Electron BPMS	1		1	A,D or BP
	1	PCM	1			A,D
	1	Emittance Measurement	1		1	SI
Transfer Path Vacuum	1	Ion Pump	6		6	S
	1	Pirg	1		1	S
	1	IMG	2		2	A,S
	1	Valve	1		1	D
Transfer Path Magnets	1	Dipole	6		6	A,S
	1	Quad	21		21	A,S
	1	Corrector	8		8	A,D
Booster Vacuum	1	Ion Pump	55		55	S
	1	Pirg	8		8	S
	1	IMG	8		8	A,S
	1	Valve	5		5	D
Booster Magnet	1	Dipole	1		1	A,S
	1	Quad	2		2	A,S
	1	Sext	1		1	S
	1	Steering	32		32	A,D
Booster RF	1	Cavity	1		1	A,D,S
	1	Amplifier	1		1	A,D,S
	1	DC Supply	1		1	A,D,S
Booster Diagnostics	1	Electron BPM	24		24	A,D or BP
	1	Fast TCM	1		1	A
	1	Screen and Camera	1		1	S,V
	1	Tune Measurement	1		1	G
	1	Jaws	1		1	S
Booster and Transfer Path Personnel Safety	1	Safety System Interface	1		1	BP
Booster Radiation Monitors	1	Monitors	5		5	A,S

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System	No. Sys	Equipment	Per Sys	Add	Total	Possible IF
Timing	1	Master Timing Generation	1		1	BP
	1	Timing Distribution and Delay	20		20	BP
	1	Event generation	1		1	BP
Injection extraction and Kickers	1	Booster Injection PSU	1		1	A,D
	1	Booster Extraction PSU	1		1	A,D
	1	Booster Kicker	4		4	A,D
	1	SR Injection PSU	1		1	A,D
	1	SR Kicker PSU	4		4	A,D
Conventional Services	1	Air Con Building	1		1	SI or O
	1	Service Water Temp	1		1	SI or O
	1	Mains Monitoring	1		1	SI or O
Wide Band Multiplexer	1	Input Channel Selector	18		18	D
	1	Output Selector	2		2	D
Analogue Multiplexer	1	Channel Selector	38		38	D
Status Monitor	1	Generation	1		1	SI
Beamline Vacuum	7	Pirg	8		56	S
	7	IMG	8		56	S
	7	Ion Pump	8		56	A,S
	7	Valve	8		56	D
	7	Radiation Shutter	1		7	D
Beamline Motion	7	Motor Drives	20		140	S
Beamline COSH	7	COSHH Systems	1		7	S
Beamline Personnel Safety	7	Safety System Interface	1		7	BP

Table 2.7-2 Key to interface types in Table 2.7-1.

IF Code	Interface Type
A	Analogue
D	Digital
BP	Back plane
V	Video
G	GPIB
S	Serial, RS232, RS422, RS485 or Field Bus
SI	System integration, e.g. Labview
O	Sub System Protocol, e.g. OPC
SC	Scaler, counter timer

From Table 2.7-1 a summary of the required numbers of interface can be produced and these are shown in

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Table 2.7-3 and shows a total of 5633 interfaces. These are then mapped on to IOCs as shown in Table 2.7-4. This gives a total requirement for 212 IOCs to support the accelerator and the first 7 beamlines.

Table 2.7-3 Summary of Interface requirements

Equipment	Linac	Transfer Paths	Booster	Storage Ring	Beam Lines (7)	Total
Main Magnets	6	27	4	553		590
Steering Magnets	8	8	32	1032		1080
RF	2		3	16		21
Vacuum	21	10	76	1761	231	2099
Diagnostics	9	7	28	240		284
Pulsed PSUs			6	5		11
Personnel Safety	1		1	4	7	13
Vessel Protection				744		744
Beam Loss Monitoring				480		480
Radiation Monitoring	5		5	48		58
Ids or Motors				18	140	158
Miscellaneous				88	7	95
Totals	52	52	155	4989	385	5633

Table 2.7-4 Mapping of interface requirements on to IOCs

IOCs	Linac	Transfer Paths	Booster	Storage Ring	Beam Lines (7)	Total
Main Magnets		1	1	25		27
Steering Magnets		1	1	24		26
RF	1		2	5		8
Vacuum	1	2	4	48	7	62
Diagnostics	1	2	4	25		32
Pulsed PSUs			1	1		2
Personnel Safety	1			2	2	5
Vessel Protection				24		24
Radiation Mons	1			2	2	5
Ids or Motors				7	7	14
Miscellaneous				5	2	7
Totals	5	6	13	168	20	212

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2.8 CONTROL SYSTEM SUPPORT SERVERS

In addition to EPICS IOCs and EPICS OPIs, a third class of machine can be identified; the Control System Support Server. These machines will host any files, databases, environments etc. which cannot be held on IOCs (since these are memory-only systems) and are inappropriate for storage on the OPIs themselves (for example, cumulative files requiring large amounts of disc space and appropriate media back-up facilities). For each Control System Support Server, a hardware platform and configuration appropriate to its function will be selected; this might take into account, for example, the need for RAID disks, disk shadowing or other fault tolerance features.

In general, the design philosophy adopted will be to allocate one Control System Server per function, so that the loss of one server does not disable a significant number of Control System facilities. The detailed design phase will further consider ways of minimising any period when the Control System has to run with reduced facilities due to loss of any one Control System Support Server.

Control System Support Servers will include :

- IOC Boot Servers, containing boot images and database text files for a each IOC.
- Development Servers (Section 2.5.1), containing the Application Development Environment.
- Relational Database Server, used to hold the Control System Relational Database Management System (Section 2.10).
- Log File Server, used to hold files for the Alarm Log and Operations Log windows of the EPICS ALH package and for files collected by the EPICS CMLOG program.
- Archive Server, used to hold data files for all history activity, from short-term back history through to long-term archive data.
- Accelerator Model File Server, containing configuration files and data files relating to the Accelerator Model.
- External Access Gateway Server, containing configuration files and data files relating to Control System access from outside of the trusted Control System network.

Requirements for any additional Control System Support Servers will be defined during the detailed design phase.

2.9 NAMING CONVENTION

2.9.1 Introduction

A binding device naming convention [19][20][21] is required not only to allow control system software to reference precisely and unambiguously accelerator components, but also to facilitate communication between the various technical groups and specialists responsible for design, construction and operation of the accelerator complex.

It is anticipated that the names will be used extensively on engineering drawings, in design documents, in control system software, in informal and formal discussions, in databases and on device labels.

It is hoped that the naming convention will provide a concise and consistent way of identifying an individual component. Also, through the use of a hierarchical structure, the name should provide some guidance as to the physical location of the device.

Ideally, device names should not be unduly restricted by the underlying software and systems, but in reality careful consideration must be given to ensuring compatibility with EPICS which has been selected as the control system toolkit for DIAMOND.

The device name will consist of a maximum of 20 alphanumeric characters. It can be broken down into 4 or 5 sections. The 'dash' character "-" is used to delimit the sections and is the only non-alphanumeric character allowed.

2.9.2 Device Name Format

The format is as follows:

DDD-[SSS]-TTT-CCCC-NN

where [...] indicates an optional section.

2.9.3 Domain (DDD)

Domain identifies a major area of the accelerator complex. It consists of a minimum of one and a maximum of three characters. The first character must be alphabetic; the remaining characters must be alphanumeric.

This section is mandatory.

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Table 2.9-1

DDD	Domain
LIN	Linac
L2B	Linac – Booster transfer line
BOO	Booster ring
B2S	Booster – Storage ring transfer line
SR	Storage ring
FE	Front Ends
BL	Experimental area
CS	Control system
SRV	Services
TST	Test systems

2.9.4 Sub-Domain (SSS)

Sub-domain is used to further sub-divide complex domains such as SR (Storage Ring). Each domain has its own separately defined list of sub-domains. It consists of a minimum of one and a maximum of three characters. The first character must be alphabetic, the remaining characters must be alphanumeric.

This section will be omitted for most simple domains but is mandatory within domains for which sub-domains have been defined.

For the Storage ring domain (SR):

Table 2.9-2

SSS	Sub-domain
Axx	Arc xx
Sxx	Straight xx

For the Front End (FE) and Beamline (BL) domains:

Table 2.9-3

SSS	Sub-domain
Ixx	Insertion device xx
Axx	Upstream dipole xx
Bxx	Downstream dipole xx
Cxx	Upstream dipole xx IR
Dxx	Downstream dipole xx IR

2.9.5 Technical Area (TTT)

Technical area defines the technical sub-system to which the device belongs. It can also be used to help identify the group or person responsible for the device. It consists of a minimum of one and a maximum of three characters. The first character must be alphabetic, the remaining characters must be alphanumeric.

This section is mandatory.

Table 2.9-4

TTT	Technical Area
MAG	Magnets
VAC	Vacuum
PSU	Power supplies
RF	RF systems
DIA	Diagnostics
AL	Alignment
PSS	Personal Safety
RAD	Radiation Safety
TIM	Timing system
H2O	Water
MON	Monochromator
MIR	Mirrors
CRY	Cryogenic systems
AIR	Compressed air
GAS	Gases
MOV	Movements (motors)
EA	Experimental apparatus

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2.9.6 Component (CCCCC)

This section defines the particular type or style of device. Each Technical Area will have a separately defined list of valid component names. It consists of a minimum of one and a maximum of five characters. The first character must be alphabetic, the remaining characters must be alphanumeric.

It is anticipated that each technical group will define their own list of names in agreement with the Controls group.

This section is mandatory.

2.9.7 Identifier (NN)

A two-digit number identifying a particular instance of a device. A leading zero (0) must be used where necessary.

Although there is no need to specify devices in numeric order, this practice is to be encouraged whenever possible.

This section is mandatory

2.9.8 EPICS Record Names

EPICS record names are constructed from device names by appending a record specifier (and optionally, a sub-system name) as follows:

DEVICE_NAME[:SUB_SYSTEM]:RECORD

where [...] indicates an optional component.

sub_system is intended to allow the use of hierarchy within the EPICS IOC database (i.e. CapFast hierarchy). Only one level will be allowed.

Both *sub_system* and *record* are no more than three characters in length. However, if the *sub_system* component is not used then *record* may be up to seven characters in length.

2.9.9 CDEV Name Space

CDEV has its own device name space that is defined in a DDL file. This name space is independent of the EPICS name space and can, in principle, use a completely separate naming convention. However, this temptation should be avoided at all costs and CDEV device names must use this naming convention without exception. This has the extra advantage that the substitution operator (<>) can be used in the DDL file to generate automatically an EPICS PV name from a device name.

It is anticipated that DDL files will be automatically generated from the system Relational Database.

2.9.10 Examples

Table 2.9-5

SR-A01-VAC-IONP-01	Storage Ring Arc 1 Ion Pump controller No. 1
LIN-PSU-FQUAD-02	Linac F-Quadrupole 2 power supply
FE-I01-VAC-VALVE-01	Insertion device 1 front end Vacuum valve No. 1
BL-I01-DIA-TVM-02	Insertion device 1 beamline TVM No. 2
TST-VAC-PIRG-03:SMON	Test system Pirani vacuum gauge No 3. Status monitor EPICS record

2.10 Relational Database

2.10.1 Introduction

The EPICS toolkit is based around the concept of a distributed, real-time database. In other words, information about the current state of the accelerator is collected from many IOCs situated around the accelerator complex. On start-up these IOCs must be provided with a local database file that defines the devices to be controlled, initialisation data, alarm limits, calibration data etc. This database is a simple ASCII text file that is downloaded to the IOC from a server on boot-up. Each IOC requires its own unique database.

Similarly, each IOC database file is usually generated using information from several different sources such as CapFast or VisualDCT schematic drawings or simple text data files.

There is also a large pool of information that is needed by the users and designers of the control system that does not reside within the distributed database provided by the IOCs. This information includes such things as magnet calibration data, lattice element survey offsets, device serial numbers, configuration data for application software, and so on. The standard EPICS distribution provides no mechanism for managing or organising this large amount of data.

Most large accelerator projects over the last 10 years that use an EPICS control system have attempted to solve this problem by storing all the information in a relational database [22][23][24]. However, because of the many intricate relationships between the different types of information to be stored, the design of these databases is very

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complex. The use of relational databases within the EPICS community has not yet matured enough for there to be a “standard” solution available so some original design work is involved.

2.10.2 User requirements

The following user requirements have been identified:

- The database will need to be a central repository, storing all the IOC database configuration data.
- Configuration scripts should be able to be retrieved and modified, then changes saved in the RDB.
- Physical elements, such as devices and logical elements in the control system will need to be stored and modified in the RDB.
- EPICS data (records/fields) will need to be stored and modified in the database.
- Alarm limits will need to be stored and modified in the database. These can be switched on and off in the database and the severity can be changed.
- A user should be able to find all records common to a particular device type.
- Devices should have data identifying who installed/checked them and when.
- RDB security will be dealt with in the database itself.
- Users will need user access rights to restrict them from accessing certain RDB areas. Access categories should include read-only, read-write and no access.
- Information and results from accelerator physics experiments will need to be stored for reference and future experiment design. The tables storing the results will have no direct effect on, or link to, the configuration data.
- The database should be made available over the Internet; this could allow remote users to control the RDB or be restricted to read-only access.
- It should be possible to add, delete or edit data in the RDB.
- The RDB should provide information to all users, with access to certain areas for only those actors who require it.
- Data about alarms and signals should be archived in the database when there is a change or it is time for an update.

- The database should be straightforward to use, with simple ways of entering and extracting data, for example using forms and barcodes.
- A user should be able to query the database to find out any information that is stored, provided he or she has appropriate access rights.
- The database should be able to produce reports, e.g. exception reports when something extraordinary occurs.

2.10.3 Implementation Details

(a) Choice of Relational Database Management System

The estimated size of the database and the anticipated transaction rates are moderate compared to many database systems in use today. Most commercial and many Open Source RDBMSs will easily be able to handle the requirements. However, ORACLE [25] has been chosen for DIAMOND for the following reasons:

- ORACLE is the market-leader RDBMS
- It is already in use at several EPICS-based accelerator laboratories
- ORACLE expertise is widely available
- ORACLE includes a very comprehensive suite of management, application design and web-publishing tools.

(b) Storage Requirements

Preliminary estimates show that the total database size will be in the region of 2 – 3 GBytes. This is based on the assumption that the database will contain all IOC, record, field and device information as well as physics parameters and application configuration information. It does not include any allowance for storing historical archive data, experimental data sets or graphical information.

(c) Data Integrity Checks

The database design will include many internal data integrity checks. This will help to ensure that the data is both valid and consistent. Careful thought will be given to the choice of data type for each field and to the specification of valid ranges of values. Data validation should be handled within the database whenever possible. Validation by database application software will also be required in more complex cases.

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(d) Database Security

Security will be built into the database. It will be possible to restrict access to each table to certain users or groups of users. The user and group lists will be defined within the database itself and access will be managed by the RDBMS.

(e) Backup and Archival

Adequate provision must be made for online backup and long-term archival of the database. Given the anticipated database size, DLT drives will be perfectly adequate for online backup. For long-term archival database snapshots can be stored to an optical storage media such as DVD-RAM.

2.10.4 Application Integration

It is important to provide a simple, co-ordinated mechanism that will allow application software to access both dynamic data from the IOCs and static data from the relational database. Subsection 2.6.8 addresses this through the adoption of CDEV as the standard API for control system applications. CDEV provides a common API that can be used to retrieve either dynamic or static information from an IOC or the RDB. It was developed to work with EPICS and has been adopted by several other accelerator labs. It also provides an object-oriented view of devices.

2.10.5 User Interface tools

A suite of interface tools will be required to perform the following tasks:

- Import CapFast/VisualDCT schematics into the RDB
- Import IOC ASCII database files into the RDB
- Create IOC ASCII database files from the RDB
- Create CDEV DDL files from the RDB
- Import Microsoft[®] Excel spreadsheets into the RDB
- Modify/Edit RDB data
- Produce reports from the database
- Execute user-defined queries on the database

These tools can be provided using either conventional programming languages such as C or Java, a scripting language (Tcl), a proprietary database application development tool such as ORACLE Forms, or a web-based interface.

2.11 SECURITY

2.11.1 Philosophy

The design of the Control System will ensure maximum ease of use within the control room and equipment hall. To achieve this, there will be very few security measures in place for users in these locations. Where security is required within the control system bounds the EPICS access control mechanisms will be used. Access to the Control System from outside these locations will be strictly controlled and managed by use of physically separate networks, a firewall mechanism and dial-in modem access.

2.11.2 EPICS Access Security

The EPICS package incorporates a sophisticated, rule-based access security mechanism, which has been designed to have minimal performance effect on database read/write times. Access security can be applied to each individual record field and is configured in an Access Security Configuration File. Access security can be enabled and disabled via an entry in the IOC download files, each of which will be held on a server in a secure, password-protected account.

As an example of what is possible with this mechanism, the following security policy for a Linac is implementable:

- A) Anyone can have read access to all fields at any time.
- B) Linac engineers, located in the injection room or control room, can have write access to most level 0 fields if the Linac is not in operational mode.
- C) Operators, located in the injection room or control room, can have write access to most level 0 fields at any time.
- D) The operations supervisor, linac supervisor, and the applications developers can have write access to all fields.
- E) Most records use the above rules, but a few (high voltage power supplies etc) are placed under tighter controls. These follow rules (A) and (D), but not (B) and (C).

EPICS access security will remain disabled during the development and commissioning stages of the Control System, to ensure that development and commissioning teams are unhindered by security issues. During this phase of the project, a set of access security rules will be clearly defined, and these will be implemented when the Control System is ready to enter the operational phase.

Access security is on a per-IOC basis. Therefore, if it proves necessary, it will be possible to run the Control System with commissioned IOC's under access control

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and non-commissioned IOC's free of access control to prevent delays to development and commissioning teams.

EPICS access security does not apply to IOC test commands. Therefore, support staff can still use these commands for database reads or writes as part of any diagnostic or debugging investigations, even on an IOC that is under access control. Separate security measures (e.g. Firewall, dial-up security, password-protected accounts) will be used to ensure that only authorised staff can gain direct access to IOC's at the VxWorks level to use these test commands.

2.11.3 Firewall

All DIAMOND Control System components will reside on a dedicated network – in security terms, this is the trusted network. All other networks are collectively referred to as the untrusted network. The trusted network will be separated from the untrusted network by a Stateful Multi-layer Inspection firewall installed on a standalone PC. This type of firewall currently offers the best combination of security and minimal performance effect.

Key aspects of this configuration include:

- The firewall PC should run a dedicated minimal operating system, sufficient only for supporting the firewall itself. This minimises the danger of the firewall being compromised.
- It will be possible to read Control System parameters from the untrusted network via web interfaces or similar mechanisms.
- Software (running on the untrusted network) obtaining data from the Control System must communicate through a known tcp port, so that a security policy can be allocated to that port on the firewall. In practice, this will mean that data requests will be channelled through a custom-written sender/receiver software combination; the sender program will reside on the trusted network side of the firewall and the receiver program will reside on the untrusted side. Transactions between the sender and receiver programs will consist of well-defined commands requesting data from the Control System. Such commands will be parsed by the sender program, and any illegal commands rejected. Commands will be defined such that no command can request a volume of data sufficient to cause any overload on the DIAMOND Control System itself.
- Ideally, the firewall should be configured to allow office-based support staff with suitable authorisation to have password-protected access to control room facilities via an X-Windows emulator such as Exceed. If provided, this type of access must be configured with a time-out, such that an auto logout occurs after a period of inactivity.

D.2 CONTROLS

External Internet access will not be permitted from the DIAMOND Control system. Instead, a Control System Intranet will provide operators with access to documentation and other content relevant to control room staff.

2.11.4 Dial-in modem access

Support staff will require dial-in access to the DIAMOND Control System, which will bypass any firewall. Only trusted users (i.e. those authorised to access the trusted network) will be allowed this type of access.

Either of the two following strategies could be used to provide secure dial-in access:

- Dial-back modem scheme. When a call is placed to a dial-up, the modem responds by hanging up and dialling back to a pre-programmed telephone number.
- Dial-in Authenticator scheme. With this security solution, a dial-in connection can only be established by successfully entering the security code for an authenticator device. The authenticator is a hardware device attached to the dial-in modem. Various authenticator mechanisms exist; some rely on a security code being entered via the initiating dialler, others rely on a separate hardware “key” being used. In the latter case, the hardware “key” matches up to one authenticator only

The latter solution has some cost implication, but offers improved security.

2.12 PHYSICAL STRUCTURE

2.12.1 Control Instrumentation Areas

The control system will interface to the technical system at 48 CIAs. The CIA will house the control system interface layer, the IOCs and the instrumentation of the technical system. The identified CIAs, racking and space required are shown in Table 2.12-1.

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Table 2.12-1 Proposed Control Instrumentation Areas

Ref No	Control Instrumentation Area	Number of	Racks Identified	Rack Space Required
1	Linac and LTB	1	18	20
2	Booster Synchrotron	6	32	60
3	Booster RF	1	5	10
4	Booster Power supplies	1	3	10
5	BTS	1	5	10
6	Storage Ring Instrumentation	24	394	480
7	Storage Ring Dipole Power Supply	1	2	5
8	Storage Ring RF	1	11	20
9	Technical Service Plant Room	1	3	5
10	Cryogenic Services	1	5	10
11	Physics Room	1	7	10
12	Main control room	1	1	
13	Control System Computer room	1	4	10
14	Beamlines	7	48	70
	Total	48	519	721

2.12.2 CIA Physical requirements

The CIAs will be located in close proximity to the equipment they are controlling. For the SR this is around the inner shield wall. Each CIA will be contained within a partition-type enclosure with a false floor and air conditioning. This ensures effective cable management, the local cooling necessary for computer systems and maintenance of a clean environment, and reduces noise to the overall building from fans within the equipment.

2.12.3 Main Control Room

The MCR will be where the DIAMOND facility is controlled. The operator interface will be through workstations on the DIAMOND control system. There will be a limited requirement for hardwired interfaces to technical system such as personnel safety lockout keys and wide band connection to monitor RF signals. The room will support the operations team, staff from the physics groups and staff from technical groups.

2.12.4 Control System Computer Room

The CSCR will house the central computer systems that make up the DIAMOND control system. In this area all signals connecting the central computers to the 48 CIAs

will be terminated. Also located in the CSCR will be central systems for generating timing and event information and managing global machine protection. The computer systems in the control room will include the computer servers for the operational control system and servers and workstation for control system development.

2.12.5 Physics Room

The PR will make key signals available to enable experiments to be set up to monitor and characterise aspects of the accelerators. To realise this, access will be provided to the DIAMOND control system and to wide-band (RF) signals from around the accelerators.

2.13 NETWORK

2.13.1 Requirements

The network infrastructure will support the control system to operate the DIAMOND accelerators and beamlines, and provide network connectivity for other computers located in or in close proximity to the accelerators and beamlines e.g. RGA monitors.

The control system network needs to support real-time access to the embedded servers and IOCs, and booting of the IOCs. To preserve real-time performance under varying load condition, the network will feature low utilisation and high network bandwidth.

Reliability of the network will have a direct impact on the operational reliability of DIAMOND. Experiences from other light sources have shown that the control system network should be structured to include an element of redundancy [26]. This will be realised in the fibre optic cables and at the server level. Analysis of network topologies has shown that a star configuration from a switched hub with redundancy has superior reliability to that of a bus or ring structure [27].

2.13.2 Network Services

There will be two physically separate computer networks provided. Each will be distributed to the accelerators and beamlines. The control system network will be used exclusively for control system connections with limited routes to the site network or Internet. A second computer network will provide connections for other computer systems required around the accelerators, which are not integral to the control system. This network will be connected to the site network and hence the Internet.

The network structure will also support the distribution of timing system event information, machine protection signals and monitoring of the IOC crates using the CAN Bus network standard.

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2.13.3 Network Physical structure

The network will be structured in star configuration running from the CSCR to each of the 48 CIAs. The CIAs will contain the network services, the control system IOCs and the plant instrumentation. The connection from each CIA to the control system computer room is likely to consist of one 12core multi-mode FO cable and one 12 core single-mode FO cable.

Multi-mode FO cables support current network standards with single-mode providing an upgrade path to multi Giga bit standards. The final mix of multi-mode fibres and single-mode will be decided nearer the installation date, taking into account the then-current state of technology.

The hub of the star structure will be in the CSCR and for the computer networks will be two network switches. All cables, fibre optic and copper, will be terminated in patch panels in racks to provide effective management and hence flexibility in connecting to the network switches and other hardware. This will also contain management of the network, the IOC crate monitoring, event distribution and machine protection.

At each CIA, a rack will contain the network distribution components and termination. The distribution will consist of two network switches, for the control network and secondary network, fan-out of the event signals and translation of the CAN bus from FO to copper signals. To manage distribution, copper and FO, cables from each of the CIA racks will be terminated in patch panels.

To manage the network load, from multiple IOCs booting concurrently, and to give redundancy in the boot process, each network rack will contain a boot server for the IOCs local to that area.

To enable remote access to each of the IOCs through the console port, each network rack will contain a terminal server. The terminal server will be accessed through the secondary (non control system) network. This ensures access to the IOC console ports in the event of a faulty IOC saturating the controls network with traffic.

Local connections will be provided to Ten Base T wall sockets around the accelerator enclosures.

Connecting each control system instrumentation rack to the network distribution rack will be four cores of multi-mode fibres and four Ten Base T copper connections. This arrangement provides for a maximum of two IOCs per rack. Each IOC will be provided with a network connection, console connection and event signal.

2.14 EQUIPMENT PROTECTION

2.14.1 Interlocking Structure

The control system will provide interlocking and protection of equipment where required. *This excludes personnel protection, which is a separate system that is monitored by the control system.* Protection will be classified as High Integrity Interlocks, Routine Interlocks or Prudent Limits.

(a) High Integrity Interlocks

High Integrity Interlocking will be used to prevent equipment from behaving in a manner that could lead to substantial damage of property or loss of operation of the facility. It will be based on hard-wired logic with no software component. For example, High Integrity Interlocking will be used to protect the vacuum vessel and dipole magnets, on the SR and possibly the Booster, from loss of cooling water.

(b) Routine Interlocks

Routine Interlocking will be used to protect equipment from damage, for example to prevent a vacuum valve being opened without good vacuum on both sides. This will be based on commercial PLCs and will use software to define the logic. Realising the interlocking in PLCs, as opposed to the IOCs, removes the need to protect IOC outputs in the event of an IOC crash, so improving reliability. Through the use of warm rebooting, it also enables an IOC to be restarted while maintaining its outputs so as not to disturb the operation of the equipment. It further provides a level of isolation from the operational parameters of the CS, ensuring that changes are not overly easy to make, but maintains flexibility to enable technical group to make changes where required.

(c) Prudent Limits

The third level of protection, Prudent Limits, will define operational limits and bounds for equipment. For example, it would be used to ensure that a power supply is only switched on at minimum current, to define the maximum operating current and rate of change of current. This will be provided by the logic in the IOC. Changes to these limits may be required when operating the accelerators in a non-routine mode. This requires that changes to prudent limits can be made through control applications.

2.14.2 Global interlocking

From around the accelerators there is a requirement to receive interlock signals and bring them together to protect equipment. Two global interlock signals have been identified for each of the SR and Booster. These are RF permit (RFP) and dipole permit (DPP).

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RFP will be produced from the water flow interlock on the storage ring vessel and front ends, the temperatures from radiation-sensitive components, and electron beam positions through IDs. The RFP will operate by removing the RF to dump the beam in the event of a fault condition.

The DPP will be produced from dipole magnet water flows and temperatures. The DPP will operate by switching off the dipole power supply.

A RFP and DPP will be produced in each cell, most probably in custom VME modules using hardwired logic, as they will be a class of High Integrity Interlocks. The modules will enable monitoring of input interlock through the IOC. All interlock transitions to a fault condition will be latched to catch momentary disturbances.

The outputs of the cell modules will be pulse streams, which will be sent to a central area, the CSCR, over fibre optic cables where they will be concatenated to produce the global permits. The overall management being carried out by VME modules provides monitoring and latching of the states of the inputs from each cell. Figure 2.14-1 shows a block diagram of the system. Such a scheme is used on CEBAF for fast protection [28], in which a 5MHz pulse stream is used to transmit interlocks. This gives a response time of 40µsec.

The use of a simple pulse stream provides for a known response characteristic, good electrical immunity and fail safe operation. The presence of the pulse stream indicates a good interlock, while absence of the pulse stream, either as a steady high or low, indicates a failure of an interlock or a fault in the system. The use of the pulse stream makes the signal suitable for distribution using balanced line differential signals, coaxial cables but most likely fibre optics. The intention is to use the network fibre optic infrastructure from each control instrumentation area to and from the CSCR.

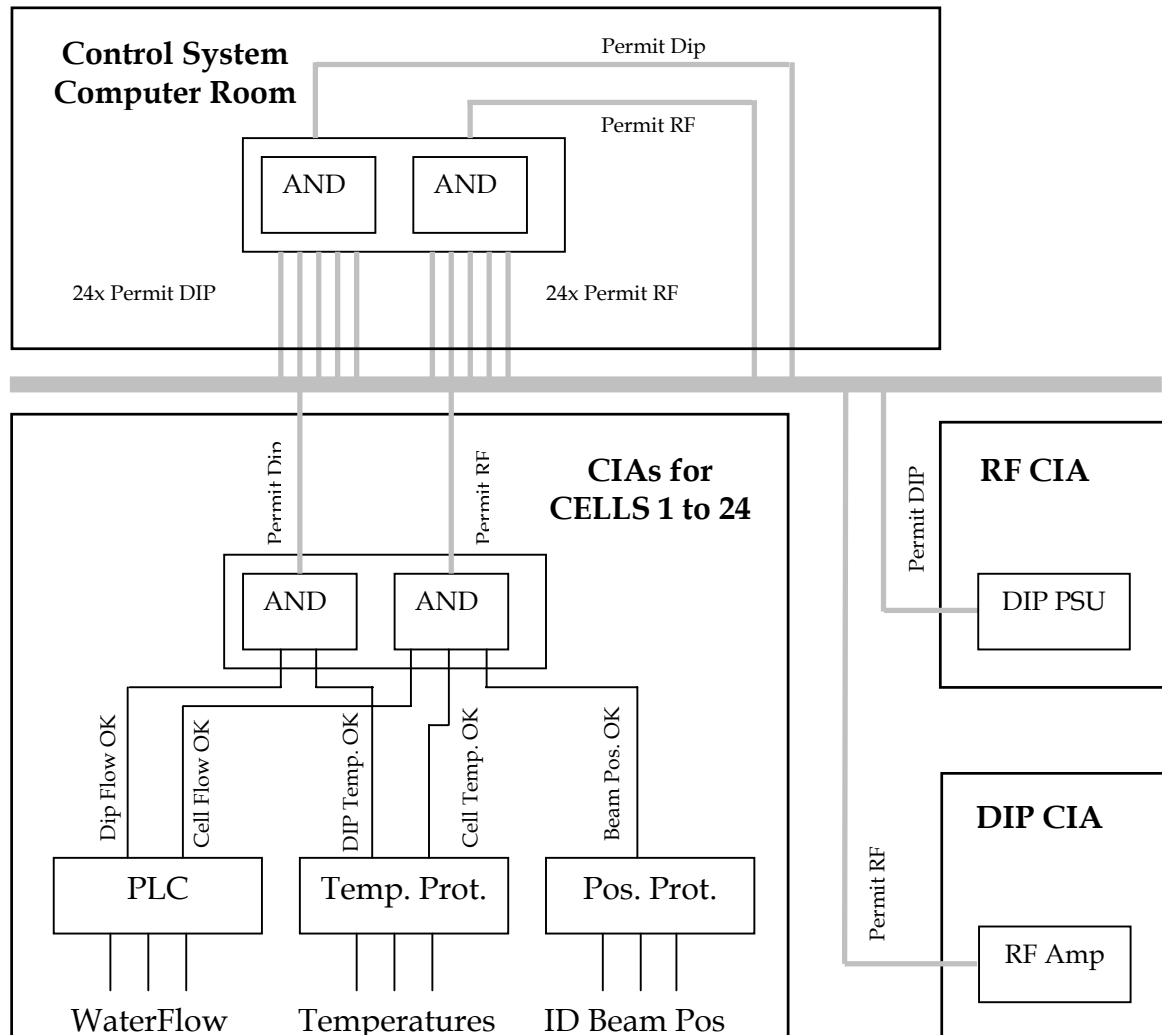


Figure 2.14-1 Block Diagram of Global Interlocking

2.15 TIMING SYSTEM

2.15.1 Introduction

The Timing System is required to provide control of the beam transfer from the electron source to the storage ring and provide diagnostic equipment and beamline equipment with synchronisation signals. The most recent light sources [29] have made use of commercial equipment and built upon equipment designed by other light sources, often in collaboration with industry; it is envisaged that the same approach will be adopted for this project.

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2.15.2 Fast Timing

The task of a timing system is to synchronise all the relevant components in an accelerator complex. One part of this task is to control the injection by triggering the particle source and firing the transfer line components like injection and extraction pulsed magnets at the correct times. Also, beam diagnostic components such as beam position monitors and current transformers have to be synchronised to the passage of the beam. This has to happen with fine time resolution, to RF frequency clock precision and low jitter, and is termed Fast Timing.

2.15.3 Event System

Other tasks for the timing system are related to synchronising components where the resolution is more relaxed, for example triggering the magnets for an acceleration ramp, triggering operational sequences such as the filling of the storage ring, BPM acquisition, feedback timing, insertion device control, and supplying the distributed control system with time synchronisation for control and correlation of data. The time resolution for these tasks is less demanding; these tasks are often termed Events. Event Signals will be produced to storage revolution frequency precision with predictable jitter.

2.15.4 Timing System Components

To realise the accelerator timing system it is important to consider what has been used at other recently constructed sources and the integration into the EPICS control system. The time-stamp system already exists within the EPICS infrastructure and can be used in conjunction with the Event System which was developed at the APS [30] and enhanced by the SLS. This APS/SLS Event System can be used to realise all slow timing requirements. The Event System is fully EPICS compatible and the required VME modules are available.

Table 2.15-1 SLS version of the APS Event System Specification

Events	8 Bit code – 255 events
Resolution	20nS
Event TX Trigger	Hardware Input, Software, Event Ram Clock.
Event RX Output	Hardware Output, Software (EPICS record process)
Transmission Medium	Gigabit Ethernet

The requirements for fast timing are more specific to a particular accelerator dimensions and operation. Two options are available for the hardware for fast timing, the KEK TD4V as a VME module delay generator and the Stanford Research DG535 as a self-contained instrument. Each is available with EPICS drivers to provide the controlled delays.

Table 2.15-2 Fast Timing hardware options

	KEK TD4V	Stanford Research DG535
Form	VME 6U	Bench / Rack mounting
Delay	16 Bit / RF clock	0 to 1000 S - 5pS steps
EPICS Support	Yes	Yes via GPIB
Channels	1	4
Jitter	4.5pS at 508MHz	<60pS

2.15.5 System Structure

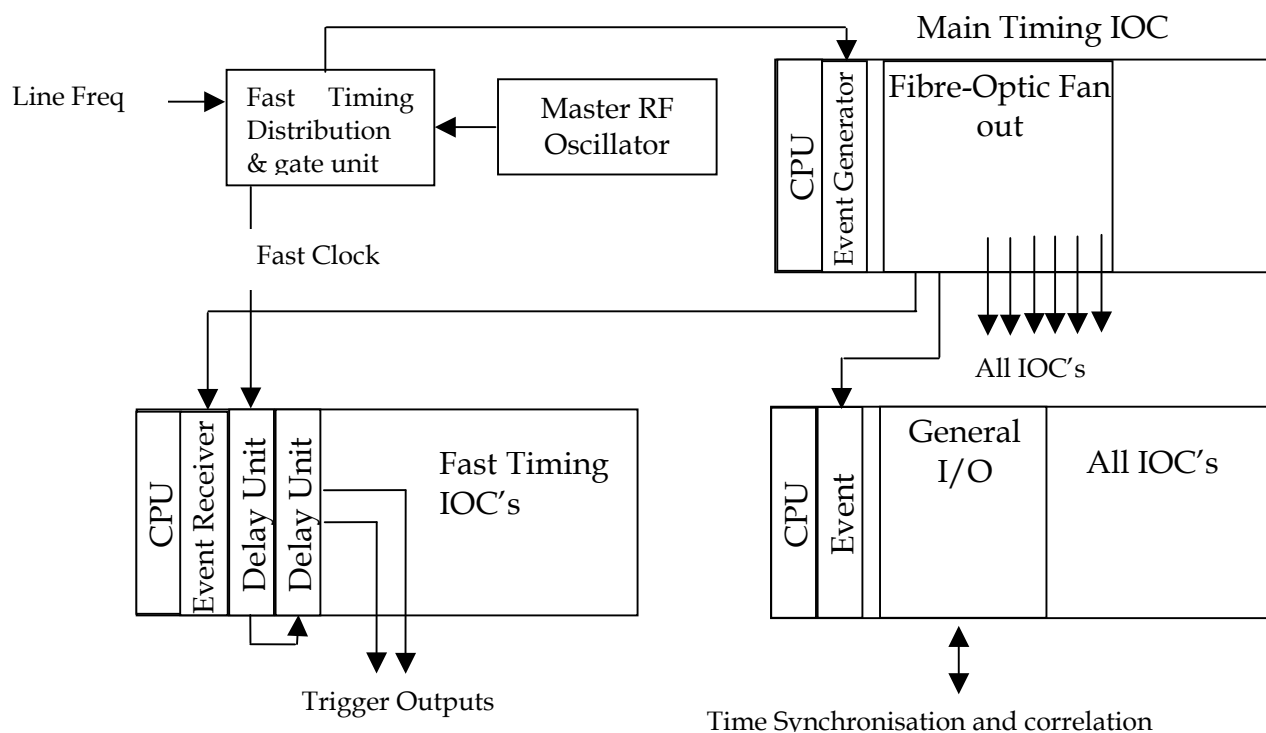


Figure 2.15-1 Block Diagram of the Event System and Fast Timing

Figure 2.15-1 gives an overview of the Event System and Fast Timing control. The Event Generator receives a start signal from the RF clock gated with a line frequency component. Events are then sent to all IOCs' Event Receivers for time stamp synchronisation and to output relevant event signals or process EPICS records. The fast timing IOCs will require a fast clock and trigger derived from the RF source but fast sequences can be initiated upon receipt of an event.

2.15.6 Signal Distribution

The Fast Timing and Event signals will be distributed over fibre-optic cable for reasons of noise immunity and distance capabilities. Further investigation is needed

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into the delay drifts that could be introduced by the fibre installation from temperature differentials and the standardisation of length-induced delays in a facility the size of DIAMOND.

2.16 BEAM POSITION FEEDBACK

2.16.1 Introduction

A beam position stabilising system is required on a 3rd generation light source to maintain orbit stability to within 10% of beam dimension and to provide dynamic correction of low-frequency orbit disturbances. The proposals presented here are very much based on the work on the APS [31], ALS [32], and SLS [33].

2.16.2 Global Feed Back

The feed back system will use measurements of the position of the electron beam in the storage ring and the photon beams in the beamline front-ends. This information will be compared against a reference orbit and the error used to calculate desired corrections to be applied to corrector magnets in the storage ring.

The response matrix relates the effect of small changes in corrector magnet fields to the resulting changes in the particle beam orbit as measured at chosen BPMs. By inverting the response matrix the relationship that maps orbit perturbations to changes in corrector magnet fields is obtained. For small orbit errors, this relationship is assumed to be linear and time-invariant. Different objectives, such as correcting the orbit in an rms sense or correcting specific locations, can be achieved by choice of BPM and corrector locations and by applying different weights to correctors or BPMs when computing the inverse response matrix.

2.16.3 Performance

Two global feedback systems, operating in parallel, are proposed to correct orbit errors on DIAMOND, namely a Slow system correcting DC drift and a Fast system correcting beam disturbances to 100Hz. These systems would use data from both the electron and photon BPMs and operate on either or both of the steering magnet or fast correctors.

Table 2.16-1 Feedback system comparisons

Feed Back	Correcting	Update Rate
Slow	DC drift	0.1Hz
Fast	0.2mHz -100Hz	2KHz

For both systems the BPMs need to be sampled synchronously, which will be achieved using Events distributed to the IOCs.

2.16.4 Slow Correction

The Slow correction will correct the orbit at ten-second intervals, using the desired correctors and BPMs to compensate for slow changes in the orbit. This will maintain the user-steered orbit applied at the beginning of each fill. Communication to the BPM and Steering IOCs will use the EPICS CA communication mechanism.

The slow correction will be realised as a dedicated application running on either a console or a computer server.

2.16.5 Fast Correction

Fast correction is not possible through EPICS CA mechanisms because of insufficient bandwidth. It will be realised at the IOC level on separate feedback processor boards dedicated to this function. This involves partitioning the correction calculation across the 24 Steering IOCs to calculate the correction values for the steering elements local to that IOC. Each steering IOC requires access to all the BPM values, to give flexibility in the correction algorithm. This requires a high speed connection to share data between the 24 BPM IOCs and 24 Steering IOCs. Two potential solutions for this are to use either reflective memory or network broadcasts.

EPICS process variables will be used to control the feedback process, by down loading algorithms to the feedback processors, setting coefficients and update rates.

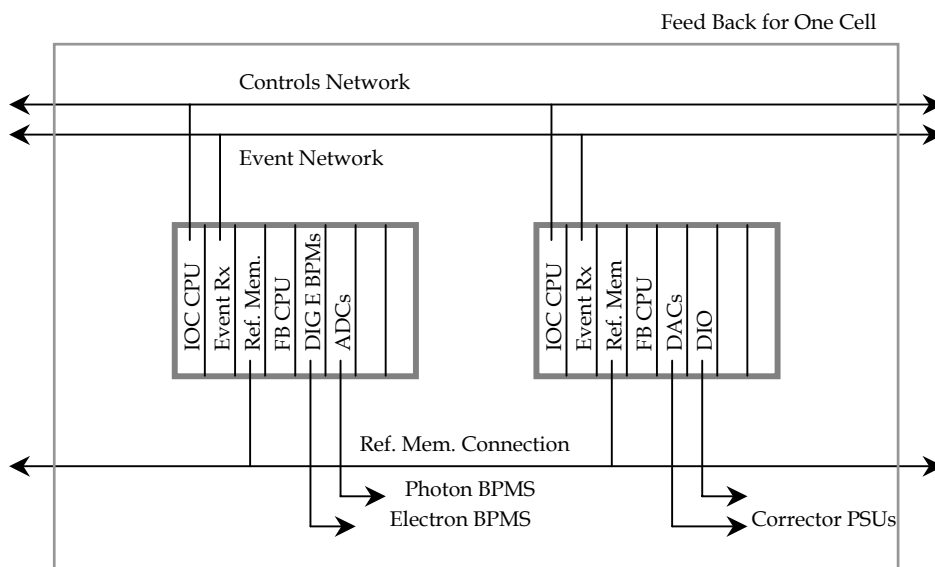


Figure 2.16-1 Reflective memory structure for one cell

(a) Reflective Memory

Reflective memory is an off-the-shelf solution to distribute information across multiple computer systems without requiring processor time. It enables BPM data to

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be written to the reflective memory module in each of the BPM IOCs and appear in memory in all the Steering IOCs.

In the system shown in Figure 2.16-1, an event received by all BPM IOCs would cause the photon and electron BPM values to be read by the feedback processor and written to the reflective memory board for each of the 24 IOCs. The data would propagate to all the steering IOCs and when all values are received, the feedback calculation would be carried out on the Steering IOC to produce the new steering settings. These values would then be written to the steering elements in conjunction with the slow system values received through EPICS process variables.

Commercially available reflective memory sizes and update rates provide for moving multi-megabytes per second across tens of boards, and so should easily meet the requirements of this application.

(b) Network Broadcast

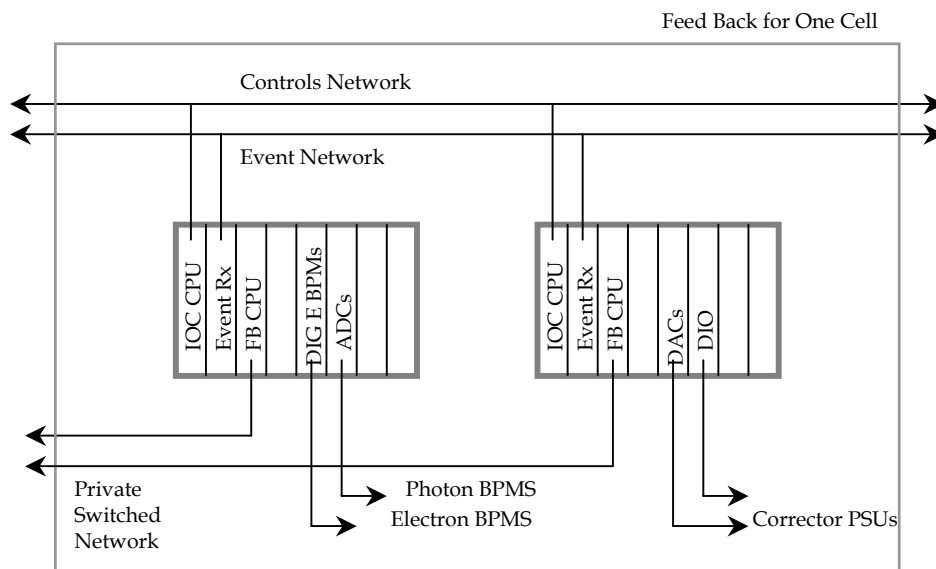


Figure 2.16-2 Network broadcast structure for one cell

In the Network Broadcast system each of 48 feedback processors, in the BPM and Steering IOCs, is connected to a private network with a central switch in a star configuration. The feedback processor in each of the BPM IOCs reads the BPM values and broadcasts them over the network to be received by each steering IOC. The broadcasts take place simultaneously, but do not collide, as the switch buffers each packet as it receives it. The switch then forwards the packets to all the Steering IOCs.

In the system shown in Figure 2.16-2 an event received by all BPM IOCs would cause the photon and electron BPM values to be read by the feedback processor and broadcast over the private network. When each of the 24 broadcasts has been received by all of the Steering IOCs, the calculation would be carried out on each Steering IOC

to produce the new steering settings. These values are then written to the steering elements in conjunction with the slow system values received through EPICS process variables.

This option is cheaper in terms of hardware because it alleviates the need for the reflective memory boards, but incurs a development overhead to produce software for the broadcasting. The performance achievable using broadcasts also needs to be determined to establish whether it would meet the requirements of this application.

2.16.6 Feedback Processor

On the Steering IOC, the calculation to produce the new steering values from BPM values and the inverse response matrix needs to be carried out. The time available to carry out this calculation is dependent on the desired update rate, the time to acquire and distribute the data and the time for the correction to propagate through the steering power supply, magnet and vessel to the beam.

While the current generation of PPC processors offer similar performance as DSP processors, in terms of operations per second they do not have the architectural feature of DSP processors for signal processing intensive calculations. However, the performance available from current PPC makes them suitable to carry out the feedback calculations at a price advantage over DSP processors.

2.17 WIDE BAND MULTIPLEXING

In order to perform diagnostics and control it is necessary to monitor various RF signals. As far as possible this will be done locally in each CIA using oscilloscopes and spectrum analysers under the control of an IOC. The IOC will provide the control and data read back of the analysis equipment through various EPICS records.

However, some functions, such as bunch statistical analysis, will require the analysis equipment to be present in the MCR. This requires a wide band network. Using high quality co-axial cable to connect each of the RF signals to a RF network switch (or multiplexer) in the Physics Room, the required signal will then be transferred to the analysis equipment in the MCR, on the control desk.

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The RF switch in the PR will be controlled by an IOC allowing the selection of between eight and sixteen signals to be transferred to the MCR. This means that the operators can select which signals to analyse from the control system

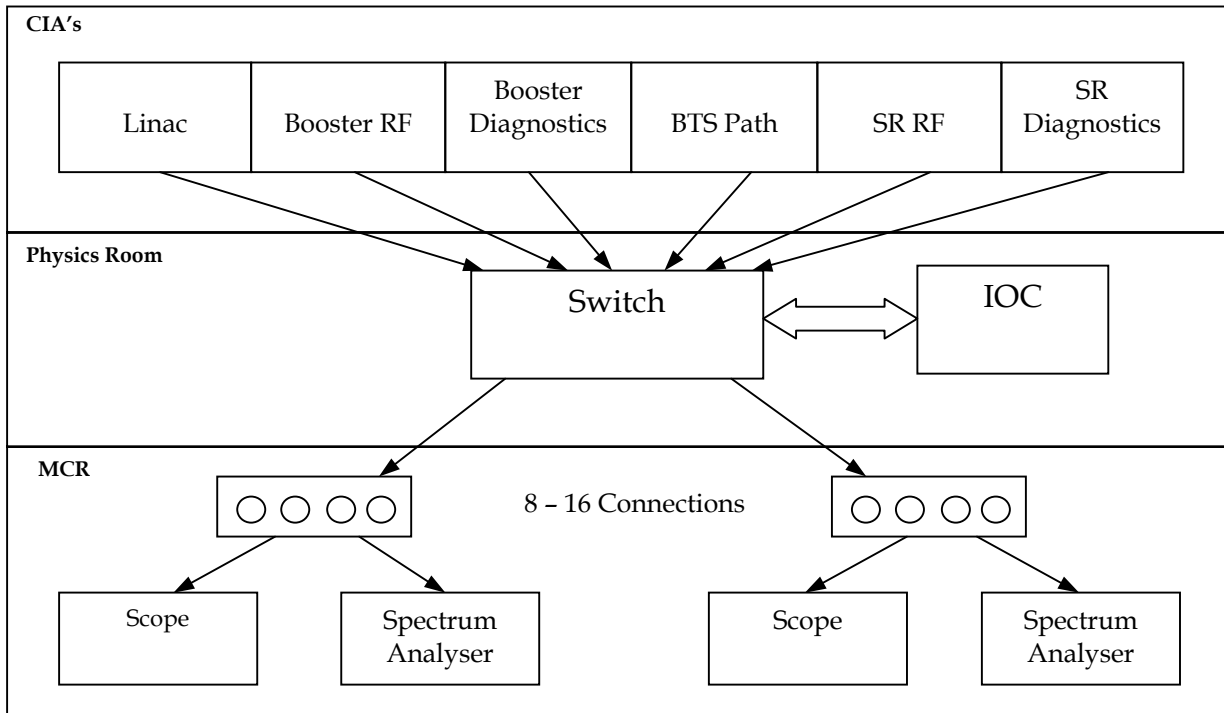


Figure 2.17-1 Block Diagram of Wide Band Multiplexing System

2.18 GLOSSARY

DEFINITIONS, ACRONYMS AND ABBREVIATIONS

ADC	Analogue to Digital Converter
ADT	Array Display Tool
ALH	Alarm Handler
API	Application Programmers Interface
ALS	Advanced Light Source
APS	Advanced Photon Source
CA	Channel Access
CDEV	Common Device
CIA	Control Instrumentation Area
CLIP	CDEV Linear Access Protocol
CORBA	Common Object Request Broker Architecture
CS	Control System
CSCR	Control System Computer Room
CVS	Concurrent Versions System
DAC	Digital to Analogue Converter

D.2 CONTROLS

DCT	Database Configuration Tool
DDL	Device Definition Language
DSP	Digital Signal Processor
DP	Display Page
DPP	Dipole Permit
EDM	Extensible Display Manager
EPICS	Experimental Physics and Industrial Control System
FO	Fibre Optic
GPIB	General Purpose Interface Bus
HEP	High Energy Physics
IF	Interface
IL	Interlock
IOC	Input Output Controller
IP	Industry Pack
KM	Knob Manager
LAN	Local Area Network
MCR	Main Control Room
MEDM	Motif Editor Display Manager
MTBF	Mean Time Between Failure
MTTR	Mean Time To Repair
OPI	Operator Interface
PLC	Programmable Logic Controller
PR	Physics Room
RDB	Relational Data Base
RDB	Relational Data Base Management System
RFP	RF Permit
SCADA	Supervisor Control and Data Acquisition
SDDS	Self Describing Data Sets
SNC	State Notation Compiler
SLS	Swiss Light Source
SNL	State Notation Language
TACO	Telescope and Accelerator Control System
TANGO	TACO and New Generation Objects
VME	Versa Module Eurocard (The meaning is now obsolete)

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D.3 Infrastructure and Support Facilities

3.1 ACCESS

Access to the Diamond facility will be through the RAL main entrance gate and along existing and modified site roads. A new road is to be provided to the east and south of the Diamond site to feed car parking outside the RAL site security fence. This road will also serve as an access to a secondary site entrance to the south-west of the main Diamond building.

Diamond roads and footpaths will link into the RAL infrastructure.

3.2 DELIVERIES

Existing site delivery points will be available to Diamond. These will be upgraded appropriately to meet the increased volume of deliveries. Existing postal infrastructure will be available to the Diamond facility.

3.3 COMPUTING/IT

The RAL site is well served by centralised and distributed computing/IT systems. It provides a reliable and secure gateway to the internet. Diamond systems will be integrated into the existing systems with appropriate upgrades.

3.4 LIBRARY FACILITIES

Whilst Diamond will have localised library facilities these will not be extensive. Use will be made of the existing RAL library facilities which are expected to be upgraded before Diamond becomes operational.

3.5 RESTAURANT FACILITIES

The Diamond complex will have minor facilities for food and drink provision. Employees and visitors will rely heavily on the existing restaurant and coffee lounge on the RAL site in buildings R1 and R22. The existing restaurant facilities will require upgrading to meet increased capacity requirements. Consideration is also being given to additional outlets.

3.6 MEETING ROOMS AND CONFERENCE FACILITIES.

A number of meeting rooms will be provided within the Diamond buildings capable of seating up to 20 people. The existing RAL meeting rooms and Lecture Theatre will

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supplement these. Consideration is being given to providing additional facilities to the RAL site in the shape of a 500 seat lecture theatre possibly before Diamond is operational.

3.7 SITE MAIN ENTRANCE

It is proposed that before Diamond is operational the position of RAL's main entrance is moved westwards along Fermi Avenue and a new Gatehouse and Reception building built. This reception building will be designed to provide a "one-stop" visitor processing centre.

3.8 TECHNICAL SUPPORT

Use will be made of existing RAL facilities, workshops, laboratories and buildings to prepare equipment prior to being incorporated into the Synchrotron. Significant work needs to be carried out to enable this to happen. This includes the provision of a 2500m² warehouse type building for multi-purpose use.

3.9 STORAGE RING GIRDER ASSEMBLY

The various components which form the sections of the achromat are:

- Girders
- Magnets
- Vacuum Vessels
- Vacuum Pumps
- Service Connections
- Supports

These components will be arriving in staged deliveries from numerous suppliers.. Assembly and pre-commissioning of the girder assemblies will be a significant task and will require special facilities for their successful completion.

A suitable building will be required to enable the work to be carried out in a controlled, clean and organised environment.

A typical size and layout of such a building is illustrated below Figure 3.9-1. The building will require a 15 tonne capacity overhead crane, since this is the weight of a fully assembled girder.

The building will require town-mains water, demineralised water. 240V mains electricity, and compressed air (5bar minimum).

D.3 INFRASTRUCTURE AND SUPPORT FACILITIES

Helium and nitrogen will also be required, but bottled supplies will be adequate.

The building will be divided into six areas as shown.

1. Loading Bay; for unloading individual items and loading complete assemblies.
2. Receipts and despatch; for logging items in and out.
3. Inspection Bay; for unpacking and inspection of delivered items.
4. Processing Bay; for assembling the components on to the girders.
5. Commissioning Bay, for testing the assemblies (open circuits, earth leaks, water leaks). This work will be carried out in close co-ordination with the vacuum processing facilities described elsewhere. Whilst cold helium leak testing of achromat vacuum vessels may be done here. It is not the intention to perform hot leak tests of assemblies here. It would therefore be most convenient if these facilities could be located adjacent to the vacuum vessel processing facilities.
6. Pre-despatch: A holding area for completed assemblies prior to despatch either to the vacuum processing facilities or the storage ring tunnel.

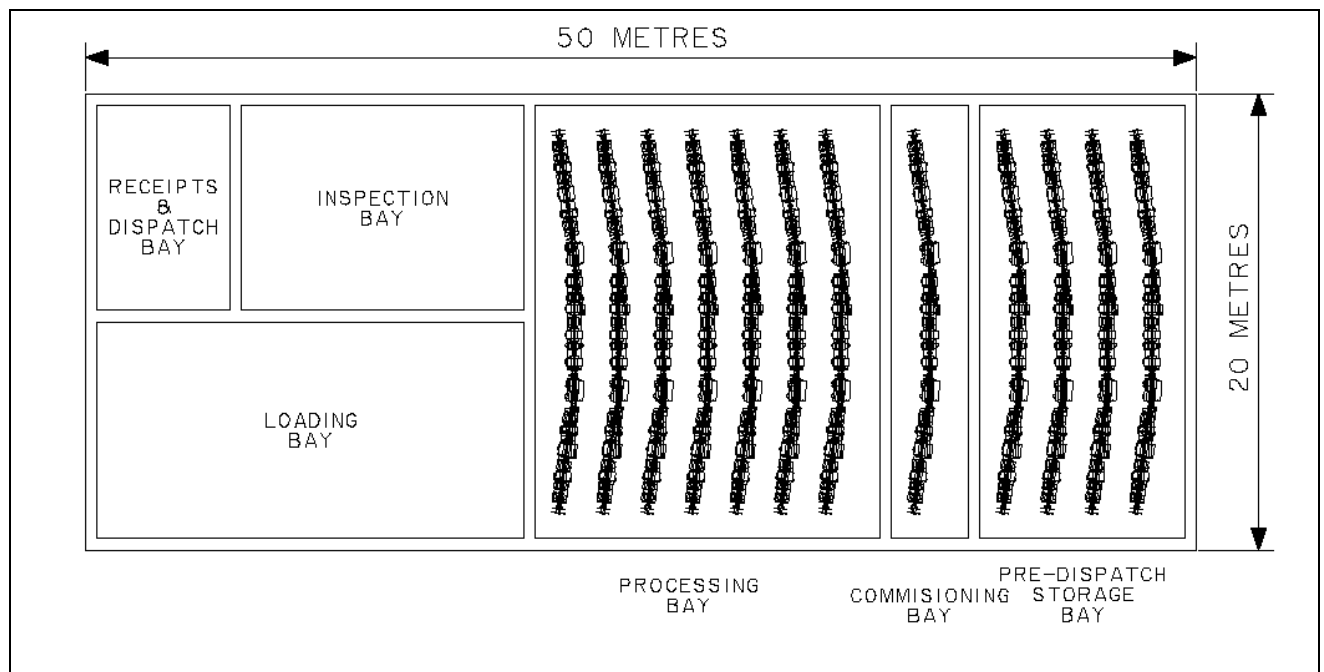


Figure 3.9-1 Plan view of Storage Ring Girder Assembly Facility.

3.10 INSERTION DEVICE ASSEMBLY

A proposed layout for assembly of the insertion devices is shown in Figure 3.10-1. It is envisaged that there will be two assembly lines, each one being similar to the

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assembly area currently used at the Daresbury Laboratory. Each assembly line will have a magnet array assembly area and a support frame assembly area. The support frame can be assembled and pre-commissioned in this area. There will be racking within this area for storage of individual magnets and support frame parts. There is a requirement for this area to be designated a controlled area because of the hazards associated with the magnets.

As well as the 15 tonne crane cover required to move the assemblies and structures, special facilities are required in this area to assemble the magnet arrays into the support structure. Because of the high attractive magnetic forces this can be a problematic phase of the assembly process.

Adjacent to the assembly lines is an area for the magnet measuring equipment, and its associated control equipment, which is used to measure the field of the magnet arrays. Shown within this area is a locker/changing room where magnetic and magnetic sensitive items are to be left prior to entering. Cleanroom facilities, such as overshoes etc, may also be required in this area to maintain an acceptable level of cleanliness within the assembly areas.

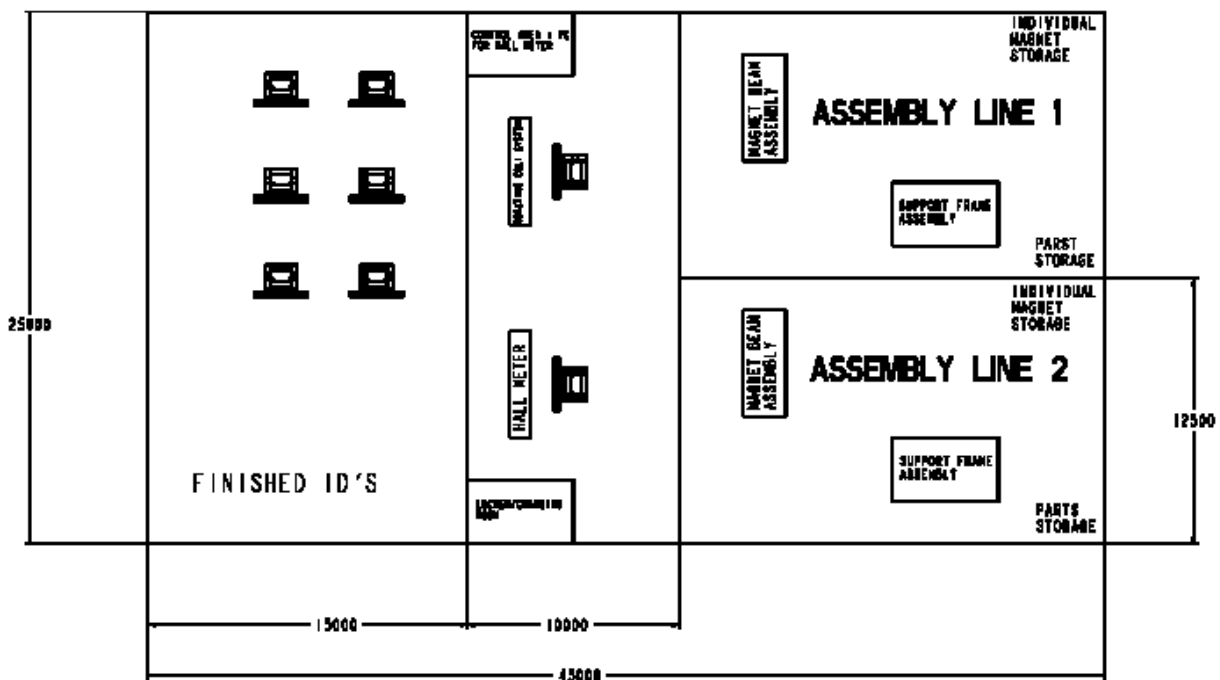


Figure 3.10-1 Insertion Device Assembly Facility

The areas described above will require communication and data, electrical, compressed air, and function specific lighting facilities. All areas will require 12 tonne minimum crane cover with a hook height of 3.5m minimum.

A holding area may be required to store eight year 1 fully assembled units prior to despatch.

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3.11 LONG BEAMLINES

An area of the RAL site to the southwest of the main building is to be reserved for two long beamlines. Because of the slope of the site these beamlines will be below current ground level.

3.12 RADIO FREQUENCY (RF) INFRASTRUCTURE

Several areas of additional infrastructure are included under the RF facilities for DIAMOND. The RF group is traditionally responsible for both high and low power RF systems, electron beam position monitoring (EBPM) diagnostics and pulse power. The close working relationship of these staff, dictates facilities that are located together. Their requirements are outlined here and should be referenced to Figure 3.12-1, showing an outline of the area requirements.

3.12.1 High Power RF Cavity Test Area

This area has four major sub areas. Due to the size and weight of some of this equipment, this area should be high and grouped together under the access of an overhead crane.

(a) Cavity Test Area

The function of this area is to provide a safe structure (sometimes referred to as a garage) where the RF cavity can be tested with full RF drive power. This means also that the cavity will need to be at LHe temperatures, with the complexities of handling that this will also entail. Hence the area will need to be shielded by sufficiently thick concrete or lead walls and roof to cope with any X-rays produced during the extensive conditioning processes.

(b) RF power supply

The RF drive to the cavity will be provided by a Klystron or IOT based RF generator. This power for this will be produced by from a 50kV DC power converter. Since both these areas have serious high voltage potential, with the dangers associated with this, considerable area will be needed for personnel safety shielding, and interlocking, both for staff safety and to prevent equipment damage.

(c) RF Cavity Clean Rooms

Although it will be policy to send the cavity away for major 'in cryostat' cleaning, some work involving the cryostat final assemblies and sub-systems will require access to a high class clean room facility (both 100-10,000 and 100-1000 class). The cavities will be moved into here both before and after conditioning, and will go directly from this area to installation within the storage ring.

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(d) Spares and Storage Compound

A large localised storage compound is required to keep cleaned cavity equipment local to the test area, and for RF power supply spares for the storage ring facility.

3.12.2 RF lab

There are many sub-systems required for an RF power supply. Low power units including power sensing, feedback and drive amplifiers will need a full development, testing and repair area, where equipment can be tested and commissioned.

3.12.3 Low Power Measurement Lab

This area is a clean area, and is used for very low power cavity resonance and perturbation testing and cavity design and development.

3.12.4 Impedance Measurement and EBPM Vessel Measurements

Normally situated together, these labs are used to test the electrical response and impedance of machine parts to high frequency signals. Within the EBPM lab, designs for these devices are actually measured and calibrated. The impedance measurement lab uses high frequency time domain reflectometry, to measure actual vessel impedance, and provide a reliable acceptance test for devices and mechanical components fitted into the storage ring beam envelope.

3.12.5 Diagnostics Lab

This is a dedicated area, where the sensitive RF diagnostics and electronics for the facility can be calibrated, repaired and developed.

3.12.6 Electronics Workshop

An area where larger machine tools (e.g. small lathe, pillar drills, and pcb production facilities).

3.12.7 Pulse Power Development and Gun Development Labs

These are both high voltage, high current labs, where development, repair and commissioning of installed pulse power supplies for fast kicker magnets, septa and klystron/gun modulators. These can be tested along side actual equipment, used as test loads under development or for calibration and commissioning.

3.12.8 Staff Facilities, Offices and Conference Rooms

Staff should wherever possible have office space local to where they work. This aids development work and allows better inter relations amongst the group.

[illegible]

3.13 VACUUM INFRASTRUCTURE

3.13.1 Vacuum Science Laboratory

It will also support all aspects of future vacuum system development on diamond.

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This Laboratory will be within ASTeC at DL and will be supported by ASTeC staff.

3.13.2 Vacuum Support Laboratory

A Vacuum Support Laboratory will be required to provide the day-to-day support for both the machine and experimental areas for the lifetime of the diamond Project. It will require a wide range of standard vacuum pump sets, pressure measurement equipment, residual gas analysis facilities, leak detectors, small fittings, etc. The Laboratory will provide the necessary testing and approval facilities for all items of vacuum equipment to be installed on the machine after the construction phase and facilities for supporting Users on the experimental floor and in their on-site laboratories.

The Laboratory will require good access to the cleaning and processing facilities described in 3.13.3 below. Both the Laboratory and the Cleaning and Processing Facility will be operated by staff within the Vacuum Operations Group, under the control of a Vacuum Operations Support Group Leader.

3.13.3 Cleaning and Processing Facility

The requirements for this facility are discussed in some detail in the report VAC-XX-rpt-013 [3]. That paper considers a number of possible scenarios for the procurement of vacuum vessels and components and the necessary facilities and resources required to meet a production schedule of approximately 102 weeks under each of these scenarios. To summarise that discussion briefly, the assumption is that the most likely requirement is for a facility which will be required during the procurement and construction phase of the diamond Project to process (i.e. clean and vacuum bake) approximately one half of the vacuum components to be installed. The remainder of the components will be processed at manufacturer's premises and will simply require quality assurance acceptance testing on site before installation. This Facility will then provide ongoing support for the diamond Project during the operational phase.

Cranes and lifting gear capable of lifting 200 kg are required in both parts of the facility, which are best situated adjacent to each other.

(a) Cleaning Facility

For the purpose of this exercise, a full cleaning cycle of the type currently employed by Daresbury Laboratory is assumed to be required.

The minimum set of cleaning equipment then comprises

- preclean wash and solvent booths
- a booth capable of housing items up to 8 m x 2 m x 2 m and containing
 - a slurry blaster.

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- a high pressure, high temperature towns water spray wash system, with detergent option
- a high pressure, high temperature demin water spray wash system
- a small self contained slurry blaster
- a solvent cleaning plant with ultrasonic and vapour wash stages capable of holding a vessel 8 m x 1 m x 1 m
- a solvent cleaning plant with ultrasonic and vapour wash stages capable of holding a vessel 2 m x 2 m x 2 m
- a detergent degreasing bath with ultrasonic agitation capable of holding a vessel 8 m x 2 m x 2m
- a washing system using detergent with a wash zone of 1 m cube.
- a specialist ultrasonic and vapour wash system using alcohol for bellows and other sensitive items
- “dirty” and “clean” storage and holding areas.

This will require a floor area of some 340 m² as shown in Table 3.13-1. This facility will also be suitable for the operational phase of the diamond Project.

On the assumption that approximately one half of installed components are to be cleaned, if the facility is operated 16 hours per day, about 72 working weeks will be required to accomplish this.

Table 3.13-1 Size and Costs of Anticipated Cleaning and Processing Facility

Facility	Floor Area (m ²)	Costs (k£)
Cleaning	340	670
Processing	150	1540
General Equipment		200
Building Plant		950
Totals	490	3360

(b) Processing Facility

This is essentially a facility for baking vacuum components prior to installation. The facility discussed here will not provide the facilities for baking an entire assembly of vacuum chambers on a girder. These will require special arrangements and may be

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carried out in a temporary area close to the Storage Ring using a purpose built oven. The facility includes the necessary equipment for carrying out acceptance testing and quality assurance for vacuum vessels and assemblies.

Again the assumption is that approximately one half of all vessels require to be processed in the facilities. Table 3.13-2 shows the number of standard ovens (i.e. capable of baking a vacuum assembly to 250°C) required and the timescale required to carry out this work on the basis of continuous 16 hour days.

Table 3.13-2 Processing Ovens Required and Timescales

Oven Type	Size (m)	No of ovens	Approx no of items	Timescale (wks)
1	8 x 1 x 1	1	65	36
3	2 x 1 x 1	10	2600	146
4	1.5 x 1.5 x 1.5	1	140	76

Although the longest timescale here exceeds the 104 week target, it is probable that by utilising the spare capacity in ovens of type 1 and 4 the timescale could be achieved. However, the facility should be provided with sufficient floor space that extra ovens can be installed should that prove necessary to meet the programme.

Other types of ovens and furnaces for more specialist items are required and are discussed more fully in the detailed paper.

This facility is actually somewhat over sized for the ongoing requirements of the operational phase of the diamond Project.

3.13.4 Vacuum Equipment and Servicing Bays

Facilities are required for servicing mechanical vacuum pumps, instrumentation and vacuum valves. Details will be clarified once the range of equipment is known.

3.14 TECHNICAL INFRASTRUCTURE

Discussions involving representatives of the user community, the technical group leaders within CLRC and the Interim Science Directors have developed a specification of the space required and the type of functions to be carried out in support of Diamond. The spreadsheet below results from these interactions and whilst it is only a guide, it has proved a useful tool to inform discussions on what the Diamond project can provide for itself within the accommodation of the main office block and the circular building, and what it may need to source from CLRC or others.

The programme dates shown in the last column offer some indication of when facilities will be required but are only indicative at this stage. Firmer dates can be included once the detailed project planning exercise has been completed. What is certain though is that significant infrastructure is required to take delivery and test of

D.3 INFRASTRUCTURE AND SUPPORT FACILITIES

accelerator components long before the main office block or circular synchrotron buildings are ready and so early action is required to provide these facilities.

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DIAMOND Office, Laboratory and Workshop inventory											
All dimensions in sq metres											
Function	Staff	Office			Laboratory			Workshop	Store	Location	When needed m/y
		Qty	Area	Total	Qty	Area	Total				
Management										I/O = Inner or Outer Ring M = Main Office Block E = Elsewhere in CLRC	
Directorate	10	5	30	150						M	Building complete 9/04
Resource control	5	2	25	50						M	Building complete 9/04
Accelerator Physics											
Acc Phys group leader	1	1	13	13						M	Building complete 9/04
Acc phys group	5	3	20	60						M	Building complete 9/04
Vacuum											
Vacuum design and development group leader	1	1	13	13						M	Building complete 9/04
Vacuum design and development staff	1	1	10	10						M	Building complete 9/04
Vacuum design and development staff	2	1	20	20						M	Building complete 9/04
Vacuum services and support group leader	1	1	13	13						M	Building complete 9/04
Vacuum services and support staff	5	5	10	50						50 I	Sync Bldg ready 1/05
Vacuum services and support staff	10	5	20	100						E	Pre prod tests 9/02
Development Lab					1	90	90			I/O	Sync Bldg ready 1/05
Valve, pump, gauges servicing bays					3	40	120			E	Vessel pTypes 3/03
General Lab					1	100	100			E	Vessel pTypes 3/03
Integrated UHV cleaning and processing facility								600			
RF											
RF group leader	1	1	13	13						M	Building complete 9/04
RF group technical staff	10	5	20	100						E	Booster Cav Dely 7/03
Low power test area					1	40	40			E	Booster Cav Dely 7/03
High power test area					1	500	500			E	Booster Cav Dely 7/03
Equipment and cryostat spares storage									100	E	SR Cav Dely 7/04

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Function	Staff	Office		Laboratory		Workshop	Store	Location	When needed m/y
RF									
Clean room									
BPM clean room and workshop								E	Booster Cav Dely 7/03
Impedance measurement								E	Booster Cav Dely 7/03
RF lab								E	Booster Cav Dely 7/03
Diagnostics lab								E	Booster Cav Dely 7/03
Electronics workshop								E	Booster Cav Dely 7/03
Computer room								E	Booster Cav Dely 7/03
Pulse power development area								E	Booster Cav Dely 7/03
Gun development lab								E	Booster Cav Dely 7/03
Equipment and spares storage							30 E		Booster Cav Dely 7/03
Survey and Alignment									
Survey group leader	1	1	13						
Survey technical staff	3	3	10	50	50			M	Building complete 9/04 Sync Bldg ready 1/05
Insertion devices									
ID group leader	1	1	13					M	Building complete 9/04
ID technical staff	2	2	10					E	Test generic structure
Magnet measurement					50			E	and assemble first
ID clean assembly lab					250			E	arrays 7/04
Clean magnet storage							150 E		Ditto
Accelerator magnets and power supplies									
Magnets group leader	1	1	13					M	Building complete 9/04
Magnets technical staff	2	2	10					E	Quad p/ypes to test
Assembly, alignment and storage						100		E	and measure 1/03
Temporary storage during construction								E	Ditto
Control Racks assembly						200		E	Racks follow 6/03
Girder assembly						200		E	Girders follow 6/03
Diagnostics									
Diagnostics group leader	1	1	13					M	Building complete 9/04
Diagnostics technical staff	2	2	10	50	50	50		E	As RF

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Function	Staff	Office		Laboratory		Workshop	Store	Location	When needed m/y
Beamline front ends									
Front ends group leader	1	1	13	13				M	Building complete 9/04
Front ends technical staff	3	3	10	30	1	50	50	100 E	Assy starts 9/04
Off-line beamline support areas Totals for 38									
Science group leaders	38	40	13	520				M	Building complete 9/04
Beamline science staff	152	160	10	1600				M	Building complete 9/04
Beamline science staff (near beamlines)	152	160	5	800				O	Sync Bldg ready 1/05
Beamline technical staff	76	12	70	840	40	50	2000	1000 O	Sync Bldg ready 1/05
Beamline users local offices	240	24	60	1440				O	Sync Bldg ready 1/05
Controls (Machine and Beamline)									
Controls group leader	1	1	13	13				M	Building complete 9/04
Development staff	15	8	20	160				25 O/I	Sync Bldg ready 1/05
Control System Development Lab 100m ²					1	100	100	E	Dev starts 1/03
Electronics Support Lab 100m ²					1	100	100	O	Sync Bldg ready 1/05
Electronics Workshop 100m ²							100	E	Dev starts 1/03
Control Areas Rooms with suspended floors									
Linac Instrumentation					1	30	30	I	Sync Bldg ready 1/05
Flight Path					1	30	30	I	Sync Bldg ready 1/05
Booster Synchrotron Instrumentation					4	40	160	I	Sync Bldg ready 1/05
Space Plant Room Booster RF					1	30	30	I	Sync Bldg ready 1/05
Space Plant Room Booster Power supplies					1	30	30	I	Sync Bldg ready 1/05
Transfer Path					1	30	30	I	Sync Bldg ready 1/05
Storage Ring Instrumentation					12	40	480	I	Sync Bldg ready 1/05
Space in Plant Room Storage Ring Power Supplies					1	20	20	I	Sync Bldg ready 1/05
Space in Plant Room Storage Ring RF					1	20	20	I	Sync Bldg ready 1/05
Space in Plant Room Services 1					1	20	20	I	Sync Bldg ready 1/05
Space in Plant Room Services 2					1	20	20	I	Sync Bldg ready 1/05
Physics room					1	100	100	O	Sync Bldg ready 1/05
Control System Computer Room Operational					1	75	75	O	Sync Bldg ready 1/05
Control System Computer Room Development and Reference					1	100	100	E	Dev starts 1/03
Facility control room									
Shift crew 3 office and mess facilities	15	3	10	30				O	Sync Bldg ready 1/05
Machine Control Room (MCR)					1	150	150	O	Sync Bldg ready 1/05

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Function	Staff	Office			Laboratory		Workshop	Store	Location	When needed m/y
Detectors										
Detectors group leader	1	1	13	13						
Detectors development staff	10	10	10	100	1	225	50	25 E	E	Provided by ID Tech Centre?
Data Aq, analysis and automation										
Data Aq group leader	1	1	13	13						
Data Aq development staff	6	6	10	60	1	75	75	25 M	M	Building complete 9/04 Building complete 9/04
Optics development										
Optics group leader	1	1	13	13						
Optics development staff	5	5	10	50	1	75	30	25 O	M	Building complete 9/04 Sync Bldg ready 1/05
Optics metrology staff	2	2	10	20	1	50	50	O	O	Sync Bldg ready 1/05
Sample environments										
Sample environments group leader	1	1	13	13						
Sample environments development staff	12	3	40	120	5	30	150	30	M	Building complete 9/04 Sync Bldg ready 1/05
Synchrotron users										
Rest area										
Seminar rooms		6	30	180					O	Sync Bldg ready 1/05
General purpose rooms		6	30	180					O	Sync Bldg ready 1/05
Dry labs		12	20	240					O	Sync Bldg ready 1/05
Wet labs					12	40	480		O	Sync Bldg ready 1/05
Workshops and storage					12	40	480	960 O	O	Sync Bldg ready 1/05
Reception	4	1	100	100					M	Building complete 9/04

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Function	Staff	Office				Laboratory		Workshop	Store	Location	When needed m/y
Beamline, Machine and building plant rooms											
Mech services group leader											
Elec services group leader	1	1	13	13							
Beamline Mech services divided into 4 quadrants	1	1	13	13							
Beamline Elec services divided into 4 quadrants	4	4	10	40				200		O	Sync Bldng ready 1/05
Water treatment and Air compressor plant room	4	4	10	40				200		O	Sync Bldng ready 1/05
Water cooling farm	2	2	10	20				400		O/I	Sync Bldng ready 1/05
Oil tank farm	2	2	10	20				450		O/I	Sync Bldng ready 1/05
Boiler house									150	O	Sync Bldng ready 1/05
He storage and delivery	2	2	10	20				200		O/I	Sync Bldng ready 1/05
He Compressor house									200	O	Sync Bldng ready 1/05
N2 storage and delivery	1	1	10	10				70		O	Sync Bldng ready 1/05
Storage ring and booster mech services									200	O	Sync Bldng ready 1/05
Storage ring and booster elec services	4	4	10	40				200		I	Sync Bldng ready 1/05
Main transformer pen	4	4	10	40				200		I	Sync Bldng ready 1/05
DC power supply plant room								450		I	Sync Bldng ready 1/05
	2	2	10	20				450		I	Sync Bldng ready 1/05
Computing Facilities											
PC support group leader											
PC support	1	1	13	13						M	Building complete 9/04
Main computer hall	3	3	10	30						M	Building complete 9/04
Ancillary computer rooms					1	30	30			E	? 1/05
Printer/plotter area					3	275	275			M	Building complete 9/04
Main computer group leader					1	25	75			M	Building complete 9/04
Computer operators	1	1	13	13		80	80			M	Building complete 9/04
Fireproof store	3	3	10	30						E	? 1/05
									50	E	? 1/05

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Function	Staff	Office		Laboratory	Workshop	Store	Location	When needed m/y
Engineering design								
Accelerators engineering group leader	1	1	13				M	Building complete 9/04
Beamlines engineering group leader	1	1	13				M	Building complete 9/04
Insertion devices engineering group leader	1	1	13				M	Building complete 9/04
Mechanical engineering design engineers	6	6	10				M	Building complete 9/04
Mechanical engineering design staff	15	15	15			30	M	Building complete 9/04
Electrical engineering group leader	1	1	13				M	Building complete 9/04
Electrical engineering design engineers	2	2	10			10	M	Building complete 9/04
Electrical engineering design staff	4	4	15			10	M	Building complete 9/04
Motor controls engineer	1	1	10	1	20		10	M
Motor controls engineering design staff	2	2	10				10	M
Print room facilities and archive staff	1	1	10	1	60		60	M
Engineering design shared support staff	4	4	10	1	20		10	M
Health Physics								
Health physics group leader	1	1	13				M	Building complete 9/04
Health physics technical staff	2	2	10	1	100	30	I	Sync Bldg ready 1/05

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REFERENCES

- [1] VAC-XX-rpt-002: Cleaning, Vacuum Processing and Testing Facilities for the DIAMOND Project; Initial Thoughts
- [2] VAC-XX-rpt-009: Vacuum Infrastructure Requirements for Diamond
- [3] VAC-XX-rpt-013: Vacuum Infrastructure Requirements for diamond (Part 2)

D.4 Diamond Safety Management

4.1 GENERAL

Diamond safety management will be the responsibility of the Chief Executive of the DIAMOND Joint Venture Company (DLS). Crystallisation of the relationships between OST, DLS and CLRC is expected early in April 2002 and will allow the CEO to determine project safety responsibilities and to define the safety management systems. The following paragraphs are indicative of the safety arrangements that will be established.

4.2 GUIDING PRINCIPLES

It is assumed throughout that DIAMOND safety management will be in accordance with best modern practice as set out principally in :

Health and Safety at Work etc Act 1974

Management of Health and Safety at Work Regulations plus ACOP 1999

Occupational Health & Safety Management Systems – Specification. OHSAS 18001 was published in 1999 and fits closely with the BS EN ISO 14001 standard for Environmental Management Systems.

“Successful Health and Safety Management” : HSG65 2000 : HSE guidance document

Ionising Radiation Regulations plus ACOP : IRR99

The Construction (Design and Management) Regulations 1994.

The model described in OHSAS 18001 and HSG65 contains guidance on six separate safety management elements : Policy, Organising, Planning & Implementation, Measuring performance and Auditing (Checking and Corrective action) and the Management Review of performance to ensure continual improvements. It is widely and successfully used in industry and satisfies the Management of Health & Safety at Work Regulations (Reg 5) which essentially requires that a systematic management approach is adopted.

It is an assumption of this document that although safety management arrangements at DIAMOND (DLSL) may not at present need to meet the most exacting standards required under COMAH or those of the National Installations Inspectorate (NII) for a radiation operating licence, on a ten year timescale the legislative environment is

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likely to tighten and it is therefore prudent to adopt their methodologies now where appropriate.

4.3 POLICY

The DLS project Health and Safety Policy will follow the Health & Safety Policy and subsequently the Safety Health & Environmental policy for CLRC. The Health & Safety policy will be contained within a Safety Health and Environmental Management System (SHEMS) which will be similar to that developed for CLRC and which will act as a top level, stand alone document for construction, operational and maintenance controls. The SHEMS for CLRC contains a series of standard operating controls which include a 'New Build, Processes and Activities' procedure. This procedure will provide direction for the proposed project in terms of the Safety Report and the Health & Safety Plan. The design, construction and operation of the facility will be based on these documents which will be developed by CLRC and DLSL. The SHEMS will be the central reference document and will follow all of the key elements in publications issued by the British Standards Institution and the Health & Safety Executive.

- 1) General intentions
- 2) Aims
- 3) Objectives
- 4) Principles
 - Integrated safety management
 - ALARP
 - Training
- 5) Responsibilities for overseeing management of SHE
- 6) Responsibilities for carrying out SHE duties
- 7) Implementation : Organisation and arrangements

Organisation to include diagrams showing the relationship between DLS/CLRC and others and how specifically safety responsibility is passed down from the CEO and the arrangements for audit and reporting back to the CEO. "An essential pre-requisite for both line and functional management arrangements!"

Arrangements to include :

- a) Reference to the Safety Report and the Safety Plan "This could flow from the New Build, Processes etc Procedure as a standard requirement"
- b) The means for identifying, investigating and recording failures. (Accident, incident and dangerous occurrence investigation, recording and reporting systems) "To be prepared or adopted from existing arrangements and incorporated into the HSEMS so that all other employees working on the site e.g. contractors, comply with CLRC procedures"

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- c) The means for selection and control of contractors and suppliers of goods and services
- d) The methods to be used to identify, assess, document, monitor and control risks
- e) The means of monitoring and measuring to ensure that health and safety standards are maintained
- f) Method statements from contractors, safe working practices, and permit to work systems (issued by or with the knowledge of CLRC)

The most significant outstanding action required to start the policy document is the production of summary organisational diagrams showing the safety management relationship between DLS, CLRC and other contracted organisations and the CEO and named individuals with specific posts and responsibilities within them.

Much more detailed information on how these relationships will work and on how safety management will be implemented may be developed from and will be contained in the Safety Report which are discussed below.

4.4 THE SAFETY REPORT

This document and the work carried out in its preparation are fundamental to successful health and safety management. It may eventually form a significant part of a DLSL SHE Management System. On completion it will allow the CEO to demonstrate that for all phases of the DIAMOND project :

- 1) All operational safety and environmental hazards and related duties under specific statutory instruments have been identified (by carrying out safety risk and environmental impact assessments).
- 2) All risks associated with these hazards have been evaluated by appropriate means
- 3) The necessary measures to prevent, control and mitigate safety and environmental risks have been determined. These measures will apply and be developed for both the engineering design and progressively for the construction, operation, maintenance and de-commissioning of the project.

The Safety Report will consider issues developed from the design and construction Health & Safety File and have a structure similar to the following :

- 1) A description of the site, its environment, the facility and the nature of its use.
- 2) A description of how the facility will be designed, constructed and eventually operated and maintained.
- 3) A section on the methods of risk assessment employed and the steps taken to ensure completeness. This will involve discussion on :

the use of predictive methods,

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how system and operator or user failure will be identified

the use of formal and /or semi-quantitative methods

how human factors in general have been included

4) A summary of the statutory requirements relevant to the project

5) An extensive section on the actual risk assessments and their relationship to the statutory requirements for all aspects of the project.

6) A section on emergency response

7) A summary of the results of the risk assessment exercise including both engineering and management implications.

8) The necessary controls which have been incorporated into the design, construction and operation/maintenance.

9) The relationship between the Safety Report and the SHE Management System-

4.5 THE SAFETY REPORT : DESIGN ASPECTS

The Safety Report must produce the general outcomes in Table 4.5-1 for all the design, engineering and operational aspects listed in Table 4.5-2. It will also cover specific legislative requirements.

There are many existing safety codes in place both at RAL and DL which relate to these aspects. The suitability of these codes for use on DIAMOND should be judged after the risk assessment procedures adopted for the project have been completed. It will not generally be sufficient to cite an existing Safety Code in response to a given risk unless that code contains a management system that is fully complementary with the overall CLRC Health & Safety Policy and the related approach to the DIAMOND Project.

D.4 SAFETY MANAGEMENT

Table 4.5-1 : General Outcomes of the Safety Report for Design Aspects

1	Demonstrate that the facility and its installations have been designed to appropriate standards
2	Demonstrate the use of a hierarchical approach in the selection of risk measures
3	Demonstrate that the facility layout is such as to avoid and minimise risk during operations, testing, maintenance, modification, repair and replacement.
4	Demonstrate that any utilities needed for safety reasons have suitable reliability
5	Demonstrate that appropriate measures have been taken to prevent and effectively contain the release of dangerous substances and radiation.
6	Demonstrate that the materials of construction used in the facility are suitable for the application
7	Demonstrate how safety related control systems have been designed to ensure safety and reliability
8	Demonstrate how systems which depend on human interaction have been designed to take into account the needs of the user and be are reliable
9	Demonstrate that systems storing or using flammable and cryogenic substances have been identified and how equipment has been designed to take account of the risk.

Table 4.5-2 : Design, engineering, operational and maintenance aspects

	Injector shielding		Power Converters
	Storage ring shielding		Electrical Distribution
	Beamline and experiment shielding		Vacuum systems
	Operational radiation protection		Air and water services
	Cryosystems		Compressed gases
	RF systems		Use of chemicals
	Magnet systems		Use of biological materials
	User operations		Access control
	Any environmental aspects		Waste gases, effluents and solids

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4.6 THE SAFETY REPORT : MANAGEMENT SYSTEMS

The Safety Report will describe the management systems that will be put in place to deliver the aims described in the corporate and site policy. The methodology to be adopted will be at least as thorough as that outlined in OHSAS 18001 and HSG65. This will demonstrate a proactive stance to the management of health and safety to a recognised standard and provides a means to ensure that all reasonably practicable steps are taken to control health and safety risks.

The OHSAS 18001 and the HSG 65 documents give guidance on successful health and safety management under five headings:

- Policy
- Planning
- Implementation and Operation
- Checking and Corrective Action
- Auditing and Management Review

The following key elements outline the content of the HSE management system under which the Safety Report will be prepared.

4.6.1 Policy

The Safety Report will be based on the corporate health & safety and environmental policies.

4.6.2 Planning

The Safety Report will describe the SHE objectives which have been agreed on an annual basis by the CEO of DLS and cascaded down through the line management system and linked, where necessary with other organisations. It will describe the SHE management programmes which have been established by DLS to prescribe how the objectives and other requirements are to be completed.

Senior management in DLSL and CLRC will ensure that sufficient resources are allocated to health, safety and environmental issues.

The performance of people with a role in safety management will be measured and they will be held accountable.

4.6.3 Implementation and Operation

Under this heading, the Safety Report will demonstrate how the requirements of OHSAS 18001 and HSG65 will be implemented to ensure that hazards are identified, risks are assessed and control measures are implemented so that consistent control, co-operation, communication and competence are achieved.

D.4 SAFETY MANAGEMENT

This key element will also describe the roles responsibilities and authorities of personnel who manage, perform and verify activities which are included in the project. Ultimate responsibility for the health and safety rests with the Council of the CLRC, the Head of DLS, the Chief Executive of CLRC and the primary Director(s) controlling the design, construction and eventual operation and maintenance of the facility.

The following requirements will be considered:

	The operator has arrangements for systematically assessing the risks arising from normal and abnormal operations and determining necessary control measures.
	The operator has systems for determining priorities and for translating the results of assessments and analysis into a properly resourced Health and Safety Plan.
	The operator has adopted and implemented procedures and instructions for safe operation of the accelerators and beam lines
	The operator has put in place the necessary safety arrangements for planning modifications to or providing additions to the facility
	The operator has arrangements in place to identify foreseeable emergencies and to prepare, test and review emergency plans
	There is a system in place for maintaining appropriate levels of management, employee and user competence
	There are systems for ensuring proper involvement of and consultation with staff and users
	There are adequate communication systems in place on safety and the environment both internally and externally

4.6.4 Checking and Corrective Action

The Safety Report will detail the active and reactive monitoring arrangements to be employed on the facility. These will include :

PART D: INFRASTRUCTURE

	Active Systems
	Routine procedures to monitor the progress of the Health and Safety Plan
	Periodic review of the documentation for all parts of the SHE safety management system
	Systematic inspection and Auditing
	Systematic observation and monitoring of work processes and procedures
	Provision of levels of training and risk assessment programmes and data
	Performance reporting to senior managers, the CEO and the Council

	Reactive Systems
	Triggered by accident, injury or ill-health
	Triggered by potential accidents, injuries or ill-health – near misses
	Triggered by damage to equipment or property

4.6.5 Management Review

The Safety Report will describe in detail “the structured process of collecting independent information on the efficiency, effectiveness and reliability of the total health, safety and environmental management system and drawing up plans for corrective action.” (HSG 65)

4.7 THE HEALTH AND SAFETY PLAN

This will describe how the safety requirements identified for all phases and aspects of the project will be delivered and integrated into the work associated with them. It will identify and give full details on the resources required for delivery of the plan and contain a programme with milestones allowing progress to be monitored and reviewed.

Like the Safety Report, it will be a living document subject to continuous refinement.

D.5 PERSONNEL SAFETY SYSTEM

D.5 Personnel Safety System

5.1 SCOPE OF THE PERSONNEL SAFETY SYSTEM

The role of the Personnel Safety (PS) system is to ensure that personnel are not exposed to the various forms of radiation which can exist inside the shielded enclosures of the diamond complex (the Linac, Booster and Storage Ring enclosures, and the optics and experimental hutches). It achieves this by ensuring that radiation cannot be generated in, or transported to, an enclosure unless:

- the enclosure has been cleared of personnel (by a monitored search procedure),
- all personnel access doors are closed and locked,
- where appropriate, radiation monitors outside the enclosure are below their trip levels,
- all removable elements of an enclosure's shielding are in place.

It is assumed that the PS system will only have to protect against 'prompt' radiation, – which ceases as soon as the source of radiation has been disabled or the appropriate radiation shutter has been closed, and therefore the protected enclosure is safe for occupation. An enclosure can, of course, be kept locked via the PS system to protect personnel from induced activity, – but this will involve some administrative, as distinct from automated, action.

It is proposed that the PS system be entirely separate from the diamond control system, and that it exercises final control over those plant items which enable radiation to be generated in an enclosure or transported to an enclosure (examples are RF systems, magnet power supplies, and radiation shutters). The control system will, however, be used to monitor the state of the PS system to provide operational information, diagnostics and testing facilities; and also operator control of non-safety-specific functions of the PS system such as enabling an enclosure search.

The interlocks provided by the PS system, together with the radiation shielding, and defined operating procedures, are intended to enable diamond to be operated in a manner which will meet the requirements of the Ionising Radiation Regulations 1999 and the supporting Approved Code Of Practice [1].

5.2 FUNCTIONS OF THE PS SYSTEM

This section outlines the basic functions which the PS system will perform. The hardware used to implement these functions is discussed in the next section. The

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functions are essentially the same as those provided for the SRS, which have been proven and refined over time.

A major function of the PS system is to provide the means for ensuring that an enclosure can be reliably cleared of personnel and then kept in this state. It is achieved by a combination of a monitored search function, warning devices and 'Emergency Stop' buttons within an enclosure, and control of an enclosure's access doors.

5.2.1 The monitored search procedure.

Small enclosures, such as experimental hutches, can be most effectively searched by a single person; while larger or more complex ones will require two searchers working together. Prior to searching, all of an enclosure's doors apart from the 'search door' must be closed and locked. The searcher(s) then operate search-point buttons inside the enclosure in a pre-defined sequence which will be designed, for each enclosure, to ensure that all parts of the enclosure are viewed and the searcher(s) follow a path which will 'sweep' people towards the search door without the possibility of anyone entering the areas already searched. The 'two person' search will require pairs of search-points to be pressed simultaneously, so that the searchers cannot get out of step with each other. It may be necessary to use photo-cells or intermediate doors to ensure that no-one can enter an area that has already been searched, - these will be activated at appropriate stages of the search procedure, and anyone passing through them thereafter will invalidate the search. On completion of the search the searcher(s) will leave the enclosure, close the search door, then press a final search-point button outside the door to complete the sequence.

Larger enclosures, such as the storage ring, will be split into several areas which can be searched independently, - if this will enhance the effectiveness of the search and/or is desirable for operational convenience.

An enclosure or area will remain 'searched' until the search is released by operator control. The search will also be released if any of the enclosure's access doors are opened, or if an 'Emergency Stop' button associated with the enclosure or area is operated.

5.2.2 Warning devices, 'Emergency Stop' buttons, and warning periods.

Audible and visual warnings will be provided to alert personnel when a search is in progress. Different, and distinct, warnings will be activated upon completion of the search, for a period sufficient to allow anyone missed by the searchers to press an 'Emergency Stop' button and leave the area. Only upon completion of this period (and if an Emergency Stop is not pressed) will radiation be allowed into the enclosure. Thereafter visual warnings will remain active within the area until the search is released. Certain warning devices will need to be made 'fail-safe' (i.e. radiation will be disabled if the devices are not functioning) to meet the IRR99 Approved Code of Practise.

D.5 PERSONNEL SAFETY SYSTEM

5.2.3 Access control – door locks

The PS system must be able to control the access doors. This can be achieved using electrically-operated door locks (bolts, or magnetic catches), by trapping a door's key in an associated 'key press', or by a combination of these. A mechanical override of the locking mechanism ('crash-out') will need to be provided on some doors.

The number and types of door locks to be used requires further consideration. The accelerator enclosures doors at the SRS are provided with mechanical locks from which the key can only be removed when the door is locked shut. The key must be inserted and turned in a key-press next to the door in order to complete the 'door closed' PS system inputs. The PS system electrically locks the key into the key-press to prevent access. A *single* electric solenoid is used for this, – whereas the door switches and key-press contacts are duplicated to provide the redundancy necessary to provide a sufficient level of protection. The use of a single locking mechanism can be justified as radiation will be disabled as soon as the key is removed from the press, and therefore will not be present in the enclosure by the time that the door is opened (and even less so by the time that a person has entered the door and traversed the labyrinth into the enclosure). It could even be argued that the purpose of the lock is mostly for operational convenience: to prevent an unwanted release of the search.

The situation is different for a hutch door: this forms part of the hutch shielding, and therefore scattered radiation can present a hazard as soon as it is opened by a few centimetres. Such an opening is sufficient to trip the magnetic switches fitted to hutch doors at the SRS, and should this happen while the hutch's radiation shutter is open the PS system closes both this shutter and the port shutter. However, the door is fitted with an electrically-operated door bolt which is activated upon completion of the search; and the PS system will not release the bolt while the hutch's shutter is open. Again only a single lock is used, but the probability of being able to open the door with the shutter open is further reduced by monitoring the bolt's position: it must be extended to allow the shutter to open. Micro-switches within the lock mechanism provide this information; and the bolt will only be operated (extended) when a further micro-switch is operated by proximity to the striker-plate.

For hutch doors at diamond the level of safety which this system provides should be re-evaluated in view of the higher radiation levels there. The speed of closure of the radiation shutters should also be taken into account – it may be slower due to the use of more massive shutters.

5.2.4 Access control – 'Limited Access'

If required, a system of Limited Access will be provided for the Linac, Booster and Storage-Ring enclosures. This will allow a limited number of personnel to enter a searched area without the need to release the search. Each person entering an area will have to carry a token, such as a key, to disable the generation of radiation in that enclosure. The means of ensuring that each person takes a token needs further

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consideration: should it be an automated system, such as one based on turnstiles; or will this task be entrusted to the diamond operations team, as is done on the SRS?

5.2.5 Monitoring

The PS system needs to monitor the classes of equipment outlined below in addition to the personnel access doors:

- Installed Radiation Monitors. These are generally used to ensure that radiation levels outside enclosures are sufficiently low for personnel safety. The Health Physics section will determine where these are required.
- Interlocked shielding. Some parts of an enclosure's shielding may need to be removed sufficiently frequently, and/or by users of the facility, that they will be designed for easy removal. These will be provided with switches or other means of indicating to the PS system when they are in place. Examples are covers on cable labyrinths, roof access panels, and beampipes and chambers on those beamlines where the radiation shielding is provided by these rather than by hutches.
- 'Permit to Work' keys. These keys, or tokens, will be provided as part of the PS system. Removal of a key will ensure that radiation cannot reach a specific part of the diamond facility. The intention is that a key can be locked away, under an administrative system, to ensure that work can be undertaken safely. In particular, an appropriate key must be removed when an un-monitored section of radiation shielding is to be removed.
- Radiation shutters. These are moveable devices which, when closed, attenuate the transmission of particles or photons through a shielding aperture to a safe level. They usually operate within a vacuum chamber.
- Other moveable devices in the vacuum chambers, such as valves, when the insertion of the device could cause a radiation hazard, for example due to beam scattering.
- Equipment, such as RF systems and magnet power supplies, which is controlled by the PS system to prevent the generation of radiation. As with the radiation shutters, these must be monitored so that a 'back-up' system for preventing radiation can be activated should they be in a state not allowed by the PS system.

5.2.6 Logic function

It should be possible to alter, and add to, the logic implemented by the PS system so as to facilitate upgrades and alterations to the facility. However, the logic 'program' must be non-volatile; and there must be a means for ensuring that modifications can only be made under strict control.

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5.2.7 Control of plant items

The PS system must have the unqualified ability to stop the generation of radiation in an enclosure, or its transportation into an enclosure. For this it must have overriding control of certain items of plant, and of radiation shutters. Requests to switch plant on, or to open shutters, will come via the diamond control system, and the PS system will only implement the request if it is safe to do so. It will switch off plant items, or close shutters, whenever it ceases to be safe for them to be on or open; or in response to a request from the control system. (This assumes that switching an item off, or closing a shutter, prevents radiation. This will normally be the case and is also the preferred, 'failsafe', mode of operation.)

A plant item that has been switched off for any reason must not automatically switch back on when the PS conditions to allow it are re-established: a new 'on' request from the control system is required. This is normal safety-system practise, and required by the IRR99 Approved Code of Practise.

The items of plant which the PS system will control have yet to be identified. They will most likely consist of: critical elements within the Linac, RF systems providing power to the accelerating cavities, and power supplies for bending magnets. These items must be designed or specified so that they can be controlled by the PS system with a very high probability that the control will be effective. This may necessitate control by two or more independent means, for example by switching off the RF drive *and* power source to a device providing RF power to accelerating cavities.

Status monitoring of plant items by the PS system (to ensure that its control is effective) may be best achieved by building the monitoring into the equipment, – for example extra contacts on a circuit-breaker; but the control input and monitor output must be designed for maximum independence. Control or monitoring implemented by software is unlikely to provide a sufficiently high level of reliability, and should be avoided.

5.3 SELECTION OF EQUIPMENT TO IMPLEMENT THE PS FUNCTIONS

This section outlines the criteria which need to be considered when selecting system components (i.e. hardware and, possibly, software) to implement the PS functions outlined above. These apply to input devices (such as the switches used to monitor doors and radiation shutters), the connections from these to the logic function, the logic function itself, and output connections to controlled plant items.

The normal practise when designing a safety system is to assess the severity of the hazard posed by the process being controlled, then select the safety system components and architecture accordingly (see for example references [2] and [3]). The IRR99 Approved Code of Practise does not give any guidance in this matter; but in

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view of the severity of the radiation hazard at diamond, system components and architecture should be selected to give the highest probability of ensuring protection.

A decision on the components and architecture to be used for the diamond PS system has not yet been made. However, it is considered that use of the Daresbury Laboratory Personnel Safety System, as used on the SRS, would give an acceptable level of protection. This system also has the advantages of being well tried and understood, and of not using proprietary equipment for which we would be reliant on a single supplier. The level of protection it provides is illustrated by the absence of any occasion on which it has failed to 'danger' on the SRS; and has been quantified theoretically by a recent study of its application to an experimental hutch [4]. This used Fault Tree methodology to determine that the probability of "Failure to ensure that no personnel are in the hutch when x-rays are present" is just over 10^{-8} per hutch search. This result is heavily dominated by the probability of human error in performing the search or responding to warning devices. Failure of the warning devices themselves is implicated in about 25% of this value (the study was undertaken before the warning signs were upgraded to 'failsafe' operation); while the PS logic functions were implicated in less than 1%.

The DL PS system achieves its high level of protection by using the techniques of 'failsafe' operating modes, redundancy, and diversity (discussed below). It is recommended that the diamond PS system should also adopt these techniques.

5.3.1 Fail-safe modes of operation

Components, wiring and logic function are selected to operate in a failsafe mode, whereby the dominant failure mode of a component or procedure will result in the generation or transportation of radiation being prohibited. Examples are that safety is indicated by the presence of a voltage or (preferably) current, by a closed switch contact, or by an operated relay. The fact that such a failure results in a loss of functionality of the facility (or part of the facility) is considered acceptable as long as safety is assured. Experience at the SRS has been that this loss is a small fraction of the total causes of loss of functionality, and this is not unexpected for a system based on robust, simple devices such as switches and relays.

Switches are used in the 'positive break' mode wherever possible. This is an extension of the failsafe principle whereby the unsafe condition, such as opening a door, is arranged to force the switch contacts open. A spring (which may break) is only used to close the contacts, to indicate safety.

5.3.2 Redundancy

The DL PS system is duplicated throughout (input devices, wiring, logic function, outputs), and is periodically tested to ensure that both 'guardlines' are operating correctly. The probability of both guardlines failing to 'danger' between tests is lower than that of a single line (by an amount discussed below). Testing is time-consuming

D.5 PERSONNEL SAFETY SYSTEM

and labour intensive, and automated assistance with this should be considered for the diamond PS system.

5.3.3 Diversity

It is generally accepted that when using two identical devices in a redundant configuration the probability of both failing (to 'danger') is less than that of a single device by a factor in the range of 0.3 to 0.03 (and *not* the square of the probability that a single device fails). This can be improved upon, down to a factor of about 10^{-3} , by the use of diversity, – i.e. devices operating on different principles. An example is the use of a mechanically-operated and a magnetically operated position switch.

5.3.4 The logic function

In addition to making use of the above techniques, the logic function should provide the following facilities:

- It should be a modular, configurable system so that additions and alterations can be made during the lifetime of diamond and, where sensible, sections can be isolated for maintenance and testing while other sections are operational. As mentioned previously, the configuration must be non-volatile, and protected from unauthorised alteration.
- It should provide the diamond control system with information on the status of all PS system inputs, internal logic functions, and outputs. This is to enable the control system to provide information to the operations team on the status of the PS system, provide other de-bugging and testing facilities, and to keep statistics and historical information about the PS system.
- It should provide the facility to latch an input into the 'off' state until a reset request is received, via the diamond control system, at the same time as the input is 'on'. This will be used, for example, to allow a temporary loss of an input to be investigated, – such as when an Emergency Stop button is pressed then reset.

5.4 DESIGN OF THE DIAMOND PS SYSTEM.

This section outlines the decisions which need to be taken before detailed design work can start on the diamond PS system. It is recommended that a formal procedure be set up to approve and record these decisions, together with all aspects of the PS system design, and its interaction with other parts of the facility. A possible framework for this is suggested in reference [5], which covers the whole safety life-cycle of a project from conception, through hazard and risk analysis, safety system design, implementation, commissioning, operation, periodic re-validation, system modifications, and finally de-commissioning.

It may be appropriate to appoint a committee to review and approve design decisions and validation procedures and, once the facility is operational, design modifications, – as is done for example at the Advance Photon Source. This body should have

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sufficient authority to ensure that all disciplines and groups within the diamond design and utilisation community comply with its requirements.

Design decisions should be recorded together with full reasons for the decisions, so that these can be referred to when design modifications are under consideration in the future. As much information as possible should be recorded, including any reasons for rejecting alternatives, – as the original designers may no longer be available when modifications are being considered. All of this information should also be recorded for any design modifications.

The following need to be determined before any detailed design work can commence:

- The division of the facility into shielded enclosures.
- The sub-division (if any) of each enclosure into areas to be searched independently.
- Which enclosures/areas will require a Limited Access facility; and how many keys/tokens should be provided for each.
- How will the use of keys/tokens be enforced.
- Is access between enclosures/areas required during Limited Access.
- Which sections of the facility are required to operate while other sections are not searched (e.g. Injector only; Storage Ring only).
- Which items of equipment will be controlled by the PS system to prevent the generation and transportation of radiation.
- For these, how will the (internal) equipment design ensure that control by the PS system will be effective; and what is the probability of it not being so.
- How will the equipment generate feedback to the PS system on its status; and what is the probability of this being correct.
- Acceptable layouts of experimental hutches so that these can be effectively searched by a single person, taking due regard of the fact that those doing the search will be mostly external users of the facility.
- The number and types of door locks required on enclosure doors and on hutch doors.

The following is a list of some aspects of the physical design and layout of the PS system which will need to be considered:

Racking

- Compatible with (same as?) the control system and/or control-room racking
- Lockable (preferably with a key unique to all PS racks)
- Provision of cooling

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Cabinets (for wiring connections, interface relays, etc)

- Lockable (preferably using the same key as the PS racks)
- Those supplied with mains power should have an internal means of isolating the supply; and a power indicator visible from outside the cabinet
- Ventilation (but should be water proof)

Cabling

- To be in separate trunking to all other services.
- Plastic (or armoured?) trunking – for identification
- Should enter cabinets and junction boxes from below (or otherwise prevent ingress of water)

Test points

- Consideration should be given to the provision of physical access to PS system input and output signals, at suitable locations throughout the facility, for signal testing, and to enable signals to be bypassed for testing and commissioning purposes. Access points should be within locked enclosures.

Power supplies

- Remote monitoring of PS system supply voltages and currents (using the same network as that used to monitor the control system's supplies?)
- Provision of uninterruptable power supplies (UPS), if no site UPS.

The provision of (voice) communication facilities at strategic points in the PS system (racks, cabinets, logic centres) if this is not provided by the diamond infrastructure.

REFERENCES

- [1] "Work with Ionising Radiation – Ionising Radiation Regulations 1999 – Approved Code of Practice and Guidance" HSE books. ISBN 0-7176-1746-7.
- [2] "Safety of machinery – Safety related parts of control systems – Part 1. General principles for design" European standard EN 954-1
- [3] "Functional safety of electrical/electronic/programmable electronic safety-related systems" International standard IEC 61508
- [4] "Reliability Assessment Of X-Ray Hutch Operations at CLRC Daresbury" Report produced for CLRC Daresbury by Serco Assurance.
- [5] "Part 1: General requirements" from reference [iii]

E.1 Accelerator Physics

1.1 INTRODUCTION

This chapter explains the basic design that has been selected for the DIAMOND storage ring and justifies a number of important conclusions that follow from a detailed accelerator physics assessment. However the design team has not so far taken all topics to an equivalent level so that it will be seen that the treatment varies considerably in detail between them. Nevertheless the design concept presented has had its basic feasibility established and this has allowed the specification of all major technical systems to be defined with confidence.

1.1.1 Critical Parameters

The Critical Parameters were defined to be those that were expected to be fixed at the start of the Design Study to set a framework around which the design would be carried out. These were parameters which if changed in the later part of a design study to meet changing demands for the facility could have required a considerable amount of redesign to occur. In practice the values were suggested at the start of the study and agreed in stages in parallel to the design study work. They were widely debated with the user community and supported by both the Scientific and Technical Advisory Committees.

Table 1.1-1 Critical Parameters for the Storage Ring Design.

<i>Parameter</i>	<i>Suggested value</i>
Number of cells / Symmetry	24 / 6
Electron beam energy	3.0 GeV
Electron beam current	300mA
Target beamline apertures	
ID full apertures	up to 10mrads h × 1mrads v
Dipole full apertures	up to 20mrads h × 3mrads v
Free straight lengths for IDs	18 × 5m
(excl 2 for machine components)	4 × 8m
Typical ID portfolio	18 Und; 2 WS, 2 MPW
Minimum beam lifetime	10 hours
Minimum ID gap	10mm
Overall circumference	560 m

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The target beamline apertures were subsequently extended to include the requirement for infrared radiation beamlines and circular dichroism beamlines and Table 1.1-2 summarises the values used.

Table 1.1-2 Target beamline apertures

<i>Beamline:</i>	<i>Horizontal Aperture (mrad)</i>	<i>Vertical Aperture (mrad)</i>
Standard ID	10	1
Standard bending magnet	20	3
Infrared	35	30
Circular dichroism	35	8

1.1.2 Summary of Main Parameters

The main parameters selected for the storage ring operating at the nominal reference tune point are summarised in Table 1.1-3.

Table 1.1-3 Principal DIAMOND Parameters

Energy	3 GeV
Beam current	300 mA
No. of DBA cells	24
Symmetry	6
Circumference	561.6 m
Harmonic no. (500 MHz)	936
ID space available	18 x 5 m, 4 x 8 m
Dipole field	1.4 T
Emittance	2.7 nm-rad
Coupling	1 %
Betatron tunes	27.2, 12.4
Natural chromaticity	-79, -35.28
Dispersion in straights (8m; 5m)	7.2, 5.2 cm
Momentum compaction	1.70×10^{-4}
Natural energy spread	9.61×10^{-4}

1.2 CHOICE OF LATTICE

1.2.1 Achromat Structure

The original concept for DIAMOND [1], [2] was a 16 cell triple bend achromat (TBA) with a circumference of approximately 300 m. The scale of the facility to accommodate sufficient insertion devices for the national user community - within the resources envisaged at the time - led to the choice of 16 cells, whilst the 3 GeV energy arose by considering the spectral output to be produced by multipole wigglers with fields

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peaking at around 1.6 T. TBA lattice cells were chosen for their ability to produce a high brilliance light source in addition to permitting the simple replacement, when required, of the central dipole by a short superconducting dipole in chosen cells to give the same deflection as previously.

This TBA version of DIAMOND was used as an example to estimate the resources and timescales which would be required to replace the SRS with a modern facility. Subsequent refinement of the scientific case for DIAMOND led to a re-evaluation of the basic lattice structure, and it became clear that more appropriate solutions could be derived for the electron beam source properties and for the lengths of the insertion device straights. As a result the lattice for DIAMOND was changed to a double bend achromat (DBA) structure with a resultant improved specification.

1.2.2 Symmetry and Number of Cells

Initial studies were carried out for a 16 cell lattice with two very long straight sections in a two-fold symmetric racetrack configuration. [3] The racetrack lattice comprised 2x20m straights and 14x5m straights (quadrupole to quadrupole separation). The length of the shorter straight sections were optimised to provide an economic source of high flux output from predominately multipole wigglers. The two very long straights were included to provide the potential for very exotic in-storage-ring devices, possibly located in bypass sections.

A further review of the design parameters and lattice layout concluded that there was no strong science case for very long - greater than 10m - straights in a medium energy light source.[4] The specification for long straights in the ring was then driven primarily by the desire to locate all the injection elements in one straight and RF components in another (each taking approximately 8m of space). These additional long straights would be included in the design to give adequate space for high brightness, long period undulators and also provide the potential to support multiple undulator sources of greater complexity, number or length than the standard straight section could provide for.

The final determination of the numbers of cells was driven by two factors, the capacity required to satisfy the current and future needs of the science community, and the delivery of high brightness beams in a flexible manner which provided the potential for improved performance.[5]

The number of cells has a significant effect on the achievable brightness because the emittance of the lattice is proportional to the cube of the bend angle. This means that a 16 cell machine could be expected to have 3 times the emittance of a similarly tuned 24 cell machine. An increase in the number of cells therefore not only increases the capacity of the facility but also relaxes the conditions required to run the machine with low emittance, and reduces the lowest achievable emittance. A 24 cell lattice was chosen as this met the capacity requirements with excellent potential for high brightness beams.

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The science and technical needs had clearly identified the requirement for two different straight lengths. Technically, it was desirable to have the RF and injection systems located in only one straight each, and the previous racetrack design studies had shown that the good dynamic behaviour required for adequate beam lifetime was difficult to achieve in a low symmetry lattice.

The decision was taken to define 6-fold symmetry, based on two advantages: two extra long straights are available for exploitation; and improved lattice dynamic aperture has been found in the 6-fold symmetric lattice.

1.2.3 Straight section lengths

The straight section lengths for DIAMOND have evolved by taking into consideration the recommendations and feedback from various quarters.

The long straight section length was determined by the technical requirements for injection and RF. The standard straight section length was set by the user requirement to provide high brightness undulator beams and the flexibility to include multiple IDs in a single straight.

(a) Accelerator System Requirements

Injection into a 3.0 GeV DIAMOND ring has been studied both for distributed and single straight schemes for the 16 cell DIAMOND racetrack machine [6], [7]. The preferred solution was injection into a single long straight since it was simpler, did not impact on the storage ring magnet aperture requirements, and restricted the competition with user IDs to the utilisation of a single long straight.

Further studies looked at a single straight injection scheme based closely on the Elettra system for various options for the DIAMOND design [8]. It was clear that around 7.0 m of free straight space would be sufficient for injection at 3.0 GeV into a single straight. Figure 1.2-1 shows a schematic for the system and Table 1.2-1 illustrates the parameters for an injection scheme for DIAMOND.

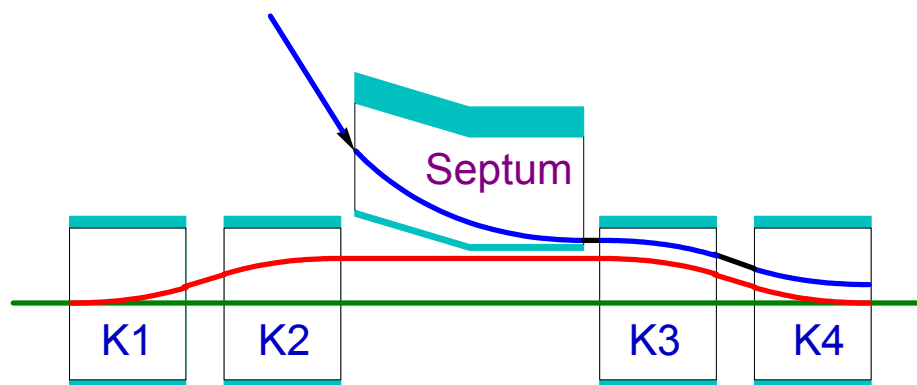


Figure 1.2-1 Schematic of single straight injection scheme.

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Table 1.2-1 Example requirements of a possible injection scheme.

<i>Parameter</i>	<i>Value</i>
Required Space [m]	8.3
Kicker Bend Angle [mrad]	7.3
Septum Bend Angle [mrad]	150
Kicker pair Separation [m]	1.98
Septum Thickness [mm]	3

It has been decided, predominantly for beam stability reasons, to use superconducting cavities. A number of options are presently under consideration, particularly the Cornell design - which is available commercially from ACCEL Instruments GmbH - and the KEK-B system. At the recent Superconductivity for Light Sources Workshop [9] it was strongly recommended that there should be built-in redundancy for reliability reasons.

A superconducting RF system can readily supply the required acceleration voltage, therefore the number of cavities is determined by the total energy loss from insertion devices and bending magnets. Allowing some redundancy 3 Cornell or KEK cavities have been specified, based on conservative operating regimes (see chapter E.3)). The space requirements have therefore been assessed assuming that all 3 cavities are located in a single 8 m straight.

Figure 1.2-2 shows the minimum space needed for 3 Cornell cavities and necessary tapers. This arrangement demonstrably fits into the 8 m allocation. If four cavities are specified for future major upgrades, then at least 10 m would be needed. However an alternative upgrade path maintains three cavities with enhanced performance.

Figure 1.2-3 shows the minimum space required for 3 KEK-B cavities. This arrangement apparently requires slightly more than 8 m, although the precise engineering implications are uncertain at this stage.

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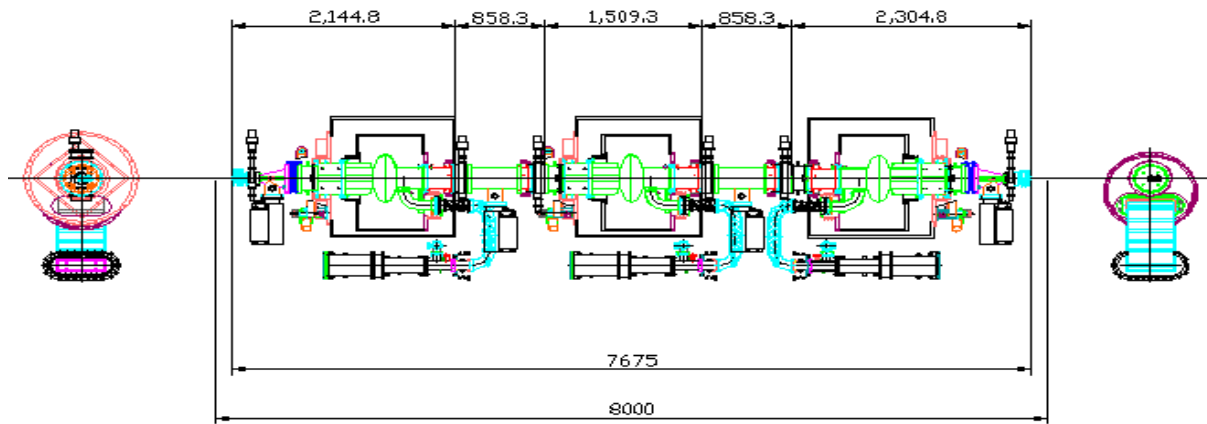


Figure 1.2-2 Three Cornell cavities in an 8m straight.

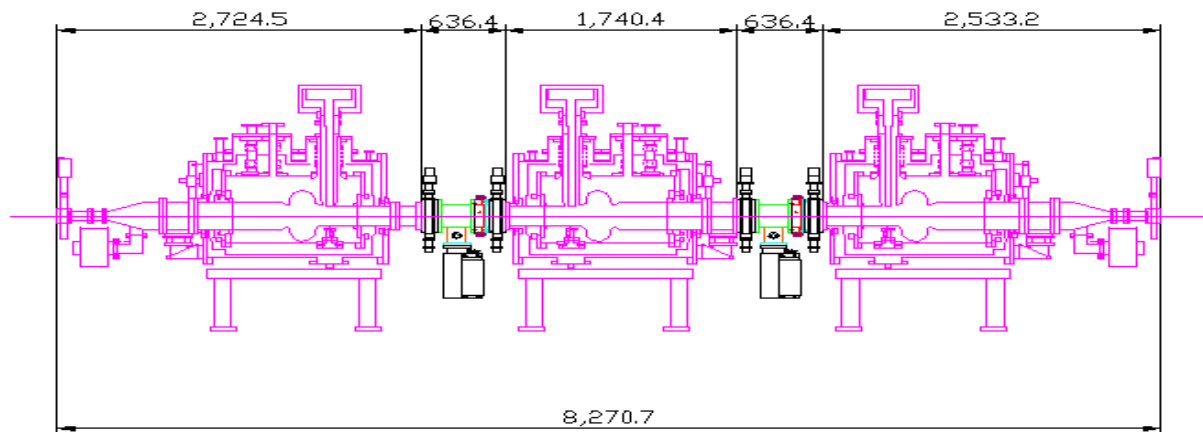


Figure 1.2-3 Three KEK-B Cavities in an 8.3m long straight.

(b) Other Issues

It is envisaged that the exploitation of DIAMOND will involve short (~ 2.0 m) small gap insertion devices. To minimise the gap in these devices the vertical beta function at the centre of the straight should be matched to the device length. As the straight section is lengthened the beta functions at the adjacent quadrupoles tend to increase [10]: Figure 1.2-4 illustrates this increase for different values of beta at the centre of the straight. It is, however, concluded that for the variations in standard straight length being considered this effect is not significant, since the vessel and quadrupole

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apertures specified will be required to accommodate a range of machine tuning to achieve the desired flexibility of operation.

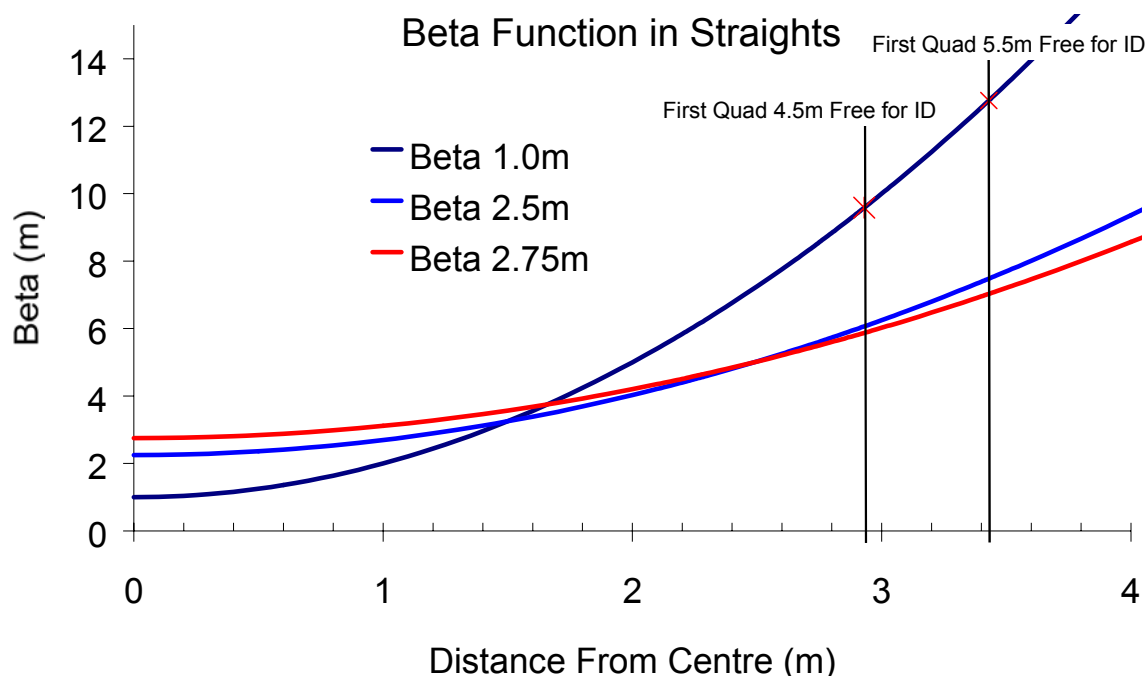


Figure 1.2-4 Variation of beta function through the straight.

Flux scales linearly with length; brightness can scale with (up to) length squared. In neither case will large gains be made by small length increases: other factors could well be more important. For shorter wavelengths, greater gains are obtained by the ability to operate with small magnet gaps. It is therefore important that DIAMOND maintains the ability to deliver small gap devices in the standard length straights. There are also machine and beamline layout issues related to the length of straights which will affect exploitation, for example how near the first optical element can be placed to the source point.

(c) Comparison with Other Light Sources

A review has been made of the straight section lengths in other 3rd generation light sources [11]; this puts the proposed straight lengths into context with other machines. Table 1.2-2 and Figure 1.2-5 summarise this data.

One reason for choosing the DIAMOND standard straight section length of 5.0 m is to allow the possible utilisation of multiple undulator carriages from other light sources. For instance, the 5.0 m DIAMOND straight can accommodate 3 ESRF carriages at 1.6 m each. At this length the standard DIAMOND straight section is towards the upper end of lengths for similar machines, and gives additional confidence that DIAMOND will be able to compete on the world scene with the use of exotic and space-hungry combinations of devices in the future.

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Table 1.2-2 ID straight lengths from a sample of 3rd-generation light sources.

Ring	Space Between Magnets (m)	Reference	Space for ID (m)	Reference
Spring 8 type 1	6.65	Facility Design 1991	4.5	ID Handbook '96
Spring 8 type 2	30.0	Facility Design 1991	25.0	ID Handbook '96
ESRF	6.34	Red Book 1987	4.8	Red Book 1987
BESSY II type 1	5.74	Light Source Data Book 1996	4.7	Parameter List March '95
BESSY II type 2	4.9	Light Source Data Book 1996	3.9	Parameter List March '95
SLS type 1	4.0	SLS Handbook 16/3/98	3.2	SLS Annual Report '99
SLS type 2	7.0	SLS Handbook 16/3/98	6.2	SLS Annual Report '99
SLS type 3	11.76	SLS Handbook 16/3/98	10.6	SLS Annual Report '99
SOLEIL type 1	7.0	SOLEIL APD	~6.0	ID Length used in APD
SOLEIL type 2	14.0	SOLEIL APD		
Elettra	6.0	CDR 1989	4.8	CDR 1989
APS	6.72	CDR 1987	5.2	CDR 1987
ALS	6.75	Light Source Data Book 1996	5	CDR 1986
PLS	6.8	Light Source Data Book 1996	4.3	WWW
CLS	4.5	Tec Rep 2.1.15D Oct99		
MAX II	3.136	Light Source Data Book 1996	2.6	WWW
DIAMOND type 1	6.36		5.0	
DIAMOND type 2	9.36		8.0	

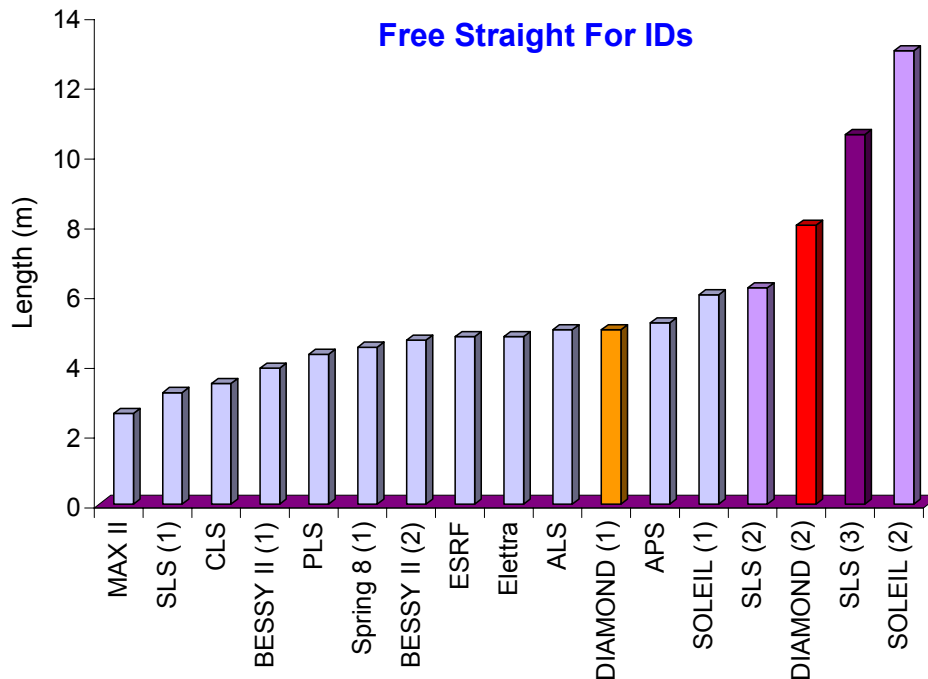


Figure 1.2-5 Comparison of straight lengths for IDs.

(d) Conclusion

To summarise, the DIAMOND free straight lengths for IDs have been set at 5 m to provide high brightness beams in a world class facility. The length of the six longer straights has been set to supply 8 m of free space, based on the requirements for RF and injection; this also meets the requirement to include some straights which have the flexibility to accommodate long period undulators, complex and space-hungry combinations of IDs, and other possible source developments.

1.2.4 Layout

The component layout of DIAMOND has evolved to take account of two sets of requirements, each of which having an impact on the other: these are the mechanical constraints on component separations and the length of components in the ring, and the linear and non-linear lattice requirements needed to produce a ring with stable high brightness sources, good lifetime, and efficient injection. The major constraints in both these area are summarised in Table 1.2-3 and Table 1.2-4.

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Table 1.2-3 Main mechanical constraints.

1	Radiation absorber space requirements
2	Required magnet to magnet separations
3	Required magnet to beam monitor separation
4	Requirements in the dipole crotch area
5	Space required to isolate the beam monitors adjacent to the ID straights
6	Valves and bellows space requirement

Table 1.2-4 Main lattice considerations.

1	Low emittance
2	Reasonable maximum beta functions
3	Reasonable source point lattice functions
4	Lattice functions matched to injection requirements
5	Adequate momentum aperture determined by off momentum dynamics
6	Monitor and correctors required for correction of fast and slow beam motion

Figure 1.2-6, Figure 1.2-7 and Figure 1.2-7 illustrate the layout for the main magnetic elements in the lattice.

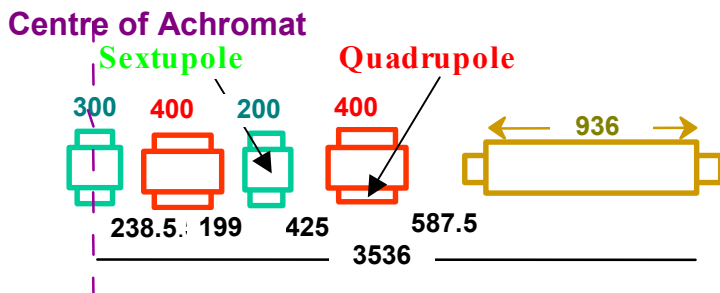


Figure 1.2-6 Half of the achromatic arc.

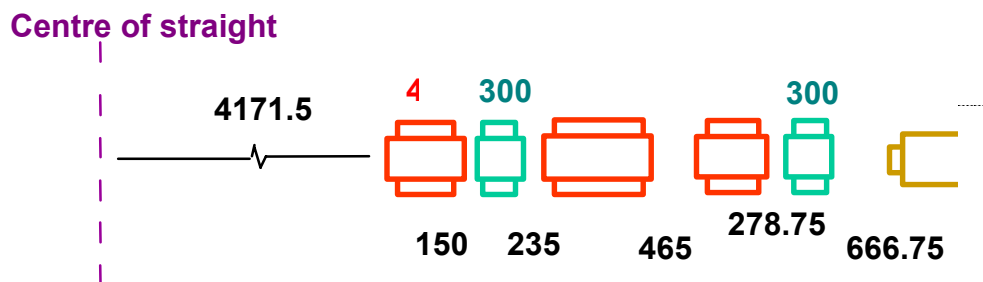


Figure 1.2-7 Half of a standard ID straight.

Centre of straight

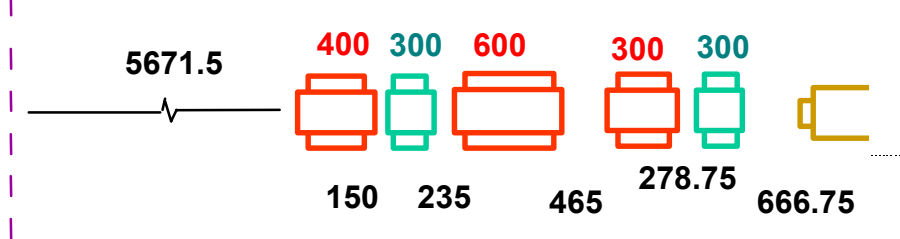


Figure 1.2-8 Half of a long straight.

1.2.5 Linear Matching

Traditionally, a double-bend achromat is tuned to give zero dispersion in the straight sections. The natural emittance of the lattice is determined by the beta and dispersion functions at the entrance to the dipoles. The minimum emittance that can be achieved under the zero-dispersion condition is [12]

$$\varepsilon_{\min} = \frac{2\pi^3 C_q \gamma^2}{\sqrt{15} N_b^3 J_x} \quad (1)$$

where C_q is the quantum constant, γ the relativistic factor, N_b the number of bending magnets in the lattice, and J_x the horizontal damping partition number.

If dispersion is allowed in the straight sections, then the minimum emittance is reduced by a factor of three; analytic expressions can be given for the required values of the beta and dispersion functions at the entrance to the dipoles to achieve this minimum [13]. Expression (1) for a 3 GeV, 24-cell lattice gives a theoretical minimum emittance of 1.9 nm-rad with zero dispersion in the straights, or 0.64 nm-rad if dispersion is allowed.

The drawback of reducing the emittance by allowing dispersion is that the effects of emittance growth due to the IDs in the straight sections can be increased. In principle, we can achieve the target emittance for DIAMOND without allowing dispersion in the straights. In practice, however, this requires stronger focusing, increased chromatic effects and a consequent reduced dynamic aperture. Also, engineering constraints make it difficult to achieve the optimum conditions for low emittance. This then leads to the necessity of allowing some limited dispersion to reach an emittance of less than 3 nm-rad.

The optimised linear solution aimed to fulfil the main lattice requirements outlined in Table 1.2-4 above, was achieved through an optimisation process which involved matching to achieve some basic linear requirements such as reasonable emittance and beta functions, followed by non-linear optimisation and characterisation of this linearly matched solution. Table 1.2-5 shows a typical set of criteria used during the

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linear matching. Several different linear solutions in various areas of the working diagram were investigated before the current reference solution was obtained with well optimised non-linear behaviour. Table 1.2-6 and Figure 1.2-9 summarise some tune points investigated during the optimisation of the DIAMOND lattice.

Table 1.2-5 Typical linear matching criteria.

1	Reasonable maximums for β_r and $\beta_v \leq 35$ m
2	Reasonable beta split at the centre of the achromat
3	Reasonable dispersion at the centre of the achromat > 0.25
4	Dispersion at the centre of the standard straight > 0.04 m but ≤ 0.1 m
5	β_r at the centre of the standard straight ≤ 5 m
6	β_v at the centre of the standard straight ≤ 2.5 m
7	β_r at the centre of the long straight > 10 m
8	β_v at the centre of the long straight ≤ 8 m
9	Integer part of horizontal tune < 0.5
10	Integer part of the vertical tune < 0.5
11	Working point clear of systematic, structure resonances
12	Working point clear of non-systematic resonances
13	Natural chromaticities $\xi_r > -120$, $\xi_v > -50$
14	Sextupoles in the high dispersion region $ K_2 < 45$ T/m
15	Natural radial emittance < 3 nm-rad
16	Natural radial emittance > 1.5 nm-rad
17	$\alpha_r, \alpha_v = 0$ at the centre of the "achromatic" arc
18	$\alpha_r, \alpha_v = 0$ at the centre of the ID straight sections

Table 1.2-6 Summary of tune points investigated

Reference No	Description	Q_x, Q_y	Plot ref.	Point
LAT02-iss01	Increased Circumference four fast correctors	28.88,10.75	Black	1
LAT04-iss01	Below $\frac{1}{2}$ integer , Correctors Adjacent to the ID	29.16,11.35	Blue	2
LAT05-iss01	Lower horizontal tune region	27.16,12.59	Red	3
LAT05-iss04	Lower horizontal tune vertical below $\frac{1}{2}$ integer.	27.23,12.36	Pink	4
LAT05-iss11	Low chromaticity	26.25,12.17	Purple	5

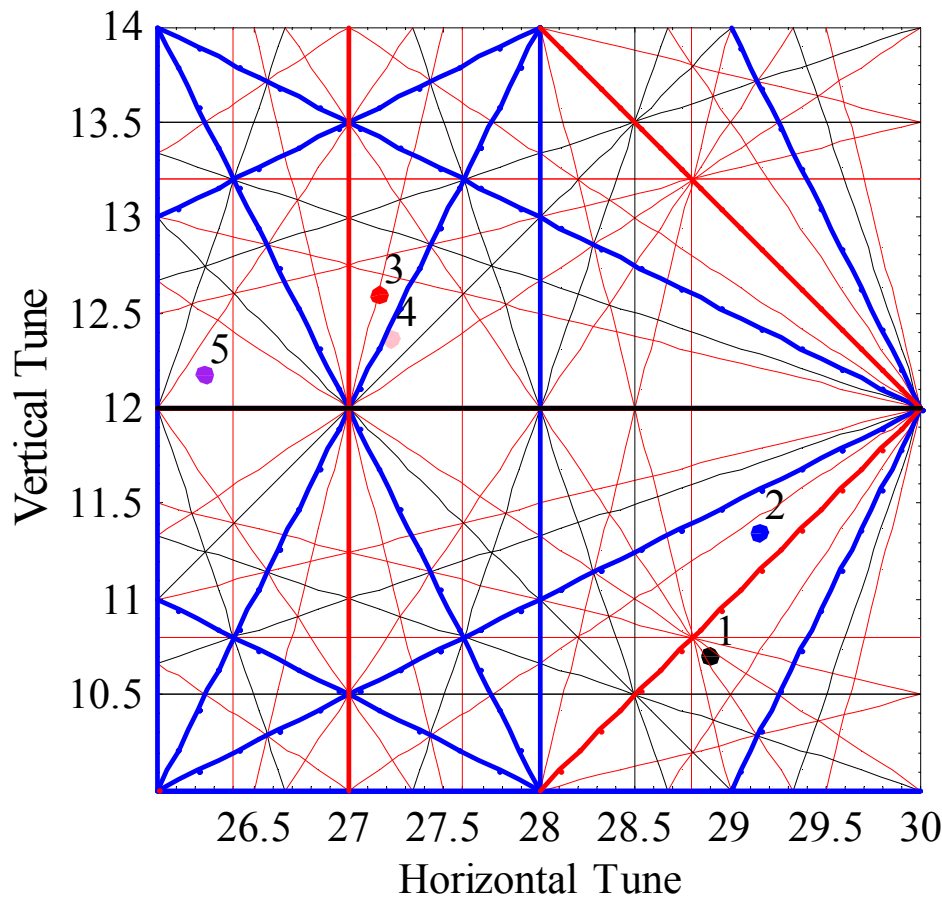


Figure 1.2-9 Some tune points investigated in detail during the lattice optimisation.

In general the natural emittance decreases with higher horizontal tune but the chromaticity and the maximum betatron functions increase.

(a) The reference point

The chosen reference lattice for the DIAMOND design study is tuned to point 4 ●. The matched solution for this tune point meets all the criteria in Table 1.2-5 and the non-linear optimisation showed that this solution was able to provide good dynamic aperture and also good momentum aperture.

The optical functions for the reference solution are shown in Figure 1.2-10 and the basic lattice properties in Table 1.2-7.

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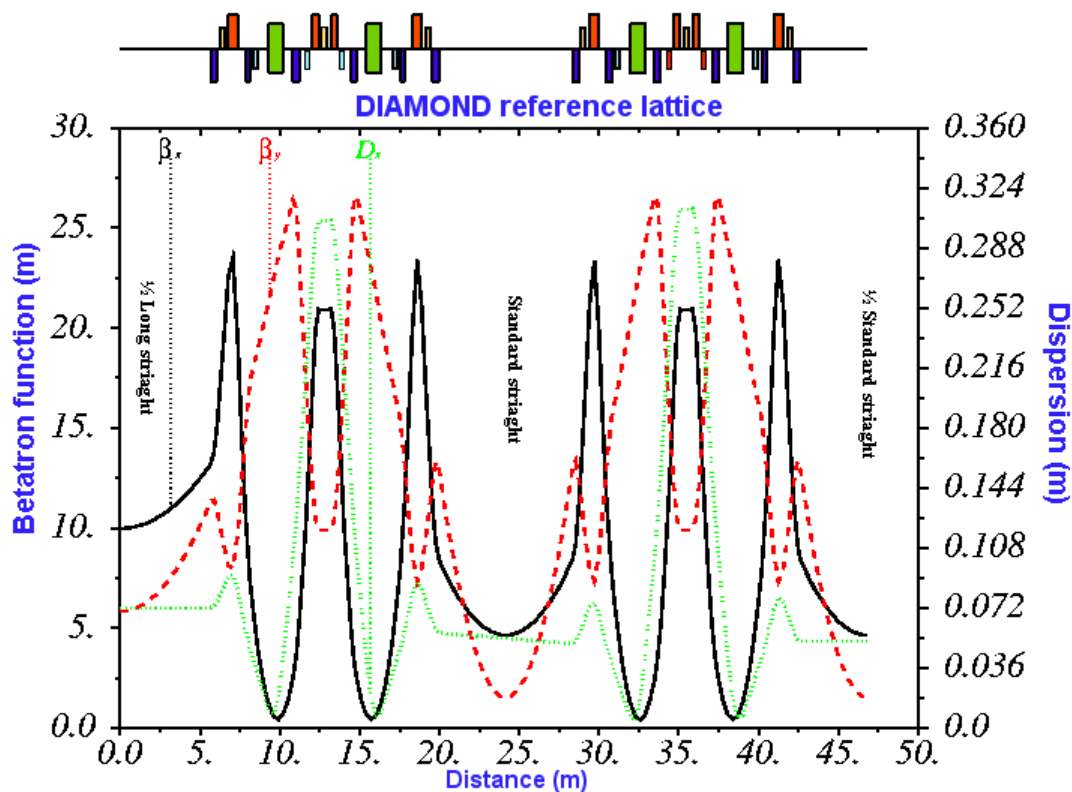


Figure 1.2-10 Lattice functions for the reference point over $\frac{1}{2}$ of a superperiod.

Table 1.2-7 Basic lattice properties of the reference lattice.

Maximum horizontal beta function [m]	22.6
Maximum vertical beta function [m]	26.6
Maximum dispersion [m]	0.311
Horizontal Beta function, rf/inj/Longer ID straight [m]	10.0
Vertical Beta function, rf/inj/Longer ID straight [m]	5.8
Horizontal Beta functions, standard ID straight [m]	4.7
Vertical Beta functions, standard ID straight [m]	1.5
Dispersion, rf/inj/Longer ID straight [m]	0.072
Dispersion, standard ID straight [m]	0.052
Horizontal Tune	27.226
Vertical Tune	12.36
Natural horizontal chromaticity	-79
Natural vertical chromaticity	-35
Natural emittance [nm rad]	2.74
Momentum compaction	0.00017
Energy Spread	0.000961
Radial damping time [ms]	11.2
Vertical damping time [ms]	11.2
Longitudinal damping time [ms]	5.6

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(b) Zero dispersion

It could be desirable to operate DIAMOND with zero dispersion in the straight sections, although this will increase the natural emittance. To illustrate the possible properties of such an operating mode, lattice solutions with fully achromatic bends - producing zero dispersion in the straight sections - have been studied. Lattice functions for an example solution are shown in Figure 1.2-11, and the basic lattice properties are summarised in Table 1.2-8.

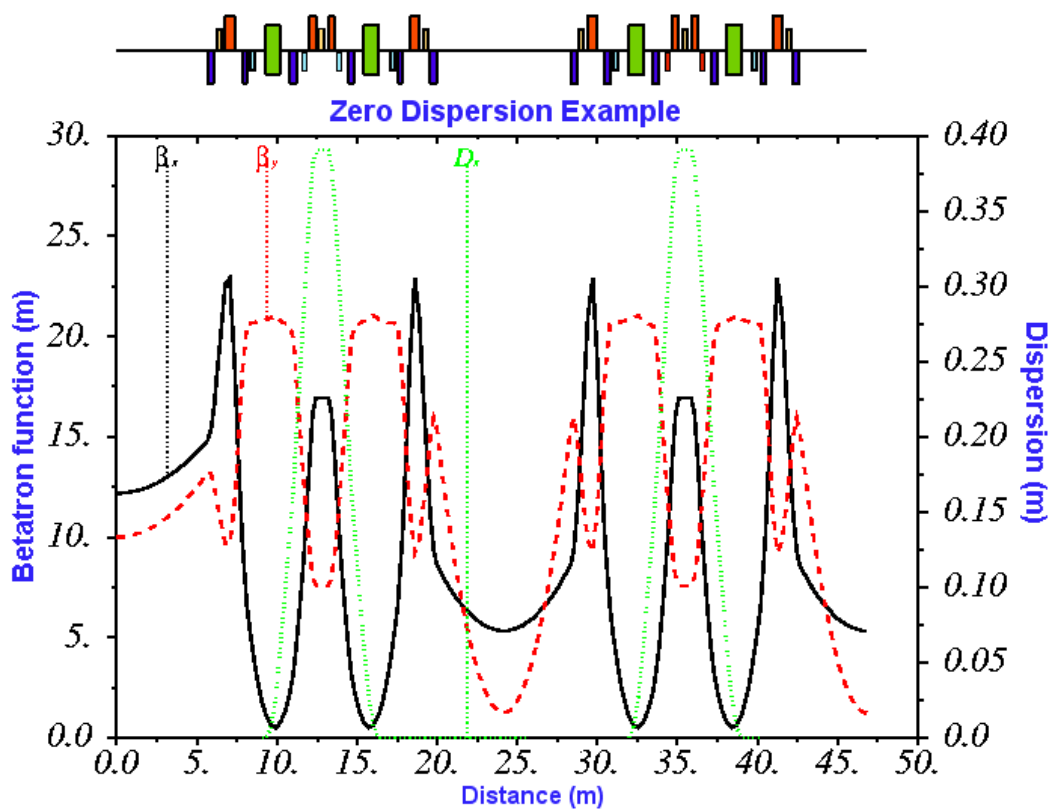


Figure 1.2-11 Lattice functions for a zero dispersion solution for $\frac{1}{2}$ of a superperiod.

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Table 1.2-8 Basic lattice properties of a zero dispersion solution.

Maximum horizontal beta function [m]	22.6
Maximum vertical beta function [m]	20.9
Maximum dispersion [m]	0.39
Horizontal Beta function, rf/inj/Longer ID straight [m]	12.2
Vertical Beta function, rf/inj/Longer ID straight [m]	10.0
Horizontal Beta functions, standard ID straight [m]	5.34
Vertical Beta functions, standard ID straight [m]	1.23
Dispersion, rf/inj/Longer ID straight [m]	0
Dispersion, standard ID straight [m]	0
Horizontal Tune	26.28
Vertical Tune	12.22
Natural horizontal chromaticity	-71
Natural vertical chromaticity	-35
Natural emittance [nm rad]	6.5
Momentum compaction	0.00023
Energy Spread	0.000961
Radial damping time [ms]	0.011243
Vertical damping time [ms]	0.011211
Longitudinal damping time [ms]	0.005597

1.3 NON-LINEAR OPTIMISATION AND DYNAMIC APERTURE

1.3.1 Driving Terms

Compact strong-focusing achromatic lattices which give a small equilibrium emittance require strong quadrupoles; the strength of these quadrupoles entails a large natural chromaticity to be corrected within the achromat, which in turn produces large non-linear kicks in the equation of motion for the circulating electrons. Achieving a large dynamic aperture is in essence the process of cancelling out the effects of these kicks by the suitable arrangement of phase advances between them, or by the use of additional sextupoles so that the overall non-linear effect is minimised. It must be stated in advance that even with a supposedly ideal arrangement of sextupoles, error effects will always place a limit on what cancellation can be achieved, and so a critical part of any optimisation procedure is to determine the significance of the errors likely to be present in the real machine

All descriptions of the dynamics in a periodic potential with non-linear terms are essentially equivalent to considering the terms in the expansion of the Hamiltonian for the equation of motion. For instance, in Bengtsson's treatment [14], sextupoles are treated as a perturbation of the linear Hamiltonian (which may not be valid for strong sextupoles and/or at large particle amplitudes). Terms in the expansion with different frequencies (i.e. different multiples of the phase advance) are collected together, and integrations over the fields from the various elements can be replaced by summations,

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which assumes that the betatron functions within each element are constant, or equivalently that the phase advance across each element is negligible. This in reality is not true, and is one of the limitations in the application of this optimisation technique.

The single resonance approach[15] attempts to suppress the overall strength of all the driving terms by an appropriate arrangement and use of sextupole families, and has been successfully applied in several lattices (for instance, the ESRF [16] and SLS [14]). This approach assumes that a single resonance dominates the dynamics; however, in modern lattices with low periodicity, many resonances may contribute to the degradation of dynamic aperture, so that again there is a limitation to the validity of this technique.

However, setting aside the above provisos, we can write the driving terms in the Hamiltonian. To first order in sextupole strength there are 9 terms [14], whose strengths are proportional to

$$h_{jkmp} \propto \sum_n^{N_{\text{sext}}} (b_3 L)_n \beta_{xn}^{\frac{j+k}{2}} \beta_{yn}^{\frac{l+m}{2}} \eta_n^p e^{i[(j-k)\varphi_{xn} + (l-m)\varphi_{yn}]} - \left[\sum_n^{N_{\text{quad}}} (b_2 L)_n \beta_{xn}^{\frac{j+k}{2}} \beta_{yn}^{\frac{l+m}{2}} \eta_n^p e^{i[(j-k)\varphi_{xn} + (l-m)\varphi_{yn}]} \right]_{p \neq 0} \quad (2)$$

The $(b_2 L)$ and $(b_3 L)$ are the integrated strengths of the individual quadrupoles and sextupoles, and the second set of terms in equation (2) only contributes to the chromatic terms ($p \neq 0$).

There are 4 chromatic terms:

- h_{11001} and h_{00111} are just the chromaticities.

From equation (2) it can be seen that the quadrupoles and sextupoles contribute additively to these terms, independent of the betatron phases φ_x and φ_y . These terms should be compared with the traditional integral form for the chromaticities, with which they are equivalent:

$$\xi_x = \frac{1}{4\pi} \oint_C [2b_3(s)\eta_x(s) - b_2(s)]\beta_x(s)ds, \quad \xi_y = \frac{1}{4\pi} \oint_C [-2b_3(s)\eta_x(s) + b_2(s)]\beta_y(s)ds \quad (3)$$

- h_{20001} and h_{00201} drive off-momentum resonances and cause beta function beats $\partial\beta/\partial\delta$

There are also 5 geometric terms:

- h_{21000} and h_{10110} drive integer resonances of type Q_x .
- h_{30000} drives 3rd-integer resonances of type $3Q_x$.
- h_{10200} and h_{10020} drive coupling resonances $Q_x \pm 2Q_y$.

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Apart from the chromaticity terms, in general each sextupole and quadrupole will contribute as a complex number to the overall summation. It is helpful to view these as vectors on the Argand diagram – see for example Figure 1.3-1. For a particular lattice layout, the individual terms from the many sextupoles (168 in the case of DIAMOND) will change as their strength changes or as the phase advances in the lattice change; these must be adjusted so as to ideally cancel with the quadrupole terms (of which there are 240 in DIAMOND), which change in the same way.

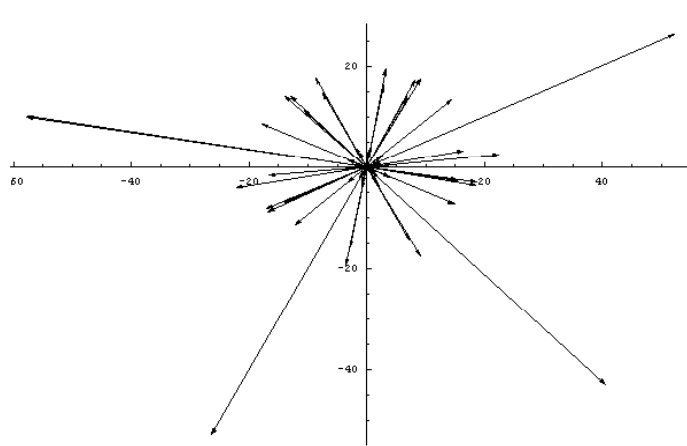


Figure 1.3-1 The contributions to h_{20001} from individual elements for an example DIAMOND solution.

There are also 13 terms of 2nd-order in sextupole strength:

- 3 terms giving linear tune shift with amplitude $\partial Q/\partial J$
- 8 octupole-like terms driving resonances $4Q_x, 2Q_x \pm 2Q_y, 4Q_y, 2Q_x, 2Q_y$
- 2 terms generating the second-order chromaticities.

Each of the standard lattice tools used in this study optimise on a subset of these driving terms. For example, MAD works upon approximate forms for the second-order chromaticities and tune shifts with amplitude, together with a generalised resonance strength term which is based around the first order resonance terms. OPA [15] (the SLS code developed from OPTICK) works principally on the 9 first-order terms; the DL tool Madtomma can work on any of the terms. The expressions for individual terms can differ by a constant due to the method used to arrive at them, but since in practical optimisation different weightings are applied to them anyway this is not a problem. However, these possible differences should be borne in mind when comparing numerical values for the same term in different codes.

A given lattice layout and sextupole setting will allow a single complex number to be arrived at for each driving term, calculated simply as a sum across all the elements. If there are n sextupole families influencing m considered driving terms, then for a particular layout these sums can be written as an $m \times n$ matrix, the object being to

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minimise each of the driving terms. The weightings are then used to adjust an overall objective function, which hopefully characterises the quality of each set of sextupole settings.

1.3.2 Numerical Optimisation

Once a set of sextupole families and starting setting have been chosen, numerical optimisation proceeds by trying to minimise the overall objective function by one of several similar methods, which differ in detail amongst different codes but which are all essentially the same, each variable (free parameter) in the objective function corresponding to one sextupole family. MAD uses the HARMON module, which works using successive minimisation along the steepest gradient (similar to Cauchy's method[17]). OPA minimises along each co-ordinate in turn, iterating around the free parameters. Madtomma utilises the downhill simplex method, Figure 1.3-2 illustrates three successive steps in a downhill simplex minimisation of Rosenbrock's function, a function often used to test the efficiency of numerical methods of optimisation. The contours of the objective function are shown (where the number of system parameters n is 2). A initial simplex is constructed comprising $n+1$ points, and an algorithm iterates this point set by eliminating the worst point at each iteration and replacing it with a new one calculated using the properties of the others points. This has been shown to be one of the most efficient of the classical minimisation methods [17]. All these methods iterate until some specified tolerance on the objective function has been reached, no further improvement is possible, or an iteration limit is gone past.

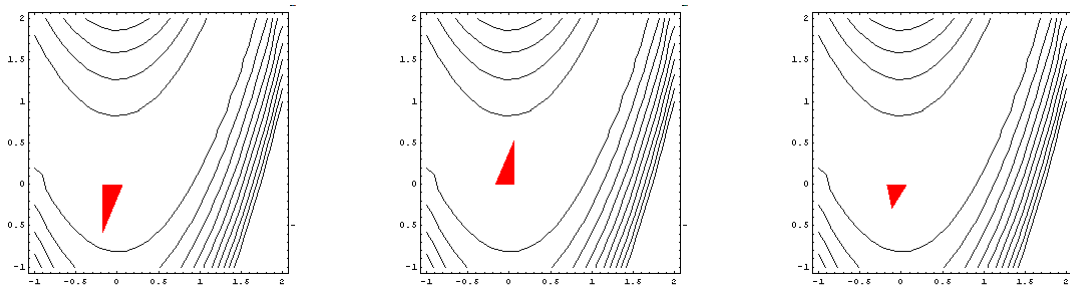


Figure 1.3-2 Three successive steps in a downhill simplex minimisation of Rosenbrock's function.

Ideally, optimisation will not just minimise the overall sum across the driving terms but will try to zero them individually, as an overall sum of zero will in general still have non-zero individual driving terms, each of which can disturb the dynamics. Since the dynamics problem above can be reduced to a linear $m \times n$ matrix, it is clear that we need at least $n = m$ sextupole families to eliminate m driving terms. Fewer sextupole families leads to an over-constrained system for which an ideal solution may not exist; this is the usual case in real problems, and a judgement must be made for each particular problem as to how to cope with this.

It is not sufficient to decide upon a sextupole arrangement, and then to allow a completely automatic minimisation to take place. The first constraint is of course on

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sextupole strengths, which will in reality have limited gradient. It is also a good idea to limit the sextupole strength as this will reduce the sensitivity of the solution to errors, and to limit the ‘competition’ of one driving term against another: automatic solutions with large strengths indicate that perhaps another arrangement is necessary.

1.3.3 Chromaticity Correction and Sextupole Location

For purely chromaticity correction 2 families are needed, which are placed in regions of large dispersion to minimise their strength; equation (3) shows that the sextupoles for horizontal correction should be at large horizontal beta and those for vertical correction at large vertical beta. Ideally there should be a phase advance of π between the sextupoles (the so-called $-I$ transformer), and no interleaving of families so as to avoid crosstalk between them (i.e. higher-order terms). Neither of these is possible in a compact lattice, so interleaved schemes are necessary, which use harmonic sextupoles to correct for the lack of cancellation. In addition, a non-interleaved scheme amplifies the chromatic mode which can lead to a limited momentum acceptance [18].

Looking at equation (2) one might think that placing sextupoles adjacent to all the quadrupoles is the best system, as this cancels all the chromatic modes where they are created. However, this reduces the flexibility of the lattice [18] and does not allow general correction of any chromaticity generated in the (almost) dispersion-free straight sections - for instance, by the insertion devices.

1.3.4 Phase Advance Selection

The usual compromise interleaved solution is to have partial cancellation over cells, selecting an appropriate horizontal phase advance for small equilibrium emittance. In DIAMOND, the solution chosen was to have a detuned $5\pi/2$ horizontal phase advance per standard straight cell, giving cancellation over 2 cells, with a detuned π phase advance vertically, as shown in Figure 1.3-3. For each sextupole family, cancellation was achieved vertically between successive sextupoles and horizontally every two sextupoles. Interleaving necessarily introduces crosstalk, and the different phase advances in the long straight triplet insertion disturbs the sextupole cancellation. The overall tune for the 24 cell DIAMOND lattice was then in the region of (29,12), (see tune points 1 and 2 in Table 1.2-6) and for the initial working point investigation this was detuned as little as possible whilst finding a relatively resonance-free working point.

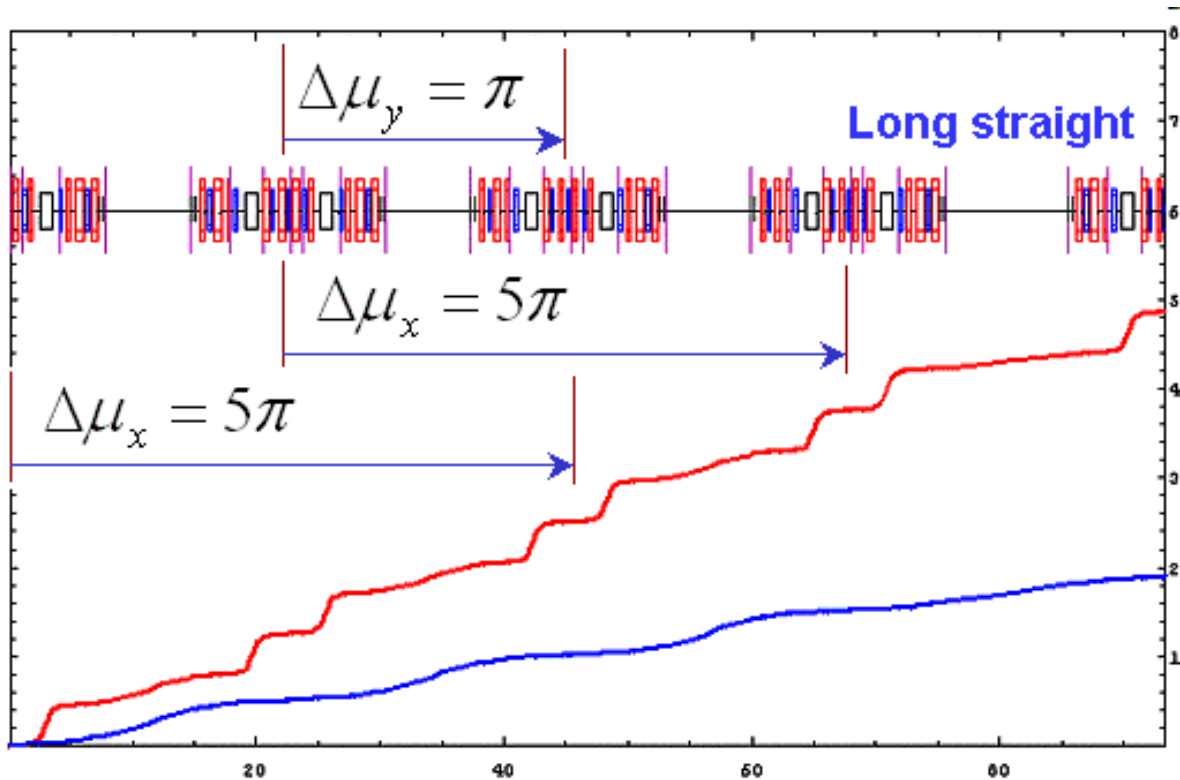


Figure 1.3-3 Phase advances at the higher horizontal tune point.

The strict requirement for phase advances in terms of phase advance per cell outlined above, combined with the other linear matching requirements resulted in lattice solutions which had relatively large betatron functions and natural chromaticity, although the high horizontal focusing in the standard cells required to reach $5\pi/2$ phase advance did produce low emittance solutions easily.

Other regions of tune space with lower horizontal phase advances in the standard cells were characterised in terms of their non-linear behaviour and dynamic stability, and found to produce comparable - if not slightly better - results with generally lower maximum betatron functions in both planes.

1.3.5 Selection of Harmonic Sextupole Families

The DIAMOND lattice consists of 6 superperiods each comprising 3 short cells followed by a long cell. Since the phase advances in the triplet sections going into the long and short straights are necessarily different, due to their different length, we would expect the strength required from the harmonic sextupoles in the long insertions to be different to that in the short insertions, even with an ideal phase advance. This suggests allowing the long insertion harmonic sextupoles to be different families from the short insertion ones, giving 4 free parameters for the optimisation.

To provide extra free parameters additional families of harmonic sextupoles can be provided. After an investigation of the effect of various sextupole family distributions,

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two extra families were chosen, placed so as to be symmetric with respect to the long straight sections. There is some justification in doing this in that a symmetric placement of the harmonic sextupoles will give a symmetric distortion of the off-momentum betatron functions.

Overall, this results in a lattice with up to 8 families of sextupoles, including the chromatic correction sextupoles between the dipoles. The arrangement of the sextupole families within half of a superperiod is shown in Figure 1.3-4. Eight families is a relatively large number, although the SLS has operated with a large number of sextupole families, and the latest SOLEIL lattice relies on having 10 families to provide enough free parameters to compensate all driving terms that need to be corrected for.

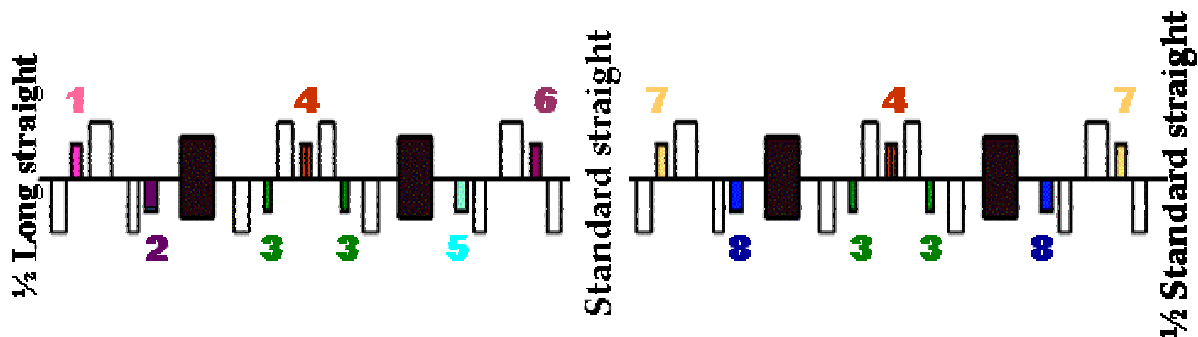


Figure 1.3-4 The sextupole family arrangement in half a superperiod.

In DIAMOND the sextupoles will be powered individually: this gives complete flexibility to increase or change the number of families in the future if required.

The general optimisation route chosen was to start from a symmetric setting of the harmonic sextupoles, i.e. as if they were only 2 families, and to use additional families as perturbations on the starting settings. For efficient correction, the chromatic sextupoles were used to correct the majority of the chromaticity.

The idea of using additional families to provide perturbations on the basic 2-family solution is justified as it can minimise the beating of the off-momentum betatron functions: if the harmonic sextupole families in each type of insertion are too different from each other, then this beating can be strong, leading to large off-momentum beta functions in some locations in the lattice and a consequent loss of momentum acceptance from the physical aperture. So this approach must be balanced against the requirement to provide free parameters for the minimisation of the driving terms in an effective manner.

1.3.6 Working Point Optimisation

The aim for the design study was to produce a reference lattice solution, which met all the requirements for DIAMOND in terms of emittance, lifetime, sensitivity to errors

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etc. The basic lattice structure that produced that solution had to be flexible enough to be tuned to operate under different conditions such as those required to run at alternative tune points and with zero dispersion.

The dynamic behaviour proved sensitive to the exact position of the sextupoles and the final position of the sextupoles was found by studying the optimisation of the sextupole position for two candidate lattice tunings independently. Figure 1.3-5 shows the tune points for the two candidate lattice tunings.

Although the exact placement of the sextupoles found independently was different in these two solutions, the differences between them were small enough that a compromise layout could be adopted that was compatible with both working regions. The final position of the sextupoles was then determined as a compromise between the optimum for these two example lattice tunings, taking also into consideration the requirement to keep the sextupoles in the high dispersion region at a reasonable value. Figure 1.3-6 shows the initial position of the sextupoles before optimisation of the off momentum dynamics and the final compromise solution for the DIAMOND lattice, which was found to give adequate off-momentum aperture for Touschek lifetime with reasonable values of sextupoles.

Once the sextupole positions had been fixed, these were adopted for both candidate points and optimisation of both the lower chromaticity point and the reference point was performed using the HARMON module of MAD. The results of this optimisation found that the reference solution had best overall dynamic behaviour; the lower chromaticity region also looks promising, in that the on-momentum dynamic aperture is good - further optimisation is needed to match the off momentum performance of the reference point.

Table 1.3-1 compares some of the basic lattice properties of the reference lattice with that of the example tuning in the lower chromaticity region of tune space. The dynamic apertures for the two solutions are shown in Figure 1.3-7 and Figure 1.3-8. The apertures shown are found using the DYNAP command in MAD which finds the boundary of stable motion by working inwards from large amplitudes, but including some checking below the stable region for 'islands' of instability. The results have proved consistent with those obtained by tracking a full 2-dimensional array of particles. The results for the low chromaticity point have a significantly larger vertical aperture but at the tune point investigated the horizontal aperture at +4% momentum deviation is limited.

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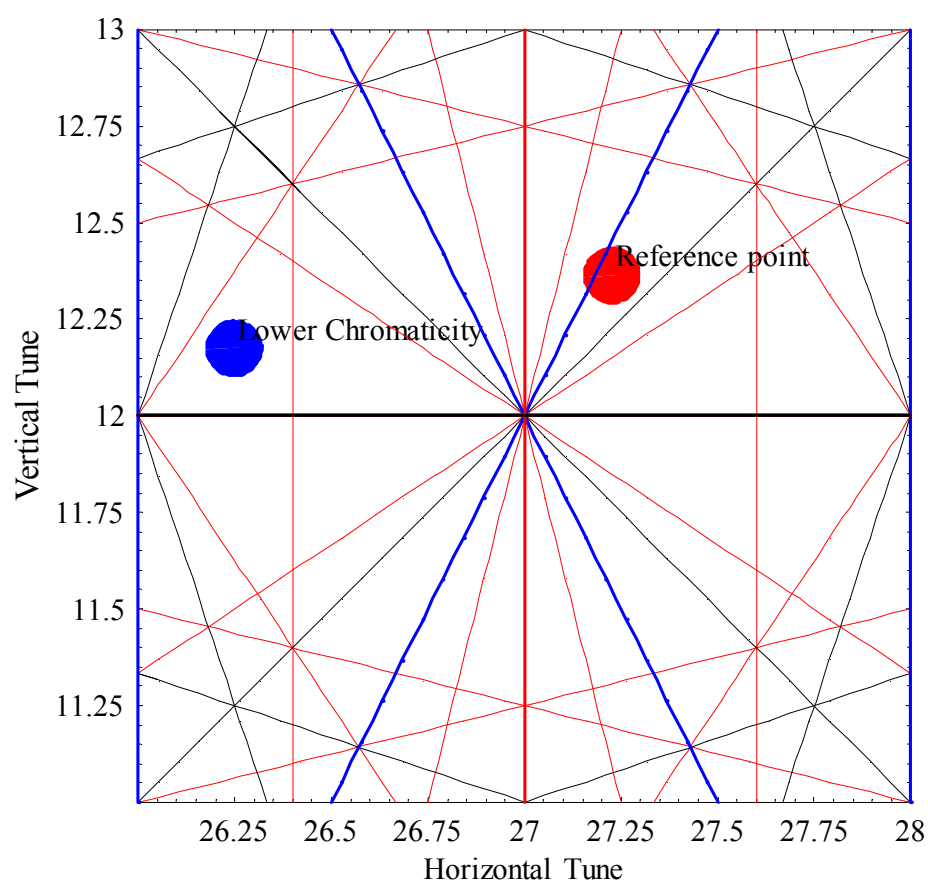


Figure 1.3-5 Tune diagram showing tune points for two candidate working points.

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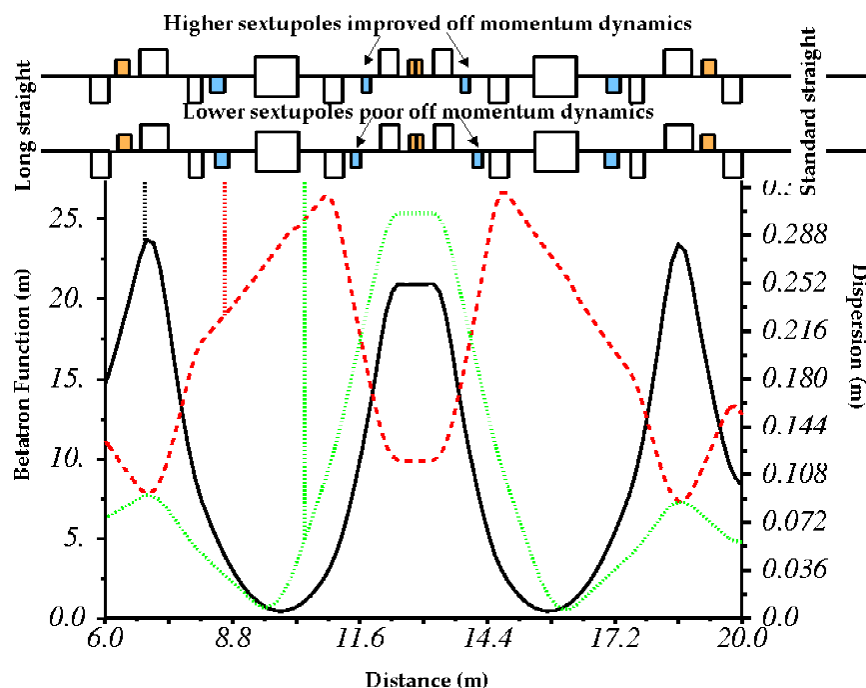


Figure 1.3-6 Sextupole position changes to optimise off momentum dynamics.

Table 1.3-1 Basic lattice properties of the reference lattice and lower chromaticity lattice.

	Low Chromaticity	Reference
Maximum horizontal beta function [m]	22.6	22.6
Maximum vertical beta function [m]	20.8	26.6
Maximum dispersion [m]	0.26	0.311
Horizontal Beta function, rf/inj/Longer ID straight [m]	10.9	10.0
Vertical Beta function, rf/inj/Longer ID straight [m]	9.2	5.8
Horizontal Beta functions, standard ID straight [m]	4.8	4.7
Vertical Beta functions, standard ID straight [m]	2.4	1.5
Dispersion, rf/inj/Longer ID straight [m]	0.115	0.072
Dispersion, standard ID straight [m]	0.086	0.052
Horizontal Tune	26.29	27.23
Vertical Tune	12.22	12.36
Natural horizontal chromaticity	-66	-79
Natural vertical chromaticity	-25	-35
Natural emittance [nm-rad]	2.40	2.74
Momentum compaction	0.00016	0.00017

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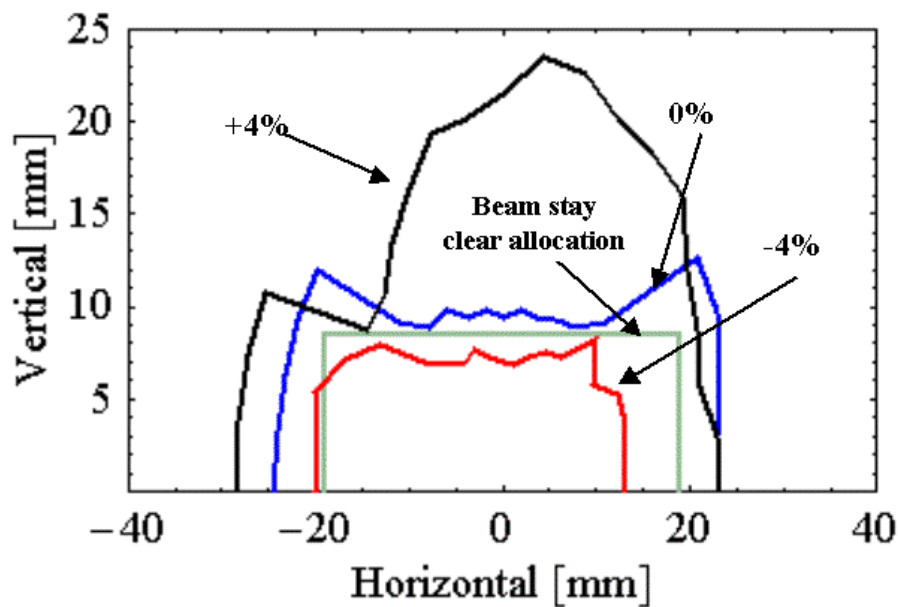


Figure 1.3-7 Dynamic aperture for the reference solution.

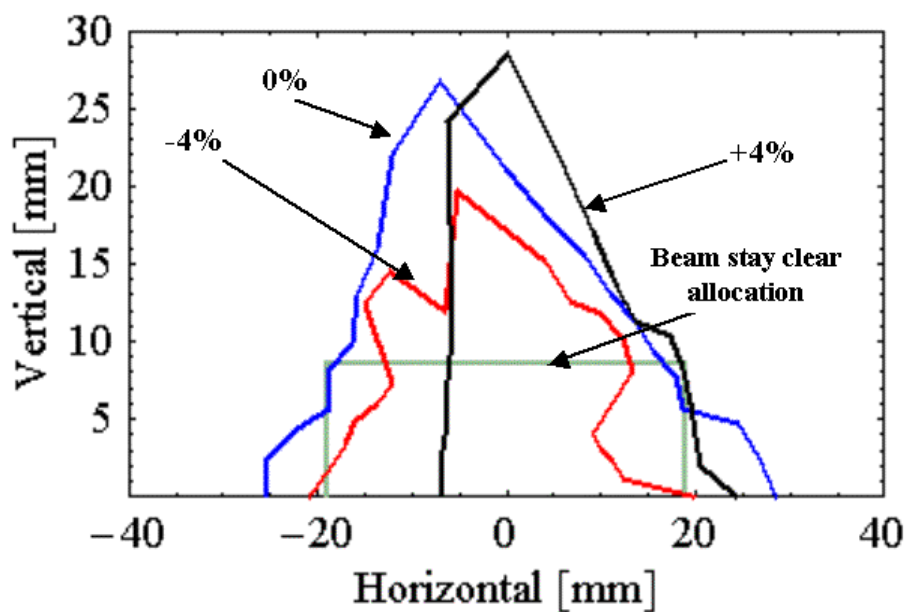


Figure 1.3-8 Dynamic aperture for the example lower chromaticity solution.

1.3.7 Characterisation of the Reference Lattice

(a) On-Momentum Behaviour

Figure 1.3-9 and Figure 1.3-10 show the horizontal and vertical phase space plots for on-momentum particles: the phase spaces are regular up to large amplitudes. The dynamic aperture is improved by tailoring the tune shifts with amplitude to minimise the effect of nearby resonances. Figure 1.3-11 and Figure 1.3-12 show the on-momentum tune shifts with amplitude for the reference solution.

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Setting slightly negative first-order tune shifts with amplitude maximised the amplitude over which particles remained stable separately in Figure 1.3-13.

To characterise which resonances limit the dynamic aperture, frequency map analysis was carried out over a fine grid of particles tracked from 2048 turns. The calculated tune diffusion rate is shown in Figure 1.3-14. The corresponding plot showing the boundary for stable motion is given in Figure 1.3-15; this agrees with the dynamic aperture found using the MAD DYNAP command (Figure 1.3-7). Figure 1.3-16 and Figure 1.3-17 show the result of a frequency map analysis of the reference lattice. The small offset of the on-axis working point is not an artefact, and is due to the slightly negative first order tune shift with amplitude.

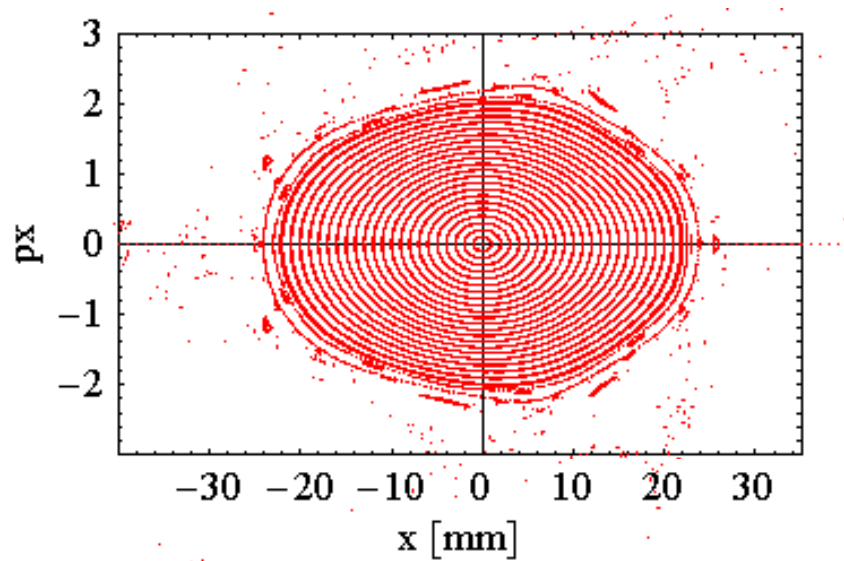


Figure 1.3-9 Horizontal phase space plot for the reference solution.

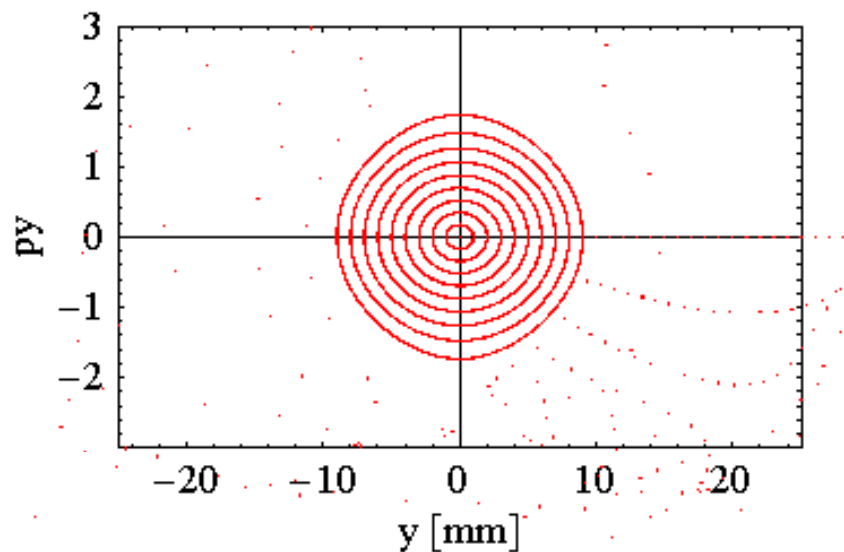


Figure 1.3-10 Vertical phase space plot for the reference solution.

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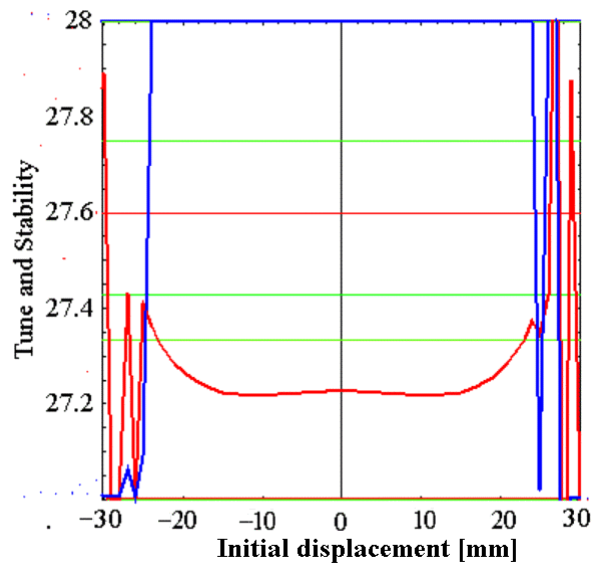


Figure 1.3-11 Horizontal tune with amplitude and stability. Structural resonances are shown up to 9th order. Stability is shown schematically in blue, with stability over 1024 turns indicated as full scale on the plot.

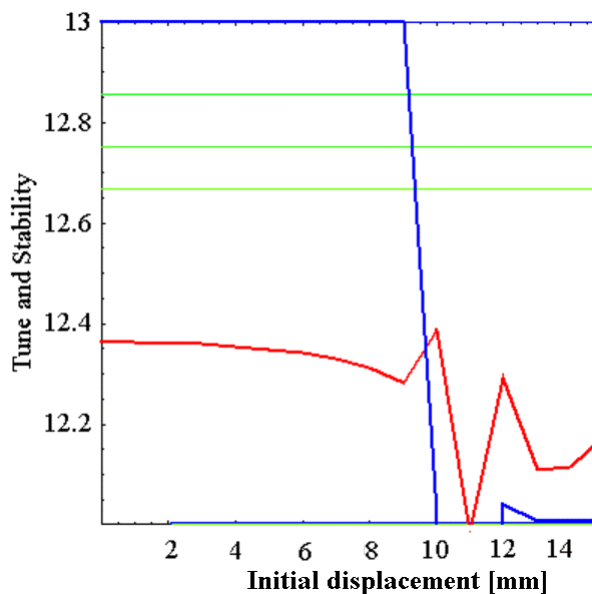


Figure 1.3-12 Vertical tune with amplitude and stability. Structural resonances are shown up to 9th order. Stability is shown schematically in blue, with stability over 1024 turns indicated as full scale on the plot.

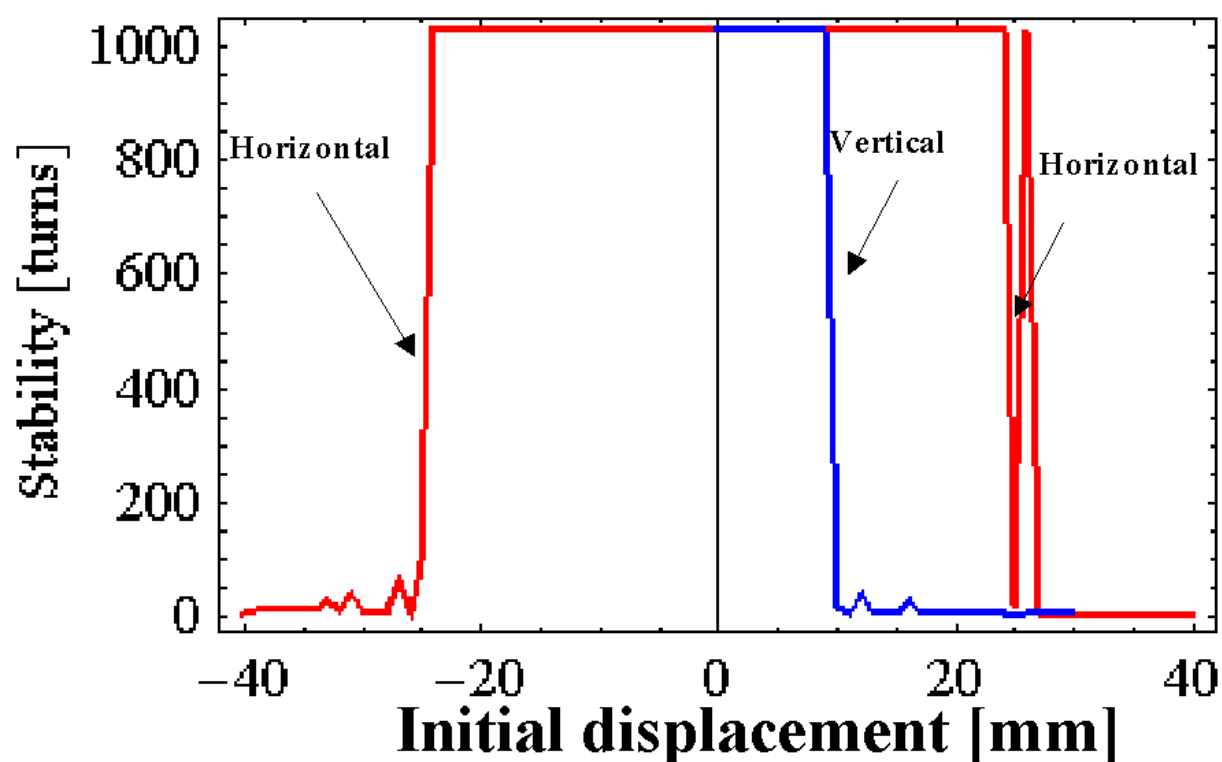


Figure 1.3-13 On-axis stability over 1024 turns. The dynamic aperture at negative vertical displacements is symmetric with the positive behaviour for the ideal lattice modelled here.

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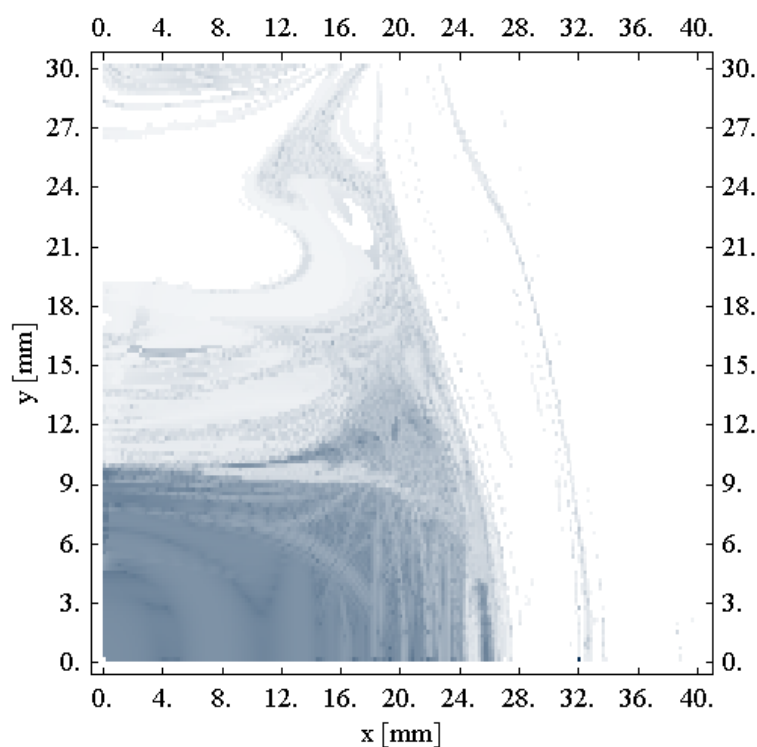


Figure 1.3-14 Diffusion rate of on-momentum particles.

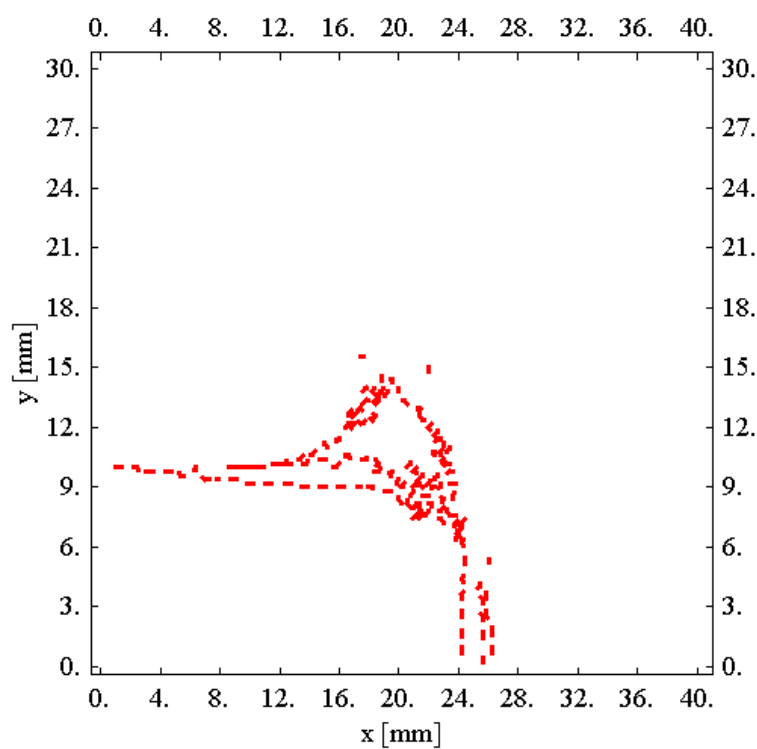


Figure 1.3-15 Boundary of on-momentum particle stability (1024/6 turns).

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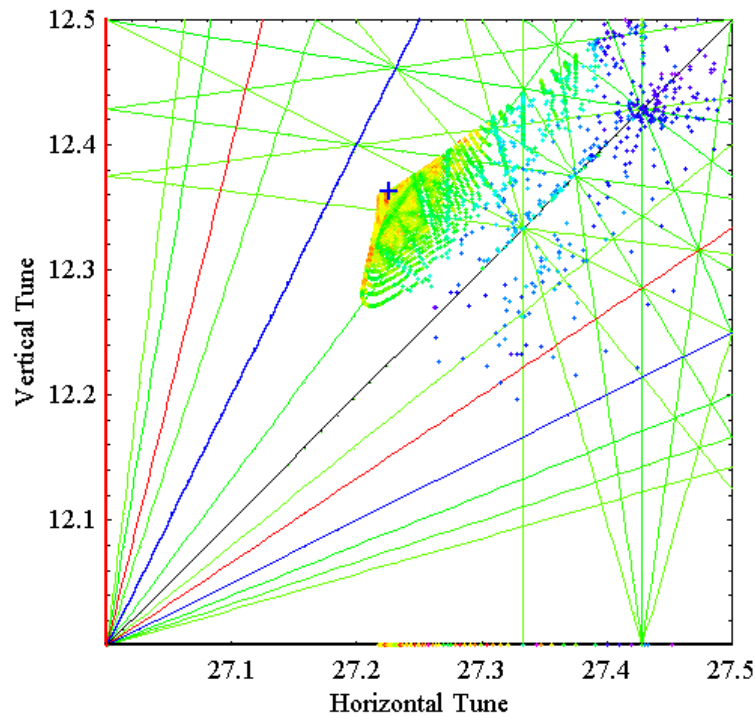


Figure 1.3-16 Frequency map analysis of particles over a grid (20 mm × 10 mm). Structural resonances up to 9th order are shown. The zero amplitude tune is shown as a cross, illustrating the slightly negative first order tune shifts.

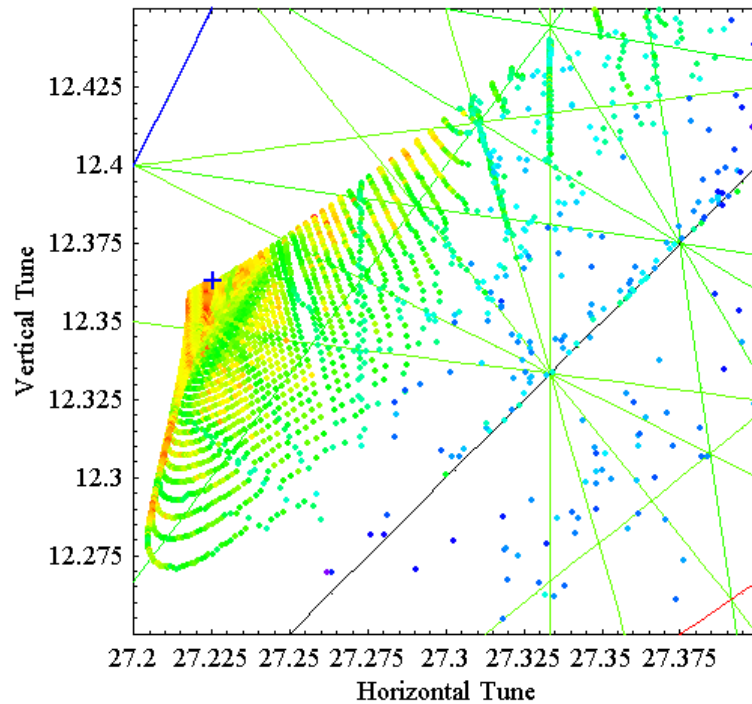


Figure 1.3-17 Detailed view of Figure 1.3-16; a collection of resonances appears to be limiting the dynamical behaviour at large amplitudes.

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(b) Off-Momentum Behaviour

The off-momentum dynamic stability is very important in DIAMOND, since the very low emittance requires a good momentum aperture to ensure a reasonable Touschek lifetime. Figure 1.3-18 show the tune shifts with momentum for the optimised reference lattice.

Figure 1.3-19 and Figure 1.3-20 show the betatron functions at $\pm 4\%$ momentum error; Figure 1.3-21 shows how the maximum β varies with momentum. These show that, with the eight families of sextupoles used, it is possible to maintain reasonable control of the optical functions at large momentum error despite the relatively low symmetry of the lattice. The maximum betatron functions are kept below 40 m, with a consequent benefit for the aperture requirements to accommodate Touschek scattered particles at the large required momentum deviations.

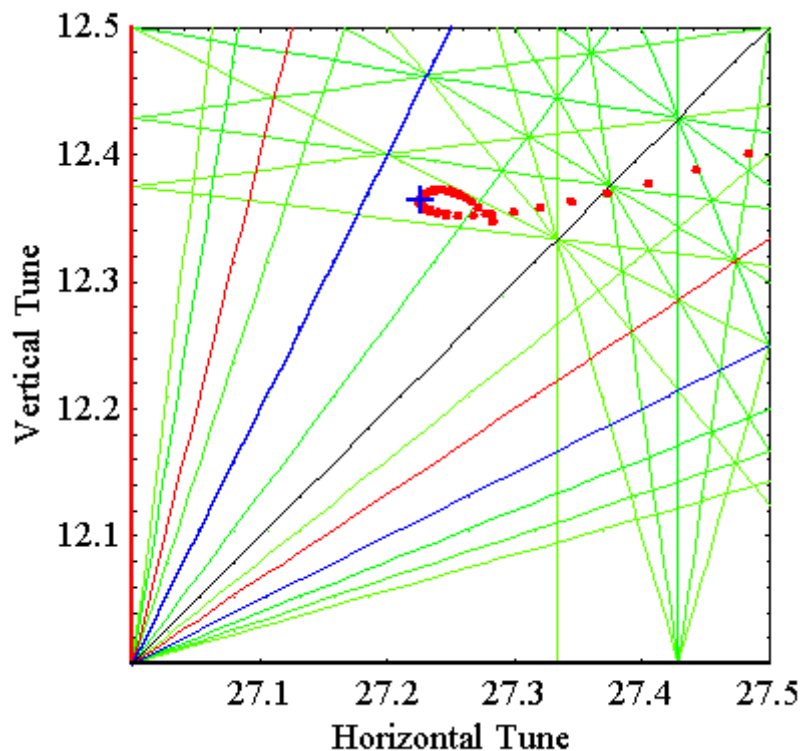


Figure 1.3-18 Tune shift with momentum for the reference lattice. The blue cross indicates the on-momentum tune.

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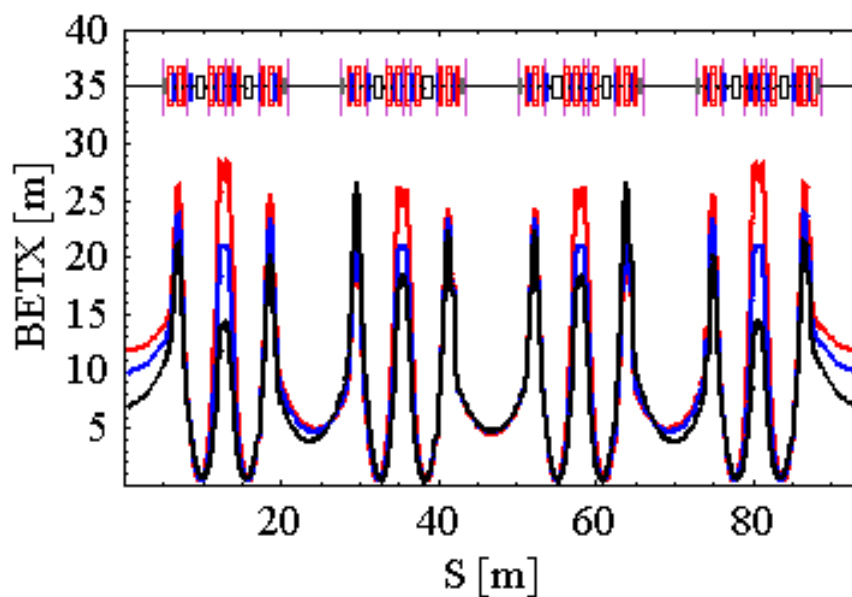


Figure 1.3-19 Radial betatron function for +4% (Black), 0 (Blue) and -4%(Red) momentum deviation.

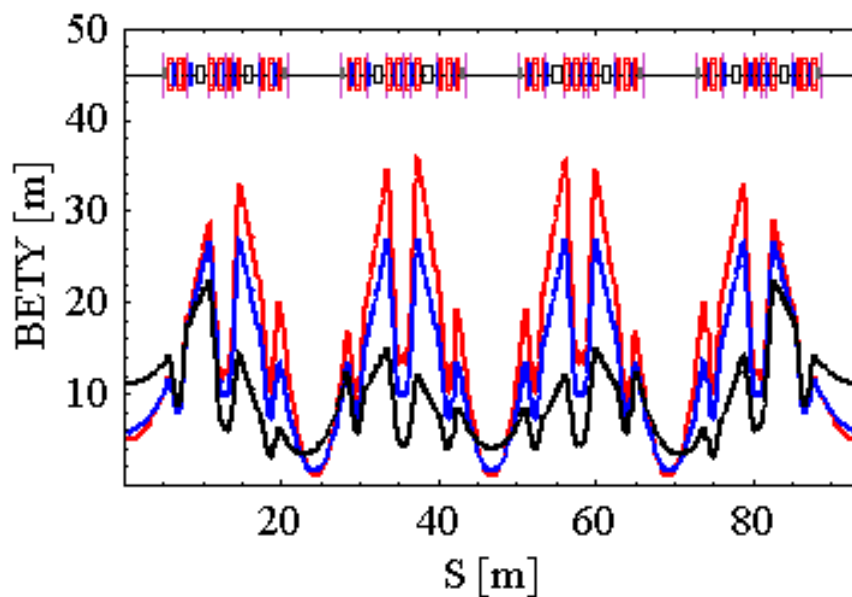


Figure 1.3-20 Vertical betatron function for +4% (Black), 0 (Blue) and -4%(Red) momentum deviation.

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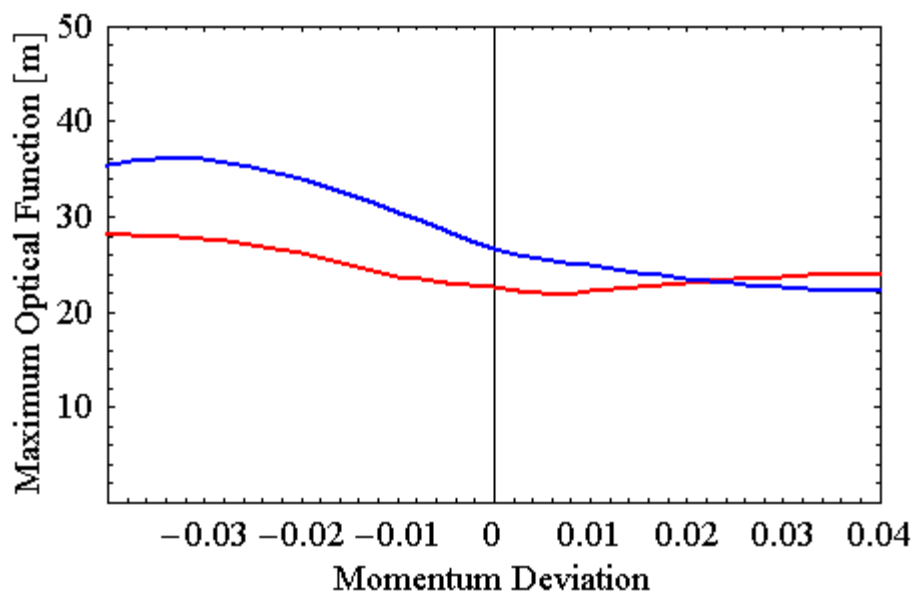


Figure 1.3-21 Variation of maximum β -function with momentum (red: horizontal, blue: vertical).

The off-momentum dynamic aperture is shown in Figure 1.3-22 to Figure 1.3-24; the momentum aperture must be sufficient to ensure a reasonable Touschek lifetime. The effect of momentum aperture upon the expected Touschek lifetime is discussed in detail in section 1.6.3.

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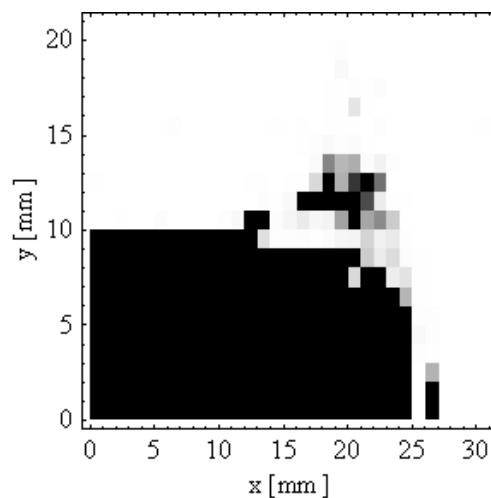


Figure 1.3-22 Dynamic aperture, $\Delta p/p = 0$, 1024 turns.

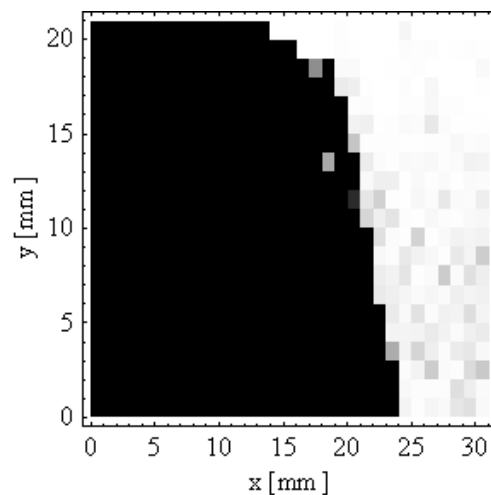


Figure 1.3-23 Dynamic aperture, $\Delta p/p = +4\%$, 1024 turns.

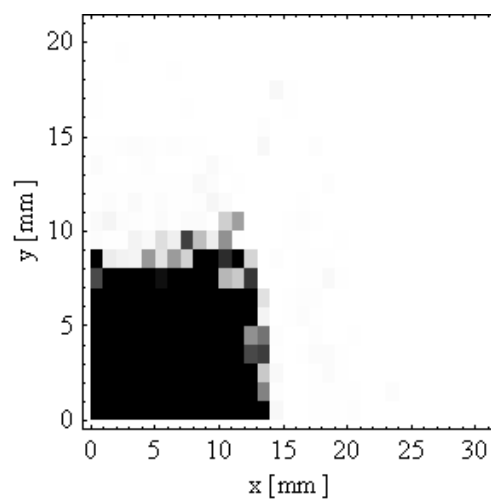


Figure 1.3-24 Dynamic aperture, $\Delta p/p = -4\%$, 1024 turns.

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1.3.8 Summary

In summary, the dynamic properties of a reference working point of the DIAMOND lattice has been characterised both on- and off-momentum and the performance appears to be adequate to guarantee the specified lifetime.

1.4 CLOSED ORBIT CORRECTION AND STEERING

1.4.1 Amplification Factors

A quadrupole displacement in either plane produces a dipole field proportional to the product of quadrupole gradient and displacement, and causes an orbit distortion in that plane. For a random distribution of quadrupole displacements the generated RMS orbit distortions are given by

$$\Delta x, y_{rms}^{CO} = \Delta x, y_{rms} \frac{\sqrt{\beta_{x,y}}}{2\sqrt{2} \sin(\pi Q_{x,y})} \left\{ \sum_i (kl)_i^2 \beta_{i,x,y} \right\}^{\frac{1}{2}}, \quad (4)$$

where

$\Delta x, y_{rms}$	:RMS quadrupole displacement
$(kl)_i$	:integrated quadrupole strength
$Q_{x,y}$	:the betatron tunes
$\beta_{i,x,y}$	:the betatron functions at the quadrupole
$\beta_{x,y}$	:the betatron functions at the observation point

The amplification factors are defined as

$$A_{x,y} = \frac{\Delta x, y_{rms}^{CO}}{\Delta x, y_{rms}} \quad (5)$$

Figure 1.4-1 shows the quadrupole amplification factors throughout the lattice.

Individual imperfections or fluctuations in the dipole field of the bending magnet can also cause horizontal orbit distortions. For a random distribution of such errors, the generated RMS orbit distortion is given by

$$\Delta x_{rms}^{CO} = \theta \left(\frac{\Delta B l}{B_0 l} \right)_{rms} \frac{\sqrt{\beta_x}}{2\sqrt{2} \sin(\pi Q_x)} \left\{ \sum_i \beta_{i,x} \right\}^{\frac{1}{2}}, \quad (6)$$

where

θ	: dipole bend angle

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$\left(\frac{\Delta B l}{B_0 l}\right)_{rms}$: RMS relative field error
 β_{ix} : the radial betatron functions at the dipoles

A roll angle error produces a horizontal field proportional to the error. The generated RMS vertical orbit distortion from such errors is given by

$$\Delta y_{rms}^{CO} = \theta \Delta \phi_{rms} \frac{\sqrt{\beta_y}}{2\sqrt{2} \sin(\pi Q_y)} \left\{ \sum_i \beta_{iy} \right\}^{\frac{1}{2}}, \quad (7)$$

where

$\Delta \phi_{rms}$: the RMS of the roll angle errors

Note that the relative field error due to such a roll angle is given by

$$\frac{\Delta B l}{B_0 l} = \frac{\theta \Delta \phi}{\theta} = \Delta \phi$$

The analogous amplification factor for dipole errors is defined as

$$\frac{\Delta x, y_{rms}^{CO}}{\left(\frac{\Delta B l}{B_0 l}\right)_{rms}} \quad (8)$$

Figure 1.4-2 shows the dipole amplification factors, which give the expected RMS orbit errors in mm when multiplied by the RMS relative field errors in units of 10^{-3} or RMS roll angles in mrad.

Since the lattice has been optimised to give low emittance, the radial beta function in the dipole is relatively small and distortions of the vertical orbit are greatest. Figure 1.4-1 shows the bending magnet amplification factors through the lattice for the reference design tunes $Q_x = 27.22$, $Q_y = 12.36$. Table 1.4-1 tabulates the maximum amplification factor for quadrupoles and dipoles in this lattice.

Figure 1.4-3 shows how the amplification factor changes with fractional tune if other parameters do not change significantly.

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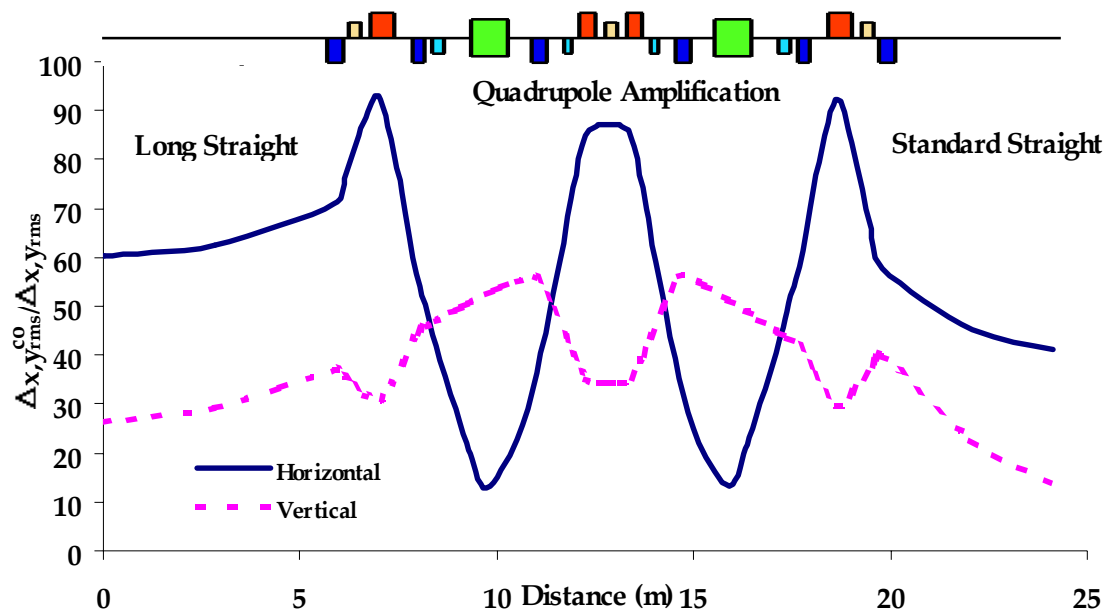


Figure 1.4-1 Quadrupole amplification factor.

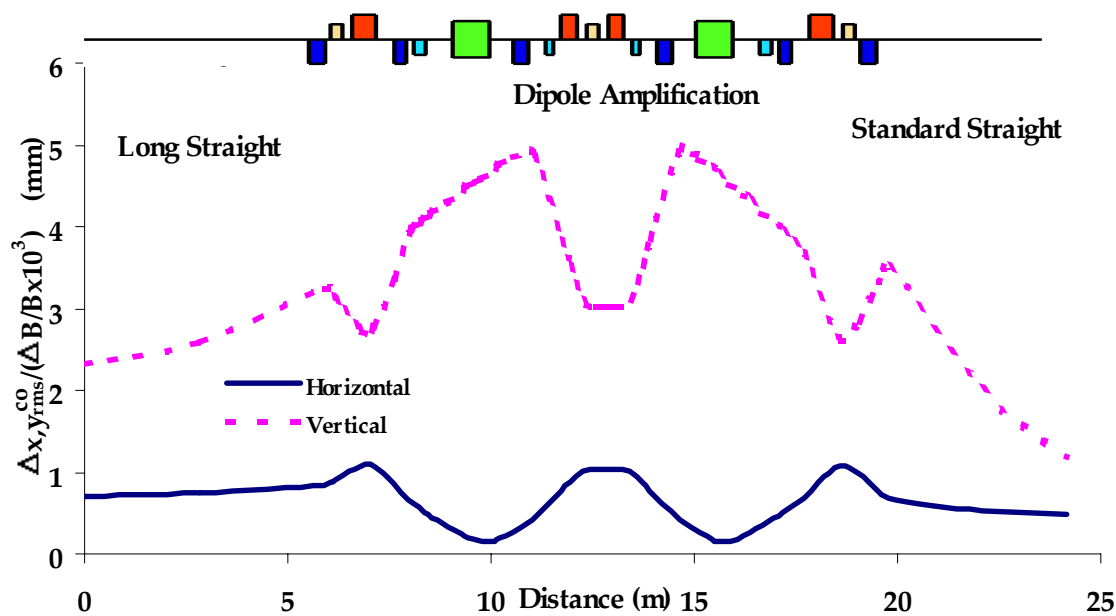


Figure 1.4-2 Dipole amplification factor.

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Table 1.4-1 Amplification factors for the reference tuning of DIAMOND.

	Horizontal	Vertical
Maximum quadrupole amplification factor	92	56
Maximum dipole amplification factor	1.1	5

Amplification Factor Vs Fractional Tune

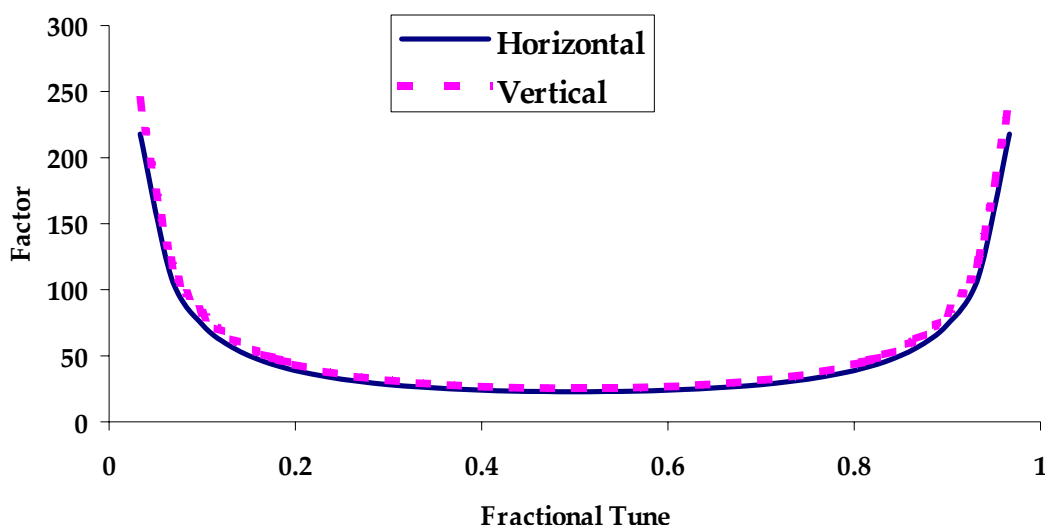


Figure 1.4-3 Variation of amplification factors with fractional tune.

1.4.2 Sensitivity to Errors

Misalignments in the storage ring elements cause closed-orbit errors in the position of the electron beam which must be corrected for [19]. Vibration gives rise to deflections in the electron beam in the same way that misalignments do, albeit that the deflection is transient. At higher frequencies the effect of vibration is to effectively degrade the brightness of the extracted photon beams, whilst at lower frequencies the motion can cause noise problems in experimental detector systems; the break-point between these two regimes depends upon the experiment. A typical specification can be given that the overall beam motion must not exceed 10% of the beam size in either plane, and this has been adopted by many light source facilities. Feedback systems can alleviate the effects of vibration to some extent, but the minimisation of the problem at its source must clearly be a goal. A 3rd-generation light source, with its very small beam sizes, is intrinsically sensitive to motions of its elements, with even μm -sized motions having a detrimental effect upon the output photon brightness. Modelling of these effects has been carried out using the MAD with the MICADO correction routines. It is intended that as part of the detailed specification of correction schemes an investigation of other algorithms such as SVD would be carried out. The initial

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specifications of the corrector and monitor systems have been carried out without consideration of the effects of girders and work is currently underway to determine the performance of these systems when movement on girders is assumed.

1.4.3 Fast and Slow Orbit Correction Scheme

Any closed orbit error induced by the misalignment of magnetic elements, and the motion on those elements induced by ground motion, must be compensated for through the use of dedicated transverse corrector magnets in order to achieve the required stability for time dependant motion of 10% of the beam size. When designing the orbit correction scheme the likely element motion was characterised into two regimes:

- Fast motion > 0.1 Hz, which includes vibration from either cultural or mechanical sources
- Slow motion < 0.1 Hz, which includes long-term drift and in this analysis static element misalignment errors

These two schemes are dealt with in turn below.

1.4.4 Fast Correction Scheme

The correction of closed-orbit errors caused by the effects of fast motion is performed with dedicated correction magnets, which can obtain high bandwidth. In DIAMOND a practical, low induction, low eddy current magnet operating at 100 Hz bandwidth, can produce up to 0.5 mrad deflection. Similar magnets have already been installed for use in fast orbit feedback system at other light sources, for instance, BESSY II [20]. They need to be positioned so as to minimise the residual closed orbit at the most important positions; these are the insertion device source points for which DIAMOND has predominantly been designed. The most efficient scheme for correcting at these locations to provide 2 fast correctors at each end of every straight section; providing local correction of the position and angle through each insertion device. However, a global correction scheme is envisaged using the beam position monitors (BPMs) distributed throughout the lattice, which should negate the need for additional fast correctors to stabilise the dipole source points. This scheme has proved successful at other facilities. [21] The layout of the fast corrector magnets and BPMs is shown in Figure 1.4-4.

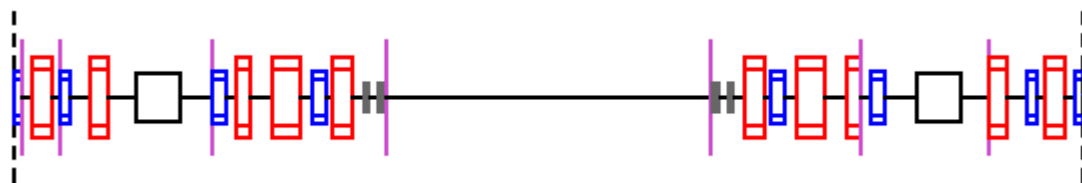


Figure 1.4-4 Layout of the fast correction scheme through one (short straight) period.

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The fast correctors are shown as grey blocks either side of the insertion device straight. BPMs locations are shown as purple lines. (Dipoles: black, quadrupoles: red, sextupoles: blue).

The positioning of the BPMs was decided by looking at the β -functions through the arcs and the phase advances between monitors and taking into consideration engineering constraints.

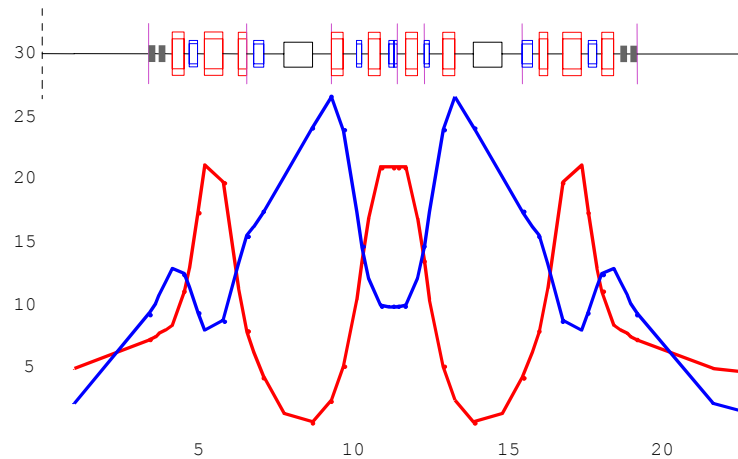


Figure 1.4-5 β -functions through one period.

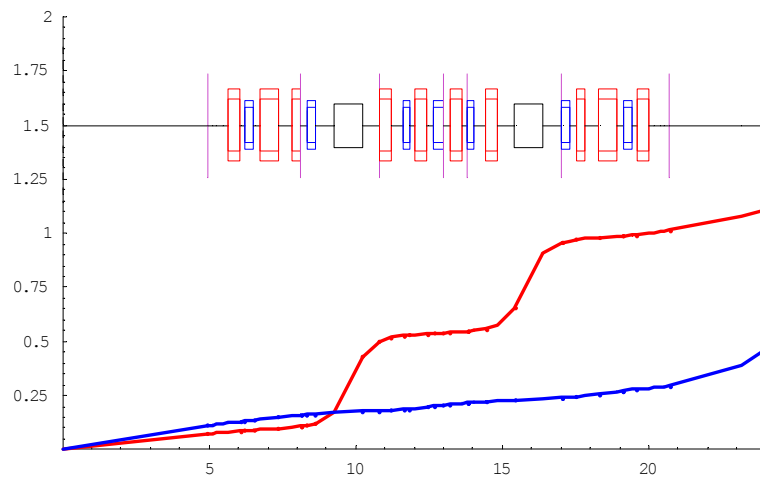


Figure 1.4-6 Phase advances through one period.

In the regime of interest to users, where correction is almost complete, a useful definition of correction efficiency is given by:-

$$100 \times \left(1 - \frac{\text{Max}[\text{error}]}{\text{BeamSize}} \right)$$

Efficiencies of greater than 90% are required to meet the 10% of beam size specification at the radiation source points.

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Correction efficiencies were assessed by applying random uncorrelated magnet displacements with the expected ground motion amplitudes $\sim 1 \mu\text{m}$ [22], and are shown in Figure 1.4-7 to Figure 1.4-10. They confirm that the fast correction scheme achieves greater than the required 90% efficiency at all of the radiation source points for errors of this magnitude.

It can be seen that the global correction scheme achieves greater than 90% correction efficiency at the dipole source points over 500 random error sets. This means that the beam stability at the dipole source points is less than the 10% stability requirement. In most cases the correction scheme achieves greater than 90% efficiency. Correction efficiency at the dipole source points in the vertical plane is better than that in the horizontal case, with efficiencies greater than 95% for all 500 random seeds.

In the straight sections - as expected - correction approaches 100% with corrected beam motion being almost negligible, both horizontally and vertically.

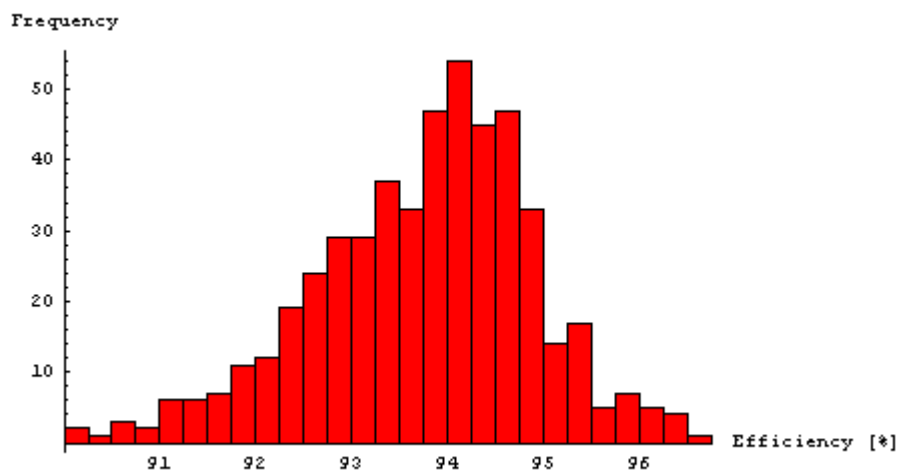


Figure 1.4-7 Histogram of the efficiency of global correction at the dipole source points in the horizontal plane.

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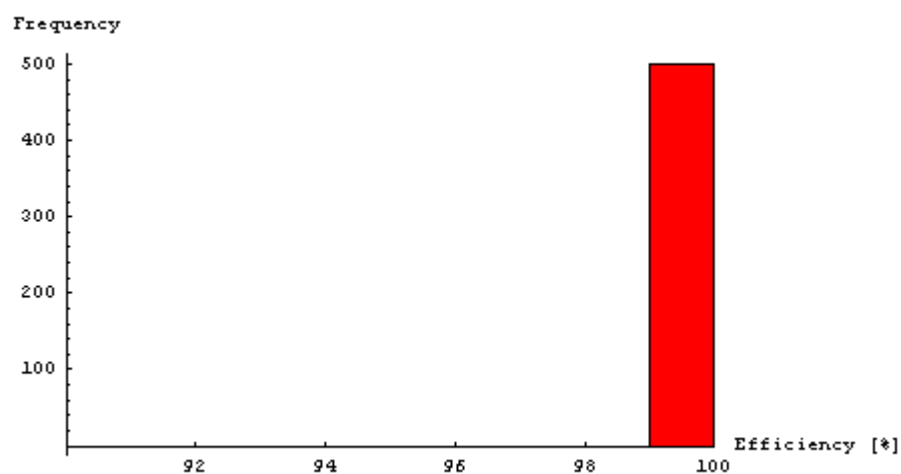


Figure 1.4-8 Histogram of the efficiency of global correction at the straight section source points in the horizontal plane.

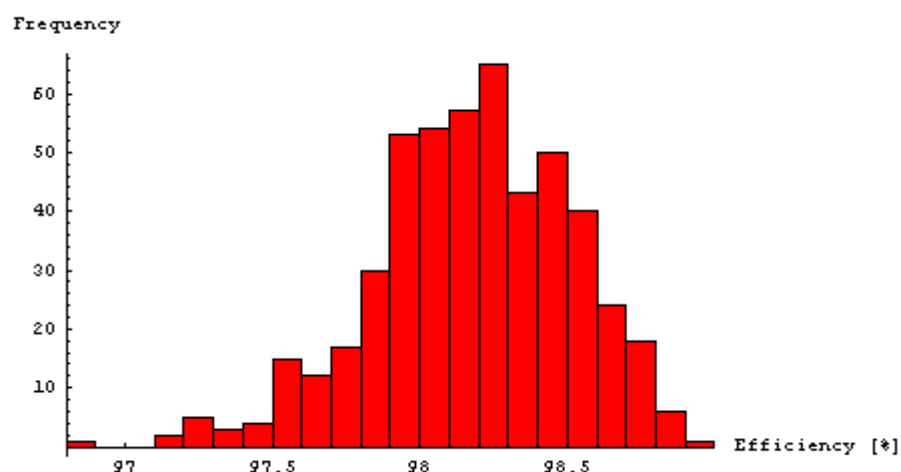


Figure 1.4-9 Histogram of the efficiency of global correction at the dipole source points in the vertical plane.

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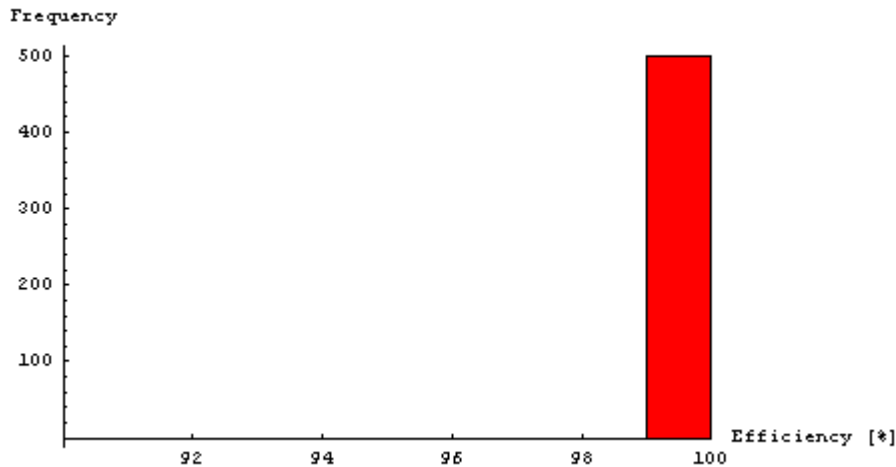


Figure 1.4-10 Histogram of the efficiency of global correction at the straight section source points in the vertical plane.

1.4.5 Slow Correction Scheme

The correction of the closed orbit due to the effects of slow motion requires a different approach than the fast correction scheme. Displacements of the magnetic elements due to long term drift, settlement of the ground under loads, movements from other seasonal and environmental effects, and the finite tolerance in surveyed element positions, are many orders of magnitude greater than in the fast correction case: the slow correction scheme is needed to keep the beam motion within tolerable limits for these DC movements. This means that the beam must be kept within the physical aperture of the machine, and that residual effects should not adversely compromise the beam dynamics; the fast correction scheme will be used to correct any residual motion at the radiation source points.

There will be a total of 7 slow correctors per cell. These are most efficiently located within the sextupoles as additional coils, since the bandwidth required does not disturb the quality of generated sextupole field[23]. This has the added advantage that significant skew quadrupole field can also be generated within each of these elements (see Section 1.5). The correction coils have been specified to provide up to 0.8 mrad deflection in both the horizontal and vertical planes[23].

The position of these in-sextupole correctors is shown schematically in Figure 1.4-11.

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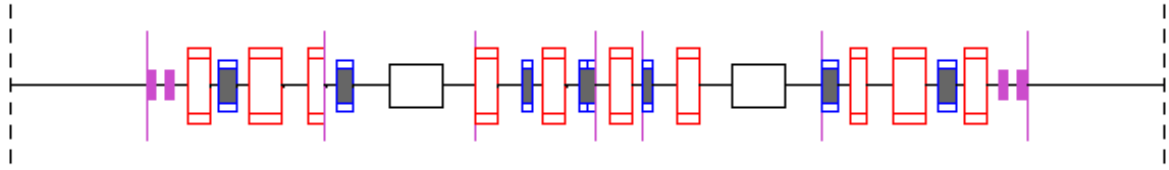


Figure 1.4-11 Positioning of the 7 in-sextupole correctors per cell – correctors shown as grey blocks.

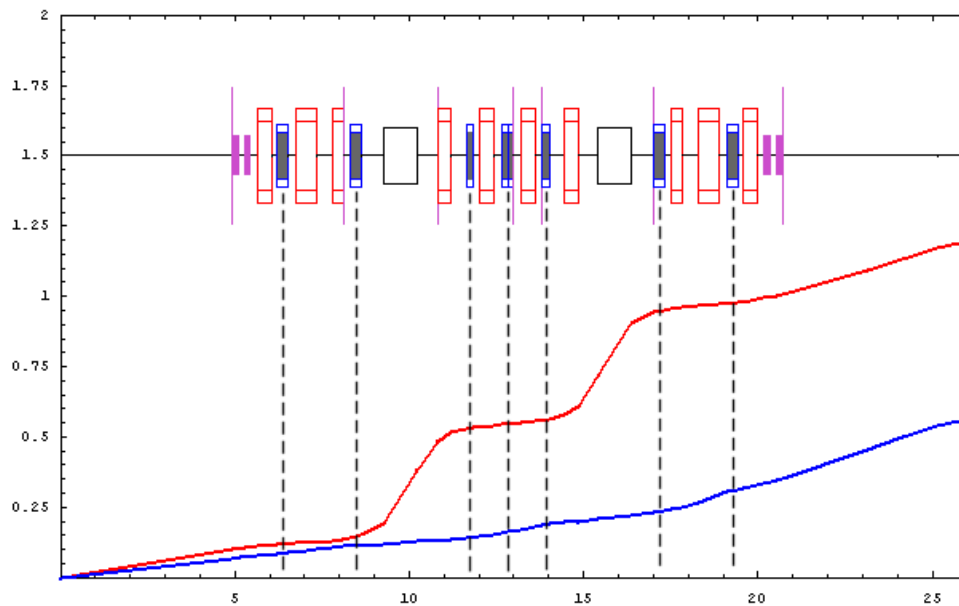


Figure 1.4-12 Phase advances at the 7 in-Sextupole correctors per cell.

1.4.6 Survey and Alignment Errors

As well as considering the effects of transient motion on the magnetic elements in the Storage Ring, due to both natural ground motion and environmental effects, the closed orbit errors resulting from a finite positioning accuracy must also be considered. These displacements from nominal position are static in nature and can be corrected by the slow corrector magnets.

Following experience at other facilities, and with present surveying/mechanical technologies, the survey/mechanical tolerances which are thought likely to occur are shown in Table 1.4-2. The effects of these alignment errors on the closed orbit is illustrated in Figure 1.4-13 and Figure 1.4-14. They show that for a selection of random uncorrelated element displacements, applied in a truncated Gaussian distribution, likely closed orbit deviations lie within the range ± 20 mm in both planes.

After correction using the 168 in-Sextupole correctors, the residual closed orbit is reduced significantly at all points around the ring. This is illustrated in Figure 1.4-15

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and Figure 1.4-16. The maximum residual closed orbit due to static alignment tolerances after correction is 181 μ m horizontally and 79 μ m vertically.

Table 1.4-2 Static alignment tolerances after surveying. These values are assumed to include all accumulated errors from girder alignments/tolerances, magnet mounting/survey errors, magnetic errors within the elements, and other mechanical tolerances.

<i>Error Type</i>	<i>RMS Magnitude</i>
Quadrupole Transverse Displacement	0.1 mm
Sextupole Transverse Displacement	0.1 mm
Dipole Transverse Displacement	0.05 mm
Dipole Longitudinal Displacement	0.05 mm
Dipole Field Error	0.1 %
Quadrupole Roll Error	0.2 mrad
Dipole Roll Error	0.2 mrad
BPM Transverse Displacement	0.1 mm
BPM Output Accuracy	1 μ m

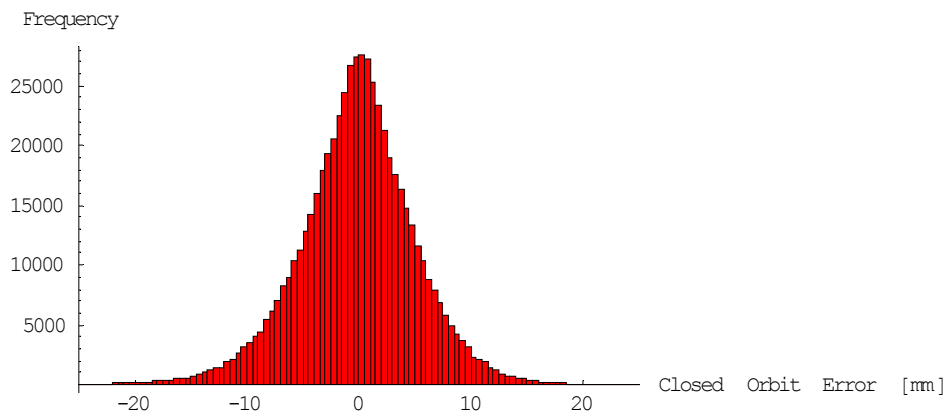


Figure 1.4-13 Histogram of the horizontal closed orbit errors over 300 randomly generated error sets at all points around the lattice *without* correction.

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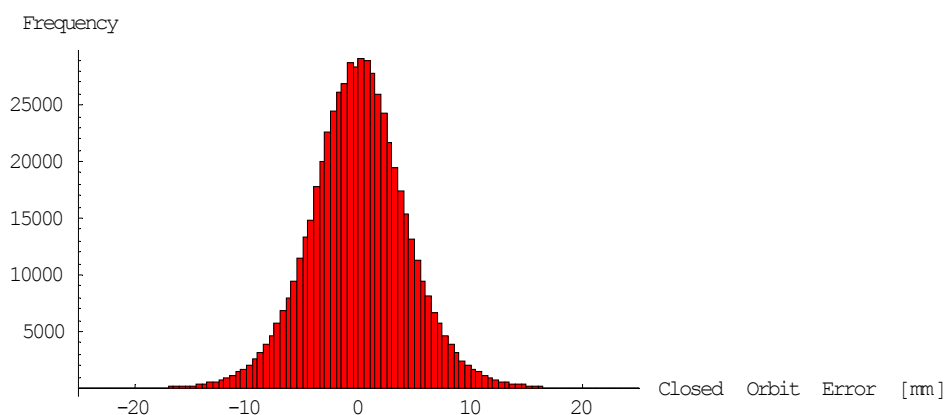


Figure 1.4-14 Histogram of the vertical closed orbit over 300 randomly generated error sets at all points around the lattice *without* correction.

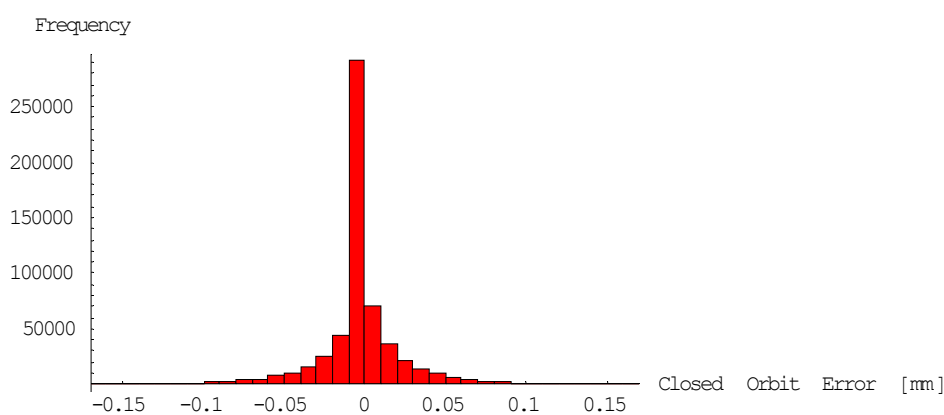


Figure 1.4-15 Histogram of the Horizontal closed orbit errors over 300 random seeds at all points around the lattice *with* correction.

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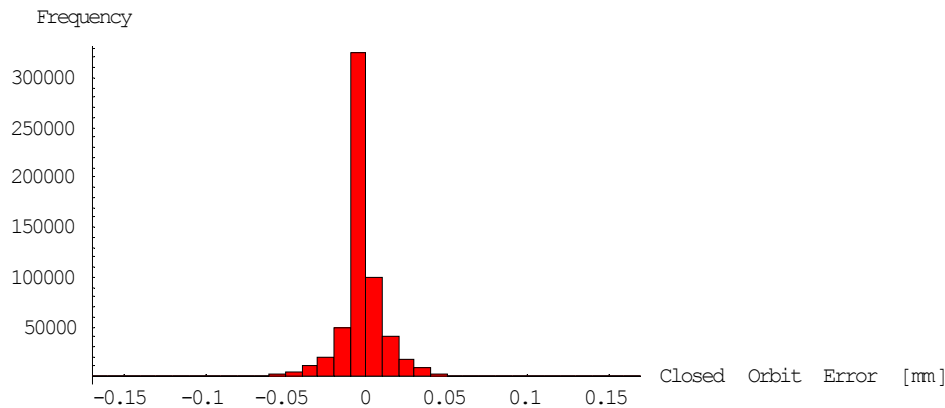


Figure 1.4-16 Histogram of the Vertical closed orbit errors over 300 random seeds at all points around the lattice *with* correction.

It is an operational likelihood that, during the commissioning phase of the DIAMOND project, the slow orbit correction scheme will not be fully operational. It is therefore instructive to model the accelerator without the correction scheme operational and attempt to assess the likelihood of achieving a circulating beam. By taking the 95% confidence limit at each point around the ring, over the 300 simulated error situations used above, and comparing these values with the Beam Stay Clear (BSC) definition (see Section 1.6.6), this likelihood can be assessed. Figure 1.4-17 and Figure 1.4-18 demonstrate this, and show that with 95% confidence an electron beam can be circulated in the storage ring without correction, and with the assumed static alignment tolerances; effects from other sources are not included.

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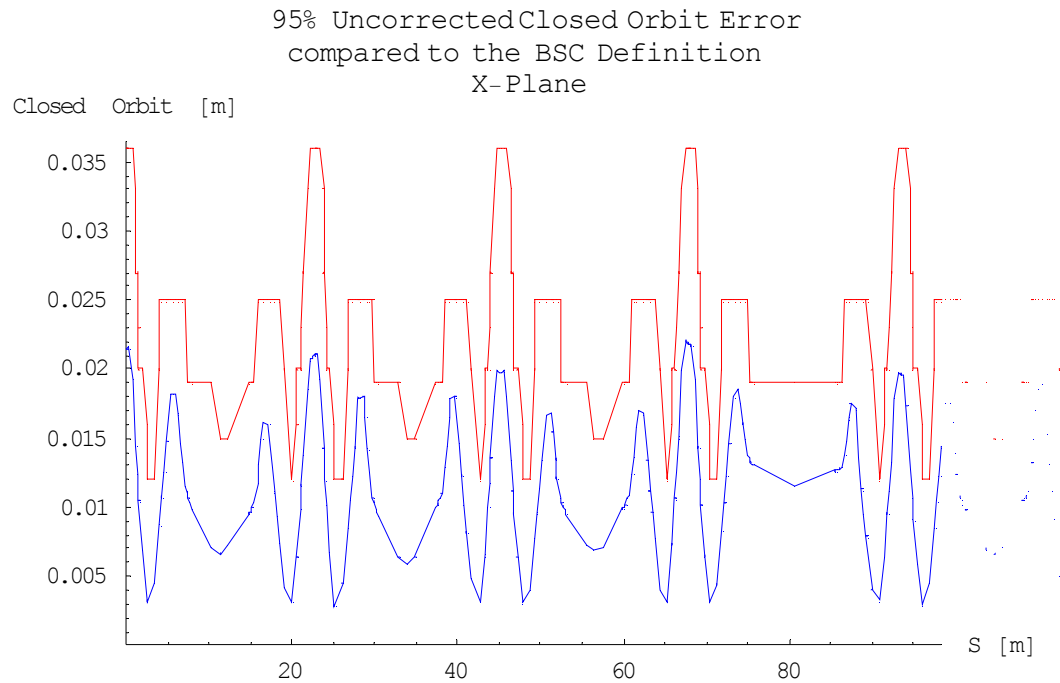


Figure 1.4-17 Comparison of the 95% confidence limit of likely closed orbit errors without correction (shown in blue) to the BSC definition in the horizontal plane (shown in red).

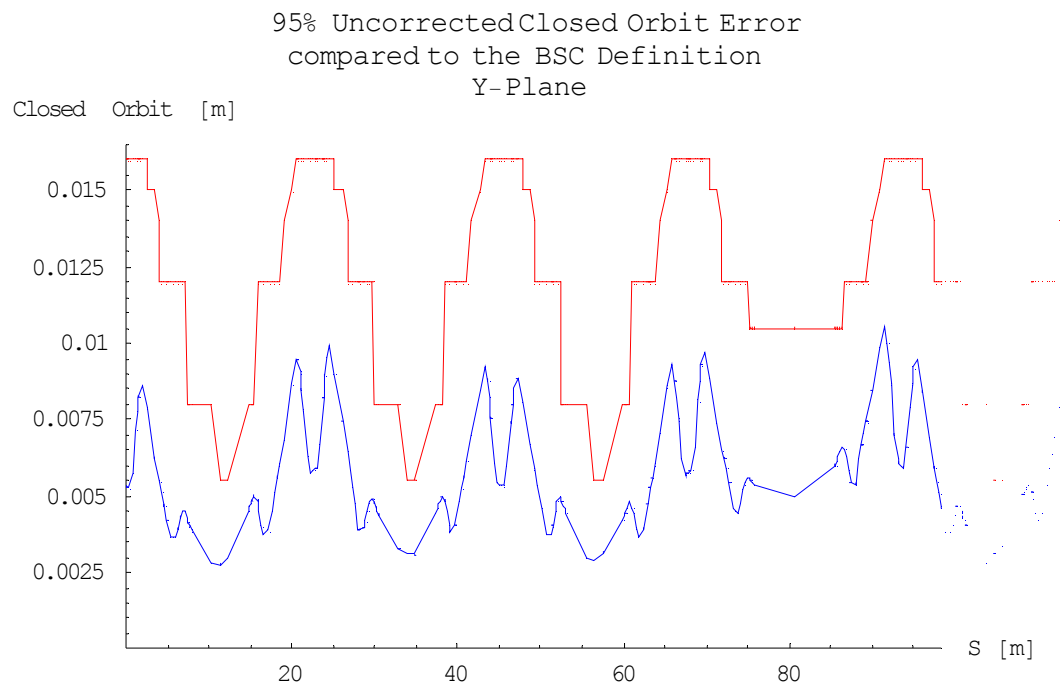


Figure 1.4-18 Comparison of the 95% confidence limit of likely closed orbit errors without correction (shown in blue) to the BSC definition in the vertical plane (shown in red).

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1.4.7 Modelling Long Term Drift

Two different approaches to the modelling of long-term drift on the DIAMOND lattice have been taken. The first model based on the so called ATL discription of motion takes into account the random nature of ground settlement, and applies correlated random errors to the lattice that can be used to approximate a wide variety of possible settlement issues. To first order it is assumed that the correction requirements are to correct the orbit back to the nominal plane of the storage ring before drift, thus approximately simulating the effects of correcting the closed orbit to a nominal position with respect to the beamlines. This model therefore assumes that the BPMs remain static relative to the nominal plane of the storage ring. The second model 1.4.6 investigates the effect of both Fourier and Gaussian distortions to the underlying structure, thus simulating the effects of localised floor deformations or correlated sags across the floor, for example between foundation piles.

The corrector magnets are limited to a maximum of 0.8 mrad kick and must also be used for correction of the survey errors; correction of the static errors utilises up to 0.3 mrad[24], leaving 0.5 mrad for the correction of long-term drift. This 0.5 mrad in turn determines the allowable ground motion which can be tolerated before re-survey must occur. Present thinking on the DIAMOND operational procedures is that a survey and re-alignment of the accelerator magnets every 6 months would be acceptable. This is needed due to the effects of slow ground motion on the relative element positioning. The misalignment of magnetic elements within the lattice causes orbit deviations, which then must be corrected by the 168 slow corrector magnets that are integrated into the sextupole elements. A specification for the allowable movement of the magnetic elements, and so the floor, is required to ensure that the resulting orbit deviations are correctable by the limited strengths of the corrector magnets, and that any residual orbits after correction have minimal effects on the dynamics of the beam.

(a) ATL Drift

In recent years the accepted method of modelling uncorrelated ground motion has been through the use of the so-called, ATL model. This model describes the diffusive motion that unconnected points on the ground (or structures attached to the ground) undergo which are uncorrelated and act as a low intensity baseline to the regular (in time and space) motion due to propagating waves in the upper Earth's crust. According to this empirical rule, the relative motion of two points scales as the product of the spatial and temporal interval between measurements. The value of the proportionality constant, A , is related to the location of the points in terms of ground stiffness and density etc. as

$$\sigma^2 = A \cdot T \cdot L. \quad (9)$$

Although it is straightforward to apply this law to a series of points along a line, it is more complicated to apply it to a series of points in a plane. This is done by

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considering the covariance matrix of their motions [25]. If the distance between any two points is given by

$$L_{ij} = |\mathbf{x}_j - \mathbf{x}_i|, \quad (10)$$

we have, from the ATL law, the *variance* relative to the origin

$$\langle y_i^2 \rangle = A \cdot T \cdot |\mathbf{x}_i|. \quad (11)$$

The variance of the *relative* motion between two points is then given by

$$\langle (y_j - y_i)^2 \rangle = A \cdot T \cdot |\mathbf{x}_j - \mathbf{x}_i|, \quad (12)$$

which expands to give

$$\langle y_i^2 \rangle - 2 \langle y_i y_j \rangle + \langle y_j^2 \rangle = A \cdot T \cdot |\mathbf{x}_j - \mathbf{x}_i|. \quad (13)$$

Since we know the variance relative to the origin from above, the covariance is then

$$\langle y_i y_j \rangle = \frac{A \cdot T}{2} (|\mathbf{x}_i| + |\mathbf{x}_j| - |\mathbf{x}_j - \mathbf{x}_i|). \quad (14)$$

By then knowing the co-ordinates of elements in the plane it is possible to create a covariance matrix with respect to a given origin. The motion of individual points can then be calculated so that the ATL law is obeyed between any two of them. An example of this calculation is shown in Figure 1.4-19. The relative displacements between any two elements which are close together is small (for example, the start and end points of the lattice should have the same displacement), but can be large across the diameter of the storage ring.

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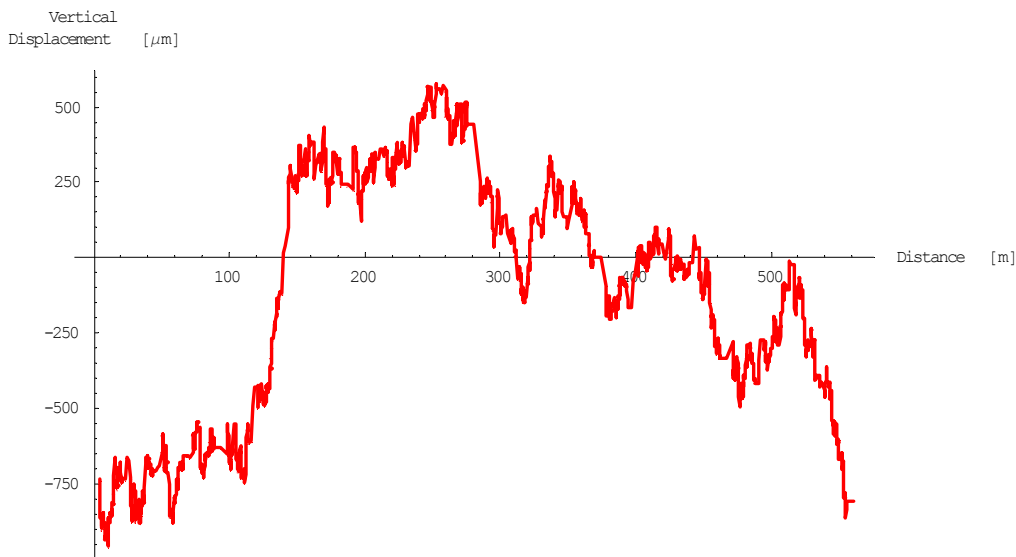


Figure 1.4-19 Vertical displacements from a representative ATL run for DIAMOND elements, for a value of A of 10^{-14} m²/m/s, and a time difference of 6 months. The horizontal axis shows the distance around the circumference.

After application of such element displacements to the lattice, it is possible, through the use of the 168 in-sextupole correctors, to minimise the displacements at the orbit monitors.

Even after correction, the orbit is only minimised at the monitors and there can be residual beam motion at other points around the ring. These orbit displacements can have a detrimental effect on the non-linear dynamics of the machine, and can limit both the allowable beam oscillation around the new closed orbit and the momentum acceptance of the machine, with a consequently reduced beam lifetime. Therefore, as well as limits due to corrector magnet saturation, the range of element displacements is also limited to that which does not greatly affect the non-linear dynamics.

The range of element displacements is quantified by the proportionality constant A . With dimensions m²/m/s, the value of A describes the average vertical element motion per unit length separation per unit time. The effect of different magnitudes of A over 6 months of running is shown in Figure 1.4-20 and Figure 1.4-21; these show that the maximum value of A that can be tolerated is 10^{-15} m²/m/s. Tune shifts also become significant above this value of A (see Figure 1.4-22) although they can be tolerated.

The effect of increasing A upon the dynamic aperture is progressive (see Figure 1.4-23), the effect for values of A above 10^{-15} m²/m/s being significant.

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One of the determining factors in choosing A is the maximum residual orbit in the centre at either the insertion device source points (Figure 1.4-24) or at the dipole source points (Figure 1.4-25). This becomes significant for values of A above 10^{-16} m²/m/s.

In conclusion then, the maximum orbit drift that should be allowed under this model is A above 10^{-16} m²/m/s. Equating this to an architectural limit on the ground slab movement corresponds to a limit for the floor motion of approximately 180 μ m/10 m/year.

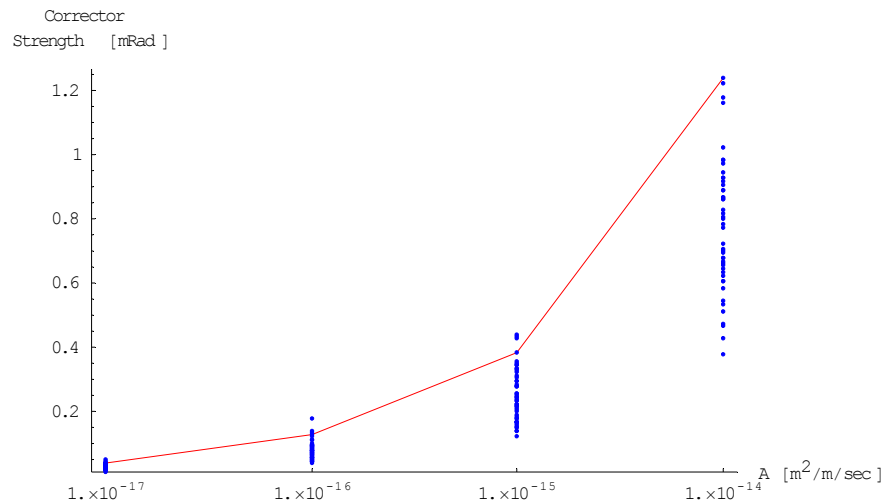


Figure 1.4-20 Corrector strength requirements from 20 ATL error sets (in red), and 95% confidence limit (shown in blue), for different values of A and a time difference of 6 months. Values over 10^{-15} m²/m/s give corrector requirements over 0.5 mrad.

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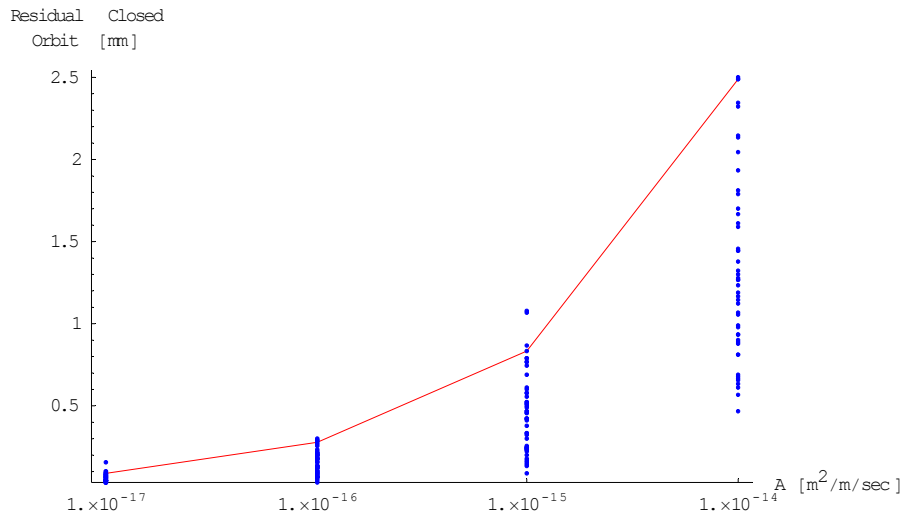


Figure 1.4-21 Maximum residual orbits after correction for 20 ATL error sets (in red), and 95% confidence limit (shown in blue), for different values of A and a time difference of 6 months. Values over $10^{-16} \text{ m}^2/\text{m}/\text{s}$ give overly large residual orbits.

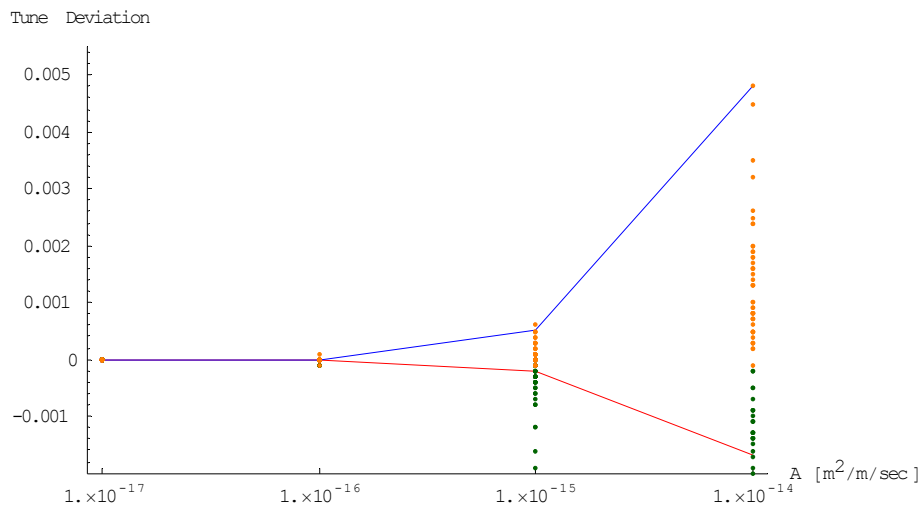


Figure 1.4-22 Tune shifts after orbit correction (horizontal: red, vertical: blue), for different values of A and a time difference of 6 months.

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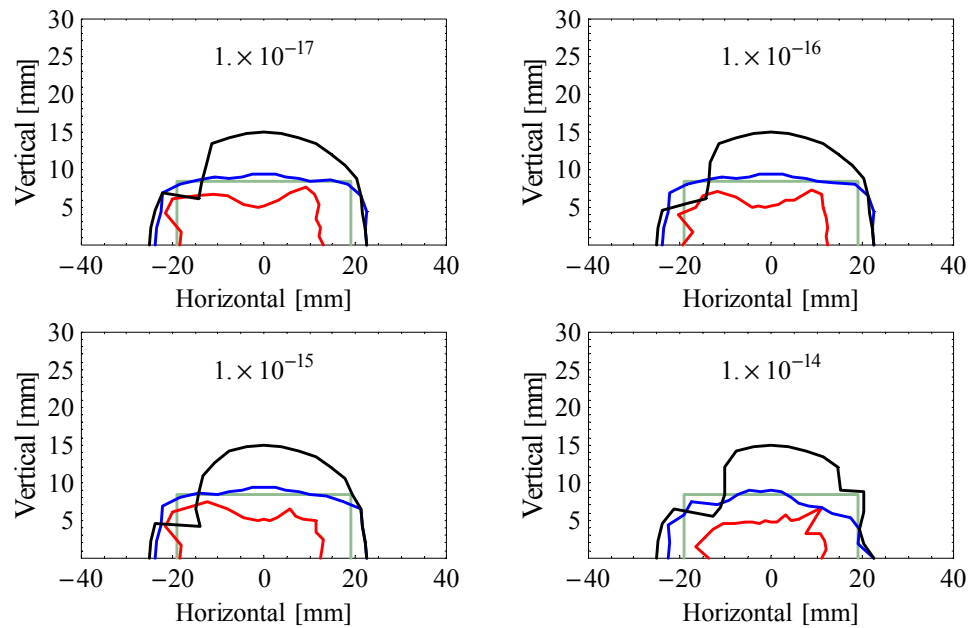


Figure 1.4-23 Dynamic Apertures at -4%, 0% and +4% momentum deviation for increasing values of A and a time difference of 6 months.

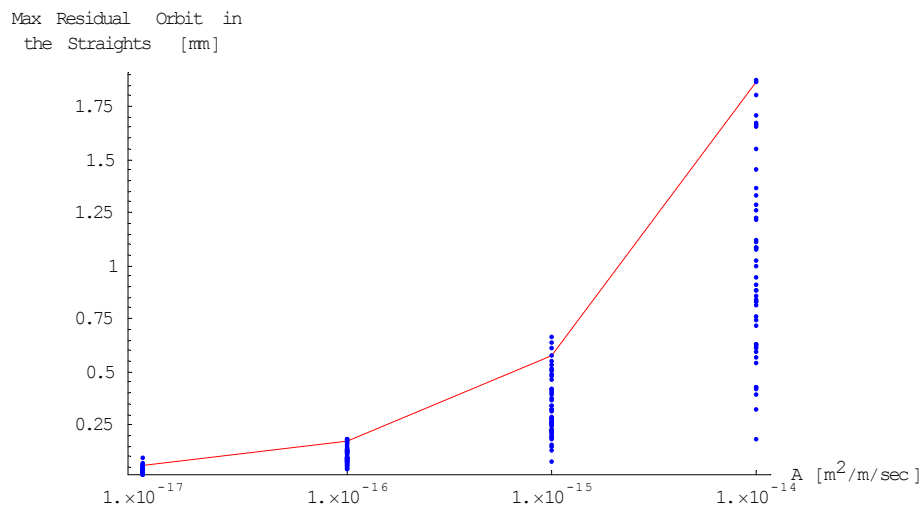


Figure 1.4-24 Residual orbit deviations at the centre of the insertion devices for 20 ATL error sets (in red), and 95% confidence limit (shown in blue), for different values of A and a time difference of 6 months. Values over 10^{-16} m²/m/s give overly large residual orbits.

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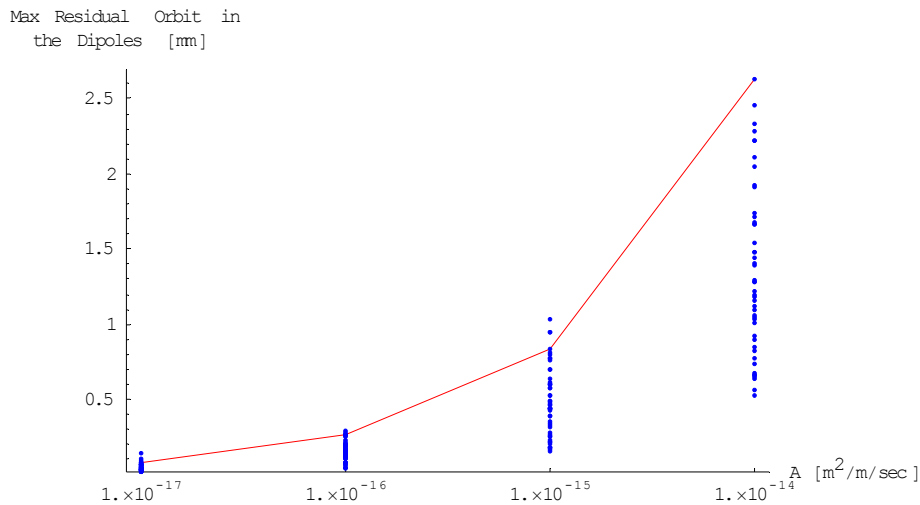


Figure 1.4-25 Residual orbit deviations at the dipole source points for 20 ATL error sets (in red), and 95% confidence limit (shown in blue), for different values of A and a time difference of 6 months. Values over 10^{-16} m²/m/s give overly large residual orbits.

(b) Fourier and Gaussian Deformations

The most likely floor deformations that can occur between the accelerator and the beamlines can be characterised in terms of Fourier and Gaussian distributed errors. As a worst case correcting the beam motion to the nominal plane – i.e monitors assumed static – is modeled. This was used as a somewhat simplistic model of a moving machine with a requirement to accommodate beamline steering. The model was set-up without knowledge of how the beamlines will move relative to the machine and the degree to which the optical elements in the beamline can be adjusted. In terms of specifying a tolerance for allowable floor movements by consideration of effects including corrector strength requirements and dynamic aperture, this is a pessimistic view.

Two typical Fourier-like error sets are shown in Figure 1.4-26 for a) the case of the 6th harmonic with an amplitude of 2mm and b) for the first harmonic case, which is representative of a tilt in the floor. In the Gaussian distribution a localised deformation is applied to elements either side of a given position in the lattice, so as to give a dip of given width and amplitude; two typical deformations are shown in Figure 1.4-27.

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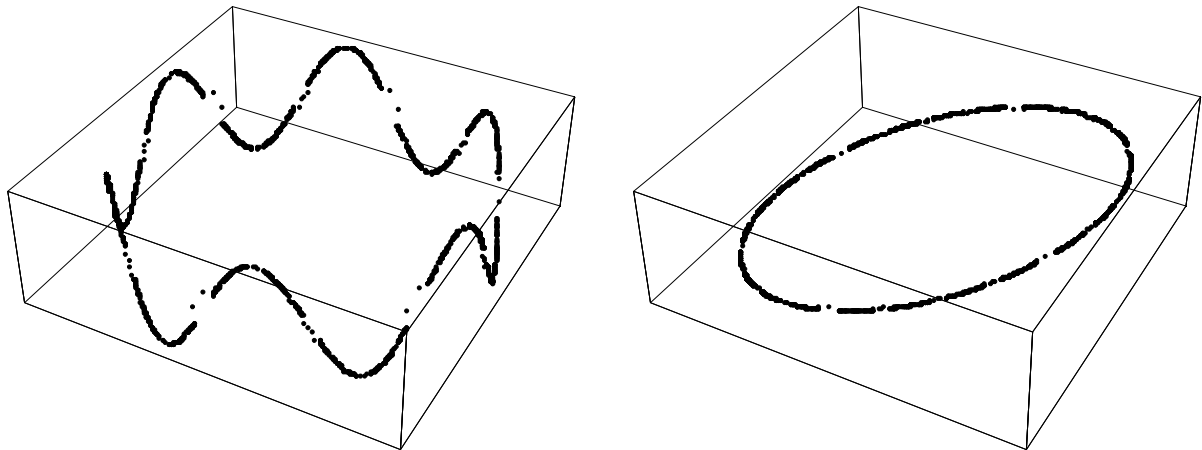


Figure 1.4-26 A Fourier error distribution. The left plot shows the 6th harmonic, whilst the right shows the first harmonic, which represents a tilt of the storage ring floor.

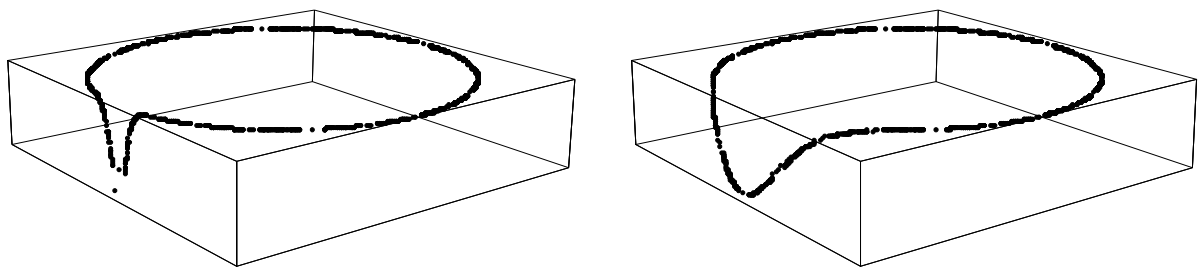


Figure 1.4-27 A Gaussian error distribution, with a 40m wide deformation shown on the left and a 160m wide deformation shown on the right.

To fully investigate the effects of both Fourier and Gaussian distributed errors, results have been calculated for various periods and amplitudes of both Fourier and Gaussian distributions. The effect of these different error distributions is then characterised in terms of the corrector requirements and non-linear dynamic effects.

For Fourier deformations the effects on the corrector strengths from increasing harmonics are minimal. In terms of the non-linear dynamics however, there are noticeable artefacts at both the first and second harmonics. This is possibly due to the fact that at lower harmonics there are longer regions where the beam does not pass through the centre of the magnetic elements; these artefacts however, are most evident at -4% momentum deviation. At the fifth harmonic artefacts can be seen at nominal momentum, the reason for this is unclear but is not correlated with corrector strength.

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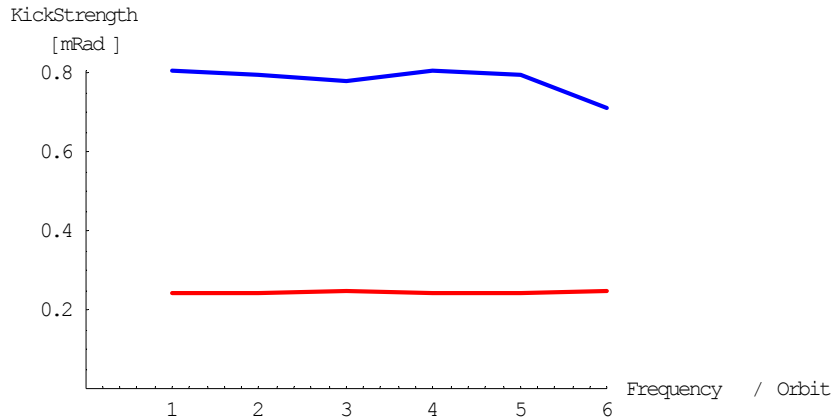


Figure 1.4-28 Kicker strength versus frequency for a Fourier error distribution of 1mm amplitude.

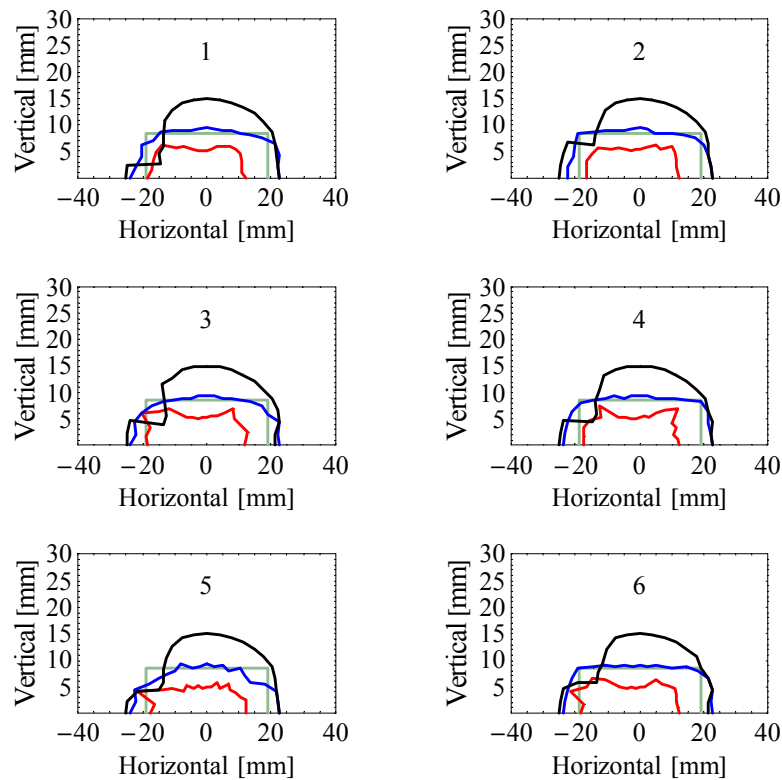


Figure 1.4-29 Dynamic aperture versus frequency for a Fourier error distribution of 1mm amplitude.

From the previous results it can be seen that the first harmonic has the most noticeable effects on the accelerator, remembering that the artificial assumption of correction to static monitors has been made, with slightly higher corrector requirements and dynamic aperture artefacts visible. Therefore the following results are presented for

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the first harmonic only. The results clearly show that the amplitude of the machine tilt has a strong effect on both the corrector requirements, which rise linearly, and the non-linear dynamics, which at higher amplitudes are noticeably worse.

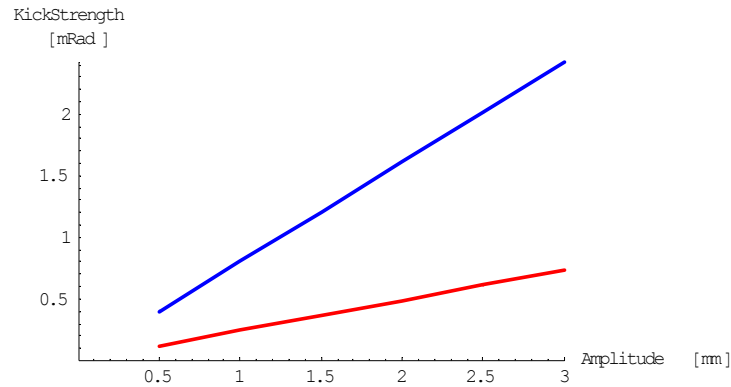


Figure 1.4-30 Kicker strength versus amplitude for a Fourier error distribution at the first harmonic of the storage ring.

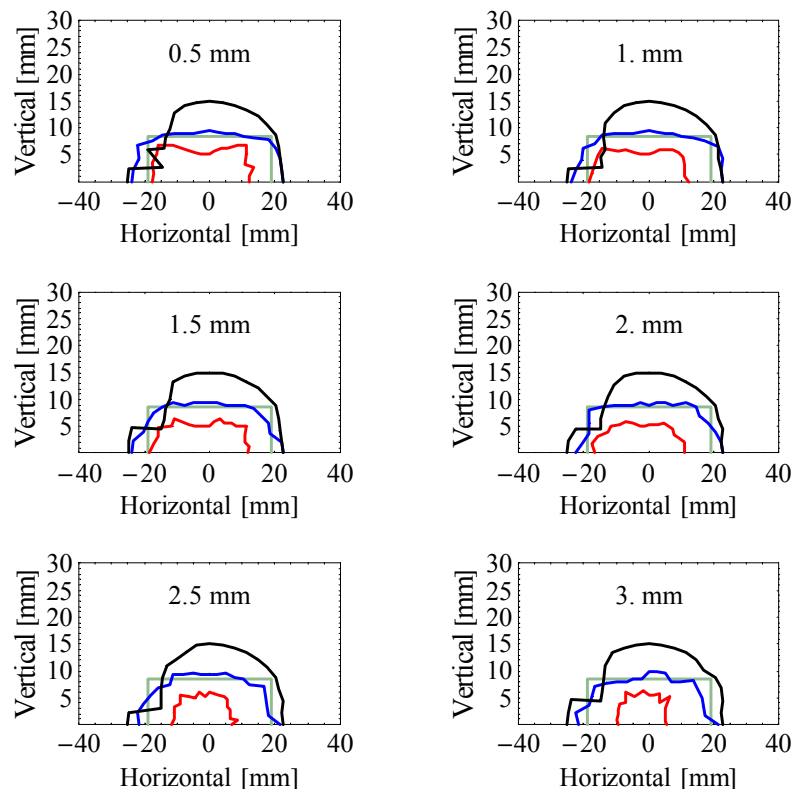


Figure 1.4-31 Dynamic aperture versus amplitude for a Fourier error distribution at the first harmonic of the storage ring.

The width of the Gaussian deformation should have a strong effect on the corrector requirements, since with larger deformations more correctors and BPMs are involved,

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and so there are more constraints on the beam. This will tend to increase the strength of the middle corrector to compensate (see Figure 1.4-32). The dynamic aperture shows little change with deformation width (Figure 1.4-33). The worst case is likely to be when there is a large difference between the start of the deformation and the first BPM that can detect the error. This then causes a large beam deviation, adversely effecting the dynamic aperture.

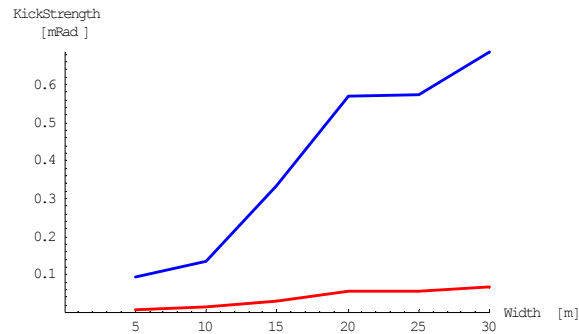


Figure 1.4-32 Kicker strength versus width for a Gaussian error distribution with 1mm amplitude.

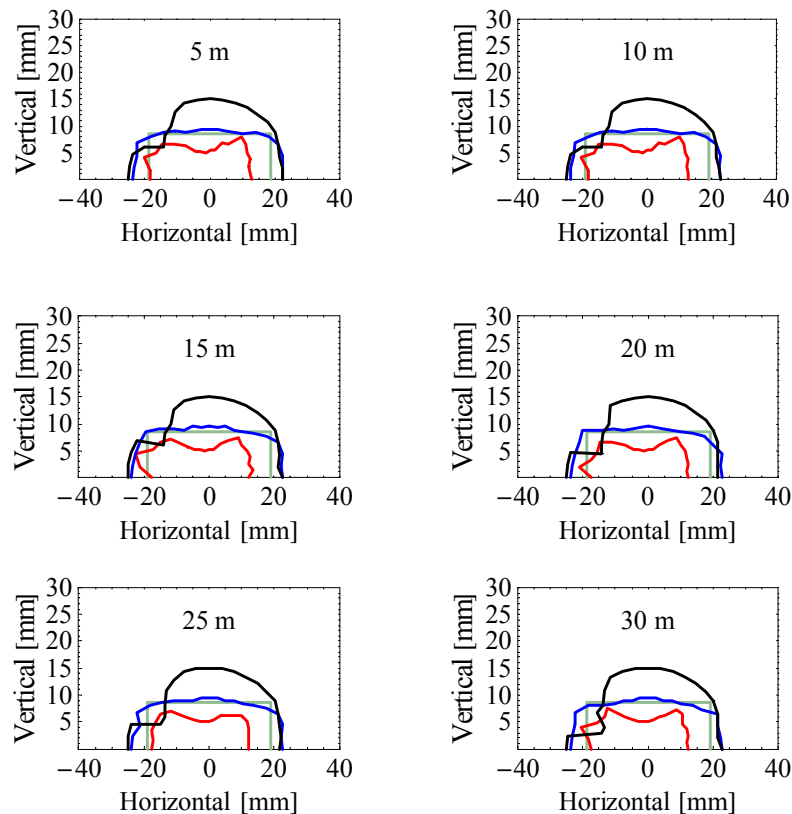


Figure 1.4-33 Dynamic aperture versus width for a Gaussian error distribution with 1mm amplitude.

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However, the effects on the corrector strengths with deformation width are also dependant on the position of the deformation around the ring. This is illustrated in Figure 1.4-34 for a deformation with a width of 40 m, centred on different positions around the ring.

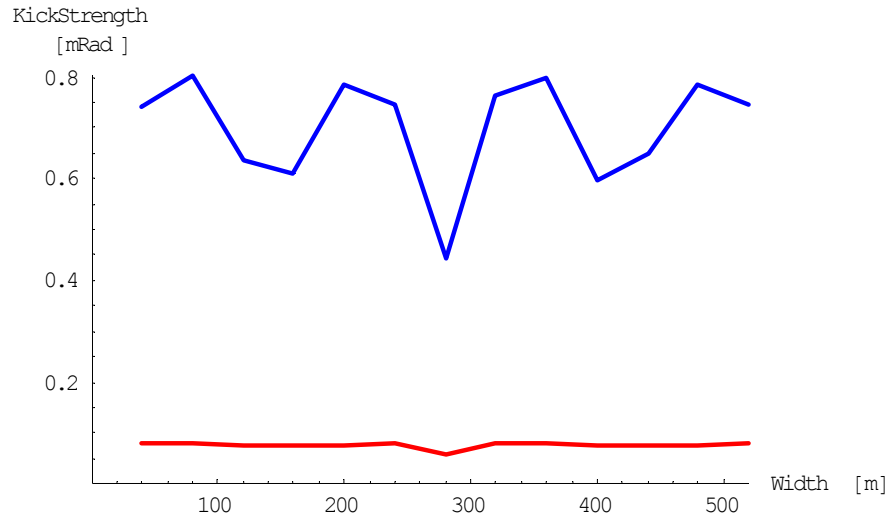


Figure 1.4-34 Kicker strength versus position for a 40 m wide Gaussian error distribution.

The reason for this dependence is probably due to how many BPMs and/or correctors are in the deformation area. This behaviour also depends on the width of the deformation.

As in the Fourier case, the effect of an increasing amplitude deformation is to linearly increase both the maximum and RMS corrector amplitudes (Figure 1.4-35). In terms of the dynamics, there is a minimal effect from increasing the amplitude of the bump, possibly because with such a small element deformation the corrected beam only 'misses' the centre of a few elements (Figure 1.4-36).

With a 0.5 mrad maximum correction angle, the maximum differential floor motion is about 0.6 mm, for the first harmonic Fourier case. If it is assumed that the accelerator is realigned every 6 months, this gives an allowable motion of 1.25 mm/year. Taking this over the 561.6m circumference machine, a final allowable differential motion of $\sim 100 \mu\text{m}/10\text{m}/\text{year}$ is arrived at.

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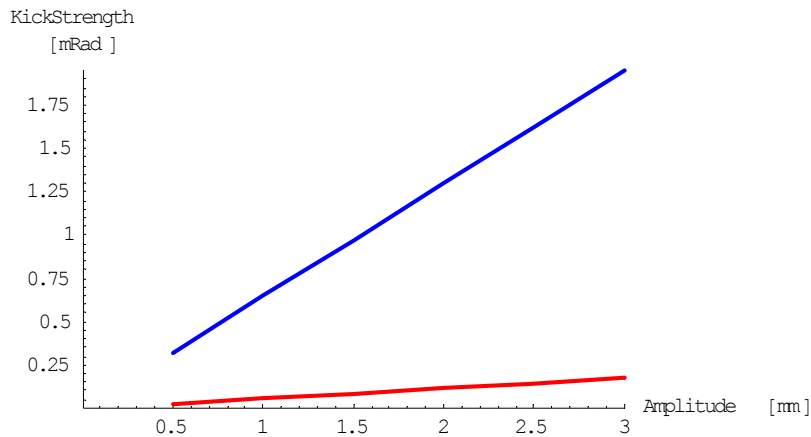


Figure 1.4-35 Kicker strength versus amplitude for a 20 m wide Gaussian error distribution.

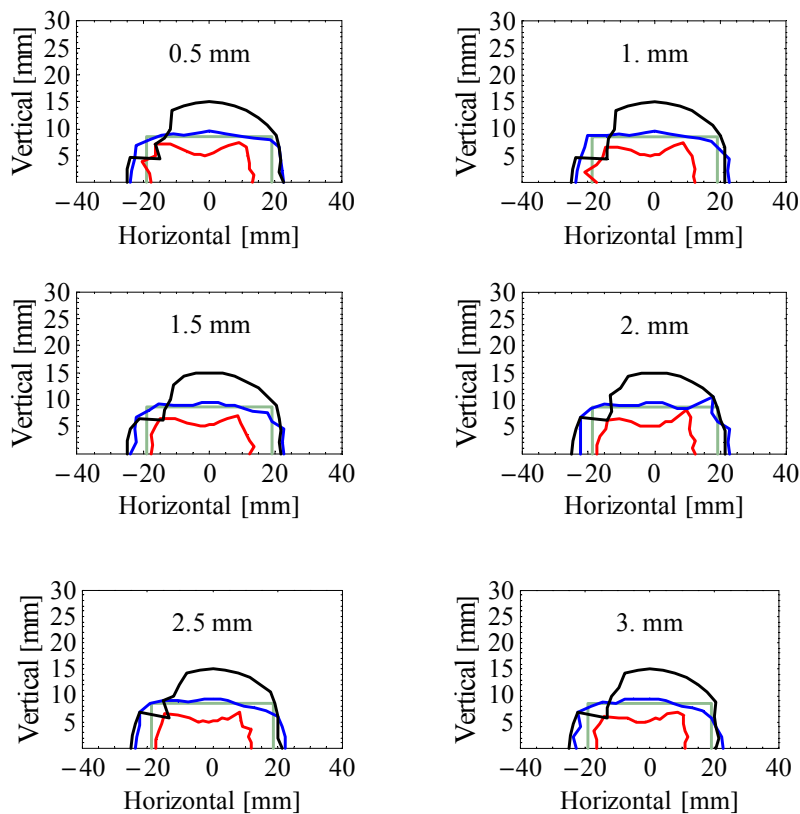


Figure 1.4-36 Dynamic aperture versus amplitude for a 20 m wide Gaussian error distribution.

(c) Summary

To help make some estimates of the allowable movement of the floor due to slow ground motion effects, studies of the effects of ATL, Gaussian and Fourier type deformations have been made. The assumption of static monitors and a disregard of

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the effects of collecting accelerator elements on girders simplified the modelling while ensuring that allowable the motion was over specified. Work is already underway to ensure that these effects are studied in greater detail before the floor specification is finalised.

1.4.8 Effect of Magnetic Errors and Misalignments

(a) Error Tables

The following tables summarises the alignment and field errors which are expected in each element type.

Table 1.4-3 Dipolar Alignment Errors

<i>Error Type</i>	<i>RMS Magnitude</i>
Dipole Transverse Displacement	0.05 mm
Dipole Longitudinal Displacement	0.05 mm
Dipole Roll Error	0.2 mrad

Table 1.4-4 Dipole Systematic Field Errors[26]

<i>Error Type</i>	<i>RMS Magnitude</i>
Systematic Sextupole Field Error	-0.0399221 m ⁻²

Table 1.4-5 Dipole Random Field Errors[27]

<i>Error Type</i>	<i>RMS Magnitude</i>
Random Quadrupole Field Error	5.0 10 ⁻⁴
Random Sextupole Field Error	2.0 10 ⁻⁴
Random Octupole Field Error	5.0 10 ⁻⁴

Table 1.4-6 Quadrupole Alignment Errors

<i>Error Type</i>	<i>RMS Magnitude</i>
Quadrupole Transverse Displacement	0.1 mm
Quadrupole Roll Error	0.2 mrad

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Table 1.4-7 Quadrupole Systematic Field Errors For the Wide Quadrupoles[28]

<i>Error Type</i>	<i>RMS Magnitude</i>
Systematic Octupole Field Error	$2.14 \ k_2 \text{ m}^{-3}$
Systematic Dodecapole Field Error	$-3.44 \ 10^4 \ k_2 \text{ m}^{-5}$
Systematic 20-Pole Field Error	$-6.9 \ 10^{12} \ k_2 \text{ m}^{-9}$

Table 1.4-8 Quadrupole Systematic Field Errors For the Normal Quadrupoles

<i>Error Type</i>	<i>RMS Magnitude</i>
Systematic Octupole Field Error	$3.2 \ k_2 \text{ m}^{-3}$
Systematic Dodecapole Field Error	$-5.16 \ 10^4 \ k_2 \text{ m}^{-5}$
Systematic 20-Pole Field Error	$-8.4 \ 10^{13} \ k_2 \text{ m}^{-9}$

Table 1.4-9 Quadrupole Random Field Errors for All Quadrupoles

<i>Error Type</i>	<i>RMS Magnitude</i>
Random Sextupole Field Error	$2.5 \ 10^{-4}$
Random Octupole Field Error	$6.6 \ 10^{-4}$
Random Decapole Field Error	$1.0 \ 10^{-4}$
Random Dodecapole Field Error	$2.0 \ 10^{-4}$

Table 1.4-10 Sextupole Alignment Errors

<i>Error Type</i>	<i>RMS Magnitude</i>
Sextupole Transverse Displacement	0.1 mm

Table 1.4-11 Sextupole Systematic Field Errors for S2A Harmonic and Family 1 Chromatic Sextupoles[29]

<i>Error Type</i>	<i>RMS Magnitude</i>
Systematic Decapole Field Error	$5.33 \ 10^{-7} \ k_3 \text{ m}^{-4}$
Systematic 14-Pole Field Error	$1.78 \ 10^{-2} \ k_3 \text{ m}^{-6}$
Systematic 18-Pole Field Error	$8.3 \ 10^2 \ k_3 \text{ m}^{-8}$

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Table 1.4-12 Sextupole Systematic Field Errors for Family 2 Sextupoles

<i>Error Type</i>	<i>RMS Magnitude</i>
Systematic Decapole Field Error	$8 \cdot 10^{-7} \text{ k}_3 \text{ m}^{-4}$
Systematic 14 Pole Field Error	$2.67 \cdot 10^{-2} \text{ k}_3 \text{ m}^{-6}$
Systematic 18 Pole Field Error	$1.24 \cdot 10^3 \text{ k}_3 \text{ m}^{-8}$

Table 1.4-13 Sextupole Random Field Errors

<i>Error Type</i>	<i>RMS Magnitude</i>
Random Sextupole Field Error	$1 \cdot 10^{-3}$
Random Octupole Field Error	$1 \cdot 10^{-3}$
Random Decapole Field Error	$1 \cdot 10^{-3}$
Random Dodecapole Field Error	$1 \cdot 10^{-3}$

(b) Effect of Alignment Errors

The effects of alignment errors on the beam dynamics, from different magnetic element types, is given below.

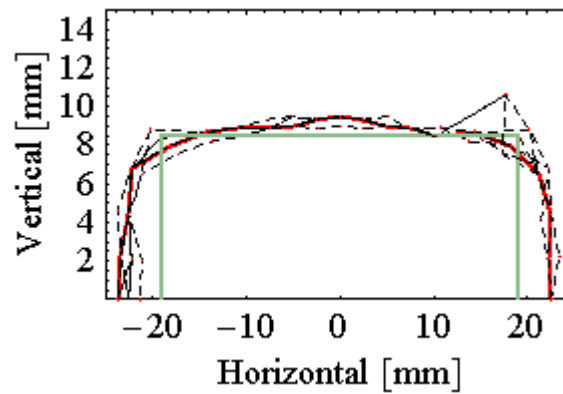


Figure 1.4-37 Dynamic aperture over 10 random seeds for dipole alignment errors.

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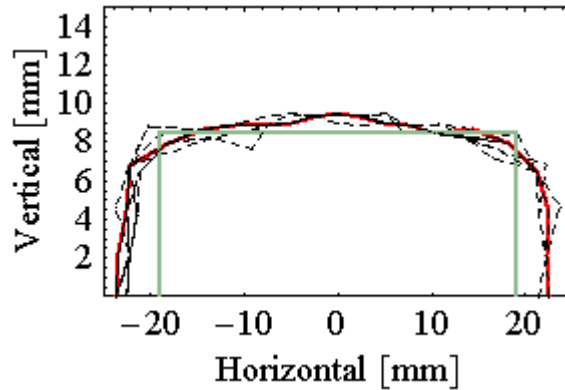


Figure 1.4-38 Dynamic aperture over 10 random seeds for quadrupole alignment errors.

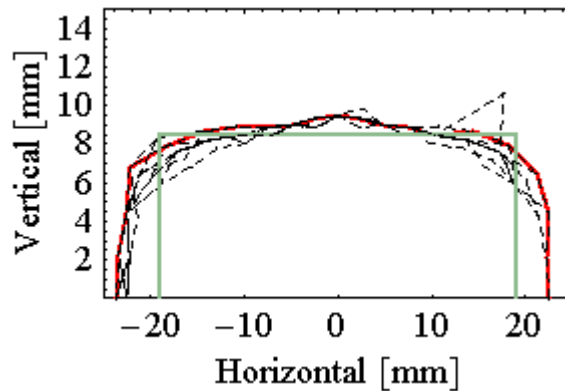


Figure 1.4-39 Dynamic aperture over 10 random seeds for sextupole alignment errors.

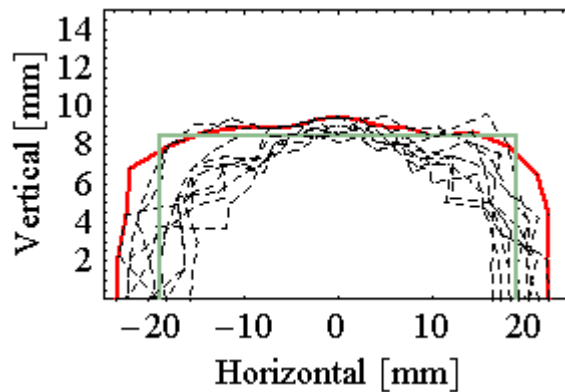


Figure 1.4-40 Dynamic Aperture over 10 random seeds for dipole, quadrupole and sextupole alignment errors.

(c) Systematic Field Errors

The Effects of systematic field errors on all magnets, given in Table 1.4-4, Table 1.4-7, Table 1.4-8, Table 1.4-11 and Table 1.4-12, and the effects of alignment errors, given in Table 1.4-3, Table 1.4-6 and Table 1.4-10, on all magnets have been investigated. The

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effects at $\pm 4\%$ momentum deviation are also included. The results are shown in Figure 1.4-41

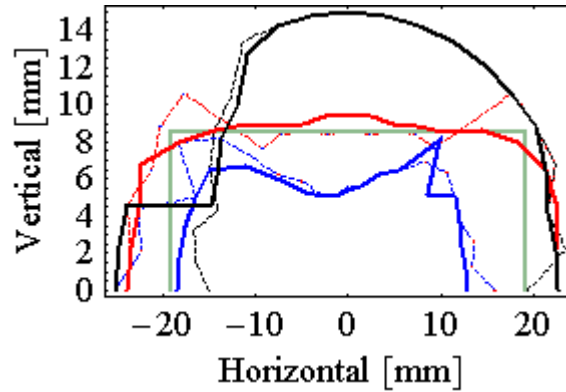


Figure 1.4-41 Dynamic aperture with systematic field errors only.

(d) Random Field Errors

The Effects of random field errors on all magnets, given in Table 1.4-5, Table 1.4-9 and Table 1.4-13, and the effects of random field errors and corrected alignment errors, given in Table 1.4-3, Table 1.4-6 and Table 1.4-10, on all magnets have been investigated. The effects at $\pm 4\%$ momentum deviation are also included. All data is taken over 50 turns around DIAMOND. The results are shown in Figure 1.4-42, Figure 1.4-43 and Figure 1.4-44.

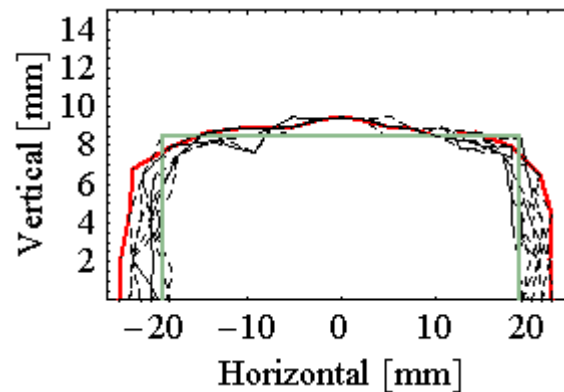


Figure 1.4-42 Dynamic aperture with random field errors for zero momentum deviation.

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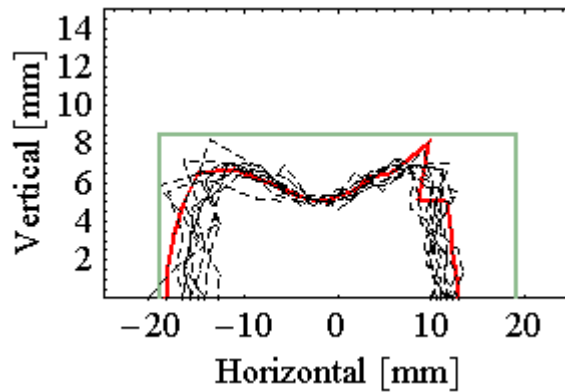


Figure 1.4-43 Dynamic aperture with random field errors for -4 % momentum deviation.

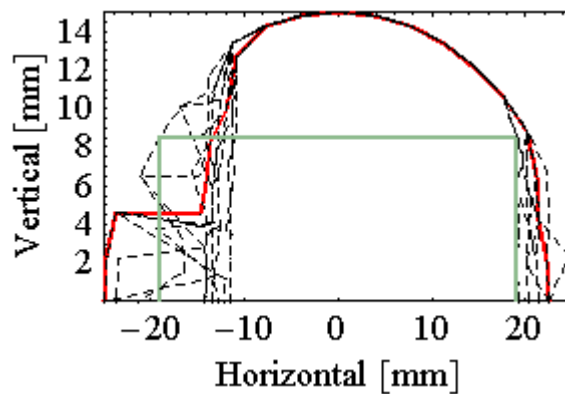


Figure 1.4-44 Dynamic aperture with random field errors for +4 % momentum deviation.

(e) Combined Effects of All Errors

The combined effect of all errors given in (a) is shown below in Figure 1.4-45, Figure 1.4-46 and Figure 1.4-47. These show that the reference design performance is not adversely affected by alignment and field errors.

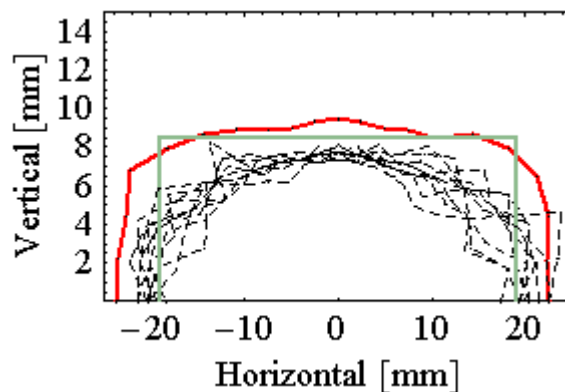


Figure 1.4-45 Dynamic aperture with all errors for zero momentum deviation.

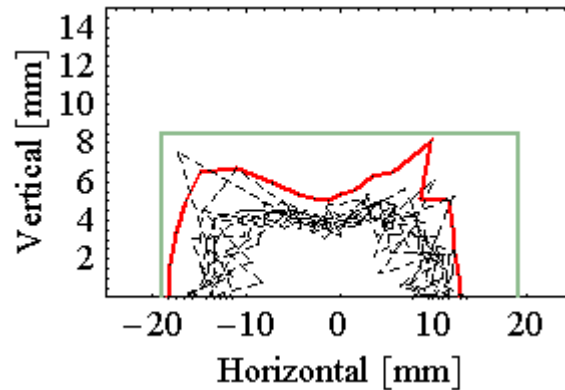


Figure 1.4-46 Dynamic aperture with all errors for -4 % momentum deviation.

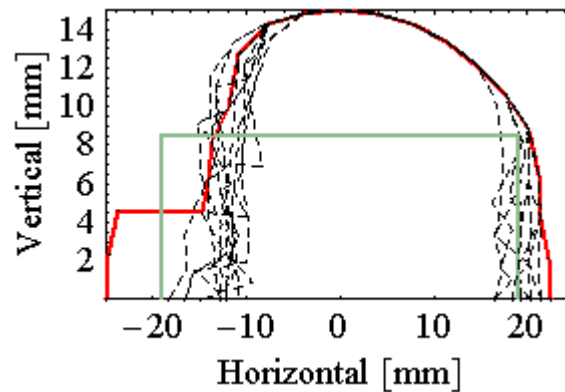


Figure 1.4-47 Dynamic aperture with all errors for +4 % momentum deviation.

1.4.9 Assessment of Ground Motion Effects

Ground motion leads to a time dependent displacement of the structure underlying the storage ring lattice. The displacement of the magnetic elements due to this motion leads to time dependant closed orbit distortions. Ground motion is built up from many components, including contributions from environmental and atmospheric effects, such as seasonal temperature variations and tidal motion; vibration caused by general human activity (“cultural noise”); and vibration from internal sources such as traffic, mechanical equipment and so forth that are associated with operation of the accelerator (“technical noise”).

Measurement[22] and analysis of the ground motion at the proposed site of the storage ring, to the east of the current RAL site, clearly shows these effects. Figure 1.4-48 shows the two positions where ground motion data was recorded, while Figure 1.4-49 and Figure 1.4-50 show the displacement power spectral density measured at position 2, at two different times of the day.

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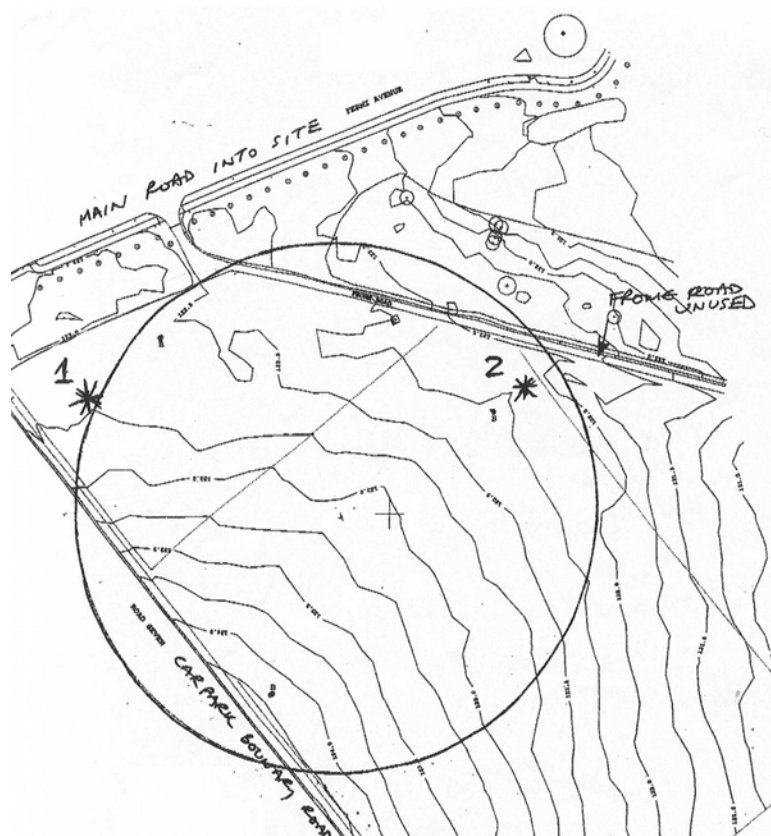


Figure 1.4-48 Locations of ground motion measurements

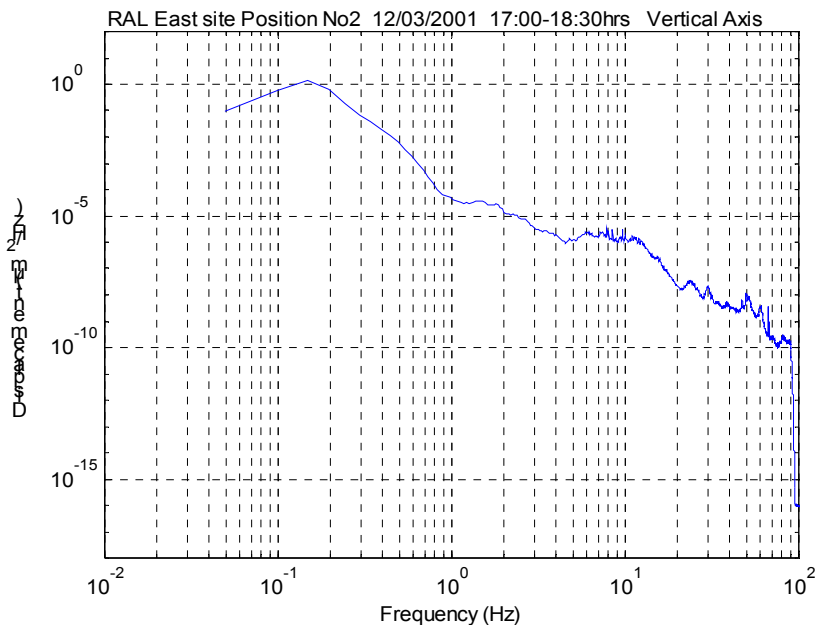


Figure 1.4-49 Power spectral density plot of measured ground motion at position 2 of the RAL site, taken between 17:00 and 18:30 on 12/3/2001

By comparing this data with that produced at times of relatively low cultural noise, such as between 21:00 and 22:00 as shown in Figure 1.4-50, both the general

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background characteristic level of the motion can be seen, as well as other distinct sources of noise.

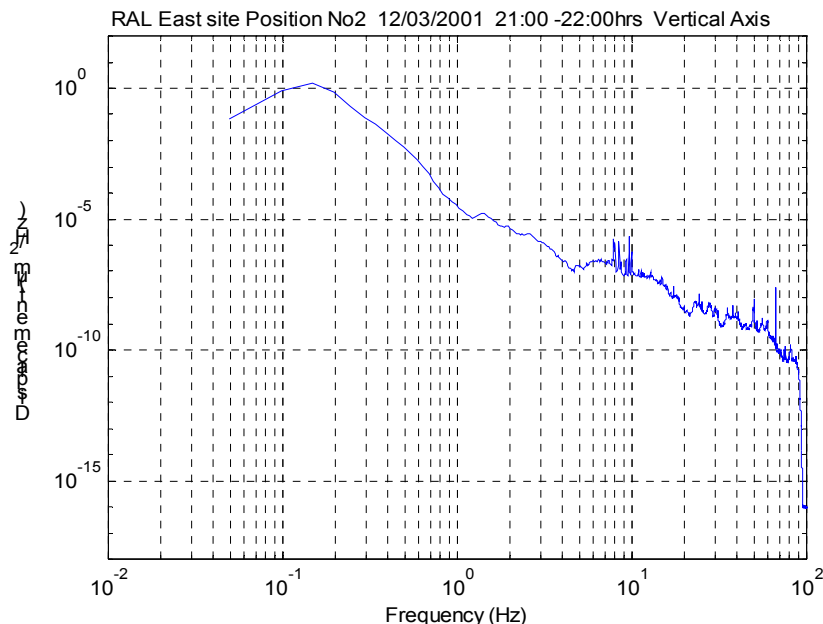


Figure 1.4-50 Power spectral density plot of measured ground motion at position 2 of the RAL site, taken between 21:00 and 22:00 on 12/3/2001.

Geological and atmospheric effects dominate the spectrum at frequencies below 1 Hz. The wide, large amplitude spike between ~ 6 Hz to ~ 11 Hz is often due to road traffic, either on the road adjacent to the site, or from the A34 trunk road nearby. The background noise level in the 1 to 100 Hz region falls significantly in the period outside of typical working hours. This then exposes the underlying peaks due to noise sources, probably either on the RAL or Harwell sites, which do not diminish. Both the overall background noise level in the 1 to 100 Hz region and these individual peaks were larger in position 1 than in position 2.

Applying displacements consistent with a plane wave incident on the storage ring at a given phase, with an amplitude relative to frequency and over the 100 Hz frequency range shown, highlights the relative effects of different frequencies of ground motion on the beam dynamics. This is illustrated in Figure 1.4-51, which shows that the relative orbit deviations follow the same line as the power spectral density data. The data does deviate significantly at around 70 Hz, which is probably a resonance effect related to the betatron tune.

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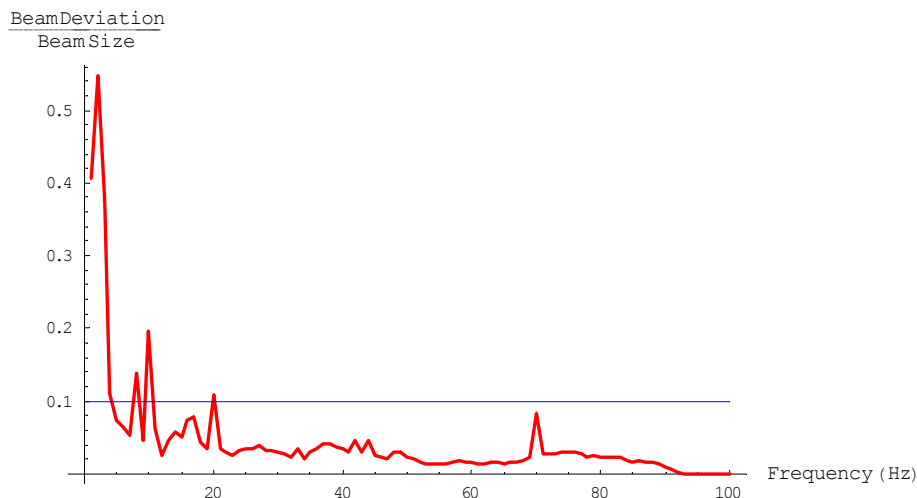


Figure 1.4-51 Maximum closed orbit deviations as a function of frequency relative to the beam sizes in the vertical plane.

Figure 1.4-51 shows that, without correction, frequencies below 25 Hz are the most important in perturbing the beam beyond the 10 % of beam size specification. However, the spike at 70 Hz clearly identifies the need for correction at much higher frequencies.

Although effects on the closed orbit can be seen at individual frequencies, in general it is the integrated displacement amplitude over the specified frequency range which is likely to give an indication of the likely effects of the ground motion on the beam dynamics. Analysis of both power spectral density plots, shows that the maximum integrated displacement amplitude, between the frequency range 1 to 100Hz, at the given position on the RAL site is of the order $1\text{ }\mu\text{m}$ rms.

This $1\text{ }\mu\text{m}$ displacement amplitude, in the vertical plane only, has been applied to the magnetic elements of the accelerator with a Gaussian distribution, truncated at 2σ , and in an uncorrelated, random manner. The effects on the closed orbit, with and without the previously defined fast correction scheme are shown in Figure 1.4-52 to Figure 1.4-57.

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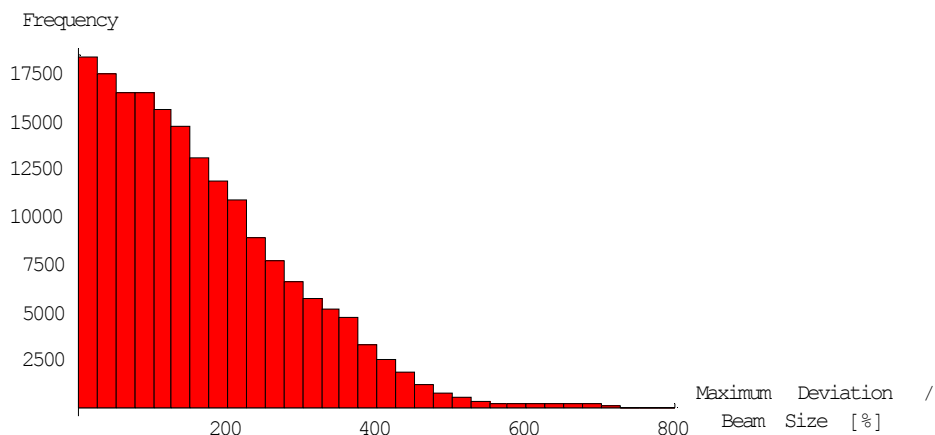


Figure 1.4-52 Histogram of the Maximum Vertical Closed Orbit Deviation as a Percentage of Beam Size at all points around the lattice *without* Correction

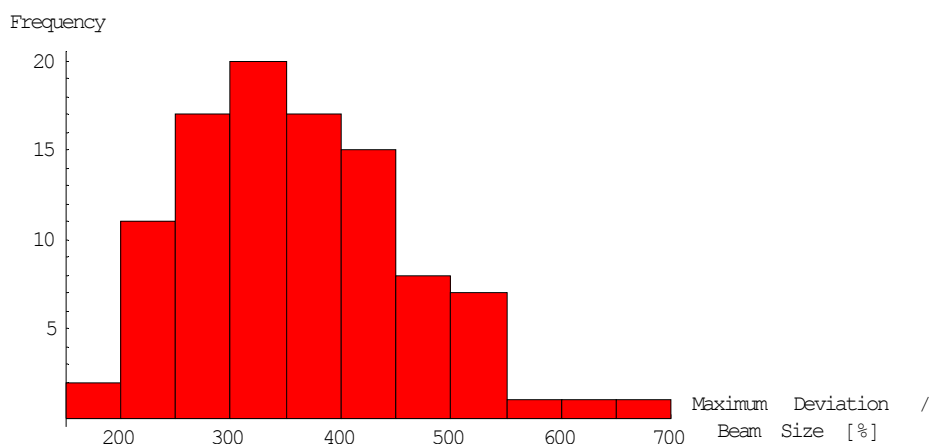


Figure 1.4-53 Histogram of the Maximum Vertical Closed Orbit Deviation as a Percentage of Beam Size at all Straight Sections around the lattice *without* Correction

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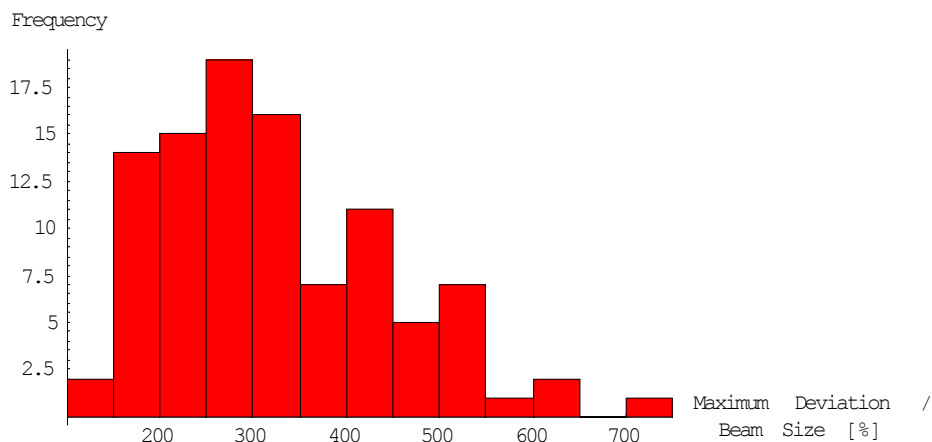


Figure 1.4-54 Histogram of the Maximum Vertical Closed Orbit Deviation as a Percentage of Beam Size at all Dipole Source Points around the lattice *without* Correction

Without correction it can be seen that at the radiation source points, beam motion is many times the relevant beam sizes. However, around the lattice as a whole, beam motion is generally less than twice the beam sizes.

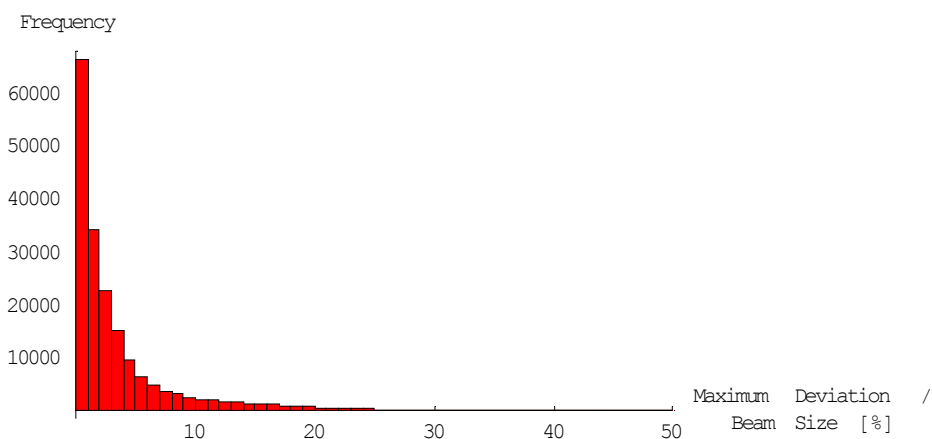


Figure 1.4-55 Histogram of the Maximum Vertical Closed Orbit Deviation as a Percentage of Beam Size at all points around the lattice *with* Correction

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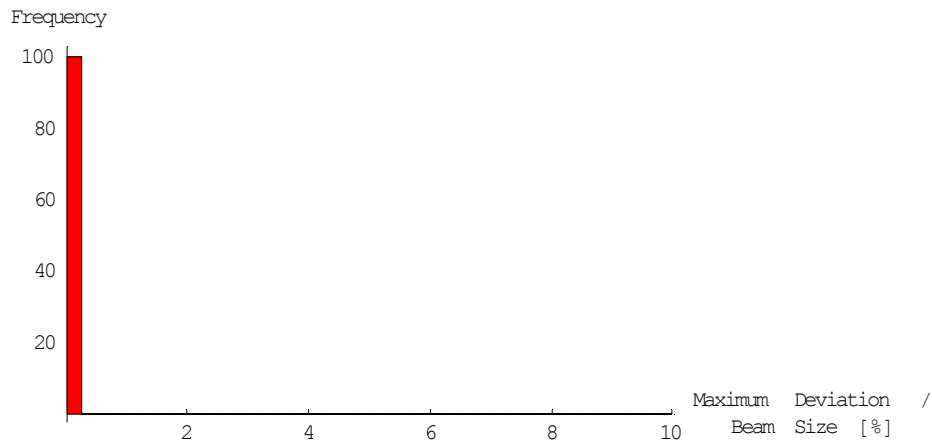


Figure 1.4-56 Histogram of the Maximum Vertical Closed Orbit Deviation as a Percentage of Beam Size at all Straight Sections around the lattice *with* Correction

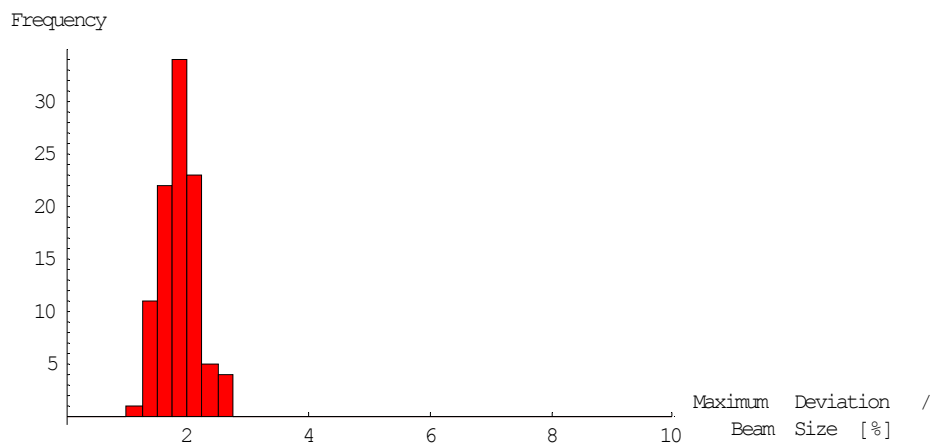


Figure 1.4-57 Histogram of the Maximum Vertical Closed Orbit Deviation as a Percentage of Beam Size at all Dipole Source Points around the lattice *with* Correction

When the Fast correction algorithm is enabled, it is immediately obvious that closed orbit distortions are reduced to significantly less than the beam sizes, and are generally less than the required 10% of beam size specification. At the radiation source points, the residual closed orbit is less than 10% at all positions .

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1.5 COUPLING AND CORRECTION

1.5.1 The Emittance Ratio

In a perfectly aligned storage ring the continuous radiation damping, coupled with the lack of quantum excitation in the vertical plane, leads to a vertical emittance determined by the synchrotron radiation opening angle; this is several orders of magnitude smaller than the typical value for the natural emittance in the horizontal plane. Imperfections in the positions, orientations and fields of the magnetic components will lead to an increased vertical emittance. The figure of merit for experimental usage is the *emittance ratio* of the equilibrium emittances in both planes, defined as

$$\chi = \frac{\varepsilon_y}{\varepsilon_x}, \quad (16)$$

where the equilibrium emittances in each plane are given in terms of the natural horizontal emittance ε_0 by

$$\varepsilon_x = \frac{\varepsilon_0}{1 + \chi}, \quad \varepsilon_y = \frac{\chi \varepsilon_0}{1 + \chi}, \quad (17)$$

χ is commonly called the *coupling*, but in reality is determined by more than just that effect. For small values of χ it can be shown that the photon brilliance B scales as

$$B \sim \frac{1}{\chi \varepsilon_0^2}, \quad (18)$$

so that for photon output the emittance ratio should be as small as possible. The caveat to this is the requirement to maintain an adequate Touschek lifetime. The specification for DIAMOND is to obtain an emittance ratio of 1%, under which conditions the target brilliance can be achieved with the specified lifetime for multibunch operation.

The two primary contributions to the emittance ratio which are brought about by imperfections are the finite vertical dispersion – generated by spurious vertical bends in the magnet elements – and coupling of the horizontal and vertical modes of oscillation – which is primarily due to skew quadrupole components in the magnet elements. These are dealt with in turn below.

1.5.2 Residual Vertical Dispersion

Imperfections in the magnet lattice will give rise to vertical bends, and therefore to a non-zero vertical dispersion. The contribution to the emittance ratio from this effect is

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$$\chi_d = \frac{J_x \oint_{\text{dipoles}} H_y ds}{J_y \oint_{\text{dipoles}} H_x ds}, \quad (19)$$

where $J_{x,y}$ are the damping partition numbers in the horizontal and vertical planes, and $H_{x,y}$ are the chromatic invariants

$$H_z = \gamma_z \eta_z^2 + 2\alpha_z \eta_z \eta'_z + \beta_z \eta_z'^2, \quad z = x, y, \quad (20)$$

integrated over the storage ring dipoles. In general both the vertical and horizontal emittances are modified by the presence of vertical bends, but for small χ_d only the vertical perturbation need be considered. A complete calculation should include the correction of closed-orbit distortion caused by the element misalignments. However, consideration of the uncorrected machine gives a reasonable estimate of the likely vertical emittance[30], and is sufficient in a weakly-coupled machine to allow a specification of the correction scheme.

To evaluate the vertical dispersion we solve the normalised equation in the vertical plane[31],

$$\frac{d^2 \tilde{\eta}}{d\phi} + \nu^2 \tilde{\eta} = \nu^2 \beta^{3/2} F(\phi), \quad (21)$$

where $F(\phi)$ is the driving term from imperfections, and the normalised dispersion function is

$$\tilde{\eta}(\phi) = \frac{\eta(s)}{\sqrt{\beta(s)}}, \quad (22)$$

The solution in $\eta(s)$ of equation (22) is

$$\eta(s) = \frac{\sqrt{\beta(s)}}{2 \sin \pi \nu} \int_s^{s+L} \sqrt{\beta(\sigma)} F(\sigma) \cos[\mu(\sigma) - \mu(s) - \pi \nu] d\sigma, \quad (23)$$

giving an rms. value at a particular position s_0 of

$$\langle \eta(s_0)^2 \rangle = \frac{\beta(s_0)}{4 \sin^2 \pi \nu} \left[\int_s^{s+L} \sqrt{\beta(\sigma)} F(\sigma) \cos[\mu(\sigma) - \mu(s) - \pi \nu] d\sigma \right]^2, \quad (24)$$

For an approximate calculation we can assume that the misalignment errors are uncorrelated; for instance this assumes that there is no correlated motion due to magnets being mounted on the same girder, which is a second-order effect. Similarly, we assume that the phase advance between misalignments is also random.

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With these two assumptions, we can re-write equation (24) as a sum over the different elements[30],

$$\langle \eta(s_0)^2 \rangle = \frac{\beta(s_0)}{4 \sin^2 \pi \nu} \frac{1}{2} \sum_i \beta_i F_i^2 L_i^2, \quad (25)$$

or

$$\frac{\langle \eta(s_0)^2 \rangle}{\beta(s_0)} = \frac{1}{4 \sin^2 \pi \nu} \frac{1}{2} \sum_i \beta_i F_i^2 L_i^2, \quad (26)$$

Since

$$\oint_{\text{dipoles}} H_y ds = \oint_{\text{dipoles}} (\gamma_y \eta_y^2 + 2\alpha_y \eta_y \eta'_y + \beta_y \eta_y'^2) ds \approx L_{\text{dipoles}} \left\langle \frac{\eta_y^2}{\beta_y} \right\rangle_{\text{dipoles}}, \quad (27)$$

this gives an approximation for the vertical emittance of

$$\varepsilon_y \approx \frac{C_q E^2}{2\pi \rho^2} \frac{1}{J_y} \left\langle \frac{\eta_y^2}{\beta_y} \right\rangle_{\text{dipoles}}, \quad (28)$$

where the quantum constant C_q is defined as

$$C_q = \frac{55\hbar}{32\sqrt{3}m_e c}, \quad (29)$$

and ρ is the dipole bending radius (assuming an isomagnetic ring).

The generating functions F_i for dominant sources of error are given in Table 1.5-1.

Table 1.5-1 Dominant sources of error driving the vertical dispersion[30].

Error Type	Quantity	F_i	$\langle \eta^2 \rangle / \beta$
Dipole Rotation	$\Delta \theta$	$\Delta \theta / \rho$	$\frac{1}{8 \sin^2 \pi \nu} \sum_i \frac{\beta_i L_i^2}{\rho^2} \Delta \theta^2$
Quadrupole Rotation	$\Delta \theta$	$k_i \eta_{\perp} \Delta \theta$	$\frac{1}{8 \sin^2 \pi \nu} \sum_i \beta_i \eta_{\perp}^2 k_i^2 L_i^2 \Delta \theta^2$
Vertical Quadrupole Position	Δy	$k_i \Delta y$	$\frac{1}{8 \sin^2 \pi \nu} \sum_i \beta_i k_i^2 L_i^2 \Delta y^2$
Vertical Sextupole Position	Δy	$k_2 \eta_{\perp} \Delta y$	$\frac{1}{8 \sin^2 \pi \nu} \sum_i \beta_i \eta_{\perp}^2 k_2^2 L_i^2 \Delta y^2$

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1.5.3 Betatron Coupling

Linear coupling between the horizontal and vertical planes of motion is principally induced by rotations of the quadrupoles around the s -axis and vertical misalignments of the sextupoles, each of which produce skew quadrupole fields, with magnitudes which are respectively

$$\begin{aligned} k_s &= 2k_1\Delta\theta \\ k_s &= k_2\Delta y \end{aligned} \quad (30)$$

There are two approaches used to estimate how these errors induce coupling, depending upon the assumption of whether the storage ring tunes are near to a coupling resonance or not. These are dealt with separately.

(a) Single Resonance Model

In the single resonance model the emittance ratio from horizontal-vertical coupling is given by [30]

$$\chi = \frac{\left| \frac{\kappa_-}{\Delta\nu} \right|^2}{\left| \frac{\kappa_-}{\Delta\nu} \right|^2 + \frac{1}{2}}, \quad (31)$$

assuming that the dominant resonance is the nearest 2nd-order difference resonance

$$\nu_x - \nu_y = p, \quad (32)$$

with p integer;

$$\Delta\nu = \text{Frac}(\nu_x - \nu_y), \quad (33)$$

The coupling coefficient κ_- is given as

$$\kappa_- = \frac{1}{4\pi} \oint_{ring} k_s(s) \sqrt{\beta_x \beta_y} e^{i\left[\mu_x(s) - \mu_y(s) - \frac{2\pi\Delta\nu}{C}\right]} ds, \quad (34)$$

with μ_x , μ_y the local phases, and C the storage ring circumference. To a similar level of approximation as for vertical dispersion, we can assume that errors are uncorrelated, giving

$$\kappa_-^2 \approx \frac{1}{16\pi^2} \sum_i \beta_{x,i} \beta_{y,i} k_{s,i}^2 L_{s,i}^2, \quad (35)$$

(b) Multiple Resonance Model

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In the multiple resonance model [31] it is assumed that the coupling is small and may be treated as a perturbation to the uncoupled motion; that operation is far from a difference resonance, so that all resonances contribute; and that the damping per turn is small compared with the betatron tune, i.e.

$$2\pi(\nu_x - \nu_y) \gg \alpha_x T_0, \alpha_y T_0, \quad (36)$$

where T_0 is the revolution time. In this case, the contributions to betatron coupling from the dominant sources is given approximately by

$$\chi \approx \frac{1}{4} \frac{J_x}{J_y} \frac{1 - \cos 2\pi\nu_x \cos 2\pi\nu_y}{(\cos 2\pi\nu_x - \cos 2\pi\nu_y)^2} \sum_i \beta_{x,i} \beta_{y,i} k_{s,i}^2 L_{s,i}^2, \quad (37)$$

1.5.4 Control of Coupling using Skew Quadrupoles

(a) Compensating the Difference Resonance

Near a difference resonance the eigenvalue tunes of the coupled motion are

$$\nu_{1,2} = \frac{1}{2} \left(\nu_x + \nu_y + p \pm \sqrt{(\nu_x - \nu_y + p)^2 + \kappa_-^2} \right), \quad (38)$$

where κ_- is given by equation (35); the closest approach of the tunes $\nu_{1,2}$ is equal to $|\kappa_-|$. This resonance can be compensated by using at least two skew quadrupoles to minimise the distance of closest approach; this has been performed at the SRS [32], amongst other light sources. In the worst case the coupling wave is in phase with just one of the skew quadrupoles [33], so that it must carry out all of the correction, requiring a strength

$$k_s = \frac{4\pi\kappa_-}{L_s \sqrt{\beta_x \beta_y}}, \quad (39)$$

where β_x, β_y are the lattice functions at the skew quadrupole location and L_s is its length. Without being able to know the overall phase of the errors, both skew quadrupoles should be of this strength.

(b) Compensating the Sum Resonance

In the vicinity of a difference resonance there is a continuous energy exchange between the two transverse planes, but particle motion remains bounded. By contrast, close to the sum resonance the particle motion is unstable for tunes satisfying

$$|\nu_x + \nu_y + p| < |\kappa_+|, \quad (40)$$

where κ_+ is the analogue of κ_- for sum resonances, with the general expression being

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$$\kappa_{\pm} = \frac{1}{4\pi} \oint_{ring} k_s(s) \sqrt{\beta_x \beta_y} e^{i \left[\mu_x(s) \pm \mu_y(s) - \frac{2\pi \Delta \nu}{C} \right]} ds, \quad (41)$$

The total width of the stop band is equal to the driving term $|\kappa_+|$. Although the determination of this term is more complicated than for $|\kappa_-|$, in principle it can again be compensated using 2 skew quadrupoles to minimise the stop band of the resonance, with typically the same strengths as for the different resonance [33].

(c) Simultaneous Correction of Vertical Dispersion and Betatron Coupling

Assuming that only a single sum and difference resonance dominate, it can be shown that to globally correct the vertical dispersion and betatron coupling a minimum of six skew quadrupoles are required [33] - one sine-like and one cosine-like corrector each for the two coupling driving terms and for the vertical dispersion. In the general case of many resonances, we would wish ideally to locally correct the coupling using skew quadrupoles adjacent to each source of error; to aid practical correction these should also be placed next to BPMs to allow the correction of the vertical dispersion [31].

Of course, we do not wish to correct the coupling to too small a value, as this will adversely affect the Touschek lifetime. A limited number of skew quadrupoles is therefore sufficient, and several light source designs have demonstrated the advantage of providing these skew corrector fields in the sextupoles. This can be done as the skew field that needs to be generated is small, and saves space by eliminating the need for additional dedicated magnets.

To first order, the average integrated skew field required per corrector is the sum of the requirement to correct the dispersion (given by equation (39) divided over all the skew quadrupoles) and the requirement to locally correct the betatron coupling, given by

$$\langle (kL)_{s,corr} \rangle \approx \frac{1}{N_{corr}} \sum_i (kL)_{s,i}, \quad (42)$$

where the $k_{s,i}$ are the spurious fields generated in each element, and N_{corr} is the number of skew correctors. A factor of safety should be included for the situation that errors add up in phase (similar to the single resonance case), and also for the change in the β -functions between error and corrector. A factor of safety of 2 seems a sensible choice.

1.5.5 Estimates for DIAMOND

A first-order estimate has been made of the emittance ratio using average values for the reference lattice; this is reasonable given that the working point may change, changing the exact distribution of quadrupole and sextupole strengths and their

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associated optical functions. The parameters appropriate for the reference lattice are shown in Table 1.5-2.

Table 1.5-2 Model parameters used for emittance ratio calculation.

Emittance	2.7 nm-rad
Circumference	561.6 m
Ring Energy	3 GeV
Dipole Field	1.4 Tesla
Average Beta Functions (x,y)	10.96, 14.18 m
Average Horizontal Dispersion	0.11 m
Betatron Tunes (x,y)	27.23, 12.36
Average Quadrupole Strength	1.15 m ⁻²
Average Sextupole Strength	28.5 m ⁻²
Average Quadrupole Length	0.42 m
Average Sextupole Lengths	0.2375 m
Average Skew Quadrupole Length	0.2375 m
# Dipoles, Quadrupoles, Sextupoles, Skew Quadrupoles	48, 240, 168, 168

(a) Estimates of Vertical Dispersion and Betatron Coupling

The errors given in Table 1.5-3 are assumed for the DIAMOND storage ring. This gives the driving terms shown in Figure 1.5-1 (see Table 1.5-1). The total vertical dispersion generated is estimated to be 0.69cm, corresponding to an emittance ratio of 0.04%. These figures will be strongly dependent upon the operating mode, upon the correction, and also the tune and the beta functions in the dipole magnets, so will vary with different operational working points. The RMS vertical dispersion around the storage ring was calculated explicitly using the same set of misalignment errors (see Figure 1.5-2), and gives a mean value of 0.93 cm, consistent with the approximate calculation.

Table 1.5-3 Assumed alignment errors which are significant for coupling and vertical dispersion.

<i>Error Type</i>	<i>RMS Magnitude</i>
Quadrupole Transverse Displacement	0.1 mm
Sextupole Transverse Displacement	0.1 mm
Quadrupole Roll Error	0.2 mrad
Dipole Roll Error	0.2 mrad

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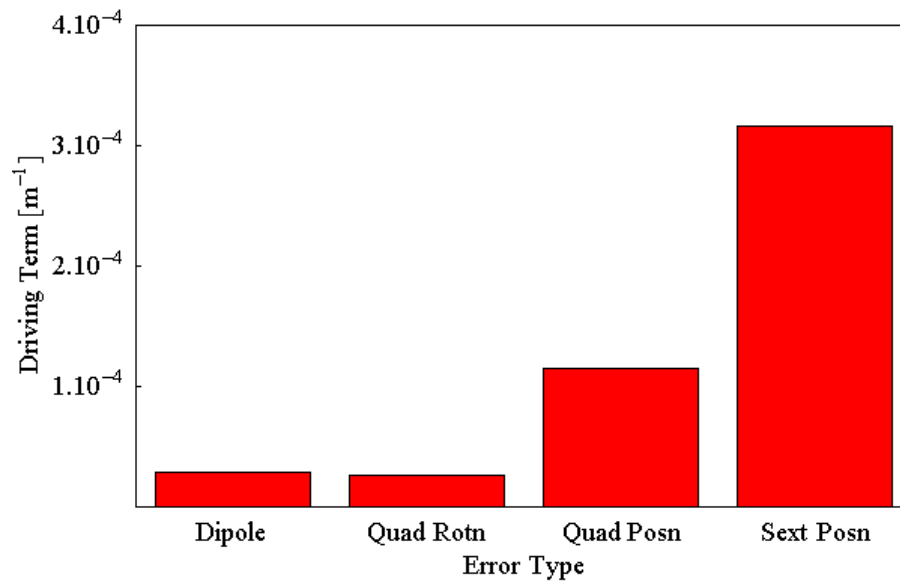


Figure 1.5-1 Significant driving terms giving vertical dispersion. Vertical position errors in the sextupoles dominate the vertical dispersion.

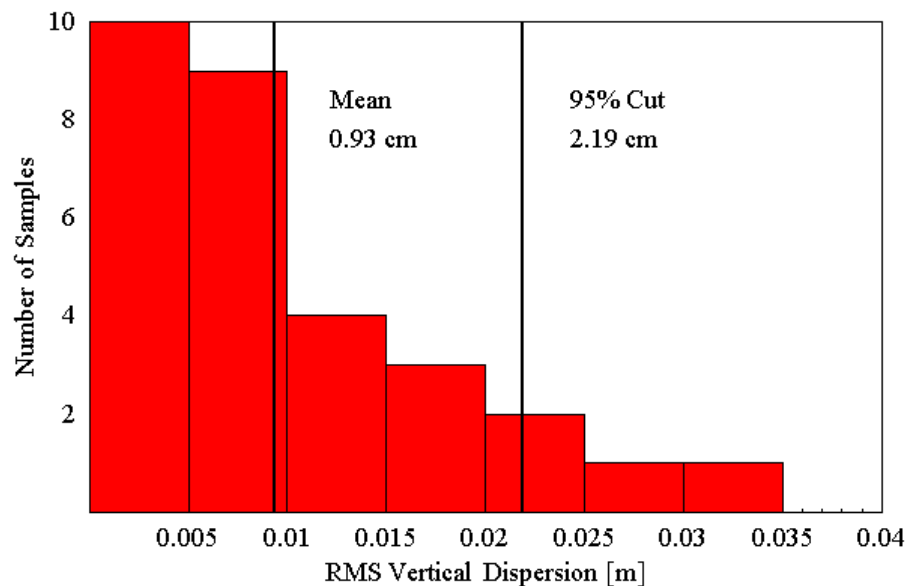


Figure 1.5-2 Simulation of RMS vertical dispersion remaining after orbit correction, for 30 sets of realistic misalignment errors. The mean value is consistent with the approximate calculation above.

Using the same errors, the single resonance model shows that the betatron coupling from sextupole position errors dominates the overall emittance ratio, with an estimated contribution of 0.79%, compared to 0.09% from quadrupole rotations; the overall betatron coupling is estimated to be 0.89%.

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The tunes are reasonably well-separated, so the multiple resonance model could be relevant for the present lattice (the tune split is 0.14). Using this model, the contributions to the betatron coupling from quadrupole rotations and sextupole position errors are 0.06% and 0.51% respectively, giving a total estimated coupling of 0.57%, smaller than that predicted by the single resonance model.

Assuming the single resonance model is correct, the total emittance ratio before correction is estimated to be 0.92%; this rises to 0.95% if the simulated mean RMS vertical dispersion of 0.93cm is used. The present 95% confidence limit of 2.19cm on the possible residual vertical dispersion (based on 30 samples) still only gives a total emittance ratio of 1.25% before correction. Further studies will numerically model the likely emittance ratio values, but requirements for the skew correction elements needed to compensate the vertical dispersion can be made using these approximate results.

(b) Skew Correction Requirements

Some error sets could result in emittance ratios greater than 1%, although this is unlikely. However, other 3rd-generation light sources have demonstrated the user benefits to be obtained by reducing the emittance ratio to values significantly below 1%. In addition, the emittance ratio results depend heavily on the assumed working point, and upon achieving the assumed alignment errors. It is therefore essential that skew quadrupoles are included in the storage ring, to allow a flexible control of the emittance ratio.

Insufficient space is available for dedicated skew elements within the lattice arcs; however, skew strength is readily obtained in the sextupoles by suitable powering of the magnet back-leg coils, especially as the horizontal and vertical dipole fields are also provided by these elements. This has the advantage of correcting the dominant sextupole errors where they are generated, minimising the field requirements.

Using equations (39) and (42) above this gives a field strength requirement, including the factor of safety of 2, of 0.031 m^{-2} , or 0.31 Tm^{-1} ($dB/dr|_{r=0}$).

This is the maximum requirement which is likely to be needed, and does not depend on the machine tune or significantly on the lattice functions, since the sextupoles are dominant and these parameters cancel out within those elements. It does however depend strongly upon the sextupole strength and alignment quality. The skew field requirement scales approximately as

$$k_s \sim k_2 \Delta y, \quad (43)$$

The actual requirement is likely to be less than the 0.31 Tm^{-1} , since it has been assumed above that the dispersive and betatron contributions add independently; this is largely not true with the presently assumed alignment tolerances, since the sextupole contribution dominates. If we assume that the error from each sextupole

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can be corrected within itself by its own skew sextupole, then the requirement is given exactly by equation (43), yielding a requirement of 0.029 Tm^{-1} , about 10% of the value above. Of course, no operational procedure exists for doing this, so in reality each sextupole error will be compensated by several skew elements. Numerical simulation of likely operational procedures is required to obtain a better estimate of the required strengths, but we can be confident at this stage that effective compensation can be provided by 0.31 Tm^{-1} gradient within each sextupole. If this proves problematic to obtain then this model can be revisited. In addition, the coupling effect from errors in high-field insertion devices and the effect of circularly-polarising insertion devices has yet to be considered, so some allocation of skew strength will be needed for this; the factor of safety gives plenty of headroom for such eventualities, and since this skew field can be readily supplied by the sextupole elements, the present specification is reasonable.

1.6 BEAM LIFETIME AND APERTURES

1.6.1 Performance Objectives

The overall electron beam lifetime in DIAMOND has been specified to be at least 10 hours ($1/e$ value) in multibunch operation, a longer lifetime being desirable if possible. The beam lifetime is determined by the rate of several scattering processes, which can lead to a change in an electron's energy or direction; these changes can take electrons outside of the acceptance of the storage ring so that they are lost. The acceptance is defined as the maximum deviation in any co-ordinate (horizontal, vertical or longitudinal) that may be sustained by an electron, and is determined by the dynamic aperture, the physical dimensions of the vacuum vessel, and by the RF system. Although both the dynamic aperture and vacuum aperture vary around a real storage ring, a particular scattered electron will typically reach a maximal oscillation amplitude at all points due to its near-irrational tune (remembering that after scattering it will typically retain its scattered amplitude for many turns before radiation damping takes effect), and so to a good approximation it is the smallest acceptance presented to the electron which causes its loss. The beam stay-clear (BSC) can be defined as being the physical aperture set needed in both planes to provide the required momentum acceptances. For the reference lattice, optimisation of the dynamic aperture has been performed to provide an equivalent momentum acceptance.

Three types of scattering are significant – electron-photon scattering, electron-electron scattering and electron-gas scattering. Electron-photon scattering occurs primarily in the dipole magnets and is the process giving rise to the emitted synchrotron radiation; this is called the quantum lifetime. A particular scattering event will lead to only an energy change of the scattered electron. Electron-electron scattering refers to the scattering of one stored electron from another within a particular bunch, and gives rise to the Touschek lifetime. Finally, electron-gas scattering is the scattering of electrons from the residual gas molecules in the storage ring vacuum system. Each of

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the contributions to the overall lifetime (quantum, Touschek and gas scattering) must be of a sufficiently large value to achieve this overall figure.

1.6.2 Quantum Lifetime

The scattering of electrons from the virtual photons of the dipole magnetic fields gives rise to an energy change in the scattered electron; since the closed orbit shifts with energy the scattered electron will have an induced oscillation amplitude after the scattering event. The equilibrium of the scattering process with the radiation damping effect leads to both an energy spread and a spread in oscillation amplitudes (the transverse emittances), giving Gaussian distributions for the particles in all three planes [34]; any particles in this distribution outside one of the acceptances will be lost. Since the electrons will try to re-distribute themselves into a Gaussian distribution in each co-ordinate, typically in a damping time τ_d , there will be a continuous loss of particles and a consequent *quantum* lifetime given by

$$\tau_q = \frac{\tau_a}{2} \frac{e^\xi}{\xi}, \quad \xi \equiv \frac{a^2}{2\sigma_a^2}, \quad (44)$$

where a , σ_a , τ_a are the acceptance, spread and damping time of the particular co-ordinate. The quantum lifetime is a very strong function of the dimensionless parameter ξ . Since the required acceptance for a very long quantum lifetime is a few σ_a explicit consideration of the quantum lifetime is generally not needed, as the required acceptances for the other scattering processes are much larger. Conventionally $a/\sigma_a \sim 6$ is used as a value below which the quantum lifetime becomes significant. In DIAMOND, since the apertures determined by Touschek and gas scattering considerations are many times larger than this, the quantum lifetime contribution can be neglected.

1.6.3 Touschek Lifetime

In the Touschek process a pair of electrons *elastically* scatter from each other leading to a transfer of their transverse momenta into the longitudinal direction; this of course gives a change in their relative energy, which may take *both* electrons outside of the longitudinal acceptance of the storage ring. Note that for typical energies $\gamma \sim 10^3$ or greater; the Lorentz transformation of the centre-of-mass scattering angles into the laboratory frame will reduce them to a negligible value, so that the particles will not be directly scattered outside of the transverse acceptance; however, the longitudinal change can give rise to a transverse amplitude via the dispersion which is outside either the physical or dynamic limits.

One of the primary factors determining the BSC is the requirement for sufficient momentum acceptance to provide an adequate Touschek lifetime. Assuming a uniform momentum acceptance of 4%, it is shown (see below) that adequate lifetime can be obtained in both the standard operating modes – 2/3 fill multibunch (300mA)

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and single bunch (10mA). Thus 4% has been adopted as the specification of momentum acceptance, such that all scattering points in the storage ring should see this acceptance or greater.

(a) Momentum Acceptance

The dynamic and vacuum apertures in a storage ring differ from the RF aperture in that they vary around the circumference; consequently, particles scattered from a particular location will experience different momentum acceptances. A particle scattered at a location i to a relative energy δ will in the linear case obtain betatron amplitudes in the horizontal and vertical planes of

$$\begin{aligned} A_{x,i} &= H_{x,i} \delta^2 + \kappa H_{y,i} \delta^2 \\ A_{y,i} &= H_{y,i} \delta^2 + \kappa H_{x,i} \delta^2 \end{aligned} \quad (45)$$

for a weak emittance coupling κ , where the chromatic invariant H is defined as

$$H_z = \gamma_z D_z^2 + 2\alpha_z D_z D'_z + \beta_z D_z'^2, \quad z = x, y. \quad (46)$$

For a typical 3rd-generation double-bend achromat lattice H_x varies between zero and $\sim 10^{-2}$, if β_x is constrained to maximum values of around 25 m and the dispersion D_x is well-behaved.

At another location k the scattered particle will reach a maximum amplitude in the horizontal plane of

$$x_k = \sqrt{A_{x,i} \beta_{x,k}} + D_{x,k} \delta = \left(\sqrt{H_{x,i} \beta_{x,k}} + D_{x,k} \right) \delta, \quad (47)$$

neglecting the betatron phase since the oscillation amplitude will persist for many turns (so that the maximum is eventually reached). The particle will be lost if $x_k > a_{x,k}$, where $a_{x,k}$ is the horizontal aperture at location k (defined by either physical or dynamic limitations). The minimum aperture defined by equation (47) gives the momentum acceptance at any location i as

$$\eta_{x,i} = \min_k \left(\frac{a_{x,k}}{\sqrt{H_{x,i} \beta_{x,k}} + D_{x,k}} \right). \quad (48)$$

The corollary of this statement is that a non-uniform aperture set will in general give rise to a non-uniform set of acceptances. This means that if we require that the acceptance be *at least* some value at all locations by adjusting the apertures, the result is that the acceptance is greater than this in most locations. If physical apertures were the only restriction on the beam then this would give rise to an increased lifetime over that expected for a constant momentum acceptance. Of course, the RF aperture provides a constant energy acceptance, but the variable physical acceptance should be

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taken account of if the RF aperture is greater than its specified 4% value and comparison of theory with experiment is made. Account is taken in these calculations of the variation of optical functions with momentum, so that the scattered particle amplitudes at the aperture limits are calculated in a self-consistent way.

Whilst this method is adequate for a 1st-order estimate of the acceptances, direct tracking was performed of particles scattered into the longitudinal plane from all points in the ring to obtain the dynamic momentum acceptance in the horizontal plane. Separate determinations of the acceptances in the positive and negative momentum deviations were performed; the results are shown in Figure 1.6-1.

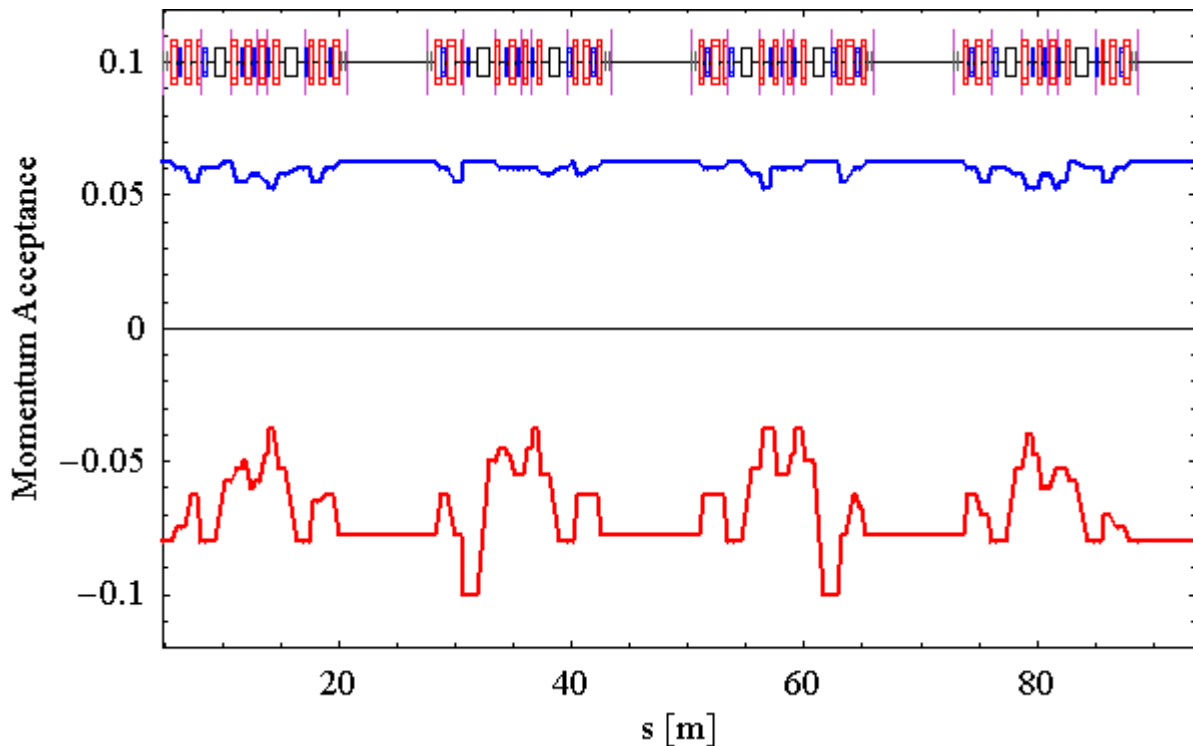


Figure 1.6-1 Dynamic momentum acceptances for positively and negatively scattered particles, obtained by tracking over 1024 turns.

(b) Vertical Momentum Acceptance

Most of the electron beam comprises small-amplitude particles which possess an emittance ratio of 1%, and determine the photon brilliance. However, the large-amplitude scattered particles which determine the lifetime limitations will be subjected to much larger non-linear perturbations, giving this halo a much larger coupling than the beam core.

The halo coupling value is difficult to predict as it depends upon the exact operating mode. Similarly to the horizontal apertures, the momentum acceptance given at a location i by the set of vertical apertures elsewhere $a_{y,k}$ can be written as

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$$\eta_{y,i} = \min_k \left(\frac{a_{y,k}}{\sqrt{H_{y,i}^{\text{eff}} \beta_{y,k}} + D_{y,k}} \right), \quad (49)$$

where symbols have their usual meanings and the chromatic invariant $H_{y,i}^{\text{eff}} = H_{y,i} + \kappa H_{x,i}$, where the halo coupling is given by κ .

Here the relevant question is what value of the halo coupling κ is to be assumed for scattered particles with large momentum deviation [35]. This question can be turned around since we already have a specified set of apertures in the insertion device straights; these apertures effectively define what κ can be tolerated before the momentum acceptance restriction they present falls below 4%. This has been found to be 6% [36], a rather small figure reflecting the small size of the ID apertures in DIAMOND. This halo coupling value has then been used to evaluate the required vertical apertures in each element type (including drift spaces) which give a momentum acceptance equivalent to those presented by the ID apertures at this coupling value [37]. As elsewhere, the variation of optical functions with momentum was taken account of in the calculations.

Account also has to be taken of the fact that significant variation in optical functions can occur within a single element - particularly in the dipole magnets and straight section elements, which can significantly affect parameters calculated from them. Elements were therefore typically divided into up to 10 slices in order to obtain sufficiently accurate values.

(c) Touschek Lifetime

The Møller cross-section determines the rate at which particles are scattered, the differential cross-section in the centre-of-mass frame of the two electrons being

$$d\sigma = \frac{r_e^2}{4} (1 - \beta^4) \left\{ \left(1 + \frac{1}{\beta^2} \right) \left(\frac{4}{\sin^4 \theta} - \frac{3}{\sin^2 \theta} \right) + 1 + \frac{4}{\sin^2 \theta} - P^2 \left[\frac{\beta^{-4} - 1}{\sin^2 \theta} + 2 \left(\frac{1}{\beta^2} - 1 \right) \left(\frac{\sin^2 \phi}{\sin^2 \theta} + \cos^2 \phi \right) + \cos 2\phi \right] \right\} d\Omega \quad (50)$$

where $\beta = v/c$ is the velocity of each particle and P the average relative polarisation between the individual electron spins [38][39]. By integrating this cross-section over angles which give rise to momenta outside the longitudinal acceptance $\eta = \Delta E_{\text{max}}/E$, the total loss rate can be obtained. For non-relativistic velocities and no average polarisation this differential cross-section reduces to

$$d\sigma = \frac{r_e^2}{4\beta^4} \left(\frac{4}{\sin^4 \theta} - \frac{3}{\sin^2 \theta} \right) d\Omega \quad (51)$$

(for small scattering angles this reduces to the Rutherford scattering cross-section). Assuming 'flat' beams - i.e. the only transverse momentum which is important is the horizontal one - Brück [40] derived the Touschek lifetime used in most design codes,

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$$\frac{1}{\tau} = \left\langle \frac{\pi^{1/2} r_e^2 c N_b}{\gamma^2 V} \frac{C(\varepsilon)}{\eta^2 \delta q} \right\rangle_{ring}, \quad (52)$$

where V is the bunch volume, $\varepsilon = (\eta/\delta q)^2$ is a scaled measure of the ‘space’ available to the beam, and $C(\varepsilon)$ a loss rate function given by the integration and the Gaussian distribution of the beam [40],

$$C(\varepsilon) = -\frac{3}{2} e^{-\varepsilon} + \frac{\varepsilon}{2} \int_{\varepsilon}^{\infty} \frac{\ln u}{u} e^{-u} du + \frac{3\varepsilon - \varepsilon \ln \varepsilon + 2}{2} \int_{\varepsilon}^{\infty} \frac{e^{-u}}{u} du. \quad (53)$$

The average is taken over the circumference of the storage ring. For small ε (for computational purposes $\varepsilon < 10^{-3}$) equation (53) reduces to $C(\varepsilon) \approx -\ln(\varepsilon) - 2.077$ [40]. δq is the RMS transverse momentum (in units of the electron mass), given by

$$\delta q = \gamma \sigma'_{x\text{mod}} = \frac{\gamma \varepsilon_x}{\sigma_x} \sqrt{1 + \frac{H \sigma_{\varepsilon}^2}{\varepsilon_x}} \quad (54)$$

where $H = \gamma_x D_x^2 + 2\alpha_x D_x D'_x + \beta_x D_x'^2$ and other lattice symbols have their usual meaning (note that the optical functions used are for on-axis particles, since before scattering most particles will be near-zero in betatron amplitude).

A scattering rate is calculated for each location in the storage ring, based on the local particle density and local momentum acceptance. This is then averaged over the storage ring, scaling with the length of each element to avoid overweighting short elements, to give the overall lifetime.

The momentum acceptance from the physical apertures is at least 4% (by design) at all locations. It can be seen in Figure 1.6-1 that the momentum acceptance from the dynamic aperture is mostly above 4%. The RF system specification is for a 4% momentum acceptance. The minimum of these three momentum acceptances at any location is used to calculate the Touschek lifetime; taking all these factors into account, the overall Touschek lifetime is calculated to be 81.1 hours (see Table 1.6-1).

The bunch length, needed to calculate the beam volume at each lattice location, is difficult to estimate without an engineering design for the superconducting RF cavities, which will have a significant contribution the broadband impedance. There is therefore a significant uncertainty in the value of the bunch length; a conservative value of 3.26mm has therefore been adopted, which is the natural zero-current length. The calculated Touschek lifetime given here should therefore be at the lower limit of what will actually be observed.

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Table 1.6-1 Parameters relevant to Touschek lifetime calculation.

Beam Current	300 mA
Bunch Filling Pattern	2/3 of bunches filled
Bunch Length	3.26 mm
Touschek Lifetime	81.1 hours

1.6.4 Scattering from Residual Gas Molecules

Electrons circulating in a storage ring can scatter off gas molecules in four different ways. Scattering from gas nuclei can be through an Elastic Coulomb interaction (C) or through an inelastic (Bremsstrahlung) collision (B). Beam and gas electrons can also interact elastically (E) or inelastically (I). The cross-sections for each type of scattering leading to the loss of a beam electron are [41]

$$\sigma_B = \frac{16r_e^2 Z^2}{411} \ln \left[\frac{183}{\frac{1}{z^3}} \right] \left(\ln \left[\frac{1}{\eta} \right] - \frac{5}{8} \right) \quad (55)$$

$$\sigma_c = \frac{4\pi r_e^2 Z^2}{2\gamma^2} \langle \beta_i \rangle \frac{\beta_i}{a_i^2} \Big|_{\max} \quad (56)$$

$$\sigma_I = \frac{16r_e^2 Z^2}{411} \left(\ln \left[\frac{5\gamma}{2\eta} \right] - 1.4 \right) \left(\ln \left[\frac{1}{\eta} \right] - \frac{5}{8} \right) \quad (57)$$

$$\sigma_E = \frac{2\pi r_e^2 Z^2}{\gamma\eta} \quad (58)$$

Scattering events lead to an exponential decay of the electron beam current with a decay constant ($1/\tau$). The loss rate for any scattering process can be given in terms of the interaction cross section as [41]

$$\frac{1}{\tau_j} = -\frac{1}{N} \frac{dN}{dt} = \sigma_j c n \quad (59)$$

The Coulomb cross section is the only component which varies with aperture. Since the Coulomb cross section is the scattering rate for particles scattered to large amplitudes, but with no change of momentum, the on-momentum optical functions should be used for this calculation; both the physical and dynamic aperture are taken into account. Similarly to Touschek scattering, there is one particular location in the ring which determines the Coulomb cross section, where the aperture (normalised

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with the β -function) is a minimum, either dynamically or physically. This is shown in Figure 1.6-2.

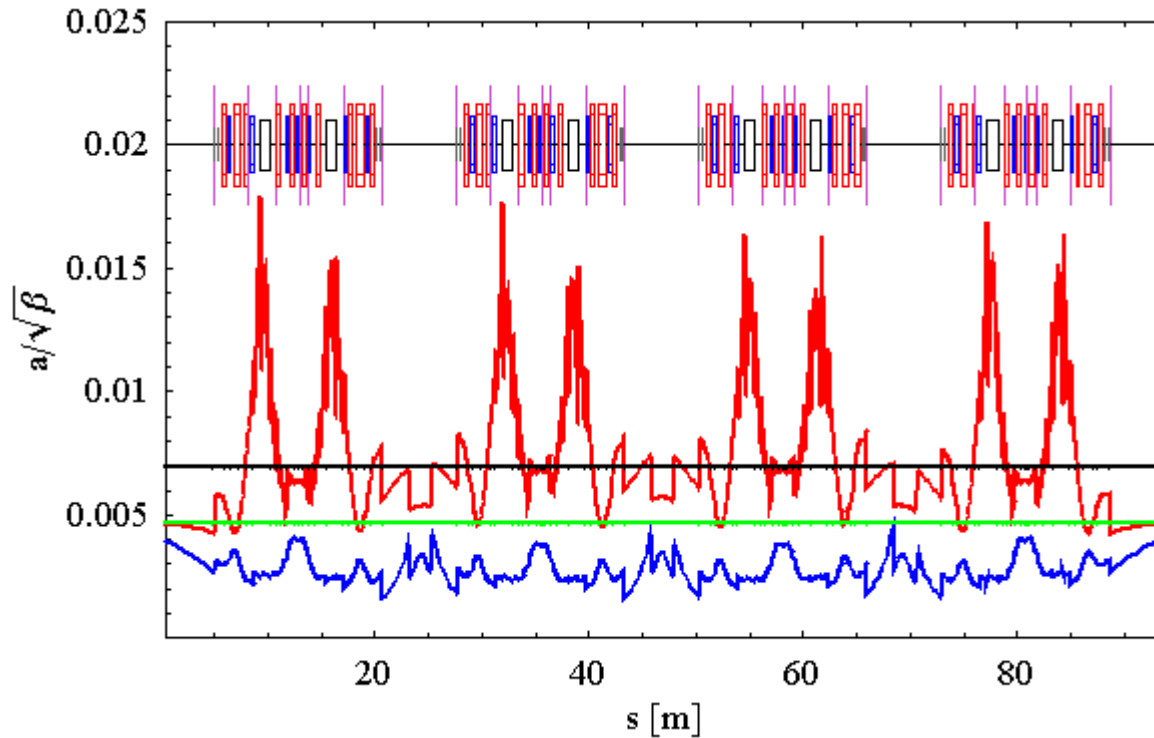


Figure 1.6-2 Aperture divided by the square root of the beta function with one lattice superperiod: horizontal physical aperture (upper oscillating line), vertical physical aperture (lower oscillating line), horizontal dynamic aperture (upper straight line), vertical dynamic aperture (lower straight line). The minimum of any of these values determines the Coulomb aperture – this minimum occurs in the end of the 5m ID straights due to the vertical physical aperture there.

The momentum acceptance which needs to be used to calculate the Bremsstrahlung, Inelastic and Elastic components is the smallest acceptance at any point in the ring due to either physical, dynamic or RF limitations; this is 3.5%. Once the lifetime for each of the components has been calculated they can be combined to give a total gas lifetime as

$$\frac{1}{\tau_{gas}} = \frac{1}{\tau_B} + \frac{1}{\tau_C} + \frac{1}{\tau_I} + \frac{1}{\tau_E} \quad (60)$$

The residual gas pressure which will be achieved is difficult to predict, and will vary both with integrated beam current and photon dose, and with beam current. Calculations for DIAMOND based in part on experience elsewhere (see chapter E.5) indicate that after some conditioning, the vacuum system will deliver a residual pressure of approximately 1 nTorr with 300 mA of circulating beam current, whose composition is equivalent in modelling terms to dry nitrogen. Gas scattering calculations are therefore based on the assumptions given in Table 1.6-2.

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Table 1.6-2 Assumed parameters relevant for gas scattering calculations.

Momentum Acceptance	3.5 %
Residual Pressure	1 nTorr
Gas Temperature	300 K
Gas Composition	N ₂

The contributions to the gas scattering lifetime are shown in Table 1.6-3. It can be seen that the most significant contributions are the Coulomb and Bremsstrahlung effects, which are approximately equal. Therefore the aperture of the standard ID straight is important in dictating the gas scattering lifetime.

Table 1.6-3 Contributions to gas scattering lifetime.

<i>Component</i>	<i>Lifetime Contribution</i>
Bremsstrahlung	76.4 hours
Coulomb	80.2 hours
Inelastic	211 hours
Elastic	8470 hours
Total Gas Lifetime	32.9 hours

1.6.5 Modelling of the Overall Lifetime

The overall lifetime is calculated by combining the contributions from the different components which in this case are the Touschek lifetime and the Gas lifetime. The total lifetime can be written as

$$\frac{1}{\tau_{total}} = \frac{1}{\tau_{Touschek}} + \frac{1}{\tau_{gas}} \quad (61)$$

Table 1.6-4 Contributions to total lifetime in multibunch operation.

Touschek Lifetime	81.1 hours
Gas Lifetime	32.9 hours
Total Lifetime	23.4 hours

It can be seen in Table 1.6-4 that the total lifetime is 23.4 hours. Since there is likely to be significant bunch lengthening, the actual lifetime after conditioning should comfortably exceed the design specification of 10 hours. The gas lifetime for a residual pressure of 1 nTorr dominates the overall lifetime; the overall lifetime is therefore expected to vary significantly with conditioning of the storage ring vacuum system.

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1.6.6 Aperture Definition

In order to determine a beam stay-clear (BSC) value, the definition of element apertures has been implemented in the Mathematica Interface to Mad (MIM) [42]. Apertures are implemented in MIM by defining an aperture for every element type. A set of apertures can then be associated with calculated optical functions around the ring, the only limitation being that a single element type (say, a particular quadrupole family) cannot be used with several different apertures in the same lattice. This is not considered to be a problem for the DIAMOND storage ring, where BSC values will be defined for each element type and not for individual locations where they are used. As above, the variation of optical functions through each element is considered by dividing elements into a sufficiently large number of slices.

(a) Injection Allowance

Injection is considered in Section 1.9, dealing with the issues of septum position, injected beam emittance, stored beam emittance and momentum error. In terms of defining the BSC, the following assumptions are made:

- The septum is set at the minimum position required to both satisfy injection requirements and not to impinge on the momentum acceptance. In practice this means that the septum position is set to give a momentum acceptance of 4 %, as this required aperture is larger than that required for injection.
- 5 mm of room is allowed for the septum, *including all alignment tolerances*. The actual thickness required for the septum must be determined by an engineering design; however, a value of 5 mm is in line with the requirements found for similar projects elsewhere.
- Calculations are made only for the linear case. To take account of non-linear effects such as filamentation of the injected beam will require additional tracking studies, but these can be allowed for by being conservative with the calculation of the required β value of the injected beam at the injection point[43]. In line with other designs [43] the β value has been overestimated by a factor of 2.
- The injected beam emittance is taken to be the largest specification value: 150 nm.rad and $\pm 3\sigma$ is allowed either side of the injected beam, corresponding to capturing 99.6% of the beam if it has a pure (non-truncated) Gaussian distribution in the horizontal plane.
- The reference design emittance of 2.7 nm may not be achieved in all operating modes: emittance values up to 20 nm are therefore allowed by the injection system. In practice this change results in only slightly increased aperture requirements. An allowance of $\pm 5\sigma$ is assumed either side of the stored beam; in practice, changing this allowance has little effect upon the required apertures.

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- There may be energy mismatch between the booster and the storage ring, or there may be particles from the booster to storage ring (BTS) transfer line that have large energy deviations. Although this value has not yet been specified, it is proposed that the storage ring accept particles with up to 1% energy deviation [44]. In practice, allowing this energy deviation adds a maximum of 1mm to the required aperture.

(b) Closed Orbit Allowance

The closed orbit with errors varies with position around the storage ring [45]. However, for the purposes of specifying apertures the maximum corrected values have been used for all locations, other than within the insertion device straights where the vertical residual closed orbit after correction is negligibly small.

The corrected closed orbit values, with 95% confidence, will not exceed the values given in Table 1.6-5.

Table 1.6-5. 95% confidence levels for maximum uncorrected and corrected closed orbits

<i>Case</i>	<i>Horizontal [mm]</i>	<i>Vertical [mm]</i>
Uncorrected	34.3	17.3
Corrected	3.0	1.4

Since apertures will be defined to the nearest millimetre, 3mm and 2mm respectively have been added to the horizontal and vertical apertures required for lifetime and injection effects.

A crucial part of the BSC definition is the allocation of aperture as contingency to allow variation of the working point and optics. This is a difficult area to quantify, as it requires an estimate to be made of what the likely lattice functions might be, and what compromises on momentum acceptance and lifetime will be allowed. The following is proposed:

- ‘Flipping’ of the optics in the matching triplet into the straight sections is allowed for, in both the standard and long ID straights. It is assumed that the largest required aperture in this section, with the nominal working point presented here, is the maximum that will be required for all working points. The aperture in this section is therefore defined to be a constant in these sections, and taken to be the maximum aperture from all the element types in this region.
- The aperture required in the achromat elements is taken to be the maximum of the values required in elements adjacent to standard straights and long straights; this is to allow a degree of flexibility in matching different dispersion values (e.g. for the zero dispersion working point).

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The aperture requirement for momentum acceptance in both transverse planes is shown in Figure 1.6-3 and Figure 1.6-4, for on-momentum particles and those with deviations of +4% and -4%. The overall resulting defined apertures are also shown. It can be seen that these apertures are sufficient for momentum acceptance from this graph.

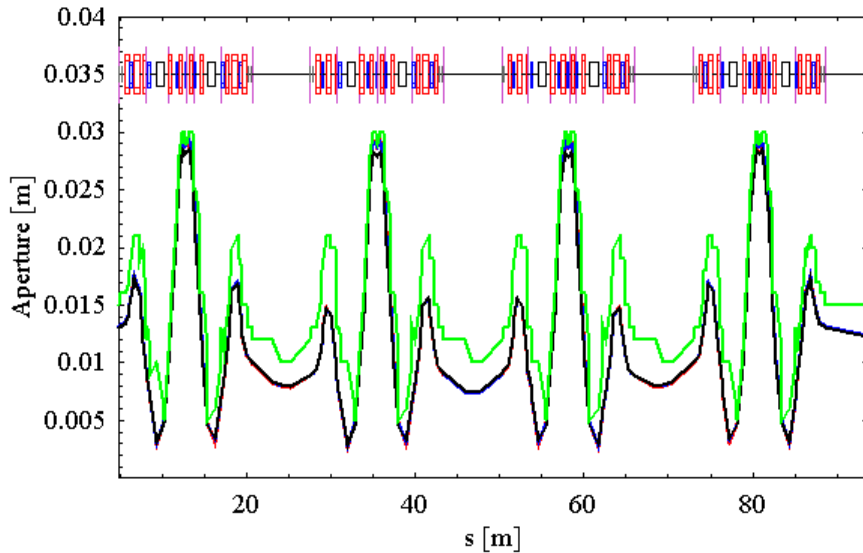


Figure 1.6-3 Horizontal aperture requirements for momentum acceptance. The BSC is shown in green, whilst the overlapping red, blue and black curves show the required aperture for 4% momentum acceptance calculated using optical functions at -4%, 0 and +4% momentum deviation respectively.

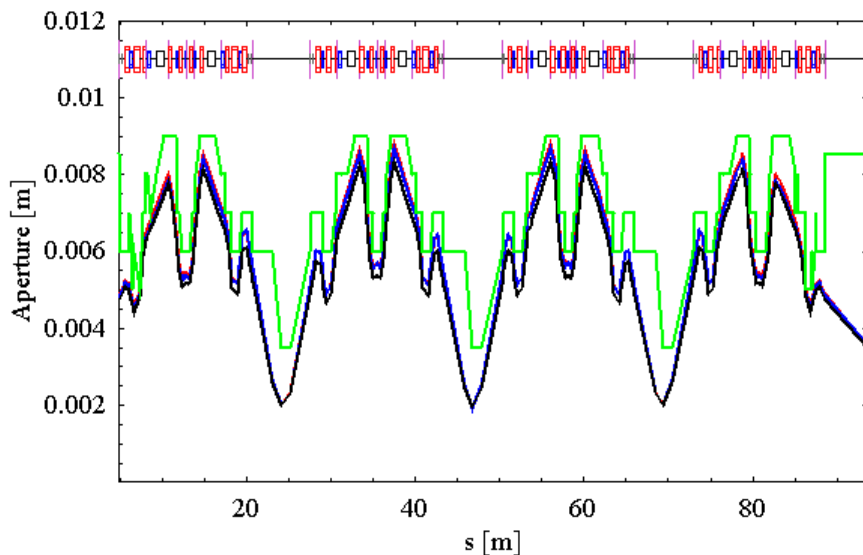


Figure 1.6-4 Vertical aperture requirements for momentum acceptance. The BSC is shown in green, whilst the overlapping red, blue and black curves show the required aperture for 4% momentum acceptance calculated using optical functions at -4%, 0 and +4% momentum deviation respectively.

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The aperture requirements for injection are shown in Figure 1.6-5. It can be seen that the defined apertures are large enough for injection.

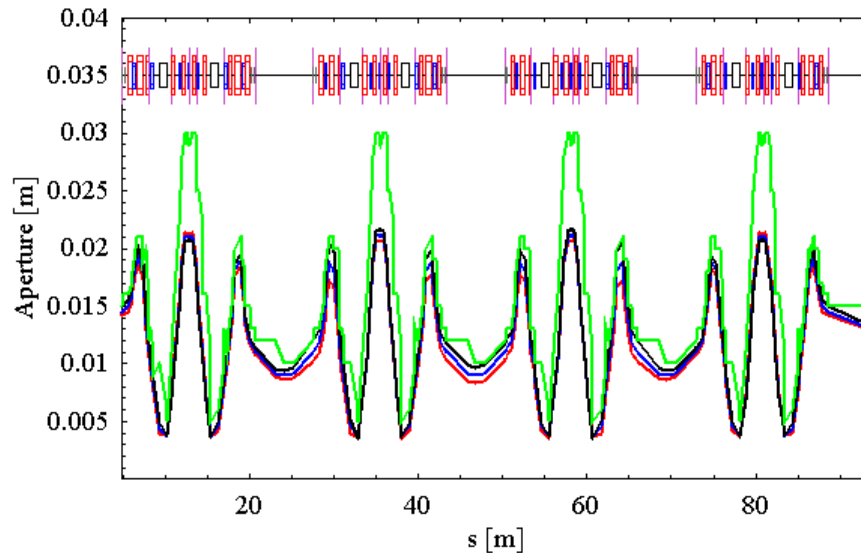


Figure 1.6-5 Aperture requirements for injection. The BSC is shown in green, whilst the overlapping red, blue and black curves show the required aperture for 4% momentum acceptance calculated using optical functions at -4% , 0 and $+4\%$ momentum deviation.

The final BSC must include some contingency and the closed orbit errors. The only place this does not apply is in the vertical apertures of the insertion devices as their values are pre-specified as discussed above. Adding the closed-orbit allowance to the requirements for momentum acceptance and injection gives the BSC defined by element in Table 1.6-6.

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Table 1.6-6 Aperture definitions by element (all values in mm). The BSC without contingency and closed orbit allowance is shown as 'BSC X' and 'BSC Y'. The contingency amount added to them is shown as 'X Cont.' and 'Y Cont.'. The total BSC is given as 'X Total' and 'Y Total'.

<i>Element Type</i>	<i>Element Name</i>	<i>BSC X</i>	<i>BSC Y</i>	<i>X Cont.</i>	<i>Y Cont.</i>	<i>X C.O</i>	<i>Y C.O</i>	<i>X Total</i>	<i>Y Total</i>
Bending Magnets	BB	6	9	3	4	3	2	12	15
Quadrupoles	Q1AB	30	7	3	7	3	2	36	16
	Q2AB	16	9	1	5	3	2	20	16
	Q1B	15	7	7	3	3	2	25	12
	Q2B	21	6	1	4	3	2	25	12
	Q3B	15	7	7	3	3	2	25	12
	Q1AD	30	6	3	8	3	2	36	16
	Q2AD	16	9	1	5	3	2	20	16
	Q1D	17	6	5	4	3	2	25	12
	Q2D	21	5	1	5	3	2	25	12
	Q3D	15	7	7	3	3	2	25	12
Sextupoles	S1A	29	6	4	8	3	2	36	16
	S2A	25	8	2	6	3	2	30	16
	S1B	19	7	3	3	3	2	25	12
	S2B	12	8	10	2	3	2	25	12
	S1D	20	6	2	4	3	2	25	12
	S2D	11	7	11	3	3	2	25	12
Drift Spaces	D1A	30	6	3	8	3	2	36	16
	D2A	28	7	2	7	3	2	33	16
	D3A	22	9	2	5	3	2	27	16
	D4A	11	9	2	5	3	2	16	16
	D1BCentre	10	3.5	2	0	3	0	15	3.5
	D1BEnd	12	6	4	0	3	0	19	6
	D2B	18	7	4	3	3	2	25	12
	D3B	21	6	1	4	3	2	25	12
	D4B	20	7	2	3	3	2	25	12
	D5B	13	8	9	2	3	2	25	12
	D6B	10	8	7	4	3	2	20	14
	D1D	15	8.5	1	0	3	0	19	8.5

1.7 COLLECTIVE EFFECTS AND INSTABILITIES

1.7.1 Overview

Stored beam currents in DIAMOND will be at a level such that collective effects will supplement the single particle processes so far addressed. High volume charge densities in 3rd generation light sources will lead to increased internal scattering rates and consequent reduction in beam brightness: this effect is considered in section 1.7.2. The intense beam current also creates a potential well that is capable of trapping residual gas ions, inducing dangerous electron-ion interactions; it is essential to incorporate some method of clearing such heavy ions from the immediate vicinity of the circulating electrons and this is discussed in Section 1.7.3.

The stored electron beam interacts with its local environment via its associated electromagnetic fields. The electrons are bunched at the radio-frequency and a variety of instabilities can be encountered, both between and within bunches: induced image currents in the vacuum chamber walls exert transient forces (via wake fields) that can drive a positive feedback process that leads to oscillations, growth and even total loss of beam. Growth rates must be computed and compared with available damping processes (eg synchrotron radiation and Landau effects) in order to predict instability threshold currents. It is often convenient to describe the interaction as being through a complex impedance that creates at the electron position an induced voltage related to the source current.

It is possible to classify two basic types of instability interaction: those coupling different circulating bunches (ie long range forces arising from resonant electromagnetic structures) and those acting within a single bunch (short range, non-resonant). These two cases are treated in Sections 1.7.4 and 1.7.5, with some discussion of counter-measures in Section 1.7.6.

1.7.2 Intrabeam Scattering

The small emittances and high currents required for DIAMOND produce a very high electron density within each bunch. Multiple Coulomb scattering – termed intrabeam scattering – can give rise to an additional growth rate in the particle amplitudes, so that the emittance increases in the transverse planes until a new equilibrium is reached with the synchrotron radiation growth and damping rates.

The ZAP code [46] uses the widely-accepted Bjorken-Mtingwa (B-M) formalism for evaluating the growth rates [47], the relative rates of growth for the emittances being given as

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$$\begin{aligned}
\frac{1}{\tau_x} &= \left\langle \frac{H_x}{\varepsilon_x} \eta_0^2 I_{zz} - 2 \frac{\eta_x \phi_{Bx}}{\varepsilon_x} \eta_0^2 I_{xz} + \frac{\eta_x}{\varepsilon_x} I_{xx} \right\rangle_s \\
\frac{1}{\tau_y} &= \left\langle \frac{H_y}{\varepsilon_y} \eta_0^2 I_{zz} - 2 \frac{\eta_y \phi_{By}}{\varepsilon_y} \eta_0^2 I_{yz} + \frac{\eta_y}{\varepsilon_y} I_{yy} \right\rangle_s, \\
\frac{1}{\tau_x} &= \left\langle \frac{1}{2} \frac{\eta_0^2}{\sigma_p^2} I_{zz} \right\rangle_s
\end{aligned} \tag{62}$$

where $\phi_{Bi} = \eta'_i + \alpha_i \eta_i / \beta_i$ is defined in terms of the usual optical parameters in each plane. The I_{ij} ,

$$I_{ij} = \frac{c r_e^2 N \log \Lambda_c}{8 \pi \beta_0^3 \gamma_0^4 \varepsilon_x \varepsilon_y \sigma_p \sigma_s} \int_0^\infty d\lambda \frac{\lambda^{\frac{1}{2}}}{\sqrt{\det \Lambda}} (\delta_{ij} \text{Tr} \Lambda^{-1} - 3 \Lambda_{ij}^{-1}), \tag{63}$$

are defined in terms of the matrix $\Lambda = \mathbf{1}\lambda + \mathbf{L}$, where the matrix $\mathbf{L}$ is

$$\mathbf{L} = \begin{bmatrix} \frac{\beta_x}{\varepsilon_x} & 0 & -\gamma_0 \frac{\beta_x \phi_{Bx}}{\varepsilon_x} \\ 0 & \frac{\beta_y}{\varepsilon_y} & -\gamma_0 \frac{\beta_y \phi_{By}}{\varepsilon_y} \\ -\gamma_0 \frac{\beta_x \phi_{Bx}}{\varepsilon_x} & -\gamma_0 \frac{\beta_y \phi_{By}}{\varepsilon_y} & \frac{\gamma_0^2 H_x}{\varepsilon_x} + \frac{\gamma_0^2 H_y}{\varepsilon_y} + \frac{\gamma_0^2}{\sigma_p^2} \end{bmatrix}. \tag{64}$$

The Coulomb logarithm $\log \Lambda_c$ is difficult to estimate, but is usually set to between ~ 10 and ~ 20 ; its value depends upon the minimum and maximum impact parameters for the collision process under consideration, whose estimation is complex. As a result, calculated IBS growth rates overestimate the equilibrium emittances.

Using ZAP, the reference lattice gives a Coulomb log value of ~ 19 ; the equilibrium emittances are shown in Table 1.7-1. If no bunch lengthening occurs then 18% emittance growth is predicted; assuming a more realistic 50% bunch lengthening this growth is reduced to around 9%. From equation (63) we would expect a strong enhancement of IBS effects $\sim 1/\gamma^4$ as storage ring energy is reduced. Since IBS effects are not seen to any significant extent at lower-energy facilities with similar emittances and currents, this phenomenon is not considered to present a problem with achieving small emittances in DIAMOND.

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Table 1.7-1 IBS results calculated using ZAP.

<i>Parameter</i>	<i>Value</i>
Natural Emittances	2.7 nm-rad, 27 pm-rad
Coupling	1 %
Beam Current	300 mA
Filling Pattern	2/3 bunches filled
Particles per Bunch	$5.62 \cdot 10^9$
Equilibrium Emittances	3.2 nm-rad, 32 pm-rad
Bunch Length	3.26 mm/4.89 mm
Energy Spread	$9.6 \cdot 10^{-4}/14.4 \cdot 10^{-4}$
Emittance Growth	18%/9%

1.7.3 Residual Ions

Ionisation of residual gas species in the vacuum chamber of an accelerator will create positively charged ions, which under certain circumstances can be trapped in the potential well of circulating electron bunches. The accumulation of trapped ions is in general detrimental to the electron beam, causing tune shifts and spreads, emittance blow-up from scattering and increased horizontal-vertical coupling. The comparison of simulations with experiment is notoriously difficult, and observational evidence can be difficult to reproduce; however, a linear theory can give an approximate prediction of the effects to be expected ([48][49][50]).

The mechanism of ion trapping can be understood by considering that the circulating electron bunches act as focusing elements on the stationary gas ions, acting on them in a manner analogous to the effect of quadrupole lenses on ordinary electron bunches. Stability criteria for trapping can then be derived in a similar way to the formalism used in accelerator optics.

(a) Linear Theory for Homogenous Bunches

Gas ions will experience a force from a passing electron bunch, which can be treated as a thin lens focusing element followed by a drift time before the next bunch passes. A transport matrix for this can be defined for this as

$$\begin{pmatrix} u \\ \dot{u} \end{pmatrix}_1 = \mathbf{M} \cdot \begin{pmatrix} u \\ \dot{u} \end{pmatrix}_0 = \begin{pmatrix} 1 & t_b \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -a_u & 1 \end{pmatrix} \begin{pmatrix} u \\ \dot{u} \end{pmatrix}_0, \quad (65)$$

where u is a general transverse co-ordinate, $\dot{u}$ is its time derivative and t_b the drift time between bunches. a_u is a linear kick parameter, which for a particular atomic weight of ion A is given by

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$$a_u = \frac{2N_b r_p c}{A \sigma_y (\sigma_x + \sigma_y)}, \quad (66)$$

where r_p is the classical proton radius, N_b is the number of particles in the bunch, and σ_x , σ_y are the horizontal and vertical beam sizes.

If the bunches are equally spaced, the stability criterion for stable focusing is

$$|Tr\mathbf{M}| < 2. \quad (67)$$

For a particular electron density this leads to a critical mass above which ions are trapped in a storage ring, given by

$$A_c > \frac{CNr_p}{2n^2 \sigma_y (\sigma_x + \sigma_y)}, \quad (68)$$

where N is the total number of particles in the beam, n is the number of circulating bunches, and C is the ring circumference.

(b) Linear Theory for Gapped Bunch Filling

The simple matrix treatment above can be extended to the case where there are gaps in the circulating bunch train, or more generally where N_b varies from bunch to bunch. For gapped trains in a storage ring, the transport matrix for a complete train becomes

$$\mathbf{M} = \left[\begin{pmatrix} 1 & t_b \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -a_u & 1 \end{pmatrix} \right]^n \begin{pmatrix} 1 & t_b \\ 0 & 1 \end{pmatrix}^{[h-n]}, \quad (69)$$

where n is the number of bunches in the train, and h is the harmonic number of the storage ring (i.e. the total number of bunches). The same stability criterion given by equation (67) applies, and can be readily evaluated for particular conditions.

(c) Homogenous Bunch Trains (Every Bunch Filled)

For the case of homogenous bunch trains – i.e. flat fills – the calculated critical mass is 1.09; in other words, we expect to trap every ion species in the DIAMOND electron beam if the fill structure is flat. As a consequence, gapped beams will be required in DIAMOND to avoid ion trapping.

(d) Non-Homogenous (Gapped) Bunch Trains

The dominant residual gas species which are encountered in an accelerator vacuum system are Hydrogen, Carbon Monoxide and Carbon Dioxide. However, several other species can also be present in significant amounts – Helium, Methane, Water, Neon,

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Nitrogen, Oxygen and Argon. Each gas type contains components whose abundance reflects the isotopic concentration of its constituent atoms. For the purposes of this analysis, only naturally-occurring isotopes whose relative Earth abundance as part of the element is 0.1% or greater have been considered. Using these isotope masses a table can be constructed of species masses which may be encountered in a vacuum system [51].

Table 1.7-2 Masses of significant gas species which may be encountered in an accelerator vacuum system.

Gas	Masses (to 4 decimal places)
Hydrogen	2.0157
Helium	4.0026
Methane	16.0313, 17.0347
Water	18.0106, 20.0148
Neon	19.9924, 20.9938, 21.9914
Carbon Monoxide	27.9949, 28.9983, 29.9992, 31.0025
Nitrogen	28.9983, 30.0002
Oxygen	31.9898, 35.9983
Argon	35.9675, 39.9624
Carbon Dioxide	43.9898, 44.9932, 47.9983, 49.0017

Using the list of significant gas species given above, a stability plot can be constructed showing which species are trapped in DIAMOND, as a function of gap size. This is shown in Figure 1.7-1 for the dominant gas species which are encountered; other masses are omitted for simplicity.

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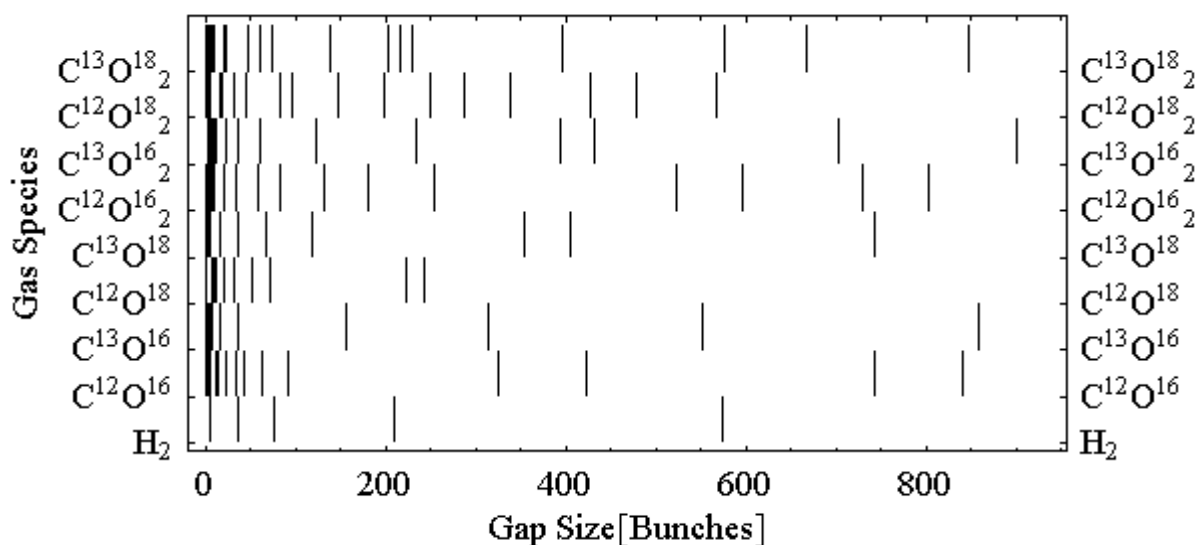


Figure 1.7-1 Trapping of dominant gas species for different sized gaps in the bunch train, for the reference lattice with 300mA of stored current. Although trapping (indicated by black bars) occurs predominantly at low gap sizes, it can occur even with large gaps.

Combining all gas species together, we find that a gap of at least 40 bunches is required before no gas species are trapped (Figure 1.7-2). Of course, this value is strongly dependent upon the operating mode and the beam current, as can be seen in Figure 1.7-2 and Figure 1.7-4.

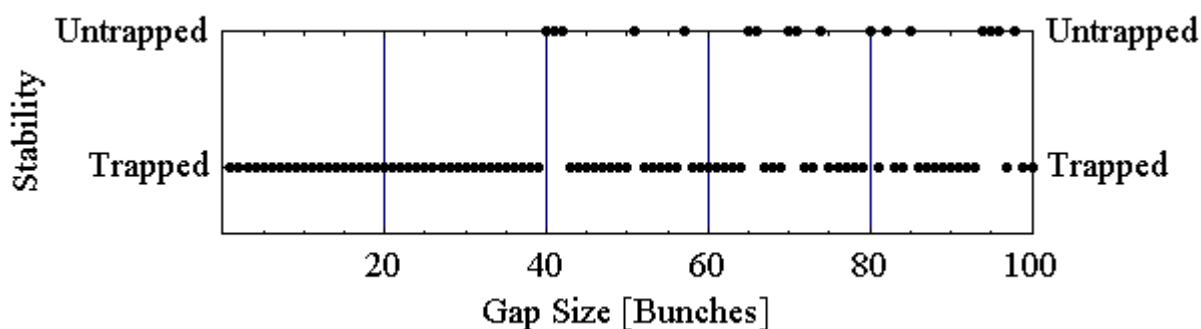


Figure 1.7-2 Trapping of any gas species in the reference design lattice, with 300mA of current.

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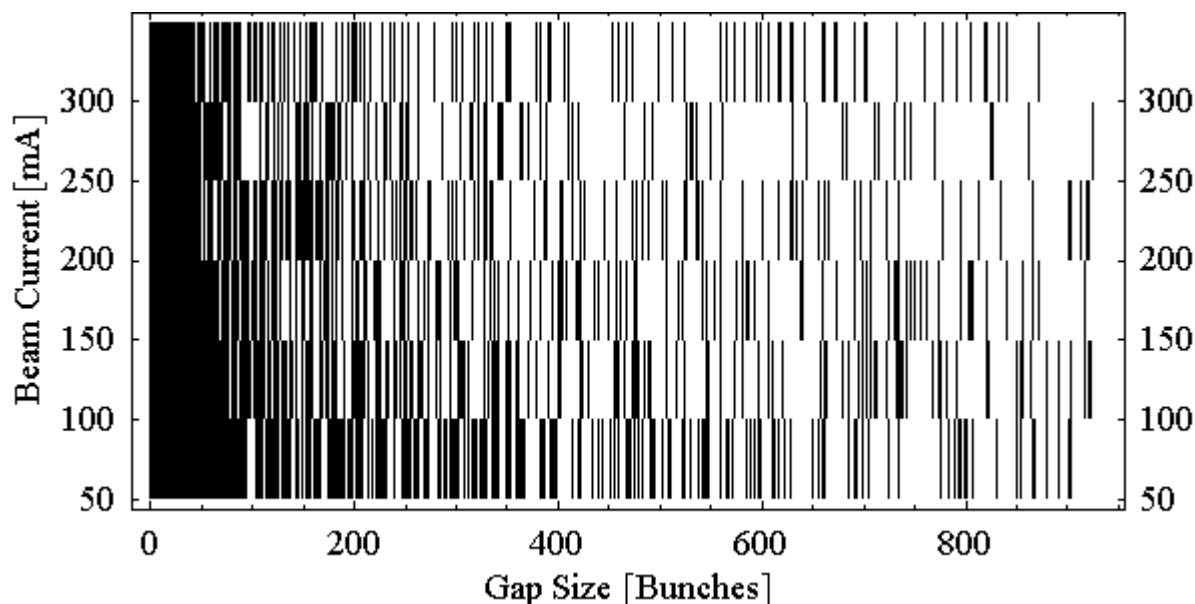


Figure 1.7-3 Trapping of any gas species in the reference design as a function of beam current. Counter to intuition, trapping occurs more at lower beam currents.

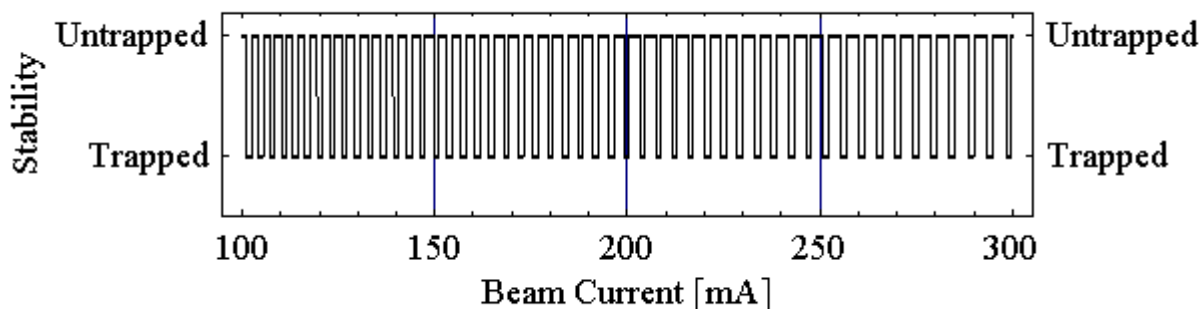


Figure 1.7-4 Trapping of residual water molecules (containing Oxygen-16) as a function of beam current. The trapping condition is repeatedly satisfied over a range of currents, even though initially molecules are not trapped.

Since the operating mode, emittance and current are all variable, we have chosen a minimum required gap size as that which is required to avoid trapping of residual gas 95% of the time over operating currents from 1 to 300mA. The trapping probability for the reference design is shown in Figure 1.7-5. The reference design fill pattern, which has a gap size of 312 bunches (1/3 of the bunches left empty) is well above this limit. Thus there is some margin for reducing the gap size if this is required later for lifetime or other reasons.

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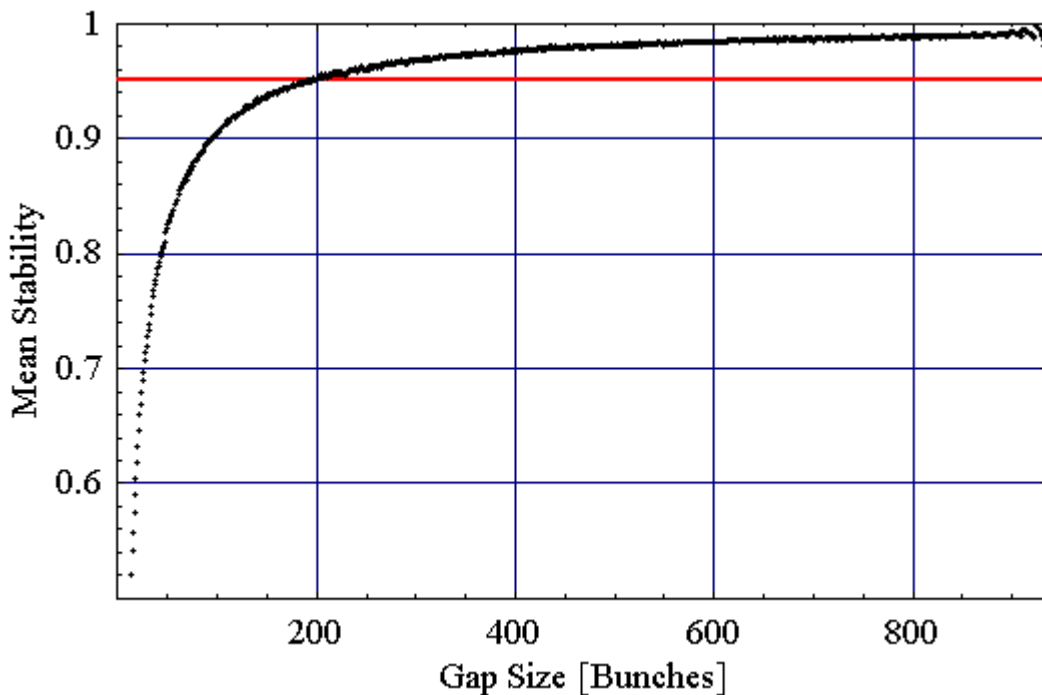


Figure 1.7-5 Mean stability over all operating currents, as a function of gap size. A gap of at least 200 bunches is required to avoid trapping 95% of the time (shown in red).

1.7.4 Coupled Bunch Effects

The main operating mode of DIAMOND will be in multi-bunch mode and therefore consideration of instabilities which will affect this mode of operation are of great importance. Coupled bunch instabilities will be driven by resonant impedances and these must therefore be minimised. As an example all potential RF resonances in the vacuum chambers must be avoided, which can be achieved by careful design of individual components. The exception is the accelerating cavities themselves, since their deliberately resonant structures can support a considerable number of higher order modes (HOMs) in addition to the main accelerating one (ie 500 MHz). The HOM design issues on DIAMOND are discussed in more detail in chapter E3.

The wake potential generated by a passing bunch changes the field that future bunches see. The equation of motion for these bunches has a damped and an anti-damped term and solutions can be analysed by a dispersion relation approach. The damped term (i.e. the damping time) must be less than the anti-damped term (i.e. the growth rate) for stability. Using this information enables calculation of a threshold beam current for the onset of these instabilities.

The thresholds in the longitudinal and transverse planes are given by:

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$$I_{th}^{\parallel} = \frac{2Q_s E}{e\tau_s \alpha_c f_{HOM}^{\parallel} N_{cav} R_{HOM}^{\parallel}}, \quad (70)$$

$$I_{th}^{\perp} = \frac{2E}{e\tau_i \beta_i^{cav} f_0 N_{cav} R_{HOM}^{\perp}}$$

where:

Q_s is the synchrotron tune (not frequency)

E is the machine energy

τ_s and τ_i are the damping times in the longitudinal and transverse directions

α_c is the lattice momentum compaction factor

$R_{HOM}^{\parallel}$ and $R_{HOM}^{\perp}$ are the dominant longitudinal and transverse HOM impedances of a single accelerating cavity unit

$f_{HOM}^{\parallel}$ is the associated longitudinal HOM frequency

N_{cav} is the number of cavity units in the ring

β_i^{cav} is the lattice betatron function at the location of the cavity.

f_0 is the orbit revolution frequency

i defines the transverse plane (ie horizontal or vertical).

The larger of the product $\beta_i^{cav} \tau_i$ in either the radial or vertical direction should be used to give a worst-case estimate.

Clearly the selection of accelerating structure will have a major impact on the instability thresholds. Both superconducting and normal cavities were considered and a comparison of their likely parameters is presented in Table 1.7-3. Either the Cornell or KEK superconducting solutions could be adopted as proven manufacturing designs, although their impedances can be seen to be very different. In contrast are shown realistic parameters for a well optimised normal conducting cavity, in this case the design produced by a recently EU funded international collaboration.

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Table 1.7-3 Lattice and cavity parameters for calculation of HOM thresholds

Parameter	Non-zero dispersion lattice	Normal conducting cavity	Cornell SC Cavity	KEK-B SC Cavity
Q_s	4.5×10^{-3}			
E	3 GeV			
τ_s	5.6 ms			
τ_i	11.2 ms			
α_c	1.7×10^{-4}			
$f_{HOM}^{\parallel}$		2530 MHz	1700 MHz	1018 MHz
$R_{HOM}^{\parallel}$		725.6 Ω	200 Ω	1000 Ω
$R_{HOM}^{\perp}$		48.2 k Ωm^{-1}	2.5 k Ωm^{-1}	850 Ωm^{-1}
N_{cav}		6	3	3
β_i^{cav}	12 m			
f_0	534 kHz			

The computed threshold currents for the reference DIAMOND lattice for normal conducting and superconducting cavities are shown in Table 1.7-4 for transverse HOM's and Table 1.7-5 for longitudinal HOM's. The parameters used to calculate these thresholds are shown in Table 1.7-3.

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Table 1.7-4 Threshold currents for transverse HOM's

	Normal conducting cavity	Cornell SC Cavity	KEK-B SC Cavity
Non-zero dispersion lattice	401 mA	15.5 A	45.5 A

Table 1.7-5 Threshold currents for longitudinal HOM's

	Normal conducting cavity	Cornell SC Cavity	KEK-B SC Cavity
Non-zero dispersion lattice	2.57 A	13.9 A	4.6 A

Although the specified operating current of DIAMOND is 300 mA it can be concluded that an instability of concern would be the transverse HOM threshold if a normal conducting cavity was used, allowing for calculation uncertainties and future current upgrades. The chosen superconducting solution (chapter E3) should have a comfortable margin of safety at all operating levels, although a transverse feedback system may be incorporated as a supplementary feature.

1.7.5 Single Bunch Effects

(a) Single Bunch Thresholds

It is likely that DIAMOND users will require occasional operation in single or few bunch circulating modes, when there will be a need for individual bunches to have increased numbers of electrons in order to maintain radiation flux levels. Single bunch instability thresholds will certainly be important when operating in these modes but may also be significant even when in multi-bunch mode if the predicted threshold bunch currents are low enough.

The single bunch effects to be considered are the longitudinal mode coupling instability, often referred to as the microwave instability, and the fast head tail effect which is the transverse equivalent. The microwave instability occurs when high frequency components of the wake field cause ripples in the longitudinal density that can amplify and grow exponentially, with multiple collective modes then able to couple and amplify. It was first analysed for unbunched beams. Stability is assessed by means of a dispersion relation for longitudinal motion and demonstrates that a beam with no momentum spread will always be unstable if the complex chamber impedance has a positive real part (i.e. it is resistive) whereas if the impedance has no real part (ie either capacitive or inductive) the stability depends on the sign of a phase slip factor. The transverse distribution of particles is usually assumed to be Gaussian, which is a reasonable assumption despite the unrealistic tails; using this

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distribution gives the Keil-Schnell criterion for stability that generates a threshold for onset of the microwave instability. In the special case of bunched beams the relevant threshold is described by the Boussard Criterion and the threshold current per bunch can be written as:

$$I_{th} = \frac{4\pi^2 E \alpha_c \sigma_p F[\Psi_0]}{\omega_0 e Z_{bb} h_{rf}} \quad (71)$$

where:

E is the machine energy

α_c is the momentum compaction

σ_p is the momentum spread

$F[\Psi_0]$ is a form factor which is taken to be one for a Gaussian bunch shape

ω_0 is the angular revolution frequency

Z_{bb} is the broadband impedance

h_{rf} is the harmonic number

The threshold current per bunch will depend on the lattice settings and also on the assumed broad band impedance. This impedance arises from an integral over all contributing components around the circumference but is often dominated by a smaller number of these that cannot be satisfactorily minimised by techniques such as smoothed aperture transitions or screened geometries. The accelerating cavities themselves will be a significant residual element even in a well engineered ring. Experience in modern light sources suggests a figure in the region of 1 Ω or less should be achievable and this will be used for reference calculations. In practice for the short DIAMOND bunches (< 10 mm) the effective impedance will be much less (SPEAR scaling). The parameters used are shown in Table 1.7-6.

Table 1.7-6 Parameters for calculating microwave instability threshold

Parameter	Reference lattice
E	3 GeV
α_c	1.7×10^{-4}
σ_p	9.6×10^{-4}
ω_0	3.36 MHz
h_{rf}	936
Z_{bb} (longitudinal)	1 Ω

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The computed single bunch average current threshold is $21 \mu\text{A}/\text{bunch}$. For a multi-bunch operating mode with $2/3$ of the circumference filled (see section 1.7.3) this is equivalent to a stored beam of little more than 10 mA so that some degree of bunch lengthening seems likely, although as pointed out above the assumed impedance is pessimistic.

The head-tail effect arises due to wake fields from the head of a bunch driving those in the tail; because of causality, the head can act on the tail but the tail cannot act on the head. However synchrotron oscillations can couple the tail particles into the head position. A head-tail instability can be very severe but is always avoided in storage rings by operating with zero or positive first order chromaticity, set by the ring sextupoles. However a residual fast head-tail effect still exists even after this correction and is the transverse microwave instability. The impedance for this effect can arise from both broadband and resistive wall impedances. Whilst broadband impedance arises from vacuum chamber breaks, bellows and other discontinuities in accelerator components and is mainly inductive, resistive wall impedance arises from wall currents due to its finite resistivity. Although it is usually small the exception occurs with the presence of any small aperture chambers such as might arise for small gap insertion devices: any future proposal for this will require a careful impedance assessment.

The threshold current per bunch for the fast head-tail effect is:

$$I_{th} = \frac{4\pi E \omega_0 v_{x,y} v_s}{ecZ_{bb}} \quad (72)$$

where:

$v_{x,y,s}$ are the transverse and longitudinal tunes.

The values used to calculate the threshold bunch currents for the fast head tail effect are shown in Table 1.7-7, supplementing those in Table 1.7-6.

Table 1.7-7 Parameters for calculating the threshold of the fast head tail effect

Parameter	Reference lattice
v_x	27.2
v_y	12.4
v_s	4.5×10^{-3}
Z_{bb} (transverse)	$286 \text{ k}\Omega \text{ m}^{-1}$

The threshold current per bunch for the fast head tail effect in DIAMOND is calculated to be 82 A per bunch and is therefore well outside the operating regime of the storage ring.

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(b) Bunch Lengthening

In addition to the coherent instability processes already discussed there will be a small amount of longitudinal effect arising from potential well distortion. The wake potentials have a contribution to the equilibrium distributions in the storage ring and in DIAMOND this is estimated to be about 10 % in bunch length. There is an associated shift in synchrotron frequency and phase. It should be noted that this bunch length change is not accompanied by any corresponding energy spread variation.

Natural bunch lengthening inevitably occurs with increasing bunch current due to the microwave instability. However in multi-bunch DIAMOND operation the bunch length only increases by about ten percent even at an operating current of 500 mA provided SPEAR scaling of bunch length is applied. If SPEAR scaling is not used the bunch length approximately triples at 500 mA. Although increased bunch lengths can be readily tolerated, and may even be desirable as a means to reduce other peak current driven instabilities, it should be noted that the accompanying increased energy spread is very undesirable (eg for undulator harmonic operation).

In single bunch mode the current per bunch will be much higher and so the bunch lengthening is greater. For a 10 mA single bunch current the increase in bunch length is six-fold with SPEAR scaling and seven-fold without. There is also an associated increase in energy spread of a similar magnitude in both cases. These major effects will set a limit on any successful single bunch operation, at least with the assumed set of storage ring parameters.

1.7.6 Countermeasures

Coupled bunch instabilities will be overcome by a variety of methods. As they are driven by the RF cavities considerable efforts will be made to minimise the dangerous HOM contributions by design, including damping techniques. Separation of the aggregated contributions from each of the three cavities will be feasible too. A transverse feedback system will also be developed, but only implemented if the need arises. At present it seems not essential.

Broadband impedance will be minimised by all means possible, including bellows screening and spring finger transitions inside chambers. Positive chromaticity capability has been included in the storage ring sextupole magnet specifications and has proven useful at a number of centres, such as ESRF; however it poses undesirable beam dynamics issues, including a threat to stored beam lifetime.

Since the overall DIAMOND stored beam lifetime will be dominated by significant Touschek scattering processes (see chapter E1.6) it would be an advantage to have a means to stretch the bunch length in order to lower its density. Most modern light sources have pursued techniques to achieve this, with two principal alternatives: either a higher harmonic cavity or injection of RF phase modulation. The latter method, despite some success at ASTRID and the Photon Factory, has the

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disadvantage of associated energy spread and is not recommended on DIAMOND, at least in its present state of development. A higher harmonic cavity, probably operating at the RF third harmonic (ie 1500 MHz), will be a useful addition to DIAMOND and might achieve deliberate bunch lengthening by a factor of 2-3; provision will be made for this, initially as a development project. Questions still to be answered include whether this cavity should be passive or driven, and if a superconducting solution should be adopted.

1.8 INSERTION DEVICE EFFECTS

1.8.1 Effect of Insertion Devices On Dynamic Aperture

DIAMOND has been designed to accommodate many insertion devices. The effect of these devices is twofold. As these devices are inserted in the lattice individually it is inevitable that the localised focusing of the insertion will break the 6-fold symmetry of the lattice and this in turn will change the non-linear dynamics of the machine. Secondly these devices will introduce their own additional non-linear field, which will also affect the dynamics.

(a) Tracking RACETRACK and MAD

RACETRACK [52] has been used to make an initial assessment of these effect on the dynamic aperture of DIAMOND. As the optimisation of the lattice and its characterisation was carried out using MAD, a comparison of the two programs has been made.

The RACETRACK lattice model that was set up was based on the HARMON optimised sextupoles found using MAD. As RACETRACK does not allow tracking with thick sextupoles each sextupole in the MAD model was replaced by a thin sextupole of equal integrated strength placed at the centre of the equivalent MAD element. A comparison of the dynamic aperture tracked over 1000 turns shows that the thin sextupole tracking gives a significantly greater aperture, particularly in the vertical plane. This is despite the fact that the pragmatically optimised HARMON weight values were used when testing the dynamic aperture by tracking with thick sextupoles. The results of the comparison are shown in Figure 1.8-1 these also show that the two programs are in agreement for thin sextupole tracking to the accuracy of the aperture step.

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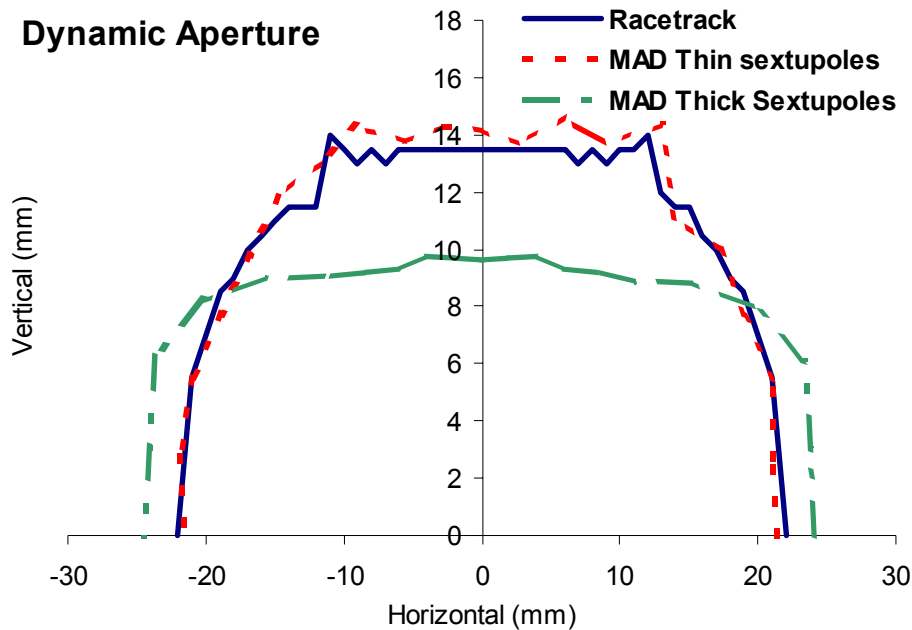


Figure 1.8-1 Dynamic aperture comparison between MAD and RACETRACK.

(b) Dynamic Aperture Effects of A Single Strong Multipole Wiggler, MPW60

All the currently planned insertion devices for DIAMOND are either multipole wigglers or undulators. The largest effect on the dynamic aperture could be expected from the devices with the largest K values. The strongest such multipole wiggler currently planned is MPW60, this is a 3.5 T magnet with 16, 60 mm periods. It is also referred to hereafter as “U60”. An initial assessment of the effect on the dynamic aperture of introducing one of these magnets into a standard straight in the DIAMOND lattice has been carried out using RACETRACK.

The alpha matching option was used with the four quadrupoles adjacent to the ID to remove the oscillations in the vertical beta function caused by the local focussing of the multipole wiggler. This corrected most of the small tune shifts associated with this multipole wiggler and removed the betatron function oscillations. The betatron functions before and after correction are shown in Figure 1.8-2 and Figure 1.8-3.

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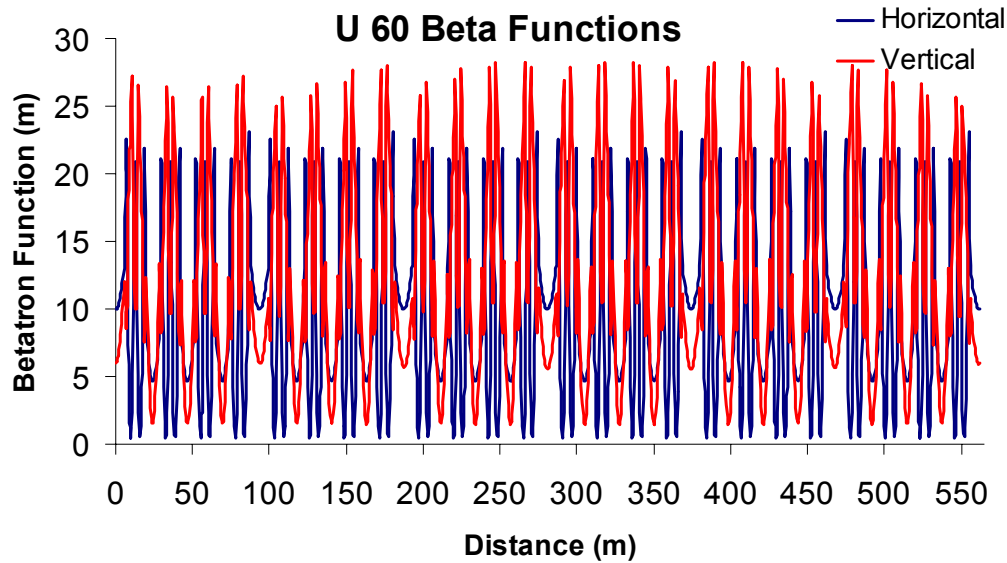


Figure 1.8-2 Betatron functions Oscillation in DIAMOND with MPW60/U60.

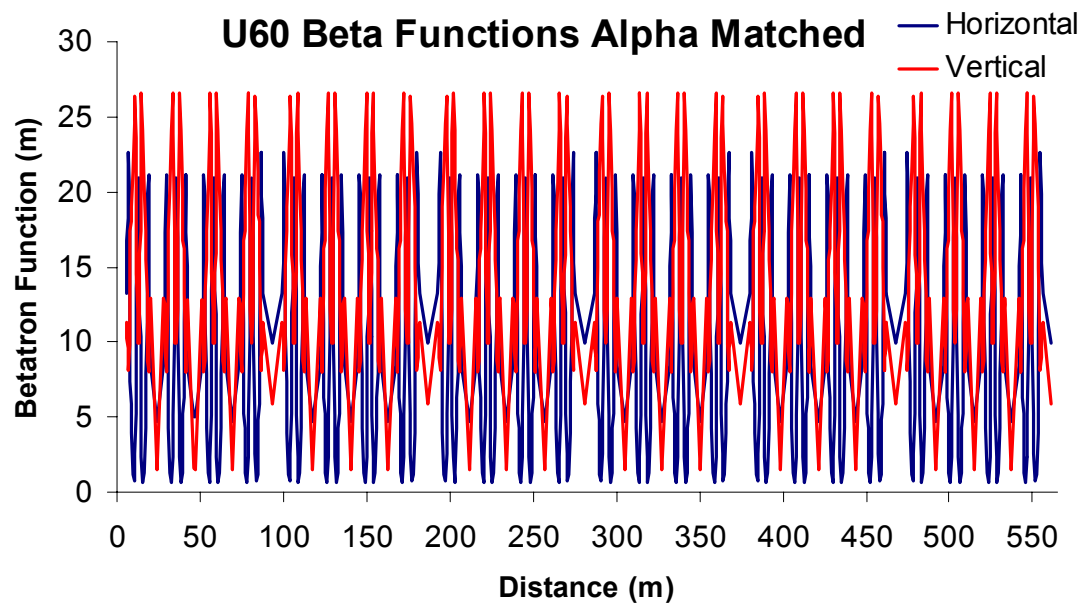


Figure 1.8-3 Betatron functions Oscillation in DIAMOND with MPW60/U60 with alpha matching.

The effect on the dynamic aperture at the reference tune point was found using tracking including linear only effect and also tracking including both nonlinear and linear effects. The tracking was carried out for 0, +4 and -4% momentum error. Figure 1.8-3, Figure 1.8-4 and Figure 1.8-6 compare the dynamic apertures found without and with MPW60 and with and without the nonlinear effect. There is clearly a significant effect due to the introduction of this multipole wiggler. There is a reduction in both

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the horizontal and vertical stable region. It should also be noted that the models used are the idealised RACETRACK models and further modelling will be necessary.

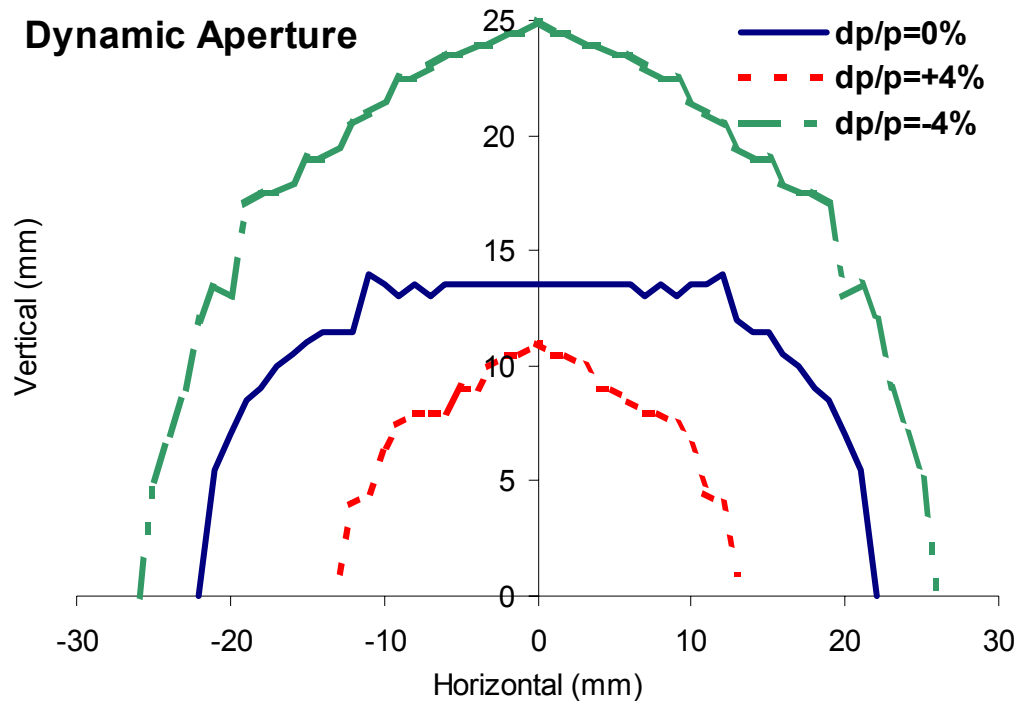


Figure 1.8-4 Dynamic aperture using RACETRACK for 0, and $\pm 4\%$ momentum error.

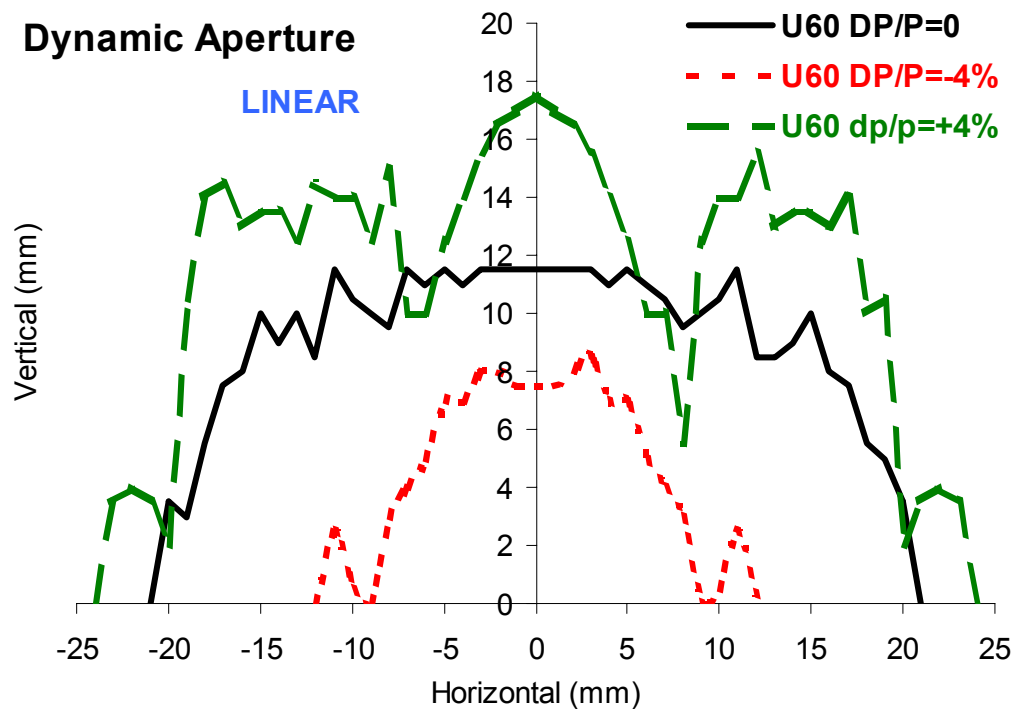


Figure 1.8-5 Dynamic aperture using RACETRACK for 0, +4 and -4% momentum error with MPW60/U60 Linear effects only.

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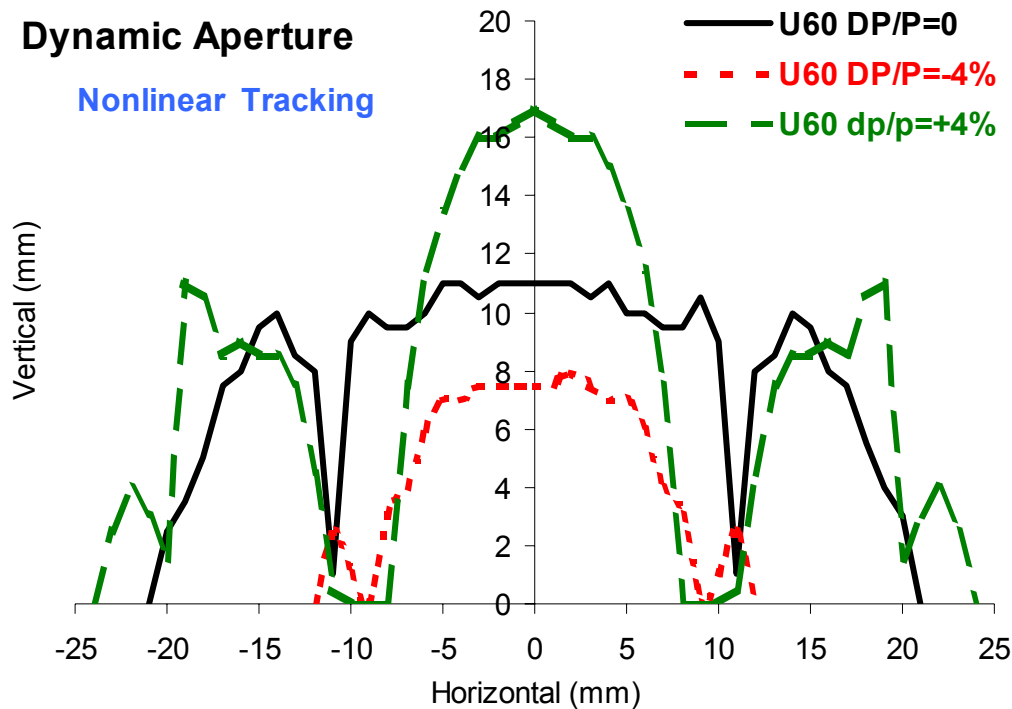


Figure 1.8-6 Dynamic aperture using RACETRACK for 0, +4 and -4 % momentum error with MPW60/U60 with nonlinear effects.

(c) Preliminary Study of a Full Complement of Insertion Devices in DIAMOND

DIAMOND has 24 straight section, 22 available for insertion devices. A full complement of insertion devices could have a significant effect on the dynamic aperture. To make a preliminary assessment of how serious this effect could be in DIAMOND, RACETRACK was used to assess the effect on dynamic aperture of introducing a set of 22 insertion devices of three different types. Table 1.8-1 tabulates the number and parameters of the insertion devices used. It could be that by considering the symmetry of the machine when introducing the insertion devices that some of the machine symmetry could be preserved. However to get a “worst” case estimate of possible effect the devices were introduced with no regard for symmetry. The distribution of the insertion devices used in the simulation is shown schematically in Figure 1.8-7. In each case the four adjacent quadrupoles were changed to reduce the betatron beat but the small changes in overall tune were not removed and the final tune point was $Q_r = 27.11$, $Q_v = 12.41$ c.f. the initial tune, $Q_r = 27.23$, $Q_v = 12.36$.

Table 1.8-1 Insertion Devices used in simulation.

Type	Field (T)	Period (mm)	Number of Periods	Number in Simulation
MPW60/U60	3.5	60	16	4
U24	0.6	24	82	9
U48	0.84	48	105	9

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Tracking was carried out in RACETRACK using the faster 1st order symplectic method but since the results for the horizontal plane were better than for a single MPW60 insertion the tracking was compared with the more time consuming 2nd order method. The results are shown in Figure 1.8-8. The horizontal aperture now only shows a moderate reduction despite the considerable number of devices introduced. The reduction apparent with one MPW60 multipole wiggler is probably due to a resonant behaviour sensitive to the precise tune point. The vertical aperture is however reduced significantly in comparison to the no undulator case but it should be noted that the aperture is reduced by only ~20% from that estimated in MAD using the thick sextupoles.

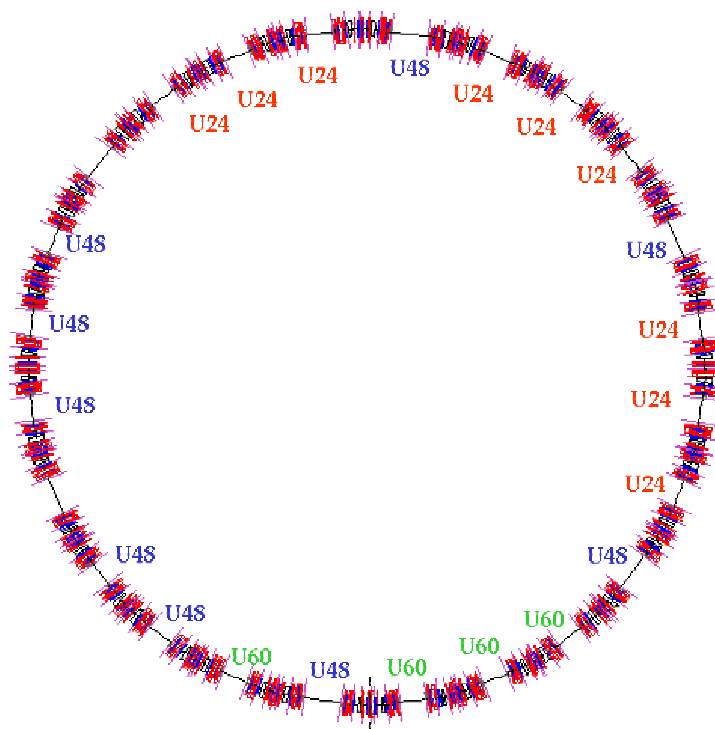


Figure 1.8-7 Distribution of the undulator used in dynamic aperture studies

Dynamic Aperture

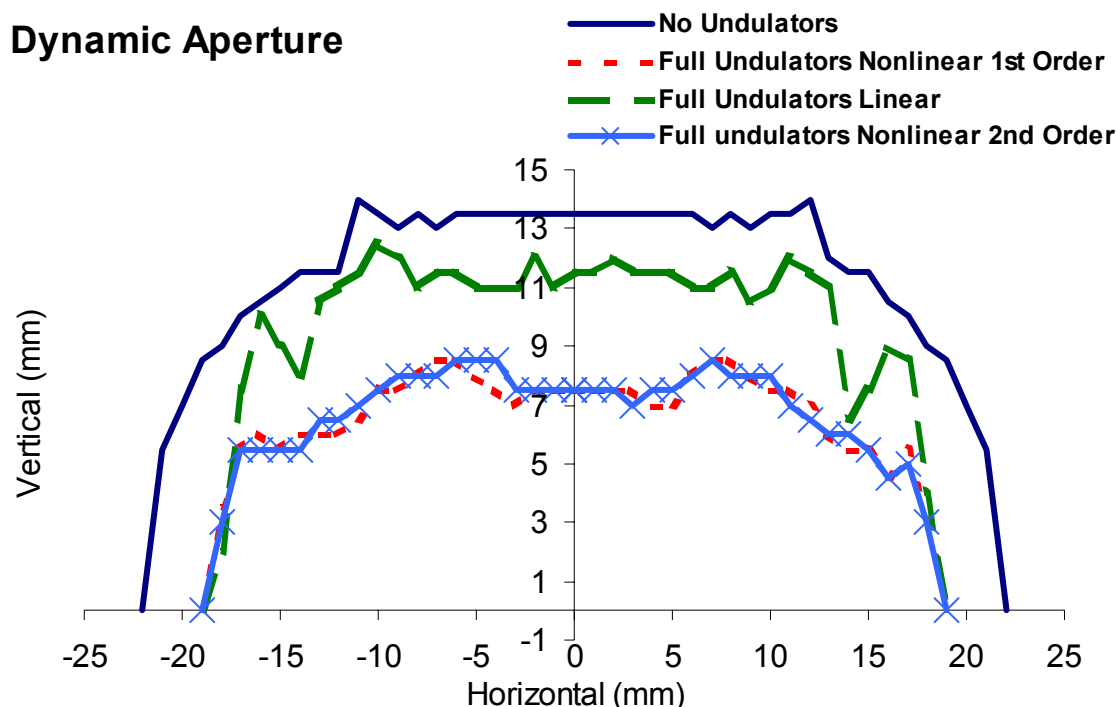


Figure 1.8-8 Dynamic aperture with a full complement of insertion devices

1.8.2 Tune Shifts and Emittance With High Field Insertion Devices

During the design period the effect of high field insertion devices was estimated for the DIAMOND lattice. The magnitude of the effects were calculated for four different lattices before the final optimisation of the storage ring lattice. However the lattice properties of the present lattice are close enough that the results presented here will be indicative of those for the reference machine.

ORBIT has been used to model the effect of high field multipole wigglers and wavelength shifters on the tune shift and emittance in four different DIAMOND storage rings. The results from ORBIT have been compared with values predicted by an analytic method [53].

Four example DIAMOND lattices have been modelled, these are tabulated in Table 1.8-2 and the properties compared with the current DIAMOND reference lattice lat-007 tuned for finite (iss01) and zero (iss02) dispersion.

Table 1.8-2 Lattices used to model the effect

Zero Dispersion	Non-zero Dispersion
a) lat-001-iss02 (EPAC'00)	b) lat-001 iss01 (EPAC'00)
c) lat-002-iss02	d) lat-004-iss01

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Table 1.8-3 Properties of lattices including the DIAMOND reference lattices

	Zero dispersion examples		Finite dispersion examples		Reference Finite disp	Reference Zero disp
	lat-002 iss02	lat-001 iss02	lat-004 iss01	lat-001 iss01	lat-007 iss01	lat-007 iss02
β_r [m]	2.97	1.83	3.00	1.98	4.65	5.34
β_v [m]	3.90	1.06	2.50	2.52	1.53	1.23
Dipersion [m]	0.00	0.00	0.05	0.04	0.05	0.00
Emittance [nmrad]	4.40	4.44	2.00	2.50	2.74	6.52

(a) The Insertion Devices

A model of the magnetic field on the axis of a 10 T wavelength shifter was created by scaling measurements of the ESRF wavelength shifter and adjusting the field to give a zero total bend angle. The wavelength shifter is 0.378 m long with a single full strength pole and two end poles. Figure 1.8-9 shows the field on axis for this magnet.

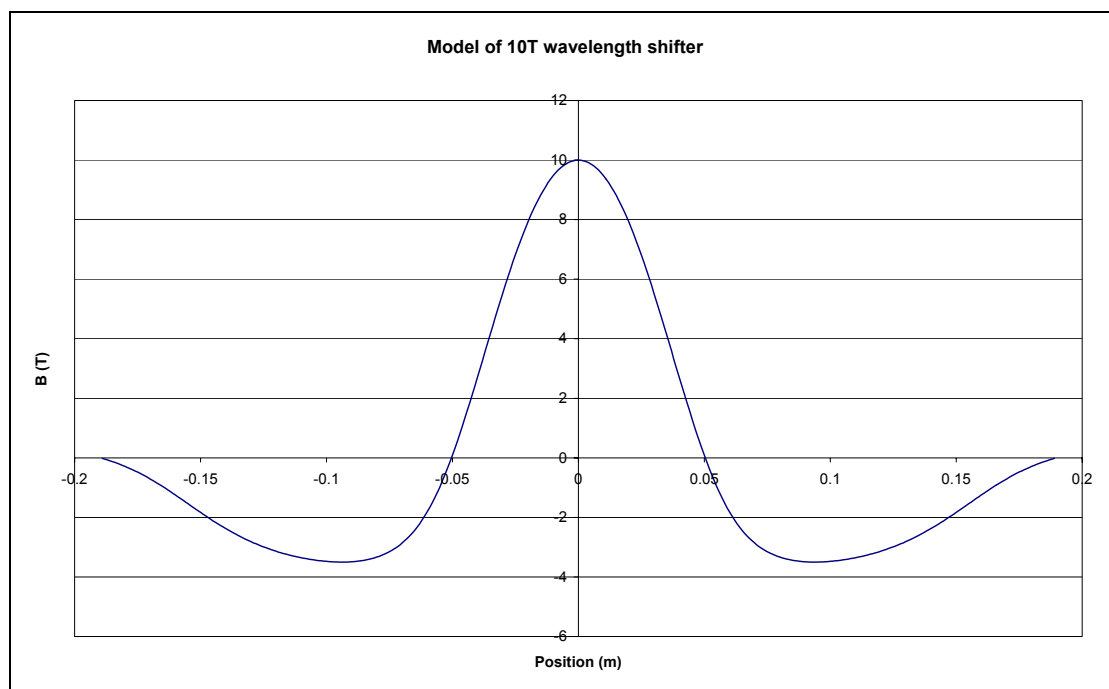


Figure 1.8-9 Model of the Field on the axis of a 10T wavelength shifter

A model of the magnetic field on the axis of a 3.5 T multipole wiggler was created using a simple sinusoidal model with half strength end poles. The multipole wiggler is 1.98 m long and has a constant period of 60 mm. The model is shown in Figure 1.8-10.

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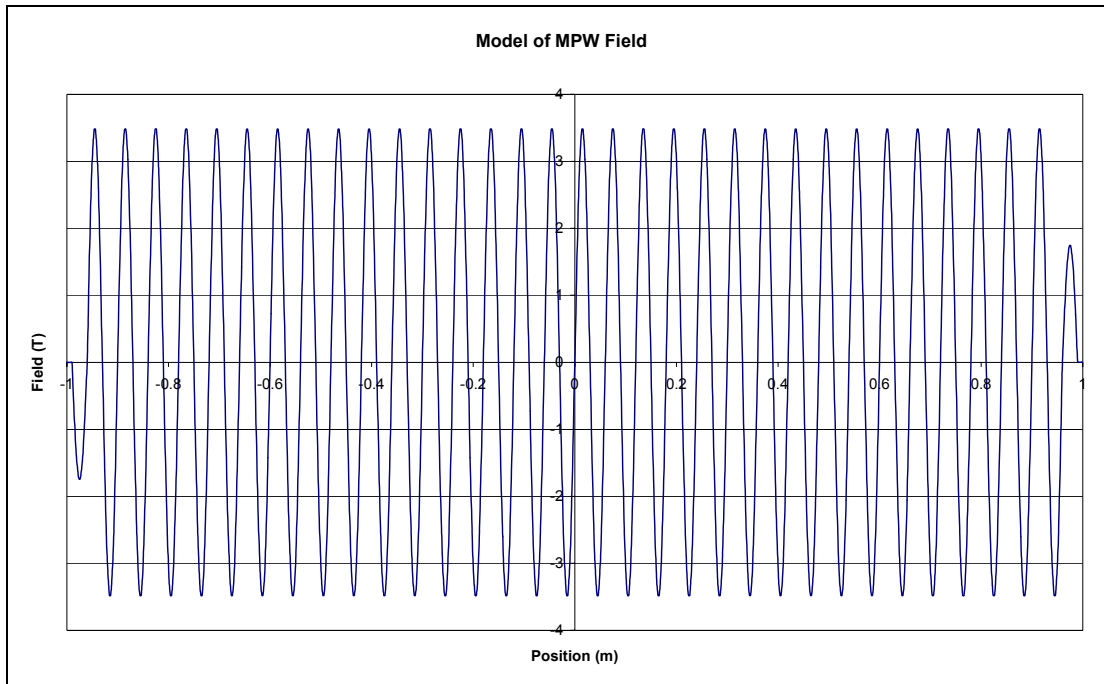


Figure 1.8-10 Model of the Field on the axis of a 3.5T multipole wiggler with 64 full strength poles and 2 end poles

(b) Hard-edged Models and ORBIT

Hard-edged models of the insertion devices were placed in the centre of a short straight of each of the lattices. The tune shift and emittance were extracted from the ORBIT output.

Hard-edged models of the two types of insertion device were created as described in [54] and [55]. The insertion devices were modelled as a series of rectangular dipole magnets separated by drift sections with zero magnetic field between the dipoles. The strength of the magnetic field in each dipole and the length of the dipoles were matched to calculations of the following integrals.

$$1) \quad \int_L B \, ds$$

$$2) \quad \int_L B^2 \, ds$$

$$3) \quad \int_L B^3 \, ds$$

B is the magnetic field on the axis of the insertion device and ds is an element of the path along the longitudinal axis of the insertion device.

The vertical tune shift due to an insertion device depends mainly on integrals 1 and 2, whilst the emittance change depends mainly on integrals 1 and 3, therefore two different hard-edged models of each insertion device are needed.

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(c) Wavelength Shifter

The Table 1.8-4 shows the values of integrals 1-3 for each dipole in a 10 T wavelength shifter and Table 1.8-5 shows the values for the hard-edged models.

Table 1.8-4 Field Integrals for a 10 T Wavelength Shifter

	$\int \mathbf{B} \cdot d\mathbf{s}$ (Tm)	$\int \mathbf{B}^2 \cdot d\mathbf{s}$ (T ² m)	$\int \mathbf{B}^3 \cdot d\mathbf{s}$ (T ³ m)
End pole	-0.3090	0.8699	-2.6365
Centre pole	0.6180	4.8131	40.7590

Table 1.8-5 Hard Edge Model

	B (T)	L (m)
"Tune Shift" model:		
end pole	-2.8153	0.1098
centre pole	7.7881	0.0794
"Emittance" model:		
end pole	-2.9210	0.1058
centre pole	8.1211	0.0761

The hard-edged poles were spaced so that the centre of each pole was at a position of maximum field strength in the original model. Figure 1.8-11 and Figure 1.8-12 illustrate the fields of the hard edge models.

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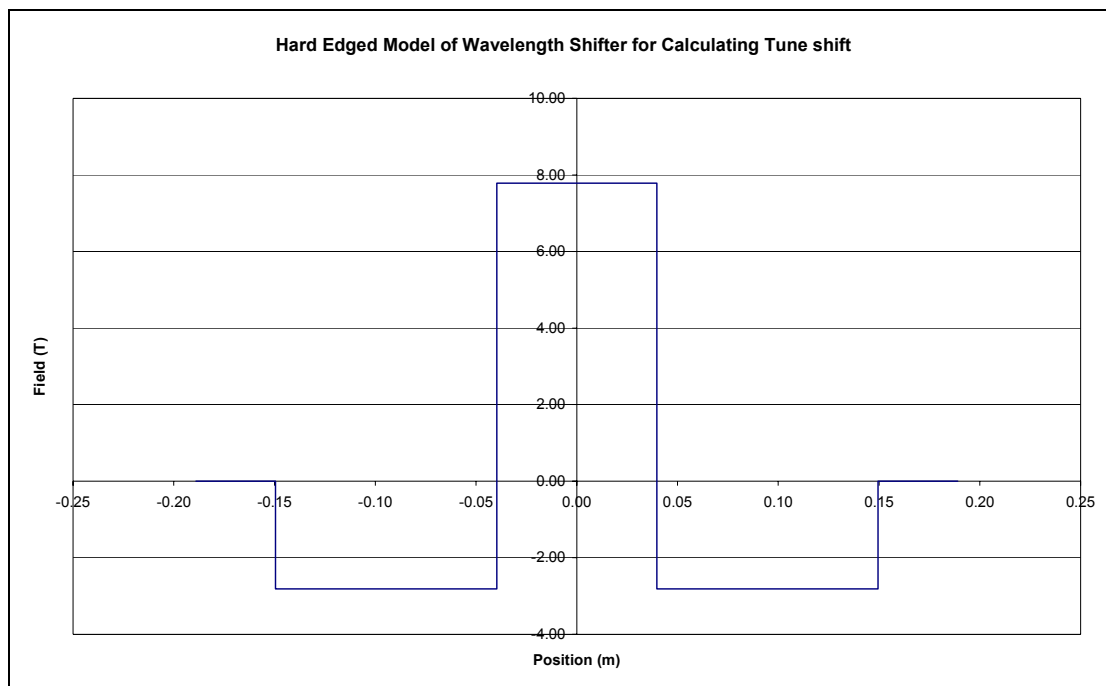


Figure 1.8-11 The hard-edged model of a 10 T wavelength shifter used to model the effect of a 10 T wavelength shifter on vertical tune

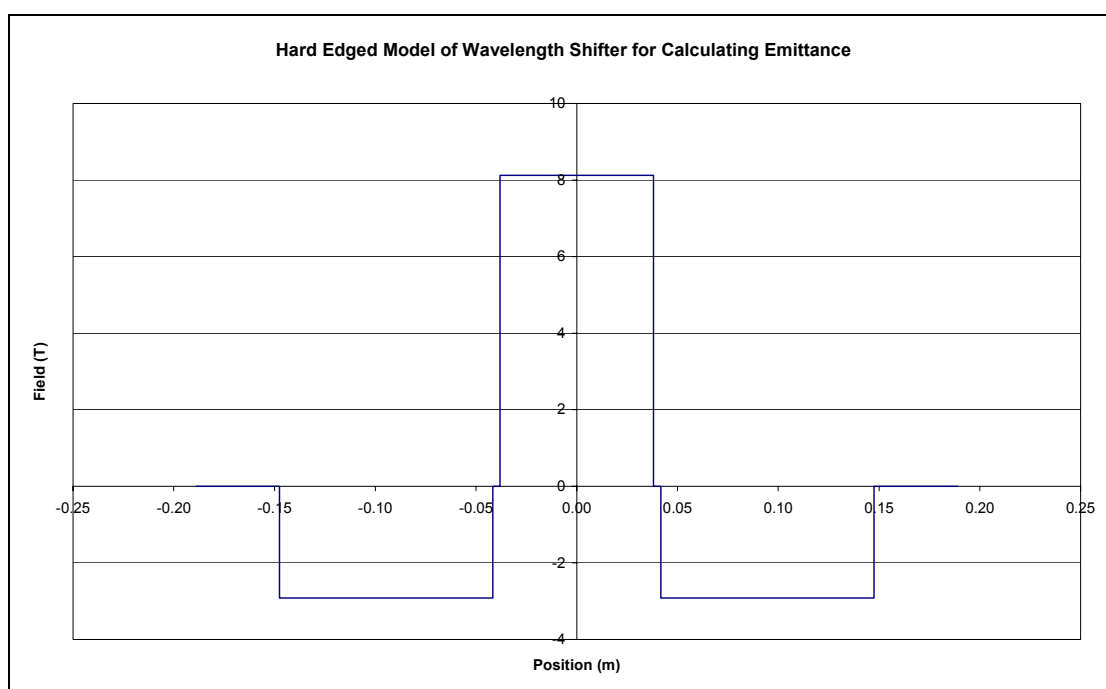


Figure 1.8-12 The hard-edged model of a 10 T wavelength shifter used to model the effect of a 10 T wavelength shifter on emittance

Models of wavelength shifters with different field strengths were produced by scaling the 10 T model by field.

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(d) Multipole Wiggler

The Table 1.8-6 shows the values of integrals 1-3 for each dipole in a 3.5 T multipole wiggler. These were then modelled by the values for the hard-edged models given in Table 1.8-7. Again the hard-edged “poles” were spaced so that the centre of each pole was at a position of maximum field strength in the original model. The two models used are illustrated in Figure 1.8-13 and Figure 1.8-14. Scaling the 3.5 T model by field produced models of multipole wigglers with different field strengths.

Table 1.8-6 Field integrals for a 3.5 T multipole wiggler

	$\int \mathbf{B} \cdot d\mathbf{s}$ (Tm)	$\int \mathbf{B}^2 \cdot d\mathbf{s}$ (T ² m)	$\int \mathbf{B}^3 \cdot d\mathbf{s}$ (T ³ m)
end pole	±0.0333	0.0459	±0.0682
Centre pole	±0.0666	0.1838	±0.5459

Table 1.8-7 - Field strength and length of dipoles in the hard-edged model of a 3.5 T multipole wiggler

	B (T)	L (m)
“Tune Shift” model:		
end pole	±1.3795	0.02414
centre pole	±2.7590	0.02414
“Emittance” model:		
end pole	±1.4315	0.023262
centre pole	±2.8630	0.023262

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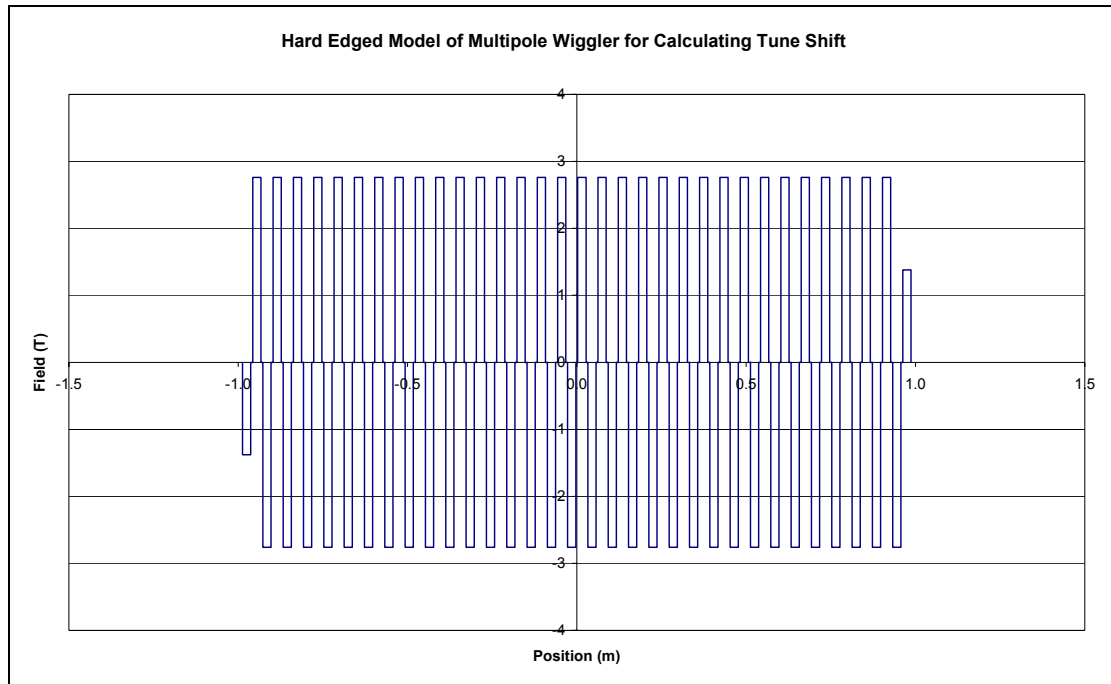


Figure 1.8-13 The hard-edged model of a 3.5 T multipole wiggler used to model the effect of a 3.5 T multipole wiggler on vertical tune

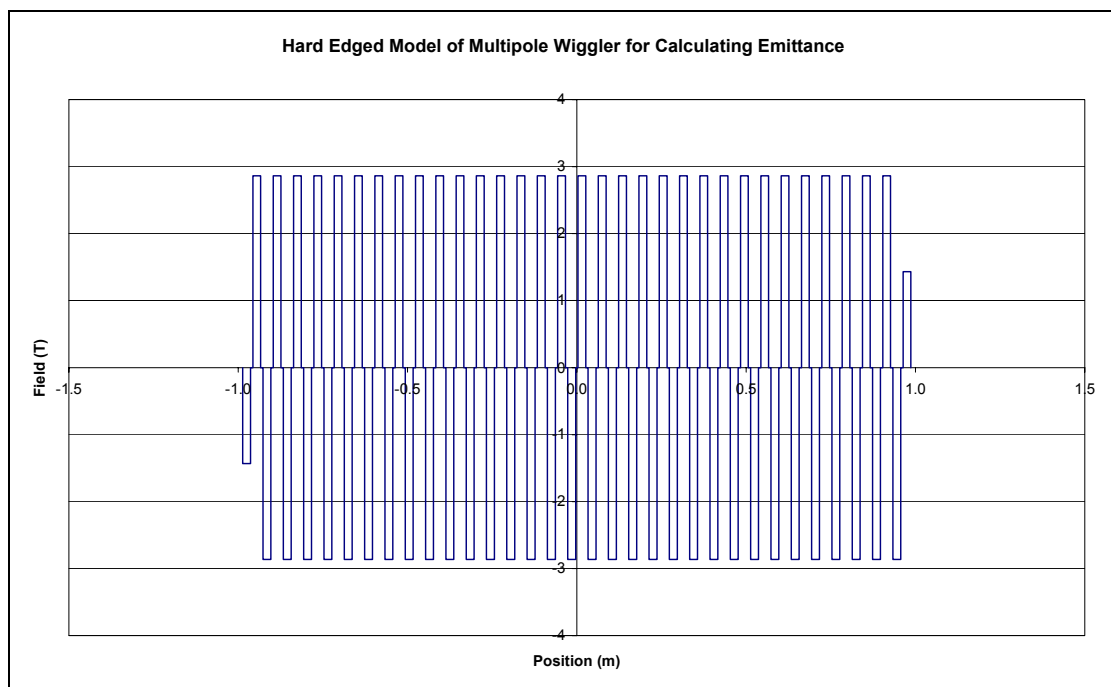


Figure 1.8-14 The hard-edged model of a 3.5 T multipole wiggler used to model the effect of a 3.5 T multipole wiggler on emittance

(e) Analytic Calculations

This theory for the analytic calculations is taken from [53]. The effect of the focusing due to the insertion devices on the tune can be calculated using matrix modelling. In

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order to perform analytical calculations, the insertion device is approximated to a thin lens acting at the centre of the device.

Provided the insertion device strength is not too large, i.e. $\sqrt{K_z} L \leq 0.5$, the tune shift ΔQ due to an insertion device can be approximated as

$$\Delta Q = \frac{K_z L \beta}{4\pi} \left(1 + \frac{L^2}{12\beta^2} \right) \quad (73)$$

β is the vertical beta function in the storage ring with no insertion device. The tune shifts shown below were calculated using the values of $\int B_z^2 ds$ shown in Table 1.8-4 and Table 1.8-6 scaled for different field insertion devices, and values of β taken from ORBIT models of the DIAMOND lattices with no insertion devices.

It is worth noting that for a 3.5 T multipole wiggler such as that shown in Figure 1.8-14, $\sqrt{K} L = 0.484$, and so equation (73) is not expected to work well for multipole wigglers with a field strength greater than 3.5 T. The multipole wigglers modelled in this experiment are also 1.98 m long, and so the thin lens approximation may result in inaccurate values of tune shift. For a 10T wavelength shifter, $\sqrt{K} L = 0.158$, and $L = 0.378$ m and so equation (73) should give a better result.

Insertion devices change the emittance of a lattice due to the emission of synchrotron radiation. The change in the emittance can be written as

$$\frac{\varepsilon'}{\varepsilon} = \frac{1 + \frac{\Delta I_5}{I_5}}{1 + \frac{\Delta I_2 - \Delta I_4}{I_2 - I_4}} \quad (74)$$

I_2 , I_4 and I_5 are synchrotron radiation integrals. ORBIT output shows that $\Delta I_2 \gg \Delta I_4$ for both insertion devices, thus equation (74) can be rewritten as

$$\frac{\varepsilon'}{\varepsilon} = \frac{1 + \frac{\Delta I_5}{I_5}}{1 + \frac{\Delta I_2}{I_2 - I_4}}, \quad (75)$$

where

$$\begin{aligned} \Delta I_2 &= \oint \frac{1}{\rho^2} \\ \Delta I_5 &= \oint \frac{H}{|\rho^3|} \\ H(s) &= \gamma D^2 + 2\alpha D D' + \beta D'^2 \end{aligned} \quad (76)$$

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α , β and γ are the horizontal lattice functions with no insertion device. For this investigation they were taken from ORBIT output for the DIAMOND lattices. Values of I_2 , I_4 , I_5 and ε were also taken from the ORBIT output.

The hard-edged emittance models of the insertion devices (Figure 1.8-12 and Figure 1.8-14) were used to calculate the emittance. The poles were sliced in order to give satisfactory integration of the dispersion through the insertion device.

The hard-edged models were chosen for the analytical calculations rather than the original models in order to allow a direct comparison between the two methods of calculating emittance. Calculating the emittance using the original insertion device models gave similar answers.

(f) Results

The results of tune shift vs field for the four lattices are given in Figure 1.8-15 to Figure 1.8-18 and the results of emittance vs field in Figure 1.8-19 to Figure 1.8-22.

For all lattices the values for tune shift obtained by the two methods agree well, although the values for the multipole wiggler do not agree as well as the values for the wavelength shifter due to the assumptions made in the analytic model as explained above in the theory.

In lattice c) multipole wigglers above about 4.5 T cause the lattice to approach a half-integer vertical tune of 11.5 causing the lattice to become unstable. For all lattices the values for emittance obtained by the two methods agree very well. The multipole wiggler reduces the emittance in the zero dispersion lattices.

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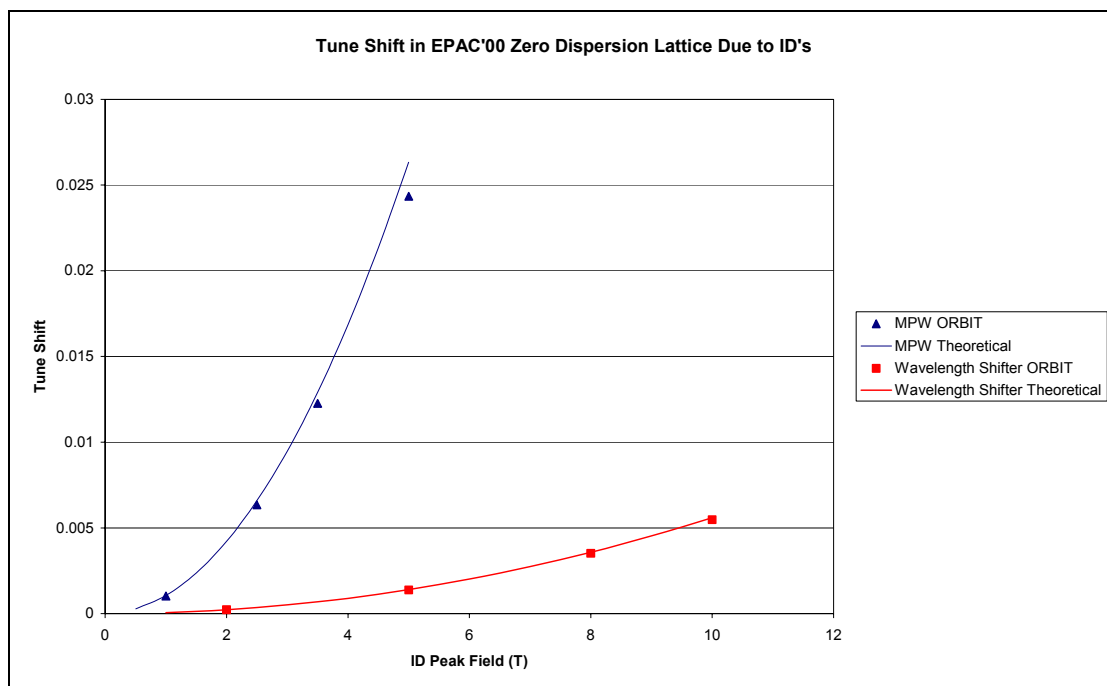


Figure 1.8-15 The tune shift due to different field insertion devices placed in lattice a) as predicted both by ORBIT and analytic calculations

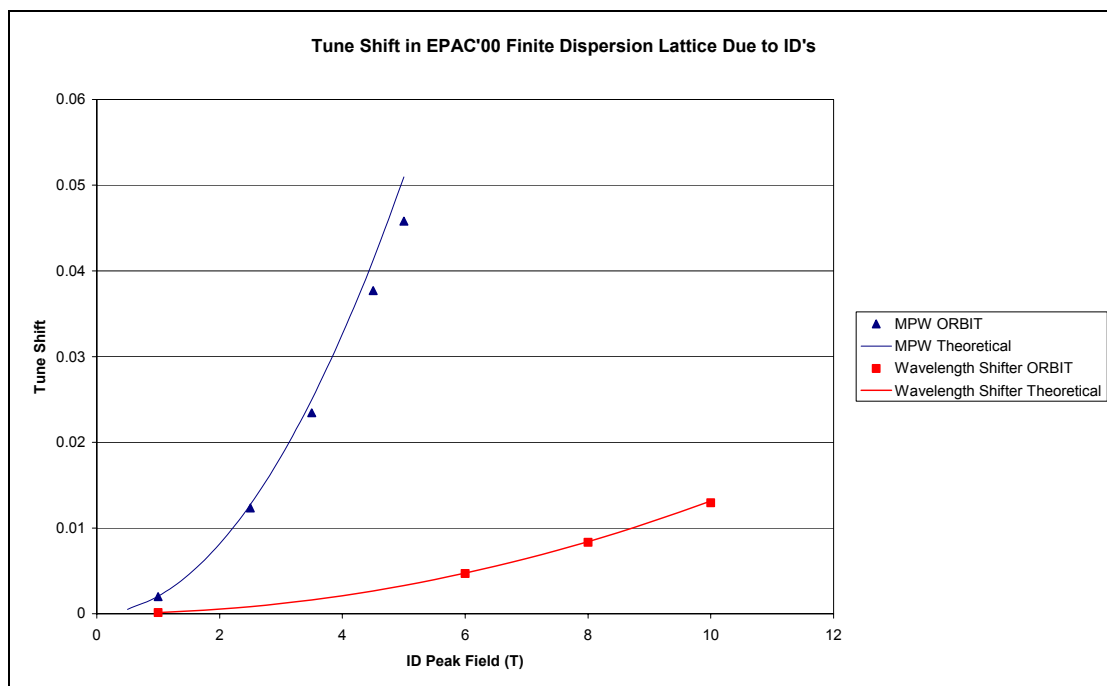


Figure 1.8-16 The tune shift due to different field insertion devices placed in lattice b) as predicted both by ORBIT and analytic calculations

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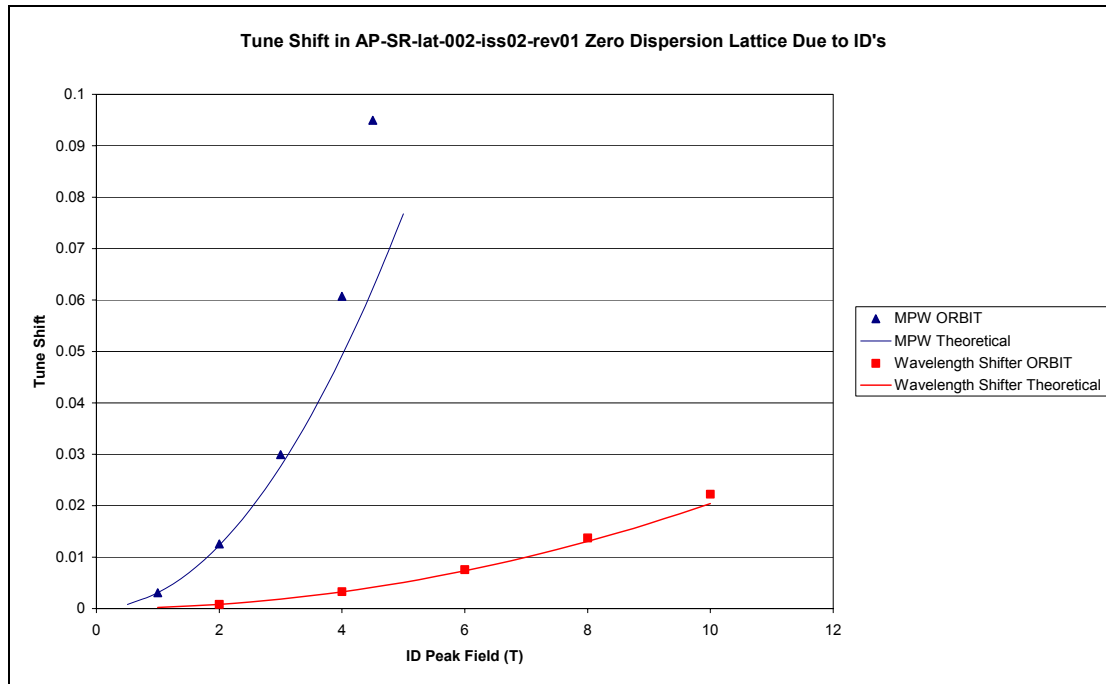


Figure 1.8-17 The tune shift due to different field insertion devices placed in lattice c) as predicted both by ORBIT and analytic calculations

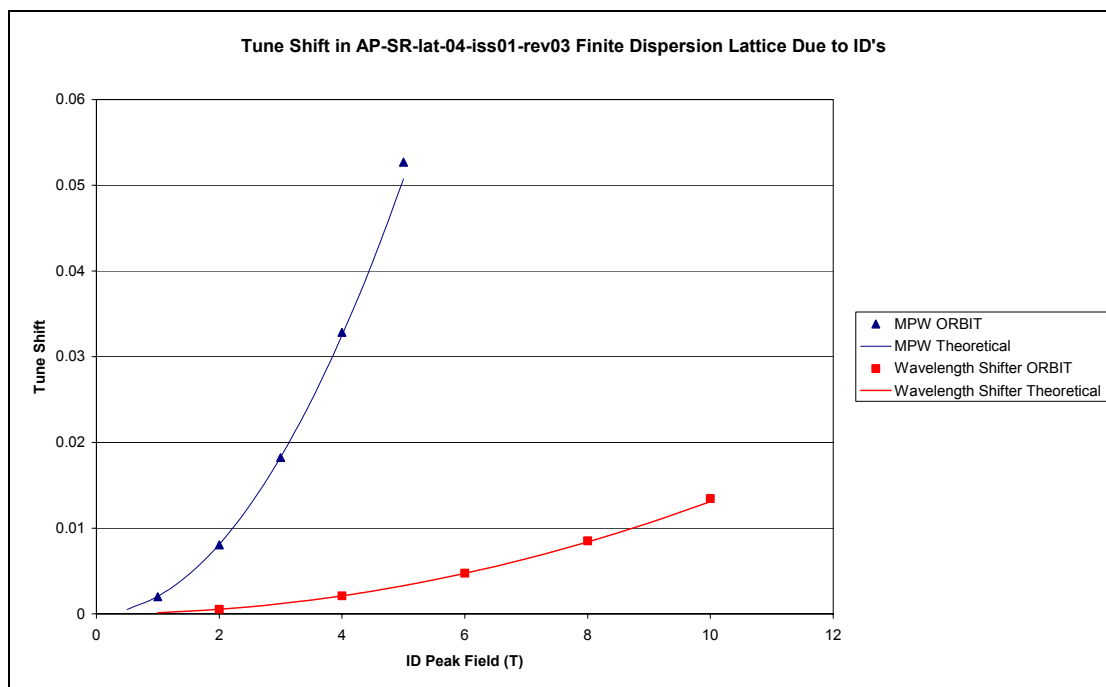


Figure 1.8-18 The tune shift due to different field insertion devices placed in lattice d) as predicted both by ORBIT and analytic calculations.

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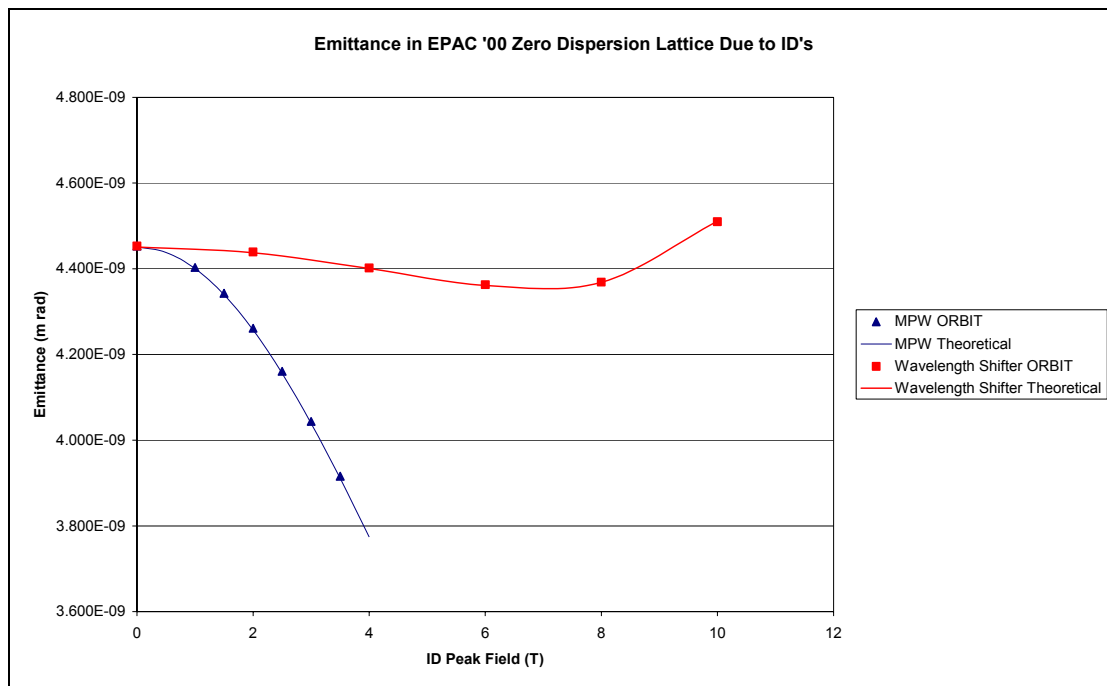


Figure 1.8-19 The emittance due to different field insertion devices placed in lattice a) as predicted both by ORBIT and analytic calculations

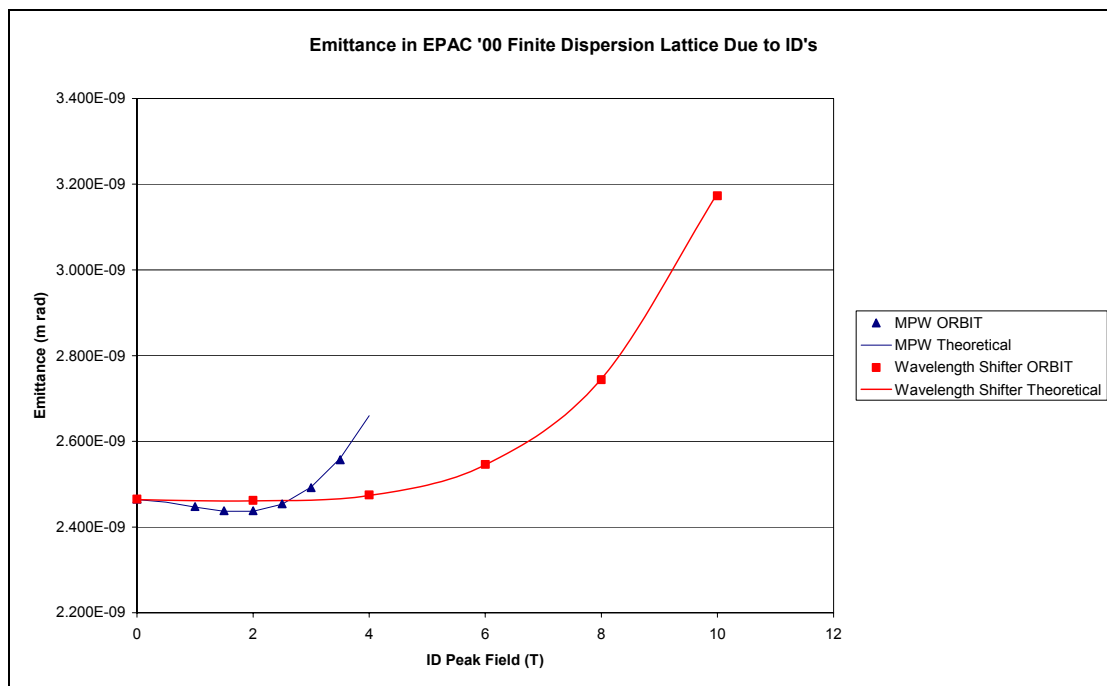


Figure 1.8-20 The emittance due to different field insertion devices placed in lattice b) as predicted both by ORBIT and analytic calculations.

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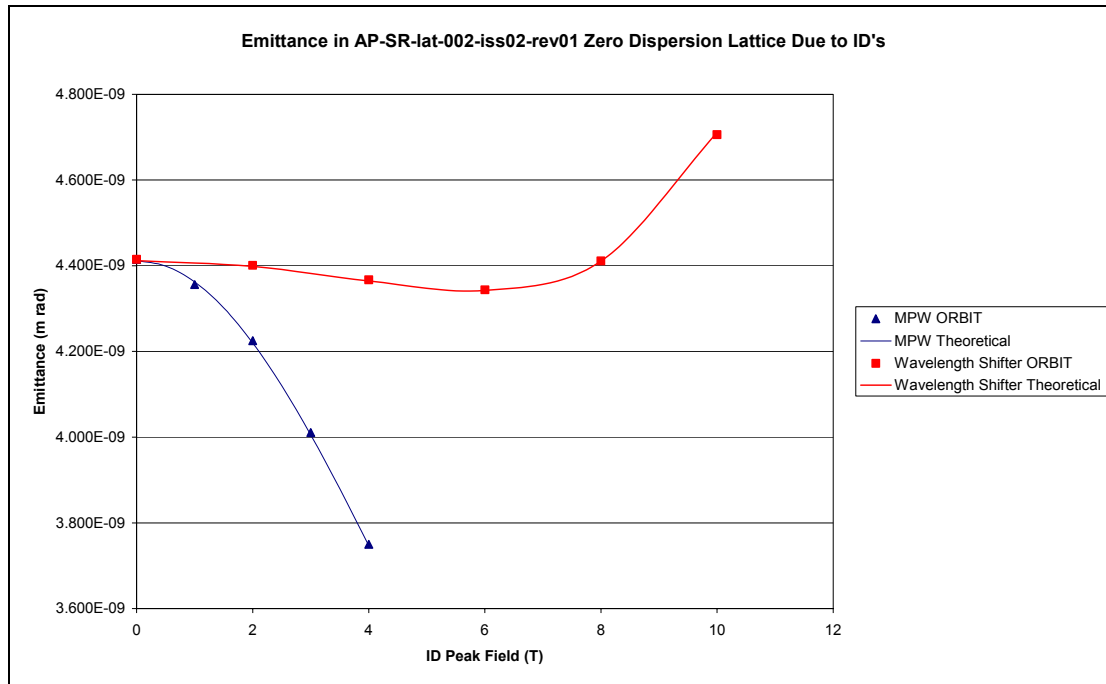


Figure 1.8-21 The emittance due to different field insertion devices placed in lattice c) as predicted both by ORBIT and analytic calculations

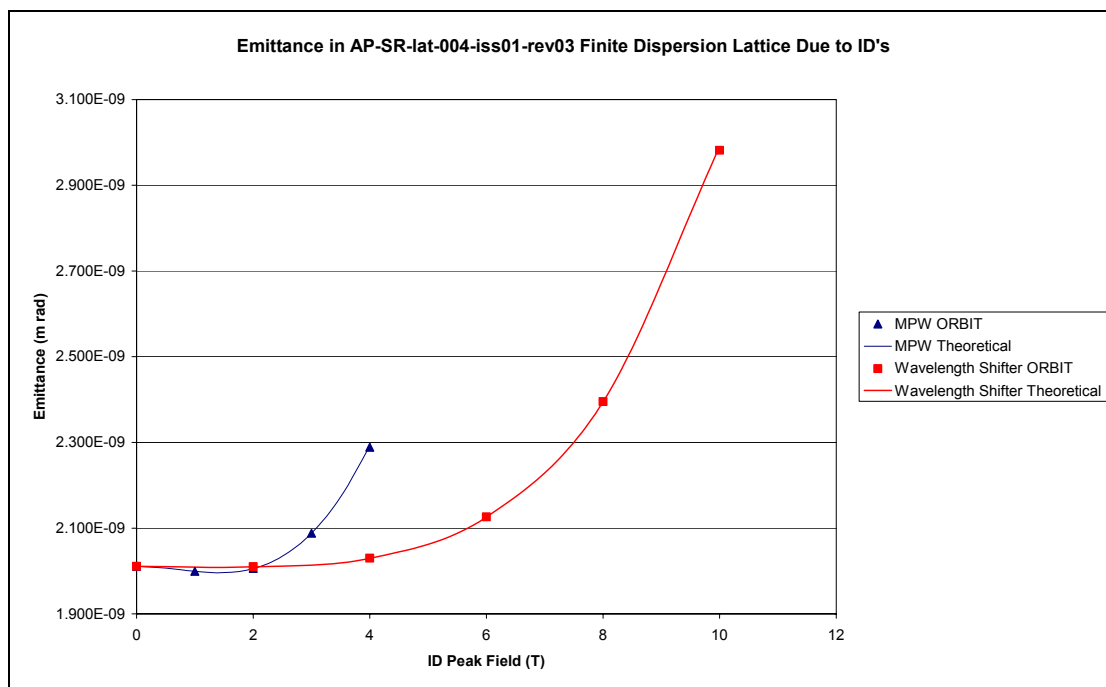


Figure 1.8-22 The emittance due to different field insertion devices placed in lattice d) as predicted both by ORBIT and analytic calculations.

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1.9 INJECTION

1.9.1 Choice of Scheme

Nearly all third-generation light source storage rings in design or operation utilise multi-turn injection. This method allows accumulation of stored current from multiple pulses from an injection system, usually a booster synchrotron or linac operating with repetition frequencies of the order of a few Hz. Between two and four fast magnets are used to produce a closed-orbit deviation of the stored electron beam so that it is brought close to a septum magnet. The injected beam, initially lying outside the septum, executes betatron oscillations about the machine closed orbit. At the same time the kickers are turned off, moving the storage ring acceptance ellipse away from the septum. When the injected beam comes back round to its original position in phase space (usually in about four or so turns) the septum is no longer in the way, and the injected beam may damp down to the equilibrium emittance (over the course of a few milliseconds, i.e. over several thousand turns). This is then repeated with the next injected pulse. The process is schematically depicted in Figure 1.9-1; injection usually takes place into the horizontal phase space to allow the smallest possible vacuum chamber height for insertion devices.

Injection schemes in third-generation light sources may be divided into two groups: lower-energy machines (up to energies of about 2.5 GeV) usually place all the kicker magnets in a single straight section (e.g. Elettra [56] and BESSY-II [57]). This scheme has the advantage that the bump produced is independent of the working point, and if a symmetrical 4-kicker bump is used all kickers can be powered together to the same field strength, giving better stability of the bump. For higher-energy machines it is not generally possible to make kicker magnets which produce a sufficient bend angle for the straight length that is usually available (e.g. APS [58], ESRF [59]), so kickers are instead distributed elsewhere in the lattice, generating a larger bump size from a given kicker field by using intervening quadrupoles to amplify the bump. However, since the bump is distributed over several cells its profile is not localised, and thus has consequences for the apertures required in the storage ring.

A single straight injection scheme has been chosen since it is simpler both technically and operationally, does not impact upon the storage ring magnet aperture requirements, and restricts the competition with user IDs to the utilisation of a single long straight.

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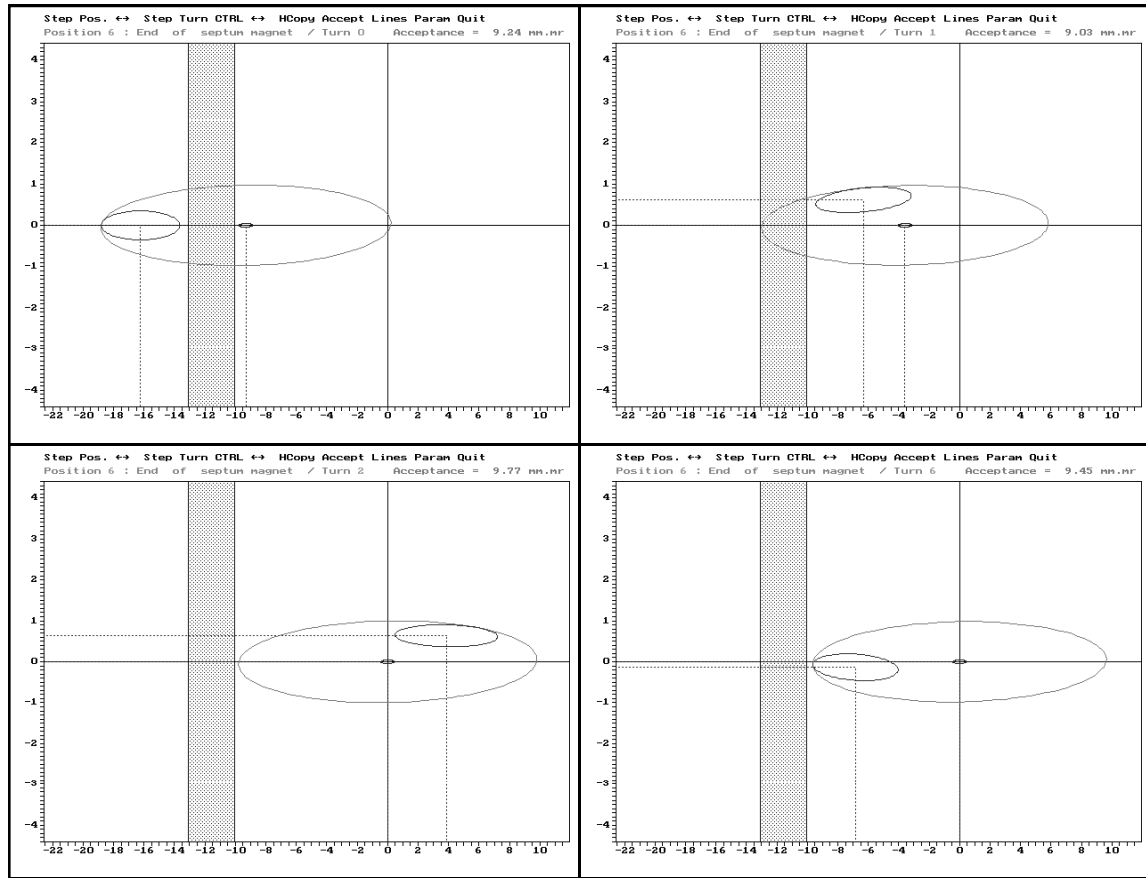


Figure 1.9-1 Illustration of Multi-Turn Injection in Horizontal Phase Space.

1.9.2 Layout

Injection will be in the horizontal plane from the inside of the ring. Four fast kicker magnets placed symmetrically around the centre of the injection straight create a closed beam bump, facilitating injection through a single septum at the centre of the straight. The injected beam enters the storage ring parallel to the design orbit, and so kicker 3 is required to have an increased aperture on its inner side (see Figure 1.9-2)

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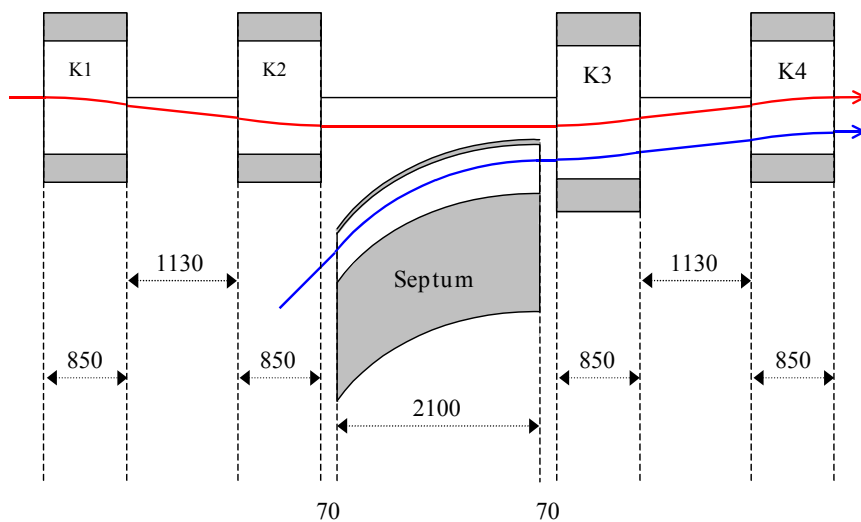


Figure 1.9-2 Storage Ring Injection Layout (distances in mm).

The injection straight has 8.3 m available for the injection components. The layout of these components is based on the ELETTRA system [56], with the length of the septum scaled up to allow for the higher strength needed to inject at 3 GeV. The spacing between kickers 1 and 2 (see Figure 1.9-2) has been maximised in order to minimise requirements on kicker strength. The symmetrical arrangement of the kickers means that all the kickers have the same nominal strength. The radial position of the septum is adjustable to allow for future operational scenarios.

Table 1.9-1 Kicker and Septum Magnet Parameters.

	<i>Septum</i>	<i>Kickers</i>
Physical Length (m)	2.10	0.85
Magnetic Length (m)	1.90	0.60
Maximum Field (T)	0.78	0.18
Deflection (mrad)	152	11.0
Effective Septum Thickness (mm)	5	

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1.9.3 Injection System Specification

Table 1.9-2 Storage Ring Injection Parameters.

Parameter	Value
Available Space [m]	8.3
Kicker Bend Angle [mrad]	7.3
Septum Bend Angle [mrad]	150
Radial β -function at Straight Centre [m]	13.202
Required Bump Amplitude [mm]	14.5
Maximum Bump Amplitude [mm]	21.8
Minimum Septum Position [mm]	19.0

The kicker amplitudes have been derived using the assumption that the stored beam is moved to within 5 standard deviations of the septum. In practice the bump will be less than this to accommodate kicker strength fluctuations without beam loss. The size of the injected beam is defined by 6 standard deviations.

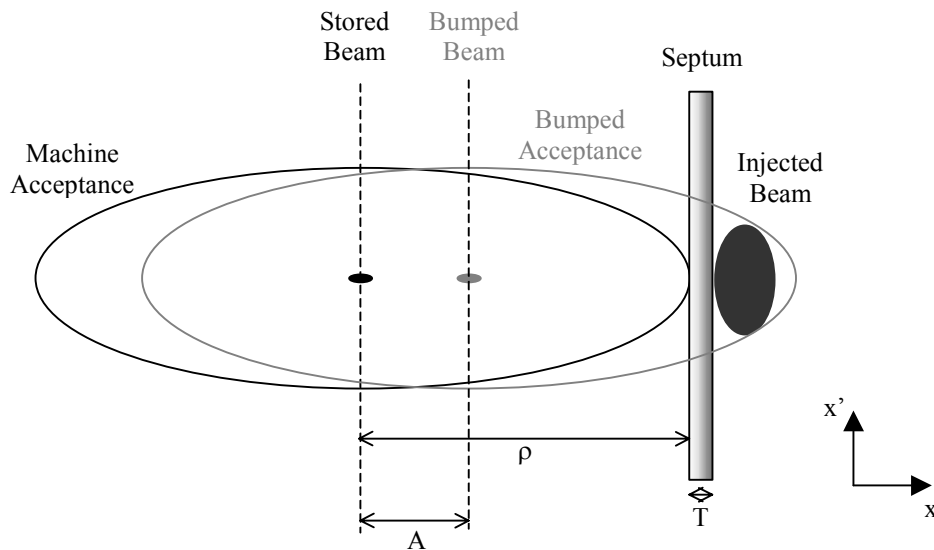


Figure 1.9-3 Positions of Stored Beam, Injected Beam and Septum at the Injection Point.

The optimum horizontal beta function of the injection channel can be derived by solving the following equation in the horizontal plane [60], [61], [62]:

$$\beta_i^2 + \frac{n\sigma_{0i} + T}{2\sqrt{\varepsilon_i}} \beta_i^{3/2} = \frac{\beta_{0i}^2}{2} \quad (77)$$

β_i is the beta function of the injected beam at the end of the septum, ε_i is the horizontal emittance of the injected beam, β_{0i} is the horizontal beta function of the stored beam at

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the injection point, $n\sigma_{0i}$ is the horizontal size of the stored beam at the injection point, T is the effective septum width including alignment tolerance.

The beta function of the injected beam is then overestimated by a factor of two to give a conservative estimate of the injected beam size. This is done to take account of non-linear filamentation of the beam. The dispersion in the injected beam at the end of the septum is assumed to be zero. The resulting beam parameters are listed in Table 1.9-3.

Table 1.9-3 Beam parameters at injection. The injection system is designed to allow storage ring operating modes with emittances up to 20 nmrad.

<i>Beam Parameter</i>	<i>Storage Ring</i>	<i>Transfer Line</i>
Emittance (3 GeV, 1σ) [nm rad]	20	150
Horizontal Beta Value at Injection Point [m]	12.1	6.84
Horizontal Beam Size (σ) [mm]	0.49	1.08

The septum strip is 3mm thick, with an additional ± 1 mm positioning tolerance giving an effective thickness T of 5mm.

The septum is set at the minimum position required to satisfy injection requirements whilst not impinging on the momentum acceptance. In practice this means that the septum is set to give a momentum acceptance of 4%, as the aperture required for this is larger than that required for injection.

The maximum septum position is the furthest position that can be obtained before the injected beam hits a physical aperture at any part of the ring.

The minimum required septum strength is that necessary to ensure that the injected beam will not impinge on kicker 2 on its way into the septum. The injected beam must be 132 mm from the stored beam at kicker 2 to allow room for both beams and the transfer line vacuum pipe. A field of 0.78 T and magnetic length of 1.9 m is more than sufficient to fulfil this criterion. With the septum at its minimum position, the injected beam will enter the storage ring parallel to and 120 mm from the stored beam.

As the kickers are all placed in the same straight, the kicker bump formed is independent of the beta functions in the straight, and so the kicker strengths all have the same nominal strength.

The minimum amplitude, A , of the kicker bump is that necessary to bump the beam acceptance over the septum and injected beam. For an effective septum thickness of 5 mm and injected beam size $6\sigma_i$ of 6.5 mm, this bump size is 14.5 mm. For a kicker separation of 1.98 m, the required kick is 7.3 mrad. A kicker with magnetic length of 0.6 m and field of 0.12 T is sufficient to create this bump.

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The maximum kicker bump required brings the stored beam as close as allowable to the maximum septum position. This would require a kicker field of 0.125 T.

1.9.4 Top-Up Mode

An additional mode of injection into DIAMOND has also been considered, in order greatly to decrease any variations in the stored beam current. Overcoming reduced lifetimes, resulting from a combination of enhanced electron beam brightness and the demand for minimum aperture insertion devices (IDs), has become a major challenge especially in low and medium electron energy rings such as DIAMOND. However even high energy rings with relatively long beam lifetimes (e.g. APS) have sought the means to impose a greater degree of stability of stored beam current, not least to achieve good thermal stabilisation both in the rings and on their beam lines. The proposed solution is to incorporate a Top-Up injection facility that will trickle feed small numbers of electrons to replace those being lost from the stored beam.

There is thus far limited world experience of such an operating mode but it has been retrofitted on APS. For the SLS with its small gaps top-up was an issue from the beginning and all technical developments around injection and monitoring were incorporated from the beginning. In order to assess the prospects for top-up on DIAMOND and understand the implications for specification of the storage ring and its injector systems an international Workshop was hosted by the DIAMOND design team at Daresbury to review international progress in the topic. This Workshop was timely for all participants from 3rd generation light sources, in view of the increasing world-wide interest in top-up. The meeting assembled together experts from APS, ESRF, SLS, ELETTRA, SOLEIL, BESSY and DIAMOND to debate these issues but in particular was able to take advantage of the extensive experience of the APS team, which has most of the world experience on top-up so far.

The major queries concerning top-up include

- Validity of injected beam loss simulations and associated radiation protection
- Necessary storage ring design features for optimum performance, including required diagnostics
- Implications for injector chain specification, including operational reliability
- Tolerance of user community to associated beam disturbances

and a summary of the key topics has been included in this section.

A highly efficient standard injection process is essential for top-up success and this must be included at the design stage, implying selection of a high quality booster synchrotron performance. However it is important to recognise that negligible orbit perturbation cannot be attained, although the disturbance to source position will last for no more than about 50 ms and might be repeated at intervals of order 100 seconds.

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The role of diagnostics is crucial too, including those in the transfer path. It should be noted that long term drifts, for example in the booster, are a problem but potentially soluble with suitable feedback monitoring and control systems.

Reliable beam loss simulation is a major topic, especially since it will be necessary to convince safety regulators of a comprehensive fault scenario treatment. A basic policy definition should be that electron losses down an open beam line are not possible with stable stored beam: in this case it is sufficient to include an interlock that senses stored beam current changes and interrupts injection. Such fault simulations require an accurate knowledge of all physical aperture restrictions within the ring (and this must be checked by regular surveys on an operational facility). A comprehensive assessment of beam loss has also been carried out at ESRF, suggesting that an injection efficiency of at least 93 % must be achieved in its case if IRR99 regulations are to be satisfied ($0.5 \mu\text{Sv/h}$); further experimental trials are planned. In contrast at the time of the workshop SLS intended to introduce operational top-up as soon as possible and is now routinely and exclusively working with top-up. It will be essential to identify all-important potential sources of Bremsstrahlung in the DIAMOND storage ring, including ring collimators introduced to protect IDs.

The question of user tolerance to top-up, including the optimum separation of injection pulses to minimise data-taking disruption, is beyond the current remit of the Design Study and depends on a detailed assessment of each experimental set-up. However it is believed that orbit position control is more important than very high current stabilisation (i.e. $< 5 \%$), since in this latter case resultant thermal variations will be acceptably small. Single pulse injection is preferred, perhaps combined with gating duration of less than 1 second at intervals of order 100 seconds. It remains true that the wide variety of user experimental arrangements means that no uniform conclusion of its impact on them is possible, although it has been suggested that gating may not even be necessary for most users; future detector development is also expected to ease this problem (e.g. CCDs no longer in use).

The requirements of the booster synchrotron need careful attention. Design solutions offering relatively low extracted beam emittance are of major advantage for efficient storage ring injection with low loss, with the range 100-150 nm rads an acceptable target that still permits standard booster lattice solutions (see Chapter F3). Another major design decision for a booster is its main magnet power supply, together with the minimum repetition rate that is acceptable for beam stacking times in a variety of operational scenarios; the general consensus of the Workshop was that this should be greater than 1 Hz. A standard White circuit is known to be inferior to alternative switched mode ones, given that intermittent top-up operation at low duty cycle is required. This topic is treated in more detail in chapter F3.

Top-up requires the whole of the injector chain to operate with very high availability, given its continual usage throughout operational periods, and the linac system is a potential weak link in terms of reliability. This can however be addressed by a planned redundancy and spares policy together with efficient installation designs:

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components with known lifetime limitations include gun cathodes and klystrons. Pulsed magnet power supplies throughout the injector chain are also vulnerable components and the need for conservative specifications in these areas is clear.

In order to establish an optimum operating regime an excellent beam diagnostics system is essential, covering not only the accelerators but also the beam transport lines between them. Turn-by-turn beam loss analysis is a high priority, as is analysis of individual electron bunches. Extremely high sensitivity monitors are necessary for the low injector current operation associated with top-up. In order to minimise beam loss problems human operator intervention must be constrained, with increased reliance on automatic sequences for all aspects of the accelerator systems; one issue to be addressed is the potential effect on the injection process of ID settings being varied by user groups.

Assisted by the advice from the Workshop and from suggestions from the DIAMOND Technical Advisory Committee, the conclusion is that top-up provision will offer many advantages and can probably be achieved with realistic solutions. Although there are many complex issues to consider the experience at the APS has raised confidence in their solution and all major light sources are now actively considering this mode of operation. Certainly schemes to minimise beam losses and maximise operational reliability are best incorporated at the earliest design stages of any project and will receive further detailed assessment for DIAMOND. The injector chain, but especially the booster synchrotron, will be specified to be fully compatible with future top-up scenarios and further debate with the user communities should clarify the implications of transient beam disturbances. Nevertheless it is not the intention to rely on top-up during initial DIAMOND operations but to introduce it as a later upgrade to improve performance.

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E.2 Lattice Magnets.

This chapter presents the designs developed for the dipole, quadrupole, sextupole and corrector magnets which are required in the DIAMOND storage ring lattice.

2.1 DIPOLES.

2.1.1 Determination of Dipole Gap.

Apertures required for the DIAMOND lattice have been investigated and specified [1]. The defined beam-stay clear and good field half apertures in the dipole are:

horizontal:	12	mm;
vertical:	15	mm.

To determine the allowed gap at the pole centre, the vacuum vessels dimensions must be considered, along with any inter-pole shim which may restrict the passage of the vessel through the jaws of the 'C' core magnet. This gives the following audit for total vertical aperture:

Beam (including tolerances)	32	mm;
vessel flexing and tolerance	2	mm;
vessel wall thickness: 2 x 5mm	10	mm;
assembly clearance	2	mm;
allowance for pole shims: 2 x 0.3mm	0.6	mm;
Total gap height at pole centre:	46.6	mm.

2.1.2 Dipole Parameters.

The other major parameters for the dipole are tabulated below:

number of dipoles;	48	
magnet type:	'C' type;	
physical length:	0.900	m;
required magnetic length:	0.935	m;
induction at beam:	1.4	T;
beam radius of curvature:	7.16	m;
magnet gap (total) at beam:	46.6	mm;
good field full aperture (h x v)	24 x 30	mm ² ;
field quality ($\Delta B/B$) in good field region:	± 0.01	%.

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2.1.3 Magnet Steel.

The material best suited for use in poles and yokes of the storage ring lattice magnets will be a low to medium silicon non-oriented grade of 1mm thick electrical sheet steel. This will provide adequate high field performance whilst, at the same time, being sufficiently magnetically stable to allow laminations to be stamped and assembled without the need for a further annealing process. The laminations can also be shuffling to randomise steel properties. The field distribution within the magnet gap and the loss of Ampere-turns in the yoke will depend on the steel's magnetic properties. It is therefore advisable, during the design of the dipoles and quadrupoles, to employ a field predicting finite element analysis code which is capable of non-linear simulation and, for the non-linear analysis, to use a magnetisation curve which is close to that expected for the steel which is to be used in the magnet yokes.

A standard steel used extensively for accelerator magnets with D.C. excitation, where low field performance is not critical, is 'Stabacor' 1300-100A, a low carbon, medium silicon 1mm sheet material. The B/H figures for this steel are made available by the manufacturers, EBG of Bochum, and these have been used as a basis for the non-linear modelling of the dipoles and quadrupoles. To preserve the competitive nature of the tendering process, which will determine the choice of manufacturer for the magnets, this material will not be formally specified; however, the specified magnetic properties of the steel will be based on these data. To provide some latitude in the material which can be accepted, the magnetic field (H) specified for each value of induction (B) has been increased by 5% above the published value for the steel. These figures have been used for the F.E.A. simulations.

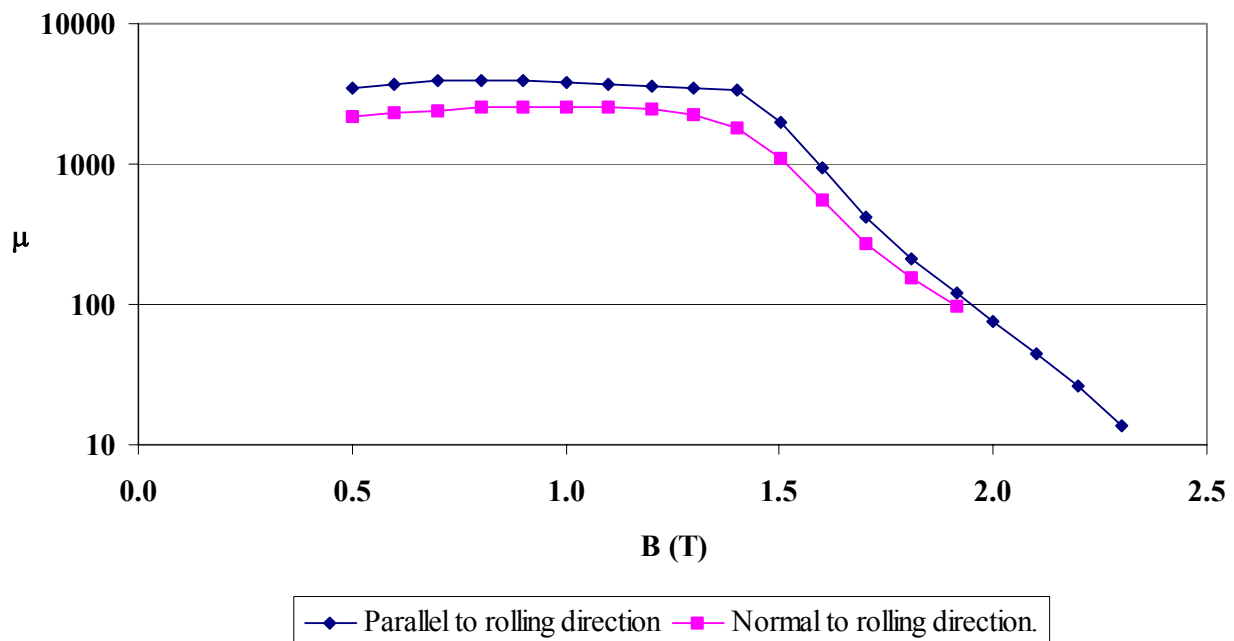


Figure 2.1-1 Variation in relative permeability (μ) with flux density (B) used for non-linear finite element analysis of the dipoles and quadrupoles.

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The resulting magnetisation curves are shown in Figure 2.1-1, with the numerical data tabulated in the detailed design report for the storage ring dipoles [2]. In spite of the Stabacor material being classified as 'non-oriented' there are significant differences in the magnetic properties of the steel parallel and normal to the rolling direction. The Figure 2.1-1 therefore shows the variation in permeability (μ) with induction (B) for both directions. The magnetic modelling of the dipole in two dimensions differentiated between the magnetic properties in these two orientations (see below).

2.1.4 Pole and Yoke Geometry.

Using the two dimensional, non-linear, finite element magneto-static code OPERA 2D, a pole and yoke geometry was developed for the dipole which met the operational requirements for the magnet. The steel in the pole and back-leg was modelled using the 'parallel to rolling direction' magnetisation curve, whilst the top and bottom yokes had 'normal to rolling direction' properties imposed. The pole face had a broad, low shim at the pole edge, to maintain the field homogeneity over the full horizontal aperture. Outside the shims, the pole was terminated by a Rogowski roll-off, followed by a linear taper to the pole root.

Parameters for the pole are given below in Table 2.1-1. The dipole will be curved, to follow the path of the circulating beam, so it is not necessary to increase the radial aperture of the magnet to accommodate any beam sagitta.

Table 2.1-1 Pole data used for dipole model.

x (mm)	y (mm)	Description
0.000	23.300	Centre of upper pole
26.000	23.300	Shim commences
34.000	23.030	
36.000	23.000	Commencement of full-height shim region.
38.000	23.000	End of shim
42.000	23.253	Start of Rogowski roll-off
46.000	23.587	
50.000	24.032	
54.000	24.621	
58.000	25.402	
62.000	26.439	
66.000	27.815	
70.000	29.640	End of Rogowski roll-off
77.000	61.000	Approx. mid point of pole taper
84.000	93.000	End of pole taper
84.000	128.000	Pole corner (symmetrical each side).

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Yoke dimensions were:

top and bottom yoke thicknesses (flux running normal to the rolling direction):

250 mm;

back-leg thickness (flux running parallel to the rolling direction):

240 mm.

Data describing the Rogowski roll-off, used to terminate the pole, are given in the detailed report on the dipole magnet design [2].

A cross-section through the half dipole, used for F.E.A modelling, is shown in Figure 2.1-2. Boundary conditions, defined on the $y = 0$ axis, imposed dipole symmetry in the model. Pole detail is shown in the expanded view of Figure 2.3-1.

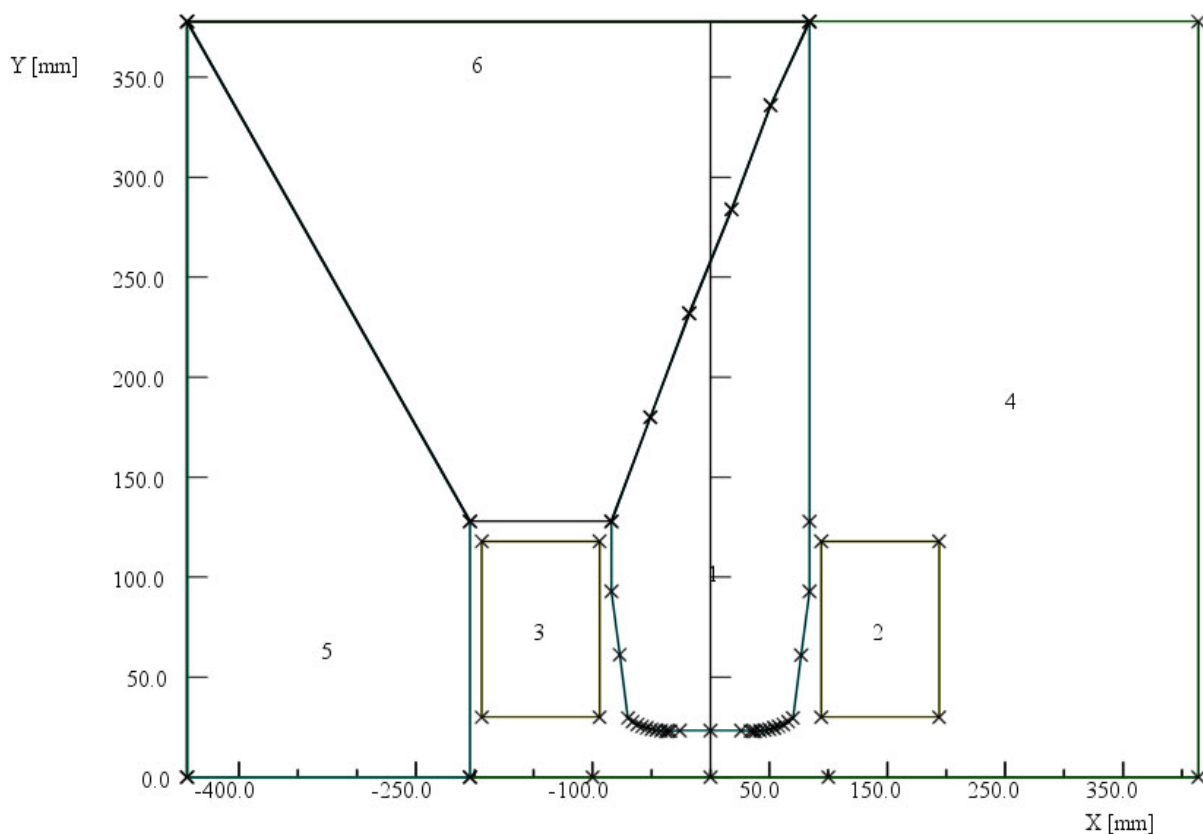


Figure 2.1-2 Geometry of half dipole used for F.E.A. model;
 regions 1 and 5: steel with flux parallel to rolling direction;
 region 6: steel with flux normal to rolling direction;
 regions 2 and 3: coils; region 4: background with $\mu = 1$.

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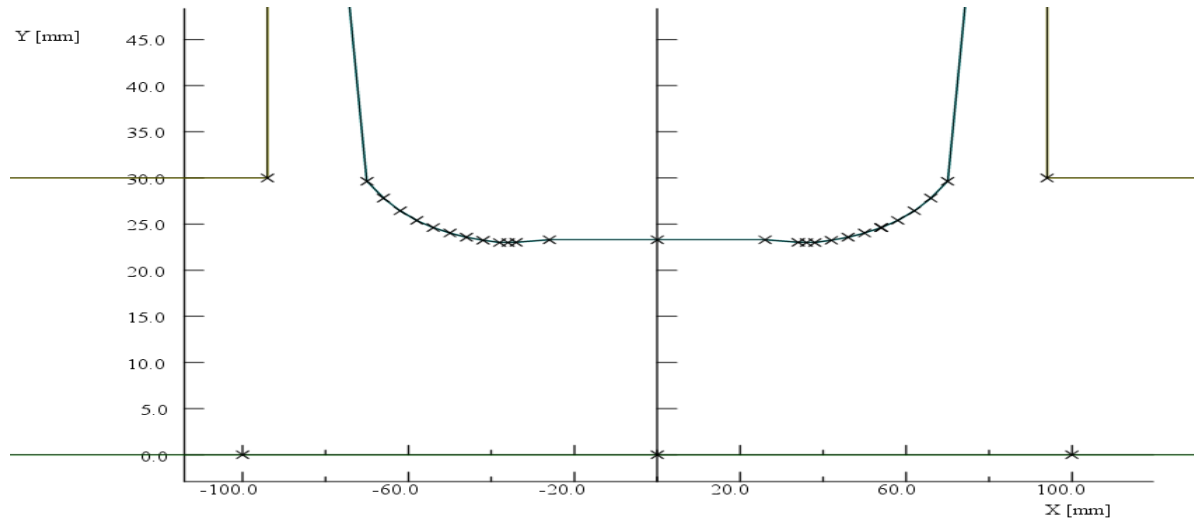


Figure 2.1-3 Detail of pole area of dipole magnet expanded from Fig 2.1-2, showing the pole edge shim translating into a Rogowski roll-off followed by a linear taper.

2.1.5 Predicted Field Quality at 3 GeV.

The F.E.A. non-linear code was used to predict the field amplitude and quality at an excitation level corresponding to 3 GeV for the geometry of Figure 2.1-2:

vertical field (B_y) at magnet centre (0,0):	1.405	T;
predicted amplitude linearity:	98.3	%.

The homogeneity in vertical field along the x axis ($\Delta B_y(x)/B_y(0)$) is shown in Figure 2.1-4.

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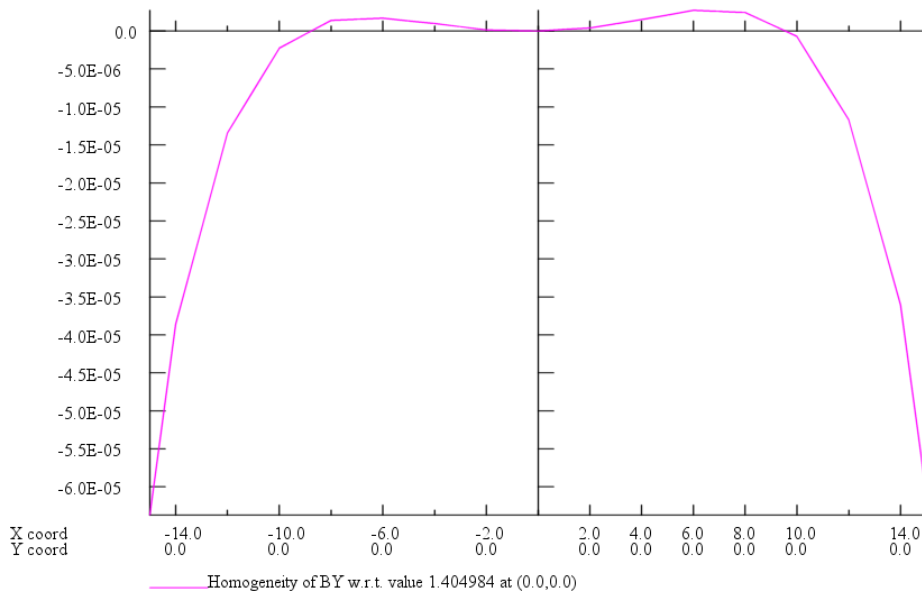


Figure 2.1-4 Non-linear prediction of field homogeneity $(\Delta B_y(x)/B_y(0))$ on $y = 0$ axis at field level for 3 GeV operation; co-ordinates in mm.

It can be seen that the flux density shows the following homogeneity:

$(\Delta B_y(x)/B_y(0))$	=	+ 0.0005 %	$x = 7$ mm;
$(\Delta B_y(x)/B_y(0))$	=	0	$x = 9$ mm;
$(\Delta B_y(x)/B_y(0))$	=	-0.0015 %	$x = 12$ mm.

The homogeneity in two dimensions, in the x, y plane, is displayed in Figure 2.1-5. This shows contour lines of $\pm 0.01\%$ in $(\Delta B_y(x)/B_y(0))$; the shaded rectangle indicates the required good field region in the transverse plane.

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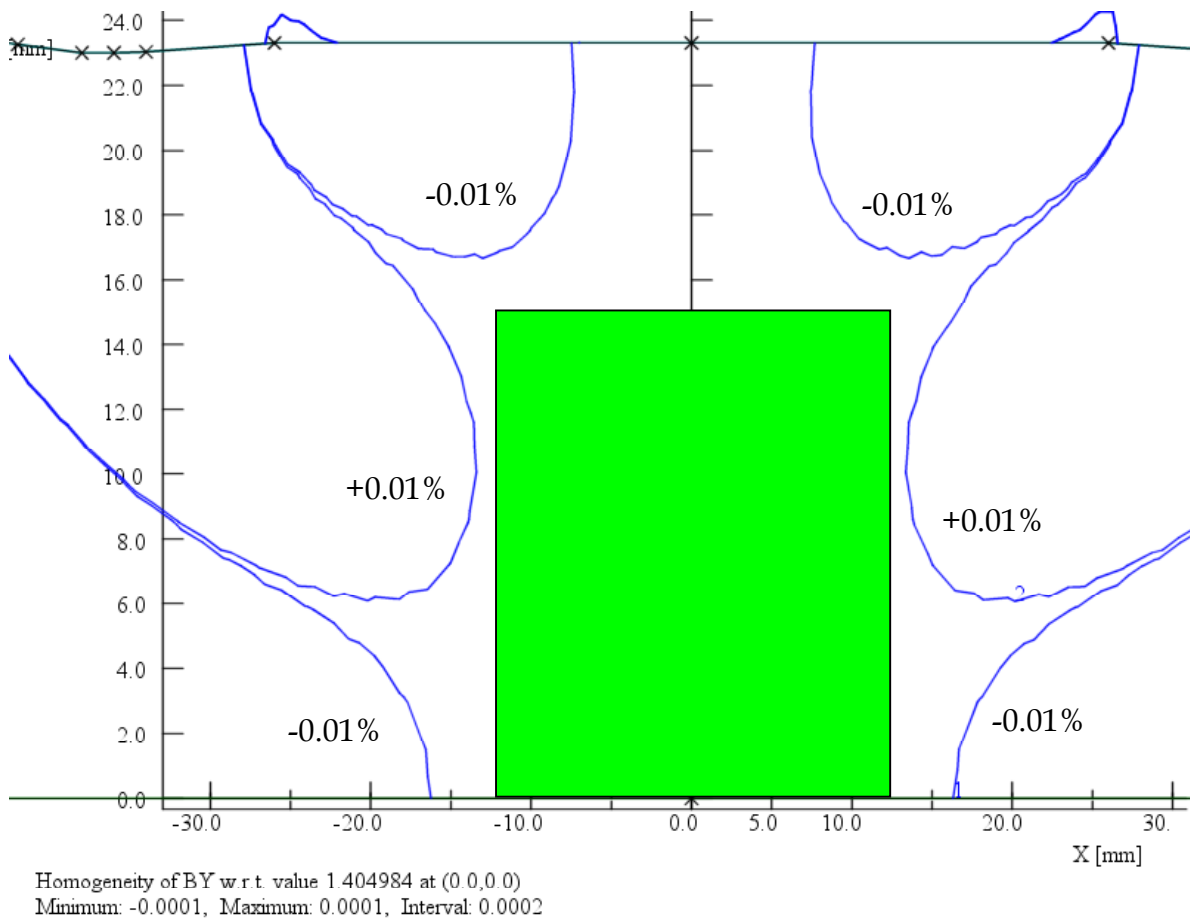


Figure 2.1-5 Field homogeneity in the dipole at 3 GeV in the transverse plane indicated by contours of $\pm 0.01\%$ in $\Delta B_Y(x)/B_Y(0)$; the shaded rectangle indicates the good field region of ± 12 mm horizontal, ± 15 mm vertical.

The figure clearly indicates that the vertical flux density is within $\pm 0.01\%$ throughout the good field region.

2.1.6 Field Quality Above 3 GeV.

The performance of the dipole design at approximately 10% above the normal operational level was investigated:

vertical field (B_Y) at magnet centre (0,0):	1.517	T;
predicted amplitude linearity:	96.9	%.

The homogeneity in vertical field at this level along the x axis is shown in Figure 2.1-6. This demonstrates the following field quality:

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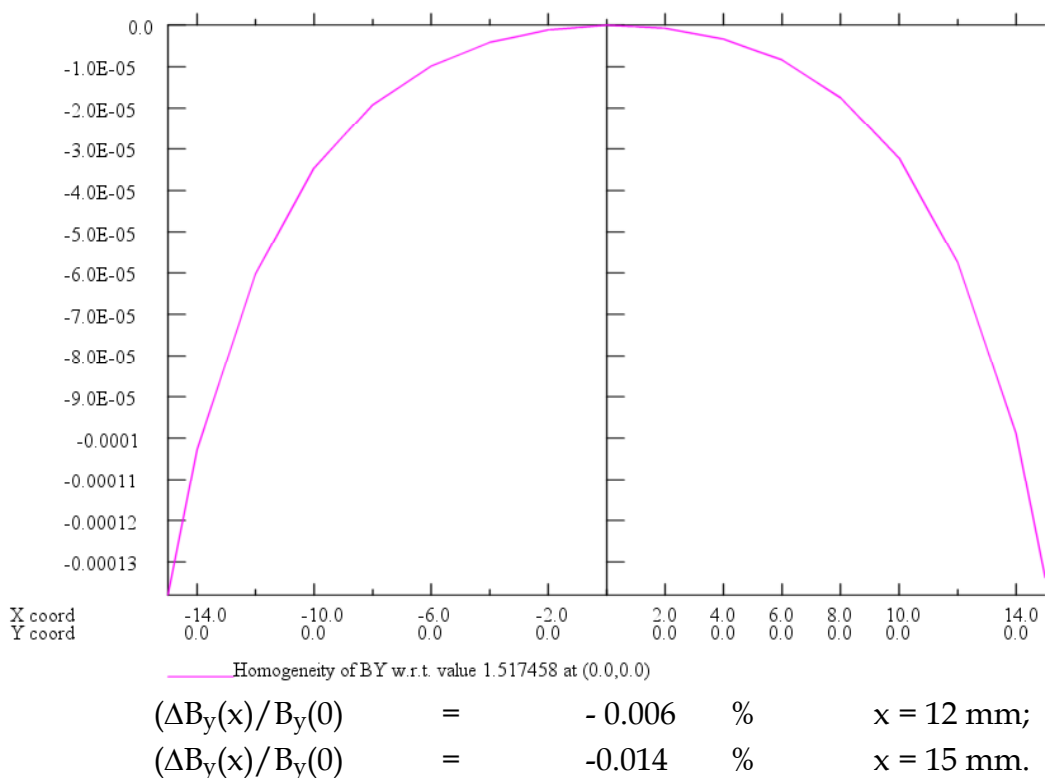


Figure 2.1-6 Non-linear prediction of field homogeneity ($\Delta B_y(x)/B_y(0)$) on $y = 0$ axis at field level corresponding to 3.25 GeV operation; co-ordinates are in mm.

The homogeneity in the transverse plane is shown in Figure 2.1-7; as in Figure 2.1-5 the quality is indicated by contour lines in ($\Delta B_y(x)/B_y(0)$) at $\pm 0.01\%$ with a shaded rectangle to indicate the good field region.

Figure 2.1-6 and Figure 2.1-7 indicate that the dipole design presented generates flux densities that meet the good field specification up to a level corresponding to 3.25 GeV operation. This is principally due to the use of the low shim and the Rogowski roll-off in the terminal geometry of the pole; these both minimise the non-linear effects that occur in the shim and edge region, where flux densities are significantly higher than in the centre of the magnet. These data indicate that, given adequate excitation current, the dipole magnet will provide adequate performance at a flux density of 1.54 T, the operational level corresponding to 3.3 GeV.

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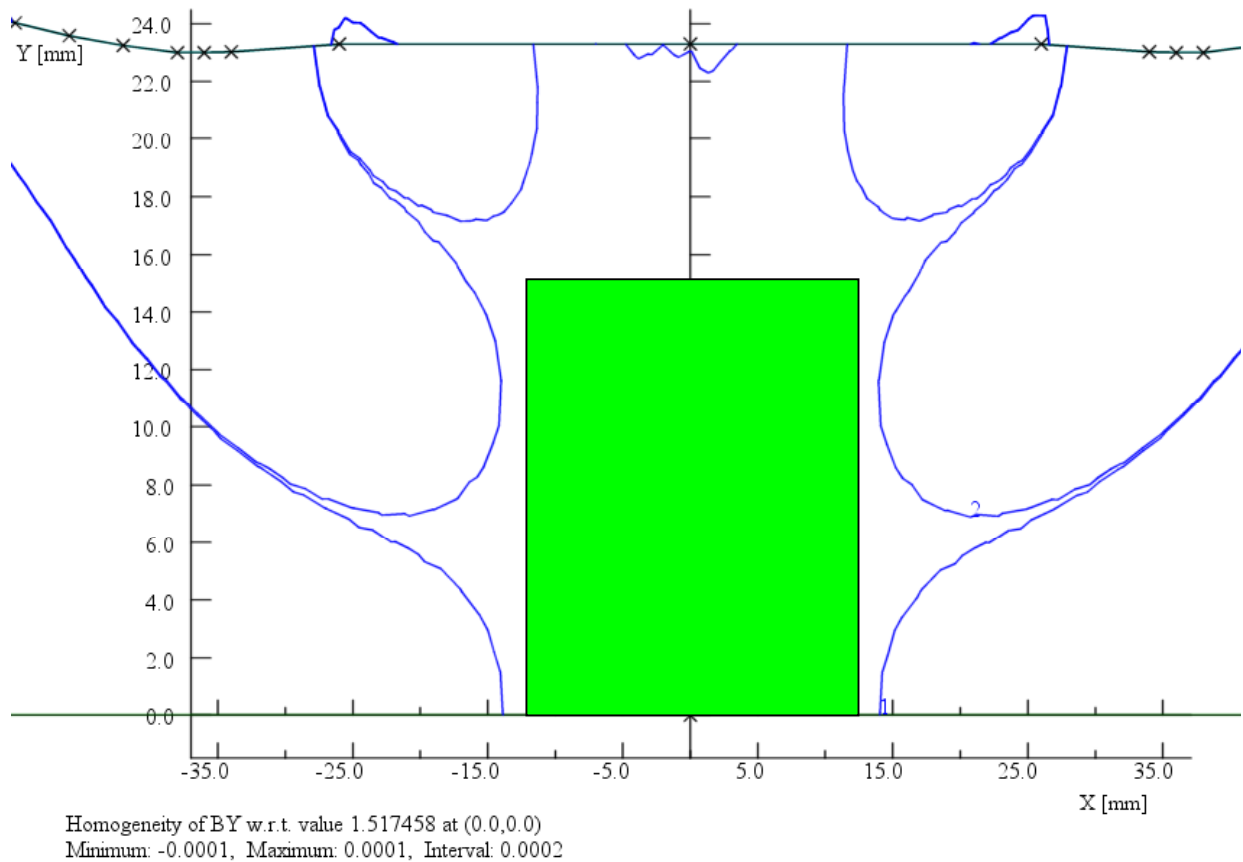


Figure 2.1-7 Field homogeneity at 3.25 GeV in the transverse plane indicated by contours of $\pm 0.01\%$ in $\Delta B_Y(x)/B_Y(0)$; the shaded rectangle indicates the good field region of ± 12 mm horizontal, ± 15 mm vertical.

2.1.7 Coil Parameters.

The coil dimensions were based on the following data:

expected minimum amplitude linearity	97%;	
required total Amp-turns for 1.4 T at beam:	53,474	At;
number of turns (total per magnet):	40;	
operating current at 1.4 T:	1,337	A;
current density in copper:	4.0	A/mm ² ;
conductor cross-section:	334.2	mm ² ;
conductor dimensions:	20 x 18.6	mm ² ;
water cooling tube diameter:	7.0	mm;
water temperature rise	10°	C
number of pancakes;	4;	
turns per pancake (2 layers of 5):	10.	

The chosen current density of 4 A/mm² in the copper conductor represents a rough optimum between lifetime operational costs of the facility, which increase with

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current density, and the initial capital costs, which fall as current density is increased. The optimisation curve is very shallow and is generally minimum between 3 and 5 A/mm².

The size of the cooling tube bore diameter has been determined using a temperature rise of 10° C in the cooling water. Given the estimated length of the coil, a total pressure drop required across each pancake to provide the necessary flow is expected to be of the order of 5 bar. The size of conductor chosen, together with the inter-turn and outer-ground epoxy-glass insulation system, produces a maximum height for each pancake which is less than the minimum clearance between shims in the magnet gap, facilitating the assembly of the coil.

The resulting coil geometry, mounted on the magnet yoke, is shown in cross-section in Figure 2.1-8; this drawing gives the overall outer dimensions of the magnet lamination (ignoring coil projection) as:

lamination total height: 760 mm;
lamination width: 520 mm.

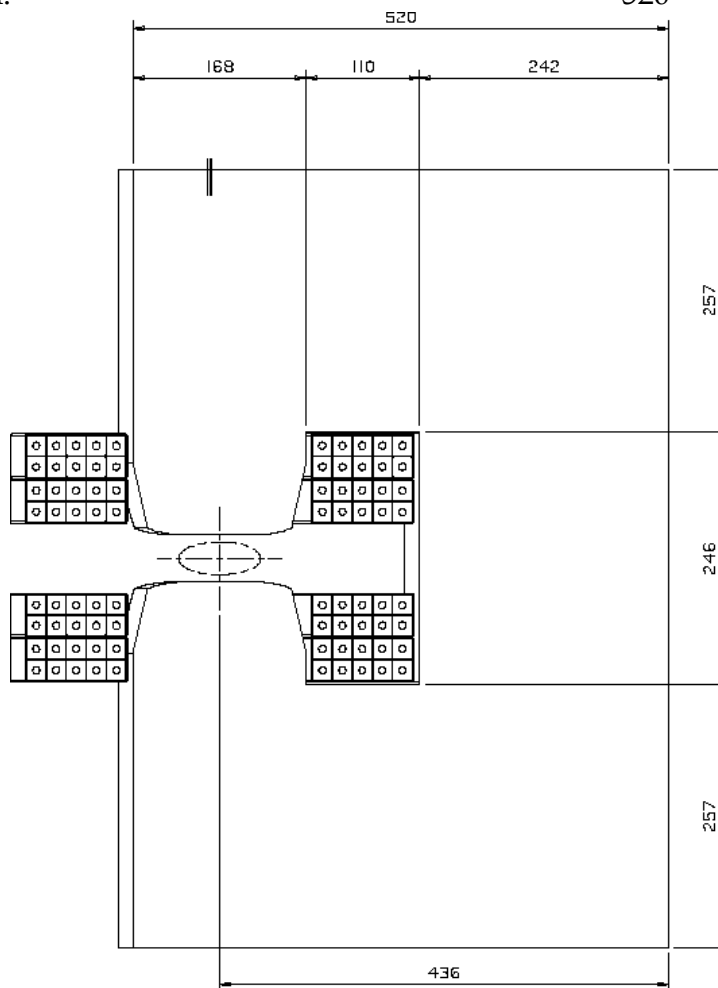


Figure 2.1-8 Engineering cross-section of dipole showing coils and magnet yoke.

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Magnet End Geometry in Two Dimensions.

It is necessary to shape the magnet ends in the azimuthal direction, using a roll-off configuration which smoothly increases the magnet gap close to the magnet end. This eliminates a sharp corner, which would lead to significant non-linear behaviour in both the magnetic strength and quality as a function of excitation level. The roll-off should:

- provide the required magnetic length for the total magnet;
- extend sufficiently far for the flux density entering the vertical magnet end to not cause any local saturation;
- allow some control of the transverse and vertical field quality in the roll-off section.

The policy to use a roll-off geometry which followed a single curve in the longitudinal plane, with axis normal to the magnet end face, was adopted. There would be no variation in form in the transverse plane. Hence, the roll-off will cut through the transverse shim and eliminate this feature over a small length of the magnet before cutting into the pole central region and commence to increase the gap; this will generate some sextupole error field in the magnet ends but will ensure maximum quality and amplitude linearity in the end region.

Axes are defined with the transverse plane designated as x,y, with x in the radial (horizontal) plane, and y vertical; the x,y origin is at the gap mid-point on the pole centre line. The longitudinal axis (z) has its origin at the magnet end; z values into the magnet are negative. Given these axes, the roll-off follows the Rogowski curve:

$$y = (g/2) + (g/\pi) \exp \left(\left(\pi (z+a)/g \right) - 1 \right)$$

where: $g = 43.734$ (the 'pseudo' gap giving $y=23.000$ at finite z);
 $a = 29$ (adjusting the roll-off position longitudinally).

A diagram showing the longitudinal cut through the magnet end, which was used for an azimuthal analysis in two dimensions, is shown in Figure 2.1-9. In this figure the steel roll-off and the coil at the dipole end (region 3) model the physical geometry of the magnet. However, the left-hand coil (region 2) and vertical steel leg are artificial features, added to balance the model's Ampere-turns and to provide a flux return path in the azimuthal plane.

The variation on vertical flux density (B_y) along the gap centre line through the end of the magnet was predicted by a non-linear simulation at the 3 GeV level. As expected, the flux extends beyond the magnet end, creating a significant fringe field in the straight section.

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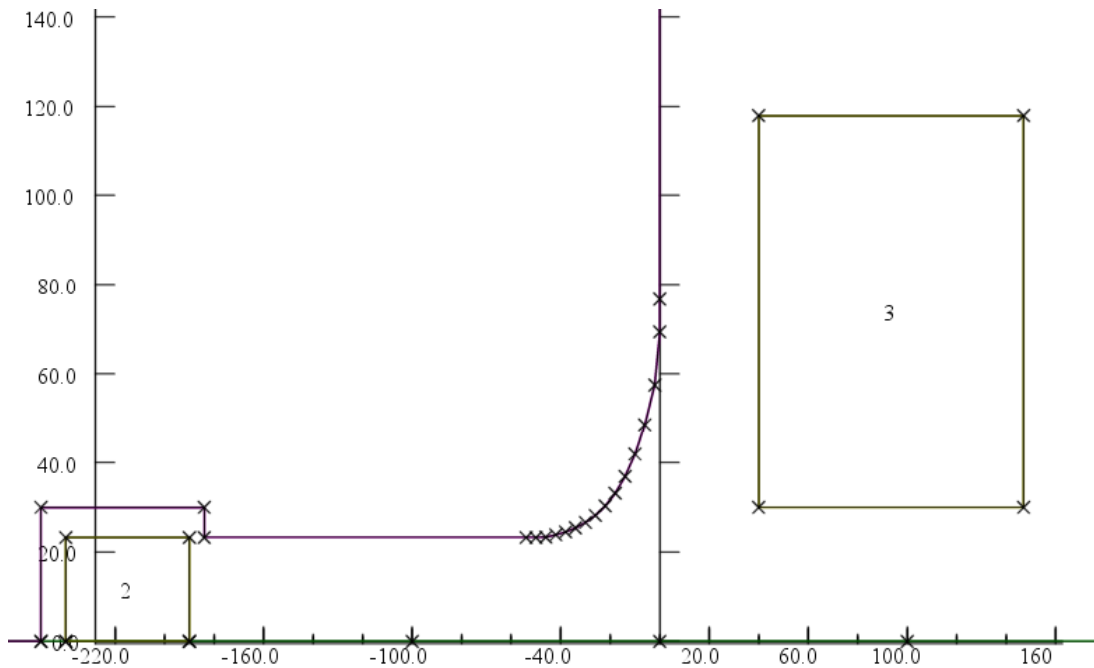


Figure 2.1-9 Geometry in the azimuthal (z) and vertical (y) plane on the pole transverse centre line ($x = 0$) used for modelling the magnet end-field distribution; dimensions in mm; region 3 is the upper coil in its correct position at the magnet end; region 2 is an artificial conductor introduced to provide a current return path remote from the region being studied.

The values of this vertical flux density predicted for the geometry of Figure 2.1-9 were numerically integrated, giving the following results:

integration limits:	$-130 \leq z \leq 200$	mm;
B_y between poles ($z = -118$ mm):	1.4013	T;
integrated field between above limits:	206.63	Tm;
corresponding B length:	147.45	mm;
physical length of magnet:	900	mm;
extension of field beyond magnet end:	17.45	mm;
resulting predicted magnet B length:	934.9	mm.

This two dimensional azimuthal analysis indicates that the magnetic length provided by the roll-off meets the required specification.

2.1.8 Magnet Geometry in Three Dimensions.

The magnet was modelled in three dimensions using the non-linear finite element magneto-static code TOSCA and this was used as a comparison with the two dimensional simulations and to provide further detail of the field distribution in the dipole end region. The three dimensional model of the dipole is shown in Figure 2.1-10, below.

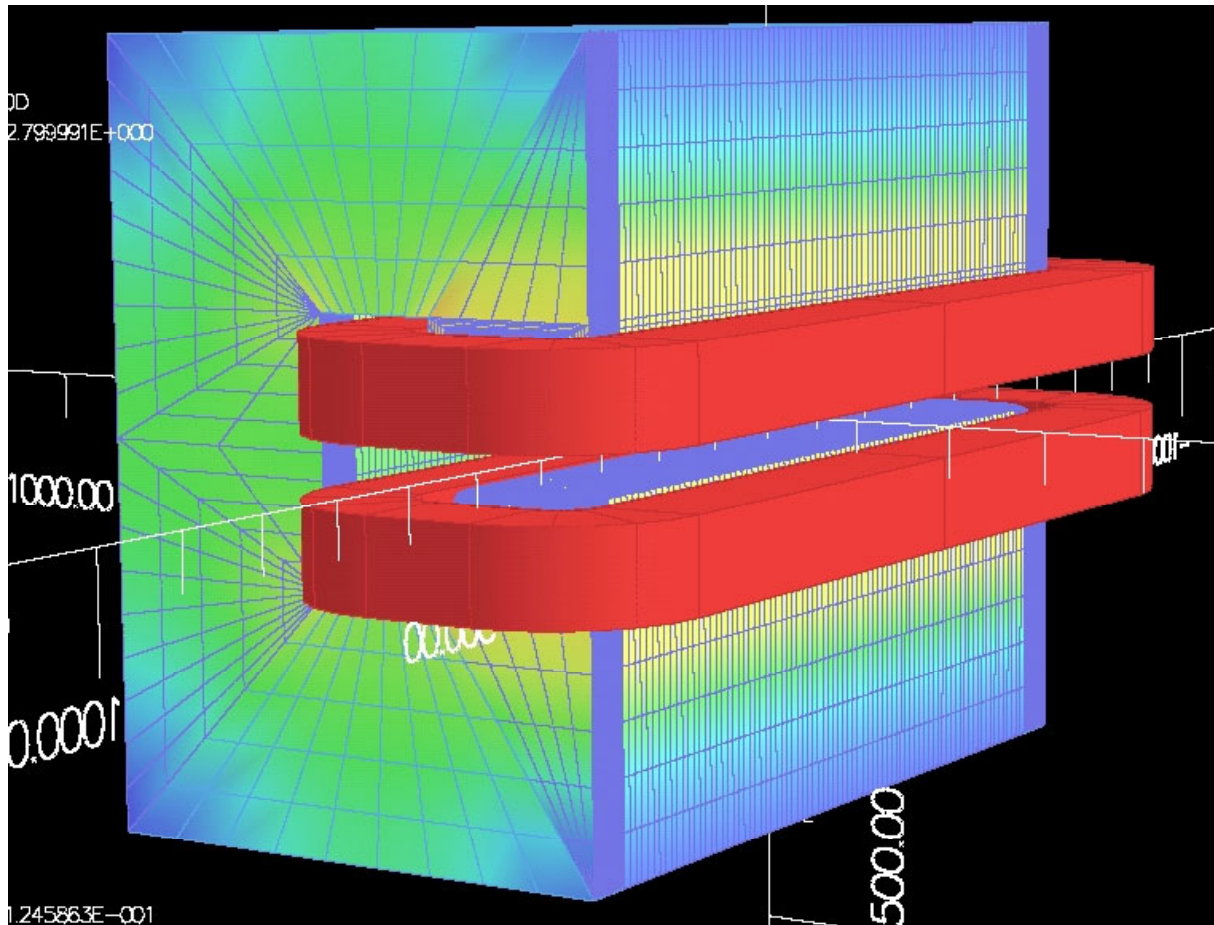


Figure 2.1-10 Three dimensional model of the dipole generated using the code TOSCA.

This model has identical geometry to the current engineering layout, with the exception that the magnet is straight, not curved. This should not affect the validity of the data predicted by the simulation but makes the three dimensional modelling quicker and easier.

A view of the dipole yoke without the coil, displaying the end profile and roll-off, as generated by the three-dimensional F.E.A code, is shown in Figure 2.1-11.

2.1.9 Transverse Field Predicted by 3D Model.

To ensure that the three dimensional and two dimensional models were consistent, the predicted homogeneity in vertical flux density in the transverse plane, on the vertical centre of the gap and at the azimuthal centre of the magnet, was examined. The simulation was non-linear, using the same magnetisation data for the steel as was used for the two dimensional modelling. The resulting homogeneity prediction is shown in Figure 2.1-12. This should be compared with Figure 2.1-4, which shows the same data for the 2D simulation. Comparison of the two curves show that the predictions from the two models are in good agreement.

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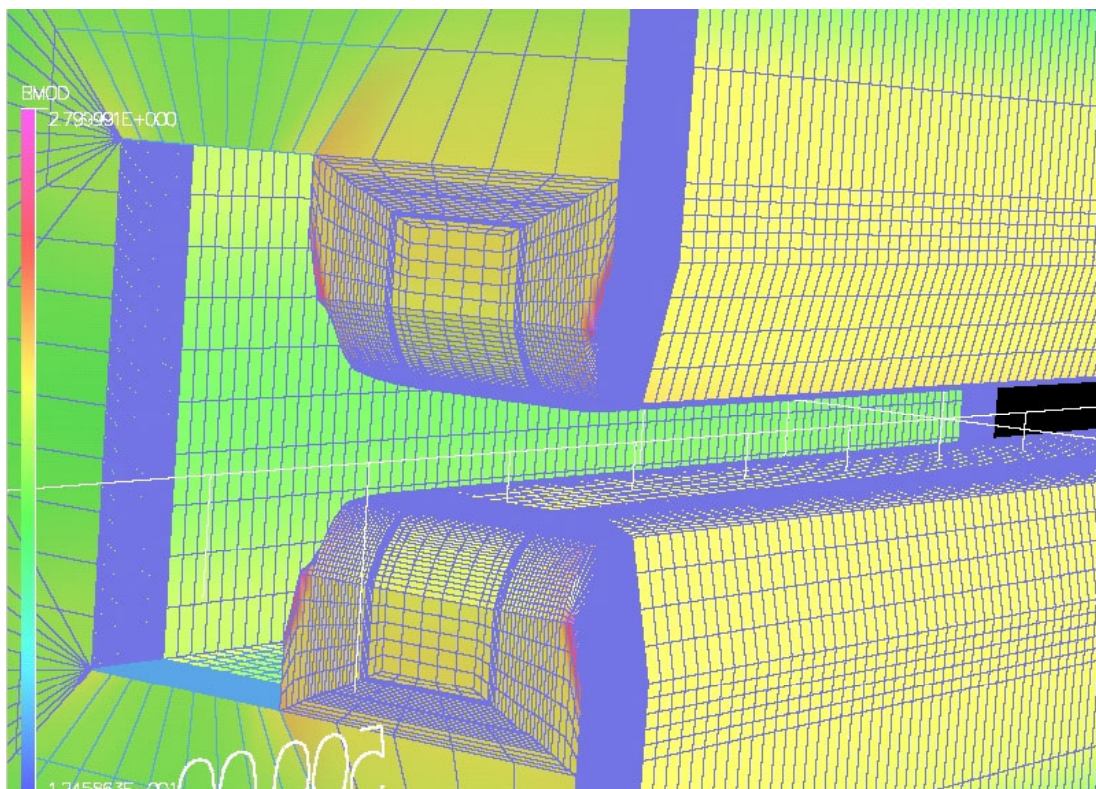


Figure 2.1-11 Three dimensional dipole yoke, showing the end profile arrangements and finite element analysis grid.

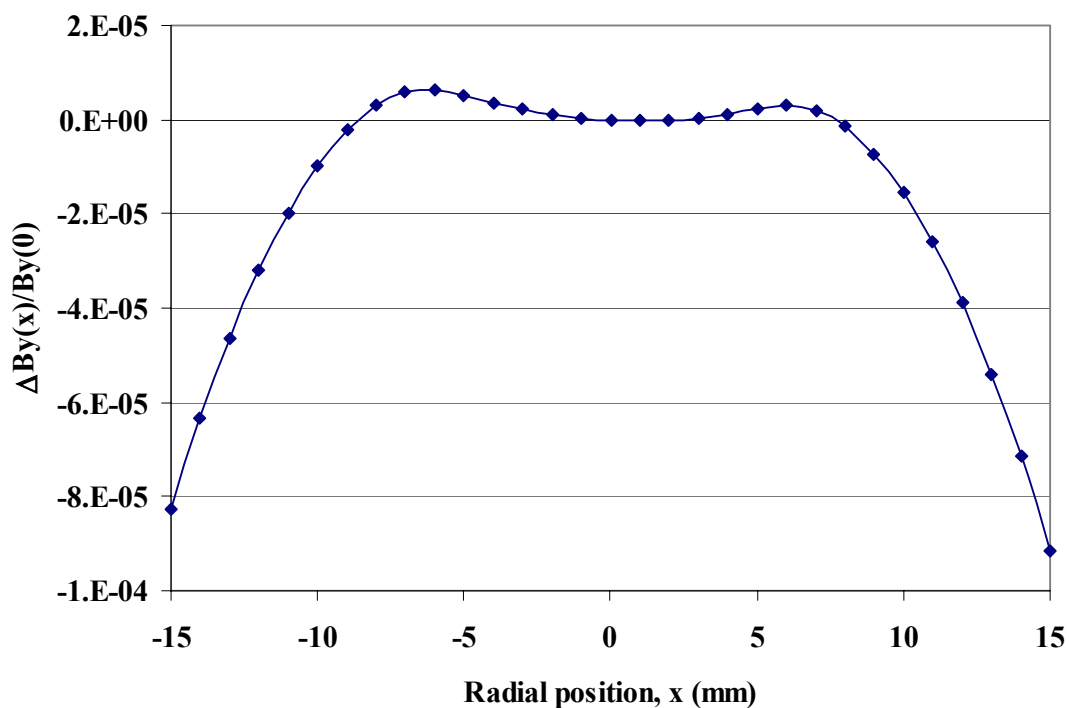


Figure 2.1-12 Non-linear prediction of field homogeneity ($\Delta B_y(x)/B_y(0)$) on $y = 0$ axis at the azimuthal centre of the dipole.

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2.1.10 End Field Distributions Predicted from Three Dimensional Model.

The predicted distribution of the vertical flux density through the end of the three dimension model was examined; the variation with azimuthal position z is shown in Figure 2.1-13. This shows the decrease in flux density at the magnet end produced by the Rogowski roll-off and, by contrast, the distribution generated by a simple square end magnet.

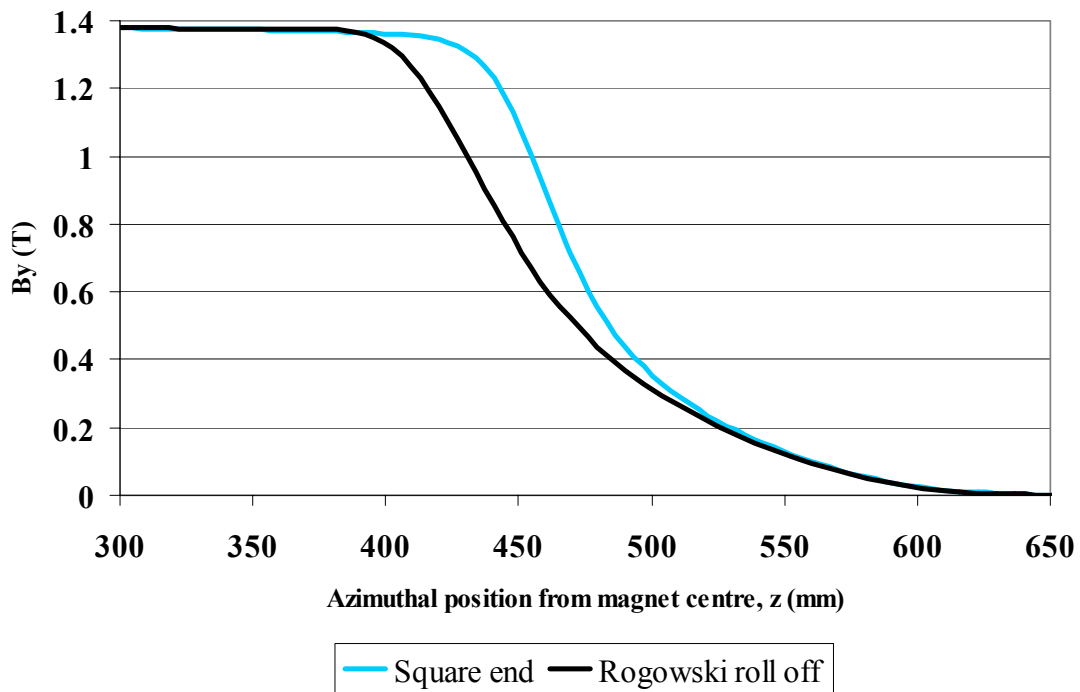


Figure 2.1-13 Variation of vertical flux density (B_y) (T) along the azimuthal plane (z) (mm) at the magnet end predicted for the three dimensional geometry of Figure 2.1-11.

To estimate the field length of the magnet resulting from the three dimensional geometry, the vertical field generated by the roll-off was integrated through the length of the magnet; the following data resulted:

magnetic length of dipole magnet: 931.4 mm.

This is 3.5 mm less than the figure obtained from the azimuthal two-dimensional analysis. These data will be further examined prior to proceeding with the procurement exercise for the dipole and, if necessary, small adjustments will be made to the end roll-off to provide the required magnetic length of 935 mm.

2.1.11 Sextupole Field in the Dipole Ends.

With the end roll-off having no variation in the transverse (x) direction, there will be completely flat poles, with no shims in this regions. This will result in the transverse

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field distribution decreasing monotonically from the pole centre, creating a negative sextupole component. To assess the likely magnitude of this the flux densities predicted by the three dimensional model were integrated azimuthally at different horizontal position; the resulting variation in integrated field across the good field aperture is shown in Figure 2.1-14 below.

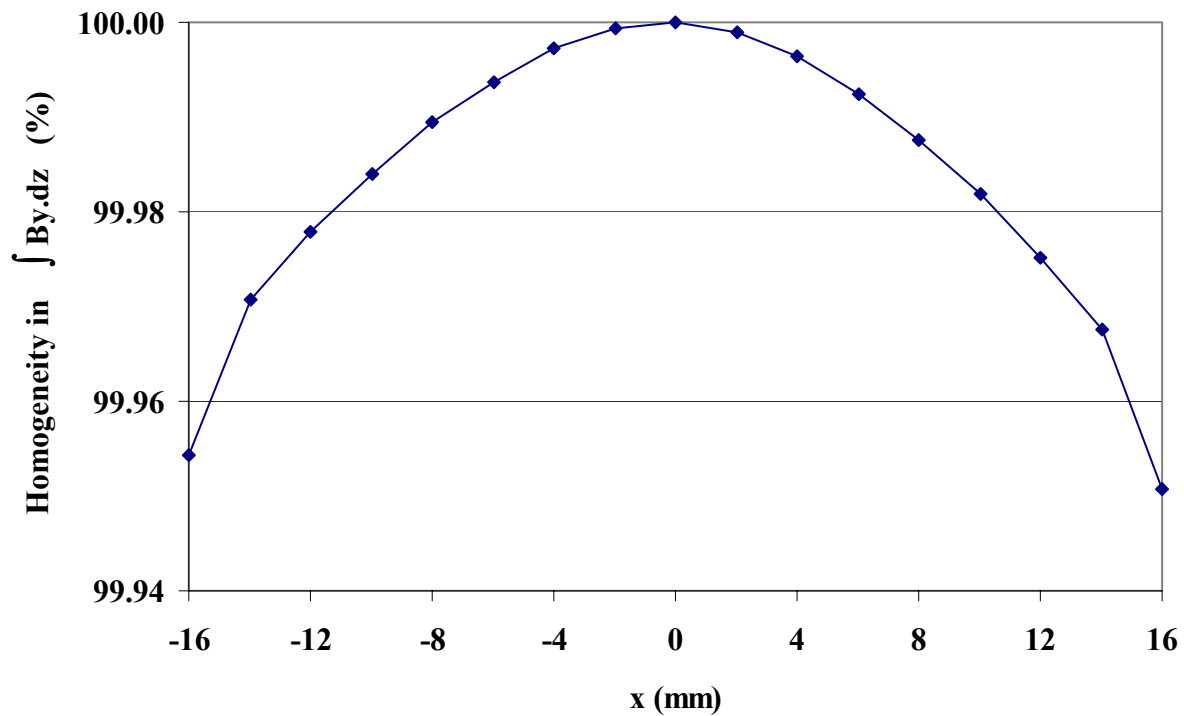


Figure 2.1-14 Homogeneity in azimuthally integrated vertical flux density (B_y) as a function of horizontal position (x) within the good field region, predicted by the three dimensional model.

The results of this prediction, as expected, show a negative integrated sextupole component which is significantly larger than the error displayed in the field homogeneity curve at the centre of the dipole. From the data of Figure 2.1-14, the integrated sextupole component, which is concentrated in the dipole ends, is calculated to be:

$$\text{integrated sextupole strength (coefficient):} \quad -2.52 \quad \text{T/m.}$$

This should be compared to the maximum strength (coefficient) of lattice sextupole magnets, which is 82.5 T/m. Hence, the estimated negative sextupole field at each dipole end resulting from a pole roll-off with no transverse shims is of the order of 1.5% of the strength of a lattice sextupole and can therefore be easily compensated by these lattice elements.

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2.1.12 Dipole engineering layout.

An isometric view of the dipole magnet is shown in Figure 2.1-15. The curved 'C' core magnet has parallel ends, with the magnet gap opening to the radially inwards part of the ring; this is to allow good accessibility for the vacuum pumping tees in the achromat.

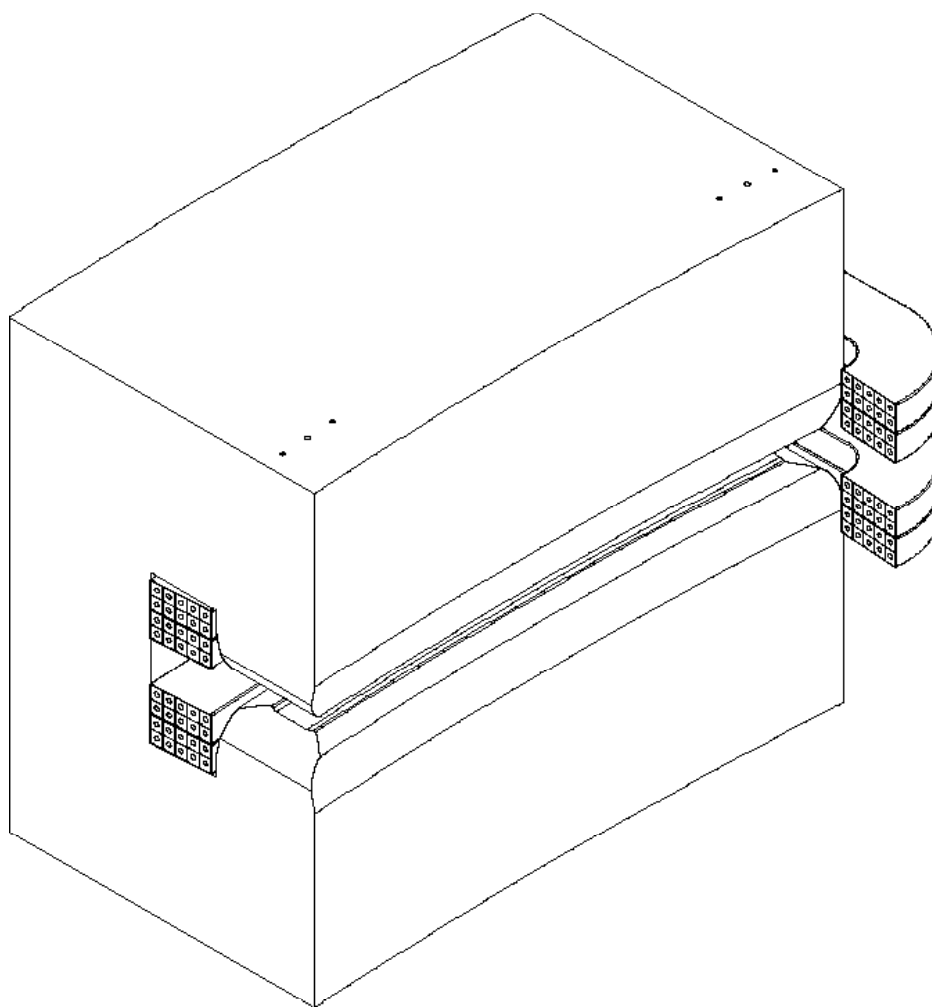


Figure 2.1-15 Isometric engineering drawing of dipole magnet, with coil partially cut away for clarity.

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2.1.13 Dipole Power Supply Parameters.

The data determining the dipole magnet power supply parameters and the resulting ratings are given in Table 2.1-2.

Table 2.1-2 Dipole magnet power supply parameters.

Magnetic field	1.4	T
Turns per magnet	40	
Current per turn	1337	A
Current stability	10 ppm	
Current density in coil	4.0	A/mm ²
Resistance per magnet at 40°C	6.2	mΩ
Voltage per magnet	8.4	V
Number of dipoles	48	
Circuit voltage (inc. cables)	421	V
Power supply rated current	1471	A
Power supply rated voltage	463	V
Power supply rated power	681	kW

The circuit voltage given in the table includes the voltage drop anticipated in the cables and at the magnet terminals. The power supply rated current and voltage include a 10% engineering contingency added to the estimated circuit current and voltage ratings.

2.2 QUADRUPOLE MAGNETS - GENERAL CONSIDERATIONS.

2.2.1 Determination of Inscribed Radius.

The specification of the quadrupole inscribed radius is determined by the geometry of the vacuum vessel containing the circulating electron beam. The relevant parameters for determining the inscribed radius are:

horizontal beam stay clear dimensions (total):	80	mm;
vertical beam stay clear dimensions (total):	34	mm;
internal tolerance clearance top and bottom:	2	mm;
vessel wall thickness:	3	mm;
external tolerance for assembly and location:	3	mm;
resulting quadrupole inscribed radius (R)	37	mm.

Figure 2.2-1 shows the outer dimensions of the octagonal vessel which will be used in the storage ring, including the necessary space for assembly and clearance, together with the 37 mm hyperbolic pole. Thus, an inscribed radius:

$$R = 37 \text{ mm} \quad \text{is close to optimum.}$$

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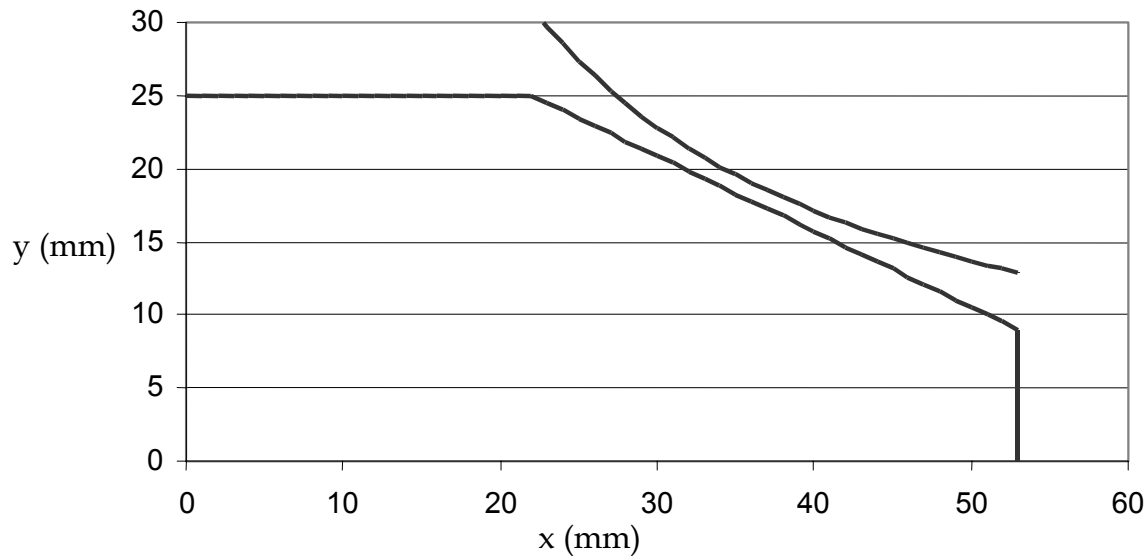


Figure 2.2-1 Cross-section showing outer dimensions of the storage ring vacuum vessel (including tolerances) and the $R = 37$ mm quadrupole magnet pole surface.

2.2.2 Gradient Quality and Amplitude Specification.

The current aperture requirements for the storage ring lattice are given in Table 4 of the report 'Proposed Storage Ring Beam Stay-Clear' [1] This gives the horizontal and vertical half-aperture requirements for the different families of quadrupoles. The resulting aperture specification of the quadrupole families, together with their required magnetic lengths, are given in Table 2.2-1, below.

Table 2.2-1 Requirements for storage ring quadrupoles with proposed cross-section:

(*) Cross-section specification: N = narrow pole; W = wide pole;

Magnet length specification: L = long; M = medium; S = short.

Quadrupole Family	Magnetic length (m)	No. per family	Required horizontal good gradient half aperture (mm)	Required vertical good gradient half aperture (mm)	Type (*)
Q1AB	0.4	36	36	16	WM
Q2AB	0.4	36	20	16	NM
Q1B	0.4	36	25	12	NM
Q2B	0.6	36	25	12	NL
Q3B	0.3	36	25	12	NS
Q1AD	0.4	12	36	16	WM
Q2AD	0.4	12	20	16	NM
Q1D	0.4	12	25	12	NM
Q2D	0.6	12	25	12	NL
Q3D	0.3	12	25	12	NS

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A wide range of lattice configurations and tunes have been examined and these were found to cover a range of different strengths for different quadrupole families. However, to provide for the wide range of operational tune points which are found to be feasible, the maximum quadrupole strengths for all families are current specified as:

$$g = 17.5 \text{ T/m};$$

with 'good gradient' within the specified apertures defined as :

$$-0.1\% \leq \Delta g/g(0) \leq 0.1\%.$$

2.2.3 Quadrupole Cross-Sections.

As explained in the detailed report on the quadrupole design [3], it is undesirable to adopt an individual design for each of these families identified in Table 2.2-1, as that leads in poor economy in tooling, components, handling, etc. during manufacture. Given the parameters shown in the table, the quadrupole families appear to fall into two groups: the small number of magnets (48) which require 36 mm half aperture, which will call for very broad poles, and the remaining much larger number of quadrupoles (192) which need either 20 mm or 25 mm half-aperture and which can be satisfied with a single cross-section design with a more conservative pole width. Thus, it is proposed to have two quadrupole cross-sections; the broad pole design being described as 'W' (for wide) types, and the more conventional magnets designated 'N' (for narrow) types.

It will be noted the N types are required in three different magnetic lengths (0.3, 0.4 and 0.6 m), and the length specifications are therefore described by the letters 'S', 'M' and 'L' (short, medium, and long). The W types are all 0.4 m, 'M' length magnets. The designated cross-section and length for each family is given in column 6 of Table 2.2-1.

The resulting audit for different quadrupole types is given in Table 2.2-2, below.

Table 2.2-2 Required number and parameters of proposed four types of quadrupole.

Type	Number	Magnetic length (m)	Inscribed radius (mm)	Max gradient (T/m)	Horizontal good gradient (mm)
WM	48	0.4	37.0	17.5	+/- 36
NL	48	0.6	37.0	17.5	+/- 25
NM	96	0.4	37.0	17.5	+/- 25
NS	48	0.3	37.0	17.5	+/- 25

Total number of quadrupoles: 240.

2.2.4 Quadrupole Symmetry and F.E.A. Modelling.

In common with quadrupole magnets designed for other synchrotron sources [4] [5], beam lines will pass close to the quadrupole in the radially outwards direction. Whilst mechanical support for the magnet will be needed in this region, the detailed size and position of the vertical spacers will vary according to the local beam-line geometry. Hence, it is the practice to remove the magnetic flux-return limb (the 'back-leg') from this region; the usual four-fold symmetry of the quadrupole is therefore lost. To preserve two-fold symmetry, the magnetic link across the median plane in the radial inwards direction is then also removed. These modifications result in the return flux between poles being conducted by the top and bottom yoke limbs, which must be doubled in width to accommodate the higher flux. The resulting two-fold symmetry now allows octupole field to be present in the magnet and the level of this contamination must be examined during the magnet design.

During the design of the quadrupoles, gradient qualities generated by defined cross-sections were examined using the two-dimensional, non-linear finite element code OPERA 2D. Geometric models of one-eighth and one-quarter of the quadrupoles were used for this work, the quadrupole symmetry being imposed by defined boundary conditions. The one-eighth geometry minimises the size of the model, allows more rapid adjustments to be made during the optimisation process and, most importantly, provides the maximum possible mesh density. However, this geometry did not allow the asymmetric quadrupole, with no return yoke across the x-axis, to be modelled, nor does it allow a complete investigation of the gradient off the $y = 0$ axis.

The one quarter model, comprising the first quadrant of the magnet, allows the gradients to be examined over the full range of the good gradient half-axes in both planes. It also permits the investigation of the possible octupole contamination generated by the required breaks of magnetic yoke in the radial plane. Hence, in the design detailed below, these two geometries are used according to the analytical requirement of the model. Examples of the two geometries used are given in Figure 2.3-1 and Figure 2.3-2 below.

2.2.5 Steel Specification.

Non-linear investigations of the quadrupole gradient quality and amplitude were performed using the steel B/μ curve specified for the dipole steel (see section 2.1.3 above). The steel data used corresponded to the 'parallel to rolling direction' parameters.

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2.3 LARGE APERTURE ('W' TYPE) QUADRUPOLES.

2.3.1 Magnet Geometry.

A pole geometry which would generate the required quality of field was developed and modelled. The pole follows the equation:

$$xy = R^2/2 \quad \text{out to } x = 49.2 \text{ mm};$$

with a liner tangent extending to the pole corner at

$$x = 60 \text{ mm}.$$

From the pole corner, the pole receded at an angle of:

$$45^\circ \quad \text{out to } x = 70.0 \text{ mm}.$$

The pole was then broadened, with each side diverging at an angle of:

$$10^\circ \quad \text{to the pole centre line}.$$

This broadening had been found to be necessary at gradients of 17.5 T/m, as reported in an early examination of the quadrupole designs [6]. The back-leg specified in the four-fold symmetry magnet had a thickness of 60 mm; the two-fold symmetry magnet with no magnetic path across the median plane would require a top and bottom yoke of twice this width.

Full details of the pole geometry are given in the detailed quadrupole design report [3]. The one-eighth and one-quarter magnet geometries used for the quadrupole modelling are shown in Figure 2.3-1 and Figure 2.3-2, below

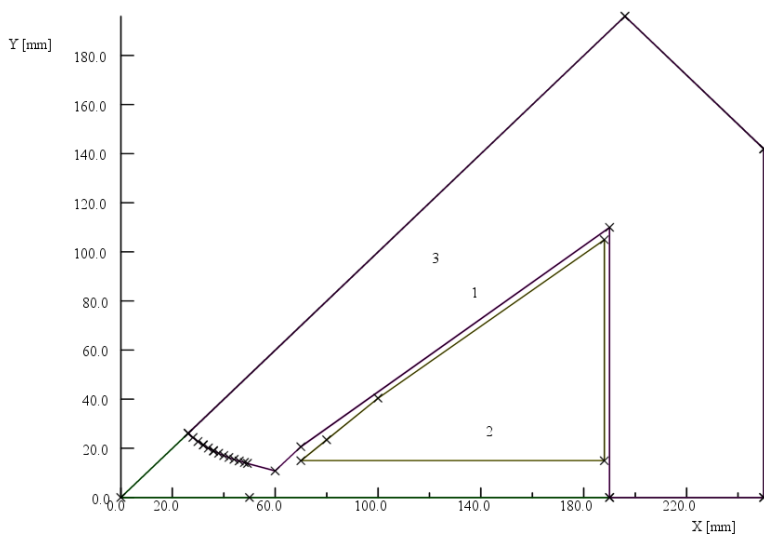


Figure 2.3-1 The one-eighth geometry used for modelling the 'W type' quadrupole.

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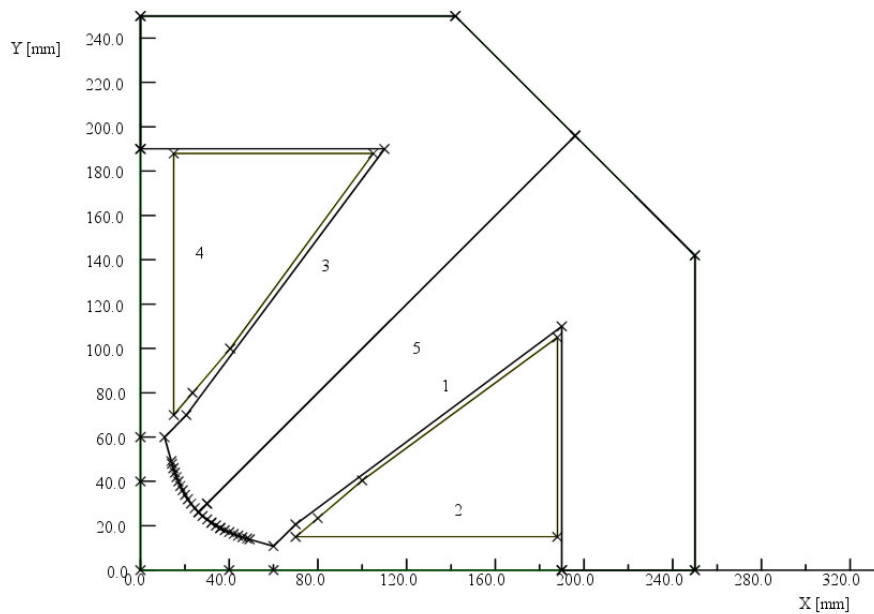


Figure 2.3-2 One quarter geometry used for modelling the 'W type' quadrupole.

2.3.2 Predicted Gradient Quality.

The homogeneity (expressed as a ratio) in the gradient of the vertical field, H_y , along the x axis, predicted by non-linear modelling is shown in Figure 2.3-3.

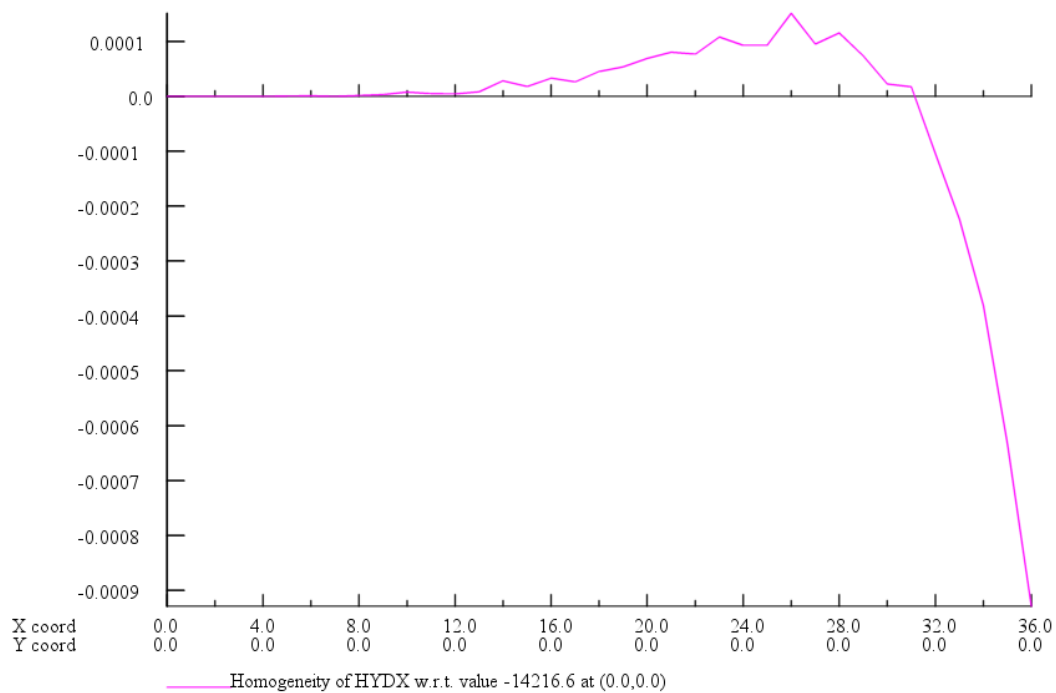


Figure 2.3-3 Homogeneity of the first differential of magnetic field H_y on the $y = 0$ axis predicted by non-linear simulation for the one eighth geometry of Figure 2.3-1.

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It can be seen from Figure 2.3-3 that the prediction indicates the following field gradient homogeneity:

$$\Delta dH_y/dx = +0.015\%, \quad x = 26 \text{ mm};$$

$$\Delta dH_y/dx = 0 \quad x = 31 \text{ mm};$$

$$\Delta dH_y/dx = -0.09\%, \quad x = 36 \text{ mm}.$$

Non-linear exploration of the gradient quality off the x axis was performed using the one-quarter geometry. Results are shown in Figure 2.3-4 below; the larger oscillation in the curves are due to the coarser mesh used in the F.E.A. analysis

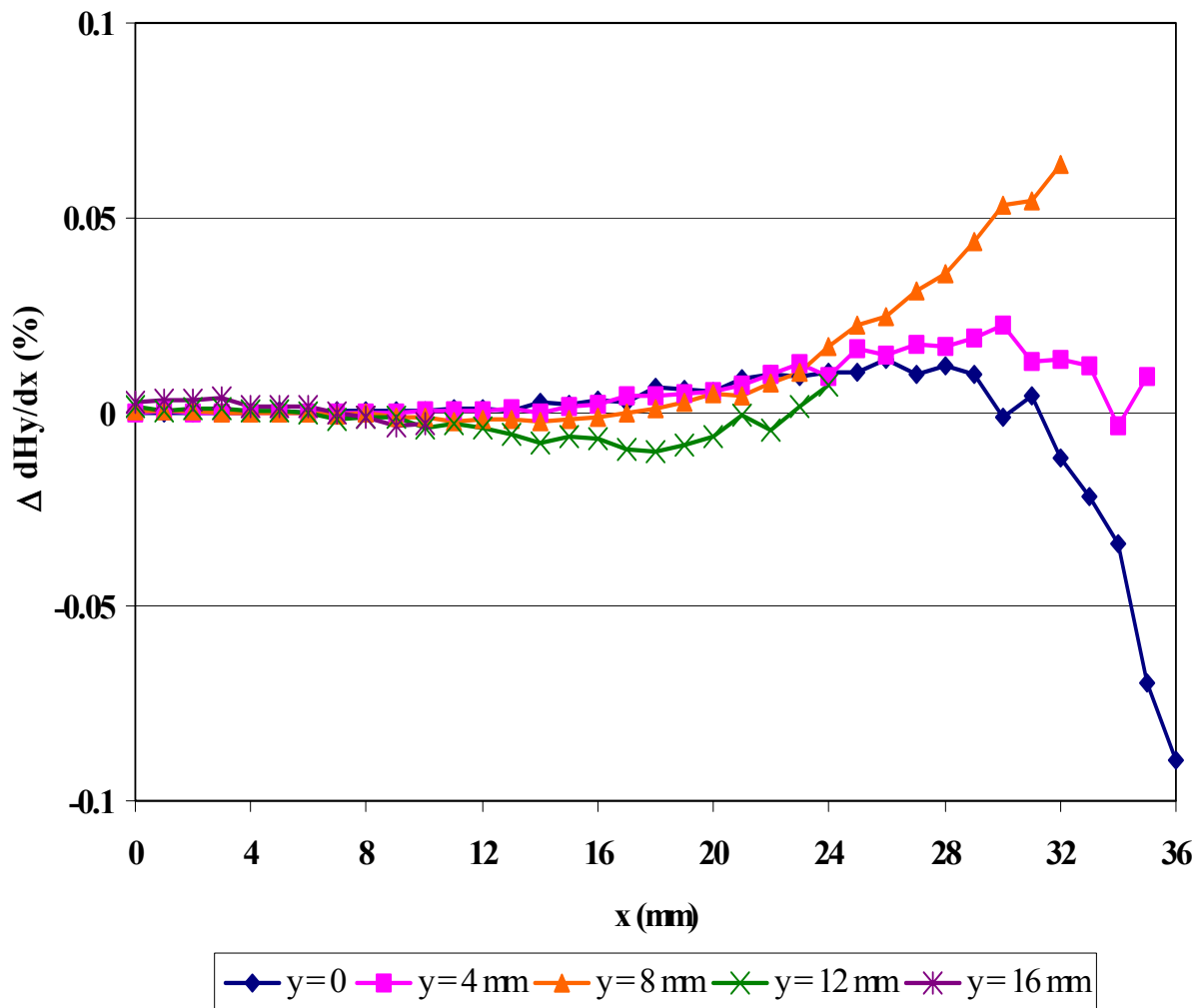


Figure 2.3-4 Homogeneity of the gradient of the vertical field H_y as a function of x , the variation expressed as a percentage of the value of dH_y/dx at the origin (0,0), at differing vertical positions ($y = 0$, to $y = 16$ mm); the data presented extends over the whole 'good gradient' ellipse.

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The amplitude linearity of the geometry was estimated by comparing the non-linear simulations with very high permeability linear models. This exercise predicted an amplitude linearity for the geometry of Fig 2.3-1 of 99.0% at a gradient level of 17.8 T/m.

2.3.3 Possible Octupole Errors.

The amplitude of octupole error that was likely to be introduced by the breaking of the flux return path across the median plane was studied using a quarter geometry with no vertical magnetic limb in the radial outward direction; the geometry used is shown in Figure 2.3-5.

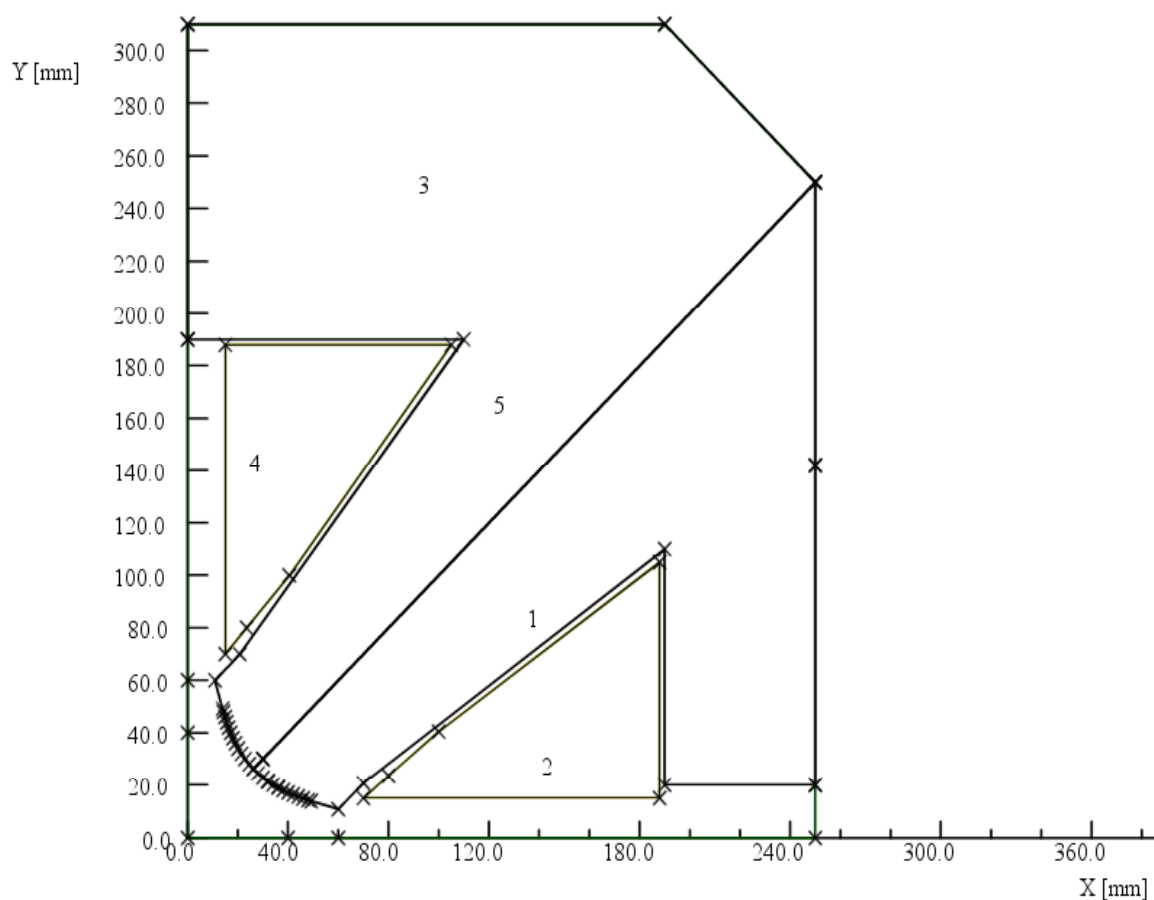


Figure 2.3-5 Geometry used to model the 'W' type quadrupole with no vertical flux return yoke across the $y = 0$ axis; regions 1 & 5: high permeability steel; regions 2 & 4: conductors.

The predicted field gradients were examined on both the $y = 0$ and $x = 0$ axes, and no significant difference could be discerned; detailed results are provided in the detailed quadrupole design report [3]. It is therefore concluded that at the rated gradient level, octupole error introduced by the break in the vertical magnetic limb is negligible.

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2.4 LOW APERTURE ('N' TYPE) QUADRUPOLE.

2.4.1 Magnet Geometry.

As with the 'W' type quadrupole, a pole and yoke geometry that would provide the required gradient was developed. The pole followed the equation:

$$xy = R^2/2 \quad \text{out to } x = 37.3,$$

with a liner tangent extending to the pole corner at:

$$x = 48 \text{ mm.}$$

From the pole corner, the pole followed an angle of:

$$45^\circ \quad \text{out to } x = 57.0 \text{ mm.}$$

The pole was then broadened, each side diverging at an angle of:

$$10^\circ \quad \text{to pole centre line.}$$

The back-leg specified in the four-fold symmetry magnet had a thickness of 50 mm; the two-fold symmetry magnet with no magnetic path across the median plane would require a top and bottom yoke of twice this width.

The one-eighth geometry used for the modelling of this quadrupole is shown in Figure 2.4-1.

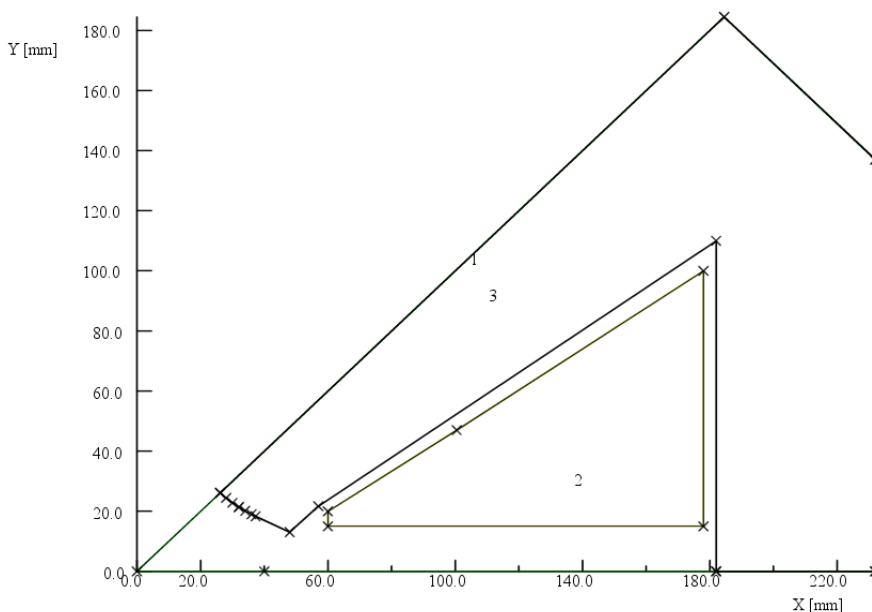


Figure 2.4-1 One-eighth geometry used for modelling the 'N' type quadrupole.

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2.4.2 Predicted Gradient Quality.

The homogeneity in the gradient of the vertical field (H_y) on the x axis is shown in Figure 2.4-2.

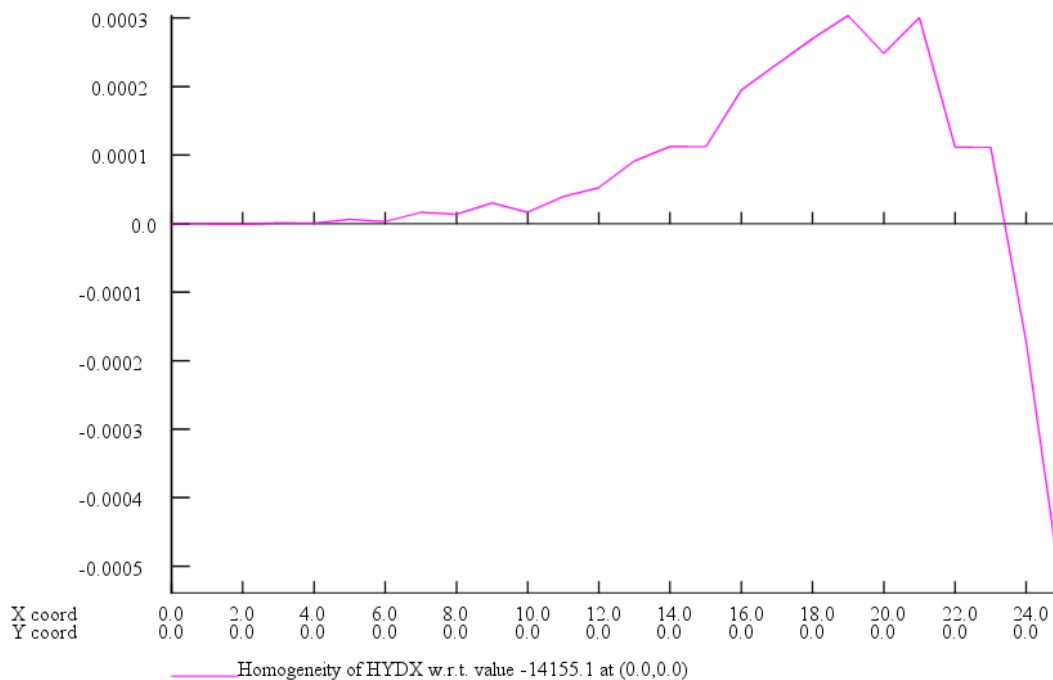


Figure 2.4-2 Homogeneity of the first differential of magnetic field on the $y = 0$ axis predicted by non-linear simulation for the one eighth geometry of Figure 2.4-1.

The prediction indicates the following field gradient homogeneity:

$$\Delta dH_y/dx = +0.03\%, \quad x = 20 \text{ mm};$$

$$\Delta dH_y/dx = 0, \quad x = 23 \text{ mm};$$

$$\Delta dH_y/dx = -0.06\%, \quad x = 25 \text{ mm}.$$

Using the one-quarter magnet geometry, the gradient qualities at multiple values of y , within the good gradient ellipse, were examined. Results for non-linear simulations are shown below in Figure 2.4-3 Gradients are within $\pm 0.1\%$ across the whole of the good gradient region in the x,y plane.

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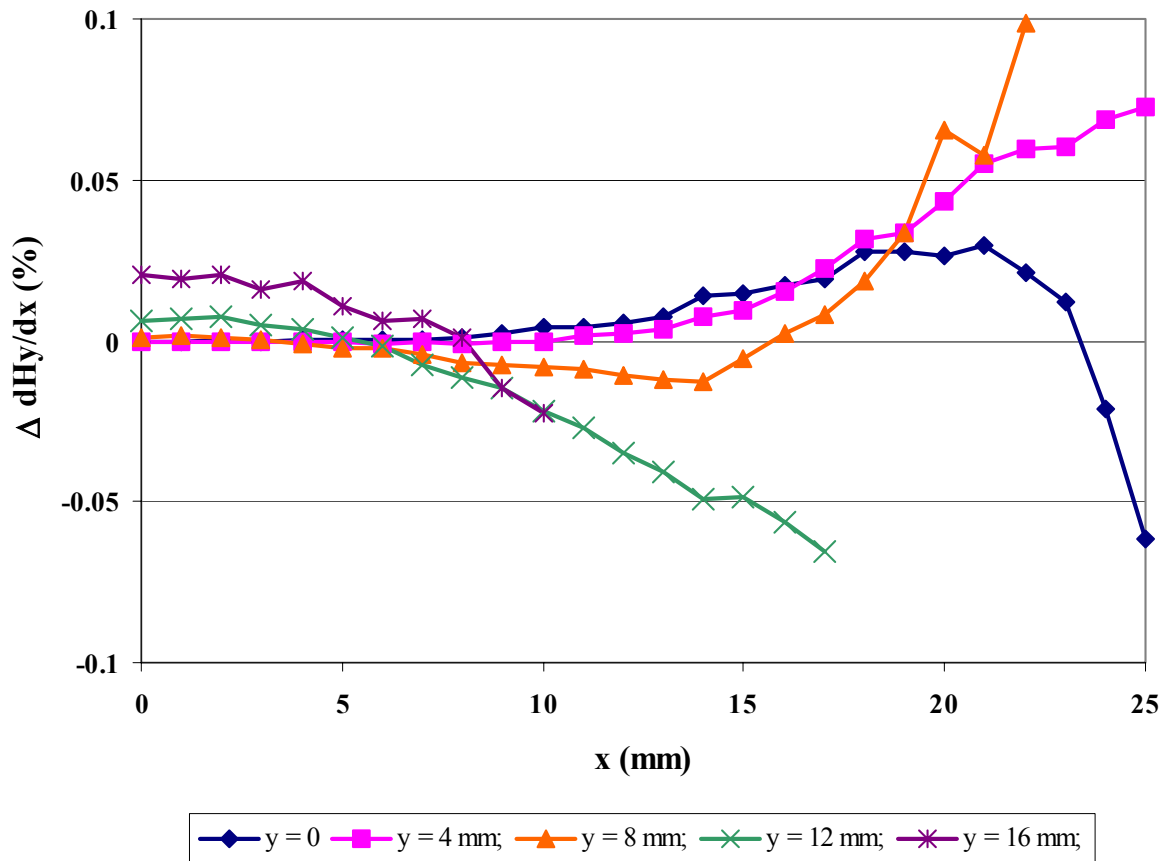


Figure 2.4-3 Homogeneity of the gradient of the vertical field H_y as a function of x , the variation expressed as a percentage of the value of dH_y/dx at the origin (0,0) at differing vertical positions ($y = 0$, to $y = 16$ mm); the data presented extends over the whole 'good gradient' ellipse.

The amplitude linearity of the design was assessed using the same techniques as that employed for the 'W' type quadrupole. At a gradient of 17.8 T/m, the predicted amplitude linearity was 99.2%.

2.5 QUADRUPOLE COIL CONFIGURATION.

2.5.1 Current Density in the Conductor.

The value of coil current density (J) used in a magnet design is usually based on an economic optimum between magnet capital cost, which falls with increasing current density (smaller coils), and the long term power costs, which are greater for higher J . The optimum is usually in the region of 3.5 to 4.0 A/mm² and as this value does not generally create cooling difficulties, designs using such values are the norm. During the early DIAMOND feasibility work a value of 4 A/mm² was used [7].

It is now appreciated that temperature stability is an important feature of a third generation light source, as magnet expansion is a major source of beam positional

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instability. This is particularly important for the quadrupoles, where movement of the magnet centre will result in beam movements of a considerably greater amplitude. It is therefore wise to limit the current density in the copper conductor in the quadrupole and sextupole magnets to lower values to limit the temperature rise in the coils and yokes. A study of the size and cooling of the quadrupole coils at three different values of current density demonstrated that at 2 A/mm², the coils were large and substantially increased the size of the magnet. At 4 A/mm², the coils could be adequately cooled, but the cooling tube diameter was becoming appreciable compared to the conductor dimensions. It was therefore decided to design the quadrupoles with a coil current density of:

$$3 \text{ A/mm}^2,$$

and limit the temperature rise in the cooling water to:

$$10^\circ \text{ C}.$$

2.5.2 Coil Parameters.

Whilst the 'W' and 'N' type magnets have differing cross-sections, both types have the same amplitude specification, they will operate at the same current density and the constraints imposed by power supply economics indicate that they will have the same maximum operating current. The coils on the two types of magnet will therefore have the same cross-section and winding geometry, though they will have different overall widths and there will be three different lengths. The common parameters of the coils for the 'W' and 'N' type quadrupoles are given below:

minimum amplitude linearity:	97%;	
quadrupole inscribed radius:	37	mm;
operating gradient:	17.5	T/m;
required total Amp-turns per pole:	9818	At;
number of turns per pole:	54;	
operating current at 17.5 T/m:	182	A;
current density in copper:	3	A/mm ² ;
conductor cross-section:	60	mm ² ;
conductor dimensions:	10.1 x 7.5	mm ² ;
water cooling tube diameter:	4.5	mm;
maximum water temperature rise:	10	°C
maximum cooling water pressure drop:	5	bar.

The cross-section of the 'W' type magnet, with the coils mounted on the yoke, is shown in Figure 2.5-1.

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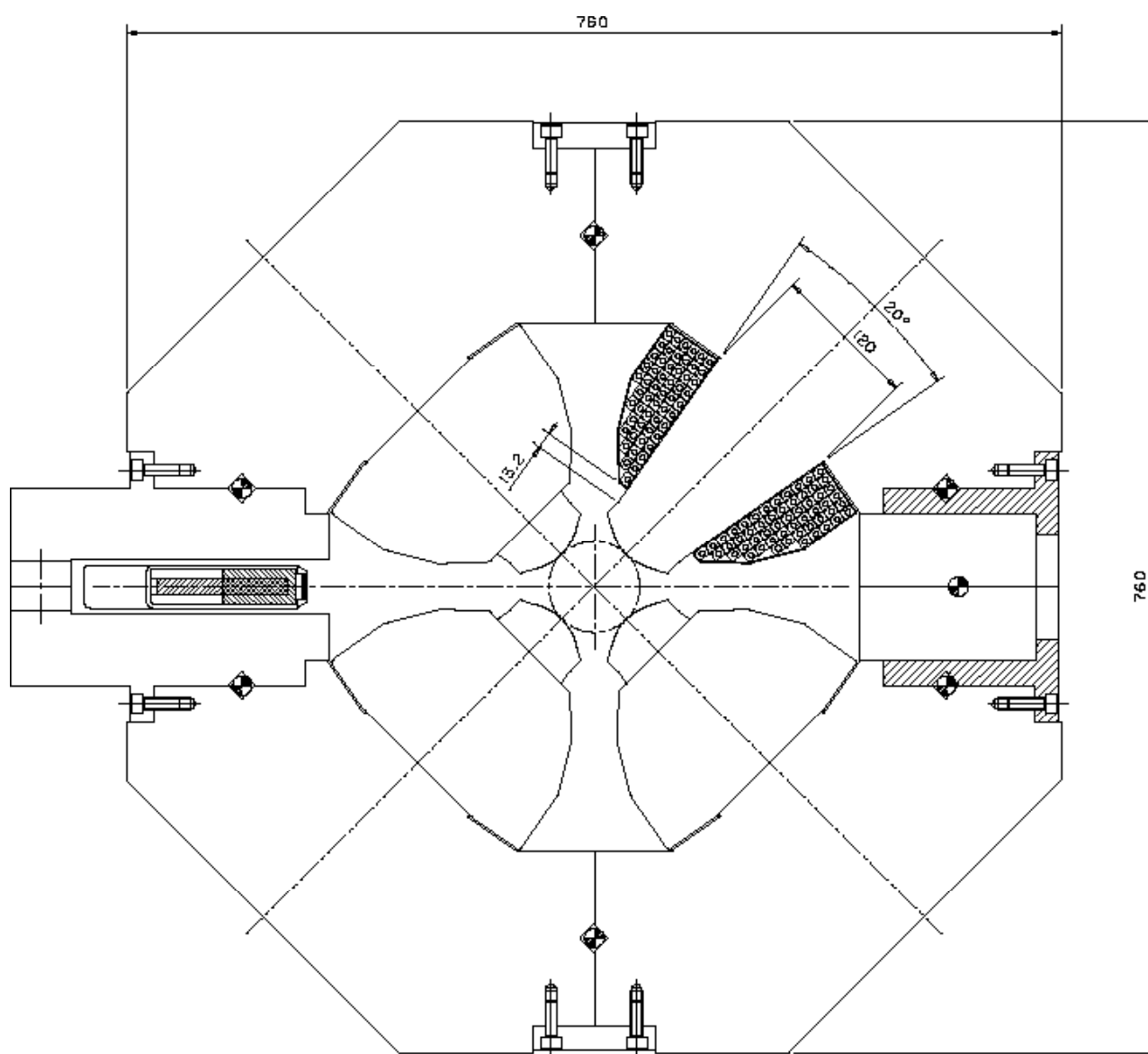


Figure 2.5-1 Cross-section of a 'W' type quadrupole, showing the coils mounted on the magnet yoke. Note the non-magnetic vertical limb on the radial outer side of the magnet, providing space for emerging synchrotron radiation and a similar non-magnetic support component in the radial inner region.

2.5.3 Quadrupole End Geometry.

The flux densities present at the pole face in a quadrupole are usually much lower than those experienced in a dipole. For example, the flux density at the pole centre of the 'W' type quadrupole is predicted to be less than 0.7 T when operating with a gradient of 17.5 T/m. Hence, the end termination in a quadrupole magnet can be of a much simpler nature than that in a dipole.

The ends of the DIAMOND quadrupoles will be terminated by making a simple 45° cut across the end of the pole face, the cut commencing at the extremity of the good gradient region. A diagram showing this feature is shown in Figure 2.5-2, below.

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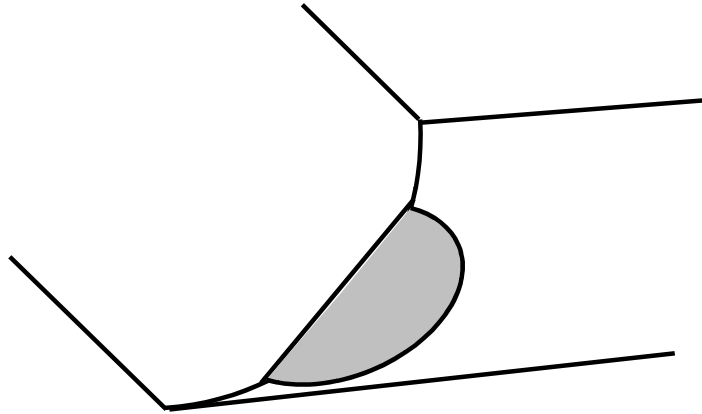


Figure 2.5-2 The 45° cut at the end of the pole in a quadrupole magnet.

Investigations in the azimuthal plane, using a square edged dipole magnet, were used to estimate the extent of flux fringing into the straight section after such a feature. This indicated that the fringe flux would lengthen the effective quadrupole length by 25 mm total per magnet.

Hence, the steel length of each quadrupole incorporated into the lattice layout drawings is:

25 mm less than the magnetic lengths specified in Table 2.2-1.

2.5.4 Engineering Layout.

An isometric projection of the 'W' type quadrupole is shown in Figure 2.5-3. The drawing shows the engineering layout of the quadrupole, with the non-magnetic side supports. In the radial outward direction, the support must provide space for the emerging synchrotron radiation beam-line which is up-stream from the magnet. A number of possible geometries will be required in this position and the quadrupoles will need to be engineered so that these components can be changed, to accommodate the local beam-line layout. In the radial inward direction, it is envisaged that a number of quadrupoles will have a circular aperture to allow access for a pumping port. This will result in a section of the magnet yoke being unsupported. The vertical forces in this limb, which will need to be restrained, have been calculated. For the largest quadrupole ('W' type) operating at 17.5 T/m, the vertical compression per metre in the side component will be:

$$15.3 \quad \text{kN/m.}$$

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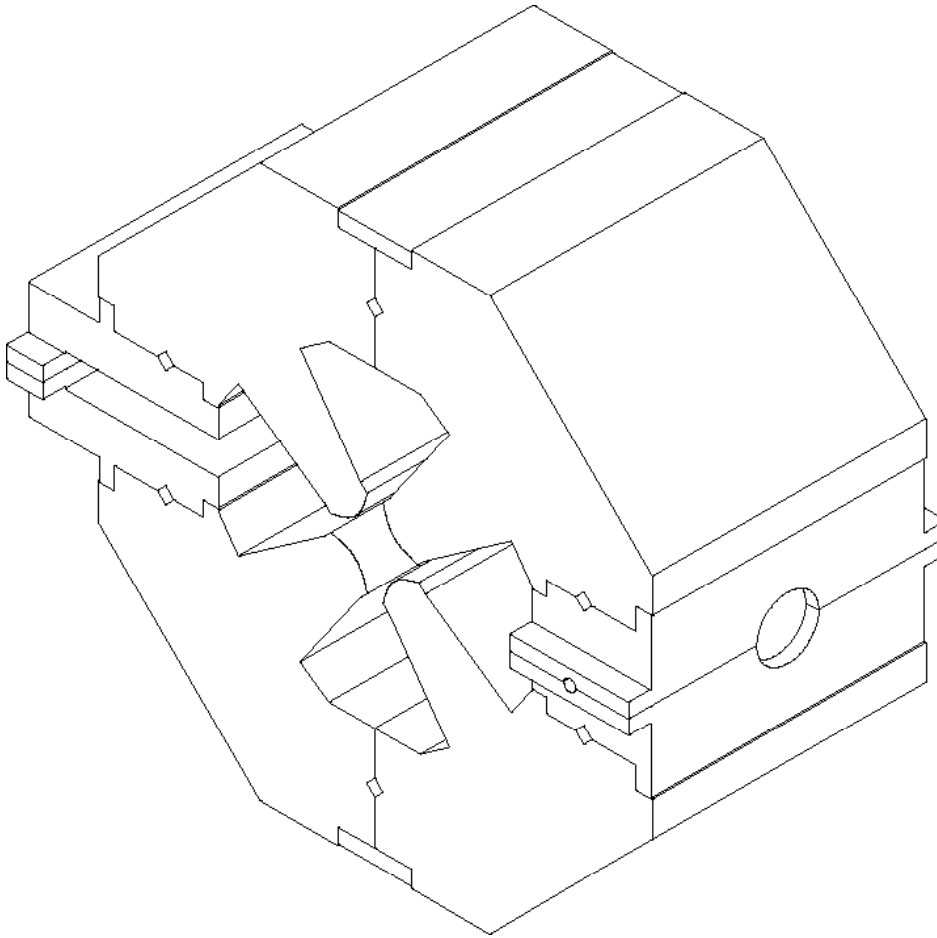


Figure 2.5-3 Isometric view of the 'W' type quadrupole yoke and poles, showing the pumping port aperture on the radial inward side of the magnet.

The construction of the magnet will need to accommodate this force over the length of the magnet which contains the circular aperture. The force can either be reacted directly by the inter-lamination bonding material but a superior solution, shown in Figure 2.5-3, uses a frame, with an aperture of the required diameter for the pumping port, to support the magnet side. The arrangement that will be used on the quadrupoles will be decided in conjunction with the quadrupole manufacturer.

2.5.5 Power Supply Ratings.

To provide maximum flexibility in the choice of beta functions and other parameters in different parts of the lattice, the quadrupole magnets will all have individual power supplies which can be adjusted to optimise the beam parameters for individual experiments. There will therefore be 240 quadrupole power supplies. Capital and running costs are therefore minimised by using as low an operating current as is technically possible, minimising cable and power supply losses. This determined the choice of 54 turns per quadrupole coil, larger numbers of turns producing an unacceptably small conductor cross-section. The resulting power supply ratings for the four different quadrupole geometries are given in Table 2.5-1.

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Table 2.5-1 Quadrupole power supply parameters.

Quadrupole type:	WM	NL	NM	NS	
Gradient	17.5	17.5	17.5	17.5	T/m
Turns per coil	54	54	54	54	
Operating current per turn	182	182	182	182	A
Current stability	1 : 10 ⁵	1 : 10 ⁵	1 : 10 ⁵	1 : 10 ⁵	
Current density	3.0	3.0	3.0	3.0	A/mm ²
Resistance per quad at 40°C	92.4	117.2	87.6	73.2	mΩ
Operating volts per quad	16.8	21.3	16.0	13.3	V
Volts (inc. cables and terminals)	17.6	22.4	16.8	14.0	V
Power supply rated current	200	200	200	200	A
Power supply rated voltage	19.4	24.6	18.4	15.3	V
Power supply rated power	3.9	4.9	3.7	3.1	kW

The power supply rated current and voltage include a 10% engineering contingency added to the estimated magnet current and voltage ratings (including cable losses).

2.6 SEXTUPOLE MAGNETS.

2.6.1 Introduction.

The sextupole magnets are required to generate the second order fields needed for correction of chromaticity and non-linear effects. Additionally, they are suitable magnets for the inclusion of static or slowly varying correction fields. The DIAMOND sextupole magnets therefore will have a magnetic circuit and associated pole coils for generating the main sextupole fields and smaller back-leg coils to generate dipole and skew quadrupole correction fields. The design which provides these required features is presented below.

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2.6.2 Inscribed Radius.

In the chapter above dealing with the design of the lattice quadrupole magnet, the choice of the inscribed radius was largely determined by the dimensions of the common vacuum vessel. The resulting quadrupole inscribed radius (37 mm) provided adequate space and engineering clearances for the octagonal vacuum vessel. In the case of the sextupole, an inscribed radius of this value would result in interference between the pole which subtends an angle of 30° to the horizontal axis and the vacuum vessel and it was found that an increase of 2 mm to the inscribed radius was necessary to prevent this. Hence, the specified inscribed radius for all sextupoles is:

$$R = 39 \text{ mm.}$$

2.6.3 Sextupole Gradient Amplitude and Quality Specification.

The current aperture requirements for the storage ring lattice are given in Table 4 of the report 'Proposed Storage Ring Beam Stay-Clear' [1], as modified in Chapter E1 Table 1.6-6 of this report. These give the horizontal and vertical half-aperture requirements for the different families of sextupoles. The resulting specification of the sextupole families, together with their required magnetic lengths, are given in Table 2.6-1, below.

Table 2.6-1 Aperture requirements for storage ring sextupole magnets.

Family	Magnetic length (m)	No. per family	Required horizontal good gradient half aperture (mm)	Required vertical good gradient half aperture (mm)
S1A	0.3	24	36	16
S2A	0.2	48	30	16
S1B	0.3	36	25	12
S2B	0.3	36	25	12
S1D	0.3	12	25	12
S2D	0.3	12	25	12

Total number of sextupoles: 168.

'Good gradient' is defined as: $-1 \% \leq \Delta G_s / G_s(0) \leq 1 \%$.

With the present lattice design, the maximum envisaged sextupole strength required for any likely set of operating parameters has been determined to be:

$$d^2B_y/dx^2 = 550 \text{ T/m}^2;$$

$$G_s = 275 \text{ T/m}^2.$$

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In the case of the quadrupoles, the variation in horizontal and vertical aperture specifications led to a decision to design two separate cross-sections, the 'W type', providing ± 36 mm of horizontal good gradient for 48 magnets, whilst the remaining 192 were 'N types', generating a usable aperture of ± 25 mm. In the case of the sextupoles, a slightly higher percentage of the total number of magnets require the maximum half aperture of 36 mm, and there is an appreciable fraction requiring the intermediate aperture of 30 mm. It was therefore decided to design a single cross-section for all sextupole magnets, which would provide the maximum required horizontal aperture. Hence,

horizontal aperture (all sextupoles): ± 36 mm.

2.6.4 Static Correction Fields.

The sextupole magnets are also required to generate static and slow dynamic correction fields; these are:

- vertical dipole;
- horizontal dipole;
- skew quadrupole.

The correction fields provide, respectively, control of:

- horizontal steering;
- vertical steering;
- vertical to horizontal coupling.

The amplitude specifications for these corrector fields are:

maximum horizontal and vertical steering:	0.8	mrاد	in each plane;
resulting dipole field in 0.3 m sextupole:	0.027	T	in each plane;
skew quadrupole:	0.36	T/m.	

These fields are generated by back-leg coils, which have different polarities for each of the required corrector configurations. The presence and location of the six poles in the magnet largely determine the resulting distribution of the correction fields; the quality of the horizontal dipole and the skew quadrupole are fully determined by the pre-defined sextupole geometry, whilst there is a single degree of freedom in the choice of the back-leg current distributions and hence the quality of the vertical dipole field. These restrictions pre-empt a specification of a required corrector field quality; the design aim therefore is 'as good as is possible'.

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2.6.5 Magnet Geometry for Sextupole Fields.

The one-quarter geometry used to investigate the pole configuration needed to generate sextupole fields is shown in Figure 2.6-1, the necessary symmetry conditions required for this field distribution being imposed on the x and y boundaries in the finite element analysis. Note that only the sextupole generating (pole) coils are included in this model.

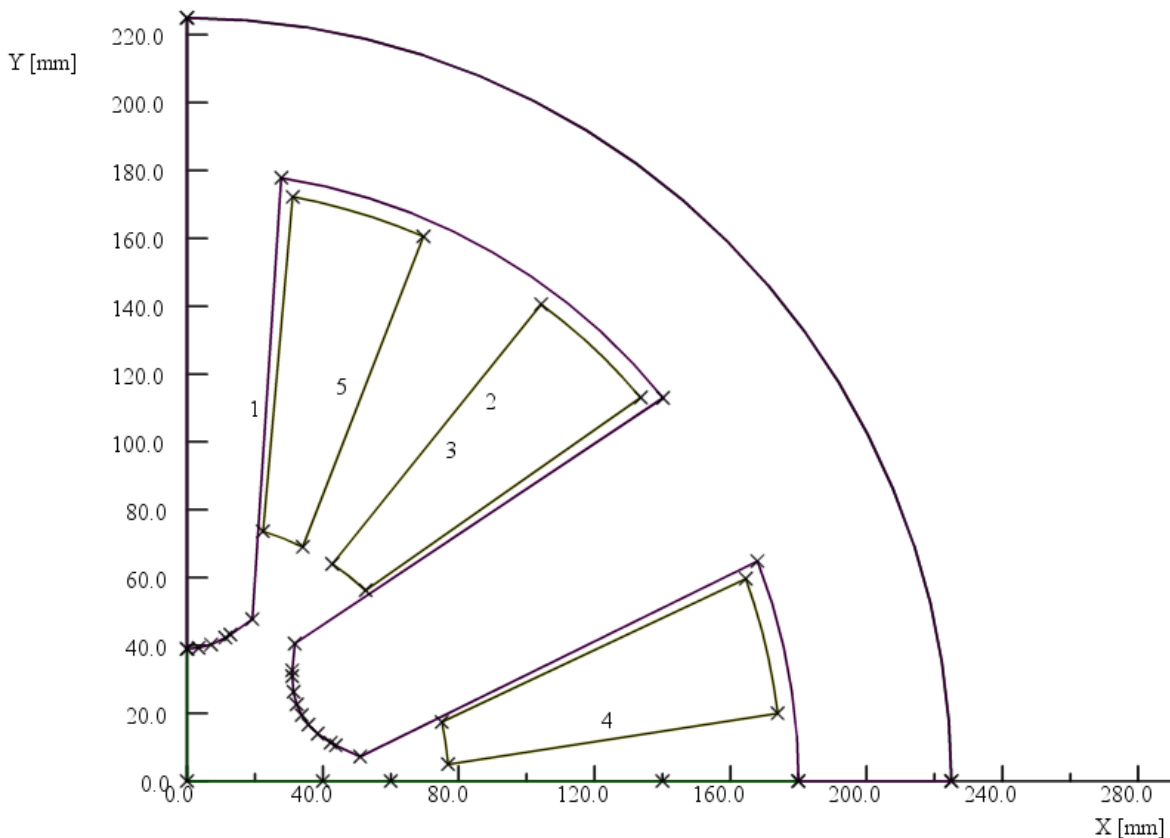


Figure 2.6-1 The one-quarter magnet geometry used to model the sextupole field quality using the F.E.A code OPERA 2D. (region 1: pole and yoke steel; regions 3, 4 and 5: sextupole coils)

The central pole region follows the equation:

$$3x^2y - y^3 = R^3; \quad \text{where } R \text{ is the inscribed radius.}$$

At either end of the pole surface the third order curve breaks to a linear shim; the break-point is symmetrical about the pole centre. The linear shim terminates at the pole corner. Cartesian co-ordinates of one half of the 90° pole, at suitable intervals, are given in Table 2.6-2, below.

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Table 2.6-2 Co-ordinates of one half of central pole of Fig 2.6-1.

x (mm)	y (mm)	Description
0.000	39.000	Centre of top pole
3.439	39.303	
7.105	40.294	
11.330	42.284	
12.791	43.180	Commencement of linear shim
19.239	47.782	Corner of top pole.

The pole sides, as shown, diverge at an angle of 4° to the pole centre line; this was found to be necessary to accommodate the flux at the maximum sextupole strength of 550 T/m^2 (differential). Without this feature, the flux in the pole roots exceeded 1.5 T , whereas, with the diverging pole, the peak flux density in the pole is of the order of 1.32 T . This will allow the flux from the correction fields to be transmitted through the poles without non-linear phenomena becoming appreciable.

The circular yoke used in this symmetrical model shown in Figure 2.6-1 had a thickness of 45 mm . In the physical magnets to be used in the DIAMOND magnet lattice, it will be necessary to break the magnetic yoke at one side in the radial outward direction, to provide space for extracted beam-lines. This will necessitate a significant increase in the thickness of the annular yoke on the inside of the magnet, to conduct the total flux across the median plane. The extent of this required change is estimated below (2.6.7).

2.6.6 Predicted Sextupole Gradient Quality on $y = 0$ axis.

The two dimensional finite element electromagnetic static code, OPERA 2D, was used to predict the sextupole gradient quality of the geometry shown in Figure 2.6-1. Due to the mesh size available, the second differential of the predicted field values shows significant oscillation. A curve fitting routine was applied to these data, using a twentieth order polynomial, with only those components allowed by full sextupole symmetry to be present (6 pole, 18 pole, 30 pole, 42 pole). Full details of the fit are given in the detailed sextupole magnet design report [8].

The homogeneity along the x axis of the second differences in the predicted vertical field (B_y) and of the second differential of the polynomial fit, are shown below in Figure 2.6-2.

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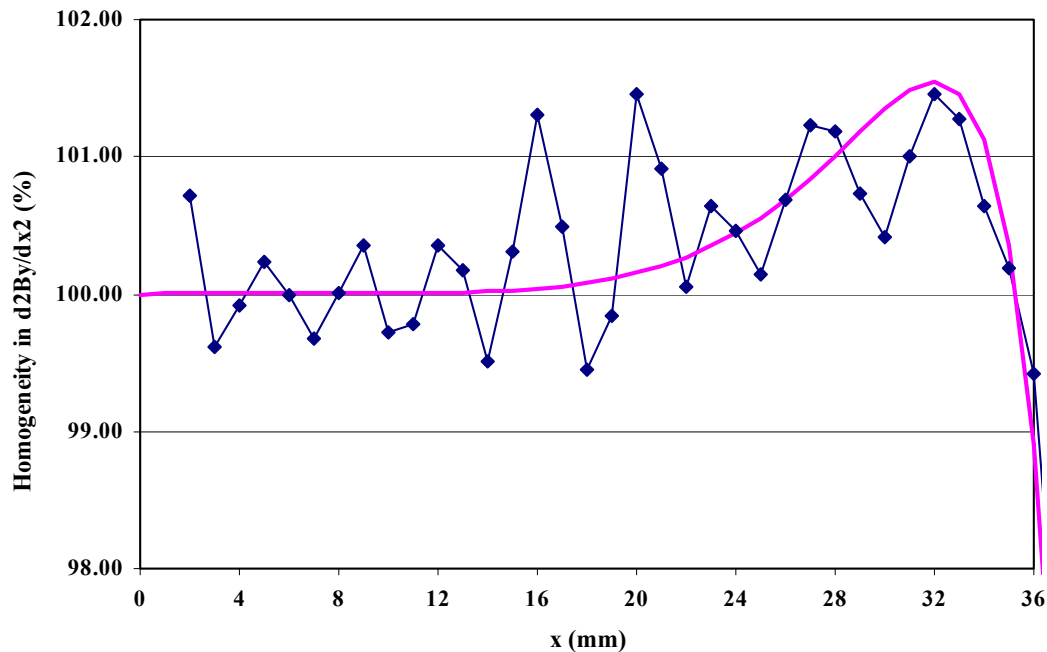


Figure 2.6-2 Homogeneity in second differential of vertical field on the $y = 0$ axis for the geometry of Figure 2.6-1; points are from raw field data; curve is from polynomial fit.

Data in Figure 2.6-2 indicates that the predicted variation in sextupole gradient quality is within 2.5%, peak to peak, out to 36 mm.

2.6.7 Amplitude Linearity.

By performing model simulations with a very high and fixed value of permeability in the poles and yoke (100,000) and comparing the resulting sextupole field with that predicted by a non-linear simulation, an estimate of the amplitude linearity for the geometry of Figure 2.6-1 was obtained; this gave:

predicted amplitude linearity: 99.0 %.

The maximum flux density predicted in the 45 mm fully symmetrical annular yoke by the non-linear simulation was:

0.8 T.

The physical magnet will have one vertical magnetic limb absent, to provide space for extracted beam-lines. Hence it is necessary to specify a thicker annular yoke.

maximum allowed yoke flux density: 1.0 T;
annular yoke thickness: 72 mm.

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2.6.8 Geometry for Slow and Static Corrector Fields.

The magnet geometry of Figure 2.6-1 was modified by the addition of back-leg coils to allow the generation of the static corrector fields; the new geometry is shown in Figure 2.6-3. In addition to the pole coils (regions 2,3 and 4) which generate sextupole fields, the revised model now includes coils 5 to 10 to generate corrector fields through the steel poles and yoke (region 1). These coils are wound around the annular yoke, so the Ampere-turns of the radially outer coil is always equal in magnitude but of opposite polarity to the radially inner coil. To model a particular corrector field, the yoke coils can be turned on or off by specifying their current density; when modelling the corrector fields the sextupole (pole) coils were specified as having zero current density. The quarter arc in the radially outer region of the diagram is the edge of the 'background' region (region 11) which is required to complete the F.E.A. model.

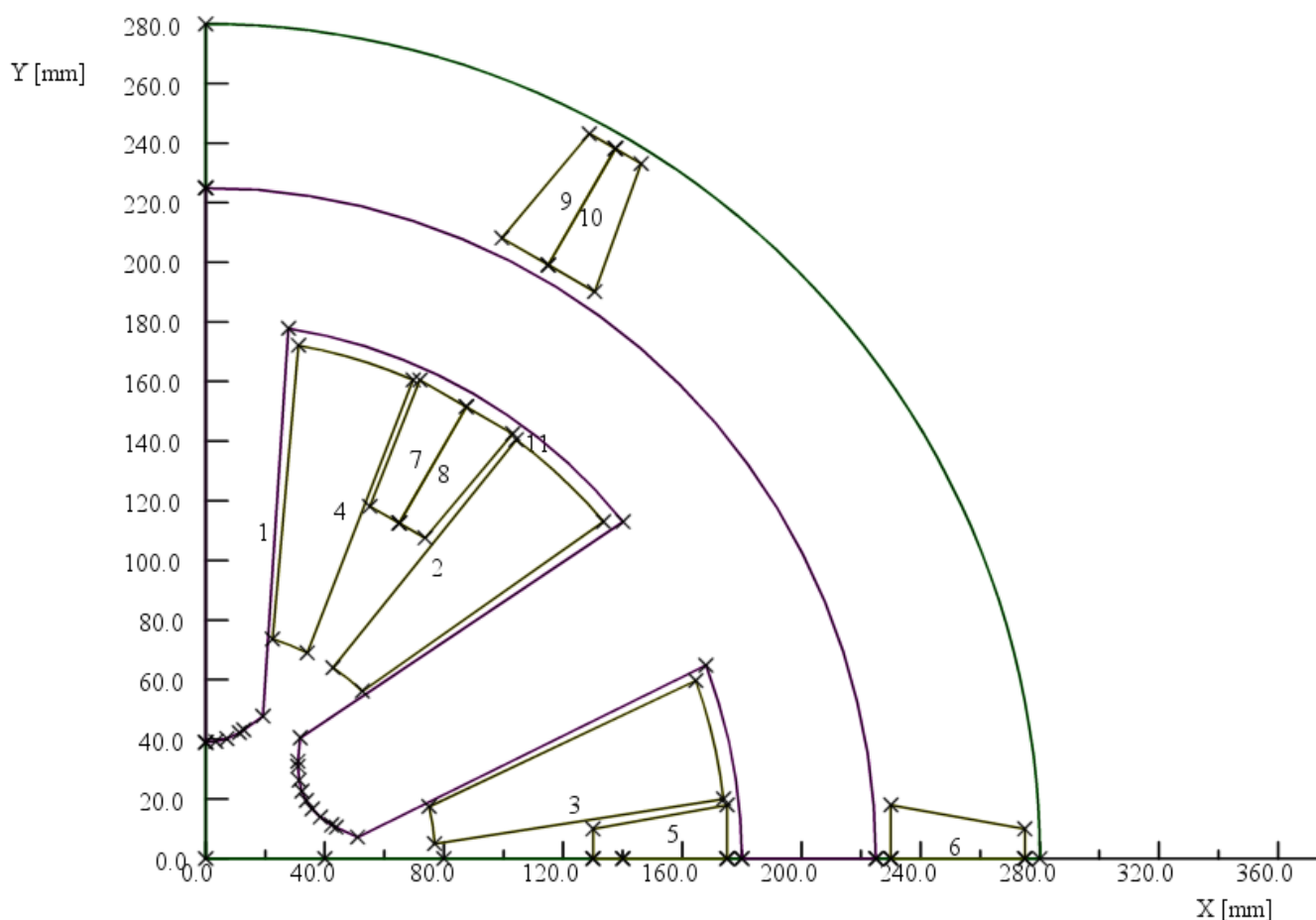


Figure 2.6-3 Geometry used to model correction fields generated by yoke coils 5 to 10.

The required yoke coil polarities and the symmetries that need to be imposed on the x and y axes, to generate the three different corrector fields, are given in Table 2.6-3.

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Table 2.6-3 Polarity of yoke coils and axes symmetries required to generate corrector fields in the sextupole magnets;

Neumann boundary: B tangential = 0; Dirichlet boundary: B normal = 0.

Type of corrector	Coils 5	Coil 6	Coils 7 & 8	Coil 9 & 10	x axis boundary	y axis boundary
Vertical dipole	+ ve	- ve	+ ve	- ve	Neumann	Dirichlet
Horizontal dipole	0	0	+ ve	- ve	Dirichlet	Neumann
Skew quadrupole	0	0	+ ve	- ve	Dirichlet	Dirichlet

2.6.9 Vertical Dipole Field.

In the case of the vertical dipole fields, the coils on the x axis (coils 5 and 6) and at the 60° position (7,8,9 and 10) need to be excited with the same polarity. However, it is possible to adjust the ratio of the Ampere-turns between the two sets of coils (and the corresponding coils elsewhere on the yoke, as determined by the dipole symmetry), presenting one degree of freedom in the excitation of vertical dipole corrector field.

Optimum vertical dipole field quality within the region:

$$0 \leq x \leq 36 \text{ mm};$$

was given with the coil excitations given below; note that the excitation given for the median plane (0°) coil is for the complete coil, including the half sector which is below the x axis, which is prescribed by the boundary conditions.

excitation of 0° coil:	733 At;
excitation of 60° coil:	698 At.

The resulting homogeneity of vertical field on the x axis is shown in Figure 2.6-4 below, the value of vertical flux density at (0,0) being 0.0170 T.

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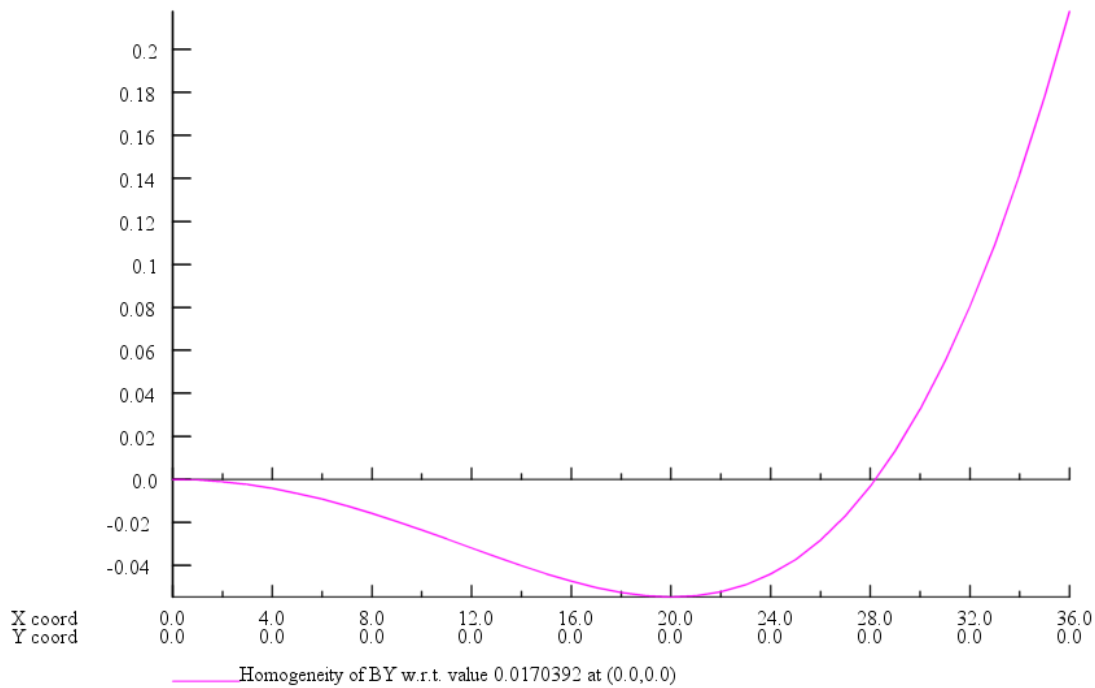


Figure 2.6-4 Homogeneity of vertical flux density generated by yoke coils optimised for a horizontal aperture of 36 mm.

Figure 2.6-4 demonstrates the following homogeneity in vertical flux density on the x axis:

$$\begin{array}{lll} \Delta B_y / B_y (0) = & -6\%; & x = 20 \text{ mm;} \\ \Delta B_y / B_y (0) = & 0; & x = 28 \text{ mm;} \\ \Delta B_y / B_y (0) = & +20\%; & x = 36 \text{ mm.} \end{array}$$

Adjustment of the ratio of the current densities in the coils allows the field quality in the range:

$$0 \leq x \leq 25 \text{ mm;}$$

to be optimised, at the expense of field quality outside this region.

With the following coil excitations:

$$\begin{array}{ll} \text{excitation of } 0^\circ \text{ coil:} & 821 \text{ At;} \\ \text{excitation of } 60^\circ \text{ coil:} & 615 \text{ At;} \end{array}$$

the field homogeneity shown in Figure 2.6-5 was obtained, with a value of flux density of 0.0171 T at (0,0).

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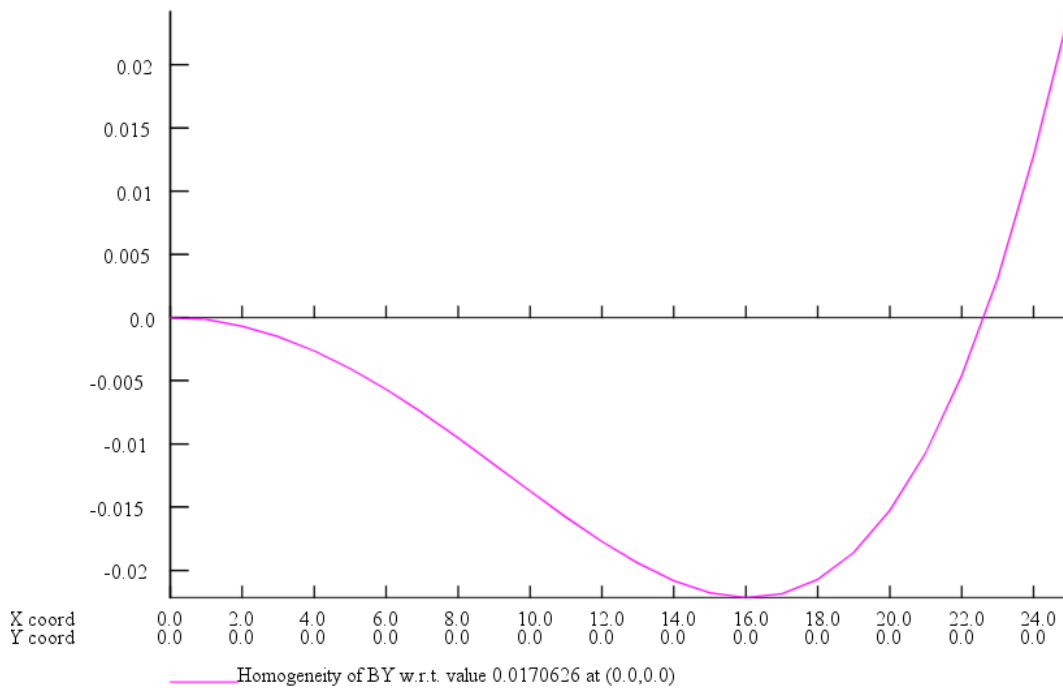


Figure 2.6-5 Homogeneity of vertical flux density generated by yoke coils optimised for a horizontal aperture of 25 mm.

Figure 2.6-5 demonstrates the following homogeneity in vertical flux density on the x axis:

$\Delta B_y / B_y (0) =$	-2.2%;	$x = 16 \text{ mm};$
$\Delta B_y / B_y (0) =$	0 ;	$x = 22.5 \text{ mm};$
$\Delta B_y / B_y (0) =$	+2.5%;	$x = 36 \text{ mm}.$

The quality shown in Figure 2.6-5 is far superior to that of Figure 2.6-4, but is less extensive. Thus, the quality of the vertical correction field generated in the sextupole magnets can be adjusted by controlling the relative amplitude of the excitation between the 0° and 60° yoke coils.

2.6.10 Horizontal Dipole Field.

There is no means of adjusting the quality of the horizontal dipole field generated by the static correction coils; the Ampere-turns in the 60° coils determine the amplitude of the resulting flux density, but the homogeneity is determined by the pole geometry alone.

With the boundary conditions defined in Table 2.6-3 and the yoke coils parameters:

excitation of 0° coil:	0 At;
excitation of 60° coil:	814 At;

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the quality of horizontal dipole field on the y axis shown in Figure 2.6-6 was predicted.

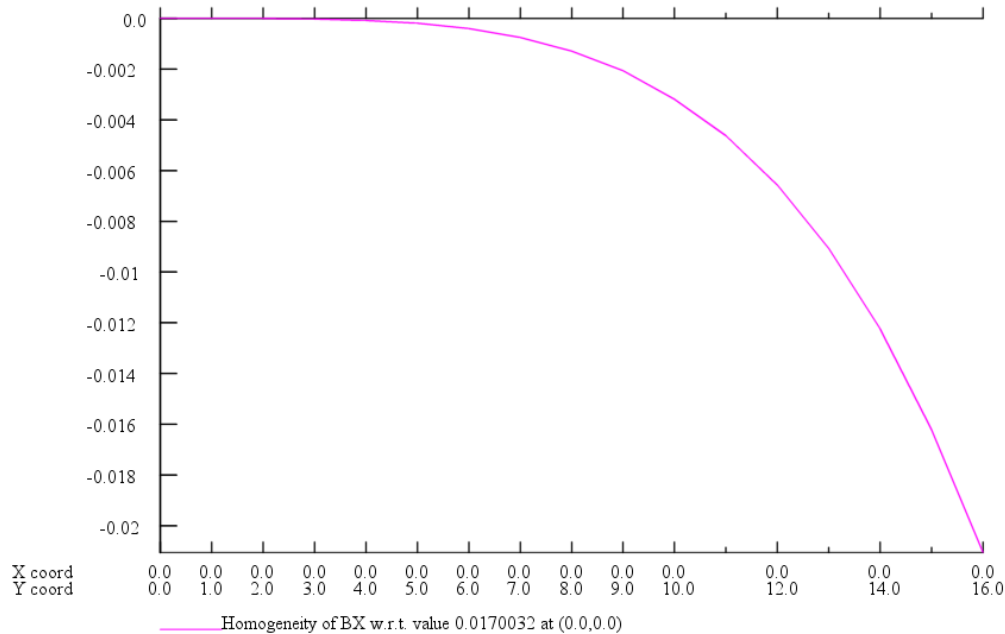


Figure 2.6-6 Homogeneity of horizontal flux density on the y axis generated by yoke coils over a vertical aperture of 16 mm.

The curve extends over the maximum specified vertical aperture and demonstrates the following homogeneity compared to a horizontal flux density (B_x) at (0,0) of 0.0170 T:

$$\Delta B_x / B_x(0) = -2.2\%; \quad x = 16 \text{ mm.}$$

2.6.11 Skew Quadrupole Field.

Skew quadrupole field was simulated using the correct boundary symmetries and the following yoke coil parameters:

excitation of 0° coil:	0 At;
excitation of 60° coil:	455 At.

The skew quadrupole field so generated was of good quality close to the centre of the magnet (0,0) but was of poor quality away from the centre. This is demonstrated in Figure 2.6-7 and Figure 2.6-8 below. Figure 2.6-7 presents the magnitude of the flux density normal to the diagonal line, $y = x$, plotted against distance along that line. Figure 2.6-8 displays the angle of flux cutting the $y = x$ line as a function of displacement along the diagonal; for pure skew quadrupole field this is required to be 90° .

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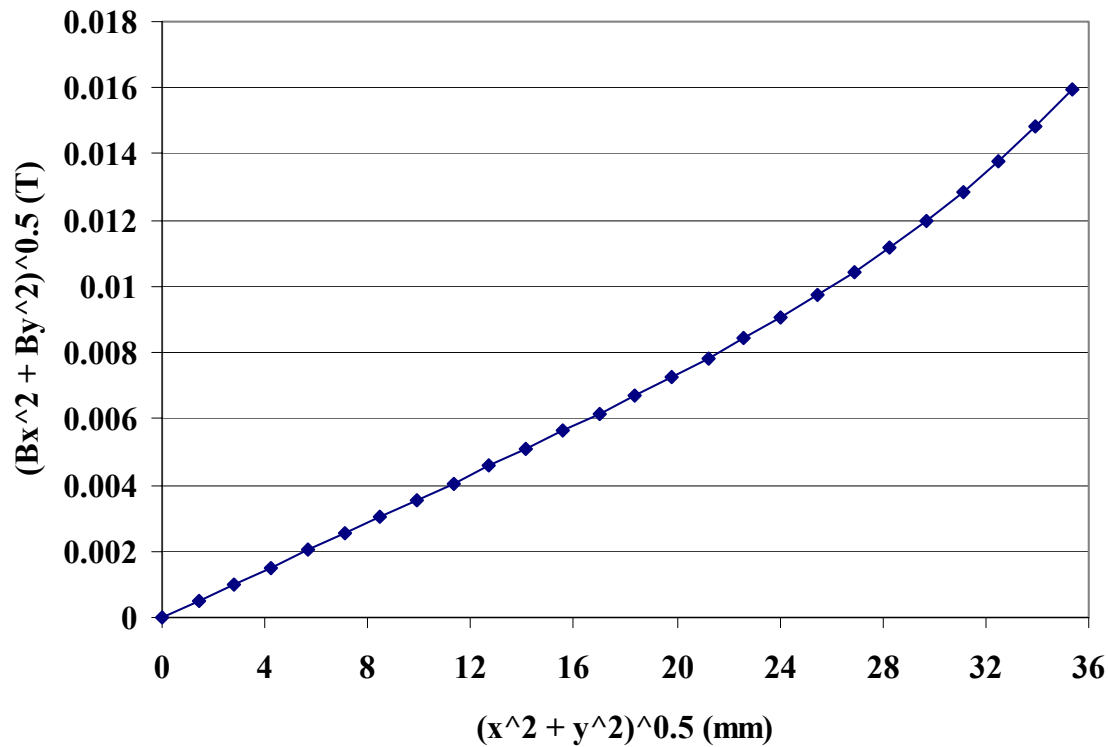


Figure 2.6-7 Variation of flux density along the diagonal $y = x$, with skew quadrupole corrector field excited.

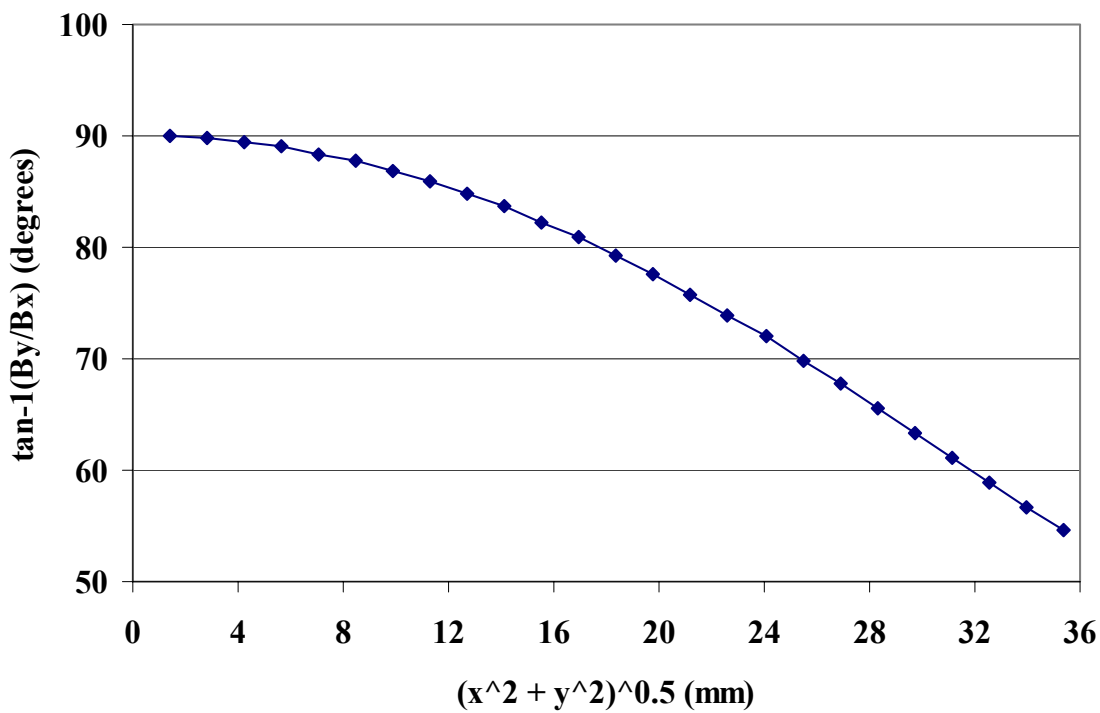


Figure 2.6-8 Angle (in degrees) subtended by flux crossing the $y = x$ axis against distance along the diagonal, with skew quadrupole corrector field excited.

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2.6.12 Dynamic Correction in Back-Leg Coils.

The dynamic control of beam position in the storage ring will be based on the use of specifically designed fast corrector magnets applying horizontal and vertical steering to the beam; it is anticipated that these magnets will have a wide bandwidth (see section 2.7). Additionally, the vertical and horizontal steering correctors incorporated into the sextupoles will be required to provide slow orbit correction. The bandwidth of this system will need to extend from D.C. to an upper limit determined by the A.C. performance of the magnets, their power supplies and the vacuum vessel.

The sextupole magnets, assembled from 1 mm laminations, will certainly support a corrector frequency response up to 5 Hz with little attenuation and modest A.C. losses. However, the vacuum vessel as presently designed will produce high attenuation to field changes of that frequency, with corresponding high power losses. The power supply performance will depend on their specification.

The power supply requirements are therefore based on a total slow corrector bandwidth of:

D.C. to 5 Hz;

but with the power supply reactive voltage specified to provide:

full amplitude deflection at 1 Hz.

At higher frequencies, the maximum amplitude available will be inversely proportional to the applied frequency, i.e. 20% of the specified deflection at 5 Hz.

The reactive volt-amperes required from the back-leg coil power supplies depends on the total alternating flux cutting the coils, and this has been assessed from the values of vector potential predicted for the vertical and horizontal dipole configuration models. The resulting parameters are given below; the values are for 'flux-turns', which have units of volt-seconds, for the back-leg coils as currently designed:

maximum in median plane coil, vertical dipole:	0.34	Vs;
maximum in 60° coil, vertical dipole:	0.30	Vs;
maximum in 60° coil, horizontal dipole:	0.32	Vs.

These parameters are the basis for the back-leg coil power supply a.c. ratings given below (section 2.6.16).

It should be noted that, because of the sextupole's symmetry, oscillations in the horizontal dipole correction field will not induce voltages in the sextupole circuit. However, the vertical dipole field has sextupole error components and any oscillations in the vertical correctors will therefore induce small alternating voltages in the main sextupole circuit. It will therefore be necessary to ensure that the main

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sextupole power supplies will be able to reject this small A.C. signal, without loss of stability in the pole coil direct current excitation.

2.6.13 Coil Parameters - Pole Coils.

As in the quadrupoles, the current density in the pole coils, which excite the main sextupole field has been fixed at 3 A/mm². This results in the following parameters for the pole coils:

minimum amplitude linearity:	98%;	
sextupole inscribed radius:	39	mm;
operating sextupole strength (differential):	550	T/m ² ;
required total Amp-turns per pole:	4414	At;
number of turns per pole:	48;	
operating current at 550 T/m ² :		92 A;
current density in copper:	3	A/mm ² ;
conductor cross-section:	30.7	mm ² ;
conductor dimensions:	6.0 x 5.9	mm ² ;
water cooling tube diameter:	2.5	mm;
maximum water temperature rise:	10	°C
maximum cooling water pressure drop:	5	bar.

2.6.14 Coil Parameters - Back-Leg coils.

The back-leg coils have different current ratings for each of the corrector fields. The independent generation of the different correctors calls for the excitation current in each back-leg coil to be the sum of the required Ampere-turns for each field type. There are two ways of meeting this requirement:

- the back-leg coils are wound with separate circuits for each corrector; the separate sets of windings are then connected to produce three separate circuits, corresponding to the three types of corrector, for each magnet;
- the back-leg coils are wound as a single circuit; the central control system then calculates the current distribution needed on each sextupole to generate the required combination of correction field.

These alternative methods lead to differing advantages and problems, as summarised below in Table 2.6-4.

The final choice in this matter will be made at a later stage; for the purposes of this design report, the number of power supplies and control parameters have assumed the single back-leg circuit, with processor calculation option. Likewise, in the coil parameters and engineering layouts given below, single circuit back-legs have been assumed. However, the number of turns in the back-leg coils, and hence the overall coil dimensions, would not change if multiple circuits were adopted.

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Table 2.6-4 Strengths and weakness of alternative connection methods for back-leg coils.

	Multiple back-leg circuits	Single back-leg circuit.
correct distribution of corrector currents:	by hard wire connection at sextupoles;	calculated by central processor;
number of corrector power supplies per sextupole:	3	5
no. of corrector control parameters per sextupole:	3	5
number of types of back-leg coil:	2 types on each magnet - types A and B;	all back-leg coils identical;
terminals per back-leg coil:	6 terminals on type A, 2 terminals on type B;	2 identical terminals on all back-leg coils;
flexibility:	maximum current fixed for each circuit - no flexibility	individual correctors can exceed specified value if low current in other fields;
current distribution and power loss:	individual coils can have equal and opposite currents in adjacent circuits, producing high loss with low excitation;	only necessary currents flow in each coil;
dynamic response:	distribution does not need calculation; speed of dynamic response not compromised;	processor needs to calculate distribution in real-time when dynamic response is required;
differing requirements for vertical dipole distribution:	vertical dipole field quality fixed by turns in individual circuit in each coil;	central processor can adjust current distribution to give optimum vertical correction field according to position in lattice.

The back-leg coil parameters are based on there being a large number of turns of small cross-section conductor. These are not water but convection cooled; current density therefore has to be low, less than 1 A/mm². Back-leg coil parameters are:

required Amp-turns for vertical dipole:	700	At;
horizontal dipole:	820	At;
skew quadrupole:	480	At;
total Amp-turns per coil:	2000	At;
number of turns per pole:	440;	
operating current at full amplitude:	4.5	A;
current density in copper:	0.9	A/mm ² ;
conductor cross-section:	5.0	mm ² ;
conductor diameter:	2.5	mm.

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2.6.15 Sextupole Engineering Layout.

A cross-section of the complete sextupole is shown below in Figure 2.6-9. The location of the six pole coils (to generate sextupole field) and the five back-leg coils (for correction fields) are shown. The drawing also shows emerging synchrotron radiation beams in a number of positions in the radial outer region of the magnet. The vertical limb which supports the sextupole in this region needs to be non-magnetic, otherwise it would 'short-out' the Ampere-turns generated by the back-leg coil on the median plane in the radial inner region of the magnet. Unlike the quadrupole, which has no magnetic limbs crossing the median plane, sextupole symmetry demands that such a feature is present at least at one position in the magnet.

The diameter of the outer steel yoke is 550 mm.

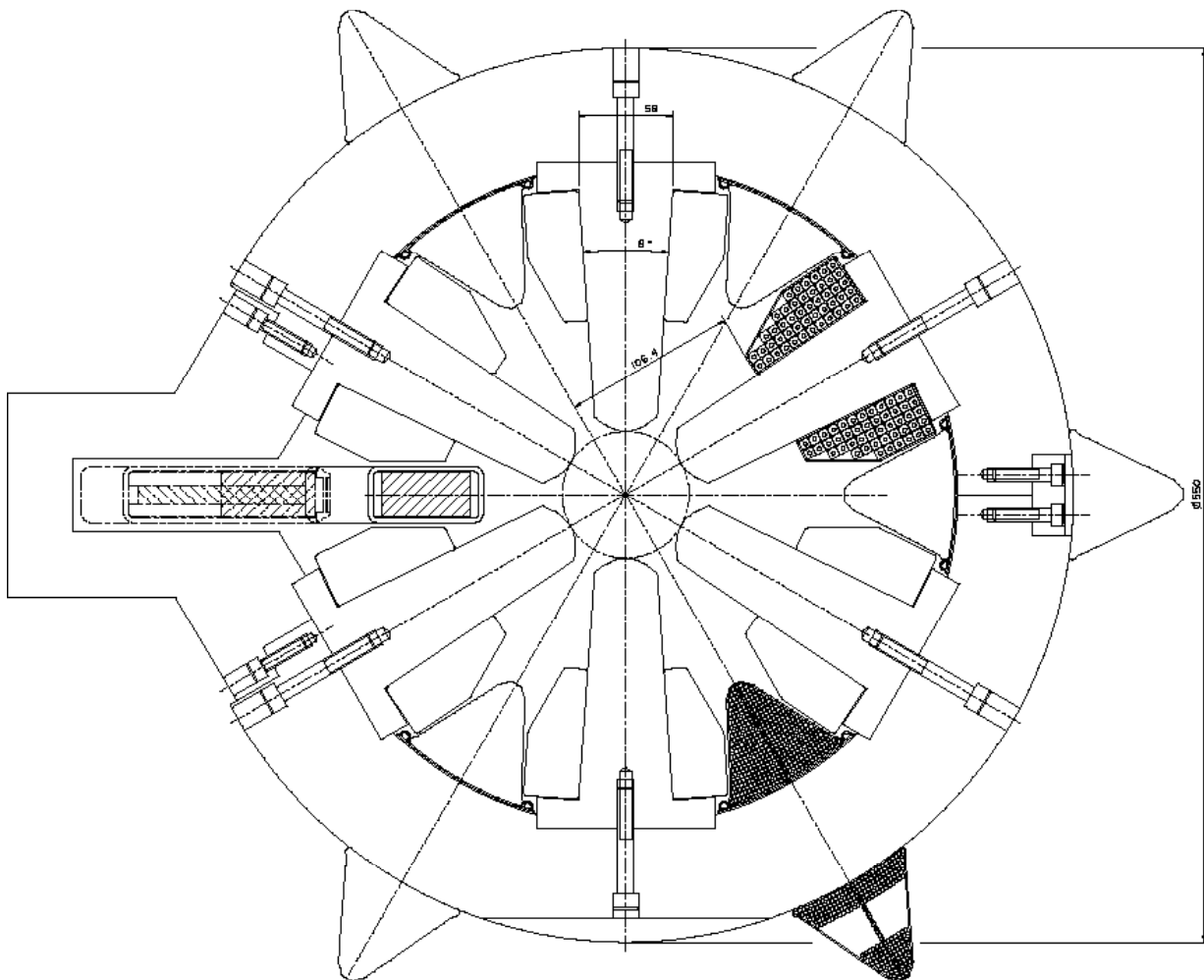


Figure 2.6-9 Cross-section through sextupole magnet, showing the possible positions of emerging synchrotron radiation beams in the radial outer region of the magnet.

Temperature variations in the yokes of the multipole elements in the storage ring are a source of positional instability in the beam, and an isothermal environment is needed to minimise these effects. It is therefore intended to locate a thin, single circuit water

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cooled heat-sink between the inner section of each back-leg coil and the magnet yoke. This will prevent the modest amount of heat generated in the inner bore of the magnet being conducted directly into the annular yoke.

An isometric view of the sextupole poles and yoke is shown in Figure 2.6-10. The magnet will be manufactured from the same laminated steel that is to be used for the dipoles and quadrupoles. However, each pole will be separately stamped and built up from a stacked assembly of glued laminations; each half of the annular yoke will also be separately manufactured. In this way it is possible to assemble the complete magnet, threading back-leg coils onto the yoke before offering up the poles, complete with their pole coils.

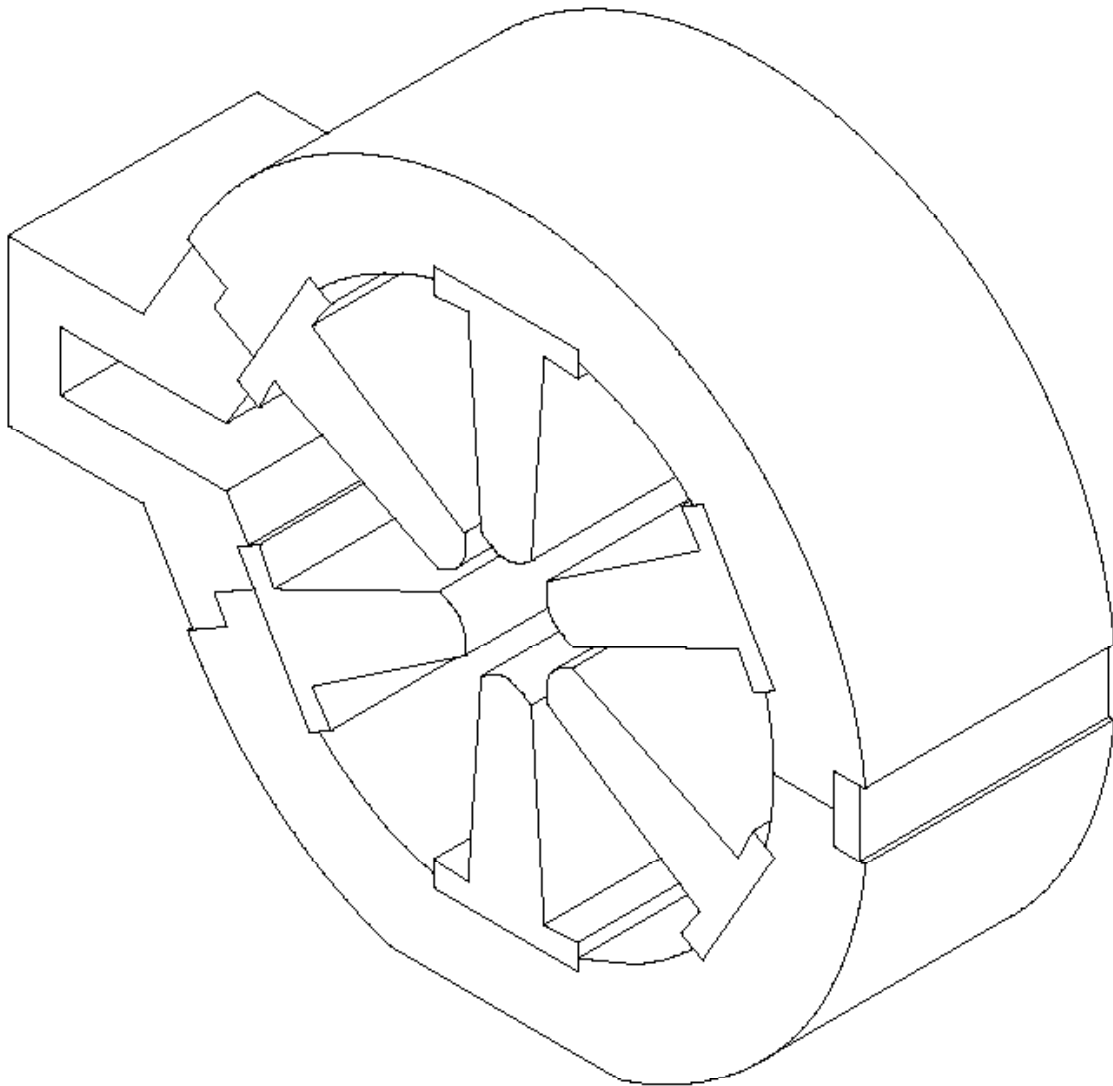


Figure 2.6-10 Isometric view of the sextupole magnet poles and yoke construction.

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2.6.16 Power Supply Ratings.

As with the quadrupoles, the sextupoles will be powered and controlled individually. This again calls for a low current specification which is compatible with coil and winding geometry. This leads to a choice of a maximum power supply current of 100 A. The resulting power supply ratings for the pole coils on the two different lengths of sextupole are given in Table 2.6-5, below.

Table 2.6-5 Power supply ratings for sextupole pole coils.

Sextupole length	0.3	0.2	m
Gradient (differential)	550	550	T/m ²
Turns per coil	48	48	
Operating current per turn	92	92	A
Current stability	1 : 10 ⁴	1 : 10 ⁴	
Current density	3.0	3.0	A/mm ²
Resistance per sext. at 40°C	144	107	mΩ
Operating volts per sext.	13.2	9.9	V
Volts (inc. cables and terminals)	13.9	10.4	V
Power supply rated current	100	100	A
Power supply rated voltage	15.3	11.4	V
Power supply rated power	1.5	1.0	kW

The corresponding ratings for the back-leg coils, are given in Table 2.6-6.

Table 2.6-6 Power supply ratings for sextupole individually powered back-leg coils.

Sextupole length	0.3	0.2	m
Number of coils per sextupole	5	5	
Turns per coil	440	440	
Operating current per turn	4.5	4.5	A
Current density	0.9	0.9	A/mm ²
Resistance per coil. at 60°C	1.6	1.2	Ω
Operating D.C. volts per coil	7.2	5.6	V
Power supply rated current	5.0	5.0	A
Power supply resistive voltage	8.3	6.4	V
Maximum power per coil	42	28	W
Maximum dynamic band-width	0 - 5	0 - 5	Hz
Max. frequency for 100% steering	1	1	Hz
Maximum reactive voltage (peak)	3.9	2.6	V

2.7 DYNAMIC CORRECTORS.

2.7.1 Requirements.

The dynamic correctors are required to apply both horizontal and vertical steering to the circulating beam in order to maintain high positional stability. These magnets will therefore be the output stage of a global feedback system, which detects the position of the electron beam at many points in the lattice and corrects errors induced by motion and stray fields. This section is not concerned with the feedback system *per se* but with the initial design of the magnetic elements and the consequential ratings of the power supplies.

Both horizontal and vertical steering can be incorporated into a single magnet assembly.

2.7.2 Geometry.

The dynamic correctors will have a classical 'window-frame' design, for this allows the inclusion of both horizontal and vertical dipole field onto the same yoke and provides the best possible field homogeneity without elaborate shimming of the pole sides. A diagram, showing a cross-section through a dynamic corrector, is shown in Figure 2.7-1.

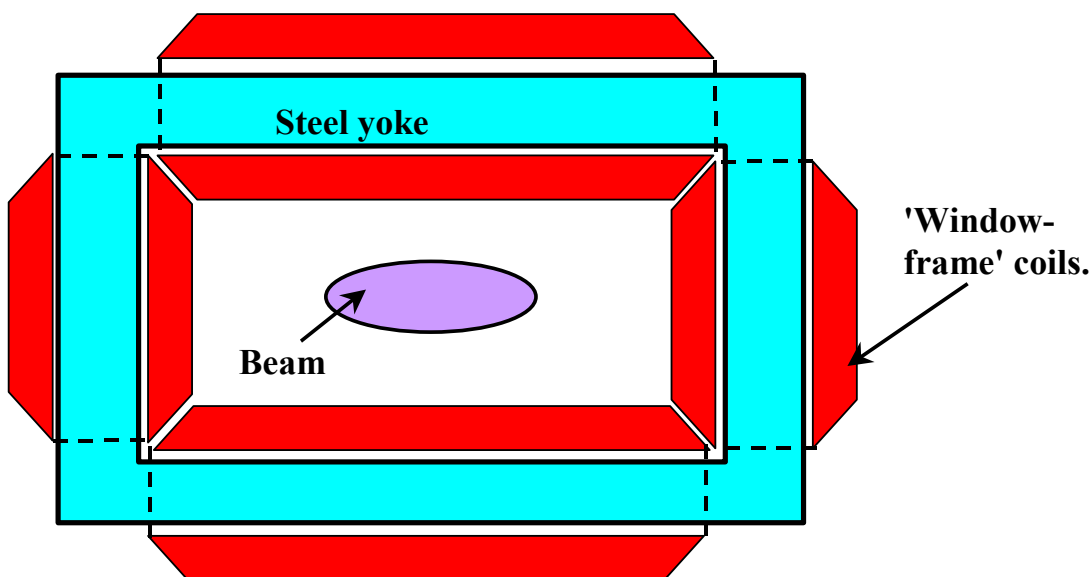


Figure 2.7-1 Cross-section through a dynamic corrector magnet.

2.7.3 Specification and magnet parameters.

The specification of the dynamic correctors must, at this stage of the DIAMOND design, be regarded as provisional. Given below is a 'reference' design, to provide a basis for further accelerator physics and engineering planning but which is subject to

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change as further information on environmental impact on beam stability accumulates. Performance parameters can then be reviewed prior to procurement.

The present design is based on the following specification:

maximum deflection (horizontal and vertical);	0.5	mrad;
maximum physical length of correctors;	0.25	m;
length of steel yoke:	0.19	m;
expected magnetic length;	0.2	m;
correction fields in each plane:	0.025	T;
horizontal vessel aperture:	84	mm;
vertical vessel aperture:	36	mm.

These requirements can be met with the following magnet parameters:

yoke horizontal aperture:	148	mm;
yoke vertical aperture:	100	mm;
coil conductor diameter:	1.5	mm;
number of turns per vertical limb	1,200;	
number of turns per horizontal limb:	1,780;	
peak current per turn:	1.7	A;
minimum frequency response:	3	Hz;
maximum frequency response:	1	kHz;
full deflection possible up to frequency	50	Hz.

2.7.4 Power Supply Requirements.

The power supply ratings are based on the current required to produce the full 0.5 mrad deflection in each plane. However, in determining the power supply voltage specification, it is necessary to define the magnet's deflection versus frequency performance. Whilst a maximum frequency response of 1 kHz is specified, it is unnecessary to apply a voltage rating which will allow the full deflection of the magnet at that frequency. The voltage specification of the fast correctors is therefore based on the full deflection being available at a frequency of 50 Hz; above this value, the maximum amplitude response of the magnet will decrease inversely with the signal frequency.

Power supply parameters are:

number of coils per fast corrector:	4;	
maximum RMS current per coil:	1.2	A;
maximum RMS voltage per coil	200	V;
resulting power supply reactive rating	240	VA.

During detailed design it will be necessary to examine the attenuation generated by the coil conductor and magnet steel at the high frequency end of the response curve and, if necessary, change the conductor cross-section, producing a series/parallel

E.2 LATTICE MAGNETS

assembly which has a smaller wire diameter but which provides the required current carrying capacity.

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E.3 Radio Frequency

3.1 INTRODUCTION

The storage ring radio frequency (RF) system provides sufficient accelerating voltage to accelerate the circulating electron beam, and is used to make up any energy lost by the beam. The loss is as synchrotron light or as parasitic loss because of the vacuum chamber impedances. The quantum lifetime is directly dependent on the RF overvoltage, as is the Touschek lifetime via the energy acceptance.

The energy lost as synchrotron light is from two sources, the bending magnets, and is fixed by the dipole field and the storage ring energy, and the insertion devices (ID), which is variable and dependent on the number and type of ID used as well as the storage ring energy. In calculating the RF power requirements an estimate is made of the maximum energy lost when all the IDs are installed.

3.2 RF SYSTEM

3.2.1 Acceleration Voltage

The acceleration voltage is determined by the storage ring energy loss per turn. As this is dependent on the total loss from the bending magnets (1.005 MeV/turn) and the IDs, an estimation of the loss per turn from the final full complement of IDs must be made; this is assumed to be 0.73 MeV/turn, based on a realistic portfolio of high and low field devices. The assumed parasitic loss is 0.05 MeV /turn. Therefore the total loss/turn is 1.785 MeV/turn.

The acceleration voltage is the energy loss/turn multiplied by the overvoltage factor q . This factor is dependent on some lattice parameters, particularly the momentum compaction, weakly on the RF frequency, the required quantum lifetime, and strongly on the RF acceptance. Clearly the RF system has to provide the acceleration voltage for the full complement of IDs.

3.2.2 Beam power

The RF power required to make up the energy lost/turn is simply the total energy lost/turn multiplied by the beam current. If the beam current is 300mA and the total energy loss/turn is 1.785 MeV, the beam power is 536 kW.

The table below shows the acceleration voltage and the beam power for:

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- a) No IDs installed
- b) Day 1 IDs installed
- c) Full complement of IDs.

Table 3.2-1 Basic RF Parameters

	No IDs		Day 1 IDs		22 IDs	
Energy (GeV)	3		3		3	
Energy lost dipoles (MeV/turn)	1.0		1.0		1.0	
Energy lost IDs (MeV/turn)	0		0.13		0.73	
Parasitic Loss (MeV/turn)	0.05		0.05		0.05	
Energy Acceptance (%)	4		4		4	
Acceleration Voltage (MV)	3.1		3.3		4.0	
Overvoltage	2.94		2.79		2.24	
Current (mA)	300	500	300	500	300	500
Beam Power (kW)	316	527	355	592	536	893

3.3 RF FREQUENCY

The choice of frequency is usually based on technical and practical arguments rather than beam dynamics, such as available power sources, cavity dimensions and shunt impedance. The lower the frequency the longer the bunch length, and the higher the single bunch instability limit, and fewer bunches in multi-bunch the easier to counteract instabilities. Touschek lifetime depends sensitively on bunch current and RF frequency, and it has recently been argued that the optimum frequency is around 500 MHz.[1]

Injection into the storage ring is also eased and optimised if the storage ring frequency is a sub harmonic of the linear accelerator (linac) frequency. The European standard linac frequency is 2997.924 MHz. So RF frequency has been chosen as 499.654 MHz, i.e. one sixth the frequency of the linac.

3.4 ACCELERATING CAVITY

3.4.1 Cavity Choice

The RF cavity provides the accelerating voltage gap and the means of transferring the power to the circulating beam. For acceleration the fundamental mode is used – TM_{010} , the electric field is longitudinal and there is no magnetic field on the axis. The cavity, however, is capable of resonating at higher order frequencies (HOMs). These HOMs can only be excited if the circulating electron beam contains these frequencies. The RF cavities take up valuable straight space in any storage ring, and for DIAMOND it has been decided that only one 8 metre straight can be used for the accelerating cavities.

The power, P_c , to provide the accelerating voltage is

$$P_c = V_c^2 / 2R_o \quad (1)$$

Where V_c is the acceleration voltage, and

R_o is the cavity shunt impedance.

The shunt impedance can be defined as

$$R_o = (R_o/Q_o) \times Q_o \quad (2)$$

Where (R_o/Q_o) is a geometric figure of merit, independent of cavity material or frequency, and

Q_o is a quality factor, defined as the cavity stored energy divided by the power dissipated in the cavity.

To minimise the number of cavities and to keep the power required to provide the accelerating voltage low, the shunt impedance needs to be large.

For normal conducting cavities this means that (R_o/Q_o) must be large, with the consequence that the re-entrant nosecones must be as big as possible and the beam pipe radius as small as possible. In general the larger the (R_o/Q_o) , there will be more and stronger HOMs, which means that the current threshold for multi-bunch instabilities will be lower. Also the larger the (R_o/Q_o) , the larger the machine broadband impedance, and consequently the lower the current threshold limit for single bunch instabilities.

There are various techniques for overcoming the effects of HOMs, but these techniques add further complication. The techniques are designing a cavity with damping waveguides. For example the EU funded project to design a normal conducting HOM damped cavity [2], accurate temperature control of the cavities,

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orbit harmonic separation of the cavity frequencies, and the use of longitudinal and transverse feedback systems.

For superconducting cavities Q_0 is very large, so that (R_0/Q_0) can be small. The cavity is a simple bell-shape with no re-entrant nosecones and a large beam pipe radius. No HOMs are trapped inside the cavity. All modes are transmitted down the beam pipe where they are either coupled out by loops or are absorbed in ferrite absorbers. In general the smaller the (R_0/Q_0) , there will be less and weaker HOMs, which means that the current threshold for multi-bunch instabilities will be higher. Also the smaller the (R_0/Q_0) , the smaller the machine broadband impedance, and consequently the higher the current threshold limit for single bunch instabilities.

Table 3.4-1 compares the relevant parameters for normal and superconducting cavities. The instability threshold currents are given in E 1.7

Table 3.4-1 Cavity Parameters

	Cornell	KEK-B	EU Cavity
Vc/cell (MV)	2.5	2	.8
Gradient (MV/m)	8.33	6.79	3.6
TM010 R_0/Q_0 (Ω)	44.5	46.5	122
Max $R_{HOM}^{\parallel}$ (Ω)	200	1000	756
Max $R_{HOM}^{\perp}$ ($k\Omega/m$)	2.5	0.85	48.2

As Daresbury Laboratory had no experience in the design, procurement and operation of superconducting cavities an international workshop was held [3] with the following remit:

- 1) Does SRF avoid HOM instabilities?
- 2) Is SRF reliable?
- 3) Is there an Optimum Frequency?
- 4) Is SRF Economical?
- 5) Can SRF be obtained from Industry?
- 6) What Infrastructure is needed?

The workshop came up with the following conclusions:

- 1) SCRF is a realistic option for DIAMOND.
- 2) The capital cost of SCRF is similar to that for a well damped room temperature system.
- 3) SCRF has lower operating costs than an equivalent well damped room temperature system, even taking into account the power consumed by the helium compressor.
- 4) A bunch by bunch feedback system is needed for beam stability for either room temperature or SCRF, but will be simpler and cheaper for the latter.

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- 5) For a laboratory without SCRF experience the optimum solution is to adopt a SC cavity and coupler design which have been proven in an operating accelerator.
- 6) A laboratory with some experience of operating cryogenic systems of the order of 100 W should find no difficulty in operating an SCRF system.
- 7) The choice of frequency is available between 350 and 500 MHz.
- 8) A system at 500 MHz based on CESR experience can be supplied by industry.
- 9) Provided that the SCRF is conservatively rated, particularly the coupler, reliable operation suitable for a Synchrotron Light Source can be achieved.
- 10) The cryogenic system capacity should be overspecified by about a factor of 2.
- 11) There should be some redundancy for major items designed into the SCRF system.

It has therefore been decided to select a superconducting cavity solution for DIAMOND, and to base this either on the Cornell CESR cavity or the KEK-B cavity. The following figures illustrate practical layouts of three such cavities in a long straight.

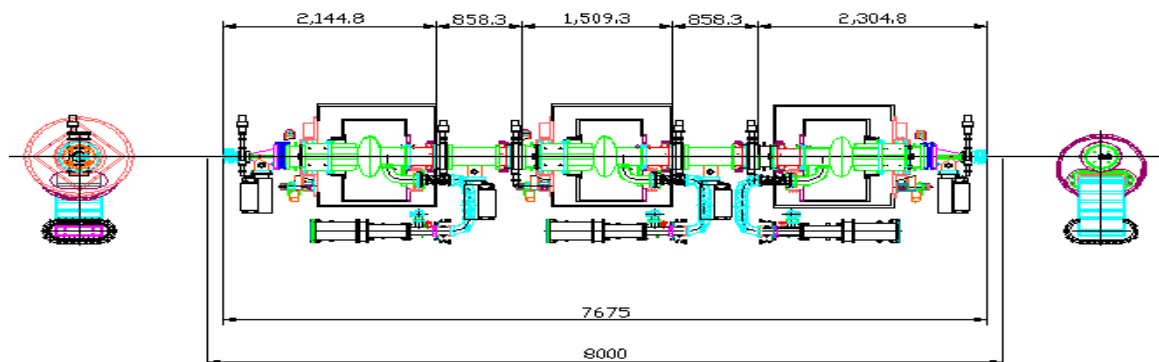


Figure 3.4-1 3 Cornell cavities in a DIAMOND long straight

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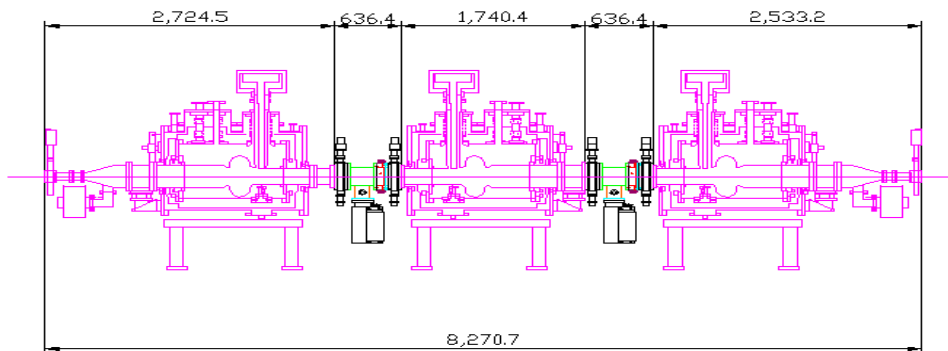


Figure 3.4-2 3 KEK-B cavities in a DIAMOND long straight

3.4.2 Cavity Power

As the (R_o/Q_o) of both the Cornell cavity and the KEK-B cavity are similar, the Cornell cavity is used to work out the cavity power requirements.

It is assumed that the Q_o of the cavity is 10^9 , and that the maximum voltage per cavity is 2MV.

Therefore from equation (1), the power required per cavity is 45W.

3.4.3 Power Coupling

(a) Cornell Cavity

The RF power is coupled to the Cornell cavity through an aperture coupling, via a waveguide feeder system. The maximum power transfer during present operations is 300kW, but development work is taking place to improve this performance.

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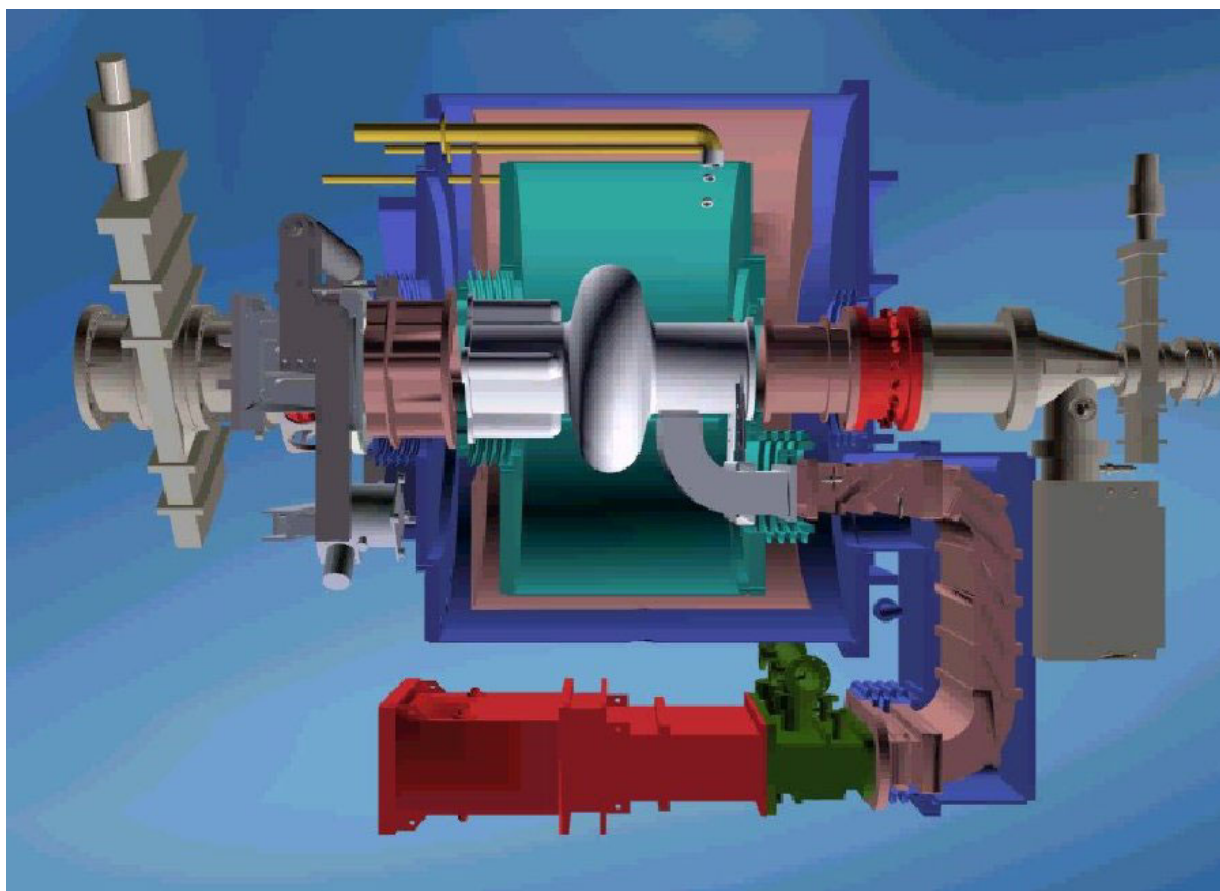


Figure 3.4-3 Model of Cornell cavity, showing waveguide aperture coupling

(b) KEK-B Cavity

The RF power is coupled to the KEK-B cavity by an input loop, and the maximum power through the coupler in normal operations at KEK is 350kW.

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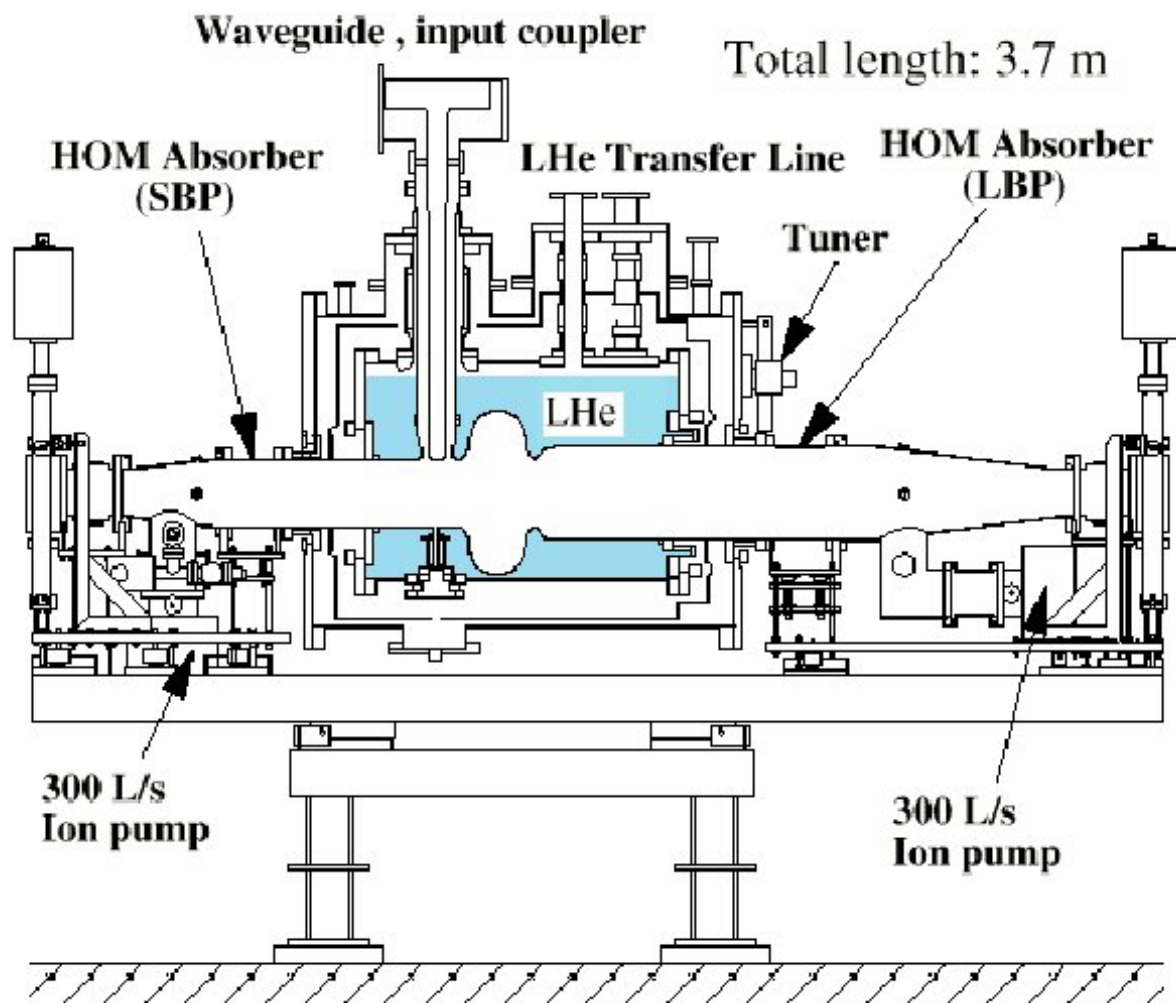


Figure 3.4-4 Schematic of KEK-B cavity, showing input coupling loop

3.4.4 Reliability

The light source has to operate reliably and efficiently, so the RF system has to also operate reliably and efficiently. Consequently the cavities will be operated at levels at least 20% of their maximum performance in terms of accelerating voltage and power coupled to the cavity.

3.5 CRYOGENIC SYSTEM

3.5.1 Introduction

The use of superconducting cavities in the storage ring will require the use of a large refrigeration system to supply the liquid helium (LHe) that cools the cavity to its operating temperature of 4.3 K. For reliability reasons, it has been decided to use a cryogenic system with at least 50% overcapacity, along with LHe and gaseous He storage.

As the Cornell and KEK-B cavities have similar cryogenic performance, all the design work has used the Cornell data.

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3.5.2 Heat load requirements

The Cornell cavity and cryostat has a dynamic heat load per cavity of 45W.

The static heat load adds an additional 30 W per cavity of cooling.

This results in a total heat load per cavity of 75 W.

Commercial LHe transfer lines require about 1 W of cooling per metre, and an allowance of up to 40m has been made for the distance between the refrigeration unit and the SC cavity location.

The total heat load, using commercial transfer lines is

$$1.5 \times 3. \times (75 + 40) = 517.5W$$

A more detailed preliminary design of the system is currently being undertaken to size the installed refrigeration system. This will also take into account other budgetary considerations.

3.5.3 Cryogen and gas storage

Each cryostat bath requires 500 litres of LHe in their present form, although there are developments in hand to reduce the LHe bath volume. It is common practice to have a gas storage unit large enough to contain more than two times the entire cryostat inventory. Under normal operation, the gas storage would only be approximately half full. The LHe storage capacity should also be large enough to store in excess of the total cryostat inventory. Under normal operation, we would have enough helium to fill the cryostats two more times, once from the LHe storage and once from the gas storage reserves. In the case of a planned warm up, the He inventory from the cavity cryostats can be stored in the gas storage and LHe storage facilities. As a rough guideline, one litre of LHe will take up about 2.3 cubic feet (65 litres) at 200 psi (1379 kPa). A LHe storage unit in excess of 1500 litres, and two 3000 cubic foot (85000 litre) gas tanks should be more than adequate. The exact storage requirements will have to be revisited in the future when cost and space requirements are better defined.

3.5.4 Vibration management

In configuring the cryogenic system there are a few things that must be kept in mind. Reliability of the system is of the upmost importance. As well, the refrigeration unit and any auxiliary equipment i.e. compressors, must conform to the vibrational requirements of DIAMOND. To minimize vibrations, there is a need to restrict the use of reciprocating machinery. Screw compressors along with turbine liquefiers have little vibration signatures, although more expensive than the reciprocating piston variety these require far less maintenance and have a longer running life. To increase reliability and flexibility the use of two or three liquefiers running in parallel would

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allow for maintenance to be done on one unit without major interruption to the operation of the storage ring.

3.5.5 Compression

Helium gas is compressed to about 13 bar in the single stage screw compressor, the compression heat being removed by an aftercooler. Residual oil is eliminated from the helium by the oil removal system to ensure that it does not contaminate the liquefier. The gas management system regulates the suction and discharge pressures to maintain maximum operating efficiency.

3.5.6 Refrigeration

Part of the compressed helium (the refrigeration stream) is expanded through two turbo expanders in series to just over atmospheric pressure. This expansion cools the gas which then flows through the low pressure pass of the heat exchangers to provide refrigeration. It returns to the suction of the compressor. Additional refrigeration to increase the liquefaction capacity can be provided by injecting liquid nitrogen into the first heat exchanger as a pre-coolant.

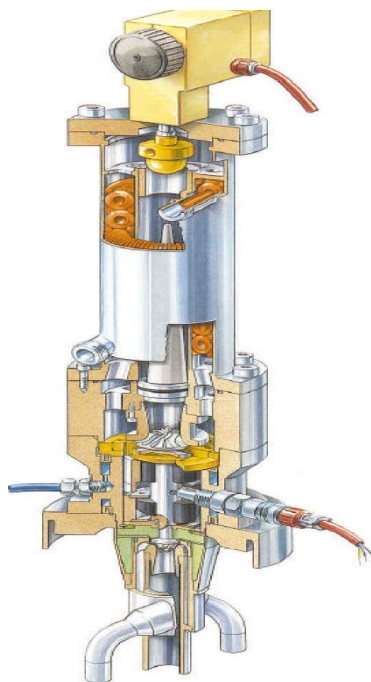


Figure 3.5-1 A Turboexpander

3.5.7 Liquefaction

The remainder of the compressed helium gas (the liquefaction stream) continues through the high pressure pass of the heat exchangers and is cooled in the counter-flow with the refrigeration stream. An absorber removes trace gases as hydrogen. The gas is then expanded by the J-T valve and this further cools and partially liquefies the helium, which then enters a dewar, the liquid helium is then ready for distribution

E.3 RADIO FREQUENCY

while the vapour part returns to the low pressure pass of the heat exchangers so that its cold is recovered as it returns to the compressor.

3.5.8 Purification

A purifier is built into the liquefier so it can operate totally on recycled helium contaminated by air. This is automatic in operation and regeneration and does not require liquid nitrogen for use.

The impure helium is initially cooled in the upper heat exchangers so that the major part of the air contamination liquefies and is discharged. The remaining air is frozen out in the final heat exchanger leaving pure helium that then enters the liquefaction circuit.

A stream of cold gas taken from the main liquefaction process provides the refrigeration for the purifier. The air frozen out in the purifier's final heat exchanger is periodically removed by warming and purging. This is an automatic process and does not interrupt the liquefaction, which continues using pure helium stored in the buffer.

3.5.9 Coldbox architecture

The vacuum insulated cold box vessel is of a vertical design. Contained within this vessel and suspended from its top plate to reduce heat conduction are all the components working at low temperature, such as heat exchangers, turboexpanders, integrated purifier, filters, piping and valves etc. To further minimize the heat in-leak to the process, some components are wrapped with multi-layer superinsulation.

3.5.10 Cooling cycle description

A pair of turboexpanders arranged in series produces the necessary refrigeration by adiabatic work extraction to pre-cool helium gas below its inversion temperature. Further cooling is then achieved by exploiting the Joule-Thomson effect.

Low-pressure gas is compressed in a separate compressor package, cooled and all remaining oil removed. The high purity gas is then fed under pressure to the coldbox and cooled in the first heat exchanger HX.1, which is already pre-cooled by a liquid nitrogen flow stream. The gas passes through HX.2 after which the flow is divided into two streams.

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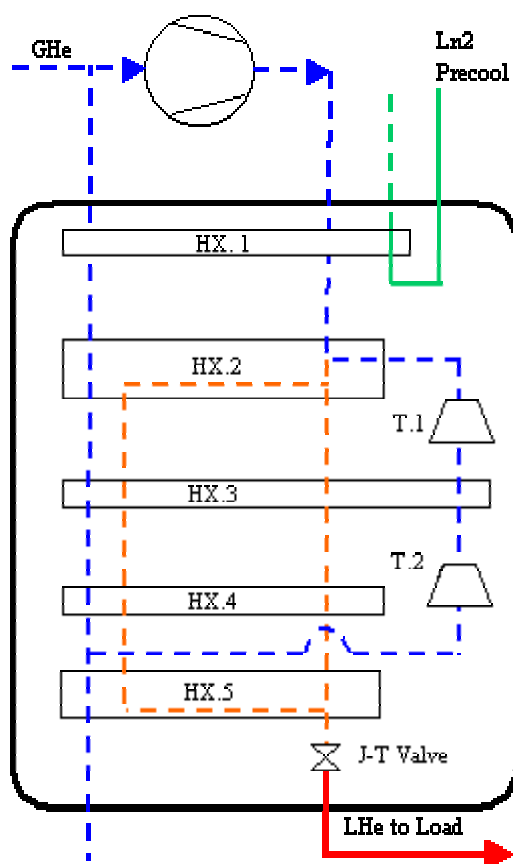


Figure 3.5-2 Liquefaction Cycle

The larger gas stream passes the first turboexpander T.1, where it is forced to do external work, then as a medium pressure gas it passes through HX.3 and is finally expanded to process low pressure in the second turboexpander. It then returns cooling heat exchangers HX.4 through HX.1 to the compressor suction.

The remaining gas stream is cooled as Joule-Thomson flow in heat exchangers HX.2 through HX.5, passing a guard absorber to remove possible impurities such as hydrogen and neon, and then being expanded at the Joule-Thomson valve, where it is partially liquefied. The two-phase mixture is then fed to a dewar vessel or experiment cryostat, where the liquid is separated from the vapour and collected. The flash gas is returned through the low-pressure side of the Heat exchangers and then fed to the suction side of the compressor.

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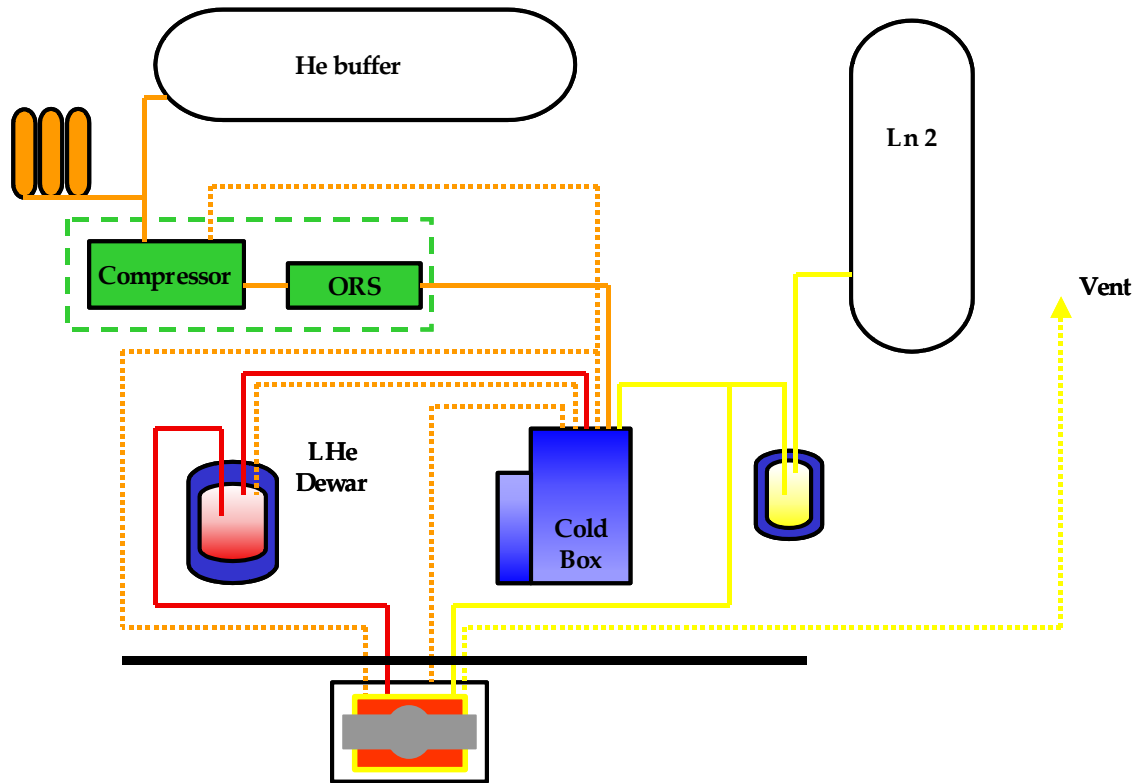


Figure 3.5-3 Typical Cryogenic Layout

3.6 AMPLIFIER

3.6.1 Introduction

As superconducting cavities are being used, the RF power requirement is dominated by the power required to make up the energy loss per turn.

The RF power required for Day 1 IDs and a circulating current of 300mA is 355kW. Assuming 10% losses in the RF feeder system, the total RF power required is 390kW.

The RF power required for a full complement of IDs and a circulating current of 300mA is 536kW. Assuming 10% losses in the RF feeder system, the total RF power required is 590kW.

The RF power required for a full complement of IDs and a circulating current of 500mA is 893kW. Assuming 10% losses in the RF feeder system, the total RF power required is 982kW.

For operational flexibility and reliability, each cavity will be fed from its own RF amplifier system, and the storage ring should be capable of operation, not necessarily with full current, with only 2 cavity systems operational.

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3.6.2 Klystron Option

The klystron is an RF amplifier that uses velocity modulation of a dc beam of electrons to amplify the RF input. It uses several bunching cavities, and is therefore a long device. If it is operated at reduced power there is a rapid reduction in the operating efficiency. For example during the life of a storage ring beam. However it is a high gain device. The bunching cavities are integral to the klystron.

Superpower klystrons operating at 500MHz with output powers of 250kW are available from industry. With further conditioning the output power can probably be increased.

For example the THALES Klystron TH2161 operates at the SRS with the following parameters:

Table 3.6-1 Klystron Parameters

DC Voltage (kV)	-51.0
DC Current (A)	8.48
RF Drive (W)	27
RF Output Power (kW)	260
Gain (dB)	40
Efficiency (%)	60

The expected life of a superpower klystron is approximately 35,000 hours. The usual failure is loss of emission from the cathode. The klystron can be re-gunned, a maximum of twice, the cost is approximately 60% of a new klystron.

The number of manufacturers of superpower klystrons is diminishing, and the cost is increasing, so this may not be the best solution.

3.6.3 Inductive Output Tube (IOT) Option

The IOT amplifier uses a grid to density modulate the electron beam, and so has no bunching cavities, making it a short device. It can have a higher gap voltage, and a higher efficiency than a klystron. The efficiency is approximately constant for reduced output power. However the gain is low.

The expected life of an IOT is approximately 35,000 hours. The usual failure is loss of emission from the cathode. The IOT can be re-gunned, a maximum of twice, the cost is

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approximately 60% of a new IOT. The RF circuits are external to the television IOTs, and a replacement IOT is approximately 67% of the initial system.

The maximum power generally available from the 3 manufacturers is 60kW, but the IOTs can be combined to give the required power output.

A novel way to combine the outputs is shown in figure 3.6-1 and 3.6-2 below. The output power is combined in a combining cavity. For initial operation 3 IOTs can be combined to give an output power of 180kW. The system can then be upgraded to give output powers up to a maximum of 360 kW. Table 3.6-2, below summarises the main parameters of a simulation combining 6 CPI CHK2500W IOT amplifiers in a TM₀₂₀ combining cavity.

Table 3.6-2 IOT Parameters

DC Voltage (kV)	-34
DC Current per IOT (A)	2.2
RF Drive per IOT (W)	160
RF Output Power (kW)	306
Gain (dB)	25
Efficiency (%)	72.6

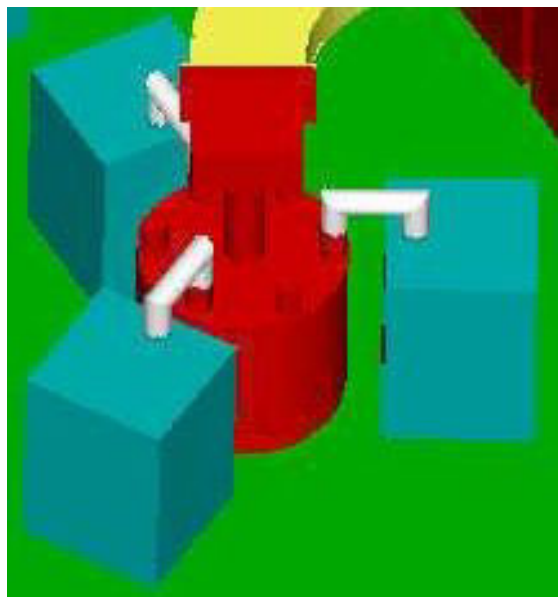


Figure 3.6-1 3 IOTs combined in a combining cavity

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Figure 3.6-2 6 IOTs combined in a combining cavity

3.7 POWER SUPPLY

The power supply required for use with a 250 kW superpower klystron would be 50KV 9A. Due to the fragile nature of a klystron to internal sparking, the power supply would have to limit any spark energy to less than 20 joules. This can be achieved using a crowbar system or using low stored energy techniques, whichever system is used the power to the klystron must be removed in <10uS. The power supply would monitor and control the all the functions of the klystron, waveguide and cavity to provide a complete system for that RF path and safe operation of the expensive klystron valve. The drive system would consist of a 50W RF amplifier, control of the RF power level could be through drive level or Klystron Mod Anode level, this being the favoured option as less cooling will be required.

The IOT system would use a 35KV 15Amp power supply with multiple 2.2Amp feeds to each IOT. The drive system would consist of a 500 Watt RF amplifier with the relative phase and amplitude of each tube monitored and controlled by an overall supervisor system. This will ensure the correct overall RF power requirements for this RF station are met. The supervisor system would also control and monitor the waveguide and cavity systems to provide a fully integrated system to the DIAMOND control system.

Klystron Power Convertor

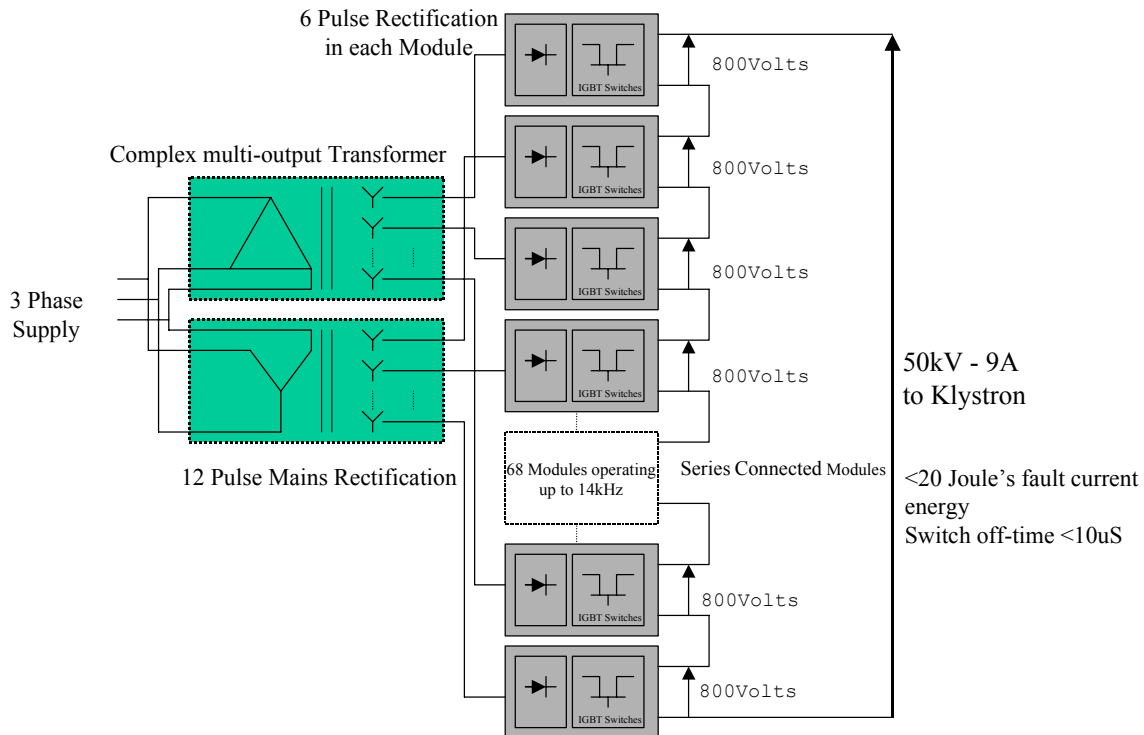


Figure 3.7-1 Klystron power converter

3.8 FEEDER SYSTEM

The distribution of High Power RF will be through WR1800 waveguide. A high power circulator and water cooled RF load will be needed, capable of in excess of 300KW. These can be supported on a high level plinth above the cryogenic system control boxes. The waveguide can then proceed through the ring tunnel wall via a labyrinth where the final connection to the cavity can be made.

RF monitoring systems for reflected power, forward power and VSWR will be needed in the waveguide at various points, immediately after the amplifier device, on both arms of the circulator and at the end of the waveguide before the cavity window.

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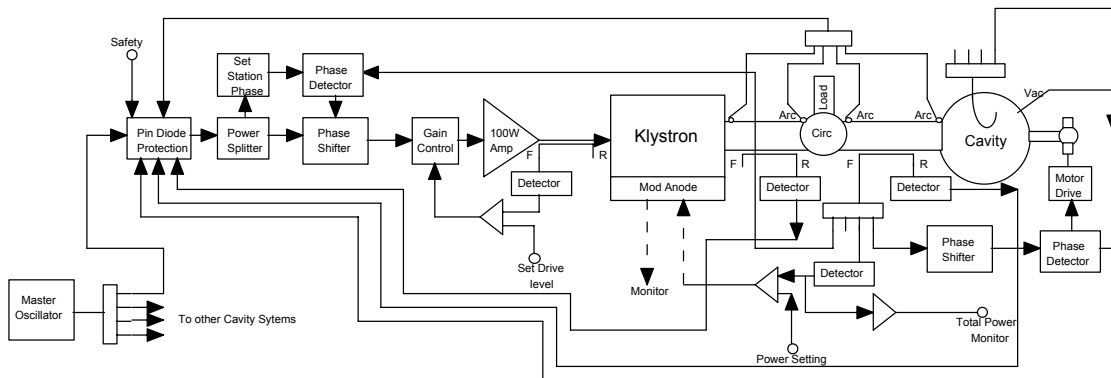


Figure 3.8-1 RF monitoring system for klystron system

Arc detectors will be installed along the waveguide, in particular around the circulator, cavity window and amplifier window.

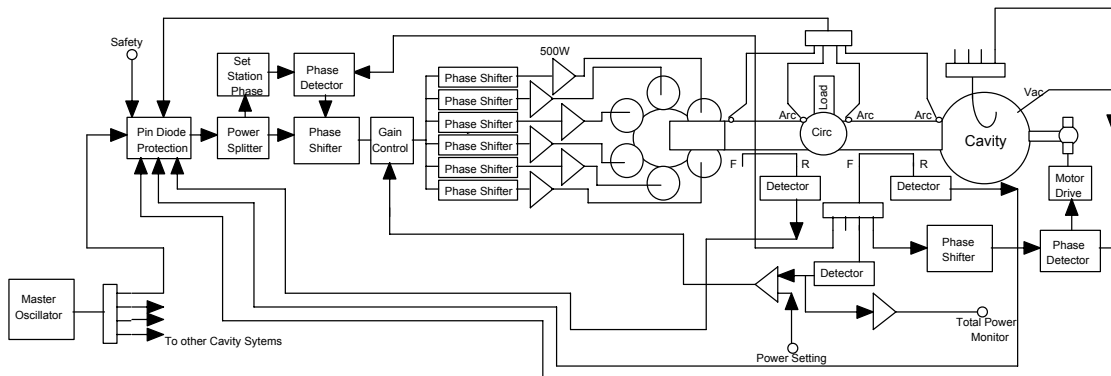


Figure 3.8-2 RF monitoring system for IOT system

3.9 AMPLITUDE AND PHASE FEEDBACK

Feedback systems for DIAMOND will include amplitude and phase loops for each RF station. A critical component of the feedback system is the cavity probe. This must be measured for both its relative phase and coupling to the cavity since this will be the reference for the feedback systems.

The amplitude control loop will take signals from the directional coupler located before the cavity and the cavity probe. These will pass into RF power level detectors that provide a linear output in response to the logarithmic nature of RF signals. They can then be compared with the set level for that RF station under computer control, any error can be used to adjust the RF drive level and hence the output power delivered to the cavity. A bandwidth response of 1KHz will be needed for the amplitude loop.

E.3 RADIO FREQUENCY

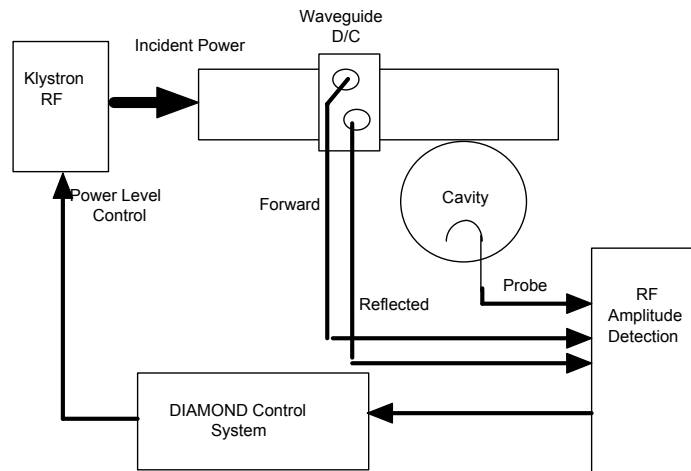


Figure 3.9-1 Amplitude feedback

The phase control loop will consist of, a phase detector to compare signals from the cavity probe and incident RF power, a phase shifter in the incident RF power signal and a motion control system connected to the cavity tuner system. The error produced by the phase detector will be used to drive the tuning system into a null condition. The station phase can be set using the phase shifter in the incident RF power signal. The phase detector and shifter must be amplitude insensitive so that no errors occur in phase information as the RF power level is changed. These RF components must also be sensitive to the 500MHz signals only and the overall bandwidth of the phase loop should be 1KHz.

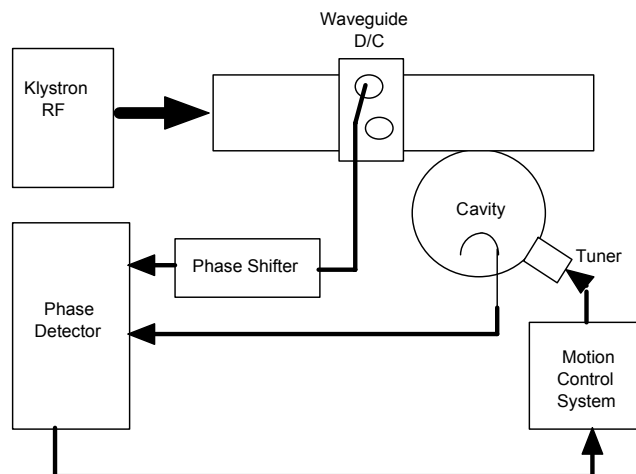


Figure 3.9-2 Phase feedback

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3.10 LOW POWER

3.10.1 Master Oscillator

The Frequency of the RF system will be 499.6 MHz. The production of this source will be a fixed high stability oscillator at 498.6MHz mixed with a Direct Digital Synthesizer (DDS) with a 2MHz span. This will provide a resultant RF signal that is phase continuous in its frequency selection and an easily controllable system for the operations crew and Accelerator Physics teams.

Stability of this RF source will need to be in the region of 0.1 ppm or better with amplitude stabilization to 0.1dBm. The quality of this source, harmonic content and phase noise level will contribute to the overall beam noise; therefore reduction of these errors must be maximized. The distribution of this signal to the machine will mean approximately 30 RF outputs at 1-watt amplitude, some coupled through 360 degree phase shifters, for distribution to the various Linac/Gun and storage ring systems.

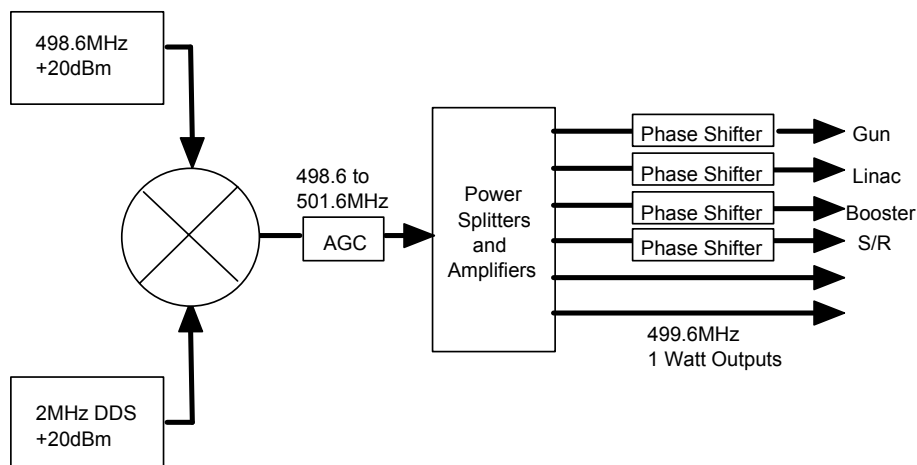


Figure 3.10-1 Master oscillator system

3.10.2 RF Timing and Orbit Clock System

RF Timing and orbit clock system

The timing of the machine bunch structure will be derived from the master oscillator. The Storage ring has 936 bunches, the Booster 262. These correspond to orbit frequencies of 536KHz and 190KHz respectively. The stability, quality and jitter free operation of the Orbit clocks will be very important to the operation of the machine. To obtain the necessary rise time for these orbit clocks, ECL logic will be necessary in the orbit clock generation electronics. The M.O. source frequency can be divided to give the orbit frequencies with a co-incidence pulse for extraction timing. Many other functions can be derived from this basic system in computer control, so that the relative timing triggers and delay generation for Gun, Linac, Booster and SR extraction will be under software control.

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Distribution of the orbit clocks and timing signals to machine experimenters and operators will be through light links. A bunch by bunch timing signal whereby the user can select the timing signal for any particular bunch can be implemented using the same ECL logic. Experience at the APS in Chicago has seen distributed signals through light links with an average jitter of 5 pS, this level of bunch timing and stability will be necessary for DIAMOND users.

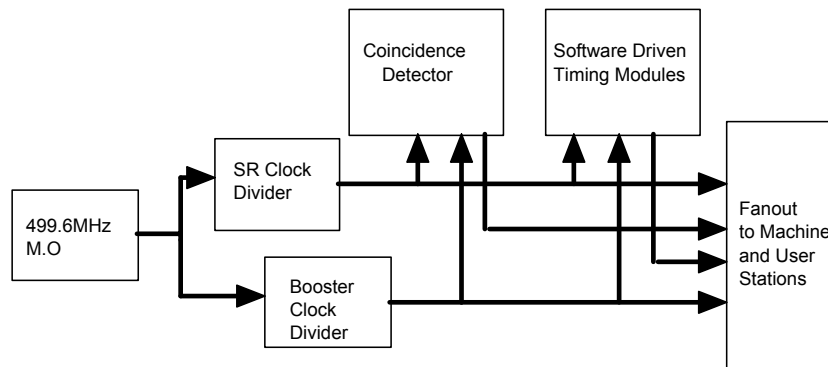


Figure 3.10-2 Timing system

3.11 LAYOUT OF RF SYSTEM IN THE STORAGE RING

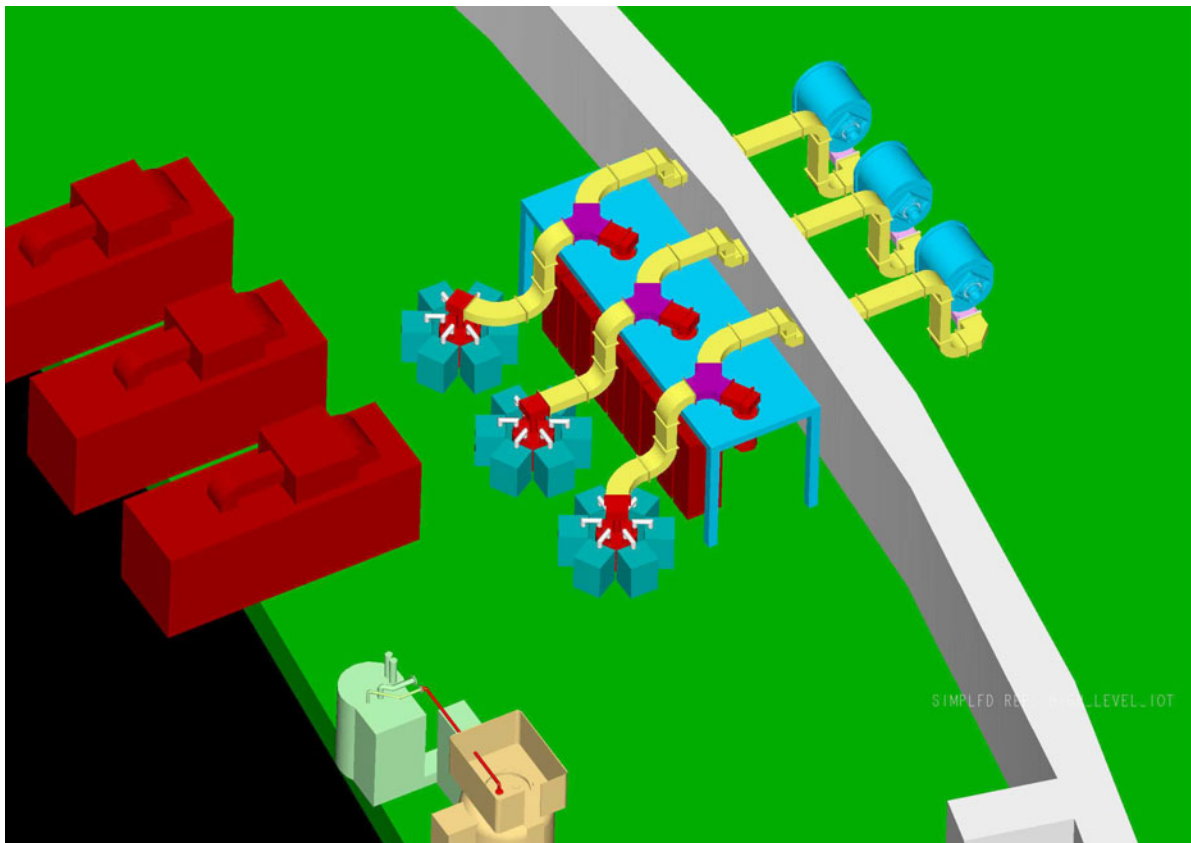


Figure 3.11-1 RF System Layout

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REFERENCES, Continued

- [1] M.Abo-Bakr et al: "On the Optimum RF Frequency for a Low Energy Synchrotron Radiation Source", EPAC 2000 p 1456-8.
- [2] F.Marhauser et al: "Numerical Simulations of a HOM Damped Cavity", EPAC 2000 p 1972-4
- [3] V.P.Suller et al: "Superconducting RF for Light Sources Workshop Chester 14-16 April 2000", DIAMOND RF-XX-rpt-001

E.4 Diagnostics

4.1 INTRODUCTION

Diagnostic systems in DIAMOND will be essential for the rapid commissioning and successful operation of the new facility. This chapter lists and gives a specification for all the expected requirements. The options to meet these requirements are discussed in turn and technical solutions are proposed to allow costs to be estimated and to inform design work in other DIAMOND systems.

Electron beam diagnostics has undergone a period of rapid technological development. A lot of this technology is now maturing and has been assessed by many long standing and newer 3rd generation light sources. This now provides the opportunity to specify and recommend, commercially available and hence more cost effective diagnostic implementations. It should be borne in mind however that the development of systems continues apace, and over the period of construction of DIAMOND, it will be necessary to review and refine some proposals at the onset of project procurement to capitalise fully on new technology and the experience of others.

Synchrotron radiation experiments depend increasingly for success on excellent source properties in terms of the stability of source dimensions and position. It has been assumed in the following that position stability to 1 micron or better will be required on all beam lines in both planes measured on time scales from milliseconds for to hours for both local and global feedbacks. In addition and on the microsecond scale, individual bunch instabilities must also be considered to further reduce the beam size and suppress beam blow up. Although high quality diagnostic systems will play a major role in achieving the required performance, beam stability specifications must be considered at the earliest design stages of all DIAMOND systems. The general problem of achieving stability at the user's sample is discussed, leading to some recommendations for consideration in the design of the facility as a whole.

4.2 ELECTRON BEAM POSITION MONITORS (EBPMs)

The proposed storage ring EBPM system is the most extensive and complex of all DIAMOND diagnostics. Each of the 24 cells will be equipped with 7 two-plane monitors. One extra EBPM position within the ring has also been earmarked for installation as a test station and another for the instability feedback system. The mechanically defined positional layout within the cell is shown in Figure 4.2-1. It is proposed to add further EBPMs within the insertion device vessels as they are installed, to provide facilities for stand alone vessel protection systems for vertical

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beam misalignment, and to provide additional high precision beam position measurement to assist with any local position servo requirements.

All results presented are by mathematical electrostatic simulations from theory[1] Further tests using an electrostatic finite element analysis package will be carried out to refine absolute button pickup positions.

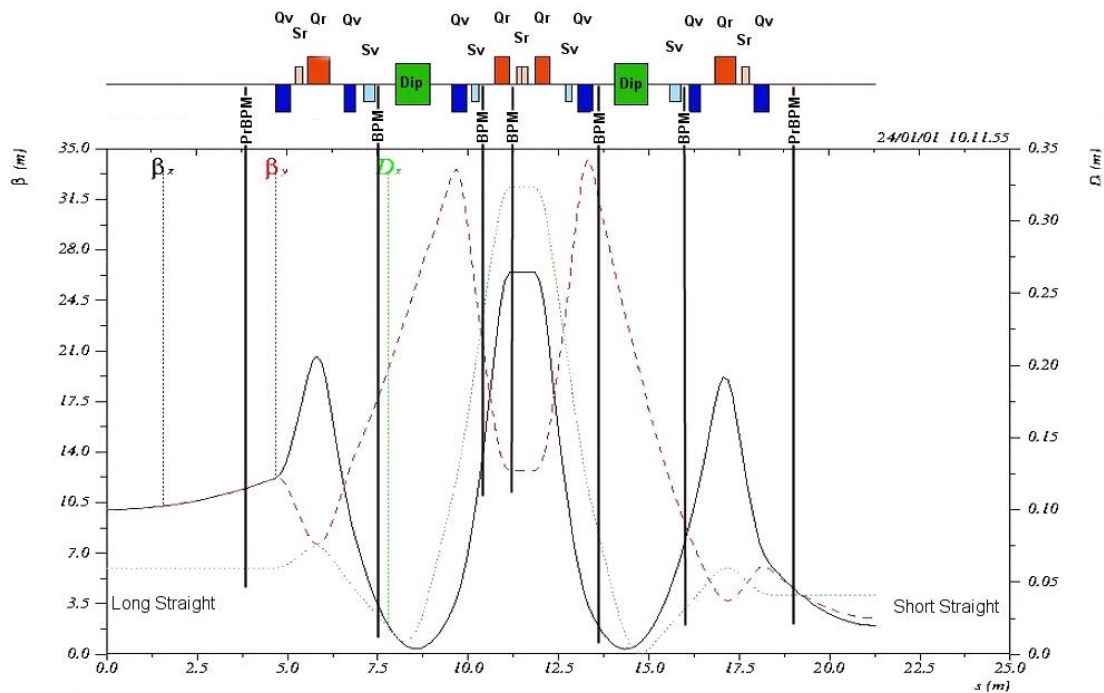


Figure 4.2-1 Positional Layout of EBPMs Within The Cell

4.2.1 Primary Electron Beam Position Monitor (PBPM) Pickups

Of the seven EBPMs in each cell, the two devices at either end of insertion straights will be of the high performance, high stability type. Mounted in such a way as to minimise any mechanical movement, their positions will be constantly measured in respect to machine survey monuments, incorporated with these devices. To facilitate this, the PBPMs will be isolated by bellows from the rest of the cell and fixed to individual rigid stands. These devices will provide a reference beam position and can also be used to determine position and angle through the insertion device for local correction. The continuous physical position measurements on these PBPM vessels will discern beam from vessel movements.

The PBPM pickup head will utilise the standard Daresbury (i.e. modified ESRF) type button feedthroughs[2] to detect the internal electric field generated by the beam. The buttons will be arranged in an overlapping pattern of four buttons, mounted on the top and bottom faces of the vessel. An additional pair of on axis vertical buttons will be added to allow complete de-coupling of the vertical measurement from the horizontal. These will provide an independent vertical position measurement if required. These vessels will be of a narrow vertical aperture, to give enhanced

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performance, with significantly improved signal to noise ratios. Although it is desirable to minimise the vertical apertures still further for the EBPM response improvement this gives, it is important to balance this against the lifetime effect that this will have. An adequate response however is still obtainable for a PBPM with a larger than ideal vertical aperture of $\approx 20\text{mm}$, and a button separation of 12mm centre to centre, configured in a longitudinally displaced overlapping configuration to permit mechanical construction and welding clearances. The resultant vertical and horizontal response and electrical calibration factors for this geometry can be seen in Figure 4.2-2 and Figure 4.2-3 and are approximately the same in both planes around the central region of interest

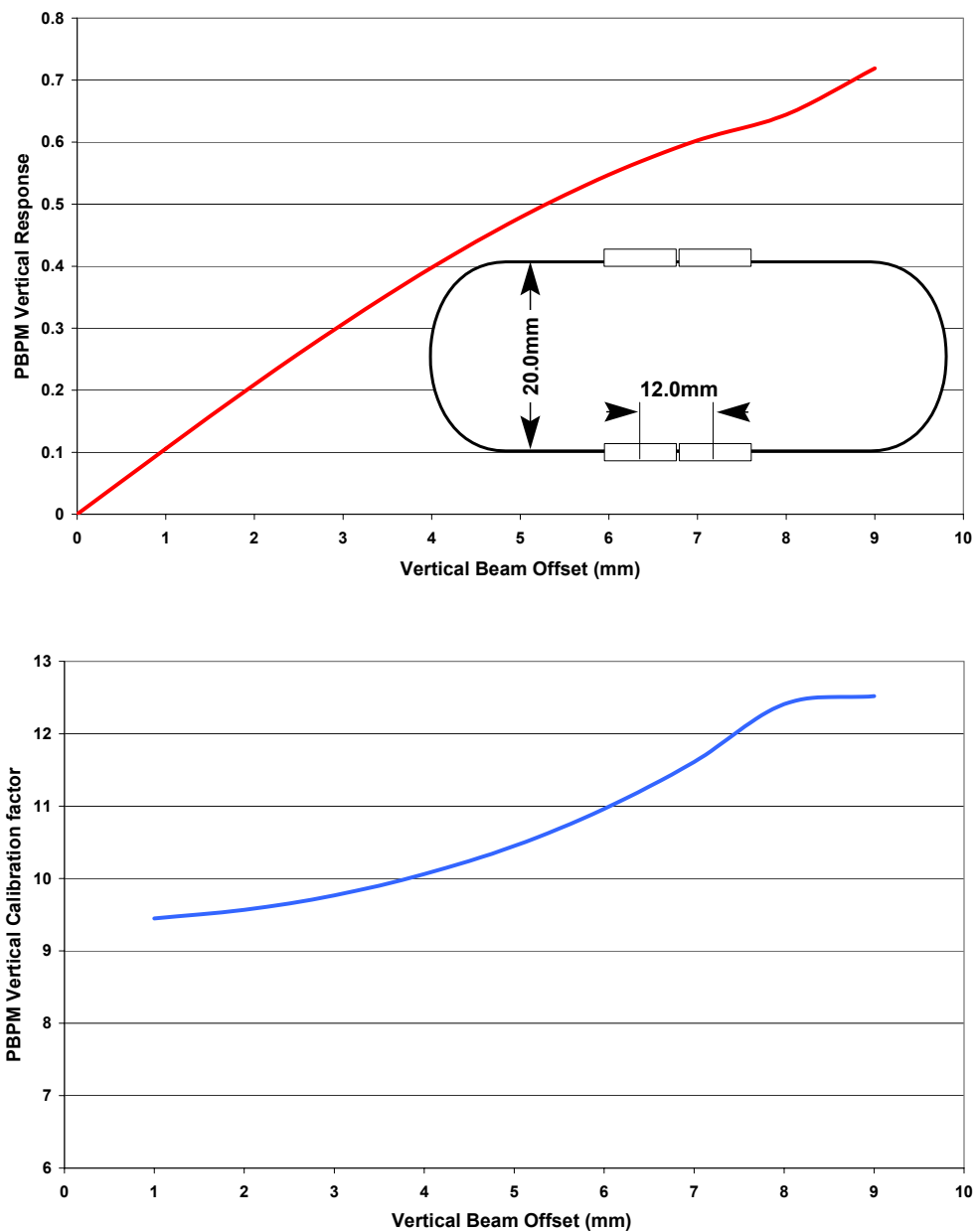


Figure 4.2-2 Vertical Response Curve for the geometry shown

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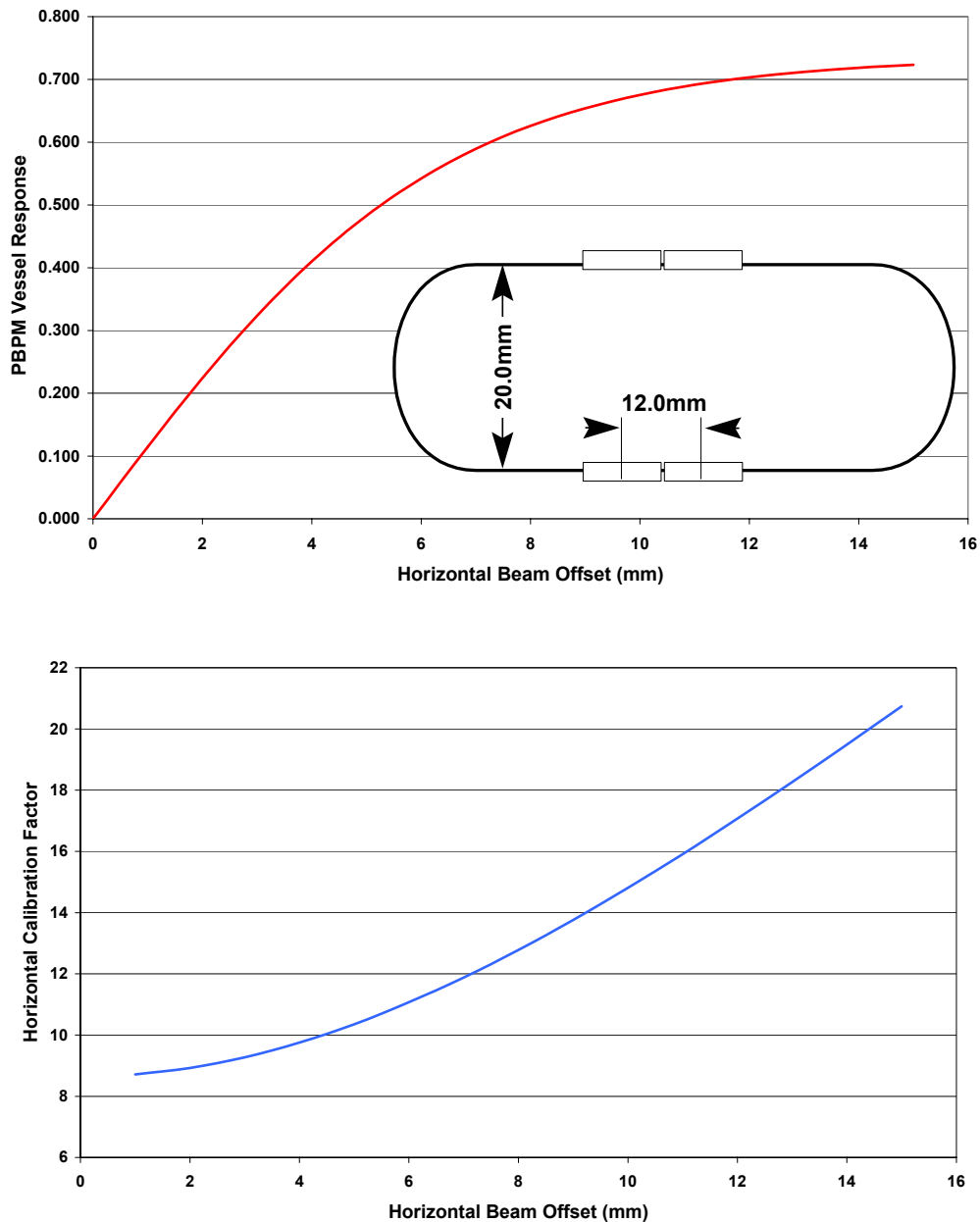


Figure 4.2-3 Horizontal Response Curve for the geometry shown

As is shown, a multiplying calibration factor of around 9 is found in both planes around the central region of interest, which will give adequate signal to noise ratios for the desired positional resolution of less than 1 micron, in the vertical plane. Further refining of the button positions, taking into account the installation of the on axis pair of buttons can result in a further improvement in calibration factors in one plane only. Using the 4 button BPM only for the horizontal plane, and adjusting the button spacing to 24.0mm can produce calibration factors as low as 7. Values below even this (~6) are obtained from the single on axis vertical buttons. These results should be balanced however against the increased cost of the detector electronics with

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which the PBPM devices will be instrumented. The improved calibration factor curves are shown in Figure 4.2-4

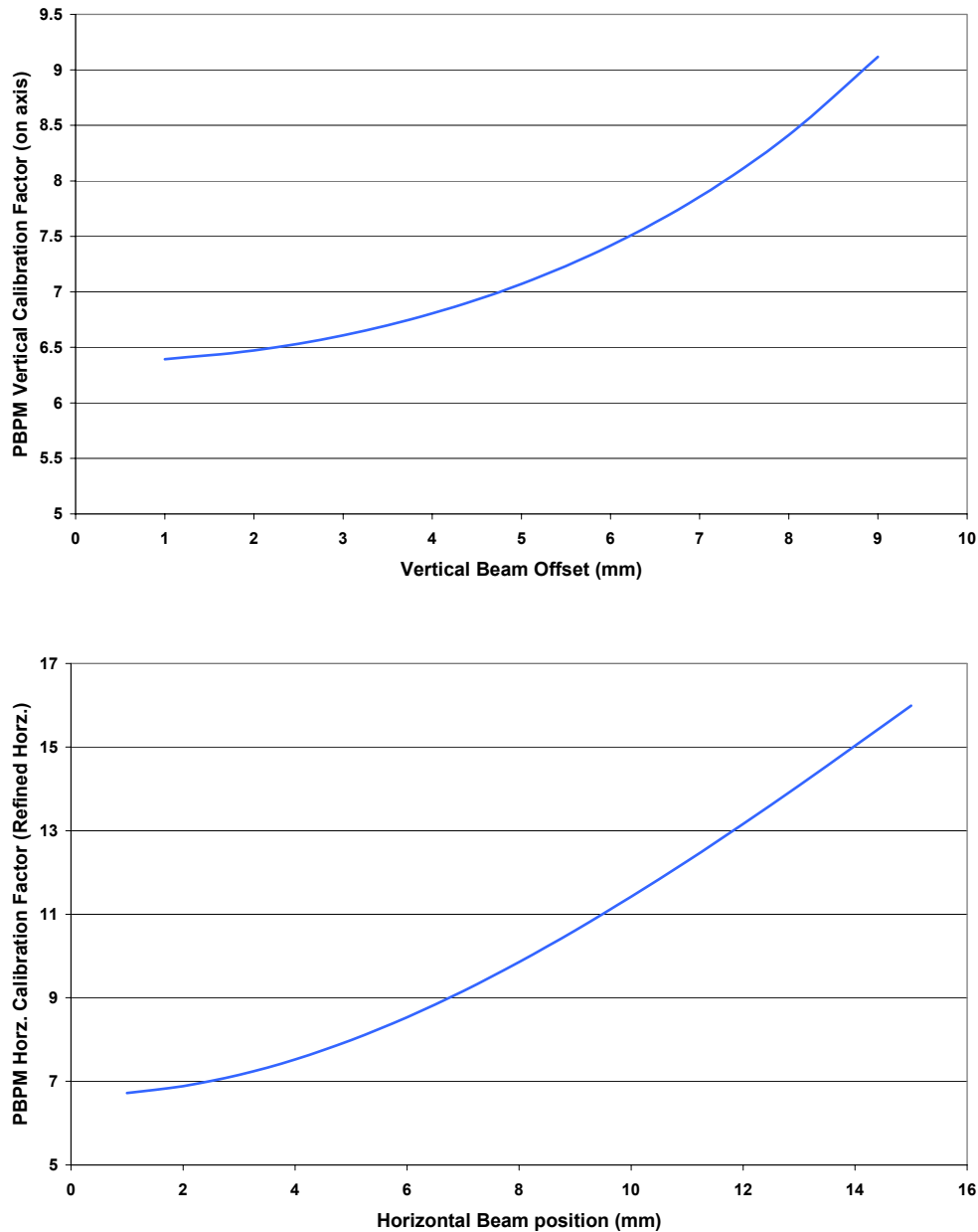


Figure 4.2-4 Calibration Curves For Single Plane Optimised Button Locations

The extent to which this high accuracy and resolution measurement is useful will depend on the relationship between the reference in which the user is working or in which his optics are located and the reference established by the local EBPMs. This in turn will depend on the details of the building and floor design and the proximity of the user or his equipment to the source. The same argument can be made for the relevance of independent white beam photon position monitors which may be remote from the user and upstream of his optics. The fast global feedback loop will

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however be capable of operating much faster than the global loop, and in conjunction with fast steering elements in the insertion device straights will allow the removal of motions due to ambient vibration and electrical interference up 100Hz.

4.2.2 Standard 'In Vessel' EBPM Pickups

It will not be practical to bellows decouple the remaining 5 EBPMs in the cell from the vacuum vessel, but they will be kinematically mounted to ensure that thermal motion is well constrained and repeatable. Global correction regimes lock the beam to a reference defined by the location of all the EBPM vessels. These in turn will be referenced to the position of the PBPMs, which define a 'standard' position. However, in the context of global correction, the reference defined by all the EBPMs is unlikely to be any more relevant to the facility users than the reference defined by the locations of the magnet systems and any benefits from this to users will have to be assessed. One solution adopted by some 3rd generation light sources, which lock the EBPMs to adjacent quadrupoles will only be effective if the mechanical engineering problems associated with differential expansion of the vacuum vessels and the magnets under the influence of varying ambient temperatures and varying stored beam power loading are solved. Substantial development work continues in this area.

The EBPM pickup head will again utilise the standard Daresbury (i.e. modified ESRF) type button feedthroughs to detect the internal electric field generated by the beam. The buttons will be arranged within the standard vessel geometry to give a reasonable response in both planes. A partially optimised example of such a vessel response is shown in Figure 4.2-5 and Figure 4.2-6 .

The offsets of the electrical centres of the EBPMs and the quadrupoles will be measured on calibration rigs before final assembly. However, experience dictates that systems allowing in situ measurement of the relationship between the electrical centres should be provided. The simplest way to make this measurement is to modulate the excitation of individual quadrupoles and look for a minimum response on the beam at the modulation frequency. The present plan for DIAMOND includes the use of individually programmed power supplies for each quadrupole which will allow simple implementation of this measurement technique.

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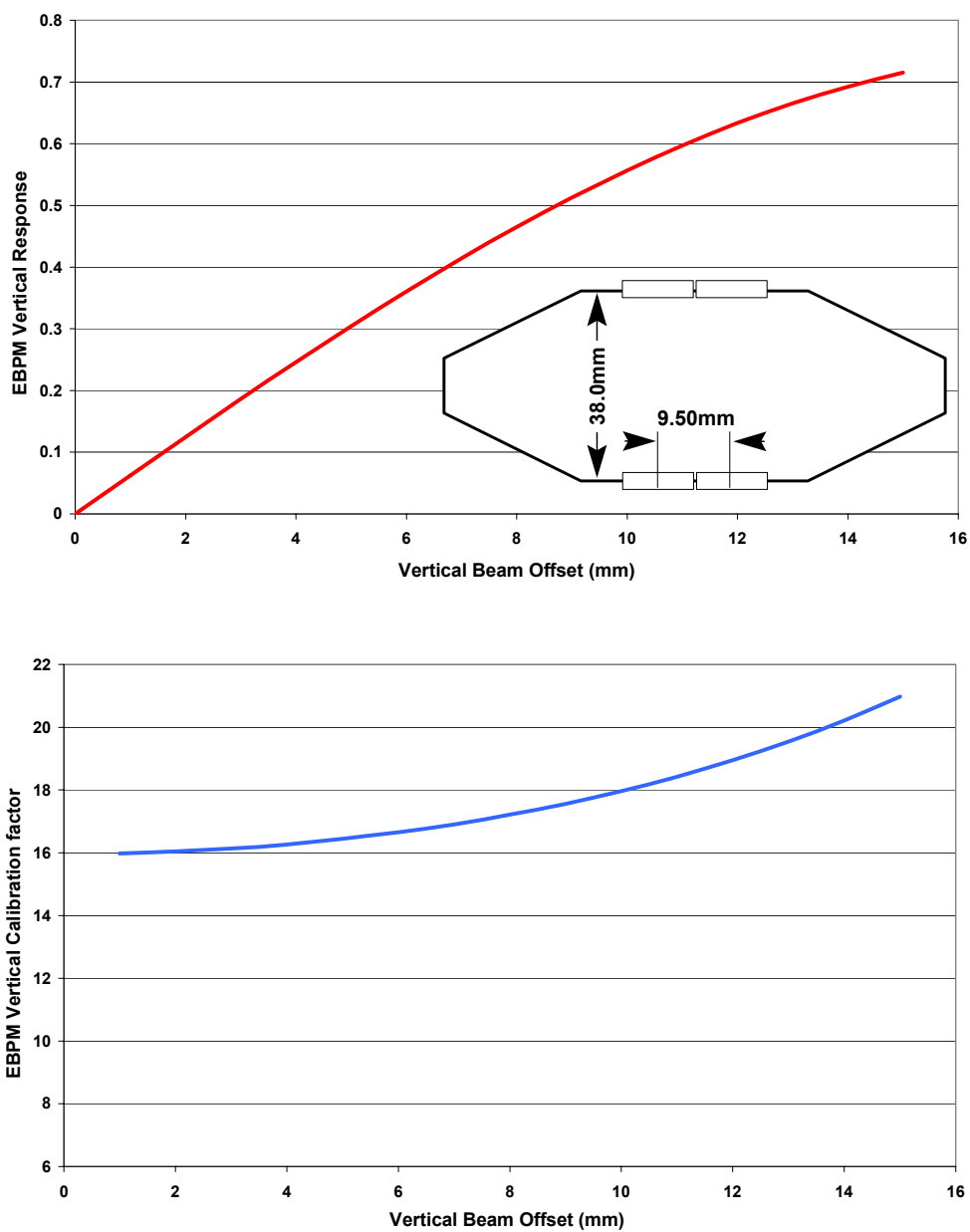


Figure 4.2-5 Standard 'In Vessel' EBPM Vertical Response

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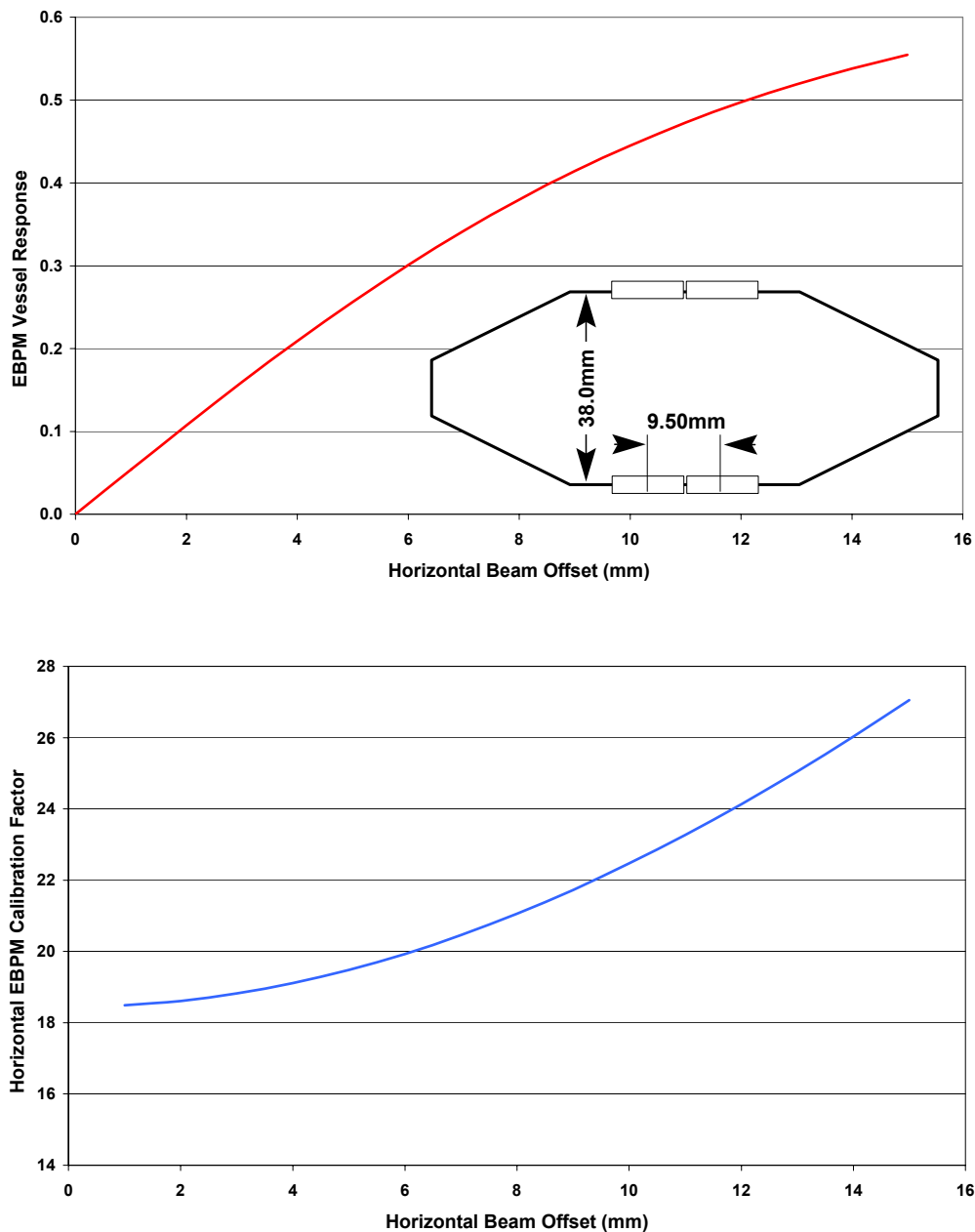


Figure 4.2-6 Standard 'In Vessel' Horizontal EBPM Response

4.3 DETECTION ELECTRONIC SYSTEMS

4.3.1 Introduction

The installed EBPM detection systems must, in combination, provide position measurement with sufficient accuracy and range in several situations. These include the storage ring, where capabilities of instantaneous single/first turn position is required, as well as during beam transportation along the flight paths, and during its time within the booster accelerator. They must in addition provide the storage ring with very high quality, stable position information at rates sufficient to allow the

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operation of global beam feedback servos, at rates up to 100Hz. This will meet the requirements of both long and short-term stability of less than 10% of beam size.

Until recently, such high precision detection electronics had to be built in house. Today however, commercial systems are available to tackle such problems. Two systems are compared and a suitable implementation presented.

4.3.2 Commercial Systems

The two systems discussed have used very different approaches to the task of EBPM signal detection, and both have merits and drawbacks. An overview of the operational techniques is given below.

(a) The Bergoz Instruments, Multiplexed BPM (MBPM)

This device is the more mature of the two commercial types, and its function is based around analogue circuitry to produce DC values, relating to X and Y beam position within a normal type four button pickup EBPM head[3]. The hardware for this system can be seen in Figure 4.3-1.



Figure 4.3-1 Bergoz Type Crate For 13 EBPMs, Including Test Station and PSU (individual EBPM card shown also)

The technique used, is based on an original design from the National Synchrotron Light Source at Brookhaven, Long Island, New York. This design was further developed at the Advanced Light Source, Berkeley, California, and then commercialised by Bergoz Instrumentation, who are well known for their Total Current Monitor devices, used on almost all of the world's light sources. Figure 4.3-2 below shows a schematic of the detection technique used.

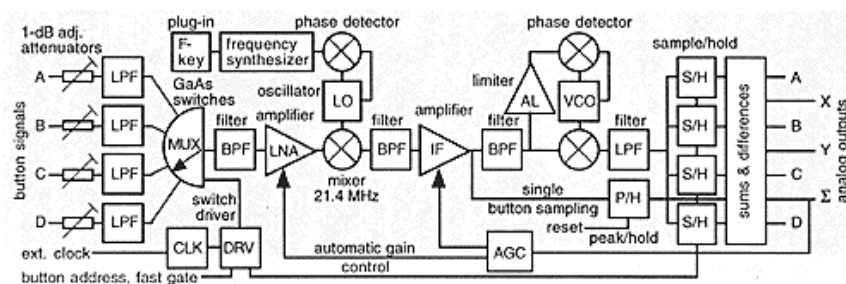


Figure 4.3-2 Bergoz Instrumentation Detector Electronics Schematic (MBPM)

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The key to the operation of this device is that each button pickup from the EBPM head, is processed through the same electronic detector. This is achieved by a switching multiplexer, that passes all signals in turn through a series of filters and gain control, to the detector chip, based around a standard television technology detector, running at 21MHz. The resultant voltages are held in sample and hold devices that allow the appropriate summing and differences to result in X and Y positions being produced as DC Voltages. These voltages are then digitised by a separate ADC to interface them to the control system.

Since this detector uses a multiplexer on its input, to uses the same detector for each button signal, it can produce excellent results, with compensated electronic drift, however the multiplexer means that it has limitations with regard to its position reading update rate. Bergoz MBPM cards have been used on the SRS for over two years for BPM measurements and active machine protection for insertion devices.

(b) The Instrumentation Technologies (I-Tech) Digital BPM (DBPM)

This device is new to the market, and its detection method is based around the technique of processing all four button pickups down identical separate channels. The results are then digitised and the summing and difference required for beam position readings carried out within the VME controller, or other higher level computer[4]. The hardware for this system can be seen in Figure 4.3-3.

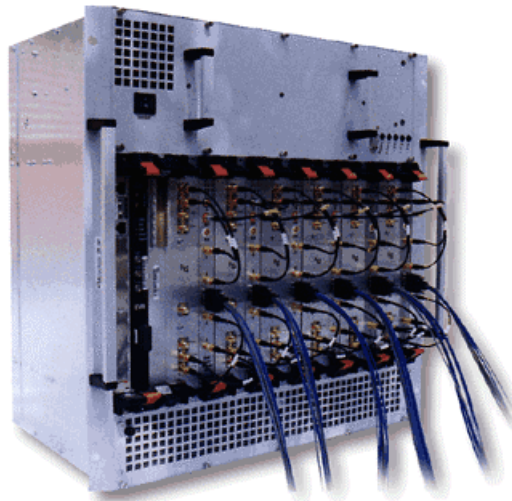


Figure 4.3-3 The I-Tech DBPM in its VME crate (6 per crate)

The technique employed was initially developed by I-Tech, along with Sincrotrone Trieste (ELETTRA). Further enhancements have followed, and it has now been commercialised and installed on the newly inaugurated Swiss Light Source.

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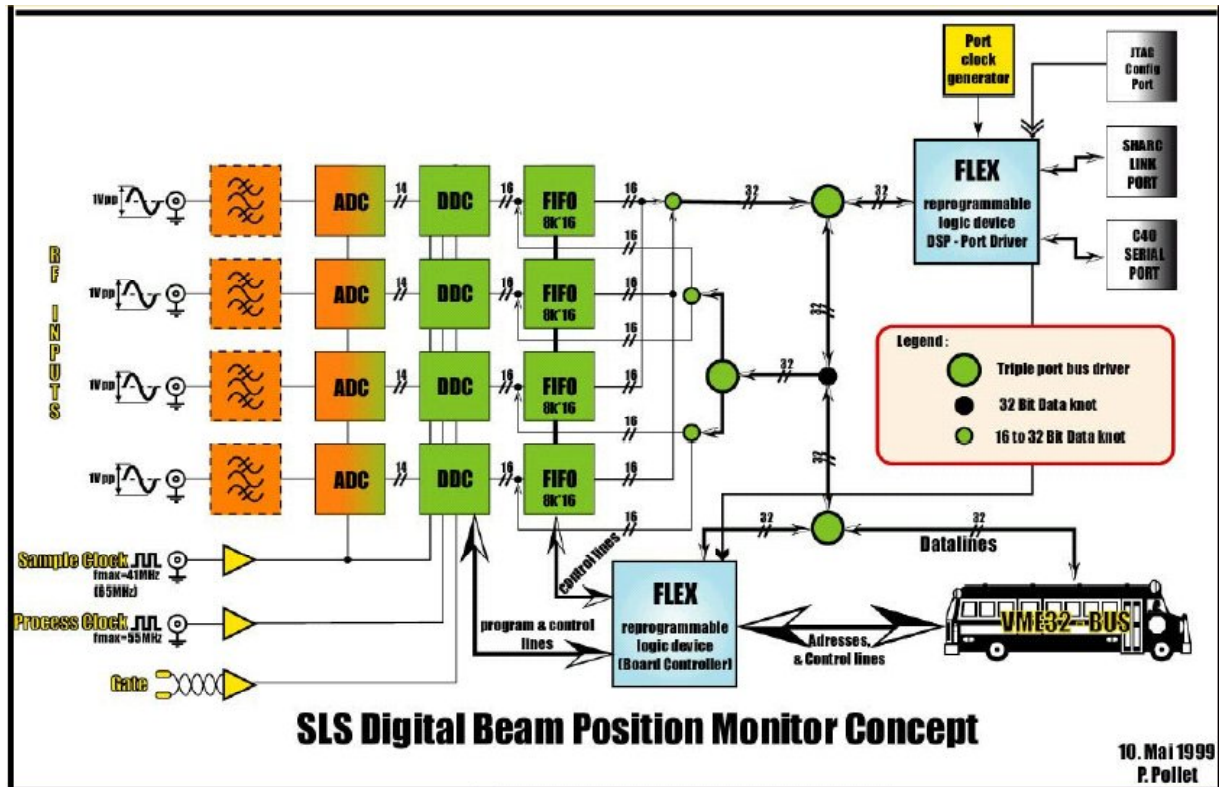


Figure 4.3-4 I-Tech Digital DBPM Schematic/Overview.

I-Tech themselves are trying to establish themselves with this and other products based around BPM technology, including tune measurement and multibunch feedback system front end detectors.

The basic methodology used here is to detect each input signal down its own detector channel, in order to provide very high speed (single/first turn) Beam position signals. A schematic showing the implementation of the I-Tech DBPM fitted to the SLS is shown in Figure 4.3-4.

Each single input channel has its 500MHz signal mixed down to an intermediate frequency of 36MHz and gain equalised against a separate pilot frequency, applied to all channels, generated on board before final filtering. This pilot frequency is essential to help keep all channel gains close together, to maintain the reading accuracy. These four 36MHz signals are now digitised by an adjacent dedicated 14 bit ADC, with 16 bit resolution being achieved by over sampling of the signals. Hence the 14 bit resolution is available for the single/first turn mode, and the 16 bit data at much slower rates for high precision read back for use with global servos, again at frequencies up to 100Hz. Further enhancements to the system include a dedicated DSP module (installed one per VME crate), to fully exploit the single turn capabilities. A major feature of this system is its ability to store up to 16,000 turns of data, allowing a 'black box' mode to investigate beam losses and some instabilities exhibiting sufficient positional change to be observed at single turn level. A development set of this DBPM electronics has been ordered, and evaluation will commence when

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sufficient hardware is available, including BPM signals from the Daresbury Synchrotron Radiation Source (SRS).

4.3.3 COMPARISON OF KEY SPECIFICATIONS

Table 4.3-1 reviews and compares the major technical specification, features and performance of the two systems.

Table 4.3-1 Comparison of The Two Commercial Systems

	<i>I-Tech</i>	<i>Bergoz</i>
Dynamic Range (Beam Current)	>100dB	>90dB
High Speed Resolution (Turn by Turn/'Pulsed')	$\pm 20\mu\text{m}$ (500kHz Bandwidth)	Not Supported
Memory Depth (No. of selectable turns)	1k to 16k	Not Supported
Low Speed Resolution (Closed Orbit)	$<1\mu\text{m}$ (2kHz Bandwidth)	$<1\mu\text{m}$ (9kHz Bandwidth)
Output X, Y, Σ	14 bits Digital (16 bits -oversampling)	Analogue +/-10V
Wide Range Beam Current Dependence	$25\mu\text{m}$ (-65dBm to -5dBm)	$1\mu\text{m}$ (SLAC Test) (-50dBm to -3dBm)
Narrow Range Beam Current Dependence	$2.5\mu\text{m}$ (in any 14dB range)	$>1.0\mu\text{m}$ (in any 14dB range)
Long Term Stability	$2.5\mu\text{m}$	$<1\mu\text{m}$ (LEP Test)
Form Factor	VME 64X Compatible	3U Eurocard

4.3.4 OTHER CONSIDERATIONS

There are also other considerations of advantages/disadvantages and relative costs of the two systems. These are reviewed in the following tables, Table 4.3-2, Table 4.3-3, Table 4.3-4 respectively.

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Table 4.3-2 Advantages of The Two Systems.

<i>I-Tech DBPM</i>	<i>Bergoz MBPM</i>
• Single global application • Digital receiver based BPM system (i.e. digital o/p) • High resolution and accuracy • Programmable bandwidth & Extremely wide dynamic range • Suits CW or pulsed beams • Real time or batch processing Feedback ready • VME 64x form factor Wide selection of software interfaces including EPICS and Lab Windows / CVI • 2 Year Warranty • Used at SLS and Elettra • EPICS support for higher level functionality (if purchased)	• Simple Fully Analogue Design • High resolution, accuracy and stability • Selectable position reading update rate from 2kHz to 9KHz • Excellent for Global Feedback • Standard card, with options for low cost upgrades • Guaranteed 10 year minimum product support. • Ideal for machine protection systems • Value for money • Used at ALS, APS, DaΦne, SRS, SSRL, LEP, Spring8 and other USA, European and Japanese light sources.

Table 4.3-3 Disadvantages of the two systems

<i>I-Tech DBPM</i>	<i>Bergoz MBPM</i>
• Complexity • Cost • Not suited to standalone machine protection • Support for the designed DSP (system if purchased)	• Unsuitable for pulsed applications • Cannot produce tune signals (at present) • Needs analogue outputs digitised

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Table 4.3-4 Relative Cost

<i>I-Tech DBPM</i>	<i>Bergoz MBPM</i>
- RF front end and 14 bit QDR :- £5,400 per BPM (4 button) - DSP (If purchased, but may not be necessary if VME back-plane fast enough):- £3,000 (one per crate) - Precision Clock Driver:- £400 (one per crate) - VME Crate, 21 slot (for 6 BPMs, one DSP and 1 precision clock driver):- £4,500	- EBPM Card:- £1,200 per BPM (4 button) - VME ADC 16 Channel, 16 bit 10kHz ADC card and IP card carrier:- £1,270 (will cater for 8 BPM Cards) 36kHz oscillator drive card :- £100 (one per crate.) - Shielded Eurocrate Crate (caters for 15 BPMs, one oscillator card and test station):- £2,000

4.3.5 Summary

Commercial systems are available for DIAMOND EBPM application, thus avoiding the considerable time/cost outlay in the development of further in-house systems, which invariably are more expensive. One is a mature, established system, the other becoming so and still under considerable development.

A Combination of the I-Tech/SLS and Bergoz is recommended for the DIAMOND application.

The inability of the Bergoz MBPM to provide EBPM signals during pulsed operation, i.e. in any part of the pre-injector means that it is at present unsuitable for that application. Therefore, the I-Tech DBPM detector is the only device available at present that can fulfil this role and so is specified for all EBPM locations within the DIAMOND Pre-injector. Its transient beam capabilities will allow instantaneous beam position within all transport lines and also provide position/tune measurement for the Booster synchrotron. The dynamic range of this system is also adequate for top up mode, low level electron beams.

Within the storage ring, a combination of the two systems following the examples given in Figure 4.3-5, will provide DIAMOND with first class EBPM systems, for the best value for money.

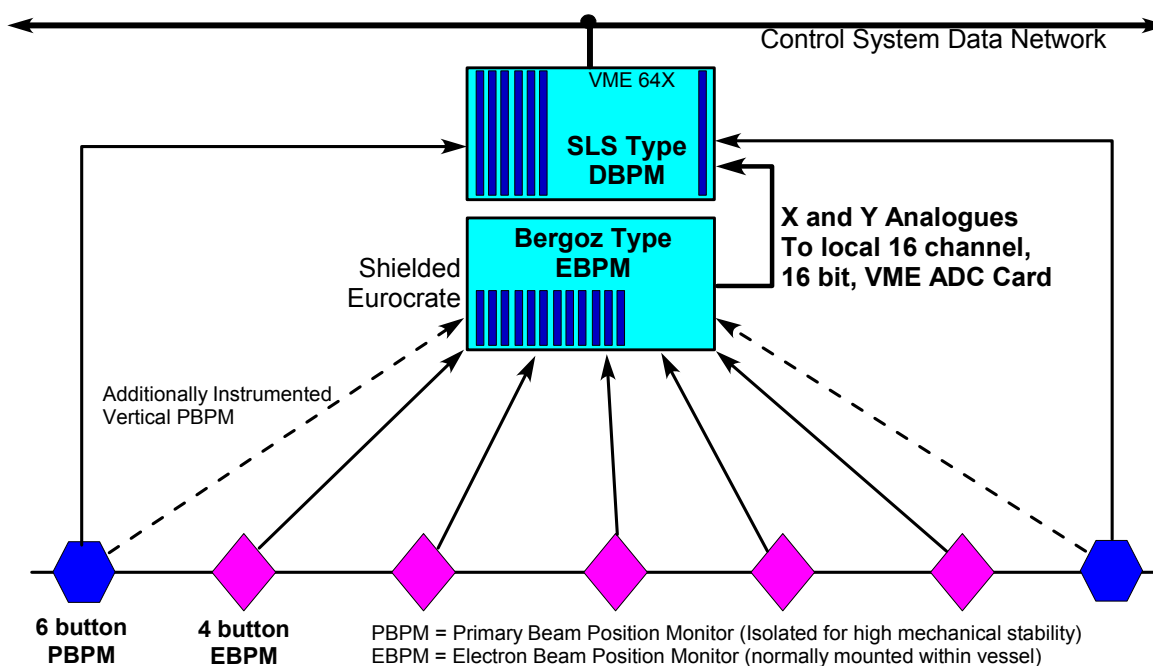


Figure 4.3-5 Proposed signal processing layout for one DIAMOND cell

4.4 BEAM POSITION FEEDBACK AND DATA ACQUISITION

4.4.1 Introduction

This area is covered in Section 2, under 'Beam Position Feedback' and should be referred to. The basic assumptions for these systems are that the entire system should correct the beam position to a specified or 'nominally' defined orbit to correct DC drift (due to thermal movements for example) and at much faster rates up to $\approx 100\text{Hz}$ (to remove higher frequency mechanical noise etc). The overall aims will be to have systems and adequate data rates to provide positional data update rates of 2KHz during normal user beams.

It is clear that the PBPMs instrumented with the I-Tech detector electronics will produce data at significantly greater rates than this, due to their turn by turn and single shot capabilities. The controls/data acquisition system takes this into account and has been specified appropriately. These systems themselves carry on-board storage and will provide an invaluable source of data in a fault finding/beam loss situation in that turn by turn data will be available over many thousands of turns prior and during beam loss for diagnosis.

4.4.2 Proposed Installation

For each DIAMOND cell there are 5 EBPMs, 2 PBPMs and X-ray or Photon BPMs (XBPMs). The I-Tech detection electronics produces direct digital data. All other BPM processing produces analogues, which will be read via multi-channel 16 bit ADCs within VME crates. These crates will interface to the data/controls network. This will

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enable the diagnostics to be monitored with a 16 bit resolution whilst performing digital filtering and averaging. The beam position information will be available at sufficient rates to the various feedback systems to apply the appropriate corrections via the magnet steering system.

4.5 INSTABILITY FEEDBACK SYSTEMS

4.5.1 Introduction

The electromagnetic fields associated with the very high intensity electron beams accumulated in third generation synchrotron light sources can generate Coupled Bunch Instabilities (CBI) through the interaction with the vacuum chamber (resistive wall effect) and/or cavity Higher Order Modes (HOMs). Multi-bunch instabilities degrade the quality of the beam (e.g. increased beam emittance, energy spread) and can lead to beam loss. Such instabilities can be dealt with, by shifting HOM frequencies by acting on the cavity temperatures and/or HOM shifters. DIAMOND will however be a superconducting RF machine. This type of cavity with its inherent high single frequency Q factor and respectively low HOM production (with in-built HOM absorbers) will produce relatively small, but still significant transverse CBIs.

In view of the operation of DIAMOND at higher currents, a feedback system to damp such multi-bunch instabilities will be installed.

Much development work has been carried out in collaboration by ELETTRA and the Swiss Light Source (SLS) to produce a modular solution[5]. DIAMONDs requirement in this area can be met by a larger implementation of this system, which has been scaled suitably. Since the SLS, ELETTRA and DIAMOND are all 500MHz machines, and DIAMOND has a harmonic number (936) divisible by 24. Its implementation will be straight forward.

4.5.2 System Parameters

Example feedback parameters are shown in Table 4.5-1. The system is designed to operate with beam currents and energies up to 300 mA and 3.0 GeV respectively. The lowest operating frequency will correspond to the first betatron sideband in the baseband signal spectrum (0-250 MHz). The RF power drive to the stripline kickers is derived from commercial amplifiers featuring the required bandwidth and response. The kicker shunt impedance refers to that of a 30cm long cylindrical stripline type kicker, which will be installed in the allocated diagnostic straight.

Table 4.5-1 Example parameters for the Multibunch Feedback Installation

PARAMETER	VALUE
Beam Current, I	300 mA
Beam Energy, E	3.0 GeV
Number of bunches	936
Bunch spacing	2 ns
Highest Frequency	250 MHz
$\beta_x, \beta_y @ \text{BPM}$	26, 12 m
$\beta_x, \beta_y @ \text{kicker}$	10.5, 10.5 m
Amplifier Power, P_k	400 W/Plane
Kicker Shunt Impedance, $R_k @ \text{DC, 250 MHz}$	16.5, 6.5 kOhm

4.5.3 System Overview

The ELETTRA based Transverse Multi-Bunch Feedback (TMBF) consists of a wide-band bunch-by-bunch system where the positions of the bunches are individually sampled and corrected. The block diagram of the TMBF for one of the two transverse planes is shown in Figure 4.5-1. Wide-band signals from a standard Beam Position Monitor (BPM) pick-up are combined into a "hybrid network" producing x, y, and sum signals. These are entered into a "RF front-end" which demodulates the inputs to baseband.

Baseband bunch-by-bunch position information is sampled by a fast 8 bit 500 Mega-sample per second (Ms/S) analogue-to-digital converter (ADC) and the amplitude of the corrective kick is calculated using digital processing electronics. The correction values are transmitted to an 8 bit 500 Ms/S digital-to-analogue converter (DAC), amplified by a RF power amplifier and applied to the beam by a kicker.

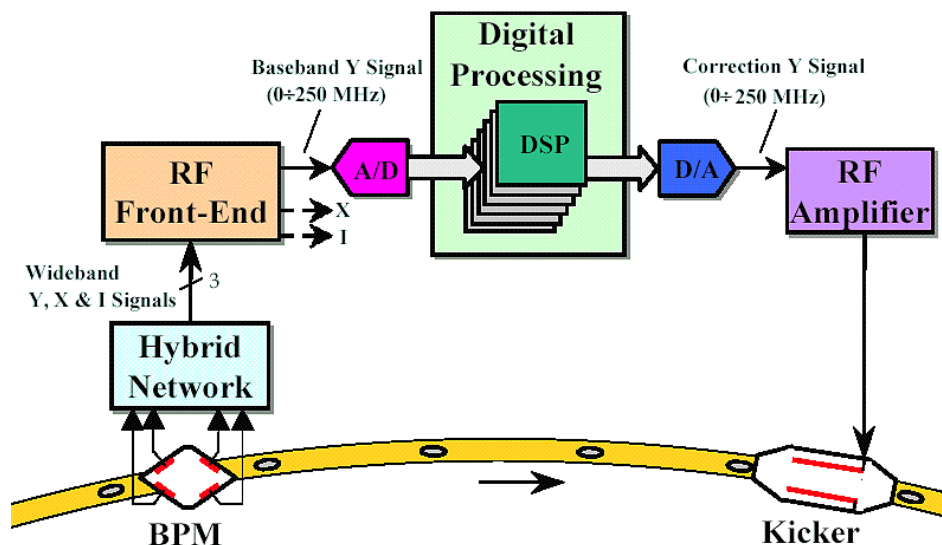


Figure 4.5-1 ELETTRA Based Transverse Multibunch Feedback (TMBF) System

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(a) RF Front End and Dedicated EBPM

It will be necessary to install a dedicated EBPM to provide the detection signals for the TMBF system. This is to ensure that the location of the buttons is such that it yields the same position sensitivity on both the x and y planes. Alternatively a combination 6 button EBPM with some normalising hybrid derived sum signal could be designed, that would allow optimisation of EBPM response, over and above that of a simple 4 button design. For improved signal to noise ratios, the 3rd harmonic of the RF frequency (1.5GHz) is detected in the RF front end.

The processing of the EBPM signals takes place in two separated modules. The first module is a hybrid network that resides in the tunnel, close to the pick-up. All cabling associated with the hybrid must be phase corrected and stable. The purpose of this module is to deliver two signals proportional to the x and y positions scaled by the bunch current and a signal proportional to the beam current. Standard Daresbury designed or commercial hybrid assemblies are suitable for this device. The three 500MHz RF output signals are then carried to the main digitising system in a local diagnostic service area.

The purpose of the RF front-end is to convert the input 1.5 GHz signals to baseband. The input signals are conditioned by a bandpass filter followed by a fixed gain low noise amplifier. A gain control in excess of 20 dB is accomplished by a variable attenuator downstream of this amplifier. The signals then enter a mixer that shifts the frequency spectrum from 1.5 GHz to baseband.

Each processing chain consists of an amplifier, a low pass filter and a further amplification stage. A block diagram is shown by Figure 4.5-2. The beam current signal is processed in a similar way with the exception that it does not have an amplifier following the input bandpass filter since the signal range is much higher than that in the x and y chains. A 500 MHz RF signal is used as a reference to generate the 1.5 GHz signal through a x3 multiplier. Two phase shifters allow independent control of the x and y chains on one side and the beam current chain on the other. In this way, any small phase errors can be resolved.

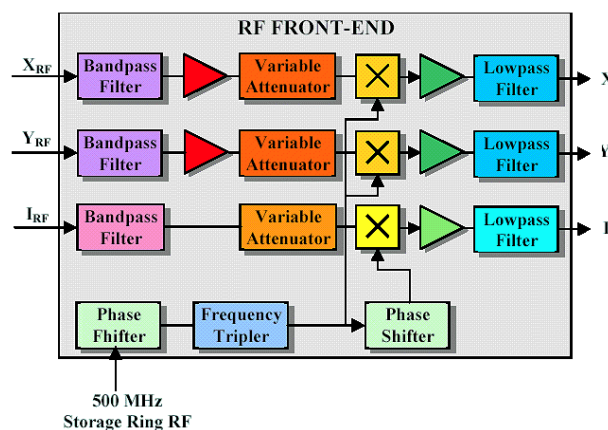


Figure 4.5-2 RF Front End Block Diagram

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(b) The Digital Processing Electronics

In order to damp the oscillations of a bunch, the correcting kick signal must be shifted by $\pi/2$ betatron phase with respect to the position signal of the same bunch in the kicker. In this scheme the kick value is determined by detecting the bunch position signal at the BPM and by shifting its phase through a digital filter in the processing block. As filters can be programmed to provide any phase, the BPM and the kicker can reside at any position in the ring.

In the bunch-by-bunch approach the feedback uses only the position information from a particular bunch to calculate the corrections for that bunch. It is therefore possible to split the required processing power among several computing units, where each of them is in charge of a number of bunches.

A block diagram of the ADC, Digital Processing and DAC blocks is shown in Figure 4.5-3. A modular upgradable design based on the VME standard, has been adopted, where the main components are interfaced through standard, high-speed communication paths. The 500 Mbyte/S data stream is de-multiplexed on the ADC board via six Front Panel Data Ports (FPDP). Each FPDP is connected to a Digital Signal Processor (DSP) board, where data is de-multiplexed again by up to four DSPs.

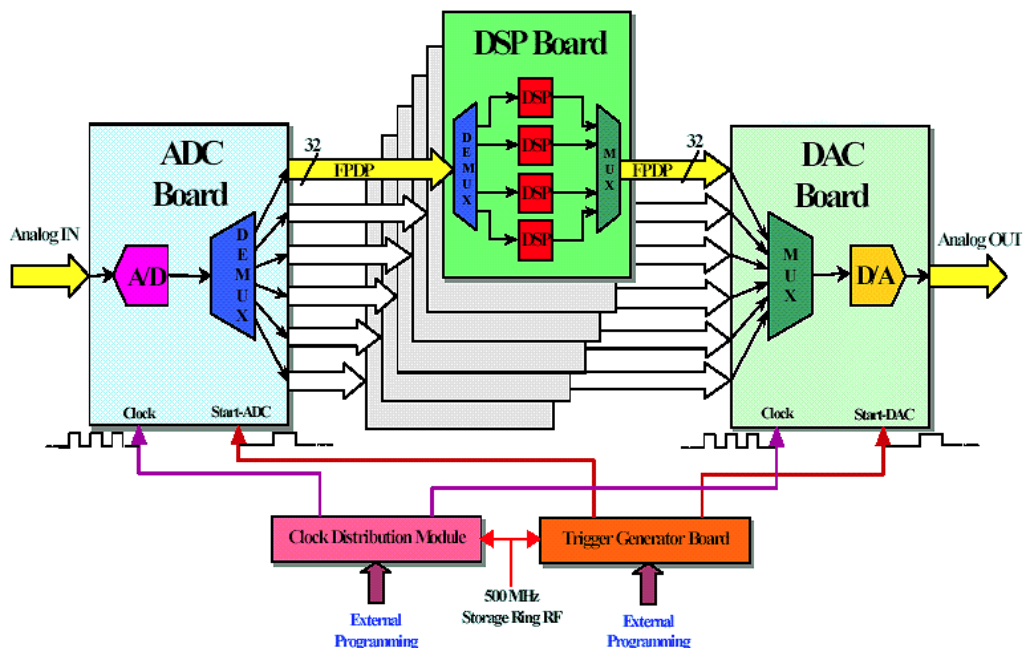


Figure 4.5-3 Block diagram of the digital processing electronics.

The calculated correction kick values are eventually transmitted to the DAC board following a symmetric multiplexing mechanism. The whole process is synchronised with the Storage Ring Clock (SRC) and the 500 MHz main RF signal through the Timing Electronics.

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The digital programmable approach for the processing block provides a very high level of flexibility, as different processing algorithms can be run on the DSPs. In parallel to this, a number of beam diagnostic tasks (e.g. tune measurement, growth/damping time measurements, oscillation mode detection) are also available. Further development will include the ability to excite a single bunch from the full bunch complement to provide continual tune measurement. This will supplement the basic tune measurement system that will be installed, but unable to be used whilst DIAMOND is in a normal user beam operational mode since the instability feedback will effectively damp these signals.

An extensive use of commercial off-the-shelf (COTS) boards is made for the digital electronics (ADC, DAC and DSP boards) to reduce development times.

4.6 MACHINE PROTECTION SYSTEMS

4.6.1 Introduction

Beam mis-steer damage protection, of narrow-gap insertion device vessels, is a fringe area of beam diagnostic systems, thus it is therefore appropriate to detail the system in this section.

DIAMOND is intended to be essentially an insertion device machine so eventually most straights will be fitted with narrow-gap beam vessels introducing attendant beam steering limitations. Theoretical analysis has shown that mis-steer of the electron beam, could cause catastrophic thermal damage to the vessel in less than one second. Front line protection systems have been developed for the SRS narrow gap vessels to help prevent such damage[6], and are suitable, with minor modification, for installation on DIAMOND insertion devices.

4.6.2 Machine Protection Hardware Installation

When dangerous conditions prevail, the electron beam will be switched off by tripping the RF power to the beam. The main interlock signals to achieve this will have been generated by excessive vertical beam displacement (shown as beam position upstream and downstream), and excessive rise in vessel wall temperature (Thermal Trip). The single Thermal Trip interlock will be generated from a strategically placed array of thermocouples, affixed to the vessel wall and monitored by a Programmable Logic Controller (PLC).

Since initial injection at low current is deemed to be a safe operating area, a current sensitive bypass will be included as shown. This will facilitate beam steering through the narrow gap of the vessel at low currents, by permitting a wider tolerance on position.

Because confidence in the reliability of beam position measurement and interlock operation is paramount, secondary interlock signals will be required to become active when the integrity of electronic hardware and associated support signals is suspect.

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These are shown in Figure 4.6-1, an expanded organisational diagram, as BPM Electronics Failure Upstream and Downstream, Total Current Monitor Failure, Power Supplies Failure and Thermal Monitoring (PLC) Failure. A key switch controlled override of Beam Position interlocks is included for possible Accelerator Physics application, to permit wider beam positioning at high current levels, or unrestricted control under special user conditions (e.g. ultra low current running).

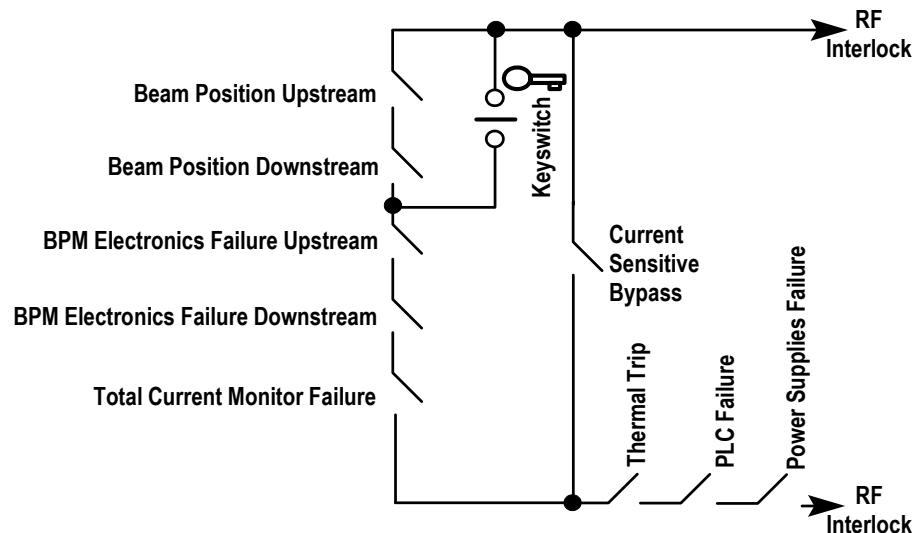


Figure 4.6-1 Full Interlock Organisation

There will be provision for full status monitoring interface to the DIAMOND control system, and local (Control Console) real time display of beam positions and current sensitive bypass status.

Because experience has shown that there is interaction between the vessel protection system and beam loss when an unrelated fault occurs, i.e. beam loss creates numerous vessel protection interlock failures, event sequence discrimination circuitry will be installed to distinguish cause from effect. The result of the discrimination process will be displayed through the control system and visually at the control console.

When the time for installation of vessel protection systems arrives, all development from both a design philosophy and engineering aspect will be complete and installation should be modular on demand. Figure 4.6-2 shows an example installation.

PART E: STORAGE RING

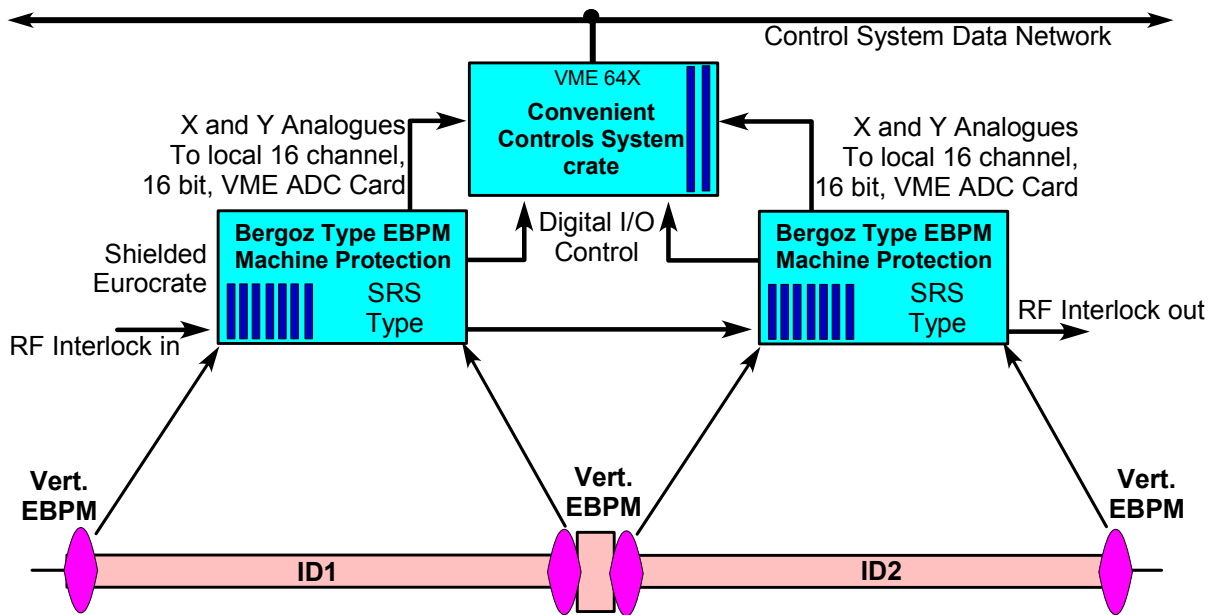


Figure 4.6-2 Suggested ID Straight Layout with Machine Protection System.

4.7 DIAGNOSTIC STRAIGHT

4.7.1 Introduction

The majority of other diagnostics for the storage ring will be installed in a single long straight, dedicated to diagnostics. A simplified mechanical layout of this can be seen in Figure 4.7-1. These will include the beam current measurements and the optical diagnostic test undulator, to provide synchrotron light for the optical diagnostics Station. Bending magnet radiation will also be catered for diagnostics using similar facilities.

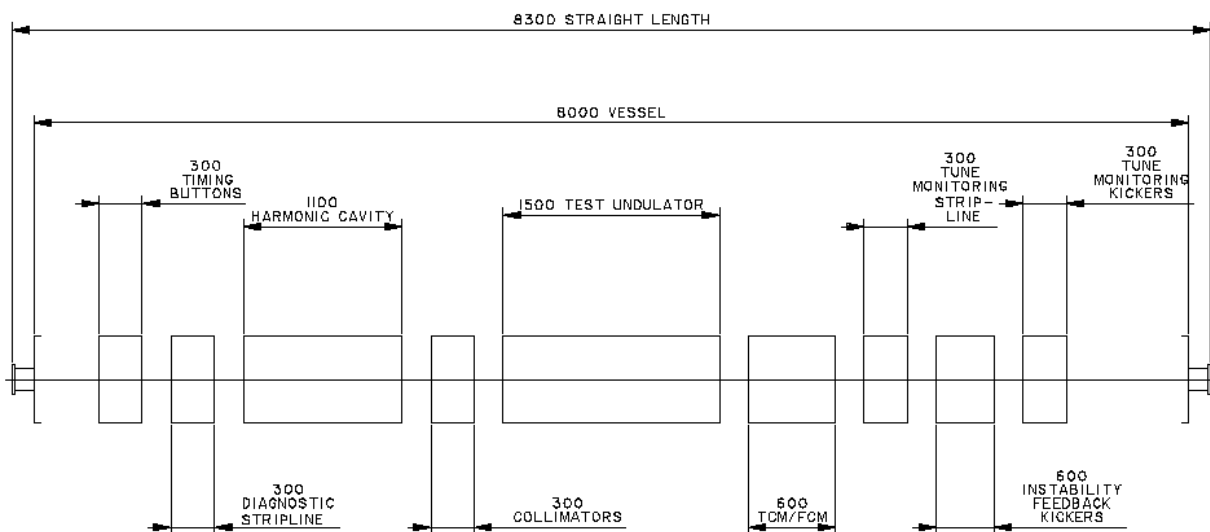


Figure 4.7-1 Diagnostic Straight Layout

4.7.2 Diagnostic Straight Sub-Systems

(a) Optical Diagnostic Station and Undulator

For the high energy third-generation synchrotron radiation sources where the particle beam emittance still determines the x-ray beam brilliance, the narrow cone of undulator radiation provides an efficient method to characterise the particle beam divergence and directional stability.

The front end of the diagnostics undulator beamline uses most components from the standard beamline front ends. However a number of special features will optimise the front end for beam diagnostics.

The divergence measurement will use a single crystal monochromator and an imaging detector using a scintillation crystal as a converter screen. The monochromatic x-ray will pass through an aluminium window to reach the imaging detector located in the open air. Such an arrangement significantly reduces ozone generation by the white undulator beam.

The cross section of the monochromatic X-ray beam will be imaged onto a scintillation crystal. A CCD camera with a photographic lens is used for the image acquisition. The pixel scale of the camera is calibrated with a grid pattern mounted on the background of the scintillator crystal. A Spiricon digitizer (120x120 pixels with 35 pm/pixel) is used to record the image.

Additional diagnostics to be used at the station include a dual sweep streak camera. This essential tool is required to image the individual bunches and observe in-bunch instabilities and blow up, with picosecond time resolution.

The analysis of single bunch purity is also only fully confirmed optically.

(b) Timing Buttons and Test EBPM

A set of individual high capacitance timing buttons, will be installed to give real beam coincidence measurements for users in single bunch operation. One button will be dedicated to a controls system interlock watchdog system to allow latching and instantaneous status readback of critical control system parameters upon beam loss, to actively improve beam loss diagnosis.

An additional EBPM incorporated in this vessel will provide an independent dedicated test location for commissioning/testing new detector electronics.

(c) Diagnostic Stripline

Essential, as the most basic diagnostic. Horizontal and vertical pairs of $\frac{1}{4}$ wave (@500MHz) striplines will be installed and connected back to the control room via high quality cabling, to provide real direct diagnostics on the injected beam.

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(d) Total Current Monitor (TCM)

Accurate and stable measurement of the DC component of the stored charged DIAMOND beam is an important requirement, since it will be a measure of the light intensity and the parameter from which lifetime will be calculated. The parameter of critical importance, for monitors which are designed to non-intrusively measure charged particle beam currents, is resolution, a specification that is dictated by zero drift. For a third generation machine such as DIAMOND a zero drift figure in the order of 5.0 microamps is required.

Zero drift of a monitor is defined primarily by the thermal properties of the core material that is employed for the toroidal monitor head. In this area the current generation of monitors use amorphous magnetic materials for the cores, materials that demand extensive expertise and resources to process. Consequently the manufacture of modern monitors has tended to remain within the province of the commercial sector !

In the commercial field a leading manufacturer of high specification Total Current Monitors TCMs (now more commonly referred to as Parametric Current Transformers, PCTs) is the French firm Bergoz Electronics. This company has supplied PCTs to most of the leading synchrotron radiation laboratories world wide; their products have a good reputation for performance and reliability and the company has demonstrated its long term commitment to product support.

Thus in line with the cost effective policy to be applied to DIAMOND of implementing systems by use of commercial instrumentation, it is intended to equip DIAMOND with a Bergoz Electronics PCT, with the assurance that the potential for obsolescence is minor.

A standard production model from the Bergoz Company offers zero drift of 5.0 microamps. This specification satisfies both the measurement and lifetime calculation demands of DIAMOND, but to achieve the quoted performance figure, careful consideration will have to be given to the magnetic and electrostatic screening requirements of the toroidal monitor head. To implement the full theoretical monitor head screening required to guarantee the demanded performance, a free beam pipe length of approximately 0.6 metres is required.

Finally, since DIAMOND is to operate in a top-up, mode it is recommended that two PCTs be installed in the DIAMOND Storage Ring to crosscheck beam current measurement by comparison. This is important if the top-up operation is to be performed at a defined and repeatable level of beam decay. Additionally a PCT is required for the DIAMOND Booster ; this device can be of a lower specification than that for the Storage Ring, but there would be little economic gain in purchasing an inferior instrument.

(e) Bunch Charge Monitor (BCM)

The potential user community for DIAMOND have expressed a desire for customised bunch charge fill patterns on request, a facility that will require selection and charge fill of individual beam bunches. This in turn will require the capability of measuring the individual bunch charge content.

Selection of an individual bunch can be achieved through the DIAMOND timing system by variable delay from the Orbit Clock ; measurement of the bunch charge content will require the installation of a Beam Charge Monitor.

Again in order to adhere to the policy of using commercial instrumentation, a Beam Charge Monitor manufactured by Bergoz Electronics will be installed. This device has an integrate - hold - reset capability on an individual pulse basis, that offers a maximum sensitivity < 60 pico Coulombs per volt and a resolution of approximately 3×10^6 particles.

These devices will also be installed as part of the beam loss monitoring throughout the DIAMOND to assist with radiation protection system, in order to assess and interlock if necessary, the effective beam injection/transport efficiency.

(f) Tune Monitoring Kickers and Striplines

This device will form part of a secondary diagnostic system, essential for machine commissioning, since the PBPM detector electronics and more specifically the instability feedback system will provide continuous tune signals without the need to excite the entire stored beam.

During machine commissioning however, it will be necessary to measure the tune of the stored beam within the storage ring independently of other systems. This can be achieved using a dedicated spectrum analyser with tracking generator, which is connected to a power amplifier that drives a kicker stripline. By sweeping appropriate frequency spans, one can obtain transfer function of the beam containing both tunes. The monitoring stripline signals are combined with 180° hybrids to form a sum signal, and horizontal and vertical difference signals. These are processed by a two-channel spectrum analyzer uses DSPs and a fast Fourier transform (FFT) to compute spectra from 0 to 10 MHz.

4.8 PHOTON BEAM MONITORS

Photon beam monitoring for light sources has been the subject of extensive development during the past three decades, development that has culminated in the opinion that currently, the superlative technique employs the Tungsten Vane Monitor (TVM). This type of photon monitor is a photo-emissive device, and is comprised of two horizontally or vertically adjacent tungsten blades (vanes), that are located in the same vertical plane within the photon beam cross-section. The blade assembly is

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mounted within the vacuum vessel and is located permanently within the fringe of the beam, surveyed such that the inter-blade gap is at beam centre. When the photon beam is centred, the blade photo-currents are balanced, and the processed output is at a null.

At least one vertical TVM should be installed in each DIAMOND beamline for steering purposes ; an additional vertical monitor will be need in those lines that require vertical angular alignment. A proven design of log ratio amplifier is available for vane current processing, which provides the null steering facility.

For initial survey purposes and periodic re-calibration, the blade assembly requires a drive capability.

4.9 BEAM LOSS MONITORS

It is intended to equip DIAMOND with two levels of beam loss monitoring facility, a high performance localised photo-multiplier based system for injection loss studies and a second, lower grade, distributed, general background monitoring PIN photodiode based system.

The distributed system will employ commercially available units that have a pulse output, one pulse per incident ionising particle, giving a pulse rate that is proportional to beam loss. Even when protectively housed, these units are small and mobile enough to enable their distribution to be customised rapidly on demand. They will probably be installed in the Booster and Storage Ring with an average distribution of one or two units per straight, with clusters around loss elements such as collimators and quadrupoles. Their flexibility with regards to redistribution will be advantageous when trying to source beam pipe obstructions.

Both the analogue photo-multiplier system and the digital PIN photodiode system will be fully interfaced to the Computer Control System.

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E.4 DIAGNOSTICS

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E.5 Vacuum

5.1 INTRODUCTION

This section considers the vacuum systems of the Storage Ring. By *vacuum systems* is meant primarily the means by which appropriate pressures are achieved (i.e. pumping) and measured (i.e. gauging) and how such pumps and gauges are controlled. This will, perforce, require some discussion on constructional materials for vacuum vessels and on processing of such vessels to achieve the necessary outgassing rates. Except for reasons of clarity, the mechanical construction of the vacuum vessels is not discussed here. Fuller details of this are to be found in Section E.7.

The Storage Ring operates in the ultra high vacuum (UHV) pressure region.

5.2 DESIGN OBJECTIVES

The following objectives were adopted in this design

- to obtain in a reasonable conditioning time (chosen to be 100 Ah) a dynamic pressure of 1×10^{-9} mbar at 300 mA stored current, thereby obtaining a beam lifetime of at least 10 hours
- to obtain this dynamic pressure without using an *in situ* bakeout of the storage ring
- to use insofar as possible only proven materials, design methods and techniques
- to use as much modularity as possible in the construction of the vacuum envelope of the storage ring
- to use insofar as possible only standard, commercially available items of vacuum equipment

These objectives have been met in the design presented here, although some details remain to be clarified during the next phase of this project.

These objectives lead to a design which is of all-metal, stainless steel construction, with all vacuum vessels rigorously pre-cleaned and vacuum baked prior to installation.

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5.3 BASIC LAYOUT

The Storage Ring is divided into 24 cells. From a vacuum point of view, each cell is divided into a “straight” and an “arc” (in that order). Most straights will, in due course, accommodate an insertion device, although some will be devoted to machine requirements, *viz.*, rf, injection and diagnostics. Each straight will have an in-line vacuum isolation valve (so called sector valves) installed at either end, although some, notably the rf straight, will include further in line isolation valves. The arc contains the achromat, short pieces of straight adjacent to each end of the achromat and the spouts to beam port front ends. There are no in-line vacuum isolation valves in the arcs, although each beam port is so isolated.

For reasons discussed elsewhere, the storage ring will be constructed on a series of girders, with five to each arc. From arc to arc, vacuum vessels and equipment installed on each corresponding girder will be identical. It is intended that for all but minor maintenance work on the vacuum vessels during the operational life of the machine, complete girders will be removed from the ring tunnel to a maintenance area. A “stand-by” preconditioned girder assembly will be installed as a replacement.

Figure 5.3-1 shows the arc layout in schematic form.

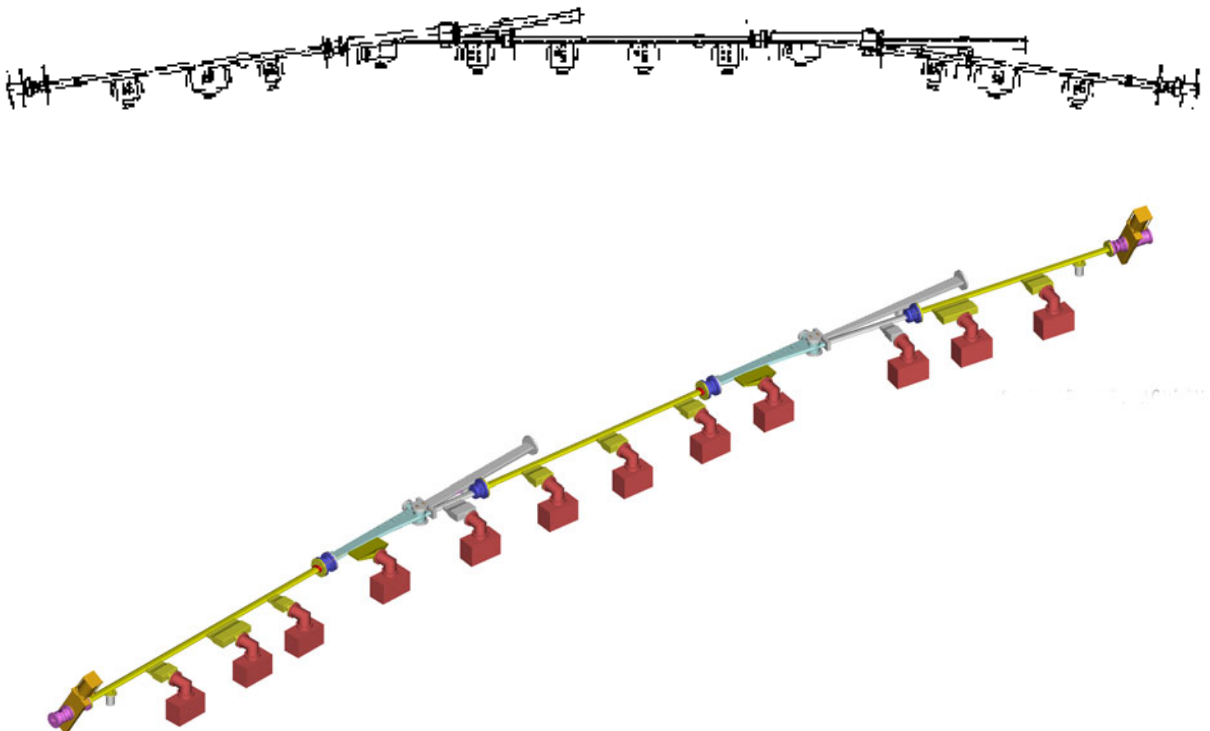


Figure 5.3-1 Schematic of arc layout

5.4 CONSTRUCTIONAL MATERIALS FOR THE VACUUM CHAMBERS

5.4.1 General

One of the major decisions concerning the vacuum system for a synchrotron light source is the material from which the vacuum chambers are to be fabricated. There are a number of points to be taken into consideration. Important ones are properties of the material (vacuum and mechanical) and economics.

Traditionally, synchrotron light source vessels are fabricated mainly from either stainless steel or aluminium. Other materials such as copper or GlidCop^{TM†} are used internally in photon stops or radiation absorbers where high heat loads have to be dissipated. Titanium is also a good candidate for special purpose vacuum vessels although it would probably prove too expensive for general use. Some machines - notably B-factories - have used copper as the vessel material.

It should be noted that although one talks about aluminium or titanium, in reality it is alloys of these materials which are used – and a range of alloys are suitable. Likewise, several grades of stainless steel are suitable. These include, *inter alia*, 304L, 304LN, 316L and 316LN.

5.4.2 Vacuum properties

In practice, the main vacuum property of concern is the photon desorption yield and its reduction with beam dose (“cleanup”), illustrated in Figure 5.4-1.

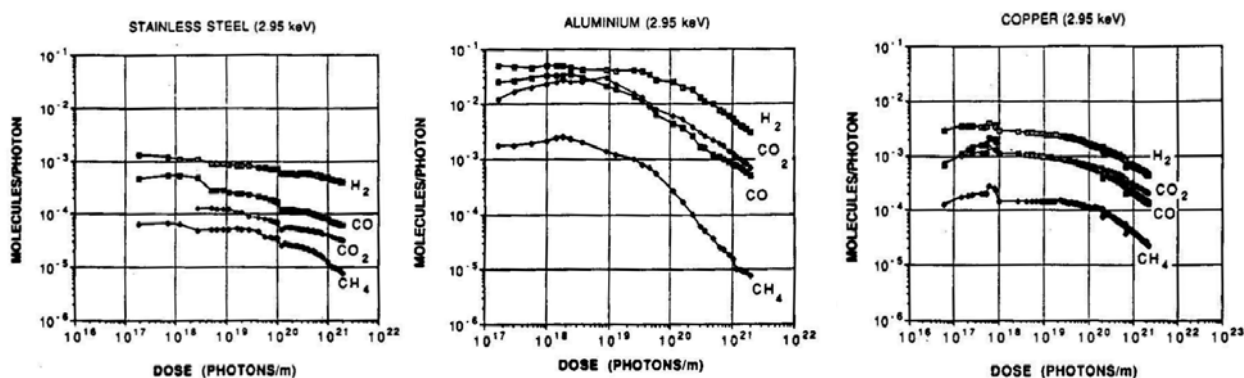


Figure 5.4-1 Photon stimulated desorption yields as a function of beam dose for stainless steel, aluminium and copper [1]

It will be noted that, apart from hydrogen which need not concern us, the three materials behave very similarly after relatively modest exposures to synchrotron light. Copper and aluminium start somewhat higher than stainless steel. All exhibit the so called memory effect in that after a period of beam exposure, subsequently exposing

[†] GlidCop: Registered trademark of OM Group, Inc., Cleveland, Ohio, USA

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surfaces to atmosphere does not lead to desorption yields as high as those from a virgin surface. Aluminium is the poorest of these materials in this respect.

Provided therefore that the vacuum system of DIAMOND is designed to cope with the appropriate gas loads generated in the early stages of commissioning and after exposure of the vacuum system to atmosphere, the use of any of these materials for the vacuum chambers should provide an adequate vacuum level for good lifetime.

Finally, in this context, it should be noted that the dynamic pressure in the machine is limited ultimately not by the desorption from the photon stops or absorbers which the emitted synchrotron light strikes directly, but by desorption by scattered and reflected photons (and by photoelectrons) at other parts of the vacuum chamber. The high intensity in the direct beams leads to rapid cleanup of these relatively small areas, but the lower intensity elsewhere gives a much slower net effect.

This will be discussed in more detail later (Section 5.6 below).

5.4.3 Other considerations

The material choice therefore comes down to factors other than pure vacuum performance. Among these will be how easy the material is to fabricate and clean, things like strength, thermal conductivity, magnetic permeability, surface resistivity and so on. The mechanical complexity of the chamber construction, necessary strengths to minimise distortion and allowable wall thickness will all play their part.

If stainless steel is chosen, then some care needs to be taken in selection of alloys for low magnetic permeability, particularly in weld regions. A value of $\mu < 1.005$ has been used in the past [2]. Such considerations do not arise for the other materials mentioned here.

If stainless steel is the principal material, then there is some concern that the surface electrical resistivity might be too high. The acceptability, complexity and cost of techniques for coating the inner surfaces (e.g. by sputtering of copper) will be considered during the construction phase of the project if it should be deemed necessary. This is also the case for titanium alloys.

One important consideration is the thermal stability of the machine. Stainless steel with its poor thermal conductivity is difficult to stabilise whereas aluminium is much easier. Extruded aluminium vessels can easily incorporate water channels to maintain uniform temperatures, and the possibility of running the machine at a somewhat elevated temperature may be attractive from the control point of view. However, aluminium has a large temperature coefficient of expansion which makes mechanical design more difficult. It is also more difficult to weld than stainless steel, and UK industry has little experience of this for UHV applications. Aluminium vessels may need to be thicker for adequate strength and therefore magnet gaps may need to be larger to accommodate this.

One area where aluminium will almost certainly be used is in the construction of long, narrow gap insertion device vessels. Here the required tolerances are difficult to achieve in a fabricated vessel, whereas a drawn or extruded vessel can so do. Likewise, vessels requiring complex machining are more easily manufactured in aluminium than stainless steel. Where aluminium is used as the vessel material, stainless steel to aluminium transition flanges are commercially available [3].

Copper (or at least copper alloys with suitable strengths) will probably prove more expensive than the other options, and again joining techniques are more difficult.

The experience at the SRS, Daresbury Laboratory, and indeed in most of the UK vacuum industry, is almost entirely with stainless steel and so there is some prejudice in its favour. It appears most likely that most of the storage ring will be fabricated from stainless steel but that aluminium and maybe copper will be used for special vessels where their properties are superior, e.g. small gap insertion device vessels.

Satisfactory cleaning techniques are known for each material. Since new facilities will have to be provided at RAL whatever the choice, there is no major predetermined influence here. (See also Chapter D.3)

5.4.4 Choice of material

Based on the above, the machine will be constructed from stainless steel. Once detailed design of individual vacuum vessels is undertaken during the construction phase of the project, considerations such as economical construction or tolerance requirements might dictate otherwise in individual cases.

5.4.5 Demountable vacuum joints

(a) Flanges

The standard demountable flange for UHV use is of the type knife-edge-on-copper-gasket. There are good, robust design implementations, widely available commercially of which the ConflatTM configuration is the best known. For flanges above 250mm od., there is no standard however and care has to be taken to ensure compatibility. For general use, such a flange will be adopted throughout the machine, particularly for the attachment of standard components such as pumps and gauges. To ensure compatibility, the Daresbury Laboratory standard series of flange types will be adopted [4]. Such flanges are manufactured from cross-forged ESR grade stainless steel, type 316LN[5]. The welding of such flange material to other grades of stainless steel is well understood.

This type of flange normally has a circular configuration. Non circular types are available, but these are not in widespread use. Circular flanges have the disadvantage of being not well matched to the general pseudo-elliptical cross section of vessels

[†] Conflat is a registered trademark of Varian, Inc, Lexington, Mass, USA

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required for the diamond storage ring, either thermally or dimensionally. In addition, there is an internal gap between the closed flange pairs which requires electrical bridging for impedance reasons where flange pairs are in line with the beam orbit.

An alternative type of flat flange using a trapped diamond cross section gasket can easily be made conformal to this vessel cross section and the gasket itself bridges this gap. A commercial implementation of this type of flange configuration (one of which is the so called VATSEAL^{TM†}) will be adopted for this use. Tests have been carried out at Daresbury Laboratory to confirm their general acceptability. A potential advantage with flange joint of this type is the possible use of a chain clamp rather than a set of fasteners. This has advantages in ease of assembly and requires less space along the beam orbit than that required for bolt insertion. However, tests on the use of such clamps have not been satisfactory and they will not be adopted.

Large joints will use flat flanges with wire seals or Helicoflex^{TM‡} seals as appropriate.

(b) Gaskets

Where a large machine is required to be bakeable, the use of high reliability gaskets is an imperative. Such gaskets are machined from OFS copper alloy (oxygen free high conductivity copper with 0.1% silver) to high tolerance and silver plated. Such gaskets have good elastic properties up to normal bake temperatures [6].

Diamond is not bakeable *in situ*, but all components require to be baked before installation. For such use, standard OFHC copper gaskets, silver plated, will be acceptable for all flange types.

5.5 VESSEL PROCESSING, TESTING AND QUALITY ASSURANCE

In common with the majority of Synchrotron Sources, diamond will employ rigorous cleaning processes to pre-condition the vacuum chambers and components before installation in the machine complex. This will include pre-installation bakeout for all vessels and components, with the possible exception of the gun/linac.

The cleaning process is described more fully in Part D.3 of this report.

Full details of cleaning, processing, test specifications and item tracking procedures are to be found in the Manual of Quality Assurance Procedures for Vacuum for the diamond Project [7].

[†] VATSEAL is a registered trademark of VAT Vakuumventile AG, Haag, Switzerland.

[‡] Helicoflex is a registered trademark of Cefilac, Saint-Etienne, France

5.6 TO BAKE OR NOT TO BAKE *IN SITU*?

As mentioned in 5.5 above, diamond will employ rigorous cleaning processes including pre-installation bakeout to pre-condition the vacuum chambers and components before installation in the electron storage ring machine complex. This is an essential step in achieving the low photon and thermal desorption rates from the vacuum chamber surfaces required for good beam lifetime. However, it is clear that there is some division of opinion as to whether or not an in-situ bakeout is also essential to reach such a state.

We recall that the main purpose of a bakeout is to desorb water from the surface. Water has a heat of adsorption on most metal surfaces which means that its thermal desorption is rather inefficient at room temperature, although sufficiently high to limit pressures in vacuum systems to around 10^{-8} mbar for very long periods of time [8]. A bakeout at temperatures above 150°C is sufficient to deplete the surface. The depletion is, of course, time dependent and it has been determined pragmatically that to reduce the time required at temperature to less than about 24 hours a temperature of 250°C is required. It is also known that synchrotron radiation desorption of water is a rather efficient process [9]. It is also useful that once the surface is depleted of water, provided that it is initially only exposed to dry gas (containing less than around 1ppm of water) resorption is a relatively slow process [10].

Taking these together, it seems that a good case can be made that bakeout is not essential for machines like diamond.

A survey of operating facilities has been undertaken to assess current practice. Little information on this is available in the published literature. Although not all sources have responded, sufficient have done so for a reasonable picture to emerge [11]. Table 5.6-1 summarises the results of the survey. It will be seen that the twelve facilities listed split evenly. There is no discernable pattern between different types of material or beam energy. Therefore the conclusion is drawn that since so many facilities are in fact capable of operating without bakeout, it is reasonable to assume that diamond can similarly.

It could be argued that some of the facilities were originally designed to be baked *in situ* and it is only later, following considerable conditioning by beam, that it became possible to operate without bakeout. The evidence does not support this since some of the facilities have never been baked.

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Table 5.6-1 Summary of use of *in situ* bakeout at various facilities

SR Facility	Material	Beam energy (GeV)	In-situ bakeout used
APS, Argonne National Laboratories, USA	Aluminium	7.0	Yes
BESSY II, Germany	Stainless steel	1.9	No
CERN, Switzerland	Stainless steel and Al	300	Yes
CHESS, Cornell, USA	Aluminium	5	No
ELETTRA	Stainless steel	2	No
ESRF, Grenoble, France	Stainless steel	6	Yes
KEKB, Japan	Stainless steel and copper	8	No
LNLS, Brazil	Stainless steel	1.15	Yes
MAX-LAB, Sweden	Stainless steel	1.5	Yes
NSLS, Brookhaven, USA	Aluminium	2.5	Yes
SLS	Stainless steel	2.4	No
SRS, Daresbury Laboratory, UK	Stainless steel	2	No

5.6.1 Surface Treatments for diamond Vacuum Vessels

To clarify the requirements for surface treatments for the vacuum vessels for diamond, a consultant, Dr E. M. Williams was engaged to carry out a literature survey in this area, supplemented by visits to various European Accelerator Laboratories [12]. A full report is in the course of preparation [13], but the following is a summary of the findings.

“There is by now a broad database on the response of gas desorption at technological materials arising from stimuli of electrons and photons available to the designer of vacuum systems for modern synchrotrons. Moreover, studies with photon stimulated desorption have progressed from observations on small samples of wall material, to the investigation of desorption yields directly at real sections of vacuum ducts, simulating the actual conditions within a storage ring. These have shown that the desorption yields are dependent upon material and surface pre-treatment mainly during the initial stage of irradiation. Furthermore, high initial desorption yields tend to reduce more speedily and the difference between material and surface-pre-treatments become smaller as beam conditioning proceeds. The cleaning process imparted by the stored beam serves to deplete both surface and sub-surface/bulk gas and involves the whole of the vacuum enclosure, not only the part directly illuminated by synchrotron light. Bakeout and glow discharge cleaning can accelerate the removal of the more immediate surface components of gas, but offer no substitute to the action of the synchrotron light in reducing the desorption response to the levels $\sim 10^{-6}$ mol./photon required to attain working beam-lifetimes.

"In assessing the role of the synchrotron light in the conditioning of third generation light source, a distinction can be drawn between the achromat regions with relatively high photon intensity and the straight sections for insertion devices (I.D.), which are illuminated mainly by radiation incident at the up-beam end. This offers realistic conditions for beam cleaning at the achromats, however, the whole of the machine is involved in the progression towards the design lifetime. For the straight sections, considerations for vacuum are not only linked to lifetime, but as recent experience has shown the utilisation of synchrotron light by users can be impeded by the build up of significant bremsstrahlung radiation over the 10-15 m linear dimensions of these regions. The design of vacuum systems for external I.D.'s has been approached along two fronts - either with an antechamber design so as to offset the low conductance inherent with the narrow vertical spacing, or using NEG coatings as a distributed pump directly at the interior. Both approaches are likely to incorporate bakeout facilities, additionally for the NEG coating, heating forms part of the activation procedure. In this regard, the discovery of ternary alloy NEG materials with activation temperatures as low as 180°C is clearly viewed with some interest.

"In the case of in-vacuum undulators, designs can be based on more conventional vacuum approaches.

"The action of beam conditioning at the achromats proceeds through primary irradiation as well as through the action of reflected and fluorescence radiation, which pervade the whole of the interior surface. Tests with sample ducts predict that the desorption yield beyond an exposure around 10^{21} photons/m follows an inverse dependence on the accumulated beam exposure, taking a form independent of the initial surface preparation. To reduce yields towards the lower limits demanded by lifetime considerations requires doses in the region of 10^{24} photons/m. Under typical conditions of operation of a third generation light source, this accumulation occurs over a period ~100 Ah of beam operation. The initial phase of gas desorption imposes the greatest load and its reduction ahead of beam cleaning has traditionally been the role of an in-situ bakeout. At this stage of operation, water is likely to dominate the residual gas spectrum. Experience at ELETTRA in the mid 90's, demonstrated that the storage ring could be commissioned on a practicable time scale with total reliance on beam cleaning and without requiring an in-situ bakeout. More recently synchrotron sources both in Europe (SLS, ANKA) and Japan (KEKB, PF) have been designed to operate with this philosophy. The most rigorous approach for the reduction of the initial gas load has been the strategy followed at the SLS. This involved a pre-bakeout of assembled achromat sectors at 250 °C and their subsequent transfer under UHV to form the storage ring. A comparison of operational data between the SLS and the ANKA storage ring, where pre-bakeout of chambers was carried out as part of a vacuum integrity test, suggests a gain by a factor of between 2 and 3 in the time scale of vacuum performance. The current-lifetime figure and specific pressure rise found at the SLS with an accumulated dose of 100 Ah are respectively 4 Ah for and $3 \cdot 10^{-8}$ mbar/A, which are quite comparable to findings quoted for ELETTRA and for the ESRF. Likewise at the electron storage ring at KEBK utilising copper duct material,

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the same figure of specific pressure rise is apparent at 100 Ah beam exposure. The procedure followed by the Japanese workers has been to bakeout individual chambers at 150 °C, followed by nitrogen purging and sealing prior to incorporation at the ring, with particular care to minimise air exposure.

“Thus, omitting in-situ bakeout is a feasible option for the achromat sections, although preparations such as pre-baking and the careful control of UHV integrity will contribute to a successful start up. The procedure to be followed is finally a matter of one’s design philosophy. There are considerations of accidental damage and problems with leaks, and this is where the procedure with an in-situ bakeout would perhaps be likely to score, although reflecting upon practice at ELETTRA the turn around while attending to repairs or modifications is not seen as a particular limitation. In this regard, the memory effect which accompanies the beam clean-up serves to advantage. For the straight sections with external I.D.’s, then from a vacuum standpoint the choice of either an ante-chamber or a NEG approach is acceptable. The decision hinges on the philosophy which relates to the whole machine, in particular, the design and utilisation of local absorber sites at the achromats which can be set closer to pumps with a full ante-chamber design.” [13]

5.7 VACUUM PUMPING

5.7.1 Rough Pumping

(a) Introduction

Rough pumping of the Diamond storage ring is an essential and important process. The need to generate pressures lower than 1×10^{-6} mbar in a reasonable time so that the UHV pumps can be started is crucial to the efficiency with which Diamond can reach base pressures and begin operation. It is also essential that the pumping systems employed are clean so that there is no possibility of contamination of the storage ring. Therefore it is most likely that clean turbomolecular pumps with magnetic suspension and backed by molecular drag pumps and either scroll or piston pumps will be used. Other combinations are possible and will be evaluated during the procurement phase of the project.

Calculations of rough pumping times have been performed using Vactran™ [14], a vacuum technology software package capable of simulating real vacuum systems in both viscous and molecular flow pressure regimes.

There are two considerations in calculating such pump down times for large vacuum systems like the storage ring. The first is the volume of the vacuum system to be pumped and the second is gas flow conductance along the beam tube, which limits the rate at which gas can reach the pumps. Conductance is the dominating factor in the diamond storage ring. When one cell of the storage ring is considered, it is clear that there are a number of different conductance elements, which will limit the pump

down time. These include the pumping ports, bending magnet vacuum chambers, multipole magnet vacuum chambers and straight sections.

Although Vactran™ has limitations, for example it only permits circular pipes to be considered, these can be overcome and test calculations on the existing SRS machine configuration gave results comparable to pump down times achieved in practice.

(b) Pumping stations

A fundamental matter to be considered is whether to use fixed (i.e. built in) rough pumping stations or mobile pumping units. The arguments for and against each type are discussed thoroughly elsewhere [15]. On the basis of the evidence presented there and on many years of operational experience of the SRS, fixed pumping stations will be provided. There are major advantages in this approach, even though it is the more expensive option. A pumping system is always available when required and it can be kept clean and free from contamination. This results in major gains in operational efficiency, especially when an emergency intervention is required.

Pumping stations will be located adjacent to each insertion device straight and to the rf straight, injection straight and diagnostic straight. The stations can be manifolded to each adjacent arc and to the straight by means of manual valves, giving some flexibility in their use.

(c) Pump down times

Figure 5.7-1 shows the pump down time for an arc using a pump set comprising a nominal 300 l sec^{-1} turbomolecular pump and a combination drag and diaphragm pump. The curves to consider are those showing pump down with gas load (composed primarily of water vapour). The upper set of curves is essentially the pump down by the primary pump set and the lower that of the turbomolecular pump. A pressure of 10^{-5} mbar is a reasonable upper limit for starting and conditioning ion pumps (see 5.11.4(b) below), so it will be seen that about two days prepumping is required per cell. This is considered to be acceptable. It can be shortened by applying pumping at each end of the arc from the pump sets in adjacent insertion device straights. This will be useful during operations when quick pump downs are desirable. On the other hand, using a single pump set to pump two adjacent arcs (i.e. installing a roughing set only every other straight produces an unacceptable pump down time of about a week for an arc without the possibility of enhancement.

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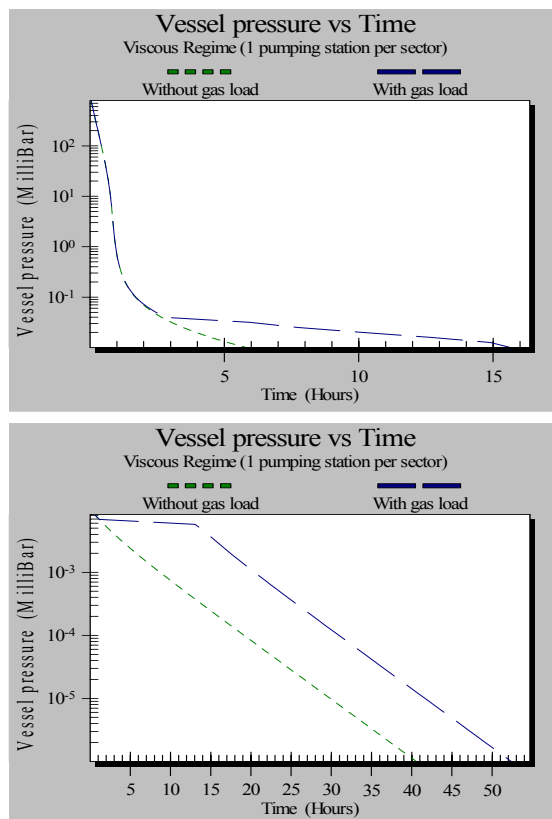


Figure 5.7-1 Pump down times for the Diamond storage ring with one pumping station per cell

5.7.2 UHV pumping philosophy

In this design, the aim is to achieve the necessary pumping by using only lumped pumps attached to the vacuum vessels by pumping spouts of some sort. This simplifies the mechanical design, since no special arrangements are required to accommodate integrated pumps within the vacuum envelope. It also improves serviceability, since, with careful attention to layout detail, individual pumps can be removed and replaced without necessarily removing vacuum vessels to strip out internal pumps. This feature is, of course, not so important if the removable girder philosophy is adopted, but is still convenient for increasing maintenance options. The types of pumps used are discussed below.

The available space in the storage ring for installing vacuum pumps is very restricted, so it appears that most of the pumps have to be attached to the electron beam tube through horizontal pumping spouts aligned along the beam tube and coming in through either the dipole magnet aperture or between the poles of the quadrupole magnets. Because the vertical aperture available is less than the dimensions of a typical pump throat, most of the lumped pumps are attached to the chambers by fin-shaped pumping spouts similar to those shown in Figure 5.7-2. The gas flow

conductance of these spouts limit the pumping speed which can be deployed. Some of the pumps can be fitted beneath the vessel containing the crotch absorber or beam port absorber and in these cases, larger aperture tubes can be used and a greater pumping effect achieved.

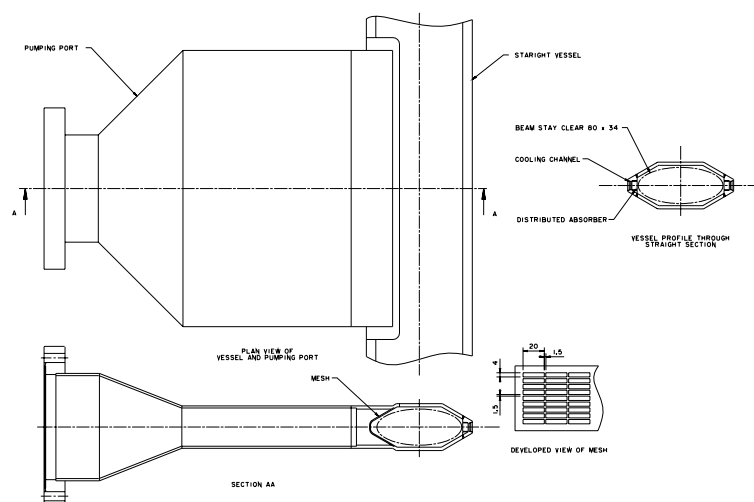


Figure 5.7-2 Schematic of a typical pumping spout

In a storage ring like diamond, apertures such as these pumping ports are usually screened with a mesh comprising a thin plate pierced by rectangular apertures with the long side of the aperture oriented along the beam direction. This is to provide radio-frequency electrical continuity along the pipe. Such meshes of course further reduce the available pumping speed at the beam orbit, although the effect can be made quite small with careful design.

5.7.3 UHV pumps

The generic types of UHV pumps to be considered for use in diamond are

- (a) Sputter ion pumps: differential ion diode configurations will be used since these display the best compromise of properties – good starting at relatively high pressures; good low pressure performance and good pumping speed for inert gases. These will be the “workhorse” pumps.
- (b) Titanium sublimation pumps: these give good pumping performance for active gases at low pressure and are relatively inexpensive. Long experience of their use in the SRS has demonstrated that with careful control and rigorous outgassing they provide useful pumping over long periods of time before requiring filament replacement. The pumping speed and capacity depends on the surface area available to be coated by the thin film of titanium (or usually titanium-molybdenum alloy)

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- (c) NEG (non evaporable getter) cartridge pumps: these also give good pumping for active gases at low pressures. They provide high pumping speeds in small pump volumes but have the disadvantage of requiring high temperature activation from time to time and are relatively expensive.

In addition to these pumps, the relatively new technology of using vessels internally coated with a sputtered film of NEG material will be adopted for special situations [16]. Although this technology provides good pumping speeds in conductance limited situations where other pumping is relatively ineffective, it is a new technology and long term efficacy is still not proven. It will therefore be adopted only for vessels which can readily be replaced without compromising the operation of the storage ring, e.g. in insertion device vessels.

5.7.4 Applied pumping speeds

As noted above, much of the pumping available in the beam tube is applied through the fin-shaped pumping spouts illustrated in Figure 5.7-2 above. The actual pumping speed available is therefore restricted by the transmission probability of gas molecules through these spouts to fixed vacuum pumps (some combination of ion pumps, titanium sublimation pumps or non evaporable getter pumps). The physical size of these spouts in the vertical plane is severely limited by the need to bring them through the pole pieces of the quadrupole magnets in the present design. There is somewhat more flexibility in pumping in the region of the dipole magnets.

The transmission probabilities for several variants of the pumping spouts (details are shown in diamond drawings A0-302/10292 to A0-302/10296) have been calculated using Monte-Carlo simulations [17]. These are referred to in Table 5.7-1 as “narrow ports” and are as shown in Figure 5.7-2. There is, however, the possibility – at the cost of some minor engineering complexity – of opening out these spouts as soon as the magnet aperture restrictions are cleared. These are referred to here as “open ports”. The table shows the effective pumping speeds available at the beam for the different pump spouts with nominal pump speeds of 200 and 500 l sec⁻¹. As may be seen, there is no benefit in using larger pumps with the narrow spout, i.e. the effective pumping speed is limited by the conductance of the pumping spout. However, the effective pumping speed can be increased by a factor of about two for the open port using a pump of nominal speed 500 l sec⁻¹.

The implications of this on the sizes (speeds) of the actual pumps to be used will be considered later (5.9.2 below).

E.5 VACUUM

Table 5.7-1 Effective pumping speeds at the electron beam orbit

	Pumping port			Effective pumping speed S_{eff} (l sec ⁻¹) for a pump with pumping speed S			
	Width (mm)	Transmission probability	Vacuum conductance (l sec ⁻¹)	S (l sec ⁻¹)			
				200	300	400	500
Dipole vacuum chamber spout	260	0.198	202	100	120	134	143
Quadrupole vessels with narrow pumping ports							
Wide gap 23 mm	200	0.155	75	54	60	63	65
	300	0.145	106	69	78	84	87
	500	0.117	143	84	97	105	111
Narrow gap 16 mm	300	0.128	62	47	52	54	55
Quadrupole vessels with open pumping ports							
Wide gap 23 mm	200	0.38	183	96	114	125	134
	300	0.352	256	112	138	156	169
	500	0.292	357	128	163	189	208
Narrow gap 16 mm	300	0.38	185	96	114	126	134

5.8 AVERAGE DYNAMIC PRESSURE

5.8.1 General considerations

The gradual reduction of pressure in an electron storage ring as it is exposed to the photons generated by the circulating electron beam is by now well known [18]. The phenomenon of beam cleaning or “scrubbing” is reasonably well understood insofar as generalised predictions of clean up rates can be made on a phenomenological basis by drawing on the experience of operational storage rings around the world. The basic physics, chemistry and materials science underlying this phenomenological approach to this complex process is not well understood. In this report, it is assumed without further discussion or justification that this approach is valid.

5.8.2 A model of dynamic desorption processes in a beam vacuum chamber

The equations of gas dynamic balance inside a vacuum chamber can be written as:

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$$V \frac{dn}{dt} = q - cn + u \frac{d^2 n}{dz^2}; \quad (1)$$

where n	[molecule m ⁻³]	is the gas volume density;
z	[m]	is the longitudinal axis of the vacuum chamber
V	[m ³]	is the vacuum chamber volume;
q	[molecule sec ⁻¹]	is the gas desorption flux;
$c = \rho A_{mesh} \bar{v} / 4$	[m ² sec ⁻¹]	is the distributed pumping speed,
ρ		is the capture factor for the pump including a pumping port and a mesh,
A_{mesh}	[m ²]	is the mesh area,
$\bar{v}$	[m sec ⁻¹]	is the mean molecular speed.
$u = A_c D$	[m ⁴ sec ⁻¹]	is the specific vacuum chamber molecular gas flow conductance per unit axial length,
A_c	[m ²]	is the vacuum chamber cross section;
D	[m ² sec ⁻¹]	is the Knudsen diffusion coefficient.

Gas desorption consists of two main sources: thermal and photon stimulated desorption:

$$q = \eta_t F + \eta_\gamma \Gamma; \quad (2)$$

where η_t	[molecule sec ⁻¹ m ⁻²]	is the thermal desorption yield,
F	[m ²]	is the vacuum chamber surface area,
η_γ	[molecule photon ⁻¹]	is the photon stimulated desorption yield,
Γ	[photon sec ⁻¹]	is the synchrotron radiation photon flux.

Here we are interested in the solutions of equation (1) in the quasi-equilibrium state when the condition $V dn/dt = 0$ is satisfied.. Therefore, equation (1) can be re-written as:

$$u \frac{d^2 n}{dz^2} - cn + q = 0. \quad (3)$$

The second order differential equation (3) for the function $n(z)$ has two solutions:

$$\text{Case (a)} \quad n(z) = -\frac{q}{2u} z^2 + C_{1a} z + C_{2a} \quad \text{for } c = 0; \quad (4)$$

$$\text{Case (b)} \quad n(z) = \frac{q}{c} + C_{1b} e^{\sqrt{\frac{c}{u}} z} + C_{2b} e^{-\sqrt{\frac{c}{u}} z} \quad \text{for } c > 0. \quad (5)$$

where the constants C_1 and C_2 depend on the boundary conditions.

As mentioned above, the longitudinal dimension of the pump aperture is much greater than the cross sectional dimensions of the beam tube, so the pump can be regarded as a pumping speed distributed along a length equal to the overall length of the mesh. Hence, the solutions for $c = 0$ corresponds to the vacuum chamber between pumps and the solutions for $c > 0$ corresponds to a vacuum chamber where there is a mesh and a pumping port.

The vacuum chamber along the beam can be considered as being divided into N longitudinal elements with $c = 0$ or $c > 0$. Every i^{th} element lying between longitudinal co-ordinates z_{i-1} and z_i will be described by equation (4) or (5) with two unknowns C_{1i} and C_{2i} . The boundary conditions are $n_i(z_i) = n_{i+1}(z_i)$ and $\partial n_i(z_i)/\partial z = \partial n_{i+1}(z_i)/\partial z$. For the first element we use the boundary conditions $n_1(z_0) = n_1(z_1)$ and $\partial n_1(z_0)/\partial z = \partial n_1(z_1)/\partial z$; and for the last one we use $n_N(z_{N-1}) = n_N(z_N)$ and $\partial n_N(z_{N-1})/\partial z = \partial n_N(z_N)/\partial z$. In this case $C_{1i} = C_{2i}$ for $i = 1$ and $i = N$. Now for the N elements of the vacuum chamber we have a system of $2N-2$ equations with $2N-2$ unknowns, which can be easily solved with the numerical calculation package MathCad-2000 [19].

One numerical problem exists in such modelling. This lies in the numerical precision when two large values have a small difference. For example, if $a=10^{80}+10$ and $b=10^{80}$ then instead of the expected value of $a-b=10$ the computer may show $a-b=0$. This happens here for large z . The problem may be successfully overcome simply by a change of variables on every element: $Z_i = z - z_i + L_i/2$, where L_i is the length of i -th element, i.e. Z_i varies between $-L_i/2$ and $L_i/2$: $-L_i/2 \leq Z_i \leq L_i/2$.

The solutions to the equations (4) and (5) can be found for three distinct pumping configurations employed in the straight section of Diamond and are given below. Consider a vacuum chamber of length L , centred at $z = 0$, then the following solutions are used:

For a finite length vacuum chamber with distributed pumping between two pumps with a pumping speed S_p :

$$n(z) = \frac{q}{C} \left[1 - \frac{\cosh\left(\sqrt{\frac{C}{u}} z\right)}{\cosh\left(\sqrt{\frac{C}{u}} \frac{L}{2}\right) \left(1 + \frac{\sqrt{Cu}}{S_p} \tanh\left(\sqrt{\frac{C}{u}} \frac{L}{2}\right)\right)} \right] \quad (6)$$

The average value of the gas density is: (7)

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$$\langle n(L) \rangle = \frac{q}{C} \left(1 - \frac{\tanh\left(\sqrt{\frac{C}{u}} \frac{L}{2}\right)}{\sqrt{\frac{C}{u}} \frac{L}{2} \left(1 + \frac{\sqrt{Cu}}{S_p} \tanh\left(\sqrt{\frac{C}{u}} \frac{L}{2}\right)\right)} \right).$$

For a finite length vacuum chamber without distributed pumping between two pumps with a pumping speed S_p :

$$n(z) = \frac{q}{2u} \left(\frac{L^2}{4} - z^2 \right) + \frac{qL}{2S_p}. \quad (8)$$

The average value of the gas density is:

$$\langle n(L) \rangle = q \left(\frac{L^2}{12u} + \frac{L}{2S_p} \right). \quad (9)$$

This solution should be also used for inert gases, CH₄ and other hydrocarbons where there is distributed NEG pumping.

This analysis is basically a one-dimensional simulation. Therefore, the question of applicability and accuracy of such a simulation to a three-dimensional problem may arise. In fact, much of the storage ring is a close approximation to a thin pipe, which is almost one-dimensional.

The analytical method described here has been benchmarked against a Monte-Carlo simulation program [17] that is used quite extensively in particle accelerator laboratories for this type of work, with the same system parameters.

Calculations were carried out for the regular vacuum chamber of elliptic cross section and for the most complicated element of the diamond vacuum chamber: the dipole vacuum vessel. The result for the dipole vessel is shown in Figure 5.8-1. There are some minor differences in the pressure profiles, but the *average* value of pressure along this vessel is in fact similar in both cases. There is no significant difference in the pressure profile or average pressure in the regular vacuum chambers with elliptic cross section calculated using either method.

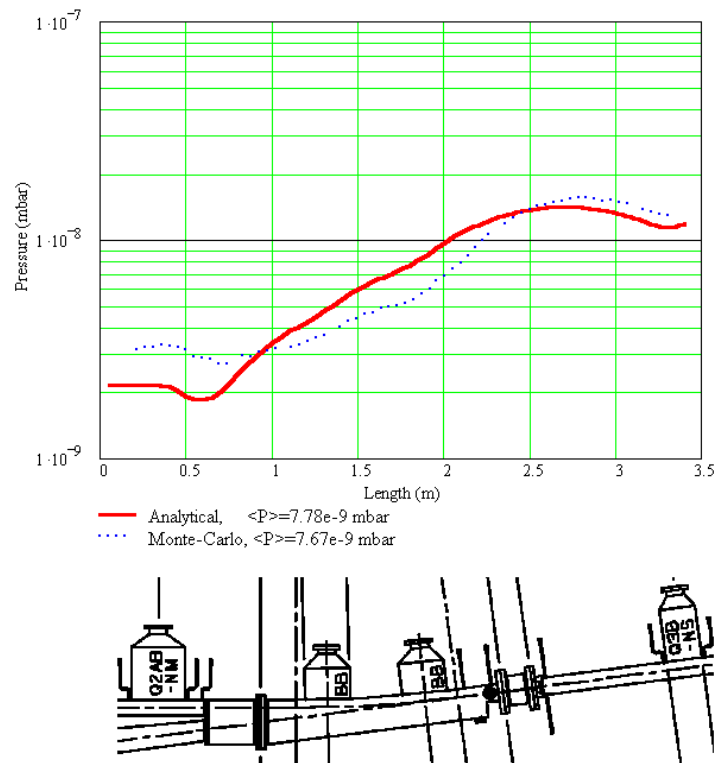


Figure 5.8-1 Comparison between the analytical methodology described here and a Monte-Carlo simulation for some elements of the diamond vacuum chamber

Therefore, it is concluded that overall estimates of pressure profiles along the diamond arc and of average pressures can be made to sufficient accuracy using the analytical method, which is much faster, more convenient and more flexible for calculations where many variations in input parameters are required.

5.8.3 Thermal desorption

All materials used to build accelerators, such as stainless steel or copper, desorb gas into the vacuum system. This thermal desorption is described by an outgassing rate q_{th} [mbar l sec⁻¹ m⁻²] or a thermal desorption yield η_t [molecule sec⁻¹ m⁻²]. These initially decrease exponentially with pumping time and a value of about 10^{-14} mbar l sec⁻¹ m⁻² (or $2.5 \cdot 10^{12}$ molecule sec⁻¹ m⁻²) will be easily obtained for carefully chosen and well-prepared materials after a few hundred hours of pumping [20]. Thermal desorption determines the base pressure in the storage ring without beam.

5.8.4 Photon stimulated desorption

In the presence of beam, the main source of gas is photon stimulated desorption (psd). Photon stimulated desorption yields have been experimentally studied in many research centres. The most appropriate results for diamond are to be found in references [21], [22], [23], [24], [25], [26], [27], [28], [29]

In general, the psd yield, η , for a vacuum chamber decreases with photon dose proportionally to D^{-a} , where D is the integrated photon dose to which it has been

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exposed. At room temperature, the exponent a lies between $2/3 \leq a \leq 1$. Proper cleaning procedures, pre-baking and baking *in-situ* will lower the dose required to obtain a given value of the psd yield. The initial desorption yield of a pre-baked and/or *in-situ* baked vacuum chamber will be lower but the cleaning rate (the exponent a in D^{-a}) is also lower. Similarly the psd yield of an unbaked vacuum chamber reaches the same low value of η and of clean-up rate $\eta \propto D^{-a}$ with $2/3 \leq a \leq 1$, but at higher photon doses. At very high photon doses there is no significant difference between baked and unbaked vacuum chambers. A comparison between baked and unbaked vacuum chambers is shown in Figure 5.8-2.

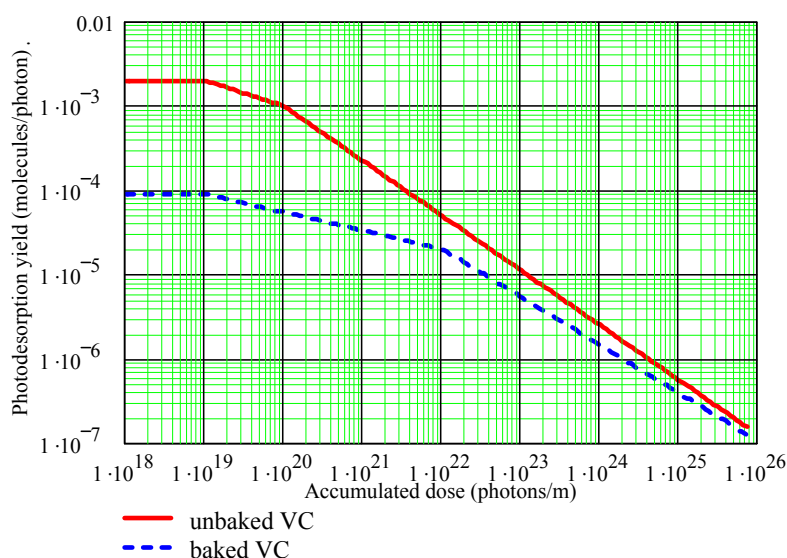


Figure 5.8-2 Photon stimulated desorption yield for CO for unbaked and baked vacuum chambers [22]. Yields for doses higher than 10^{23} photons/m are extrapolations.

Herbeaux *et al* [21] and Foerster *et al* [22] describe desorption from a stainless steel vacuum chamber pre-baked at 200°C for 24 hrs (but not baked *in-situ*) by synchrotron radiation with $E_c=3.35$ keV and 500 eV respectively. Additionally, the dependence of PSD yields on different pre-treatments has been studied by Foerster *et al* [22] and by Malyshev [23]. The results of both studies are in good agreement. Although the initial values of the psd yield at a dose of 10^{19} photon m^{-1} found by Herbeaux is about four times higher than that measured by Foerster, the difference at doses of 10^{22} to 10^{23} photon m^{-1} is already negligible and may be related to the different diameters of the sample tubes and/or the different photon critical energies. The complication for predicting the pressure in diamond is that the experimental measurements were obtained for doses of up to $2 \cdot 10^{23}$ photon m^{-1} (about 1.7 Ah in the most intensively irradiated part of the vacuum chamber). Therefore some extrapolation must be done to a dose of $1.2 \cdot 10^{25}$ photon m^{-1} (about 100 Ah). Herbeaux finds $a=1$ while $a=2/3$ in Foerster. Thus an extrapolation of Foerster's data gives higher psd at high doses. To avoid underestimating the pressure and therefore the necessary conditioning time in diamond we use the more pessimistic extrapolation in this estimation.

Photon stimulated desorption yields from an OFHC copper vacuum chamber are described in references [24] to [29]. The main conclusion from this work is that copper has about the same psd yield as stainless steel after a dose of about 10^{23} photon m^{-1} . This means that using elements made of copper inside the vacuum chambers should not affect the predicted pressure significantly.

Anashin *et al* [26] describe psd measurements at $E_c=2.66$ keV from a crotch absorber made of copper. The values in that paper are used for the psd estimates for the diamond crotch absorbers.

5.8.5 Desorption yields

It should also be noted that thermal and photon stimulated desorption yields are not constant or, indeed, well defined. They vary between materials and with preparation techniques and the previous history of irradiated samples. However, there is a sufficient body of information in the literature that their magnitude and behaviour can be determined pragmatically as noted above. However, even with a very good model and precise calculation, the real and predicted values may nevertheless differ by a factor two or even more because of these uncertainties.

5.8.6 Photon fluxes

There are two main sources of photons in the storage ring: synchrotron radiation from dipoles and synchrotron radiation from the insertion devices. About 30% of the synchrotron radiation from the dipoles irradiates the walls of the vacuum chamber; about 45% strikes the crotch absorber and the remainder (~25%) is transmitted down the beamlines. The synchrotron radiation from the insertion devices should all pass along the beamline. However, a vertical undulator will partially irradiate the dipole vacuum chamber upstream of its beamline. Hence it may be seen that the pressure in the beam pipe is mainly affected by synchrotron radiation from the dipoles.

(a) Photon flux from dipoles

The total photon flux from the dipoles along the main ring can be estimated from:

$$\Gamma_{tot} \left[\frac{\text{photons}}{\text{sec}} \right] = 8 \cdot 10^{20} \cdot E[\text{GeV}] \cdot I[A], \quad (10)$$

where E is the beam energy and I is the beam current.

For diamond at $E = 3.0$ GeV and $I = 300$ mA the total photon flux from the dipoles is $\Gamma_{tot} = 7.24 \cdot 10^{20}$ photon sec^{-1} . In other words each of the 48 dipoles radiates a photon flux of $\Gamma_{dip} = 1.5 \cdot 10^{19}$ photon sec^{-1} into an angle of 131 mrad (7.5°). Synchrotron radiation from about 30 mrad is passed to users through the beamlines, the rest of the synchrotron radiation from the dipoles is intercepted by the walls of the vacuum

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chamber and the crotch absorber (about 50 mrad each). It is important to know how the photon flux is distributed along the diamond vacuum chamber.

The photon flux distributed per meter of vacuum chamber length depends on the total photon flux and the distance from the source point to the point of impact. For practical use it is more convenient to write a formula for the photon flux per meter, Γ_m , as a function of distance, z , from the end of dipole, which has a bending radius R_d , and horizontal half-aperture of vacuum chamber, a :

$$\Gamma_m(z) = \frac{\Gamma_{tot}}{2\pi} \left[\frac{(R_d + a)}{(R_d + a)^2 + z^2} - \frac{R_d z}{((R_d + a)^2 + z^2) \sqrt{z^2 + 2R_d a + a^2}} \right] \quad (11)$$

The estimate for a vacuum chamber with $a=4.0$ cm is shown in Figure 5.8-3. The photon flux varies from $1.5 \cdot 10^{19}$ photon $\text{sec}^{-1} \text{ m}^{-1}$ just after the dipole down to $1.5 \cdot 10^{17}$ photon $\text{sec}^{-1} \text{ m}^{-1}$ at about 5 m away from there (the distance between the two dipoles in the achromat is 5.2 m and the straight from the dipole to the first insertion device vacuum isolation valve is 5.1 m). The photon flux along the insertion device straights will be even lower: between $2 \cdot 10^{16}$ and $1 \cdot 10^{17}$ photon $\text{sec}^{-1} \text{ m}^{-1}$. The minimum photon flux will be incident on the walls of the vacuum chamber from the valve after the insertion device to the following downstream dipole.

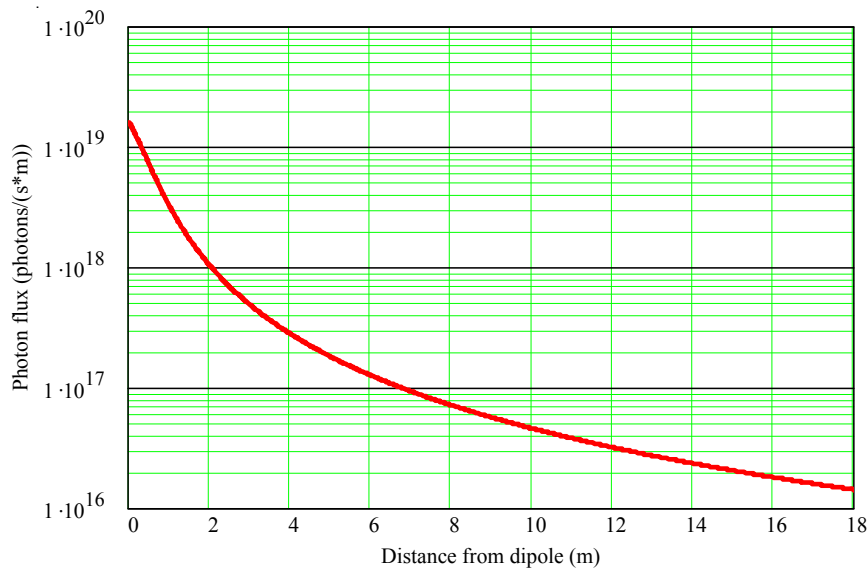


Figure 5.8-3 Photon flux incident on the vacuum chamber walls along the straight sections as a function of distance from a dipole

It should also be noted that some of the photons can be reflected and therefore the real photon distribution along the beam vacuum chamber will be more uniform than indicated. However, this will affect only the parts which receive a very low direct photon flux, i.e. mainly the vacuum chamber of the insertion devices and the region from the valve between the insertion device and the downstream dipole. There are two independent studies of photon reflectivity in synchrotron radiation beam lines:

one on EPA at CERN [30] and a second on VEPP-2M at BINP [31]. Both demonstrate that, for an average grazing incidence angle of 11 and 20 mrad respectively, the forward scattered photon reflectivity may range from 2% up to 20% for a stainless steel vacuum chamber. Hence, for a forward scattered reflectivity of 20% the uniformly reflected photon flux along the insertion device straights cannot be higher than $1 \cdot 10^{17}$ photon $\text{sec}^{-1} \text{ m}^{-1}$.

Some photons will be scattered diffusely and there will also be the emission of some fluorescent photons. However, the amounts will be less than for specular reflection – although dependent on the optical properties of the surfaces. It is safe to assume, based on experience at many synchrotron sources, that any effects induced by such photons will be at the 10% level or less – well within the other uncertainties in analyses of this type.

It should also be noted that some of the emitted synchrotron radiation photons have energies below the threshold energy for desorption, the cut-off conventionally being taken to be 10 eV. Since equation (10) yields total photon fluxes, there is an element of conservatism in these calculations

(b) Photon flux from insertion devices

All of the synchrotron radiation from the ID's should pass along the beamlines. The front of the beamports are, however, in the same vacuum system as the storage ring. There is a movable synchrotron radiation absorber in front of the first vacuum valve, and we need to ensure that the vacuum system is capable of handling the desorption from this absorber when closed. Table 5.8-1 shows the estimated parameters for the first tranche of beam lines.

Table 5.8-1 Parameters for the first tranche of beamlines

Beam-line	ID	E_γ (keV)	ID length (m)	Straight length (m)	Gap (mm)	Γ (photon sec^{-1})
1	3.5 T MPW	2-200	1.5	5	10	$\sim 3.6 \cdot 10^{19}$
6, 8-11, 13	Undulators	3-20	2	5	7	$\sim 3.4 \cdot 10^{18}$
14	Helical undulator	0.1-1.5	5	5	12	$\sim 2 \cdot 10^{19}$

5.8.7 Photodesorption

(a) Photodesorption along the straights

As was discussed above, the psd yields for CO from a stainless steel vacuum chamber as measured by Foerster [22] were used in these simulations. The psd yield, the desorption yield and the flux dependence on the distance from a dipole magnet are shown in Figure 5.8-5.

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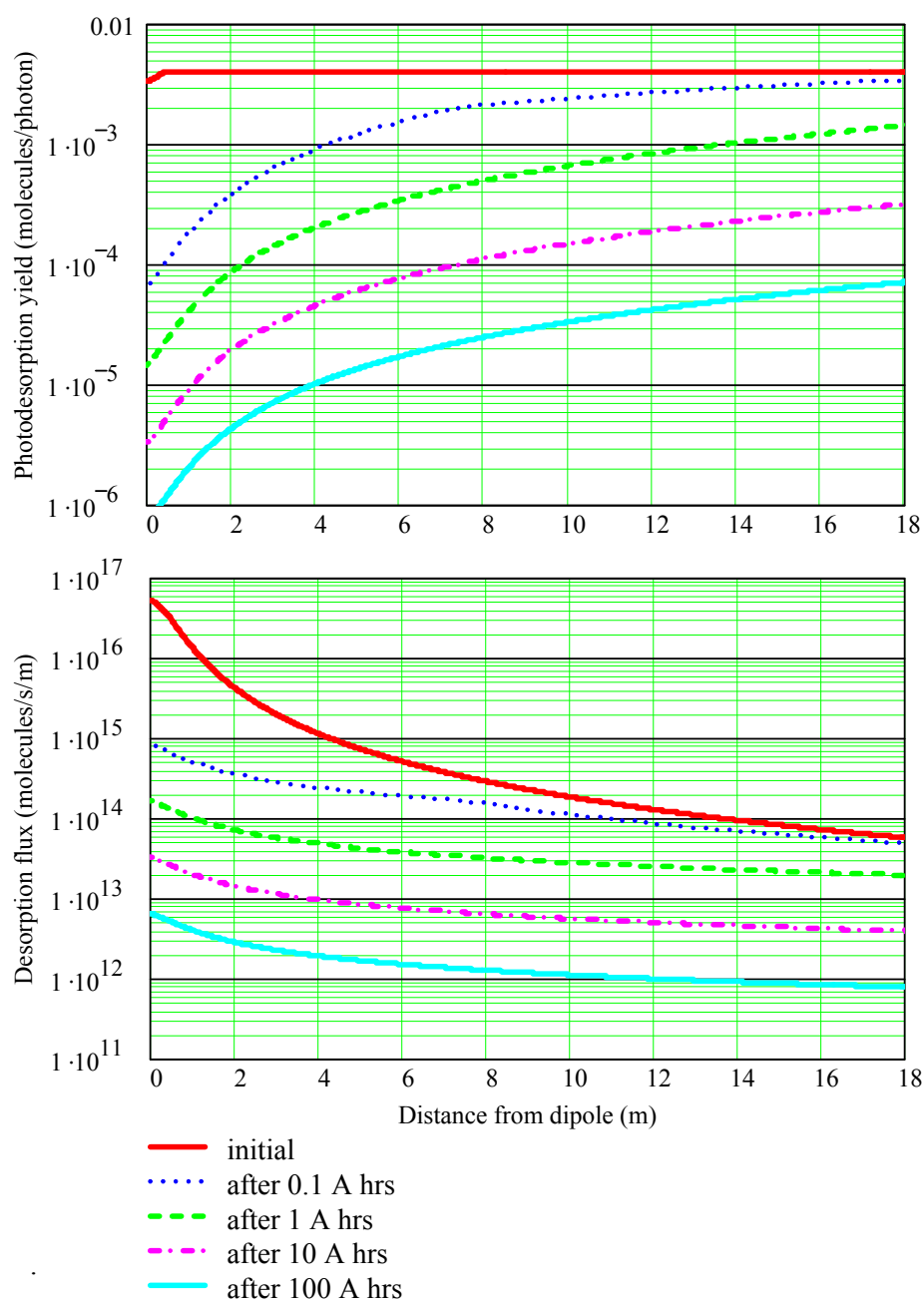


Figure 5.8-4 Photodesorption yield, the desorption yield and the flux dependence on the distance from a dipole magnet.

(b) Photodesorption flux from a crotch-absorber

Desorption from a typical design of crotch-absorber was estimated using the psd yield data from Anashin [26] and is shown in Figure 5.8-5. The experimental data are for doses up to $8 \cdot 10^{23}$ photons and are extrapolated to higher doses

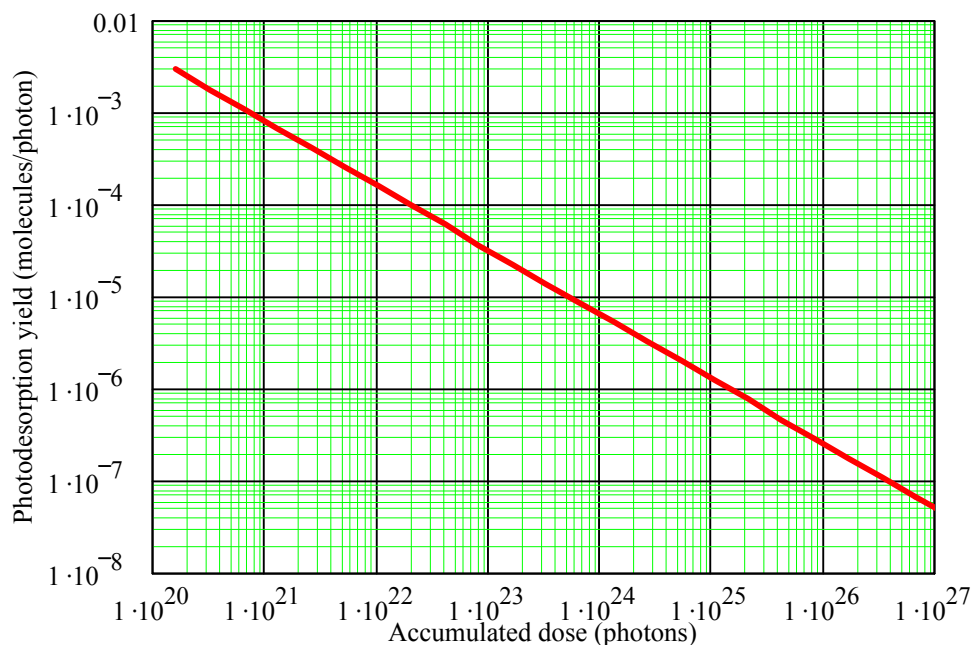


Figure 5.8-5 Photodesorption yield from a 35-mm wide strip of an OFHC copper crotch-absorber as a function of photon dose

After 10 Ah the desorption yield is estimated to be $\eta \approx 10^{-6}$ molecule photon⁻¹, and the corresponding photodesorption flux is $\sim 4 \cdot 10^{12}$ molecule sec⁻¹ = $9 \cdot 10^{-8}$ mbar l sec⁻¹.

5.8.8 Pressure profile along the arc during and after 100 Ah beam conditioning

Separate pressure profiles along the arc were calculated for thermal desorption and photon stimulated desorption. The former gives the base pressure in the arc without beam while summing the two profiles gives the dynamic (operational) pressure profile at a given beam current.

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Table 5.8-2 Average dynamic pressure along the diamond arc during machine conditioning

Beam Dose (Ah)	Specific dynamic pressure (mbar mA ⁻¹)	
	Narrow ports	Open ports
First injection	$8 \cdot 10^{-9}$	$3 \cdot 10^{-9}$
0.1	$3 \cdot 10^{-10}$	$2 \cdot 10^{-10}$
1	$8 \cdot 10^{-11}$	$3 \cdot 10^{-11}$
10	$1.5 \cdot 10^{-11}$	$1 \cdot 10^{-11}$
100	$4 \cdot 10^{-12}$	$3 \cdot 10^{-12}$

Table 5.8-3 shows the pressure along the arc after a beam dose of 100 Ah. There are two cases shown: static pressure, (i.e. without a beam: only thermal desorption) and dynamic (i.e. with the 300-mA beam: thermal desorption + photodesorption). These estimates are made using pumps with a nominal pumping speed of 500 l sec⁻¹. In the case of both narrow and open ports (see 5.7.4 above), there are significant pressure bumps at the ends of the arc. This is because of the distance between pumps in the initial layout of the arc. These bumps may be reduced by the addition of a small pump with an effective pumping speed of about 150 l sec⁻¹ situated between the two fast corrector magnets at each end of the arc. It can also be demonstrated that one of the two pumps on the dipole spouts can be removed with little change to the average pressure.

Table 5.8-3 Average pressures along the diamond arc after 100 Ah of beam conditioning. $\langle P_{th} \rangle$ is the average pressure due to thermal desorption only; $\langle P_{ph} \rangle$ that due to photon desorption with a 300 mA beam only and $\langle P_{dyn} \rangle$ the summation of these two

	Pressure (mbar)		
	Narrow ports	Open ports	Open ports and an additional pump between the Fast Corrector magnets
$\langle P_{th} \rangle$	$4.1 \cdot 10^{-10}$	$2.7 \cdot 10^{-10}$	$2.2 \cdot 10^{-10}$
$\langle P_{ph} \rangle$	$9.5 \cdot 10^{-10}$	$6.4 \cdot 10^{-10}$	$5.2 \cdot 10^{-10}$
$\langle P_{dyn} \rangle = \langle P_{th} \rangle + \langle P_{ph} \rangle$	$1.4 \cdot 10^{-9}$	$9.1 \cdot 10^{-10}$	$7.4 \cdot 10^{-10}$

The pressure profiles for each case considered in Table 5.8-3 are shown in Figure 5.8-6, Figure 5.8-7 and Figure 5.8-8 respectively.

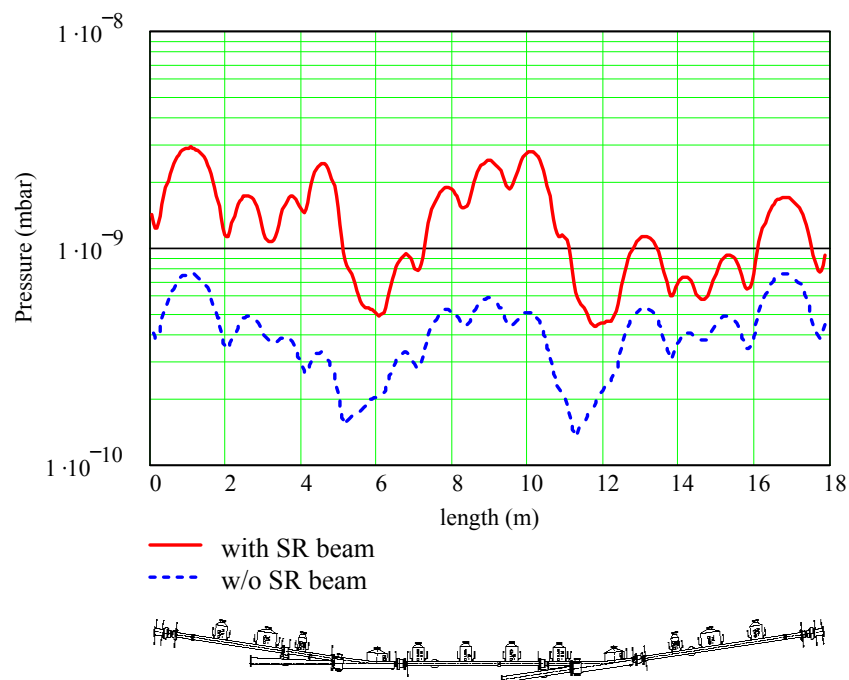


Figure 5.8-6 Pressure profile along the arc with 'narrow' ports with a 300 mA beam after 100 Amp·hrs of beam conditioning.

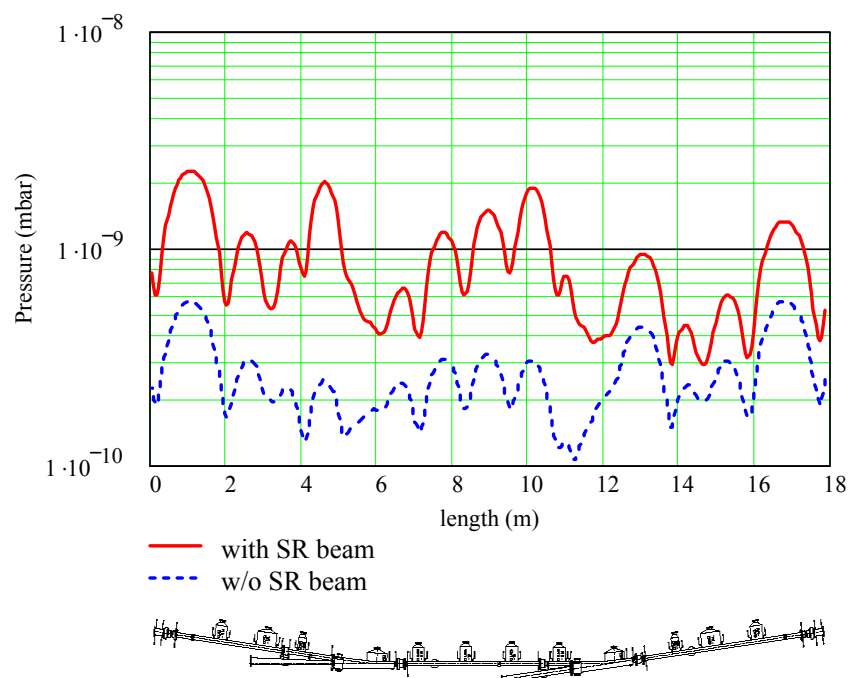


Figure 5.8-7 Pressure profile along the arc with 'open' ports with a 300 mA beam after 100 Amp·hrs of beam conditioning.

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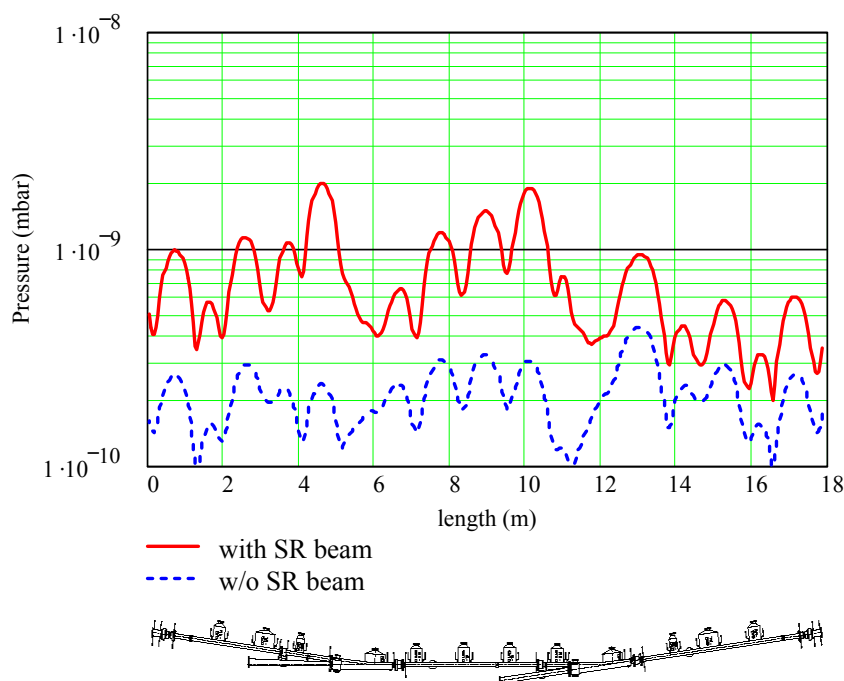


Figure 5.8-8 Pressure profile along the arc with 'open' ports with two additional pumps between FC's with a 300 mA beam after 100 Amp·hrs of beam conditioning

5.8.9 Pressure profile along insertion device straights after 100 Ah beam conditioning with synchrotron radiation from the dipoles

Several different cross sections of the insertion device straight vacuum chambers, which have lengths of either 5.5 or 8.5 m, have been considered at this stage -

- a simple make-up pipe with a diameter of 100 mm;
- an elliptical pipe with a height of 7 to 12 mm and a width of 80 mm (the same as in the arc);
- the same pipe as in (b) but with an ante-chamber added (assumed to be a simple tube with a diameter of 60 mm)
- the same vessel as in (b) but with the inside surface coated with a film of non evaporable getter material.

As was discussed in 5.8.6(a) above, the photon flux from the dipole along the insertion device straights is less than $1 \cdot 10^{17}$ photon $\text{sec}^{-1} \text{ m}^{-1}$ and the estimated photon stimulated desorption flux is about 10^{12} molecule $\text{sec}^{-1} \text{ m}^{-1}$. The estimated thermal desorption flux is $5 \cdot 10^{11}$ molecule $\text{sec}^{-1} \text{ m}^{-1}$ for the elliptical cross section pipe and about 10^{12} molecule $\text{sec}^{-1} \text{ m}^{-1}$ for both the make-up pipe and for that with an antechamber.

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Table 5.8-4 shows the average dynamic pressure (i.e. with beam) within an insertion device straight for the first tranche of beam lines insofar as these are known at present. The estimates were made for two straight lengths: 5.5 m and 8.5 m, and for two or three pumps per insertion device, i.e. 2 pumps located at the ends of the insertion device straight section or two pumps at the ends with one in the middle of the insertion device straight section. The effective pumping speed is assumed to be 400 l sec^{-1} in each case. The pressures are calculated in a manner similar to that in the arcs (except for the NEG coated chamber). The pressures without beam are lower by a factor of about 2.

Table 5.8-4 Pressures in mbar along various assumed insertion devices in the presence of a 300 mA beam.

Beam-line	Cross section (mm)	Straight length (m)	Average pressure (mbar)				
			2 pumps	3 pumps	Ante-chamber with 2 pumps	Ante-chamber with 3 pumps	NEG coated vessel with 2 pumps
Make-up pipe	100	5.5	$1.3 \cdot 10^{-9}$	$4.8 \cdot 10^{-10}$	—	—	—
6, 8–11, 13	7×80	5.5	$9.5 \cdot 10^{-8}$	$2.4 \cdot 10^{-8}$	$8.8 \cdot 10^{-9}$	$2.2 \cdot 10^{-9}$	$1.9 \cdot 10^{-10}$
1	10×80	5.5	$4.8 \cdot 10^{-8}$	$1.2 \cdot 10^{-8}$	$8.8 \cdot 10^{-9}$	$2.2 \cdot 10^{-9}$	$1.9 \cdot 10^{-10}$
14	12×80	5.5	$3.3 \cdot 10^{-8}$	$8.5 \cdot 10^{-9}$	$8.8 \cdot 10^{-9}$	$2.2 \cdot 10^{-9}$	$1.9 \cdot 10^{-10}$
Make-up pipe	100	8.5	$2.9 \cdot 10^{-9}$	$9.5 \cdot 10^{-10}$	—	—	—
6, 8–11, 13	7×80	8.5	$2.4 \cdot 10^{-7}$	$6.1 \cdot 10^{-8}$	$2.4 \cdot 10^{-8}$	$5.8 \cdot 10^{-9}$	$4.6 \cdot 10^{-10}$
1	10×80	8.5	$1.2 \cdot 10^{-7}$	$3.1 \cdot 10^{-8}$	$2.4 \cdot 10^{-8}$	$5.8 \cdot 10^{-9}$	$4.6 \cdot 10^{-10}$
14	12×80	8.5	$8.5 \cdot 10^{-8}$	$2.1 \cdot 10^{-8}$	$2.4 \cdot 10^{-8}$	$5.8 \cdot 10^{-9}$	$4.6 \cdot 10^{-10}$

It is important to know the sensitivity of these values to the effective pumping speed, i.e. to the choice of the pump and its connection to the insertion device vessel. The average dynamic pressure as a function of effective pumping speed for a 5 m long insertion device vacuum chamber with three pumps is shown in Figure 5.8-9. Only the make-up pipe exhibits a significant variation in pressure for effective pumping speeds between 50 and 800 l sec^{-1} ; the pipe with an antechamber is rather insensitive to pumping speeds above 400 l sec^{-1} and the elliptical vacuum chambers are seen to be completely conductance limited and insensitive to effective pumping speeds above about 100 l sec^{-1} .

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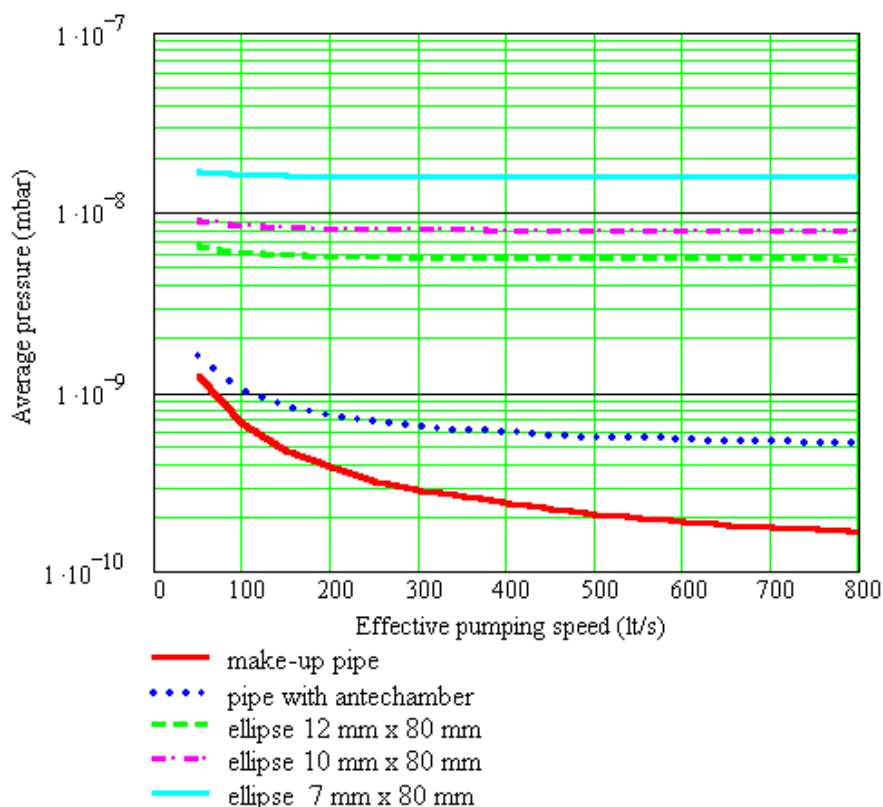


Figure 5.8-9 Average pressure as a function of effective pumping speed for various 5 m long insertion device vacuum chambers with 3 pumps with a 300 mA beam

The use of NEG (non evaporable getter) coating as an effective pumping solution for conductance limited vacuum chambers has been developed at CERN over the last few years [16], [32], [33], and is available commercially. Independent confirmation of its efficacy has been obtained in studies performed at BINP in collaboration with CERN [34].

The estimates for the NEG coated insertion device vacuum chamber shown in Figure 5.8-10 were made using the recent experimental data from BINP [34]. In the NEG coated vacuum chamber, CH_4 and H_2 dominate the residual gas spectrum, in contrast to that in a conventional, well conditioned ultra high vacuum chamber where the main gas species are H_2 , CO and CO_2 . The pressure inside the NEG coated vacuum chamber without a beam is below the gauge sensitivity limit of 10^{-12} mbar.

Using the above values we can conclude that in the insertion device straights, a make-up pipe can be efficiently pumped by 2 or 3 pumps each of effective pumping speed 400 l sec^{-1} . An insertion device vacuum chamber with an elliptic cross section but which has neither an antechamber nor NEG coating or some other form of distributed pumping is unacceptable because of the high average pressure.

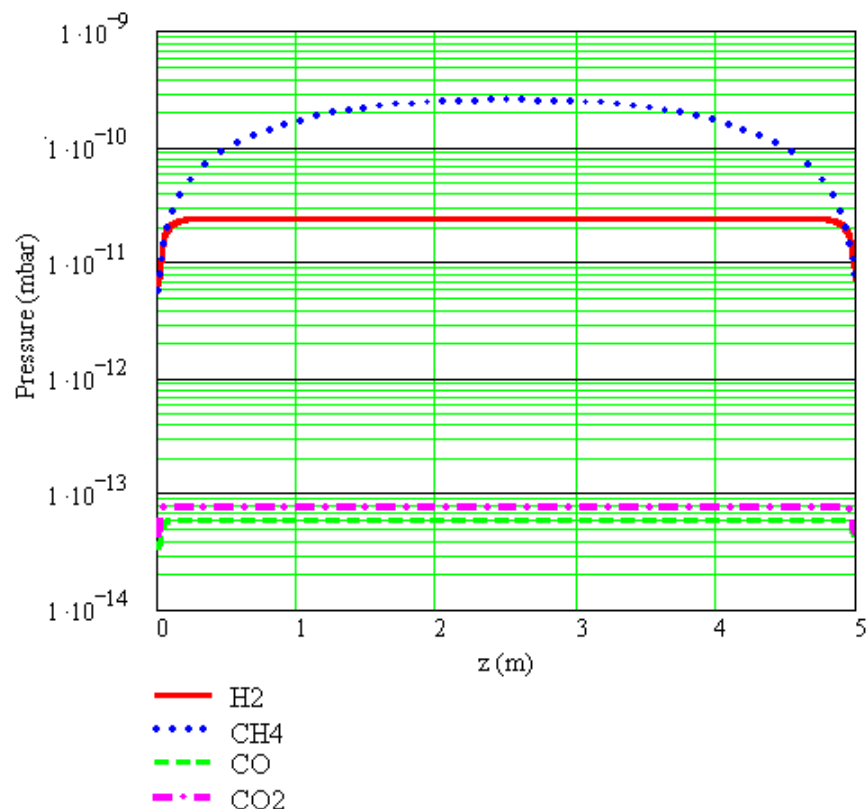


Figure 5.8-10 Pressure profile along a 5 m long NEG coated insertion device vacuum chamber with a 300 mA beam

This analysis has concentrated on average pressures that do not give rise to excessive gas scattering which is detrimental to beam lifetime. It is assumed that such pressures will also give rise to sufficiently low bremsstrahlung along the beamlines for safe operation.

ESRF has had about two years experience of operating some insertion device vessels with NEG coatings [35], [36] and Elettra has also recently installed such a vessel [37]. In both cases, the conditioning time of a new vessel has been dramatically reduced. The main problem with their using narrow gap insertion device vessels was bremsstrahlung passing along the beam lines to the experimental areas. With the NEG coated vessels, the radiation levels dropped by over an order of magnitude, enabling beam lines to be opened very quickly.

5.9 ARC PUMPING SCHEME

5.9.1 Generic vacuum pumps

In line with the comments in 5.7.4 above regarding the applied pumping speeds through the pumping spouts, the generic pumps listed in Table 5.9-1 have been selected for use in this design.

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Table 5.9-1 Generic vacuum pumps

Pump Type	Nominal Pumping Speed (l sec ⁻¹)
Ion Pump	240
Ion Pump	500
NEG Cartridge	180
TSP	1000

Although these are all specified generically, the values are chosen to correspond to real, commercially available pumps at the time this report was prepared. It should be noted that at 10^{-9} mbar, ion pumps will exhibit a reduction in pumping speed of about 30% from their nominal value. This has been taken into account in the calculations.

A TSP (Titanium Sublimation Pump) is different from other pumps in that it works by intermittently evaporating a film of titanium onto a surface, and the pumping speed generated for nitrogen may be taken to be about $1 \text{ l sec}^{-1} \text{ cm}^{-2}$ [38]. Therefore in this case, it is necessary to have a surface area of about 1000 cm^2 . A pump configuration similar to that used in the SRS could be adopted, although consideration will be given to utilising an integrated ion pump/TSP assembly.

5.9.2 Pumping spouts

As noted, every pump is connected to the beam pipe by means of a spout of some sort. These spouts are listed in Table 5.9-2 and the molecular flow conductance of each type is shown. Types 1 to 4 are the relevant ones selected from those discussed in 5.7.4 above. The table shows two additional spouts -

- Type 5 is used to connect a pump between the two fast corrector magnets and is assumed to be a pipe of minimum diameter 10 cm and maximum length 3 cm.
- Type 6 is mounted underneath the crotch absorbers at the downstream ends of the dipole vessels and is assumed to be a pipe of minimum diameter 20 cm and maximum length 10 cm.

Table 5.9-2 Pumping spouts

Spout Type	Location	Molecular Flow Conductance (l sec ⁻¹)
1	Quadrupole Q1B	256
2	Quadrupole Q2B	357
3	Quadrupole Q3B	183
4	Dipole Chamber	202
5	Between Fast Correctors	720
6	Crotch Absorber	2500

Note that the quadrupole magnet type designations in Table 5.9-2 and Table 5.9-3 are as shown in the drawing A0-302/10297.

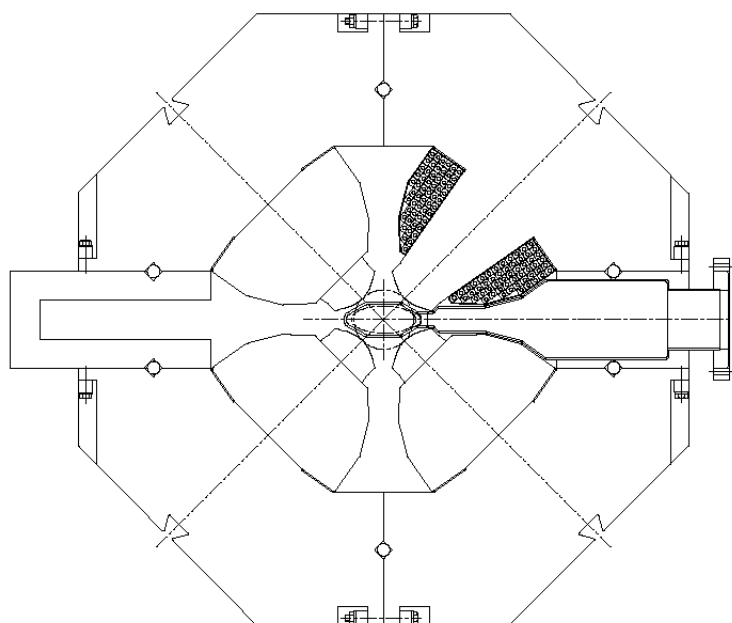


Figure 5.9-1 Schematic of an 'open' pumping port in a quadrupole.

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5.9.3 Pump locations

Table 5.9-3 shows the pumping speed required (at 10^{-9} mbar) at each of the pumping positions along the arc. These are *nominal* speeds applied at the end of the spout, not on the beam orbit. It also shows how these speeds can be achieved with a suitable combination of the generic pumps listed in Table 5.9-1. With this suite of pumps the expected average pressure along the arcs after about 100 Ah of beam conditioning is 9.6×10^{-10} mbar. The pressure distribution along the arc is shown in Figure 5.9-2.

Table 5.9-3 Actual pumps with their locations along the arc

Position	Pump location	Required speed (l sec ⁻¹)	Pump complement to achieve speed			
			Ion Pump (240 l sec ⁻¹)	Ion Pump (500 l sec ⁻¹)	NEG pump (180 l sec ⁻¹)	TSP (1000 l sec ⁻¹)
1	Between FC	180			✓	
2	Q1B-NM	170	✓			
3	Q2B-NL	170	✓			
4	Q3B-NS	170	✓			
5	Dipole	350	✓		✓	
6	Crotch	1300		✓		✓
7	Q2AB-NM	170	✓			
8	Q1AB-W	170	✓			
9	Q1AB-W	170	✓			
10	Q2AB-NM	170	✓			
11	Dipole	350	✓		✓	
12	Crotch	1300		✓		✓
13	Q3B-NS	170	✓			
14	Q2B-NL	170	✓			
15	Q1B-NM	170	✓			
16	Between FC	180			✓	

Figure 5.9-3 gives a schematic view of the location of the pumps along one of the arcs. This so-called vacuum flow diagram also shows the position of vacuum gauges and vacuum valves along the arc. These will be discussed later in this chapter. Not shown are the locations of beam port front end valves.

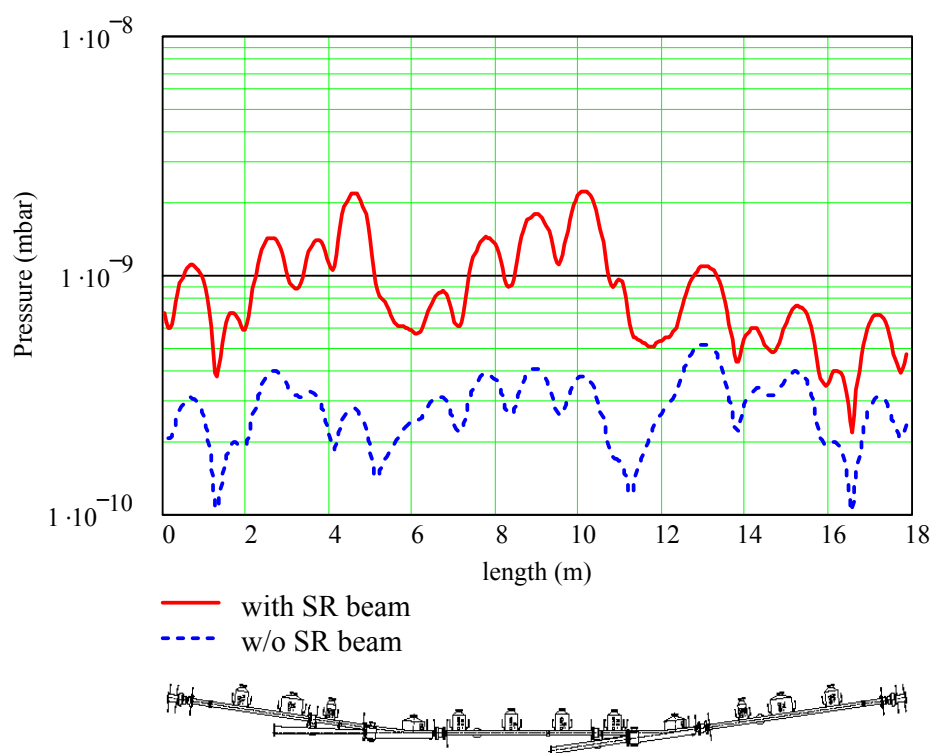


Figure 5.9-2 Pressure distribution along the arc with the suite of pumps listed in Table 5.9-3

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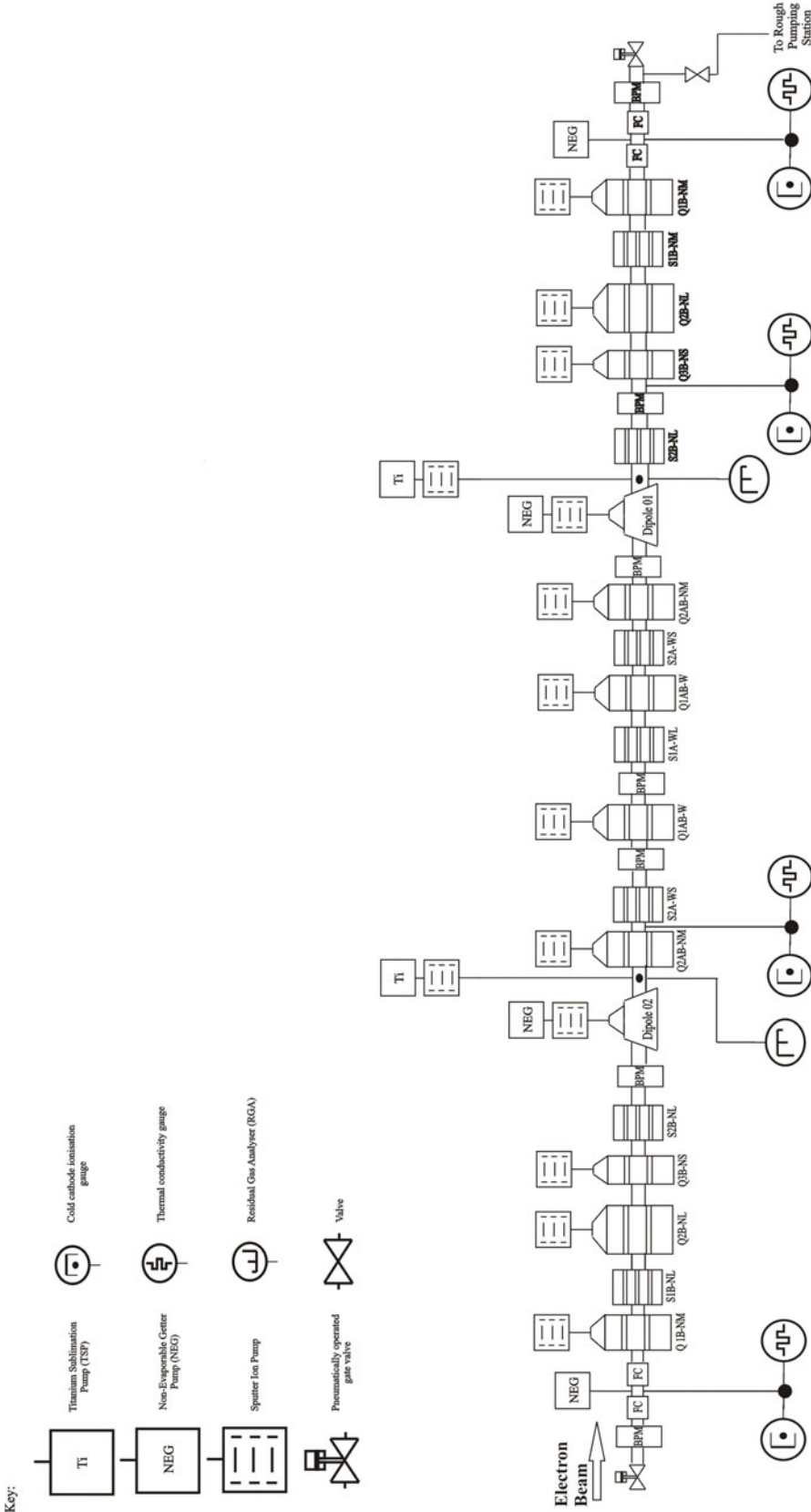


Figure 5.9-3 Vacuum flow diagram of an arc

5.9.4 Caveats

In order to derive the pumping scheme of Subsection 5.9.3, some assumptions have been made. If these assumptions turn out not to be substantiated in practice, this pumping scheme will need to be revisited.

The assumptions made include -

- little or no synchrotron radiation from the insertion devices impinges on the surface of the main ring vacuum vessels: it all passes along the beam ports to the beam lines. Any collimation, aperture restriction, etc., takes place in the beam port/line and the consequent desorption is handled locally by pumps installed for that purpose.
- the beam port front end absorber (in front of the first vacuum valve isolating the beam port from the storage ring vacuum) is situated close to the storage ring crotch absorber vessel so that desorption from the absorber when closed can be handled by the pump stack there.
- in normal operations, the front end absorber will not be closed when the full synchrotron radiation output of the insertion device is being generated.
- all arcs are identical.

If any of these should be untrue, then additional pumps may have to be installed at the appropriate positions.

5.9.5 Some specific points regarding the positions and mounting of the UHV pumps

(a) Dipole chamber pumps

Only one pump stack is required. This is in the position of the original upstream pump shown in the figures in Subsection 5.8.8 above. The spout should be lengthened along the vessel – a length of 400 mm was used in this calculation. The NEG pump will be installed integral with the ion pump body.

(b) Crotch absorber pumps

The pump stack on the crotch absorber is mounted below that absorber and connected to the vessel by as short and wide a spout as practicable, using a knife-edge flange of 250 mm nominal diameter (Type DL19 or 20).

(c) Pumps between the fast corrector magnets

The additional pump provided between the fast correctors is physically quite a small pump - a NEG cartridge. It will probably take the form of a SAES CapaciTorr D 400 [39] or similar. The pump housing will be a tube of length 150 mm and diameter 100

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mm connected to a knife-edge flange of 150 mm nominal diameter (Type DL13 or 14) on the beam tube (with as short a connecting tube as possible). The pump cartridge requires a type DL4 or 5 knife-edge flange. The connecting flange should be underneath the beam tube and the pump housing should be vertically down.

(d) Ion pumps; titanium sublimation pumps and NEG pumps

All of these types of pumps generate particulates to a greater or lesser degree at some times during their operation. It is important that the possibility of these particulates finding their way into the beam tube is minimised. Such a circumstance can result in two effects. If a particle gets into the electron or photon beam, it can ablate and generate a local pressure pulse, possibly resulting in either partial or complete beam loss. Secondly, if a hard particle gets onto the seal mechanism of a vacuum valve, it can generate a leak across the seat when the valve is closed.

It is therefore recommended that all such pumps be mounted vertically with the pump throat on top and below the beam orbit. Side pumps should be connected to the pumping spouts through a large diameter short right angle elbow.

5.10 STRAIGHT PUMPING SCHEMES

5.10.1 Injection Straight

Little is yet known in detail about the exact nature of the components which will be in the injection straight. They will include the injection septum magnet, four kickers and some diagnostics.

From a vacuum point of view, the only real problem will be if the injection septum is a laminated *in vacuo* magnet similar to that installed on the Daresbury SRS. Because of the massive surface area, such magnets can generate a high degree of outgassing, particularly water, after atmospheric excursions. This gas load can be handled by the adoption of two stratagems. Clearly adequate pumping speed has to be installed. Secondly, the septum magnet will be one of the few vacuum items on diamond which will require routine baking. It will be warmed before the straight is vented to minimise water sorption and will be kept hot while the system is pumped out. Integral heaters will be provided for this.

Although this will be subject to detailed review once the septum magnet design is undertaken, we will assume that two 500 l sec⁻¹ ion pumps each with 1000 l sec⁻¹ of TSP will be adequate. The possibility of using NEG wafer modules close coupled to the magnet will also be investigated.

The kickers, if again modelled on those in the SRS, should not present any problems. Each will require one 240 l sec⁻¹ ion pump. Any necessity for additional speed from TSP's or NEG's will be assessed once the design is finalised.

5.10.2 Radio Frequency Cavity Straight

The superconducting rf cavities are expected to be supplied as a complete assembly from a manufacturer. Therefore the detail of the vacuum system will be a matter of discussion with that manufacturer. However, the approach of the diamond Project should be similar to that adopted for the injector train, *viz.*, that the diamond Project will type approve particular pumps, gauges, valves, etc., which will most likely be supplied on free issue to the cavity manufacturer.

There will be three cavities in a single 8.5 m straight, and each will form an independent vacuum system. There will be an in-line vacuum valve at each end of the straight as usual, and there will be a pair of valves with a short interspace between each pair of cavities. Each cavity and each interspace will be linked to the roughing pump set in the straight via manual valves leading to a pumping manifold.

Each cavity will be fitted with a 500 l sec⁻¹ ion pump on the beam tube close to the cavity and will have a 240 l sec⁻¹ ion pump fitted to the waveguide (which is part of the cavity vacuum). It is anticipated that the interspaces will have no permanent pumping, although consideration may be given to fitting a small cartridge NEG pump once details of the design become available.

5.10.3 Diagnostic Straight

Little is yet known about the diagnostic straight and its contents. It will probably contain a short insertion device. Pumping appropriate to an insertion device straight will therefore be required.

5.10.4 Insertion Device Straights

For the initial assessment of the vacuum performance of the insertion device straights, we consider two simple vessel designs. From the generic pumps listed in Table 5.6-1, the 240 l sec⁻¹ ion pumps have been selected as standard for use here. Four location options for these pumps have been considered.

- A two pump option with a single pump at each end of the vessel
- A three pump option with an additional pump in the middle of the straight
- A four pump option with one pump located at each end of the vessel and two more spaced equidistant along the vessel.

(a) A simple cylindrical make-up pipe with a diameter of 100 mm.

On day one of machine operations, it is expected that of the 24 insertion device straights, 15 will have a simple make-up pipe installed. Currently, it is expected that two of these will be 8.5 m straights and thirteen will be 5.5 m straights.

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The 5.5 m long straights will require the three pump option to give an average pressure of $8.6 \cdot 10^{-10}$ mbar and the 8.5 m long straights need the four pump option to give an average pressure of $9.5 \cdot 10^{-10}$ mbar. Both these pressure will be obtained after 100 Ah of beam conditioning.

No *in-situ* baking is foreseen for these makeup pipes.

- (b) An elliptical pipe with a height between 7 and 12 mm and a width of 80 mm with the inside surface NEG coated.

On day one of machine operations, it is expected that six straights will have a narrow gap insertion device installed with the internal height of the vacuum chamber between 7 and 12 mm. This will limit the longitudinal vacuum molecular flow conductance significantly. It is anticipated that the chambers will therefore be coated internally with NEG material. This new advanced vacuum technology needs quite careful maintenance but means that the required pressure can be reached in a very simple vacuum pipe with no ante-chamber or other distributed pumps).

Both 5.5 m and 8.5 m long straights will only require a single 240 l sec^{-1} ion pump installed at each end. The average pressure along the chamber will then be $2.0 \cdot 10^{-10}$ mbar and $4.7 \cdot 10^{-10}$ mbar respectively with the NEG activated.

Activation of the NEG coating by *in-situ* baking for 20 hours at the *activation temperature* which varies between 180°C and 350°C depending of choice of the NEG material, structure and others parameters is essential. This bakeout can be performed using very simple removable heater jackets and a portable control system.

5.10.5 Pumping spouts

Every discrete pump is connected to the beam pipe by means of a pumping spout of some sort. The spouts attached to the insertion device vacuum chambers should be made as short and wide as possible to avoid molecular flow conductance limitation of the available pumping speed.

All spouts are mounted underneath the vacuum vessels and are assumed to be cylindrical pipes of diameter 80 or 100 mm and of maximum length 100 mm. In this case the effective pumping speed is about the same as actual one, i.e. $\sim 170 \text{ l sec}^{-1}$ (The nominal pumping speed of 240 l sec^{-1} is reduced by $\sim 30\%$ at a pressure of $\sim 10^{-9}$ mbar).

Table 5.10-1 Pumping spouts for insertion device vessels

Spout Type	Location	ID (mm)	L (mm)	Molecular Flow Conductance (l sec ⁻¹)
1	Make-up chamber	100	100	1230
2	Elliptical chamber	80	100	630
3	Elliptical chamber	80	80	790

5.11 VACUUM PUMP CONTROL

5.11.1 Control system

In common with all other instrumentation on the diamond machine complex, the vacuum pumps will be controlled and monitored through the main machine control system (Part D.2). This will be accomplished by each control unit being equipped with a standard communications interface such as RS-232. Protocols will be defined by the equipment manufacturer and the necessary interface layer to the EPICS control system software will be written by the Machine Controls Group.

5.11.2 Interlocks

The majority of interlocks to vacuum pumps will be implemented either by firmware in the pump control units or in software in the control system. However, where there is a possibility of a dangerous situation arising from the operation of a vacuum pump, then an additional, parallel, hardwired interlock chain will be implemented. "Dangerous" is defined here as being a situation which can lead to a possible compromise of the integrity of the vacuum envelope of the machine complex or to damage to an item important to the operation of the machine whose replacement requires part of the machine to be vented to atmosphere. An example of such a possible failure is switching an ion pump on at too high a pressure so that an internal arc discharge occurs in the ht feedthrough, leading to cracking of the insulator.

Interlock chains will be identified during the procurement phase of the diamond Project.

5.11.3 Location of power supplies and control units

It is considered desirable to locate all electronics outside the ring tunnels. This makes for ease of servicing – tunnel searches do not have to be interrupted to replace a faulty unit for instance. Radiation levels in the tunnel are high during operations and this adversely affects the life of electronics. However, this has to be balanced by the economics of installing long cable runs, especially where relatively high currents are

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involved. Cables also have to enter the tunnel through labyrinths which, inevitably, have limited capacity. Cables need to be compatible with the radiation environment.

Control units will therefore normally be installed in control racks situated outside the machine shield walls. Cable runs should be kept to a minimum and there should be no joints, except in proper junction boxes. Cables in the racks should be terminated in connectors interfaced directly to the control units. In the machine tunnels, cables will be terminated in marshalling boxes attached to the machine mounting girders. Cables to the equipment from these marshalling boxes will have no joints and will be as short as practicable.

5.11.4 Vacuum pump power supplies and control units

(a) Rough pump stations

The operation of rough pump stations will be essentially a manual one carried out by skilled operatives. However a certain amount of monitoring and datalogging information will be available – e.g. running hours for turbomolecular pumps. This will be collected by the Control System and stored in a history system of some sort.

(b) UHV pumps

Ion pumps

Each ion pump will have its own dedicated ion pump power supply that will operate the pump throughout the pressure range 5×10^{-3} to 1×10^{-10} mbar. The ion pumps will not normally be operated above 1×10^{-5} mbar. This gives a good lifetime for the ion pumps (in excess of 10 years) and reduces “regurgitation” which limits the ultimate pressure achievable in the pump. Power supplies which are available commercially have two high voltage channels in each power supply. Where a vacuum section has an odd number of ion pumps, a spare channel will be available for back up to any pumps in the section. The ion pump power supplies will be required to provide the following:

- a high voltage supply to a range of ion pump sizes and types that may be up to 100m away.
- a front panel reading that can display pump set up information and operational status e.g. voltage, current, pressure.

Criteria influencing the choice of ion pump power supplies will include -

- each power supply should provide at least one external interlock.
- size: there is only a limited amount of space available in the facility for control racks.
- minimising heat dissipation in the control racks is advantageous.

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- manufacturer(s) should have considerable experience (over many years) in producing reliable electronic systems for ion pumps. Experience in providing solutions for synchrotron light sources will be advantageous.
- life time cost will be a major factor. Cost of ownership will be considered as well as installation costs.
- control units should be easy to use by vacuum and controls technicians.

A generic specification for ion pump control units is shown in Table 5.11-1

Table 5.11-1 Generic specification for ion pump control units

Ion Pump Control
Fully selectable range of ion pump sizes from 50 l sec ⁻¹ to 500 l sec ⁻¹
Fully selectable high voltage from 5 kV-7.5 kV.
Provision to change the polarity of the high voltage without return to manufacturer.
Overload protection in the event of pump sparking, short circuit and high pressure.
Provide failsafe interlock protection in the event of disconnected high voltage connector.
Provide at least one interlock relay set point for each ion pump high voltage channel.
Interlock set point to be adjustable in the range 5x10 ⁻³ -1x10 ⁻⁹ mbar.
Provide a control interface that will be suitable for EPICS (EPICS, RS-232, RS 485 or other). Interface to provide full status information.
19 inch rack mountable in a minimum of space.
Provide front panel information regarding the set up of the power supply and the current status including high voltage, current and pressure.

During the initial part of the procurement phase of the diamond project, detailed evaluation will be undertaken regarding the possible use of so called “holding” ion pump power supplies. The current drawn by an ion pump (and hence supplied by the control unit) is a function of pressure as well as the size (pumping speed) of the pump. If all the ion pumps are only operated at low pressure (below about 10⁻⁵ mbar) a relatively small (and therefore cheaper) power supply can be used. This saves on rack space and heat dissipation. However, it will not be sufficient simply to install only such power supplies on diamond even though pumps will normally operate far below 10⁻⁵ mbar. During pump down of any part of the machine, ion pumps undergo a manually controlled conditioning process at higher pressures (referred to as “flashing”). This results in lower outgassing of the pump and therefore better ultimate pressures. It also removes embedded contaminants which can be pumped away. Larger power supplies capable of delivering higher currents will be required for this process.

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The evaluation will therefore be to determine the cost advantage of installing mainly holding supplies plus a few larger power supplies which can be switched to each ion pump as required against the decrease in operational flexibility during conditioning.

Titanium sublimation pumps

Each Titanium Sublimation Pump (TSP) will have its own dedicated power supply. The power supply will consist of two separate units, a high current power supply located close to the TSP in the storage ring tunnel and a control unit that will provide remote operation of the power supply. Each control unit/power supply combination will be capable of selecting and powering one filament at a time in a multifilament TSP cartridge. The TSP power supplies will be required to provide the following:

- low voltage/high current power output capable of driving a TSP up to 3m away.
- control of power output by operating the TSP power source up to 100m away.
- front panel indication of filament status and operational status.
- quick and simple provision to select the TSP filament required.

Criteria influencing the choice of TSP power supplies will include -

- each power supply should have the provision to accept at least one external interlock to prevent operation at high pressure.
- size: there is only a limited amount of space available in the facility for control racks and equipment in the storage ring tunnel.
- minimising heat dissipation in both the control racks and ring tunnel is advantageous.
- manufacturer(s) should have considerable experience (over many years) in producing reliable electronic systems for TSP's. Experience in providing solutions for synchrotron light sources will be advantageous.
- life time cost will be a major factor. Cost of ownership will be considered as well as installation costs.
- control units should be easy to use by vacuum and controls technicians.
- selection of the TSP filament should be a simple procedure

A generic specification for the TSP control units is shown in Table 5.11-2

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During the initial part of the procurement phase of the diamond project, detailed evaluation will be undertaken regarding the possible integration of ion pump power supplies and TSP control units. A separate power unit would still be required to provide the high current to the filaments. The aim will be to save on rack space, reduce heat dissipation and provide an economic solution.

Table 5.11-2 Generic specification for TSP control units

TSP Control
Output POWER to the TSP filament should be fully controlled and adjustable.
Provision for fully programmable 'fire' sequence including power ramp rate, dwell time and off periods.
Capacity to provide control of TSP cartridges from different manufacturers (details to be negotiated)
Provide overload protection in the event of filament short circuit.
Provide interlock protection in the event of a filament open circuit.
Accept over pressure interlock from total pressure gauge controller.
Provide a control interface that will be suitable for EPICS (EPICS, RS-232, RS 485 or other). Interface to provide full status information.
Ring tunnel power supply to be stand-alone and to be radiation hard, robust and able to withstand water ingress.
Remote control unit to be 19 inch rack mountable in a minimum of space.
Provide front panel information regarding the set up, current operational status, power output, interlock and filament status.

TSP's need to be fired intermittently – at pressures below 10^{-9} mbar only once every few days – and this sequence will be carried out automatically by a scheduled control system task. This will generate a slow power ramp up to the preselected sublimation level, a short dwell and a ramp down of power. This will be repeated a predetermined number of times per fire cycle. However, before using a TSP filament, it has to be carefully degassed and conditioned over a period of some hours. This is essentially a manual operation so the control unit and control system will need to cater for this.

NEG pumps

Non Evaporable Getter (NEG) Pumps require a power supply to condition or activate the pump. Once activated the pump will remain operational for a period of time that is directly proportional to the gas load being pumped (limited by the capacity of the pump). For diamond it is anticipated that the NEG pumps will not require many re-activations in a year, perhaps only one. To reactivate the pump it will be necessary to bake the pump cartridges which have integral heaters. The power supply required to do this is relatively simple.

Since activation of these pumps is infrequent, it will not be necessary to have a dedicated power supply for each pump. For diamond it is intended to provide a

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number of portable power supplies that can be connected to the NEG pump in the ring tunnel. These power supplies will only be used during maintenance periods when the machine is not operating. The exact number of power supplies required has not been determined and will be part of a pump/power supply package through the same manufacturer. The NEG power supplies should meet the following criteria –

- provision to accept at least one external interlock to prevent operation at high pressure.
- adequate protection to prevent overheating of the NEG cartridge.
- ability to operate the NEG heaters through a connection lead up to 3m long.
- size will be important as there is only a limited amount of space available in the facility for storage of infrequently used equipment and working space will be limited in the storage ring tunnel.
- easy to use by vacuum technicians.

During the initial part of the procurement phase of the diamond project, detailed discussions will take place with the manufacturers of NEG power supplies to ensure that the power supplies are easy to transport around the ring tunnel.

The NEG coating on insertion device vacuum vessels is activated by baking the vessel, probably to about 180°C for a few hours. Control of this bakeout will be achieved by using a portable bakeout control system with datalogging facilities.

5.12 VACUUM VALVES

5.12.1 In-line valves (gate valves)

For operational convenience, in-line gate valves are used to separate the storage ring into small sections. This allows for relatively quick pump downs and limits the amount of storage ring exposed to atmosphere for maintenance, upgrading, etc., during operations. It is anticipated that after the initial installation and commissioning phase, the only parts of the ring to be let up with any frequency will be the insertion device straights. Therefore a gate valve of all metal construction will be installed at each end of the straight. In the open position, these valves will have an aperture conforming in shape to the elliptical vessels on each side. The aperture will be screened by a cage of spring fingers to provide rf electrical continuity along the beam orbit. The valves will be of the so-called fast closing type (operating in about 1 second).

In the case of the rf straight, there will be a pair of such valves installed between each cavity.

Similar valves, but with circular apertures and no rf screens will be used to isolate each beam port front end and the transport line from the Booster synchrotron. The beam port front end valves will, in the closed position, be protected by cooled synchrotron radiation absorbers.

All these valves will be pneumatically operated and fully interlocked to pressure gauges in each adjacent vacuum system. The valves in the electron beam path will be interlocked so that beaming is inhibited if any one is not open.

5.12.2 Roughing valves

Manual right angle, all metal valves of 63 mm aperture will be used to isolate the roughing stations from the storage ring. They will require position indicators to provide safety interlocks to the control system. Other valves in the roughing stations may be elastomer sealed (probably Viton^{TM†}).

5.12.3 Other valves

Many small, manual all-metal right angle valves will be required at convenient locations. Dry nitrogen let up valves will be of small-bore all metal manual construction and will be required on each roughing station. For reliability, the storage ring will be let up through the roughing station and not by valves directly on the ring.

5.13 PRESSURE MEASUREMENT

5.13.1 Total pressure gauges

It will be necessary to measure total pressures to $< 10^{-9}$ mbar throughout the vacuum system for the diamond facility. The gauge system will need to provide such capability. The storage ring and beam port front ends will require reliable readings of total pressure at 1×10^{-10} mbar.

There is no one gauge technology available that can measure over the full required range. Therefore gauges measuring the rough vacuum range (1000 to 10^{-3} mbar) and medium vacuum to UHV (10^{-3} to 10^{-10} mbar) will be required

(a) General criteria influencing the choice of total pressure gauges

Wherever possible, commercially available equipment will be purchased with no 'specials' or purpose built equipment. This will reduce operational costs and down time whilst increasing flexibility.

Gauge heads (measuring tubes) should be robust enough to remain unaffected by normal handling and processing associated with the building and operation of a synchrotron light source and present a minimal risk of vacuum failure during normal

[†] Viton is a registered trademark of DuPont Dow Elastomers, Wilmington, Delaware, USA

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machine operation. This latter requires that any electrical feedthrough/connector combinations be intrinsically robust or be suitably protected.

Life time cost will be a major factor in selecting the gauge where technical differences between different technological solutions are small.

The gauge manufacturer(s) should have considerable experience (over many years) in producing reliable UHV gauge systems (experience in accelerator systems will be of benefit).

The gauge heads must be vacuum bakeable to 250°C, and it will be advantageous if the gauges are able to be operated during such a bake.

The electronics required to operate the gauges should be located outside any radiation areas or be radiation hard.

Other components of the accelerator system should have a minimum influence on the pressure measurement system. Magnetic, electrical and mechanical noise may be significant and although careful positioning of the gauges can reduce these effects it will be necessary to consider such influences when selecting the gauge supplier.

The gauge heads should contain no materials that will have a deleterious effect on the ultimate vacuum.

(b) Rough vacuum gauges

The purpose of rough vacuum gauges will be mainly to provide an indication of the total pressure in the system when monitoring the progress of a pump down or when there is a degree of vacuum failure. The selection criteria noted in (a) above apply equally to these gauges, but because the gauge need not be very accurate, an economical solution is important. The Pirani gauge offers a good solution for measuring pressure in the range 1000- 1×10^{-3} mbar (in the so-called convection Pirani configuration). Although there are other gauges available (such as the thermocouple gauge) these offer no real advantages over the Pirani.

(c) UHV gauges

Among the many types of UHV gauge available, there are three in particular that could be suitable for diamond. There are two acceptable variants of cold cathode gauges (Penning and Inverted Magnetron gauges) and a hot cathode gauge (Bayard-Alpert gauge) which need to be considered. All are commercially available from more than one manufacturer and are in common use on other accelerators around the world.

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Table 5.13-1 Typical pressure ranges for hot and cold cathode gauges

Gauge Type	Typical Pressure Range (mbar)
Hot Cathode (Bayard-Alpert with Tungsten filaments)	5×10^{-4} - 3×10^{-11}
Cold Cathode (Based upon Penning discharge)	5×10^{-3} - 1×10^{-9}
Cold Cathode (Inverted Magnetron discharge)	5×10^{-3} - 1×10^{-11}

Table 5.13-1 shows typical pressure ranges for commercially available gauges. Economical rough vacuum gauges do not measure below 1×10^{-3} mbar, so it is not possible to cover the full pressure range with a hot cathode gauge and one such gauge. The ion pump power supplies could be used as pressure indicators but the best solution for ion pumps could be compromised. An intermediate pressure gauge could be used but the costs would be significantly higher. There are hot cathode gauges which work to higher pressures, but the UHV performance is compromised. Therefore the hot cathode gauge solution will not be pursued.

The Penning gauge does not measure reliably to sufficiently low pressures for the diamond Storage Ring so the inverted magnetron cold cathode gauge (IMG) will be adopted. Although the Penning gauge is slightly less expensive than the inverted magnetron gauge and could in principle be used in the injector, in the interests of standardisation only inverted magnetron gauges will be used in the machine complex.

(d) Generic specification of total pressure gauge heads

This is shown in Table 5.13-2.

Table 5.13-2 Generic specifications of total pressure gauge heads

Pirani Gauge	Cold Cathode Gauge (Inverted Magnetron Type)
Pirani or Convection Pirani configuration	Inverted Magnetron configuration cold cathode gauge.
Bakeable to 250°C (preferably while operating)	Bakeable to 250°C (preferably while operating)
Inlet flange to be decided at a later date (probably 70 mm od knife edge)	Inlet flange to be decided at a later date (probably 70 mm od knife edge)
Pressure range 1000 - 1×10^{-3} mbar	Pressure range 5×10^{-3} mbar - 5×10^{-11} mbar
Interlock provision set anywhere in pressure range (single channel)	Interlock provision set anywhere in pressure range (three channels)
“On-board” electronics (if necessary) to be radiation hard.	On-board electronics (if necessary) to be radiation hard.
	Gauge starting times to be of the order of a few seconds at 1×10^{-9} mbar.

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(e) Guidelines for positioning of gauge heads

The following general guidelines for gauge head positioning should be observed -

- gauge heads should be positioned in a convenient location that will allow reasonable access to the gauge for maintenance.
- gauge heads can be mounted horizontally or vertically. If mounted vertically, the inlet flange must be below the gauge tube.
- gauge heads should be kept out of the plane of synchrotron radiation.
- gauge heads should be mounted inside the electron orbit and as close as possible to the vacuum chamber and should be screened from direct exposure to synchrotron radiation or secondary electrons
- magnetic, electrical and mechanical noise sources should be avoided as far as is practical. Gauge heads should be at least 1m away from magnets that produce strong fringe fields (e.g. dipoles) or adequate magnetic screening should be installed
- stray magnetic fields caused by the gauge head should be small or screened.
- the beam pipe has a small gas flow conductance so it is necessary for a control gauge to be close to the vacuum component it controls. For reliability, gauges controlling items critical to operation of the machine (e.g. in line valves) should have a spare gauge head installed.
- each vacuum section (area between two gate valves) may contain more than one UHV gauge but may require only one Pirani.

(f) Location of gauge heads

Arcs

The gauges should be positioned such that they are located in the areas where the pressure profile calculations indicate that the highest pressures will be found. The pressure profile calculations indicate that four gauge pairs will provide sufficient information and control. Preliminary locations are shown in Figure 5.9-3.

Pirani gauges will interlock the ion pumps, which are spaced throughout the achromat, and so ideally the gauges should be equally spaced as well. The Pirani gauge also interlocks the cold cathode gauges that will be located close to the Pirani. Some cold cathode gauges will interlock the partial pressure gauges which will need to be close by (see 5.13.2 below). Some cold cathode gauges will also need to be close to the sector valves and the beam port front-end valves which they will interlock.

RF cavity straight

There will be three pairs of gauges, one dedicated to each rf cavity and a pair of gauges on each interspace.

Injection straight

There will be two pairs of gauges, exact position to be decided.

Diagnostic straight

There will be two pairs of gauges, exact position to be decided.

Insertion device straights

There will be one gauge pair located at the down stream end of each straight. A second cold cathode gauge head will be installed close by the first head to provide safety back-up in the event of failure. In some cases (very small gap insertion device vacuum chambers for example) more than one UHV gauge may be required. This will be assessed for each individual insertion device design.

Rough pump sets

In addition to Pirani gauges and inverted magnetron gauges as detailed above, the roughing pump sets installed in the machine complex (Section 5.7.1 above) will require simple local indication of pressure between 1200 mbar and 1 mbar. This will be provided using a mechanical gauge such as a Bourdon tube gauge or diaphragm gauge. These will not be monitored by the Control System.

The dry nitrogen gas line to the let up valves located near each rough pump set will require permanently installed dew point meters. In-line digital instruments are commercially available for this purpose. If possible, these will be monitored by the control system.

5.13.2 Partial pressure measurement

(a) Introduction

A vital diagnostic tool used on all synchrotron light source vacuum systems is the partial pressure gauge, typically a quadrupole radio frequency mass spectrometer used as a residual gas analyser (rga). It is important that the vacuum system for diamond incorporates a sufficient number of rga's and that they are located so as to take full advantage of their diagnostic capabilities.

The provision of such a full complement of instruments greatly enhances the operational flexibility of a source, enabling accurate diagnosis of problems associated with the "health" of the vacuum system. This can reduce machine down time to a minimum.

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(b) Criteria influencing choice of residual gas analysers

Wherever possible, commercially available equipment will be purchased for diamond with no 'specials' or purpose built equipment. This will reduce operational costs and down time while increasing flexibility.

The gauge heads should be robust enough to remain unaffected by normal handling and processing associated with the building and operation of a synchrotron light source and present a minimal risk of vacuum failure during normal machine operation. This latter issue requires that any electrical feedthrough/connector combinations be intrinsically robust or be suitably protected.

Life time cost will be a major factor in selecting the residual gas analyser system to be used, although the technical specification must be met.

The residual gas analyser manufacturer(s) should have considerable experience (over many years) in producing reliable residual gas analyser systems. Experience in providing solutions for synchrotron light sources will be particularly important and will need to be demonstrated.

The residual gas analyser gauge heads must be able to withstand a vacuum bake to 250°C, and it will be an advantage if the residual gas analyser will be able to be operated during bakeout, using a thermal extender if necessary.

The electronics required to drive the residual gas analyser system should be located outside any radiation areas or be radiation hard.

The effects from other components of the accelerator system on the operation of the residual gas analyser system should be minimal. Magnetic, electrical and mechanical noise may be significant and although careful positioning or shielding of the residual gas analyser head and electronics can reduce these effects it will be necessary to consider such influences when selecting the gauges and their position.

The residual gas analyser software should be commercially written, capable of networking, able to record data for each head continuously and be easy to use by a vacuum technician.

(c) Generic specification of the residual gas analyser system

This is shown in Table 5.13-3.

Table 5.13-3 Generic specification of the rga system

Residual Gas Analyser System
Quadrupole radio frequency mass spectrometer type.
Range of all instruments to be 1-200 atomic mass units (amu).
All instruments to have two detection systems (dual detector) consisting of a Faraday cup and a secondary electron multiplier (SEM – either channeltron or channelplate (lifetime/cost issues will determine which)).
The ion source to be designed for UHV operation (open source).
Two independent tungsten filaments to be available and independently switched through software.
Analyser head to be bakeable to 250°C (some degree of operation during bakeout will be desirable).
Inlet flange to be decided at a later date (probably 70 mm od knife edge).
The analyser to be supplied complete with a housing that includes one 90° bend between ion source and inlet flange.
Minimum detectable partial pressure to be less than 1×10^{-13} mbar.
The electronics to be capable of accepting an external interlock (typically pressure) to inhibit filament operation.
The electronics to be networked using the EPICS platform or one that EPICS can support.
The software to be networked and be optimised for remote operation through a PC. It should also be user friendly for operation by scientists and technicians.

(d) Guidelines for positioning of residual gas analyser gauge heads

The following general guidelines for gauge head positioning should be observed -

- gauge heads should be positioned in a convenient location that will allow reasonable access to the gauge for maintenance.
- gauge heads should be mounted vertically in a housing with the inlet flange at the bottom.
- gauge heads should be mounted inside the electron orbit and as close as possible to the vacuum chamber.
- gauge head ion sources and detectors should be kept out of the plane of synchrotron radiation
- magnetic, electrical and mechanical noise sources should be avoided as far as is practical. Gauge heads should be at least 1m away from magnets that produce strong fringe fields (e.g. dipoles) or adequate magnetic screening should be installed.

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- (e) Location of residual gas analyser gauge heads

Arcs

There will be two residual gas analysers in each arc. In order to provide maximum coverage of the arc vacuum system and diagnostics of the dipole crotch absorbers, it will be necessary for the residual gas analysers to be located down stream of each of the two dipole magnet vacuum chambers and if possible close to a total pressure gauge for comparison. Preliminary locations are shown in Figure 5.9-3.

RF cavity straight

There will be three residual gas analysers, one dedicated to each rf cavity.

Injection straight

There will be one residual gas analyser, exact position to be decided.

Diagnostic straight

There will be one residual gas analyser, exact position to be decided.

Insertion device straights

There will be at least one residual gas analyser in each straight, dependent on the nature of the device. If there is only one, it will be located at the down stream end of the straight.

5.14 CONTROL OF VACUUM GAUGES

5.14.1 Control system

In common with all other instrumentation on the diamond machine complex, the vacuum gauges will be controlled and monitored through the main machine control system (Part D.2). This will be accomplished by each control unit being equipped with a standard communications interface such as RS-232. Protocols will be defined by the equipment manufacturer and the necessary interface layer to the EPICS control system software will be written by the Machine Controls Group.

5.14.2 Interlocks

The majority of interlocks to vacuum gauges will be implemented either by firmware in the gauge control units or in software in the control system. However, where there is a possibility of a dangerous situation arising during the operation of a vacuum gauges, then an additional, parallel, hardwired interlock chain will be implemented. “Dangerous” is defined here as being a situation which can lead to a possible compromise of the integrity of the vacuum envelope of the machine complex or to damage to an item important to the operation of the machine whose replacement

requires part of the machine to be vented to atmosphere. An example of such a failure might be burning out the filament of a residual gas analyser by switching on at high pressure.

Interlock chains will be identified during the procurement phase of the project.

5.14.3 Location of vacuum gauge power supplies and control units

It is considered desirable to locate all electronics outside the ring tunnels. This makes for ease of servicing – tunnel searches do not have to be interrupted to replace a faulty unit for instance. Radiation levels in the tunnel are high during operations and this adversely affects the life of electronics. However, this has to be balanced by the economics of installing long cable runs, especially where relatively low currents are to be measured or where high currents have to be delivered. Cables also have to enter the tunnel through labyrinths which, inevitably, have limited capacity. Cables need to be compatible with the radiation environment.

Control units will therefore normally be installed in control racks situated outside the machine shield walls. Cable runs should be kept to a minimum and there should be no joints, except in proper junction boxes. Cables in the racks should be terminated in connectors interfaced directly to the control units. In the machine tunnels, cables will be terminated in marshalling boxes attached to the machine mounting girders. Cables to the equipment from these marshalling boxes will have no joints and will be as short as practicable.

During the initial part of the procurement phase of the diamond project, detailed evaluation will be undertaken regarding the possible use of so-called “smarthead” gauges. Here, the bulk of the gauge control electronics (if not all) is located in a pod attached directly to the gauge head. This pod typically simply requires a low voltage dc electrical supply (usually 24 V) and a standard data interface connection (e.g. RS232 or Ethernet). Potential advantages of using such gauges include reduced cabling cost, reduced requirement for rack space and reduced heat dissipation in the control racks. Potential disadvantages include the possible reduced lifetime of the electronics caused by radiation and possibly reduced functionality.

5.14.4 Total pressure gauge power supplies and control units

(a) General requirements

The total pressure gauge control units selected for diamond will be required to provide -

- the necessary power requirements and signals to drive gauge heads that may be up to 100m away.
- a front panel total pressure reading.

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- control interlocks for other equipment.
- interfacing with the high level EPICS control system of the diamond facility.
- the capability of driving four gauges: two Pirani gauges and two inverted magnetron gauges. In some cases, there may not be a full complement of gauges installed in the control unit. This will be acceptable in the interests of standardisation.

A number of different manufacturers offer solutions that would be suitable with the main differences being the size and cost of the equipment. The 'ideal' package does not exist, but as already stated 'specials' will not be used unless absolutely necessary.

(b) Criteria influencing choice of total pressure gauge control units

These will include -

- the pressure measurement display shall be capable of being read from a distance of a few metres.
- the pressure readings on all gauges installed in a control unit shall be available simultaneously.
- at least two fully variable external interlocks shall be provided from each cold cathode gauge and one from each Pirani gauge. A further interlock will be required from the Pirani to control the start-up operation of the cold cathode. This may be either an external interlock or embedded in the firmware of in the control unit.
- size will be a factor that will need to be considered. There is only a limited amount of space available in the facility for control racks. Similarly, minimising heat dissipation in the control racks is advantageous.
- manufacturer(s) should have considerable experience (over many years) in producing reliable electronic systems for vacuum gauges. Experience in providing solutions for synchrotron light sources will be an advantage.
- life time cost will be a major factor. Cost of ownership will be considered as well as installation costs (some systems require heavy duty cables for example).
- control units should be easy to use by vacuum and controls technicians.

(c) Generic specification of total pressure gauge control units

This is shown in Table 5.14-1.

Table 5.14-1 Generic specification for total pressure gauge control units

Simultaneous control of gauge heads	Two cold cathode and two Pirani gauges.
Fully variable set point relay interlocks	Minimum of two for each cold cathode and one for each Pirani.
Cold cathode interlock range.	1×10^{-3} - 1×10^{-9} mbar.
Pirani gauge interlock	Atmosphere- 5×10^{-3} mbar.
Control interface	Suitable for EPICS (EPICS, RS-232, RS 485 or similar).
Display of pressure	Each of the four gauge heads simultaneously. (Display of Pirani gauges may be a simple indication when the cold cathode gauges are on.)
Size	19 inch rack mountable in a minimum of space and to fill a full rack width in multiples of control units (fixing kits and spacers can be used).
Cable length	The control units should be capable of driving gauges through cables up to 100m long.
Radiation resistance	If the gauge control requires electronics at the gauge head then it should be radiation hard with a lifetime of at least 1 year, preferably 10 years.

5.14.5 Partial pressure gauge power supplies and control units

(a) General requirements

The partial pressure gauge control units selected for diamond will be required to provide –

- the necessary power requirements and signals to drive the gauge heads that may be up to 100m away. Some of the electronics required to do this may need to be very close to the gauge head and will need to be radiation resistant.
- user friendly control software.
- capability of receiving control interlocks from a total pressure measurement device and the capability of generating interlocks from set points associated with at least four individual mass spectra peaks.
- interfacing with the high level EPICS control system of the diamond facility.
- the capability of networking the control software so that multiple gauge heads can be observed simultaneously and all gauges heads can be gathering/storing data simultaneously.

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A number of different manufacturers offer solutions that would be suitable with the main differences being the software interface, networking capability and cost of the equipment. A detailed study of the market will be carried out before selecting the final package for diamond.

(b) Criteria influencing choice of partial pressure gauge control units

These will include -

- vulnerability of electrical feedthrough assembly to breakage/stress.
- suitability of electronics for radiation environment.
- software features.
- software user friendliness.
- mass spectrometer specifications, namely minimum detectable partial pressure, resolution, spectrometer scan speed and immunity to ion source contamination/memory effects.
- provision of set point interlocks to accept total pressure gauge interlock and provide at least four external interlocks from individual mass spectra peaks.
- size will be a factor that will need to be considered. There is only a limited amount of space available in the facility for control racks. Similarly, minimising heat dissipation in the control racks and ring tunnel is advantageous. The requirement for support structures for any electronics inside the ring tunnel will also be considered.
- manufacturer(s) should have considerable experience (over many years) in producing reliable electronic systems for mass spectrometers. Experience in providing solutions for synchrotron light sources will be an advantage.
- life time cost will be a major factor. Cost of ownership will be considered as well as installation costs (some systems require bulky multi-core cables for example).

(c) Generic specification of partial pressure gauge control units

This is shown in Table 5.14-2.

Table 5.14-2 Generic specification for partial pressure gauge control units

Software	Commercial software shall be used to control the rga's with demonstration of use on at least one other synchrotron facility. Software must include the following modes of operation as a minimum: Analogue, multi trend and leak detect.
Control interface	Suitable for EPICS (EPICS, RS-232, RS 485, Ethernet or other)
Data storage	Continuous data storage available for all modes of operation. Data to be stored in a user defined file structure and in a commonly used file format.
Data recall	The stored data should be easily recalled into spectral display software.
Size	19 inch rack mountable in a minimum of space and to fill a full rack width in multiples of control units (fixing kits and spacers can be used). If essential some parts of the equipment can be located in the ring tunnel. Such parts should be relatively small and if connected directly to the gauge head should not require any support structures.
Cable length	The control units should be capable of driving gauges through cables up to 100m long.
Radiation resistance	If the gauge control requires electronics at the gauge head then it should be radiation hard with a lifetime of at least 1 year, preferably 10 years. Radiation dose to be specified.

5.15 RING TUNNEL SERVICES FOR THE VACUUM SYSTEM

5.15.1 Electrical supplies

It is proposed that all the electrical equipment for vacuum components will be housed in racks in small enclosures around the outside of the machine (see Part D.2). The initial estimates for all controls and instrumentation equipment are that there will be 5 instrumentation rooms with 30 racks per room. it is likely that the vacuum equipment will be distributed around these rooms in order to maintain cable lengths to a reasonable value.

The total estimated power requirements are shown in Table 5.15-1. These are all single phase 230V ac supplies with the exception of Valves, where the supply is 24V dc.

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Table 5.15-1 Estimated power supply requirements for vacuum equipment. Some diversity factor must be applied to these values.

Equipment Type	Number required	Power consumption (maximum) per Item	Total Maximum power requirements
Total Pressure Gauges	145 (of each gauge)	<1W	<145W
Total Pressure Gauge Control Units	95 (2 pairs of gauges)	35W	3325W
Partial Pressure Gauges	72	75W	5400W
Partial Pressure Gauge Control Units	72	No information	No information
Ion Pumps (500 l sec ⁻¹)	120	240W (400 l sec ⁻¹) at maximum sustainable pressure	28800W
Ion Pumps (300 l sec ⁻¹)	288	160W (220 l sec ⁻¹) at maximum sustainable pressure.	46080W
Ion Pump controllers	408	Medium 100mA HV section: Min - 5W, Max - 325W	2040W Min., 132600W Max.
Titanium Sublimation Pumps	48	400VA (max. when sublimating)	19200VA
NEG pumps	48	90W under activation	4320W
NEG pump controller	48	1500W maximum when activating the NEG	72000W
Forevacuum pumps	24	400W maximum	9600W
Turbomolecular pumps	24	No information	No information
Turbo pump controllers	24	500W	12000W
Valves	400	2.5W	1000W

5.15.2 Dry nitrogen

Dry nitrogen is required for venting the vacuum systems of diamond to atmospheric pressure. This enables quick pumping of a well outgassed system back down to UHV without baking. The requirement is for a supply of nitrogen of purity > 99.998%, with dew point < -70°C (i.e. $\approx$ 1 ppm of water) at a pressure $\sim$ 0.5 psi.

Such a supply may conveniently be provided from liquid nitrogen boil-off. Supply lines will be of stainless steel, cleaned and dried to a high standard. In-line dew point meters will be provided near the take-off points, which will be at the rough pumping stations.

5.15.3 Compressed air

A compressed air supply is required to operate the vacuum gate valves and other pneumatic actuators at various points around the machine. The upper pressure limit is determined by the safe operation of the gate valves. Cleanliness is an important issue for the compressed air supply. In the case of one of the actuators failing from bellows rupture, compressed air can enter the vacuum system and contaminate it. The requirement is for an “oil free” supply (i.e. < 1 ppm of oil) at 8 bar.

5.15.4 Helium

A piped helium supply at a few psi is required for leak chasing the vacuum system with take off points situated conveniently around the ring. The specification for the supply is not very critical. It should be oil free as for the compressed air, but the helium concentration need not be greater than 80%. The balance should be substantially nitrogen, although some oxygen is acceptable.

5.16 SAFETY

All items of vacuum equipment will be required to adhere to the general safety requirements of the diamond Project.

Specific points to note include –

- Ion pumps operate at high voltages (3 – 7 kV), so cables and connectors will have to be adequately protected. The power supplies can deliver modest currents (up to 500 mA). Safety interlocks switch this voltage off if connectors are disconnected.
- Inverted magnetron gauges operate at voltages of about 3kV so cables and connectors will have to be adequately protected. Currents are limited to very low values.
- RGA gauge heads contain hot filaments so housings can get hot to the touch.

5.17 REFINEMENT OF THE DESIGN

There are a number of areas in which further work needs to be done in order to optimise the vacuum design. These can be accomplished in the first few months of the procurement phase of the diamond Project without compromising the overall schedule.

The main work items are as follows –

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5.17.1 Arc Pumping Scheme

The arc pumping scheme derived in 5.9 above is based on the emitted photon flux being distributed in some part along absorbers integral with the sides of the vacuum vessels. It may be possible to optimise the pumping rather better by “catching” most of it on discrete photon stops. Although there are significant engineering complexities in doing this, a full investigation needs to be undertaken.

5.17.2 Pumping Spouts

As noted 5.9.2 above, much of the pumping relies on fin shaped spouts penetrating the quadrupole magnets. It would be desirable to eliminate these. Partially this depends on the possibility of using discrete photon stops as discussed in 5.17.1 above, although the two are not inextricably linked. Some preliminary work has indicated that this is possible in the centre part of the arc, but further work needs to be done to assess if this is possible elsewhere and the overall benefits.

The advantage of doing this is that it simplifies the design of the magnets.

5.17.3 Beam Port Front Ends

The detailed layout of the first few components of the beam ports and their interaction with the vacuum system of the storage ring has not yet been assessed.

5.17.4 Injection and Diagnostic Straights

Detailed analysis remains to be done once design details are available.

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E.6 Radiation Shielding

6.1 INTRODUCTION

As well as the synchrotron radiation that the storage is designed to produce, there will be other types of radiation present around the accelerators which are created unintentionally. All the radiation, which penetrates the accelerator or hutch shield walls or roofs, is potentially harmful to the people present in the areas. The types of radiation are described and quantified and appropriate shielding specified. An initial environmental impact assessment is presented.

6.2 ACCELERATOR PRODUCED RADIATION

The mechanisms by which high-energy electrons interact when lost from a particle beam are now well understood [1], [2].

6.2.1 Gamma radiation

High-energy electrons lost from the accelerator beams undergo bremsstrahlung interactions with the components that they strike. During bremsstrahlung interactions, the electron radiates a photon whose energy can extend up to the energy of the incident electron. These photons then undergo pair production interactions. The positron annihilates to form more photons and the electrons still possess enough energy to undergo bremsstrahlung interactions. This process, the electromagnetic cascade or shower, repeats many times, the number of particles increasing and the average particle energy decreasing. After many interactions, the energy of the individual particles is so low that the particles in the shower are absorbed by collision processes, rather than radiative processes, and the cascade halts. Eventually, the particles lose energy by ionisation within the target or shield material. This ionisation energy is finally dissipated as heat.

These electromagnetic processes are grouped together as the gamma component of the radiation. The main features of this gamma component can be summarised as follows;

- a) For constant beam power, the bremsstrahlung in the forward direction (0°) is a strong function of the original electron energy. At energies below about 20 MeV the output varies as E_0^2 , while above 20 MeV it varies as E_0 .
- b) At 90° , the absorbed dose rate is assumed to be independent of beam energy for constant beam power.

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c) The intensity is strongly peaked in the forward direction with this trend increasing as the electron energy increases.

6.2.2 Neutron radiation

Some of the energetic cascade photons undergo neutron production in the target or shield materials. Neutrons can be produced from the photo-pion and the giant resonance reactions. Several others are possible but do not contribute significantly to the total dose. The neutrons from the photo-pion reaction have energies of hundreds of MeV and are forward peaked. The neutrons from the giant resonance reaction have energies of 1 to 10 MeV and are produced isotropically.

6.2.3 Muons

Medium energy storage rings are relatively low power and muon production is usually insignificant.

6.2.4 Target

The atomic number, shape and orientation of the target, plays an important role in the production of the secondary radiation. A thin target will not initiate the maximum cascade, possibly leading to a series of thin targets. Attenuation in a thick target can be significant. Radiation impinging on the target at shallow angles will be scattered away from the target. Absorption of the scattered radiation will be greatest at the angle of the incident beam. In accelerators, the details of the target are rarely known. The incident beam could be incident normally on a very thick tungsten slit mechanism or at grazing incident on a thin copper heat absorber. It is rare that the target can be considered to be optimum for neutron production.

6.2.5 Shielding model

It can be seen that the production processes involved are complex. Only calculations using Monte Carlo programs such as the combined EGS/Fluka codes can attempt to model these processes exactly. For practical shielding calculations it is necessary to make simplifications and assumptions concerning the target geometry, beam loss patterns and attenuation factors etc. before a shielding model can be adopted.

Nelson and Jenkins [3] have comprehensively modelled the above reactions and coded them into a program known as SHEILD11 [4]. This model has been revised [5] to use the GAMD gamma radiation and the HEN and GRN neutron components corresponding to the photo-pion and giant resonance reactions. Any attenuation of the target is neglected because of the lack of detailed knowledge of the target. There is some disagreement between the expressions quoted in various references. To ensure the correct expressions are used, they have been taken directly from the Fortran code listing [6]. The geometry used is shown in figure 6.2-1

E.6 RADIATION SHIELDING

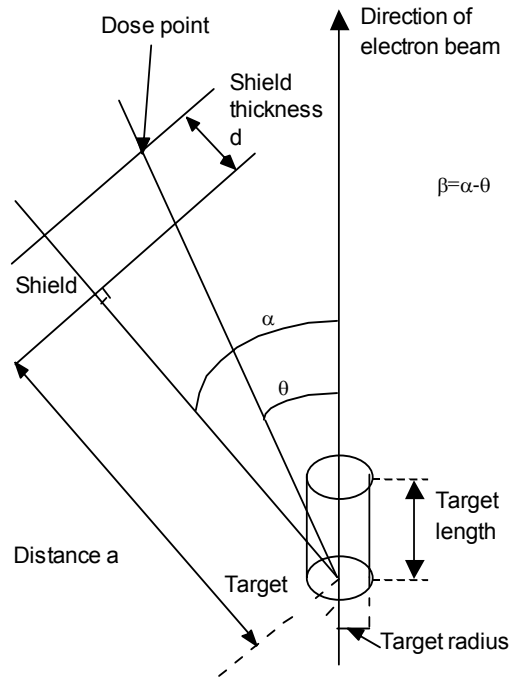


Figure 6.2-1

The total dose equivalent rate is:

$$H_{\text{total}} = H_{\text{GAMD}} + H_{\text{HEN}} + H_{\text{GRN}}$$

where H_{GAMD} , H_{HEN} and H_{GRN} are the photon, high energy neutron and giant resonance neutron dose rates in $\mu\text{Sv/h}$ per electron/s at an angle θ at a distance of 1m and:

$$H_{\text{GAMD}} = K. [\cos\beta / (a + d)]^2. [1.06E6.E_0.\exp(-0.959\theta^{0.5}) + 684.\exp(-\theta/72.2)]. \exp(-d\lambda_3\cos\beta)$$

$$H_{\text{HEN}} = K. [\cos\beta / (a + d)]^2. [1.0 - 0.72\cos\theta]^{-2}. (13.69/A^{0.65}). \exp(-d\lambda_1\cos\beta)$$

$$H_{\text{GRN}} = K.E_0. [\cos\beta / (a + d)]^2. 4.94Z^{0.66}. \exp(-d\lambda_2\cos\beta)$$

Where:

E_0 =Incident electron energy (GeV)

$K = 3.6E-8.E_0$

a = distance from source point to inside of shield wall (m⁻¹)

d = thickness of shield (m)

A = mass number of the target

Z = atomic number of the target

ρ = density of shield (g/cm³)

λ_1 = attenuation coefficients of HEN in shield (m⁻¹)

λ_2 = attenuation coefficients of MIDN in shield (m⁻¹)

λ_3 = attenuation coefficients of GRN in shield (m⁻¹)

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6.2.6 Attenuation Coefficients

The attenuation coefficients used are shown below.

Table 6.2-1 Attenuation Coefficients

	Attenuation Coefficients m^{-1}		
	Ordinary concrete	Barytes concrete	Lead
Bremsstrahlung	5.50	8.0	47.0
Giant Resonance Neutrons	5.90	7.50	4.00
High Energy Neutrons	2.60	3.20	5.70

These attenuation coefficients have been used to calculate the shielding for several accelerators and have proved effective.

6.2.7 Dose limits

Ryder [7] discussed the regulatory requirements of the Ionising Radiations Regulations, 1999. He stated that it was obvious that most statutory obligations are met and bureaucracy considerably reduced if an annual dose limit of 1 mSv was adopted. A constraint of 0.3mSv was also mentioned. This was later decided to be appropriate only for the general public off site, and not for people working around Diamond. The annual dose limit of 1 mSv was interpreted to mean that a person working around the accelerator should not receive more than 1mSv per year. For a storage ring operating for around 6000 hours a year and assuming a person works 2000 hours a year, an occupancy factor of 3 has been agreed to be conservative. The annual dose immediately outside the shielding is therefore calculated to be less than 3mSv.

An annual dose of 1mSv is only 5% of the dose limit for employees. This dose is pessimistically high because it is highly unlikely that a person will work 100% of his time around the accelerators and geographically the dose rate will be less as people move further away from the shielding. It is considered to be As Low As reasonably Practicable (ALARP). To decrease the dose further will considerably increase the cost and place constraints on the width of the fan of synchrotron radiation that is designed to pass into the experimental areas.

Using a shielding design limit of 3mSv for 6000 hours operation a year will ensure that the annual dose to the public offsite will be less than 1mSv even for 8760 hours occupation a year.

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6.2.8 Electron losses

The electrons lost from the beam on route from the gun to the stored beam in the storage ring have been analysed [8]. These are summarised in table 6.2-2 and 6.2-3 below. It is assumed that all the linac and booster are operational with beam for 250 hours a year. Electrons will be injected into the storage ring for 250 hours a year of which 10 hours will allow for operation with abnormal (i.e. non optimum) settings. The storage ring will be operational for 6000 hours a year.

Table 6.2-2 Electron losses for normal operation

Location of electron loss	Loss rate (electrons per second)
Gun to Linac	2.08×10^{12}
Linac	2.31×10^{10}
Linac to Booster Transfer	1.04×10^{11}
Booster Injection	5.20×10^{10}
Booster Acceleration	5.20×10^9
Booster Extraction	2.34×10^{10}
Booster to Storage Ring Transfer	0
Storage Ring Injection Septum	9.35×10^9
Storage Ring Injection Elsewhere	2.34×10^9

Table 6.2-3 Electron losses for operation with abnormal (i.e. non optimum) settings

Location of electron loss	Loss rate (electrons per second)
Booster Injection	1.04×10^{11}
Booster Extraction	4.68×10^{10}
Storage Ring Injection Septum	9.35×10^9
Storage Ring Injection Elsewhere	1.40×10^{10}

6.2.9 Proposed shielding

It is proposed to use ratchet style shielding for the outer wall of the storage ring tunnel.

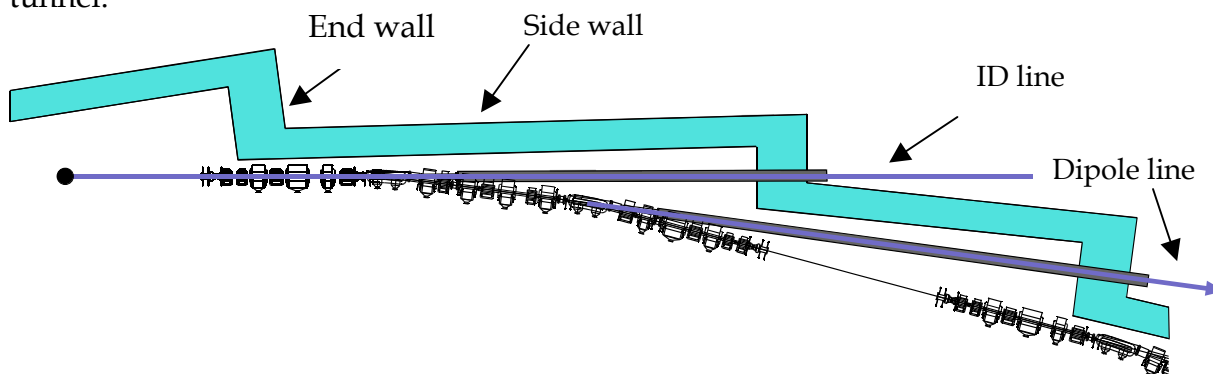


Figure 6.2-2 Proposed to use ratchet style shielding

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A scheme (Table 6.2-4) has been drawn up which uses a combination of barytes concrete and lead for the outer shield wall of the storage ring. For a 24 cell storage ring, the beamlines initially diverge away from the electron beam at only 7.5 degrees. The position and thickness of the end and sidewalls of the ratchet constrains the width of the fan of synchrotron radiation which can pass through the shielding. The proposed scheme allows from 0 to 25 mrad and 10 mrad fan of radiation from the dipole and insertion device beamlines to pass through the shield wall without the use of optical elements located inside the shield. It is possible to reduce the thickness of the concrete and avoid the use of costly lead, by using iron loaded concrete with a density greater than 5 tonnes/m³. However, this alternative is much more expensive than barytes concrete.

Table 6.2-4 Details the thickness of the shielding for each part of the accelerator complex.

Location			Minimum distance /m	Material thickness / m	
				Ordinary concrete	Barytes concrete (+ lead)
Storage ring	Injection region ¹	Ratchet side wall (Dipole)	0.5		1.30
		Ratchet side wall (ID)	1.36		1.18
		Ratchet end wall (Dipole)	12		1.78
		Ratchet side wall (ID)	19		1.68
		Roof	1.5	1.60	
		Inner wall ²	3.3	1.43	
	Elsewhere	Ratchet side wall (Dipole)	0.5		1.15
		Ratchet side wall (ID)	1.36		0.95 (+0.03) ³
		Ratchet end wall (Dipole)	12		1.65
		Ratchet side wall (ID)	19		1.55
		Roof	1.5	1.43	
		Inner wall ²	3.3	1.25	
	Booster ⁴	Outer wall	3.0	1.90	
		Inner wall	1.0	2.10	
		Roof	1.5	2.05	
	Linac ⁵	Walls	2.0	1.20	
		Roof	1.5	1.25	

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- Notes
1. The injection region is considered to be 1 cell before the septum to 2 after.
 2. The inner wall excludes the wall common to the booster, which will be the same thickness as the booster outer wall.
 3. This lead should be +/- 0.65m high centred on the beam height and sufficiently long to end 2.5m from the orbit.
 4. The thicknesses specified for the booster shielding is for the transverse direction only. This supplies sufficient shielding even for the longitudinal case because of the extra distance and start thickness. The shielding around the transfer path will be finalised when the design is complete.
 5. The thicknesses specified for the linac shielding is for the transverse direction only. A fixed lead beam stop must be provided at any place where the electron beam changes direction. This beam stop must be 0.15m long for the linac and be made of lead.
 6. The density of the barytes concrete is a minimum of 3.47 tonnes/m³ after 7 days curing, compared with 2.3tonnes/m³ for ordinary concrete.

The roof and inner wall of the storage ring and all the linac and booster shielding will be made of ordinary concrete. Cast concrete will be used for the shielding except for the storage ring roof, which will be made from removable blocks to allow access to the ring for large items of plant. These blocks must be designed in at least two layers with overlapping joints to avoid gaps through which x-rays can penetrate.

The thicknesses specified for the linac and booster shielding are for the transverse direction only. A fixed lead beam stop must be provided at any place where the electron beam changes direction. This beam stop must be 0.15 and 0.35m long for the linac and booster and be made of lead.

It is essential that the shielding be built exactly to the specification for type of concrete, thickness and distance from the source for the outer wall of the storage ring. The thicknesses for the outer wall are given to the nearest 0.01m. This precision may impose significant civil engineering problems. The thicknesses of the other walls and roofs are not critical and can be increased to the nearest convenient number.

6.2.10 Labyrinths and shield penetrations

All personnel must enter the accelerator enclosures through shielded labyrinths. All services must enter the accelerator enclosures through shielded ducts. The dose rate of neutrons and gamma radiation penetrating such labyrinths and ducts have been estimated[9][10]. Suitable labyrinths are shown schematically.

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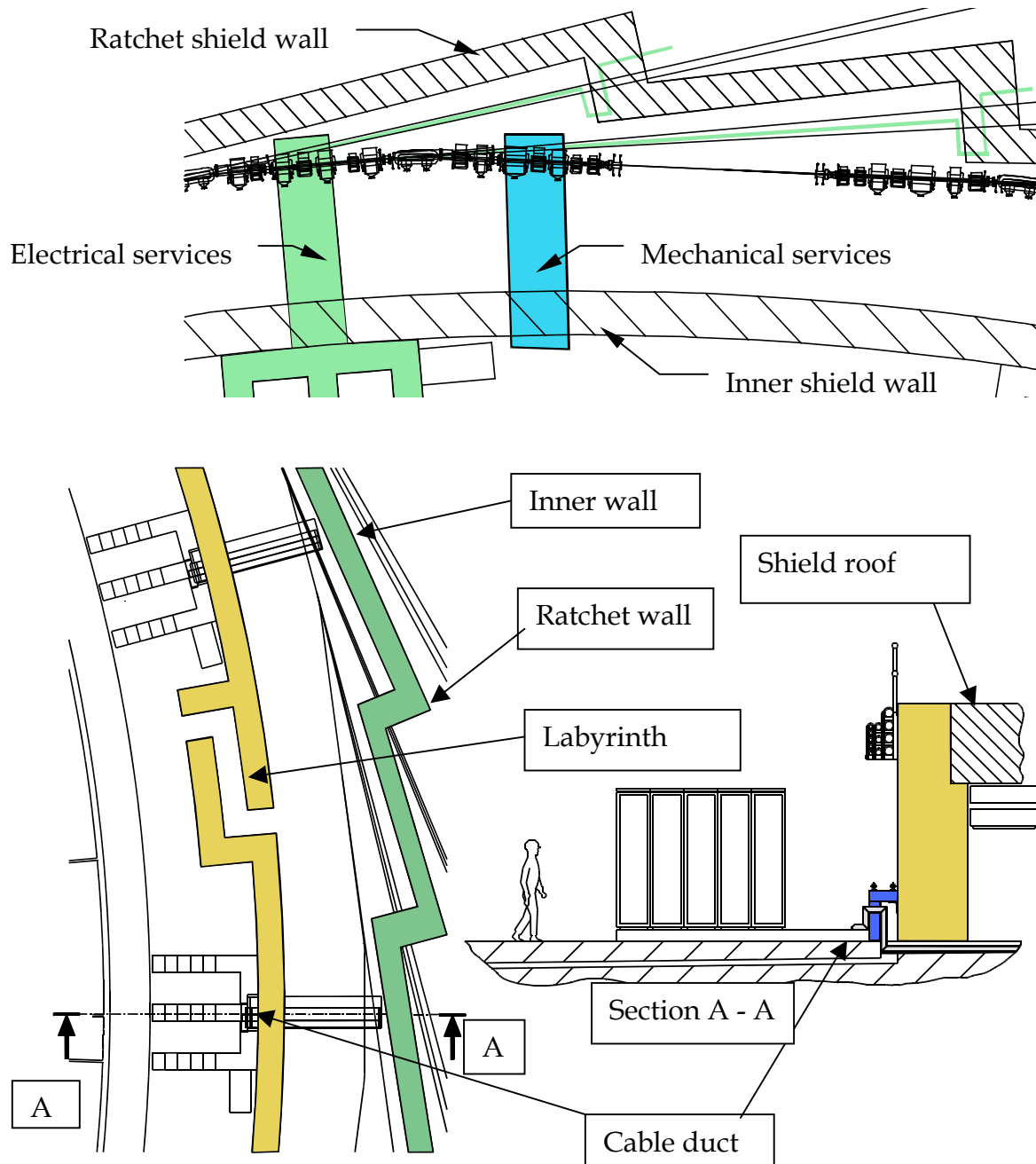


Figure 6.2-3 Suitable labyrinths are shown schematically

6.3 BEAM LINE SHIELDING

The dose rate from gas bremsstrahlung has been calculated [11][12][13][14] from a 20mrad dipole line and 5 and 8 m insertion device lines. The appropriate beamline shutter thickness to reduce these dose rates to $0.5\mu\text{Sv.h}^{-1}$ is tabled below. It is assumed that the shutter is located 20m from the source point (centre of straight for insertion

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device lines). The dose rate of gas bremsstrahlung depends on the vacuum pressure at the source point. A pressure of 10^{-8} Torr has been conservatively chosen.

Table 6.3-1 Shutter material and thickness

Type of line	beamline shutter material	minimum beamline shutter thickness /mm
20mrad dipole	Heavymet (tungsten alloy)	130
5m straight	Heavymet (tungsten alloy)	245
8m straight	Heavymet (tungsten alloy)	250

The code Photon [15] has been used to calculate the shielding necessary to reduce the synchrotron radiation on the beamlines to $0.5\mu\text{Sv.h}^{-1}$. It is assumed that the beam current was 300mA and the hutch is located 20m from the source point. The hutch walls are 1m from the scatter point. Table 6.3-2 details the shielding for the first agreed day one undulator lines[16] and also the future dipole lines. These thicknesses should be checked by use of the Stac8[17] code which treats scatter geometry more correctly.

Table 6.3-2 Beamline shielding specification

Field /T	Number of poles	Beamline shutter material	Beamline shutter thickness /mm	Hutch material	Minimum hutch thickness /mm
1.4	Dipole	Lead	8.5	Lead	3.5
0.7	85	Lead	6.5	Lead	2.0
0.7	72	Lead	6.5	Lead	2.0
0.8	72	Lead	7.5	Lead	2.5

It will be necessary to shield even 'non x-ray' lines originating from dipole sources for part of their length due to x-rays scattered from slits, apertures, mirrors and other optical elements.

The thicknesses of the beamline shutters and hutches specified above must be regarded as the absolute minimum required. Experience at ESRF and Elettra[18] and also APS[19] strongly indicates that small numbers of electrons can strike various components of the vacuum vessel near small aperture insertion device vessels leading to high dose rates of energetic radiation penetrating down the beamline which is more intense than the gas bremsstrahlung and synchrotron radiation. Some conditioning takes place with time. At ESRF, some insertion device vacuum vessels have taken months after being positioned in the ring to condition sufficiently to allow the beamline shutters to be opened.

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6.4 ENVIRONMENTAL IMPACT

The Diamond electron accelerators are relatively low power particle accelerators. The Diamond booster uses around 20W of electrons and the storage less. The operation of Diamond will create several pathways whereby people living and working on the land outside the perimeter of the Diamond site will be exposed to radiation. These are direct and scattered radiation, activated accelerator components, activated air, and cooling and ground water.

An Initial Environmental Impact Assessment for Diamond has been prepared [20]. This indicates that there are no significant hazards arising from activated air, cooling water and ground water. The shielding will be designed to reduce the annual exposure on site to less than 1mSv. It will reduce the offsite direct and scattered radiation to exposures, which are small percentages of statutory dose limits and suggested constraints for the public. The volume of activated components generated over the life of the accelerator is very small and disposal routes for the activity already exist. The radiological impact of Diamond to the surrounding people and environment will therefore be extremely small.

This assessment should be revised when the final performance specification and design of Diamond is confirmed.

6.5 RADIATION MONITORS

A comprehensive system of radiation monitors will have to be provided to ensure that the radiation penetrating the shielding is within the annual design limit of 3mSv. A specification must be written.

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E.6 RADIATION SHIELDING

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E.7 Mechanical Engineering

7.1 INTRODUCTION

This chapter explains the basic design that has been selected for the DIAMOND storage ring and justifies a number of important conclusions that follow from a detailed accelerator physics assessment. However the design team has not so far taken all topics to an equivalent level so that it will be seen that the treatment varies considerably in detail between them. Nevertheless the design concept presented has had its basic feasibility established and this has allowed the specification of all major technical systems to be defined with some confidence.

7.2 DIAMOND STORAGE RING LATTICE

7.2.1 Storage Ring Nomenclature.

The component groups that form the storage ring are:

(a) Straight Sections.

Straight sections will either be 5m 'short' straights or 8m 'long' straights. Each straight section will contain either an Insertion Device (ID), be dedicated to other systems, or be a plane vacuum vessel if unused. It is the intention for all straights to contain systems eventually. But the build up to full usage will be gradual.

The other systems to which 8m straights will be allocated are injection, RF and beam diagnostics in straights 1, 17 and 21 respectively. Figure 7.2-1 shows the straight numbering sequence.

(b) Achromat sections

Achromats consist of two dipole magnets and three straight sections containing beam-adjusting magnets.

The first straight section from the ID to dipole 1 is termed the incoming straight. The middle straight between dipole 1 and 2 is termed the common straight. The third straight leaving dipole 2 is termed the outgoing straight.

7.2.2 Storage Ring Layout

The diamond storage ring is a 24-cell double bend achromat (DBA).

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The bend angle at each dipole is 7.5° , and therefore 48 are required to form a full circle.

The storage ring will have $18 \times 5\text{m}$ long straight sections and $6 \times 8\text{m}$ straight sections for insertion devices. A machine 'super-cell' will comprise of $3 \times 5\text{m}$ and $1 \times 8\text{m}$ sections, hence a 6-fold lattice.

To optimise the use of harmonics of the RF, and to enable a variety of electron bunches to be circulated for experiments, a circumference of 561.6m is to be used. This choice is related to a harmonic number of 936 with a bunch spacing of 60cm and an RF frequency of approximately 500MHz. (Ref., AP-SR-cal-003-iss02 Harmonic Number).

To minimise thermal expansion stresses in the storage ring, and to allow clearance for removal, metal bellows are located between each straight section. There will be 4 bellows per achromat, resulting in a total of 96. Additionally bellows isolated Primary Beam Position Monitors will be located at each end of the achromat.

None of the achromat or dipole magnets are superconducting.

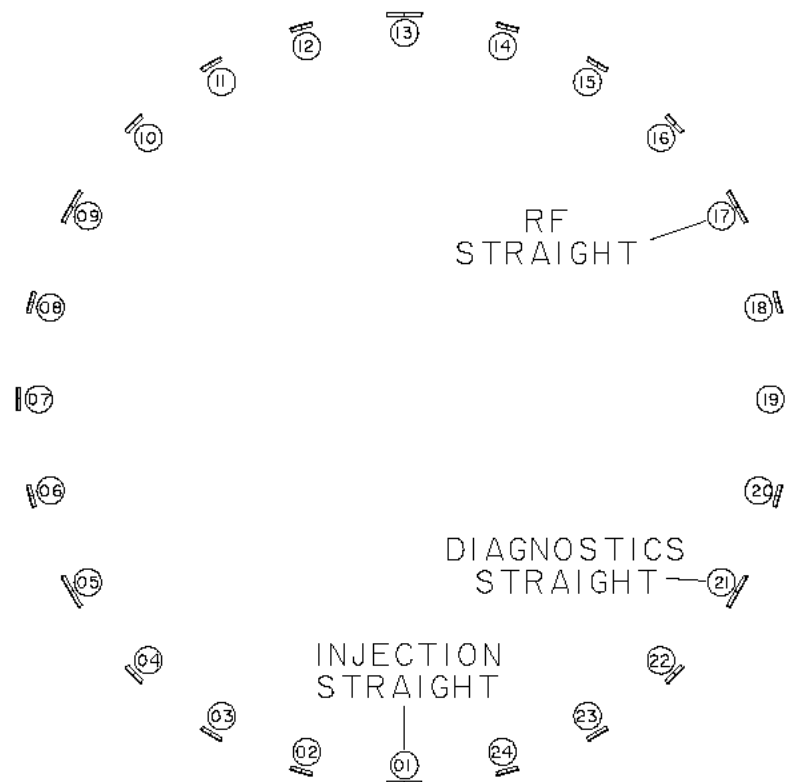


Figure 7.2-1 Storage Ring Straight naming convention.

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7.3 SURVEY AND ALIGNMENT PHILOSOPHY

This section is based on research carried out into survey and alignment at other 3rd generation sources. It is an example of how survey and alignment could be implemented at DIAMOND and is intended as a discussion document, not a definitive proposal.

The purpose of survey and alignment is to translate theoretical co-ordinates into 'real world' locations. The definitions of survey and alignment in this context are:

SURVEY: The actual location of an item as it now exists.
ALIGNMENT: Moving an item to a pre-determined position.

To be able to carry out this task to the accuracy required, see Table 7.3-1, the survey and alignment group must have input into the design of the accelerator from an early stage, particularly in the areas of:

- 1) Shielding
- 2) Tunnel size and roof height
- 3) Stay clear areas
- 4) Fiducial placement
- 5) Magnet support and adjustment
- 6) Water and power routing

The proposed positional tolerances for the storage ring are shown below in Table 7.3-1. Positional tolerances for the Booster and Linac are more relaxed.

Global positioning is described as the absolute position of the component in space.

Relative position is the most critical and describes the position of the component relative to its adjacent component. These values are general, and may ultimately vary from one component type to another.

Table 7.3-1 Proposed positional tolerances for the Storage Ring

Description	Value
Global Vertical	1.00mm
Global Horizontal	1.00mm
Relative Vertical	0.10mm
Relative Horizontal	0.10mm
Relative Longitudinal	0.25mm
Angular	0.15mRad

It follows from the requirement of Table 7.3-1 that the horizontal/vertical resolution of any individual adjusting device must be a suitably small fraction of the relative

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position. Typically $\pm 2\mu\text{m}$ with a typical repeatability of $\pm 10\mu\text{m}$. This should give a girder resolution of $\pm 5\mu\text{m}$ a repeatability of the order of $\pm 10\mu\text{m}$. These values are consistent with those found at other 3rd generation light sources and should minimise adjustment time. The survey control network is broken down into four main components:

1. The primary control survey network
2. The secondary control survey network
3. The accelerator control survey network(s).
4. The beamline control survey network.

The primary control network is used to correctly locate and orientate each of the other control networks; it is also used as the building reference. The primary network nodes consist of one central node in the nominal centre of the facility, and 6 nodes sufficiently distant to be unaffected by gross ground movement. There are three accelerator control networks, Storage Ring, Booster and Linac. Finally there is one beamline network.

The most critical feature of any survey philosophy is the storage ring tunnel network. The survey network must take into account, instrument limitations, lines of sight and spatial requirements for instruments and personnel to survey with relative ease. The secondary control network comprises key points within the storage ring network which relate back to the primary control network

The diagram Figure 7.3-1 shows a typical primary control network applied to the DIAMOND building. The network of survey monuments lies on the extremities of the site.

Creating the storage ring network inside the tunnel by looking at successive previous monuments will build up unacceptable accumulative errors. To prevent this, some points are selected as part of the secondary control network; these can be seen by the 'central monument' and each other. The lines between these points are the 'primary lines of sight' and must not be obstructed. Figure 7.3-2 illustrates the secondary network.

Due to the size of the booster ring and the necessary plant rooms required, removable plugs will be placed in the storage ring tunnel walls to maintain lines of sight and allow measurements to be taken across it.

The storage ring network (and also the Booster and Linac), must have enough survey reference points to be able to cross reference to all positions within the storage ring. Figure 7.3-3 illustrates a typical arrangement.

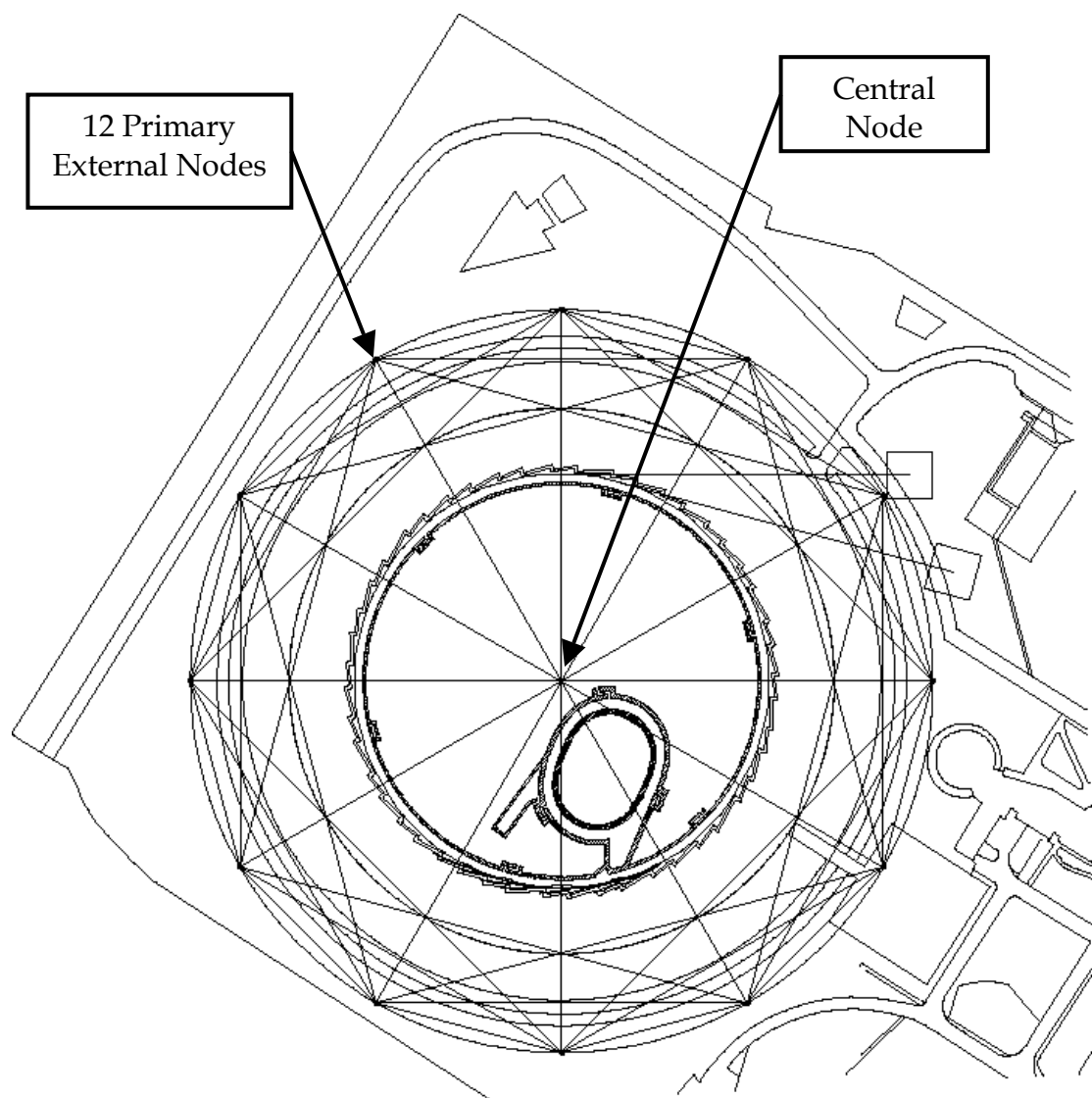


Figure 7.3-1 Proposed Primary Survey Network

There are three types of measurements required to position a magnet in the correct position within the accelerator:

- 1) Elevation
- 2) Direction (angle)
- 3) Distance

The 'Distinvar' and 'Ecartometer' techniques, used at the ESRF, have proved to be time consuming to use, alternative methods have been investigated 1. These are firstly a commercially available motorised theodolite with automatic target recognition (Leica TDS5000), and secondly a laser tracker (Leica LTD500). The ESRF have concluded that the motorised theodolite is the most accurate system. SLS use the laser tracker and a digital level (N3) [2]. Close range photogrammetry has also been used successfully in similar installations [3]

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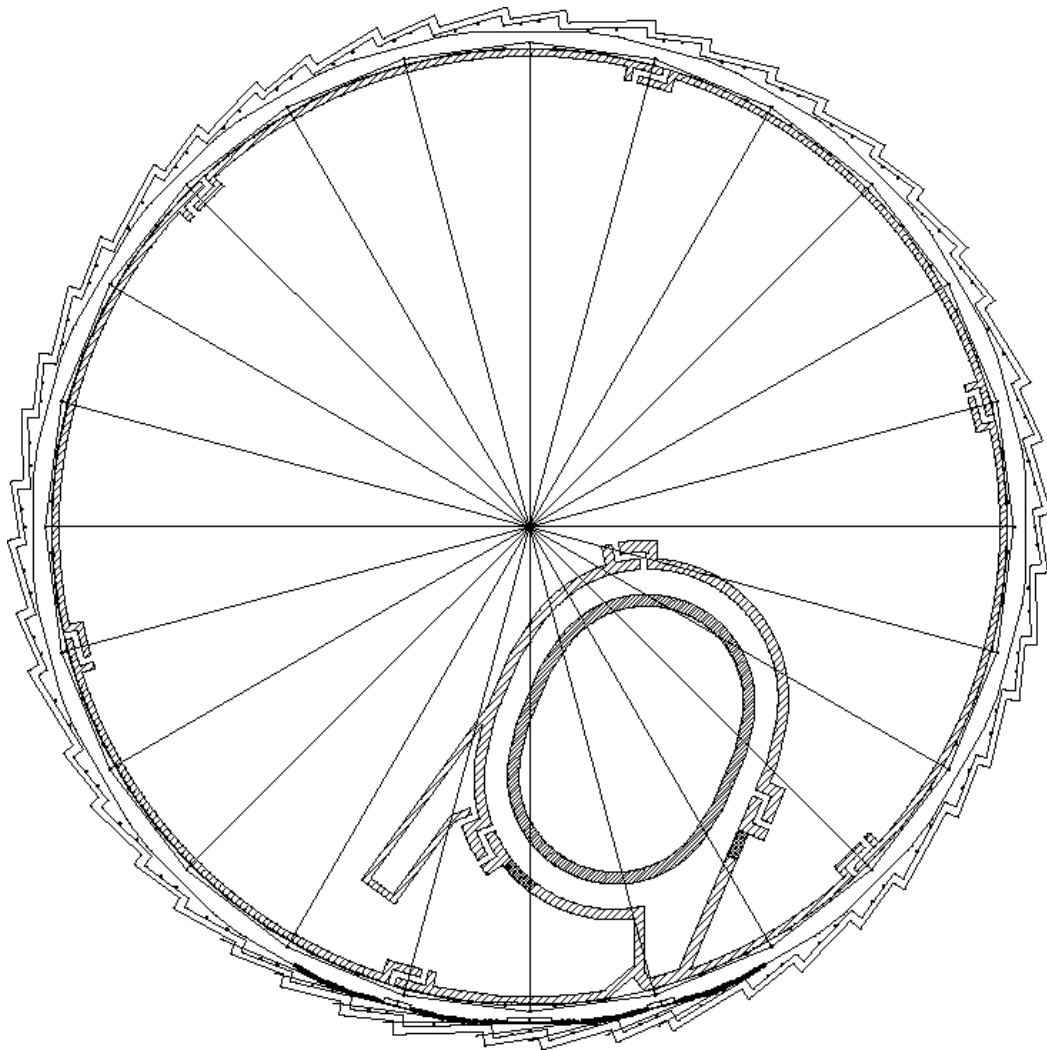


Figure 7.3-2 Secondary Control Survey Network

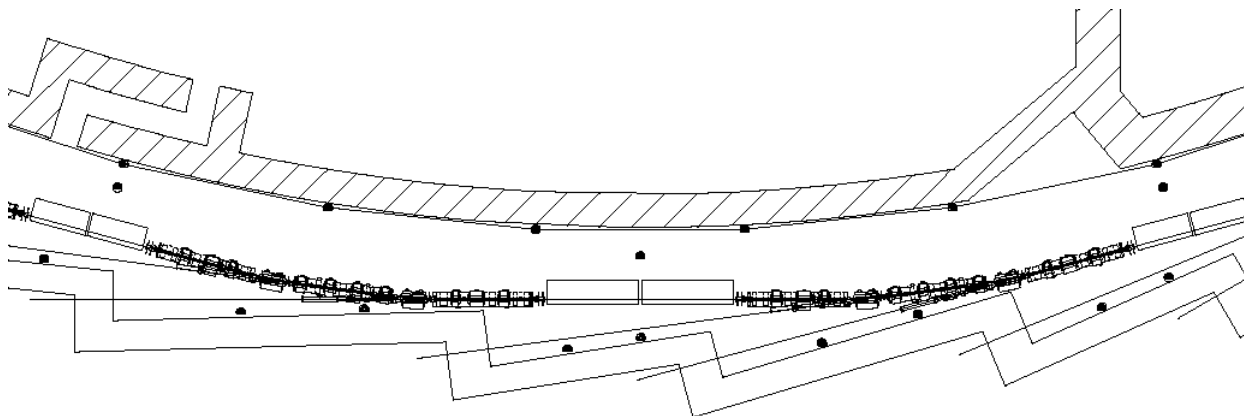


Figure 7.3-3 Typical arrangement of Storage Ring Network.

Four fiducials should be placed on each component to be surveyed, three are required to locate the component in six degrees of freedom. One is redundant and used to confirm the location determined by the other three fiducials.

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It is not possible to put every girder on its ideal fiducial co-ordinates, some tolerance has to be present. A smoothing technique can be used to achieve the best orbit with the minimum of girder movements. The as installed/surveyed co-ordinates are inputted into a smoothing software programme and critical girders are selected for alignment. These girders are then moved to the positions specified by the programme (even if they are moving further away from the ideal positions).

Dynamic (electron) beam based girder alignment techniques will be investigated. This is the same principle as described in the last paragraph, but in real time. This method of correction presupposes that fully motorised girder adjustment is included.

A survey will have to be taken when the storage ring tunnel is completed. This will be the original reference information for the primary network. After the accelerator components have been installed the primary network will have to be rechecked. During early commissioning and operation several surveys will be required to check ground settlement vs. time to ensure that an asymptotic characterist prevails; i.e. that the ground settlement rate is decreasing with time.

7.4 MACHINE CONSTRUCTION

7.4.1 Girder philosophy

Two options normally exist when considering how to construct an accelerator. Should the accelerator be constructed piece by piece in the storage ring tunnel, or should it be built remotely in larger modules, that are then installed in the storage ring tunnel at a later stage?

For the DIAMOND Storage ring and Booster, the latter option is considered best and the large module is referred to as a 'girder assembly' or 'girder' for short. The benefit of the modular construction is that all the elements associated with a module can be assembled, surveyed and tested in relative ease, away from the close confines of the storage ring tunnel. This is especially important for survey of the magnetic elements, which generally requires space and distance around the assembly to align elements accurately. With accurate jigs and fixtures, it is perfectly practicable to align individual components on the girders away from the machine, and then survey the girder assembly into position in the tunnel, rather than the individual elements on it's back. A further advantage of the modular construction is the potential to have the girder assembled in an area specifically arranged for that task. Also, after the initial installation, a spare set of girder assemblies can be kept ready to be installed if there is a failure on the machine. This gives DIAMOND the option of removing individual components or a complete girder assembly depending on which is quickest and therefore minimising down time.

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7.4.2 Girder Design

The girder is basically a hollow box section, steel fabrication which will be used to support a section of the storage ring accelerator components. It will need to support magnets, vacuum chambers, pumps and diagnostic devices.

A design study has been carried out to look at the most practical and economical way of splitting the achromat into girder assembly sub sections. As this is a double bend achromat, the most practical options were to look at having three straight girder assemblies, with the dipoles either on the girders or spanning the gap between them. However, due to the mass of the dipoles, these arrangements resulted in assemblies that were excessively heavy. The way around this problem is to split the achromat into five sections, one girder for each straight and one for each dipole. Figure 7.4-1 below shows this arrangement.

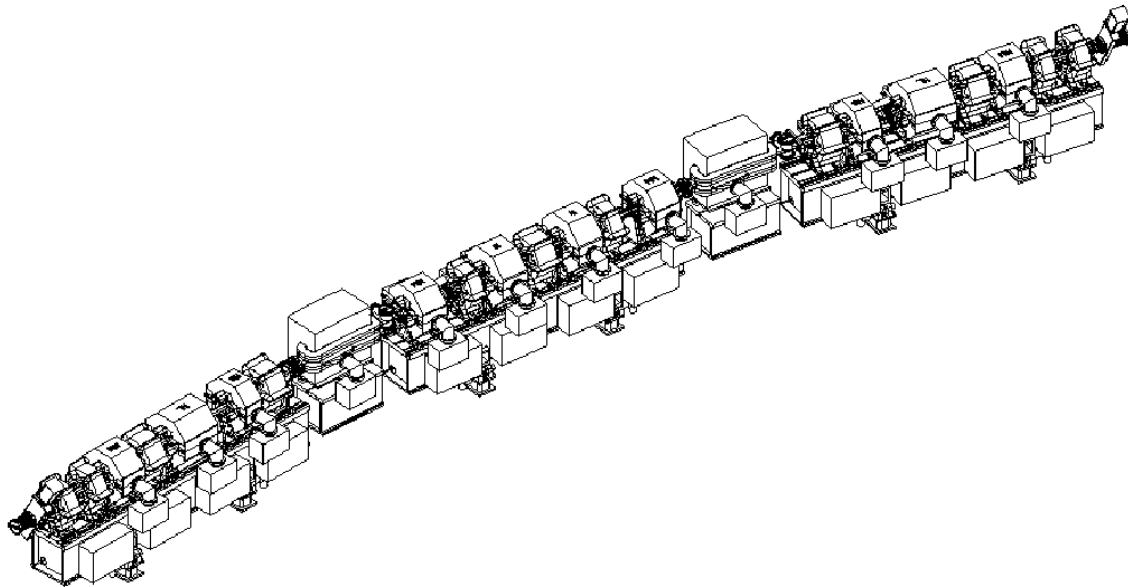


Figure 7.4-1 Achromat Arrangement

The result of this arrangement is to keep the weight of a girder assembly below 15 tonne. Any increase in this figure will affect the crane capacity and building support steelwork and increase the building cost accordingly.

The magnets, which sit on the girder, control the electron orbit and therefore the source point of the synchrotron radiation. Any movement in the girder will result in misalignment of the magnets and have a significant deleterious effect on electron trajectories. Due to this, the girders need careful design to minimise deflection and the amplitude of ground induced vibration. Because the ground is always vibrating, standing any structure on it will cause the structure to also vibrate. An infinitely stiff structure will vibrate at the same frequency and with the same amplitude as the ground. A real structure will not be infinitely stiff and will have a natural frequency at which a small excitation force will cause relatively large vibration amplitudes. At

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frequencies other than this natural frequency, the ground motion will still be magnified but not by as great a value. Ground vibration measurements have been taken at the RAL site and it can be seen that the amplitude of these vibrations diminishes with increasing frequency as shown in Figure 7.4-2. To minimise the beam motion, the girder assembly should have a natural frequency as high as possible, with a lower limit being set at 40Hz. 50Hz should also be avoided as it coincides with the frequency of AC electrical supply and therefore, to pump, fan and general electrical machinery noise. In addition to this, the amplification of the system should be minimised. The SLS stated that RMS photon beam movement at the experiment had to be less than 10% of the beam size. A similar limit has been set for DIAMOND. These factors must be balanced against cost, and weight considerations.

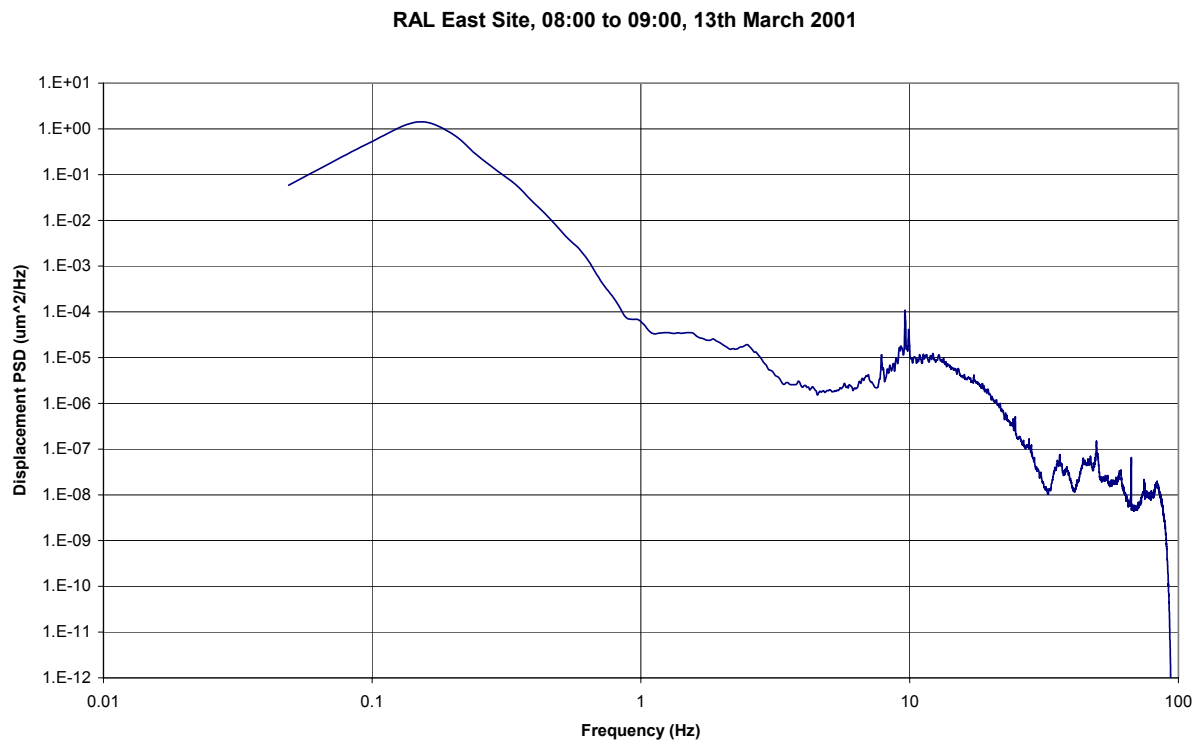


Figure 7.4-2 RAL Site ground vibration characteristic

The temperature response of the girder is also to be considered as part of assessing the overall temperature stability of the machine. Therefore the air temperature in the storage ring tunnel must be tightly controlled.

BESSY II has adopted a philosophy of large stiff girders that are full of sand. This has a dual purpose of providing mass and damping to the girder, whilst also introducing a massive thermal inertia to resist changes to girder dimensions arising from changes in tunnel temperature. Unfortunately, increasing mass reduces natural frequency, but because of the large mass, the amplification factor is low and the beam motion is within the design limits. Due to the complexity of these factors, a detailed study of all these effects is underway, utilising Finite Element Analysis (FEA) techniques.

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7.4.3 Girder Support and Adjustment

The DIAMOND magnet support girders, as previously described are used to support all major machine elements. Subsequently it is vital that the girders themselves are rigidly restrained in position, whilst having the ability for the position of the whole girder to be altered as and when required to maintain machine alignment. Different methods of supporting the girders have been investigated along with position monitoring systems such as Hydrostatic Levelling Systems (HLS)

At the ESRF and the SLS, a HLS is used. This uses a system of communicating vessels (three or four per girder). A fluid defining a reference altimetric level circulates freely inside a tube connecting the various measuring vessels. The difference in height is then measured by means of a capacitive sensor attached to the vessels. This principle allows the height differences between different points to be determined. The height information provided by the various sensors can then be used to drive high precision movers. It should be understood that HLS is not a dynamic system that endeavours to provide continuous alignment of the girders, HLS is used to facilitate rapid re-alignment, this primarily being due to ground movement. The ESRF has anticipated ± 1 mm ground movement over a 12-month period, subsequently it was expected that a re-alignment would have to take place approximately every month. Both the ESRF and SLS have experienced problems with these systems and cannot currently use them for the alignment purposes. They can only be used as a general indicator of movement. More modern systems may be more reliable, but they are also expensive, and as such will not be included on the initial installation. However provision will be made to allow future installation, should a system become available which is proven to work accurately in the long term and be cost effective. It should also be noted that BESSY II does not have a HLS and during a recent visit it was noted that they have very few problems with alignment (ground conditions will have a large effect on alignment stability). When they see the beam move at one of the experiments, they shut the machine and re-align the girders at that location only.

Many different types of girder mover systems are currently in use at light sources around the world. These are all currently being considered in terms of reliable operation, cost and ease of use. Some systems can be actuated remotely so that alignment can be carried out with the beam on. This is only of use if some measurement of beam motion is also available remotely. As HLS systems are unreliable, some investigation work is required to look at the possibility of beam based alignment using data from beam position monitors in the front ends and beamlines. When this work is complete a decision on girder mover actuators can be made. If actuators are not included in the initial installation, provision must be made to allow the fitting of a system at a later date. Any system that is installed must allow adjustment in all three planes with a minimum accuracy of 0.025 mm and a total travel of at least ± 4 mm, the final extent of travel will may need refining with regard to the expected variation in settlement for the storage ring tunnel. In any event provision will be made for gross adjustments by shimming of the supports Vertical and horizontal transverse motion should be considered for use with actuators.

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Alignment of the magnets in the longitudinal direction is less sensitive to errors and can therefore be done manually as required. The Swiss girder mover system uses actuators, and has a proven accuracy of ± 3 to $5 \mu\text{m}$ and a repeatability of better than $\pm 10 \mu\text{m}$.

Girder support design and location will affect the girder assembly natural frequency and amplification factor. The ESRF for example, has long screw jacks supporting the girder and has recently undergone an expensive modification process to add vibration dampers to all the girders. They were experiencing excessive vibration amplitudes at 7Hz. The fitting of dampers has reduced the amplitude and moved the natural frequency to 10Hz. The girder support / mover system for DIAMOND should be accounted for in the girder assembly natural frequency calculations to ensure that the whole system is operating within design limits. It should be remembered that at the ESRF and ALS, the transverse mode eigen-frequency was the lowest, steps must also be taken to ensure that the torsional mode eigen-frequency is also maximised.

As part of the modular design philosophy, the number of connections / joints that require attention when fitting the girders (e.g. bolting the girder to a jack top) needs to be minimised, as do the number of service connections.

The currently favoured girder positioning system for diamond is to use the method developed for the SLS. The reasons for favouring this system are listed in Table 7.4-1.

Table 7.4-1 Reasons for favouring SLS girder positioning solution

1. Proven design
2. 5 degrees of freedom catered for (axial 'z' adjust omitted) .
3. High natural frequency of the cam assembly compared to a screw jack.
4. Pure rolling motion, no large contact areas to stick over time
5. Horizontal and vertical motion can be achieved individually or together.
6. Motorised system allows remote adjustment.
7. Acceptable resolution and repeatability.
8. No dismantling required in for craning out girder.
9. Control software is available, tested and compatible with EPICS.

The system uses rotating cams to provide a kinematic mount for the girder. The longitudinal (axial) adjustment is done manually using a separate mechanism. This sixth degree of freedom could also be automated if required. The operation of the device is illustrated below in Figure 7.4-3.

A kinematic mount function by presenting a cone, a groove and a flat at three actuating points. This gives adjustment with six degrees of freedom. The adjustment is provided by rotation of the cams. The 'flat' is reproduced exactly as can be seen in the top left-hand portion of Figure 7.4-3 this allows vertical adjustment with no lateral constraint. The groove is reproduced by the two single angled faces at the

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bottom end of the girder (in Figure 7.4-3), movement of one or both of these cams can produce vertical, and/or lateral displacement; which can if desired produce slew and heave. Finally the 'cone' is partially reproduced by the 'V', however the use of a 'V', instead of a cone at this point results in no control over the axial degree of freedom.

DIAMOND is proposing to have storage ring girders that are readily removable and replaceable as part of a maintenance procedure. Since the girders are not fastened to the roller cams in any way, no dismantling of the actuating mechanism is required to remove and replace girders. This alone is a major benefit to the overall maintenance philosophy. Suitable jigs can be used to positioning the reference 'V' surface accurately and consistently from one girder to another. This would minimise the amount of adjustment that a replacement girder would require during re-alignment.

The cams can be placed on the side or beneath the girders, these design options will be considered further.

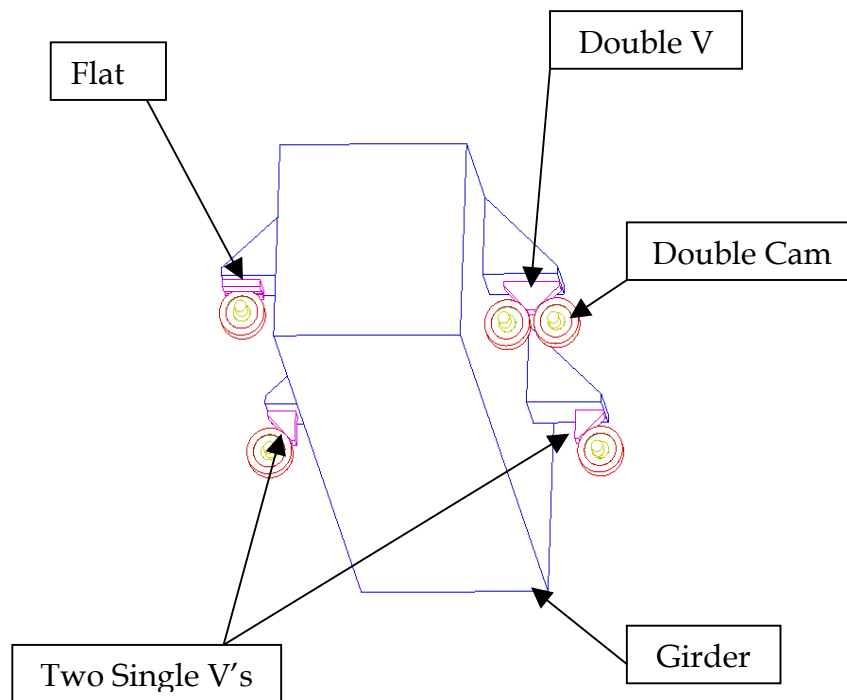


Figure 7.4-3 Principle of Girder Kinematic Mount.

7.4.4 Magnet mounts

There are many ways to support a magnet on the girder top. Some light sources use kinematic mounts, while others use complex six strut systems. When selecting an appropriate mounting arrangement we must consider how much movement we need for alignment and how stiff the arrangement is, as any movement of the magnet will be magnified and transferred to the beam. After considering the different systems, it

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has been decided that the best solution for DIAMOND is one that based on the principles used at the SLS. The girder tops have two vertical, and one horizontal, datum faces which are machined flat and straight to within a $\pm 15\mu\text{m}$ tolerance band along the entire length of the girder see Figure 7.4-4.

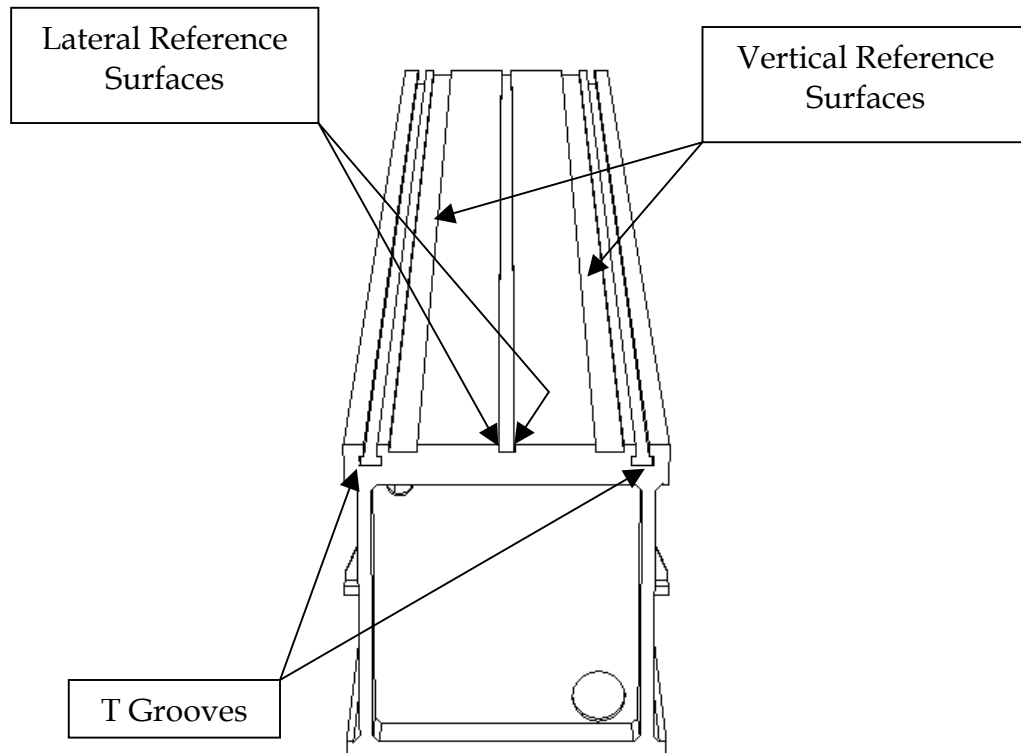


Figure 7.4-4 Girder top reference features.

The magnets are supplied with corresponding horizontal and vertical datum faces and shims and keys are used to locate each magnet of the girder in all but the axial direction. The manufacturer supplies each magnet with a unique set of shims. By determining the magnetic centre of each magnet on a reference girder each one can be provided with its own unique set of shims and key. This method can also account for girder deflection. The magnets can then be quickly but accurately positioned on the girder and clamped into position. The clamps can then be simple and robust tooling clamps with no need for additional adjustment. Magnet feet should be designed to maximise contact area between the magnet and the girder so that once positioned and clamped, the joint will be stiff, reducing the possibility of movement and vibration problems. Figure 7.4-5 illustrates a typical magnet to girder fixture.

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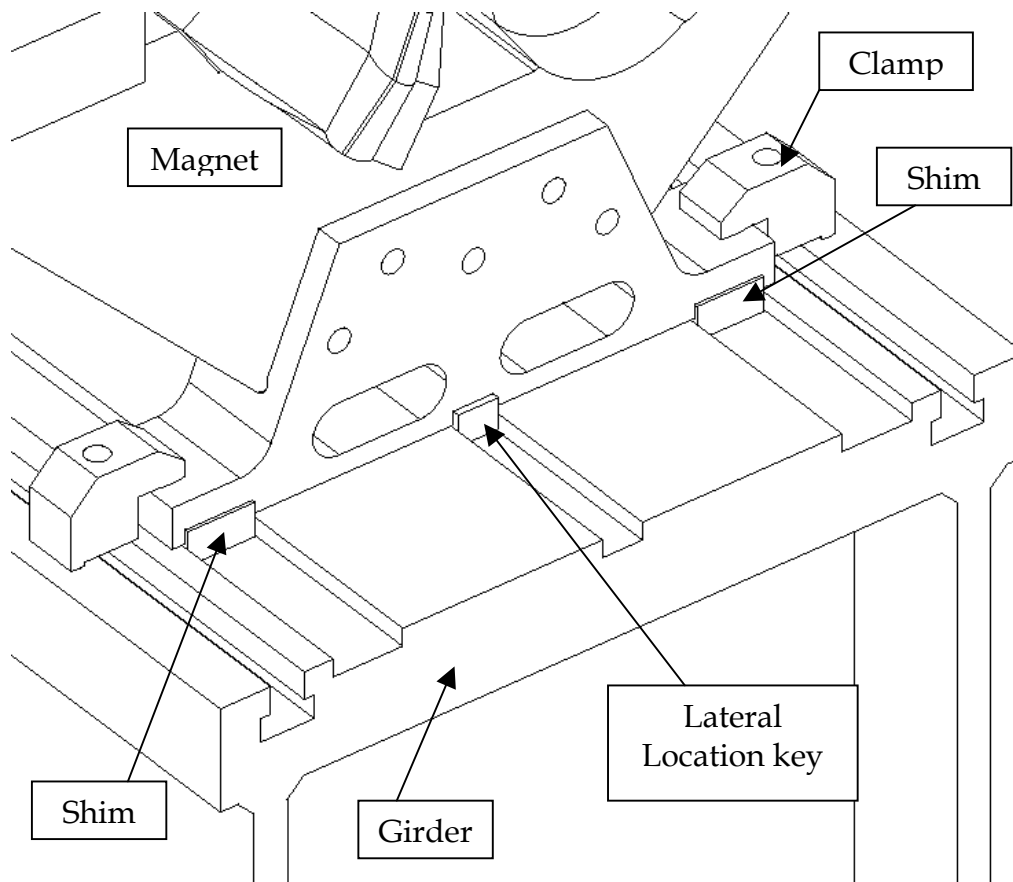


Figure 7.4-5 Typical Magnet to Girder Fixture.

7.4.5 Installation

Girder components will be assembled in a suitable enclosed clean area, away from the machine tunnel as it is predicted that components will be delivered before the tunnel is completed. This will also allow more room around the girder assemblies for alignment of the components relative to each other and pre-commissioning of the services and components before installation. The girder should be stood on the surfaces that will be used to support it in its final location so that when the component alignment is checked, the girder deflection is as it will be when the girder has been installed. Once access to the tunnel has been given, the assemblies will be transported to the DIAMOND building and delivered to one of the loading bay areas. From there, the crane will be used to lift the girders over the shield wall and lower them into position in the storage ring tunnel. The supports / mover systems will need to be in place and ready to accept the girder before it is delivered. The lifting equipment needs to be designed so that it causes minimal deflection during installation / removal as excessive movement may not settle out once the girder is in position and therefore the magnets may be fractionally out of line. Once in position, the girder will be aligned and connected to the power, cooling water, compressed air and dry nitrogen supplies, ready for commissioning.

7.5 VACUUM VESSELS

7.5.1 Design

(a) Straight vessels

The philosophy chosen is to incorporate fixed pumping positions, as per the red book. The design shows no distributed pumping such as getter strips inside the vacuum chambers. An isolation valve is positioned at each end of an insertion device to enable replacement of portions of the storage ring without venting the whole facility see Figure 7.5-1.

A cooled absorbing copper strip, to intercept photons from bending magnets and insertion devices, runs along the straight section vacuum chambers, see Figure 7.5-2. This is a change from discrete cooled photon absorbers as described in the red book (refer to section 7.6).

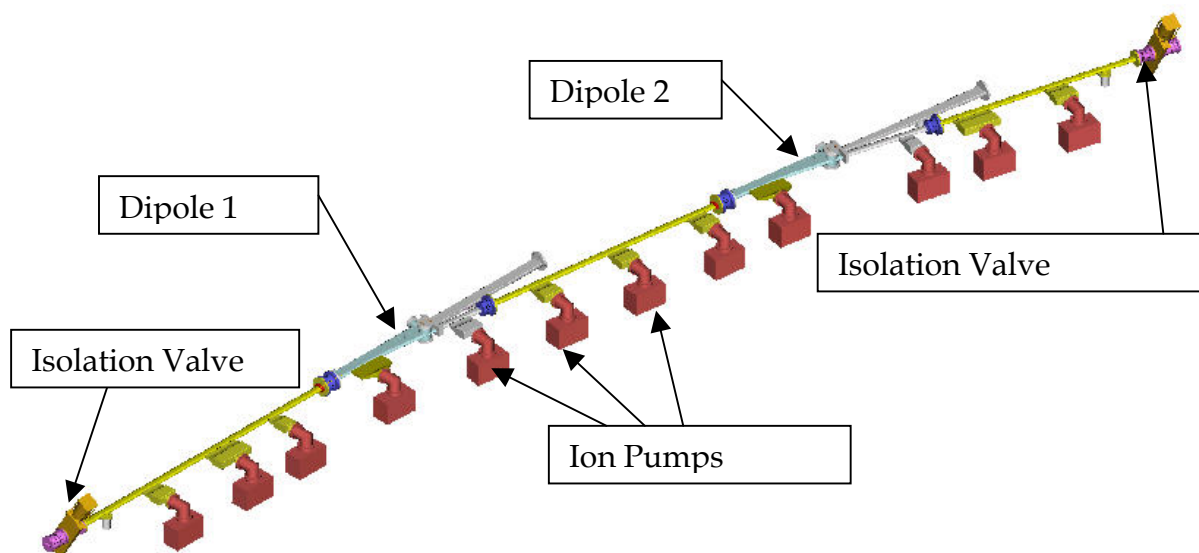


Figure 7.5-1 Achromat Vacuum Vessels

Possibilities for side pumping ports through the sides of quadrupole magnets are shown in Figure 7.5-3. Smooth internal profiles are also required, to minimise electron beam induced heating and disruptive resonant electromagnetic fields. Steps no greater than 2 mm inside the vacuum chamber should be tolerated, which results in valves, flanges and bellows having special designs specified to expose smooth surfaces. RF contact fingers are also required on internal components where small gaps are present to provide continuity for surface currents and allow movement of mating components during thermal expansions.

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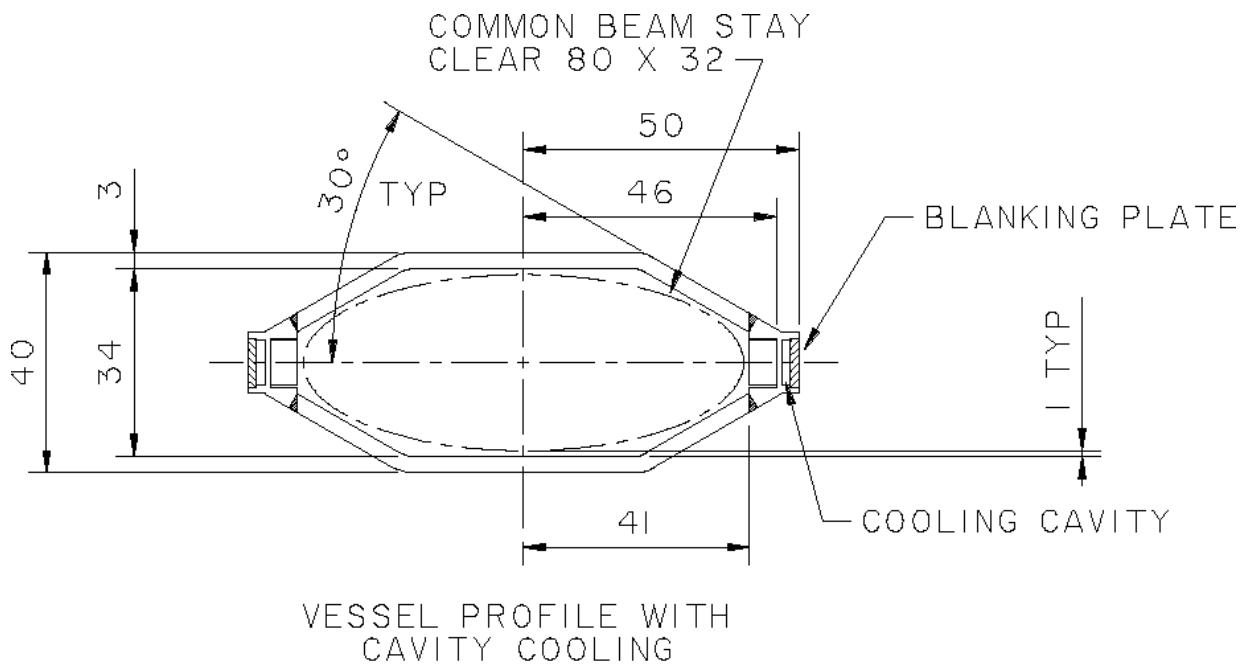


Figure 7.5-2 Vacuum Vessel section showing distributed absorber.

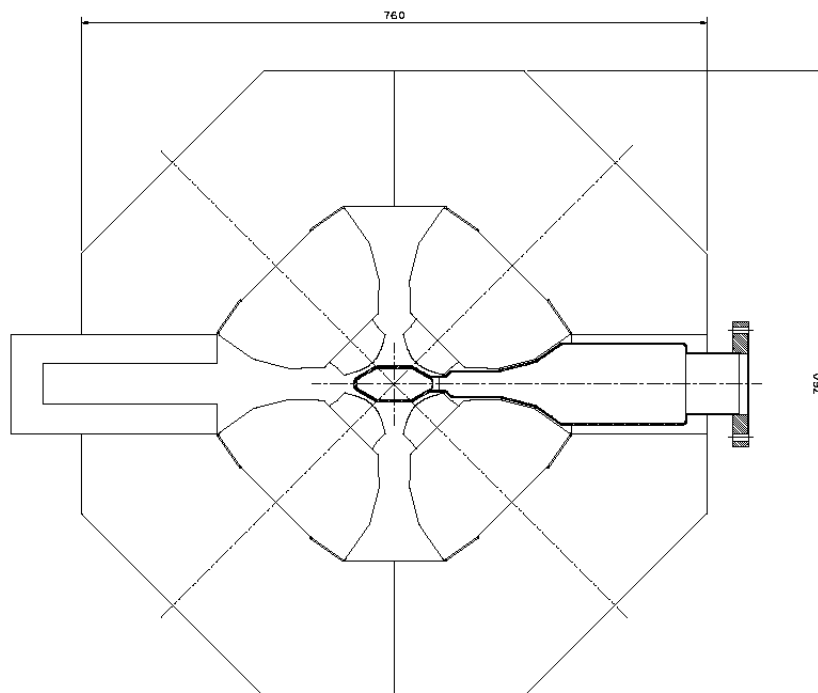


Figure 7.5-3 Quadrupole Magnet with Side Pumping Port

The design for the storage ring vacuum chambers (except the insertion devices and slots in the bending magnet chambers to extract the photon beams) shows a constant internal stay clear aperture, which is an elliptical cross-section. The actual vacuum

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chamber cross section is an elongated octagon for practical reasons, with major and minor axis dimensions of:

± 40 mm horizontal

± 16 mm vertical

A detailed study has been carried out comparing the vessel cross sections with electron beam apertures defined by lattice studies. It has been agreed that at key points, such as the crotch, an asymmetric cross-section can be applied to the vessel with changes in cross section at 1:10.

This is a development from the red book, which had vacuum chambers with a constant internal vertical aperture of ± 17 mm, but had two internal horizontal apertures. A large horizontal aperture in the achromat (± 40 mm) and a smaller horizontal aperture in the straight sections (± 25 mm). To achieve a smooth transition in aperture, the bending magnet vacuum chambers had a complicated arrangement with the ID beamline bending magnet vacuum chamber increasing in horizontal aperture along the electron beam path and the dipole beamline bending magnet vacuum chamber decreasing in aperture. Resulting in a difficult manufacturing arrangement and two different chamber designs.

There are a number of advantages in maintaining the constant vacuum chamber cross-section, which include:

- Simplified vacuum chamber construction of both the straight and bending magnet chambers.
- Increasing the horizontal aperture in the straight section immediately after the insertion devices allows an increase in the ID horizontal photon beam acceptance to ± 5 mrad (zero mrad being the electron beam centreline).

(b) Dipole Vessels

Side pumping ports positioned on the inside of the storage ring are shown on both the straight and the bending magnet chambers. To achieve this the yoke of the bending magnet needs to be positioned on the outside of the ring, which is opposite to that described in the red book. This arrangement will allow also for the easier installation and maintenance of the bending magnet chamber from the inside of the ring.

The design aim was originally for a common dipole vessel, however the compact arrangement of magnets in the region of the dipole vessels has required the vessels for dipole 1 and 2 to differ in order to fit other components in the space available. Finite element stress analysis of the dipole vessel has determined that a minimum wall thickness of 3mm is required for stainless steel vessels and 5mm for aluminium alloy vessels. The limiting factor is the maximum allowable deflection of 0.5mm. The analysis work is ongoing, as the dipole vessel design is refined.

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One option being considered is to incorporate the dipole cooling, at the aperture, into the structure of the vessel. The other option being the inclusion of separate cooling elements. A typical cross section is illustrated in Figure 7.5-4

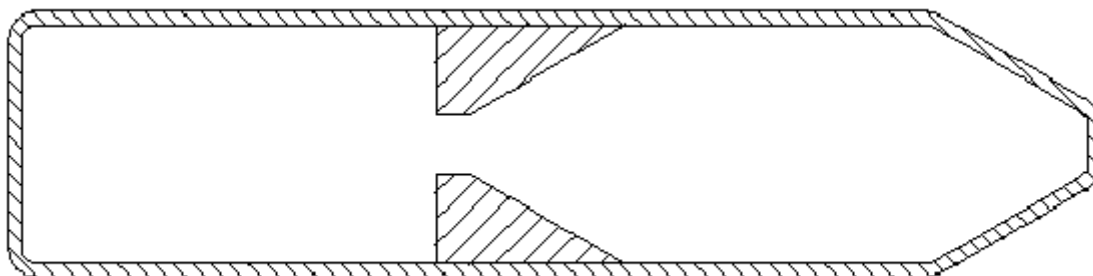


Figure 7.5-4 Cross section of Dipole Vacuum Vessel

(c) Bellows

Hydro-formed bellows will be used wherever possible rather than edge-welded construction to reduce the risk of leaks to vacuum.

However, it is highly likely that golden BPM assemblies will have to be constructed using edge welded bellows to give the required lateral flexibility in a limited length. Any bellows assemblies based on a circular cross-section must be fitted with a sliding RF shield within the bellows.

The bellows must allow for expansion of the storage ring from 20°C to 100°C.

All bellows to be installed at nominal free length at ambient conditions, only compressive movement is allowed (Meng-SR-min-005).

Additionally they will be compressed to achieve a 50mm clearance with adjacent storage ring component flanges to enable crange of the relevant sub assembly.

(d) Tapers

Tapered transition components at ~250 mm long are included both upstream and downstream of the insertion device vacuum chamber to accommodate a smooth change in profile from the common aperture to the reduced apertures within the insertion device vacuum chambers.

7.5.2 Materials

The materials tabulated below in

Table 7.5-1 to Table 7.5-8 below are suitable for use in constructing DIAMOND vacuum chambers and internal features. Some relevant alternative material specifications and material properties are indicated where information is available:

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Table 7.5-1 304L Material Properties. (Source BS5500 + manufacturer's data)

AISI 304L		WN 1.4306	BS 304 S11		UNS S30403	
0.2% yield stress	0.2% yield stress	Modulus of Elasticity	Thermal Cond.	Coef. of thermal exp.	Density	Specific heat cap
MNm ⁻²	MNm ⁻²	GNm ⁻²	Wm ⁻¹ K ⁻¹	x 10 ⁻⁶ K ⁻¹	Kgm ⁻³	Jkg ⁻¹ K ⁻¹
20°C	250°C	20°C				
215	142	200	15	16	7900	500

Table 7.5-2 304LN Material Properties (Source BS5500 + manufacturer's data)

AISI304LN		WN 1.4311	BS 304 S61		UNS S30453	
0.2% yield stress	0.2% yield stress	Modulus of Elasticity	Thermal Cond.	Coef. of thermal exp.	Density	Specific heat cap
MNm ⁻²	MNm ⁻²	GNm ⁻²	Wm ⁻¹ K ⁻¹	x 10 ⁻⁶ K ⁻¹	Kgm ⁻³	Jkg ⁻¹ K ⁻¹
20°C	250°C	20°C				
305	190	200	15	16	7900	500

Table 7.5-3 316L Material Properties (Source BS5500 + manufacturer's data)

AISI 316L		WN 1.4435	BS316 S13		UNS S31603	
0.2% yield stress	0.2% yield stress	Modulus of Elasticity	Thermal Cond.	Coeff. of thermal exp.	Density	Specific heat cap
MNm ⁻²	MNm ⁻²	GNm ⁻²	Wm ⁻¹ K ⁻¹	x 10 ⁻⁶ K ⁻¹	Kgm ⁻³	Jkg ⁻¹ K ⁻¹
20°C	250°C	20°C	20°C	(0-100°C)	20°C	20°C
225	154	200	16.3	16	8000	500

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Table 7.5-4 316LN Material Properties (Source BS5500 + manufacturer's data)

AISI 316LN		BS 316 S 63		WN 1.4429		UNS S31653
0.2% yield stress MNm ⁻²	0.2% yield stress MNm ⁻²	Modulus of Elasticity GNm ⁻²	Thermal Cond. Wm ⁻¹ K ⁻¹	Coeff. of thermal exp. x 10 ⁻⁶ K ⁻¹	Density Kgm ⁻³	Specific heat cap Jkg ⁻¹ K ⁻¹
20°C	250°C	20°C	20°C	(0-100°C)	20°C	20°C
315	200	200	15	16	8000	500

Table 7.5-5 OFHC Copper Material Properties (yield stress varies greatly with temper and cold working)

OFHC Copper UNS C10100, C10200, C10300 are all loosely referred to as OFHC ASTM B187 Bar, ASTM B152 F68 Plate						
0.2% yield stress MNm ⁻²	0.2% yield stress MNm ⁻²	Modulus of Elasticity GNm ⁻²	Thermal Cond. Wm ⁻¹ K ⁻¹	Coeff. of thermal exp. x 10 ⁻⁶ K ⁻¹	Density Kgm ⁻³	Specific heat cap Jkg ⁻¹ K ⁻¹
20°C	250°C	20°C	20°C	(0-100°C)	20°C	20°C
63	55	117	391	17	8930	394

Table 7.5-6 Glidcop™ Material Properties (Source: ITER Material Assessment Report)

Glidcop™ AL-25 (0.5% wt Al ₂ O ₃), other grades of Glidcop will also be considered.						
0.2% yield stress MNm ⁻²	0.2% yield stress MNm ⁻²	Modulus of Elasticity GNm ⁻²	Thermal Cond. Wm ⁻¹ K ⁻¹	Coeff. of thermal exp. x 10 ⁻⁶ K ⁻¹	Density Kgm ⁻³	Specific heat cap Jkg ⁻¹ K ⁻¹
20°C	250°C	20°C	20°C	(0-100°C)	20°C	20°C
332	255	126	345	16.2	8860	386

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Table 7.5-7 Copper Chrome Zirconium Material Properties (Source: ITER Material Assessment Report).

Copper Chrome Zirconium Alloy C18150; CuCrZr; DIN 17666; ISO 1187 Solution annealed and aged.						
0.2% yield stress MNm ⁻²	0.2% yield stress MNm ⁻²	Modulus of Elasticity GNm ⁻²	Thermal Cond. Wm ⁻¹ K ⁻¹	Coeff. of thermal exp. × 10 ⁻⁶ K ⁻¹	Density Kgm ⁻³	Specific heat cap Jkg ⁻¹ K ⁻¹
20°C	250°C	20°C	20°C	(0-100°C)	20°C	20°C
293	257	128	379	15.7	8920	388

Table 7.5-8 Aluminium Alloy Material Properties

Aluminium Alloy BS EN 485 5083 H321 (Non Heat treatable) ISO Al Mg 4.5 Mn Strain Hardened (¼ hard)						
0.2% yield stress MNm ⁻²	0.2% yield stress MNm ⁻²	Modulus of Elasticity GNm ⁻²	Thermal Cond. Wm ⁻¹ K ⁻¹	Coeff. of thermal exp. × 10 ⁻⁶ K ⁻¹	Density Kgm ⁻³	Specific heat cap Jkg ⁻¹ K ⁻¹
20°C	250°C	20°C	20°C	(0-100°C)	20°C	20°C
215		71	109	23.5	2670	880

The default material of construction for the vacuum chambers is 304L/LN stainless steel, which CLRC is most familiar with, lends itself to some of the more difficult constructions, and is readily available. There is scope for 4 dipole vessels for IR and CD to be manufactured from aluminium alloy; ID straights could also be manufactured from this material. The copper materials will be considered for the construction of absorbers. Material property information will be completed and confirmed as more sources of information are found.

7.5.3 Mounts

At some of the 3rd generation light sources (e.g. ESRF & BESSY II) storage ring vacuum vessels are supported by mounting brackets attached to the quadrupole or

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sextupole magnets, alternatively other sources (e.g. SLS) prefer to support storage ring vacuum vessels from the top of the girder.

Diamond has the opportunity to be able to have the storage ring vacuum vessels mounted to the top of the girders via a certified fixture. The form of the fixture should provide transverse stiffness but provide some longitudinal flexibility. A proposed arrangement is illustrated in Figure 7.5-5

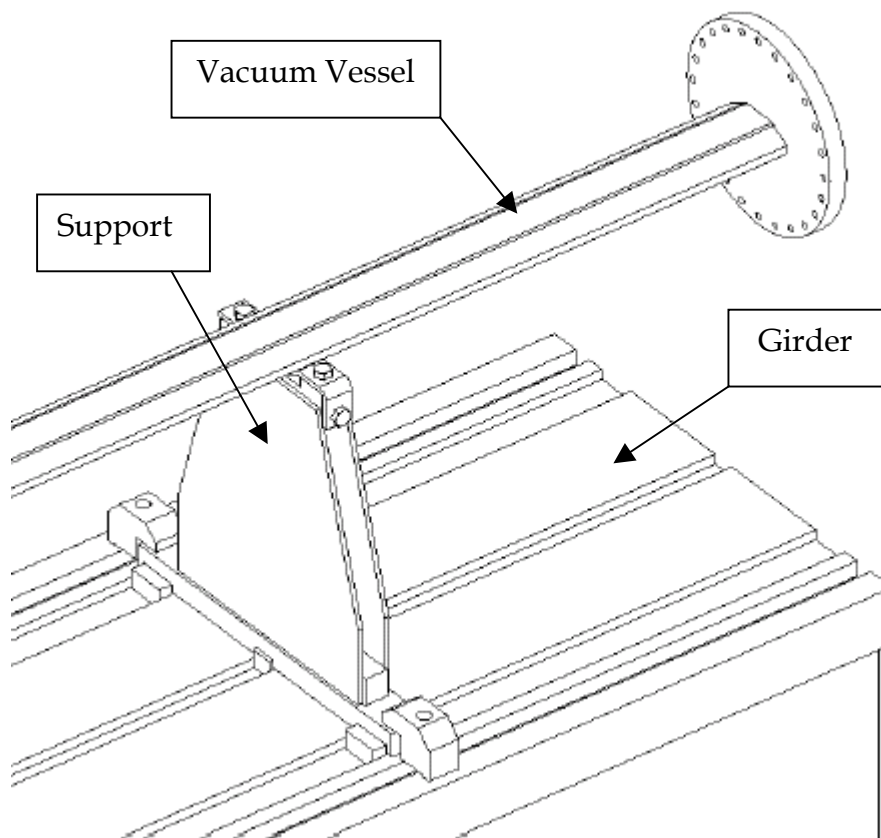


Figure 7.5-5 Typical Vacuum Vessel Support

Each girder section vacuum vessel is to have one anchor point (position of which is to be determined with reference to vessel expansion properties and assembly bellows). Other support points positions will be determined by space available. Therefore two design variations of the fixture are required. The anchor point fixture should be relatively stiff in the longitudinal direction.

The vessel-mounting fixture is installed on to the top of the girder without the presence of the vessel, it is checked for correct alignment by survey utilising the fiducial mount and any errors are to be removed by adjustment. The shim packers & key arrangement allow vertical positioning of the vacuum vessel fixture, this is achieved by the machining of individual shim blocks at the foot of the mount whilst transverse positioning is achieved by a key in a tennon slot. The fixture is then given a certificate of alignment conformity.

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The design of the vacuum vessels should facilitate good manufacturing practices in order to minimise errors during fabrication, distortions resulting from bad profile, bend & twist should be kept within close tolerances. In achieving the close tolerances, any small remaining manufacturing errors can be taken up when the vessel is bolted into position on to the fixture. The vacuum vessel should include several location brackets (not all which have to be used) with fixing holes from above and the side to facilitate this.

The vessel mounting fixture & ultimately the vacuum vessel is secured the top of the girder by means of a commercially available tooling clamp.

7.5.4 Bakeout

There is no longer a requirement for in-situ bakeout of the vacuum vessels. However pre-baking of the vacuum vessels will be required prior to installation. Because this is to be carried out in a non-vacuum oven, then the vacuum vessel will have to be designed with reduced allowable stresses appropriate for the proposed pre-bake temperature of 250°C.

7.6 RADIATION ABSORPTION

7.6.1 Vacuum Vessels

The red book proposes that all synchrotron radiation from bending magnets or from insertion devices will be intercepted by discrete cooled photon stops, which have pumping stacks positioned directly below them. This has the advantage of positioning pumps where the gas loads are highest.

An alternative approach is a distributed photon absorber arrangement, with local photon absorber positioned only at the crotches.

Distributed absorbers are required on both sides of the straight section directly after the insertion devices to absorb mis-steered photon beams and insertion devices beams creating more than 10 mrad, such as Multi-Pole Wigglers and wavelength shifters. This double-sided cooling arrangement is also applied to all straight sections in the achromat to provide the following advantages:

- Creating more space in the lattice, since the distributed system requires no space between magnets in comparison to ~150 mm per local photon stop.
- Simpler vacuum chamber construction, without the need to provide wide anti-chambers to clear non cooled surfaces from photon beams between each photon stop.
- Most of the pumps can be on the inside of the ring where the main access route is located, rather than on the outside, which is difficult to maintain (Red book

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arrangement has photon stops and pumps on the outside of the ring). The only exception would be 2 pumps per cell at the crotch locations.

- The chambers with cooling running down both sides will be thermally more stable. Heating of thermal stops produces localised heating causing distortions, particularly with stainless steel.

7.6.2 Crotch

Dipole radiation is an intense fan of photon radiation generated by each of the 48 dipole magnets. The dipole vacuum vessel forms a bifurcation in the storage ring. The electrons continue on their orbit of the storage ring. The dipole radiation departs tangentially from the curved electron trajectory in the dipole, and exits down the other leg of the dipole vessel. This is illustrated for a typical dipole vessel in Figure 7.6-1.

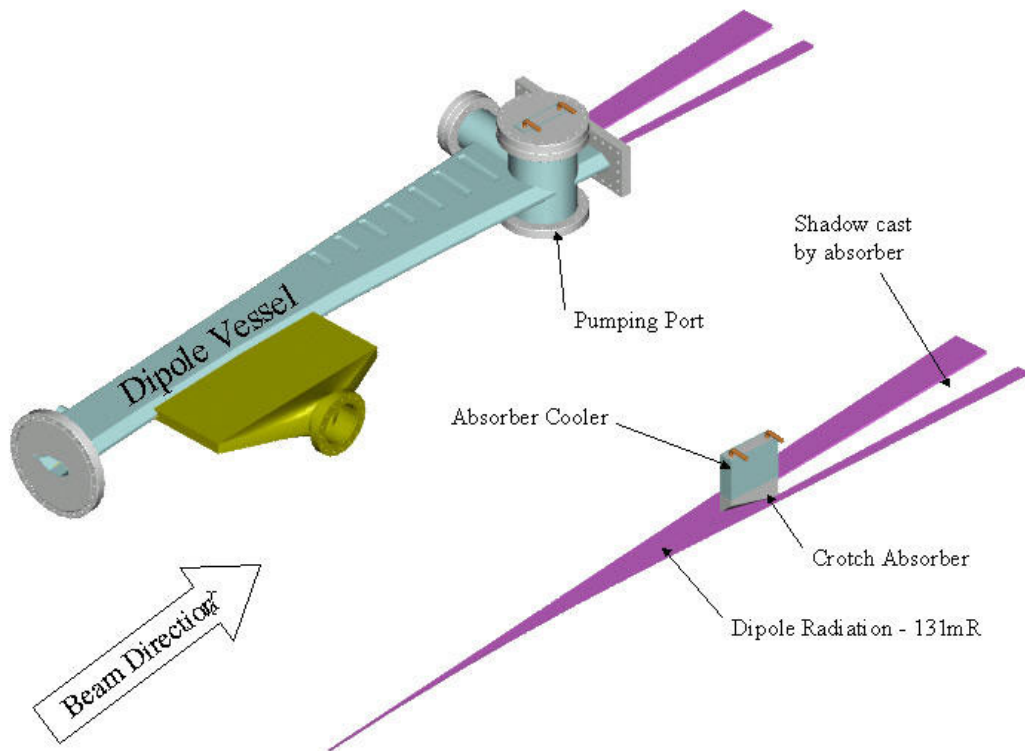


Figure 7.6-1 Illustration of Dipole Radiation Fan Impinging on Absorber

In order to avoid excessive heating of the bifurcation crotch by the dipole radiation, an actively cooled element of a material which retains its strength at elevated temperatures, must be inserted. A major compromise that has to be made is compact design vs. area of heat dissipation. In other words the proximity of the dipole to the crotch.

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The crotch absorber for the first dipole must also absorb unwanted ID radiation, but because the ID is much further away, the divergent beam from this source has a much lower power density than the dipole 1 radiation.

The diamond crotch absorber in the first dipole must be so positioned to allow the first $\pm 5\text{mrad}$ of horizontal ID radiation to pass, but absorb all of the dipole radiation that is not coincident with the ID radiation. The absorber in the second dipole must allow the first 35mrad horizontal dipole 2 radiation passed, and absorb all of the remaining dipole 1 radiation.

The power density of a dipole magnet is typically 267Wmm^{-2} for 3GeV and 533Wmm^{-2} for a 10% margin 3.3GeV , assuming a distance of the order of 1m between generation point and absorption [4]. The vertically integrated linear power density is 115Wmm^{-1} for the most pessimistic assumption of 3.3GeV storage ring energy, which whilst being higher than ESRF (65Wmm^{-1}), is not as high as the APS (145Wmm^{-1}). It should be noted that $+10\%$ on storage ring energy is a very pessimistic assumption, $+10\%$ on radiated power will be used in future design work. Design and analysis work is underway to determine the best arrangement. Based on the APS experience, materials and fabrication methods will present the biggest challenge [5]. Because DIAMOND is operating within the boundaries of proven experience it is not anticipated that diathermanous or other specialist materials will be required. Glidcop™ has been used with success on other 3rd generation machines. It is anticipated that techniques of extending the external and/or internal surface areas by the use of shallow fins will assist in limiting the temperature excursions experienced by the absorbing surface. It is also proposed to attach a horizontal plate to the base of the absorber to minimise the area subjected to secondary photon emission, hence minimising outgassing.

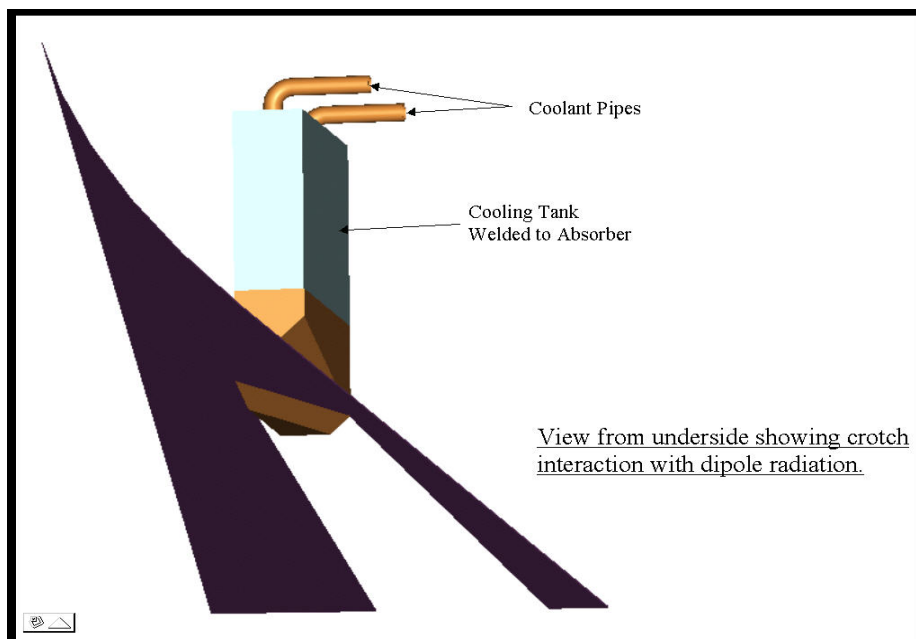


Figure 7.6-2 Schematic Illustration of Double Inclined Absorber Surface.

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Apart from mechanical properties at elevated temperature, another consideration in the design is the photodesorption and outgassing which will occur from the photon-absorbing surface. The design must keep the temperature rise to a minimum, and suitable additional local pumping provided. It is necessary to incline the vertical plane in order to provide an increased area of beam incidence and hence reduced power density into the absorber body. It has also been recommended that the surface be inclined in the horizontal plane as well, with the local pumping located normal to this surface. This causes an increased probability that the trajectories of desorbed molecules will be towards the pumping port as illustrated in Figure 7.6-2.

It is intended to build and cycle-test a prototype unit as soon as possible.

7.7 SERVICES

7.7.1 Type

(a) Mechanical

A mechanical services distribution panel is to be located on the inner surface of the inner shield wall, local to each achromat. This will provide water from the different systems, as well as compressed air, dry nitrogen and helium connection points. An in line damper should be installed at the main water feed pipes to reduce the amount of pressure pulsation transmitted through the water to the girder assemblies that may cause vibration.

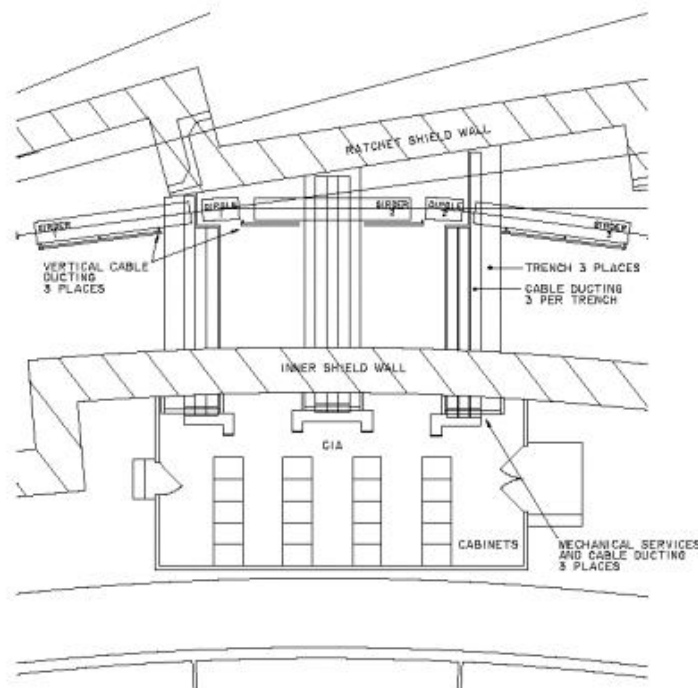


Figure 7.7-1 Services Schematic - Plan View

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Figure 7.7-1 above and Figure 7.7-2 below show a typical achromat / girder and the position of the mechanical services panel. Connection pipes will run from these panels through one of three labyrinths on the inner shield wall and into a service trench in the floor. These pipes will emerge from the trench at the girder, ready for connection. Under normal operating conditions, the trenches will be covered.

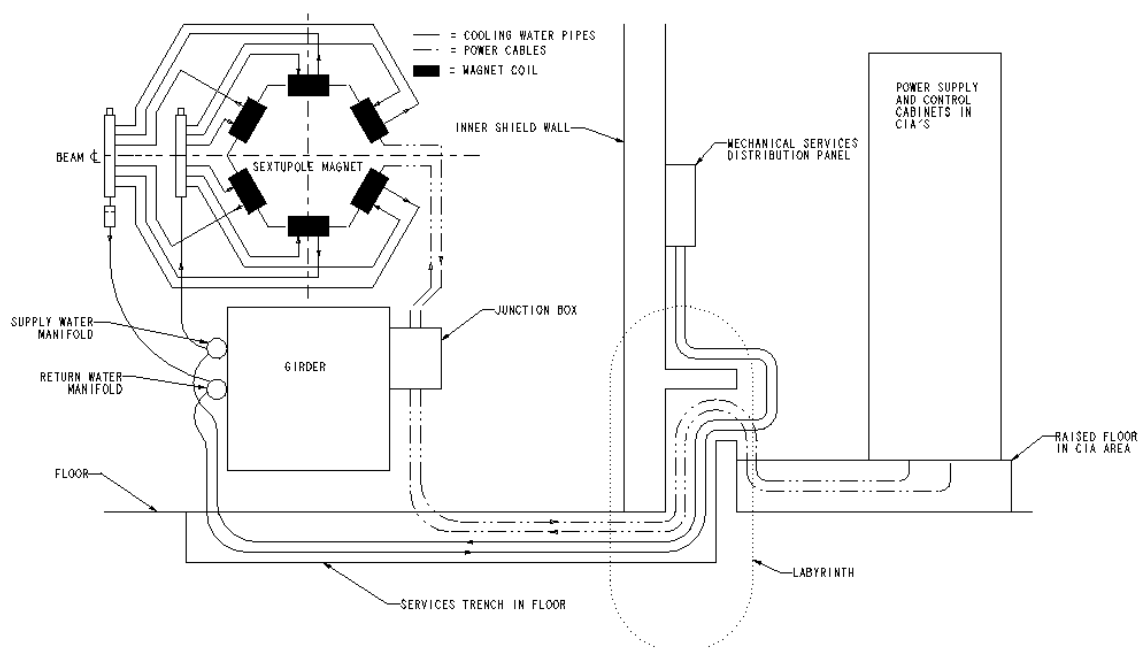


Figure 7.7-2 Services Schematic – Section Through Tunnel

DIAMOND will require a number of separate water systems with a combined cooling capability currently estimated at 9.2MW including some stand-by and maintenance capacity.

The ESRF uses one demineralised water system to cool its magnet copper coils, absorbers and vessels, which are a mixture of copper, stainless steel and aluminium. Due to a chemical interaction between the water and deposits from the different metals, small deposits of copper oxide and other salts build up and then are washed around the system, contaminating all components. The deposits grow in size until they are big enough to get trapped in the system and block the cooling channels. For this reason, the copper and stainless parts can go on the same system but aluminium must be cooled on a separate circuit.

A ring main of chilled town water is required for the air conditioning units. This will be specified by the civil contractor.

Cooling of components where the water comes into contact with electrical conductors e.g. on magnets, requires a separate demineralised (non-conducting) chilled water system. This system can also be used for cooling all copper and stainless steel absorbers. Figure 7.7-3 to Figure 7.7-5 below show sextupole, quadrupole and dipole

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cooling and wiring schematics. Note that a region has been labelled as the “radiation stayclear”. This region will cover the central third of the magnet height and no pipes or wires / cables should cross this region except bare stainless steel and copper. This is due to the fact that the electron orbit plane is the area of the most intense radiation exposure and this has been known to cause plastic / rubber pipes and coated wires / cables to age harden quickly and fail. Each magnet, cooling water return pipe is to be fitted with an orifice plate to enable flow balancing.

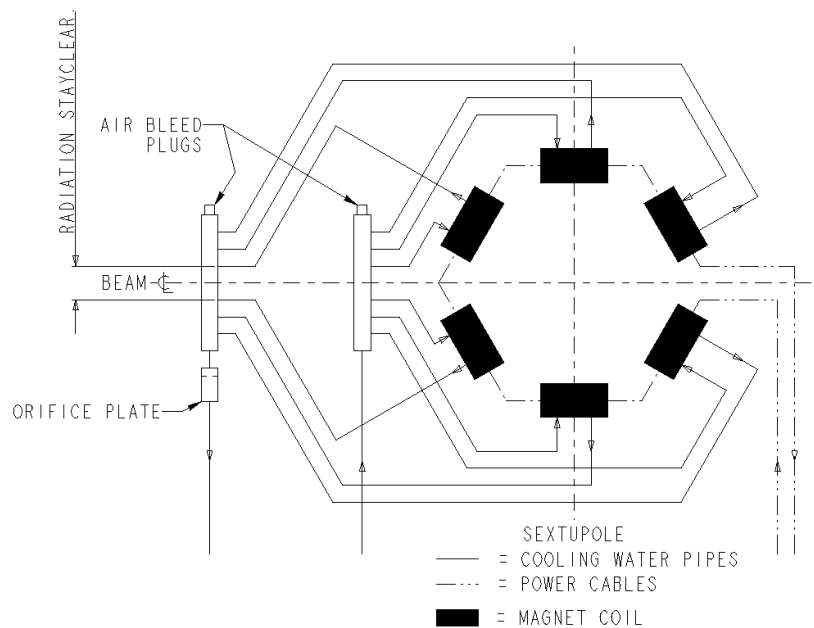


Figure 7.7-3 Sextupole Schematic

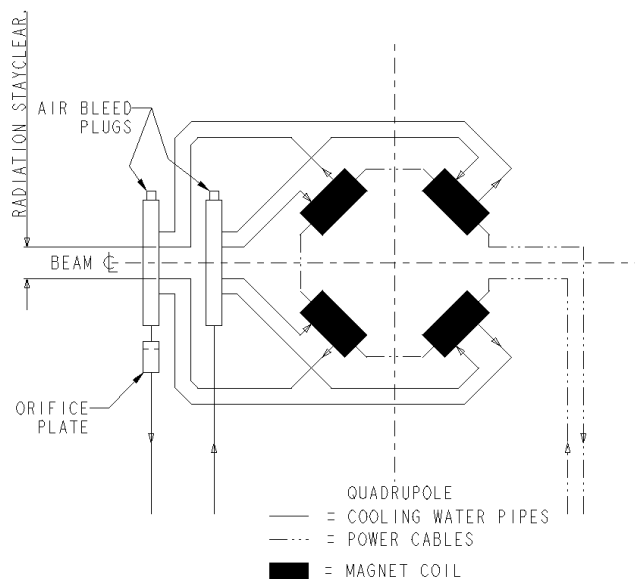


Figure 7.7-4 Quadrupole Schematic

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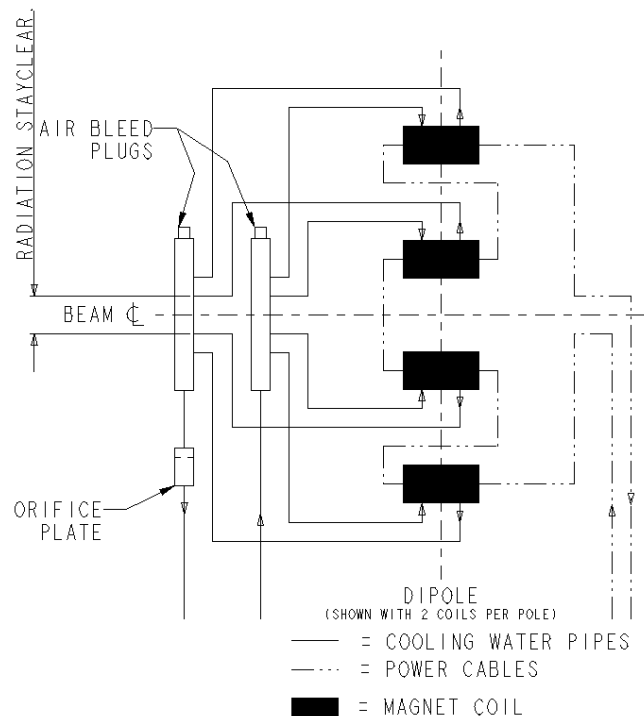


Figure 7.7-5 Dipole Schematic

Some aluminium components will need cooling, but the number of these is expected to be small, but could ultimately be 12 of the 24 cells. Either a dedicated ring-main or a local secondary circuit could accomplish the cooling of these special vessels. A value engineering exercise will inform the final choice. A local water circuit would be fed from the main chilled town water system but a shut off valve which would be closed after the initial fill. The local system will consist of a pump and a heat exchanger. Warm water from the vessel will go through the exchanger on one side while water from the chilled air conditioning supply will go through the other side, thereby cooling the water returning to the vessel. This small system can be fitted as and when aluminium vessels are added. The system should also include a thermocouple connected to a motorised 3-way valve so that the heat exchanger can be bypassed if the water returning to the vessel is too cold. Connection points for adding these systems should be included on every mechanical services panel. Figure 7.7-6 below shows a simple schematic of this system.

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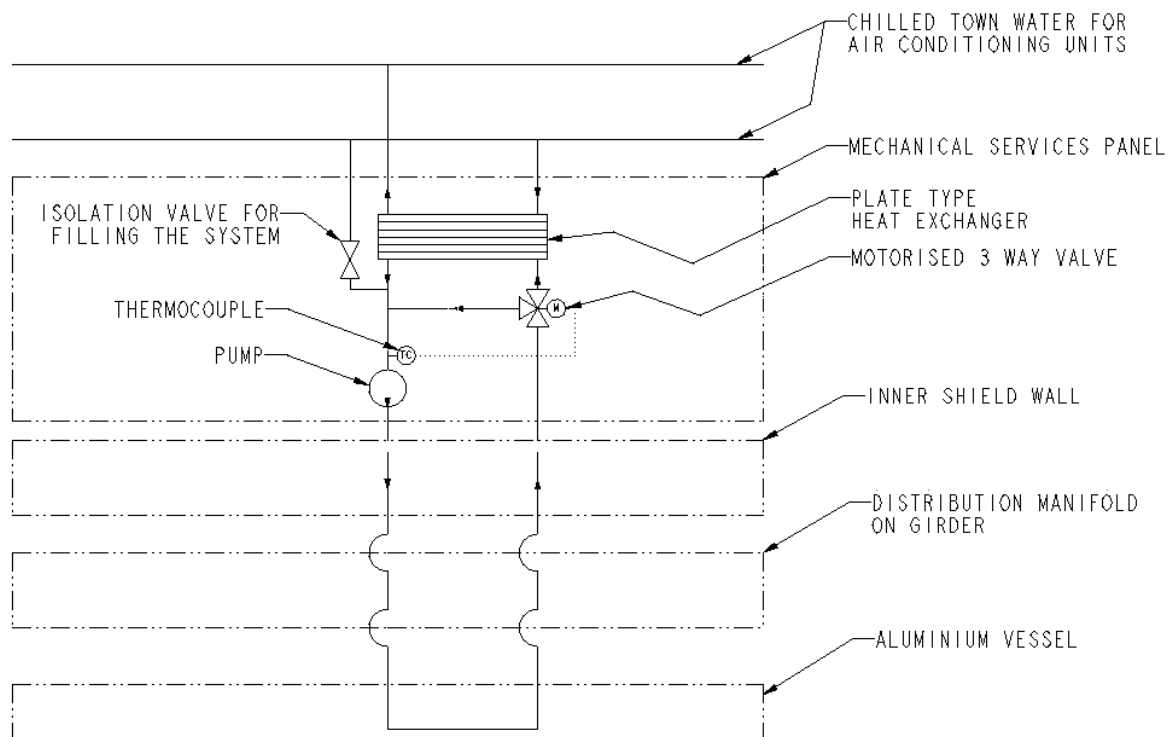


Figure 7.7-6 Aluminium Cooling Circuit Schematic

Other components such as RF cavities require a local temperature controlled demineralised cooling water system. A number of systems could be required, depending on the amount of cooling required and the location of the cavities. There are currently three superconducting cavities in the main RF straight, with a further one in the diagnostic straight. Then there will be a non-superconducting cavity in the booster and two more small, non-superconducting cavities in the Linac.

As part of the modular girder design, the number of connections that need to be made at installation should be kept to a minimum. For this purpose, a cooling water distribution manifold should be mounted on the outboard side of the girder, facing towards the ratchet wall (see Figure 7.7-2). This would be attached using vibration-damping mounts, connections from this manifold to the magnets will be made with an insulating length of high pressure polymeric flexible hose. All components on the girders should be piped to this manifold so that there are no loose pipes, which could be overlooked during changeover. When the girder is lowered into place, only two connections are required per circuit and these can be made in the one location. Flexible pipes should be used to make the connection from the stainless steel feed / return pipes in the supply trench, to the manifold on the girder. This will allow girder movement for alignment and cut down on the amount of vibration being transmitted to the girder from the water system.

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(b) Electrical

Electrical Control and Instrumentation Areas (CIA) will be located in purpose built rooms on the inner surface of the inner shield wall, local to each achromat (see Figure 7.7-1 and Figure 7.7-2). These will be powered from the different building ring systems and the required connections will be made from the CIA's to the equipment in the storage ring tunnel through the appropriate labyrinth and service supply tunnel.

Connection of these supplies at the girder should be via a similar system to that used for the cooling water supply. A junction box for all electrical equipment should be bolted to the inside face (facing towards the inner shield wall) of the girder body (see Figure 7.7-2). All components on the girders should be wired to this box via a neat cable loom so that there are no loose wires. When the girder is lowered into place, all the connections can be from the wires / cables in the service trench to the junction box.

7.7.2 Penetrations

Penetrations will be required in the inner shield wall to allow cables, pipes, air-conditioning and RF waveguides to enter the tunnel. This must be done through suitable labyrinths, so that radiation cannot escape. The size, number of, and location of these penetrations have not yet been fixed. Each will be designed to give the best solution in terms of access for feeding through the necessary equipment, radiation shielding and cost. Figure 7.7-7 shows a arrangement of a possible labyrinth.

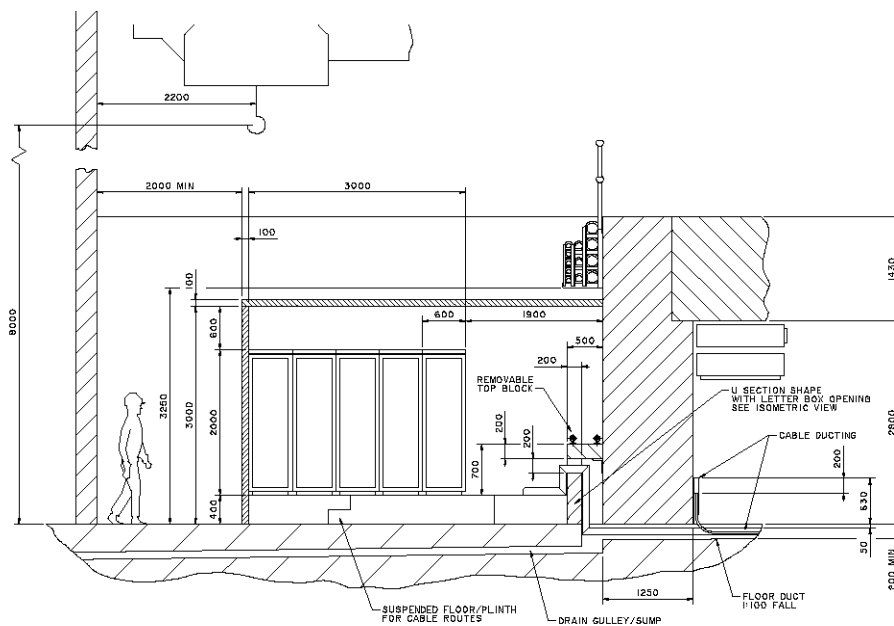


Figure 7.7-7 Section through Penetration

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7.7.3 Distribution

Services to / from the storage ring will run from distribution panels / CIA's on the inner surface of the inner shield wall to the storage ring through a labyrinth and radial floor channel as shown in Figure 7.7-1 and Figure 7.7-2. To reduce the number of cable trays required alongside the girders and minimise cable lengths, one labyrinth / channel will be used per main girder (3 in total per achromat). Cables will emerge from the channel just before the girder and will run up to the appropriate terminal on the girder mounted connection box. Pipes will emerge from the channel just after the girder. The stainless steel pipe will then stop and the connection to the girder mounted water manifold will be made using a flexible hose. Compressed air and Nitrogen will be mounted on the side of the girder with the most space available. This needs some investigation before a final decision can be made. A Helium supply line is required within the tunnel for locating vacuum leaks. A supply pipe should emerge from the floor channel at each girder so that a flexible hose can be connected locally to a possible leak when required.

7.8 CRANAGE

7.8.1 Crane Cover

The red book covered various options from 'no crane cover' to 'full crane cover'.

Since then the ideas have been carried forwards until the following choice was made.

Complete crane coverage of the synchrotron building will be provided, 3 radio controlled beam cranes will operate on concentric circular tracks. Each crane will cover a third portion of the building, but will be able to run all the way around the building.

The inner and outer diameters of crane cover are 159.06m and 212.18m respectively. The inner and outer building extents are, for comparison, 235m and 154.66m.

As stated in the red book, this option has great advantage during machine construction when many thousands of tonnes of concrete and shuttering need to be moved, as well as many thousands of components. Also during the operating phase of the machine, when many beamlines are 'built in' an overhead crane is very useful to gain equipment access without dismantling lines or hutches.

Since the build up to full beamline capacity will be over several years. The provision of full crane cover will be a major contributor to their efficient construction.

As there is no road provision to the centre of the synchrotron building ring, the only means of transferring Booster and Linac components to their respective tunnels is via the main building. This makes the provision of crange an absolute requirement in this region.

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Vibration from crane operation will affect storage ring beam stability, therefore it is recommended that the storage ring tunnel floor is separate from the crane supporting floor. (As has been done in other 3rd generation machines).

7.8.2 Crane Capacity

The overhead crane capacity is 15 tonnes. The choice of crane capacity is related closely to the fully populated girder mass, because this is the heaviest item that must be lifted easily and efficiently in the post-construction phase. Any increase in crane capacity has a major influence on cost, since it impacts on building design loads. Twelve tonnes is seen as a reasonably achievable maximum girder mass. However there is a compromise to be made since girder eigen-frequency must be above 40Hz (refer to section 7.4.2) and generally speaking increased girder mass results in a higher eigen-frequency.

The crane provides the only route to lift equipment to the inner zone, and the height from the tunnel roof to the crane hook is to be maintained at 4 metres. The volume to be rigged and transported over the storage ring tunnel is 3m x 2.5m x 6m (H, W, L) and so all equipment for the inner zone must fit within this volume. Figure 7.8-1 shows the building cross section with crane clearance information.

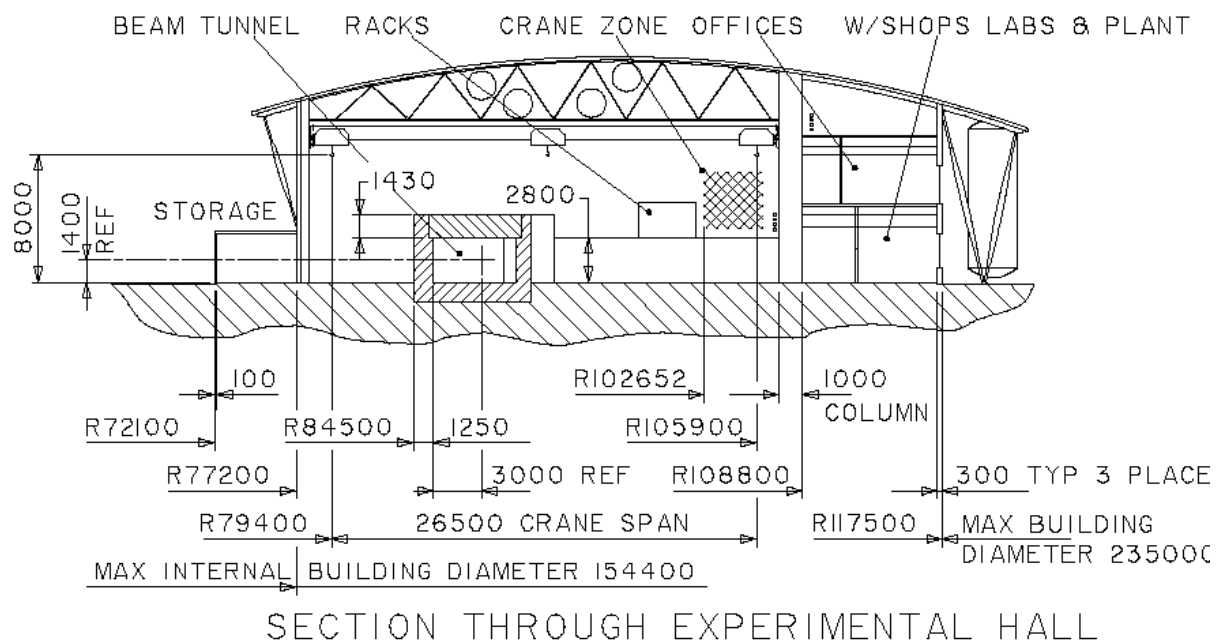


Figure 7.8-1 Experimental Hall Cross Section indicating Crane clearance

Crane lifting zones are nominated at the end of ID beamlines 1, 17, 21 and between CIA's 15 and 16.

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E.8 Magnet Power Supplies

8.1 INTRODUCTION

The Storage Ring magnet power converters are, with the exception of the injection elements, DC supplies. All the power converters are rated for 3 GeV operation plus a 10% safety factor on both current and voltage, plus an additional 5% on the voltage to allow for cable voltage drop.

The DIAMOND Storage Ring lattice has a 24 cell configuration, each cell consisting of two Dipole magnets, ten Quadrupole magnets, seven Sextupole magnets, thirty five slow correctors and four dynamic corrector magnets. The power converters for the Dipole, Quadrupole and Sextupole are all unipolar, as opposed to the correction power supplies, which are bipolar. For each cell of the Storage Ring there is an associated Control Instrumentation Area (CIA). These house racks for magnet power supplies, vacuum pump supplies and Control & Instrumentation equipment. The high power rating of the Dipole converter can not be supplied from the CIA and will be located in, sector four inner annulus room.

The voltage drop in cables from the CIA to each magnet, have non-negligible effects. The access arrangements (labyrinths) into the Storage Ring tunnel and the cable cross sectional area, determine both the voltage drop and the power loss in each cable. These calculations should be considered when assessing the loading on the heat management systems of the Storage Ring tunnel and the output voltage ratings of the power supplies.

The Dipole magnets are connected as a series string and will only require a single high power current converter. The Quadrupole and Sextupole magnets are all individually powered, to provide optimum versatility in adjusting the lattice functions in the insertion regions. This arrangement has a large impact on cost, with a total of 408 individual converters required.

The current ratings for the Quadrupole magnets, and the Sextupole magnets, were standardised during the design stage. The current for each magnet family was optimised to ensure a balance between simplification and feasibility of the magnet design, against minimising the losses in the cable and power converter efficiencies. A simplistic view is the number of turns and the current density for each magnet are fixed and only the conductor length increased. The power rating for each magnet type will then be controlled by the voltage level only.

This allows common power converter units to be specified, with a standardised output rating for the Quadrupole magnets and similarly for the Sextupole magnets,

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and minimises the required spares and simplifies replaceability. It is envisaged that the power ratings for the individual units will be 6kW for the Quadrupole magnets and 2kW for the sextupole magnets.

The additional power rating for the Quadrupole power converters will allow the output voltage limits to be increased. This can then be used for beam based alignment exercises which have proved very successful on the SRS and at other accelerator. It is anticipated that this will be required for DIAMOND. The actual performance parameters and the effects on the power converter rating need to be assessed before the specification is written.

Table 8.1-1 Power converter ratings for the Dipole magnets

Family	No. per family	Volts per magnet V	Current per magnet A	Volts per magnet Family V	Volts per Family +5% voltdrop V	Volts per Family +10% V	Current per magnet +10% A	Total power per Family kW
Dipole	48	8.35	1336.8	400.8	420.84	462.92	1470.5	681.0

Table 8.1-2 Power converter ratings for the Quadrupole magnets

Family	No. per family	Volts per magnet V	Current per magnet A	Volts per magnet + 5% voltdrop V	Volts per magnet + 10% V	Current per magnet + 10% A	Total power per magnet kW	Total power per Family kW
Q1AB	36	16.83	181.8	17.67	19.44	200.0	3.89	139.9
Q2AB	36	15.95	181.8	16.75	18.43	200.0	3.68	132.6
Q1B	36	15.95	181.8	16.75	18.43	200.0	3.68	132.6
Q2B	36	21.30	181.8	22.37	24.61	200.0	4.92	177.1
Q3B	36	13.27	181.8	13.93	15.32	200.0	3.07	110.4
Q1AD	12	16.83	181.8	17.67	19.44	200.0	3.89	46.6
Q2AD	12	15.95	181.8	16.75	18.43	200.0	3.68	44.2
Q1D	12	15.95	181.8	16.75	18.43	200.0	3.68	44.2
Q2D	12	21.30	181.8	22.37	24.61	200.0	4.92	59.0
Q3D	12	13.27	181.8	13.93	15.32	200.0	3.07	36.8

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Table 8.1-3 Power converter ratings for the Sextupole magnets.

Family	No. per family	Volts per magnet V	Current per magnet A	Volts per magnet + 5% voltage drop V	Volts per magnet + 10% V	Current per magnet + 10% A	Total power per magnet kW	Total power per Family kW
S1A	24	13.22	92	13.88	15.3	101.1	1.55	37.1
S2A	48	9.87	92	10.36	11.4	101.1	1.15	55.3
S1B	36	13.22	92	13.88	15.3	101.1	1.55	55.6
S2B	36	13.22	92	13.88	15.3	101.1	1.55	55.6
S1D	12	13.22	92	13.88	15.3	101.1	1.55	18.5
S2D	12	13.22	92	13.88	15.3	101.1	1.55	18.5

The need for such a large number of low power <6kW power converters, means the reliability and replaceability of the units is a major consideration. The size and weight of each unit will depend on the technology chosen, and also effects operating efficiency, input supply harmonic levels and power factor correction. All these topics will be addressed, along with their commercial availability and cost.

8.1.1 Control system

The preferred method of controlling the regulation of a modern power converter is, undertaking a transition phase, between conventional analogue control and the advancing digital system. The operating principles, and advantages and disadvantages for both systems have been considered and recommendations made. Issues relating to resolution and update rate (bandwidth) are mainly governed by the ADC or DAC depending on which type of control system is used. The high resolution hinders the conversion speed and advances in this area will have to be investigated before the final specifications are produced.

Standardisation of the control system is expected, but this may compromise the tender exercise, as the power converters may have to be purchased from one company. This is unlikely with the quantity involved, and there are alternatives. One option is to use a dedicated power converter interface module, which operates in conjunction with any standard analogue supply. This provides the intelligent processor as an external unit, simplifying the converter design. Power converters associated with the different magnet families can be purchased from separate companies, but their interfaces must be compatible.

The chosen power converters system must be equipped with a comprehensive diagnostic facility, which can be incorporated into the power converter control system or in the control interface. This must include a transient recorder, with trigger signal select. The reliability and operating efficiency of a modern accelerator, with a high converter count, is dependent upon this facility.

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8.1.2 AC distribution network

The total loading for each of the twenty four control and instrumentation areas (CIA) will be ten Quadrupole converters rated at 6kW, plus seven Sextupole converters rated at 2kW, plus forty three correctors at 0.3kW, giving a maximum DC loading of 85kW. If the nominal current figures are used, then the total DC power falls to approximately 60kW. The average operating efficiency for the power converters at this level is estimated at 80%, equating to a total AC input power consumption at nominal current of 75kW.

The Storage Ring power converters have been designed with a dedicated AC distribution network, coupled to the general site distribution at MV (11kV). There will be four separate transformers, each feeding a quarter of the Storage Ring magnet power converters with an expected nominal loading of 0.5MW. This type of distribution will allow, if required, phase displacement of the transformers enabling 12 pulse or even 24 pulse rectification, to minimise harmonics resulting from the power converter load.

The four transformers will be equipped with dedicated monitoring systems to provide information on power factor, power consumption, harmonic levels and mains disruptions. These will be intelligent systems enabling information downloads for analysis.

The Dipole power converter will also have a dedicated transformer, which can either be independent or an integral part of the converter depending on the technology chosen. The DC power at the maximum rated output is 681kW, with an estimated efficiency of 95%, the expected input AC load is 716kW.

8.1.3 Performance specification

All power converters will be measured against the following performance parameters:

Table 8.1-4 Performance Specification for Power Converters

	Dipole and Quadrupole	Sextupole
Long-term Stability (8 hrs to 6 mths)	50 ppm	200ppm
Short-term Stability (100 sec to 8 hrs)	10ppm	100ppm
Resolution (minimum)	18 bit	16 bit
Ripple (perturbation error)	<10ppm	<100ppm
Reproducibility	10ppm	100ppm

Output current ripple - the specified current ripple and noise is gauged on that required for other accelerators. Their impact on the closed orbit of the chosen lattice needs to be assessed, taking into account the filtering effects of the vacuum chamber and the magnets. The ripple frequency and amplitude will depend on the power converter technology employed.

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Reproducibility- after a period of interruption of 24 hours with all the electronics turned off, the power converter should be capable of returning to within 10ppm or 100ppm, depending on magnet type, of the former value after one hour with the same reference.

Short term stability – this depends on the control technology employed, but a major contributor to this is the current transducer. It is understood that actual precision can only be measured with warm electronics and there will be an initial period of settling time. The power converter controls will maintain warm electronics to minimise drift at turn-on and actual short term stability will be measured over an eight hour period. The drift will then be a result of the self-heating of the current transducer burden resistor, the input reference and the conversion (A to D or D to A).

Long term stability – again governed by the output transducer and the conversion quality. The absolute precision of the ADC conversion is related to its internal reference voltage. Any drift in this reference will effect the precision, similar effects are seen due to ageing of the burden resistor for the current transducer. These can be avoided with regular calibration checks.

Resolution – conversion dictates the resolution, but with high sampling rates necessary to achieve the dynamic performance, noise will always show on the output signal. It is expected that some filtering may be required to ensure step changes on the output, can be both set and monitored at the 10ppm and 100ppm level, relating to magnet family.

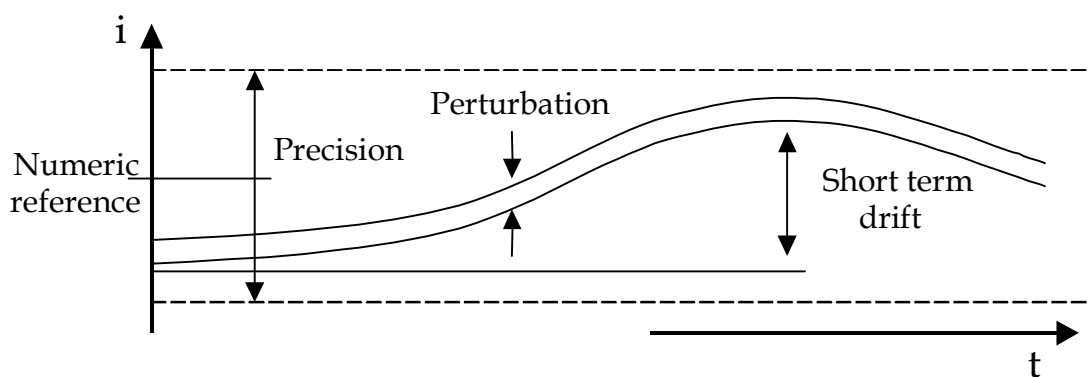


Figure 8.1-1 Illustration of the precision, long term drift and perturbation.

Suppression of input supply voltage changes – the input operating voltage range for LV is $400V \pm 10\%$ and the maximum output ratings must be maintained over these limits. Verification that a step change on the input supply of 1% does not effect the output current by more than 10ppm for Quadrupole and Dipole magnets, and 100ppm for the sextupole magnets.

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8.2 LEAKAGE CURRENT RESULTING FROM CONDUCTIVITY OF WATER COOLING CIRCUIT

This section details the calculation of leakage current within the storage ring dipole circuit, due to conduction between the magnet coils and ground by means of the water cooling circuit. The following figure shows a possible arrangement for electrically isolating the bore of the cooling duct from the rest of the cooling system. However, there remains some conduction by virtue of the conductivity of the water. The insulated pipe would be placed at both ends of the cooling duct to isolate both incoming and outgoing feeds.

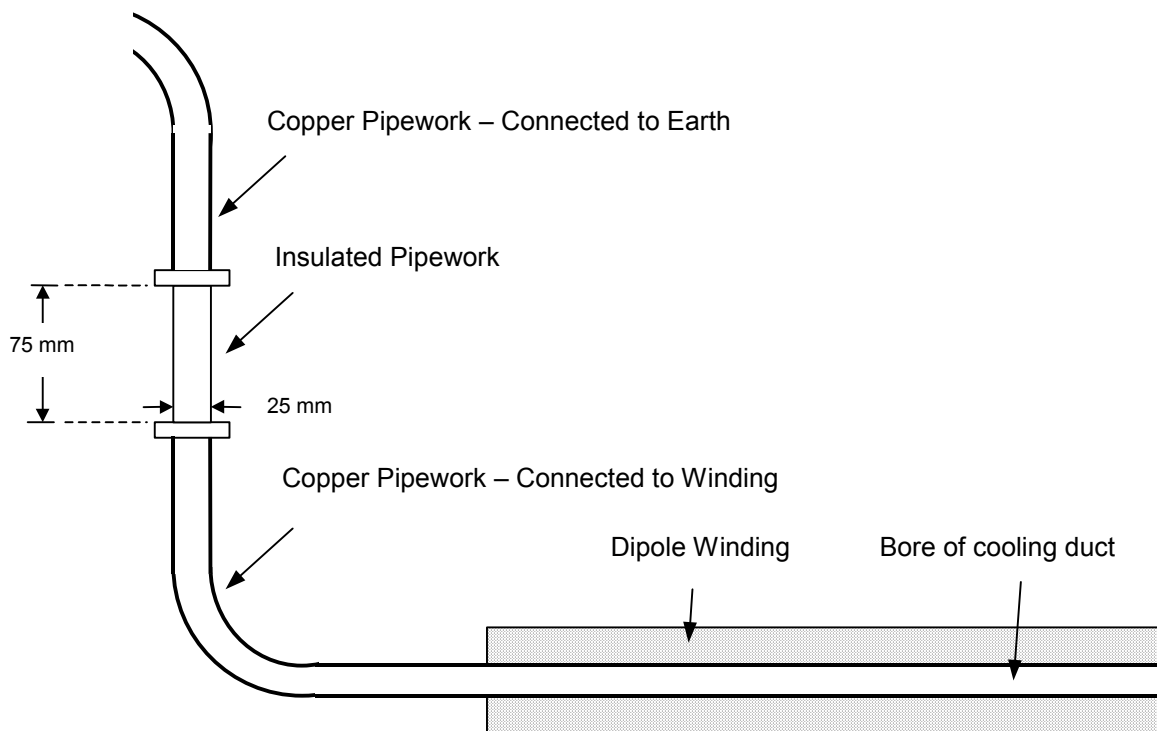


Figure 8.2-1 Typical de-mineralised water cooling configuration for a Dipole magnet

8.2.1 Conductivity of de-mineralised water

The conductivity of water depends upon the purity. Pure water has a resistivity of 18.3 MOhm-cm at 25°C, but the addition of impurities reduces this value. A good quality distilled water has a resistivity of 1 MOhm-cm, tap water might have a resistivity of say 33 kOhm-cm, and seawater has a resistivity of about 33 Ohm-cm.

For the purposes of this study, a water resistivity of 1 MOhm-cm is to be used. This value would be reasonable to specify.

Based upon the cooling circuit used in the SRS, the copper pipe feeding directly from the dipole winding is isolated at each end by means of a 75 mm length of plastic pipe

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with a diameter of 25 mm. The electrical resistance of the distilled water within this pipe is thus calculated:

$$R = \frac{\rho \cdot l}{A}$$

ρ is the electrical resistivity, l is the length of the plastic pipe, and A is the cross-sectional area

In the case of the plastic pipe given above, $R = 1.5 \text{ MOhm}$.

8.2.2 Path to earth via cooling circuit.

The path to earth through the cooling water is illustrated in the following figure. For each dipole there are two windings electrically connected in series. Each winding has its own cooling circuit where there two paths to ground, one at each end of the cooling circuit. The resistance in every case is the same, 1.5 MOhms. If the chain of dipole magnets is earthed in the middle as shown in this diagram, the conduction to earth is minimised as the average magnitude of potential difference between the dipole winding and earth is minimised.

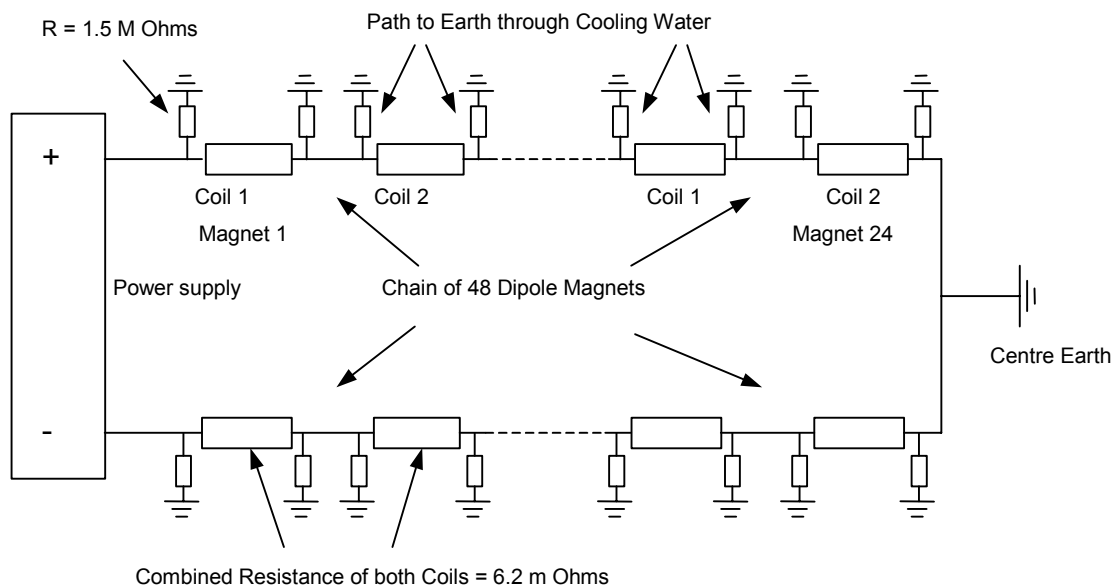


Figure 8.2-2 Electrical equivalent of water connections to Dipole circuit.

8.2.3 Circuit simulation

This circuit was modelled to determine the effect of these resistances to earth. The following parameters were used for the dipole circuit.

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Table 8.2-1 Major parameters of dipole circuit

Voltage across magnet chain	400.8 V
Resistance of each dipole magnet	6.2 mOhms
Resistance of earth through cooling water circuit	1.5 MOhms
Design value of current	1337 A

The results from the simulation are given below:

Table 8.2-2 Simulation of current leakage through cooling circuit

Magnet	Current
Magnet 1	1346.778336
Magnet 24	1346.772057
Difference	0.006279

After performing the simulation, the worse case differential current from one dipole to another was identified. The difference between the current in the dipole nearest to the power supply and the current in the dipole nearest to the earth point was the largest at 0.0063A. This value represents 4ppm of the nominal current and is acceptable, but must be considered when writing the final specification.

8.3 POWER CONVERTER TOPOLOGIES

8.3.1 Introduction

This section explains the operation of power converter technologies currently available and compares their performance and suitability for applications associated with the DIAMOND Storage Ring magnets.

Three main power converter topologies are considered:

Linear power converters – these were used extensively 30 years ago, but their popularity has since declined, and are now mainly used for noise sensitive applications such as telecommunications, science and medicine;

Line-commutated thyristor power converters – commonly used 15 years ago for medium and high power levels, from 5kW up to and beyond 1MW. At present they are mainly manufactured for high power applications and can be adapted to the load by altering their configuration.

Switch-mode power converters – these supplies are commonly found in a wide range of applications, from personnel computers to high power modulators and have power outputs from tens of watts, up to hundreds of kWatts. Their versatility and availability have developed rapidly over the past 15 years.

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The design of each technology will be reviewed in detail, but only a limited number of structures discussed. The choice of configurations, and the depth of operation and performance covered, will depend on its suitability to the project.

8.3.2 Linear power converters

The structure of a typical linear power supply is shown in and normally consists of a pre-regulation stage, provided by a roller regulator and a bridge rectifier, followed by a filter. For low power applications the input supply is transformed directly and rectified to match the impedance of the load. The roller regulator allows for coarse voltage control across the series regulation unit. The output from the pre-regulation stage is filtered and connected to the load via the series regulation stage. The series regulation stage stabilises the current by controlling the demand to its associated semiconductors to ensure equilibrium between the reference and the output current transducer.

This technology has low efficiency due to the number of incorporated magnetic elements and the losses in the series regulation stage. The inclusion of a roller regulator increases the number of electro-mechanical components that can reduce reliability.

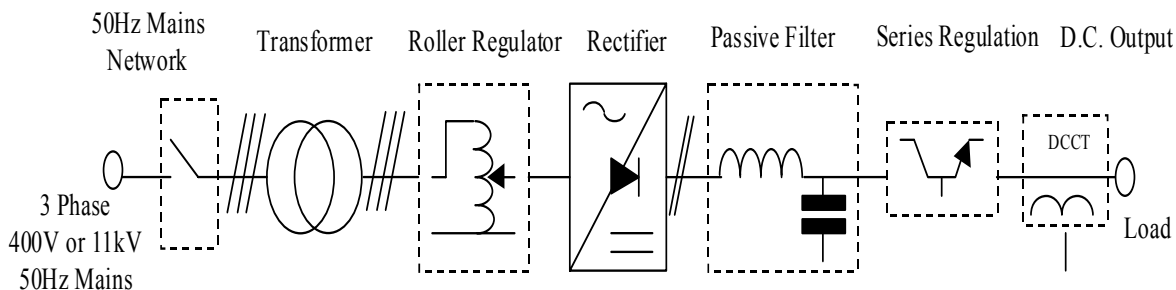


Figure 8.3-1 Schematic of a typical linear power converter.

The linear converter has near unity power factor and low noise levels, as no switching elements are required. (thyristors and IGBTs) The output ripple is good and the small signal response due to the bandwidth of the series regulation is effective, but the large signal response is poor, if a pre-regulation stage is used.

(a) Summary of Linear power converter issues

- The size of an individual unit would be increased significantly compared with a switch-mode supply, due to the line transformer, and series and pre-regulation stages.
- Their efficiency is low compared with line commutated thyristor and switch-mode converters. This is due to the series regulation stage, as it requires a

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variable voltage drop depending on the output level, but can be optimised for specific output voltages. This would result in higher running costs and increased demand on the thermal management system.

- There are reliability issues caused by the electro-mechanical components and downtime will be compromised by their slow replaceability, due to the unit weight and volume.

8.3.3 Line-commutated thyristor power converter

This type of technology is widely used and mainly suited to high power applications. The basic structure of a conventional 50Hz line-commutated thyristor power converter is shown in Figure 8.3-2. It consists of an isolation and load matching transformer operating at 50Hz, a phase controlled thyristor bridge forming a voltage source, and a filter network consisting of choke and capacitor.

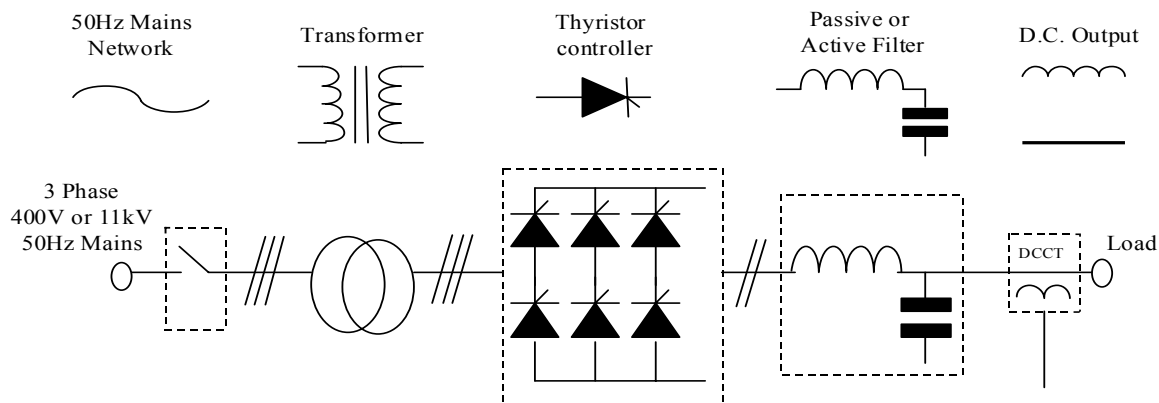


Figure 8.3-2 Schematic of a Conventional Line-Commutated Thyristor Power Converter

The output current is regulated by controlling the phase angle firing of the thyristor bridge. This is calculated from the voltage control loop to provide short-term precision and compensates generally for mains perturbations. The current loop ensures the absolute precision between the input reference and the current transducer and caters for long term drift, but its effectiveness depends on the quality of the DAC, error amplifier and the transducer. This loop has a relatively slow bandwidth and only makes small adjustments to the phase angle firing pulses.

The selection of the filter components depends on the output ripple specification and the calculated attenuation from the magnet load. If a 6 pulse configuration is used then the voltage ripple shown in Figure 8.3-3(a) is typical. The firing delay angle α defines the firing time of one of the thyristors. The average d.c output can then be regulated by means of this angle.

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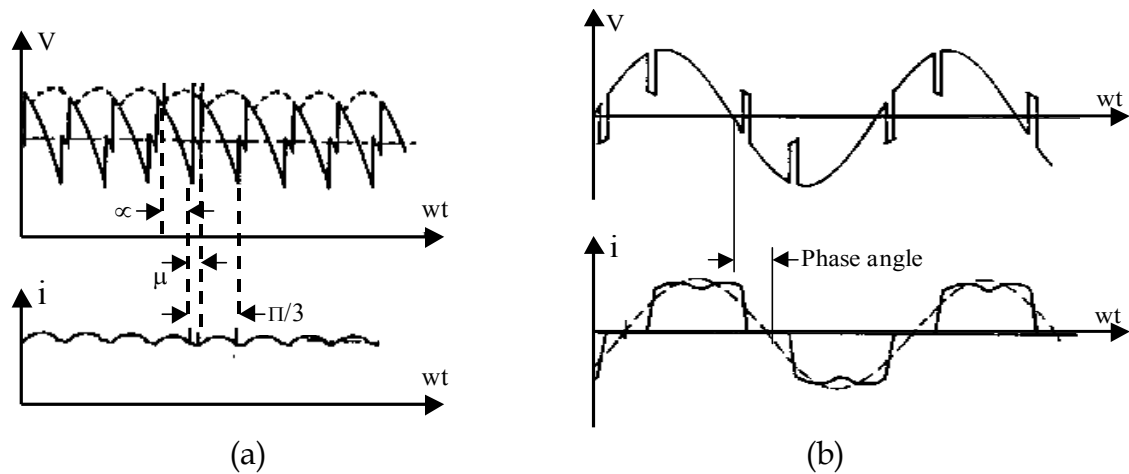


Figure 8.3-3 Waveforms of current and voltage for a) three phase thyristor bridge; b) transformer secondary;

When the conduction is switched from one thyristor to another there is a brief moment when the two phases are short circuit. This causes a drop in the d.c voltage, known as the inductive voltage drop. The supply current produced from this technology is not sinusoidal and has almost a rectangular waveform. An additional effect is that the fundamental ripple of the current is out of phase with the mains voltage by the firing angle ($\alpha + \mu/2$). This then requires reactive power to adjust the power factor back to near unity. Pulses also appear in the voltage waveform owing to the commutation of the DC current from one phase to another.

The current and voltage waveforms drawn by the input supply are shown in Figure 8.3-3(b), and their harmonic content can have harmful effects on other users. This can be overcome by mains filters or by increasing the pulse number.

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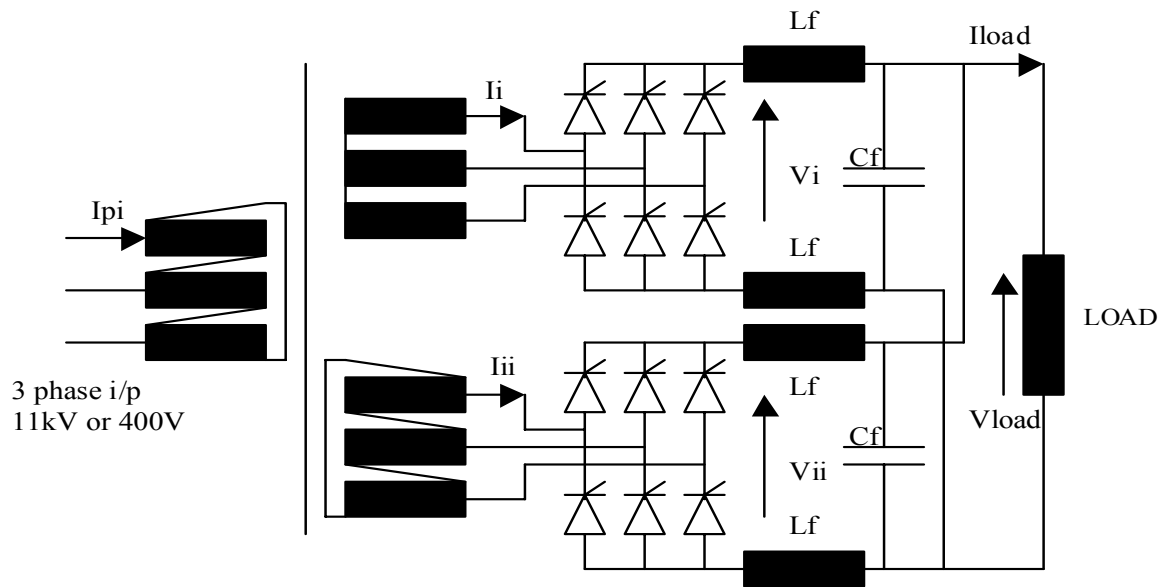


Figure 8.3-4 Twelve pulse line-commutated thyristor power converter.

An example of a twelve pulse system is shown in Figure 8.3-4, the two three phase supplies can be configured in series or parallel to match the impedance of the load. The twelve pulse rectification is produced by staggering two three-phase systems by 30° . This generates an AC current on the primary as shown in Figure 8.3-5, with a stepped waveform closely resembling a sinusoidal waveform. This results in improved harmonics and a higher ripple frequency with smaller amplitude.

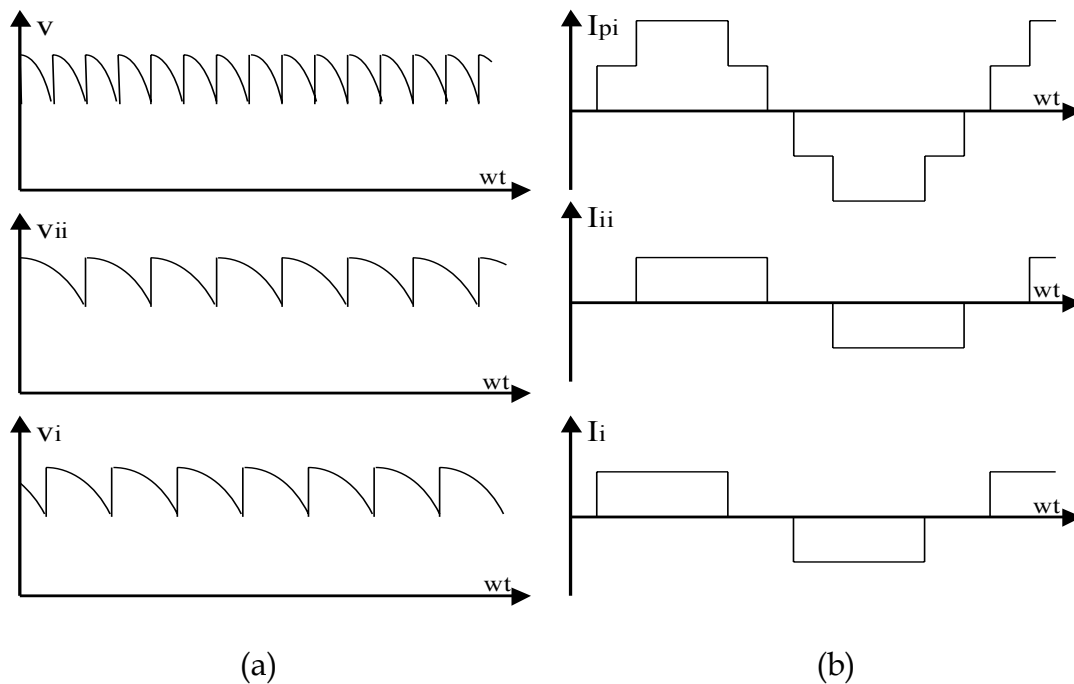


Figure 8.3-5 Two three phase bridges: a) DC voltage waveforms, b) AC current waveforms.

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(a) Summary of Line-commutated thyristor power converter issues

- Power factor produced is directly related to the thyristor firing angle and is variable from 0 to 0.8, will incur additional costs of power factor correction;
- Harmonic input currents can be minimised if twelve pulse (or higher) design employed, but moves in phase;
- Produces thyristor firing notches in the network and noise spikes which could effect other users;
- Large and heavy magnetic elements, such as transformers and chokes make it unsuitable for low power levels;
- Large residual ripple produced unless twelve pulse configuration used, combined with effective filtering;
- Bandwidth is dependent on the pulse number and at best is moderate;
- Extensively used technology for a wide range of applications, with competitive market;
- Simple design with minimal components required, high reliability guaranteed.

8.3.4 Switch-mode Power Converters

A typical switch-mode power converter structure is shown in Figure 8.3-6, and can normally be separated into 3 distinct stages;

Input Stage – this provides the interface to the 50Hz network, combined with rectification and filtering to form a DC bus.

Intermediate Stage – high frequency switching (inverter or chopper) and modulation of an AC output.

Output Stage – Impedance matching to the load requirements, by transformer if necessary, rectification and filtering.

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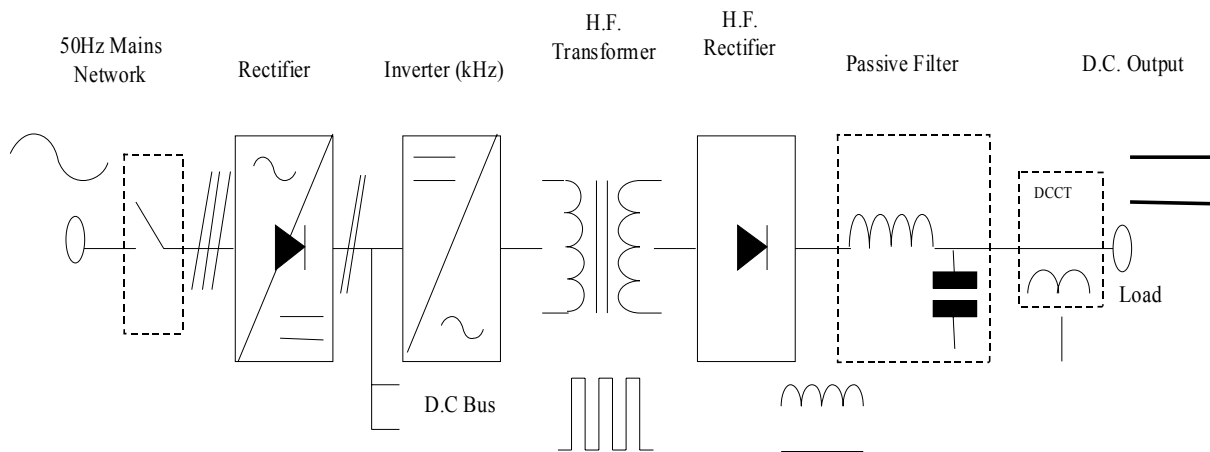


Figure 8.3-6 Schematic of a switch-mode power converter.

The topologies of switch-mode converters are normally more complex than those of the line-commutated converter. In this type of converter the line frequency is no longer the synchronising and commutating element, and the frequency of operation is determined by the type of structure employed.

(a) Input Stage

Its basic function is to provide a DC bus to the inverter or chopper circuit. There are two options to be considered for this purpose, individual or common input designs.

- Individual Input Stage

A dedicated input stage for a switch-mode supply would consist of an AC circuit breaker, RFI filter, diode bridge rectifier and pre-filter. These filters have an important role in the performance and reliable operation of the supply and must be considered carefully.

The RFI filter reduces conducted noise into the network and the pre-filter reduces both the voltage spikes etc, coming from the network and the residual ripple. It will also improve the input current form factor.

If large numbers of converters were used, such as in the DIAMOND Quadrupole and Sextupole magnets, the input design must avoid large peak inrush currents.

The individual input stage offers complete independence and autonomy, minimising the interaction between converters, such as transients on the DC bus and common rectifier instabilities. The protection circuit is simplified and switching at AC is standard practice.

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- Common Input Stage

There are a variety of common input stages that can be considered. The simplest is a six-pulse diode bridge connected to the network and feeding all units, with individual input filters provided for each converter. An extension to this is to have one large filter.

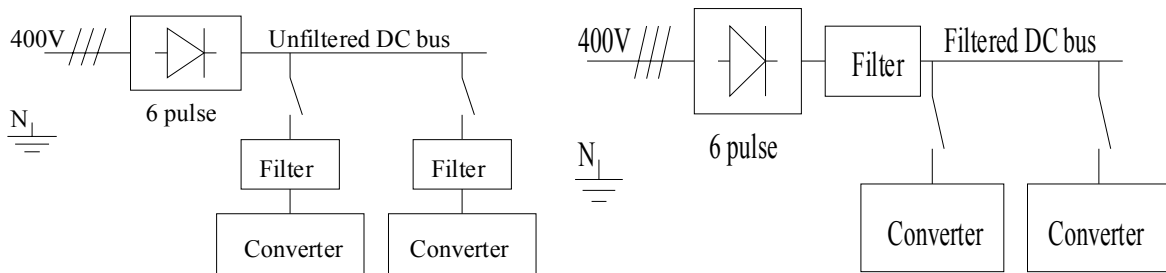


Figure 8.3-7 Six pulse DC bus configuration

If a common input stage was used then the preferred option would be to phase shift the secondary for a 12 pulse solution as shown in

Figure 8.3-8. This would then require a line transformer, but would have the advantages:

- Earthing of the DC bus with the possibility to limit earth fault currents, that can cause severe damage to the load;
- Matching the voltage to the load avoiding the installation of unnecessary switching capacity;
- Reduced input harmonics, with smaller residual ripple that is easier to filter;
- Increased safety due to low voltages and earthing;
- Reduction of noise on the DC side.

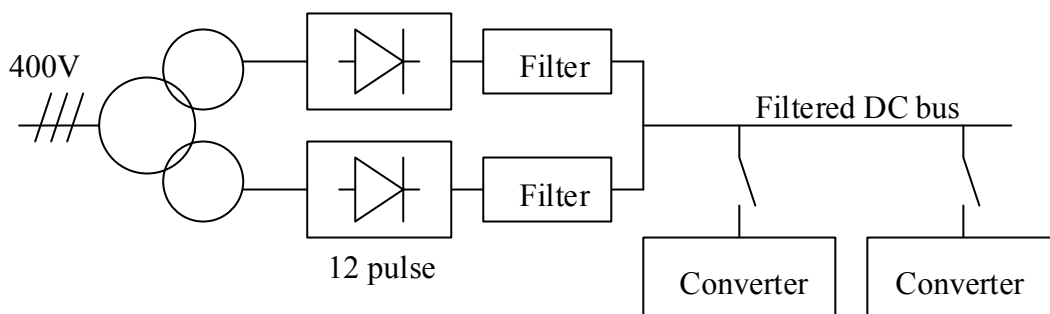


Figure 8.3-8 Twelve pulse DC bus configuration

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The success of this configuration depends on the DC bus stability and must be considered carefully when designing the system. The isolation and switching of individual converters must be performed at the DC level and is difficult compared to AC networks. The peak fault currents can be excessive and results from the size of filter capacitors and the impedance of the DC bus.

(b) Intermediate Stage

The DC bus generated by the input stage will maintain the voltage source to the high frequency switching unit. This unit converts the DC supply into an alternating source to drive a transformer and rectifier at high frequency, which will minimise size and maximise response. The choices of design available for this stage are numerous, but will basically consist of a complete (symmetric) H bridge, half H bridge (asymmetric) or the chopper. The two distinct converter types that are being considered are the resonant inverter and the chopper.

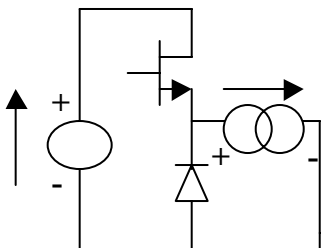
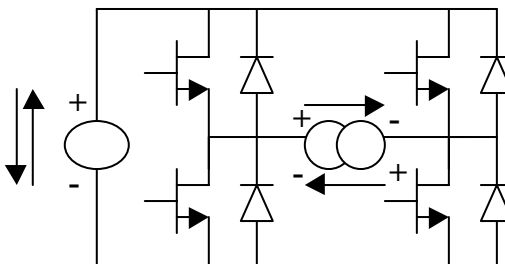


Figure 8.3-9 (a) Simple Chopper circuit



(b) Full (symmetric) H bridge

The function of the converter depends on its structure and the circuit interfacing to the load. The H bridge shown in Figure 8.3-9(b) would be a typical resonant inverter if the horizontal branch providing the interface was a resonant circuit. Several types of resonant circuits exist, series, parallel and combined series and parallel.

The high operating frequency used by this technology has the benefit of reducing the power converter size, as the smoothing filter, and if used the impedance matching transformer, is minimised. The resonance of the smoothing filter must be less than the ripple frequency to obtain the necessary attenuation. The size and cost of a smoothing filter increases as the resonant frequency decreases, making them more economical and smaller than for linear and line-commutated thyristor supplies.

- Chopped DC regulator

The chopped DC regulator consists of a constant DC voltage produced from the transformer, rectifier and pre-filter, which is connected to a fast switching semiconductor element. (normally IGBT (isolated gate bipolar transistor) or MOSFET (metal oxide semiconductor field effect transistor)) The actual configuration of the circuit depends on whether bidirectional or unidirectional regulation is required.

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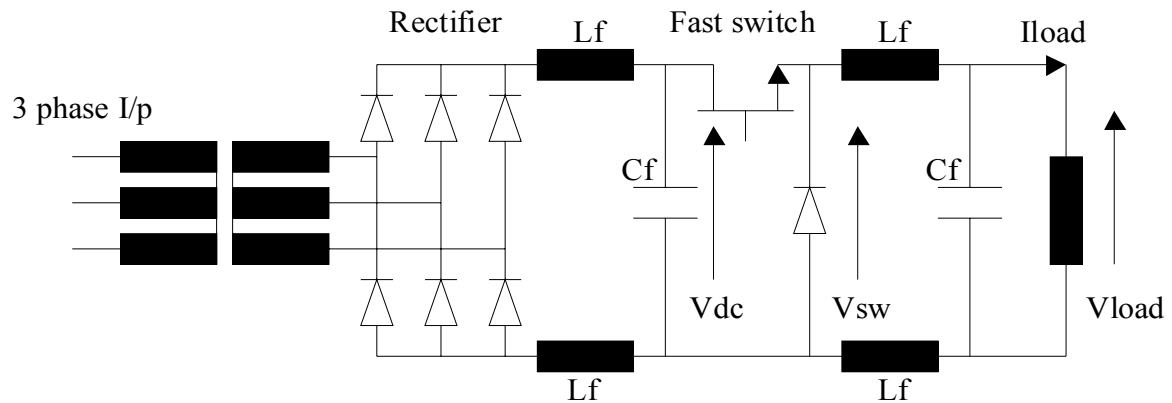


Figure 8.3-10 Configuration of a unidirectional Chopped DC regulator.

A unidirectional regulator is shown in Figure 8.3-10, its average DC output relates to the pulse width modulation of the transistor. When the transistor is conducting the diode is blocked and when the transistor is blocked the diode conducts. The waveforms shown in

Figure 8.3-11 are typical for a chopped DC regulator. The DC current has a triangular-shaped ripple that depends on the inductance of the smoothing filter. The switching frequency is limited by switching losses and by the transistor turn-on and turn-off times. The major disadvantage for this design is the entire current has to be switched at each transition.

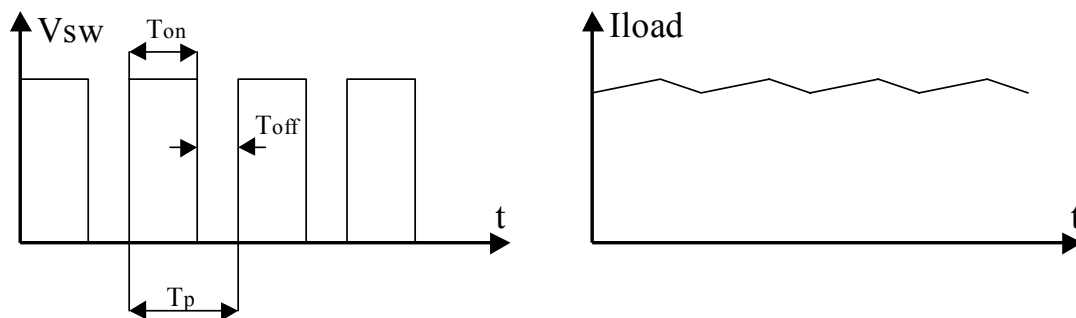


Figure 8.3-11 Waveforms of DC output voltage and current of a chopped DC regulator.

The bidirectional regulator operates on the same principle, but the fast switching circuit is a H bridge design.

The noise emissions from a chopper circuit can be significant and must be considered carefully. The switching of large currents can cause mains disturbances, and the recovery charge of fast diodes increase the switch-on current of the transistor when current is rapidly commutating out of the diode. This can cause strong emissions at high frequency (0.1 to 5MHz) which can become intolerable at the medium and high power levels. The use of resonant converters helps this effect and is considered next.

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- Resonant converter

This technology has the advantage of switching at zero current and is not limited by switching losses as in the chopper design. This enables higher switching frequencies to be reached.

The configuration of a typical resonant converter is shown in Figure 8.3-12 and operates as follows; the DC voltage from the input stage is fed to the inverter that houses on the horizontal branch an oscillating circuit comprising of inductance, capacitance and a transformer. By switching the two branches of the inverter alternately an AC current is generated in the primary of the transformer. The secondary voltage from the transformer is then rectified by a single-phase bridge, and the output capacitor acts as a buffer to absorb the high current ripple.

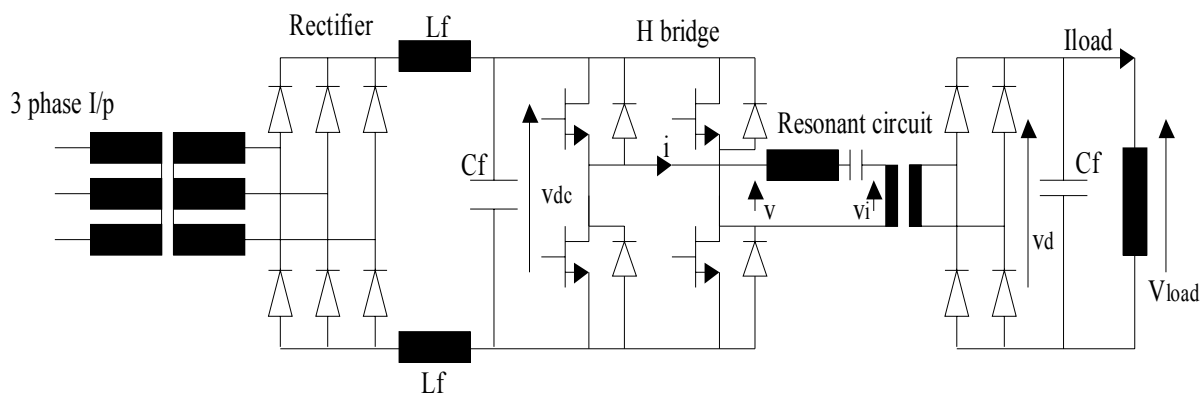


Figure 8.3-12 Configuration of a Resonant converter.

The switching frequency of the series resonant converter will depend on whether the inverter is controlled above or below the resonant frequency. The switching of the alternate branches of the inverter will produce a rectangular waveform (v) applied across the series resonant circuit. The current (I) in the oscillating circuit will have a near sinusoidal waveform. If the switching frequency is higher than the resonant frequency then the current will lag the applied voltage (v). This current applied to the primary of the transformer has the same waveform as the secondary accounting for the transformation ratio.

The switching frequency of the resonant inverter can be relatively high from tens of kHz to a few hundreds of kHz without any switching loss problems. When the current through the transistors is blocked, a capacitor in parallel with the transistor limits the dv/dt and significantly reduces the blocking losses. The diode bridge on the output also switches when the secondary current passes through zero.

The resonant inverter employs what is commonly known as “soft” commutation, with zero current switching and a near-sinusoidal appearance of relatively moderate

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slope. This not only provides low switching losses, it limits the losses in conductors and ferrites due to the absence of high harmonics.

The output of a resonant inverter is controlled using a high precision transducer to measure the DC current, which is compared with the reference to calculate the switching times of the transistors. This stabilisation will compensate for perturbations from both the input supply and the load, and normally needs to function at low frequency. The bandwidth of a converter is related to the switching frequency and needs to be at least a decade lower than the switching frequency to achieve the desired performance. An inverter operating at 20kHz would have a bandwidth limit of 2kHz.

(c) Output Stage

The output stage provides the interface to the load and filtering of the high frequency ripple. The resonant inverter includes a small transformer that gives electrical isolation and adapts the impedance of the load to the inverter. The size of the transformer (or choke) is inversely proportional to the frequency of operation. However since flux levels have to be kept lower, and losses due to high frequency are greater, the size ratio between line transformers and switch-mode is approximately 20:1. The output filter is also smaller due to the high operating frequencies.

(d) Summary of switch-mode power converters issues

- Power factor of 0.95 if designed well, but the form factor can be poor;
- The power requirements of <6kW will allow small and light weight units, enabling fast replaceability;
- High bandwidths are possible due to the switching frequencies;
- A small residual ripple on the output, due to high frequency and minimal output filtering required;
- Well proven technology, with a variety of specialist suppliers to choice from;
- Reliability issues of 10 years ago are now unfounded, and this technology is widely used in the major scientific facilities around the world.

8.3.5 Recommendations for DIAMOND

The Linear power converter offers a low noise, small output ripple solution, but is considered unsuitable for a modern accelerator. Its extra volume and weight, needs additional rack space and will hinder replaceability. This coupled with poor operating efficiency that increases running costs and the loading on the thermal management system.

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(a) Dipole power converter

There are two design options available for the Dipole power converter, these are line-commutated thyristor and switch-mode.

- Line-commutated thyristor power converters

The line-commutated thyristor converter is a simple technology that is well understood, with a moderate purchase price. This high power application is suited to 12 pulse rectification, minimising the input supply harmonics and enabling direct connection to the MV network at 11kV.

To achieve the specified ripple voltage, the smoothing circuit is critical and will probably require an active filter. It has the highest operating efficiency of all the designs reducing running costs and loading on the thermal management system.

Its power factor depends on the thyristor firing angle and even with load impedance matching a power factor of only 0.75 is realistic. This is caused by the allowances required for mains disturbances and the input operating range. A power factor better than 0.95 will be quoted as the performance requirement, ensuring that correction is included in the manufacturer's proposal.

- Switch-mode power converters

If switch-mode technology is offered it may require series and/or parallel connection of a number(n) of lower power modules rated at 50 or 100kWatts each. This would allow redundancy as n+1 modules could be installed, minimising downtime. The resulting increased components level and design complexity will have a negative effect on reliability.

The efficiency is good, but lower than the line-commutated thyristor, so there will be an increase in running costs and loading on the thermal management system. The harmonics on the input supply must be minimised, with careful consideration to the input filtering and phase displacement of the three phase supply. The power factor is close to unity, and the connection to the supply network would probably occur at LV (400V) that will need a dedicated transformer.

The choice of power converter topology will be made at the tender evaluation stage after considering the manufacturers proposals against the design issues raised.

(b) Quadrupole and Sextupole power converters

The switchmode resonant converter is considered the most suitable solution for the Storage Ring Quadrupole and Sextupole magnets. There are various configurations available and the choice will depend on the design preferences of the manufacturer, measured against their performance specification.

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This is a well proven technology which has developed rapidly, and is widely available from a competitive commercial market. It offers a compact solution that is modular and light-weight, requiring minimal installation space that simplifies replaceability. It's high operating efficiency and close to unity power factor are also major benefits.

The specification will not make any distinction between, common or individual input stage, as they are both viable options. The common input will give significant cost saving to the project, and with the reduced number of components a better reliability. The negatives are it presents switching problems at the DC bus and can generate high fault currents. The design offered must be the twelve pulse rectifier type, to minimise the harmonics and gain the benefit from incorporating a transformer.

The individual input does offer complete independence and a switching occurs at the AC network. This will provide a complete modular solution as no additional rack is required for the DC central source.

The input AC network must cater for 2 and 6 pulse converters due to the low power levels required and minimise harmonics, at source (power converter) and using phase displacement techniques or harmonics filters.

8.4 CONTROL SYSTEMS FOR POWER CONVERTERS

8.4.1 Introduction

The specified output stability of commercially available power converters has always, until recent developments, been achieved through conventional analogue control circuitry. CERN for the LHC project, and a number of power converter manufacturers have made major advances in this area, and are now offering a fully digital solution. This report investigates the structure and operating principles associated with each system, and comments on their suitability for the DIAMOND Storage Ring magnet power converters.

8.4.2 Conventional Analogue Control

Stabilisation using analogue control technology is well understood and extensively developed. The basic structure of a typical system is shown in Figure 8.4-1.

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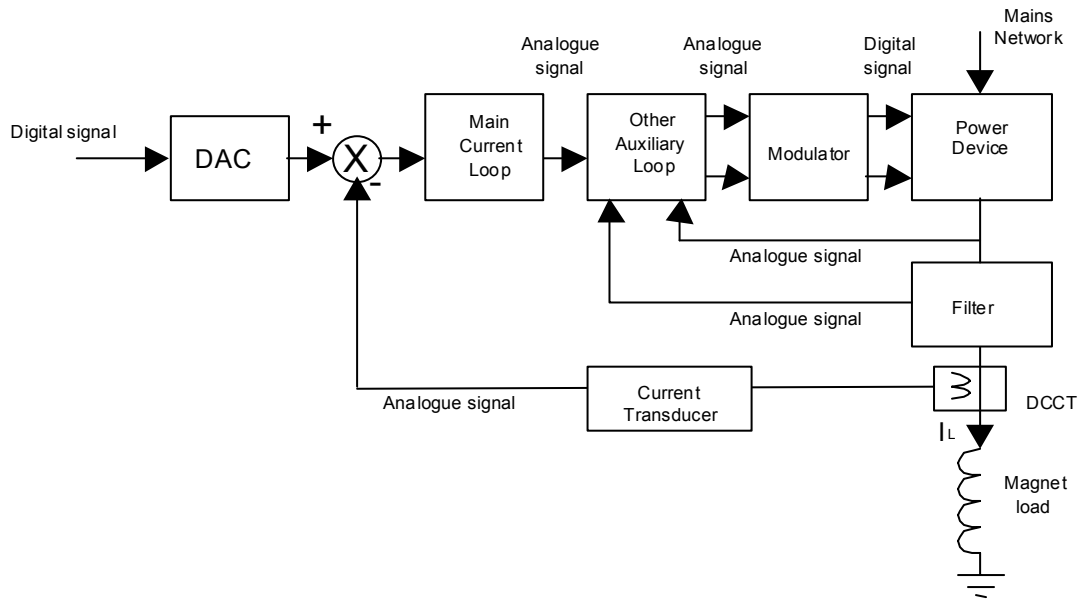


Figure 8.4-1 Schematic of standard analogue control circuitry.

In a modern accelerator any designed or procured power converter would incorporate an intelligent processor. If analogue control were employed, this would require a dedicated system whose function is to provide the interface between the control system and the power converter. The processor would translate the commands from the external control system and initiate the appropriate action, such as representing the set output current as a digital input to the DAC.

The precision of an analogue controlled system would rely on the quality of the DAC that derives the analogue reference signal for the current stabilisation circuit. The DAC can only be set to discrete values defined by the required resolution. This results in a setting error of up to $\pm \frac{1}{2}$ LSB. Apart from this setting error, the precision of the actual output value is given by the analogue errors of the DAC, the feedback loop, and the output measuring transducer.

A DCCT (direct current current transformer) generates the high precision feedback signal proportional to the output current. This signal is compared with the reference and an error signal is produced that regulates the stability.

The analogue error signal derived from the comparator is converted back to a digital signal to generate timing pulses for the modulator. The closed loop control of these pulses will regulate the output. This is normally achieved via the high bandwidth of the inner voltage control loops, which compensate for short-term stability.

The manufacturers preferred choice of DCCT topology is the zero flux transducer, as it gives galvanic isolation from the power circuit and has a high signal output that contributes to low noise levels. Its operation is to detect the absence of field in its core when injecting a balancing ampere-turn, resulting in an accurate secondary current equivalent to the load current. This secondary current is then converted into

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a voltage, with a precision that depends on the quality of the burden resistor used. The burden resistor must be designed with a very flat temperature co-efficient, with low self-heating. Ageing effects must also be minimised.

An additional output transducer can be incorporated into the design and used as a means of confirming that the output is within a certain tolerance. This is achieved by comparing its output with the transducer in the closed loop circuit. This would be an important feature for DIAMOND, considering the stringent stability requirements and the regular routine re-calibration necessary to maintain these tolerances.

The closed loop stability of a power converter is governed by its structure and the choice of compensating network. In an analogue system this is achieved through amplifiers and passive components. The calculation of these compensating resistors and capacitors is critical to its performance, and are often chosen during the commissioning stage.

Noise must be considered as one of the most important sources of error in high precision applications. In addition to the environmental noise, the various noise sources inside the power converter can be some of the worst to counteract. Noise is generally defined as an unwanted AC signal superimposed on the wanted signal and are caused by such things as:

- Mains frequencies (50Hz) and higher harmonics
- Commutation of power switches, IGBT, MOSFETS;
- Auxiliary switching power supplies;
- Digital circuits, microprocessors, buses, etc;
- Spark generators, such as relays, circuit breakers, etc;

The frequency components of these noise sources extend from very low frequencies up to several hundreds of megahertz. Analogue circuits can malfunction when subjected to noise. For example, operational amplifiers, which are used for many purposes in the power converter, can produce apparent DC offsets which vary both with the frequency and amplitude of the noise. Even differential circuits cannot always provide adequate noise rejection for wide-band noise.

Summary of main points

- Proven technology that is well understood and extensively developed;
- Widely available from a competitive commercial market, with a range of suitable supplies;

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- Uses PI control for stabilisation, which requires manual changing of the CR components for optimisation and commissioning;
- Any major changes to the control system will require a redesign;
- Diagnostics are limited , with LED type display.
- Communication system will be a separate dedicated system, which is interfaced to the power converter.

If a digital DCCT could be designed with the same speed and accuracy as the analogue equivalent, then an adaptive digital control loop and elimination of the DAC would be possible.

8.4.3 Modern Digital Control Systems

A typical digital control circuit is shown in Figure 8.4-2, and the intelligent processor has now become an integral part of the power converters control system. The major difference between these systems, is that the resolution now depends on the ADC associated with the output transducer and not the DAC, which provided the analogue reference.

The digital signal associated with the reference (set output current) is directly compared with the digital signal produced from the DCCT and its associated ADC. The corresponding digital timing pulses are generated by the microprocessor, this is equivalent to the error signal of the analogue design. These pulses are applied to the switching element that controls the power electronics and regulates the output current.

Additional control circuitry is usually incorporated to compensate for short-term drift. A feedback signal can be derived from the DC output, smoothing filter and/or the bridge rectified output, and each requires a dedicated ADC. Their resolution is not as accurate as the current control loop, but their bandwidth needs to be high to compensate for mains disturbances.

Optimisation of the control loops can be achieved by software adjustments. The processor can evaluate the load characteristics and apply the appropriate compensation. A number of algorithms and filters exist for digital controllers and can be chosen to suit the application.

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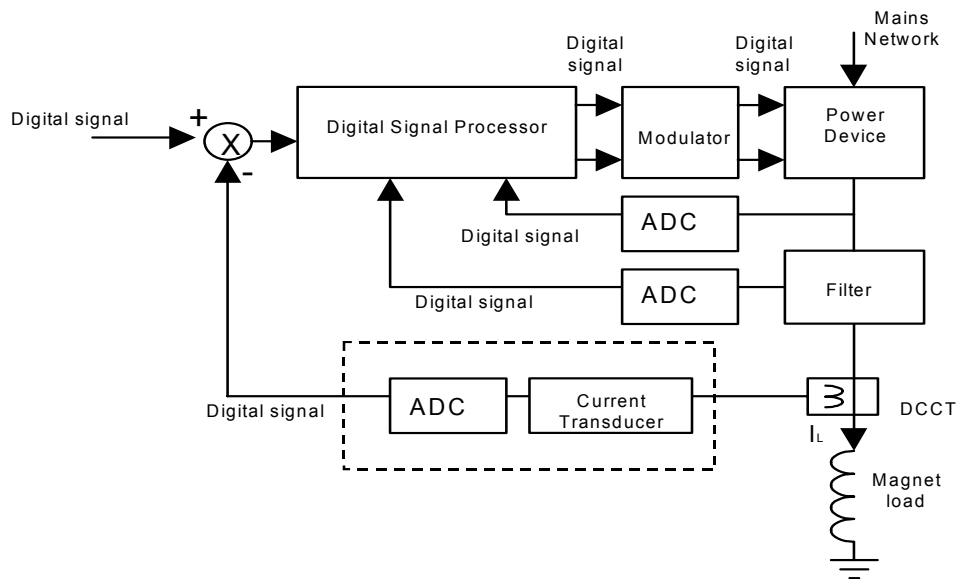


Figure 8.4-2 Schematic of a standard Digital control circuitry.

The advances in digital technology have relied upon the production of the digital current transducer. The output precision required from this is 10ppm (even 1ppm in some cases) with conversion speeds fast enough not to compromise the overall systems bandwidth. This has now apparently been successfully achieved, but there is a limited commercial availability for this accuracy. Although lower precision, fully digital systems have a wider commercial availability.

Digital systems can equally be effected by noise, although in general the levels must be considerably higher than for analogue circuits. Sequential logic such as microprocessors can be particularly vulnerable to impulse noise.

Summary of main points:

- Still developing, but is the technology of the future;
- Limited commercial availability, competition between companies low, possible cost implications;
- Adaptive state controller, allowing software changes to optimise control parameters during commissioning;
- Major and minor changes to the control system can be made in software, no redesign required;
- Diagnostics available to PC with full dataset;
- Communication system is an integral part of the controller.

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8.4.4 Recommendations

The performance specification for the power converters can be achieved using analogue or digital technology and the eventual choice should be made at the tender evaluation stage. Each proposal must be considered carefully against the specification and the summary points raised for each topology.

When writing the specification for the main Storage Ring magnet power converters it will state a fully digital control system is preferred. This will not be an essential criteria as it will limit the competitive tender process, due to the limited number of companies who can achieve the requirements.

The specification will also ask for the additional costs of including a second DCCT, to give independent output current monitoring.

8.5 POWER CONVERTER RACK LAYOUT ISSUES

8.5.1 Overview

Rack layout for quadrupole and sextupole converters

The following section describes the proposed rack layout for the individual power converters of the Storage Ring quadrupole and main sextupole windings. The power converters are to be grouped by cell and their racks housed in the control and instrumentation areas (CIA). There are ten quadrupole converters and seven sextupole main winding converters required for each cell.

These power supplies are to be mounted in dedicated racks positioned at each cell. The racks will provide the necessary cooling, in the form of water or forced air and control system hardware, integral or dedicated to each converter.

The AC supply distribution will depend on whether common input or independent input stages are used. If common input is preferred then, only one AC supply is necessary to feed the 12 pulse rectifier, with the other units powered by the DC bus. If an independent input stage is used then each converter will have separate AC supplies.

The following rack layouts are generated from the information supplied by power converter companies. The converter sizes were taken for the different power levels and the appropriate rack cooling and controls interface added, to assess the options available, and the quantity of racks required.

8.5.2 Arrangement 1

This is a switch-mode solution, with 3U modules proposed for the Quadrupole power converters and 2U for the Sextupole power converters. The supplies are

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forced air cooled, but additional rack mounted forced air cooling and ventilation has been included.

The power supplies are analogue units that require an external interface to the control system. This interface is an intelligent processor, which communicates the serial information to and from the control system and converts it into status, analogue signals and interlocks. This then simplifies the power converter design, with its performance mainly dependent on the quality of the closed loop controller.

The advantage of having an independent controller is the interface to the control system is standardised, irrespective of who manufactured the analogue power converter. The VME system is integrated with the racks and marshalls all the serial links to the power converter interface units.



Figure 8.5-1 Arrangement 1 for Quadrupole and Sextupole power converters

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8.5.3 Arrangement 2

This solution is as before switch-mode technology, with forced air cooling and again additional rack forced air cooling and ventilation has been provided. The power converter design is different and requires additional space to that of the previous option. One reason for the increase in size is the inclusion of the intelligent processor within the units.

The interface to the power converter is now a digital serial communication and not analogue as before. The internal closed loop stability circuitry is still an analogue design. The problem with this design is the power converter interface will not be standardised unless all the supplies are purchased from the same company.

The Quadrupole power converters are 6U and the Sextupoles are 4U, this increase in size means an additional rack is required. This does have the advantage of reducing the losses within each rack, due to power converter inefficiencies.

The VME crate again provides the marshalling point to all individual converters from the main control system.

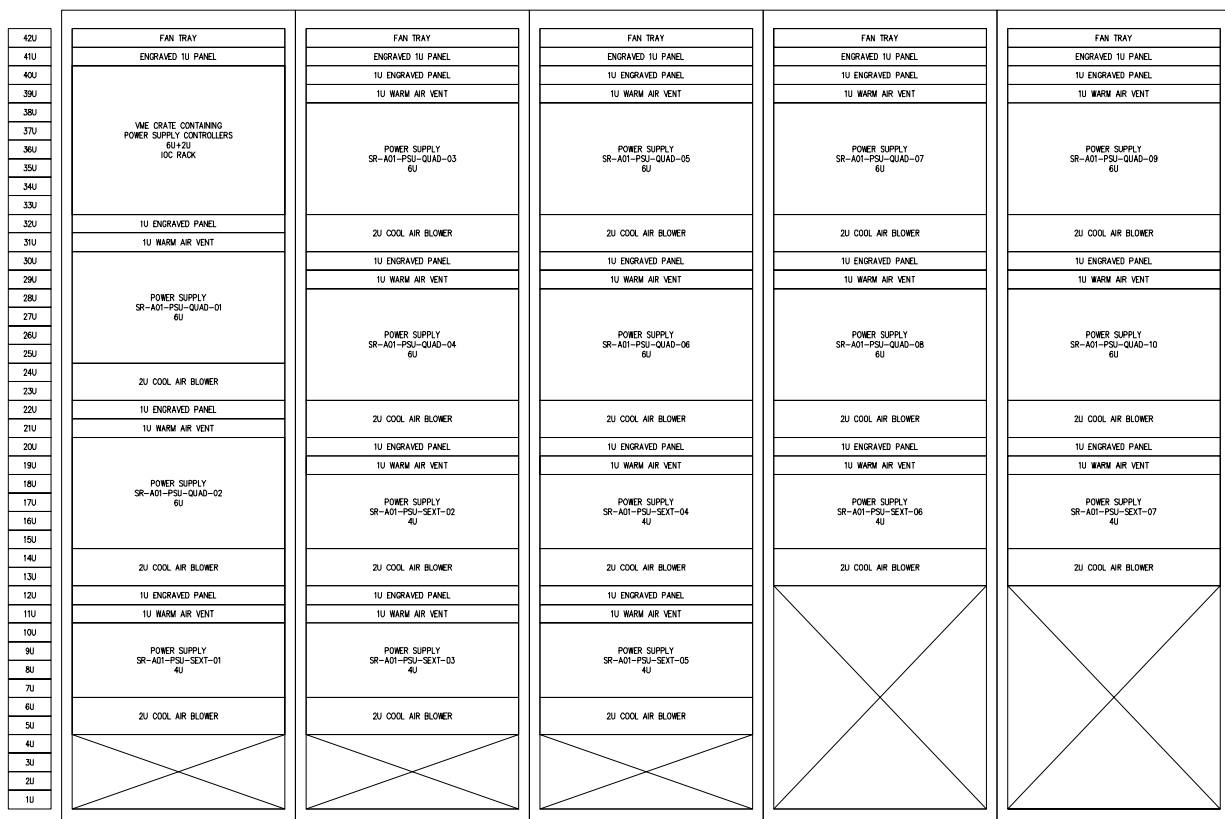


Figure 8.5-2 Arrangement 2 for Quadrupole and Sextupole power converters

8.5.4 Arrangement 3

This is the same as arrangement 2 except that the power converters are water cooled rather than air cooled. This allows for more compact housing of the power supplies

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and makes use of fewer racks, as the additional rack forced air and ventilation is not included. The heat generated by those components not water cooled, such as chokes and electronics, will be removed by extraction fans mounted in the top of the racks.

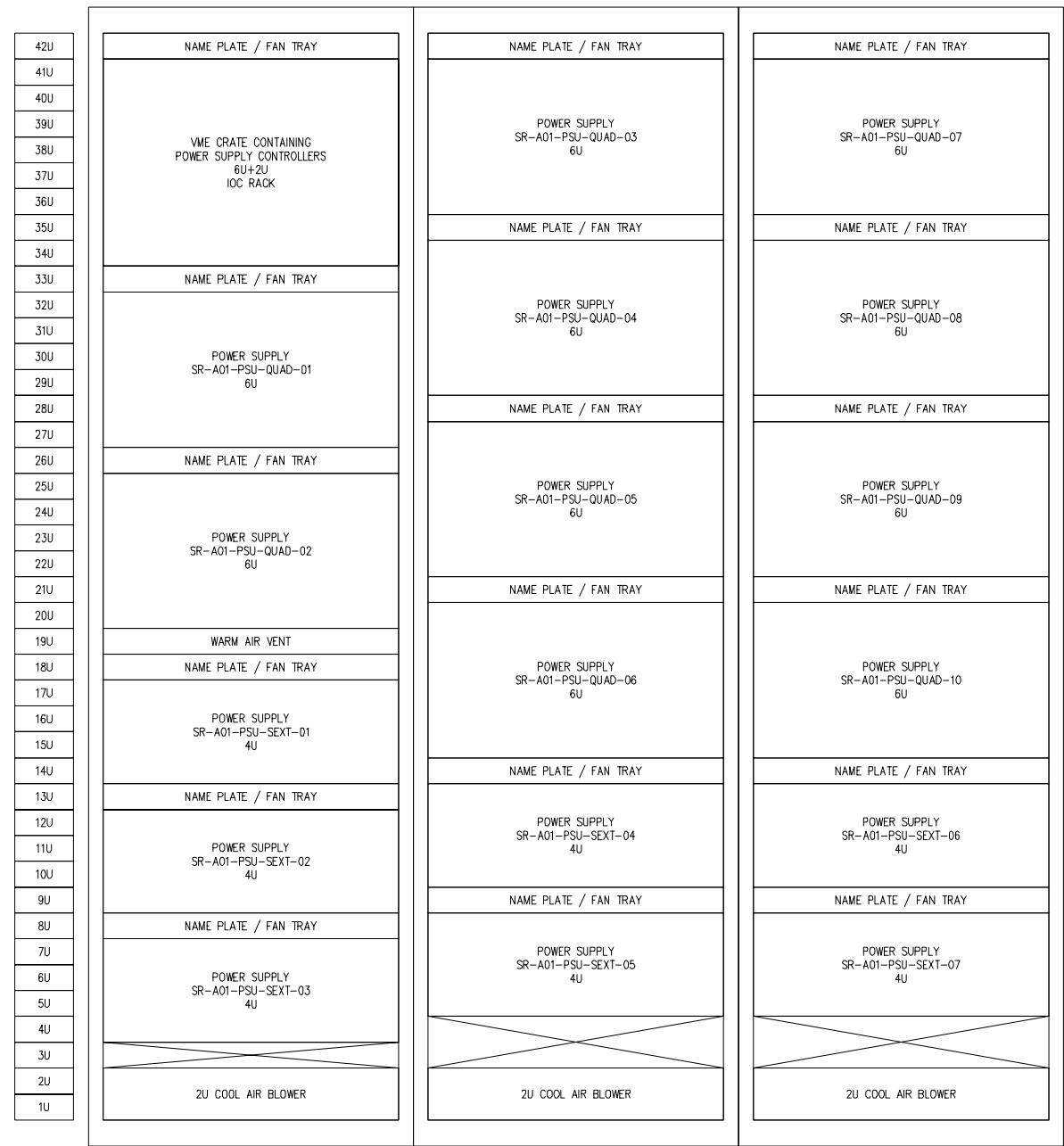


Figure 8.5-3 Arrangement 3 for Quadrupole and Sextupole power converters

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8.6 DC MAGNET CABLES ISSUES

8.6.1 Introduction

A number of issues associated with the installation of power supplies, cables and controls to the various and numerous magnets for the DIAMOND Synchrotron Storage Ring need to be considered and addressed at this stage of the project.

This section will initially focus on the issues relating to Dipole, Quadrupole and Sextupole magnet cables and associated voltage drops due to cable resistance and the current flowing. Other issues concerning cable sizing and routing will also be considered here. Cable routing will include discussion on options of the number of routes (labyrinths) into each of the 24 cells of the storage ring. The number of labyrinths into each cell directly affects the average cable length, thus affecting voltage drop and resulting power loss. Increasing the number of labyrinths into each cell will reduce the average cable length, minimising voltage drop and power loss. Power loss being an issue for the storage ring tunnel, temperature control.

8.6.2 Labyrinth Options

Access routes for cables from the power supply to magnet require consideration, as they will have a bearing on total cable lengths and the amount of cable inside the storage ring tunnel. The cable length of the individual magnets will have an effect on the power supply output terminal voltage. An allowance will need to be made for voltage drop along the cable, ensuring the designed voltage appears at the magnet terminals.

Power loss in the cable produce heat and it is important to minimise heat build-up particularly inside the storage ring tunnel. Minimising the length of cable inside the storage ring tunnel will help, and cable routing will have a direct effect on the length required. Three options exist for cable entry these being one, two or three labyrinths. Average cable length calculations for each of these options have been estimated. From these estimates, power losses have been calculated and the results tabulated. Cable cross-sectional area must be considered when calculating cable power losses. From these calculations charts have been produced showing cable power losses. Included in the tables is a comparison of estimated voltage drop based on cable losses and the voltage drop allowed for in the magnet design parameters.

Typical Cell - Magnet arrangement shown in Figure 8.6-1 is the magnet layout of a typical cell structure. The two dipole magnets are supported on their own mountings with ten quadrupole, seven sextupole and other steering and focusing magnet types distributed on the three girder structure. The wiring scheme to this layout is considered for different labyrinth options.

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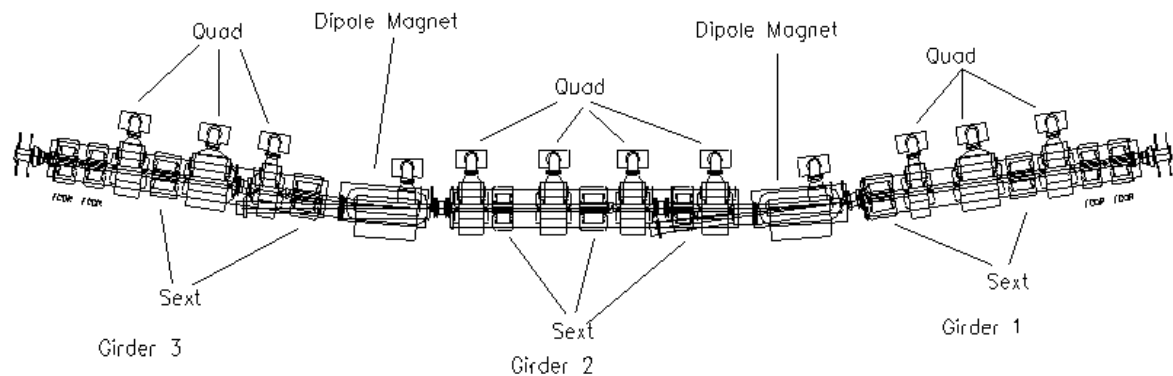


Figure 8.6-1 Typical Cell Arrangement

(a) Single Labyrinth

The initial design for cable access was to use a single entry point between the power supplies and magnets. As a result of the amount and size of cables to be used, a more flexible access method was reviewed.

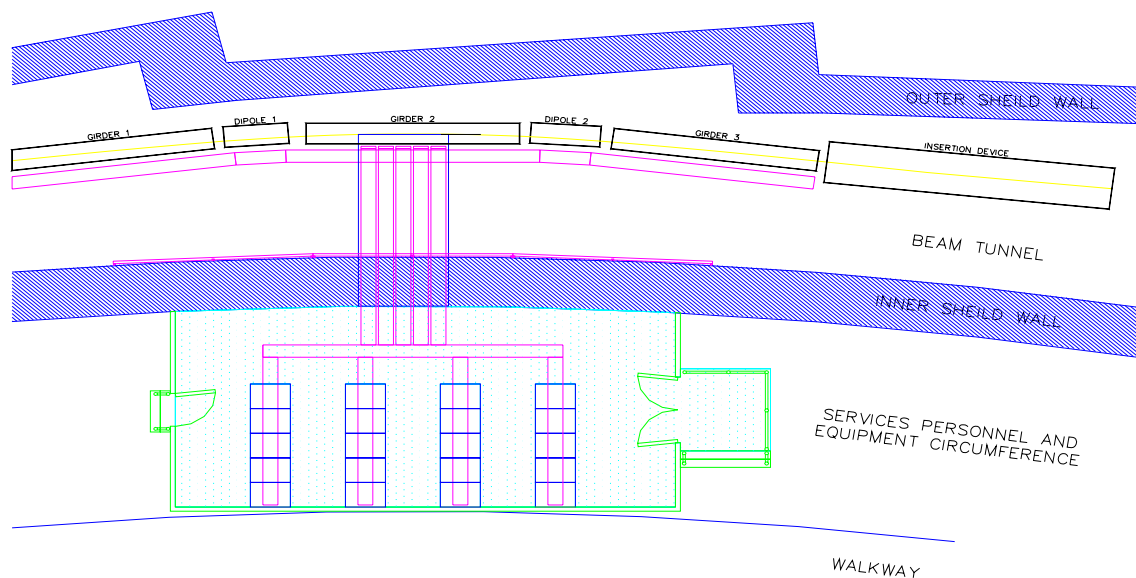


Figure 8.6-2 Single labyrinth cable access

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(b) Double Labyrinth

A double labyrinth cable access arrangement was considered. This option has not been drawn, but consists of two access points, in line with the two, dipole magnets.

(c) Triple Labyrinth

The triple labyrinth cable access way consisted of two sub-options. The first where the two end labyrinths entered the storage ring tunnel angling out from the centre labyrinth meeting the lattice at the centre of each of the girders, providing even distribution of cabling but making it difficult for dipole magnet cabling. The second sub-option again brings the centre labyrinth into the middle of the centre girder but the two outer labyrinths, line-up with the lattice at the dipole magnets. This provides improved cable distribution for the large dipole cables but less optimum cable distribution, for cables to magnets on girders one and three.

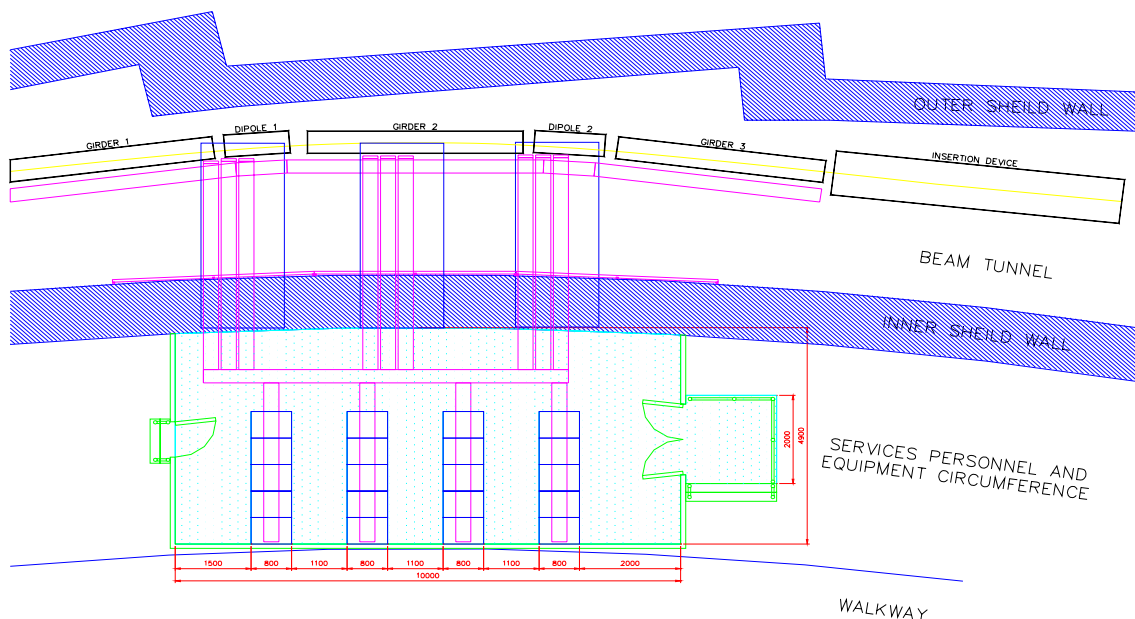


Figure 8.6-3 Triple labyrinth cable access

8.6.3 Dipole Magnet System

Table 8.6-1 shows comparisons between the two possible cable routes and the three cable size options. Considering cable route options, running the cable at the same circumference as the lattice the cable route is shorter, keeping losses and heating effects to a minimum. Running the cable along the inner storage ring tunnel wall taking the cable to and from the dipole magnets, increases cable length by 78% and

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thus increases cost and losses by this amount. Offsetting these increases are factors such as reduced EM fields close to the lattice by running the cables to and from the magnets side by side. This provides a cancelling effect and by running the bulk of the single cable away from the storage ring, sensitive measuring equipment at the lattice will be less affected. Cable size issues such as bending radius and power losses due to voltage drop also needs to be considered. Figure 8.6-4 shows comparisons of cable route and cable size. Bending radius is an issue due to limited space and this would decide the case for using $4 \times 400\text{mm}^2$ even though this gives a slight increase in losses. The 1 amp per mm^2 of cable would be met using either $2 \times 800\text{mm}^2$ or $4 \times 400\text{mm}^2$.

Table 8.6-1 Dipole power supply to magnet, cable power loss calculations

Cable route	Cable Length (m)			Cable CSA mm ²	# of cables	Current capacity Amps per cable	Supply		Resistivity mV/A/m (IEE 16 th Ed)	Volt drop (V)	Power Losses	
	Total (m)	Tun (m)	Ave (m)				V	A			Total (kW)	Tun (kW)
Storage ring	610	530		1000	1	1520	466	1451	0.045	39.83	57.79	50.21
				800	2	1358	466	1451	0.056	24.78	35.96	31.24
				400	4	915	466	1451	0.120	26.55	38.53	33.48
Inner wall	1090	1010		1000	1	1520	466	1451	0.045	71.17	103.27	95.67
				800	2	1358	466	1451	0.056	44.29	64.27	59.55
				400	4	915	466	1451	0.120	47.45	68.85	63.80

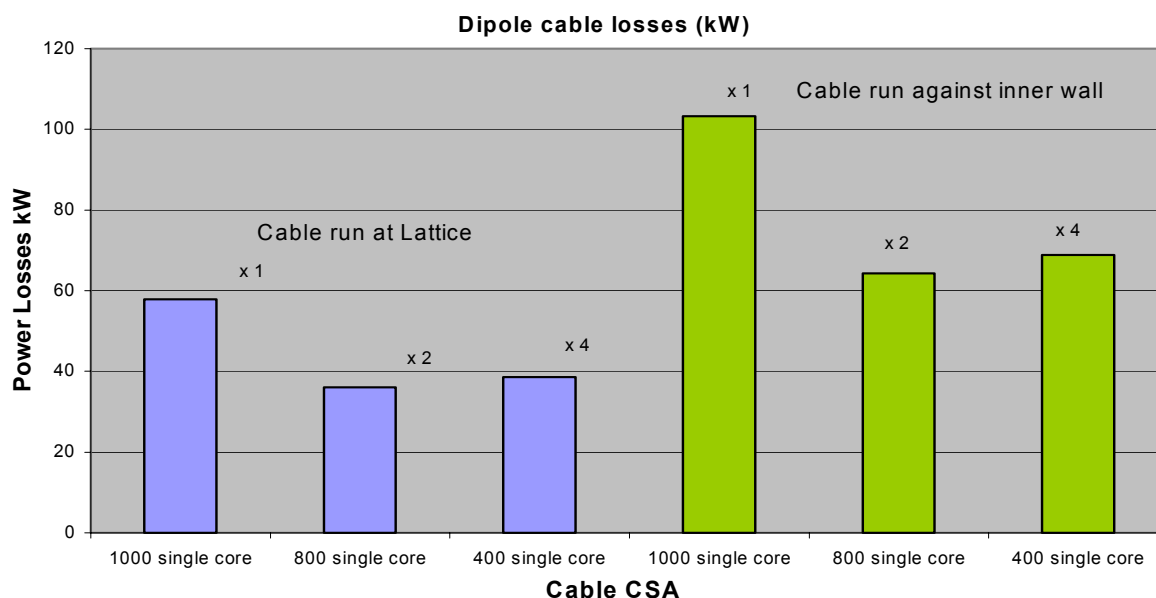


Figure 8.6-4 Dipole power supply to magnet cable power losses

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8.6.4 Quadrupole Magnet System

Table 8.6-2 shows results of calculations for cable requirements for overall, tunnel, and average cable length between the power supplies and the magnets based on the labyrinth options. Cable lengths have a direct effect on voltage drop in the cable between the power supplies and magnets resulting in power losses leading to heat loading. Results of the cable power loss calculations are also shown in Table 8.6-2.

Table 8.6-2 Quadrupole power supply to magnet, cable power loss calculations

Cable route	Cable Length (m)			Cable CSA mm ²	# of cables per circuit	Current capacity	Supply		Resistivity	Volt drop		Power Losses	
	Total Length (m)	Tunnel Length (m)	Ave Length (m)			Amps per cable	V	A	mV/A/m (IEE 16 th Ed)	Calc (V)	Ant (V)	Total (kW)	Tun (kW)
One Labyrinth	380	200	38	120	1	200	15.3	200	0.36	27.36	5%	5.48	2.88
				185	1	200	to	200	0.25	19.00		3.80	2.00
				240	1	200	24.6	200	0.195	14.82		2.96	1.56
Two Labyrinths	300	140	30	120	1	200	15.3	200	0.36	21.60	5%	4.32	2.02
				185	1	200	to	200	0.25	15.00		3.00	1.40
				2430	1	200	24.6	200	0.195	11.70		2.34	1.09
Three Labyrinths	260	130	26	120	1	200	15.3	200	0.36	18.72	5%	3.74	1.87
				185	1	200	to	200	0.25	13.00		2.60	1.30
				240	1	200	24.6	200	0.195	10.14		2.02	1.14

Terms used in Table 8.6-2 and Table 8.6-6

Cable Length	Total Length (m)	Cable length from power supply to magnet
	Tunnel Length (m)	Total cable length situated in lattice tunnel
	Ave Length (m)	Average cable length from power supply to magnet
Cable CSA	mm ²	Standard available cable sizes commercially available
Current capacity	Amps per cable	Maximum design current
Supply	V	Range of voltage required at the magnet terminals
	A	Maximum output current from power supply
Resistivity	MV/A/m	Resistance of cable due to length and current flowing
Volt Drop	Calc (V)	Total volt drop per cell for magnet family
	Ant (V)	Designed volt drop percentage allowance
Power Losses	Total (kW)	Power loss in the total length of cables for this magnet family
	Tunnel (kW)	Power losses in the cables inside the lattice tunnel

Figure 8.6-5 indicates the cable power losses for one cell with 10 quadrupole magnets. Compared on the chart are cable sizes and number of labyrinths against overall losses and storage ring tunnel losses.

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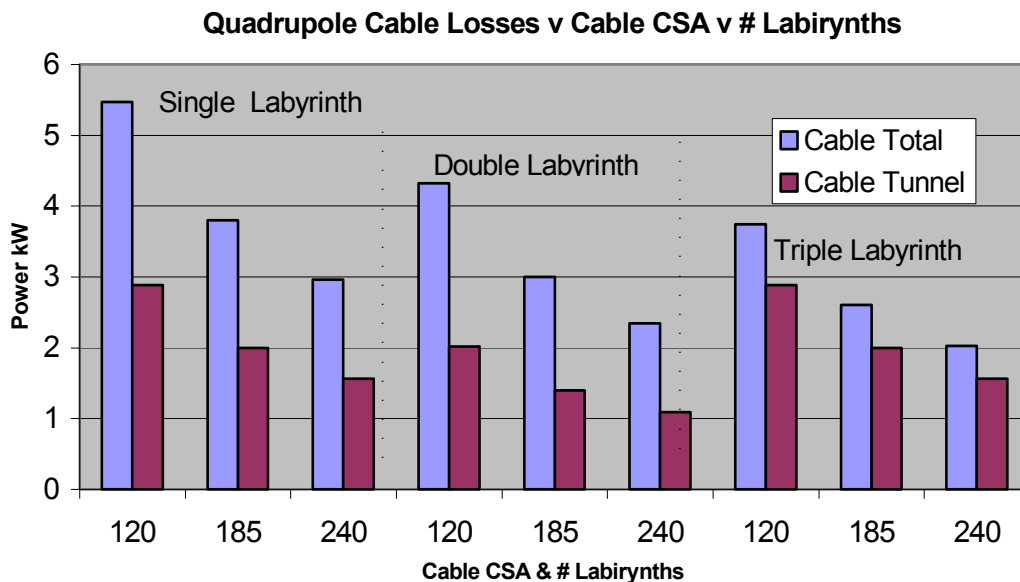


Figure 8.6-5 Comparison of power losses for labyrinth and cable size options.

Table 8.6-3, Table 8.6-4 and Table 8.6-5 tabulate the calculated results of actual average cable voltage drop due to maximum current flowing between the power supply and the magnets. Also shown is the permissible voltage drop in the cable between power supply and magnet. A further factor to take into consideration is the “rule of thumb” that the cable should be sized on the principle of 1mm^2 of cross-sectional area of cable/amp flowing. On this basis the cable should be sized close to 200mm^2 . Using a three-labyrinth design, average cable length will be 26m.

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Table 8.6-3 Comparison of designed and calculated voltage drop for single labyrinth

Average cable length 38 m. Assuming max current flow (200 Amps)		Design volt drop allowed	One labyrinth using 120mm CSA cable	One labyrinth using 185mm CSA cable	One labyrinth using 240mm CSA cable
Power supply output volts	Magnet terminal volts	(5%)	Average cable length V drop	Average cable length V drop	Average cable length V drop
15.30	13.27	0.77	2.74	1.90	1.48
18.40	15.95	0.92	2.74	1.90	1.48
19.40	16.83	0.97	2.74	1.90	1.48
24.60	21.30	1.23	2.74	1.90	1.48

Table 8.6-4 Comparison of designed and calculated voltage drop for double labyrinth

Average cable length 30m. Assuming max current flow (200 Amps)		Design volt drop allowed	Two labyrinth using 120mm CSA cable	Two labyrinth using 185mm CSA cable	Two labyrinth using 240mm CSA cable
Power supply output volts	Magnet terminal volts	(5%)	Average cable length V drop	Average cable length V drop	Average cable length V drop
15.30	13.27	0.77	2.16	1.50	1.17
18.40	15.95	0.92	2.16	1.50	1.17
19.40	16.83	0.97	2.16	1.50	1.17
24.60	21.30	1.23	2.16	1.50	1.17

Table 8.6-5 Comparison of designed and calculated voltage drop for triple labyrinth

Average cable length 26m. Assuming max current flow (200 Amps)		Design volt drop allowed	Three labyrinth using 120mm	Three labyrinth using 185mm	Three labyrinth using 240mm
Power supply output volts	Magnet terminal volts	(5%)	Average cable length V drop	Average cable length V drop	Average cable length V drop
15.30	13.27	0.77	1.872	1.30	1.014
18.40	15.95	0.92	1.872	1.30	1.014
19.40	16.83	0.97	1.872	1.30	1.014
24.60	21.30	1.23	1.872	1.30	1.014

Terms used in Table 8.6-3, Table 8.6-4, Table 8.6-5, Table 8.6-7, Table 8.6-8, and Table 8.6-9

Average Cable length for one, two or three labyrinths	Power supply output volts Magnet terminal voltage	Designed power supply output terminal voltage + 5% allowance for cable voltage drop + 10% contingency. Required magnet terminal voltage to produce designed magnetic flux
Design voltage drop	5%	Designed value of voltage drop allowed for
Cable size for labyrinth option	120mm 185mm 240mm	Calculated voltage drop due to average length and cable size Calculated voltage drop due to average length and cable size Calculated voltage drop due to average length and cable size

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8.6.5 Sextupole Magnet System

Table 8.6-6 shows results of calculations for cable requirements for overall, tunnel, and average cable length between the power supplies and the magnets based on the labyrinth options. Cable lengths have a direct effect on voltage drop in the cable between the power supplies and magnets resulting in power losses leading to heat loading. Results of the cable power loss calculations are also shown in Table 8.6-6.

Table 8.6-6 Sextupole power supply to magnet, cable power loss calculations

Cable route	Cable Length (m)			Cable CSA	# of cables	Current capacity	Supply		Resistivity	Volt drop		Power Losses	
	Total (m)	Tun (m)	Ave (m)	mm ²		Amps per cable	V	A	mV/A/m (IEE 16 th Ed)	Calc (V)	Ant (V)	Total (kW)	Tun (kW)
One Labyrinth	245	126	35	70	1	100	11.4	100	0.63	15.43	5%	1.54	0.79
				95	1	100	to	100	0.46	11.27		1.13	0.58
				120	1	100	15.3	100	0.36	8.82		0.88	0.45
Two Labyrinths	168	91	24	70	1	100	11.4	100	0.63	10.58	5%	1.06	0.57
				95	1	100	to	100	0.46	7.73		0.77	0.42
				120	1	100	15.3	100	0.36	6.05		0.60	0.33
Three Labyrinths	154	77	22	70	1	100	11.4	100	0.63	9.70	5%	0.97	0.49
				95	1	100	to	100	0.46	7.08		0.71	0.35
				120	1	100	15.3	100	0.36	5.54		0.55	0.28

Figure 8.6-6 indicates the cable power loss for one cell with 7 sextupole magnets. Compared on the chart are cable size and number of labyrinths against cable losses and storage ring tunnel cable losses.

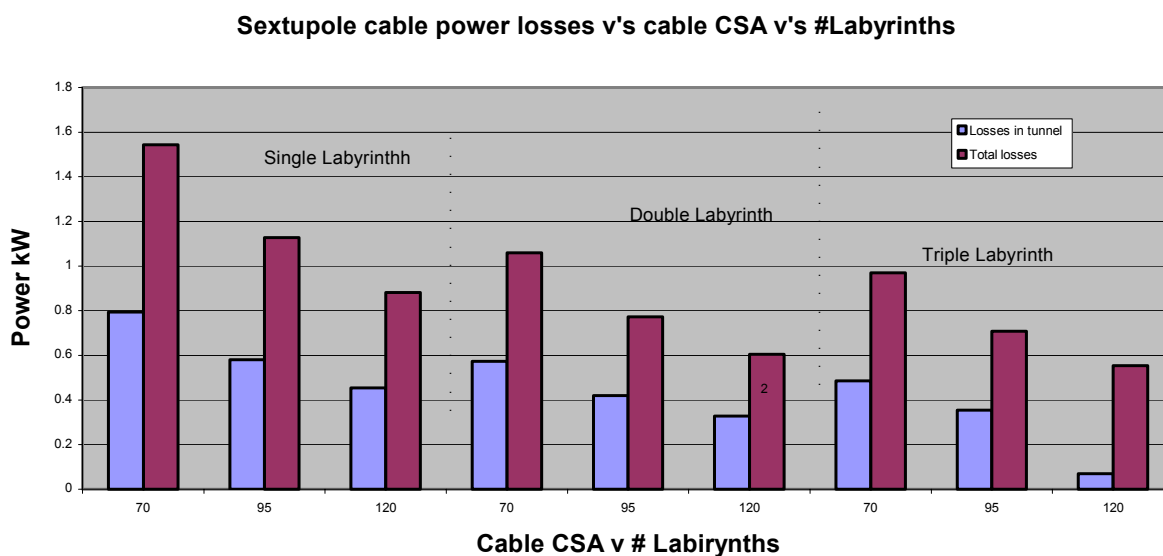


Figure 8.6-6 Comparison of power losses for labyrinth and cable size options

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Table 8.6-7, Table 8.6-8 and Table 8.6-9 tabulate the calculated results of actual average cable voltage drop due to maximum current flowing between power supply and the magnets. Also shown is the permissible voltage drop in the cable between power supply and magnet. In this instance the “rule of thumb” is being applied as both the 95mm² and the 120mm² cable comply. However the voltage drop still exceeds that of the design value, a 120mm² cable providing the closest match.

Table 8.6-7 Comparison of designed and calculated voltage drop for single labyrinth

Average cable length 35 m. Assuming max current flow (100 Amps)		Design volt drop allowed	One labyrinth using 70mm ² CSA cable	One labyrinth using 95mm ² CSA cable	One labyrinth using 120mm ² CSA cable
Power supply output volts	Magnet terminal volts	(5%)	Average cable length V drop	Average cable length V drop	Average cable length V drop
11.4	9.87	0.57	2.21	2.10	1.26
15.3	13.22	0.77	2.21	2.10	1.26

Table 8.6-8 Comparison of designed and calculated voltage drop for double labyrinth

Average cable length 24m. Assuming max current flow (100 Amps)		Design volt drop allowed	Two labyrinth using 70mm ² CSA cable	Two labyrinth using 95mm ² CSA cable	Two labyrinth using 120mm ² CSA cable
Power supply output volts	Magnet terminal volts	(5%)	Average cable length V drop	Average cable length V drop	Average cable length V drop
11.4	9.87	0.57	1.51	1.10	0.86
15.3	13.22	0.77	1.51	1.10	0.86

Table 8.6-9 Comparison of designed and calculated voltage drop for triple labyrinth

Average cable length 22m. Assuming max current flow (100 Amps)		Design volt drop allowed	Three labyrinth using 70mm ²	Three labyrinth using 95mm ²	Three labyrinth using 120mm ²
Power supply output volts	Magnet terminal volts	(5%)	Average cable length V drop	Average cable length V drop	Average cable length V drop
11.4	9.87	0.57	1.39	1.01	0.79
15.3	13.22	0.77	1.39	1.01	0.79

8.6.6 Storage Ring Tunnel Temperature

The temperature within the area of the storage ring tunnel is an important parameter, and needs to be controlled to high accuracy. The emphasis is to reduce contributory factors at the design stage.

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Factors contributing to the temperature are; length of cable run, cross-sectional area of cable, cable route based on number and design of cable labyrinth into beam tunnel and number of terminations in the supply route.

Table 8.6-10 Cable Space Requirements

	Cable size mm ²	Outside diam mm	Number of cables per labyrinth	Overall space required (mm ²) for cable	Cable bend radius mm	Number of diameters for bend radius
Dipole cables	400	32	8	8192	192	6 (10 if possible)
	800	48	4	9331	288	
	1000	52	2	2704	312	
Quadrupole cables	120	16.2	20	5249	65	4 (10 if possible)
	185	20.4	20	8323	82	
	240	22.9	20	10488	92	
Sextupole cables	70	12.6	14	2223	50	
	95	14.7	14	3025	59	
	120	16.2	14	3674	65	

8.6.7 Cost Considerations

In any installation there has to be a balance between costs at the design and installation stage and the long-term consideration for running costs. This section of the DIAMOND project is no different, and the considerations here are:-

Initial procurement cost of increased dipole cable length against EM field cancellation

Initial procurement cost of increased dipole cable size against reduced losses and running costs

Initial procurement cost of increased quadrupole cable size against reduced running costs and implications on power supply design.

Initial procurement cost of increased sextupole cable size against reduced running costs and implications on power supply design.

Table 8.6-11 compares the cost of using the recommended cable and a cable one size down on running costs. At this stage cable costs are not available.

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Table 8.6-11 Running costs comparison

	Cable CSA mm ²			Running costs	Cable CSA mm ²			Running costs
	Recommended				One size down			
	CSA mm ²	Loss kW	Total number		CSA mm ²	Loss kW	Total number	
Dipole	4 x 400	68	x 1	100%	2 x 800	64	x 1	95%
Quadrupole	185	2.60	x 10 x 24	100%	120	3.7	x 10 x 24	142%
Sextupole	120	5.54	x 7 x 24	100%	95	7.08	x 7 x 24	127%
TOTAL		13x10 ⁶ (kW)		100%		9.5x10 ⁶ (kW)		132%

The following assumptions have been made in producing these cost estimates

- All cables will be single core non-armoured, welding type cable. Cable data based on Pirelli tables to BS 7271.
- Cables will be run on perforated tray or ladder as per Tables 4D1A/1B and 4E1A/1B method 11; IEE 16th Edition (BS 7671) Requirements for Electrical Installations 2001.
- Only cable losses accounted for.

8.6.8 Recommendations

(a) Dipole Power Supply to Magnets cabling

Table 8.6-1 and Figure 8.6-4 indicate that running the dipole magnet cable along the lattice circumference and using four cables of cross-sectional area 400mm² provides for the best power loss performance. However a further issue of stray EM fields also requires consideration. Taking the second option of routing the cable along the inside of the inner tunnel wall and running the cables out to the magnets and back, cancellation is likely to be achieved, reducing these effects in the area where they could be most harmful to the sensitive instrumentation. Recommendation therefore would be to use this second option taking into account the extra cost, increased voltage drop, and associated 20kW of power dissipated in the storage ring tunnel.

(b) Quadrupole & Sextupole Power Supply to Magnets cabling

The options for consideration here are slightly more complex due to not only cable size and number considerations but also the option of one, two, or three cable access routes, (labyrinths), into the storage ring tunnel from the power supply rack areas. From scale drawings, estimates have been made of the lengths of cable runs and associated cable power losses for the different labyrinth arrangements. These are shown in Table 8.6-2 & Figure 8.6-5 for quadrupole magnets and Table 8.6-6 & Figure 8.6-6 for sextupole magnets.

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(c) Quadrupole System

From the charts it can be seen that there is little to choose between the two or three labyrinth option. However, the three-labyrinth option lends itself to improved cable distribution providing for ease of installation, less congested cable trays and reduced cable costs. In making the selection of cable size, consideration needs to be given to a number of points, power loss, cost and ease of installation. Dealing with the issue of power loss, then in the case of the Quadrupole magnet cables, 240mm²/triple labyrinth provides the best solution. However, there may be a cost implication, but consideration for the 1mm² of cable cross-sectional area per Amp rule requires that the cable size should be at least 185mm². The impact of this is one of cost and installation in the form of bend radius considerations and increased cable space requirements.

(d) Sextupole System

In the case of Sextupole power supply to magnet cables only 120mm²/triple labyrinth option provides the lowest voltage drop to meet the design criteria. Power losses are minimised but increased cable costs and space requirements need consideration. The 1mm² of cable cross-sectional area per Amp rule requires that the cable size should be at least 95mm².

8.6.9 Summary

In summary the recommendation of this report is to: -

Labyrinth Options – Overall the three-labyrinth option provides the optimum cable distribution, minimising average cable lengths reducing losses.

Dipole System - Install 4 x 400mm² cables taking the inner wall route for reasons of minimising magnetic interference close to the beam-line and to ease installation by reduced bend radius and ease of handling.

Quadrupole System – Installing 240mm² cables, design voltage drop requirement can be met, see Table 8.6-3, Table 8.6-4, and Table 8.6-5. However using 185mm² only just exceeds the design specification and would ease the space requirements issue, see Table 8.6-7, Table 8.6-8, and Table 8.6-9.

Sextupole System – Installing 120mm² cable meets the allowed voltage drop specification and exceeds the current carrying capacity complying with the standard design rule of thumb for cable current carrying capacity. The next cable size down increases the cable voltage drop by 30% above the required design value.

Installation and running costs – In providing cable sizing sufficient to stay within the design voltage drop specification and to minimise operating costs due to cable losses, there will be an increased up-front cable installation cost. However, the longer-term issue of running cost needs to be considered and comparisons made

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between the two issues. Taking the triple labyrinth as the option of choice and comparing operating costs for Dipole, Quadrupole and Sextupole cable size options, of the recommended and one cable size down, Table 8.6-11 has been produced. This shows the comparison between the two cost considerations.

Power supply design - In the event that the selected cable is not sized to reduce voltage drop to at or below the designed value for the magnets, then the power supply terminal voltages will have to be increased to compensate.

Operating costs due to magnet cable losses - Installing cable sizes appropriate to staying within, or as close as is reasonably practicable to the designed voltage drop criteria, significant operating cost savings can be achieved.

8.7 COMPLIANCE WITH HARMONIC RECOMMENDATIONS

8.7.1 Introduction

The sextupole and quadrupole power converters for DIAMOND will have a total power load on the electricity supply of approximately 1.5 MW. There will be 408 identical power converters required for these magnets using three phase and possibly some single phase power supplies.

The input harmonics produced from these converters must be assessed and gauged against the Electricity Council's recommendations.

This section describes the method proposed for reducing the extent of supply harmonics introduced by the switch mode power converters.

The input stage of a dc power converter normally consists of a bridge rectifier. This may be 2 pulse for a single-phase unit, 6 pulse for a three-phase unit, or 12 pulse with two three-phase supplies produced by an integral phase shifting transformer. Depending upon whether 2, 6 or 12 pulse rectification is used, this rectification will introduce harmonics in the current drawn by the power supply.

The level of harmonics introduced by the rectification stage of the power converters can be controlled by the use of filters before the input stage to the power converter and by the configuration of the input transformer to the power supply.

The harmonic distribution of a single or three-phase power supply varies from manufacturer to manufacturer and according to loading.

In the case of single phase power supplies, the odd harmonics are significant. In the case of 6 pulse three phase rectification, the $6n \pm 1^{\text{th}}$ harmonics are significant. (where n is a positive integer) In the case of 12 pulse rectification of two 3 phase supplies, high values of current are seen at the $12n \pm 1^{\text{th}}$ harmonics.

8.7.2 Levels of current harmonics

The following tables detail the harmonic currents drawn by a typical power supply, which could be used for the diamond storage ring quadrupoles. It employs six pulse rectification of the three phase mains as the first stage. Table 8.7-1 lists manufacturer's data and Table 8.7-2 shows experimental data obtained by CLRC.

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Table 8.7-1 Manufacturer's test values of harmonics

Harmonic Number	40V, 150A, 6 kW output		40V, 75A, 3 kW output	
	Current (rms) Ih	Ih/If	Current (rms) Ih	Ih/If
1 (If)	9.62 A	-	4.89 A	-
5	1.39 A	0.14	1.67 A	0.34
7	2.22 A	0.23	1.4 A	0.28
11	0.86 A	0.09	3.37 A	0.68
13	2.42 A	0.25	2.94 A	0.60
Total rms	10.66 A	-	7.22 A	-
ATHD	43.06%		73.51%	

Table 8.7-2 CLRC test values of harmonics at a variety of loads

Harmonic Number	50A, 6.08V, 304W dc output		100A, 7.47V, 746W dc output	
	Current (rms) Ih	Ih/If	Current (rms) Ih	Ih/If
1 (If)	0.74 A	-	1.56 A	-
5	0.62 A	0.84	1.04 A	0.68
7	0.63 A	0.85	0.9 A	0.57
11	0.49 A	0.65	0.95 A	0.61
13	0.49 A	0.66	0.98 A	0.63
Total rms	1.45 A	-	2.63 A	-
ATHD	86.0 %		80.4 %	

Table 8.7-3 CLRC test values of harmonics at a variety of loads

Harmonic Number	100A, 12.12V, 1.21 kW dc output		150A, 11.21 V, 1.68 kW output		150A, 18.19V, 2.73 kW dc output	
	Current (rms) Ih	Ih/If	Current (rms) Ih	Ih/If	Current (rms) Ih	Ih/If
1 (If)	2.20 A	-	3.01 A	-	4.43 A	-
5	1.23 A	0.56	1.18 A	1.96	1.19 A	0.27
7	0.84 A	0.38	1.06 A	1.38	1.34 A	0.30
11	1.18 A	0.54	0.98 A	1.71	0.88 A	0.20
13	1.34 A	0.61	1.54 A	2.01	1.61 A	0.36
Total rms	3.37 A	-	4.10 A	-	5.48 A	-
ATHD	75.7 %		67.8 %		58.9 %	

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The current waveform for the 150A, 18.19V example is given in Figure 8.7-1 below. The load voltage and current that this waveform relates to is conveniently close to the quadrupole design value.

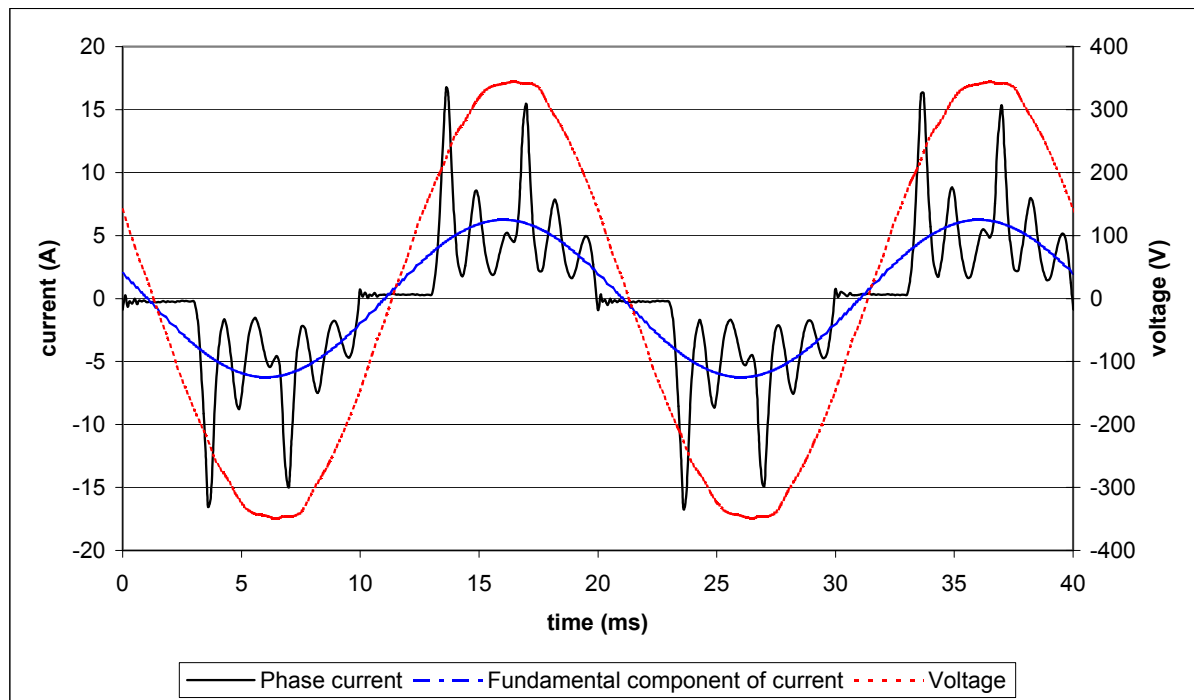


Figure 8.7-1 Mains current drawn by three phase supply employing 6 pulse rectification

8.7.3 Requirements of Engineering Recommendation G5/4 published by The Electricity Council

This document specifies the limits that apply to the harmonic emissions of the equipment connected to the mains supply. The recommendation classifies a consumer's load into one of three types based upon the total load and amount of harmonic emission, and the total pre-existing voltage distortion. These are known as Stage 1, Stage 2, and Stage 3 assessments.

A Stage 1 assessment is not appropriate to the diamond storage ring converters because the aggregate size of the equipment is greater than 16 A per phase, and the anticipated harmonic emissions exceed the certain values given for Stage 1 assessment in the G5/4 document. A Stage 2 assessment is most likely to apply in the case of the storage ring converters as it is expected that the Point of Common Coupling (PCC) with other consumers will be above low voltage but below 33 kV. In the event that the harmonic currents exceed the Stage 2 assessment limits, a Stage

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3 assessment will become necessary. On the assumption that the point of common coupling will be at 11 kV, the maximum permissible harmonic currents are given in table 12 of the recommendation. If these values are exceeded, a voltage distortion calculation will need to be performed and this will require knowledge of the system impedance.

The total load requirement of the quadrupole and sextupole power supplies is approximately 1 to 1.2 MW. Based upon the higher value and an efficiency of 80%, the total load drawn by the quadrupole and sextupole power supplies is 1.5 MW. This equates to a phase current of 80 A at 11 kV.

Based upon the experimental values of harmonic distortion shown in Table 8.7-3 of this report (for the 2.73 kW output), the harmonic currents drawn at the point of common coupling are as shown in Table 8.7-4.

Table 8.7-4 Predicted harmonic currents at Point of Common Coupling (11 kV) using 6 pulse conversion due to combined load of quadrupole and sextupole power supplies.

Harmonic Number	Current drawn at point of common coupling (rms per phase)	Limit in G 5/4 recommendation
1	80 A	-
5	21.6 A	6.6
7	24 A	7.4
11	16 A	6.3
13	28.8 A	5.3

It is clear from these values that some form of mitigation of the harmonic currents is required for the load to be acceptable to the supply authority.

8.7.4 Twelve Pulse Rectification

The use of a transformer with two separate secondary windings, one star and one delta to obtain two outputs, one being phase shifted by 30 degrees is well established. The effect of twelve pulse rectification is to reduce the magnitude of the 5th and 7th harmonics.

The effect of introducing 12 rectification upon the harmonics is shown in Table 8.7-5. These figures are based upon the experimental values obtained as shown in Table 8.7-2 and Figure 8.7-1.

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Table 8.7-5 Effect of introducing 12 pulse rectification

Harmonic Number	Current expressed as multiple of fundamental	
	6 pulse rectification	12 pulse rectification
5	0.27	0.062
7	0.30	0.091
11	0.20	0.20
13	0.36	0.36

The introduction of 12 pulse rectification has reduced the levels of 5th and 7th harmonics to acceptable levels. However, the levels of 11th and 13th harmonics are still unacceptable but it might be possible to satisfy the G5/4 recommendations using filters.

8.7.5 Twenty-four pulse rectification

Another possibility is to introduce twenty four pulse rectification. This can be achieved using 4 secondary windings which may be on the same transformer but are more likely to be on different transformers. The secondary windings would be phase shifted by 15 degree intervals and would supply the load to the quadrupoles and sextupoles of one quarter of the storage ring. The effect of the introduction of 24 pulse rectification upon the harmonics seen at the point of common coupling is shown in Table 8.7-6.

Table 8.7-6 Effect of introducing 24 pulse rectification

Harmonic Number	Current expressed as multiple of fundamental	
	6 pulse rectification	24 pulse rectification
5	0.27	0.048
7	0.30	0.041
11	0.20	0.01
13	0.36	0.10

This system would have a number of disadvantages in relation to the separation of multiple 3 phase distribution systems with phase shifts between systems. Further the harmonic currents introduced by these power converters will need to be considered in the light of all of the other power converters systems in use within the facility including the booster synchrotron, the r.f. system and the vacuum system.

8.7.6 Further work.

It is clear that further work is required to consider the effect of filters on the harmonic currents. In addition, the acceptable degree of harmonic current will depend upon the supply impedance from the distribution network.

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8.8 POWER CONVERTER THERMAL MANAGEMENT

8.8.1 Introduction

The power converters for the Storage Ring are housed in twenty four control and instrumentation areas (CIA), distributed evenly to match the lattice structure, with the exception of the Dipole power converter. This section considers the options available for cooling the power converter racks installed within these areas. The amount of heat generated is dependent upon the method of power conversion, the rating of the power supply and its operating load.

The switch-mode power converter is the preferred topology for the Quadrupole and Sextupole magnets, with efficiencies up to 85% when operated close to their specified maximum output level. On this basis there is a 15% power loss, resulting in heat generation within the power supplies and racks. The heat loss has to be controlled and this is achieved through cooling. This heat can be removed by air natural, air forced or water cooling. The calculated maximum total power loss per rack eliminates an air natural solution, but the advantages and disadvantages of the two remaining systems are assessed.

The thermal management system must be designed using the maximum loading figures, these are 6kW for the Quadrupoles and 2kW for the Sextupoles, then a total DC loading of 74kW per cell is expected. With an estimated efficiency of 85%, the calculated input power is 87kW. The total power loss from the units per cell is 13kW and will be dissipated within the racks.

8.8.2 Arrangement of Power Converters

The power converters types have been distributed evenly throughout the racks to minimise the losses and to match the lattice configuration. The maximum power lost in any rack is 3.88kW and contains three Quadrupole power converters and two sextupole power converters. This rack layout was designed with a single labyrinth access, but will be re-assessed for a three labyrinth access. The final layout will be optimised before the specifications are written. The specification for the power converters will be for a full rack assembly, to ensure that the rack thermal management system is included in the design. The performance of the converters is then the responsibility of the supplier and not the procurer. The thermal management is related to both the configuration and arrangement of the cables and the arrangement of the power converters within the racks.

Table 8.8-1 shows the thermal loading within the rack arrangement that is described in sub-section 8.5.2.

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Table 8.8-1 Thermal Loading of Power Supplies in Racks

Power supply family	Power supply DC rating	Designed operating current	Input power level at 85% efficiency	Power loss at 85% efficiency	Suggested Rack layout			
					Rack 1	Rack 2	Rack 3	Rack 4
					Controls	Quad	Quad	Quad
					Quad	Quad	Quad	Quad
Quad	6.0kW	181A	7.05kW	1.05kW	Quad	Quad	Sext	Sext
Sext	2.0kW	90A	2.35kW	0.35kW		Sext	Sext	
Heat loading per rack					3.15kW	3.85kW	3.15kW	2.8kW
Heat loading per cell					12.95kW			
Total heat loading for 24 cells					310.8kW			

The calculated rack losses are based on the maximum output rating of the converters, but nominal loads of at least 30% less can be expected. The preferred method of cooling for each power converter manufacturer were assessed, but proved inconclusive as both options were considered viable.

8.8.3 Cooling System

If the two systems are compared, then the water system appears to be 33% more efficient than the forced air solution. This is because a force air solution will still require air conditioning, to ensure the dissipated heat is removed from the area.

The water system has one less stage of efficiency losses, as it provides direct cooled water from the chiller that is pumped through the power converters. The returning water is specified with a calculated temperature rise of 5°C for maximum power converter losses.

The forced air-cooled system will not only require a large amount of power converter fans, but also rack fans to ensure circulation within the cabinets. This temperature rise then needs to be removed by the air conditioning system that is cooled by a chilled water system. The chilled water temperature needs to be regulated accurately, but is only providing secondary cooling, unlike the direct water-cooling.

A direct water cooling system is a more economic method of removing heat from the power electronics, and has the benefit of reducing the volume and weight of power converters compared with an equivalent air-cooled system.

If close control air conditioning was used it is very important that the load is kept as constant as possible. If the power converters are turned on and off or ramped this may cause room temperature instabilities. The power converter load is expected to be constant, as full energy injection is required, with no synchronisation of ramps.

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The initial start-up after a shutdown could cause fluctuations in the heat loading and may need some settling time.

The efficiency of both systems could be increased by combining the cooling requirements for the different areas, allowing the utilisation of a cooling tower. The system must also have built in redundancy, to allow maintenance without disruption to the converters.

A disadvantage of using a water cooling system is that not all the losses within the power converter are removed. Often with water-cooled supplies, there is still a cooling fan incorporated to remove the heat generated by chokes, electronics and passive components. Air conditioning at a lower level would still be required. The other problems are the installation of the water pipes, the hazards of mixing electronics and water and the effects on replaceability.

An investigation into the percentage of power removed by direct water against forced air needs to be considered, before deciding on the solution. The CIA has been specified with close air conditioning systems based on the maximum power loss from all the racks in the area.

8.9 POWER CONVERTERS FOR THE CORRECTOR MAGNETS

8.9.1 Overview

This section details the system requirements and the proposed solutions for the fast dynamic and slow dynamic corrector power converters associated with the Storage Ring.

(a) Slow dynamic correctors

The slow correction is generated from the back-leg coils on the Sextupole magnet. These provide vertical and horizontal dipole fields and if required skew Quadrupole fields. There are five coils per Sextupole magnet, evenly distributed, and with seven Sextupoles per cell, this equates to thirty five power converters. A total of 840 slow correctors are needed for the Storage Ring. Early calculations suggest that a frequency response, up to 5 Hz, with little attenuation and modest AC losses can be supported. The power converter performance will depend upon the vacuum vessel specification. This can produce high attenuation and corresponding power losses to field changes of this frequency.

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Table 8.9-1 Slow dynamic corrector power converter requirements

Sextupole length (m)	Nominal current (A)	DC voltage per coil (V)	Coil resistance at 60°C (Ω)	Power converter rated current (A)	Reactive voltage maximum (V)	Power per Coil (W)
0.3	4.5	7.2	1.6	5.0	3.9	42
0.2	4.5	5.6	1.2	5.0	2.6	28

The five back-leg coils will be individually powered with a common converter rated at 5.0 A, 15 V, taken into account both the DC and reactive voltages, and parameters for both Sextupole lengths. A frequency response from DC to 5 Hz is specified, with 100% modulation expected at 1 Hz.

(b) Fast dynamic correctors

The fast dynamic correctors are used in conjunction with the beam position monitors to correct for errors induced by motion and stray fields. These magnets apply both horizontal and vertical steering to the circulating beam. Their amplitude is controlled by the global feedback system.

They have a classic ‘window frame’ design that allows both horizontal and vertical dipole fields to be wound onto the same yoke. This design will require two power converters, one connected to the two horizontal coils in either a series or parallel arrangement, the other connected to the two vertical coils in either a series or parallel arrangement. Two magnets are positioned at the beginning and end of the straight sections, making a total of 4 per cell. Thus a total of 96 dynamic corrector magnets are required, with wide bandwidths.

The power supply ratings are based on the current required to produce the full 0.5 mR deflection in each plane. A maximum frequency response of 1 kHz is specified, but this is only necessary for small signal response. The voltage specification of the fast correctors is therefore based on the full deflection being available at a frequency of 50 Hz; above this value, the maximum amplitude response of the magnet will decrease inversely with the signal frequency.

8.9.2 Power converter performance

The power converter specification has been based on the preliminary calculated parameters, and on other accelerator requirements. The performance figures for different accelerators range widely. Modern accelerators have improved the stability and resolution requirements from that of the SRS by a factor of at least ten. The parameters listed in Table 8.9-2, have a high specification, but are best estimates, until the detailed design is completed.

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Table 8.9-2 Power Converter Parameters for Dynamic Correctors

Parameters	Slow dynamic correctors	Fast dynamic correctors (based upon each pair of windings being connected in parallel)
Number of power converters	840	192
Current (nominal)	5 A	2.4 A (1.2 A per coil)
Current (minimal)	0 A	0 A
Voltage	15 V (DC max 7.2 V)	200 V (rms per coil)
Operating quadrants	4 Q	4 Q
Dynamic bandwidth	0 to 5 Hz	3 to 1kHz
Max frequency for 100% steering	1 Hz	50 Hz
Stability (100 s to 100ms) referred to In	15 ppm	15 ppm
Stability (0 s to 100ms) referred to In	15ppm	15ppm
Accuracy referred to In	100ppm	100ppm
Reproducibility long term	100ppm	100ppm
Resolution referred to reference	30ppm	30ppm

There are two types of power converter topology available for this application these are linear and switch-mode. The linear system will provide a low ripple and a low noise solution, but size and efficiency will increase significantly. The low power levels required for these units will minimise these disadvantages. The performance of the converters is the critical parameter.

In a modern accelerator, switch-mode technology is normally preferred, as it not only achieves the specification required, but offers a compact, light weight and efficient solution.

A number of companies were contacted to assess the availability of these power converters and the proposed solutions are presented as rack assemblies.

The most compact solution is housed in a 6U eurocard subrack with a modular architecture. An important feature of this design is the ability to change a module during operation, and not disturb adjacent channels in the same crate. This will improve the overall availability of the accelerator, since in most cases the beam lattice can tolerate the loss of a single corrector, but could not handle the loss of an entire crate of correctors during the repair.

E.8 MAGNET POWER SUPPLIES

It is expected that the individual modules will provide DC to DC conversion with either dedicated unipolar DC sources or unipolar bulk DC power supplies feeding a number of units (ten or fifteen). There are cost implications, performance and design considerations for both options, which need to be investigated further before a final decision is made. The output is bipolar and is achieved by a standard H bridge for switch-mode solutions and typically a class B amplifier for linear.

The 1000 plus corrector power converters required for Diamond have the potential to be a major factor in its future operational efficiency. It is important during the design stage to ensure high MTBF, by minimising complexity and component count and employing a proven technology.

As there is a high converter count a comprehensive diagnostic facility becomes a vital asset in minimising accelerator downtime. The inclusion of a transient analyser for all units has significant cost implications, but is considered a good investment.

The total system bandwidth depends on the power converter technology, load requirements, vacuum vessel specification and significantly the control system. The fast corrector requires bandwidths of up to 1kHz for small signal response, but the external control system update rate is only specified as 2kHz. This means that the realistic closed loop bandwidth is only 100Hz.

A typical arrangement for the dynamic corrector power supply modules is shown in Figure 8.9-1. This consists of a switch-mode topology mounted in a 6U eurocard subrack with a modular architecture. This technology typifies the compact and lightweight design that can be incorporated for the low power levels associated with the dynamic correctors. If this were compared with a linear power supply rack layout, the space occupied would be more than doubled, and an additional rack would be required. The overall efficiencies of the unit are maximised with a switch-mode unit.

PART E: STORAGE RING

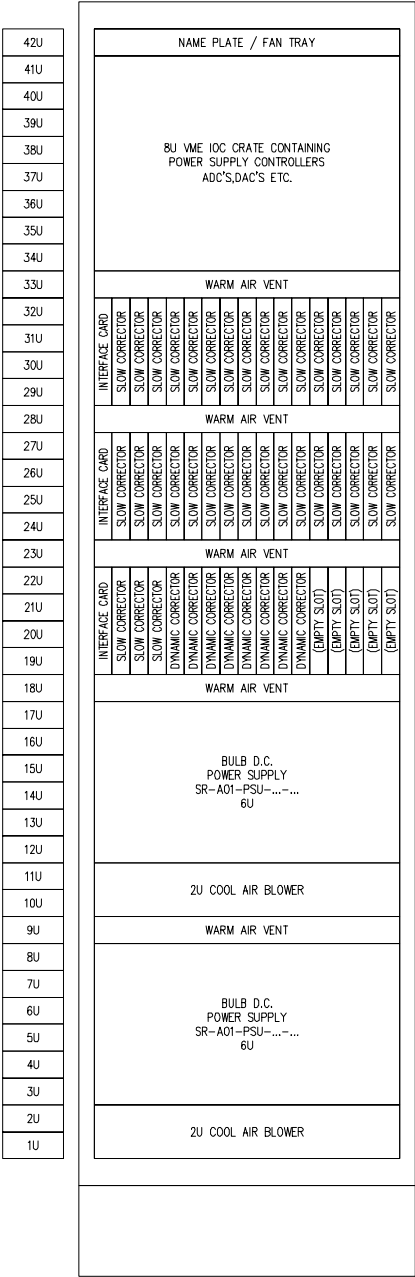


Figure 8.9-1 Typical Rack Layout for Dynamic Corrector Modules

F.1 Electron Gun

1.1 INTRODUCTION

The electron gun will be purchased from industry, and will be the subject of a performance specification. It will consist of the electron gun itself, together with the high voltage supply, pulser system, and complete diagnostics.

1.2 ELECTRON GUN

The electron gun will be a thermionic triode with Pierce geometry. As the storage ring will be capable in operating in a number of modes, such as all bunches filled (multi bunch), gapped beam, single bunch and hybrid mode, the gun needs to produce the required pulse trains. It will also be required to perform top-up injection.

For single bunch operation the cathode will be pulsed with respect to the grid, and the maximum pulse width will be 1ns, with a charge of 1.5nC. In the multi bunch mode either the cathode will be pulsed with respect to the grid or the grid will be modulated at 499.654 MHz with respect to the cathode.

1.3 HIGH VOLTAGE POWER SUPPLY

The gun high voltage power supply will be a pulse power supply with a flat top of 2 μ s and a repetition rate between 1Hz and 10Hz. The voltage will be variable between 70kV and 100kV.

1.4 DIAGNOSTICS

There will be two principal diagnostic monitors associated with gun current, a retractable coaxial Faraday Cup and a Bunch Charge Monitor. Both will be installed immediately downstream of the gun.

Output from the Faraday Cup will provide real time broadband oscilloscope pictures of the gun pulse RF structure, to facilitate optimisation of pulse form. The Beam Charge Monitor, measuring average gun current, will assist in optimising maximum beam. This latter monitor will be a Bergoz Electronics instrument, the same model as that to be employed for user request bunch charge patterns (Section E4), but the continuous average version, rather than the integrate-hold-reset version. It will also give an indication of the decay in the electron emissive efficiency of the gun with time.

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1.5 VACUUM

The Gun is expected to be supplied as a complete assembly from a manufacturer. Therefore the detail of the vacuum system will be a matter of discussion with that manufacturer. However, the approach of the diamond Project should be that the diamond Project will type approve particular pumps, gauges, valves, etc., which will most likely be supplied on free issue to the gun manufacturer.

In any case, the Gun vacuum system should essentially be a clean, all metal system with an operating pressure in the region of 10^{-8} - 10^{-9} mbar

F.2 Linac

2.1 INTRODUCTION

The linac will be purchased from industry, and will be the subject of a performance specification. It will consist of prebunching and bunching cavities, accelerator sections, RF supplies with modulators, focussing and steering magnets, controls and complete diagnostics.

As the storage ring will be capable in operating in a number of modes, such as all bunches filled (multi bunch), gapped beam, single bunch and hybrid mode, the gun will have to produce the required pulse trains. The injection system will also be capable of performing top-up injection.

2.2 RF FREQUENCY

The Diamond master oscillator frequency is 499.654MHz and the linac frequency will be synchronised to this. The frequency of the linac will be 2997.924MHz.

2.3 LINAC ENERGY

The linac output energy is determined by the required injection energy of the booster synchrotron. The required magnetic field at injection and the design of the booster magnet power supply require the linac energy to be in the region of 100MeV.

2.4 LINAC SPECIFICATION

2.4.1 Single bunch mode

The beam parameters for single bunch operation are given in the table below.

Table 2.4-1 Single bunch beam parameters

Max. Bunch train width (nS)	1
Charge in single bunch (nC)	<1.5
Energy (MeV)	>100
Pulse to pulse energy stability (%)	<0.25
Relative energy spread (%)	<0.5 (rms), +/- 1.5 (fullwidth)

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Normalised Emittance (1σ) ($\pi\text{mm mrad}$)	<50 (both planes)
Single bunch purity (%)	0.01
Repetition Rate (Hz)	1 minimum, 10 maximum

2.4.2 Multi bunch mode

The beam parameters for multi bunch operation are given in the table below.

Table 2.4-2 Multi bunch beam parameters

Max. Bunch train width (μS)	1
Charge in single bunch (nC)	<3
Energy (MeV)	>100
Pulse to pulse energy stability (%)	<0.25
Relative energy spread (%)	<0.5 (rms), +/- 1.5 (fullwidth)
Normalised Emittance (1σ) ($\pi\text{mm mrad}$)	<50 (both planes)
Single bunch purity (%)	0.01
Repetition Rate (Hz)	1 minimum, 10 maximum

2.4.3 Top-up mode

The linac will be capable of performing top-up injection. In this mode the storage ring beam current will be kept constant to 10^{-4} by frequent injections from the injector system.

2.5 VACUUM

The Linac is expected to be supplied as a complete assembly from a manufacturer. Therefore the detail of the vacuum system will be a matter of discussion with that manufacturer. However, the approach of the diamond Project should be that the diamond Project will type approve particular pumps, gauges, valves, etc., which will most likely be supplied on free issue to the linac manufacturer.

In any case, the Linac vacuum system should essentially be a clean, all metal system with an operating pressure in the region of 10^{-8} - 10^{-9} mbar

2.6 DIAGNOSTICS

2.6.1 Introduction

The diagnostic systems for the DIAMOND LINAC will be most challenging, due to the vast dynamic range that has to be covered due to the different operational modes. These are Single bunch, multi-bunch, and top up mode. In these various regimes, charge currents (per bunch) will vary from less than 1pC to less than 2 nC. A combination of diagnostics systems, similar to those specified for the Swiss Light Source (SLS) will provide sufficiently for the requirements of this accelerator.

Current related measurements electron beam parameters such as bunch charge, 'micro' bunch length and duration of the 'macro' bunch train are particularly important following the initial electron generation by the electron gun and in the bunching section. Average current, transmission and transmission efficiency are measured and optimised throughout the LINAC. The following diagnostics monitors are used to perform these current related measurements.

2.6.2 Faraday Cup

A coaxial Faraday cup, which can be moved into the beam through a pneumatic actuator and hence is a destructive diagnostic to the beam, allows the determination of the micro as well as the macro bunch configuration of the electron beam directly following the gun.

This is designed as a 50W device with a bandwidth of 4 GHz. The measured beam signals are transmitted directly into high quality coaxial cable and fed into an RF multiplexer before display on a diagnostic oscilloscope.

2.6.3 Wall Current Monitor

Whereas the Faraday cup is a destructive diagnostics device, which will mainly be used during gun tests and optimisation, a wall current monitor represents a non destructive monitor which measures the micro as well as the macro bunch configuration behind the electron gun during normal LINAC operation. It consists of a ceramic gap, bridged by 13 resistors in parallel, resulting in a total gap resistance of 1W. In addition a highly inductive ferrite core is placed around the gap in order to expand the lower limit of the bandwidth. A gap voltage, which is proportional to the image current flowing along the vacuum chamber, is detected at the resistors. It fully reflects the longitudinal charge distribution with a bandwidth as high as 4GHz and a cut-off frequency of < 100 kHz. This signal can be sent down high quality coaxial cable for analysis on oscilloscope.

2.6.4 Bunch Charge Monitors (BCMs)

Bunch Charge Monitors in front of the first structure and behind the second structure of the LINAC measure the average current and the transmission as well as the

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transmission efficiency with relatively high accuracy and can resolve to less than 60pC of charge. They are standard commercial diagnostic devices from Bergoz, which are fundamentally acting like current transformers having a tape wound core of high permeability metal alloy. By integrating the secondary current over the bunch duration this will measure a fraction of the beam charge. After some amplification and scaling, a sample and hold circuit in the front end electronics holds the signal for reading by an ADC card within the LINAC control system.

2.6.5 Electron Beam Position Monitor

EBPMs for the LINAC will be of the quarter wavelength directional stripline type, constructed to be low Q resonant at 500MHz and optimised for the beam aperture available. This is necessary to maximise the signals for the processing electronics, since the potentially small currents produced during top up mode injection will not provide adequate coupling and hence signals for detection. This design will allow the implementation of the commercial I-Tech EBPM detector in its First turn/LINAC pulse mode (please refer to Chapter E4. Diagnostics) without any modification.

2.6.6 Optical Monitors

Optical monitors similar to those of the SLS devices will be installed in the LINAC system to measure beam position as well as transverse beam parameters like emittance, energy and energy spread. All optical stations will have multi stage pneumatics. This will allow either a highly sensitive YAG:Ce detector to visualise the transverse beam distribution during commissioning or an Al-foil for production of transition radiation (TR) during low current top-up mode. The optical part of TR represents a linear radiation source, which is used for the measurement of transverse electron beam parameters. The coherent, far infrared part of TR can be used for controlling of the bunching process in the LINAC as well as for bunch length measurements.

F.3 Booster Synchrotron

3.1 INTRODUCTION

A programme of work was undertaken to identify the best technical solution to the requirements for the DIAMOND booster, including performance, procurement, installation and operation issues. The following list of criteria were developed against which the alternative booster concepts could be tested:

- Capital Cost
- Running Cost
- Procurement Issues
- Installation Complexity
- Commissioning Complexity
- Operational Complexity
- Injection Issues:
 - Repetition Rate
 - Injection Efficiency
 - Booster Emittance
 - Injection Energy
 - Coupling
- Layout Issues:
 - Number of Buildings
 - Shielding Requirements & Cost
 - Tunnel Logic:
 - Single Tunnel
 - Parallel Tunnel
 - Separate Tunnel
 - Services
 - Cranes
 - Transfer Line Design
- Power Supplies
- Booster / Storage Ring Interaction
- RF System Implications
- Upgrades (Future Usage)

Not all of these issues are fully dealt with in this report, with some remaining to be resolved as part of the procurement phase.

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3.2 TUNNEL LOGIC

For installation and operational reasons, it was deemed necessary to be able to work on and operate the DIAMOND storage ring and booster synchrotron independently. The choice of tunnel logic was therefore between a separate building for the booster synchrotron (with its own self-sufficient radiation shielding provision), or a layout which utilised the inner shield wall of the storage ring as the outer shield wall of the booster.

A previous DIAMOND Booster Working party had reported [1] on the relative economic impact of choosing a large booster synchrotron, with many smaller (and therefore cheaper to purchase and operate) magnets, in the style of the Swiss Light Source (SLS). This concluded that unless the booster synchrotron could share the same tunnel as the storage ring, there was no overall economic benefit from a large circumference.

Thus the booster synchrotron will be housed in an independent building with its own bespoke shielding. In order to maximise the space available for experimental users and to make best use of the land available, it is then clear that the booster synchrotron should be located within the centre of the annular building housing the storage ring.

There was therefore considerable scope for optimising the booster synchrotron design free from constraints of a non-technical nature.

3.3 LATTICE DESIGN

3.3.1 Introduction

The evolution of the lattice design is recorded in [2]. Because of the concentration of effort on the storage ring design, and the plan for the procurement of the booster synchrotron to proceed via a turn-key contract, much of the detailed booster synchrotron remains to be completed. Thus the lattice outlined here is a concept only and gives a basis from which an actual booster design can be developed. Thus some aspects of the design still remain to be defined, such as whether separate sextupoles will be included, but these issues will also be addressed as the more detailed concept is developed.

3.3.2 Design Requirements

The outline design requirements that the DIAMOND booster synchrotron must satisfy are shown in Table 3.3-1:

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Table 3.3-1 Booster synchrotron design requirements.

Injection Energy	~ 100	MeV
Extraction Energy	3	GeV
Maximum Beam Emittance	150	nm rad
Repetition Rate	1 ~ 10	Hz
Nominal Current	15	mA
Quantum Lifetime	~ 10	s

3.3.3 Proposal

The DIAMOND booster synchrotron is a two-fold symmetric missing dipole magnet design with 22 cells. The missing dipole sections are to accommodate the injection and extraction system as well as the RF system. There are 36 dipole magnets and 44 quadrupole magnets in the entire lattice. There are no sextupoles magnets. It is assumed that the beam is injected into the booster at 100 MeV and ramped up to 3 GeV with a repetition rate of ~5 Hz.

3.3.4 Super-Cell Layout

The total circumference of the booster is 157.3 m. Each super-period comprises of three different types of cell, A, B, and C, shown in Figure 3.3-1, Figure 3.3-2 and Figure 3.3-3.

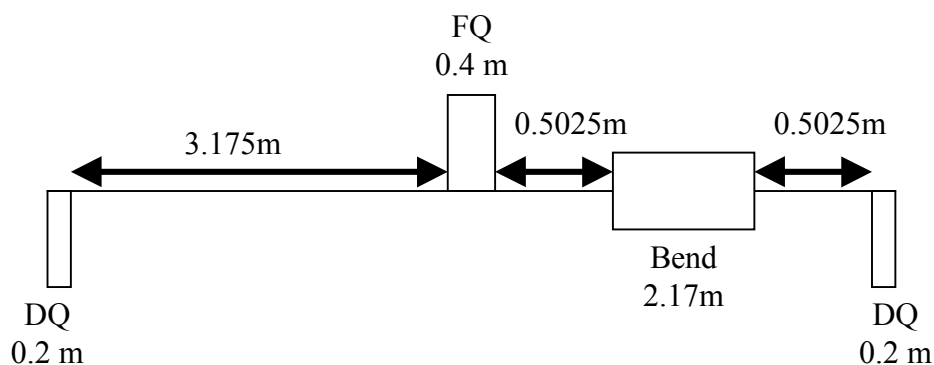


Figure 3.3-1 Booster synchrotron cell type A.

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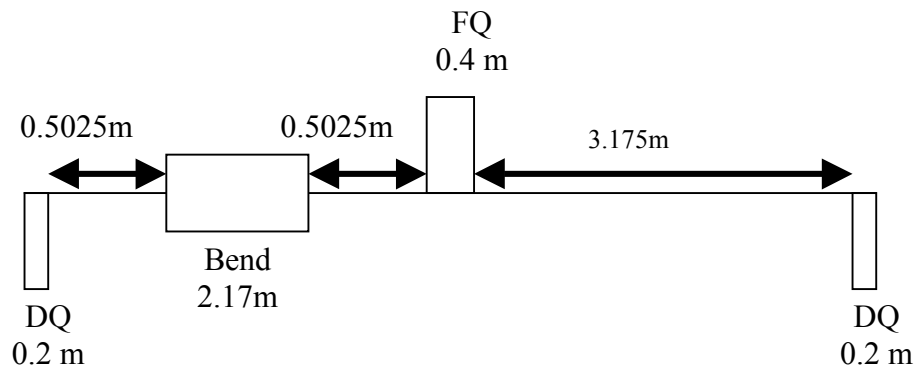


Figure 3.3-2 Booster synchrotron cell type B.

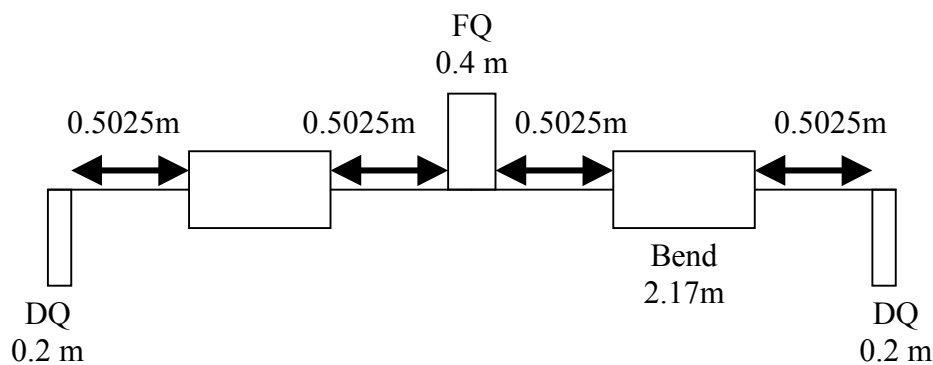


Figure 3.3-3 Booster synchrotron cell type C.

Arranging the cells in the following order forms one super-period of the booster:

A - A - C - C - C - C - C - C - C - B - B

3.3.5 Tune Point

A tune point was chosen based on the additional criteria in Table 3.3-2, and the need to keep the working point away from any low-order resonance lines.

Table 3.3-2 Tune point selection criteria.

F-Quadrupole Field	<17	T/m
D-Quadrupole Field	<17	T/m
Maximum Radial Beta	<20	m
Maximum Vertical Beta	<20	m

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The chosen tune point is at $Q_x = 6.825$ $Q_y = 4.57$, and can be seen in the resonance diagram Figure 3.3-4.

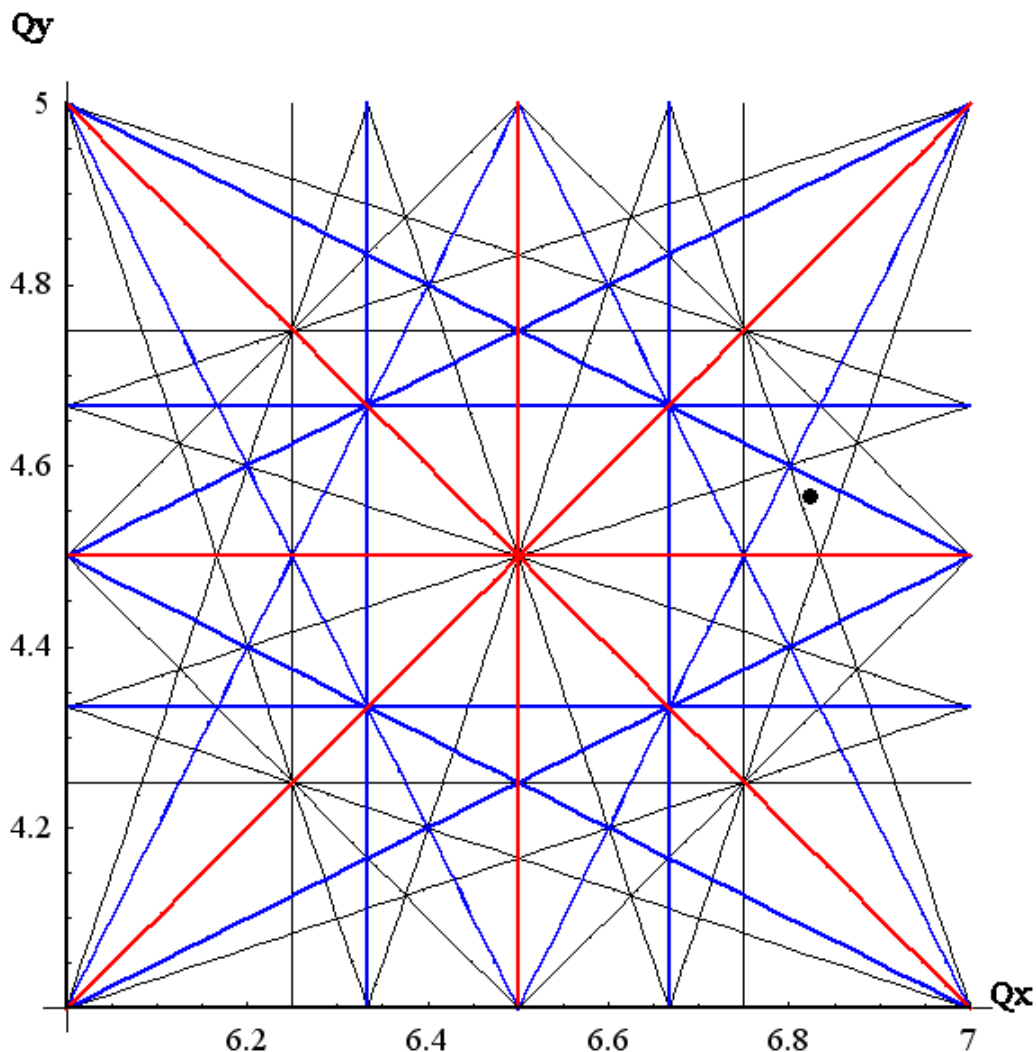


Figure 3.3-4 Resonance diagram (to 4th order) and the chosen tune point.

3.3.6 Lattice Parameters

At the selected tune point and 3 GeV, the magnet strengths are shown in Table 3.3-3, and the lattice parameters are shown in Table 3.3-4.

Table 3.3-3 Magnet parameters at the selected tune point and 3 GeV

Dipole Length	2.17	m
Dipole Field	0.804	T
F-Quadrupole Field	11.50	T/m
D-Quadrupole Field	-9.44	T/m

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Table 3.3-4 Lattice parameters at the selected tune point.

Momentum Compaction Factor	0.02782	
Energy Loss/turn	576	keV
Radial Oscillation Damping Time	0.0054	s
Vertical Oscillation Damping Time	0.0055	s
Energy Oscillation Damping Time	0.0027	s
Vertical Chromaticity	-6.212	
Horizontal Chromaticity	-8.359	
Radial Emittance	144	nm rad

The lattice functions are shown in Figure 3.3-5.

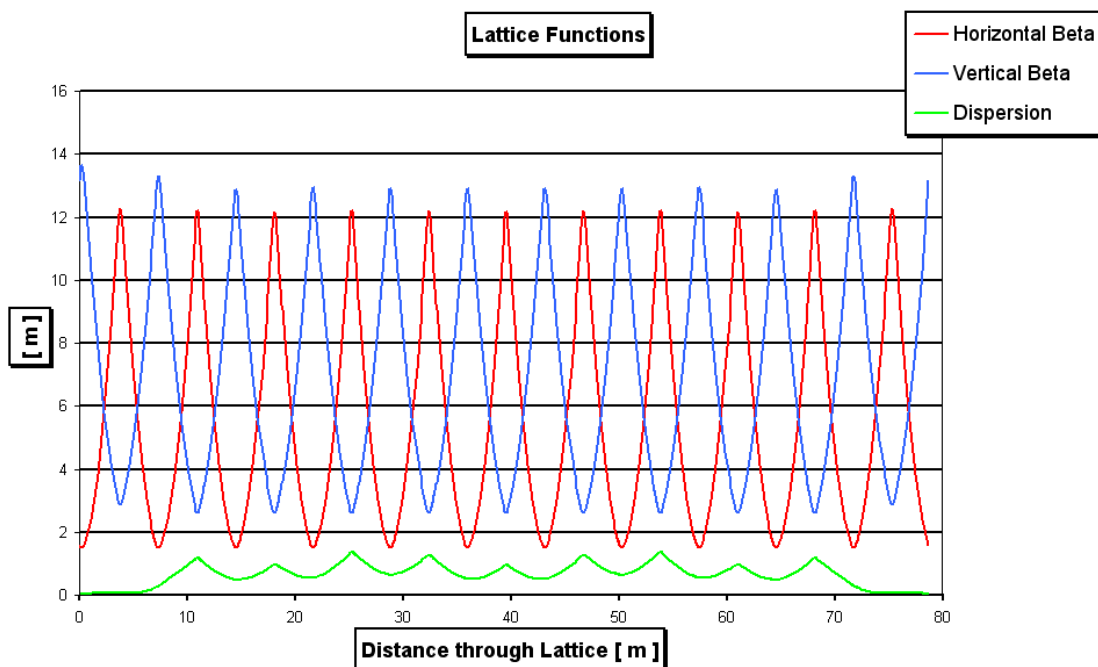


Figure 3.3-5 Lattice functions.

3.4 HALF APERTURE REQUIREMENTS

3.4.1 Beam size

It has been assumed that at injection into the booster the radial and vertical emittance of the beam from the linac is 1000 nm rad. The momentum spread is assumed to be 0.15%. From these assumptions and the lattice functions the beam sizes were calculated and are shown for one super-period in Figure 3.4-1.

F.3 BOOSTER SYNCHROTRON

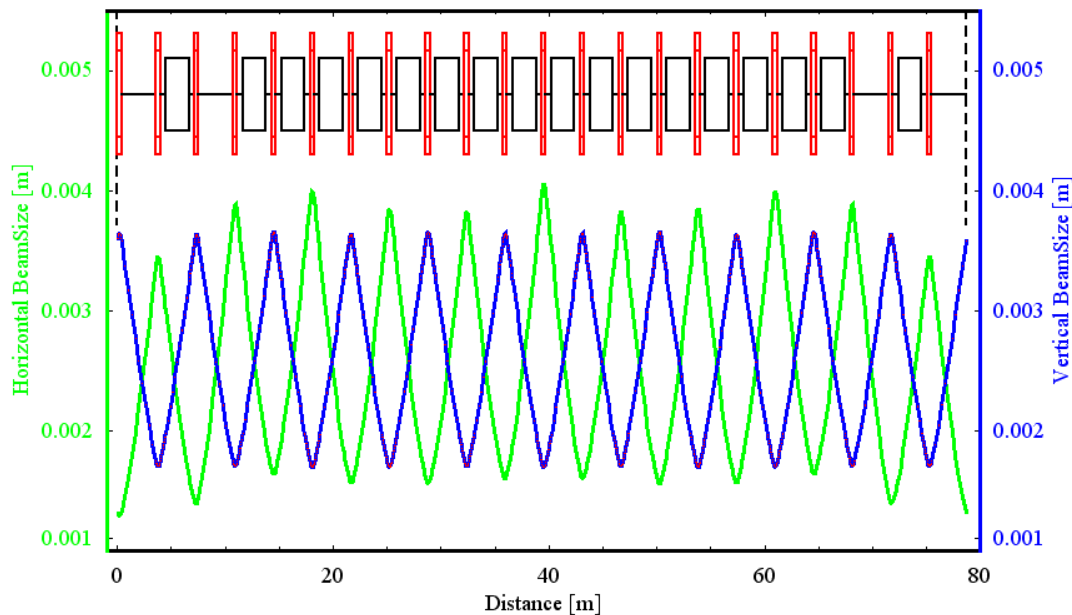


Figure 3.4-1 Beam sizes through one super-period.

As can be seen the maxima and minima of the beam size occurs through the quadrupoles. For the dipole aperture we are interested in the maximum beam size through the dipole. From the data for Figure 3.4-1 the maximum beam size through the dipole is shown in Table 3.4-1.

Table 3.4-1 Maximum beam size in the dipoles.

	Horizontal	Vertical	
Maximum beam size in dipole	3.532	3.262	mm

3.4.2 Closed orbit with magnet errors

The closed orbit distortion due to random errors in quadrupole position, dipole position, dipole field and dipole roll angle for the lattice design were calculated [3]. The standard deviations of the errors are shown in Table 3.4-2.

Table 3.4-2 Standard deviations of assumed magnet errors.

Quadrupole Transverse Displacement	0.1	mm
Dipole Transverse Displacement	0.05	mm
Dipole Longitudinal Displacement	0.05	mm
Dipole Field Error	0.1 %	
Quadrupole Role Error	0.2	mrاد
Dipole Role Error	0.2	mrاد

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The maximum values of the closed orbit with magnet errors, both horizontal and vertical, was modelled in three hundred simulations, at the centre and the ends of each element in the lattice. The rms and the 95% confidence limit of the closed orbit errors were also calculated. For the dipole aperture we are interested in the maximum of the 95% confidence limit of the closed orbit errors through all of the dipoles in the lattice. This is shown in Table 3.4-3.

Table 3.4-3 Maximum value of 95 % confidence limit of the closed orbit error.

	Horizontal	Vertical	
Maximum of 95 % confidence limit	6.883	1.708	mm

3.4.3 Resultant half aperture requirement.

The half aperture required is equal to three times the maximum beam size through the dipole (Table 3.4-1) plus the largest value of the 95% confidence limit closed orbit error through the dipoles (Table 3.4-3). The resultant half aperture requirements in the horizontal and vertical planes are given in Table 3.4-4.

Table 3.4-4 Half aperture requirements in the horizontal and vertical planes.

	Horizontal	Vertical	
Half aperture requirement	17.478	11.460	mm

3.5 DIPOLE MAGNETS AND POWER SUPPLIES.

3.5.1 Introduction.

This section presents the design for the booster dipole magnets, based on the current booster lattice, and summarises the conclusions reached concerning the nature and repetition rate of the booster dipole power supplies.

It is currently envisaged that the booster will be capable of operating in a top-up injection mode and whilst this does not have direct ramifications on the magnet design, it leads to a strong preference for a switch mode power supply solution, which will provide greater flexibility compared to the more conventional inductive/capacitive resonant circuits used in the past. The switch mode power supply also promises lower capital cost and greater operational economy, so it is clearly a solution which should be strongly favoured. The impact on the magnet design is that stored energy in the dipole should be minimised, so that the equipment ratings in the switched system meets the specification of currently available commercial components. This requirement has been uppermost during the design of the booster dipole magnet.

F.3 BOOSTER SYNCHROTRON

To date, little effort has been expended on the design of the booster quadrupole magnets. This is because these magnets will be of a conventional nature and will not have the stringent aperture and geometry demands that dominate the detailed design of the storage ring quadrupoles. Additionally, quadrupoles have magnetic stored energy which is very much less than that of a dipole magnet; hence, with the dipole power supply configuration resolved, there will be no difficulty in obtaining similar systems for the quadrupole power supplies.

3.5.2 Magnet Parameters

The basic lattice design for the booster, as described earlier in this chapter, provides the parameters for the dipole magnet brought together in Table 3.5-1.

Table 3.5-1 Magnet parameters A.

Number of dipoles	36	
Dipole field at 3 GeV	0.8	T
Injection energy	100	MeV
Dipole field at injection	26.67	mT
Dipole magnetic length	2.17	m
Good field half aperture (vertical)	11.5	mm
Good field half aperture (horizontal)	17.5	mm

To determine the physical magnet gap, it is necessary to make an allowance for the vacuum vessel wall thickness and the beam/vessel and vessel/magnet tolerances. A booster vacuum vessel design has been studied and this indicates that an allowance of 6.5 mm needs to be added to the full beam-stay-clear aperture to accommodate the chamber; a further 1.5 mm is required for the vessel/magnet steel tolerance. It is envisaged that the booster dipole will be an 'H' type magnet; vacuum vessel access will be by removing the magnet top. Hence, when the gap dimension is being determined, no allowance is required for the passage of the vacuum vessel through the outer shimmed region of the pole. These considerations give the magnet parameters in Table 3.5-2.

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Table 3.5-2 Magnet parameters B.

Vertical beam aperture (total)	23	mm
Allowance for vessel and tolerances	8	mm
Magnet gap at centre	31	mm
Assuming amplitude linearity of	97	%
Required ampere-turns at 3 GeV	20,327	At
Required ampere-turns at 100 MeV	677.6	At

3.5.3 Finite Element Study of Magnet geometry

To establish the pole geometry necessary to achieve the required good field region and to provide values for the total magnetic flux (and hence inductance), the magnet design was studied using the finite element magneto-static code 'OPERA 2D'. The parameters resulting from the pole optimisation are given in Table 3.5-3, below; co-ordinates are for one half of the upper pole, the origin (0,0) being at the centre of the gap.

Table 3.5-3 Co-ordinates of the pole geometry used for F.E.A modelling.

x (mm)	y (mm)	Notes
0	15.5	Pole centre
25.000	15.5	Edge of shim
30.000	14.770	Commencement of shim plateau
35.000	14.770	End of shim
38.000	18.000	Pole side

The one-quarter cross section of the 'H' magnet used for the F.E.A. modelling is shown in Figure 3.5-1, below, whilst Figure 3.5-2 shows the predicted homogeneity in vertical flux density expressed as $\Delta B_y(x)/B_y(0)$.

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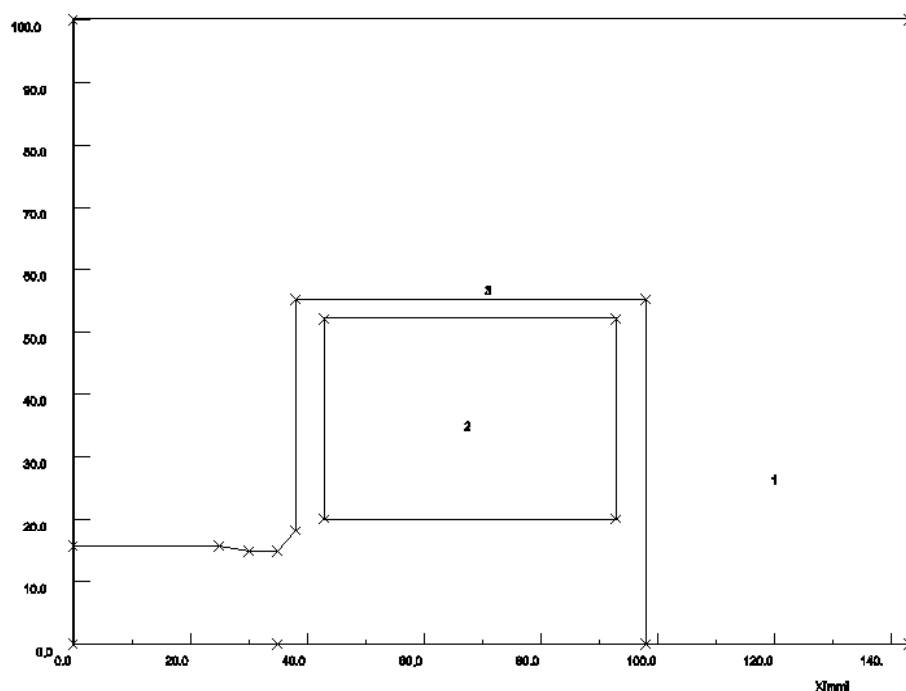


Figure 3.5-1 Geometry used to model $\frac{1}{4}$ of 'H' magnet dipole: region 1 is high permeability steel; region 2 is current carrying conductor; dipole symmetry has been imposed on the $y = 0$ and $x = 0$ axes.

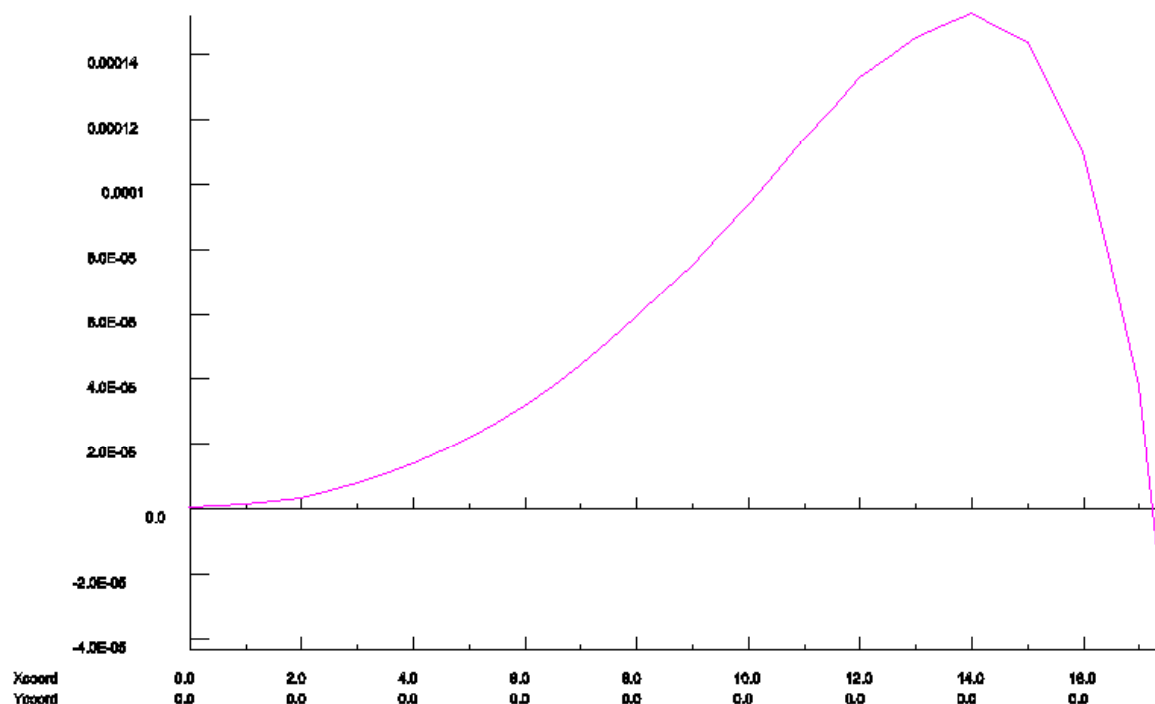


Figure 3.5-2 Quality of vertical induction B_y on the $y = 0$ axis predicted by the F.E.A. code, expressed as $\Delta B_y/B_y(0,0)$.

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The data in Figure 3.5-2 indicate the values for homogeneity in Table 3.5-4.

Table 3.5-4 Field homogeneity.

x (mm)	$\Delta B_y/B_y(0,0)$
14	$+ 1.4 \times 10^{-4}$
17	0
17.5	$- 4 \times 10^{-5}$

The total flux cutting the coil is indicated by the value of the vector potential at the centre of the coil; data from the F.E.A code gave the values in Table 3.5-5.

Table 3.5-5 Flux values from F.E.A. modelling.

Predicted vertical induction at (0,0)	0.839	T
Predicted flux cutting at coil centre	0.0468	Webers/m
Effective flux width across pole	112	mm

3.5.4 Power Supply Considerations

With the flux cutting the coil now determined, the reactive power rating of the dipole power supply can be established and the impedance match between magnet and power supply considered.

In the past, fast cycling synchrotrons have been powered using a resonant system, the so called White Circuit. More recently, advances in power electronics have allowed switch-mode circuits, which use capacitive energy storage, to be employed; in these circuits the magnet waveform and the direction of energy flow are controlled by the rapid switching of insulated gate bi-polar transistors (IGBTs) [4] [5].

This switch-mode circuit has a number of major advantages compared to the White Circuit:

- The switch-mode circuit stores energy in electrolytic capacitors; these provide by far the most economic devices for storing electrical energy;
- The White circuit requires a large inductor and resonating capacitors, which have high capital costs;
- The resonant components add significantly to the circuit losses and hence to operating costs;
- The switch-mode system has the flexibility to control the waveform of the current ramp in the dipoles from injection to peak field, within the limits of the voltage

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and current ratings of the system; the White circuit predisposes the use of a biased sine-wave which, in general, is not the optimum waveform for R.F. power or accelerator physics considerations;

- The White circuit has a high quality factor, hence presenting long (multi-second) time constants during switch-on and switch-off; this is highly inconvenient if discontinuous operation is required for top-up injection [6]; the switch-mode circuit can be halted immediately and subsequently re-activated in a small number of cycles.

The use of a switch-mode circuit to power the DIAMOND booster is therefore strongly favoured and the engineering feasibility of this approach has been explored. A study of the power ratings of currently available IGBTs has been carried out [7]. The results indicate that power electronic devices could meet the voltage and current ratings summarised above, providing the correct impedance match between the magnet and power supply was ensured by the correct selection of the number of turns on the dipole.

Discussions with a manufacturer, prominent in the field of accelerator magnet power converters and a potential supplier for the DIAMOND booster power system, confirmed that a switch-mode power source to meet the above ratings could be purchased.

3.5.5 Dipole Magnet Power Supply

On the basis of the data presented, it is clear that the preferred solution for the DIAMOND booster dipoles is a switch-mode power system, with electrolytic capacitor energy storage, cycling at a repetition rate of between 3 and 5 Hz. A schematic diagram of such a switch-mode circuit used to power the SLS [4], which would be suitable, with modification, for powering the DIAMOND booster dipole magnets, is shown in Figure 3.5-3. The stored energy in the DIAMOND booster is substantially higher than that in the SLS system, with a corresponding higher volt-amp rating. As indicated above, power semiconductors are now available at the higher power level. However, the circuit would need to be re-engineered and suitable electrolytic capacitor components identified.

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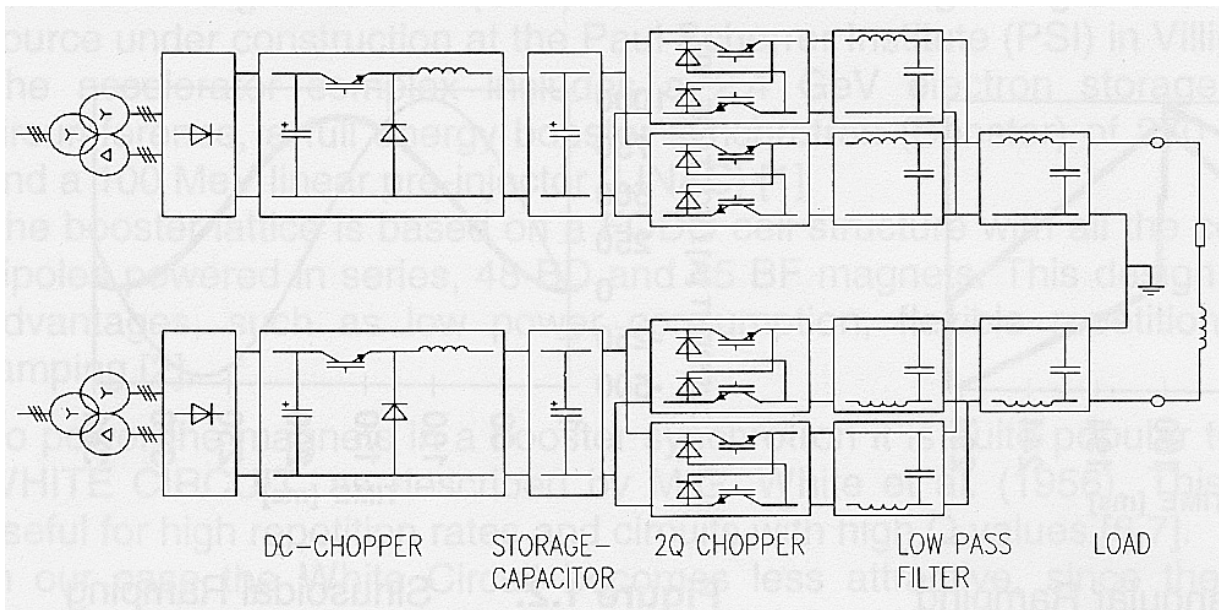


Figure 3.5-3 Schematic diagram of the switch mode circuit used to power the dipole magnets in the SLS booster synchrotron.

Investigations indicate that a maximum circuit voltage of 2 kV appears to be acceptable. Whilst the electrolytic capacitors used as the energy storage elements are typically rated at 500 V, various options are available for the DIAMOND booster configuration:

- The dipoles could be powered by four power converter units distributed within the series connected dipole circuit; these would need to be galvanically isolated from earth, with one of the four operating as a current source and the other three as 'slaved' voltage sources;
- Commercial contacts indicate that a single commercial unit, operating with a output voltage in the region of 2 kV, is technically possible and could be designed as a bespoke unit; this would need to have a centre point at earth potential, so that the magnet string voltages are evenly distributed about ground;
- A further alternative would be to use four separate coil bobbins on each magnet; these would be powered by four galvanically isolated power converters, each powering a series connection of individual magnet pancakes; this solution ensures current is shared identically between magnets, limits the voltage to 500 V per power converter and because of the nature of the components in the switch-mode system, does not lead to an appreciable increase in capital cost due to the multiplicity of power sources.

Coil and power supply parameters, based on two possible choices of turns on the dipole are presented below in Table 3.5-6. The final choice of the power supply design and impedance level will be made after further discussions with manufacturers.

F.3 BOOSTER SYNCHROTRON

Table 3.5-6 Magnet coil and power supply parameters for the booster dipole, for two options of numbers of turns per dipole.

Parameter	low turns	high turns	
Number of turns per dipole	16	20	
Peak current	1271	1016	A
D.C. and peak A.C. component	635	508	A
Total RMS current (for fully biased sine-wave)	778	622	A
Conductor cross-section	195	156	mm ²
Cooling hole diameter	5	5	mm
Conductor width	14.5	13.5	mm
Conductor height	14.8	13.0	mm
Total ohmic loss	188	188	kW
Inductance per magnet	2.52	3.94	mH
Inductance all dipoles in series	0.091	0.142	H
Peak stored energy all dipoles	73.3	73.3	kJ
Cycling frequency	5	5	Hz
Peak reactive alternating volts across circuit	1.81	2.26	kV

3.5.6 Conclusion

The parameters presented above are not finally frozen, for the various options for the procurement of the booster synchrotron may lead to adjustments in lattice and engineering design. However, such changes will certainly not result in any significant increase in ratings or dimensions. Hence the voltage and current figures presented above are not expected to be exceeded when the final design is established.

It is concluded that the present excitation requirements can be met using a switch-mode power converter design and that the booster magnets should be powered by such a switch-mode system, using electrolytic capacitors for energy storage and with a cycling repetition rate of 5 Hz.

PART F: INJECTOR ACCELERATORS

3.6 RF SYSTEM

The RF system provides the accelerating voltage and makes up the energy lost by the electron beam. The required accelerating voltage for a booster synchrotron is largely dependent on the required quantum lifetime and the momentum compaction, both given in Table 3.3-1.

To be able to achieve the nominal 15 mA booster beam current, 20 mA maximum is assumed for the RF system design. The design is dominated by the 3 GeV requirements, and further design work will be required to assess the performance during the energy ramp. However, Table 3.6-1 gives the main parameters of the proposed RF system for the booster synchrotron.

Table 3.6-1 DIAMOND booster synchrotron RF system parameters.

RF Frequency	MHz	499.654
Loss/turn	keV	576
Overvoltage		1.9
Cavity (number of cells)		5
Cavity Shunt Impedance	MΩ	12.4
Accelerating Voltage	MV	1.1
Synchrotron Frequency	kHz	~30
Quantum Lifetime	s	~45
Beam Power (@ 20 mA)	kW	11.5
Cavity Power	kW	48.5
Total RF Power (inc. losses)	kW	66

A multi-cell cavity, possibly 5 cells, with a shunt impedance of around 12 MΩ could be used as the accelerating structure. A modified PETRA cavity to be used by the Canadian Light Source and ELETTRA is suitable. The power source would be one of the modules that will be used in the Storage Ring RF system.

3.7 VACUUM SYSTEM

3.7.1 Approach

The design approach to the booster synchrotron is at present unclear. No substantive vacuum design work has yet been undertaken, except for some very preliminary work at an early stage in the DIAMOND project, primarily for costing purposes [8].

F.3 BOOSTER SYNCHROTRON

3.7.2 Model

The model assumed for the vacuum system comprises a single ion pump at the downstream end of each dipole magnet (i.e. 2 per cell), arbitrarily chosen to be 120 l sec⁻¹, with a 400 l sec⁻¹ ion pump on each RF cavity. A suitable distribution of total pressure gauges and residual gas analysers is assumed (including one per cavity).

The booster synchrotron is isolated from the gun/linac and from the transfer path by an all metal gate valve. Each cavity is also isolated by such valves. No other in-line valves are installed in this model.

3.7.3 Assumptions.

It is assumed that the booster is manufactured from stainless steel, is unbaked *in situ* but is pre-baked before installation. It can therefore be assumed that a thermal desorption rate of 10⁻¹⁰ mbar l sec⁻¹ cm⁻² can be achieved after some weeks of pumping. Provided that the construction of the booster vessels lends itself to the process, it is possible that most components could be air baked as part of the manufacturing process. This would reduce the thermal outgassing rate by 3 or 4 orders of magnitude and therefore pump down times should be very quick – days not weeks. If the system were made from aluminium, air baking is not a possibility and outgassing rates would be at least an order of magnitude higher than have been assumed.

Photon stimulated desorption will not be negligible in a 3 GeV machine, even though the currents are quite low. In the calculations, it was assumed that a desorption coefficient of 10⁻⁴ mol photon⁻¹ is realised. For unbaked stainless steel, this should be reached after a photon dose of the order of 10²² photon m⁻¹ [9] Photon fluxes are as calculated in [10]. At a flux of 1 × 10¹⁴ photon sec⁻¹ mA⁻¹ mrad⁻¹ (slightly higher than the values quoted) then the dose for the booster is 2 × 10¹⁸ photon sec⁻¹ m⁻¹ (at a distance of 1 m from the tangent point). Hence after a few hours of operation, this desorption rate should be obtained.

For the purposes of these calculations, it was assumed that the synchrotron radiation strikes the walls at essentially one point downstream of each dipole magnet and that the ion pump is located just at that point. It was also assumed that the full pumping speed was available, i.e. there is good conductance from pump to chamber. These assumptions are probably not justified, but within the parameters of these calculations the assumption is acceptable.

The final assumption is that a satisfactory pressure for booster operation is better than about 5 × 10⁻⁸ mbar. The cavities will require to be somewhat better than this, say at 1 × 10⁻⁸ mbar.

3.7.4 Pressure achieved

With this set of assumptions a working pressure of 2 × 10⁻⁸ mbar was calculated.

PART F: INJECTOR ACCELERATORS

3.7.5 Procurement Model

If the booster is supplied as a complete assembly from a manufacturer, the detail of the vacuum system will be a matter of discussion with that manufacturer. In this case, the approach of the DIAMOND project should be that the DIAMOND project will type approve particular pumps, gauges, valves, etc., which will most likely be supplied on free-issue to the booster manufacturer.

If a design and build model is chosen, then further detailed work is required to arrive at a satisfactory design of the booster vacuum system.

3.8 DIAGNOSTICS

3.8.1 Introduction

The diagnostic systems for the DIAMOND booster will be most challenging, due to the vast dynamic range which has to be covered due to the different operational modes. These are single bunch, multi-bunch, and top up mode. In these various regimes, charge currents (per bunch) will vary from less than 1 pC up to 2 nC. A combination of diagnostics systems, similar to those specified for the Swiss Light Source (SLS) should however prove sufficient for the requirements of this accelerator.

Current related measurements and electron beam parameters such as bunch charge are particularly important since beam losses will result in significant radiation being generated. Hence a combination of diagnostic systems will be implemented.

3.8.2 Faraday Cup

A coaxial Faraday cup, which can be moved into the beam through a pneumatic actuator and hence is a destructive diagnostic to the beam, allows the determination of the micro as well as the macro bunch configuration of the electron beam injected at the LINAC exit energy into the booster.

This device is designed as a 50 Ω device with a bandwidth of 4 GHz. The measured beam signals are transmitted directly via high quality coaxial cable into an RF multiplexer along with other LINAC and transfer path signals before display on a diagnostic oscilloscope. Its design will be similar to that following the LINAC.

3.8.3 Bunch Charge Monitors (BCMs) and Integrating Current Transformers (ICTs)

Two bunch charge monitors will be installed, immediately after the booster injection septum and immediately before the extraction septum. An ICT will also be installed to measure the booster beam current. The BCMs will be used in concert with those of the transfer lines to measure the average current as well as the transmission efficiency

F.3 BOOSTER SYNCHROTRON

with relatively high accuracy (<60 pC of charge). All devices are standard commercial diagnostic devices from Bergoz Instrumentation. Measurement of the transmission efficiency from stage to stage of the accelerator will allow interlocking of the pre-injector for beam losses, and thus help to reduce radiation levels to acceptable limits for the shielding.

3.8.4 Electron Beam Position Monitors (EBPMs)

EBPMs for the booster will be of the quarter wavelength directional stripline type, constructed to be low Q resonant at 500 MHz. This is necessary to maximise the signals for the processing electronics, since the potentially small currents produced during top up mode injection will not provide adequate coupling and hence signals for detection. This design will allow the implementation of the commercial I-Tech EBPM detector in its first turn/LINAC pulse mode (refer to Chapter E4. Diagnostics, for more information on this system) without any modification. The operation of the I-Tech detector is such that individual turn by turn tracking of the beam will produce tune signals directly, so no dedicated tune measurement system will be required.

3.8.5 Optical Monitors

An optical monitoring station similar to that used at the SLS will be installed to measure beam position as well as transverse beam parameters like emittance, energy and energy spread. Similar to those in the LINAC transfer line, it will use multi-stage pneumatics. This will allow either a highly sensitive YAG:Ce detector to visualise the transverse beam distribution during commissioning or an aluminium foil for production of transition radiation (TR) during low current top up mode. The optical part of TR represents a linear radiation source, which is used for the measurement of transverse electron beam parameters. CCD cameras will record the images and processed on a frame-grabbing suite.

3.8.6 Beam Loss Monitors

It is intended to equip the DIAMOND booster with a high performance localised photomultiplier-based system for injection loss studies and a second, lower grade, distributed, general background monitoring PIN photodiode based system.

The distributed system will employ commercially available units that have a pulse output, one pulse per incident ionising particle, giving a pulse rate that is proportional to beam loss. Even when protectively housed these units are small and mobile enough to enable their distribution to be customised rapidly on demand. They will probably be installed in the booster and storage ring with an average distribution of one or two units per straight, with clusters around loss elements such as collimators and quadrupoles and pulsed magnets. Their flexibility with regards to redistribution will be advantageous when trying to source faults.

PART F: INJECTOR ACCELERATORS

3.9 EXTRACTION

The current extraction scheme is described in [11]. The extraction magnets are positioned in three of the missing magnet cells. Three slow kickers create a closed orbit bump, then the beam is extracted in one turn using a fast kicker and two pulsed septa magnets. Table 3.9-1 shows the length and strength of the extraction elements, and Figure 3.9-1 shows the path of the extracted beam through the extraction scheme.

Table 3.9-1 DIAMOND booster extraction elements.

Component	Nominal deviation at 3 GeV	Length
	(mrad)	(m)
Fast Kicker	1.50	0.72
Slow Kicker 1	3.00	0.72
Pre-septum	8.30	0.36
Slow Kicker 2	2.26	0.72
Main Septum	110	1.20
Slow Kicker 3	1.90	0.72

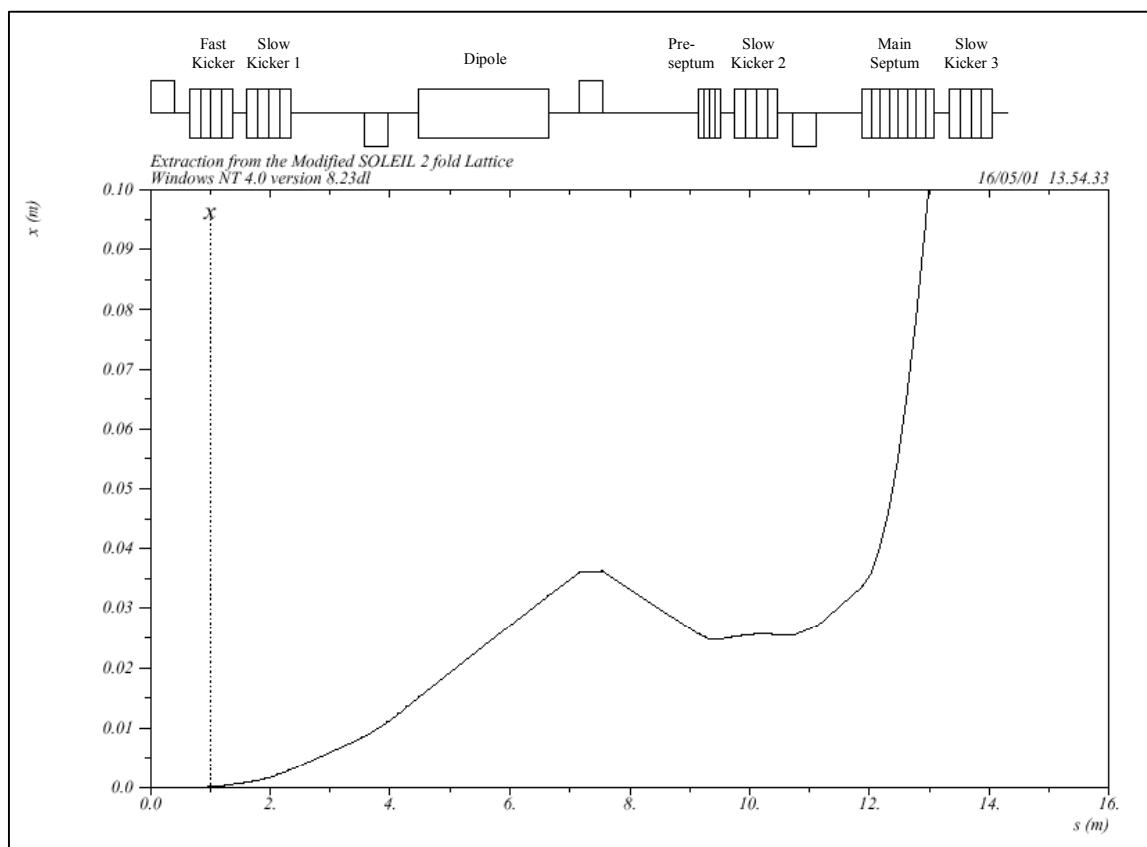


Figure 3.9-1 The path of the extracted beam through the extraction scheme.

3.10 PROCUREMENT PLANS

It is feasible to consider procuring the DIAMOND booster by a turn-key contract under which the supplier takes responsibility for the delivering and commissioning a booster to meet a comprehensively written performance specification. The detailed design would be the supplier's responsibility. Because of the requirement for the booster to have system compatibilities with other parts of the facility (vacuum, diagnostics, radio frequency, etc) it is unlikely that the contract could be 100% turn-key. Nevertheless, the savings of in house staff time would make even partial turn-key procurement a worthwhile process.

It has been established already that there is sufficient capability and interest amongst suppliers with proven experience in delivering turn-key systems to other projects to make it a procurement option which should be carefully considered.

It is also relevant that the design of the booster for the SOLEIL project has strong similarities with the DIAMOND booster and there could be opportunities for making cost savings by both projects adopting common designs for such items as magnets, vacuum chambers, power supplies, injection and extraction elements.

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- [1] N. Marks et al; 'The Economic Optimisation Of The Main Parameters of the 3 GeV Electron Booster Synchrotron for DIAMOND', EPAC 2000.
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- [4] W. Joho, et al; 'The SLS Booster Synchrotron', Proc. of the 6th European Particle Accelerator Conference, Stockholm, June 1998.
- [5] H.U.Boksberger et al; 'A 3 Hz 1MW peak bending magnet power supply for the Swiss Light Source', Proc. of the second EP² Forum, Grenoble, 1998.
- [6] J.A.Varley (ed); 'Top-up Injection Workshop', DPG-XX-rpt-012, Daresbury Laboratory, March 2001.
- [7] J.T.Theed; 'The Study of Current and Voltage Ratings of IGBTs and Thyristors', PWSP-XX-rpt-001, Daresbury Laboratory, May 2001.
- [8] R.J.Reid; 'A Comparison of Costs of the Vacuum System for 12, 16 and 20 Cell Booster Designs', VAC-BO-rpt-001-Issue 2, Daresbury Laboratory, August 1999.

PART F: INJECTOR ACCELERATORS

REFERENCES, Continued

- [9] Herbeaux *et al*: J Vac Sci Technol **A17**, 1999, 635
- [10] J.A.Clarke; 'The Calculation of the Total Number of Photons Emitted Above 10eV', Revised DPG/99/86, Daresbury Laboratory, September 1999.
- [11] J.A.Varley; 'Extraction from a Two-Fold Symmetric Missing Magnet Booster Lattice', DPG-BO-rpt-010, Daresbury Laboratory, May 2001.

F.4 Transfer Lines

4.1 INTRODUCTION

There are two transfer lines required for the DIAMOND complex. A Flight Path: to transfer the 100 MeV beam from the LINAC to the booster and a Transfer Path: to transport the 3 GeV beam from the booster synchrotron to the storage ring. The following considerations were taken into account when designing the Transfer Path:

- The ends of the Transfer Path must be matched to the booster extraction scheme and the storage ring injection scheme.
- The beta functions along the Transfer Path must not get too high. A limit of no more than 30m was set for both the radial and vertical beta functions.
- There should be a zero dispersion section for diagnostics.
- There needs to be a drift space of suitable length and in an appropriate position to allow for the shield wall to isolate the injector complex from the storage ring.
- There needs to be adequate drift space to allow for the positioning of diagnostics and correction magnets.
- There must be enough bend angle along the Transfer Path to keep elements from the storage ring and transfer path sufficiently separate.

Detailed engineering requirements have not been considered explicitly for this design. These include the exact position of the booster relative to the storage ring, and the positioning of shield walls. There is also a practical limit on how close the transfer path magnets can get to the storage ring and booster magnets.

4.2 FLIGHT PATH

The Flight Path will guide the electron from the linear accelerator to the injection system of the booster. To keep particle loss at a minimum the ability to modify the beam size and position will be needed. This will require diagnostics giving information on the beam energy, energy spread and also optical parameters. The Flight Path will also have to match LINAC beam to the phase space parameters of the booster synchrotron injection scheme.

An illustration of how the Flight Path will fit in the injector complex is shown in Figure 4.2-1.

PART F: INJECTOR ACCELERATORS

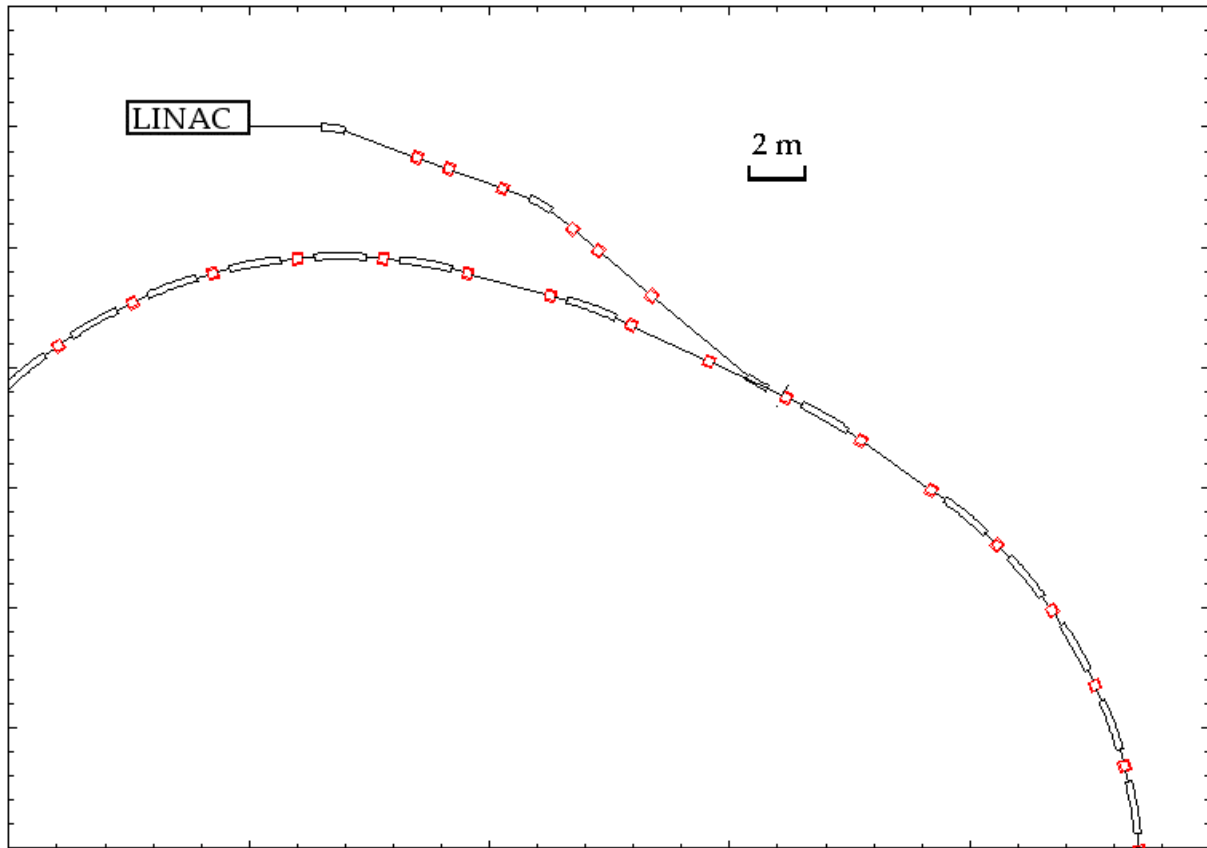


Figure 4.2-1 Schematic of LINAC, Flight Path and booster Synchrotron.

The quadrupoles are shown in red and dipoles as clear rectangles. Injection into the booster is in one of the missing dipole sections of the booster lattice. The layout has been chosen so that there is space after the two Flight Path dipoles for diagnostics. The drift spaces will also contain diagnostics and corrector magnets. The shield wall has not been shown in Figure 4.2-1.

4.3 TRANSFER PATH

4.3.1 Designing the Transfer Path

A design for the Transfer Path has been achieved using MAD. To make sure the matching is accurate the booster and booster extraction scheme were first modelled and then the start of the transfer path matched to the end of the booster extraction septum. The beta functions and dispersion in the extraction system, up to the end of a 1.22 metre drift after the extraction septum, are shown in Figure 4.3-1.

F.4 TRANSFER LINES

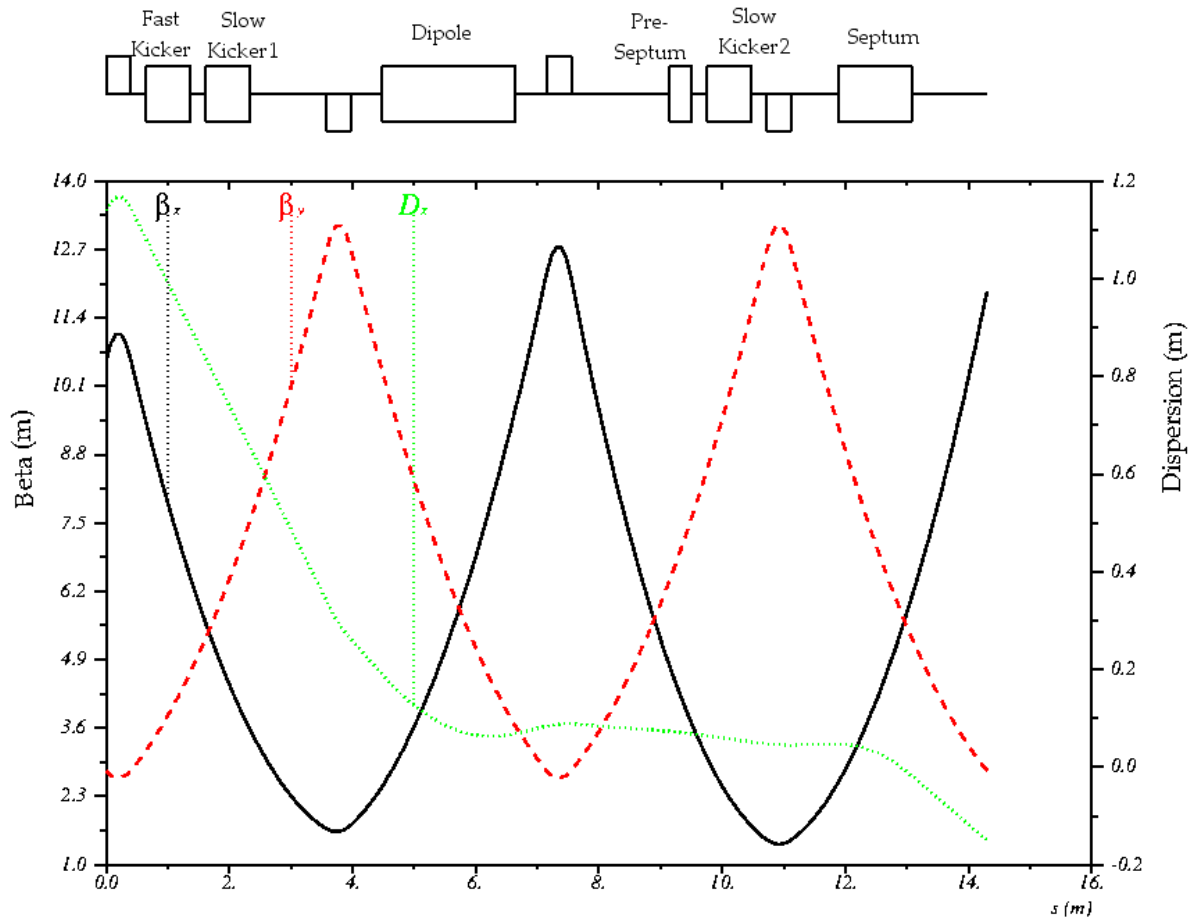


Figure 4.3-1 Lattice functions through the booster extraction system.

The first section of the Transfer Path starts with a FODO lattice similar to the booster FODO lattice. There is then a quadrupole triplet followed by a dipole. The triplet is used to match the dispersion to zero after this first Transfer Path dipole. The zero dispersion section contains four quadrupoles between the first and second dipoles. These are positioned to keep the beta functions below 30m. After the second dipole the final section of the Transfer Path contains seven quadrupoles, to match the lattice functions to the storage ring, and one final dipole to bend the beam onto the storage ring axis. The matching was done to the values of the lattice functions at the start of the quadrupole at the end of the storage ring long straight. This means that the storage ring septum and two injection kickers were included in the model. Table 4.3-1 gives the values of the lattice functions at the first storage ring quadrupole seen by the injected beam.

PART F: INJECTOR ACCELERATORS

Table 4.3-1 Values of storage ring parameters used for matching the end of the Transfer Path.

Parameter	Value
β_x	13.202 m
α_x	-0.568
β_y	11.347 m
α_y	-0.973
η_x	0.072 m
η_x'	0

It is through this third section that the shield wall between the booster and storage ring will pass.

4.3.2 Transfer Path Components

It is planned to use quadrupole and dipole magnets from the booster synchrotron. This will save production costs. In total 18 quadrupoles have been used and three dipoles. In the booster the dipoles operate at 0.804 Tesla, giving a bend angle of 10° [1]. For the Transfer Path this has been increased to 1.2 Tesla, giving a bend angle of 15°. For matching purposes the quadrupoles were assumed to have a maximum field gradient of $\pm 15 \text{ T m}^{-1}$. Table 4.3-2 summarises the basic parameters of the Transfer Path magnets.

Table 4.3-2 Basic Transfer Path magnet properties.

	Number of Elements	Length [m]	Field
Bending Magnets	3	2.17	1.2 Tesla
Quadrupoles	18	0.4	$\pm 15 \text{ T m}^{-1}$ (max)

4.3.3 Transfer Path Layout & Lattice Functions

The first section of the transfer path, from the booster extraction septum to the first Transfer Path dipole is 20.79 metres long. Section two, from the first dipole to the second dipole is 7.85 metres long. The final section, from the second dipole to the storage ring septum is 24.04 metres long. The layout of the Transfer Path and the lattice functions are shown in Figure 4.3-2.

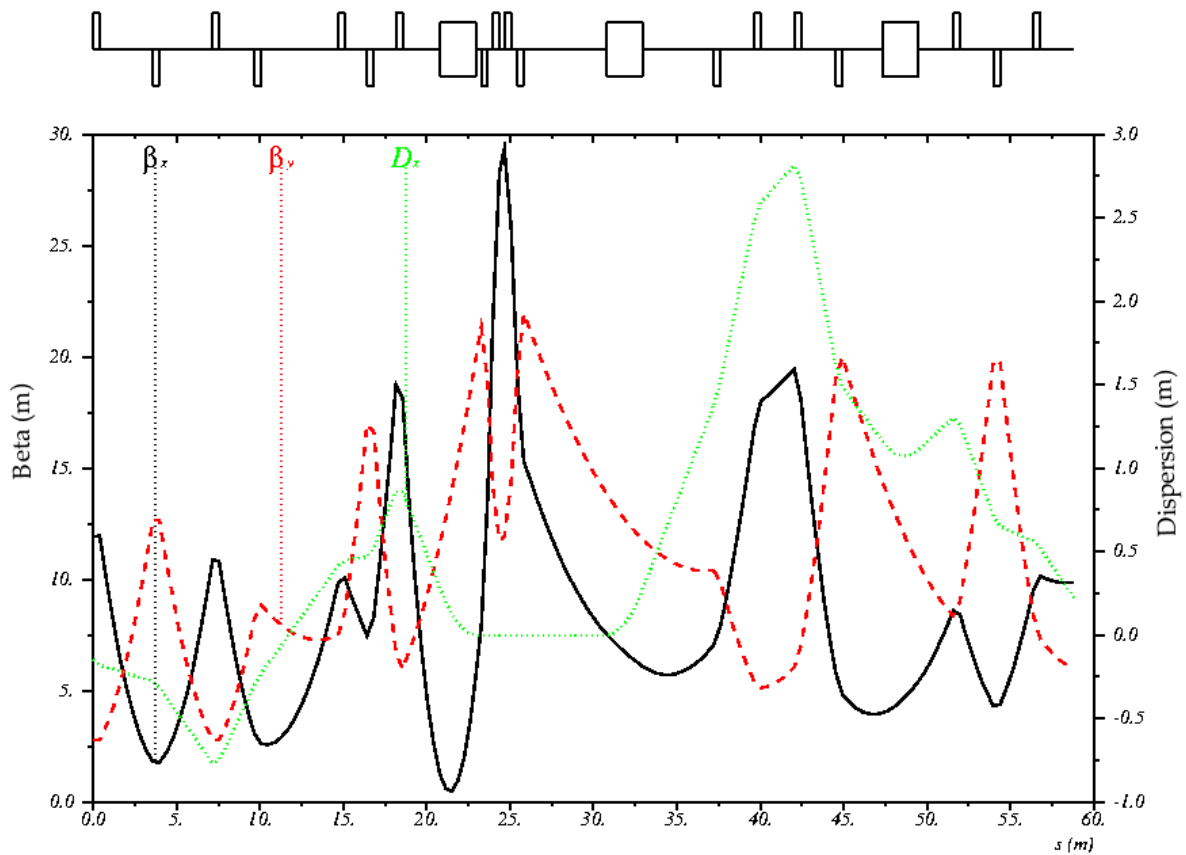


Figure 4.3-2. Lattice functions through the Transfer Path

4.3.4 Layout of Booster, Transfer Path & Storage Ring

The Transfer Path defines the position of the booster synchrotron relative to the storage ring. Figure 4.3-3 shows, schematically, how the booster, transfer path and storage ring will lie relative to each other.

PART F: INJECTOR ACCELERATORS

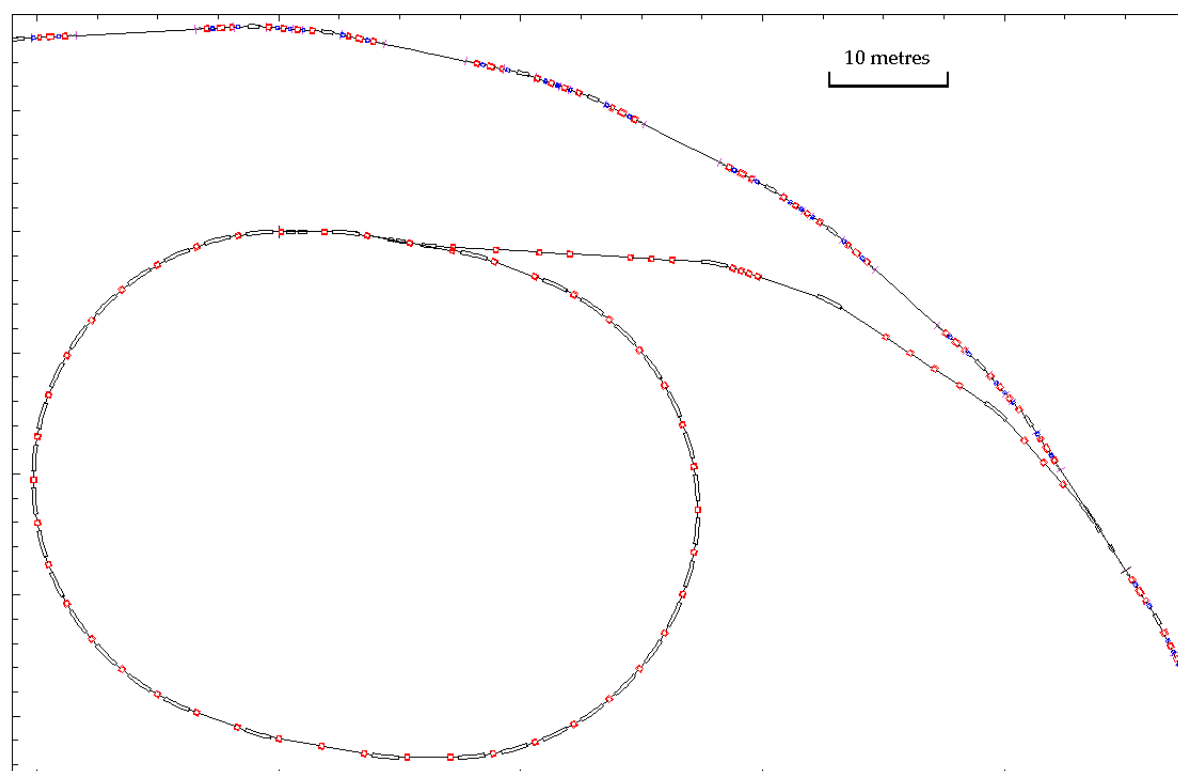


Figure 4.3-3 Schematic of booster synchrotron, transfer path and storage ring

For this figure only the bend angles of the dipoles, septa and kickers have been considered. There is no shield wall shown in this figure.

A close up schematic of the Transfer Path and the storage ring injection straight is shown in Figure 4.3-4. It shows there is plenty of space between the storage ring and Transfer Path. It can also be seen that there are a number of drift spaces that can be chosen for the shield wall to pass through

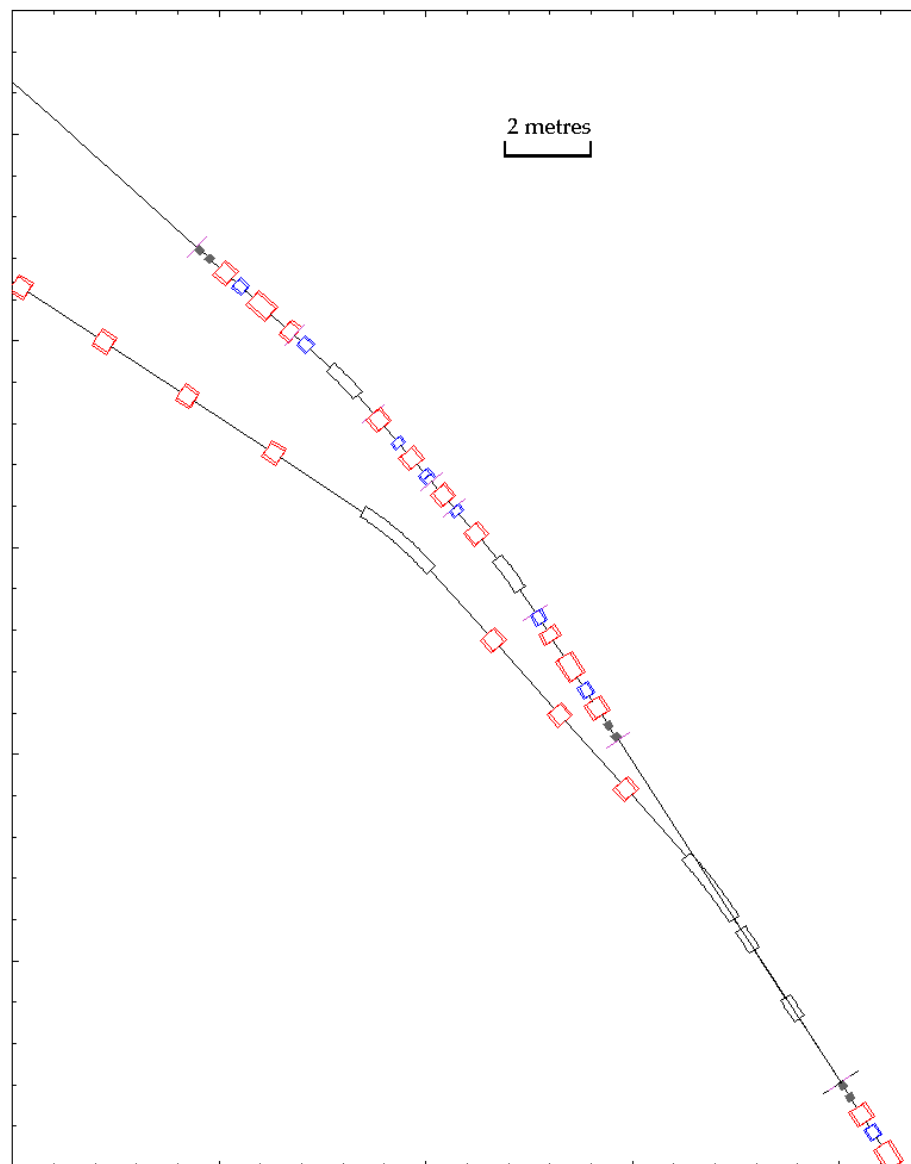


Figure 4.3-4 Close up of transfer path and storage ring injection.

4.4 DIAGNOSTICS

4.4.1 Introduction

The diagnostic systems for the DIAMOND Booster will be challenging, due to the vast dynamic range that has to be covered due to the different operational modes. These are single bunch, multi-bunch, and top-up mode. In these various regimes, charge currents (per bunch) will vary from less than 1pC to less than 2 nC. A combination of diagnostics systems, similar to those specified for the Swiss Light Source (SLS) will provide sufficiently for the requirements of this accelerator.

PART F: INJECTOR ACCELERATORS

Current related measurements and electron beam parameters such as bunch charge are particularly important since beam losses will result in significant radiation being liberated. Hence a combination of diagnostic systems will be implemented.

4.4.2 Faraday Cup

A coaxial Faraday cup, which can be moved into the beam through a pneumatic actuator and hence is a destructive diagnostic to the beam, allows the determination of the micro as well as the macro bunch configuration of the electron beam for both the LINAC and storage ring beam transport lines. These devices will be of 50 Ω characteristic impedance design with a bandwidth of 4 GHz. The Faraday cup on the booster to storage ring line will be of a larger design, since it will be absorbing directly the beam charge, should the injection system be under test on normal multi-bunch fill conditions. The measured beam signals are transmitted directly into high quality coaxial cable and fed into an RF multiplexer along with other LINAC and Transfer Path signals before display on a diagnostic oscilloscope.

4.4.3 Bunch Charge Monitors (BCMs) and Integrating Current Transformers (ICTs)

Commercially available BCMs will be installed on the entrance and exits of the beam transfer lines. ICTs will also be installed to measure the beam current. The BCMs will be used in concert with those of the booster and storage ring to measure the average current as well as the transmission/injection efficiency with relatively high accuracy (<60pC of charge). Measurement of the transmission efficiency from stage to stage of the accelerator will allow interlocking of the pre-injector for beam losses, and thus help to reduce radiation hazards to acceptable limits for the shielding.

4.4.4 Electron Beam Position Monitors (EBPMs)

EBPMs for the Beam Transfer lines will be of the quarter wavelength directional stripline type, constructed to be low Q resonant at 500MHz. This is necessary to maximise the signals for the processing electronics, since the potentially small currents produced during top-up mode injection will not provide adequate coupling and hence signals for detection. This design will allow the implementation of the commercial I-Tech EBPM detector in its First turn/LINAC pulse mode (please refer to Chapter E4. Diagnostics for more information on this system) without any modification. The operation of the I-Tech detector is such that individual single pass tracking of the beam position will be adequate for beam trajectory measurement.

4.4.5 Optical Monitors

Optical monitoring similar to that of the SLS devices will be installed to measure beam position as well as transverse beam parameters like energy and energy spread. These are similar to those in the LINAC and will use multi-stage pneumatics. This will allow either a highly sensitive YAG:Ce detector to visualise the transverse beam distribution during commissioning or an Al-foil for production of transition radiation

F.4 TRANSFER LINES

(TR) during low current top-up mode. The optical part of TR represents a linear radiation source, which is used for the measurement of transverse electron beam parameters. CCD cameras will record the images and be processed on a frame-grabbing suite.

4.5 VACUUM SYSTEM

No design work has been carried out on the transfer lines.

However, the vacuum system of the Linac to Booster flight path should essentially be a clean, all metal system with an operating pressure in the region of 10^{-8} mbar. That of the Booster to Storage ring transfer path should essentially be a clean, all metal system with an operating pressure in the region of 10^{-9} mbar.

The Booster to Storage Ring transfer path will be isolated from the storage ring by a thin aluminium window.

REFERENCES

- [1] D.J.Scott & D.J.Holder; 'Preliminary Booster Concept Conclusions for DIAMOND', DPG-BO-rpt-011-iss02, Daresbury Laboratory, June 2001.

Diamond Project Master Schedule

ID	Task Name	Duration	Early Start	Early Finish	03				04				05				06							
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	
0	Diamond Technical Project Master Schedule	1177d?	Thu 02/05/02	Fri 03/11/06																				
1	1.0 Diamond Technical Project	1177d?	Thu 02/05/02	Fri 03/11/06																				
2	1.1 Building	696d?	Thu 02/05/02	Fri 31/12/04																				
4	1.1.2 Synchrotron building - Suresh Patel	109d?	Mon 02/08/04	Fri 31/12/04																				
5	CIA's and Tunnels available	0d	Mon 02/08/04	Mon 02/08/04																				
708	1.7 Storage Ring	1132d	Thu 02/05/02	Fri 01/09/06																				
1033	1.7.4 Magnets – Neil Marks	842d	Thu 02/05/02	Fri 22/07/05																				
1034	1.7.4.1 Quadrupoles	842d	Thu 02/05/02	Fri 22/07/05																				
1035	AP Storage Ring Lattice finalised	1mo	Thu 02/05/02	Wed 29/05/02																				
1036	Magnet Parameters frozen	0d	Wed 29/05/02	Wed 29/05/02																				
1037	Prepare Design Spec	70d	Thu 30/05/02	Wed 04/09/02																				
1050	1.7.4.2 Dipoles	617d	Thu 05/09/02	Fri 14/01/05																				
1051	Prepare Design Spec	30d	Thu 05/09/02	Wed 16/10/02																				
1052	EC Supplies Directive for Restrictive Tenders	137d	Thu 17/10/02	Fri 25/04/03																				
1053	Place Order	0d	Fri 25/04/03	Fri 25/04/03																				
1054	Design	11w	Mon 28/04/03	Fri 11/07/03																				
1055	Complete Design	0d	Fri 11/07/03	Fri 11/07/03																				
1056	Manufacture and test Prototype	15w	Mon 14/07/03	Fri 24/10/03																				
1057	Approve Prototype	0d	Fri 24/10/03	Fri 24/10/03																				
1058	Manufacture and Works Test	30w	Mon 27/10/03	Fri 21/05/04																				
1059	Deliver equipment	0d	Fri 18/06/04	Fri 18/06/04																				
1175	1.7.6 RF system – Mike Dykes	877d	Thu 02/05/02	Fri 09/09/05																				
1188	1.7.6.2 Power source	877d	Thu 02/05/02	Fri 09/09/05																				
1196	Install equipment	48w	Mon 02/08/04	Fri 01/07/05																				
1197	Complete installation	0d	Fri 01/07/05	Fri 01/07/05																				
1198	Test equipment	10w	Mon 04/07/05	Fri 09/09/05																				
1199	Testing Complete	0d	Fri 09/09/05	Fri 09/09/05																				
1404	1.7.8 Girder system – Nigel Hammond	877d	Thu 02/05/02	Fri 09/09/05																				
1405	1.7.8.1 Girders	877d	Thu 02/05/02	Fri 09/09/05																				
1412	Assemble Components to Girders	240d	Mon 21/06/04	Fri 20/05/05																				
1414	Install Girders	52w	Mon 13/09/04	Fri 09/09/05																				
1415	Complete Girder Installation	0d	Fri 09/09/05	Fri 09/09/05																				
1814	1.7.17 Commissioning with beam - Vic Suller	255d	Mon 12/09/05	Fri 01/09/06																				
1815	Pump & Leak Test	13w	Mon 12/09/05	Fri 09/12/05																				
1816	Commission Vacuum System	12w	Mon 12/12/05	Fri 03/03/06																				
1817	Commission Storage Ring with Beam	26w	Mon 06/03/06	Fri 01/09/06																				
1818	Commission Front Ends & Insertion Devices with Beam	4w	Mon 05/06/06	Fri 30/06/06																				
1819	1.8 Beamlines	1177d	Thu 02/05/02	Fri 03/11/06																				

ID	Task Name	Duration	Early Start	Early Finish	03			04				05				06				
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	
1820	1.8.1 Very High Energy Beamline	1177d	Thu 02/05/02	Fri 03/11/06																
1821	1.8.1.1 High energy beamline (1) – Colin Nave	1177d	Thu 02/05/02	Fri 03/11/06																
1834	Commission with Beam (incl HP monitor commissioning)	90d	Mon 03/07/06	Fri 03/11/06																
1835	Beamline complete	0d	Fri 03/11/06	Fri 03/11/06																
1838	Beam OK	0d	Fri 30/06/06	Fri 30/06/06																
1849	1.8.2 Materials Beamline	1177d	Thu 02/05/02	Fri 03/11/06																
1850	1.8.2.1 Materials beamline (6) – Colin Nave	1177d	Thu 02/05/02	Fri 03/11/06																
1863	Commission with Beam (incl HP monitor commissioning)	90d	Mon 03/07/06	Fri 03/11/06																
1864	Beamline complete	0d	Fri 03/11/06	Fri 03/11/06																
1867	Beam OK	0d	Fri 30/06/06	Fri 30/06/06																
1878	1.8.3 Macromolecular Beamline 1	1177d	Thu 02/05/02	Fri 03/11/06																
1879	1.8.3.1 Macromolecular beamline1 (8) - Colin Nave	1177d	Thu 02/05/02	Fri 03/11/06																
1892	Commission with Beam (incl HP monitor commissioning)	90d	Mon 03/07/06	Fri 03/11/06																
1893	Beamline complete	0d	Fri 03/11/06	Fri 03/11/06																
1896	Beam OK	0d	Fri 30/06/06	Fri 30/06/06																
1907	1.8.4 Macromolecular Beamline 2	1177d	Thu 02/05/02	Fri 03/11/06																
1908	1.8.4.1 Macromolecular beamline2 (9) - Colin Nave	1177d	Thu 02/05/02	Fri 03/11/06																
1921	Commission with Beam (incl HP monitor commissioning)	90d	Mon 03/07/06	Fri 03/11/06																
1922	Beamline complete	0d	Fri 03/11/06	Fri 03/11/06																
1925	Beam OK	0d	Fri 30/06/06	Fri 30/06/06																
1936	1.8.5 Macromolecular Beamline 3	1177d	Thu 02/05/02	Fri 03/11/06																
1937	1.8.5.1 Macromolecular beamline3 (10) – Colin Nave	1177d	Thu 02/05/02	Fri 03/11/06																
1950	Commission with Beam (incl HP monitor commissioning)	90d	Mon 03/07/06	Fri 03/11/06																
1951	Beamline complete	0d	Fri 03/11/06	Fri 03/11/06																
1954	Beam OK	0d	Fri 30/06/06	Fri 30/06/06																
1965	1.8.6 Microfocus XAS beamline– Colin Nave	1177d	Thu 02/05/02	Fri 03/11/06																
1966	1.8.6.1 Microfocus XAS	1177d	Thu 02/05/02	Fri 03/11/06																
1979	Commission with Beam (incl HP monitor commissioning)	90d	Mon 03/07/06	Fri 03/11/06																
1980	Beamline complete	0d	Fri 03/11/06	Fri 03/11/06																
1983	Beam OK	0d	Fri 30/06/06	Fri 30/06/06																
1994	1.8.7 SXR for nanostructures Beamline	1177d	Thu 02/05/02	Fri 03/11/06																
1995	1.8.7 SXR nanostructures beamline(14) – Colin Nave	1177d	Thu 02/05/02	Fri 03/11/06																
2008	Commission with Beam (incl HP monitor commissioning)	90d	Mon 03/07/06	Fri 03/11/06																
2009	Beamline complete	0d	Fri 03/11/06	Fri 03/11/06																
2012	Beam OK	0d	Fri 30/06/06	Fri 30/06/06																
2419	Facility Fully Operational (Ops Live)	0d	Fri 03/11/06	Fri 03/11/06																

Diamond Project Master Schedule

ID	Task Name	Duration	Early Start	Early Finish	03				04				05				06							
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	
0	Diamond Technical Project Master Schedule	1177d?	Thu 02/05/02	Fri 03/11/06																				
1	1.0 Diamond Technical Project	1177d?	Thu 02/05/02	Fri 03/11/06																				
2	1.1 Building	696d?	Thu 02/05/02	Fri 31/12/04																				
4	1.1.2 Synchrotron building - Suresh Patel	109d?	Mon 02/08/04	Fri 31/12/04																				
5	CIA's and Tunnels available	0d	Mon 02/08/04	Mon 02/08/04																				
6	Services and power on	0d	Tue 31/08/04	Tue 31/08/04																				
7	Half experimental hall floor available	0d	Fri 31/12/04	Fri 31/12/04																				
11	1.3 Pre-Injector	857d	Thu 02/05/02	Fri 12/08/05																				
12	1.3.1 Gun - Mike Dykes	687d	Thu 02/05/02	Fri 17/12/04																				
13	1.3.1.1 Gun and Linac (Turnkey contract)	686d	Fri 03/05/02	Fri 17/12/04																				
16	Place Order	0d	Mon 06/01/03	Mon 06/01/03																				
18	Complete Design	0d	Mon 03/03/03	Mon 03/03/03																				
20	Deliver equipment	0d	Mon 05/07/04	Mon 05/07/04																				
22	Complete installation	0d	Fri 08/10/04	Fri 08/10/04																				
24	Testing Complete	0d	Fri 17/12/04	Fri 17/12/04																				
25	1.3.1.2 Services	637d	Thu 02/05/02	Fri 08/10/04																				
28	Place Order	0d	Fri 03/01/03	Fri 03/01/03																				
30	Complete Design	0d	Fri 28/02/03	Fri 28/02/03																				
32	Deliver equipment	0d	Fri 04/07/03	Fri 04/07/03																				
34	Complete installation	0d	Fri 08/10/04	Fri 08/10/04																				
35	Test equipment	0d	Fri 08/10/04	Fri 08/10/04																				
36	Testing Complete	0d	Fri 08/10/04	Fri 08/10/04																				
37	1.3.1.3 Plant Control	420d	Thu 02/05/02	Wed 10/12/03																				
39	Contract placed	0d	Wed 15/05/02	Wed 15/05/02																				
41	Issue Hardware to Manufacturer	0d	Wed 10/07/02	Wed 10/07/02																				
44	Linac installed	0d	Wed 26/11/03	Wed 26/11/03																				
48	1.3.5 Health Physics Installed Monitors System – Roy Ryder	857d	Thu 02/05/02	Fri 12/08/05																				
51	Place Order	0d	Wed 19/03/03	Wed 19/03/03																				
53	Complete Design	0d	Wed 30/04/03	Wed 30/04/03																				
55	Deliver equipment	0d	Wed 05/05/04	Wed 05/05/04																				
57	Complete installation	0d	Fri 17/06/05	Fri 17/06/05																				
59	Commissioning Complete	0d	Fri 12/08/05	Fri 12/08/05																				
63	1.4 Linac to Booster Transfer Path - Mike Dykes	867d	Thu 02/05/02	Fri 26/08/05																				
64	1.4.1 Linac to Booster (Turnkey contract) – Graham Duller	842d	Thu 02/05/02	Fri 22/07/05																				
67	Place Order	0d	Fri 31/01/03	Fri 31/01/03																				
69	Complete Design	0d	Fri 01/08/03	Fri 01/08/03																				
71	Deliver equipment	0d	Fri 07/05/04	Fri 07/05/04																				
73	Complete installation	0d	Fri 17/12/04	Fri 17/12/04																				
75	Testing Complete	0d	Fri 22/07/05	Fri 22/07/05																				

Diamond Project Master Schedule

ID	Task Name	Duration	Early Start	Early Finish	03				04				05				06			
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	
76	1.4.2 Services - Graham Duller	622d	Thu 02/05/02	Fri 17/09/04																
79	Place Order	0d	Fri 08/11/02	Fri 08/11/02																
81	Complete Design	0d	Fri 06/12/02	Fri 06/12/02																
83	Deliver equipment	0d	Fri 31/01/03	Fri 31/01/03																
85	Complete installation	0d	Fri 10/09/04	Fri 10/09/04																
87	Testing Complete	0d	Fri 17/09/04	Fri 17/09/04																
88	1.4.3 Plant Control LTB Mags, Vac, Diag – Mark Heron	782d	Thu 02/05/02	Fri 29/04/05																
89	Interface Requirements from tech group	0d	Thu 02/05/02	Thu 02/05/02																
98	1.5 Booster	967d	Thu 02/05/02	Fri 13/01/06																
99	1.5.1 Injection system – Neil Marks	777d	Thu 02/05/02	Fri 22/04/05																
100	1.5.1.1 Kickers	342d	Thu 02/05/02	Fri 22/08/03																
102	AP Parameters available	0d	Wed 24/07/02	Wed 24/07/02																
106	Place Order	0d	Fri 07/03/03	Fri 07/03/03																
108	Deliver equipment	0d	Fri 27/06/03	Fri 27/06/03																
111	Testing complete & available for installation	0d	Fri 22/08/03	Fri 22/08/03																
112	1.5.1.2 Septum	327d	Thu 22/08/02	Fri 21/11/03																
116	Place Order	0d	Fri 02/05/03	Fri 02/05/03																
118	Deliver equipment	0d	Fri 22/08/03	Fri 22/08/03																
121	Testing Complete & Available for Installation	0d	Fri 21/11/03	Fri 21/11/03																
122	1.5.1.3 Pulsed power supplies	307d	Wed 21/08/02	Fri 24/10/03																
123	Kicker power supply	262d	Wed 21/08/02	Fri 22/08/03																
129	Septum power supply	267d	Wed 16/10/02	Fri 24/10/03																
130	Parameters available	0d	Wed 16/10/02	Wed 16/10/02																
132	EC Supplies Directive for Restrictive Tenders	137d	Wed 13/11/02	Fri 23/05/03																
133	Complete Preparation of Tender / Contract Docu	0d	Wed 13/11/02	Wed 13/11/02																
134	Notice	37d	Wed 13/11/02	Fri 03/01/03																
135	Send Notice to OJEC	0d	Wed 13/11/02	Wed 13/11/02																
136	Notice Issued in OJEC	0d	Wed 27/11/02	Wed 27/11/02																
137	Suppliers Respond to OJEC	0d	Fri 03/01/03	Fri 03/01/03																
140	Tender & Award	70d	Fri 14/02/03	Fri 23/05/03																
141	Invite Tenders from Qualified Suppliers	0d	Fri 14/02/03	Fri 14/02/03																
144	place contract	0d	Fri 23/05/03	Fri 23/05/03																
146	deliver	0d	Fri 24/10/03	Fri 24/10/03																
147	available for installation	0d	Fri 24/10/03	Fri 24/10/03																
148	1.5.1.4 Support structure	607d	Thu 02/05/02	Fri 27/08/04																
151	Place Order	0d	Fri 03/01/03	Fri 03/01/03																
153	Complete Design	0d	Fri 17/01/03	Fri 17/01/03																
155	Deliver equipment	0d	Fri 14/03/03	Fri 14/03/03																
157	Complete installation	0d	Fri 13/08/04	Fri 13/08/04																

Diamond Project Master Schedule

ID	Task Name	Duration	Early Start	Early Finish					03				04				05				06			
					2	3	4		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
159	Testing Complete	0d	Fri 27/08/04	Fri 27/08/04																				
161	1.5.1.6 Plant Control Injection and Kickers - Mark Heron	777d	Thu 02/05/02	Fri 22/04/05																				
162	Interface Requirements from tech group	0d	Thu 02/05/02	Thu 02/05/02																				
169	Plant and service available	0d	Fri 11/03/05	Fri 11/03/05																				
171	1.5.2 Vacuum system – Ron Reid	777d	Thu 02/05/02	Fri 22/04/05																				
172	1.5.2.1 Vacuum Pumps	31d	Thu 02/05/02	Thu 13/06/02																				
173	Mechanical layout available from MDO	0d	Thu 02/05/02	Thu 02/05/02																				
175	Type info on pumps available	0d	Wed 12/06/02	Wed 12/06/02																				
177	1.5.2.2 Vacuum Gauges	6d	Thu 02/05/02	Thu 09/05/02																				
178	Mechanical layout available from MDO	0d	Thu 02/05/02	Thu 02/05/02																				
180	Type info on gauges available	0d	Wed 08/05/02	Wed 08/05/02																				
182	1.5.2.3 Valves	2d	Thu 02/05/02	Fri 03/05/02																				
183	Mechanical layout available from MDO	0d	Thu 02/05/02	Thu 02/05/02																				
185	Type info on valves available	0d	Thu 02/05/02	Thu 02/05/02																				
187	1.5.2.19 Plant Control Vacuum - Mark Heron	777d	Thu 02/05/02	Fri 22/04/05																				
188	Interface Requirements from tech group	0d	Thu 02/05/02	Thu 02/05/02																				
195	Plant and service available	0d	Thu 02/05/02	Thu 02/05/02																				
197	1.5.3 Vacuum Mechanical Engineering - Jim Kay	717d	Thu 02/05/02	Fri 28/01/05																				
198	1.5.3.1 Vessels - Graham Duller	717d	Thu 02/05/02	Fri 28/01/05																				
202	Place Order	0d	Fri 25/04/03	Fri 25/04/03																				
204	Complete Design	0d	Fri 12/09/03	Fri 12/09/03																				
206	Deliver equipment	0d	Fri 18/06/04	Fri 18/06/04																				
209	Complete installation	0d	Fri 05/11/04	Fri 05/11/04																				
211	Testing Complete	0d	Fri 28/01/05	Fri 28/01/05																				
212	1.5.3.2 Bellows - Graham Duller	687d	Thu 02/05/02	Fri 17/12/04																				
216	Place Order	0d	Fri 04/04/03	Fri 04/04/03																				
218	Complete Design	0d	Fri 13/06/03	Fri 13/06/03																				
220	Deliver equipment	0d	Fri 09/01/04	Fri 09/01/04																				
223	Complete installation	0d	Fri 05/11/04	Fri 05/11/04																				
225	Testing Complete	0d	Fri 17/12/04	Fri 17/12/04																				
226	1.5.3.3 Services - Graham Duller	622d	Thu 02/05/02	Fri 17/09/04																				
229	Place Order	0d	Fri 22/11/02	Fri 22/11/02																				
231	Complete Design	0d	Fri 20/12/02	Fri 20/12/02																				
233	Deliver equipment	0d	Fri 14/02/03	Fri 14/02/03																				
235	Complete installation	0d	Fri 10/09/04	Fri 10/09/04																				
237	Testing Complete	0d	Fri 17/09/04	Fri 17/09/04																				
238	1.5.4 Magnets – Neil Marks	647d	Thu 02/05/02	Fri 22/10/04																				
239	1.5.4.1 Quadrupoles	647d	Thu 02/05/02	Fri 22/10/04																				
241	Booster Magnets Parameters available	0d	Wed 16/10/02	Wed 16/10/02																				

Diamond Project Master Schedule

ID	Task Name	Duration	Early Start	Early Finish	03				04				05				06			
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	
244	Place Order	0d	Fri 18/07/03	Fri 18/07/03																
246	Complete Design	0d	Fri 17/10/03	Fri 17/10/03																
248	Approve Prototype	0d	Fri 16/01/04	Fri 16/01/04																
250	Deliver equipment	0d	Fri 18/06/04	Fri 18/06/04																
252	Complete installation	0d	Fri 22/10/04	Fri 22/10/04																
253	1.5.4.2 Dipoles	527d	Thu 17/10/02	Fri 22/10/04																
256	Place Order	0d	Fri 06/06/03	Fri 06/06/03																
258	Complete Design	0d	Fri 22/08/03	Fri 22/08/03																
260	Approve Prototype	0d	Fri 21/11/03	Fri 21/11/03																
262	Deliver equipment	0d	Fri 23/04/04	Fri 23/04/04																
264	Complete installation	0d	Fri 22/10/04	Fri 22/10/04																
265	1.5.4.3 Sextupoles	447d	Thu 09/01/03	Fri 24/09/04																
268	Place Order	0d	Fri 29/08/03	Fri 29/08/03																
270	Complete Design	0d	Fri 31/10/03	Fri 31/10/03																
272	Approve Prototype	0d	Fri 30/01/04	Fri 30/01/04																
274	Deliver equipment	0d	Fri 02/07/04	Fri 02/07/04																
276	Complete installation	0d	Fri 24/09/04	Fri 24/09/04																
277	Test equipment	0d	Fri 24/09/04	Fri 24/09/04																
278	Testing Complete	0d	Fri 24/09/04	Fri 24/09/04																
279	1.5.5 Magnet power supplies – Steve Griffiths	837d	Thu 02/05/02	Fri 15/07/05																
280	1.5.5.1 Quadrupoles	667d	Thu 02/05/02	Fri 19/11/04																
283	Place Order	0d	Fri 25/04/03	Fri 25/04/03																
285	Complete Design	0d	Fri 10/10/03	Fri 10/10/03																
287	Deliver final equipment	0d	Fri 26/03/04	Fri 26/03/04																
289	Complete installation	0d	Fri 22/10/04	Fri 22/10/04																
291	Power Convertor Available	0d	Fri 19/11/04	Fri 19/11/04																
292	1.5.5.2 Dipoles	667d	Thu 02/05/02	Fri 19/11/04																
295	Place Order	0d	Fri 25/04/03	Fri 25/04/03																
297	Complete Design	0d	Fri 10/10/03	Fri 10/10/03																
299	Deliver final equipment	0d	Fri 26/03/04	Fri 26/03/04																
301	Complete installation	0d	Fri 22/10/04	Fri 22/10/04																
303	Power Convertor Available	0d	Fri 19/11/04	Fri 19/11/04																
304	1.5.5.3 Sextupoles	667d	Thu 02/05/02	Fri 19/11/04																
307	Place Order	0d	Fri 25/04/03	Fri 25/04/03																
309	Complete Design	0d	Fri 10/10/03	Fri 10/10/03																
311	Deliver final equipment	0d	Thu 13/11/03	Thu 13/11/03																
313	Complete installation	0d	Fri 22/10/04	Fri 22/10/04																
315	Power Convertor Available	0d	Fri 19/11/04	Fri 19/11/04																
316	1.5.5.4 Steerers	667d	Thu 02/05/02	Fri 19/11/04																

Diamond Project Master Schedule

ID	Task Name	Duration	Early Start	Early Finish	03				04				05				06							
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	
319	Place Order	0d	Fri 25/04/03	Fri 25/04/03																				
321	Complete Design	0d	Fri 10/10/03	Fri 10/10/03																				
323	Deliver final equipment	0d	Fri 26/03/04	Fri 26/03/04																				
325	Complete installation	0d	Fri 22/10/04	Fri 22/10/04																				
327	Testing Complete	0d	Fri 19/11/04	Fri 19/11/04																				
328	1.5.5.5 Services	707d	Thu 02/05/02	Fri 14/01/05																				
331	Place Order	0d	Fri 25/04/03	Fri 25/04/03																				
333	Complete Design	0d	Fri 21/11/03	Fri 21/11/03																				
335	Deliver final equipment	0d	Fri 18/06/04	Fri 18/06/04																				
337	Complete installation	0d	Fri 17/12/04	Fri 17/12/04																				
339	Testing Complete	0d	Fri 14/01/05	Fri 14/01/05																				
340	1.5.5.6 Plant Control Main Mags and Steer - Mark Heron	837d	Thu 02/05/02	Fri 15/07/05																				
341	Interface Requirements from tech group	0d	Thu 02/05/02	Thu 02/05/02																				
348	Plant and service available	0d	Thu 02/05/02	Thu 02/05/02																				
350	1.5.6 RF system – Mike Dykes	777d	Thu 02/05/02	Fri 22/04/05																				
351	1.5.6.1 Cavities	687d	Thu 02/05/02	Fri 17/12/04																				
355	Place Order	0d	Fri 10/01/03	Fri 10/01/03																				
357	Complete Design	0d	Fri 24/01/03	Fri 24/01/03																				
359	Deliver equipment	0d	Fri 24/10/03	Fri 24/10/03																				
362	Complete installation	0d	Fri 05/11/04	Fri 05/11/04																				
364	Testing Complete	0d	Fri 17/12/04	Fri 17/12/04																				
365	1.5.6.2 Power source	637d	Thu 02/05/02	Fri 08/10/04																				
368	Place Order	0d	Fri 03/01/03	Fri 03/01/03																				
370	Complete Design	0d	Fri 17/01/03	Fri 17/01/03																				
372	Deliver equipment	0d	Fri 17/10/03	Fri 17/10/03																				
374	Complete installation	0d	Fri 08/10/04	Fri 08/10/04																				
375	Test equipment	0d	Fri 08/10/04	Fri 08/10/04																				
376	Testing Complete	0d	Fri 08/10/04	Fri 08/10/04																				
377	1.5.6.3 Feeder	767d	Thu 02/05/02	Fri 08/04/05																				
380	Place Order	0d	Fri 03/01/03	Fri 03/01/03																				
381	Design	0d	Fri 03/01/03	Fri 03/01/03																				
382	Complete Design	0d	Fri 03/01/03	Fri 03/01/03																				
383	Manufacture and Works Test	0d	Fri 03/01/03	Fri 03/01/03																				
384	Deliver equipment	0d	Fri 03/01/03	Fri 03/01/03																				
386	Complete installation	0d	Fri 28/01/05	Fri 28/01/05																				
388	Testing Complete	0d	Fri 08/04/05	Fri 08/04/05																				
389	1.5.6.4 Low level RF	687d	Thu 02/05/02	Fri 17/12/04																				
392	Place Order	0d	Fri 03/01/03	Fri 03/01/03																				
394	Complete Design	0d	Fri 09/05/03	Fri 09/05/03																				

Diamond Project Master Schedule

ID	Task Name	Duration	Early Start	Early Finish	03				04				05				06						
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
396	Deliver equipment	0d	Fri 07/11/03	Fri 07/11/03																			
398	Complete installation	0d	Fri 08/10/04	Fri 08/10/04																			
400	Testing Complete	0d	Fri 17/12/04	Fri 17/12/04																			
401	1.5.6.5 Services	637d	Thu 02/05/02	Fri 08/10/04																			
404	Place Order	0d	Fri 03/01/03	Fri 03/01/03																			
406	Complete Design	0d	Fri 28/02/03	Fri 28/02/03																			
408	Deliver equipment	0d	Fri 04/07/03	Fri 04/07/03																			
410	Complete installation	0d	Fri 08/10/04	Fri 08/10/04																			
411	Test equipment	0d	Fri 08/10/04	Fri 08/10/04																			
412	Testing Complete	0d	Fri 08/10/04	Fri 08/10/04																			
413	1.5.6.6 Plant Control RF - Mark Heron	777d	Thu 02/05/02	Fri 22/04/05																			
414	Interface Requirements from tech group	0d	Thu 02/05/02	Thu 02/05/02																			
421	Plant and service available	0d	Thu 02/05/02	Thu 02/05/02																			
423	1.5.7 Diagnostics – Rob Smith	777d	Thu 02/05/02	Fri 22/04/05																			
424	1.5.7.1 Standard EBPMs	637d	Thu 02/05/02	Fri 08/10/04																			
428	Place Order	0d	Fri 03/01/03	Fri 03/01/03																			
430	Complete Design	0d	Fri 28/02/03	Fri 28/02/03																			
432	Deliver equipment	0d	Fri 28/11/03	Fri 28/11/03																			
435	Complete installation	0d	Fri 08/10/04	Fri 08/10/04																			
436	Test equipment	0d	Fri 08/10/04	Fri 08/10/04																			
437	Testing Complete	0d	Fri 08/10/04	Fri 08/10/04																			
438	1.5.7.2 Total Current Monitor	592d	Thu 02/05/02	Fri 06/08/04																			
442	Place Order	0d	Fri 10/01/03	Fri 10/01/03																			
443	Design	0d	Fri 10/01/03	Fri 10/01/03																			
444	Complete Design	0d	Fri 10/01/03	Fri 10/01/03																			
447	Deliver equipment	0d	Wed 10/09/03	Wed 10/09/03																			
449	Complete installation	0d	Fri 06/08/04	Fri 06/08/04																			
450	Test equipment	0d	Fri 06/08/04	Fri 06/08/04																			
451	Testing Complete	0d	Fri 06/08/04	Fri 06/08/04																			
452	1.5.7.3 Beam Loss Monitors	607d	Thu 02/05/02	Fri 27/08/04																			
455	Place Order	0d	Fri 03/01/03	Fri 03/01/03																			
457	Complete Design	0d	Fri 31/01/03	Fri 31/01/03																			
459	Deliver equipment	0d	Fri 09/05/03	Fri 09/05/03																			
461	Complete installation	0d	Fri 27/08/04	Fri 27/08/04																			
462	Test equipment	0d	Fri 27/08/04	Fri 27/08/04																			
463	Testing Complete	0d	Fri 27/08/04	Fri 27/08/04																			
464	1.5.7.4 Fluorescent Screens and Cameras	637d	Thu 02/05/02	Fri 08/10/04																			
467	Place Order	0d	Fri 03/01/03	Fri 03/01/03																			
469	Complete Design	0d	Fri 28/02/03	Fri 28/02/03																			

Diamond Project Master Schedule

ID	Task Name	Duration	Early Start	Early Finish	03				04				05				06						
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4				
471	Deliver equipment	0d	Fri 29/08/03	Fri 29/08/03																			
473	Complete installation	0d	Fri 08/10/04	Fri 08/10/04																			
474	Test equipment	0w	Fri 08/10/04	Fri 08/10/04																			
475	Testing Complete	0d	Fri 08/10/04	Fri 08/10/04																			
476	1.5.7.5 Collimator Systems	607d	Thu 02/05/02	Fri 27/08/04																			
480	Place Order	0d	Fri 07/02/03	Fri 07/02/03																			
482	Complete Design	0d	Fri 04/04/03	Fri 04/04/03																			
484	Deliver equipment	0d	Fri 02/01/04	Fri 02/01/04																			
487	Complete installation	0d	Fri 27/08/04	Fri 27/08/04																			
488	Test equipment	0d	Fri 27/08/04	Fri 27/08/04																			
489	Testing Complete	0d	Fri 27/08/04	Fri 27/08/04																			
490	1.5.7.6 Plant Control Diagnostics - Mark Heron	777d	Thu 02/05/02	Fri 22/04/05																			
491	Interface Requirements from tech group	0d	Thu 02/05/02	Thu 02/05/02																			
498	Plant and service available	0d	Thu 02/05/02	Thu 02/05/02																			
500	1.5.8 Girder system – Graham Duller	777d	Thu 02/05/02	Fri 22/04/05																			
503	Place Order	0d	Thu 02/05/02	Thu 02/05/02																			
505	Complete Design	0d	Wed 19/06/02	Wed 19/06/02																			
507	Deliver equipment	0d	Wed 09/10/02	Wed 09/10/02																			
510	Complete installation	0d	Fri 25/02/05	Fri 25/02/05																			
512	Testing Complete	0d	Fri 22/04/05	Fri 22/04/05																			
513	1.5.9 Services – Jim Kay	662d	Thu 02/05/02	Fri 12/11/04																			
514	1.5.9.1 Water systems	647d	Thu 02/05/02	Fri 22/10/04																			
517	Place Order	0d	Fri 06/12/02	Fri 06/12/02																			
519	Complete Design	0d	Fri 28/02/03	Fri 28/02/03																			
521	Deliver equipment	0d	Fri 28/03/03	Fri 28/03/03																			
523	Complete installation	0d	Fri 24/09/04	Fri 24/09/04																			
525	Testing Complete	0d	Fri 22/10/04	Fri 22/10/04																			
526	1.5.9.2 Gas systems	662d	Thu 02/05/02	Fri 12/11/04																			
529	Place Order	0d	Fri 06/12/02	Fri 06/12/02																			
531	Complete Design	0d	Fri 28/02/03	Fri 28/02/03																			
533	Deliver equipment	0d	Fri 28/03/03	Fri 28/03/03																			
535	Complete installation	0d	Fri 24/09/04	Fri 24/09/04																			
538	Testing Complete	0d	Fri 12/11/04	Fri 12/11/04																			
539	1.5.9.3 Electrical systems	647d	Thu 02/05/02	Fri 22/10/04																			
542	Place Order	0d	Fri 06/12/02	Fri 06/12/02																			
544	Complete Design	0d	Fri 28/02/03	Fri 28/02/03																			
546	Deliver equipment	0d	Fri 28/03/03	Fri 28/03/03																			
548	Complete installation	0d	Fri 24/09/04	Fri 24/09/04																			
550	Testing Complete	0d	Fri 22/10/04	Fri 22/10/04																			

Diamond Project Master Schedule

ID	Task Name	Duration	Early Start	Early Finish	03				04				05				06							
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	
551	1.5.9.4 Trunking distribution	647d	Thu 02/05/02	Fri 22/10/04																				
554	Place Order	0d	Fri 06/12/02	Fri 06/12/02																				
556	Complete Design	0d	Fri 28/02/03	Fri 28/02/03																				
558	Deliver equipment	0d	Fri 28/03/03	Fri 28/03/03																				
560	Complete installation	0d	Fri 24/09/04	Fri 24/09/04																				
562	Testing Complete	0d	Fri 22/10/04	Fri 22/10/04																				
563	1.5.10 Alignment - Jim Kay	607d	Thu 02/05/02	Fri 27/08/04																				
564	1.5.10.1 Tunnel Network	607d	Thu 02/05/02	Fri 27/08/04																				
567	Place Order	0d	Fri 06/12/02	Fri 06/12/02																				
569	Complete Design	0d	Fri 03/01/03	Fri 03/01/03																				
571	Deliver equipment	0d	Fri 14/03/03	Fri 14/03/03																				
573	Complete installation	0d	Fri 13/08/04	Fri 13/08/04																				
575	Measurements Complete	0d	Fri 27/08/04	Fri 27/08/04																				
577	1.5.12 Personnel Safety System Linac and Booster – Mark Heron	712d	Thu 02/05/02	Fri 21/01/05																				
578	Interface Requirements from tech group	0d	Thu 02/05/02	Thu 02/05/02																				
585	Plant and service available	0d	Thu 02/05/02	Thu 02/05/02																				
587	CS Operational Injector	0d	Fri 21/01/05	Fri 21/01/05																				
588	Plant available	0d	Fri 21/01/05	Fri 21/01/05																				
590	Commission Personal Safety Systems Linac & Booster with Beam	0d	Fri 04/03/05	Fri 04/03/05																				
592	1.5.13 Plant Control – Mark Heron	185d	Fri 22/04/05	Fri 06/01/06																				
593	CS Operational Booster	0d	Fri 22/04/05	Fri 22/04/05																				
594	All system available to operate (Services,Shielding,PS,Rad mon)	0d	Fri 16/12/05	Fri 16/12/05																				
596	Booster Operational	0d	Fri 06/01/06	Fri 06/01/06																				
597	1.5.14 Health Physics Installed Monitors System – Roy Ryder	422d	Wed 05/05/04	Fri 16/12/05																				
598	Deliver equipment	0d	Wed 05/05/04	Wed 05/05/04																				
600	Complete installation	0d	Fri 17/06/05	Fri 17/06/05																				
602	Commissioning Complete	0d	Fri 16/12/05	Fri 16/12/05																				
603	1.5.15 Extraction system - Neil Marks	777d	Thu 02/05/02	Fri 22/04/05																				
604	1.5.15.1 Kickers	385d	Thu 02/05/02	Wed 22/10/03																				
606	AP Parameters available	0d	Wed 24/07/02	Wed 24/07/02																				
610	Place Order	0d	Fri 21/03/03	Fri 21/03/03																				
612	Deliver equipment	0d	Fri 08/08/03	Fri 08/08/03																				
615	Testing complete, available for installation	0d	Wed 22/10/03	Wed 22/10/03																				
616	1.5.15.2 Septum	587d	Thu 25/07/02	Fri 22/10/04																				
620	Place Order	0d	Fri 04/04/03	Fri 04/04/03																				
622	Deliver equipment	0d	Fri 22/08/03	Fri 22/08/03																				
625	Complete installation	0d	Fri 24/09/04	Fri 24/09/04																				
627	Testing complete, available for installation	0d	Fri 22/10/04	Fri 22/10/04																				
628	1.5.15.3 Pulsed power supplies	290.33d	Wed 04/09/02	Thu 16/10/03																				

Diamond Project Master Schedule

ID	Task Name	Duration	Early Start	Early Finish	03				04				05				06							
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	
629	Kicker power supply	140d	Wed 04/09/02	Wed 19/03/03																				
634	Septum power supply	280.33d	Wed 18/09/02	Thu 16/10/03																				
641	1.5.15.4 Support structure	607d	Thu 02/05/02	Fri 27/08/04																				
644	Place Order	0d	Fri 03/01/03	Fri 03/01/03																				
646	Complete Design	0d	Fri 17/01/03	Fri 17/01/03																				
648	Deliver equipment	0d	Fri 14/03/03	Fri 14/03/03																				
650	Complete installation	0d	Fri 13/08/04	Fri 13/08/04																				
652	Testing Complete	0d	Fri 27/08/04	Fri 27/08/04																				
655	1.5.15.6 Plant Control Injection and Kickers - Mark Heron	777d	Thu 02/05/02	Fri 22/04/05																				
656	Interface Requirements from tech group	0d	Thu 02/05/02	Thu 02/05/02																				
663	Plant and service available	0d	Fri 11/03/05	Fri 11/03/05																				
668	1.6 Booster to Storage Ring Transfer Path - Vic Suller	987d	Thu 02/05/02	Fri 10/02/06																				
669	1.6.1 Booster to Storage Ring (Turnkey contract) – Graham Duller	677d	Thu 02/05/02	Fri 03/12/04																				
672	Place Order	0d	Fri 03/01/03	Fri 03/01/03																				
674	Complete Design	0d	Fri 25/04/03	Fri 25/04/03																				
676	Deliver equipment	0d	Fri 26/03/04	Fri 26/03/04																				
678	Complete installation	0d	Fri 22/10/04	Fri 22/10/04																				
680	Testing Complete	0d	Fri 03/12/04	Fri 03/12/04																				
681	1.6.2 Services – Graham Duller	622d	Thu 02/05/02	Fri 17/09/04																				
684	Place Order	0d	Fri 22/11/02	Fri 22/11/02																				
686	Complete Design	0d	Fri 20/12/02	Fri 20/12/02																				
688	Deliver equipment	0d	Fri 14/02/03	Fri 14/02/03																				
690	Complete installation	0d	Fri 10/09/04	Fri 10/09/04																				
692	Testing Complete	0d	Fri 17/09/04	Fri 17/09/04																				
693	1.6.3 Plant Control BTS Mags, Vac, Diag – Mark Heron	797d	Thu 02/05/02	Fri 20/05/05																				
694	Interface Requirements	0d	Thu 02/05/02	Thu 02/05/02																				
701	All system available to operate (Services,Shielding,PS,Rad mon)	0d	Fri 29/04/05	Fri 29/04/05																				
708	1.7 Storage Ring	1132d	Thu 02/05/02	Fri 01/09/06																				
709	1.7.1 Injection system – Neil Marks	777d	Thu 02/05/02	Fri 22/04/05																				
710	1.7.1.1 Kickers	432d	Thu 02/05/02	Fri 26/12/03																				
712	AP Parameters available	0d	Wed 24/07/02	Wed 24/07/02																				
716	Place Order	0d	Fri 18/04/03	Fri 18/04/03																				
718	Deliver equipment	0d	Fri 05/09/03	Fri 05/09/03																				
721	Testing complete and available for installation	0d	Fri 26/12/03	Fri 26/12/03																				
722	1.7.1.2 Septum	337d	Thu 19/09/02	Fri 02/01/04																				
726	Place Order	0d	Fri 02/05/03	Fri 02/05/03																				
728	Deliver equipment	0d	Fri 19/09/03	Fri 19/09/03																				
731	Testing complete and available for installation	0d	Fri 02/01/04	Fri 02/01/04																				
732	1.7.1.3 Pulsed power supplies	297d	Wed 16/10/02	Fri 05/12/03																				

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ID	Task Name	Duration	Early Start	Early Finish	03				04				05				06					
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3
733	Kicker power supply	130d	Wed 27/11/02	Wed 28/05/03																		
738	Septum power supply	297d	Wed 16/10/02	Fri 05/12/03																		
745	1.7.1.4 Support structure	607d	Thu 02/05/02	Fri 27/08/04																		
748	Place Order	0d	Fri 03/01/03	Fri 03/01/03																		
750	Complete Design	0d	Fri 17/01/03	Fri 17/01/03																		
752	Deliver equipment	0d	Fri 14/03/03	Fri 14/03/03																		
754	Complete installation	0d	Fri 13/08/04	Fri 13/08/04																		
756	Testing Complete	0d	Fri 27/08/04	Fri 27/08/04																		
758	1.7.1.6 Plant Control Injection and Kickers - Mark Heron	777d	Thu 02/05/02	Fri 22/04/05																		
759	Interface Requirements from tech group	0d	Thu 02/05/02	Thu 02/05/02																		
766	Plant and service available	0d	Fri 10/09/04	Fri 10/09/04																		
768	1.7.2 Vacuum system – Ron Reid	777d	Thu 02/05/02	Fri 22/04/05																		
777	1.7.2.3 Roughing Pumps	275d	Thu 02/05/02	Wed 21/05/03																		
779	Issue call for tenders	0d	Wed 29/05/02	Wed 29/05/02																		
781	Place Order	0d	Wed 27/11/02	Wed 27/11/02																		
782	Design	0d	Wed 27/11/02	Wed 27/11/02																		
783	Complete Design	0d	Wed 27/11/02	Wed 27/11/02																		
788	Complete installation	0d	Mon 19/05/03	Mon 19/05/03																		
790	Testing Complete	0d	Wed 21/05/03	Wed 21/05/03																		
791	1.7.2.4 Ion Pumps	425d	Thu 02/05/02	Wed 17/12/03																		
793	Issue call for tenders	0d	Wed 29/05/02	Wed 29/05/02																		
795	Place Order	0d	Wed 27/11/02	Wed 27/11/02																		
796	Design	0d	Wed 27/11/02	Wed 27/11/02																		
797	Complete Design	0d	Wed 27/11/02	Wed 27/11/02																		
799	Deliver equipment	0d	Wed 26/11/03	Wed 26/11/03																		
801	Equipment ready for installation	0d	Wed 17/12/03	Wed 17/12/03																		
802	1.7.2.5 Ion Pump Control Units	420d	Thu 02/05/02	Wed 10/12/03																		
804	Issue call for tenders	0d	Wed 29/05/02	Wed 29/05/02																		
806	Place Order	0d	Wed 27/11/02	Wed 27/11/02																		
807	Design	0d	Wed 27/11/02	Wed 27/11/02																		
808	Complete Design	0d	Wed 27/11/02	Wed 27/11/02																		
810	Deliver equipment	0d	Wed 26/11/03	Wed 26/11/03																		
812	Equipment ready for installation	0d	Wed 10/12/03	Wed 10/12/03																		
813	1.7.2.6 NEG Pumps and Control Units	210d	Thu 02/05/02	Wed 19/02/03																		
815	Issue call for tenders	0d	Wed 29/05/02	Wed 29/05/02																		
817	Place Order	0d	Wed 07/08/02	Wed 07/08/02																		
818	Design	0d	Wed 07/08/02	Wed 07/08/02																		
819	Complete Design	0d	Wed 07/08/02	Wed 07/08/02																		
821	Deliver equipment	0d	Wed 25/12/02	Wed 25/12/02																		

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ID	Task Name	Duration	Early Start	Early Finish	03				04				05				06					
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3
823	Equipment ready for installation	0d	Wed 19/02/03	Wed 19/02/03				◆														
824	1.7.2.7 NEG Pump Housings	395d	Thu 02/05/02	Wed 05/11/03	◆																	
826	Issue call for tenders	0d	Wed 26/06/02	Wed 26/06/02	◆																	
828	Place Order	0d	Wed 04/09/02	Wed 04/09/02		◆																
830	Complete Design	0d	Wed 18/09/02	Wed 18/09/02		◆																
832	Deliver equipment	0d	Wed 05/02/03	Wed 05/02/03				◆														
834	Equipment ready for installation	0d	Wed 05/11/03	Wed 05/11/03							◆											
835	1.7.2.8 TSP Cartridges	385d	Thu 02/05/02	Wed 22/10/03	◆																	
837	Issue call for tenders	0d	Wed 29/05/02	Wed 29/05/02	◆																	
839	Place Order	0d	Wed 07/08/02	Wed 07/08/02		◆																
840	Design	0d	Wed 07/08/02	Wed 07/08/02		◆																
841	Complete Design	0d	Wed 07/08/02	Wed 07/08/02		◆																
843	Deliver equipment	0d	Wed 25/12/02	Wed 25/12/02				◆														
846	Equipment ready for installation	0d	Wed 22/10/03	Wed 22/10/03							◆											
847	1.7.2.9 TSP Bodies	415d	Thu 02/05/02	Wed 03/12/03	◆																	
849	Issue call for tenders	0d	Wed 26/06/02	Wed 26/06/02	◆																	
851	Place Order	0d	Wed 04/09/02	Wed 04/09/02		◆																
853	Complete Design	0d	Wed 18/09/02	Wed 18/09/02		◆																
855	Deliver equipment	0d	Wed 05/02/03	Wed 05/02/03				◆														
858	Equipment ready for installation	0d	Wed 03/12/03	Wed 03/12/03							◆											
859	1.7.2.10 TSP Control Units	420d	Thu 02/05/02	Wed 10/12/03	◆																	
861	Issue call for tenders	0d	Wed 29/05/02	Wed 29/05/02	◆																	
863	Place Order	0d	Wed 27/11/02	Wed 27/11/02		◆																
864	Design	0d	Wed 27/11/02	Wed 27/11/02		◆																
865	Complete Design	0d	Wed 27/11/02	Wed 27/11/02		◆																
867	Deliver equipment	0d	Wed 26/11/03	Wed 26/11/03							◆											
869	Equipment ready for installation	0d	Wed 10/12/03	Wed 10/12/03							◆											
870	1.7.2.11 Low Vacuum Gauges (Mechanical)	395d	Thu 02/05/02	Wed 05/11/03	◆																	
872	Issue call for tenders	0d	Wed 29/05/02	Wed 29/05/02	◆																	
874	Place Order	0d	Wed 07/08/02	Wed 07/08/02		◆																
875	Design	0d	Wed 07/08/02	Wed 07/08/02		◆																
876	Complete Design	0d	Wed 07/08/02	Wed 07/08/02		◆																
878	Deliver equipment	0d	Wed 25/12/02	Wed 25/12/02				◆														
881	Equipment ready for installation	0d	Wed 05/11/03	Wed 05/11/03							◆											
882	1.7.2.12 Medium Vacuum Gauges (Pirani Gauge Heads)	405d	Thu 02/05/02	Wed 19/11/03	◆																	
884	Issue call for tenders	0d	Wed 29/05/02	Wed 29/05/02	◆																	
886	Place Order	0d	Wed 07/08/02	Wed 07/08/02		◆																
887	Design	0d	Wed 07/08/02	Wed 07/08/02		◆																
888	Complete Design	0d	Wed 07/08/02	Wed 07/08/02		◆																

Diamond Project Master Schedule

ID	Task Name	Duration	Early Start	Early Finish	03				04				05				06					
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3
890	Deliver equipment	0d	Wed 25/12/02	Wed 25/12/02																		
893	Equipment ready for installation	0d	Wed 19/11/03	Wed 19/11/03																		
894	1.7.2.13 UHV Gauge Heads (IMG)	405d	Thu 02/05/02	Wed 19/11/03																		
896	Issue call for tenders	0d	Wed 29/05/02	Wed 29/05/02																		
898	Place Order	0d	Wed 07/08/02	Wed 07/08/02																		
899	Design	0d	Wed 07/08/02	Wed 07/08/02																		
900	Complete Design	0d	Wed 07/08/02	Wed 07/08/02																		
902	Deliver equipment	0d	Wed 25/12/02	Wed 25/12/02																		
905	Equipment ready for installation	0d	Wed 19/11/03	Wed 19/11/03																		
906	1.7.2.14 Total Pressure Gauge Control Units	290d	Thu 02/05/02	Wed 11/06/03																		
908	Issue call for tenders	0d	Wed 29/05/02	Wed 29/05/02																		
910	Place Order	0d	Wed 27/11/02	Wed 27/11/02																		
911	Design	0d	Wed 27/11/02	Wed 27/11/02																		
912	Complete Design	0d	Wed 27/11/02	Wed 27/11/02																		
914	Deliver equipment	0d	Wed 28/05/03	Wed 28/05/03																		
916	Equipment ready for installation	0d	Wed 11/06/03	Wed 11/06/03																		
917	1.7.2.15 Partial Pressure Gauge Systems	405d	Thu 02/05/02	Wed 19/11/03																		
919	Issue call for tenders	0d	Wed 29/05/02	Wed 29/05/02																		
921	Place Order	0d	Wed 27/11/02	Wed 27/11/02																		
922	Design	0d	Wed 27/11/02	Wed 27/11/02																		
923	Complete Design	0d	Wed 27/11/02	Wed 27/11/02																		
925	Deliver equipment	0d	Wed 28/05/03	Wed 28/05/03																		
928	Equipment ready for installation	0d	Wed 19/11/03	Wed 19/11/03																		
929	1.7.2.16 UHV Gate Valves	535d	Thu 02/05/02	Wed 19/05/04																		
931	Issue call for tenders	0d	Wed 29/05/02	Wed 29/05/02																		
933	Place Order	0d	Wed 07/08/02	Wed 07/08/02																		
934	Design	0d	Wed 07/08/02	Wed 07/08/02																		
935	Complete Design	0d	Wed 07/08/02	Wed 07/08/02																		
937	Deliver equipment	0d	Wed 05/02/03	Wed 05/02/03																		
940	Equipment ready for installation	0d	Wed 19/05/04	Wed 19/05/04																		
941	1.7.2.17 UHV Right Angle Pneumatic Valves	465d	Thu 02/05/02	Wed 11/02/04																		
943	Issue call for tenders	0d	Wed 29/05/02	Wed 29/05/02																		
945	Place Order	0d	Wed 27/11/02	Wed 27/11/02																		
946	Design	0d	Wed 27/11/02	Wed 27/11/02																		
947	Complete Design	0d	Wed 27/11/02	Wed 27/11/02																		
949	Deliver equipment	0d	Wed 28/05/03	Wed 28/05/03																		
952	Equipment ready for installation	0d	Wed 11/02/04	Wed 11/02/04																		
953	1.7.2.18 Other Vacuum Valves	405d	Thu 02/05/02	Wed 19/11/03																		
955	Issue call for tenders	0d	Wed 29/05/02	Wed 29/05/02																		

Diamond Project Master Schedule

ID	Task Name	Duration	Early Start	Early Finish	03				04				05				06					
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3
957	Place Order	0d	Wed 07/08/02	Wed 07/08/02																		
958	Design	0d	Wed 07/08/02	Wed 07/08/02																		
959	Complete Design	0d	Wed 07/08/02	Wed 07/08/02																		
961	Deliver equipment	0d	Wed 05/02/03	Wed 05/02/03																		
964	Equipment ready for installation	0d	Wed 19/11/03	Wed 19/11/03																		
965	1.7.2.19 Plant Control Vacuum - Mark Heron	777d	Thu 02/05/02	Fri 22/04/05																		
966	Interface Requirements from tech group	0d	Thu 02/05/02	Thu 02/05/02																		
973	Plant and service available	0d	Fri 11/03/05	Fri 11/03/05																		
975	1.7.3 Vacuum Mechanical Engineering	687d	Thu 02/05/02	Fri 17/12/04																		
976	1.7.3.1 Vessels - Nigel Hammond	687d	Thu 02/05/02	Fri 17/12/04																		
980	Place Order	0d	Fri 25/04/03	Fri 25/04/03																		
982	Complete Design	0d	Fri 06/06/03	Fri 06/06/03																		
987	Complete installation	0d	Fri 17/12/04	Fri 17/12/04																		
988	Test equipment	0d	Fri 17/12/04	Fri 17/12/04																		
989	Testing Complete	0d	Fri 17/12/04	Fri 17/12/04																		
990	1.7.3.2 Absorbers - Nigel Hammond	587d	Thu 02/05/02	Mon 02/08/04																		
994	Place Order	0d	Fri 04/07/03	Fri 04/07/03																		
996	Complete Design	0d	Fri 25/07/03	Fri 25/07/03																		
998	Deliver equipment	0d	Fri 20/02/04	Fri 20/02/04																		
1000	Install equipment	0d	Mon 02/08/04	Mon 02/08/04																		
1001	Complete installation	0d	Mon 02/08/04	Mon 02/08/04																		
1002	Test equipment	0d	Mon 02/08/04	Mon 02/08/04																		
1003	Testing Complete	0d	Mon 02/08/04	Mon 02/08/04																		
1004	1.7.3.3 Tapers - Nigel Hammond	557d	Thu 02/05/02	Mon 21/06/04																		
1008	Place Order	0d	Fri 21/03/03	Fri 21/03/03																		
1010	Complete Design	0d	Fri 11/04/03	Fri 11/04/03																		
1012	Deliver equipment	0d	Fri 07/11/03	Fri 07/11/03																		
1014	Install equipment	0d	Fri 05/12/03	Fri 05/12/03																		
1015	Complete installation	0d	Mon 21/06/04	Mon 21/06/04																		
1016	Test equipment	0d	Mon 21/06/04	Mon 21/06/04																		
1017	Testing Complete	0d	Mon 21/06/04	Mon 21/06/04																		
1018	1.7.3.4 Bellows - Nigel Hammond	587d	Thu 02/05/02	Mon 02/08/04																		
1022	Place Order	0d	Fri 25/04/03	Fri 25/04/03																		
1024	Complete Design	0d	Fri 23/05/03	Fri 23/05/03																		
1026	Deliver equipment	0d	Fri 14/11/03	Fri 14/11/03																		
1028	Install equipment	0d	Mon 02/08/04	Mon 02/08/04																		
1029	Complete installation	0d	Mon 02/08/04	Mon 02/08/04																		
1030	Test equipment	0d	Mon 02/08/04	Mon 02/08/04																		
1031	Testing Complete	0d	Mon 02/08/04	Mon 02/08/04																		

Diamond Project Master Schedule

ID	Task Name	Duration	Early Start	Early Finish	03				04				05				06							
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	
1033	1.7.4 Magnets – Neil Marks	842d	Thu 02/05/02	Fri 22/07/05																				
1034	1.7.4.1 Quadrupoles	842d	Thu 02/05/02	Fri 22/07/05																				
1036	Magnet Parameters frozen	0d	Wed 29/05/02	Wed 29/05/02	◆																			
1039	Place Order	0d	Fri 14/03/03	Fri 14/03/03				◆																
1041	Complete Design	0d	Fri 13/06/03	Fri 13/06/03					◆															
1043	Approve Prototype	0d	Fri 31/10/03	Fri 31/10/03						◆														
1045	Delivery complete	0d	Fri 15/10/04	Fri 15/10/04									◆											
1047	Complete installation	0d	Fri 22/07/05	Fri 22/07/05															◆					
1048	Test equipment	0d	Fri 22/07/05	Fri 22/07/05															◆					
1049	Testing Complete	0d	Fri 22/07/05	Fri 22/07/05															◆					
1050	1.7.4.2 Dipoles	617d	Thu 05/09/02	Fri 14/01/05																				
1053	Place Order	0d	Fri 25/04/03	Fri 25/04/03				◆																
1055	Complete Design	0d	Fri 11/07/03	Fri 11/07/03					◆															
1057	Approve Prototype	0d	Fri 24/10/03	Fri 24/10/03						◆														
1059	Deliver equipment	0d	Fri 18/06/04	Fri 18/06/04								◆												
1061	Complete installation	0d	Fri 14/01/05	Fri 14/01/05															◆					
1062	Test equipment	0d	Fri 14/01/05	Fri 14/01/05															◆					
1063	Testing Complete	0d	Fri 14/01/05	Fri 14/01/05															◆					
1064	1.7.4.3 Sextupoles	707d	Thu 17/10/02	Fri 01/07/05																				
1067	Place Order	0d	Fri 06/06/03	Fri 06/06/03				◆																
1069	Complete Design	0d	Fri 08/08/03	Fri 08/08/03					◆															
1071	Approve Prototype	0d	Fri 02/01/04	Fri 02/01/04						◆														
1073	Delivery complete	0d	Fri 05/11/04	Fri 05/11/04									◆											
1075	Complete installation	0d	Fri 01/07/05	Fri 01/07/05															◆					
1076	Test equipment	0d	Fri 01/07/05	Fri 01/07/05															◆					
1077	Testing Complete	0d	Fri 01/07/05	Fri 01/07/05															◆					
1078	1.7.4.4 Fast Dynamic correctors	592d	Thu 28/11/02	Fri 04/03/05																				
1081	Place Order	0d	Fri 18/07/03	Fri 18/07/03				◆																
1083	Complete Design	0d	Fri 17/10/03	Fri 17/10/03					◆															
1085	Approve Prototype	0d	Fri 12/12/03	Fri 12/12/03						◆														
1087	Delivery complete	0d	Fri 20/08/04	Fri 20/08/04									◆											
1089	Complete installation	0d	Fri 18/02/05	Fri 18/02/05															◆					
1091	Testing Complete	0d	Fri 04/03/05	Fri 04/03/05															◆					
1092	1.7.5 Magnet power supplies – Steve Griffiths	1063d	Thu 02/05/02	Mon 29/05/06																				
1093	1.7.5.1 Quadrupoles	966d	Mon 16/09/02	Mon 29/05/06																				
1096	Place Order	0d	Tue 09/09/03	Tue 09/09/03				◆																
1098	Complete Design	0d	Tue 24/08/04	Tue 24/08/04									◆											
1100	Deliver final equipment	0d	Tue 18/10/05	Tue 18/10/05															◆					
1102	Complete installation	0d	Mon 29/05/06	Mon 29/05/06																◆				

Diamond Project Master Schedule

ID	Task Name	Duration	Early Start	Early Finish	03				04				05				06																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																															
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																									
1104	Power Convertors Available	0d	Mon 03/10/05	Mon 03/10/05																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																												</

Diamond Project Master Schedule

ID	Task Name	Duration	Early Start	Early Finish	03				04				05				06								
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4		
1187	Testing Complete	0d	Fri 08/04/05	Fri 08/04/05																					
1188	1.7.6.2 Power source	877d	Thu 02/05/02	Fri 09/09/05																					
1191	Place Order	0d	Fri 03/01/03	Fri 03/01/03																					
1192	Design	0d	Fri 03/01/03	Fri 03/01/03																					
1193	Complete Design	0d	Fri 03/01/03	Fri 03/01/03																					
1194	Manufacture and Works Test	0d	Fri 03/01/03	Fri 03/01/03																					
1195	Deliver equipment	0d	Fri 03/01/03	Fri 03/01/03																					
1197	Complete installation	0d	Fri 01/07/05	Fri 01/07/05																					
1199	Testing Complete	0d	Fri 09/09/05	Fri 09/09/05																					
1200	1.7.6.3 Feeder	767d	Thu 02/05/02	Fri 08/04/05																					
1203	Place Order	0d	Fri 03/01/03	Fri 03/01/03																					
1204	Design	0d	Fri 03/01/03	Fri 03/01/03																					
1205	Complete Design	0d	Fri 03/01/03	Fri 03/01/03																					
1206	Manufacture and Works Test	0d	Fri 03/01/03	Fri 03/01/03																					
1207	Deliver equipment	0d	Fri 03/01/03	Fri 03/01/03																					
1209	Complete installation	0d	Fri 28/01/05	Fri 28/01/05																					
1211	Testing Complete	0d	Fri 08/04/05	Fri 08/04/05																					
1212	1.7.6.4 Services	637d	Thu 02/05/02	Fri 08/10/04																					
1215	Place Order	0d	Fri 03/01/03	Fri 03/01/03																					
1217	Complete Design	0d	Fri 28/02/03	Fri 28/02/03																					
1219	Deliver equipment	0d	Fri 04/07/03	Fri 04/07/03																					
1221	Complete installation	0d	Fri 08/10/04	Fri 08/10/04																					
1222	Test equipment	0d	Fri 08/10/04	Fri 08/10/04																					
1223	Testing Complete	0d	Fri 08/10/04	Fri 08/10/04																					
1224	1.7.6.5 Cryogenic system	837d	Thu 02/05/02	Fri 15/07/05																					
1227	Place Order	0d	Fri 28/03/03	Fri 28/03/03																					
1229	Complete Design	0d	Fri 12/09/03	Fri 12/09/03																					
1231	Deliver equipment	0d	Fri 28/01/05	Fri 28/01/05																					
1233	Complete installation	0d	Fri 20/05/05	Fri 20/05/05																					
1235	Testing Complete	0d	Fri 15/07/05	Fri 15/07/05																					
1236	1.7.6.6 Low level RF	687d	Thu 02/05/02	Fri 17/12/04																					
1239	Place Order	0d	Fri 03/01/03	Fri 03/01/03																					
1241	Complete Design	0d	Fri 09/05/03	Fri 09/05/03																					
1243	Deliver equipment	0d	Fri 07/11/03	Fri 07/11/03																					
1245	Complete installation	0d	Fri 08/10/04	Fri 08/10/04																					
1247	Testing Complete	0d	Fri 17/12/04	Fri 17/12/04																					
1248	1.7.6.7 Plant Control RF - Mark Heron	777d	Thu 02/05/02	Fri 22/04/05																					
1249	Interface Requirements from tech group	0d	Thu 02/05/02	Thu 02/05/02																					
1256	Plant and service available	0d	Thu 02/05/02	Thu 02/05/02																					

Diamond Project Master Schedule

ID	Task Name	Duration	Early Start	Early Finish	03				04				05				06							
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	
1258	1.7.7 Diagnostics – Mike Dykes	777d	Thu 02/05/02	Fri 22/04/05																				
1259	1.7.7.1 Standard EBPMs	687d	Thu 02/05/02	Fri 17/12/04																				
1263	Place Order	0d	Fri 10/01/03	Fri 10/01/03																				
1265	Complete Design	0d	Fri 07/03/03	Fri 07/03/03																				
1267	Deliver equipment	0d	Fri 05/12/03	Fri 05/12/03																				
1270	Complete installation	0d	Fri 17/12/04	Fri 17/12/04																				
1271	Test equipment	0d	Fri 17/12/04	Fri 17/12/04																				
1272	Testing Complete	0d	Fri 17/12/04	Fri 17/12/04																				
1273	1.7.7.2 Primary EBPMs	687d	Thu 02/05/02	Fri 17/12/04																				
1277	Place Order	0d	Fri 10/01/03	Fri 10/01/03																				
1279	Complete Design	0d	Fri 07/03/03	Fri 07/03/03																				
1281	Deliver equipment	0d	Fri 05/12/03	Fri 05/12/03																				
1284	Complete installation	0d	Fri 17/12/04	Fri 17/12/04																				
1285	Test equipment	0d	Fri 17/12/04	Fri 17/12/04																				
1286	Testing Complete	0d	Fri 17/12/04	Fri 17/12/04																				
1287	1.7.7.3 Total Current Monitor	597d	Thu 02/05/02	Fri 13/08/04																				
1291	Place Order	0d	Wed 31/07/02	Wed 31/07/02																				
1292	Design	0d	Wed 31/07/02	Wed 31/07/02																				
1293	Complete Design	0d	Wed 31/07/02	Wed 31/07/02																				
1295	Deliver equipment	0d	Wed 09/10/02	Wed 09/10/02																				
1298	Complete installation	0d	Fri 13/08/04	Fri 13/08/04																				
1299	Test equipment	0d	Fri 13/08/04	Fri 13/08/04																				
1300	Testing Complete	0d	Fri 13/08/04	Fri 13/08/04																				
1301	1.7.7.4 Other Electron Beam Monitors	687d	Thu 02/05/02	Fri 17/12/04																				
1305	Place Order	0d	Fri 10/01/03	Fri 10/01/03																				
1307	Complete Design	0d	Fri 07/03/03	Fri 07/03/03																				
1309	Deliver equipment	0d	Fri 05/12/03	Fri 05/12/03																				
1312	Complete installation	0d	Fri 17/12/04	Fri 17/12/04																				
1313	Test equipment	0d	Fri 17/12/04	Fri 17/12/04																				
1314	Testing Complete	0d	Fri 17/12/04	Fri 17/12/04																				
1315	1.7.7.5 Beam Loss Monitors	627d	Thu 02/05/02	Fri 24/09/04																				
1318	Place Order	0d	Wed 07/08/02	Wed 07/08/02																				
1320	Complete Design	0d	Wed 18/09/02	Wed 18/09/02																				
1322	Deliver equipment	0d	Wed 25/12/02	Wed 25/12/02																				
1324	Complete installation	0d	Fri 24/09/04	Fri 24/09/04																				
1325	Test equipment	0d	Fri 24/09/04	Fri 24/09/04																				
1326	Testing Complete	0d	Fri 24/09/04	Fri 24/09/04																				
1327	1.7.7.6 Fluorescent Screens and Cameras	637d	Thu 02/05/02	Fri 08/10/04																				
1330	Place Order	0d	Wed 04/09/02	Wed 04/09/02																				

Diamond Project Master Schedule

ID	Task Name	Duration	Early Start	Early Finish	03				04				05				06										
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4				
1332	Complete Design	0d	Wed 30/10/02	Wed 30/10/02			◆																				
1334	Deliver equipment	0d	Wed 30/04/03	Wed 30/04/03					◆																		
1336	Complete installation	0d	Fri 08/10/04	Fri 08/10/04												◆											
1337	Test equipment	0w	Fri 08/10/04	Fri 08/10/04												◆	◆	◆									
1338	Testing Complete	0d	Fri 08/10/04	Fri 08/10/04												◆	◆	◆									
1339	1.7.7.7 ID Diagnostics / Optics Test beamline	687d	Thu 02/05/02	Fri 17/12/04																							
1343	Place Order	0d	Fri 10/01/03	Fri 10/01/03				◆																			
1345	Complete Design	0d	Fri 07/03/03	Fri 07/03/03					◆																		
1347	Deliver equipment	0d	Fri 05/12/03	Fri 05/12/03							◆																
1350	Complete installation	0d	Fri 24/09/04	Fri 24/09/04												◆											
1352	Testing Complete	0d	Fri 17/12/04	Fri 17/12/04													◆										
1353	1.7.7.8 BM Diagnostic beamline	687d	Thu 02/05/02	Fri 17/12/04																							
1357	Place Order	0d	Fri 10/01/03	Fri 10/01/03				◆																			
1359	Complete Design	0d	Fri 07/03/03	Fri 07/03/03					◆																		
1361	Deliver equipment	0d	Fri 05/12/03	Fri 05/12/03							◆																
1364	Complete installation	0d	Fri 24/09/04	Fri 24/09/04												◆											
1366	Testing Complete	0d	Fri 17/12/04	Fri 17/12/04													◆										
1367	1.7.7.9 Instability Feedback system	697d	Thu 02/05/02	Fri 31/12/04																							
1370	Place Order	0d	Fri 03/01/03	Fri 03/01/03				◆																			
1372	Complete Design	0d	Fri 14/02/03	Fri 14/02/03					◆																		
1374	Deliver equipment	0d	Fri 14/11/03	Fri 14/11/03							◆																
1376	Complete installation	0d	Fri 08/10/04	Fri 08/10/04												◆											
1378	Testing Complete	0d	Fri 31/12/04	Fri 31/12/04													◆										
1379	1.7.7.10 Collimator Systems	607d	Thu 02/05/02	Fri 27/08/04																							
1383	Place Order	0d	Fri 07/02/03	Fri 07/02/03				◆																			
1385	Complete Design	0d	Fri 04/04/03	Fri 04/04/03					◆																		
1387	Deliver equipment	0d	Fri 02/01/04	Fri 02/01/04							◆																
1390	Complete installation	0d	Fri 27/08/04	Fri 27/08/04												◆											
1391	Test equipment	0d	Fri 27/08/04	Fri 27/08/04												◆	◆	◆									
1392	Testing Complete	0d	Fri 27/08/04	Fri 27/08/04												◆	◆	◆									
1393	1.7.7.11 Plant Control Diagnostics - Mark Heron	777d	Thu 02/05/02	Fri 22/04/05																							
1394	Interface Requirements from tech group	0d	Thu 02/05/02	Thu 02/05/02	◆																						
1401	Plant and service available	0d	Thu 02/05/02	Thu 02/05/02	◆																						
1404	1.7.8 Girder system – Nigel Hammond	877d	Thu 02/05/02	Fri 09/09/05																							
1405	1.7.8.1 Girders	877d	Thu 02/05/02	Fri 09/09/05																							
1408	Place Order	0d	Fri 29/08/03	Fri 29/08/03						◆																	
1411	Final Girder delivery	0d	Fri 14/01/05	Fri 14/01/05												◆											
1415	Complete Girder Installation	0d	Fri 09/09/05	Fri 09/09/05														◆									
1416	1.7.8.2 Girder Positioning System	837d	Thu 02/05/02	Fri 15/07/05																							

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ID	Task Name	Duration	Early Start	Early Finish					03				04				05				06			
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	
1419	Place Order	0d	Fri 21/02/03	Fri 21/02/03				◆																
1422	Deliver final equipment	0d	Fri 28/05/04	Fri 28/05/04								◆												
1424	Complete installation	0d	Fri 15/07/05	Fri 15/07/05													◆							
1425	1.7.8.3 Girder Positioning Control System	687d	Thu 02/05/02	Fri 17/12/04																				
1428	Place Order	0d	Fri 03/01/03	Fri 03/01/03			◆																	
1430	Complete Design	0d	Fri 17/01/03	Fri 17/01/03			◆																	
1432	Deliver equipment	0d	Fri 17/10/03	Fri 17/10/03						◆														
1434	Complete installation	0d	Fri 24/09/04	Fri 24/09/04											◆									
1436	Testing Complete	0d	Fri 17/12/04	Fri 17/12/04												◆								
1437	1.7.9 Services – Nigel Hammond	702d	Thu 02/05/02	Fri 07/01/05																				
1438	1.7.9.1 Water systems	687d	Thu 02/05/02	Fri 17/12/04																				
1441	Place Order	0d	Fri 28/03/03	Fri 28/03/03				◆																
1443	Deliver equipment	0d	Fri 24/10/03	Fri 24/10/03						◆														
1445	Complete installation	0d	Fri 17/12/04	Fri 17/12/04												◆								
1446	1.7.9.2 Gas systems	702d	Thu 02/05/02	Fri 07/01/05																				
1449	Place Order	0d	Fri 28/03/03	Fri 28/03/03				◆																
1451	Deliver equipment	0d	Fri 06/06/03	Fri 06/06/03					◆															
1453	Complete installation	0d	Fri 17/12/04	Fri 17/12/04												◆								
1455	1.7.9.3 Electrical systems	647d	Thu 02/05/02	Fri 22/10/04																				
1458	Place Order	0d	Fri 06/12/02	Fri 06/12/02			◆																	
1460	Complete Design	0d	Fri 28/02/03	Fri 28/02/03				◆																
1462	Deliver equipment	0d	Fri 28/03/03	Fri 28/03/03					◆															
1464	Complete installation	0d	Fri 24/09/04	Fri 24/09/04												◆								
1466	Testing Complete	0d	Fri 22/10/04	Fri 22/10/04												◆								
1467	1.7.9.4 Trunking distribution	647d	Thu 02/05/02	Fri 22/10/04																				
1470	Place Order	0d	Fri 06/12/02	Fri 06/12/02			◆																	
1472	Complete Design	0d	Fri 28/02/03	Fri 28/02/03				◆																
1474	Deliver equipment	0d	Fri 28/03/03	Fri 28/03/03					◆															
1476	Complete installation	0d	Fri 24/09/04	Fri 24/09/04												◆								
1478	Testing Complete	0d	Fri 22/10/04	Fri 22/10/04												◆								
1479	1.7.10 Alignment - Jim Kay	667d	Thu 02/05/02	Fri 19/11/04																				
1480	1.7.10.1 Tunnel Network	667d	Thu 02/05/02	Fri 19/11/04																				
1483	Place Order	0d	Fri 06/12/02	Fri 06/12/02			◆																	
1485	Complete Design	0d	Fri 31/01/03	Fri 31/01/03				◆																
1487	Deliver equipment	0d	Fri 11/04/03	Fri 11/04/03					◆															
1489	Complete installation	0d	Fri 24/09/04	Fri 24/09/04												◆								
1491	Measurements Complete	0d	Fri 19/11/04	Fri 19/11/04												◆								
1493	1.7.12 Personnel Safety System – Mark Heron	777d	Thu 02/05/02	Fri 22/04/05																				
1494	Interface Requirements from tech group	0d	Thu 02/05/02	Thu 02/05/02	◆																			

Diamond Project Master Schedule

ID	Task Name	Duration	Early Start	Early Finish	03				04				05				06					
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3
1501	Plant and service available	0d	Thu 02/05/02	Thu 02/05/02	◆																	
1504	Storage Ring Operational	0d	Wed 22/05/02	Wed 22/05/02	◆																	
1506	1.7.14 Health Physics Installed Monitors System – Roy Ryder	517d	Wed 05/05/04	Fri 28/04/06																		
1507	Deliver equipment	0d	Wed 05/05/04	Wed 05/05/04																		
1509	Complete installation	0d	Fri 17/06/05	Fri 17/06/05																		
1511	Commissioning Complete	0d	Fri 28/04/06	Fri 28/04/06																		
1512	1.7.15 Front Ends – Don Clarke	777d	Thu 02/05/02	Fri 22/04/05	◆																	
1513	1.7.15.1 Very High Energy Beamline	628d	Thu 02/05/02	Mon 27/09/04	◆																	
1516	Determine max power requirements	0d	Wed 24/07/02	Wed 24/07/02		◆																
1518	Place Order	0d	Fri 02/05/03	Fri 02/05/03					◆													
1520	Complete Design	0d	Fri 25/07/03	Fri 25/07/03						◆												
1522	Deliver equipment	0d	Fri 14/11/03	Fri 14/11/03							◆											
1526	Complete installation	0d	Mon 27/09/04	Mon 27/09/04																		
1527	Test equipment	0d	Mon 27/09/04	Mon 27/09/04																		
1528	Testing Complete	0d	Mon 27/09/04	Mon 27/09/04																		
1529	1.7.15.2 Materials Beamline	688d	Thu 02/05/02	Mon 20/12/04	◆																	
1533	Place Order	0d	Fri 10/01/03	Fri 10/01/03					◆													
1535	Complete Design	0d	Fri 07/02/03	Fri 07/02/03					◆													
1537	Deliver equipment	0d	Fri 02/05/03	Fri 02/05/03						◆												
1540	Complete installation	0d	Mon 20/09/04	Mon 20/09/04																		
1543	Testing Complete	0d	Mon 20/12/04	Mon 20/12/04																		
1544	1.7.15.3 Macromolecular Beamline 1	688d	Thu 02/05/02	Mon 20/12/04	◆																	
1548	Place Order	0d	Fri 10/01/03	Fri 10/01/03					◆													
1550	Complete Design	0d	Fri 07/02/03	Fri 07/02/03					◆													
1552	Deliver equipment	0d	Fri 02/05/03	Fri 02/05/03						◆												
1555	Complete installation	0d	Mon 20/09/04	Mon 20/09/04																		
1558	Testing Complete	0d	Mon 20/12/04	Mon 20/12/04																		
1559	1.7.15.4 Macromolecular Beamline 2	688d	Thu 02/05/02	Mon 20/12/04	◆																	
1563	Place Order	0d	Fri 10/01/03	Fri 10/01/03					◆													
1565	Complete Design	0d	Fri 07/02/03	Fri 07/02/03					◆													
1567	Deliver equipment	0d	Fri 02/05/03	Fri 02/05/03						◆												
1570	Complete installation	0d	Mon 20/09/04	Mon 20/09/04																		
1573	Testing Complete	0d	Mon 20/12/04	Mon 20/12/04																		
1574	1.7.15.5 Macromolecular Beamline 3	688d	Thu 02/05/02	Mon 20/12/04	◆																	
1578	Place Order	0d	Fri 10/01/03	Fri 10/01/03					◆													
1580	Complete Design	0d	Fri 07/02/03	Fri 07/02/03					◆													
1582	Deliver equipment	0d	Fri 02/05/03	Fri 02/05/03						◆												
1585	Complete installation	0d	Mon 20/09/04	Mon 20/09/04																		
1588	Testing Complete	0d	Mon 20/12/04	Mon 20/12/04																		

Diamond Project Master Schedule

ID	Task Name	Duration	Early Start	Early Finish	03				04				05				06							
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	
1589	1.7.15.6 Microfocus XAS Beamline	688d	Thu 02/05/02	Mon 20/12/04																				
1593	Place Order	0d	Fri 10/01/03	Fri 10/01/03																				
1595	Complete Design	0d	Fri 07/02/03	Fri 07/02/03																				
1597	Deliver equipment	0d	Fri 02/05/03	Fri 02/05/03																				
1600	Complete installation	0d	Mon 20/09/04	Mon 20/09/04																				
1603	Testing Complete	0d	Mon 20/12/04	Mon 20/12/04																				
1604	1.7.15.7 SXR for nanostructures Beamline	688d	Thu 02/05/02	Mon 20/12/04																				
1608	Place Order	0d	Fri 10/01/03	Fri 10/01/03																				
1610	Complete Design	0d	Fri 07/02/03	Fri 07/02/03																				
1612	Deliver equipment	0d	Fri 02/05/03	Fri 02/05/03																				
1615	Complete installation	0d	Mon 20/09/04	Mon 20/09/04																				
1618	Testing Complete	0d	Mon 20/12/04	Mon 20/12/04																				
1619	1.7.15.8 ID Diagnostics / Optics Test Beamline	688d	Thu 02/05/02	Mon 20/12/04																				
1623	Place Order	0d	Fri 10/01/03	Fri 10/01/03																				
1625	Complete Design	0d	Fri 07/02/03	Fri 07/02/03																				
1627	Deliver equipment	0d	Fri 02/05/03	Fri 02/05/03																				
1630	Complete installation	0d	Mon 20/09/04	Mon 20/09/04																				
1633	Testing Complete	0d	Mon 20/12/04	Mon 20/12/04																				
1634	1.7.15.9 BM Diagnostics Beamline	688d	Thu 02/05/02	Mon 20/12/04																				
1638	Place Order	0d	Fri 10/01/03	Fri 10/01/03																				
1640	Complete Design	0d	Fri 07/02/03	Fri 07/02/03																				
1642	Deliver equipment	0d	Fri 02/05/03	Fri 02/05/03																				
1645	Complete installation	0d	Mon 20/09/04	Mon 20/09/04																				
1648	Testing Complete	0d	Mon 20/12/04	Mon 20/12/04																				
1649	1.7.15.10 Spare Front End	637d	Thu 02/05/02	Fri 08/10/04																				
1653	Place Order	0d	Fri 07/02/03	Fri 07/02/03																				
1655	Complete Design	0d	Fri 25/07/03	Fri 25/07/03																				
1657	Deliver equipment	0d	Fri 09/01/04	Fri 09/01/04																				
1660	Complete installation	0d	Fri 24/09/04	Fri 24/09/04																				
1663	Testing Complete	0d	Fri 08/10/04	Fri 08/10/04																				
1664	1.7.15.11 Plant Control Front Ends - Mark Heron	777d	Thu 02/05/02	Fri 22/04/05																				
1665	Interface Requirements from tech group	0d	Thu 02/05/02	Thu 02/05/02																				
1672	Plant and service available	0d	Thu 02/05/02	Thu 02/05/02																				
1674	1.7.16 Insertion Devices – Jim Clarke	990d	Thu 02/05/02	Wed 15/02/06																				
1675	1.7.16.1 Super-Conducting Multi-Pole Wiggler	642d	Wed 24/07/02	Fri 07/01/05																				
1676	Front End FEA Finalised	0w	Wed 24/07/02	Wed 24/07/02																				
1681	Award contract	0d	Fri 15/08/03	Fri 15/08/03																				
1683	Deliver	0d	Fri 05/11/04	Fri 05/11/04																				
1685	Ready for installation	0d	Fri 31/12/04	Fri 31/12/04																				

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ID	Task Name	Duration	Early Start	Early Finish	03				04				05				06					
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3
1686	Storage Ring Installation Starts	0d	Fri 31/12/04	Fri 31/12/04																		
1688	1.7.16.2 Conventional Undulators	592d	Thu 02/05/02	Fri 06/08/04																		
1689	1.7.16.2.1 Magnet Array Assembly	400d	Thu 02/05/02	Wed 12/11/03																		
1702	1.7.16.2.2 Support Structure Assembly	355d	Tue 01/10/02	Mon 09/02/04																		
1713	Ready for installation	0d	Mon 12/04/04	Mon 12/04/04																		
1714	Storage Ring Installation Starts	0d	Mon 02/08/04	Mon 02/08/04																		
1716	1.7.16.3 In-Vacuum Undulators	990d	Thu 02/05/02	Wed 15/02/06																		
1717	1.7.16.3.1 Magnet Array Assembly Prototype	400d	Thu 02/05/02	Wed 12/11/03																		
1732	1.7.16.3.2 Support Structure Assembly Prototype	355d	Thu 02/05/02	Wed 10/09/03																		
1748	Prototype Complete	0d	Wed 25/02/04	Wed 25/02/04																		
1750	1.7.16.3.3 Magnet Array Assembly Production	390d	Wed 25/02/04	Wed 24/08/05																		
1760	1.7.16.3.4 Support Structure Assembly Production	340d	Thu 26/02/04	Wed 15/06/05																		
1773	All In Vacuum Undulators Ready for Installation	0d	Wed 01/02/06	Wed 01/02/06																		
1774	Storage Ring Installation Starts	0d	Wed 01/02/06	Wed 01/02/06																		
1776	1.7.16.4 Helical Undulators	882d	Thu 02/05/02	Fri 16/09/05																		
1777	1.7.16.4.1 Magnet Array Assembly	360d	Thu 02/05/02	Wed 17/09/03																		
1790	1.7.16.4.2 Support Structure Assembly	405d	Thu 02/05/02	Wed 19/11/03																		
1801	Ready for installation	0d	Wed 25/02/04	Wed 25/02/04																		
1802	Storage Ring Installation Starts	0d	Mon 02/08/04	Mon 02/08/04																		
1804	1.7.16.5 Plant Control Insertion Devices - Mark Heron	777d	Thu 02/05/02	Fri 22/04/05																		
1805	Interface Requirements from tech group	0d	Thu 02/05/02	Thu 02/05/02																		
1812	Plant and service available	0d	Fri 07/01/05	Fri 07/01/05																		
1819	1.8 Beamlines	1177d	Thu 02/05/02	Fri 03/11/06																		
1820	1.8.1 Very High Energy Beamline	1177d	Thu 02/05/02	Fri 03/11/06																		
1821	1.8.1.1 High energy beamline (1) – Colin Nave	1177d	Thu 02/05/02	Fri 03/11/06																		
1823	Call for first tenders	0d	Wed 16/10/02	Wed 16/10/02																		
1825	Place order/ prelim design review	0d	Wed 11/12/02	Wed 11/12/02																		
1827	Design complete	0d	Wed 05/01/05	Wed 05/01/05																		
1829	Deliver equipment	0d	Wed 08/12/04	Wed 08/12/04																		
1831	Assemblies complete	0d	Wed 10/11/04	Wed 10/11/04																		
1833	Test complete	0d	Thu 26/01/06	Thu 26/01/06																		
1835	Beamline complete	0d	Fri 03/11/06	Fri 03/11/06																		
1836	Assembly area ready	0d	Thu 02/05/02	Thu 02/05/02																		
1837	Experimental area sealed & clean	0d	Fri 31/12/04	Fri 31/12/04																		
1838	Beam OK	0d	Fri 30/06/06	Fri 30/06/06																		
1839	1.8.1.2 Plant Control Beamline Vacuum/Motors/PS - Mark Her	886d	Thu 02/05/02	Thu 22/09/05																		
1840	Interface Requirements from tech group	0d	Thu 02/05/02	Thu 02/05/02																		
1847	Plant and service available	0d	Thu 02/05/02	Thu 02/05/02																		
1849	1.8.2 Materials Beamline	1177d	Thu 02/05/02	Fri 03/11/06																		

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ID	Task Name	Duration	Early Start	Early Finish					03				04				05				06			
					2	3	4		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1850	1.8.2.1 Materials beamline (6) – Colin Nave	1177d	Thu 02/05/02	Fri 03/11/06																				
1852	Call for first tenders	0d	Wed 16/10/02	Wed 16/10/02			◆																	
1854	Place order/ prelim design review	0d	Wed 11/12/02	Wed 11/12/02			◆																	
1856	Design complete	0d	Wed 05/01/05	Wed 05/01/05														◆						
1858	Deliver equipment	0d	Wed 08/12/04	Wed 08/12/04														◆						
1860	Assemblies complete	0d	Wed 10/11/04	Wed 10/11/04														◆						
1862	Test complete	0d	Thu 26/01/06	Thu 26/01/06																	◆			
1864	Beamline complete	0d	Fri 03/11/06	Fri 03/11/06																				◆
1865	Assembly area ready	0d	Thu 02/05/02	Thu 02/05/02	◆																			
1866	Experimental area sealed & clean	0d	Fri 31/12/04	Fri 31/12/04														◆						
1867	Beam OK	0d	Fri 30/06/06	Fri 30/06/06																		◆		
1868	1.8.2.2 Plant Control Beamline Vacuum/Motors/PS - Mark Her	886d	Thu 02/05/02	Thu 22/09/05																				
1869	Interface Requirements from tech group	0d	Thu 02/05/02	Thu 02/05/02	◆																			
1876	Plant and service available	0d	Thu 02/05/02	Thu 02/05/02	◆																			
1878	1.8.3 Macromolecular Beamline 1	1177d	Thu 02/05/02	Fri 03/11/06																				
1879	1.8.3.1 Macromolecular beamline1 (8) - Colin Nave	1177d	Thu 02/05/02	Fri 03/11/06																				
1881	Call for first tenders	0d	Wed 16/10/02	Wed 16/10/02			◆																	
1883	Place order/ prelim design review	0d	Wed 11/12/02	Wed 11/12/02			◆																	
1885	Design complete	0d	Wed 05/01/05	Wed 05/01/05														◆						
1887	Deliver equipment	0d	Wed 08/12/04	Wed 08/12/04														◆						
1889	Assemblies complete	0d	Wed 10/11/04	Wed 10/11/04														◆						
1891	Test complete	0d	Thu 26/01/06	Thu 26/01/06																	◆			
1893	Beamline complete	0d	Fri 03/11/06	Fri 03/11/06																				◆
1894	Assembly area ready	0d	Thu 02/05/02	Thu 02/05/02	◆																			
1895	Experimental area sealed & clean	0d	Fri 31/12/04	Fri 31/12/04														◆						
1896	Beam OK	0d	Fri 30/06/06	Fri 30/06/06																		◆		
1897	1.8.3.2 Plant Control Beamline Vacuum/Motors/PS - Mark Her	886d	Thu 02/05/02	Thu 22/09/05																				
1898	Interface Requirements from tech group	0d	Thu 02/05/02	Thu 02/05/02	◆																			
1905	Plant and service available	0d	Thu 02/05/02	Thu 02/05/02	◆																			
1907	1.8.4 Macromolecular Beamline 2	1177d	Thu 02/05/02	Fri 03/11/06																				
1908	1.8.4.1 Macromolecular beamline2 (9) - Colin Nave	1177d	Thu 02/05/02	Fri 03/11/06																				
1910	Call for first tenders	0d	Wed 16/10/02	Wed 16/10/02			◆																	
1912	Place order/ prelim design review	0d	Wed 11/12/02	Wed 11/12/02			◆																	
1914	Design complete	0d	Wed 05/01/05	Wed 05/01/05														◆						
1916	Deliver equipment	0d	Wed 08/12/04	Wed 08/12/04														◆						
1918	Assemblies complete	0d	Wed 10/11/04	Wed 10/11/04														◆						
1920	Test complete	0d	Thu 26/01/06	Thu 26/01/06																	◆			
1922	Beamline complete	0d	Fri 03/11/06	Fri 03/11/06																				◆
1923	Assembly area ready	0d	Thu 02/05/02	Thu 02/05/02	◆																			

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ID	Task Name	Duration	Early Start	Early Finish					03				04				05				06			
					2	3	4		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1924	Experimental area sealed & clean	0d	Fri 31/12/04	Fri 31/12/04																				
1925	Beam OK	0d	Fri 30/06/06	Fri 30/06/06																				
1926	1.8.4.2 Plant Control Beamline VacuumMotors/PS - Mark Her	886d	Thu 02/05/02	Thu 22/09/05																				
1927	Interface Requirements from tech group	0d	Thu 02/05/02	Thu 02/05/02																				
1934	Plant and service available	0d	Thu 02/05/02	Thu 02/05/02																				
1936	1.8.5 Macromolecular Beamline 3	1177d	Thu 02/05/02	Fri 03/11/06																				
1937	1.8.5.1 Macromolecular beamline3 (10) – Colin Nave	1177d	Thu 02/05/02	Fri 03/11/06																				
1939	Call for first tenders	0d	Wed 16/10/02	Wed 16/10/02																				
1941	Place order/ prelim design review	0d	Wed 11/12/02	Wed 11/12/02																				
1943	Design complete	0d	Wed 05/01/05	Wed 05/01/05																				
1945	Deliver equipment	0d	Wed 08/12/04	Wed 08/12/04																				
1947	Assemblies complete	0d	Wed 10/11/04	Wed 10/11/04																				
1949	Test complete	0d	Thu 26/01/06	Thu 26/01/06																				
1951	Beamline complete	0d	Fri 03/11/06	Fri 03/11/06																				
1952	Assembly area ready	0d	Thu 02/05/02	Thu 02/05/02																				
1953	Experimental area sealed & clean	0d	Fri 31/12/04	Fri 31/12/04																				
1954	Beam OK	0d	Fri 30/06/06	Fri 30/06/06																				
1955	1.8.5.2 Plant Control Beamline Vacuum/Motors/PS - Mark Her	886d	Thu 02/05/02	Thu 22/09/05																				
1956	Interface Requirements from tech group	0d	Thu 02/05/02	Thu 02/05/02																				
1963	Plant and service available	0d	Thu 02/05/02	Thu 02/05/02																				
1965	1.8.6 Microfocus XAS beamline– Colin Nave	1177d	Thu 02/05/02	Fri 03/11/06																				
1966	1.8.6.1 Microfocus XAS	1177d	Thu 02/05/02	Fri 03/11/06																				
1968	Call for first tenders	0d	Wed 16/10/02	Wed 16/10/02																				
1970	Place order/ prelim design review	0d	Wed 11/12/02	Wed 11/12/02																				
1974	Deliver equipment	0d	Wed 30/03/05	Wed 30/03/05																				
1976	Assemblies complete	0d	Wed 02/03/05	Wed 02/03/05																				
1978	Test complete	0d	Wed 29/03/06	Wed 29/03/06																				
1980	Beamline complete	0d	Fri 03/11/06	Fri 03/11/06																				
1981	Assembly area ready	0d	Thu 02/05/02	Thu 02/05/02																				
1982	Experimental area sealed & clean	0d	Fri 31/12/04	Fri 31/12/04																				
1983	Beam OK	0d	Fri 30/06/06	Fri 30/06/06																				
1984	1.8.6.2 Plant Control Beamline Vacuum/Motors/PS - Mark Her	886d	Thu 02/05/02	Thu 22/09/05																				
1985	Interface Requirements from tech group	0d	Thu 02/05/02	Thu 02/05/02																				
1992	Plant and service available	0d	Thu 02/05/02	Thu 02/05/02																				
1994	1.8.7 SXR for nanostructures Beamline	1177d	Thu 02/05/02	Fri 03/11/06																				
1995	1.8.7 SXR nanostructures beamline(14) – Colin Nave	1177d	Thu 02/05/02	Fri 03/11/06																				
1997	Call for first tenders	0d	Wed 16/10/02	Wed 16/10/02																				
1999	Place order/ prelim design review	0d	Wed 11/12/02	Wed 11/12/02																				
2001	Design complete	0d	Wed 05/01/05	Wed 05/01/05																				

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ID	Task Name	Duration	Early Start	Early Finish	03				04				05				06			
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	
2003	Deliver equipment	0d	Wed 08/12/04	Wed 08/12/04																
2005	Assemblies complete	0d	Wed 10/11/04	Wed 10/11/04																
2007	Test complete	0d	Thu 26/01/06	Thu 26/01/06																
2009	Beamline complete	0d	Fri 03/11/06	Fri 03/11/06																
2010	Assembly area ready	0d	Thu 02/05/02	Thu 02/05/02	◆															
2011	Experimental area sealed & clean	0d	Fri 31/12/04	Fri 31/12/04																
2012	Beam OK	0d	Fri 30/06/06	Fri 30/06/06																
2013	1.8.7.2 Plant Control Beamline Vacuum/Motors/PS - Mark Her	886d	Thu 02/05/02	Thu 22/09/05	◆															
2014	Interface Requirements from tech group	0d	Thu 02/05/02	Thu 02/05/02	◆															
2021	Plant and service available	0d	Thu 02/05/02	Thu 02/05/02	◆															
2023	1.8.8 Generic Experimental Control – Colin Nave	1080d	Thu 02/05/02	Wed 21/06/06	◆															
2024	Build programming environment	30d	Thu 02/05/02	Wed 12/06/02	◆															
2028	Environment complete	0d	Wed 12/06/02	Wed 12/06/02	◆	◆														
2029	Requirements gathering	75d	Thu 13/06/02	Wed 25/09/02	◆	◆	◆													
2038	Requirements complete	0d	Wed 25/09/02	Wed 25/09/02		◆	◆													
2039	R&D	100d	Thu 26/09/02	Wed 12/02/03	◆	◆	◆	◆												
2047	R&D Complete	0d	Wed 23/10/02	Wed 23/10/02		◆														
2048	Specifications	155d	Thu 26/09/02	Wed 30/04/03		◆	◆	◆												
2060	Specification complete	0d	Wed 30/04/03	Wed 30/04/03				◆												
2061	Implementation	200d	Thu 01/05/03	Wed 04/02/04				◆	◆	◆										
2071	Implementation complete	0d	Wed 04/02/04	Wed 04/02/04					◆	◆										
2072	Integration	160d	Thu 05/02/04	Wed 15/09/04					◆	◆	◆									
2076	Integration complete	0d	Wed 15/09/04	Wed 15/09/04						◆	◆									
2077	Testing	120d	Thu 16/09/04	Wed 02/03/05						◆	◆	◆								
2080	Testing complete	0d	Wed 02/03/05	Wed 02/03/05							◆	◆								
2082	Generic data acq complete	0d	Wed 02/03/05	Wed 02/03/05								◆	◆							
2083	Beamline Automation	1080d	Thu 02/05/02	Wed 21/06/06	◆															
2091	Beamline automation	0d	Wed 21/06/06	Wed 21/06/06														◆		
2092	1.9 Controls	1130d	Thu 02/05/02	Wed 30/08/06	◆														◆	
2099	1.9.7 Timing & Event Generation – Mark Heron	777d	Thu 02/05/02	Fri 22/04/05	◆															
2100	Interface Requirements from tech group	0d	Thu 02/05/02	Thu 02/05/02	◆															
2107	Plant and service available	0d	Thu 02/05/02	Thu 02/05/02	◆															
2109	1.9.8 Radiation Monitors – Mark Heron	777d	Thu 02/05/02	Fri 22/04/05	◆															
2110	Interface Requirements from tech group	0d	Thu 02/05/02	Thu 02/05/02	◆															
2117	Plant and service available	0d	Thu 02/05/02	Thu 02/05/02	◆															
2119	1.9.9 Multiplexing System – Mark Heron	747d	Thu 02/05/02	Fri 11/03/05	◆															
2120	Interface Requirements from tech group	0d	Thu 02/05/02	Thu 02/05/02	◆															
2128	1.9.11 Storage Ring Machine Protection - Mark Heron	777d	Thu 02/05/02	Fri 22/04/05	◆															
2129	Interface Requirements from tech group	0d	Thu 02/05/02	Thu 02/05/02	◆															

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ID	Task Name	Duration	Early Start	Early Finish	03				04				05				06					
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3
2136	Plant and service available	0d	Thu 02/05/02	Thu 02/05/02	◆																	
2138	1.9.12 Storage Ring Conventional facilities - Mark Heron	1037d	Thu 02/05/02	Fri 21/04/06	◆																	
2139	Interface Requirements from tech group	0d	Thu 02/05/02	Thu 02/05/02	◆																	
2146	Plant and service available	0d	Thu 02/05/02	Thu 02/05/02	◆																	
2148	1.9.13 Procure Standard Interface Hardware - Mark Heron	300d	Thu 02/05/02	Wed 25/06/03	◆																	
2151	Appoint electrical contractor	0d	Wed 11/12/02	Wed 11/12/02				◆														
2156	Racking available	0d	Wed 25/06/03	Wed 25/06/03							◆											
2160	Crates available	0d	Wed 25/06/03	Wed 25/06/03							◆											
2164	VME Processors available	0d	Wed 25/06/03	Wed 25/06/03							◆											
2168	Interface Modules available	0d	Wed 25/06/03	Wed 25/06/03							◆											
2169	1.10 Technical Infrastructure	805d	Thu 02/05/02	Wed 01/06/05	◆																	
2170	1.10.1 Vacuum Lab – Ron Reid	410d	Thu 02/05/02	Wed 26/11/03	◆																	
2171	Info available from MDO on vacuum vessels	0d	Thu 02/05/02	Thu 02/05/02	◆																	
2173	Issue call for tenders	0d	Wed 29/05/02	Wed 29/05/02	◆																	
2175	Place Order	0d	Wed 11/12/02	Wed 11/12/02				◆														
2176	Design	0d	Wed 11/12/02	Wed 11/12/02			◆	◆														
2177	Complete Design	0d	Wed 11/12/02	Wed 11/12/02			◆	◆														
2180	Building Ready	0d	Thu 02/05/02	Thu 02/05/02	◆																	
2181	Deliver Equipment	0d	Wed 09/07/03	Wed 09/07/03							◆											
2183	Ready for Work	0d	Wed 26/11/03	Wed 26/11/03								◆										
2184	1.10.2 Vacuum cleaning and Processing– Ron Reid	345d	Thu 02/05/02	Wed 27/08/03	◆																	
2185	Info available from MDO on vacuum vessels	0d	Thu 02/05/02	Thu 02/05/02	◆																	
2187	Issue call for tenders	0d	Wed 29/05/02	Wed 29/05/02	◆																	
2189	Place Order	0d	Wed 11/12/02	Wed 11/12/02				◆														
2190	Design	0d	Wed 11/12/02	Wed 11/12/02			◆	◆														
2191	Complete Design	0d	Wed 11/12/02	Wed 11/12/02			◆	◆														
2194	Building Ready	0d	Thu 02/05/02	Thu 02/05/02	◆																	
2195	Deliver Equipment	0d	Wed 09/04/03	Wed 09/04/03						◆												
2197	Ready for Work	0d	Wed 27/08/03	Wed 27/08/03								◆										
2198	1.10.3 RF test and development lab – Mike Dykes	347d	Thu 02/05/02	Fri 29/08/03	◆																	
2201	Place Order	0d	Fri 06/12/02	Fri 06/12/02				◆														
2203	Complete Design	0d	Fri 17/01/03	Fri 17/01/03				◆														
2205	Deliver equipment	0d	Fri 28/02/03	Fri 28/02/03				◆														
2207	Complete installation	0d	Fri 09/05/03	Fri 09/05/03						◆												
2209	Testing Complete	0d	Fri 29/08/03	Fri 29/08/03								◆										
2210	1.10.4 Diagnostics lab – Rob Smith	347d	Thu 02/05/02	Fri 29/08/03	◆																	
2213	Place Order	0d	Fri 06/12/02	Fri 06/12/02				◆														
2215	Complete Design	0d	Fri 17/01/03	Fri 17/01/03				◆														
2217	Deliver equipment	0d	Fri 28/02/03	Fri 28/02/03				◆														

Diamond Project Master Schedule

ID	Task Name	Duration	Early Start	Early Finish	03				04				05				06					
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3
2219	Complete installation	0d	Fri 09/05/03	Fri 09/05/03						◆												
2221	Testing Complete	0d	Fri 29/08/03	Fri 29/08/03							◆											
2222	1.10.5 ID Assembly and Measurement lab – Jim Clarke	220d	Thu 02/05/02	Wed 05/03/03	◆					◆												
2223	Building Identified	0d	Thu 02/05/02	Thu 02/05/02	◆																	
2235	Lab Ready for Magnet Measurements	0d	Wed 05/03/03	Wed 05/03/03						◆												
2236	1.10.6 Girder assembly – Nigel Hammond	457d	Thu 02/05/02	Fri 30/01/04	◆								◆									
2239	Place Order	0d	Fri 06/06/03	Fri 06/06/03							◆											
2241	Complete Design	0d	Fri 04/07/03	Fri 04/07/03								◆										
2243	1.10.7 Front end assembly – Don Clarke	717d	Thu 02/05/02	Fri 28/01/05	◆																	
2246	Place Order	0d	Fri 06/12/02	Fri 06/12/02				◆														
2248	Complete Design	0d	Fri 17/01/03	Fri 17/01/03					◆													
2250	Deliver equipment	0d	Fri 28/02/03	Fri 28/02/03						◆												
2252	Complete installation	0d	Fri 08/10/04	Fri 08/10/04															◆			
2254	Testing Complete	0d	Fri 28/01/05	Fri 28/01/05																◆		
2255	1.10.8 Power supply test and development lab – Steve Griffiths	763d	Thu 02/05/02	Mon 04/04/05	◆																◆	
2258	Place Order	0d	Fri 20/06/03	Fri 20/06/03							◆											
2260	Complete Design	0d	Fri 27/06/03	Fri 27/06/03								◆										
2262	Deliver equipment	0d	Fri 22/08/03	Fri 22/08/03									◆									
2264	Complete installation	0d	Mon 21/03/05	Mon 21/03/05																◆		
2266	Lab Available	0d	Mon 04/04/05	Mon 04/04/05																	◆	
2267	1.10.10 Pulsed magnet measurement lab – Rob Smith	347d	Thu 02/05/02	Fri 29/08/03	◆																	
2270	Place Order	0d	Fri 06/12/02	Fri 06/12/02				◆														
2272	Complete Design	0d	Fri 17/01/03	Fri 17/01/03					◆													
2274	Deliver equipment	0d	Fri 28/02/03	Fri 28/02/03						◆												
2276	Complete installation	0d	Fri 09/05/03	Fri 09/05/03							◆											
2278	Testing Complete	0d	Fri 29/08/03	Fri 29/08/03									◆									
2279	1.10.11 Goods in, Inspection, Stores – Jim Kay	677d	Thu 02/05/02	Fri 03/12/04	◆																	
2282	Place Order	0d	Fri 06/12/02	Fri 06/12/02				◆														
2284	Complete Design	0d	Fri 28/03/03	Fri 28/03/03						◆												
2287	Complete installation	0d	Fri 19/11/04	Fri 19/11/04																◆		
2289	1.10.12 Controls lab – Mark Heron	717d	Thu 02/05/02	Fri 28/01/05	◆																	
2292	Place Order	0d	Fri 06/12/02	Fri 06/12/02				◆														
2294	Complete Design	0d	Fri 17/01/03	Fri 17/01/03					◆													
2296	Deliver equipment	0d	Fri 28/02/03	Fri 28/02/03						◆												
2298	Complete installation	0d	Fri 08/10/04	Fri 08/10/04																◆		
2300	Testing Complete	0d	Fri 28/01/05	Fri 28/01/05																	◆	
2301	1.10.13 Data acquisition support area – Colin Nave	44d	Fri 21/06/02	Wed 21/08/02	◆	◆																
2312	Room ready	0d	Mon 19/08/02	Mon 19/08/02		◆																
2314	Complete	0d	Wed 21/08/02	Wed 21/08/02		◆																

Diamond Project Master Schedule

ID	Task Name	Duration	Early Start	Early Finish	03				04				05				06					
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4			
2315	1.10.14 Survey lab – Jim Kay	687d	Thu 02/05/02	Fri 17/12/04																		
2318	Place Order	0d	Fri 06/12/02	Fri 06/12/02			◆															
2320	Complete Design	0d	Fri 28/03/03	Fri 28/03/03				◆														
2323	Complete installation	0d	Fri 03/12/04	Fri 03/12/04											◆							
2325	1.10.15 Computing and network support area – Mark Heron	717d	Thu 02/05/02	Fri 28/01/05																		
2328	Place Order	0d	Fri 06/12/02	Fri 06/12/02			◆															
2330	Complete Design	0d	Fri 17/01/03	Fri 17/01/03				◆														
2332	Deliver equipment	0d	Fri 28/02/03	Fri 28/02/03				◆														
2334	Complete installation	0d	Fri 08/10/04	Fri 08/10/04											◆							
2336	Testing Complete	0d	Fri 28/01/05	Fri 28/01/05												◆						
2337	1.10.16 Health Physics lab – Roy Ryder	146d	Tue 09/11/04	Wed 01/06/05																		
2338	First Access	0d	Tue 09/11/04	Tue 09/11/04											◆							
2340	Purchase Portable Monitors	145d	Thu 11/11/04	Wed 01/06/05																		
2343	Place Order	0d	Wed 23/02/05	Wed 23/02/05												◆						
2345	Deliver equipment	0d	Wed 18/05/05	Wed 18/05/05													◆					
2347	Testing Complete	0d	Wed 01/06/05	Wed 01/06/05														◆				
2348	1.10.17 Beamline Assemby Area (Colin Nave)	140d	Thu 02/05/02	Wed 13/11/02																		
2355	Lab Ready	0d	Wed 13/11/02	Wed 13/11/02			◆															
2356	1.11 Co-ordination & Handover	1000d	Thu 02/05/02	Wed 01/03/06																		
2358	1.11.2 Operations & Maintenance manuals – Jim Kay	675d	Thu 02/05/02	Wed 01/12/04																		
2361	Place Order	0d	Fri 06/12/02	Fri 06/12/02			◆															
2363	Complete Design	0d	Fri 17/01/03	Fri 17/01/03				◆														
2365	Deliver equipment	0d	Fri 28/02/03	Fri 28/02/03				◆														
2367	Complete installation	0d	Wed 11/08/04	Wed 11/08/04											◆							
2369	Testing Complete	0d	Wed 01/12/04	Wed 01/12/04												◆						
2370	1.11.3 Servicing schedules– Jim Kay	347d	Thu 02/05/02	Fri 29/08/03																		
2373	Place Order	0d	Fri 06/12/02	Fri 06/12/02			◆															
2375	Complete Design	0d	Fri 17/01/03	Fri 17/01/03				◆														
2377	Deliver equipment	0d	Fri 28/02/03	Fri 28/02/03				◆														
2379	Complete installation	0d	Fri 09/05/03	Fri 09/05/03					◆													
2381	Testing Complete	0d	Fri 29/08/03	Fri 29/08/03						◆												
2382	1.11.4 Spares– Jim Kay	347d	Thu 02/05/02	Fri 29/08/03																		
2385	Place Order	0d	Fri 06/12/02	Fri 06/12/02			◆															
2387	Complete Design	0d	Fri 17/01/03	Fri 17/01/03				◆														
2389	Deliver equipment	0d	Fri 28/02/03	Fri 28/02/03				◆														
2391	Complete installation	0d	Fri 09/05/03	Fri 09/05/03					◆													
2393	Testing Complete	0d	Fri 29/08/03	Fri 29/08/03						◆												
2394	1.11.5 Warranty management– Jim Kay	347d	Thu 02/05/02	Fri 29/08/03																		
2397	Place Order	0d	Fri 06/12/02	Fri 06/12/02			◆															

Diamond Project Master Schedule																											
ID	Task Name	Duration	Early Start	Early Finish					03				04				05				06						
					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4				
2399	Complete Design	0d	Fri 17/01/03	Fri 17/01/03					◆																		
2401	Deliver equipment	0d	Fri 28/02/03	Fri 28/02/03					◆																		
2403	Complete installation	0d	Fri 09/05/03	Fri 09/05/03						◆																	
2405	Testing Complete	0d	Fri 29/08/03	Fri 29/08/03							◆																
2406	1.11.6 Operations & Maintenance Training-- Jim Kay	347d	Thu 02/05/02	Fri 29/08/03	◆				◆																		
2409	Place Order	0d	Fri 06/12/02	Fri 06/12/02					◆																		
2411	Complete Design	0d	Fri 17/01/03	Fri 17/01/03					◆																		
2413	Deliver equipment	0d	Fri 28/02/03	Fri 28/02/03						◆																	
2415	Complete installation	0d	Fri 09/05/03	Fri 09/05/03							◆																
2417	Testing Complete	0d	Fri 29/08/03	Fri 29/08/03								◆															
2419	Facility Fully Operational (Ops Live)	0d	Fri 03/11/06	Fri 03/11/06																					◆	◆	

X.1 Parameter List

1.1 INTRODUCTION

This chapter explains the basic design that has been selected for the DIAMOND storage ring and justifies a number of important conclusions that follow from a detailed accelerator physics assessment. However the design team has not so far taken all topics to an equivalent level so that it will be seen that the treatment varies considerably in detail between them. Nevertheless the design concept presented has had its basic feasibility established and this has allowed the specification of all major technical systems to be defined with some confidence.

1.2 PRINCIPAL PARAMETERS

Table 1.2-1 Principal Parameters

<i>Parameter</i>	<i>Value</i>
Electron beam energy [GeV]	3
Number of cells	24
Symmetry	6
Electron beam current [mA]	300
Target Beamline apertures	
ID full apertures	up to 10mradsH 1mradsV
Dipole full apertures	up to 20mradsH 3mradsV
Free straight lengths for Ids	18x5m; 6x8m
Type of IDs	18 UND, 2 WS, 2 MPW
Minimum beam lifetime [hrs]	10
Minimum vertical aperture at ID [mm]	10
Overall circumference [m]	561.6
Revolution Frequency [MHz]	0.534188034
<i>Straight lengths (quad to quad)</i>	
rf/inj/longerID [m]	11.343
standardID [m]	8.343

PART X: APPENDICES

1.3 NON-ZERO DISPERSION LATTICE

Table 1.3-1 Basic lattice properties for the non-zero dispersion lattice

Natural emittance [nm rad]	2.74
Maximum horizontal beta function [m]	22.590352
Maximum vertical beta function [m]	26.583551
Horizontal Beta function, rf/inj/Longer ID straight [m]	9.979
Vertical Beta function, rf/inj/Longer ID straight [m]	5.832
Horizontal Beta functions, standard ID straight [m]	4.651
Vertical Beta functions, standard ID straight [m]	1.532
Dispersion, rf/inj/Longer ID straight [m]	0.072
Dispersion, standard ID straight [m]	0.052
Horizontal Tune	27.2256
Vertical Tune	12.3632
Natural horizontal chromaticity	-78.986241
Natural vertical chromaticity	-35.286894
Chromatic sextupole strengths ¹	-39.6,43.9
Second order horizontal chromaticity ¹	-658
Second order vertical chromaticity ¹	-290
Momentum compaction	1.70E-04
Energy Spread	0.000960864
Horizontal dynamic aperture	-24.5,24.5
Vertical dynamic aperture	9.5

¹ Chromatic sextupoles only set

Table 1.3-2 General parameters for the non-zero dispersion lattice

<i>Synchrotron Radiation Integrals</i>	I1	0.09524
	I2	0.87871
	I3	0.12289
	I4	0.00186
	I5	0.00018
<i>Partition Number</i>	Jx	0.99788
	Jy	1.00000
	JE	2.00212

X.1 PARAMETER LIST

Table 1.3-3 Optical functions at the source points for the non-zero dispersion lattice

	$Betax$ [m]	$Alphax$ [m]	$Betay$ [m]	$Alphay$ [m]	Dx [m]	Dpx
<i>rf/inj/Longer ID str. Centre</i>	9.979	0.00E+00	5.832	0.00E+00	7.20E-02	0.00E+00
<i>Standard ID Str. Centre</i>	4.651	0.00E+00	1.532	0.00E+00	5.20E-02	-1.00E-03
<i>Dipole Centre adjacent rf/inj/longer ID str.</i>	0.460644	0.231442	22.8796	-1.70458	1.22E-02	3.40E-02
<i>Dipole Centre adjacent standard ID str</i>	0.476615	0.338219	22.1163	-2.11487	8.32E-03	3.71E-02

Table 1.3-4 Beam dimensions at the source points for the non-zero dispersion lattice

	σ_x [μm]	σ'_x [μrad]	σ_y [μm]	σ'_y [μrad]
<i>rf/inj/Longer ID str. Centre</i>	178.4	16.5	12.6	2.2
<i>Standard ID Str. Centre</i>	122.9	24.2	6.4	4.2
<i>Dipole centre rf/inj/longer ID str</i>	37.2	85.3	24.9	2.2
<i>Dipole Centre standard str.</i>	36.8	87.2	24.5	2.6

Table 1.3-5 Natural bunch length for the non-zero dispersion lattice

Natural bunchlength	3.26 mm

PART X: APPENDICES

Table 1.3-6 Quadrupole strengths for the non-zero dispersion lattice

<i>Family</i>	<i>Magnetic Length [m]</i>	<i>Gradient K1 [m⁻²]</i>	<i>Field Strength [Tm⁻¹]</i>
Q1AB	0.4	1.29	12.9
Q2AB	0.4	-1.04	-10.5
Q1B	0.4	-1.25	-12.5
Q2B	0.6	1.48	14.8
Q3B	0.3	-0.88	-8.8
Q1AD	0.4	1.26	12.6
Q2AD	0.4	-0.99	-9.9
Q1D	0.4	-0.71	-7.1
Q2D	0.6	1.27	12.7
Q3D	0.3	-1.01	-10.1

Table 1.3-7 Sextupole strengths for non-zero dispersion lattice

<i>Family</i>	<i>Magnetic Length [m]</i>	<i>Gradient K2 [m⁻³]</i>	<i>Field Strength [Tm⁻²]</i>
S1A	0.3	35.5	355.2
S2A	0.2	-33.0	-329.9
S1B	0.3	19.9	199.4
S2B	0.3	-30.0	-300.2
S1C	0.3	16.1	160.6
S2C	0.3	-19.5	-195.1
S1D	0.3	15.5	155.5
S2D	0.3	-31.4	-314.7

1.4 ZERO DISPERSION LATTICE

Table 1.4-1 Basic lattice properties for zero dispersion lattice

Natural emittance [nm rad]	6.52
Maximum horizontal beta function [m]	22.6
Maximum vertical beta function [m]	20.9
Horizontal Beta function, rf/inj/Longer ID straight [m]	12.188
Vertical Beta function, rf/inj/Longer ID straight [m]	9.998
Horizontal Beta functions, standard ID straight [m]	5.341
Vertical Beta functions, standard ID straight [m]	1.232
Dispersion, rf/inj/Longer ID straight [m]	0
Dispersion, standard ID straight [m]	0
Horizontal Tune	26.28
Vertical Tune	12.222
Natural horizontal chromaticity	-70.789
Natural vertical chromaticity	-34.648
Chromatic sextupole strengths	-38.0,41.4
Second order horizontal chromaticity	-472
Second order vertical chromaticity	-209
Momentum compaction	2.27E-04
Energy Spread	0.000960698

Table 1.4-2 General parameters for zero dispersion lattice

<i>Synchrotron Radiation Integrals</i>	I1	0.12737
	I2	0.87870
	I3	0.12289
	I4	0.00249
	I5	0.00043
<i>Partition Number</i>	Jx	0.99717
	Jy	1.00000
	JE	2.00283

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Table 1.4-3 Optical functions at the source points for the zero dispersion lattice

	<i>Betax</i> [m]	<i>Alphax</i> [m]	<i>Betay</i> [m]	<i>Alphay</i> [m]	<i>Dx</i> [m]	<i>Dpx</i>
<i>rf/inj/Longer ID str. Centre</i>	12.188	0.00E+00	9.998	0.00E+00	0.00E+00	0.00E+00
<i>Standard ID Str. Centre</i>	5.341	0.00E+00	1.232	0.00E+00	0.00E+00	0.00E+00
<i>Dipole Centre adjacent rf/inj/longer ID str.</i>	0.525433	0.210875	20.8001	4.53E-02	1.53E-02	6.54E-02
<i>Dipole Centre adjacent standard ID str</i>	0.525495	-0.211022	20.7959	-4.33E-02	1.53E-02	-6.54E-02

Table 1.4-4 Beam dimensions at the source points for the zero dispersion lattice

	σ_x [μm]	σ'_x [μrad]	σ_y [μm]	σ'_y [μrad]
<i>rf/inj/Longer ID str. Centre</i>	280.4	23.0	25.4	2.5
<i>Standard ID Str. Centre</i>	185.6	34.8	8.9	7.2
<i>Dipole centre rf/inj/longer ID str</i>	60.0	129.5	36.6	1.8
<i>Dipole Centre standard str.</i>	60.1	129.5	36.6	1.8

Table 1.4-5 Natural bunch length for zero dispersion lattice

Natural bunchlength	3.26 mm

X.1 PARAMETER LIST

Table 1.4-6 Quadrupole strengths for zero dispersion lattice

<i>Family</i>	<i>Magnetic Length [m]</i>	<i>Gradient K1 [m⁻²]</i>	<i>Field Strength [Tm⁻¹]</i>
Q1AB	0.4	1.22	12.2
Q2AB	0.4	-0.80	-8.0
Q1B	0.4	-1.23	-12.3
Q2B	0.6	1.56	15.6
Q3B	0.3	-1.41	-14.1
Q1AD	0.4	1.22	12.2
Q2AD	0.4	-0.80	-8.0
Q1D	0.4	-0.55	-5.5
Q2D	0.6	1.24	12.4
Q3D	0.3	-1.32	-13.2

Table 1.4-7 Sextupole strengths for zero dispersion lattice

<i>Family</i>	<i>Magnetic Length [m]</i>	<i>Gradient K2 [m⁻³]</i>	<i>Field Strength [Tm⁻²]</i>
S1A	0.3	35.5	355.2
S2A	0.2	-33.0	-329.9
S1B	0.3	19.9	199.4
S2B	0.3	-30.0	-300.2
S1C	0.3	16.1	160.6
S2C	0.3	-19.5	-195.1
S1D	0.3	15.5	155.5
S2D	0.3	-31.4	-314.7

1.5 MAGNET SPECIFICATION

Table 1.5-1 Storage ring magnet inventory

Dipole Magnets	48
Quadrupole Magnets	240
Sextupole/Steerer/Skewquad Magnets	168
Septum Magnets	2
Kicker Magnets	4
Fast correctors	4 per cell

PART X: APPENDICES

Table 1.5-2 Magnet field quality specification

Dipole Magnets	$\Delta B/B$	+/-0.02%
Quadrupole Magnet	$\Delta g/g$	+/-0.05%
Sextupole Magnet	$\Delta S/S$	+/-1%

Table 1.5-3 Dipole magnet properties

Number	N	48
Length	[m]	0.935
Field	[T]	1.4
Magnet Gap	[mm]	50
Good-Field Aperture	[mm]	12 x 15

Table 1.5-4 Quadrupole magnet properties

<i>Family</i>	<i>Magnetic Length [m]</i>	<i>Number</i>	<i>Good Field Aperture [mm]</i>	<i>Max Field Strength [Tm⁻¹]</i>
Q1AB	0.4	36	36x16	17.5
Q2AB	0.4	36	20x16	17.5
Q1B	0.4	36	25x12	17.5
Q2B	0.6	36	25x12	17.5
Q3B	0.3	36	25x12	17.5
Q1AD	0.4	12	36x16	17.5
Q2AD	0.4	12	20x16	17.5
Q1D	0.4	12	25x12	17.5
Q2D	0.6	12	25x12	17.5
Q3D	0.3	12	25x12	17.5

X.1 PARAMETER LIST

Table 1.5-5 Sextupole magnet properties

<i>Family</i>	<i>Magnetic Length [m]</i>	<i>Number</i>	<i>Good Field Aperture [mm]</i>	<i>Max Field Strength [Tm⁻²]</i>
S1A	0.3	24	36x16	520
S2A	0.2	48	27x16	520
S1B	0.3	36	25x12	520
S2B	0.3	36	25x12	520
S1C	0.3	12	25x12	520
S2C	0.3	12	25x12	520
S1D	0.3	12	25x12	520
S2D	0.3	12	25x12	520

Table 1.5-6 Drift space apertures

<i>Element Name</i>		<i>Good Field Aperture HxV (mm)</i>
D1A	Achromat	36x16
D2A	Achromat	33x16
D3A	Achromat	23x16
D4A	Achromat	16x16
D2B	Insertion Drifts	25x12
D3B	Insertion Drifts	25x12
D4B	Insertion Drifts	25x12
D5B	Insertion Drifts	25x12
D6B	Insertion Drifts	20x14

1.6 INITIAL “DAY1” INSERTION DEVICES

Table 1.6-1 Summary of the parameters of the first insertion devices.

Name	Beamline	Technology	B _{Max} (T)	K _{Max}	Period (mm)	N _{Periods}	Length (m)
MPW60	VHE	SC MPW	3.5	19.6	60	16	1.0
U33	Materials	Und	0.54	1.66	33	149	5.0
U23 IV a	PX	IV Und	0.70	1.49	23	85	2.0
U23 IV b	PX	IV Und	0.70	1.49	23	85	2.0
U23 IV c	PX	IV Und	0.70	1.49	23	85	2.0
U27 IV	XAS	IV Und	0.80	2.02	27	72	2.0
HU64	SXR	Helical Und	0.57	3.4	64	75	5.0
U27	NCD	Und	0.70	1.76	27	72	2.0

PART X: APPENDICES

1.7 MISALIGNMENT AND ERRORS

Table 1.7-1 Misalignment Table

<i>Error Type</i>	<i>RMS Magnitude</i>
Quadrupole Transverse Displacement	0.1 mm
Sextupole Transverse Displacement	0.1 mm
Dipole Transverse Displacement	0.05 mm
Dipole Longitudinal Displacement	0.05 mm
Dipole Field Error	0.10%
Quadrupole Roll Error	0.2 mrad
Dipole Roll Error	0.2 mrad

Table 1.7-2 BPM resolution

BPM resolution	1 μ m