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Specification for the TITANIA KrF Laser System

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SUMMARY

M H Key and M J Shaw

INTRODUCTION

This document presents a specification of the 'Titania' laser system including its physics design, performance characteristics, laser hardware, building layout, control systems, services and target irradiation facilities. Costings and time schedules for the construction of the new laser are also given. The document is comprised of a set of technical appendices (A1 to 10) which have been written by working groups, which together make up the Titania Task Force whose membership is given in A11.

BACKGROUND

The exploitation of KrF lasers for the generation of high power and high UV brightness in short pulses has been an ongoing theme of activity of the SERC Central Laser Facility for the last decade. Electron beam pumped KrF laser amplifiers are robust and efficient and have relatively low cost compared to solid state laser amplifiers of comparable energy capability. Their much higher pulse repetition rate is also a major advantage.

The large aperture electron beam pumped KrF laser 'Sprite' has been in operation for more than six years. It has more recently been used as the power source for a novel KrF laser-pumped Raman-laser configuration which has been providing a single Raman beam at 0.5 TW power in 12 ps pulses to user teams for the last 2 years. The Raman beam has achieved exceptional brightness (10^{20} Wcm^{-2} st^{-1}), and has shown that the KrF laser pumped Raman laser can produce greater beam brightness in the UV than any other laser system. More recently, chirped pulse amplification and compression (CPAC) has been applied to the 'Sprite' system to generate 1 TW pulses recompressed to 300 fs and the bandwidth of the KrF medium is sufficient to envisage further pulse length reduction to 150fs. Higher brightness than in the Raman beams has been obtained with these compressed pulses.

The current development programme for the KrF laser facilities at the CLF was approved by the Science Board of SERC in 1990 and began in the financial year 1991/2. It has two parts.

The first, separately funded by the Board, was a highly successful two year project, carried out jointly with St Andrews University and Imperial College and now almost complete to upgrade the performance of the operational facility 'Sprite'. It involved both the implementation of CPAC for the first time on a KrF laser and most recently the enhancement of the Raman beam power and energy by provision of more multiplexed KrF pump beams.

The second part of the programme planned as a four year project funded within the main line of the CLF involved designing, on the basis of the 'Sprite' system, and constructing a greatly enhanced KrF laser system 'Titania'. This second project is the subject of this document. The pricipal laser power source for the new system , a larger amplifier of longer run time has already been built off-line in the first two years of the project. The new optical system has been designed to utilise as efficiently as possible the higher total energy capability of the new amplifier to produce a user facility with versatile capabilities and unique properties.

'Titania' will provide 4 Raman beams which together generate one hundred times more energy than the present 'Sprite' Raman beam. It will also provide a single CPAC beam with an energy capability six times greater than that of 'Sprite', of which an increasing fraction will be deliverable to target as compression grating technology improves. 'Titania' will produce UV light which has many advantages for laser plasma experiments. It will be unique in the world in its Raman mode and will produce higher brightness than any other laser in the UV, it will also be unique in its CPAC mode which promises to provide the highest brightness and shortest pulse of any high power laser worldwide.

The design work which is presented in the document has been constrained by the need to construct 'Titania' within in a very tight budget and the rate of funding has controlled the phasing of the plan. The aim has been to minimise the down time of the operational laser facility in the transformation of 'Sprite' into 'Titania'. Another objective has been to create a facility which has the potential for future development. In order to minimise costs, maximum reuse has been made of the present 'Sprite' system including its building. Incorporation of an adjacent building (R7) into the new system has enabled a low cost expansion to the 'Titania' configuration and will provide space for future upgrades.

PERFORMANCE

Perhaps the most significant aspect of the existing Sprite laser system is that it has demonstrated that KrF lasers can offer users some major advantages (compared with glass) which accrue from short wavelength , high repetition rate and exceptional brightness. The Sprite system was however not constructed for the most efficient extraction of of the basic energy of the KrF amplifier, the number of multiplexed pulses being too small and intended only for proof-of-principle of the KrF laser-pumped Raman-laser concept.

The new Titania system has been designed to provide a major upgrade in performance by increasing the number of multiplexed pulses (from 8 to 88), the final aperture (from 270 mm to 420 mm) and the final module run time from 60 ns to 170 ns. These changes will give about a one hundred-fold increase in the energy available to target (to over 360 J in the Raman mode) whilst the beam brightness is expected to be a factor of 10 higher than the existing Sprite Raman beam.

In the CPAC single pulse mode of operation the ultimate improvement in energy capability and brightness could be over twentyfold, but here the grating damage threshold is the limiting factor with improvements expected from use of dielectric coatings rather than aluminium as at present. Pulse length reduction to 150 fs will also improve the brightness. Potentially, brightness approaching 10^{22} W cm^{-2}sterad^{-1} could be obtained.

Auxiliary beams in a glass laser system are added simply by increasing the number of parallel channels. In a KrF multiplexed system more channels can be added in series if sufficient amplifier run time is available. Two such auxiliary KrF channels have been incorporated in the design to provide short pulse probe beams or long pulse uniform irradiation at low intensity.

Special requirements such as shaped pulses, two frequency operation or multi-frequency generation are under consideration for the existing Sprite system. Such additions to laser performance could in future be applied to the new Titania system.

Table 1. gives a summary of the on-target performance of the various modes of operation of the new laser system.

1. Raman Mode	
Number of beams	4
Beam diameter	150 mm
Wavelength	268 nm
Bandwidth	Transform Ltd
Pulselength range	30 - 500 ps
Maximum energy on target	365 J (Tp > 300 ps)
Maximum power on target	7.6 TW (Tp = 30 ps)
Beam divergence	< 3 μRd (1.7xDL)
Beam brightness	10^{21} W cm^{-2} st^{-1}
Focal irradiance (per beam f/4 optics)	5×10^{19} W cm^{-2}
Repetition Rate	20 shots per hour

2. CPAC Mode	
Number of beams	1
Beam diameter	150 mm
Wavelength	248 nm
Minimum pulselength	150 fs
Maximum energy on target*	2.5 J
Peak power on target	> 15 TW
Beam brightness	5×10^{21} W cm^{-2} st^{-1}
Focal irradiance (f/4 optics)	3×10^{20} W cm^{-2}
Repetition Rate	10 shots per hour

3. Auxiliary Beams	
a. KrF probe beam (narrow band or chirped)	$\Delta v > 100$ cm^{-1} chirped
Pulselength	30 - 500 ps
Energy	5 - 8 J
b. KrF broadband	$\Delta v > 60$ cm^{-1}
Pulselength	1 - 6 ns
Energy	10 - 40 J

*CPAC energy limit assumes a factor of 3 increase in the damage threshold of gratings. Larger improvements could give higher energies up to a laser limited energy of 7 J.

***Table 1.** Predicted on-target performance of the Raman, CPA and auxiliary beams available from the Titania laser system.*

SITE

The proposed site for the new Titania laser system is shown in Fig 1. in appendix 5 and will occupy the whole of the presently used building R2, the ground floor of the link building between R2 and R7 and most of building R7. The bulk of the laser is accommodated in R2 with the pulsed power amplifier modules at the East end as at present . A new oscillator room and extended multiplexer room occupy the remainder of the building. The Raman system is housed in the link building together with the laser control room and support areas.

This leaves the whole of building R7 available for target areas. Initially a single target area for CPAC work and 4-beam Raman work is proposed together with a large control room. The floor area of the proposed new target area is comparable to the Vulcan TAE and TAW areas and the area available for the new TA control room is twice that provided on Vulcan. The target area and laser control rooms are adjacent for ease of communication. The area in R7 on the east side is available for expansion as an additional target area. The area to the South of R7 is not built on and is available for future expansion of the whole system

THE LASER SYSTEM

The new laser system is based on technologies which have already been demonstrated and performance is a reasonable extrapolation, using bench marked codes, from the existing state-of-the-art (A1).

In the front end (A2) it is proposed to operate two oscillators at 746 nm simultaneously (and eventually synchronously) to provide short (CPAC) and long (Raman) pulses. A new solid state 746 nm amplifier is proposed to obtain much higher energy than at present before tripling and provide sufficient UV output at 10 Hz rep. rate for alignment of the main optical systems.

In modelling the KrF amplifier chain (A1) it has been found that sufficient drive for the Titania output module can be obtained from Sprite alone and so the present Goblin amplifier stage is not required thus reducing the system complexity and reducing ASE. The two e-beam-pumped KrF modules fit easily into the existing R2 bay and the old Sprite Marx tank can accommodate the modified Marx with minimal modifications (A6).

Energy is extracted from the final KrF amplifier module in 24 beams (A3). Two beams provide the CPA channel and the KrF probe channel, two beams pump the Raman preamplifier and 20 beams pump the final Raman amplifier. Each of the KrF pump beams contains a four-pulse train and so energy is efficiently extracted from the final KrF amplifier by a continuous train of 88 pulses with a 1.5 ns separation. The final Raman amplifier is pumped four times with extraction on four Stokes beams each carrying up to 100 J energy.

The four Raman beams propagate to the target area in helium or argon-filled pipes which are necessary to reduce B-integral effects in the propagation path (A8). A number of illumination geometries are envisaged including same side line focus or cluster and opposite side line focus or cluster (A4). With piped beams, the ease of making changes becomes an issue. A simple, versatile system of beam piping is being tried on Sprite for the Raman Upgrade and experience gained there will be very useful.

The single KrF CPAC beam will be the first beam to be amplified in the Titania module and after separation from the other beams will enter a vacuum pipe which will relay an image from the early part of the amplifier chain onto the compressor gratings. These will be situated close to the target area in the east end of R7. The chamber will be designed to be capable of accommodating both long and short focal length experiments with this very bright beam.

PROGRAMME AND COSTINGS

The build programme for the Titania system is limited by the CLFs funding, by the the requirement to maintain operation of Vulcan during the build phase and the need to minimise the KrF facility shut down. It is therefore planned to extend the development of Titania over a further two years after the start of partial operation at the originally planned date of April 1996. Table 2 gives a breakdown of the cost of the equipment for Titania which is in line with the CLF forward look and assumes an approximate equipment-to-staff cost ratio of 55:45.

A build programme which is consistent with this expenditure has been put together and is presented in detail below (A10). Briefly, the programme is as follows. In the present financial year work on the Titania module proceeds and the new buildings will be taken over and prepared. In 1994/95 Sprite will continue to operate and the majority of expenditure will go on building the new target area and completing the Titania module.

F/Y	93/ 94	94/ 95	95/ 96	96/ 97	97/ 98	Totals
Pulsed Power	190	90	10			*290
Optics	100	30	40	220	190	580
Building Mods		90	100			190
Controls		30	80	20		130
Front end		40	170	20	100	330
Target Areas	5	90	160	130	45	430
Total Equipment	295	370	560	390	335	1950

***Table 2**. Spend profile in £K for the Titania laser system. (*excludes £170K already spent on the Titania pulsed power system in1992/93)*

In 95/96 Sprite will be shut down and the installation of the major part of the new system will proceed. At the end of this financial year Titania will provide the CPAC beam to target. In 1996/97 half of the multiplexer optics will be installed and the Raman beams will be brought on stream operating at half power over a limited pulselength range. In 1997/98 the remainder of the KrF optics will be installed and the oscillator upgraded to provide synchronous short and long pulses to provide the performance as specified in table 1.

A1. SYSTEM MODELLING

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INTRODUCTION

In this appendix we describe two codes which have been used to model the proposed Titania laser system, and present results from both. The first code models amplification in a chain of e-beam pumped KrF amplifiers and the second models the Raman amplification process in a chain of Raman amplifiers.

1. KRF MODELLING

1.1 Introduction

The code used to model the KrF amplifier chain is a 1D code based on that used previously to model the Sprite system [1-4]. The original code has been modified to include the Titania amplifier, multiplexing between Sprite and Titania and to enable modelling of long pulse (1ns) amplification.

The code models the amplification of a train of 24 pulses in a chain of e-beam pumped, double passed KrF amplifiers. (In reality there will actually be 48 input pulses to the KrF chain.) Losses due to linear and non-linear absorption in the inter-stage optics, unpumped fluorine absorption and absorption in the amplifier windows are taken into account. ASE gain depumping is also included in the model, though the contribution arising from ASE coupling between amplifiers has previously been found to be negligible, and is therefore not included. Between each amplifying stage the energy of each pulse is measured, and this enables the input/output characteristics of each amplifier, and of the system as a whole, to be derived.

For all the results presented, the pulse separation is 1.5 ns and the code has been run with pulse lengths of 10ps, 30ps, 100ps, 300ps and 1ns. In the case of the 1ns pulses a Gaussian pulse envelope was assumed and in all other cases a top-hat profile was used. Initially a system, consisting of 3 KrF amplifiers, Goblin, Sprite and Titania, was modelled for input energies to Goblin, the first KrF amplifier in the chain, of between 1pJ and 100μJ per pulse. A second system excluding the Goblin amplifier has also been modelled.

The input energy to these model systems is a variable. In practice, the present front end produces a KrF energy of about 2.5mJ which, after pulse stacking and multiplexing, would correspond to an energy of 30 μJ per pulse at the input to the KrF chain. With the proposed modifications to the front end (Appendix A2), the input energy per pulse should be raised to about 100μJ.

1.2 Amplifier Parameters

Table 1 lists the values of the significant amplifier parameters which have been used in the model to obtain the results given later.

Table 1-Amplifier parameters

Amplifier	Goblin	Sprite	Titania
Aperture diam. (cm)	8	27	42
Area fill factor	.8	.8	.84
Amp. length (cm)	40	100	150
o/p window area (cm^2)	50	575	1257
o/p window thickness (cm)	1	2	1.5
i/p lens thickness (cm)	.5	.5	n/a
o/p lens thickness (cm)	.5	.5	n/a
beam dia. at i/p lens (cm)	2	2	n/a
beam dia at o/p lens (cm)	2	9	n/a
duration of e-beam	150ns	150ns	150ns
upper state lifetime	2ns	2ns	1ns
gain-length product	4.2	7.35	8
gain/loss ratio	10	10	10
unpumped F2 length (front) (cm)	10	57	30
unpumped F2 length (back) (cm)	25	25	25

nb. Fluorine absorption coefficient is taken to be .1%/cm. in Goblin and Sprite and .2%/cm in Titania.

1.3 Optics

The transmissive optics consist mainly of fused silica lenses and windows, although the Sprite output lenses are calcium fluoride. Single surface losses due to Fresnel reflection are taken to be 5% and the two photon absorption coefficient is taken to be 0.07 cm/GW for fused silica and 0.008 cm/GW for calcium fluoride. Beyond the Sprite output lenses there are no more transmissive elements except for the Titania windows. All mirrors are assumed to be 100% reflective except the amplifier back mirrors which are 99% reflective.

1.4 Results

1.4.1 Input/output characteristics

One of the main purposes of developing and running this code was to characterise the input / output behaviour of the Titania laser system. Originally it was envisaged that the KrF system beyond the front end would comprise Goblin and Sprite, the two amplifiers currently in operation, and Titania, a new 42cm aperture amplifier. Twelve beams would be multiplexed through Goblin and Sprite and the twelve output beams from Sprite would be split to produce 24 beams for amplification in Titania. Figures 1 to 3 show the predicted output pulse energy as a function of input pulse energy for each of the individual amplifiers, with the system operating in this configuration. The pulse used in these graphs was the 16th in the train of 24 input pulses, and it was chosen to represent a 'typical' pulse. It occurs at a point in the pulse train where the gain has settled down to a steady value in each amplifier (see figure 7.) Figure 4 shows the overall gain characteristics of the system.

The system output pulse energy is plotted against pulse energy into Goblin. The shapes of the graphs in figures 1 to 3 differ due to the different levels of saturation in each amplifier. While Goblin is hardly saturated even with the highest energy input pulse, Sprite and especially Titania are saturated even for quite low initial pulse energies. Ideally we would like to run the system with Goblin and Sprite operating in the small signal regime and with Titania just reaching saturation. Avoiding saturation in the first two amplifiers will reduce unwanted effects such

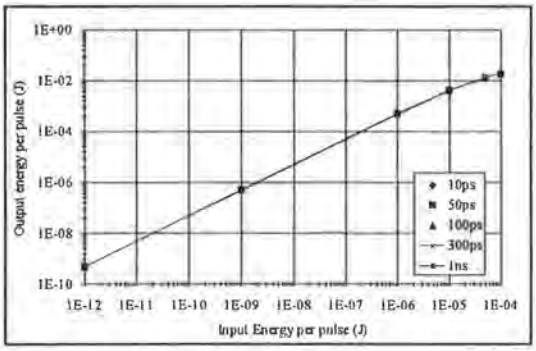


Figure 1: Goblin input / output characteristics

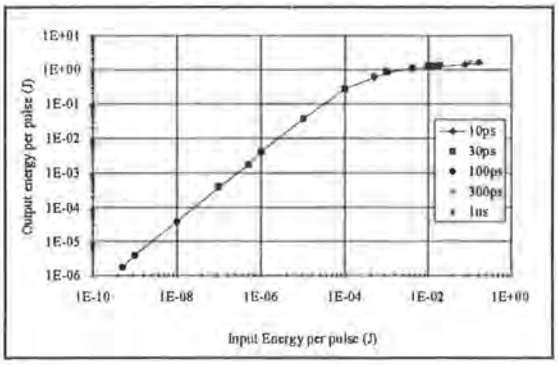


Figure 2 Sprite input/output characteristics

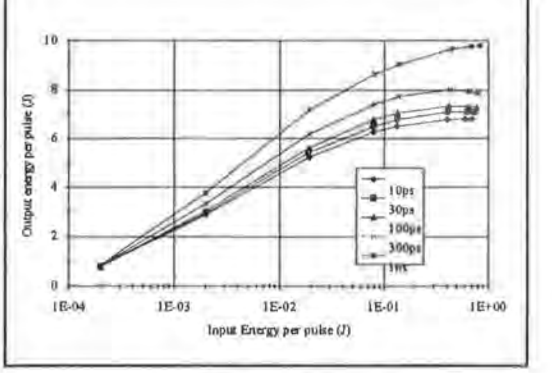


Figure 3 Titania input / output characteristics

as pulse sharpening (see figure 8) between the oscillator and the target.

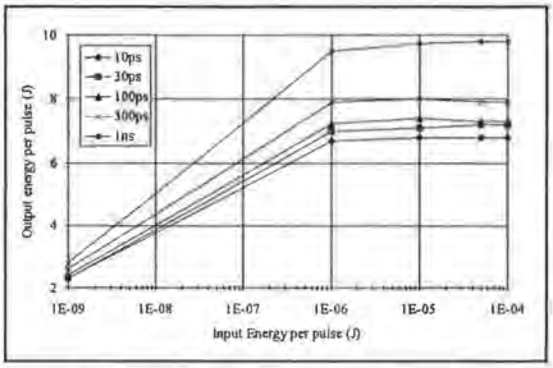


Figure 4 System input output characteristics

As expected, the highest output energy is achieved with the longest pulse length. The code predicts that for a 10ps pulse of energy greater than about 1μJ input into Goblin an output energy of about 6-7 J will be achieved and this increases to almost 10 J for a 1ns pulse. A significant part of the difference in energies obtained at different pulse lengths is accounted for by two photon absorption in the Titania output window. This is negligible for 1ns pulses but can be up to 8% for 10 ps pulses.

As was mentioned earlier, a typical pulse energy into Goblin may currently be about 30 μJ, and from the graphs in figures 1 to 3, this will produce enough energy to saturate Sprite. It would be desirable to run Sprite below saturation and this will mean reducing, in some way, the output energy from the initial stages of the system. The most efficient way to do this may be to dispense with the Goblin amplifier altogether and to run the system with just the Sprite and Titania amplifiers. From figure 3, an input pulse energy of approximately 100-150mJ is sufficient to saturate Titania, and this represents an output from Sprite of 200-300mJ per pulse. This is achieved well below saturation, for an input pulse energy to Sprite of approximately 70-100μJ. Figure 5 shows the predicted input / output characteristics of the system with the Goblin amplifier stage removed. The output pulse energy from Titania is shown as a function of pulse energy into Sprite.

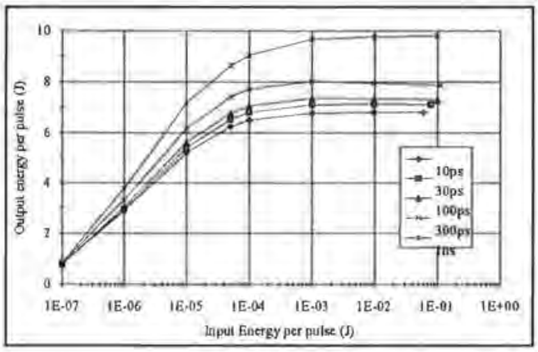


Figure 5 System input/output characteristics without Goblin

As can be seen, a pulse energy greater than about 70μJ at the entrance to Sprite should be enough to weakly saturate the Titania amplifier, at least in the short pulse regime, and 100 to 200μJ will move the system well into the region of saturated operation for pulse durations of up to 300ps. Indeed the system would be weakly saturated even for a 1ns pulse. In reality we would expect a significant increase in the amount of energy available at the entrance to Sprite as the pulse length is increased, due to improved operation of the front end high gain amplifier at long pulse durations, so it should be possible to run the system with Titania saturated for pulse durations up to at least 1ns. It appears then, that with the introduction of the upgraded front end to the KrF system, it should be possible to run this system without the Goblin amplifier. This will lead to a large simplification in the design and operation of the final system.

To lend some credence to the code predictions discussed above, figure 6 shows a comparison of some experimental input / output data from Sprite, and the corresponding code predictions. The data shown were recorded with Sprite operating in single shot mode with a pulse length of 40ps. Figure 6 shows that, if anything, the code predictions are slightly pessimistic and experimentally measured gain was slightly higher than the code would suggest.

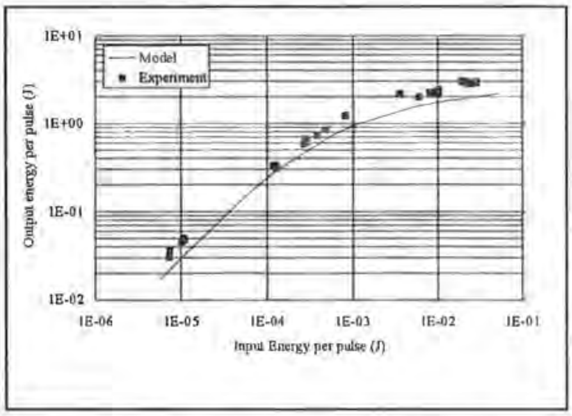


Figure 6: Sprite single shot data and code prediction

1.4.2 Individual Pulse Characteristics

i) Gain variation along pulse train

Titania should ideally produce a train of 96 identical pulses, each having the same shape and the same energy. Whether or not this is achieved will depend on the operating conditions in the individual amplifiers. Figure 7 shows the variation in the output pulse energy according to the position of the pulse in the pulse train for two different sets of operating conditions. In figure 7(a), the system is running with both the Sprite and Titania amplifiers saturated. This example shows the energies of the 48 system output pulses resulting from 24 1ns, 100mJ system input pulses. The general shape of the curve is typical for any case in which Sprite and Titania are reasonably saturated.

The first pulse in figure 7(a) is amplified to a much higher level than the following pulses, since this pulse sees the undepleted (except for ASE depletion) gain in each amplifier. The gain does not have enough time to recover fully before the next pulse arrives so the level of amplification drops. The slight rise in the middle of the pulse train occurs because the twenty-fifth pulse is derived from the first pulse into Sprite; it is split off from that pulse by the multiplexing between Sprite and Titania. The first pulse out of Sprite is larger than the rest for the reasons given above. Towards the end of the pulse train the gain again begins to rise. This is because at the end of the pulse train pulses are only travelling through the amplifier in one direction; there are no oncoming pulses to deplete the gain.

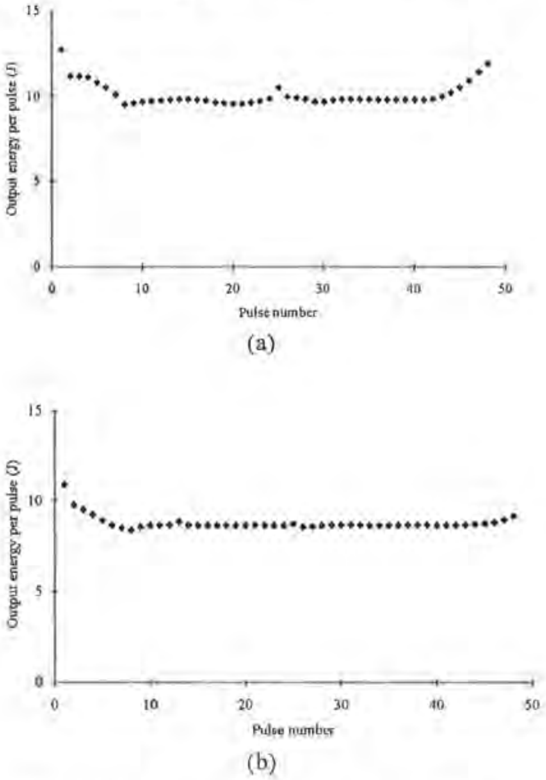
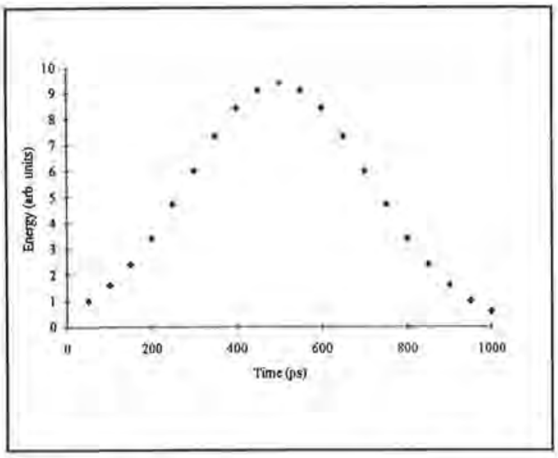


Figure 7 Gain variation along pulse train with (a) Sprite and Titania saturated, and (b) unsaturated Sprite and weakly saturated Titania.

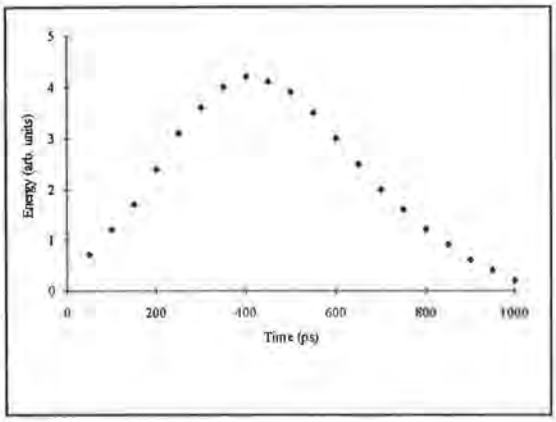
A different situation is shown in figure 7(b). Here Sprite is operating in the small signal regime (50μJ per 1ns input pulse) and Titania is only just reaching saturation. The gain in this case is seen to be much more uniform, with only the first pulse having a noticeably larger gain than the average.

ii) Gaussian pulse sharpening in the amplifier chain

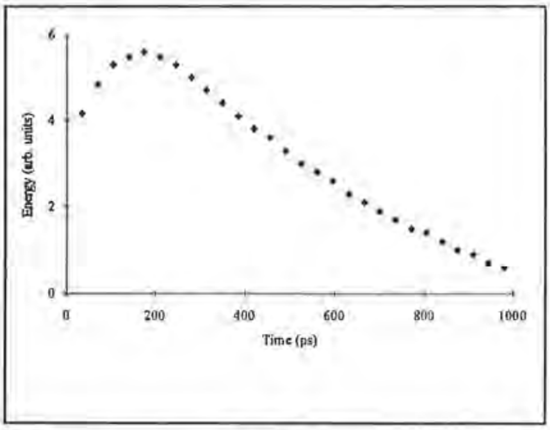
Figure 8 shows another unwanted effect of running the system with both Sprite and Titania saturated. Here, the amplification of a Gaussian pulse through Sprite and Titania is shown. A slight steepening of the leading edge of the pulse is evident in the Sprite output and this steepening is accentuated in Titania which is running further into the saturated regime. This pulse sharpening effect is well known in saturated amplifiers and its magnitude depends to a large extent on the initial pulse shape. In order to avoid this problem, it will be necessary to choose the operating conditions of the system carefully; Sprite should be operated in the small-signal regime and Titania should be only weakly saturated.



a) Sprite input: symmetric Gaussian



b) Output from Sprite: Saturation causes a sharpening of the leading edge of the pulse.



c) Output from Titania: Further sharpening of the pulse occurs if Titania is saturated.

Figure 8: Amplification of a Gaussian Pulse in a saturated chain of KrF amplifiers.

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2 RAMAN MODELLING

2.1 Introduction

The amplification of 268nm Stokes pulses, of different energies and durations, in a chain of Raman amplifiers has been modelled using a 1 dimensional code. The code has been described before [1] and has previously been used to model the amplifiers RA0, RA2 and RA3 in the current Sprite Raman system [2-4].

The code models the amplification of a single Stokes pulse in a Raman amplifier pumped by a single KrF pulse. The 'real' situation, in which each amplifier is pumped with several off-axis pump beams, is modelled by allowing the simulated pump beam to move through the amplifier at a slower speed than the Stokes beam. Thus, if the pulses are coincident at the entrance to the amplifier, then the Stokes pulse will emerge form the amplifier before the pump --as is the case in a real amplifier. Although this is a rather crude approximation, in that it takes no account of other problems arising from a 2-dimensional geometry, recent tests of a new 2D code suggest that the 1D code does, in fact, take account of most of the essential elements of the amplification process; the results from the 2D code differ very little from those obtained from the 1D code. The code treats one amplifier at a time and takes no account of losses due to windows, spatial filters etc between stages. (For the results presented here, these losses have been calculated separately and are included.) Also, no account is taken of losses arising from second Stokes generation or first Stokes self-generation in the direction of the pump beams. However, although both these effects have been observed experimentally in the past, it should be possible to reduce their impact by an appropriate choice of operating parameters for each amplifier. Effects resulting from the use of non-transform-limited pump pulses can be modelled with the code, which has the facility to generate random phase fluctuations on the pump (or Stokes) pulse. This is particularly important for short pulses (<100 ps) because, in this regime, pulse intensities in the inter stage air paths are likely to be high enough to induce self-phase-modulation, which will result in the spectral broadening of what may initially have been a transform limited pulse. Experimental observations suggest that the gain of a Raman amplifier can be greatly reduced by the presence of noise on the pump pulse.

2.2 Amplifier Parameters

Table 2 summarises the configurations of the three Raman amplifiers that will form the Raman chain in the Titania laser. RA0 is a simple methane filled pressure cell situated in the oscillator room.

	RA0	RA4	RA5
Aperture (cm^2)	π/4 (r=5cm)	30 (6x5)	256 (16x16)
Length (cm)	270	100	100
Stokes beam diameter (cm)	.6	5	15
Pump beam diameter (cm)	.8	6	16
Pump beam angle (deg)	0	3	3
Pump energy (J) per Stokes beam	$\geq 3 \times 10^{-3}$	2 (10ps)-10(1ns)	35 (10ps)-170 (1ns)
Pump source	1 beam from oscillator	2 beams from Titania	20 beams from Titania
No. of Stokes beams	1	2	4

Table 2: Raman amplifier operating parameters

It contains no light guide and is already in operation in the current Sprite Raman set-up. RA4 and RA5 are two new light guide amplifiers which will replace the amplifiers RA2 and RA3 in the current set-up.

2.3 Gain Characteristics of Raman Amplifiers.

For unsaturated operation, the gain of a Raman amplifier depends on the Raman gain coefficient, $\Gamma = \gamma I_p L$, where γ is a constant proportional to methane pressure in the amplifier, Ip is the pump intensity and L is the length of the gain medium. Thus, for a given amplifier operating at a fixed pressure and with a fixed input energy, the achievable gain will be dependent on pulse length. As the pulse length increases, the pump intensity drops and this leads to a reduction in the amplifier gain. This gain dependence on pulse duration is shown in figure 9, where, as an example, we plot the predicted gain of RA3 (one of the amplifiers currently in use) as a function of pulse length for different Stokes input energies. The pump energy here is 10J and the amplifier is operating at atmospheric pressure. It can be seen that for the short pulses the amplifier is clearly saturating with, in the case of a 1mJ input, a gain of up to 6000, while for the longer pulses the gain is much lower, falling very rapidly from about 5000 at 100ps (for 1 mJ) to about 5 at 1ns. In practice we wish to extract the maximum possible energy from

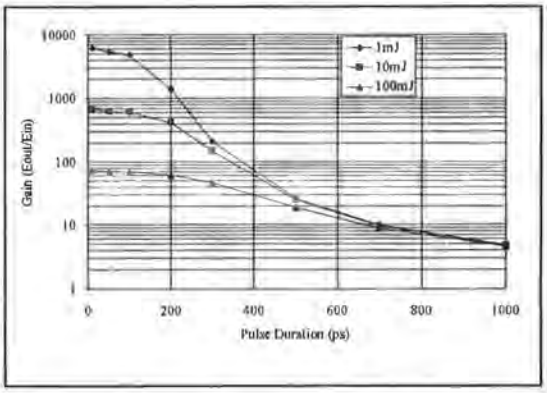

Figure 9: Gain dependence on pulse length for transform limited pulses

the Raman amplifier in the Stokes pulse, and this requires that we operate the amplifier in the saturated regime. In the saturated regime, the Stokes output energy depends only on the input pump energy (neglecting any losses that may occur due to noise, second Stokes generation etc). The graph plotted in figure 9 suggests that to ensure saturation, it may be necessary to boost Γ when operating with longer pulses. This can be done in RA0 by decreasing the pump beam diameter (to increase the pump intensity) and increasing the methane pressure. In RA4 and RA5 the pump intensity is fixed by the light guide dimensions but at long pulse lengths, where non-linear effects do not need to be considered, it will be possible to use thick windows on the ends of the amplifiers and to increase the methane pressure in order to boost the gain. The results plotted later on show that for the pump energies and pulse durations applicable in the Titania Raman system, it should in fact be possible to run the final Raman amplifier, at least, in the saturated regime for pulse durations of between 10ps and 1ns.

2.4 Noise effects in the short pulse regime

The Raman system in Titania is expected to operate at pulse lengths ranging from about 10ps up to about 1ns. As far as the Raman amplifiers are concerned this wide range of pulse durations covers two very different operating regimes: the long pulse regime (τ>100ps), and the short pulse regime (τ<100ps). It would appear from figure 9 that operation should be most straightforward in the short pulse regime where saturation is easily achieved. However, it should be noted that figure 9 assumes transform limited pulses. While this is likely to be a reasonable assumption in the long pulse regime, the shorter pulses will be non transform limited due to intensity dependent self-phase-modulation, and in reality this will make it more difficult to achieve maximum efficiency in the short pulse regime. Previous comparisons of the Raman code predictions with experimental results for 10 and 40ps pulses show reasonable agreement only when a 10 times transform limited pulse bandwidth is assumed (see figure 10). For a 10ps pulse of bandwidth ten times the transform limit, much of the pump energy will lie outside the Raman linewidth and so the efficiency of the Raman amplifier will be reduced. Phase noise in the long pulse regime does not present a problem for two reasons. Firstly, spectral broadening of the pump pulse is less likely to occur in the first place, and secondly, even if it does occur, it will have less effect on the Raman gain. In the case of a 300ps pump pulse of spectral width ten times the transform limit, for example, all the energy of the pulse will still be contained in a spectral width less than the Raman linewidth. (To check this the code has been run with 300ps transform limited pulses and with ten times transform limited pulses of the same duration: the resulting gain and efficiency were the same in each case.)

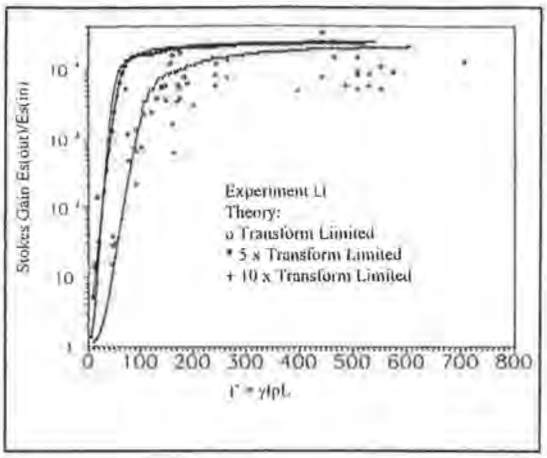

Figure 10: Experimental measurements of Raman gain as a function of Γ in RA2 for ~10ps pulses. Also shown, for comparison, are code predictions for transform limited, 5 x transform limited and 10 x transform limited pulses.

We conclude that, for saturated operation, the efficiency of the Raman system is likely to be reduced from its maximum possible value in the short pulse regime due to noise, but that this noise will not be a problem in the long pulse regime. Noise has therefore been included in the code runs for short pulses ($\tau <$ 100ps) but not for longer pulses.

2.5 Energy Limits for saturated operation

If the Raman amplifiers are operated in the saturated regime, the output Stokes energy from a given amplifier should simply depend on the available pump energy at the entrance to the amplifier (apart from losses due to noise, second Stokes generation etc.). Table 3, which summarises the expected pump energies for the final two Raman amplifiers, shows a very wide range of energies available to pump RA4 and RA5 from Titania. These energies will, in fact, depend on the operating pulse length.

For the longest pulses (1ns), the Titania amplifier yields the highest energy per pulse and the only losses between Titania and the Raman amplifiers are due to Fresnel reflections in windows and imperfect mirror coatings.

Table 3: Raman amplifier pump energies

Pulse length	10ps	30ps	100ps	300ps	1ns
Pump energy (J) (RA4)	2.0	6.3	7.2	8.0	9.4
Pump energy (J) (RA5)	35	99	130	140	170

As the pulse becomes shorter, however, two effects reduce the available pump energy. Firstly, Titania produces a little less energy to start with and secondly, due to the shorter pulse duration and hence higher intensity, non-linear losses such as two photon absorption begin to become important and the energy passing through the amplifier windows and reaching the Raman medium becomes limited. In the case of the shortest pulses (10ps), the energy available to pump the Raman amplifiers is limited by the B integral between them and Titania; although higher energies are actually available, they cannot be used because they would cause an unacceptably large non-linear phase shift. As a result of these effects, we can expect to observe markedly different gains at different pulse lengths.

2.6 Results

In this section we present the code predictions for the operation of RA4 and RA5 in the Titania Raman system. Results are presented for pulse durations of 10ps, 30ps, 100ps, 300ps and 1ns. The pump energies given in figures 11 and 12 are based on the Titania output energies obtained in the first part of this appendix for a 100μJ/pulse input to Sprite. These output energies have then been operated on to take account of linear and non-linear losses between Titania and the Raman amplifier to produce the pump energies shown. In the case of the 10ps pulses, where B-integral considerations impose a limit on the usable pump energy, a pump energy equal to that limit has been assumed.

Results of code runs performed for RA0 are not shown, but such results predict that by a reduction in the diameter of the pump beam (from .8cm to about 0.5cm) and an increase in methane pressure in this amplifier (from 3atm to 4atm) for the longer pulse durations, given a seed energy of 1μJ from the Raman generator, a Stokes output of 1mJ per pulse will be possible at all pulse durations between 10ps and 1ns.

The Stokes energy input/output characteristics for RA4 and RA5 are shown in figures 11 and 12 respectively. The pressure in both amplifiers is 1atm unless stated, and this can be seen to be sufficient for saturated operation, with the given pump energies, for all pulse lengths except 1ns. In fact, saturated operation at 1ns can be achieved in RA5 by increasing the pressure in that amplifier to 2atm (figure 12).

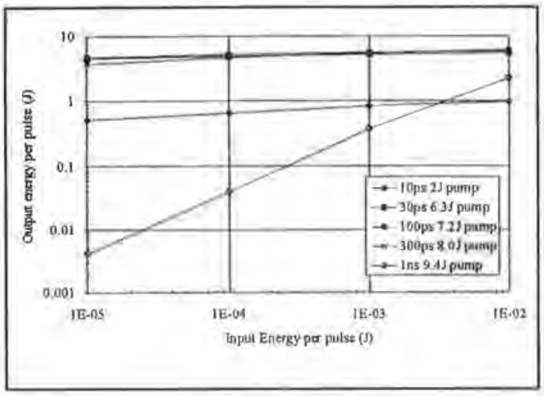

Figure 11: RA4 Input / Output characteristics

For the results shown in these graphs, input pulses of duration greater than or equal to 100ps were taken to be transform limited, while those of duration 10ps and 30ps were broadened to ten times transform limited. This takes account of the arguments given in section 2.4 concerning the influence of noise on Raman amplification at different pulse lengths.

Given a Stokes energy of 1mJ from the front end of the system (RA0), we can expect to put about 0.25mJ per Stokes pulse into RA4. This takes account of the two way split between RA0 and RA4, and assumes a loss of 50% between these amplifiers. From figure 11, with an input of .25mJ we can expect to generate an output of about 5J per pulse for pulse durations

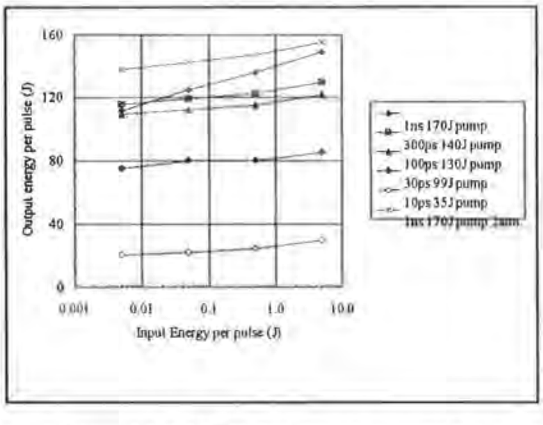

Figure 12: RA5 Input/Output Characteristics

between 30ps and 300ps. For 10ps pulses the output energy is limited to 0.7J due to the B-integral limit on the pump energy and for 1ns pulses an output of only 0.1J is achieved if we operate at atmospheric pressure.

Between RA4 and RA5 there is another two way split of each Raman beam and if we again assume an inter-stage loss of 50%, then the Stokes input energies to RA5 will be about 0.17J for 10ps pulses, 1.25J for pulses of duration 30ps to 300ps, and 0.025J for 1ns pulses. For these input energies the code predicts output energies of about 25J per pulse at 10ps, where a B-integral limit is again imposed, and 100 to 130J per pulse at longer pulse lengths. If we operate at 2atm pressure for the 1ns pulses, then the output energy may be increased to about 140J.

It must be stressed that these code predictions do not take account of effects such as 2nd Stokes generation, which will occur in the saturated regions of the amplifiers, or 1st Stokes self-generation, and so it is unlikely that efficiencies quite as high as those predicted will be observed in practice. However, efficiencies greater than 60% [1,4] have been observed in the present Raman system for short pulses and higher efficiencies are expected for longer pulses due to the absence of noise effects.

It should be possible to reduce the effect of second Stokes generation by operating the Raman amplifiers in such a way that heavy saturation is only achieved in the last few centimetres of the amplifier. This may be arranged by reducing the methane pressure in the amplifiers in order to reduce Γ. Figure 13 shows the variation of Stokes energy along RA5 for a 100ps pulse, pumped by 130J, at three different methane pressures, and demonstrates how the methane pressure inside the amplifier can be adjusted to control this variation to suit specific requirements. The amount of second Stokes energy generated in the amplifier is given by $E_{2s} = \Gamma_{2s}\int_0^l I_s dl$ (where Γ_{2s} is a constant, I_s is the Stokes intensity and l is the amplifier length) and so, at a given pressure, is proportional to the area under a curve of the form shown in figure 13. Thus, although reducing the pressure in the Raman amplifier may cause a small reduction in the predicted pump to first Stokes conversion efficiency (see figure 13), it will also cause a significant reduction in the amount of energy lost as second Stokes radiation. For a given pump energy, pulse length etc. it should be possible to find an optimum methane pressure at which to operate the Raman amplifiers. At such a pressure, the reduction in efficiency of the amplifier at the first Stokes wavelength will be outweighed by the reduction in the amount of energy lost in the form of second Stokes light. It is proposed to incorporate a full treatment of second Stokes generation in future modifications to the Raman code.

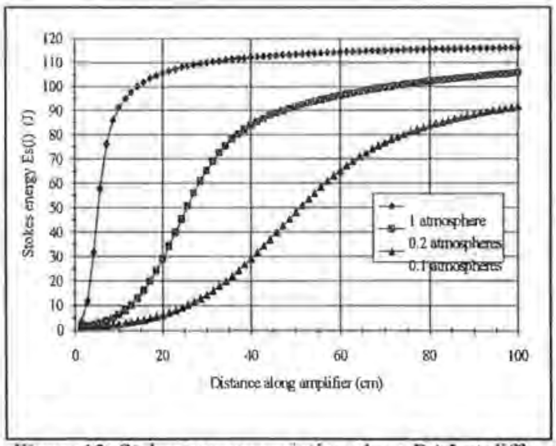

Figure 13: Stokes energy variation along RA5 at different methane pressures

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[4] E C Harvey, C J Hooker, J R Houliston, M H Key, A K Kidd, J M D Lister, I N Ross and M J Shaw *12 ps Operation of the Sprite KrF pumped Raman laser at exceptionally high brightness.* CLF Annual Report 1991 p77

A2. FRONT END SYSTEM

I N Ross, J M D Lister and C N Danson

GENERAL REQUIREMENTS AND SPECIFICATIONS

Titania will be a multi-user facility capable of meeting the needs of a wide variety of experiments. Within the limitations of the budget it is important to make the system as flexible as possible so as to encompass as many as possible modes of operation. The importance of providing a particular mode will be determined by the currently foreseen importance of experiments possible with that mode and by the uniqueness and strength of the KrF system to operate in that mode. Both the specification and the design of the front end is strongly influenced by the operating experience on the VULCAN glass Laser.

The front end specification arises from the requirements in three principle modes of operation together with some general facility operational requirements.

1. Raman Mode

a) Pulse duration
The Raman system can operate with pulses as short as 10ps and will be required to provide pulses up to 500ps.

b) Pulse quality
It is especially important for both fundamental and Stokes pulses to be very close to the transform limit. Stokes beam should also be close to diffraction limit.

c) Pulse energy
Output energy at 249nm must be at least 10mJ. Stokes beam energy for efficient extraction from the Raman system > 1mJ.

d) Pulse contrast ratio
Due to the transient nature of the Raman amplifiers the contrast of the output Stokes pulses is high with low contrast on the input pump and Stokes. Front end background levels should be $<10^{-2}$ into beam solid angle to prevent significant extraction of energy from later amplifiers.

2. CPA Mode

a) Pulse duration
The oscillator should generate pulses of duration less than 100fs and as short as possible. The front end output pulse is stretched and chirped with a pulse duration of ~50ps.

b) Pulse quality
The generated pulse should be transform limited and its spectral width is required to be preserved through the third harmonic generation stage, stretcher and up to the front end output. This is to ensure the shortest possible pulse after recompression.
Close to diffraction limited performance is also required to maximise focusable intensity on target. Pulse front distortion must be controlled to ensure cancellation for complete system.

c) Pulse energy
A front end output energy of at least 100μJ should be provided to ensure efficient energy extraction from TITANIA.

d) Pulse contrast ratio
The front end must satisfy two requirements to ensure adequate contrast for the recompressed pulses on target. The prepulse level on target should be less than $10^9\ \mathrm{W\,cm^{-2}}$ for ASE and less than 10^{-9} for prepulses. Hence, considering the ASE generated in Sprite and Titania and the saturation in Titania respectively, the front end should have zero ASE and $<10^{-10}$ prepulse level. The chirp on the stretched pulse should be capable of complete cancellation at the compressor. This requires that the nonlinear component of chirp due to GVD is small, and that the chirp due to SPM is negligible.

3. Spatially Uniform Beam (SUB) Mode

This mode will be a useful addition to modes 1 and 2 to give TITANIA some 'ISI' capability. Since a full ISI design in which an ASE source is image-relayed through the entire KrF system is not compatible with the Raman configuration, it is proposed to use a broadband longpulse source (temporally incoherent) but with high spatial coherence and to generate smooth profiles on target using beam smoothing techniques (such as random phase plates) at the end of the system. The specification of the front end ISI output beam is similar to that for the CPA stretched pulse except in the following respects:

The pulse duration should be from 100ps to a few ns.
There are no stringent requirements on pulse quality.

4. Facility Operations

There are a number of other requirements which arise both from the need for a flexible and reliable facility and from specific additional modes of operation.

a) Flexibility
The ability to switch quickly and easily between different modes of operation is an important aspect of a facility. This has an influence for example on the design of oscillator such that a change in pulse duration can be achieved quickly. A further implication is that rapid beam switching using mirror translators is built into the scheme so that all possible modes of operation are achieved without disruption to the system.

b) Reliability
One aspect requiring considerable improvement is in pulse to pulse stability. Gain saturation in TITANIA relaxes this requirement to some extent so a ± 20% pulse energy stability is considered an adequate specification.

Due to increased complexity of the front end it is important to build in sufficient redundancy and back up to minimise down time in the event of a failure.

More extensive diagnostics will be required to ensure increased reliability and reduced operator effort.

c) Synchronised long and short pulse
This mode of operation will require simultaneous generation and amplification of long and short pulses and the ability to synchronise them to an accuracy less than the short pulse duration. As much flexibility in pulse duration as possible is desirable.

d) Alignment
This is best carried out using the front end beam at 8-10 Hz and places an energy requirement on the front end to enable visual or CCD observation of beams through the complete TITANIA system. Estimates indicate that the energy specifications for Raman modes are 5mJ @ 249nm and 1mJ at 268nm and for CPA mode is 100μJ for alignment. These are close to the requirements for system operation. However, for alignment only, it is possible to boost the front end output by amplification in the EMG 103. The front end should be configured to allow this option.

SYSTEM DESIGN

1. Raman Front End design

Figure 1 shows a schematic of the proposed Raman front end. This includes two major new items : a "long pulse" oscillator and a high energy solid state amplifier. The rationale leading to this proposal is as follows:

a) The current oscillator is unable to supply pulses at the longest pulse durations and its stability is not good over the range (10-60 ps) that it can cover.

b) A second oscillator, especially if it has a large overlap in performance with our existing oscillator, will provide important back up in case of breakdowns.

c) The requirement for synchronised long and short pulses will require a second oscillator.

d) The present amplifier system has limited reliability and the shot to shot variations (often >2:1) are not acceptable.

e) The energy capability of the present system is marginal.

f) The contrast ratio (especially important for CPA operation) is considerably improved if a discharge KrF excimer is not used.

Two Pockel' s cell optical gates are shown before and after the 746nm amplifier. Either or both may be necessary, depending on the design of amplifier, to reduce the level of pre- and post-pulses before the THG to an acceptable level.

The third harmonic generation (THG) stage must operate at high efficiency for these long pulses. Demonstrated efficiencies of >70% have been achieved. A reasonable specification for the TITANIA THG is 35-40% efficiency.

No changes are anticipated for the Raman generation.

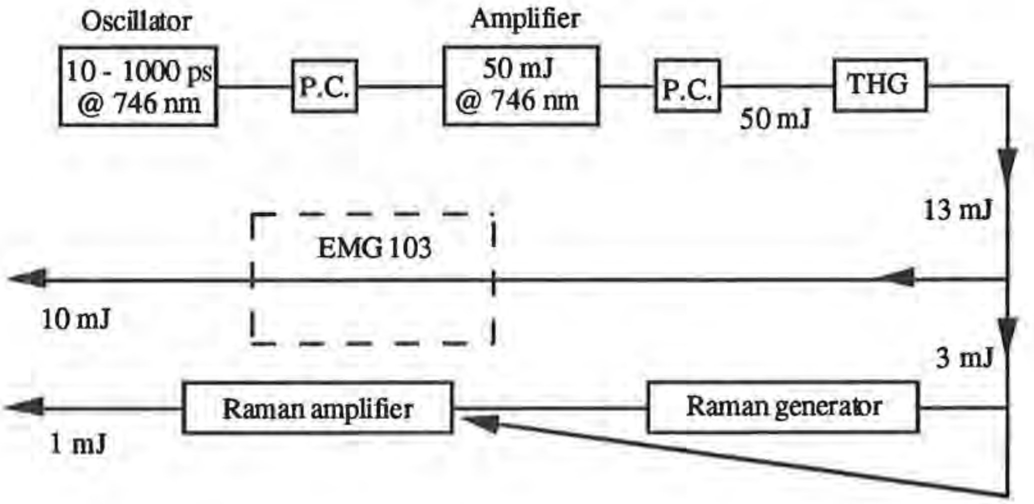


Figure 1 : Raman front end

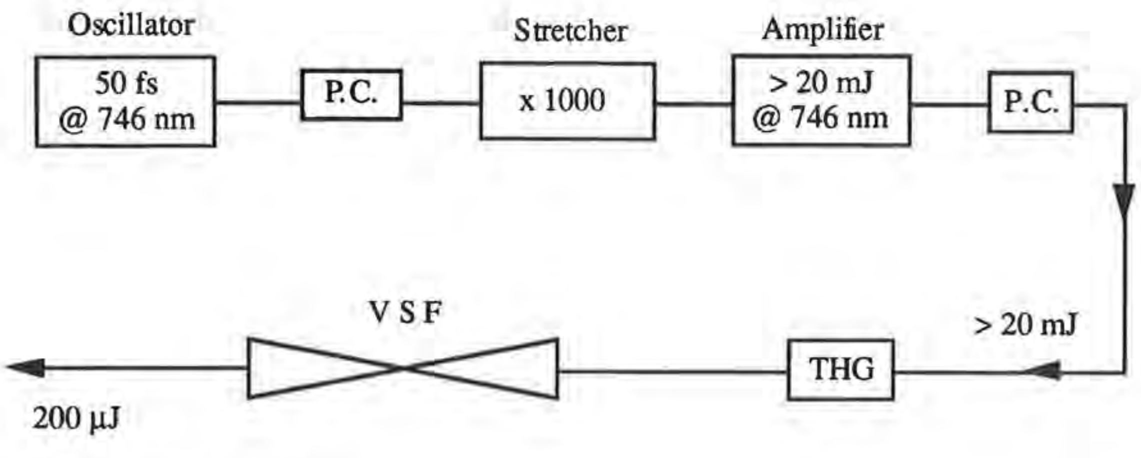


Figure 2 : CPA front end

2. CPA Front End Design

Figure 2 shows the schematic of the CPA front end. Pulses are generated with as short duration as possible from the existing TSUNAMI oscillator. They are stretched in a grating stretcher to a pulse duration such that after amplification and tripling the duration is about 50ps. This ensures an absence of nonlinear effects in the visible amplifier and sets up the correctly chirped pulse for the KrF amplification. A third harmonic efficiency of 1% can be expected with the chirped pulse. By using large bandwidth (thin) crystals or by angularly dispersing to phase match over the full bandwidth in a longer crystal, up to 10% efficiency may be possible.
A spatial filter is the final front end element to ensure high spatial beam quality for projection into the KrF system.

It should be noted that replacement of the frequency tripling stage by a pulse compressor stage would give a front end capability of ~50mJ in perhaps as short as 50fs at 746nm. Such a 1TW system at 10 Hz would be of interest to facility users in itself and could be upgraded to the several TW level by addition of a further amplification stage.

The zero ASE front end requirement demands the absence of KrF amplifiers in this mode.

3. Spatially Uniform Beam (SUB) Front End Design

Within the hardware existing or proposed for Raman and CPA operation there are two options for a SUB mode source. If a short pulse (<100ps) is required the front end in CPA mode supplies a useable pulse since it is very broad band and has a pulse duration of about 50ps. If a long pulse (>1ns) is required it is possible to operate the EMG 103 laser as a broad band oscillator followed by fast optical gates to generate the required pulse duration with good contrast ratio. Although the CPA mode generates a broader bandwidth pulse, it is a chirped pulse and its effective coherence time is greater leading to less effective beam smoothing characteristics.

INTEGRATION, DIAGNOSTICS AND SERVICES

1. System Integration

The design is considering the installation of two oscillators together with two amplifier systems with the possibilities of CPA, Raman, SUB and synchronised operation. The two oscillator configuration is a starting point and we should provide the room for at least a third oscillator with diagnostics, and good access around the tables.

It would be impossible to cater for every user request from the outset so a mode of operation could be used which allows a "fast" response time to requests for pulse width/bandwidth changes.

This would involve the ability to switch oscillator outputs into the two beamlines. This does not need to be too sophisticated but requires a small aperture mirror arrangement with three point mounts together with many apertures/alignment points. Depending on the beam-line configuration this could be done on a 2x4 table. If timing dog-legs are required for synchronisation then obviously more room would be required.

A similar scenario to that described above can also be seen following the third harmonic crystals. With similar arrangements for available table space and access.

2. Diagnostics

It is important to have dedicated diagnostics on a versatile front end system for the following reasons:

(i) To set-up the system.
(ii) Monitoring of system to optimise performance.
(iii) As a user facility it is necessary to minimise down-time.

It is proposed that the pump lasers should not be externally diagnosed. Being commercial systems they have internal monitors which can be observed locally.

It is important to monitor the output of the short pulse oscillators. This should include:

(i) Scanning a/c for pulse-width.
(ii) Spectrometer for bandwidth.
(iii) Diode/oscilloscope for cw mode-locking behaviour at shot time.

These diagnostics will have to be doubled up if a second oscillator is used. (two 2x4 tables)

For certain experiments we will also require a monitor of the synchronisation. Depending on the degree of synchronisation required this could be a streak camera. (one 2x4 table)

In the CPA system it would not be necessary to monitor the stretched pulse on a routine basis but only during set-up. Therefore we will need access between tables for scopes etc.

To monitor the performance of the optical pre-amplifier(s) it will be important to monitor the energy on the beam-lines prior to injection into the third harmonic crystals, followed by energy and spectral monitoring. (one 2x4 table)

A further diagnostics package will also be required following both the EMG 103 (or its replacement) and the Raman amplifier. This is the final point of monitoring prior to injection onto Sprite/Titania and would therefore need to be reasonably thorough. The following diagnostics are felt necessary:

(i) Energy (on both beam lines).
(ii) Spectrum (probably an both beam lines).
(iii) Pointing stability (Raman mode).
(iv) Focusability.

This will require two 2x4 tables.

a) Oscillators

1. Scanning autocorrelator x 2 → Pulse widths
2. Spectrometer x 2 → Wavelength
   → Bandwidth
   → Imperfect modelocking
3. Diode and fast scope x 2 → Imperfect modelocking
4. Synchronisation monitor → Diode and fast scope
   → X-correlator e.g. S.A
   → Streak camera
5. Power meter

b) 746 nm amplifiers

1. Energy monitor x 2 → Output Energy
   → Pulse to pulse stability
2. Spectrometer → CPA Spectrum
3. CCD→ beam profile @ aperture → NF profile
   → Alignment
4. Energy monitor on pump laser

c) Third harmonic generation / Spatial Filtering

1. Energy monitor
2. Spectrometer → UV wavelength
   → Bandwidth
3. CCD→ beam profile @ aperture → Output NF profile
   → Alignment
   → F.F. profile → Pointing
   → Beam quality

d) Raman front end

1. Energy monitor
2. CCD → Beam NF profile @ aperture
   → F.F. profile

e) General

1. Streak camera
   - must be available for 20 ps → 1 ns pulses
2. Single shot autocorrelator
   - must be available for sub 20 ps pulses

f) Priorities

These are determined by the most common failure modes, for which on-line diagnostics must be available. Less common failure modes together with set-up procedures require plug-on availability of diagnostics. From past experience a priority list of failure modes is as follows:

1. Reduction in energy
   - All energy monitoring should be on-line.
2. Oscillator pulse length and wavelength drift
   - Autocorrelator and spectrometer on-line.
3. Modelocking error
   - Diode + fast scope on-line.
   - May need a fast activation device to protect 746 nm amplifier in case of CPA bandwidth collapse.
4. Alignment drift
   - Front end output CCD profile diagnostic on-line.
5. CPA Spectrum change
   - Front end output spectrometer on -line.
6. Pulse shape degradation and prepulse (particularly for longer pulses)
   - Streak camera on-line

3. Services

All the present services to the oscillator room will be required.
Additional services:

1. Water and power for a second Argon ion laser (if Ti:S option is chosen for second oscillator).
2. Diagnostics transfer to control room for
   a) shot data recording
   b) preshot monitoring to maximise shot success rate.
3. Front end room should be a clean room with temperature, humidity and dust control. It could double as an optics store and general optics cleaning area given sufficient space. There should be a class 100 clean air cabinet and a sink.
4. Water and power for a second Nd:YAG laser or similar.
5. Remotely operated mirror slides

N.B. It is important that electrical noise in no way affects the operations of the front-end and the transfer of signals between front-end and control room.

REQUIRED RESOURCES

1. Costs

Item	Cost £ K.
Long pulse oscillator + diagnostics	100
High energy 746 nm amplifier	100
Diagnostics	
- energy monitoring	
- spectrometry	
- synchronisation	
- streak camera	90
System integration	
- beam manipulation	
- oscillator synchronisation	
- amplifier synchronisations	20
CPA stretcher, THG, VSF	20
Total	£ 330 K.

2. Manpower

The majority of the front end will need to be operational in the autumn of 1995. This is consequently a two year programme with the greater part of the effort required in the final six months, after the shut down of SPRITE.

Prior to SPRITE shut down, available R&D manpower is 1.3 MY (Grade 7), 0.3 MY (HSO) 0.15 MY (SSO), while during shutdown the HSO is available full time. Additional effort will be required to help design, purchase, build and test the front end to its completion in 1998. This should amount to 1-2 MY of SO or equivalent over the period from 1994-98.

It is assumed that engineering effort required to prepare and to fit out the oscillator room and to supply the required services will be accounted for elsewhere. Some additional engineering effort of perhaps 0.5 MY will be required for the following:

a) Oscillator synchronisation, electrical timing, interlocking

b) Small scale engineering (Mounts, brackets, holders, slides, etc.) required to set up and integrate the optical layout and diagnostics.

STAGED INSTALLATION

Stage 1 (April 1996)

Operation of the front end for CPA mode is required. This uses the present oscillator with a new solid state high energy amplifier to ensure that ASE levels on target are kept below acceptable limits.

Work package:
1) Transfer to new area and install new layout for compatibility with later stages of upgrade,
2) install new solid state amplifier,
3) modify stretcher for 50ps stretched pulse,
4) improve diagnostics.

Estimated cost : £210K

Stage 2 (April 1997)

Raman operation mode will be required at 50% of full power with pulse durations up to 100ps. This is within the scope of the present oscillator with some modification.

Work package:
1) Upgrade oscillator for 30-100ps operation,
2) install Raman/CPA switchyards,
3) improve diagnostics.

Estimated cost : £20K

Stage 3 (April 1998)

Full system brought into operation.

Work package:
1) Install long pulse oscillator,
2) set up parallel amplifier systems and switchyards,
3) implement synchronised two pulse operation,
4) upgrade diagnostics,
5) set up spatially uniform beam source.

Estimated cost : £100K

TECHNICAL ISSUES

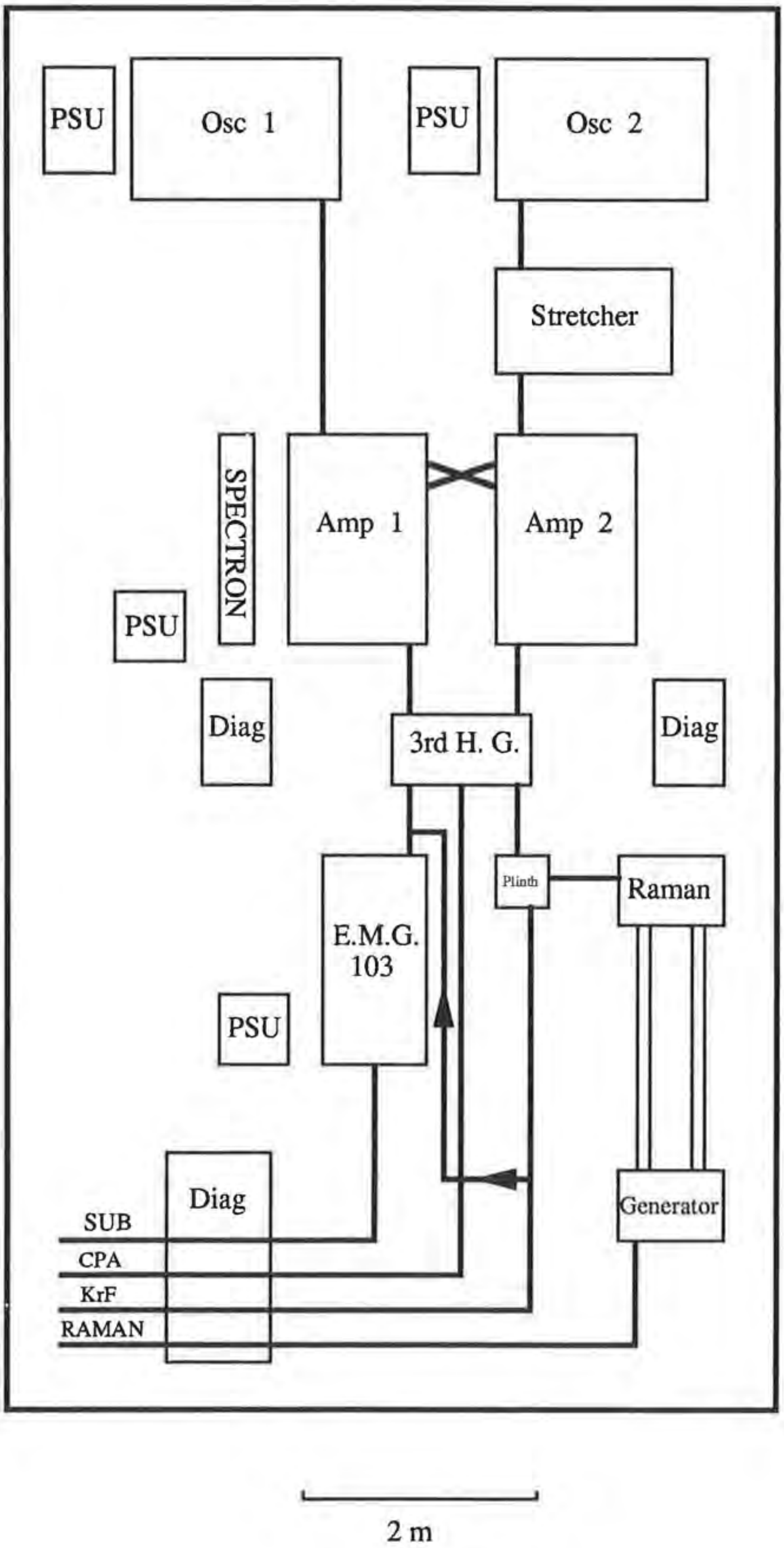
A number of technical issues need to be resolved before detailed final designs of the front end can be devised and before purchase of new components and systems.

a) Long pulse oscillator
The best design of this oscillator is not clear at present. Options include a modified argon pumped Ti:S, a diode pumped Ti:S (via Nd:YAG and SHG), and a diode laser (tuned to 746 nm). A more detailed analysis of the options in terms of the technical issues as well as the commercial availability will be conducted and a system bought or constructed (possibly in collaboration with a university group).

b) 746 nm amplifier
As with the long pulse oscillator, a survey of possible contenders will need to be carried out before purchase or construction. The active material may for example be Ti:S (laser pumped) or Alexandrite (flash pumped) or LiCAF and the amplifier may be multipass or regenerative. A point design has been carried out for a YAG pumped multipass Ti:S amplifier similar to one reported by LeBlanc (PhD thesis). Expected performance for the shortest pulse (10ps) is 50mJ at a B-integral of 1 for a pump energy of 500mJ.

c) The CPA scheme requires about 1% third harmonic conversion efficiency. It is expected that much higher efficiencies are possible using dispersion compensation techniques. These have been demonstrated in the literature, but not as yet at RAL.

Titania Oscillator Room



A 3. OPTICAL SYSTEM

C J Hooker
Rutherford Appleton Laboratory

1. SUMMARY OF OPTICAL LAYOUT AND DESIGN

The Titania system will provide four Raman beams to target, with high brightness, very low prepulse, a range of possible pulse lengths and near diffraction-limited quality. In addition to these, two good-quality KrF beams will be available for backlighting, CPA, broadband irradiation and other specialized applications. The Raman chain will consist of two new amplifiers, with lightguide apertures of 5 cm and 16 cm, which will be called RA4 and RA5 to avoid confusion with names in existing reports and publications. Both will be angularly multiplexed, with two extracting beams in the first and four in the second. The KrF pump beams for these amplifiers will carry trains of four pulses, rather than single pulses as in the Sprite system.

The KrF chain will consist of Sprite and Titania only. If Goblin were included, the overall small-signal KrF gain would be too large, leading to unacceptable levels of ASE. It is also the least reliable of the pulsed-power machines. Sprite will have twelve angularly multiplexed beam channels, each of which will drive two of the twenty-four channels in Titania. The overall optical layout is shown in Figure 1, and schematics of the KrF and Stokes beams in Figure 2, with various optical parameters indicated.

1.1 BASIC DESIGN CONSIDERATIONS

The first question to resolve is the distribution of pump beams to each of the Raman amplifiers. Recent code modelling indicates that the first amplifier needs around 10% of the pump energy in order to achieve reasonable efficiency and provide enough input to the final amplifier. This condition is met by using two beams from Titania to pump the first amplifier and twenty to pump the second. The remaining two channels in Titania provide the KrF beams for CPA or backlighting.

In the start-up configuration, there will be one KrF channel in Sprite, carrying a chirped pulse of around 50ps duration. This will feed either one or two channels in Titania, and the pulses can either be recompressed in a grating pair to give a pulse of 100-200 femtoseconds on target, or used without compression for backlighting or as an irradiation beam.

A later upgrade, which will increase the flexibility of the system, will be to make the two KrF beams independent by using two channels in both Sprite and Titania. This will allow, for example, simultaneous operation of CPA and long-pulse, high-uniformity KrF. One of the remaining ten channels in Sprite must then carry two groups of pulses, which can be done using a delayed second group with horizontal polarization. At the output of Sprite these extra pulses will be separated from the normal, vertically-polarized pulses on a polarizing beamsplitter, and used to drive two of the Titania inputs. A preliminary design study by Technical Optics indicates that sufficiently good polarizing beamsplitters can be fabricated, with an S reflectivity of 85% and a P transmission of 85% at 45 degrees. Pre- or post-pulses will not affect the Raman amplifiers, because they will have the wrong polarization.

The above considerations lead to the following numbers of beams in the KrF system:

Initial system:

Amplifier:	Sprite		Titania
CPA beam	1	not split	1
RA4 pump	1	split x 2	2
RA5 pump	10	split x 2	20
Total	**12**		**23**

Final system:

Amplifier:	Sprite		Titania
KrF beams	2	not split	2
RA4 pump	1	split x 2	2
RA5 pump	10	split x 2	20
Total	**13**		**24**

2. ELEMENTS OF THE KrF OPTICAL SYSTEM

2.1 KrF MULTIPLEXING

There will be two KrF inputs to the multiplexing area: a stretched chirped pulse for CPA, and a beam with a single pulse of the required length for the Raman chain. A pulse stacker will generate two trains of four equally-spaced pulses from the single pulse, and each of these will then be split into six to give a total of twelve beams. Eleven of these will be sent into Sprite, and the twelfth will be used for diagnostics and to provide trigger signals. The interval between pulses in the train will be 1.5 ns, and the beam multiplexing interval will be 6 ns, so that the individual pulses are equally spaced in the amplifiers. The twelfth channel of Sprite will be occupied by the CPA beam.

2.2 OPTICAL CONFIGURATION OF SPRITE

Input beam:	1.8 cm diameter
Input optic:	F = 1.12 m silica lens
Back mirror:	R = 19.14 m concave
Output optic:	F = -9.59 m CaF_2 lens
Output beam:	9 cm diameter

The optical configuration of Sprite is being changed as part of the Raman upgrade. The image-relaying properties of the system are being improved by using positive lenses at the input, requiring the beam pipe to be filled with helium. Recent measurements of the non-linear refractive index of helium indicate that there will be no problem with spectral broadening due to self-phase modulation in the focus. The output lenses and back mirror are also being changed, so that the beam will expand by a factor of five instead of four. The CPA beam will use the beam line closest to the axis of Sprite in order to minimise aberrations, and will be timed so it is the first pulse to be amplified.

Following Sprite, the beam lines carrying the Raman amplifier pump beams will be split and delayed to give twenty-two equally-spaced groups of pulses into Titania. The CPA beam will not be split, and will be the first beam to be amplified in Titania, again using one of the beam lines closest to the axis to minimise aberrations.

2.3 OPTICAL CONFIGURATION OF TITANIA

Input beam:	9 cm diameter
Input optic:	R = 18.41 m convex mirror
Back mirror:	R = 48.00 m concave
Output optic:	R = 41.54 m convex mirror
Output beam:	16 cm diameter

The beams entering Titania will be expanded using convex mirrors rather than lenses, and the output beams will be recollimated using mirrors. This reduces the number of transmissive optics and 45-degree mirrors in the system, and allows the best use of the space available in the optics bay. In order to maximise the extracted volume of the amplifier, the beams will expand to 42 cm diameter at the back mirror, leading to a loss of around 7% of the beam area as a result of vignetting of off-axis beams.

The use of convex mirrors inevitably involves some off-axis reflections, and will result in a few waves of aberration on the pump beams; the calculated amount of aberration will not in any way affect the operation of the Raman amplifiers. Because the CPA beam will be used directly on target, it is very sensitive to optical aberrations, but they can be eliminated either by using lenses to expand and recollimate this one beam, or by careful choice of reflection angles from the input and output convex mirrors. No decision has yet been taken as to which of these methods is most appropriate.

The input/output array has been designed to be as compact as possible in order to fit into the optics bay. The layout of the mirrors in this array is shown in Figure 3(a). The gaps in the array at the top and bottom could be used for a helium-neon laser to monitor the alignment of the back mirror, and for a photodiode channel to monitor the ASE.

2.4 THE KrF OPTICS BAY

The northern side of R2 is occupied by the KrF optics bay, which will contain the input and output beams for Sprite and Titania and the delay paths following the 12-to-24 beam split after Sprite. The demultiplexing mirrors for the pump beams to RA4 and RA5 will also be placed in this bay. After demultiplexing, the pump beams will be steered into RA5 by arrays of 45° mirrors opposite the entrance to the Raman optics bay. Figure 3(b) shows the layout of these turning mirrors, which also form the pumping array for RA5.

3. ELEMENTS OF THE RAMAN OPTICAL SYSTEM.

3.1 THE RAMAN OPTICS BAY

The Raman optics bay lies in the link building between R2 and R7, and contains the Raman delay lines, vacuum spatial filters and the two main Raman amplifiers. The output beams from RA5 will be propagated to the Raman target area in helium-filled beam pipes, and the CPA beam will be propagated to its target area in an image-relaying beam pipe.

3.2 RAMAN AMPLIFIER 4

Recent code modelling of the Raman system indicates that with with 10% of the total pump energy available for RA4, the aperture of the lightguide needs to be around 5 cm, in order to achieve reasonable efficiency and provide enough input to the final Raman stage. The present RA3 has been redesigned for the forthcoming Raman upgrade, but its aperture is 10 x 12 cm, so it is not suitable for the Titania system. However, a new lightguide can be installed in the cell, allowing the hardware to be re-used. The cross-section of the new lightguide will be a rectangle 6 cm wide by 5 cm high, with the pump beams entering from above and below the guide axis, and the Stokes beams entering from either side and crossing over in the guide. The length of the guide will be 1 metre as before. Two of the off-axis beams from Titania will be used as pumps: these beams are vignetted such that their major and minor diameters are 16 and 13.6 cm respectively, almost exactly the 6:5 ratio required to fill the guide. These beams will not be recollimated at the Titania output array, but will instead be allowed to converge to reach the desired size, before being recollimated using negative lenses. The detailed design of the optical path will need to ensure that no problems arise from the high intensity in these beams.

Multiplexed extraction of the Raman amplifier makes it possible for light from the leading Stokes pulse to be scattered from the amplifier windows into the second beam line. Such scattered light would form a prepulse, which could then be amplified in RA5 by one of the pump pulses. Although it is not possible to avoid the scatter in RA4, Figure 4 shows that with correct timing of pump and Stokes pulses in the two amplifiers, the prepulses from RA4 will not be amplified in RA5. The only prepulse on the output beams will be due to the scatter in the windows of RA5 itself.

3.3 RAMAN AMPLIFIER 5

RA5 will be a completely new amplifier, with a 16 cm square lightguide aperture. The code modelling indicates that the proposed length of 1 metre is adequate for long-pulse operation, and may be too great for short pulses with atmospheric-pressure methane. However, the gas can be diluted with helium to give the required gain-length product. RA5 will be pumped by 20 beams from Titania, arranged in four groups of five at an average angle of 3° from the axis. The Stokes beams will be 15 cm in diameter, and will move diagonally across the aperture as they pass along the guide, each making an angle of 0.81° with the axis. The windows will be 1 mm thick silica, and as with RA4 they will be at normal incidence.

The size difference of 1 cm between the KrF and Stokes beams allows the Stokes to move transversely by 1 cm per metre (assuming a 1 metre long lightguide) in each coordinate. The beams cross over in the centre of the guide and separate by a few centimetres in the length of the Raman optics bay, which is 25 metres. The beams cease to overlap after they have travelled about eight metres, but around ten metres of path will be required before they are separated sufficiently for each to be received on its own steering mirror.

3.4 THE PANCAKE EFFECT

The pancake effect refers to the apparent increase in pump pulse length due to the inclination of the pump beams to the axis of the lightguide. The magnitude of the effect is proportional to the aperture of the guide, and hence to the beam diameter. The increase in pulse length from the effect is $\Delta t = A \sin\theta / c$, for a guide aperture A and a pump beam angle of θ. For a pump angle of 4 degrees and an aperture of 16 cm, Δt is 37 ps, which for a 30 ps pulse is 1.23 times the pulse length. A two-dimensional Raman code developed at Imperial College indicates that the pancake effect begins to degrade the amplifier performance when the pancake time Δt is equal to the pulse length. However, RA3 is currently operated with a Δt of 1.2 times the pulse length without apparent loss of efficiency, so provided that RA5 is operated in a similar regime it, too, is unlikely to be adversely affected by the pancake effect. If the Titania system were to be operated at 10 ps, compensation for the pancake effect would certainly be required.

3.5 DELAY LINES

The existing delay line functions very well and will be retained, with slight modifications, in the Titania system. The delay needs to be increased to compensate for the longer path length of the KrF beams in Titania, and this can be done by adding extra mirrors to increase the number of passes. The delay line will be situated in the Raman optics bay before RA4. The delay between RA4 and RA5 is relatively short, and will be taken up with beam expanding VSFs.

3.6 BEAM QUALITY CONTROL

A new vacuum spatial filter between RA4 and RA5 is being constructed for the Raman upgrade, using a telephoto-type optical construction to maximise the focal lengths of the lenses. This spatial filter will be used in the Titania system between the delay line and RA4, with a change to the input lens to give an output beam of 5 cm diameter.

To maintain the Stokes beam quality, and to minimise second Stokes seeding of RA5, VSFs are also needed between RA4 and RA5. However, the energy after RA4 will be several joules, which will severely reduce the pinhole lifetime unless the diameter of the focal spot can be increased by using focal lengths of the order of 15 to 20 metres. This in turn leads to long Stokes propagation paths between RA4 and RA5, and may require all the RA5 pump beams to be delayed. An alternative is to use non-diffraction-limited pinholes in these final VSF's: this would allow the use of existing shorter-focus lenses, and restrict the propagation of second Stokes without the problems of pinhole damage. Operational experience with the new VSF will help to resolve this question.

3.7 LASER DIAGNOSTICS

At the low-energy end of the system, silica plates can be inserted into the laser paths to obtain diagnostic beams for energy monitoring, etc. After Titania, however, the B integral that would be introduced by the silica becomes significant, so it will be preferable to use the small fractions of the energy transmitted through turning mirrors for diagnostic purposes. To make this possible, fused silica will be used for the the mirror substrates. This is satisfactory for some purposes, but energy measurements taken through mirrors are unsatisfactory, because the transmission is seldom known with sufficient accuracy and may change over time or if the beam angle is altered. Other techniques for energy monitoring need to be investigated; one possibility is to introduce a single 96% reflector at the output end of the system, which would provide enough energy for accurate measurements while being less lossy than a silica plate. Diagnosing the Stokes beams is more difficult, because their intensity is much greater, thus increasing the problems of obtaining small fractions for diagnostics.

The ASE signals from Sprite and Titania will be monitored with simple photodiodes as at present, to give a useful timing diagnostic for the pulsed power. A dedicated streak camera will almost certainly be needed for preliminary timing of the pump beams, and for synchronising the diagnostic and irradiation beams.

4. IMAGE RELAYING

4.1 KrF CHAIN

The introduction of positive lenses at the input to Sprite makes a big difference to the image-relaying properties of the KrF chain. Calculations based on the layout in Figure 1 show that a plane 0.7 metres in front of the input lens of Sprite is imaged onto the output mirrors of Titania. It will be straightforward to arrange for a near-field plane in the oscillator to be imaged into this position by a spatial filter before the multiplexer. The different path lengths introduced by the multiplexer make it impossible to image relay the same plane in all the KrF beams; however, the near-field profiles of the Raman pump beams will be improved significantly by the image relaying on their beam lines. It is intended to propagate the CPA beam to its target area in an evacuated beam pipe with image-relaying lenses, set up so that the output plane of Titania is imaged onto the first grating in the compressor. This will give the best possible near-field, and minimise the risk of damage to the gratings.

4.2 STOKES BEAMS

The beam transport optics in the Raman chain include vacuum spatial filters between amplifiers, and an optical delay line consisting of a series of concave mirrors. Both of these have good image-relaying properties, and by careful choice of focal lengths in the VSFs, it will be possible to re-image a near-field plane in the oscillator at a point very close to the target chamber.

5. POWER LIMITS IN THE TITANIA SYSTEM

5.1 FACTORS LIMITING THE LASER POWER

The maximum energy available from the laser at various pulse lengths is fixed by the design of Titania, so the system as a whole will become power-limited at some pulse length determined by non-linear processes in the optical path. The factors which limit the power are the B integrals in the target chamber windows and the beam propagation paths, and two-photon absorption in the windows of the Raman amplifiers and the target chamber. The beam diameter must also be considered, since in conjunction with the pulse length and energy it defines the intensity in the beam, and hence sets the non-linear optics limit to the system performance. The minimum beam diameter will be set by the damage threshold of the mirrors, and the maximum possible diameter by the cost of optics and by geometrical factors in the multiplexing.

The energies used to calculate the non-linear optical limits were obtained using the code models of the KrF and Raman systems described in Appendix 1, and for convenience the KrF output energies obtained with the expected inputs of 50 μJ per pulse (10ps and 30ps) and 100 μJ per pulse (100ps, 300ps and 1ns) are reproduced below. The KrF energies given in the table are those obtained from Titania, but the figures quoted for the RA5 pump energy take account of absorption and reflection losses in the path to the Raman amplifier. The energies listed are the maximum of which the lasers are capable; in practice, imposing a limit of B = 3 in the longest demultiplexing path severely limits the usable energy at 10ps.

Pulse length (ps):	10	30	100	300	1000
KrF energy (J)					
Per pulse:	6.3	6.5	7.1	7.7	9.0
Total:	504	520	568	616	720
RA5 pump (J)					
With losses:	329	420	520	560	680
B-integral limit:	138	420	520	560	680

The pump energies from the above table were used in the Raman code to model the performance of the Raman amplifiers, assuming Stokes input energies of 250μJ at each pulse length, which is within the specification for the front end. However, the results of the modelling have to be interpreted with care. The highest pump-to-Stokes conversion efficiencies predicted by the Raman code are in the region of 90%. Experience with Raman amplifiers suggests that the efficiency will be reduced by a number of experimental factors which are not accounted for in the code, such as the effects of beam spatial profile and second Stokes generation, so that in practice the maximum efficiency is more likely to be around 80%.

The table shows the code predictions of Stokes energy and the energy expected in practice, and also the total power and energy on target in four beams.

Pulse length (ps):	10	30	100	300	1000
Stokes output (J)					
Code prediction:	94	380	472	500	480
Expected:	83	332	416	437	422
RA5 efficiency (%):	60	79	80	78	71
On target (4 beams)					
Energy (J):	60	227	328	365	362
Stokes power (TW):	6.0	7.6	3.3	1.2	0.36

5.2 DAMAGE THRESHOLD LIMITS

The lower limit on the beam diameter is set by the damage threshold of the Stokes beam mirrors. Data on coating damage at 249 nm is shown in Figure 5, which gives the fluences at which oxide-based and fluoride-based coatings survive for more than 100 shots. In practice, oxide coatings in use on Sprite showed laser damage, confined to hot spots, after about 2000 shots at an average fluence of 30 mJ/cm^2. On measuring recorded near-field profiles from Sprite, the peak intensity was found to be about twice the average, and allowing a possible further factor of 1.4 for the diffraction fringe caused by an edge, the peak fluence giving rise to the observed damage could have been three times the average, or 90 mJ/cm^2. This is 4.5 times lower than the 100-shot survival fluence. If the same factor is applied to the fluoride coatings, scaled-down fluences for 2000-shot survival are as low as 310 mJ/cm^2.

A measurement of the long-term survival of gadolinium fluoride/cryolite HR coatings for 249 nm was made using 10 ps pulses from the CPA oscillator on Sprite. The energy per pulse was lower than was used for previous damage tests, so the samples had to be placed very close to the focus of the lens, and the spot was rather non-uniform. However, the test coating survived more than 2000 shots at a peak fluence between 400 and 560 mJ/cm^2. The scaled-down figures appeared to be a little conservative, so they were revised on the basis of this measurement. In combination with the energies in the Stokes beam, the revised fluences were used to calculate the minimum beam diameter required at the different pulse lengths. The results are shown in the table below, from which it can be seen that the beam diameter must be at least 14.5 cm.

Pulse length (ps):	10	30	100	300	1000
Pulse energy (J):	21	95	118	125	120
Survival fluence in mJ/cm^2 at 0°:	400	602	717	960	1316
Beam area (cm^2):	53	158	165	130	92
Diameter (cm):	8.2	14.2	14.5	12.9	10.8

A diameter of 15 cm has been chosen for the Stokes beams, which gives an added margin of safety and is also the same as the large-aperture beams on Vulcan.

The proposed geometry of the Raman multiplexing in RA5 requires the KrF beams to be 1 cm greater in diameter than the Stokes, ie 16 cm. In that case the fluences on the mirrors at the output of Titania will be between 125 and 180 mJ/cm^2. The use of fluoride coatings for these mirrors is therefore essential.

The above beam diameters are the minimum consistent with avoidance of laser damage problems. Any increase in beam diameter above this would incur a heavy cost penalty, as the price of optics increases approximately as the cube of their diameter.

5.3 B-INTEGRALS IN PROPAGATION PATHS

There are several points in the system where the power is limited by B integral, in particular the target chamber windows, the various beam propagation paths and the input windows of the Raman amplifiers.

The only significant contribution to the B integral in the KrF beams arises after Titania. Clearly, the distances travelled by the beams between Titania and RA5 must be minimised, subject to the constraints of demultiplexing. The minimum path for the first pulse is the sum of two quantities: the demultiplexing distance for the 20 beams and the distance of the pumping array from RA5. The first is 19 x 6 ns x 0.3 m ns^{-1} = 34.2 metres. The second is approximately 10 metres, giving a minimum of 44.2 metres for the longest path after the Titania output array. Whether this minimum is achievable depends on the actual layout, but with the present design the actual path length should be very close to the figure stated. The value of B was calculated for the maximum and minimum path lengths between Titania and RA5, using the KrF pulse energies in the table, and the results are shown below. The maximum value of B is less than 3 for all pulse lengths except 10 ps. In order to operate the system at 10 ps, the energy in each KrF pulse must be reduced to 2.3 Joules.

Pulse length (ps):	10	30	100	300	1000
KrF energy (J)					
Per pulse:	6.3	6.5	7.1	7.7	9.0
B (longest path):	8.2	2.8	0.9	0.3	0.1
Energy (J) for B<3:	2.3	6.5	7.1	7.7	9.0

The intensity in the Stokes beams is much greater than in the KrF, and B integral effects are more severe. The chamber windows are assumed to be made from calcium fluoride, and are required to support a 1 bar pressure difference. The thickness needed to do this varies linearly with aperture; for a 10 cm clear aperture a 1 cm thick window is normally used, thus $t = r/5$. The intensity-length product is given by

$$IL = Pt/\pi r^2 = P/5\pi r \text{ TW/cm} \quad (1)$$

where P is the power in the Stokes beam in TW. For calcium fluoride at 268 nm the B integral is 68 x IL (in TW/cm), thus $B = 68P/5\pi r$, and the limiting power at which B = 3 is

$$P_{max} = 15\pi r/68. \quad (2)$$

Using the proposed beam radius of 7.5cm, the value of P_{max} is 5.2 TW. However, the beam path from RA5 to the target chamber is around 30 metres, and this path must be considered in addition to the chamber window. The total B integral then becomes

$$B = 0.34\, IL(air) + 68\, IL(CaF_2), \quad (3)$$

where $L(CaF_2) = r/5$ and r is the beam radius, as before.

Consequently, $$B = \frac{0.34\, PL(air)}{\pi r^2} + \frac{68\, Pr}{5\pi r^2}, \quad (4)$$

where P is the laser power in TW. Solving this equation for P, with B = 3, r = 7.5cm and L = 30m gives the maximum power that can be propagated to the target area as only 0.11 TW. The corresponding energies are tabulated below, together with the energies limited by the window alone.

Pulse length (ps):	10	30	100	300	1000
Stokes power (TW):	2.1	3.2	1.2	0.42	0.12
Stokes energy (J):	21	95	118	125	120
Energy (J) for B=3					
In window only:	52	156	520	1560	5200
With air path:	1.1	3.3	11	33	110
Beams in argon:	15.5	46.5	155	465	1550
Beams in helium:	52	156	520	1560	5200

It is clear that the limiting factor is the propagation path rather than the chamber window. The Stokes beams cannot propagate to the target chamber in air unless the energy is kept unacceptably low, hence the beam pipe must be filled with either argon or helium. The above table shows that the use of argon would limit the energy available at 30ps, so it is essential for the beams to propagate in helium.

5.4 TWO-PHOTON ABSORPTION

Two-photon absorption losses will occur principally in the windows of RA5 and the target chamber, as these are the components where the intensity is highest. The four-fold multiplexing of RA5 means that one quarter of the total KrF energy will pass through the window at one time. The window of RA5 will be at least $16\sqrt{2} = 23$ cm in diameter (for normal incidence), and it is unlikely that its thickness will be less than 1 mm at that aperture if silica is used. The window transmission is

$$T_{TPA} = 1/(1+\beta LI) = 1/(1 + \beta LP/\pi r^2), \quad (5)$$

where P is the laser power in GW (corresponding to 20 overlapping pump pulses). Assuming a window thickness of 1 mm, a beam radius of 8 cm and $\beta = 0.07$ cm/GW (for silica), equation (5) gives the following values for the transmission:

Pulse length (ps):	10	30	100	300	1000
KrF power (GW):	2900	3500	1300	470	170
TPA transmission:	0.9	0.88	0.96	0.98	0.99

Note that the power used for the 10ps pulses was derived from the B-integral-limited pulse energy. At the longer pulse lengths the TPA losses are less than those due to Fresnel reflections, so it will be advantageous to anti-reflection coat the window if a coating with a high enough damage threshold can be fabricated. The TPA losses in the output Stokes beams are almost exactly the same as the above figures, because the effects of the smaller beam area and the smaller TPA coefficient at 268nm cancel one another out.

The calculation for the target chamber window is more complicated, because the thickness is a function of the aperture, as noted during the discussion of B integrals above. The TPA transmission of the chamber window is given by

$$T_{TPA} = \frac{1}{\left(1 + \beta \cdot \frac{r}{5} \cdot \frac{P}{\pi r^2}\right)} = \frac{5\pi r}{5\pi r + \beta P}. \quad (6)$$

The transmission of the chamber window at the various pulse lengths is shown in the table below, using a value of 0.008 cm/GW as the TPA coefficient for calcium fluoride, and a radius of 7.5 cm.

Pulse length (ps):	10	30	100	300	1000
Laser power (TW):	2.1	3.2	1.2	0.42	0.12
TPA transmission:	0.88	0.83	0.93	0.97	0.99

As before, the Fresnel losses are greater than TPA losses for pulse lengths of 100ps and greater, so anti-reflection coating of the chamber window would be advantageous, as long as a coating with a sufficiently high damage threshold can be fabricated.

6. COMPONENTS, COSTINGS AND MANPOWER

6.1 COMPONENT INVENTORY (LARGE OPTICS)

KrF chain:

Component	Needed +	Spares	Available
Sprite windows	2	3	5
Sprite back mirror	1	1	ordered
Sprite output lenses	12	2	14
Turning mirrors	26	2	24
50% splitters	12	2	-
Steering mirrors (0°)	11	2	6
Titania input mirrors	24	3	-
Titania windows	2	2	ordered
Titania back mirror	1	1	ordered
Titania output mirrors	24	3	-
Demultiplexing mirrors	22	3	-
RA4 pump mirrors	4	-	-
45° mirrors (235 mm)	22	2	-
CPA relay lenses	2	-	-

Raman chain:

Component	Needed +	Spares	Available
Delay line	1	-	1
Expanding VSF	1	-	1
50% beamsplitters	3	1	-
Steering mirrors	20	2	-
RA4 - RA5 VSFs	2	-	-
RA4 windows	2	2	-
RA5 windows	2	2	-
RA4 lightguide	1	1	-
RA5 lightguide	1	1	-

6.2 OPTICS ACCEPTANCE TESTS

A set of acceptance tests is required for optical components. At the time of ordering new optics, it should be specified that a witness piece be supplied from each coating run, so we can test the transmission and the damage threshold of each batch of mirrors. Each mirror should also be tested in the interferometer for flatness. Windows should be tested for wavefront distortion in the interferometer, and for scatter in the UV scatterometer. Manufacturers will generally not undertake to reduce the scatter below a specified level, but by testing we can reject components which are not good enough, and have them repolished.

6.3 COST AND MANPOWER ESTIMATES

The figures given below are based on budgetary quotes for the KrF optics alone from Technical Optics, plus costs for the new back mirrors and windows of Sprite and Titania. The figures for the Raman chain were based on these, with the assumption that no mirrors of larger size than 180 mm would be needed to handle the 150 mm Stokes beams (ie the mirrors are all used at normal incidence). The costs of mirror mounts, frameworks, etc are included in a separate table.

KrF chain:

Component	Needed +	Spares	Cost £k
Sprite windows	-	-	-
Sprite back mirror	1	1	10.8
Sprite output lenses	-	2	25
Turning mirrors	26	2	19.8
50% splitters	12	2	4.8
Steering mirrors (0°)	6	2	5.6
Titania input mirrors	24	3	18.9
Titania windows	2	2	31.9
Titania back mirror	1	1	20.7
Titania output mirrors	24	2	40.5
Demultiplexing mirrors	22	3	33.3
RA4 pump mirrors	4	-	2.8
45° mirrors (235 mm)	22	2	42.8
CPA relay lenses	2	-	5
TOTAL COST	ex VAT		261.9
	incl VAT		307.7

Raman chain:

Component	To buy +	Spares	Cost £k
Delay line mirrors	4	-	1.5
Expanding VSF	1	-	3.5
50% beamsplitters	3	1	4.8
Steering mirrors	20	2	29.3
RA4 - RA5 VSFs	2	-	8
RA4 windows	2	2	1
RA5 windows	2	2	4
RA4 lightguide	1	1	2
RA5 lightguide	1	1	3
TOTAL COST	ex VAT		57.1
	incl VAT		67.1

Total cost for the large optics is £374.8k, including VAT. Many small aperture optics and their mounts will become available once Goblin is no longer incorporated in the system. For this reason no additional costs have been included for optics before Sprite.

An estimate of the costs of mechanical components, principally mirror mounts and support frames, is given below. Budgetary quotations have been obtained for mirror mounts suitable for the largest optics, of 120 and 180 mm diameters. The figures quoted vary between £360 and £750 per mount for a quantity of 100. The best option appears to be a customised version of a commercially-available mirror with different sizes of mirror cell on a standard adjustable base. The cost of this option is £480 per mount for 100. A reasonable estimate of the cost of the 80 large mounts that are needed is therefore £40k. No allowance has been made in these costings for motorised adjustments on any of the mounts.

Mechanical component costings:

Item		Number	Cost £k
Support frames (various, small)		5	20
Support frames RA5 pump		4	16
Titania I/O array frame		1	12
Timing adjustment slides		22	22
CPA beam pipe		1	45
Mirror mounts (120 & 180 mm)		80	40
Mirror mounts (235 mm)		24	20
TOTAL COST	ex VAT		175
	incl VAT		205.6

Adding the cost of the optics themselves, the estimated total spend on the optical system is £580k.

The amount of design work required for the mirror mounts, support frames, VSFs, a new Raman amplifier and new delay line is estimated at 2 man-years. Some of this will probably be contracted out, and hence will appear as spend in the final total. It is estimated that the testing of all the optical and mechanical components will take one man-year, and the installation a further man-year. The total effort required for the optical system is therefore 4 MY.

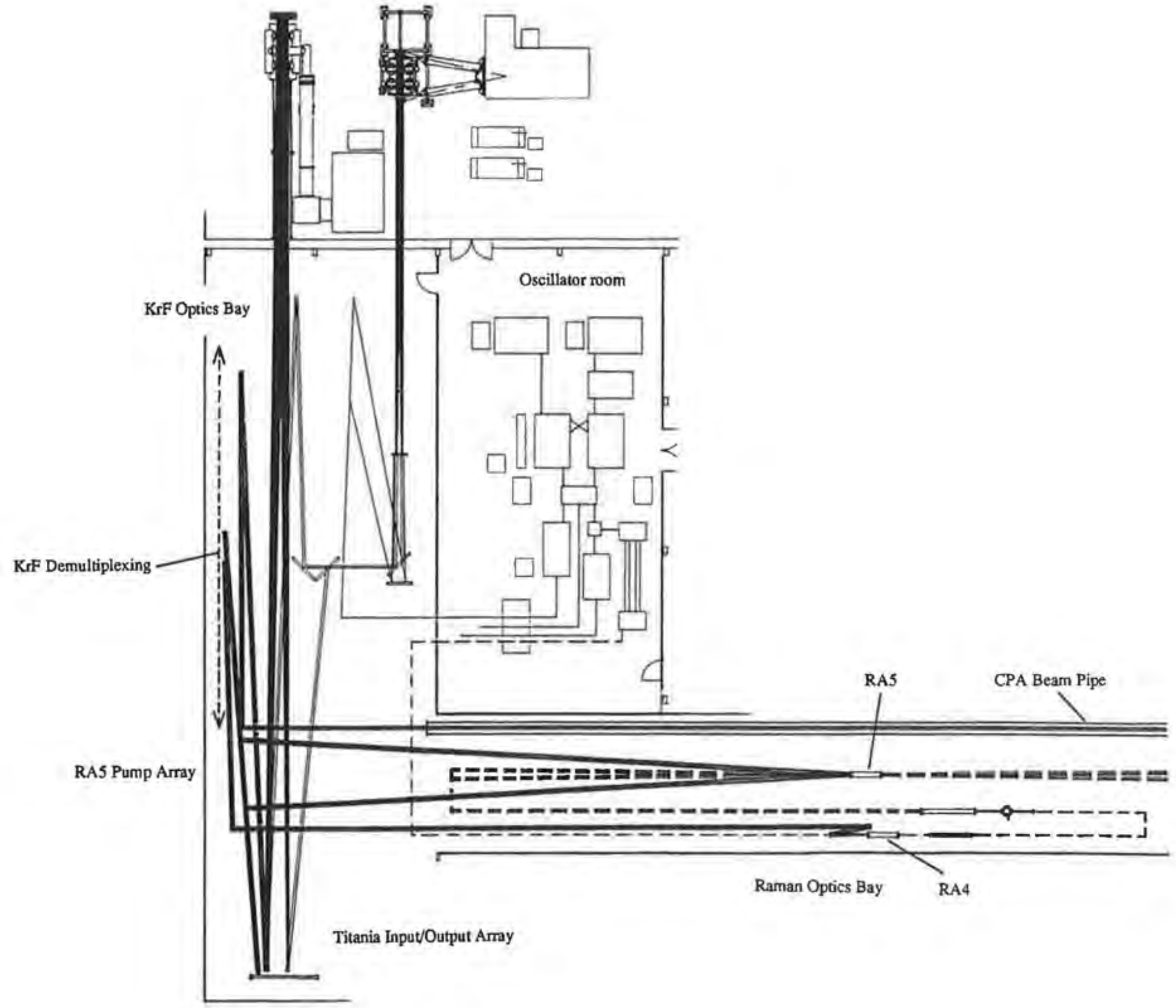


Figure 1. Schematic layout of the Titania system optics with major components indicated.
The KrF beams are shown with solid lines and the Stokes beams with dashed.

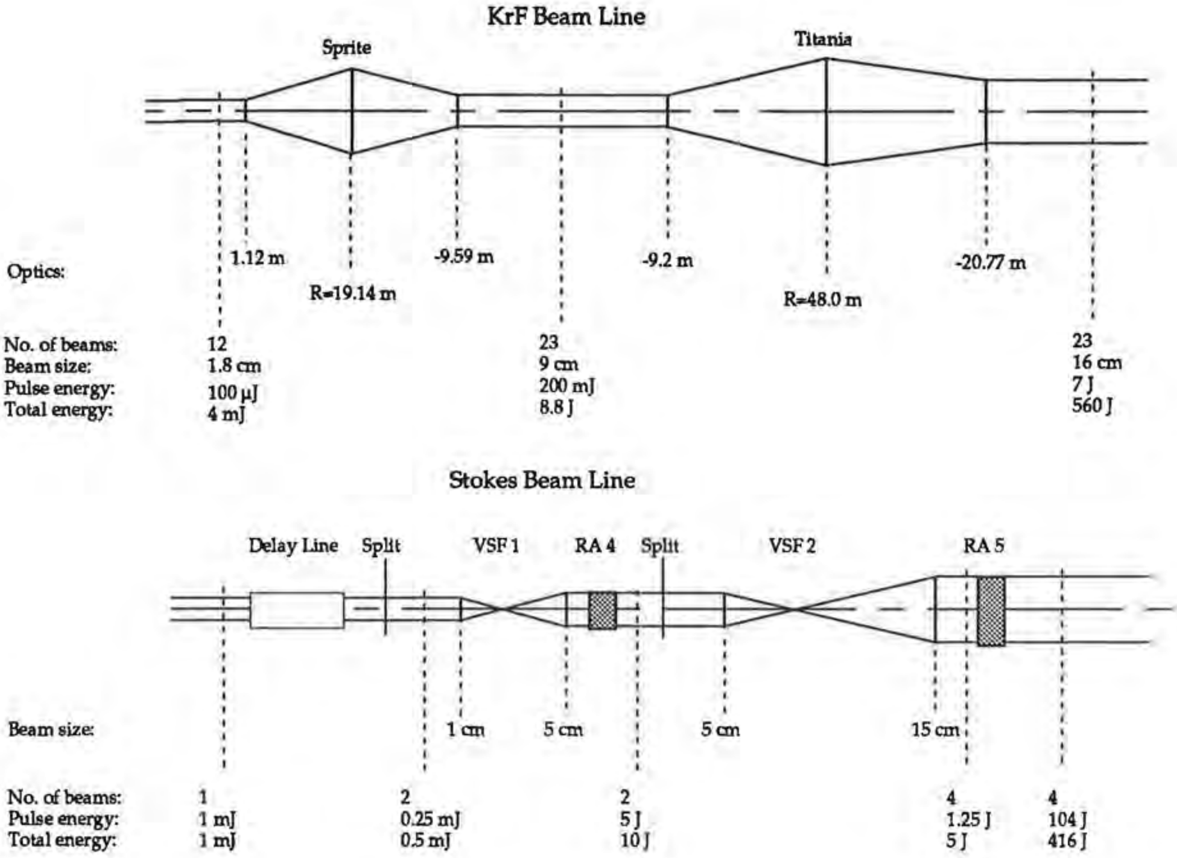


Figure 2. Beam line schematics

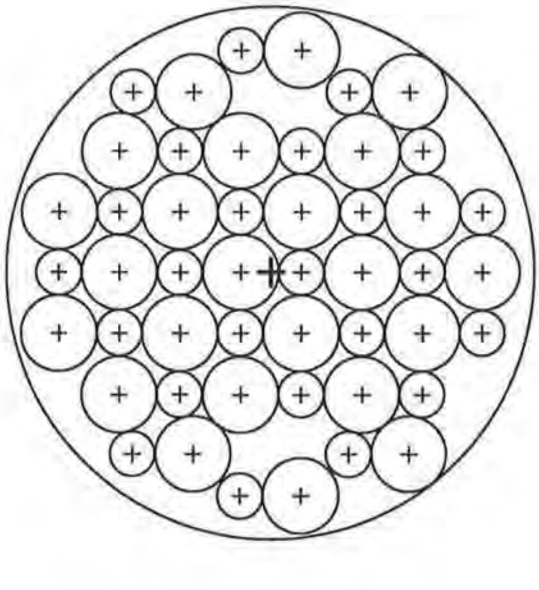


Figure 3(a) Titania input/output array.

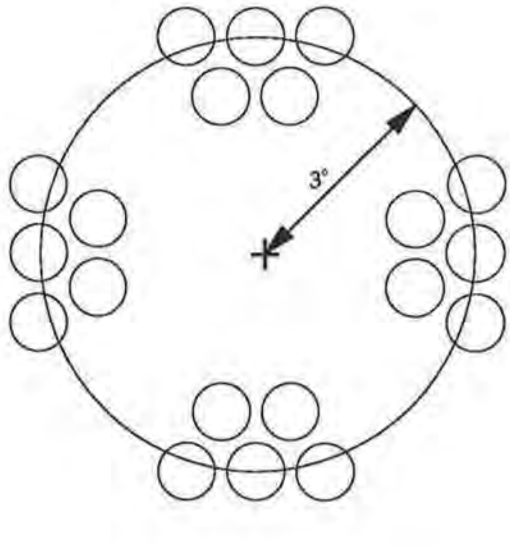


Figure 3(b) RA5 pump array.

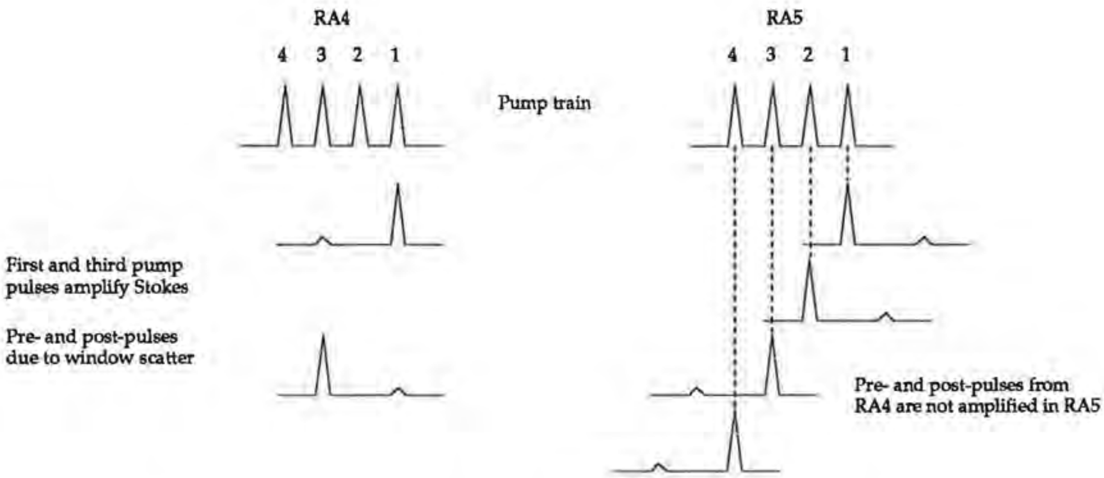


Figure 4. Technique for avoiding amplification of scattered prepulses.

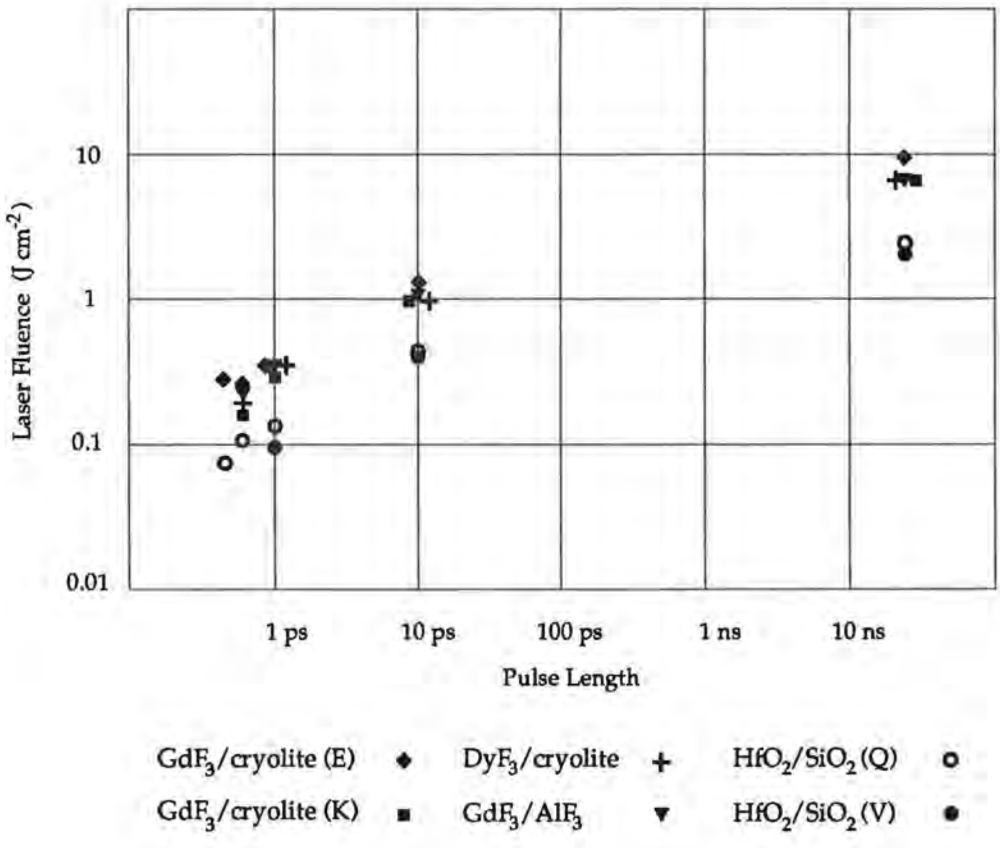


Figure 5. Damage behaviour of oxide and fluoride HR coatings at 249 nm. Fluences plotted are those at which the coating survived more than 100 shots without damage.

A4. THE TITANIA TARGET AREA

P.A.Norreys, D.Neely, C.B.Edwards, C.N.Danson, A.R.Damerell

1. Experimental Requirements.

High brightness optical drivers have a number of advantages for plasma physics studies. The experimental programme of the UK university user community has fallen recently into four broad categories: high intensity interactions with matter, x-ray lasers; ICF related physics; and applications of laser produced plasmas. These research themes will continue up to the commissioning of Titania in 1995/96 and help identify some of the specifications for the Titania target area, chamber and related equipment.

2. Location/site

The Titania target area facilities including control room, a dark room, an instrument and optics storage facilities will be located in building R7 A floor plan of the target areas and associated support space is shown in Fig. 1.

3. Options.

Three target areas are envisaged for the Titania facility in the medium term,. comprising a four beam line-focus area, a four beam F3 Cluster plus two KrF probe beams, and an area dedicated to CPA operations. A draft floor plan of the proposed target areas is shown in Figure 1.

It will be necessary to introduce target area facilities progressively as funding permits, and to this end, a single target area has been costed as part of the initial Titania build phase.

It can be seen in Figure 1 that a primary consideration in the design and construction of Titania has been the requirement that the target area be sufficiently large to allow for complex diagnostic configurations, as well as allowing sufficient space in the Target Area Control Room to accomodate two large experimental teams and their associated computer controlled data acquisition systems.

1. Titania Target Area: Raman Beam Operations

Four high brightness Raman beams of 150mm diameter will be delivered to a new target chamber and brought to target either in a line focus or single/double sided point focus in cluster geometry. The focused intensity will be over 10^{19} Wcm^{-2} in 1997 rising to around 10^{20} Wcm^{-2} in 1998. Schematics of the new irradiation geomtries are shown in Fig.'s 2 - 5 and are discussed in detail in section 4.

The target area will be equipped with dedicated calorimetry, pointing and timing capabilities. The final pointing optics and timing slides will be under remote control to allow beam delivery in argon. A stand alone alignment system will be provided based on a c.w. green argon ion laser. Intra-cavity second harmonic conversion to the UV is a possibility for alignment at the laser wavelength.

Separate beam focusing, target positioning and manipulation hardware will be provided for cluster and line focus configurations. This will be accomplished by an interchangable target chamber insert to facilitate changes of irradiation geometry between experiments.

The two KrF probe beams and the alignment optics will be implemented at 10 cm aperature. This will enable useful savings to be made by re using existing mirror mounts and beam steering optics.

2. CPA Operations

In CPA mode, the energy to target is limited by the damage threshold of the final compression optics. It is belived that improvments of ~ factor x 3 are available over currently available gratings, in which case the estimated power to target is 15 -20 TW in a pulse of 150 fsec duration with a focused intensity of 10^{20} Wcm^{-2}.

To preserve the beam quality, the CPA beam will be image relayed from the Titania output to target. This will prevent deterioration of the near field intensity distribution, enabling the large aperture compression gratings to be run at the highest possible average fluence.

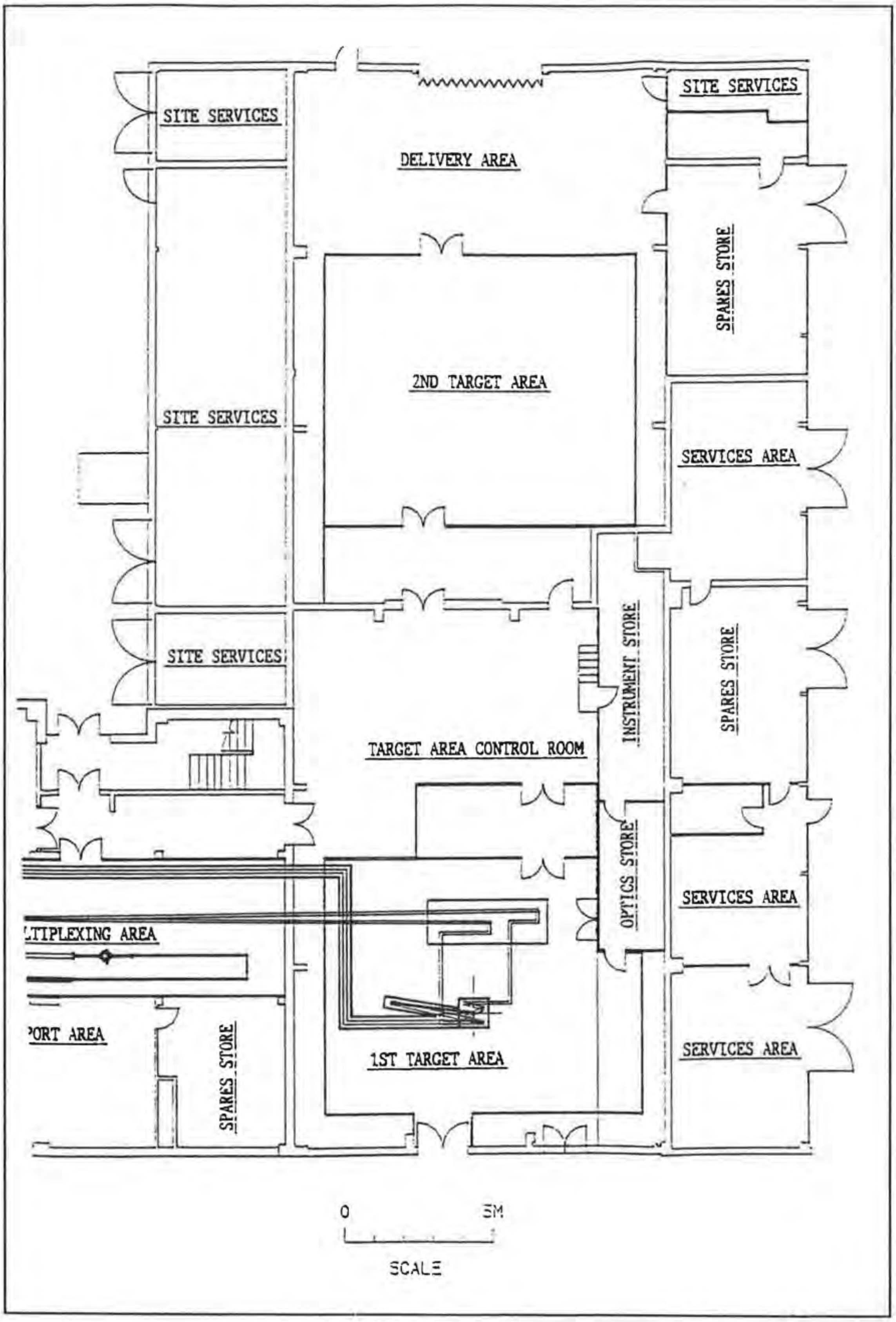


Fig 1. Floor layout of Titania Target Areas

4. Target Chamber Beam Layouts.

Four beam Target Chamber

For x-ray laser research, the requirement will be for a narrow line focus arrangement, precluding a cylindrical lens approach. This, together with the requirement of reducing the B-integral, indicates the use of reflecting optics in both configurations. 165mm diameter, 500 mm focal length off-axis parabolas will be used.

A rigid cylindrical chamber of 1m diameter is proposed with two hinged end flanges that will hold the input beam windows. The different optical arrangements are set on independent platforms that can be inserted into the chamber. These platforms will be bolted to supports bolted to the floor of the target area through the vacuum vessel. This "insert" will be changed for different optical arrangements of the target chamber. Access ports of 40 cm diameter will be provided in the perpendicular viewing direction.

A number of initial target chamber beam layouts are included for comments by the user community.

The requirement for a line focus optical system is that it be flexible and can accomodate a number of different line focus lengths and irradiation geometries. These considerations have been incorporated in the initial layouts of the chamber. Water window operation of the Ta laser, for instance, require irradiances of 2×10^{15} Wcm^{-2} on target. With conservative assumptions on delivered energy, ie a 50% loss of energy from the Raman amplifier to the target (170J in 100 psec), then lengths of 20 μm x 4mm are required. Figure 2 shows a line focus arrangement with these lengths. For longer line focus lengths and lower irradiances, Figure 3 shows the optical arrangement for 20μm x 1.7 cm line foci.

The beams are delivered from the top and bottom of the chamber leaving the horizontal plane unobstructed for plasma diagnostics. Flexibility has been incorporated in the design as both single sided and double sided irradiation are possible. However, it should be noted that it is not possible to have double sided line focus irradiation with reflecting optics without have a primary focus position on each side of the line focus. Injector / amplifier configurations can easily be accomodated in this scheme by rotating two of the off-axis parabolic mirrors by 180 degrees and moving the off axis spherical mirrors.

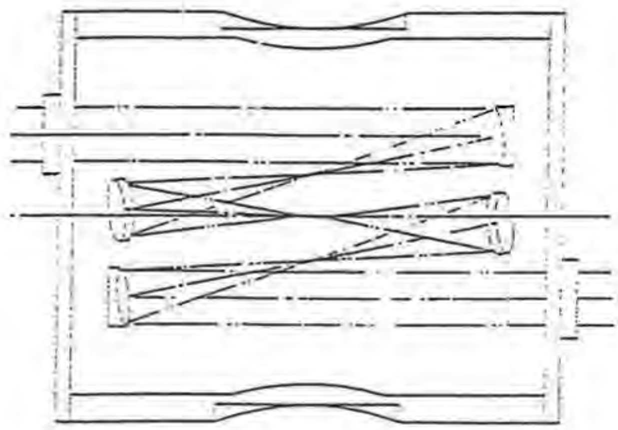


Fig 2. 4mm Line Focus (double sided)

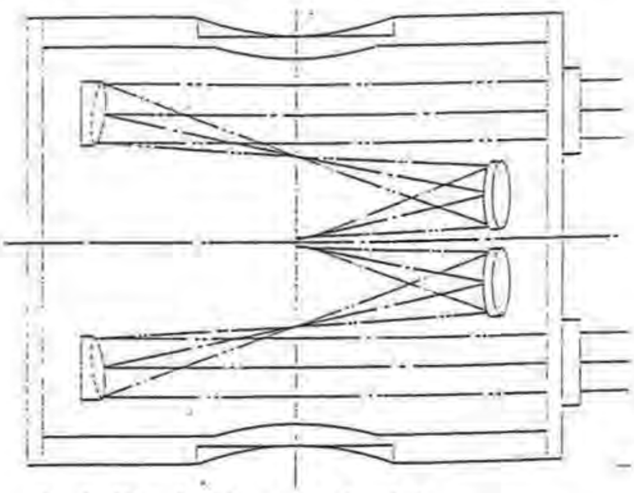


Fig 3. 17mm Line Focus (single sided)

Figure 4 shows the optical arrangement for single sided and double sided cluster irradiation. The use of off axis parabolic mirrors, while necessary to reduce B - integral and two photon absorption losses, does restrict the positioning of diagnostic equipment and this will have to be taken into account when designing experiments. To assist in positioning diagnotic equipment, the horizontal plane has been kept clear. The gap between the beams in the vertical dimension is about 5 cm. Optical diagnostics can be attached to the independent platform via support pillars. X-ray diagnostics will be attached to the chamber and modificaitons may be required to take into account the gaps between the beams.

It is anticipated that eventually two 5J / 10cm KrF probe beams will be available for interaction studies. These will however have to be brought on line after the Raman target area is on line, as funding permits.

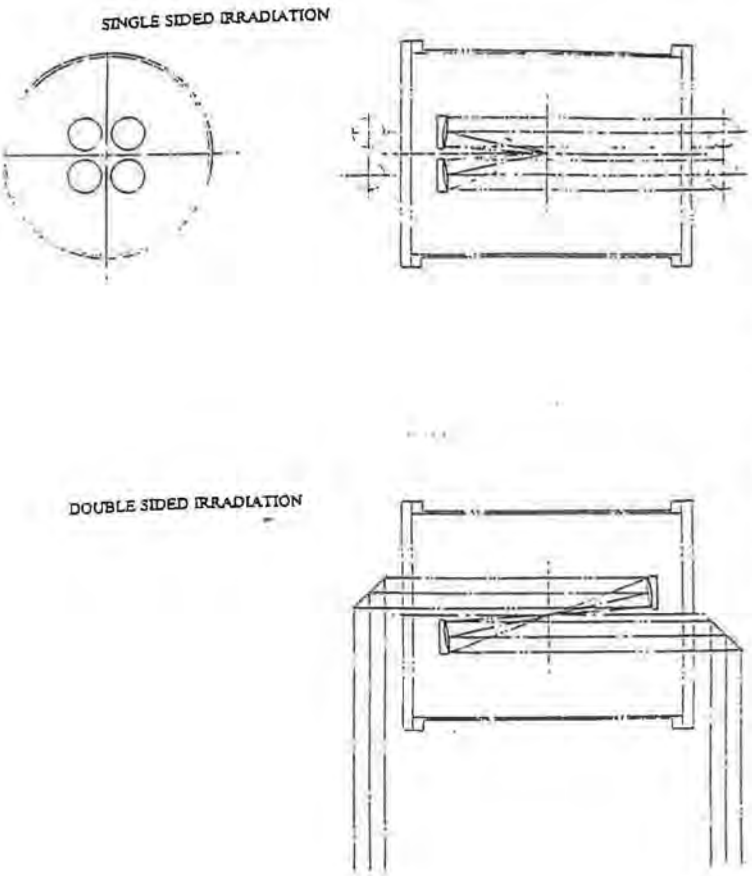


Fig 4 Cluster beam optical layouts.

CPA Target Chamber

One 15cm KrF beam will be delivered to the CPA target area in helium. A new target chamber will be commisioned that will be fitted with an extension chamber to house the compression gratings. The new chamber will be cylindrical in design. A schematic outline fo the new chamber is shown in figures 5 & 6.

A flat steering mirror will reflect light from the gratings onto the off-axis spherical mirror. This has been incorporated into the design of the new chamber so that the back-reflections from the plasma can be diagnosed more easily and which also allows a different colour diagnostic beam to co-propagate with the CPA pulse.

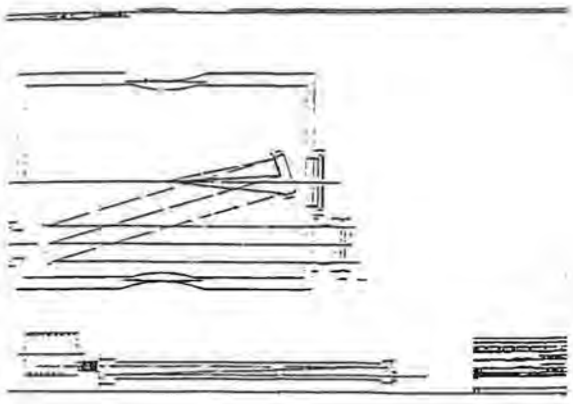


Fig 5 F3 focusing system

Costings allow for two different focal lengths: F3 and either F10 or F20 (comments on which focal lengths are preferred are welcomed from the user community). The latter option requires two extension ports to house the off axis parabola and the expanded beam.

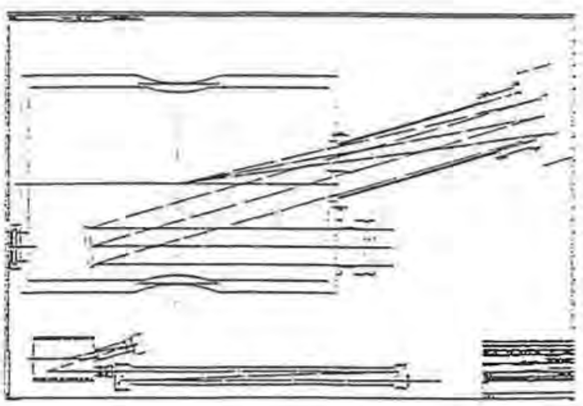


Fig 6 F10 focusing system

5. Implementation timetable

SPRITE will be closed in March 1995. After this date, most of the engineering effort will be concentrated on building the Titania system in R2. In order to avoid overloading the engineering support, the specifications for the optical layout of the target areas is plaaned to proceed rapidly. The design of the target area and the target chamber will start in January 1994 and be completed by April 1994. The new target chamber will be manufactured while building modifications to R7 are made. This will start in July 1994 and be completed in November 1994. The new target chamber will then be installed in January 1995 and be completed by March, ready for the switch over of effort to laser system building. Titania will begin operations in CPA mode in April 1996.

At the same time, optics for the new 4 Raman beam target chamber will be purchased in March and delivered by November 1996. The 4 beam target area will be commissioned sometime between November 1996 and March 1997 ready for 4 beam experiments in April 1997.

6. Expenditure profile 93-98

These costs are the minimum requirements for setting up the target areas for experimental use. They do not include costs for Target Area Control systems which are costed elsewhere. Some expenditure is required from the user community and this is indicated in the right hand column.

1. RAMAN BEAM SYSTEM

4 x 4 235 mirrors per beam		
+ mounts	£ 80 k	
Timing slides	£ 15 k	
Target chamber	£ 50 k	
Vacuum pumps	£ 25 k	
Mounts Parabolas	£ 50 k	
Mounts OAS		£ 30k
parabolas	£ 40 k	
spherical mirrors		£ 10k
windows	£ 20 k	
alignment system (from TA East/West)	£ 20 k	
Alingment Tables	£ 10 k	
	£300k	£ 40k

2. CPA INTERACTION SYSTEM

Grating compression chambe	£ 50 k
steering mirrors	£ 10 k
collimating lens	£ 5 k
Parabola mount	£ 10 k
Parabolas	£ 15 k
Gratings	£ 40 k
	£ 130k

Total £ 430 k + £ 45 k

7. Beam Piping

It is necessary to pipe the beams in argon in order to preserve B-integral. An isolation system will be provided to enable replacement of optics with miminal disruption to normal operations. Other features to beincorporated in the final design include remote control of timing slides and fianl pointing optics to enable adjustments to be made without compromising the integrity of the beam piping system.

8. Expansion/upgrade programme.

The present funding situation for Titania means that costs will have to be closely monitored and further refinements to the target chamber and areas are viewed as additional and incorporated into an upgrade / expansion programme. The working group has put forward the following suggestions:

Phase II Target area developments

The Raman target area becomes a dedicated line focus target area and is upgraded to injector/amplifier configuration in preparation for providing a water window coherent x-ray laser beam for the UK scientific community. The applications of the X-ray laser beam will include three dimensional biological imaging, high density plasma probing, chemistry and materials research. This will require a major input of funds toutilise fully the high repetition rate of the laser and to make the target area "user friendly" for new scientific groups that will wish to use the facility.

A second major 6 beam target area is commissioned for plasma experiments. This will primarily be devoted to Cluster focusing and a full set of ancillary equipment (including independent alignment system) will be provided.

Beam piping in helium will be introduced. This will significantly reduce the B - integral, allowing 10 psec pulses to target.

A5. BUILDINGS AND SERVICES

B E Wyborn and S Hancock

INTRODUCTION

This appendix sets out the specifications for the buildings and services required for the proposed Titania laser system.

The specifications are based on the following axioms:

Firstly it is assumed that the Titania system will become a major high power laser facility capable of meeting the needs of multi-users for a wide variety of experiments. It will initially be constructed to a baseline specification and will in future years be modified, developed, enhanced and expanded as has the Vulcan glass laser in the past. As such its scale and quality of facilities should be capable of being developed to be comparable with Vulcan. Therefore the buildings and services specifications must lend themselves to accommodate this expansion.

Secondly there is a need to maximise the use of the spend and effort within the yearly financial budgets. Therefore some requests for facilities have to be deemed necessary, some as desirable, some as future enhancements and some as unobtainable within the scale of funds likely to be available. Wherever possible use will be made of existing buildings and facilities. Therefore the proposed buildings and services specifications fit within existing building frameworks at RAL although allowing for expansion at a later date. The buildings and services specifications and the phasing of the spend need to be broken down into acceptable packages. Items which are considered to be minimum requirements are listed under Phase 1 below. Desirable upgrade facilities and enhancements are listed under Phase 2.

Thirdly there is a need to minimise Sprite down time and to get Titania on air within one year. Therefore the building phases of Titania have to be designed accordingly and the programme has been split into the relevant financial years.

REQUIREMENTS

Overall

The following rooms and facilities will be required in the fully developed Titania laser system:

<u>Phase 1 (necessary)</u>
Oscillator Room
Pulsed Power Area
Multiplexing and Demultiplexing Area(s)
Laser Control Room
Target Area Control Room
1st Target Area
Services Area(s)
Engineering Support Area(s)
Instrument & Optics Storage Area(s)
Spares Storage Area(s)

<u>Phase 2 (desirable)</u>
Additional Target Areas
Clean Room
Preparation Laboratory
Dark Room
Laser R&D Laboratory

The following features need to be incorporated in the buildings and services specifications:

To eliminate over-rideable interlocked doors between laser designated areas.

To provide convenient routes from area to area both for personnel and for equipment.

To provide each area with satisfactory means of ingress and egress for both personnel and equipment, including emergency situations.

To maximise overall safety of operation of the laser system.

To provide required services which are conveniently sited.

To provide enough space for the removal and maintenance of equipment.

To enable possibilities for future upgrading and development.

Oscillator Room

The present Sprite Oscillator Room is short of space. It is crowded and beam paths necessarily cross passages etc. Additional optics are needed to fold the system to allow it to fit in the room. There is no room for development of further oscillators. Access is not good and includes a door linking two hazardous areas with an over-rideable door. The room is relatively dirty and air temperature fluctuations and movement cause beam degradation. There is also a suggestion that the floor plinth of the oscillator room moves with relation to the rest of the system thus causing laser alignment drift and that beams from the oscillator room to the multiplexer room are propagated through several areas which are at different temperatures and pressures thus affecting beam quality.

The new Titania Oscillator Room needs to be large enough to offer a flexible front end system including the building of a second oscillator, two amplifier systems and room for a third oscillator with diagnostics and good access around the tables. The room needs to be clean, thermally and humidity stable and free from massive air turbulence. Electrical noise needs to be minimised. All the services to the present oscillator room will be required plus the additional services of water and power for a second Argon Ion Laser (if Ti:S option is chosen for second oscillator) and a second Nd:YAG laser or similar, plus diagnostics transfer to the control room.

Pulsed Power Area

The present Sprite pulsed power area is adequate for Sprite and Goblin and has all the services required.

The new Titania Pulsed Power Area will require good cranage, good access for maintenance etc., and requires services as presently available for Goblin and Sprite. Adequate X-ray shielding will be required.

Multiplexing and Demultiplexing Area(s)

The present Sprite multiplexing and demultiplexing area is adequate for Sprite but will be inadequate for Titania.

The new Titania Multiplexing and Demultiplexing Area(s) should be similar in construction to the existing Sprite room but much larger. The area(s) may eventually require propagation in He. The building design of the optics bay(s) should be such that a He filled enclosure could be facilitated at a later date.

Laser Control Room

The present Sprite Control Room is somewhat cramped and poorly air conditioned. It is also situated such that reaching the oscillator room involves movement through another designated area.

The new Titania Control Room needs to be easily accessible to the areas that laser operators are most concerned with. This is listed in order of importance as: Oscillator Room, Multiplexer Room, Pulsed Power Areas, User Areas, Services Bays, Target Areas, Engineering Support Areas. It needs to be air conditioned and larger.

Target Area Control Room

The present Sprite and Vulcan Target Area Control Rooms are ideally situated i.e. close to the Target Areas.

The new Titania Target Area Control Room needs to be similarly close to the Target Areas and ideally on the same level. Communication with the Laser Control Room is also required. They need to be air conditioned.

Target Areas

The present Sprite Target Area is somewhat small and limits the experiments that can be carried out.

The new Titania Target Area(s) should be of a size and flexibility comparable to Vulcan Target Area's. The target areas need to be air conditioned. Although initially costs etc. will preclude more than one target chamber being built, space needs to be identified for future expansion to 3 target areas.

Services Area(s)

The present Vulcan and Sprite laser systems have various service areas which have built up in an ad hoc basis.

The following services are required for Titania and need space or service runs:
Single and three phase Electrical Supplies
Cooling Water
De ionised Water
Oil
Air conditioning
Excimer gases
SF_6, Methane, other gases and storage as required
Helium
Clean dry compressed air or N_2 gas supply
Gas venting
Cranage
Vacuum for VSFs - clean & dry but not very high

Although the requirements for service areas are not stringent i.e. cleanliness etc. they do need to be catered for and should be close to the facilities that they service. There is an opportunity to plan them from the outset.

Engineering Support Area(s)

The present Sprite Engineering Support Areas are very usefully placed i.e. close to the equipment they support especially the Pulsed Power Area and have space for stripping down equipment and assembly.

The new Titania Engineering Support Areas need to be similar to the existing facilities.

Instrument & Optics Storage Area(s)

The present Sprite and Vulcan Instrument and Optics Storage Area(s) are haphazard, widely spread out unwanted rooms.

The new Titania Instrument and Optics Store should be positioned close to the laser system, clean and could double as the general optics cleaning area if space is sufficient

Spares Storage Area(s)

The present Sprite and Vulcan Spares Storage Area(s) are haphazard, widely spread out unwanted rooms.

Although the requirements for Titania Spares Storage Area(s) are not stringent i.e. cleanliness etc. they do need to be catered for.

<u>All requirements listed after this point are not deemed to be priority items and will be fitted into any available areas at minimum cost or will be added at a later date i.e. they are Phase 2</u>

Clean Room

Presently Sprite has no Clean Room facilities although Vulcan does.

A Titania general cleaning area is required with class 100 clean air cabinet and a sink. This could be combined with the Instrument & Optics Storage Area.

Preparation Lab

Presently Sprite has no Preparation Lab and part of the Target Area Control Room is used.

A Titania Preparation Lab is required. It needs to be easily accessible to experimenters.

Dark Room

The present Sprite dark room is shared with ISIS.

A Titania Dark Room for film development is required. It needs to be easily accessible to experimenters.

R&D Lab

The present Sprite R&D Lab will be displaced from R2. Also the R&D Lab previously in R1 has already been displaced.

The new Titania R&D Lab needs to be of a size similar to the previous lab in R1. It needs to have all the services associated with a Laser Lab. It does not however need to be close to any other areas of the Titania system.

PROPOSAL

Overall

The existing R2 complex offers possibilities for an upgrade to the Sprite facility. Cranage is good and the 1m thick level concrete floor excellent for optical stability. All necessary services already exist although will need upgrading. The overall size, however, limits the optical path length available for multiplexing etc. thus limiting beam energy to target. Therefore expansion into adjacent areas will be needed. The adjoining ISIS electrical workshop is too obstructed by pillars etc. to consider putting target areas in but could be used for beam transport. This would enable the system to link to building R7 thus increasing the options available.

The proposal (see Fig 1) involves resiting some of the areas but in positions which are most advantageous to the development of the facility. The proposal lends itself to phased development both of the beams and the buildings. In particular phase 1 would include all the rooms, areas and services to enable the laser system to operate, but would not include some of the ancillary areas or upgraded services which can be added at later phases. Table 2 lists the comparisons of size for various areas between Sprite, Vulcan and the proposed Titania layout.

Buildings which need to be allocated to Titania are:

ISIS Electrical Workshop
R7 West
R7 external rooms on South

Access is required to most areas for equipment etc. some of which could be quite large and heavy. Some will be moved in and will be relatively fixed i.e. laser amplifier modules, concrete X-ray shielding. Additional equipment may need moving i.e. surface tables mirror arrays etc. Therefore double doors and wide, flat corridors to the outside will be needed throughout the Titania buildings.

The detailed specifications and consequent costs of the various rooms/areas are being drawn up. The following sections are outline requirements as foreseen at present.

Oscillator Room

Phase 1
Lino/vinyl covered floor
Insulated partitioning walls
Insulated false ceiling
Single door controlled entrance
Double door equipment access
Emergency exit(s)
Air conditioning
Normal lighting
Dimmable corner lighting
Single phase 13 amp sockets
3 phase supplies
Water cooling
Exhaust system for vac pumps
Exhaust system for laser gases

Phase 2
Upgrade to clean room standards Class 10,000
Upgrade air conditioning

Pulsed Power Area

Reposition concrete blocks for X-ray shielding
No roof
Single door controlled entrance
Double door equipment access
Emergency exit(s)
Single phase 13 amp sockets
3 phase supplies
Water cooling
Exhaust system for vac pumps
Exhaust system for laser gases
Oil system

Multiplexing and Demultiplexing Area(s)

Multiplexing area

Phase 1
Lino/vinyl covered floor
Insulated partitioning walls
Insulated false ceiling
Single door controlled entrance
Double door equipment access
Emergency exit(s)
Normal lighting
Dimmable corner lighting
Single phase 13 amp sockets
Exhaust system for vac pumps
Exhaust system for laser gases

Phase 2
Upgrade to clean room standards Class 10,000
Install He enclosure

Demultiplexing area

Phase 1
Lino/vinyl covered floor
Insulated partitioning walls
Insulated false ceiling
Single door controlled entrance
Double door equipment access
Emergency exit(s)
Normal lighting
Dimmable corner lighting
Single phase 13 amp sockets
Exhaust system for vac pumps
Exhaust system for laser gases

Phase 2
Upgrade to clean room standards Class 10,000
Install He enclosure

Laser Control Room

Phase 1
Standard floor, walls and ceiling
Single door entrance
Double door equipment access
Emergency exit
Normal lighting
Single phase 13 amp sockets

Phase 2
Upgrade air conditioning

Target Area Control Room

Phase 1
Standard floor and walls
Single door entrance
Double door equipment access
Emergency exit
Normal lighting
Single phase 13 amp sockets

Phase 2
Upgrade air conditioning

1st Target Area

Phase 1
Lino/vinyl covered floor
Insulated partitioning walls
High false insulated ceiling
Single door controlled entrance
Double door equipment access
Entrance/viewing vestibule
Emergency exit(s)
Normal lighting
Dimmable corner lighting
Single phase 13 amp sockets
Exhaust system for vac pumps

Phase 2
Air conditioning
Upgrade to clean room standards Class 10,000
3 phase supplies
Water cooling

Services Areas

Some external areas will be utilised.
Some very basic areas will be needed

Engineering Support Area(s)

Basic accommodation is required.
Space for machines and benches.
Single phase 13 amp sockets

Spares Storage Area(s)

Basic accommodation is required.

COSTINGS

Table 1. Costings for the Titania buildings and services. All costings are in £K.

	93/94	94/95	95/96
Breakthrough walls, make good Elect W/S area and modify crane in R2. Clear and make good West and South ends of R7.	100		
Construct 1st Target Area, Target Area Control Room, Laser Control Room and Demultiplexing Area.		90	
Construct Oscillator Room, Pulsed Power Area, Multiplexing Area, and Engineering Support Area.			100

PROGRAMME

RAL Management Board has approved funds for the renovation of areas required for Titania which are currently being used by other RAL facilities. During the FY 93/94 the west and south ends of building R7 should be cleared and returned to a neutral state. Alterations to stanchions and breaking through walls between the present Sprite area and the ISIS Electrical Workshop, alterations to the crane in R2 and removal of redundant plant in R7 should be carried out. Some of the above work may carry over into the next financial year.

During FY 94/95, whilst Sprite is operational and Titania laser module testing continues in R7, work should be carried out to build the 1st Target Area and Target Area Control Room. Also the Demultiplexing area , Laser Control Room and other areas in the former Electrical Workshop should be built.

During FY 95/96 Sprite will be shut down. R2 should be gutted and the new Oscillator Room, Multiplexing Area and Engineering Support Area built. The Goblin laser module can be removed from R2. The Sprite laser module will be modified and repositioned. The Titania laser module will be installed in R2. Reconnection of services should be carried out such that by the end of the year the laser system can deliver beam to the 1st Target Area.

Table 2. Comparison of areas (m^2)

	Vulcan	Sprite	Titania
Laser Front End			
Capacitor Room	126		
Laser Area 1	135		
Laser Area 2	67		
Laser Area 3	97		
Beam Transport Area	43		
Oscillator Room		60	115
Pulsed Power		89	145
Multiplexing Area		102	185
Demultiplexing Area			115
Laser Control Room	58	28	40
Total	526	279	600
Target Areas			
TAW	130		
TAE	125		
TA2	54		
TA4	10		
TA		68	
1st TA			100
T.A. Control Room	48	34	65
Total	367	102	165
Overall Total	893	381	765

THE TITANIA LASER SYSTEM

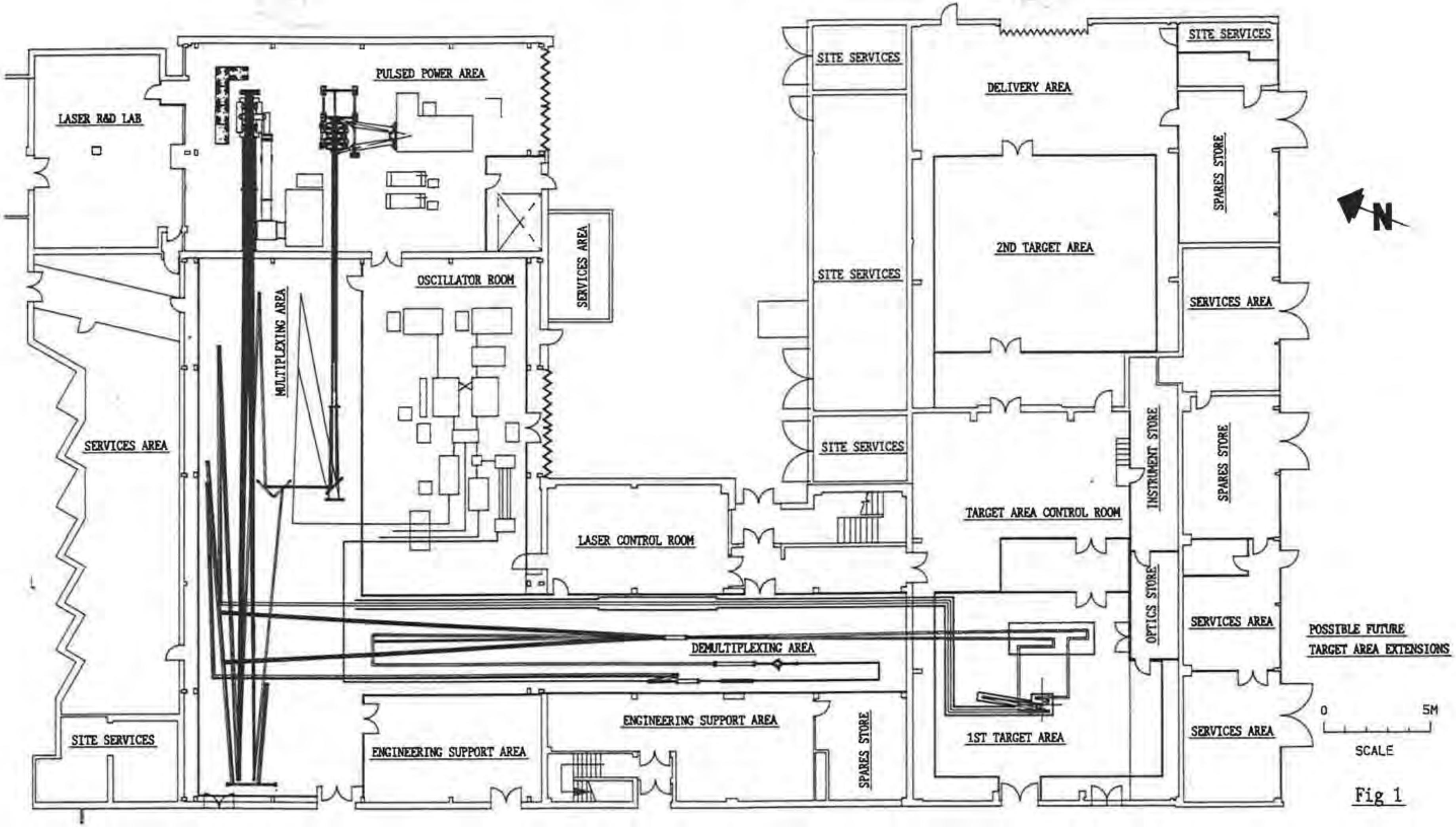


Fig 1

A6. THE TITANIA KrF AMPLIFIER MODULES

A K Kidd, S Angood and M J Shaw

INTRODUCTION

This paper summarises the specification of the KrF amplifier modules of the TITANIA laser system. The technical description is divided into three sections: the design of the Titania module, the results obtained with the Titania pulsed power system and the required modifications to the Sprite pulsed power system.

1. DESIGN OF THE TITANIA KrF MODULE

The Titania amplifier module is to have an aperture of 420mm and a pumped length of 1.5m. The module will amplify a total of 96 pulses of 1.5ns separation implying a gain window of 144ns. Allowance for gain rise-time and amplifier fill time increase the required pumping pulse duration to 168ns. The module capability as a long pulse oscillator is 1.7kJ.

The gas mix and operating pressure determine the electron beam voltage. A 50% Ar/Kr mix was chosen at a pressure of 1000 Torr so that a relatively high e-beam voltage of 600kV could be used. The machine is designed to give a deposited energy in the gas of 20kJ. Assuming a transmission efficiency from diode to gas of 35%, the required diode energy is 57kJ which at 600kV and 168ns implies a machine impedance of exactly 1Ω. Calculation suggests that the 1200kV line charge voltage should be reached with a transfer efficiency from the Marx of 80% at a capacitor charge voltage of 80kV. For the purpose of simulating the performance of the module, we assume a deposited energy of 18.8kJ which gives a pump rate of 0.53MWcm^{-3}. Using a value for I_{sat} of 2MWcm^{-2} (which gives an upper state lifetime of 1ns with E_{sat} taken as 2mJ), this pump rate is expected to produce a small signal gain coefficient of 5.3%cm^{-1} and a g_0L value of 8.0.

The layout of the Titania pulsed power system is shown in Figure 1. Eight 8Ω radial diodes are proposed. Pairs of diodes are connected together inside the vacuum vessel and powered by one of four 4Ω pulse forming lines. Pulse reflections between the diode and the switch have been modelled. The results indicate that the cleanest pulses arise when the output lines between the diodes and the switches have the same length as the PFLs. This configuration has been adopted for Titania.

1.1 Marx Generator and Pulse Forming Lines

The Marx generator is an 8 stage generator (16 capacitors of 1.35μF) of the Hermes type. The erected capacitance is 84nF which is exactly matched to the capacitance of the four PFLs.

For the pulse duration of 168ns, the line length is 2.8m using water as the dielectric medium. The diameter of the lines is determined by breakdown at the positive electrode given by the formula

$$Ft^{0.3}A^{0.1} = 0.3 \qquad (1)$$

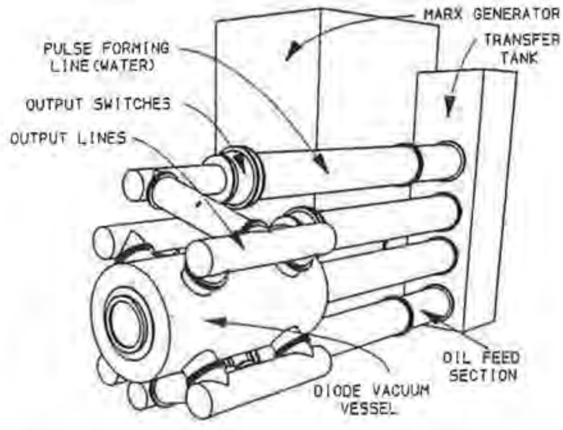


Figure 1: Layout of the Titania laser module showing the main pulsed power components.

where F, the breakdown field, is in MVcm^{-1}, t, the effective charge time, is in μs and A, the stressed area, is in cm^2. Using standard tube sizes of 448mm i.d. for the outer and 240mm o.d. for the inner, the field at the outer is 86kVcm^{-1} for a 1200kV charge and the breakdown field (calculated for a single line) is 133kVcm^{-1}. The peak working field is thus 65% of the breakdown field, a suitable safety margin.

1.2 PFL Switch

The Titania PFL switches are based on the radial diaphragm design that has been successfully tested at larger size on the Oberon pulsed power system. However, due to the lower line impedance and shorter pulse duration, a much lower inductance is required without increasing the electrical stress on the insulator surfaces.

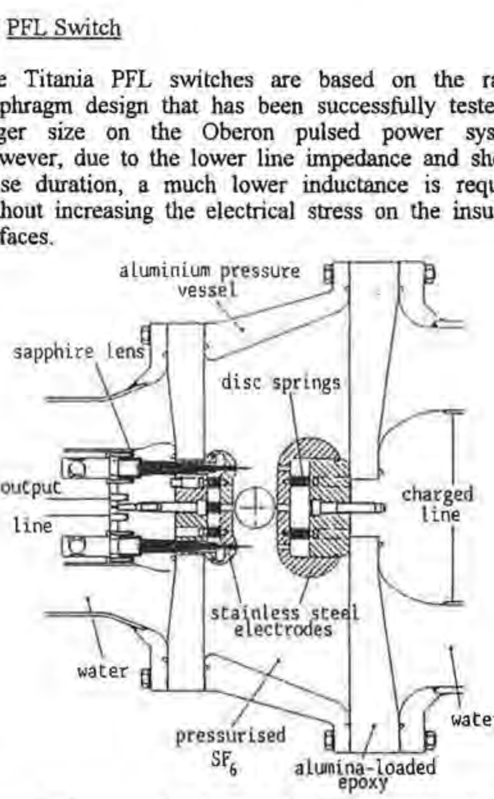


Figure 2: Cross-section through the PFL output switch.

The Titania switch is shown in Figure 2. The operating pressure is 4 bar of SF_6 and the minimum anode-cathode spacing is 50mm. Two alumina-loaded epoxy diaphragms support the pressure load. Shock isolation from the electrodes is obtained by spring washer stacks.

The calculated electric field distribution is calculated using the Magnet code and is shown in Figure 3. The peak cathode field is 285 kV cm^{-1} and the peak field on the insulator on the gas side is 95 kV cm^{-1}. The cathode breakdown field at 60psia SF_6 and 1.5μs charge time is 320 kV cm^{-1}.

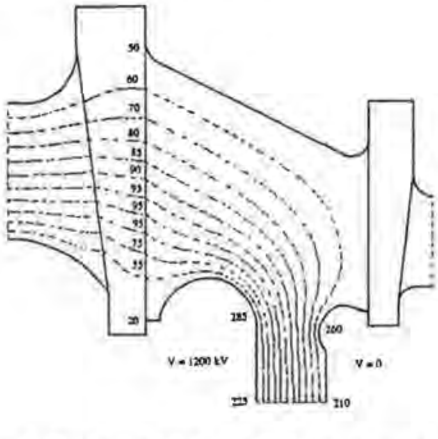


Figure 3: Equipotentials in the PFL output switch at peak charge volts. The field magnitude is shown in $kVcm^{-1}$.

1.3 Electron-Beam Diode

The four 4Ω output lines each bifurcate into two 8Ω sections to feed through into the diode vacuum chamber. Figure 4 shows a section through one of the quadrants of the chamber.

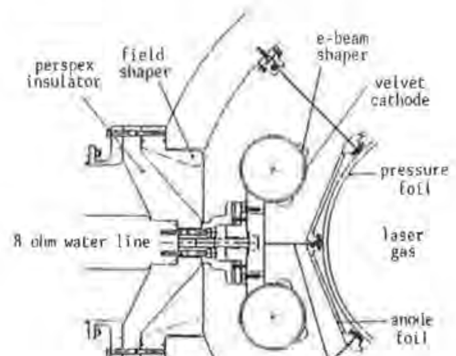


Figure 4: One quadrant of the Titania diode vessel.

The vacuum insulator is a single piece of Perspex and a field shaper is used to grade the field along the insulator length and keep the field angle close to 45° with respect to the vacuum interface. The field distribution is calculated using the MagNet code (Figure 5) and the peak field is $40kVcm^{-1}$. The breakdown field is estimated to be $80kVcm^{-1}$. The insertion inductance for each 8Ω feed is 25nH.

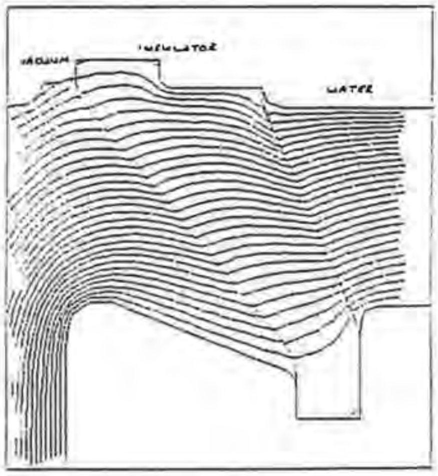


Figure 5: Equipotentials in the diode insulator.

Pairs of feeds are connected in parallel to the cathode support structure shown in Figure 6. This in turn is divided into two cylindrical 8Ω sections which gives an octagonal symmetry to the pumping of the laser gas. In order to reduce beam pinch and diode inductance, current returns are carried through the double diode where possible (avoiding the feedthrough regions). Each 4Ω diode is thus divided into two magnetically isolated 8Ω sections.

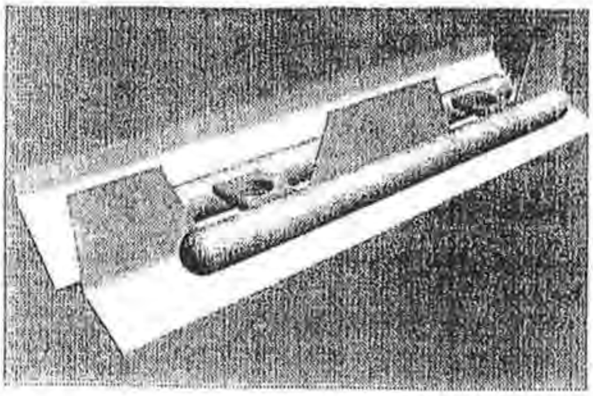


Figure 6: The Titania cathode support structure showing location of midplane current return.

1.4 Laser Vessel

The diode vacuum vessel is constructed from a 7.5cm thick steel forging which avoids the need for any welding and more importantly provides a very significant degree of shielding from X-rays produced by the electron beam. Approximately two orders of magnitude reduction of dose is expected from the 3.5 Tonne vessel. The Hibachi foil-support structure, which has an 88% geometrical transparency, is cut from a flat stainless steel sheet before rolling to its final cylindrical shape. The clear laser aperture is 420mm. Figure 7 shows a cut-away view of the diode and laser vessels with the midplane current returns removed.

Figure 7: Cut-away view of the Titania diode and laser vessels. Mid-plane current returns removed for clarity.

The midplane current returns are fixed to the outer vessel and they slide in contact with rails fixed to the laser gas vessel. The inter-diode current returns do the opposite. For servicing, the gas vessel and inter-diode current returns can be extracted along the axis on rails. They are then transferred to a trolley which allows the whole laser vessel to be rotated for foiling. The cathode support structure will be made from nickel-plated aluminium as will the emission inhibitors which define the edge of the emitting area.

2. RESULTS OBTAINED WITH THE TITANIA PULSED POWER MODULE

2.1 Titania Switch

Figure 8 shows results of over 50 self-break shots performed on a single PFL switch.

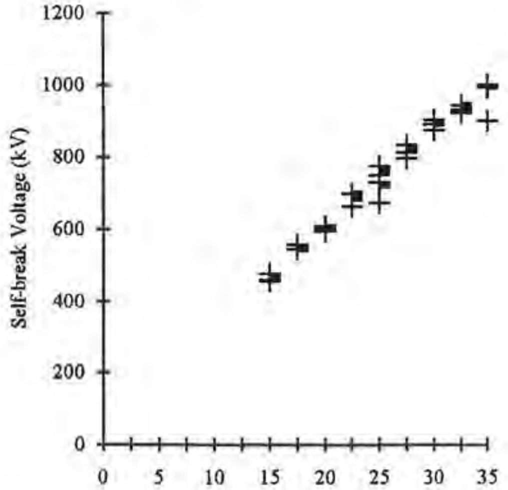


Figure 8: Self-break curve

The self-break curve was obtained by adjusting the Marx charge voltage at each value of switch pressure such that the switch self-broke at the same point on the PFL charging waveform. Apart from three shots for which the switch self-broke early (possibly due to pre-ionization due to contaminants), all the data points within +/-3.0% of a straight line of slope 27.5kV/psi. The switch was tested in self-break mode at voltages up to 1.0MV (83% of the design voltage).

The laser triggering tests have been carried out at around 600kV. Two laser triggering channels are used since significant improvement in rise-time can be obtained this way. It is calculated that the effective insertion inductance of the switch is 110nH for a single channel and 60nH for two channels. A Lambda Physik EMG150 KrF discharge laser is used to deliver 25mJ of energy in each of two trigger laser beamlets to each spark channel. Each beamlet passes through a quartz window located in the output section of the PFL and is turned by a prism to be focussed by a 10cm focal length sapphire lens into the spark gap. Figure 9 shows two-channel laser triggering at 22.5psia. The switch was successfully triggered in two channels on 100% of shots.

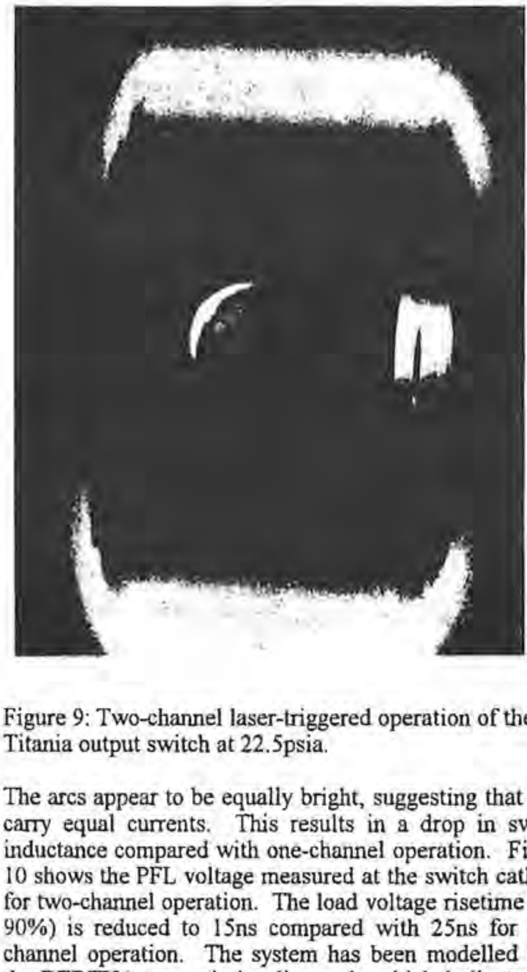


Figure 9: Two-channel laser-triggered operation of the Titania output switch at 22.5psia.

The arcs appear to be equally bright, suggesting that they carry equal currents. This results in a drop in switch inductance compared with one-channel operation. Figure 10 shows the PFL voltage measured at the switch cathode for two-channel operation. The load voltage risetime (10-90%) is reduced to 15ns compared with 25ns for one-channel operation. The system has been modelled with the BERTHA transmission line code which indicates the risetimes to be 15ns and 28ns. These results confirm the improvement in switch inductance by two-channel operation.

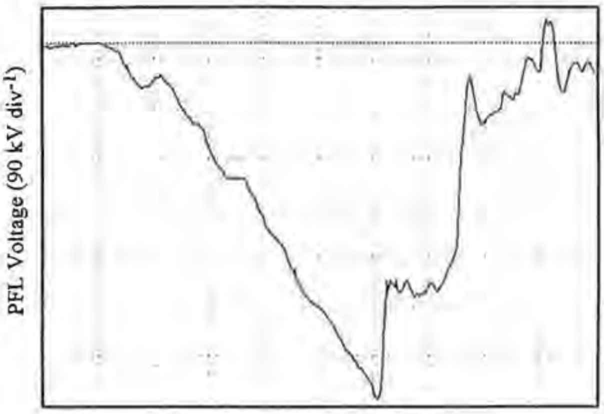


Figure 10: PFL voltage measured at the switch cathode for two-channel laser-triggered operation at 22.5psia.

The dependence of switching delay on the percentage of self-break voltage at which the switch was triggered is shown in Figure 11 for a SF_6 pressure of 35 psia. The self-break voltage is 1MV. The delay is defined as the period of time between the initiation of the laser pulse in the gap and the start of cathode voltage collapse. The experimental data indicates that the switching delay is a minimum of 10ns at 95% of self-break voltage, increasing to 95ns at 30%. The theoretical delay times τ (ns) are obtained from T H Martin's formula.

$$\rho\tau = 9.78x10^{13}\left(\frac{E}{\rho}\right)^{-3.44} \qquad (2)$$

where ρ is the gas density (g cm^{-3}) and E is the average electric field in kVcm^{-1}.

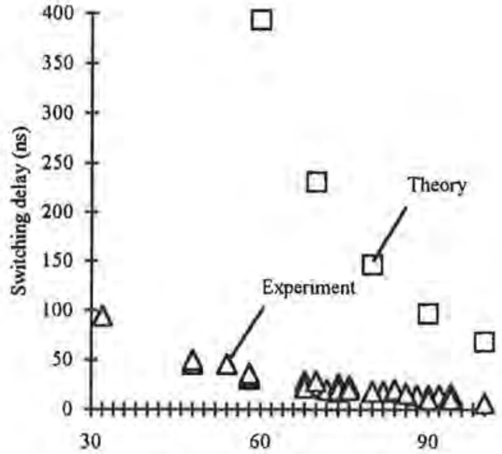


Figure 11: Switching delay as a function of percentage of self-break voltage.

We are able to obtain delays which are 80-90% shorter than those predicted by equation (2) since the laser beams short out a large fraction of the inter-electrode gap during triggering, hence increasing the average electric field, E.

Switch jitter was measured at 85-95% of self-break voltage to be 2ns (1σ) over 10 shots. This figure increased to 3ns at 70-80% of self-break voltage.

2.2 Test Diode Results

The cathode support structure shown in Figure 6 is made of electropolished stainless steel tubes and the electron emitter (cotton velvet) is simply attached to the surface with double-sided adhesive tape. The dual diode was tested as a 4Ω unit in a diode test facility which was modified to have the same geometry as one quadrant of the laser module. The diode was powered by a 250ns, 5.4Ω PFL with a significantly slower risetime and longer pulse length than that delivered by the Titania PFL.

In addition to current and voltage monitors, the performance of the diode was assessed using radiachromic film placed behind the anode foil. This showed that there was a significant halo outside the expected deposition region shown in Figure 12a due to emission from the exposed edge of the cotton velvet. This problem was overcome by placing emission inhibitors at the edge of the emitting area as shown in Figure 12b. These calculations were performed with the EGUN code.

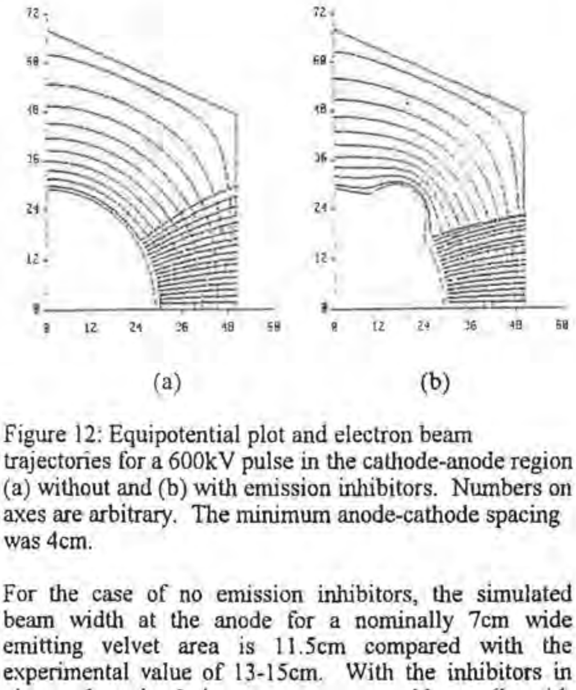


Figure 12: Equipotential plot and electron beam trajectories for a 600kV pulse in the cathode-anode region (a) without and (b) with emission inhibitors. Numbers on axes are arbitrary. The minimum anode-cathode spacing was 4cm.

For the case of no emission inhibitors, the simulated beam width at the anode for a nominally 7cm wide emitting velvet area is 11.5cm compared with the experimental value of 13-15cm. With the inhibitors in place, the simulations agree reasonably well with experiment - the code indicates the beam width to be reduced to 8.6cm, compared with the experimental value of 7.6-9.0cm.

The behaviour of the Titania diode impedance was investigated over a range of diode voltages from 475 to 625kV. The impedance settles down to 4.2Ω 100ns after the start of the diode voltage pulse and decreases steadily to 3.8Ω at 250ns due to cathode plasma drifting towards the anode. The Titania diode impedance can then be described by Child-Langmuir physics, with a cathode plasma having a closure velocity of 3.5-4.0 cm μs^{-1}.

The effect on diode impedance of replacing the velvet emitter with a tantalum cheese grater has been investigated. The diode impedance falls by about 25% over the latter part of the voltage pulse and there is no recovery on the trailing edge.

2.3 Diode-to-Gas Transport Efficiency

The Titania diode is designed to have a titanium anode foil 12μm thick and a pressure foil 35μm thick bonded to a cylindrical support structure. To test transmission through this foil arrangement, a 50cm long section of the diode was provided with a pressure foil and support structure so that electrons could penetrate through into a 1m diameter gas target vessel, containing nitrogen at 1 bara pressure.

The foil transmission efficiency, η, is defined as:

$$\eta = \frac{E_{gas}}{E_{diode}} \qquad (3)$$

where E_{gas} is the energy deposited in the gas. Figure 13 shows the foil transmission efficiency as a function of diode voltage. The efficiency is 50% at the lowest energy and falls to 40% as the electrons are lost to the far wall of the vessel at higher voltage.

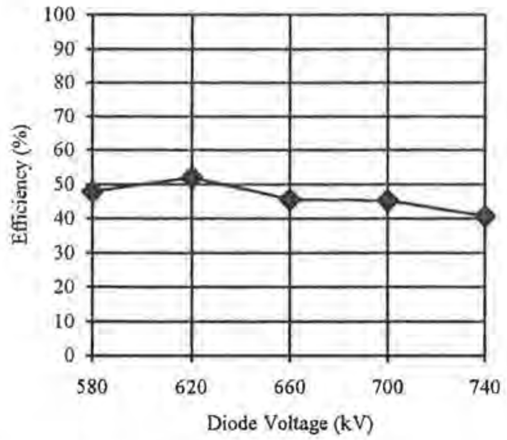


Figure 13: Foil transmission efficiency vs. diode voltage.

3. SPRITE MODULE UPGRADES

The Sprite amplifier module is to be modified for incorporation into the TITANIA laser system. The main modifications are the elimination of the water capacitor, the replacement of the old Marx generator with a new Hermes type and an increase in diode pulse length to accomodate the longer pulse train. There will be 14 beams (12 beams with 2 carrying orthogonal polarisations) with 6ns between each beam implying a gain window of 84ns. Allowance for amplifier fill time (10ns), jitter and gain rise-time increase the required pumping pulse duration to 120ns. The module will amplify a total of 48 pulses with 1.5ns separation.

An intrinsic efficiency of 8.4% is based on a pump rate of 0.8MWcm^{-3} into a 400:400:4 Ar:Kr:F_2 gas mix. The achieved g_0 will be 8%cm^{-1}. The module capability as a long pulse oscillator is 460J, which should be achieved with an optimum stable cavity and is not corrected for intra cavity window losses. The gain achieved should be the same as that obtained with the existing Sprite amplifier and is that which is assumed for the Titania system model.

3.1 Marx Generator and Pulse Forming Lines

The diameters of the PFLs will be the same as on the present Sprite and Goblin: id of outer = 264mm, od of inner = 130mm. The overall length will be 2.0m. The line impedance will be 4.75Ω and the line capacity 12.63nF. The total capacity is thus 50.5nF.

Making an allowance of 2.5nF for a transfer section, we get a total capacitance to be charged of 53nF. The Marx generator is a 6 stage generator (12 capacitors of 0.7μF) of the Hermes type. The erected capacitance is 58.3nF which is which gives an 82.5% transfer efficiency to the four PFLs. The time to peak charge volts is 1.0μs. For a maximum line voltage of 900kV, the required Marx charging voltage is 77kV. The total Marx capacitance during charging is 8.4μF and the charge stored at 77kV is 0.647C. This charge is supplied from two supplies (for + and - charged capacitors) so the average charge current required per supply for a 60 second charge is 5.4mA. This is well within the capability of the existing Sprite Marx charging unit. The stored energy at 77kV is 25kJ.

It is proposed to use the present Sprite Marx tank for the new Marx. Figure 14 shows that if the capacitors are arranged in three rows of two (rather than in two rows as in the Titania Marx), they fit easily into the existing tank.

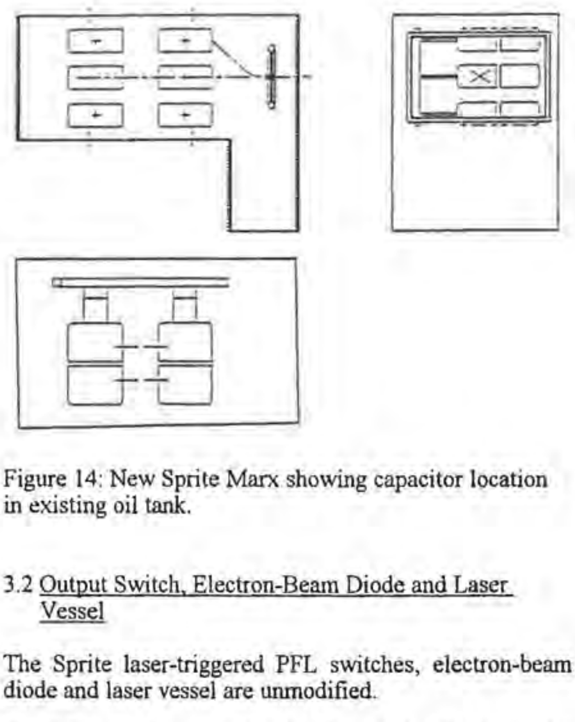


Figure 14: New Sprite Marx showing capacitor location in existing oil tank.

3.2 Output Switch, Electron-Beam Diode and Laser Vessel

The Sprite laser-triggered PFL switches, electron-beam diode and laser vessel are unmodified.

The PFLs are however doubled in length. Doubling the pulse length at the Sprite diode is not expected to cause any major problems since a very similar pulse length and impedance has already been successfully demonstrated on the Ashura 30cm amplifier at ETL in Japan. This has a very similar cheese grater cathode and dual foil anode to Sprite and lends confidence to the proposed pulse length increase.

4. COSTINGS

Table 1. Costings for the Titania amplifier development programme. All costings are in £K.

	94/95	95/96
Titania window mounts	20	-
Titania rear mirror mount	10	-
Titania gate valve	5	-
Titania gas handling system	20	-
Sprite Marx internals	20	-
Sprite PFL modifications	15	-
Oil, water, gas replumbing for relocation	-	20
Totals	**90**	**20**

5. PROGRAMME

The present status (Autumn '93) of the Titania amplifier development is that the Marx, a single PFL and a single laser triggered switch have been tested. The arrival of a complete set of epoxy diaphragms is imminent, which will permit testing of the four PFLs into four dummy loads. In the Spring of '94, the diode vessel will be installed and the transport of the electron beams into the gas vessel will be tested. When satisfactory performance and foil longevity is obtained, the laser optics can be installed and full energy tests conducted (Summer/Autumn '94). In the Spring of '95, the pulsed power components can be stripped down in readiness for moving into R2.

Whilst Sprite is operational during FY 94/95, it will not be possible to make any working pulsed power modifications. All of the components for the new Marx can however be assembled and left on its lifting cradle. The components for the extensions to the PFLs can be purchased. At the shutdown of Sprite in April '95, Goblin will be removed from R2, the existing Sprite Marx disassembled and replaced with the new Marx in its new position. The Titania module will be rebuilt in its new position and the two systems connected to a single trigger Marx. There should be ample time for fully testing the two amplifier modules before the Titania system begins operations in April '96. The Titania amplifier development programme is shown in Table 2.

Table 2. Schedule for the Titania amplifier development programme.

	1993	1994				1995				1996
	OND	JFM	AMJ	JAS	OND	JFM	AMJ	JAS	OND	JFM
Install four PFL switches	—>									
Test switches into dummy loads	—	->								
Install laser diode vessel		——>								
Test energy transfer to gas			——>							
Install full aperture optics				——>						
Test module at full aperture					——>					
Strip down ready for transfer to R2						——>				
Test solid resistors	—	->								
Build new Sprite Marx			——	——	->					
Purchase PFL extensions for Sprite				——	—>					
Strip down Sprite and Goblin							——>			
Rebuild Titania in new position								——	—>	
Rebuild Sprite in new position									—	->
Test repositioned modules										—>

A7. CONTROL AND OPERATIONS

G J Hirst, C N Danson, P Gottfeldt and C J Reason

INTRODUCTION

This appendix specifies the control and data acquisition system needed to operate Titania. It is based on experience gained with Vulcan and Sprite and some of the existing subsystems will be used with almost no changes. The fundamental requirement is that "the control system will allow operation of Titania in a safe and reliable way". Where possible it will relieve the Operators of standard and repetitive tasks and make more difficult tasks easier to carry out. Standard operation will be possible without the presence of senior staff. It will also be possible for a single Operator to fire shots without having to leave the control console. The shot rate will not be limited by the combined capacities of the Operator and the control system.

The control system will be divided into self-contained subsystems for ease of development and maintenance. Individual components (both hardware and software) will be chosen so that they can be used as widely as possible. This will minimise the number of learning curves which need to be climbed and the number of spares which need to be held.

Software will be written in a single language with a uniform style and will run on a single operating system across all subsystems. Allowances will need to be made for interfacing with manufacturers' proprietary material.

The design of the control system both depends on and has an influence on the design of each of the other elements of Titania. These interactions will be considered from the outset to prevent, for example, decisions about the connections between the laser areas leading to complications in the design of the interlock system.

This appendix sets out a number of general principles which have been agreed and which will be preserved. Many of its details, however, will be subject to change as the project progresses. They should not be regarded as final.

The control system will be considered under the following general headings:

★ Safety

★ Continuous operation

★ Full-energy shots

★ Target areas

Each one covers a number of *functional* subsystems. These are not completely independent of one another in hardware, in software or even in functionality and to that extent they are not *true* subsystems. They do, however, involve groups of components which interact with other groups to the least practical extent. They can also be developed and run largely independently of one another. Dividing the system on this basis thus allows sensible programmatic decisions to be made.

The next four sections of this appendix comprise brief functional specifications for each of the subsystems. The fifth section considers the resources needed to provide each one and sets a priority order. An implementation schedule based on available resources is included.

SAFETY

The operation of Titania will give rise to a number of hazards. They will be discussed in the Titania Risk Assessment whose specification forms a separate appendix to this document. To control the risks associated with some of these hazards it will be necessary to use safety subsystems involving hardware. Some of these, in turn, may produce "alarms" and/or "warnings". In what follows a distinction is made between these two. Alarms arise when a situation is detected which threatens the safety either of personnel or, possibly, of the environment. They require immediate action and are of overriding importance. They must be clear and unambiguous and people must not be desensitised to them by false-alarms or by exposure to the more trivial "warnings". These result from the detection of a fault which threatens the hardware, or its performance.

A logical system will be devised to prevent the Operator being swamped by too many alarms should a catastrophic accident occur. Warnings will also be managed by the control system and may involve the interlocking of parts of the laser to prevent damage. The Operator will be made aware of warnings but they will not, in general, be broadcast publicly.

The hazards which need hardware control are:

★ Laser light

★ Mains electricity

★ High-voltage electricity

★ Hazardous gases

★ X-radiation

The associated safety subsystems are:

★ Interlocks

★ Emergency Shutdown

★ Monitoring

The interactions between these and the hazards are indicated in Table 1.

The interlock subsystem will be an enlarged and extended version of the "Cerberus" package[1] presently running on Sprite. Titania will initially be divided into 4 hazardous areas (the same as Sprite) but there will be a substantial increase in the number of controlled elements. The control CPU will therefore be upgraded. The communications network linking the interlock crates in different areas will

	Interlocks	Emergency Shutdown	Monitoring
Laser light	Cerberus	Cerberus	Cerberus, surveillance
Mains electricity		Central shutdown	
High-voltage electricity	Cerberus, local key-control	Cerberus, mains shutdown	Meters in Control Room or local to equipment
Hazardous gases		Automatic bottle isolation	Crowcon leak detectors
X-radiation	Controlled via high-voltage	Controlled via high-voltage	Film-badges, surveillance

Table 1: Interactions between hazards and functional safety subsystems.

continue to be separate from the rest of the control network.

Functional extensions of the interlock subsystem will allow a junior Operator to fire full-energy laser shots without having full Operator status. The firing of full-energy shots will also be key-controlled to prevent unauthorised firing even in safe conditions.

The emergency shutdown subsystem will allow the whole Titania installation to be made safe in response to an event requiring immediate action (e.g. fire, flood, major gas leak). It will be operable from the Control Room and from at least one other independent location. It will seal off the gas bottles from their respective mains and will shut down the Cerberus interlocks. It will also activate all of the local "laboratory power shutdown" circuit-breakers. An emergency shutdown will involve considerable operational disruption and some risk to the laser hardware. This subsystem must therefore be robust enough to make false shutdowns very rare.

A set of surveillance cameras will be installed to monitor hazardous areas and to allow indirect observation of dangerous processes. Where necessary they will be capable of operating in a low-light environment. There will be a total of twelve cameras switched through three monitors in the Laser Control Room. Those cameras in the Target Area will also be switched through monitors in the Target Area Control Room.

The present gas detectors will be moved and supplemented to cover the new Target Area and the new Raman/excimer laser layout. Equipment in the Laser Control Room will monitor 8 detectors (4 H_2/CH_4 and 4 F_2) and the Target Area Control Room will be equipped for 3 detectors (H_2/CH_4). The local alarms will also be improved.

CONTINUOUS OPERATION

These subsystems run continuously from start-up in the morning to close down in the evening. Some also continue overnight. They manage the laser when only the oscillators and front-end amplifiers are working. They also monitor and, in some cases, control services such as vacuum, gases, coolant and deionised water. Many of them continue to operate during the firing of full-energy shots. The subsystems are:

- ★ The Control Network
- ★ Diode Vacuum Management
- ★ Gas Management
- ★ Communications
- ★ Laser Diagnostic Monitors
- ★ Mirror Alignment
- ★ Amplifier Timing Control
- ★ Automated Switch On/Off
- ★ Support Service Monitors

As a general principle it has been decided to position the control "intelligence" as near as possible to the hardware being controlled. This minimises the number of signal and control lines which need to run to the Laser Control Room and, in turn, saves money and reduces the problems of noise and signal degradation. It also makes the full suite of diagnostics and controls available locally to staff who are investigating faults.

A corollary of this decision is that a network will be needed to allow the local CPUs to communicate with the Laser Control Room. This will handle all of the traffic in and out of the Control Room except for the interlocks, which will have their own network, and the emergency shutdown, surveillance, communications, gas-detection and shot-firing subsystems, which will be partly or wholly hard-wired.

The control network will be based on fibre-optics which have both high noise-immunity and high bandwidth. It will include a bridge onto the RAL backbone which will allow data to be backed up to the mainframes and transferred to remote sites via JANET. It will also control external access to CPUs on the network so, for instance, users will be able to interact with Target Area and diagnostic CPUs but not with those controlling the laser gases or the high-voltage power supplies.

Since the network is fundamental to the design of the control system its installation cannot be deferred. The exception to this is the bridge, which could be added later. A substitute terminator would, however, be needed until the bridge was installed.

The vacuum system for each e-beam diode chamber will consist of an oil-diffusion pump backed by a rotary or rotary/roots combination which will double as the chamber roughing pump. Each system will need monitoring of the chamber pressure (Pirani and interlocked Penning, or Baratron), of the backing pressure (Pirani), and of the coolant (pump temperature will suffice, or coolant temperature *and* flow). The vacuum valves will be automated and the control subsystem will permit automatic chamber pump-down from atmospheric pressure to high vacuum. The subsystem will revert to a safe state in the event of power or coolant failure. Foil failure, detected by a *long-term* rise in the chamber pressure, will cause the pumps to be isolated from the chamber. The only information which will be fed back to the Laser Control Room will be the diode chamber pressures. A steady pressure rise will flag up a "foil failure" warning. Pulsed power firing will be interlocked to diode pressures below 3×10^{-4} mbar.

There will be two gas management subsystems handling two separate supplies i.e. the excimer laser gases and the SF_6 for the e-beam pulsed power. The discharge-pumped lasers (the trigger lasers and any front-end amplifiers) will need Helium, Neon, Krypton and Helium/Fluorine and, as a minimum, manual isolation valves to allow them to be disconnected. Older lasers would benefit from an automated filling system, which is supplied as standard on the newer ones.

The e-beam pumped lasers (Sprite and Titania) need Helium, Argon, Krypton and Argon/Fluorine and a pump-down vacuum line. The valves associated with these lasers will be solenoid operated (with manual bypass where necessary) and the control system will allow automatic pump-down, purge and gas-fill. The pressure in each laser cell will be continuously compared with that in the corresponding diode vacuum chamber and the system will prevent either from being altered in a way that would lead to foil collapse.

The system will also prevent attempts to change the gas in any two lasers at the same time and will monitor the pressure in the mains to detect when bottles are empty. A warning will result when this occurs.

The gas in the e-beam pumped lasers will be circulated through particle and HF filters. The circulators will need to be controllable from the Control Room and, from time to time, the particle filters will need to be replaced and the HF filters regenerated. These two processes will not need to be automated.

The valves controlling the supply of gas to the mains will be connected to the emergency shutdown system. They will also be used when bottles are changed. The bottles will be stored in a single rack outside the main building, to allow easy changing and safe removal in the event of fire.

The second gas subsystem will control the SF_6 used to insulate the e-beam machines' spark-gaps. Each gap will be flushed between shots and the valves and pressure sensors therefore need to be fully automated. The weight of the SF_6 bottle will be monitored to indicate when the gas is about to run out. A warning will result. The charging of the Marx generators will be interlocked to the pressures in the spark gaps.

Communication between different parts of the Titania system will involve intercoms and a set of walkie-talkies. The intercoms may be an extension of the existing R1 system, thereby allowing contact with Vulcan and the LSF.

There will be a suite of diagnostics attached to the front-end lasers which will need to be monitored. The monitoring hardware will be 10 oscilloscope channels, 6 imaging channels (cameras, framestores and control CPUs) and 2 power meter channels. These diagnostics will be used mainly in the Oscillator Room for set-up and optimisation of the laser performance. They will however, be connected to a local CPU which will return selected data to the Laser Control Room for operational monitoring. Some of the data will also be incorporated into the full-energy shot diagnostics (see below).

The 24 KrF beamlines between Sprite and the input to the final Raman amplifier will have either 6 or 8 turning mirrors each. Assuming two-axis (tilt) mounts this will result in a total of 336 control axes. This total substantially exceeds that for the whole of the rest of the laser and adjustment of these mirrors will, if routinely necessary, dominate the whole alignment exercise. Fortunately these mirrors are localised in arrays and the beamlines associated with them do not include any spatial filters so they are ideally suited for automatic alignment.

The process will involve introducing a screen in front of each mirror array and imaging the beams with an appropriate camera. Once the image is digitised the beam centres can be located and compared either with preset positions or with an image of the array. The controlling CPU will then be able to adjust earlier mirrors to centre the beams on the array. The adjustment onto the final amplifier will have to be carried out beam-by-beam since they overlap there. The shutters used to isolate individual beams will also function as operational attenuators to control the pump energy and thus the Raman output.

Assuming reasonable system stability it should be necessary to adjust fewer than half of the mirrors routinely. Indeed if the arrays are really stable then adjustment may not need to be carried out very often at all. In view of the substantial expense of the alignment subsystem further studies are justified before design and procurement begin.

Optimum performance of the Titania front-end will depend on precise synchronisation of the oscillators and their respective amplifiers. This will fluctuate on both a shot-to-shot basis ("jitter") and on much longer timescales ("drift"). The drift can be corrected by monitoring the relative timings and feeding the results back to a compensator. This will be necessary if the front end is to run without constant Operator attention. Synchronisation of the oscillators with one another is a separate issue and will be incorporated in the front-end design.

The warm-up time of the Titania front-end is likely to be of the order of one hour, during which the laser alignment will not be stable. An automated switch-on subsystem will begin this warm-up before the Operations staff arrive each morning. As well as the front-end lasers it will also start the trigger lasers and pulsed power thyratron unit. The same subsystem will allow an automated switch-off, ensuring the correct shutdown sequence. Some hardware modifications to the lasers may be necessary to facilitate automatic control and complete automation may be constrained by safety requirements which prevent any area from "automatically" becoming hazardous.

The support services which will be monitored will be: deionised water, coolant, air-conditioning, vacuum spatial-filter (VSF) pressure, and helium purity.

The deionised water returning from each e-beam machine will be checked for resistivity and flow. Both the flow status (Adequate or Inadequate) and the resistivity (Adequate, Marginal or Inadequate) will be returned to the Control Room. Pulsed power firing will be interlocked to Inadequate flow status or resistivity. Marginal resistivity will result in a warning.

The primary coolant ring-main will be monitored for flow (Adequate or Inadequate) and temperature. Both these data will be returned to the Control Room. Automatic switch-on of the cooled lasers will be interlocked to Inadequate flow. Out-of-range temperature or Inadequate flow will flag up a warning.

The air temperature in the Oscillator Room will be controlled to maintain the stability of a number of systems including the Tsunami and the frequency-multiplying crystals. The temperature will be fed back to the Control Room and an out-of-range value will flag up a warning.

Poor vacuum in the VSFs will lead to degradation of the laser spectrum and the spatial beam-uniformity. Pressures will be monitored with Pirani gauges (or equivalent) and will be fed back to the Control Room. Out-of-range pressures will flag up warnings and the firing of the pulsed power may need to be interlocked to some of them.

Helium purity affects beam transport and will reveal any failure of the containment envelope. The purity, monitored at several points, will be returned to the Control Room and low values will result in a warning. This subsystem will be needed once any of the beams is propagating in helium.

FULL-ENERGY SHOTS

These subsystems are involved only with the firing of the pulsed power. They will need to be activated just before, during and after the shot. They are considered under the following headings:

★ Shot-firing

★ Laser Diagnostics

★ High-Voltage PSU Control

★ Trigger Laser Timing

The shot-firing subsystem will include the CPU which will take overall control of the shot-firing process. The Operator will preset the shot conditions and will have access to "monitoring" and "abort" facilities but the process will otherwise be fully automated The subsystem will include the hard-wired fast logic circuitry which will actually trigger all of the shutters, switches and lasers. It will also deliver triggers to the Target Area and log and store the data produced by the laser diagnostic subsystem. Finally it will carry out the post-shot procedures needed to return the laser to a safe condition.

The laser diagnostics monitored on each shot will include energies, spectra, pulse durations and near and far-field images throughout the system, voltages within the pulsed power machines, and ASE waveforms and pressure jumps from the e-beam laser gas cells. In total 23 numbers, 16 waveforms and 12 images will be available, although not all will be monitored on all shots. It is proposed that the final sets of diagnostics will be sufficiently close to the target chambers to obviate the need for further detectors in the Target Area itself.

Some of the data will be supplied by front-end diagnostics whose monitors (oscilloscopes, imaging channels etc.) will be costed in this appendix. Both monitors *and* diagnostics (calorimeters, spectrometers etc.) will be costed for the full-energy subsystem.

The Titania system will include 3 high-voltage power supplies which will charge the Marx generators for the two e-beam machines and their single trigger unit. These power supplies will be hard-wire interlocked to the Cerberus subsystem. Once the shot-firing sequence has been initiated the dumpswitches will be raised and the power supplies switched on. The Marxes will be charged at constant current (as nearly as possible) with the start times adjusted so that the cycles reach completion synchronously. The supplies will be switched off when the preset charging voltages are reached. The shot will then be fired and the dumpswitches dropped in. During the charging the supplies will be monitored for overcurrent (suggesting premature breakdown in the generator) and overvoltage (suggesting failure of the charge controller). Either will result in the shot being aborted. The Marx voltages will be continuously returned to the Laser Control Room.

As well as controlling the Marx supplies this subsystem will supervise the thyratron unit. This needs to be switched on at the beginning of each day and allowed to warm up before its internal HT supply is energised. The HT will be monitored and its status (On or Off) will be returned to the Control Room. Shot-firing will be prevented unless the HT is On.

This subsystem will be coupled intimately to the Marx generators and thyratron unit and it will therefore need to be well-protected against EMI.

The trigger laser timing subsystem will be similar to the amplifier timing package described above. It will only be needed, however, just before the Marx generators are charged, and the lasers will be kept in a quiescent state at other times. The success (or otherwise) of the timing exercise will need to be confirmed to the shot-firing subsystem which will not charge the Marxes until confirmation is received.

TARGET AREA

Most of the Target Area installations are described and costed in a separate appendix. The following control subsystems will, however, be considered here:

★ Vacuum Control

★ Mirror and Target Alignment

★ TA Data Links

The target chamber is repeatedly cycled up and down in pressure and therefore needs an effective, user-friendly vacuum control system. The chamber pressure will be relayed to the Target Area Control Room as will the status of the pumps (i.e. whether the high-vacuum pump is powered up or not).

The alignment subsystem will be driven from a local CPU which will be networked to allow some control from the Control Room. The extent of this control has yet to be decided. A subsystem already exists for the Sprite Target Area and this will be transferred directly to the Titania TA. As activities there become more complex it is likely that significant expansion will be needed.

The Target Area and the TA Control Room will have networked CPUs allowing data transfer between them. They could also transfer user-experimental data if the diagnostics were provided with appropriate interfaces. The Control Room CPU will be supplied with relevant laser performance data on a shot-by-shot basis. Hard-copy records will be available from the Laser Control Room.

Once the network bridge is installed users will be able to transfer data directly to the RAL mainframes either for processing or for further transfer to remote sites over JANET.

The flexibility required by different user groups will mean that hard-wired coaxial data links between the Target Area and the TA Control Room will need to be retained. It is hoped, however, that diagnostics will gradually be converted to CPU-compatible forms allowing more reliable digital links to replace the coaxial analogue ones.

PROGRAMME AND RESOURCES

Table 2 summarises the estimated cost of implementing each of the control subsystems. These costs are set at present (1993) levels and include VAT at 17½%. The subsystems have been prioritised in the following order:

i) safety-critical subsystems,
ii) subsystems which are fundamental to Titania's operability,
iii) infrastructure components which would be difficult to retro-fit or whose absence would distort the system layout,
iv) remaining subsystems.

Also shown in Table 2 are the funds required for the Phase 1 control system which will be in place for the start of Titania operations. This system will allow the laser to be fully controlled and diagnosed but will retain a number of manual subsystems whose automation will be deferred.

The control system will be widely distributed and will cover a very wide range of diverse functions. The hardware involved will be relatively inexpensive but its assembly into working subsystems and its installation in the Titania building will be labour intensive. The ratio between the control system's manpower requirement and its financial cost will therefore be significantly above the Titania average.

The schedule for implementation of the control system will be dictated by the needs of the rest of the programme. In FY 94/95 the only subsystem which will be required operationally will be for Titania gas management. Off-line development of the interlocks and the front-end diagnostic monitors will, however, be needed to allow rapid start-up of the new Oscillator Room in FY 95/96. The pulsed power systems will be unavailable for much of that year so the high-voltage psu and the shot-firing subsystems should also be produced and tested in FY 94/95.

The Sprite shutdown year will see most of the control hardware installed and commissioned. The fibre-optic networks and the coaxial and communications cables will be laid during the initial building works, when the internal walls and ceilings are being erected. The interlock, safety monitoring and communications subsystems will follow. Finally most of the laser diagnostics will be purchased.

In FY 96/97 the remainder of the control subsystems will be put in place. These will be the Raman laser diagnostics and the alignment and vacuum systems for the TA.

CONCLUSION

A long-term plan for the Titania control and diagnostics system has been described. The individual subsystems have been detailed and costed. A programme for implementation of a Phase 1 package, allowing safe and efficient operation of the Titania laser, has been presented. This initial installation will provide a base for further control automation as funds and manpower become available.

REFERENCES

1. P Gottfeldt and C J Reason, "Cerberus: a laser interlock system using Arcnet", Computing & Control Engineering Journal, 4 (6) p.281 (Dec. 1993).

Subsystem	Total Cost £k	Phase 1 Funds £k	Comments
Interlocks	30.0	30.0	This is safety-critical and is therefore fully-funded.
Safety Monitoring	12.3	4.8	Upgrading of the gas-detectors is funded, surveillance cameras are deferred.
Emergency Shutdown	0.5	0.5	Implemented via automated switch on/off hardware.
Shot-Firing	8.5	4.5	The control hardware is funded, the control console and extra optical memory are deferred.
Control Network	13.3	13.3	This is operationally fundamental and so is fully funded.
Laser Diagnostics (full-energy shots)	65.8	40.8	Essential diagnostics are funded. Some calorimetry, three imaging channels and one spectrometry channel are deferred.
Communications	6.5	5.0	New intercom system is funded, walkie-talkies are deferred.
High-Voltage PSU Control	6.2	6.2	Operationally fundamental so fully funded.
Gas Management	21.2	9.7	Only Titania gas handling is funded. The Sprite system will be funded from Operations. The present SF_6 system will be retained and the laser gas mains will not be automated.
Mirror and Target Alignment (TAs)	6.0	6.0	The existing Sprite system will be transplanted to the Titania TA. Expansion to accommodate increased operational complexity will be fully funded.
Vacuum Control (TAs)	4.0	4.0	The existing Sprite system will be transplanted to the Titania TA. Necessary improvements will be fully-funded.

Diagnostic Monitors (front-end)	32.0	5.0	A fast scope (monitoring oscillator modelocking), three imaging channels and extra cameras are deferred.
Automated Switch On/Off	2.8	2.8	Fully funded.
Diode Vacuum Management	4.5		Existing manual systems will be retained.
TA Data Links	5.6	1.0	Coaxial links from TA to Control Room are funded. Digital links are deferred.
Trigger Laser Timing Control	0.0		The existing hardware will be retained. The software will be integrated into the shot-firing subsystem.
Amplifier Timing Control	4.5		A manual system using existing hardware will be implemented.
Support Service Monitors	8.0		Manual systems will be retained.
Mirror Alignment (laser)	75.0?		Needs further study, not presently funded.
Totals	310	130	

Table 2: Costs of implementing all control subsystems and funds required for Phase 1 subset.

A8. BEAM PROPAGATION

M J Shaw, C J Hooker and D C Wilson

INTRODUCTION

As shown in appendix A3, the power limit of the Titania system is determined by the nonlinear index of the major propagation medium, namely air. Measurements of the nonlinear indices of air and other gases have been made recently at 248 nm and for 10 ps pulses [1]. The results are shown in table 1.

Table 1. Relative values of nonlinear index of air and other gases at 248 nm. The absolute value for air was determined to be $2.9 \pm 1.0 \times 10^{16}$ esu.

Gas	Relative n_2
Air	1.00
N_2	0.62 ± 0.03
O_2	2.50 ±0.25
Ar	0.24 ± 0.01
CH_4	0.94 ±0.07
Ne	0.005 ± 0.001
He	-0.002 ±0.001

The negative value for helium is an indication of the effect of ionization in these measurements. Theoretical calculations suggest that the nonlinear index of helium is several hundred times smaller than air.

BEAM PIPING

The CPA beam will need to propagate from the KrF beam separation array to the target area with (preferably) image relaying so that the near field is as uniform as possible on the compression gratings, since these are the most vulnerable components in the system. Vacuum propagation will thus be required and some degree of spatial filtration could be used to control the beam divergence.

With the Raman beams the problem is that air propagation will give an unacceptably large B-integral and vacuum piping of the four beams would be prohibitively expensive as well as very inflexible to target area beam layout changes. Beam piping in rare gas solves this problem and with the powers involved this must be helium rather than argon.

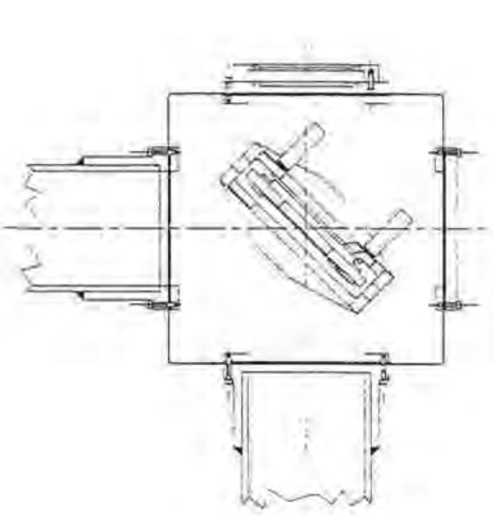


Fig 1. Gas tight turning mirror turret as proposed for the Sprite Raman upgrade.

A reasonably flexible solution to beam piping is shown in Fig. 1 which shows a turning mirror enclosed in a gas tight box mounted on a plinth. Boxes are connected by beam pipes which can either be rigid PVC with sliding O ring seals (as proposed initially for the Sprite Raman upgrade) or using flexible gas bags which may be of greater interest for helium propagation since the total volume can be collapsed to a small value to aid filling and purging. Each turning mirror turret can have windows in the unpiped arms which can be used for diagnostics of the incident or reflected beam.

The 4 Raman beams are coincident at the final Raman amplifier and will be allowed to propagate as a bundle contained within a single gas bag until they arrive at the beam timing table. Here the 4 beams are individually timed and sent in separate beam tubes (possibly also flexible) to the target chamber. The mirrors on the timing table will need to be located in a gas tight container. The use of flexible tubes after the table means that a relayout of the beam paths to accommodate a new experiment may be made rather quickly.

The technology for building flexible helium enclosures has been well-developed by the airship industry and is unlikely to pose many problems, particularly as no buoyancy is required. The problems of UV degradation of airship envelopes have been solved by appropriate choice of materials.

COSTINGS

CPA image relay pipe	£40k
Raman beam piping	£20k

The CPA piping is included in section A3 and the Raman beam piping in section A4.

[1] M J Shaw, C J Hooker and D C Wilson, Optics Comm. **103**, 153, (1993)

A9. RISK ASSESSMENT & SAFETY

G J Hirst

INTRODUCTION

The safety of the Titania project is subject to UK and EC legislation and to the Laboratory's internal rules. These will be applied specifically to Titania through the framework of the Titania Risk Assessment, which is required to be produced before the project begins[1].

The Risk Assessment will be carried out in accordance with the guidelines published by the Institution of Occupational Safety and Health (IOSH)[2]. This appendix forms the specification for the Assessment, detailing its scope, the procedure for producing it and the timetable for its completion. The specification has been discussed with the RAL Health and Safety Group.

SCOPE

The IOSH guidelines stress the importance of including *all* of the risks associated with the activities being assessed. It is therefore necessary to set boundaries to those activities to prevent the assessment from becoming unmanageably large. For example it would be unreasonable to expect the COSHH implications of the foil-etching process to be included *if*, as is being proposed, that process will be carried out by an off-site subcontractor.

The scope of the Assessment will therefore be limited to "The Operation and Maintenance of the Completed Titania System at RAL". It will *not* cover:

1. The development and testing of the Titania amplifier, which is presently taking place in R7,
2. The installation phase of the project, which will happen in R2 and R7 in 1995/6,
3. Activities associated with the completed system but which are carried out off-site,
4. Hazards/risks arising from possible upgrades to the Titania system,
5. Hazards/risks whose consequences do not involve harm to people or damage to the environment.

PROCEDURE

The procedure for producing the Risk Assessment is described in detail in the IOSH guidelines[2]. This section summarises them and identifies some salient points. The elements of the process are:

★ identification of **all** the hazards
★ evaluation of the risks
★ measures to control the risks.

Several approaches are suggested, the most appropriate of which is a hazard-by-hazard assessment. This makes best use of the paperwork which already exists and minimises the need for the assessor to call upon large groups of people as (s)he compiles each section of the Assessment.

The guidelines include a list of hazards which should be considered. It is not necessarily comprehensive, but it does illustrate how extensive the range is. The list is:

Fall of person from height
Fall of object from height
Fall of person on same level
Manual handling
Use of machines
Fire, including static electricity
Electricity
Drowning
Stored energy
Explosions (chemicals/dust)
Contact with cold/hot surfaces
Compressed gases
Mechanical lifting operations
Noise
Biological agents
Ionising radiation
Non-ionising radiation
Hand tools
Adverse weather
Chemicals/substances
Stacking
Housekeeping
Lighting
Confined spaces
Cleaning
Display screen equipment
Operation of vehicles
Excavation work
Vibration

It would seem that all but the last three of these could occur, to some greater or lesser extent, during Titania operations or maintenance.

The guidelines distinguish between two classes of methods for evaluating the risks associated with each hazard: "In simple terms if there is a risk of a single event/fault killing many people then a *complex* method is justified. On the other hand if the worst case is a single fatality occasionally, then a *simple* method is justified." The guidelines' *simple* method will be used initially. It will reveal any situations where it is inadequate (e.g. analysis of a major methane explosion might show that multiple deaths could result) and a more sophisticated assessment technique can then be applied.

Much of the risk evaluation will be a paper exercise, but there will need to be both experimental and observational inputs. Examples include measurements of the acoustic noise from the e-beam pumped amplifiers and a practical study of the manual handling involved in servicing the Titania foil assembly. The assessor may also need to take advice from the appropriate experts.

Once the risks have been evaluated it will be necessary to decide the measures needed for their control. The underlying principle will be that the risk should be comtrolled to the point where its effects are "as low as reasonably practicable". Where this involves balancing control against cost due regard will be given to existing "standard practice".

There are a number of ways of controlling those risks which have been shown, in the evaluation process, to need it. Some of these controls are statutory and/or required by internal Laboratory rules. If these are found to be adequate then the Assessment need only make reference to the relevant documentation. More commonly, however, the rules require that details of the control procedures (e.g. Standing Orders, Local Rules) be worked out and recorded locally. In this case the results will be included in the Risk Assessment.

The guidelines include a list of solutions to the problem of unacceptable risk. They are:

1. Elimination (e.g. by buying pre-etched Titanium foil rather than etching it on-site),

2. Substitution by something less hazardous and/or risky,

3. Enclosure (eliminating or controlling the hazard/risk),

4. Guarding/segregation of people,

5. Operation of a Safe System of Work,

6. Operation of written procedures that are known and understood by those affected,

7. Adequate supervision,

8. Identification of training needs,

9. Information/instruction (signs, handouts),

10. Use of personal protective equipment.

These solutions are presented in decreasing order of effectiveness and increasing order of management effort needed to enforce them. They will therefore be used in the order shown unless prevented by exceptional practical or financial constraints. Combinations will, of course, be considered.

The appointment of Responsible Persons to manage certain hazards is frequently required. The Risk Assessment will address any problems of conflicting responsibility and will lay out the safety hierarchy with the aim of clarifying who is responsible for what. The principle that "responsibility needs to be supported by a corresponding degree of authority" will apply.

The Risk Assessment will need to be recorded and the guidelines list those points which must be included if, as is legally required[3], it is to be "suitable and sufficient". They also point out that the Assessment will need maintenance. It will therefore include details of its own review procedures and timetables.

TIMETABLE

The requirement that the Assessment be completed "before the start" of the project[1] is interpreted here to mean "before the installation phase begins". This will allow the Assessment to be carried out using data produced during the development phase. It will also allow the assessor to contribute to the system design.

The installation phase will begin with Target Area building modifications in R7, scheduled for Summer 1994. The deadline for completion of the Assessment will therefore be July 1st 1994. The next milestone is the shutdown of Sprite on April 1st 1995. The first revision of the Assessment will be scheduled for that date and will include any corrections which have arisen during the final part of the design process.

REFERENCES

1. Rutherford Appleton Laboratory Safety Policy Statement, RALN 1/90, January 1990 + Annexes, Section 4.6.

2. Risk Assessment - A Practical Guide, B M Kazer, publ. by the IOSH as a supplement to The Safety and Health Practitioner, May 1993.

3. The Management of Health and Safety at Work Regulations 1992.

A10. PROGRAMME FOR THE CONSTRUCTION OF TITANIA

M J Shaw

INTRODUCTION

This paper gives a breakdown of the goals, the tasks necessary to achieve them and the costs associated with the construction of the Titania laser system. Costs are for equipment only, ie they do not include staff costs or overheads. The unit of time is the financial year and the tasks are divided into the following sections: Pulsed Power, Optics, Buildings and services, Controls, Front end and Target areas.

FY 93/94

At the end of this financial year the pulsed power system for the Titania module should be complete and tested and the large optics for the amplifier module purchased. The new optics for the Sprite system should be installed and tested as part of the Raman upgrade. The Electrical workshop should be taken over and W end of R7 cleared out. The shell of the target area should be erected.

93/94		cost £k
Pulsed power	Test switches, install diode vessel and test	190
Optics	Purchase Titania module optics purchase new Sprite optics	100
Buildings	Move ElecW/S, gut W end R7. Breakthrough EWS to R2 and support. New crane access Design and cost R2/R7 mods	(100)
Controls		
Front end		
Target Area	Preliminary Target Chamber design	5
Total 93/94		295

(£100k from RAL Management Board)

FY 94/95

In this financial year Sprite remains fully operational with the enhanced Raman beam and CPA target shooting capability. The Titania module should be fully tested at full aperture and ready to move to R2. The target area, Raman multiplex area and the target and laser control rooms should be completed and their services installed. The shell of the new target chamber should be designed, constructed and installed in R7. The components required for the new Sprite Marx should be purchsed and dry assembled. The Titania and Sprite gas control systems should be purchased and installed. The front end/R & D group should develop better CPA gratings.

94/95		cost £k
Pulsed power	Test Titania laser module at full aperture, purchase new Sprite components - dry assemble.	90
Optics	Detailed design of complete optical system	30
Buildings	Construct TA,TA and laser control rooms and Raman MPX area.	90
Controls	Titania and Sprite gas control systems.	30
Front end	Develop CPA gratings. Develop better diagnostics	40
Target Area	Design and construct new TC and install in R7	90
Total 94/95		370

FY 95/96

In this financial year Sprite is shut down and the remainder of the Titania System is constructed. The new oscillator room and KrF MPX area will be constructed. The Sprite pulsed power system will be modified and repositioned. The Titania module will be installed in the R2 pulsed power bay. A new high energy 746nm amplifier will be installed in the front end. Sufficient frames for the optical system will be installed to provide a single CPA beam to target. Safety critical and essential operational controls will be installed.

By year end the performance on target will be: 2.5J, 150 fs in a single 150 mm dia CPA beam.

95/96		cost £k
Pulsed power	Move Titania to R2, install New Sprite Marx, scrap Goblin	10
Optics	Purchase CPA Optics. Install mirror mounts required	40
Buildings	Construct Osc Rm, KrF MPX area.	100
Controls	Install safety critical and necessary operational controls	80
Front end	Move to new room and install new high energy amplifier and diagnostics. Start long pulse oscillator development	170
Target Area	Install CPA compression chamber and transport optics. Install CPA diagnostics and operate CPA target chamber.	160
Total 95/96		560

FY 96/97

In this financial year 1/2 of the KrF MPX optics are installed and the 4 beam Raman target area is brought on line operating at 1/2 full power.

Performance: Dual purpose target area operating with 150J/30 - 100 ps in 4 150 mm dia beams + 2.5J 150 fs CPA beam.

96/97		cost £k
Pulsed power		
Optics	Install 1/2 of the KrF MPX optics and all Raman optics	220
Buildings		
Controls	Install additional laser beam diagnostics	20
Front end	Variable pulselength oscillator development	20
Target Area	Install Raman beam transport optics and diagnostics.	130
Total 96/97		390

FY 97/98

In this financial year the remaining KrF multiplexing optics are installed together with a new variable pulselength oscillator in the oscillator room. The spatially uniform beam oscillator is brought on line.

Performance to target: 360J /500 ps and 7.5 TW in 4 150 mm dia Raman beams. 2.5J/ 150 fs CPA beam. 1 spatially uniform beam. Possibility of synchronous long/short pulse operation.

97/98		cost £k
Pulsed power		
Optics	Install remaining KrF MPX optics	190
Buildings		
Controls		
Front end	Install new variable pulse length oscillator and spatially uniform beam oscillator	100
Target Area	Enhance Raman beam diagnostics	45
Total 97/98		335

A11. COMPOSITION OF THE TITANIA TASK FORCE

This document has been produced by the TITANIA TASK FORCE. The task force was split up into working groups to study the various aspects of the TITANIA design. Groups and sections in this document have a close but not exact correspondence.The groups and membership are as follows:

Group	Membership
Programme and finances	M H Key, M J Shaw, W T Toner
Front End	I N Ross, J M D Lister, C Danson
Optical System / System Modelling	C J Hooker, I N Ross, M J Shaw, D C Wilson, M H Key
Target Areas	C B Edwards, C N Danson, P A Norreys, D Neely, A R Damerell
Buildings and Services	B E Wyborn, S Hancock
Pulsed Power System	A K Kidd, M J Shaw, S Angood
Control and Ops	G J Hirst, C Reason, P Gottfeldt C N Danson