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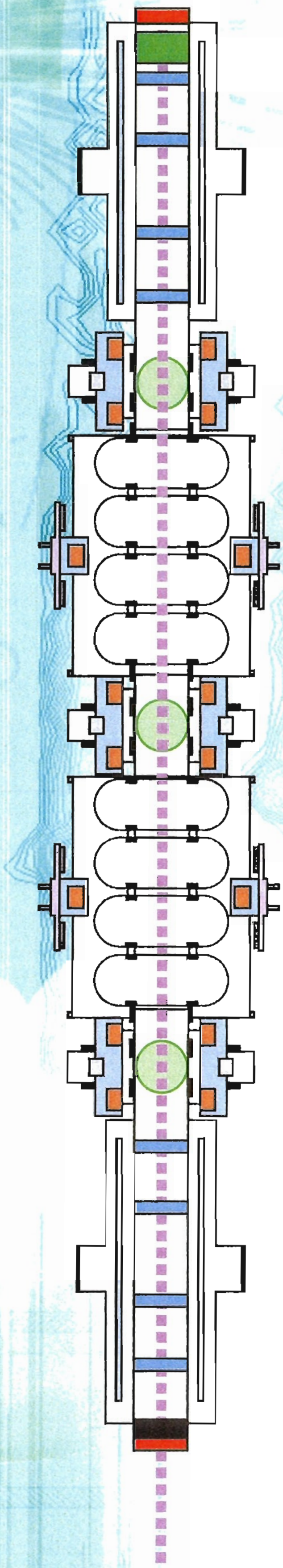

Report on the first three years of the initiative in

Accelerator R&D for Particle Physics

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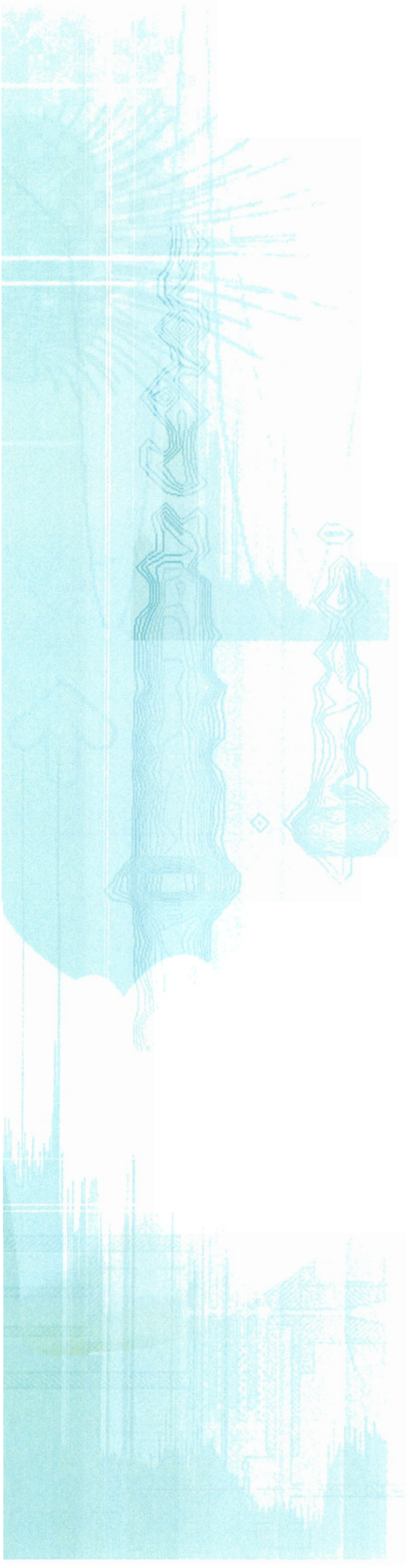

Report on the first three years
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Accelerator R&D for Particle Physics

This report describes the work undertaken during the three year programme in accelerator R&D for particle physics between 1999 and 2002 funded by PPARC and CCLRC.

August 2002

Edited by P R Norton,
Particle Physics Department,
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Foreword

The UK has a distinguished record in the design and construction of accelerators for particle physics and in the provision of trained machine builders for facilities overseas. However since the closure of the domestic machines, this activity has waned. In order to redress this situation in April 1999 PPARC made available the sums of £300k per year for 3 years. This was matched by amounts of £150k per year from CCLRC's internal funds. The work was to be carried out under the direction of Professor Peach, but at the outset it was expected that scientists from the universities as well as from within CCLRC would participate. In order to monitor the progress of this work and the use of the PPARC funds on a regular basis the External Particle Accelerator Advisory Panel (EPARD) was set up. The terms of reference of the Panel and its membership are given in Appendix A. The Panel has met 11 times during the past 3 years.

An interim report on the work carried out using the PPARC and CCLRC funds was issued in July 2002. The present report brings this up to date and covers the entire period of the Particle Accelerator R&D initiative. We are of the opinion that the breadth and quality of the work are truly remarkable. The sums of money involved have been relatively modest, but they have enabled UK scientists to play important roles in several areas where major new facilities for particle physics are in active preparation. It has been very timely that the UK strengthens its involvement in particle accelerator R&D when, in particular, the electron linear collider and neutrino factory projects are rapidly gaining momentum worldwide.

Impressive though the results achieved are, the work is far from over and it is most important that funding for this activity be maintained and increased over the next few years in order to bring these developments to fruition. Having shown that there exists in the UK a pool of competent and enthusiastic accelerator scientists, it is now urgent that the UK makes concrete proposals for one or more of the new facilities. This will necessarily involve funds of a considerably larger size, but the aims of the initiative for the UK to become a major participant in the construction of accelerators for particle physics and a training ground for future machine builders can only be fulfilled in this way.

G.Myatt

University of Oxford

Chair of EPARD

Executive Summary

1. The 'Particle Accelerators for Particle Physics' initiative was jointly funded by PPARC and CCLRC for three years, starting in 1999. The main objective was to re-create and re-establish within the UK the tradition of research and development into accelerator technology for particle physics applications, either at the high energy or the high luminosity frontier. This would enable the UK to evaluate for itself how it would wish to contribute to future international particle physics facilities, with the option of making the contribution to the machine 'in kind' (as is done with the detectors).
2. It had the support of particle physicists, accelerator physicists and other specialists in a variety of technologies (r/f power, superconductivity, high-brightness electron guns, high-power lasers...) within CCLRC and in university departments in Physics and Engineering, as well as making contact with and involving UK industrial partners. There has been excellent interaction between the particle physics community in the UK and the accelerator scientists at Daresbury and at the Rutherford Appleton Laboratory.
3. The major international particle physics laboratories (CERN, DESY, FNAL, SLAC) with whom the UK particle physics community has worked over the past twenty years warmly welcomed this initiative.
4. The scientific case for the next generation of facilities beyond the LHC, HERA, the B-factories and the Tevatron is now well developed. There is general agreement, underlined by the OECD Global Science Forum report by the Consultative Group on High Energy Physics, on the need for a linear e^+e^- collider with energy around 0.5TeV to make precision measurements on the discoveries expected at the LHC. There is a strengthening case for a 'neutrino factory' producing intense beams of neutrinos of well-understood flavour composition, for long baseline studies of oscillations and potentially the observation of CP violation. In the far future, there is interest in a muon ($\mu^+\mu^-$) collider as a 'Higgs factory' and as a potential alternative route to a multi-TeV lepton collider.
5. The linear e^+e^- collider presents some formidable challenges, and there is still much work to be done even following the publication of the TESLA Technical Design Report. The UK has concentrated its efforts in three areas: the beam delivery system (including instrumentation and control systems), the damping rings, and the photo-injector for the CLIC drive beam. The UK has been innovative in all of these areas.
6. The neutrino factory studies have addressed a broad range of issues, with the UK taking a lead in several areas, including the proton driver, target issues and the measurement of the basic physical distributions governing the pion production and muon scattering that will determine the overall efficiency.
7. There are some key generic technologies that are needed for any future frontier machine. These include superconducting magnets, high brightness electron sources, high-power r/f systems and power supplies, and novel r/f sources.

8. There have been a number of interesting new developments that have raised the profile of accelerator science in the UK. The 'Opportunity Fund' supported two accelerator projects, and the Particle Physics Experiments Selection Panel supported other accelerator projects with Responsive RAs and with travel and equipment. Within the CCLRC, a new Accelerator Science and Technology Centre (ASTeC) was established to promote the culture of accelerator development in the UK. A Faraday Partnership in High Power Radio Frequency engineering has been established with funding from PPARC and the DTI, with the support of University groups and industry. The CCLRC has entered into agreements on specific particle physics projects with a number of laboratories, including DESY and CERN.

9. The report reviews briefly the scientific case for a new generation of accelerators beyond the LHC. The work on the linear collider (beam delivery systems, damping rings, photo-injectors, laser-wire scanners, fast feedback and collimator wake-fields) is described, followed by the work on neutrino factories (proton driver designs, high power target studies, the pion production experiment (HARP), muon multiple scattering studies (MuScat) and cooling studies (MICE). Finally, the generic work on superconducting magnets, high brightness electron sources and novel RF sources is described.

10. This ambitious and continuing programme has been achieved within the modest resources allocated, and has benefited from the close collaboration with many people in many institutions. The initiative has established that the UK has relevant expertise in many of the key technologies, that there is a role for the UK in this frontier research area, that the UK academic and research sector is keen to make a strong and innovative contribution, and that UK industry wants and is able to benefit. This progress and success needs to be used to define and resource a full R&D programme targeted to address to of the major issues discussed in this report.

11. The aim of this three-year programme was to explore whether there was still the capability in the UK to make a substantial contribution to accelerator research at the high energy/high luminosity frontier. The success of this programme has established beyond doubt that the capability exists, and that there is an enthusiastic group of particle and accelerator physicists and engineers with both the technical skills and the committed interest to make an important and innovative contribution. The challenge now is to build upon this solid foundation and to create a vibrant and viable future programme, with the aim of making a major contribution, both intellectually and technically, to the next generation of major particle physics facilities.

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Introduction

The UK Particle Physics community has a first rank reputation in experimental physics, confirmed by numerous international reviews [1], [2]. The leadership which has been manifest in the LEP, HERA and LHC experiments needs to be carried forward to the next generation of accelerators which will follow LHC. The most obvious candidates for such machines are an e^+e^- linear collider (LC) working at a collision energy of 0.5-1 TeV, and a neutrino factory (νF). On a longer timescale one can envisage a multi-TeV μ^+- μ^- collider.

These new machines are likely to be built by regional or global consortia, and contributions to both the detectors and the machines will be required. If we are to be in an influential position, it is vital that we contribute our UK accelerator expertise in both design and construction, rather than just making cash payments towards the cost of the machine(s).

The UK has a distinguished record in the design and construction of accelerators, but during the 1970s the domestic machines (NIMROD and NINA) were closed and experiments were conducted at CERN and elsewhere. The accelerator science and technology lived on in the new machines (ISIS and SRS) built for use by other branches of science. Hence there is a pool of talent in the UK which has not contributed to the developments of accelerators for Particle Physics. If we are to make a contribution to the development of new PP machines this talent must be used to the full while building up teams of younger machine builders. Accelerators are both technologically challenging and vital for scientific development, but they also generate demand for technologies with other wider applications. The maintenance of a core base of accelerator expertise is vital to the capability of UK industry.

The awareness of the urgency of the situation led to an initiative begun in April 1999 in which modest funds (£450k per year in total over three years) were provided by PPARC and CCLRC for this purpose. This report records the progress made over this three year funding period.

Initiatives have been taken over a wide range of different projects. These include:

- Direct contributions by the accelerator physicists at both RAL and DL on LC beam delivery systems and damping rings, high intensity proton drivers and high power targets for νF studies.
- Beam diagnostic studies for the LC
- Work on a laser photoinjector for CLIC (the LC under design at CERN) using expertise from CCLRC CLF Department.
- Experimental studies essential for progress in the design of a νF.
- Development of the underlying and supporting technologies necessary to progress the designs.

Significant new developments have taken place during the period of this initiative:

- The founding of ASTeC (Accelerator Science and Technology Centre) in CCLRC to promote the culture of accelerator development in the UK.
- The setting-up of a Faraday Partnership in High Power Radiofrequency engineering, funded by the DTI and PPARC, between various university groups and industrial partners.
- The signing of a Co-operation Agreement between CCLRC and DESY to cover various aspects of electron accelerators.

Despite the modest resources allocated, substantial work has been done and is recognised and welcomed by the international community of accelerator physicists. We now need to build on this to secure the future of the quality and quantity of PP accelerator activities in the UK.

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2

Particle Physics at Future Accelerators

2.1 Introduction

United Kingdom particle and accelerator physicists are currently playing an active and significant role in research and development for two future international facilities: an electron-positron linear collider and a neutrino factory. In this section we outline the physics opportunities which will be made available by the operation of these accelerators. These are summaries of the physics cases contained in two reports to the PPC [1], [2].

2.2 Electron-Positron Linear Collider

Particle physics experiments conducted over the last 25 years have tested the Standard Model and confirmed many of its predictions to very impressive levels of precision. Despite this success, the Standard Model of Particle Physics leaves many fundamental questions unanswered: What is the origin of mass? What determines a particle's mass and other properties? Why are there three generations of fermions? Are all the forces unified? Why are matter and antimatter subtly different? To answer these questions requires an understanding of physics beyond the Standard Model. Although there exist many theoretical ideas, only experimental measurements can tell us which is correct.

Current data point to the energy range of a few hundred GeV as being the region where new physics will be revealed. The long-sought Higgs boson, or several Higgs bosons, might be discovered. Supersymmetric or other new particles might be produced. Completely new types of interaction might become apparent at higher energies. All that is known is that something must happen at about this energy, otherwise the Standard Model becomes inconsistent.

The Large Hadron Collider (LHC) is being constructed at CERN to probe this energy range, from 2007 onwards. Physicists in the UK will be leaders in analysing and interpreting LHC data. There is a firm consensus [3], however, that the LHC alone will be insufficient to explore fully the physics at this critical energy scale. It will indicate the general direction in which the Standard Model evolves into a more complete theory, but will not constrain this to a single theory which could be used to describe, for example, the evolution of the early universe immediately after the Big Bang. The LHC is a 'discovery machine' which will indicate where to look for the new physics. An electron-positron linear collider (LC) operating in the energy range 0.5-1 TeV would provide the ideal complement to the LHC physics programme. It will have a unique discovery potential for particles with only electroweak couplings and it will allow precise measurements of any new particles or new interactions discovered either at LHC or LC. This is essential to give us a complete picture of the underlying physics.

Many workshops examining the physics case and design for such a linear collider have been held, in several different countries and with major UK participation. This has resulted in the recent publication by the DESY Laboratory in Germany of a Technical Design report for its TESLA linear collider [4], and designs are also well advanced in the USA and Japan. CERN also has designs for a higher energy LC (CLIC). In January 2002 the US High Energy Physics Advisory Panel strongly supported, as its highest priority, the construction of a high energy, high luminosity electron-positron linear collider, to be the next major step in this field [5]. Decisions regarding the funding and construction of LC accelerator facilities are imminent.

A linear collider is complementary to the LHC; the main differences and strengths compared with the LHC are:

- Signal processes have similar rates to the background, whereas at LHC background rates are orders of magnitude higher. This will make it much more straightforward to recognise the emergence of new effects.

- The initial e^+e^- state is simple and well-understood. Predictions for the standard electroweak interactions can be calculated with very high precision.
- Polarization of the initial electron and positron beams is possible. This improves some signals and allows flexibility in the study of electroweak effects, which are sensitive to the left- or right-handedness of the particles involved.
- The electron and positron beam energies can easily be varied to optimize rates or to examine new particle states.
- In addition to e^+e^-, also e^-e^-, e-γ and γ-γ collisions are feasible, which enhances the physics potential of the machine.
- The relatively low radiation environment will allow particle detectors to be placed very close to the beam pipe, leading to improved resolution and hermeticity. This is crucial for tagging of long-lived particles, necessary for quark flavour separation, and for searches involving "missing energy", that is final states including neutrinos or other particles which pass through the detectors without interacting.

If there is a fundamental Higgs boson then it will, most likely, be found at the Tevatron or the LHC. It will be necessary to measure all the Higgs couplings, as well as its spin-parity and CP quantum numbers, to establish that it is, indeed, a Higgs, and whether it is a Standard Model or a supersymmetric Higgs. LHC experiments will be sensitive only to a few of the possible Higgs decay mechanisms, because of the high backgrounds in hadronic collisions. In contrast, a linear-collider experiment will be able to record all Higgs decay modes, through $e^+e^- \rightarrow ZH$. It will yield precise measurements of Higgs couplings to $b\bar{b}$, $c\bar{c}$, WW, ZZ, $\tau^+\tau^-$, $\gamma\gamma$ and gluon-gluon, and sensitivity to the $Ht\bar{t}$ coupling and the Higgs total width and self-coupling. Experiments at a linear collider would do for Higgs physics what experiments at LEP and SLD have done for Z and W physics, testing the fundamental gauge theory at the level of quantum-loop corrections and imparting sensitivity to any particles which couple to the Higgs boson, even those too massive to be produced directly.

The theoretical idea of supersymmetry (SUSY) is central to all current attempts to unify gravity with the other fundamental forces. It predicts a whole new dynasty of particles, with a SUSY partner to each of the known Standard Model particles. The fact that these have so far eluded all attempts to detect them implies that SUSY must be broken at low energies, but if SUSY is correct then they cannot have masses above a few hundred GeV, and are hence within the energy range of the LHC and proposed LC. Strongly interacting SUSY particles could be found at the LHC, but a linear collider is essential to make systematic studies of all kinematically accessible SUSY particles. The ability to polarize the beams and scan the energy means that a LC will be able to separate states which are nearby in mass and precisely measure their individual couplings. However, SUSY embraces a whole class of theories, and it is important, in order to understand grand unified theories, to learn which type of SUSY nature has chosen.

In addition to studies of new particles, dedicated runs of a linear collider at specific energies will allow measurements of the masses, widths and couplings of the top quark and the W and Z bosons with much improved precision compared to earlier experiments. These combined electroweak measurements provide an indirect determination of the mass of the Higgs boson, in the Standard Model. Comparison with the direct Higgs mass measurement will constrain the structure of any new physics contributions, giving sensitivity to energy scales well above that which can be probed directly.

In the longer term, a higher-energy linear collider, working in the energy range of 1-5 TeV, would allow further study of any new phenomena discovered at the LHC or the LC. The experience and knowledge necessary to build such a machine will be gained by operation of a 0.5-1 TeV collider. Linear collider technology will therefore be central to the particle physics programme for at least the next 20-30 years.

2.3 Neutrino Factory

Recent experimental results lead to the conclusion that neutrinos undergo flavour oscillation. This is based on many years of measurements of neutrinos from the Sun, most startlingly in the recent results from SNO, but also from studies of atmospheric neutrinos, that is neutrinos produced by cosmic ray interactions in the upper atmosphere. Comparison of the observed rates and angular distributions of electron-type and muon-type atmospheric neutrinos reveal a deficit of the latter. The most likely explanation in both cases is that neutrinos have transformed into a different type, or flavour, before reaching the detector close to the Earth's surface.

The implication of neutrino flavour oscillation is that the neutrino mass is not zero, contrary to one of the assumptions of the Standard Model of Particle Physics, although the SM can accommodate neutrino masses relatively easily, albeit at the cost of introducing very massive new particles at the GUT scale. It also admits the possibility of CP violation in the lepton sector, in the same way that quark-flavour mixing leads to CP violation in weak hadronic transitions. Both of these neutrino properties would have profound consequences in cosmology.

A number of theories have been proposed to explain the experimental observations. These necessarily involve physics beyond the Standard Model, such as Grand Unified Theories, supersymmetry or extra dimensions. Further study of neutrino phenomena, to distinguish amongst the candidate theories, will therefore provide a probe of this higher-energy physics, of which the Standard Model is merely a low-energy approximation. Information on neutrino masses should also provide further clues to the origin of quark and lepton masses and the number of generations.

It is therefore vital to pursue an extensive programme of neutrino physics. Several experiments to be run over the next ten years will provide much new data on solar and atmospheric neutrinos. There are also experiments running, or under construction, in Japan, the USA and Europe which will direct neutrino beams produced at accelerator laboratories through the Earth, to be intercepted by detectors sited hundreds of kilometres away. These long-baseline experiments, in which the neutrino source can be controlled and monitored directly by the experimenters, will either confirm or reject the hypothesis of neutrino-flavour oscillation. If confirmed, they will provide the first set of measurements of parameters of the lepton-mixing matrix, the analogue of the CKM quark-mixing matrix. Despite this anticipated progress, there are many vital lepton-mixing parameters which will not be well measured in ten years time. These include the important CP-violating phase, which determines the degree of CP violation in lepton interactions. This is related to the asymmetry in nature between matter and antimatter, which has led to our matter-dominated universe.

Still more precise experiments will therefore be required to continue neutrino research and to discriminate amongst the possible theories. They will require very intense laboratory neutrino beams, possible to produce from muon decays in a stored muon beam. To meet the physics objectives, such a facility will need to store a muon beam of energy ~20-50 GeV and to deliver of the order of 10^{21} muon decays per year.

These are challenging specifications, but recent developments in accelerator physics make it conceivable that a realistic technical proposal could be produced in the next 5-10 years. Studies, with UK involvement, are ongoing in Europe, USA and Japan.

Neutrino beams derived from stored muon beams have two distinct advantages over conventional neutrino beams: both muon and (anti)electron neutrinos are present, allowing a more complete study of flavour mixing; and the neutrino spectrum is very well-known. Experiments at a neutrino factory will be able to make precise measurements of the lepton-mixing parameters and the results will distinguish between different possible neutrino-mass hierarchies. Comparison of results between running with a stored μ^+ beam and a stored μ^- beam will reveal any possible deviation between the oscillation properties of neutrinos and antineutrinos, and hence be sensitive to CP-violating effects.

In addition, a neutrino factory will provide the opportunity for a new programme of precise measurements in the field of neutrino deep-inelastic scattering. The high-intensity collimated neutrino and antineutrino beams could be used to disentangle different structure functions, study the EMC nuclear effect with different targets, measure the CKM matrix elements between quarks $|V_{cd}|$ and $|V_{cs}|$ and D^0- $\bar{D}^0$ mixing and investigate spin physics using polarized targets. It would be an excellent complement to the deep-inelastic electron-scattering experiments at HERA.

A fraction of the high-intensity stored muon beams could also be extracted to give a flux of muons for experimentation exceeding that of any other muon source by several orders of magnitude. This could be used for measurements of muon properties, such as magnetic and electric moments and searches for lepton-flavour violating decays. The muons could also be utilised in atomic and condensed matter physics research.

Further into the future an exciting possibility is the construction of a μ^+-μ^- collider. This has all the physics possibilities of an e^+e^- collider, but in addition would be an abundant source of Higgs particles produced through μ^+-$\mu^- \rightarrow H$. The cross-section for this process is 40000 times higher than the corresponding e^+e^- cross-section, because the Higgs coupling is proportional to the lepton mass, and the muon is more than 200 times heavier than the electron. This mass difference also makes muons far less susceptible to synchrotron radiation energy losses, which are the limiting factor in designing e^+e^- storage rings. In fact, a 4 TeV μ^+-μ^- collider would be relatively "compact" — it could be built in the existing SPS tunnel at CERN. However, there are severe technical difficulties associated with a μ^+-μ^- collider, because of the challenge of obtaining a high enough intensity source of muons and then capturing, cooling, accelerating and colliding the muons before they decay. Many years of R&D will be required to overcome these problems, but the knowledge and experience gained in building and operating a neutrino factory, with its high current stored muon beam, would be very valuable in this respect.

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[3] OECD Global Science Forum: Report of the Consultative Group on High-Energy Physics http://www.oecd.org/pdf/M00032000/M00032800.pdf (June 2002)

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3 Accelerator Studies for Linear Colliders

3.1 Beam delivery systems for LC

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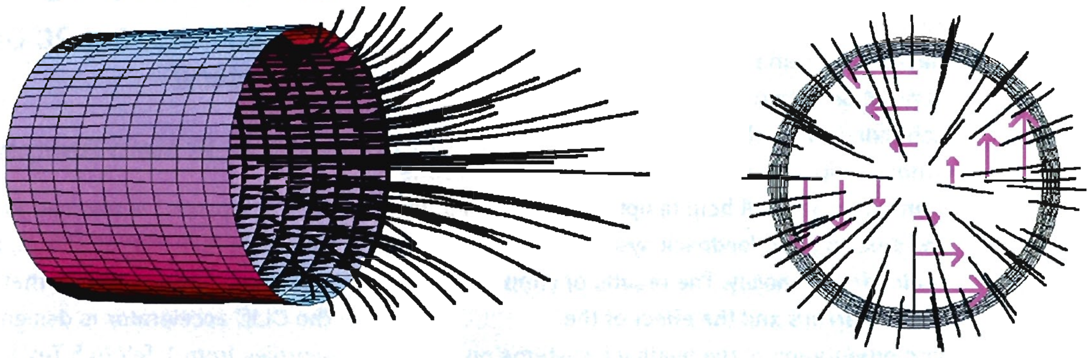
3.1.1 Introduction

The beam delivery system (BDS) of the collider is the region between the ends of the accelerating linacs and the interaction point (IP). In this section the beams are focussed by quadrupole magnets to the nanometre-scale vertical sizes required to produce high luminosity. The beams are also collimated to remove halo particles and hence minimise the beam-related backgrounds seen by the detector. Other parts of the beam delivery system include a chromatic correction section, diagnostics section, and final focus. Often included in this system are sections beyond the interaction point, including the beam extraction and transfer lines to the beam dumps. The tolerances and performances of all the parts of the beam delivery system between the main linac and the interaction point have an effect on the luminosity. They also have a strong effect on backgrounds in the detector and are thus of great interest to the detector design and to the LC physics programme.

3.1.2 Solenoidal Field Compensation

One of the effects of a solenoid field in a high-energy beam line is to introduce strong coupling between the horizontal and vertical motion of particles travelling along the beam line. This is a concern for a linear collider such as TESLA, where the vertical beam size is much less than the horizontal, and any uncorrected coupling from the detector solenoid at the interaction point blows up the vertical beam size and significantly reduces the luminosity. To initiate work in the beam delivery area and to provide a useful contribution to the TESLA TDR an assessment was made of the compensation of coupling effects at the interaction region due to the solenoidal field and the Final Focus quadrupoles. These quadrupoles need to be inside the solenoid to provide the necessary focusing. However their presence gives rise to this beam coupling (see diagrams below) and if uncorrected to an increased vertical beam size resulting in much lower luminosity.

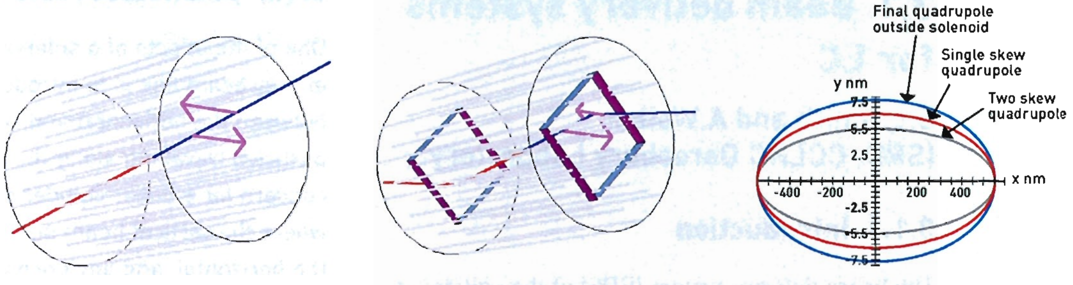
The required skew quadrupole compensation was calculated analytically using Mathematica, and confirmed numerically using DIMAD (numerical accelerator simulation code). This initial study does not include nonlinear effects, which also need to be assessed.



Fringe field at end of solenoid

Kicks on particles from fringe field
The kicks result in coupling between horizontal and vertical motion. The size of the kick is proportional to the distance of the particle from the solenoid axis.

Figure 1: Effects of the solenoidal field.



No focusing inside solenoid
The kick from the fringe field is cancelled out by the field within the main body of the solenoid...

Quadrupole inside solenoid
...unless there is a focusing quadrupole. Small spot sizes require the final quadrupole close to the IP. In this case, the coupling kicks do not cancel, and skew quadrupoles are then needed to compensate the coupling forces.

Effect of solenoid compensation on beam sizes at the interaction point.

Figure 2: The effects of the skew quadrupole compensation.

3.1.3 TESLA Beam Delivery System: Error Sensitivity and Correction

Several codes can model the BDS in the ideal case. However, the luminosity is strongly affected by non-ideal effects, e.g. misalignments from vibration and drift, and wakefield effects and these effects are not well modelled using most simulation codes. An improved code is being developed to completely simulate these effects called MERLIN. By applying existing skills to the continued development of the software, the UK were able to quickly make an important contribution to the TESLA Technical Design Report (TDR) [1], while developing expertise in many of the systems comprising the beam delivery system. There are good opportunities for close collaboration with groups working on backgrounds and complete beam delivery simulation within Universities and a fledgling collaboration is already underway involving a studentship at Manchester University. The results from this code will help to optimise the design of the steering and feedback systems necessary to maintain luminosity. The results of simulations of various errors and the effect of the implementation of the feedback systems on TESLA performance are shown below.

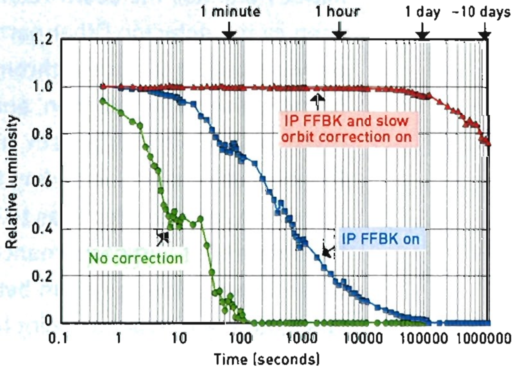


Figure 3: Evolution of the luminosity at the primary interaction region with time, depending on whether fast feedback (FFBK) and slow orbit correction are active or not.

3.2 LC Damping Ring Design

H.Owen (SRD, CCLRC Daresbury Laboratory)

3.2.1 CLIC Main Damping Ring

The CLIC project is planned to run over a longer timescale than that of TESLA, partly due to the challenging design issues that must be resolved. The CLIC accelerator is designed to operate at energies from 1 TeV to 5 TeV (centre of mass), with 3 TeV as the nominal operating energy. Reaching this energy at reasonable cost and therefore main linac length implies an extremely high accelerating gradient of 150 MV/m, potentially achieved by using a novel two-beam acceleration system which is presently under intense development at CERN. As well as providing the required energies, to provide a useful luminosity to experimenters at the interaction region extremely small emittances must be provided at high intensity, which leads to challenging requirements for the damping rings which feed the main linac sections. Indeed, these emittances approach fundamental limits, and the present collaboration of Daresbury seeks to examine these limits to enable a practical design to be achieved.

Previous designs for the 1 TeV CLIC option have assumed a conventional 1.98 GeV energy for the damping rings, as a balance between increased intra-beam scattering growth rates at low energy and the expense of providing the specified emittance at higher energies, as with the NLC design. However, the order of magnitude reduction in required emittance for the 3 TeV option has been shown to preclude operation at 1.98 GeV – due to the dominant intra-beam scattering at this energy – and so higher-energy options must be examined. At present a layout at 4.63 GeV has been examined based as before on arcs of TME-type cells with additional damping wiggler sections (energies must lie in 440 MeV steps to allow particle polarisation to be preserved in the damping rings). The present layout is shown schematically in Figs 4 to 6, which show that a very large number of cells (400) is needed to circulate the beam through the damping wigglers without generating too much emittance, leading to a circumference of 2419 m.

This is a preliminary design, and it is intended that alternative layouts be looked at, especially with regard to achieving good dynamic behaviour, and providing the presently assumed tolerances which determine the coupling into the vertical emittance. There is a great deal of overlap with both the TESLA project and the light source design activities undertaken at Daresbury Laboratory.

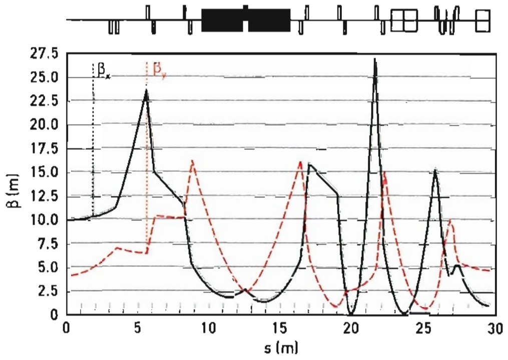


Figure 4: Optics in the injection/acceleration region, damping wigglers, phase matching and dispersion matching insertions of the present CLIC main damping ring design.

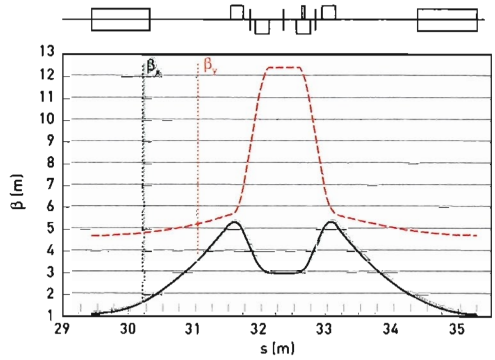


Figure 5: Optical functions in one of the TME-type cells of the main arcs. There are 400 of these cells in the damping rings.

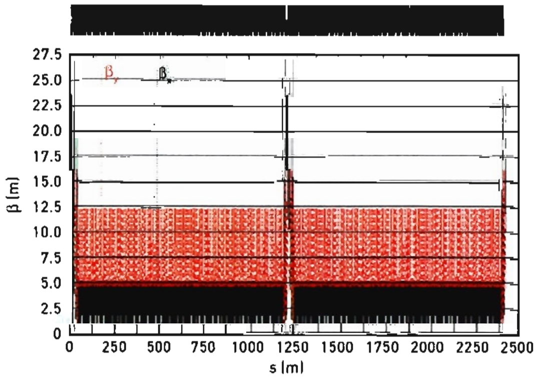


Figure 6: The complete optics of the present positron damping ring design. The very large number of elements required is reflected in the dense optical structure of the design.

3.3 CLIC Laser Photoinjector design

I.N.Ross (Central Laser Facility, CCLRC RAL) in collaboration with CERN

3.3.1 Introduction

Both 'main' and 'drive' beams of the CERN linear collider (CLIC) require the injection of a train of short electron bunches, and one of the two options for this electron injector is a photo-cathode illuminated by short pulses from a laser system. If the feasibility of the photo-injector can be demonstrated, this option offers major advantages over the traditional rf gun source in terms of both performance and cost.

A collaboration between CERN, the Central Laser Facility (CLF) and Particle Physics Department at RAL, and the Institute of Photonics, University of Strathclyde, was established in 2000 to investigate the feasibility of a laser based photo-injector for the proposed next generation linear accelerator at CERN (CLIC). This project has been jointly funded by CCLRC, PPARC and CERN.

3.3.2 Design study

The requirements on the laser were challenging. In particular the high average power during the pulse train of 47kW, the high overall average power of 1kW, the sub-picosecond pulse synchronisation between the laser pulses and the accelerator machine reference and, probably most difficult of all, the 0.1% stability for the pulse energy in both short and long term (far tighter than previously demonstrated for any laser system).

An initial detailed study was conducted to optimize the design of a suitable laser system and this included a selection of the laser medium, an analysis and optimization of the laser dynamics, a consideration of the optical design and a recommendation of an experimental programme to resolve uncertainties and establish confidence in the proposed scheme. The heart of the design is a novel high efficiency diode-pumped laser amplifier (Figure 7), which would be operated in 'quasi-steady-state'. This new mode of operation would ensure high stability for the amplifier and, using multi-pass geometries, enable the simultaneous achievement of high stability, high gain and high efficiency. The conclusion of the paper study was optimistic and predicted a system cost well within expected budget levels.

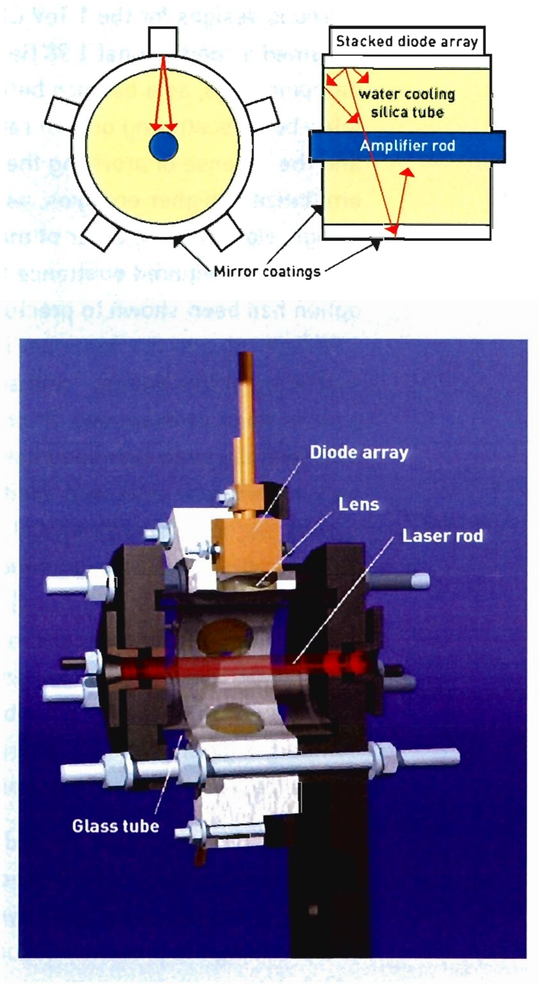


Figure 7. Design of RAL diode-pumped high power laser amplifier.

3.3.3 Experimental Programme

Following the design study, funding was obtained to proceed to an experimental programme to verify the critical results of the study and to further optimise the design. The CLF undertook the work on the final laser amplifier, this being the key element of the system, while CERN conducted studies on the harmonic generation, photocathode performance and diode pump power supplies and the Institute of Photonics proceeded with development of high power laser oscillators. The results of the CLF's amplifier studies have verified the anticipated performance in all key elements and enable us to conduct further modelling with greater confidence. In general terms we have verified the expected gain, efficiency and level of output beam quality. In particular we have demonstrated the establishment of quasi-steady-state operation (Figure 8) and shown that this can be achieved even at amplification factors as high as 10000 in multi-pass operation. In this mode excellent short term (0.1%) and long term (0.7%) stability (Figure 9) was measured, a performance that can certainly be improved by better control of diode current and temperature. With the addition of a closed cycle feedback control system the prospects are good for achieving the required stability for CLIC.

During 2001 a new programme was developed within the project, with the goal of setting up a demonstration test (known as PILOT) of the photo-injector on the current test system (CTF2) at CERN. The purpose of this programme will be to establish confidence in the photo-injector approach at a time when a final selection will have to be made between the photo-injector and the thermionic source. If this demonstration is successful and the photo-injector approach is adopted a substantial project will follow to develop a prototype laser system for the final test facility (CTF3) for CLIC. The first stage of the PILOT programme is to build, at RAL, the complete laser system including oscillator, amplifier, harmonic generator and feedback stabilization system, and verify its performance. The working system will then be transferred to CERN for the PILOT tests on the CTF2 machine, expected during 2003.

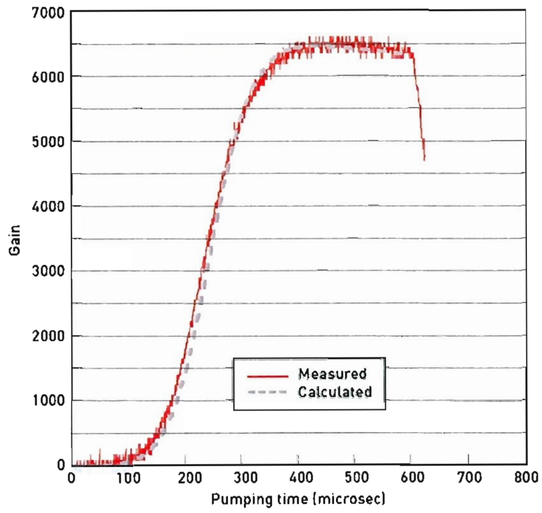


Figure 8: The establishment of high gain quasi-steady-state operation of the RAL amplifier following initiation of the diode pump. The amplifier is in four-pass mode.

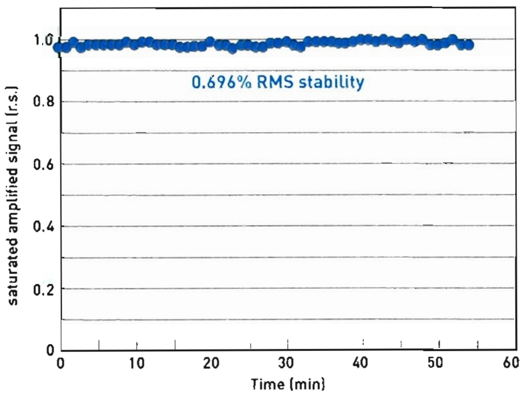


Figure 9: Long-term stability of the RAL amplifier output pulse energy.

3.4 Laser-wire beam scanner

G.A.Blair and T.Kamps (RHUL),
I.N.Ross (CLF, CCLRC RAL)

3.4.1 Introduction

The work reported here was first initiated by a PPARC Responsive RA award in September 2000. It involves a new experimental activity in the field of laser based beam diagnostics (LBBD[1]) and also novel simulation techniques for the beam delivery system (BDS) of the future linear collider (LC). With the help of the accelerator funding line, additional support in the PPARC rolling grant, a PPARC R&D award and a Royal Society Joint Project with Japan, the LBBD project has grown to a sizeable international collaboration involving the UK (RHUL and RAL) and CERN, DESY, KEK and SLAC. The LBBD work was presented at the 21st ICFA Beam Dynamics Workshop on Laser-Beam Interactions and at PAC 2001. The simulation activity reported here was enhanced by a PPARC Senior Fellowship and by additional support from a British Council ARD (Germany) grant. It has also grown quickly and has formed the basis of a new approach within the UK GEANT4 simulation group, generating wide international interest The early simulation work resulted in a contribution to the TESLA Technical Design Report[2] and was also presented PAC 2001 and LC02. Papers have also been submitted to EPAC 2002 and accepted to appear in the proceedings for both the simulation and the LBBD projects.

3.4.2 Laser-Based Beam Diagnostics

The success of any LC hinges on the provision of high luminosity to the experiments and this in turn requires the ability to focus the size of the colliding bunches to very small transverse sizes, of order nanometres. Achieving this requires the emittance (given by the beamspot size multiplied by the beam angular divergence) of the electron and positron beams to be small on leaving the linac and to remain small as the beams pass through the BDS on their way to the interaction point. Throughout the BDS care must thus be taken to avoid any emittance growth, caused for example by time dependent effects such as misalignment due to ground motion, leading to a loss of luminosity. Consequently the emittance of the beams must be continually measured and monitored and the results fed back in real time to the BDS and linac correction systems.

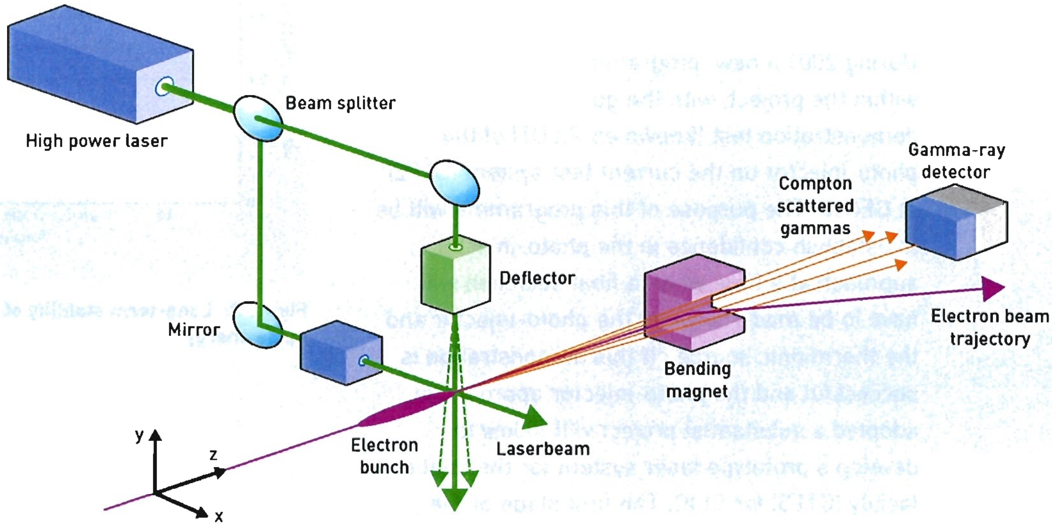


Figure 10: A schematic of the prototype laser-wire scanner.

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[1] LBBD Collaboration. http://www.hep.rhul.ac.uk/~kamps/lbbd/

[2] R. Brinkmann, N. Walker, G. Blair The TESLA Post-linac Collimation System, DESY TESLA-2000-01-12, 2001.

As the beams pass through optical components, the dimensions of the beam will vary in a well-defined way, as determined by the optics and the value of the emittance. Thus by measuring the transverse profile of the bunch as a function of position along the BDS, the transverse emittance can be determined. Traditionally, solid wire scanners have been used to measure the beam profiles by sweeping the wire through the beam; the backgrounds created by the resulting electromagnetic shower are then measured downstream as a function of wire position. This technique has the disadvantage that the presence of the wire is a significant disruption to the beam and so it cannot be used during normal luminosity running. In addition, at the LC, the bunch intensities are so great that solid wires would not survive for long. Each bunch contains about 10^{10} particles and, in the regions where the measurements will be made, the bunch transverse dimensions are a few tens of microns. The solution being pursued by the LBBD collaboration is to replace the solid wire with a narrow waist of laser light and the electromagnetic shower either by the Compton scattered photons or by detecting the scattered electrons/positrons downstream (the principle is illustrated in Fig.10). This technique was pioneered at the SLC at SLAC and was used more recently at the Accelerator Test Facility (ATF) at KEK to measure the emittance. The aim of the LBBD collaboration is to raise the level of design to produce a reliable and very fast device that can be used in real time during routine operation of the LC.

Our technical challenge is to achieve a micron-scale (diffraction limited) laser waist, positioned to micron precision inside the beam-pipe, scanned at high frequencies to intersect successive electron bunches and operating at high laser-pulse power. These are all significant technical challenges and, to tackle them, a laser laboratory has been set up at RHUL. The first goal was to design a suitable optic to focus the laser beam through a vacuum window for application at the CTF2 laser-wire at CERN. We used a low-power continuous wave laser for these first laboratory tests and have subsequently installed our optics in the CTF2 beamline [fig 11] for operation with a high power pulsed laser.

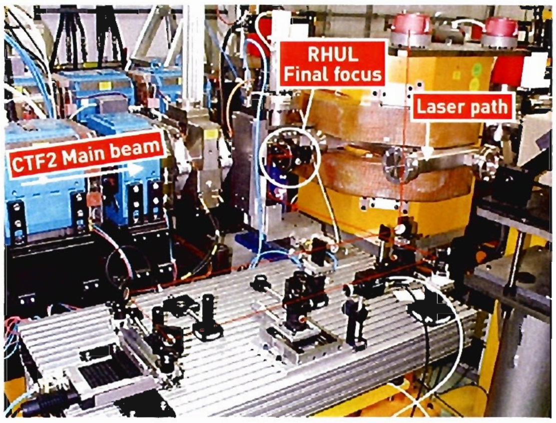


Figure 11: The RHUL laser final focus installed in the CLIC CTF2 beam line at CERN.

The quality of the laser waist from our optic design was tested using a system involving a knife-edge driven by a piezo stepper with the resulting intensity read out via a photo-diode plus ADC. The results of these measurements are shown in Fig.12. A PC, running a Labview application, drives the entire process and this environment will be extended later to drive the complete laser-wire system. The next major challenge is to design a fast scanning system and we are presently investigating a variety of techniques, concentrating initially on piezo-driven mirrors. Initially the scanning tests will be performed on the bench at RHUL and suitable software will be developed to drive the system from the PC. The whole system will then be installed at DESY in the autumn of 2002, to be operated initially at the PETRA storage ring. This is a stable machine, providing transverse bunch sizes of order 10 microns and a bunch-timing structure similar to that of TESLA. We are currently collaborating with DESY on the design of a suitable vacuum vessel. The energy of the scattered photons will be measured by a lead tungstate crystal array with photomultipliers and we have been collaborating with DESY here too, on background measurements and simulation

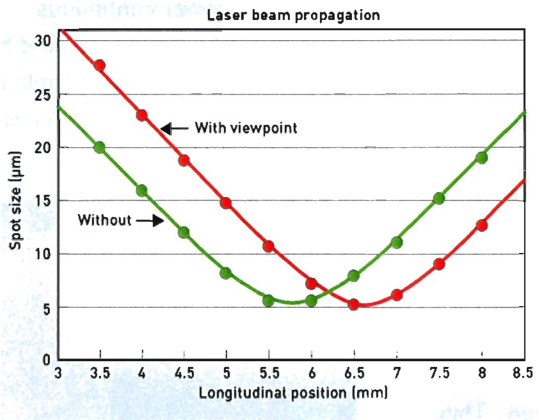


Figure 12: Laser waist size obtained by cutting the beam precisely with a blade, as a function of the longitudinal position. A measurement of the laser waist to better than 0.08 micrometres has been achieved by this method.

studies. Both a PhD and an MSc student are gaining vital experience through this work.

3.4.3 Beam Delivery Simulation

The simulation of the BDS is currently a hot topic. The tools traditionally used by particle physicists, such as GEANT tracking code, have generally been too slow and inaccurate for use by accelerator designers. On the other hand, the tools used by the accelerator physicists do not easily include effects such as muon production, showering in collimators and secondary generation and tracking. For the LC these effects are significant. For example, muons created by interaction in the linac will head straight to the detector, unlike the case at circular machines. The high energy density of the beams means that collimation is a major issue and whether the collimation system can both do its job and be robust against beam loss will require detailed simulations to determine, in advance of prototype tests.

We are presently leading the simulation arena into new directions by incorporating accelerator style tracking codes into GEANT4 and are using them to design the collimation systems for TESLA and CLIC (Fig.13). As a result of this work we are now members of the GEANT4 collaboration and this work is attracting much interest internationally, notably in the ongoing study for the Loew Technical Review Committee.

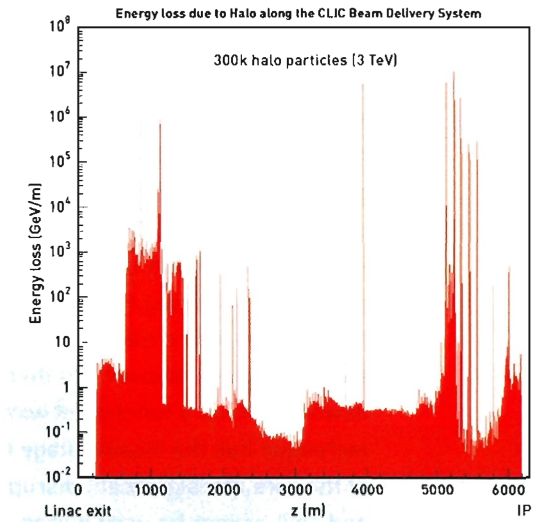


Figure 13: An example of energy absorption due to 300 000 beam halo particles in a beam delivery system (for the baseline CLIC 3 TeV design). The spikes are due to absorption of halo particles and the lower-energy continuum is due to synchrotron radiation. All secondaries are generated and tracked using RHUL code based on Geant4.

3.5 Feedback on nanosecond timescales (FONT): a fast feedback system for luminosity operation at the high energy Linear Collider

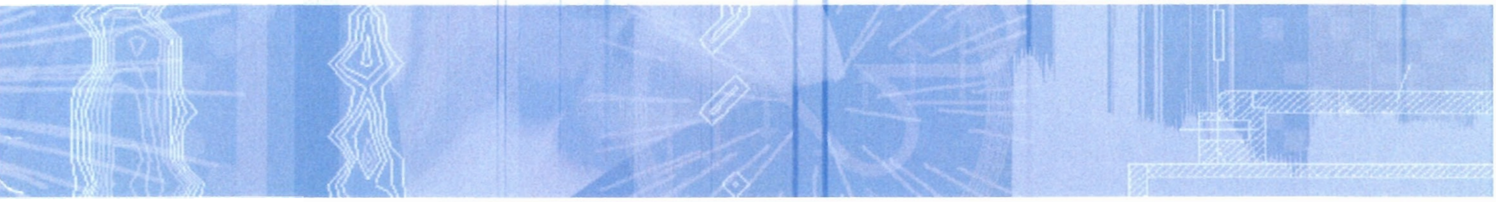
P.N.Burrows, S.Jolly, G.Myatt,
G.Nesom, C.Perry and G.White
(Oxford University)

3.5.1 Introduction

The luminosity achievable in a colliding-beam accelerator may be written:

$$L = (f\,N\,N_1\,N_2\,H)/(4\,\pi\,\sigma_x\sigma_y)$$

Where f is the number of machine cycles per second, N is the number of bunches per machine cycle, N_1 and N_2 are the number of particles per bunch, and σ_x, σ_y are the transverse overlaps of the colliding bunches. For an e^+e^- collider, H is the beam-beam self-focussing parameter or 'pinch enhancement'. The table shows the values of several of these parameters for the various



Design	Technology	c.m.energy (GeV)	f (Hz)	N	Δt (ns)	σ_x (nm)	σ_y (nm)
TESLA	Superconducting	500-800	5	2820	337	553	5
JLC/NLC	X-band	500-1000	120	190	1.4	245	3
CLIC	2-beam	3000	100	154	0.6	43	1

designs of a next-generation e^+e^- linear collider currently under consideration. Δt is the separation between the N bunches in the train.

The nanometre-level vertical beam overlap is a particularly challenging goal for these designs, most notably CLIC. Any source of beam motion which results in relative vertical offsets of the two beams at the interaction point (IP) at the nm level will clearly reduce the luminosity from the nominal value. In all of the collider designs stabilization below the 1-σ level is required to keep the luminosity loss below 10%.

The many kinds of potential beam motion may be characterized in two classes:

(i) slow drifts resulting from, e.g., thermal excursions or component settling, with characteristic timescales varying from seconds to months;

(ii) jitter on a timescale comparable with the machine repetition time.

Both kinds of motion were experienced in the decade-long experience at SLC, and were dealt with by employing slow and fast feedback systems respectively.

We are addressing the design of an intra-bunch-train fast-feedback (FB) system for the next-generation linear collider. The system comprises a fast beam position monitor (BPM) to detect the relative misalignment of the leading electron and positron bunches at the IP, a feedback loop, and a fast kicker for kicking the trailing bunches back into collision. Without such a system none of the LC designs will get within an order of magnitude of their nominal luminosity, and the physics potential will not be realised.

The system time-response requirements for JLC/NLC and CLIC are clearly very different from those for TESLA. At JLC/NLC and at CLIC the bunch trains are very much shorter O(100 ns) than the 1 ms at TESLA and the inter-bunch spacing is roughly 1 ns compared with 337 ns. In order to salvage a useful fraction of the luminosity it is clear that the JLC/NLC and CLIC cases require a system with a BPM local time resolution of roughly 1 ns and an overall system response within a few tens on nanoseconds. We have therefore chosen the more challenging case of JLC/NLC and CLIC as the primary focus of our efforts to develop a working prototype hardware system. However, from the timing point of view, a system which works on the 10 ns scale could clearly be applied to the less demanding TESLA timescale.

3.5.2 Simulation studies

During the past 18 months we have created powerful software tools for the simulation of a nanosecond timescale feedback system for correcting the relative displacement of nanometre-sized beams.

- We have imported and installed the code GUINEAPIG. This allows us to simulate the beam-beam interaction between colliding electron and positron beams of arbitrary size and bunch charge. When they do not collide head-on, each bunch gives the other a strong transverse EM kick which can be detected in a downstream BPM. This forms the physical input to the FB system (Figure 14).

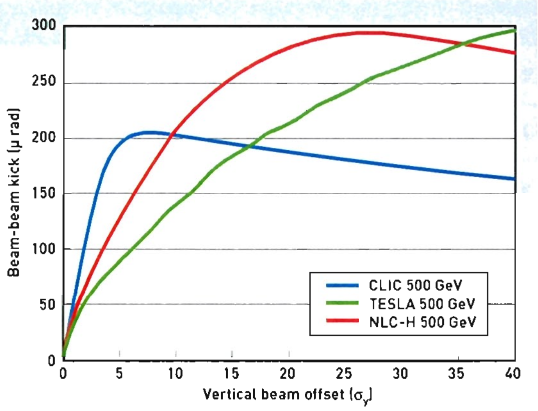


Figure 14: Simulation of the beam-beam kick that results from beam misalignments at the IP. This is illustrated for the NLC, TESLA and CLIC machine parameters.

- We have installed MATLAB and SIMULINK to create a modular FB system simulation (Figure 15). The response times of the BPM, feedback loop and kicker magnet, as well as cable delays, can all be chosen arbitrarily. The feedback algorithm can similarly be programmed at will.
- We have set up a GEANT model of the NLC interaction region to allow us to incorporate the FB system components. The location of the BPM and kicker directly affect the system latency (due to signal propagation times). In addition, the material of these components can contribute to knock-on backgrounds in the detector resulting from the showering beam-produced photons and e^+e^- pairs. A corresponding model of the CLIC interaction is currently being implemented.
- We have set up an equivalent FLUKA model to allow us to calculate background neutron production.

We have used this software infrastructure to optimise the design of the FB system for the NLC case in terms of the minimization of the response time and the knock-on backgrounds, subject to the constraints imposed by the locations of the other components in the crowded IR, principally the final-focus quadrupole magnets and the vertex detector. Figure 16 shows the performance for the optimal hardware layout in terms of the luminosity loss vs beam offset and kicker gain. For offsets below 10 σ there is a comfortable 'valley' in which the specific gain choice is not critical. However, for offsets significantly larger than 10 σ the choice of gain is delicate; an unfortunate choice could lead to catastrophic luminosity loss. We are now in a position to perform similar design optimisation studies for CLIC and TESLA.

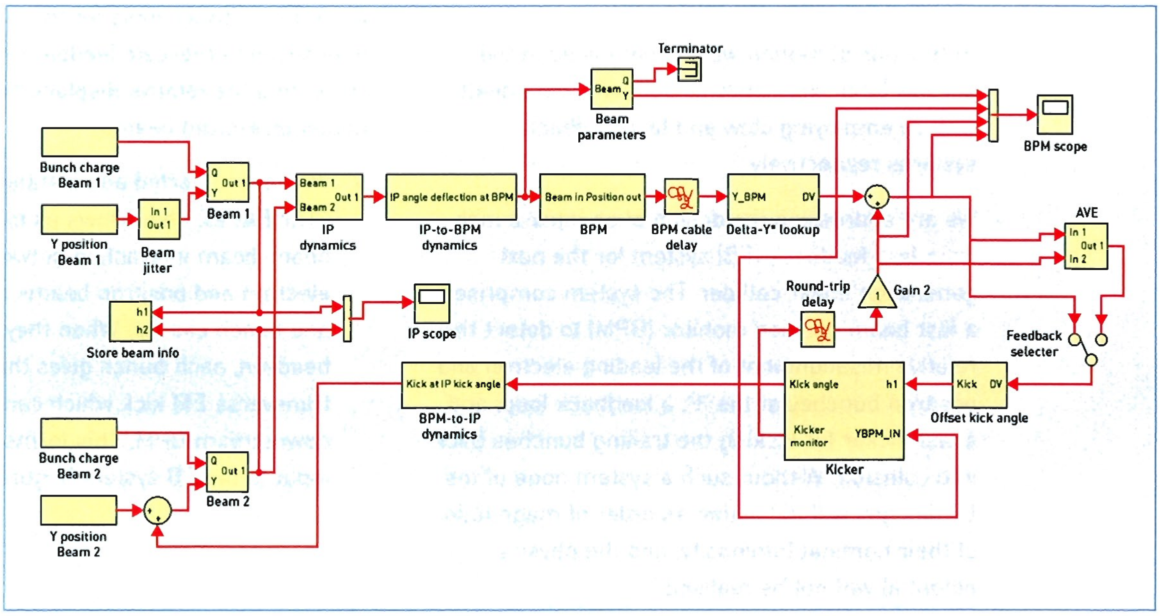


Figure 15: Schematic of the NLC FB system embedded in MATLAB.

3.5.3 Hardware prototyping and beam tests

As a result of these simulation studies we have developed a detailed understanding of the critical performance issues required of the FB system. We have been pursuing, in parallel, the design of prototype hardware components for a beam test at the NLC Test Accelerator (NLCTA), at SLAC. NLCTA can be operated in a 'long-pulse' mode, which provides a train of bunches filled at X-band frequency, 11.4 GHz, typically of 120 ns (but up to 250 ns) duration. This train length is within a factor of two of JLC/NLC and CLIC requirements, and the total train charge is comparable.

At NLC we are using a dipole magnet to perturb the whole train, a fast BPM to monitor the displacement at a given point, an analogue FB circuit, and a kicker to attempt to correct the displacement as fast as possible. Figure 17 shows the dipole and kicker assembly, and Figure 18 the new X-band BPM that we have installed in the beamline. We are currently commissioning this system, and are fabricating a high-power amplifier to drive the kicker. All the hardware was in place by summer 2002. The first round experiment will aim to make a correction within about 30 ns.

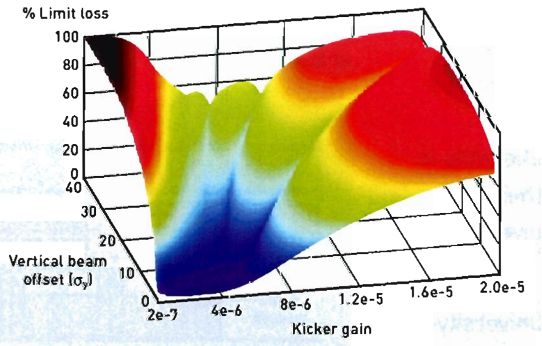


Figure 16: Simulated luminosity loss for NLC, with feedback. The 'valleys' are a feature of the latency of the system.

Without pre-empting the results of these tests, it is possible to envisage an extended R&D programme for investigation of a number of issues germane to the real FB system

- Testing of improved analogue processing algorithms.
- Handing of correlated 'jitter' within the bunch train, e.g. sinusoidal or other transverse position oscillations.
- Dynamic gain choice, either from adaptive learning or using *a priori* information from upstream systems.
- Interplay between position-correction and angle-correction; here we have addressed only the former.
- Correction in both planes: dealing with transverse beam coupling.
- Dealing with bunch tails in highly non-Gaussian (i.e. realistic) bunches.
- Upgrade to digital technology as signal processing speed improves.

Some of these could be carried out at the NLCTA, and/or at other facilities such as TTF at DESY, or CTF3 which is under construction at CERN. We shall consider an extended R&D programme at these facilities in the light of our experience with FONT In parallel we are continuing with our simulation studies. We are already collaborating with D Schulte (CERN), N Walker (DESY) and G Blair (RHUL) on the simulation of wakefield-induced beam tails (the 'banana' effect) and their impact on the beam-beam interaction, the design and operation of the FB system and production of background particles.

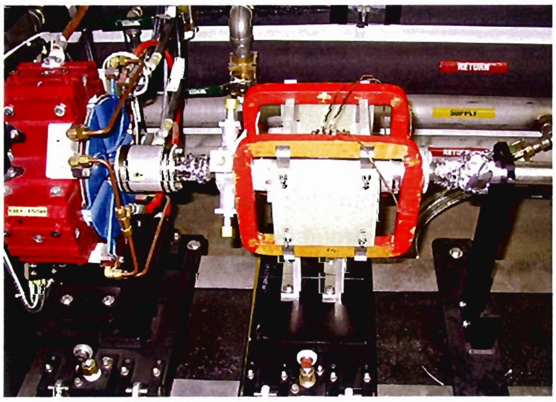


Figure 17: Dipole and kicker installation on the NLCTA beam line.

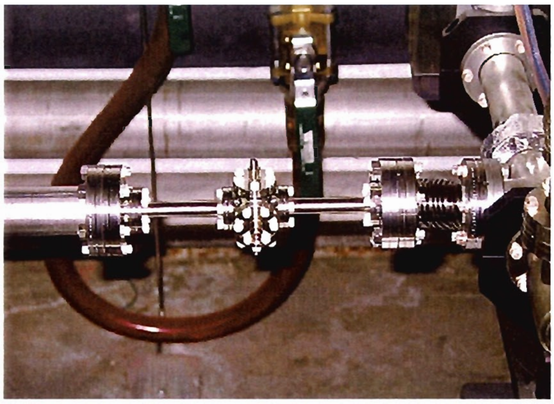


Figure 18: New X-band 'button' type BPM fabricated for the NLCTA experiment.

3.6 Collimator Wakefield Experiment

A.McKemey and D.Onoprienko (Brunel) in collaboration with SLAC

In linear colliders, mechanical collimators are used to remove large-amplitude particles from the beam and to protect downstream components from particle bunches that follow unsafe trajectories. In order to accomplish these goals, the collimators must be positioned very close to the beam; as a result, the electromagnetic field of the beam interacts with the collimator material. The altered field acts back on the beam and may destroy its quality. Accurate prediction of such self induced wakefields and their effects on the machine luminosity is therefore critical for the design of a high performance linear collider. However, present understanding of collimator wakefields is not adequate for reliable prediction of their impact on the beam dynamics for any given collimator design.

In order to address this issue, Brunel University and the Stanford Linear Accelerator Centre NLC group are working on a project aimed at studying short range collimator wakefields, and developing methods for their accurate analytical description and numerical simulation.

In order to address the absence of reliable experimental data, we designed, constructed, and installed a test facility at the SLAC linear accelerator (Figures 19 and 20) that allows for precise measurement of wakefields of different types of collimators. In the first two sets of measurements, we studied geometric wakefields due to changes in the beam pipe cross section, and resistive wakefields due to ohmic losses resulting from the finite conductivity of the collimator material.

At Brunel University, a collimator wakefield numerical simulation code, based on the FDTD method, is being developed. After being tested by comparison with the experimental data (Figure 20), the code will be used for studying the collimator design options proposed for the future linear collider.

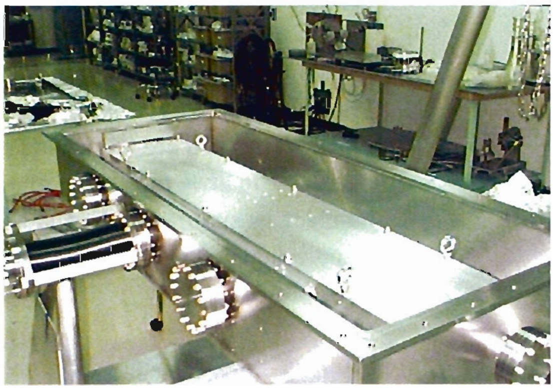


Figure 19: The collimator vessel prior to its installation at SLAC.

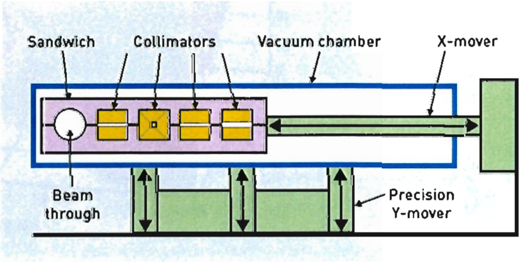


Figure 20: Schematic of the collimator wakefield apparatus.

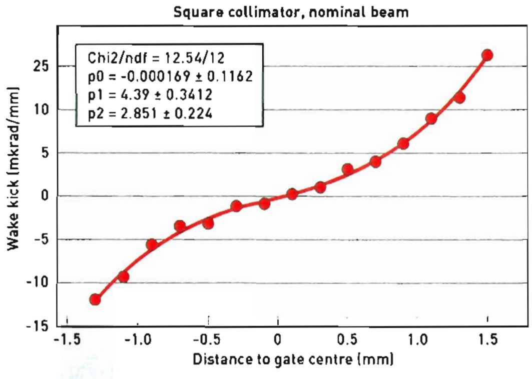


Fig 21. An example of the measured angular deflection of the beam by the wakefield as a function of the distance from the collimator gate centre.

References

[1] TESLA Technical Design Report 2001 (DESY Report 2001-011)

4

Accelerator Studies for Neutrino Factory

4.1 Proton driver design

G.H.Rees and C.R.Prior (ISIS Dept, CCLRC RAL)

4.1.1 Introduction

The ISIS Accelerator group has been investigating a possible design for the Proton Driver of the Neutrino Factory which could be built at the Rutherford Appleton Laboratory. In parallel, similar studies have been undertaken in the context of a CERN design. These designs, outlined below, provide for 4 MW of beam power at a number of different energies, and are based either on combinations of Rapid Cycling Synchrotrons (RCS) or on a full energy linear accelerator feeding accumulator and compressor rings. In all cases, the design has focused on the provision of very short (~1 ns duration) intense proton pulses on the target.

4.1.2 RCS Design Studies

An economical means of accelerating particles to high energy is through the use of synchrotrons, provided sufficient RF power can be provided in the acceleration phase. Two sets of design parameters have been developed for the synchrotron options. One at 5 GeV, operating at 50 Hz and the other at 15 GeV and 25 Hz operation. A beam of negative hydrogen ions from a low energy linear accelerator is conventionally injected into a rapid cycling synchrotron (RCS) using foil stripping. The low energy accelerator is common to all RCS options. To accumulate the desired intensity and to compress the beam to a narrow pulse demands the use of separate synchrotrons since these functions cannot be optimised simultaneously.

4.1.3 Low Energy H$^-$ Linac

The low energy negative hydrogen linac is adopted from the European Spallation Source (ESS) study, but extended to an energy of 180 MeV (Figure 22). This energy is sufficient to allow for reasonable space charge forces and small bunch lengths to be used for injection from the linac. An ion source delivering of the order of 57 mA is required, operating with a duty cycle of 2% and with a chopping duty cycle of 60-70%. The beam is first accelerated by a four rod RFQ, the design of which is a development of the ISIS 202.5 MHz RFQ currently undergoing commissioning.

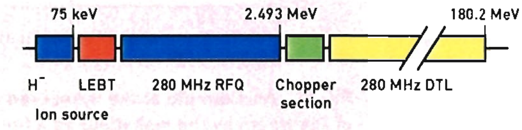


Figure 22: Schematic of the injector linac, common to both RCS studies.

The H- beam from the RFQ is chopped before further acceleration. Chopping is required to avoid beam loss during the injection of the beam into the first synchrotron. Chopping is achieved by a pair of travelling wave electrodes which deflect the beam on to collector plates. This requires exacting specifications on the rise and fall times of the deflecting fields. The chopper is combined with beam elements and bunching cavities which provide matching of the beam into the drift tube linac (DTL), an Alvarez type, extended from the ESS design by the addition of further accelerating structures to take the beam to an energy of 180.2 MeV. A small radial beam size is maintained in the structure, allowing space for electromagnetic quadrupoles.

Following the DTL the beam is transferred to be accumulated in the first ring. A beam transfer line which joins the linac and booster rings has an initial focussing section, an intermediate achromatic bending region and a final section with vertical beam separation and output matching for the rings. The initial region provides transverse matching and horizontal betatron collimation, followed by debunching and momentum spread reduction; the intermediate region has momentum and vertical betatron collimation, and the final region includes vertical beam separation, momentum ramping and beam size control at the injection stripping foils.

4.1.4 5 GeV, 50 Hz Study

Beam from the linear accelerator is injected into two 50 Hz 1.2 GeV synchrotrons, operating almost in phase, with the rings stacked one over the other, as shown in Figure 23. The synchrotrons have a circumference of the order of 200 m. The synchrotrons accelerate the beam with a peak rf voltage of 0.25 MV at second harmonic (h=2) of the revolution frequency. This generates two bunches per ring which are extracted sequentially and injected in alternate cycles into a pair of 5 GeV synchrotrons operating at 25 Hz and the eighth harmonic. The 5 GeV rings are also vertically stacked, and contain 4 bunches each. The beam is accelerated to 5 GeV with maximum voltages of 0.575 MV. In the final stages of the acceleration process, the beam is compressed in time by the addition of the h=24 harmonic, and an extra 0.5 MV of RF field. The combined output of the latter two rings is (on target) 5 GeV at 50 Hz.

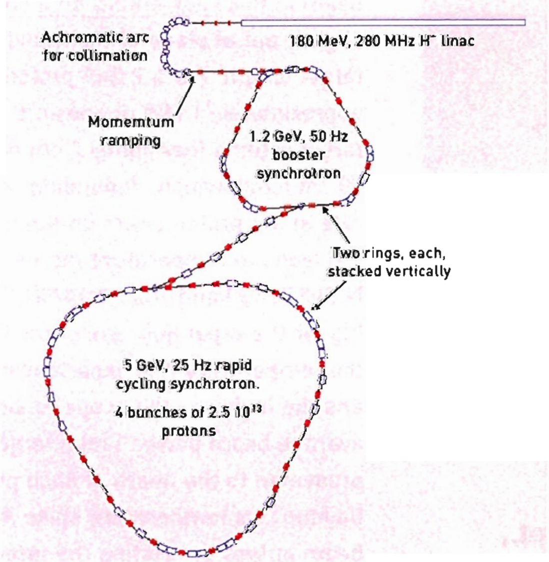


Figure 23: Schematic of the 5 GeV, 50 Hz RCS Design.

4.1.5 15 GeV, 25 Hz Study

To achieve a higher energy, a scheme similar to the 5 GeV study is adopted at half the repetition rate, as shown in Figure 24. Beam is injected into the first pair of rings which accelerate the beam to 3 GeV (h=3), and are transferred in alternate cycles to one or other of the 15 GeV rings operating at a frequency of 25 Hz (h=36). The 15 GeV rings accelerate the beam at a repetition rate of 12.5 Hz, and the combined output delivers beam to the target at 25 Hz.

The operation of this machine is similar to the 5 GeV, design where compression is achieved by a natural adiabatic compression of the bunch. This design can be upgraded to 5MW.

4.1.6 Other studies

The design options described above for synchrotron based driver accelerators cover an energy range between 5 and 15 GeV. Additional designs of rings have been made in collaboration with CERN at energies of 2.2 GeV and at 25 GeV (8 Hz RCS). The former relies on a proposed full energy linear accelerator, the superconducting proton linac (SPL) and provides one ring for accumulation and one for bunch compression. The 25 GeV design is a similar scheme to that described for the 15 GeV study, combining the 180 MeV linac described above, a 2.2 GeV 50 Hz synchrotron and a 25-30 GeV ring cycling at 8.33 Hz, and containing eight bunches.

Further studies have included lattices for an 8 GeV proton driver which could be injected from ISIS, and a 30 GeV driver designed to fit in the CERN ISR tunnel.

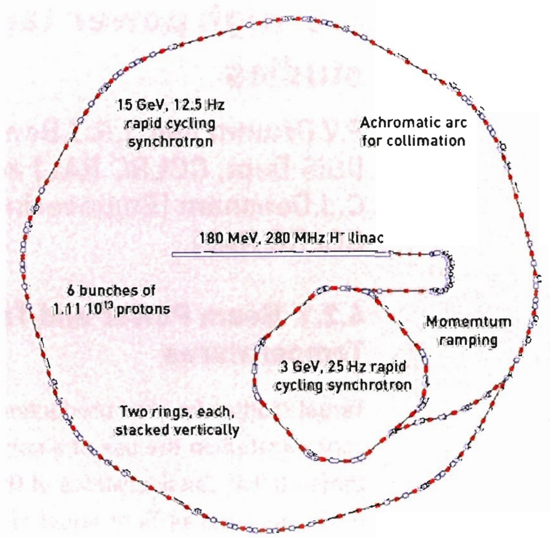


Figure 24: Layout of the 15 GeV, 25 Hz RC Design.

4.1.7 Muon front-end system

Work has begun on a study of the front end system which matches the initial π to μ decay channel to the muon linac used to accelerate the muons. Rather than use a linac phase-rotation system, the proposal is to correct for the large energy spread of the decay muons by sending them through a chicane of triplets of magnets (Figure 25). In this way the non-linearities in the subsequent acceleration are reduced.

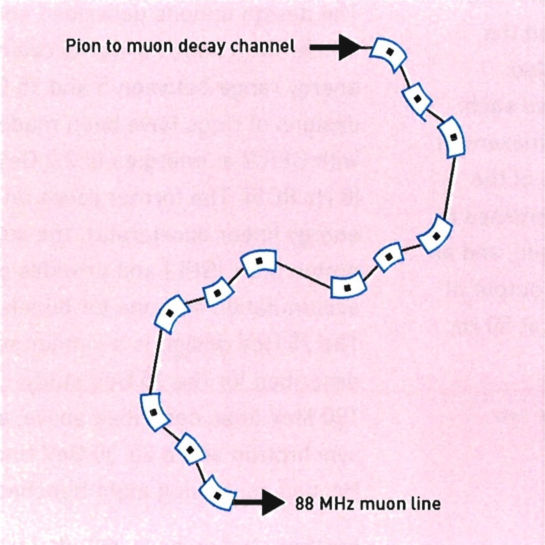


Figure 25: Schematic configuration of the bending magnet chicane.

4.2 High power target studies

P.V.Drumm and J.R.J.Bennett (ISIS Dept, CCLRC RAL) and C.J.Densham (Engineering Dept., CCLRC RAL)

4.2.1 Beam Power and Target Temperatures

Target studies for pion production have concentrated on the use of a solid heavy metal target. Initial considerations of the limitations of materials such as Ta or liquid-Hg to absorb high beam powers in small volumes and without direct cooling indicated a limitation of about 1 MW of power deposited in the target This corresponds to a beam power of about 4 MW at a few GeV, and is determined largely by material properties such as the melting point of solid targets or the boiling point of liquid jets. As well as the mean beam power deposited in the target, a key parameter for target design and the suitability of materials is the maximum power density per pulse. This is related to beam shape and size compared with the target size and the beam repetition rate. Our considerations have led us to adopt a radiation-cooled target as a means of dissipating large amounts of average power and sustaining large temperature rises from pulsed beams. It also provides an alternative study to a proposed water cooled rotating band target and to liquid metal jet targets. Such a target, for example in the form of a toroid (Figure 26), is made to rotate and can be many meters in circumference providing a large volume with which to absorb the deposited beam power. The beam in this case enters on a tangent and is slightly out of plane of the toroid so as to limit the target length. For a 2 GeV proton beam, approximately 1 MW of power is deposited in the target volume (nominally 2 cm diameter and 20 cm long), which, depending on the repetition rate of the proton beam (in the limits of 15-100 Hz) leads to temperature increases per pulse of between 400 and 1000 degrees C. Clearly, the higher the repetition rate of the beam, the lower the temperature rise experienced by the target, and the higher is the scope to increase the average beam power. Fresh target material is presented to the beam at each pulse to avoid the buildup of a temperature spike from adjacent beam pulses by rotating the target toroid. The minimum speed of rotation is determined by the target length and the repetition rate, typically this might be at least 10 m/s (e.g. for a 20 cm long target operated at 50 Hz). The circumference of the ring and the ring velocity dictate the cooling time for the material between pulses, and also determines the average power that can be dissipated. For example, at the extreme repetition rates of the proton beam, say 10 and 100 Hz, a 20 m circumference toroid would have to rotate

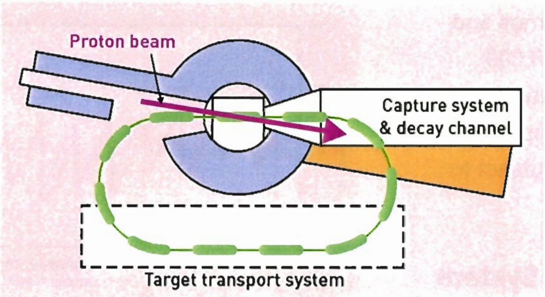


Figure 26: A schematic of the target transport system.

once every 10s and 1s respectively so as to present fresh target material to the next proton pulse. The amount of energy absorbed at each pulse is very different (by a factor of 10) but the average power will be the same. Since radiation is being used to cool the target, a high final temperature will be reached in both cases to benefit from the T^4 cooling law, albeit with very different variations in temperature with time. A toroid of twice the circumference can be rotated at the same minimum speeds, and thus obviously offers the possibility to dissipate twice the average power.

4.2.2 Beam Energy, Pion Production and Target Energy Density

Calculations of the production of pions as a function of beam energy for graphite and tantalum targets clearly show that energies of a few GeV are optimal from the point of view of power efficiency (4-5 GeV for a Ta target). Interestingly, graphite, although with a lower production, is dominated by the production of π^+ at low beam energies.

Consideration must also be given to the peak energy deposition as a function of beam energy. Although per proton this increases with energy, when normalised to the beam power the inverse is true, and the conclusion is that from the point of view of the energy absorbed by the target per MW of beam power, that a higher beam energy is better: the peak power in the target decreases and the uniformity of the energy deposition improves. For example, at 1-2 GeV approximately 25% of the beam's energy is deposited in a 20 cm long target, while at 20 GeV, it is closer to 10%.

4.2.3 Target Stress Issues

During the impact of the beam, the target material is heated. If this were done slowly, the target volume would expand. Since the heating is effectively instantaneous, the beam deposition, through the elevated temperature, exerts a compressive stress in the body of the target material. The response of the material to this stress impulse is to eventually relax, but initially, the stress propagates at the speed of sound and has a wave like behaviour. Finite element calculations of the shock waves generated in the proposed target ring have shown that the expected magnitude of the stress waves are comparable with the calculated stresses generated in the existing FNAL antiproton source (p-bar) targets. While this is encouraging, a difference in the construction of these targets makes a strong conclusion difficult. However, it seems reasonable to make an initial conclusion that a pulsed power density of 100 J/g that would be generated by a deposited power of 1 MW at 10 Hz on target is possibly over-ambitious, or would give a very short target life. On the other hand, a 1 MW load at 50 Hz generating a power density of 20 J/g per pulse is probably feasible. Further work is needed to optimise the choice of material and geometry.

It is important that information be gained about the behaviour of materials under beam induced shock conditions. To this end a programme of electron-beam testing has been started which should allow some lifetime and material strength information to be obtained. Samples of thin Tantalum foil have been subjected to intense high power electron beams where the power deposition per unit volume is sufficient to generate shock stresses in the range expected at the NF. The layout of the experiment is shown in Figures 27 and 28. An intense high power electron beam (from a welding machine) is scanned at high speed across the foils to generate the shock wave. The temperature of the foils as a function of time can be recorded with a multiscaling spectrometer (Figure 29). Initial measurements have been encouraging. The foils were subjected to high temperature jumps and high energy density cycling for about 10,000 cycles with a 60kW beam. Longer duration tests are soon to be carried out: with the e-beam scanning at 100 Hz, a sample can be subject to 10^6 cycles in less than 3 hours.

4.2.4 Inductive Lift and Drive System

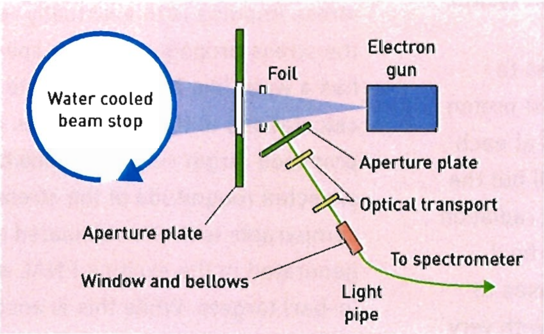


Figure 27: Plan view of the electron beam experiment. The experiment is contained in the large vacuum chamber of a welding machine.

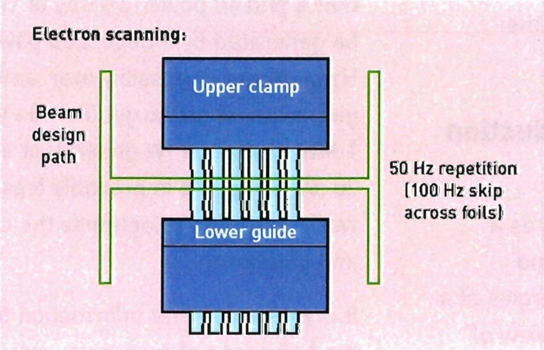


Figure 28: Front view of the foil samples showing the scan pattern of the electron beam on the tensioned foil samples. The deflection of the electron beam is controlled to generate a fast sweep across the samples every 10ms.

Since the target is to be held at an elevated temperature, mechanical means of supporting the target may not be successful. In this case, a magnetically driven levitation and drive system has been considered.

Levitation System

A simple model of the levitation system can be viewed as a pair of conducting loops set one above the other The lower is a fixed current carrying loop and the upper the target toroid. By flowing an AC current in the lower loop a voltage is induced in the target toroid which drives a current which then interacts with that in the driving loop. Although sufficient force can be generated to overcome gravity, the nature of the force is oscillatory and unstable to motion in the plane of the loops. Hence some form of damping and stabilisation needs to be considered. Calculations show that sufficient force can be obtained from a current of 3 kA at 100 Hz, dissipating approximately 50 kW/m of power. In turn, this generates a current of some kA in the target ring which leads to a heating load of 24 kW/m. It is envisaged that the driving ring would be water cooled, but that the power generated in the target ring would be a perturbation on the much larger beam power and be radiated away.

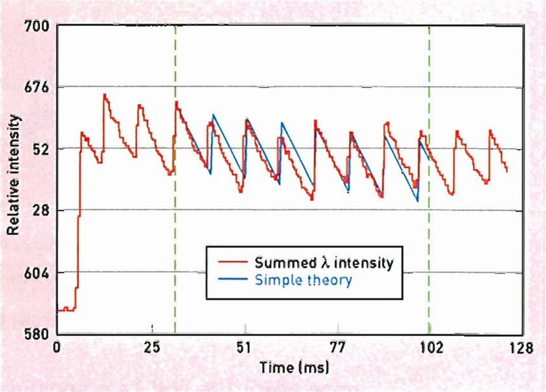


Figure 29: Spectrometer output for visible light as a function of time for data taken during the iniial tests. The relative variation in intensity is due to the impact of the electron beam heating the foil and the foil radiating the heat away. A simple numerical model of this gives the results shown by the blue line.

Magnetic Induction Motor

A magnetic induction motor, consisting of fixed coils which generate a travelling sinusoidal magnetic field, can be used to generated forces that induce motion. Initial calculations show that some 150 kW are needed to power the motor with approximately 15 kW dissipated in the target ring. In such a system, if the target motion is frictionless (because the device is in a vacuum), the force exerted by the drive system falls as the target ring accelerates to meet the speed of the driving wave. The presence of the 20 T capture solenoid through which the target ring has to thread presents an effective brake on the target ring which is likely to keep the drive current high. Eddy current losses in the target ring as it enters and leaves the capture solenoid are estimated at some 20 kW. These eddy currents are induced in the target ring and cause radial constriction and longitudinal compressive forces as the target leaves and enters the solenoid, the radial forces being some three orders of magnitude above the longitudinal forces and cause stresses in the MPa range. More complete finite element calculations are now in progress to investigate these effects in detail.

A Possible Target System

A number of practical issues arise from the above model of a continuous toroid. The target is subject to fatigue from the stresses imparted by the pulsed proton beam. Should any section of the toroid be damaged, a rather lengthy process would need to be undertaken to replace the target. However, this model of the target is useful for calculation. A more practical approach, using discrete shaped targets (to reduce stress) allows sections of the target to be replaced on-line. It is still possible to use the levitation and magnetic drive system in this case. The threading of the target through the shielding, capture system and so on is also simplified. Indeed, the path of the target no longer needs to be constrained to a circular track, and can be better integrated into the target environment. Automated checking of the discrete targets would be possible, with robotic exchange and monitoring.

4.2.5 Conclusion

Radiation cooling presents a feasible method of handling high average and peak powers for the neutrino factory targets. The major uncertainty is the effect of the repetitive beam induced shock on the target integrity, and this will require experiments to understand and evaluate, although it is encouraging that existing targets currently operate at, and survive comparable energy densities. The electron beam experiments will provide valuable information on cycle lifetime, information that is unlikely to be obtained in any other way. The use of discrete targets (as opposed to a continuous ring) is a preferred path since it removes the danger of a catastrophic failure, and allows the target state to be monitored and controlled.

The initial outline of the levitation and drive system for the target shows that the power levels required are at least an order of magnitude below the power deposited by the proton beam, both from the point of view of the drive and the eddy current generation. Stability issues and the presence of the high field solenoid indicate the importance of a demonstration device.

4.3 The HARP experiment

T.R.Edgecock, M.Ellis, S. Robbins and P.Soler (PPD, CCLRC RAL), C.N.Booth, C.M.Buttar, P. Hodgson, L.Howlett and R.Nicholson (Sheffield), G.Barr, A. de Santos and K.Zuber (Oxford), together with an international collaboration.

4.3.1 Introduction

The primary aim of HARP is the measurement of the differential cross-sections for pion, proton and kaon production in a number of targets, both solid and liquid. These measurements will be of importance in three main areas: (1) the neutrino factory target, (2) the systematic error on the atmospheric neutrino flux and (3) hadron production models such as GEANT4 [1], FLUKA [2] and MARS [3]. In the case of the Neutrino Factory the HARP results will allow the target material and the proton beam energy to be optimised for pion production. HARP will also measure pion production rates for the K2K [4], MiniBooNE [5] and Karmen [6] experiments.

4.3.2 The Experiment

The two most important requirements for the HARP detector are a very high acceptance for charged tracks and a very good particle identification efficiency. The detector designed to achieve these requirements is shown schematically in figure 30.

The most upstream part of HARP is a TPC with an active volume of radius 42 cm and length 150 cm. This is surrounded by solenoid with a 0.7 T field. The targets for the experiment are inserted 50 cm into the active volume and are surrounded by a trigger counter. At the outer circumference of the TPC are RPCs for time-of-flight (TOF) measurements. The TPC provides good tracking, momentum measurement and particle identification by dE/dx for low momentum, high angle tracks. In addition, the RPC TOF is used for separating pions and electrons at low momentum.

Downstream of the TPC is a spectrometer built from a 0.5 T dipole magnet sandwiched between two modules built from NOMAD drift chambers[7]. This provides tracking and momentum measurement for the small angle, high momentum tracks that miss the TPC. The spectrometer is followed by a threshold gas Cherenkov, which gives identification for pions at momenta above 3 GeV/c. At momenta below this, particle identification comes from a time-of-flight wall placed downsteam of the Cherenkov. This is constructed from three overlapping modules consisting of 39 scintillator panels, each with a time resolution of 250 ps. The Cherenkov and the TOF wall are the only two completely new detectors in HARP.

The next component of the detector is an electron identifier. The first part of this is a 2 cm thick passive absorber to convert γs from π^0 decays to e^+e^- pairs to allow identification of the π^0. This is followed by a detector wall made from three overlapping NOMAD chambers, one plane of CHORUS electromagnetic calorimeter modules and one plane of CHORUS hadronic calorimeter modules [8].

The most downstream component is a beam muon identifier. This uses the Aleph hadron calorimeter test module [9], which is 140 cm wide, 6 interaction lengths deep and consists of alternate planes of iron and scintillator There is

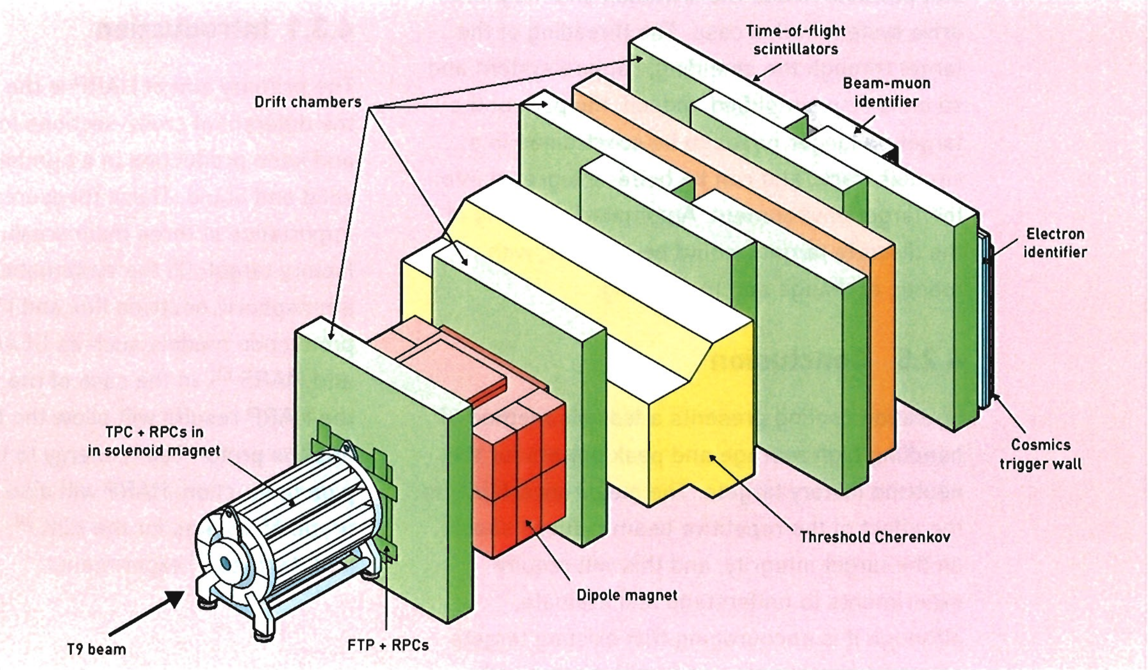


Figure 30: A schematic layout of the HARP detector, showing the TPC and RPCs in a solenoid magnet, four planes of drift chambers, the spectrometer magnet, a Cherenkov detector, a time-of-flight wall and a small part of the electron identifier.

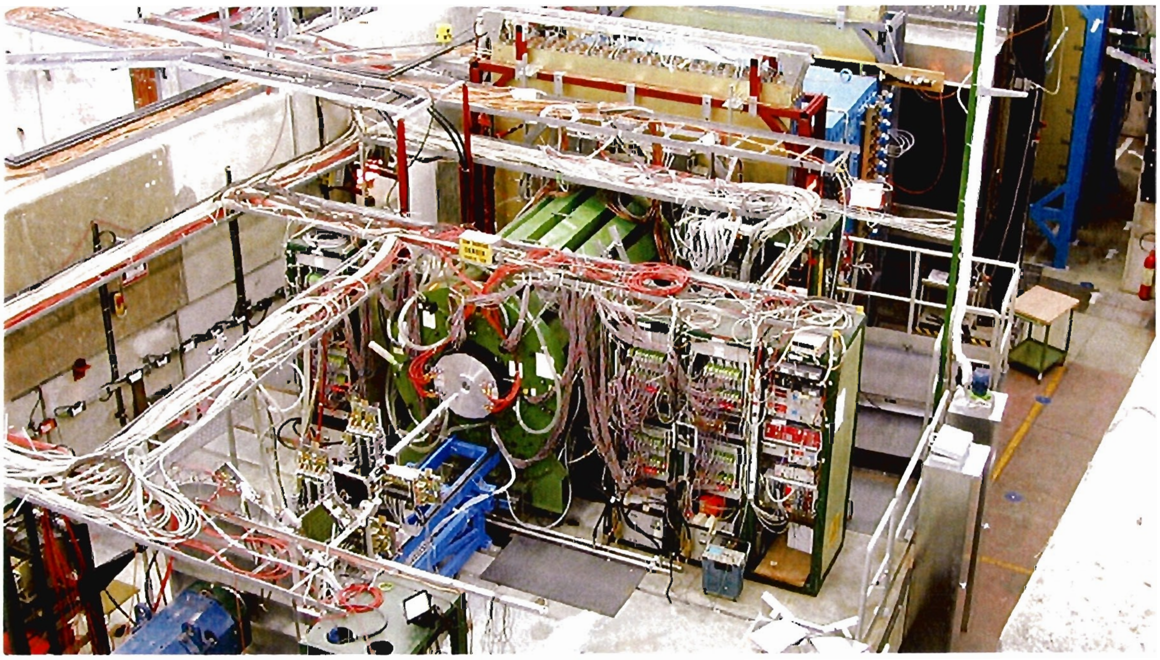


Figure 31: Photograph of HARP at the start of the running in 2001.

a 32 cm thick passive Fe wall in front of this module.

In addition to the above, there are several detectors in the beam, upstream of the TPC. In particular, there are beam Cherenkov and TOF counters for particle identification and five MWPCs to measure precisely the position and direction of the incoming particles. The last of the MWPCs is mounted on the same structure as supports the targets in the TPC.

Data-taking so far

So far, HARP has had two technical runs, the first from 25th September to 25th October 2000 and the second during April 2001. The first real data-taking run with the complete detector started in the second week of August 2001 and lasted for three months. Figure 31 shows the HARP experiment at the start of April 2001. During the three months of data-taking in the second half of 2001, a total of 27M physics triggers were recorded, under 37 different conditions of beam momentum and polarity and target type and thickness. These are data are currently being analysed and the contributions of the UK members of HARP to this are outlined below.

UK Contributions

During the construction of HARP, the UK provided all the solid targets, as listed in table 1, and the mechanism for supporting them in the TPC and changing them quickly. These targets had to be pure enough and their properties well enough known to make a contribution to the experimental systematics which is negligible at the level of 2%, the expected precision on the measured total cross-sections.

Material	Thin targets (cm)		Thick target (cm)
Solid			
Be	0.81	2.025	40.50
C	0.76	1.900	38.00
Al	0.79	1.975	
Cu	0.30	0.750	14.00
Sn	0.45	1.125	
Ta	0.22	0.550	11.14
Pb	0.34	0.850	17.05
Special			
Structured target (Cu)	≤1.5		
Skew target (Cu)	0.79		

Table 1: HARP targets provided by the UK.

The target insertion mechanism is the blue structure sitting in front of the green TPC solenoid in figure 31. As well as inserting the targets into the TPC, this is also used for inserting the inner trigger counter and the TPC itself into the solenoid. The final trigger counters and beam chambers supported by this structure can also be seen in the figure. The targets themselves are mounted on the aluminium pole pointing towards the TPC.

As far as software and analysis are concerned, a member of the UK groups is responsible for the reconstruction program and has written a track finding algorithm for the drift chambers.

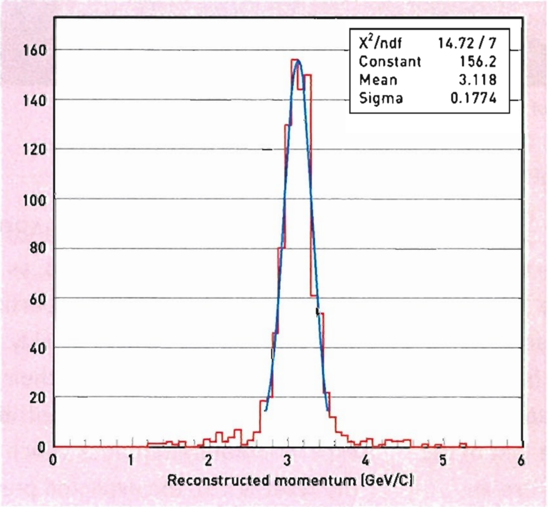


Figure 32: Momentum distribution of 3 GeV tracks reconstructed by the forward spectrometer.

Figure 32 shows the measured momentum of 3 GeV beam particles that have not interacted by the forward spectrometer using this track fitting algorithm. The resolution achieved is about 5%.

In addition, contributions are being made to the reconstruction code for the beam MWPCs and to the tracking finding code in the TPC. The performance of the latter is also being studied using cosmic ray events and this is forming a valuable contribution to the initial attempts to analyse the so-called wide-angle data. As an example of this work, figure 33 shows the position along the beam direction of tracks found in the TPC and extrapolated back to the beamline.

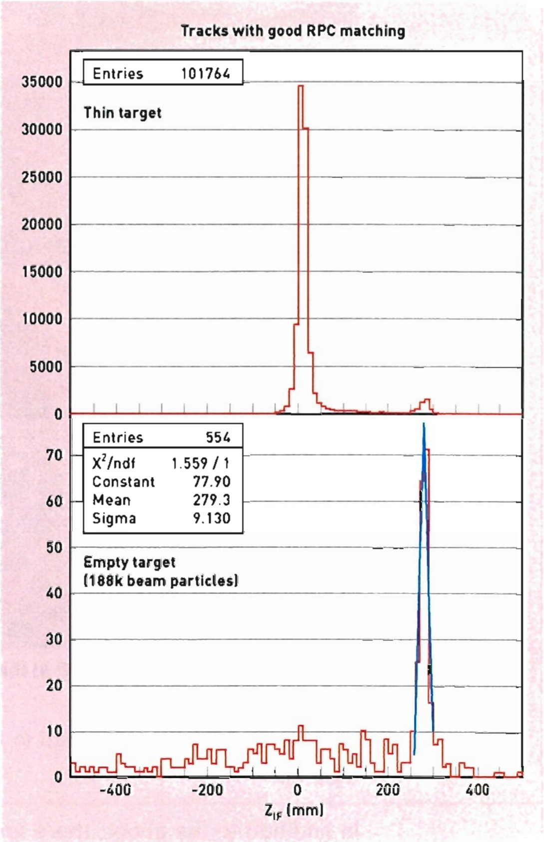


Figure 33: z-position of the extrapolation of reconstructed TPC tracks to the beamline. The position of a "thin" target is clearly visible (upper plot), in contrast to "no-target" data (lower plot). The second peak corresponds to the position of a 2mm thick stesalite wall that forms the end of the slot in the TPC into which the target is inserted.

Finally, work has recently started on the reconstruction code for the RPCs.

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4.4 The MuScat experiment

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4.4.1 Introduction

A vital requirement of the neutrino factory accelerator complex is the ability to cool the muons in the transverse plane. Without this, the neutrino intensity will be reduced by a factor of about 10 [1]. Due to the muon lifetime, such cooling needs to be fast and the currently prefered technique is ionisation cooling [2]. In the case of the transverse cooling required for a neutrino factory, this involves passing the muons through an absorber in which they lose both longitudinal and transverse momentum. The lost longitudinal momentum is then restored using rf cavities following the absorber.

As well as a cooling effect coming from the ionisation energy loss, there is heating coming from multiple scattering and the final cooling achieved is a balance between these. Theory suggests this balance is most favourable for elements with low atomic number, in particular, liquid hydrogen [3]. However, an extensive literature search has failed to find any measurements of the muon scattering distribution in light elements [4]. The most relevant data found comes from the scattering of 2.7 MeV/c electrons on Al, Be and Li [5]. These data show a clear trend: as Z decreases, the agreement with Moliere theory [6] gets worse. If this trend continues to hydrogen, there will be two effects:

- The level of cooling achieved would be less than expected.
- Due to the increased scattering in the tails, the fraction of muons scattered out of the cooling channel could be much bigger than expected.

Due to the importance of this to ionisation cooling, the MuScat experiment has been created to measure the scattering of muons of various momenta in a number of low atomic number materials, in particular liquid hydrogen. As well as checking these observations, MuScat will compare a range of muon scattering models with the data.

A four week test period was allocated to the MuScat experiment in the M11 beamline at TRIUMF in June and July 2000. The following sections will describe the experiment and show what was learnt about it during the run. The plans for a further run in 2002/3 will also be outlined.

4.4.2 The Experiment

As the aim of the experiment is to make a precise measurement of the multiple scattering of muons, the amount of material that the muons must pass through has to be kept to a minimum. For this reason, it is not possible to do any tracking before the target and a collimation system must be employed to reduce the beam dimensions so that the incoming particle position is known accurately enough. In addition, the measurement of the position of the scattered muon relies on the first tracking detector as all subsequent detectors will be effected by scattering in the first. Any additional detectors can only be used to aid in noise rejection and for checking systematics. To minimise scattering in air, as much of the experiment as possible must be mounted in vacuum. Finally, to eliminate particles other than muons, a good time-of-flight system is required.

The detector designed to satisfy these requirements and used in the M11 beam is shown in figure 34. The most upstream parts are a veto shield and veto scintillator to eliminate beam halo. These are followed by the first trigger counter, which also acts as the TOF start, built from two fingers of scintillator, each 1 mm thick, 28 mm long and 3 mm high. These overlap by 20 mm in length and 3 mm in height. The timing resolution is about 250 ps. The TOF stop comes from the following RF-bucket of the TRIUMF cyclotron. This is almost a square-wave of length 1.9 ns, the smearing of the edges corresponding to a resolution of about 500 ps.

The trigger scintillator is followed by a 1 m long vacuum tube containing the collimation system. This consists of a 40 mm thick lead block at the front and a 160 mm lead block at the back, plus 4 intermediate blocks each 10 mm thick. The first block has a slit 20mm long by 2 mm high cut in it, while the slot in the second block is tapered to prevent large angle scatters off the internal face. With this arrangement, the scattering distribution is measured vertically, in the narrow direction of the slot. The second dimension is longer to increase the particle intensity.

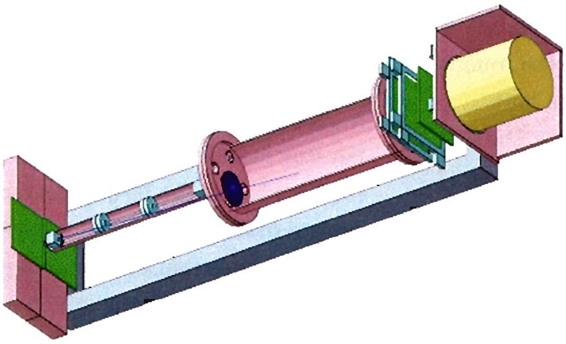

Figure 34: Schematic layout of the MuScat experiment.

The vacuum tube is connected to the main vacuum vessel. The nine targets used in the 2000 run are mounted on a wheel in this vessel, as close to the collimation system as possible. They are:

- Lithium, 10 mm and 2.5 mm thick
- Beryllium, 2 mm and 0.5 mm thick
- Carbon, 2.5 mm thick
- Aluminium, 1 mm thick
- CH2, 2 mm thick
- Iron, 0.15 mm and 2 mm thick.

The target wheel can be controlled from outside the vacuum so it is unnecessary to break this each time a target is changed. The wheel has 10 slots, the last of which has no target mounted and is used to measure the intrinsic properties of the beam. These are monitored on a regular basis.

The tracking detectors used in 2000 were delay-line chambers borrowed from TRIUMF. These are multi-wire proportional chambers with two 2 cathode planes and 1 anode plane. Each chamber gives 2-dimensional readout, but with better resolution from the cathode plane perpendicular to the anode plane, ~0.6 mm compared to 1-2 mm. Rather than each wire being readout, the number of electronics channels required are reduced by recording only two signals from each plane. These are time values, giving the position along the delay-line from which the signal originated. As shown in Figure 34, three of these chambers were used, each 300 mm by 300 mm in size. The most important of these was the first, which is orientated such that the dimension with the better resolution is vertical. It was approximately 1 m from the target wheel. Between the second and third chambers was the second trigger scintillator.

The final part of the detector is MINA, a NaI calorimeter of 360 mm diameter and 360 mm depth from TRIUMF [7]. It has a measured energy resolution (fwhm) of 5.2% at 90 MeV with an energy dependence of $E^{-0.55}$. It is used for both a muon energy measurement and additional pion/muon separation.

4.4.3 Technical Run

The performance of the detector from the technical run in 2000 is summarised in figures 35-37 The first shows the efficiency of the most upstream delay-line chamber as a function of horizontal and vertical position. This is clearly not uniform and would introduce large systematics on the scattering distribution. As a result, it has been concluded that these data cannot be used for the measurement and that new detectors are required for the future runs of the experiment.

Figure 36 shows the difference in time between the arrival of a particle in the TOF scintillator and the next RF beam pulse, in TDC counts, versus the signal in MINA at 180 MeV/c. Note that as the time difference is taken with respect to the next beam pulse, the particle velocity increases along the x-axis. There is a clear separation between the muons and the other particles.

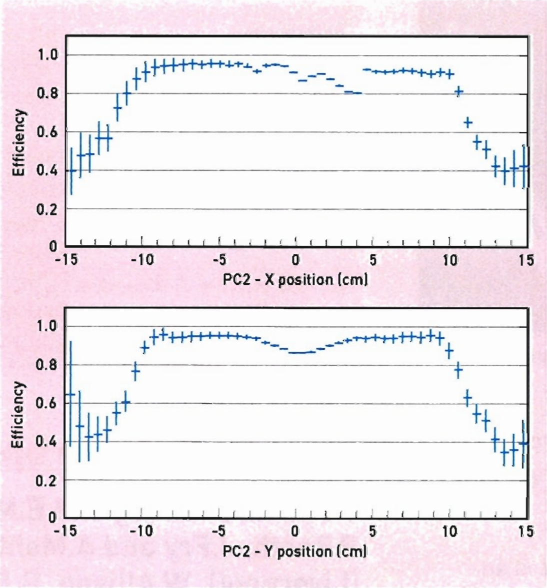

Figure 35: Efficiency of the most forward delay-line chamber as a function of X (horizontal position) and Y (vertical position).

Figure 37 shows a comparison between the distribution of hits in the most upstream delay-line chamber with no target with Monte Carlo expectations. Note that there is very good agreement, giving confidence that the collimation system is well understood.

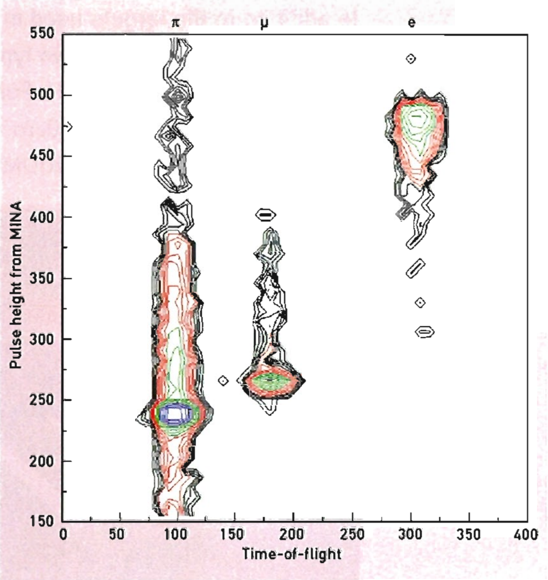

Figure 36: Measured time-of-flight at 180 MeV/c versus the signal from the MINA calorimeter. Note that the TOF gives a good separation between all the particle types and that further discrimination between muons and electrons is available via MINA.

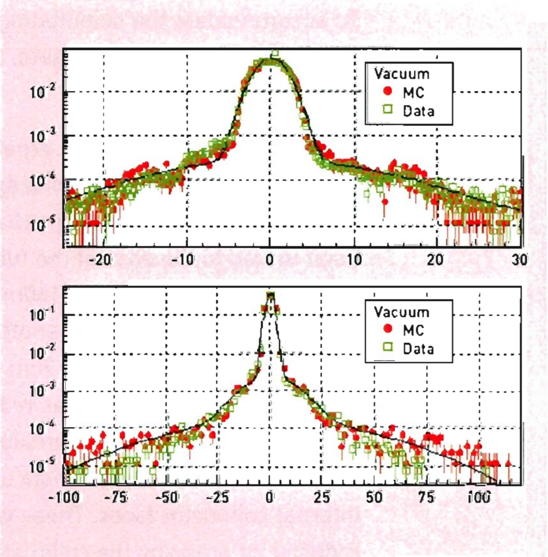

Figure 37: Vertical projection of particle distribution in the first delay-line chamber from both data and Monte Carlo, with no target. The lines are a fit using three Gaussians. The top plot shows the distribution over ±30mm, while shows it over ±100mm.

4.4.4 Improvements for the next run

Although most of the experiment worked well in 2000, it has been decided to make a number of improvements based on the experienced gained. The most significant of these is a new set of tracking detectors, this time using scintillating fibres. Each detector will consist of two offset planes of fibres in each dimension. They will have a number of advantages over the delay-line chambers used in 2000. In particular, they will have a position resolution of about 200μm in each plane and a uniform efficiency. In addition, it will be possible to use them inside the vacuum, thus eliminating any material between the target and the first detector

These detectors are shown under construction in figure 38.

In addition to the targets used in 2000, it is planned to study another two types in a further run: liquid hydrogen and LiH. For the former, two liquid hydrogen targets of 10cm and 15cm length have been constructed at TRIUMF.

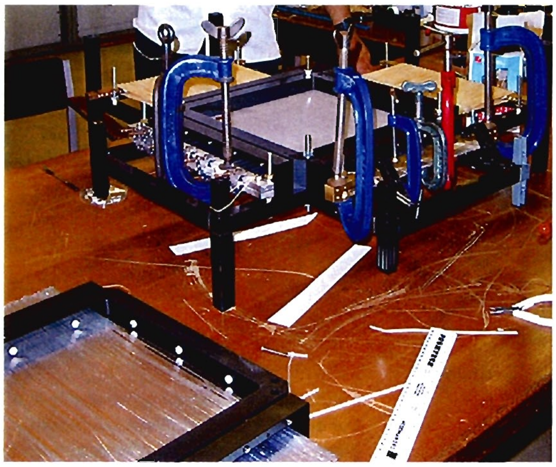

Figure 38: Two scintillating fibre detectors under construction at Imperial College.

To accommodate the scintillating fibre detectors and the liquid hydrogen targets, a new vacuum vessel has been built.

The final modification to the experiment is an improvement to the collimation system. In particular, the existing intermediate disks have been moved to the ends of the tube to increase the thickness of the 40mm and 160mm collimators. They have been replaced by another four disks, each 10mm thick but with a 2cm radius hole through the center. As well as reducing the penetration through the collimators, this will dramatically reduce large angle scatters off the internal collimator faces. These will further be reduced by wrapping the collimator with 6mm thick lead sheet and doubling the thickness of the front plate of the main vacuum vessel. Finally, thin scintillator rods will be placed above and below the front face of the 160mm collimator to create an "active collimator". This will eliminate particles which just clip this edge of the collimator.

4.4.5 Further data-taking

The construction of the new version of MuScat is almost complete. In particular, the new detectors exist and are currently being formed into a cosmic rig for further testing. Once this is done, the whole experiment will be tested in the HEP test beam. It is then planned to run the experiment in a Riken beam at RAL, to get collect data at a lower energy than is available at TRIUMF, before having a final run there using both solid and liquid hydrogen targets.

References

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4.5 The MICE proposal

P.Dornan, K.Long and E.McKigney (IC), P.Booth, J.Fry and A.Mehta (Liverpool), W.Allison, G.Barr, J.Cobb, S.Cooper, H.Jones, W.Lau, A.Weber and S.Yang (Oxford), E.Baynham, T.Bradshaw, I.Ivaniouchenkov and J.Lidbury (ED, RAL), D.Adams, P.Drumm, D.Findlay, I.Gardner, A.Morris and P.Wright (ISIS, RAL), R.Edgecock, M.Ellis, P.Norton and K.Peach (PPD, RAL), C.Booth, C.Buttar and P. Hodgson (Sheffield), together with an international collaboration.

4.5.1 Introduction

While the MuScat Experiment, described in section 4.4, is the first of R&D projects used to investigate the process of ionisation cooling, the Muon Ionisation Cooling Experiment (MICE) will be the last. It is being designed to show that cooling cells from a Neutrino Factory cooling channel will cool and to learn more about the cooling process itself. It will be a major project for the UK as it has been decided to locate it in the HEP Test Beam Hall at RAL and use ISIS to make the muon beam. We will, therefore, be responsible for providing the beam and the infrastructure of the experiment and some significant components of the experiment itself. As this will be the first real HEP accelerator project in the UK for nearly 30 years, we will also have to adapt to scientists from the US, Europe and Japan coming to RAL to work!

The following sections will describe MICE, the possible UK contributions, the work currently going on in this country and milestones for the experiment.

4.5.2 The Experiment

The aim of MICE is to take two SFOFO (solenoid plus focusing) cooling cells from US Study II, pass a muon beam through them and demonstrate that they cool. This will be done by placing instrumentation sections before and after the cooling cells to measure the parameters of the muons going into and coming out of the cells (see Figure 39). The cells themselves are most likely to contain liquid hydrogen absorbers, about 70-80 cm thick. These will cause a 200 MeV muon to lose about 20 MeV, corresponding to approximately 10% cooling. Thus the instrumentation sections will need to measure the emittance of the muons with a total precision, statistical plus systematic, of about 1%. This precision requirement will preclude the use of a bunched muon beam, as the highest precision emittance measurement obtained with such a beam is 10%. Instead, a beam with a single muon per few ns time period will be used and the muon bunch created offline in software. The large emittance of the "beam" will be created using lead diffusers placed upstream of the experiment.

As well as the liquid hydrogen absorbers, the cooling cells will contain two 4-cell RF cavities, which will be used to restore the lost 20 MeV. If sufficient RF-power could be found, these would be able to supply 32MV of acceleration on the peak. In practice, due to the cost, the RF power is likely to be limited so that only 23 MV can be provided. The remaining component of the cooling cells will be super-conducting coils, creating a magnetic field in the range 3-6T to produce a large divergence in the beam and hence minimise the effect of multiple scattering. Two types of coil are envisaged, focus coils sitting around the absorbers and coupling coils outside the RF-cavities.

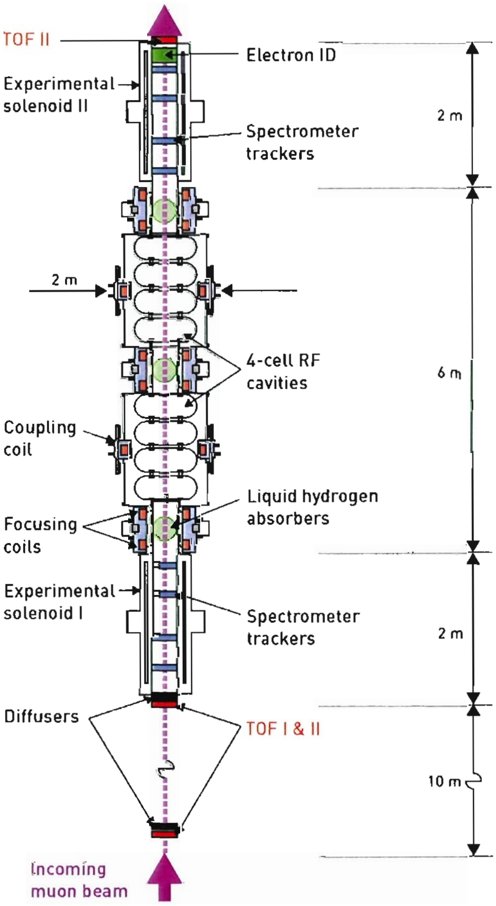


Figure 39: Schematic layout of the MICE experiment.

A number of different detector types are required for the instrumentation sections, to perform a number of different roles. The baseline tracking detectors are scintillating fibres very similar in principle to those used for MuScat. Four or five planes will be required both before and after the cooling cells. These will be inside super-conducting solenoids to allow the measurement of the muon momentum. A backup solution, using TPGs, Time Projection Chambers using GEMS, also exists.

In addition, a number of planes of high precision, ~50ps, time of flight counters are required both to determine the time of arrival of the muons with respect to the phase of the RF and also for background rejection. In the latter case, these will ensure that the particle entering the cooling cells is a muon. An electron identifier will be placed after the downstream instrumentation section so that muon decays within the experiment can be eliminated. This could be either a threshold Cherenkov or a sampling calorimeter.

Figure 40 shows the statistical resolution of both the 6-D and 4-D muon emittance measurement achieved using four scintillating fibre detectors as a function of the separation between the first and last detector. It can be seen that a precision of 1% and 0.5%, respectively, is obtained if this separation is greater than about 1m.

4.5.3 Likely UK Contributions

Beam and infrastructure: As the host laboratory for MICE, the UK will be responsible for providing both the beam and much of the infrastructure. The current plan is to modify the existing HEP test beam to provide the single particle muon beam. The main change will be the installation of a super-conducting decay solenoid, possibly borrowed from PSI. This allows a dramatic reduction in the background to the muons, mainly protons, pions and electrons, by selecting pions into the solenoid at one momentum and muons out at a lower momentum. In addition, it is envisaged to increase the muon production rate by collecting the pions produced in the test beam target at a smaller angle, 20-30° rather than 40°, and increasing the ISIS energy at which the production takes place, 800 MeV rather than 630 MeV.

The UK will also have to provide much of the infrastructure for MICE. In particular, cryogenics for the super-conducting magnets and liquid hydrogen, power and cooling for the RF-power supplies, magnets, detectors and electronics, the controls for the beam and experiment, some of the safety systems and possibly some of the RF-power sources. There will be a significant requirement for staff at CCLRC to achieve all these responsibilities.

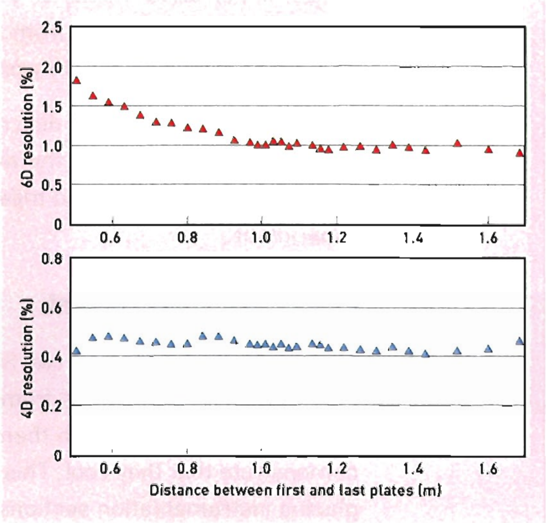


Figure 40: The resolution of the measurement of the 6-D (upper) and 4-D (lower) muon emittance as a function of the distance between the first and last scintillating fibre detectors.

Scintillating fibre detectors: These are the baseline tracking detectors for MICE. The current layout has four or five detectors in each instrumentation section, which each detector having three planes of fibres offset by 120°. Each plane will have two offset rows of 0.35mm or 0.5mm fibres in a similar arrangement to the MuScat detectors to give a uniform coverage. The readout of the detectors is still under consideration, but does not look to be a problem.

Super-conducting coils: The UK is fortunate in having two labs able to design and construct super-conducting coils and it is envisaged that we will provide at least one of the types required by MICE. At the moment, it is not decided whether this will be the focus coils or the coupling coils or even both.

Liquid hydrogen absorbers: Significant contributions have already been made to the design of the windows for the LH2 absorbers through 3-D Ansys simulations. It is planned to continue this work and perhaps also contribute to the hardware.

Software and simulations: Simulations of MICE have already been performed using the ICOOL programme and work has started on incorporating the scintillating fibre detectors in the general MICE Geant 4 simulation. It is planned to continue with both the Geant 4 work to understand the MICE systematics with scintillating fibres and with simulations of the cooling performance of the experiment to have a better understanding of its design. Contributions will also be made to the MICE reconstruction program.

4.5.4 Timescale

MICE has been asked to submit a proposal to RAL by the end of 2002. Once approved and funded, serious construction will start in 2003 with the aim of having the instrumentation sections on the floor at RAL in 2004/5. The first cooling cell will then be added in 2005/6 and the second in 2006/7. If everything goes to plan, the first phase of the experiment should be completed in 2007. It is possible there will be another phase, investigating ring cooling channels, at a later date.

5 Generic Technologies

5.1 Superconducting magnets

D.E.Baynham (Engineering Dept, CCLRC RAL) and colleagues

5.1.1 General

This status report relates to generic studies on superconducting magnets for Neutrino Factory and Muon Collider applications. The aim has been to evaluate the magnet technology requirements of these machines against existing magnet technology, in order to identify the feasibility and cost drivers of these machines. From this evaluation we have begun a programme of generic studies, modelling and experimental, which we believe will be necessary to realise reliable and cost-effective magnet designs. This report summarises the status of these studies and their future development.

5.1.2 Magnet Technology

Capture Magnet System

This capture system will present severe demands for the operation of the superconducting magnets at high field and in a high, pulsed radiation environment. We have begun studies of two design drivers, which could affect magnet performance:

(i) Thermal behaviour of the magnet in terms of overall heat load and localised transient heating

(ii) Long term radiation damage to magnet composite insulation materials. In superconducting magnets the structural integrity of the composite materials is essential for reliable operation since small conductor movements can lead to magnet quenches. A programme of theoretical studies combined with the development of practical materials characterisation tests has been defined and preliminary measurements of parameters such as "work of fracture" have been made. These need to verified and extended to irradiated and radiation hard materials formulations.

Muon Cooling Magnet Systems for Neutrino Factory

The muon-cooling channel for a neutrino factory will require several hundred super conducting solenoids integrated with a system of alternating liquid hydrogen absorbers and RF cavities. Typically, these magnets will be required to produce a field of 4T in a warm bore of more than 1m. Preliminary studies of magnet feasibility vs cost have been started in order to develop criteria for design optimisation and prototype fabrication.

In order to simplify the cryogenic and mechanical design of the magnet systems it will probably be necessary to utilise a design based on indirectly cooled magnet coils. While this technology has been applied to large detector magnets with generous operating margins its applicability to a muon cooling channel needs to be established. This will be one of the technical issues driving the cost of a muon cooling channel and the choice of design parameters i.e. on-axis field, magnet diameter, rf frequency, field reversal/forces and magnet protection.

Initial studies have shown that superconductor costs for a cooling channel will be strongly influenced by the choice of on-axis field, the corresponding peak field, at the superconductor and the operating temperature margin. For example in a magnet system designed to deliver a 4T field on axis with a 1.5K temperature margin the superconductor required will scale with peak field as: peak field 5T; sc 100%; peak field 6T; sc 179%; peak field 7.5T; sc 492%. This means that lumped coil periodic designs required for access for rf power and LHe absorber cooling could be very inefficient in terms of superconductor usage.

A preliminary evaluation of the impact of superconductor cost on overall system cost has begun, but it should be applied to a real cooling channel design in combination with magnet fabrication and protection studies. This will be a primary focus of the next design stage.

5.2 High brightness electron sources, RF and power supplies

A.D.R.Phelps (Strathclyde University) and colleagues

5.2.1 General

There are several areas of accelerator technology R&D in progress at UK universities and a few of these are highlighted here, including high brightness electron beam production (Strathclyde University), multi-beam klystrons and RF structures relevant to accelerators (Lancaster University), novel high power RF sources (Strathclyde University) and pulse power sources (Oxford University).

A very significant new development is the approval and implementation of a Faraday Partnership, formed in November 2001 and funded by the DTI and PPARC, in High Power RF Engineering. The partners are CCLRC, the universities of Lancaster, Oxford and Strathclyde, The Welding Institute and Capenhurst, with industrial partners Alan Dick & Co., Elekta, E2V (formerly Marconi Applied Technologies) and TMD Technologies. Further partners are anticipated. The area covered by the partnership includes the components and subsystems that are required to generate and apply High Power RF and all applications that make use of these components and subsystems. The total funds earmarked by PPARC are £1M.

5.2.2 High brightness electron beam production

High brightness electron beams are needed for several applications. It is possible to reduce the emittance of an electron beam while it is propagating through an accelerator but this requires considerable technological effort. A complementary approach is to produce a very low emittance, high-current electron beam at the outset from the electron gun. Photocathode electron guns are capable of producing low emittance beams but involve high power laser systems and typically can cost £Ms. The low cost and very effective alternative approach being developed at Strathclyde University (Prof A Phelps) employs a pseudospark discharge (Figure 41). The aim of this work has been to extract an electron beam from a pseudospark discharge and measure the time-dependent current, emittance and brightness of the beam. Following design and in-house construction a pseudospark discharge has been experimentally studied and a low emittance, high current density ($>10^2$ A mm^{-2}), very high brightness (up to 10^{12} A m^{-2} rad^{-2}) electron beam has been measured. This performance compares very favourably with the very brightest available sources and only costs a small fraction of the competitive systems. Recent progress has been made in extracting this high brightness electron beam and post-accelerating it. The proof of principle of extraction and post-acceleration is crucial for useful accelerator applications of this novel electron source.

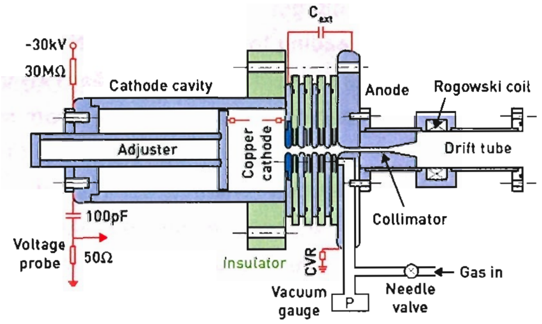


Figure 41: Pseudospark electron source experimental configuration.

In parallel with the development of the novel pseudospark electron sources, work is continuing at Strathclyde on innovative thermionic electron guns, cold-cathode electron sources and plasma flare, very high current, sources as well as a photocathode electron gun. The experimental work is well-supported by computational modelling of electron gun dynamics and electron beam trajectories using a suite of computer codes that include some of the well-known accelerator codes as well as Strathclyde's own custom-designed electron trajectory codes.

5.2.3 RF source technology

Klystrons

Amongst RF sources the very successful accelerator workhorse has been and still is the klystron. UK companies that have klystron design and manufacturing capability include E2V (formerly Marconi Applied Technologies) and Thorn Microwave Devices (TMD). At Lancaster University (Prof R Carter) there is a centre of expertise in klystron theory, design and modelling. Accelerator klystrons must be as efficient as possible, to minimise the cost of running the accelerator, and as reliable as possible to maximise its availability. The conversion efficiency of a klystron is given by the empirical formula.

$$\eta = (0.78 - 0.16P)$$

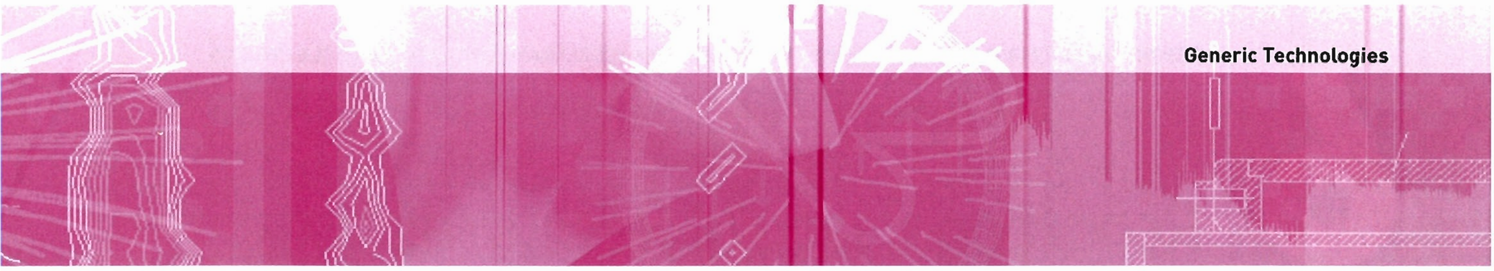
where P is the microperveance of the electron beam (= $10^6 \times I/V^{3/2}$, I = beam current, V = beam voltage). P is typically in the range 0.5 to 2.0 leading to efficiencies in the range 46% to 70%. In a conventional single beam klystron a low perveance, high voltage, beam must be used to get high efficiency and that is likely to lead to reduced reliability because of voltage breakdown. It has been recognised that the solution to this problem is to use a multi-beam klystron (MBK) in which a number of low-perveance electron beams are arranged within the same vacuum envelope so that their outputs are combined in parallel and high power can be obtained without the use of excessively high voltages. Although it would be possible to achieve the same result by operating a number of single-beam klystrons in parallel such a system would be more expensive and less reliable than an MBK.

Thomson Tubes Electroniques have recently developed a prototype MBK tube that has been operated successfully at DESY with a conversion efficiency of 65%. This falls short of the design specification for TESLA, which requires an efficiency in the range 70% to 75%. The specification for CLIC is even more demanding with a requirement of 100 MW per accelerating section which is well beyond the power (47 MW) which is predicted at present for a single MBK. Research into high power and multi-beam klystrons is needed urgently in order to ensure that this vital enabling technology is in place when it is needed for future linear collider projects. At Lancaster University, Prof R.Carter is leading a PPARC-funded research project to discover ways of improving the performance of MBKs so that they can meet the full requirements for TESLA and CLIC. This project intends to develop the design methodology for MBKs through the use of existing computer simulations and the development of new ones.

Gyro and other novel RF sources

The aim of the RF source R&D at Strathclyde University has been to explore novel RF sources which may supplement the more conventional RF sources used in accelerators and in specialised cases even become future replacements. Microwave free electron lasers, backward wave oscillators, Cherenkov masers, relativistic klystrons, gyrotrons, cyclotron autoresonance masers (CARMs) and gyro-travelling wave amplifiers have been explored in a series of modelling projects followed by laboratory experiments. The main frequency range of interest in this work has been 8GHz to 40GHz but the total range explored has been from 1 to 200GHz. Peak power levels up to 100's of MWs have been obtained.

It has been known for some time that the accelerating field gradient that can be achieved in RF accelerating structures is significantly greater for frequencies of 30 to 40GHz than for 1 to 2 GHz. This can provide either a higher ultimate accelerator energy for a given maximum length, or a more compact accelerator for a given energy requirement. The inevitable reduction in the dimensions of certain types of RF vacuum tubes, such as klystrons, as their operating frequency



increases to 30GHz, means that the power output of these devices decreases. In examining gyro and other novel RF sources the aim is to identify and develop an RF source that retains the desired high power output capability even in the 30 to 40 GHz frequency range. At Strathclyde a short pulse, superradiant 30-40 GHz source has been designed, constructed and operated at peak power levels above 100MW. However this is an oscillator, rather than an amplifier, so phase-synchronisation of the output is not so readily achieved. Work is continuing to understand the fundamental physical limits to the peak power obtainable.

Ongoing work on other new RF sources includes an FEL amplifier and a gyro-Travelling Wave amplifier. Both of these MW level amplifiers have been successfully designed, constructed and operated at Strathclyde. The FEL has demonstrated more than an octave measured bandwidth, whereas a smaller 20% bandwidth has been measured for the gyro-TWA. For typical accelerator applications, however, these bandwidths are considerably in excess of what is needed. The gyro-klystron has sufficient bandwidth for most accelerator applications. Hence this is one of the RF sources being studied that shows promise for the 30 to 40GHz frequency range.

Power Supply Technologies

One of the accelerator technologies that is sometimes overlooked is that of the power supply required to drive the RF source, which in turn feeds the RF accelerating structure. Included in this general area are also the various power supplies needed for magnets, beam control and other accelerator systems. UK universities have centres of excellence in pulse power research, such as that led by Dr. Paul Smith at Oxford University, which is making valuable and innovative contributions to the switching and energy storage and transmission technologies that underpin the accelerator power supplies. Apart from the pulse power research expertise within the UK, the development of the more specific types of high voltage, repetitively operated, modulator power supplies needed to drive the accelerator RF power sources is possibly not developing and accessing the latest high power solid state device technology to the fullest extent. This may be a consequence of the mature development of the conventional circuitry that has been very successfully used hitherto for RF source power supplies and there may be a need for a stimulus to develop novel, more compact, efficient power supplies to drive the RF sources for the next generation of accelerators.

6 Report on Usage of Resources

6.1 Staff

The average staff utilisation within CCLRC is shown in Fig 42 by quarter year since the start of the project. PPD and non-PPD effort are shown separately. The accompanying pie-chart shows CCLRC staff distribution among the different activities. Fig 43 shows the corresponding evolution of the university effort.

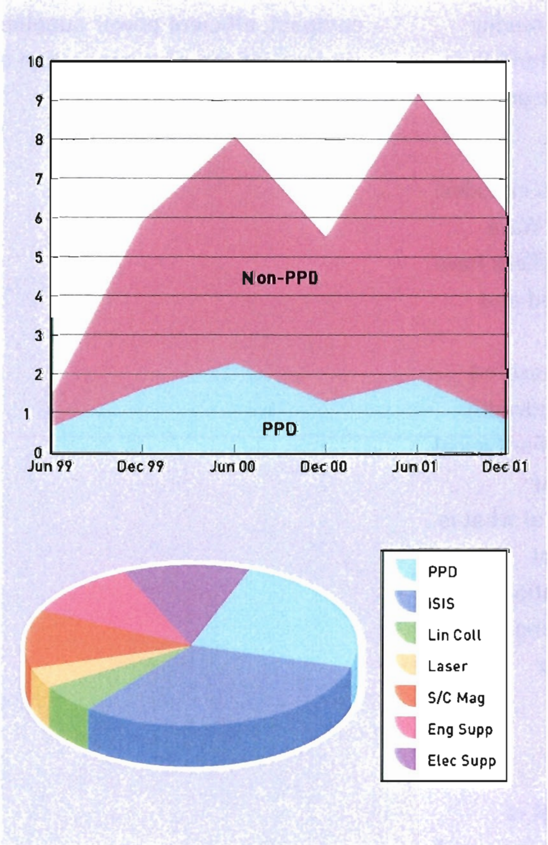


Figure 42: CCLRC effort profile during the three years of the project, and the breakdown of effort among the different disciplines.

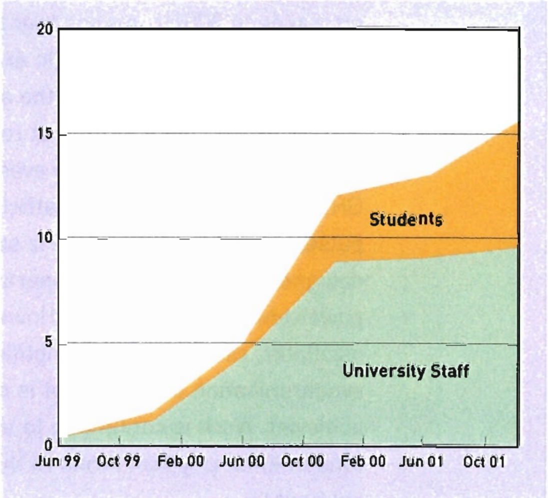


Fig 43: The growth of university effort during the three years covered by this report.

6.2 Expenditure

The expenditure on the R&D programme during the first three years is shown in the following table, in which PPARC and CCLRC funds are not listed separately. This is dominated by staff costs. The CCLRC funding of £100k for the laser photoinjector project in 2000-01 is not included, and nor is £52k from ASTeC in 2001-2.

£k	1999-2000	2000-2001	2001-2002
Staff costs including overheads	216	388	375
Requisitions and travel	32	145	261
Total	**248**	**533**	**636**

A Appendices

Appendix A:

Membership and Terms of Reference of EPARD

External Particle Accelerator Advisory Panel

Membership:

G Myatt (Oxford) – Chair

A Phelps (Strathclyde)

G Blair (RHBNC)

P Burrows (Oxford)

C Hawkes (Birmingham)

J Dainton (Liverpool)

C Buttar (Sheffield)

K Long (IC)

In attendance

KJ Peach

PR Norton

ISIS (ISK Gardner)

SRS (SL Smith)

Engineering (DE Baynham)

The Chairman of the External Panel will be invited to meetings of the Internal Particle Accelerator Advisory Panel

The Panel should meet at least three times each year.

Terms of Reference

1. To advise the Director, Particle Physics on proposals for accelerator research and development funded by PPARC through CCLRC;
2. To comment upon the allocation of resources;
3. To review the progress and report to the Director, Particle Physics;
4. To consider the long-term implications of accelerator research and development in the UK, and to report to the Director, Particle Physics.

Appendix B:

Appointments in accelerator R&D

Research Associates:

PPARC Opportunities Fund

Ed McKigney	ICSTM
Malcolm Ellis	RAL
Dima Onoprienko	Brunel

PPARC Responsive RA scheme

Thorsten Kamps	RHUL

EMR agreement with RAL

Glen White	Oxford

ASTeC posts

Kay Roscoe	Daresbury
Deepa Angal-Kalinin	Daresbury

Appendix C:

Meetings and seminars organised

BDIR 2000: Beam Delivery and Interaction Region Systems for Linear Colliders
(Workshop at Daresbury Laboratory,
3-5 July 2000)

UK HEP Forum on accelerator R&D: 'Developments in particle accelerators: what can theUK do?' held at Cosener's House, Abingdon, on 30 Sept-1 Oct 2000.

Workshop on Instrumentation for Muon Cooling Studies,
Imperial College, 23-24 February 2001

TESLA Information Meeting
Oxford, June 4th 2001

Summer Institute on Neutrino Factories
The Cosener's House, Abingdon, June 2002

NuFact02: Annual International Meeting on Neutrino Factories
Imperial College, July 2002

International MICE Collaboation Meeting
St.Catherine's College, Oxford July 2002

In addition, numerous seminars have been given on the UK programme, MuScat and HARP.

Appendix D:

Submissions to conferences (to July 2002)

T.R.Edgecock (RAL):
invited talk at NuFact2000 (Monterey)

A High Power radiation cooled target for a neutrino factory.
R.Bennett (RAL): poster at EPAC, Vienna, 2000

Neutrino factory studies at RAL.
C.Prior (RAL): poster at EPAC, Vienna, 2000

Ideas for an intra-train fast feedback system for luminosity optimisation
P.N. Burrows (Oxford)
Talk at Beam Delivery/Interaction Region 2000, July 2000, Daresbury.

M Ellis (RAL): invited talk at NuFact2001 (Tsukuba)

Proposing a Laser Based Beam Size Monitor for the Future Linear Collider
G.A.Blair, T.Kamps, F.Poirier (RHUL), I.N.Ross (RAL), et al.
Submitted to the PAC (Particle Accelerator Conference), Argonne 2001

Simulation Studies and Background Measurements for a Laser Based Beam Size Monitor for the Future Linear Collider
G.A.Blair, T.Kamps, F.Poirier (RHUL), et al.
Submitted to the PAC (Particle Accelerator Conference), Argonne 2001

Feedback on nanosecond timescales: IP feedback simulations
G. White (Oxford)
Invited talk at LC02, SLAC, February 2002

FONT experimental status
S. Jolly (Oxford)
Invited talk at LC02, SLAC, February 2002

A fast feedback system for luminosity optimisation at the Linear Collider
G. White (Oxford)
Invited talk at Institute of Physics High Energy Particle Physics annual conference, Brighton, April 2002

Interaction Point feedback simulations
G. White (Oxford)
Invited talk at ECFA/DESY Linear Collider Workshop, St. Malo, April 2002

Experiences working on machine R&D: the FONT project
P.N Burrows (Oxford)
Invited talk at Linear Collider R&D Workshop, SLAC, May 2002

Optimising the collider luminosity: the Feedback on Nanosecond Timescales project
P.N. Burrows (Oxford)
Invited talk at American Linear Collider Workshop, Santa Cruz, June 2002

Design status of the CLIC beam delivery system
G.A.Blair (RHUL) et al.
Accepted contribution to EPAC, Paris 2002

Comparison of different tracking codes for beam delivery systems of linear colliders
G.A.Blair (RHUL) et al.
Accepted contribution to EPAC, Paris 2002

Background simulation for the CLIC beam delivery system with Geant
G.A.Blair (RHUL) et al.
Accepted contribution to EPAC, Paris 2002

R&D towards a laser wire beam size monitor for the future linear collider
T.Kamps (RHUL) et al.
Accepted contribution to EPAC, Paris 2002

MuScat: status and plans
W.Murray (RAL)
Invited talk at NuFact 02 (London)

International Muon Ionisation Cooling Experiment: status and plans
R.Edgecock (RAL)
Invited talk at NuFact02 (London)

HARP status and plans
M.Ellis (RAL)
Invited talk at NuFact02 (London)

Muon front end chicane and acceleration
G.H.Rees (RAL)
Parallel Session talk presented at NuFact02 (London)

Magnets for a front end muon chicane
M.R.Harold (RAL)
Parallel Session talk presented at NuFact02 (London)

Scintillating fiber R&D
E.McKigney (IC)
Parallel Session talk presented at NuFact02 (London)

Hydrogen absorber window design
W.Lau (Oxford)
Parallel Session talk presented at NuFact02 (London)

Calculations of energy loss and multiple scattering in molecular hydrogen
W.Allison (Oxford)
Parallel Session talk presented at NuFact02 (London)

Lattices for 8 and 30 GeV proton drivers
G.H.Rees (RAL)
Parallel Session talk presented at NuFact02 (London)

Appendix E:

Studentships

Birmingham (Msci)

D.Attwood	MuScat design, testing and simulation
A.May	MuScat analysis

Liverpool (PhD)

D.Scott	Effect of errors in the magnets used for undulators and undulator design for the polarised positron source for TESLA.
J.Varley	Top-up injection into DIAMOND and Linear Collider damping ring design.

Oxford (DPhil)

G.Nesom	Design and fabrication of FONT and its associated electronics and charge correction circuitry.
S.Jolly	Assembly of FONT, characterization of the dipole and kicker, design and prototyping of BPM processor circuitry, and cabling, control and readout of beamline components.

RHUL (PhD)

F.Poirier	Design, simulation and testing of a laser-wire beam scanner.

Sheffield (PhD)

C.Warsop	Special diagnostic methods and beam loss control on high intensity proton synchrotrons and storage rings.
L.Scotchmer	HARP studies of low energy hadron production and consequences for a neutrino factory source.