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Petawatt Enhancement of the Vulcan High Power Nd:Glass Laser - Phase I

C Danson et al

January 1998

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Petawatt Enhancement Of The Vulcan High Power Nd:Glass Laser - Phase I

RAL-TR-98-004

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January 1998

PETAWATT ENHANCEMENT OF THE VULCAN HIGH POWER Nd:GLASS LASER - PHASE I

Grant Ref: GR/K74180

RESEARCH GRANT FINAL REPORT

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PETAWATT ENHANCEMENT OF THE VULCAN HIGH POWER Nd:GLASS LASER - PHASE I

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RESEARCH GRANT FINAL REPORT

Executive Summary

Phase I of the Vulcan Petawatt Upgrade, supported by EPSRC grant GR/K74180, was composed of four key phases to upgrade the existing Chirped Pulse Amplification (CPA) [1] capabilities to target. These were:

- the installation and commissioning of a new short pulse oscillator and high bandwidth stretcher at the front end of Vulcan;
- the construction and commissioning of a new purpose designed target chamber and associated beam handling optics to support the high irradiance interaction science programme;
- installation of a new large aperture pulse compression and focusing system to give target irradiance of 10^{20}W.cm^{-2} on target;
- provision of new laser instrumentation to assist in the diagnosis of the irradiance conditions achieved.

At the end date of the grant, these phases were either completed and on-line to users or awaiting final delivery of long lead-time optical components. Additional elements of the programme included harmonic conversion tests and preliminary implementation of second harmonic for experiments, installation of a regenerative amplifier and mixed glass in the Vulcan amplifier chain to enable experiments in the sub-500fs regime. Progress in all of these areas is summarised below and reported in detail in separate sections of this report.

The upgrade project was managed by a steering committee which gave advice to project staff on the scientific and technical priorities. The membership of the committee is shown in Appendix I. The committee recognised from the outset that the application of ultra-high intensity, CPA-based laser systems is an extremely fast moving area. To ensure that the project delivered the best possible value to the scientific community, the committee recommended that the views of the high power laser users be sought. A consultation exercise was carried out and its findings used to inform the project on user requirements, scientific opportunities and priorities. The results of this consultation are presented in Appendix II.

Much of the development work undertaken during the project has been at the leading edge of laser technology, resulting in significant publications and conference presentations, these are included in Appendix III. It is very satisfying to note that the enhancements, brought on-line to users progressively during this two year upgrade, are already enabling the community to extend its science programme into exciting new regimes. Some indicative "highlights" of recent work are included in Appendix IV. These advances will be described in full in the scientific literature and in the Annual Reports of the CLF in due course.

Oscillator and pulse stretcher system

A new CPA Front End for Vulcan was designed and commissioned as part of the Phase I PetaWatt Upgrade. This comprises an ultra-short pulse oscillator, a new variable length pulse stretcher based on an aspheric design, an optical '"switchyard" for input / output selection, a new suite of diagnostics and the ability to accurately frequency lock two CPA oscillators opening up the possibility of dual CPA operations by time multiplexing.

The new stretcher system was required to increase the stretched pulse length and to minimise the bandwidth clipping to allow the shortest possible pulses to be generated. The efficient and productive operation of a large laser system such as Vulcan depends entirely on the reliability and versatility of the front end systems. The new components provided by the grant were integrated into the Vulcan front end, fully tested and commissioned during the grant period and are now available routinely for experiments requiring CPA pulses. The units have increased substantially the capability of the Vulcan facility and have already made a major contribution to the recent success of high profile collaborative experiments on short pulse interactions.

Target chamber and beam handling system

The most visible enhancement to the facility installed during the Phase I upgrade is the new target chamber and beam handling systems in Target Area West. Prior to the upgrade, high irradiance interaction experiments were performed in a target chamber originally designed for twelve beam spherical implosions.

The grant has funded the design and installation of a dedicated short pulse interaction chamber and uprated vacuum system, featuring large diameter access ports, faster pump-down and greatly increased versatility. The chamber has been in use since mid 1997 and is universally acclaimed by users as a substantial improvement to the experimental capabilities.

At the same time as the installation of the new chamber, all the existing twelve-beam director tables and hardware were removed and the area reconfigured to bring all eight of the Vulcan laser beams to target. Users now have access to the two Chirped Pulse Amplified (CPA) lines (beams 7 and 8) and six 108 mm diameter long pulse lines (beams 1-6).

Pulse compression and focusing system

The increase in energy to target needed to meet the Phase I irradiance specification of 10^{20}Wcm^{-2} required the construction of a new, larger aperture pulse compression system. The hardware is now in place, commissioned with the existing diffraction gratings pending the delivery of the new larger aperture units from Jobin-Yvon. The laser induced damage threshold of these gratings has been measured at ~0.45 Jcm^{-2}. Operational considerations including beam uniformity and reproducibility from shot to shot give an operational fluence limit of~0.15 Jcm^{2}, which will produce a maximum beam energy incident on the first grating of 114 J. This is an increase of more than a factor of two currently available. Delivery is expected early in 1998.

Parabolic mirrors are required to focus the beam at high irradiance to avoid beam break-up due to self focusing. A new 0.6 m focal length off axis parabola to match the increased aperture of the new pulse compressor will be used for ultra- interactions in the 10^{19} Wcm^{-2} regime. A 3 m focal length unit for long focal length gas target interactions and a 0.225 m focal length On-Axis Parabola for interactions in excess of 10^{20} Wcm^{-2} are currently on order.

Laser diagnostics

An important part of the upgrade was the provision of improved laser diagnostics for optimisation of the system and better target interaction diagnostics. An ultra-high resolution **streak camera** was a major part of this package. The chosen device, a state of the art Hamamatsu 200 fs resolution streak camera (FESCA-200, C6138), will be available early in 1998. The camera has been specified with an S1 streak tube, giving sensitivity from the ultra-violet through to the near infrared, and a high dynamic range CCD read-out.

A new design of optical pulse **autocorrelator** for single or multiple pulses has arisen from instrumentation development covered by the Phase 1 grant. The design offers a number of improvements over existing designs including simplicity of alignment and operation, a substantial reduction in size and reduced component cost. Full details are available elsewhere in this report.

The wavefront uniformity of the Vulcan Nd:glass laser system is important because it affects both the focusability of the beam and the compressibility of the stretched pulse. An on-line interferometric system has been installed to provide wavefront fidelity information on each laser shot.

A three channel **soft X-ray spectrometer** has been constructed to resolve the angular intensity distribution of laser generated high harmonics. Significant advances have been made recently using Vulcan for the production of coherent soft X-ray sources from CPA driven laser matter interactions. The new spectrometer has enabled high resolution, angularly resolved measurements to be made at up to the 93rd harmonic for the first time.

Acknowledgements

The advances and enhancements to the Vulcan laser described in this report have involved substantial changes to almost every area of the system, from the pulse generators in the oscillator room right through to the target area diagnostics systems. The outstanding success of the project has established Vulcan as the world's leading source of ultra-high irradiance laser radiation to target. This success is due to the dedication, ingenuity and hard work of a large team of engineers, scientists and students who have achieved a very great deal in an extremely short time. To this team the authors wish to extend their congratulations and thanks.

The financial support of the Engineering and Physical Sciences Research Council and the Ministry of Defence and the encouragement and help of the CLF High Power Laser User Community is gratefully acknowledged.

C B Edwards, W T Toner & C N Danson
January 1998

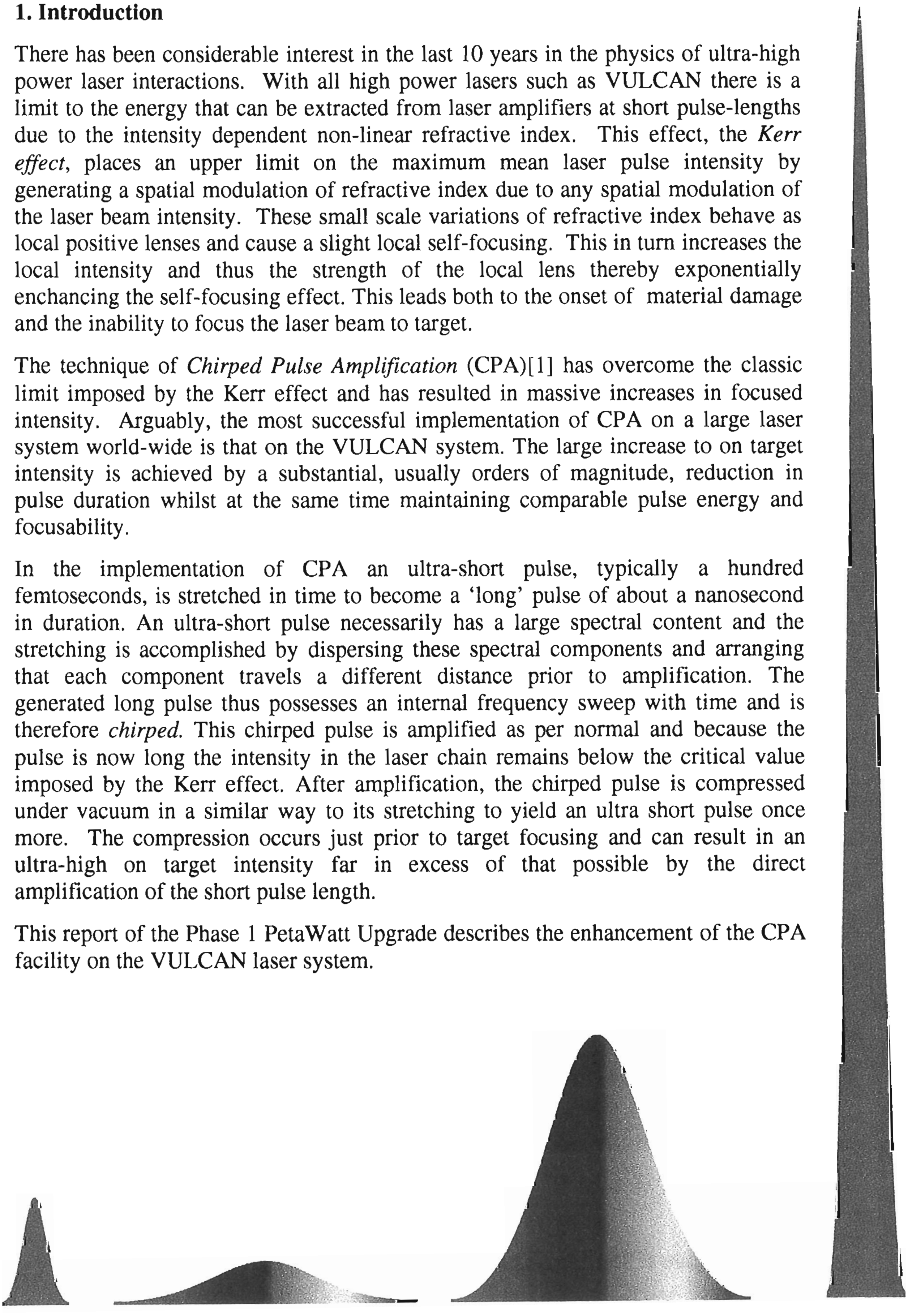
1. Introduction

There has been considerable interest in the last 10 years in the physics of ultra-high power laser interactions. With all high power lasers such as VULCAN there is a limit to the energy that can be extracted from laser amplifiers at short pulse-lengths due to the intensity dependent non-linear refractive index. This effect, the *Kerr effect*, places an upper limit on the maximum mean laser pulse intensity by generating a spatial modulation of refractive index due to any spatial modulation of the laser beam intensity. These small scale variations of refractive index behave as local positive lenses and cause a slight local self-focusing. This in turn increases the local intensity and thus the strength of the local lens thereby exponentially enchancing the self-focusing effect. This leads both to the onset of material damage and the inability to focus the laser beam to target.

The technique of *Chirped Pulse Amplification* (CPA)[1] has overcome the classic limit imposed by the Kerr effect and has resulted in massive increases in focused intensity. Arguably, the most successful implementation of CPA on a large laser system world-wide is that on the VULCAN system. The large increase to on target intensity is achieved by a substantial, usually orders of magnitude, reduction in pulse duration whilst at the same time maintaining comparable pulse energy and focusability.

In the implementation of CPA an ultra-short pulse, typically a hundred femtoseconds, is stretched in time to become a ‘long’ pulse of about a nanosecond in duration. An ultra-short pulse necessarily has a large spectral content and the stretching is accomplished by dispersing these spectral components and arranging that each component travels a different distance prior to amplification. The generated long pulse thus possesses an internal frequency sweep with time and is therefore *chirped.* This chirped pulse is amplified as per normal and because the pulse is now long the intensity in the laser chain remains below the critical value imposed by the Kerr effect. After amplification, the chirped pulse is compressed under vacuum in a similar way to its stretching to yield an ultra short pulse once more. The compression occurs just prior to target focusing and can result in an ultra-high on target intensity far in excess of that possible by the direct amplification of the short pulse length.

This report of the Phase 1 PetaWatt Upgrade describes the enhancement of the CPA facility on the VULCAN laser system.



2. The 'front end' for the Petawatt upgrade

A completely new CPA Front End for VULCAN has been designed and implemented for the Phase I PetaWatt Upgrade. This comprises three new complimentary ultra-short pulse oscillators (one of which was purchased on the grant), a new variable length pulse stretcher based on an aspheric design, a completely new optical 'switchyard' for input / output selection, a new suite of diagnostics and the ability to accurately frequency lock two CPA oscillators opening up the possibility of dual CPA operations through time multiplexing. These systems are individually detailed below.

2.1 Oscillators

Three CPA oscillators are currently available in the Front End. These are

- The Ti:S Oscillator - The *Tsunami* [2] is a commercial Kerr Lens Modelocked (KLM) oscillator using Ti:Sapphire as the active medium. It is pumped by all lines of a pointing stabilised Argon Ion laser. The 80 MHz cavity produces 5 nJ pulses of duration 120 fs.
- The SAM Oscillator - The GLX-100 [3] is a commercial oscillator with Nd:Glass as the active medium. It is mode locked by a state of the art device known as a SEmiconductor Saturable Absorber Mirror (SESAM). The 80 MHz cavity produces 170 fs pulses at 1nJ per pulse. The SESAM is mounted on an intra-cavity piezo which is in turn mounted on a picomotor. The position of the piezo and picomotor are determined by a microprocessor controlled phase locked loop that is synchronised to an externally applied RF signal.
- The YLF2 Oscillator - The final oscillator is an in house designed Nd:YLF[4] Additive Pulse Modelocked (APM) [5,6] oscillator similar to the other Nd:YLF oscillator (YLF1) that has been in use for a number of years. It is a coupled cavity oscillator that produces pulses of 1.8 ps duration at 1 nJ per pulse.

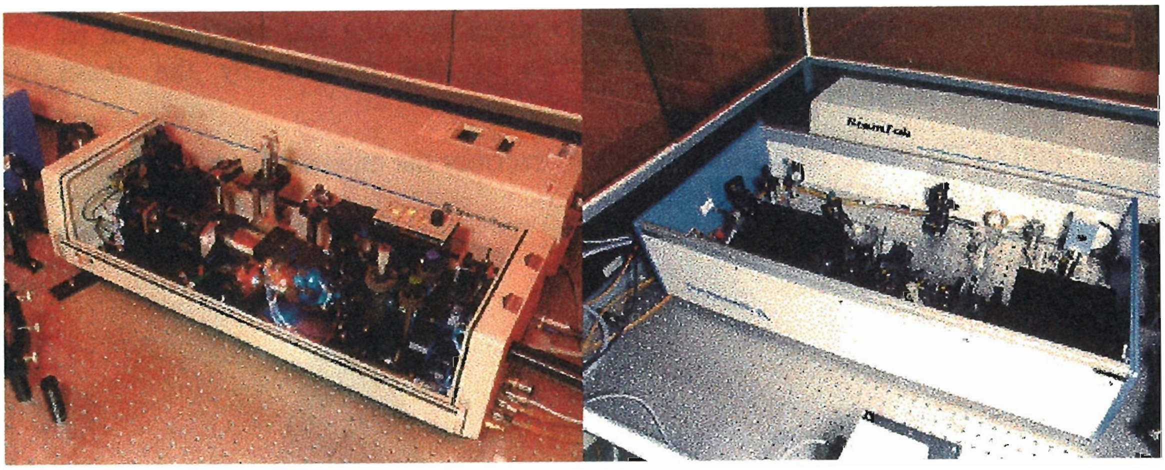


Figure 1. The Ultra-short pulse Tsunami and SAM oscillators

2.2 Stretcher

A new stretcher system has been designed to increase the stretched pulse length passing through the system and to maximise the bandwidth clipping to allow the shortest possible pulses to be generated. Several new additional new features have also been introduced into the stretcher design.

The stretcher, shown in Figure 2, is a refractive confocal telescopic design operated in a double pass mode using aspheric optics. The two lenses have a focal length of 1.5 m, about the minimum focal length possible to match the 3.5 m compressor length. Both lenses are plano-convex manufactured from BK7. Lens 1 has a diameter of 70 mm and Lens 2 a diameter of 150 mm. The spherical aberration of Lens 2 means that, if not corrected, there will be a residual angular dispersion at the output of the system. Therefore Lens 2 is of an aspheric design with a conic coefficient of -1.07 to correct for this aberration.

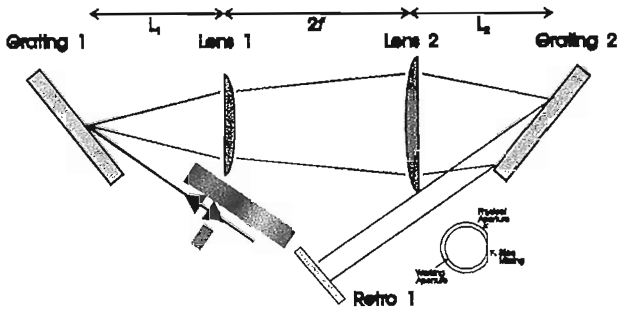


Figure 2. The pulse stretcher

The maximum bandwidth that the system can pass at 1053 nm is 16 nm. This is 4 times the expected output bandwidth of VULCAN after the upgrade has been completed. This is also about the maximum bandwidth that could be passed by a refractive design without 3rd order phase distortions from chromatic aberrations becoming important.

One final important feature of the stretcher is the ability to vary the effective grating separation without changing the beam alignment. With reference to Figure 3, this has been achieved by mounting Grating 3 and the retro-reflector on a separate 'L' shaped breadboard which is in turn mounted on a Hepco rail system [7]. This allows significantly easier tuning of the pulse compression which gives the option of adjustment in the Front End as well as in the Target Area. This also provides the ability to 'dial up' a User specified pulse length up to 20 ps which can be positively or negatively chirped.

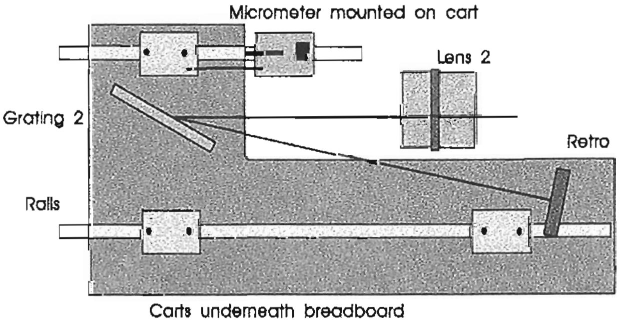


Figure 3. The variable length stretcher configuration

2.3 Optical Switching

A schematic of the Front end for the Phase I PetaWatt Upgrade is shown in Figure 4. The use of three oscillators, a stretcher for each target area and a number of possible output directions has meant a new system to provide the necessary switching. A scheme has been devised based on McNielle polarisers which transmit or reject a beam based on its polarisation. The special feature of a McNielle polariser is the transmission and rejection directions are at 90 degrees with respect to each other which make them ideally suited for use on optical tables. The relevant beams are then switched by a combination of drop in beam blocks and wave plates. This drop in nature is achieved by mounting these components on a rotary solenoid. A miniature switch picks up the status of the mount. The solenoids are driven and read by a specially developed unit that can interface to the main VULCAN control computer system. The stretcher and input / output switching are housed on a single 3mx1.5m optical table.

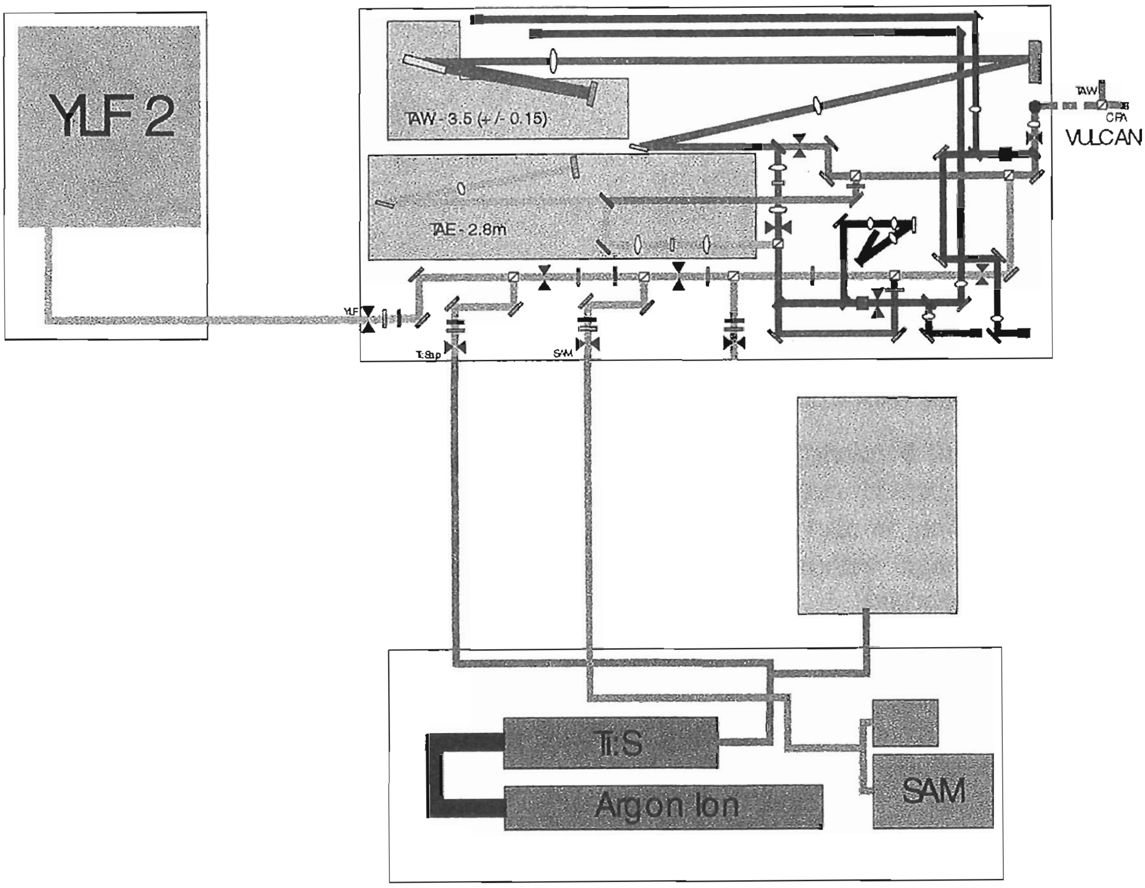


Figure 4. Schematic of the VULCAN Front End

2.4 Diagnostics

A number of fixed diagnostics have been implemented to improve the speed of alignment between the Front End and the main VULCAN system. Each oscillator has its own low resolution spectrometer to confirm wavelength and the Modelocked status. The SAM oscillator has an additional monitor to confirm the frequency locking status. There is an Input Near Field and an Input Far Field monitor which determine the position and pointing of each oscillator into the stretcher system. A second Near Field and Far Field pair is located at the exit of the Front End to determine position and pointing into VULCAN. All four outputs are available on a single monitor using a quadrant framer. A high resolution spectrometer is used on the stretcher input line to diagnose any oscillator problems such as low level double pulsing. All of the outputs from these diagnostics are displayed in the Main Control

Room. There are a number of diagnostics which have been developed to be used as and when required, which include: the 2nd order autocorrelator [8] for pulse length measurement; the scanning 3rd order cross correlator [8] for an instant measurement of pulse contrast; and a 2nd order cross correlator for the measurement of the quality of oscillator frequency locking.

2.5 Pulse Contrast Measurements of the CPA Oscillators

When commissioning the oscillators it was important to measure the pulse fidelity. When operating in CPA mode, the VULCAN laser system is capable of producing an on target power density of $>10^{19}$ W.cm^{-2}. An important aspect in this mode of operation is the contrast of the pulse that is delivered to target with respect to any low level activity that may be present. This arises because low level activity can have sufficient intensity to cause the breakdown of the target before the arrival of the main pulse. The ultimate limiting factor in the low level activity is the Amplified Spontaneous Emission (ASE) from the laser chain. For VULCAN, the ASE intensity on target is of the order 10^{11} W.cm^{-2}, some eight orders of magnitude below the main pulse intensity. This is in the threshold region that will cause a solid target to break down and as such any activity or pre pulse above this level is therefore very likely to cause plasma formation on target ahead of the main interaction pulse. One possible source of pre pulses is the ultra short pulse oscillator that is used to seed the amplifier chain. We have therefore conducted an examination of the pre pulse activity from two of the ultra short pulse oscillators that are used to seed the chain covering a 10^7 dynamic range.

The pulse contrast of the two shortest pulse oscillators on VULCAN has been measured over an extended time range using two different techniques. The contrast of the Ti:S was measured using a 3rd order cross correlation technique and that of the SAM using a 2nd order auto-correlation technique.

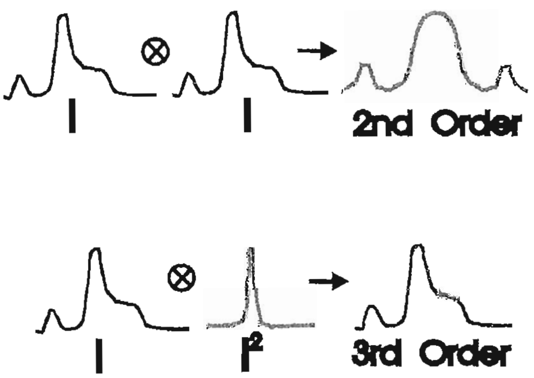


Figure 5. 2nd and 3rd order cross correlation

2.5(i) Ti:S Contrast

Referring to Figure 5, the 3rd order cross correlation technique used provides an auto correlation between a pulse at its fundamental wavelength and the same pulse at its second harmonic wavelength. A main advantage of using a 3rd order technique is the initial frequency doubling process, being non linear, effectively 'cleans up' the incident pulse with any low level pulse activity being effectively removed. Therefore, the auto correlation process becomes asymmetrical and effectively provides a cross correlation of a pulse sequence with a single 'clean' pulse. This enables one to determine whether any detected low level pulse activity occurs in front of or behind the main pulse in addition to providing a more accurate measurement of pulse shape. A secondary advantage of this technique is that one detects the third harmonic light derived from the frequency mixing of the first and second harmonic input pulses. This is therefore a technique capable of high dynamic range operation since the mixing crystal phase matching condition and the detection systems can be configured to be sensitive to third harmonic light only.

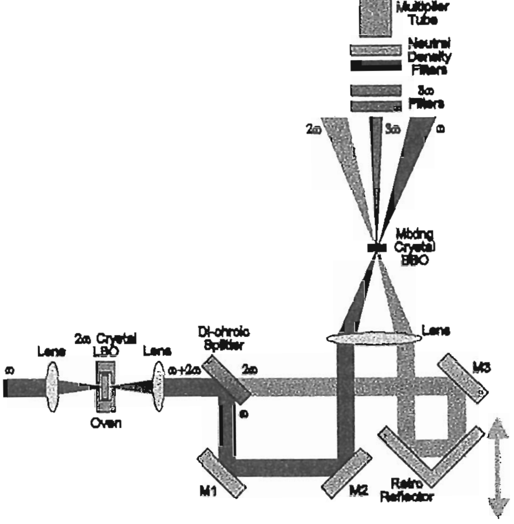


Figure 6. A third order cross correlator

A schematic of the device is shown in Figure 6. The 400 mW incident beam at 1053 nm (80 MHz, 100 fs) is partially converted into a 526 nm beam with an approximate 20% conversion efficiency. The frequency doubling is performed in a 1mm length of Lithium Tri-Borate (LBO) used in a confocal geometry and non critically phase matched by heating the crystal to 163°C. The 1053 nm and 526 nm beams are then separated using a di-chroic separator and directed to a focusing lens by appropriate mirrors. The 526 nm beam is directed via a retro-reflector as shown to provide variability of arm length and thus the scanning range. The two beams are focused into a correctly cut β-Barium Borate (BBO) frequency mixing crystal and phased matched by angle tuning. The 3rd harmonic mixed signal is detected by a Photomultiplier tube. The input aperture to the tube is filtered by narrow band 351 nm filters with a 10^{-12} off centre extinction. Additional calibrated filtration is used to ensure the detector operates within fixed limits over the full dynamic pulse contrast range of interest. The output of the photomultiplier is processed by a Boxcar signal averager to improve the signal to noise ratio. Figure 7 shows the results for the Tsunami oscillator over a 40 ps and a 5 ps range respectively. Points were taken every 66 fs. The plethora of low level pulses in Figure 7(a) are Fresnel reflections generated within the instrument from the frequency doubling crystal, the mixing crystal and the splitter. The source of each one has been identified. The short time scale trace 7(b) shows slight wings in the pulse starting at the 10^{-4} level. This is consistent with previous observations in KLM cavities indicating an incorrect amount of negative dispersion.

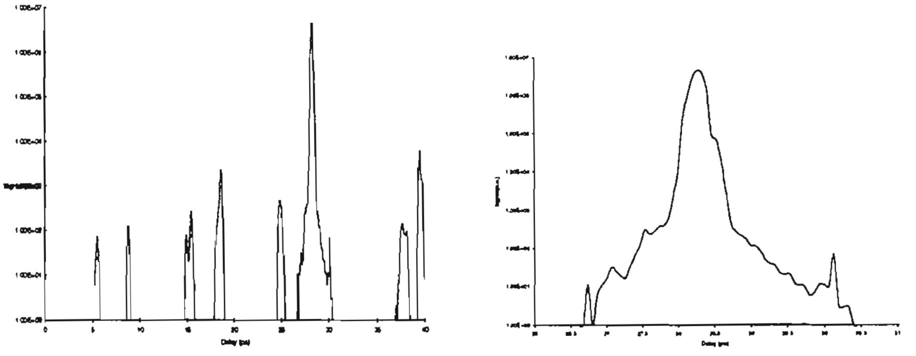


Figure 7. Ti:S cross correlation

2.5(ii) SAM Contrast

The pulse contrast of the SAM Oscillator was measured using a background free 2nd order technique. A schematic of the device is shown in Figure 8. The input 70 mW beam (80 MHz, 200 fs) was equally split into two separate beams that were recombined in a thin frequency doubling crystal. The two beams were arranged to cross at a slight angle so that any 2nd harmonic light generated by either beam could be prevented from entering the detector system by means of an appropriate aperture. The mixing signal (auto-correlation) is emitted at the half angle and passes through the aperture and into the detector system. The dynamic range of this technique is intrinsically limited to about 10^5 by the scattering of 2nd harmonic radiation generated by either of the two beams into the detector system off the mixing crystal. However, this range can be increased by using an optical chopper that chops each of the incident beams at a slightly different frequency. The mixing signal will then occur at the sum and difference frequencies. A lock-in amplifier is used to lock to the mixing signal at, in this instance, the difference frequency. Approximately two additional orders of magnitude can be obtained in the dynamic range of the instrument by this method. However, even though this technique exhibits a large dynamic range it remains a 2nd order process and it is therefore not possible to deduce whether any activity is before or after the main pulse.

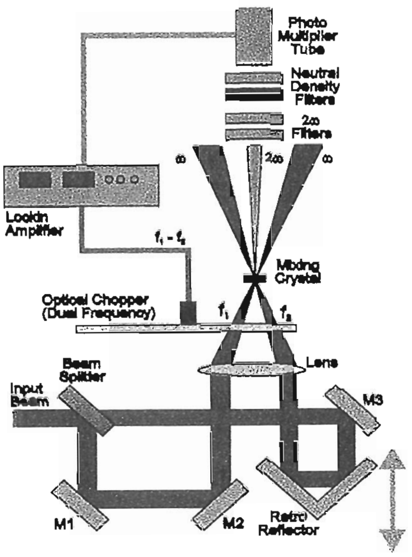


Figure 8. 2nd order cross correlator

The long time scale and short time scale results for the SAM oscillator are shown in Figure 9. The long time scale trace is significantly cleaner than that for the Ti:S but this is to be expected given the lower number of optics involved in the measurement technique.

The single low level pulse is due to the beam splitter. An examination of the short time scale situation shows a pulse shape that adheres quite closely to that of a sech^2 type shape.

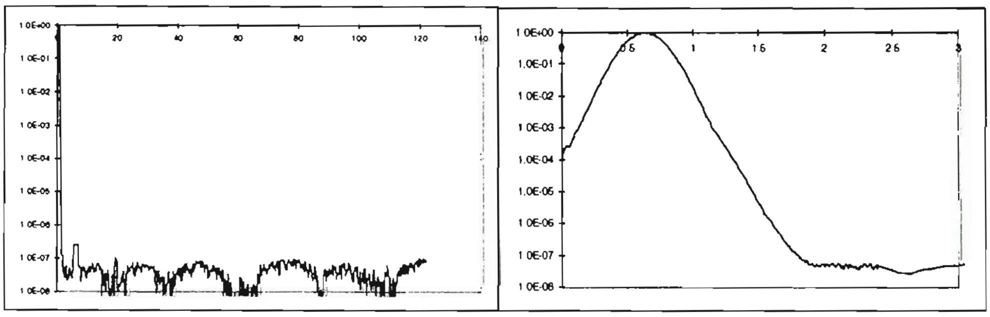


Figure 9. SAM auto-correlation [9]

2.5(iii) Experimental Summary

Over a long time scale both oscillators have been shown to be pre-pulse free over seven orders of magnitude. The pulse shapes are slightly different but is not of significant consequence because the pulse shape that is ultimately produced at the end of VULCAN is dictated by the significant gain narrowing that occurs during amplification; asymmetric spectral clipping in the pulse compressor; and accumulated phase distortion due to self phase modulation [10].

3. Pre-amplification

An integral part of the Front End for the PetaWatt upgrade is the development of an alternative mechanism of amplification covering the first six orders of gain. This is currently performed by a series of double passed Nd:glass amplifiers, with the drawback that a significant amount of gain narrowing occurs, ultimately limiting the minimum pulse duration available to target.

The originally proposed solution was to use a regenerative amplifier using Ti:S as the gain medium operating at 1053 nm. In a regenerative amplifier the low energy pulse is injected into a cavity containing the gain medium. The pulse is then allowed to pass many times through the gain medium until the required pulse energy is achieved, usually limited by damage to cavity components. The pulse can then be switched out of the cavity and injected into the main amplifier chain.

Researchers at other institutes, in particular those at Lawrence Livermore National Laboratories, have used regenerative amplifiers for many years [11]. There has been recent evidence that when operating in these ultra-high intensity regimes the pulse fidelity has been seriously degraded in the regenerative amplifier itself. This effect is caused by the multi-pass nature of the device, in that it is very easy to generate satellite pulses within the cavity which when switched out manifest themselves as pre-pulses. These pre-pulses would not be acceptable to our users for the highest intensity experiments. The decision was therefore taken not to install the regenerative amplifier but to take a longer term approach to look at other viable options.

There are a number of possible solutions that we are currently evaluating. These include:

- An Optical Parametric Amplifier operating at near degeneracy and seeded with the chirped pulse [12];
- A diode pumped Ytterbium doped fibre amplifier with the possibility of a second stage of amplification in bulk Yb:glass [13];
- Generating the pulse at 750 nm, the peak of the gain of Ti:S, followed by a regenerative amplifier. The pulse after extraction is then compression and converted to 1053 nm pulse by an Optical Parametric Generator. Being a non-linear process this method should eliminate any pre-pulses generated at 750 nm [14].

4. Mixed glass implementation

The use of mixed glass would only be a viable option on Vulcan if the pre-amplifier solution was in place. This will be considered in the future when appropriate.

5. Compression

5.1 Large aperture gratings

The limit to the energy that can be delivered to target is ultimately the laser induced damage threshold of the compressor gratings. Therefore to increase the energy larger aperture compression gratings have been acquired. These are gold coated holographic gratings with 1740 lines per mm with a limiting aperture of 40 x 19 cm (760 cm^2) [15]. The laser induced damage threshold has been measured at ~0.45 Jcm^{-2}. In operation this means they can be operated at ~0.15 Jcm^{-2}, giving a maximum beam energy incident on the first grating of 114 J. The new large aperture compression gratings give a final output beam size of 111 x 190 mm.

To maximise the energy onto the first grating the beam has to be as uniform as possible and completely filling the first grating. To achieve this the aperture of the output laser beam was increased by modifying the final vacuum spatial filter in the system. The 135 mm beam at the output of the 150 mm amplifier was expanded to 205 mm using lenses of 2814 mm and 4272 mm i.e. a magnification of 1.52. The lenses were anti-reflection coated to minimise losses.

5.2 Vacuum chamber and pump

Details of the vacuum mounting of the second compressor grating and the vacuum pumping system itself are dealt with in section 8.

5.3 Mirror/grating mount design

The reduction in pulse length, increase in grating size and grating tunability requirements for the Phase 1 PetaWatt upgrade required more stringent recompression grating alignment tolerances i.e. during grating tuning, which involves changing the separation of the grating pair, their parallelism needs to be maintained at $\leq$ 0.050 mrad. In addition the upgrade required that a significant number of large optics had to be supported, manipulated and accurately aligned during routine operations with a number of different motion requirements. In order to achieve these requirements a new mirror/grating mount was designed and installed which met these criteria and was also easy to handle, reliable and flexible in operation.

The mirror/grating mounts comprise of three major sub assemblies namely:

- The Optics Handling Frame
- The Mid Level Swivel Assembly
- The Base Assembly

The optic is mounted into the handling frame and held securely in position. The frame is equipped with carrying handles and is located in the mid level swivel assembly by two dowels. The mid level swivel assembly is kinematically mounted on to the base assembly and locked in position with two bolts. A fine adjustment screw is fitted to tilt the optic in the vertical plane. Two Hepco 90^0 slide segments are incorporated into the mid level swivel assembly to allow for tilting the optic in the vertical plane, with movement provided either by fine adjustment screws that are manually operated or by a motorised micro positioner. The base assembly incorporates a Hepco 360^0 slide ring and grooved bearings giving a full 360^0 rotation of the optic in the horizontal plane. The optic can be locked in any segment and finely adjusted about the vertical axis using either a fine adjustment screw or a motorised micro positioner.

An important feature of the design of the mirror/grating mount assembly is that all movements of the optic are about the optic front face centre. Movement of 10 arc seconds can be achieved on all axes. The modular design means that a number of variations are achievable to cater for different optical operational needs. Various optics handling frames have been designed to accommodate different optics i.e. gratings 420mm x 210mm (as shown in the figure below), 350mm x 260mm and 235mm ϕ beam mirrors. The grating mount can accommodate up to 500mm circular gratings if required. The base assembly can be fitted to an additional stage to facilitate x,y movement. Two assemblies have also been mounted on a stage which has been adapted to run on a 3 metre long Hepco rail system to enable precise beam timing to be carried out. One assembly has been specially adapted to give a full 180^0 motorised drive capability for a beam injection mirror thus minimising the space requirements for this optic.

Twelve optic mount assemblies have been manufactured, two to house gratings and ten for mirrors. The design of the mount assembly is modular leading to its being able to be adapted to a number of optic holding and manipulating parameters. The design is based on proprietary high accuracy slide systems. The mounts have been tested in TAW and found to be operationally highly successful.

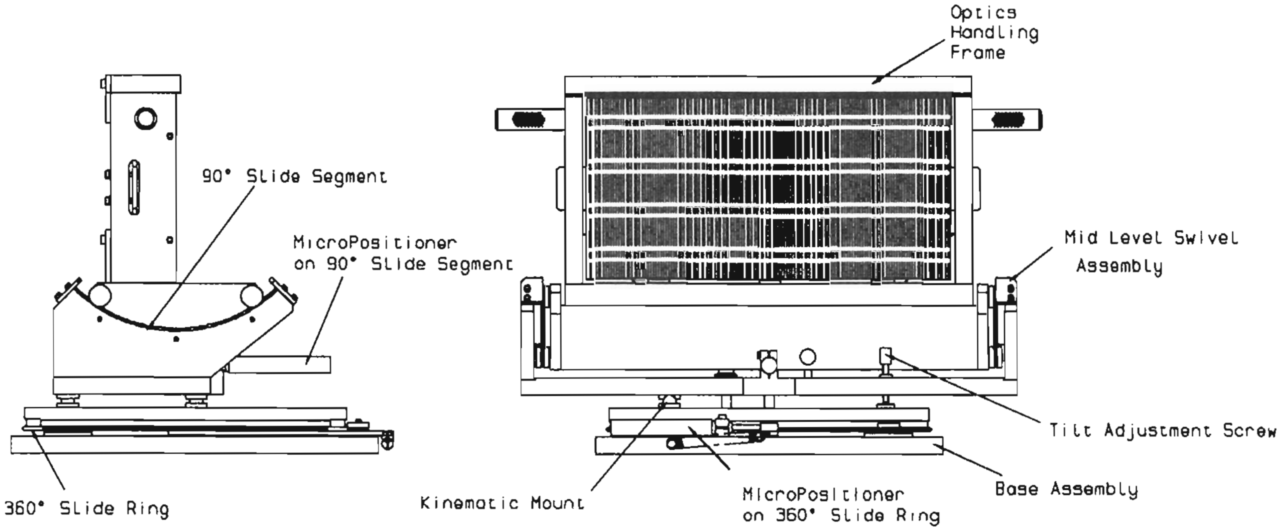


Fig 10. Grating Mount Assembly

6. Second harmonic generation

Interest in using the second harmonic of the CPA Nd:glass laser system arises for a number of reasons. There is a reduction of the pedestal level by virtue of the non-linear nature of the doubling process and a shorter wavelength interaction beam can be advantageous in laser-plasma experiments [16].

A feasibility study of frequency doubling the VULCAN short pulse (picosecond), CPA 1,054 nm beam for laser matter interaction studies was conducted in TAW. Optical non-linear KDP crystals of various thicknesses between 1 - 4 mm were characterised at incident intensities up to 300GWcm^{-2}. The crystals used type I phase matching which has almost equal group velocities for the fundamental and second harmonic components.

Beam focusability is determined by the incident beam quality, the optical quality of the crystal and undesirable B-integral effects. The B-integral decreases with reducing crystal thickness therefore, the thinnest crystal which maintains high conversion efficiency and optical quality is the optimum choice. Results on the second harmonic conversion efficiency are shown in figure 11. This shows that for incident intensities of 150 GWcm^{-2} the 4 mm Type I KDP crystal is ideal [17]. Discussions with manufacturers have also indicated that large aperture 158 mm diameter 4 mm thick crystals with a wavefront transmission quality of $\lambda/4$ which will preserve beam focusability can be produced and are awaiting delivery. The crystal production technology is rapidly advancing and it is intended that a 2 mm thick 158 mm diameter crystal will be used in due course. This crystal will be ideal for pulse lengths of less than 1 ps which is the intended operating regime for the new target area.

Initial tests have also been carried out on frequency quadrupling the CPA beam. A CPA probe line providing up to 10 mJ of 263 nm beam has already been commissioned. Further progression along this route would lead to the provision of a full aperture 263 nm Vulcan CPA beam within the near future for this target area.

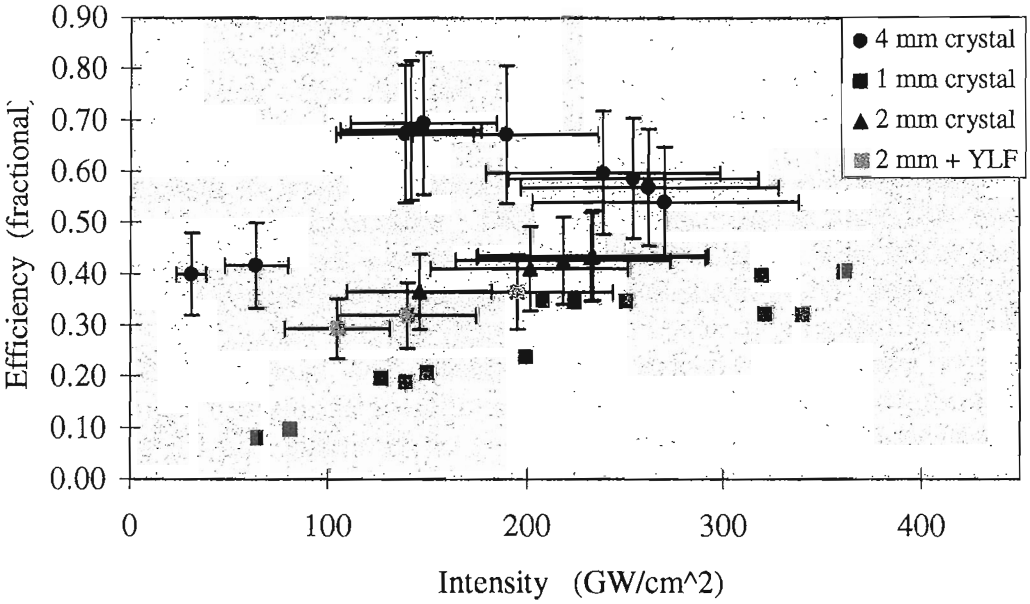


Fig 11. Frequency doubling efficiencies of CPA beams

6.1 Contrast ratio - separation of 1053 and 527 nm

Type I frequency conversion facilitates experiments where contrast ratios $> 10^6$ are required for laser matter interactions, since it is easier to separate the orthogonally polarised fundamental and second harmonic components.

Separation of the fundamental from the second harmonic can be achieved with high contrast ratios $> 10^6$ by reflection from three dielectric mirrors placed between the non-linear crystal and the target plane. However, new and innovative techniques are being explored utilising diffractive optics in which complete separation of the two wavelengths is achieved. The beams can be spatially separated with the unwanted wavelength dumped before the focusing optic or if limited by the geometry, angular separation employed such that only the harmonic required is focused onto the target.

7. Phase 1 Petawatt Chamber configuration and design

The Phase 1 PetaWatt Vulcan upgrade will provide a 200 TW sub-picosecond CPA beam in TAW for ultra high intensity (10^{20} Wcm^{-2}) laser plasma interaction experiments. This will be achieved by delivering a larger CPA beam of shorter pulse duration to the interaction region. Requirements also include the provision for frequency doubling the CPA beam and the simultaneous use of a multi-joule frequency shifted CPA probe beam and of the six full energy 108 mm diameter long pulse (80 ps - 1.5 ns) beams in either cylindrical, spherical, cluster or line focus geometry. This report will concentrate on the design of the grating compressor chamber and a new interaction chamber to accommodate these requirements. The developments to the laser, transport system and diagnostics are detailed in separate sections elsewhere in this document.

7.1 Chamber Geometry and Stability

The optimum Phase 1 PetaWatt chamber design selected to fulfil all the experimental requirements was a cylinder of diameter 1.8 m, length 0.95 m and wall thickness 0.075 m, as shown in figure 12. It is constructed from mild steel and is electroless over-coated with a protective 25 micron nickel film. Two large 0.8 m diameter flat end section hinged doors are provided for internal access. When necessary, the doors can be replaced by the existing six 108 mm diameter beam cluster or line focus housings normally used on Target Area East.

Finite element analysis has shown that significant movement of the main vacuum vessel wall will occur as the chamber is pumped. Measurements have confirmed that the centre of the end flange deflects by 1.75 mm and the rectangular side flange moves by 0.3 mm. To eliminate this wall movement from effecting the optical beam path, all critical optics are mounted on an internally vacuum isolated table onto which a number of smaller bread-boards can be added. The internal bread-boards are removable allowing a user group to initially pre-align externally and then afterwards, store a given set-up between experiments saving on rebuilding time for a future use. All internal optics and alignment systems are supported from this table and tests have shown that angular deflections between air and vacuum are below the 0.05 mrad level.

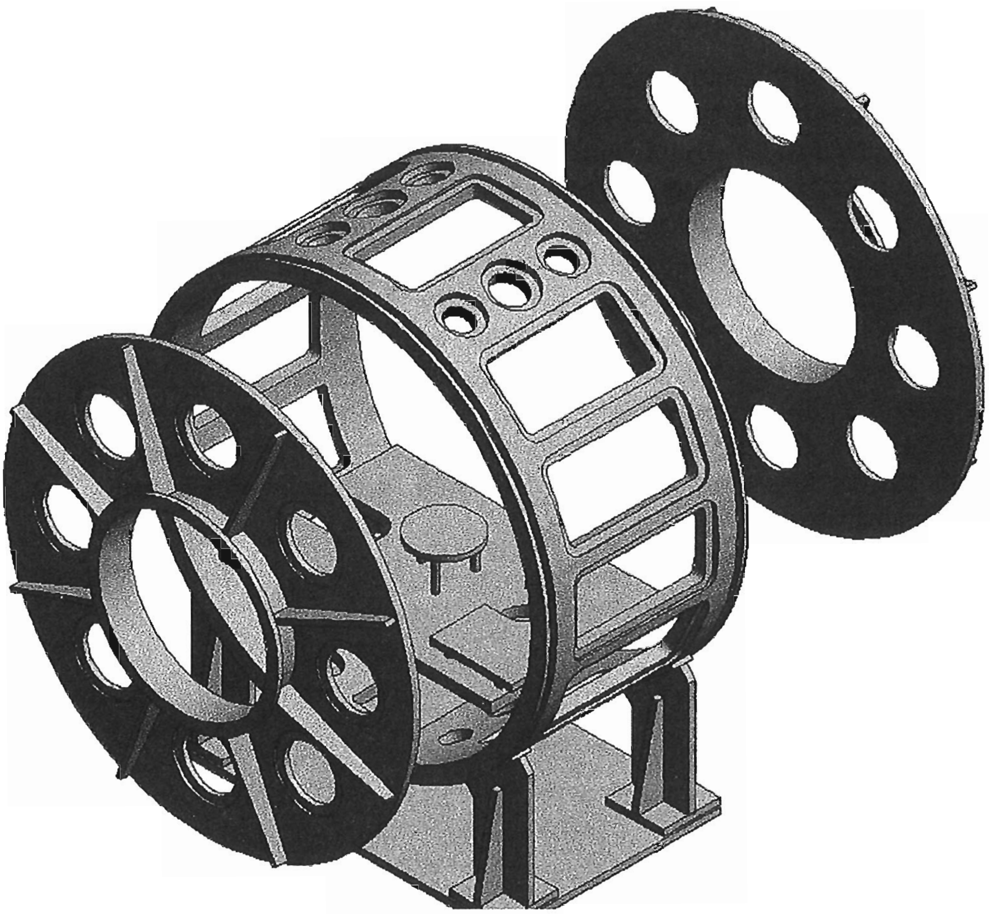


Figure 12. PetaWatt Interaction Chamber

7.2 Port Design

Experimental design requirements and engineering considerations demonstrated that rectangular ports are optimum for the side wall of the main chamber body. Circular ports require significantly increased chamber wall thickness compared to rectangular ports and give less beam access.

An equally spaced symmetrical port geometry was initially considered, however, after examining the options for 6, 8, 12 and 16 fold port layouts none were found suitable. The final optimised design incorporates 12 rectangular ports centred at 0°, ±25°, ±50° and ±90° w.r.t. the horizontal. Each port has a beam clearance of 600 mm (width) and 300 mm (height). These ports allow two 108 mm diameter beams to enter at angles of up to ± 5.8° from port centre in the same vertical plane. For two such 108 mm diameter beams entering at 11.6° separation a minimum F optic of F7 may be used to focus at chamber centre, or the existing f10 optics located just external to the chamber wall and pillar mounted to the floor to avoid vacuum displacement.

Twelve small circular ports are located at ± 20° from the top and bottom of the cylinder and these are used mainly for alignment systems and internal table vacuum isolation. An additional set of eight equally spaced 300 mm diameter circular ports are located in each of the end sections of the chamber. These are intended primarily for diagnostic purposes.

7.3 Grating Chamber

In a similar fashion to the previous CPA configuration, the first recompression grating is in air and the second grating placed in a purpose built vacuum vessel as shown in figure 13. A 30 mm thick BK7 anti-reflection coated vacuum interface window is located between the two gratings. To avoid misalignment problems during pump down and let-up the second grating and turning mirror are supported on mechanically isolated mounts tied to the floor. A gate valve containing a 100 mm diameter circular plane parallel BK7 window is located between the grating and main chamber. This enables an alignment beam to propagate through the grating compressor and onto the chamber optics whilst the main chamber is at atmospheric pressure and the grating under vacuum. Tests have shown that the vacuum isolation of the grating and turning mirrors ensure that between air and vacuum the interaction beam suffers less than 0.1 mrad deflection, which is significantly less than with previous hardware.

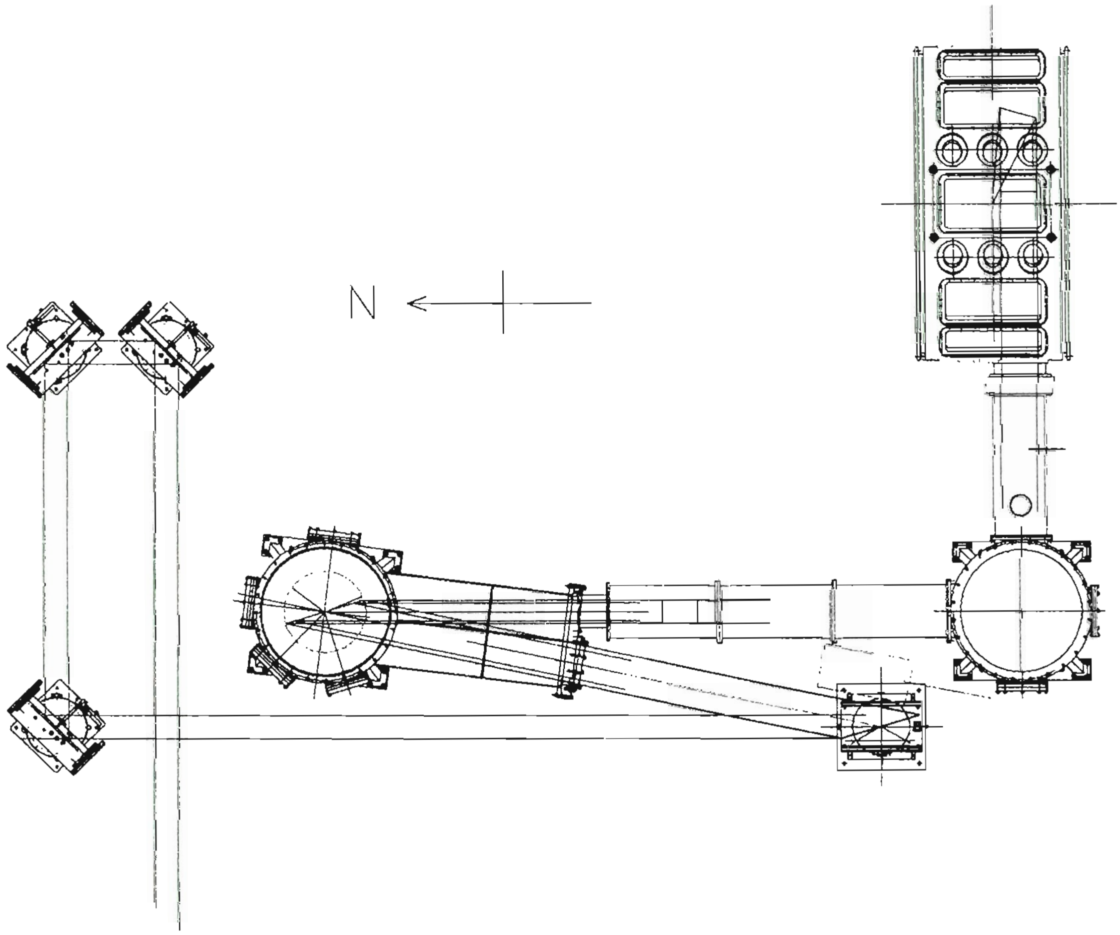


Figure 13. Plan view showing layout of grating and interaction chambers in TAW

7.4 Beam Configurations

There are four main configurations for the CPA and long pulse beams which the chamber has been designed to accommodate. These are, spherical, cluster, cylindrical and line focus. The following paragraphs detail the necessary beam configurations:

7.4(i) Spherical 6 beam geometry. Four of the 108 mm diameter beams would be brought in through the side wall rectangular ports, four at ± 45° and the remaining two beams through the end flanges as shown in figure 14. The f10 focusing optics would be located externally to the chamber and random phase plates internally. The CPA Off Axis Parabola (OAP) [18] would be located along the East-West axis, with the beam focusing to within 12 degrees of the East-West axis.

7.4(ii) Cylindrical 6 beam geometry. Five of the 108 mm diameter beams would be brought in through the side wall rectangular ports, four at ± 30° and one at + 90° from the horizontal. The f10 focusing optics would be located externally to the chamber, with random phase plates placed inside of the chamber to avoid problems of bulk damage in the windows. The remaining 108 mm diameter beam would be brought in through a window (vertically below chamber centre) in one of the end flanges with the f10 and turning mirror located inside the chamber. The CPA OAP would be located along the NS axis with the beam focusing axis orthogonal to the cylindrical beams. A ~39° steering mirror located inside the main chamber would deflect the input beam onto the OAP. The OAP mount would be supported on a bolt on extension to the central table.

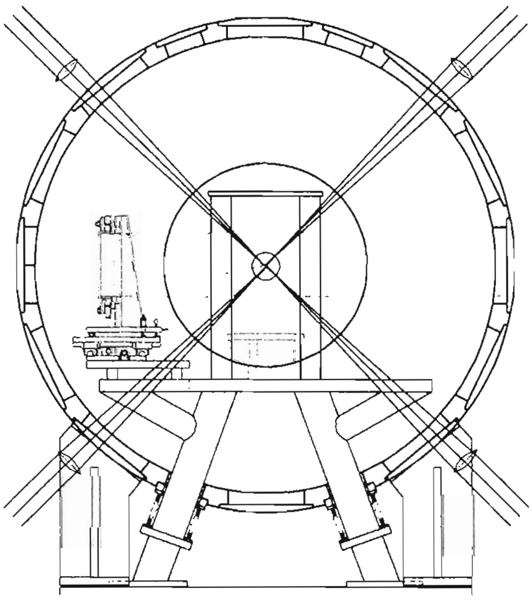


Figure 14. End view showing the interaction chamber configured for six beam spherical geometry with the CPA drive beam.

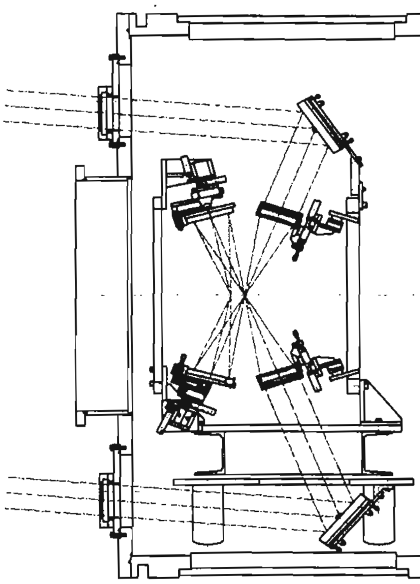


Figure 15. Side view showing two of the six beams used in the line focus set-up.

***7.4(iii)Cluster geometry*.** The standard f10 ϕ108 cluster focusing optics can be attached to one of the CPA chamber end flanges and the six ϕ108 beams brought to a focus at chamber centre. Alternatively, the two existing cluster flanges can be attached to either end of the CPA chamber and three beams brought in on each. The CPA focused beam axis can either be along the cluster axis or orthogonal to it by using suitable beam steering mirrors.

***7.4(iv) Line focus geometry*.** The line focii are generated [19] using the existing F2.5 internal optics for the 108 mm diameter beams. Four of the 108 mm diameter beams are brought in through the side wall rectangular ports, at ± 30° and the remaining two beams through the end flanges at ± 90°. The internal optics consist of a set of six aspheric doublets and concave mirrors mounted on two supporting rings which can be used to produce line foci between 0.5 - 40 mm in length. Figure 15 shows a schematic of the geometry. The CPA beam enters on the horizontal and is focused by an OAP before being re-imaged using a spherical mirror.

8. TAW Vacuum System

The need for a large volume target chamber and grating chamber operating under vacuum conditions and requiring a quick pump down and let up cycle for the Phase 1 Petawatt upgrade resulted in the specification and instalment of a new upgraded vacuum system in TAW.

Routine vacuum operation involves letting the target chamber up to atmospheric pressure, replacing targets and diagnostics and re-pumping to 10^{-4} mbar within the 20 minute duty cycle of the Vulcan laser. The volume of the target chamber is 2.5 m^3 and the grating chamber 1.5 m^3.

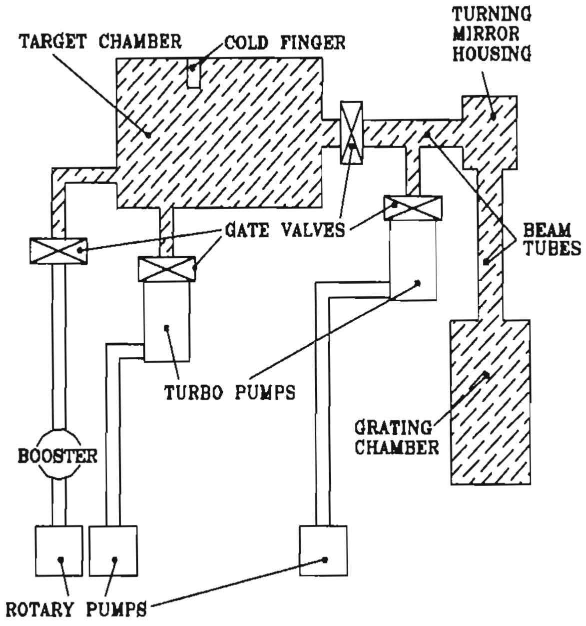


Fig 16. Schematic of Vacuum System

In order to design the pumping system to achieve its specification the complete vacuum system was modelled on a computer simulation package [20]. This enabled the optimum combination of vacuum pumps to be determined interactively. Pumping is achieved using a combination of rotary, booster and turbo pumps and a cryogenic cold finger (see figure 16).

To achieve the necessary pump down times the grating chamber is normally constantly maintained at 10^{-4} mbar and only the target chamber volume cycled to atmospheric pressure with dry nitrogen. The vacuum system is controlled from either a control panel, which has pump down and let up controls only, or via a table driven computer program that has further controls and drives a mimic diagram. The pump down and let up sequences are automatic, the appropriate valves etc., opening when required. The target and grating chambers are initially both pumped through a 501 m^3h^{-1} booster pump [21] and a 170 m^3h^{-1} rotary roughing pump [21]. These are connected to the chamber through a 6 m long 160 mm diameter pipe connected to the bottom port on the target chamber. As these pumps produce significant noise, air heating and turbulence when running both pumps are located in a sealed soundproofed under-floor services pit which has forced ventilation to the exterior of the room. This avoids possible interference with the beam paths and makes the operational conditions acceptable.

After initial pump-down to 0.5 mbar, two 1000 ℓs^{-1} [21] turbo pumps are brought on. One turbo pump is located on the target chamber and the other is located between the final turning mirror housing and the pneumatically operated beam gate valve to the target chamber. This configuration ensures that no oil or debris contamination can propagate from the main chamber to the grating chamber during chamber let ups for target changes etc. These turbo pumps are backed by a $40m^3h^{-1}$ rotary pump [21] and lower the pressure to 10^{-4} mbar. It is important that the grating chamber pressure is never lower than the target chamber pressure when the gate valve is open so the control system ensures that the target chamber turbo pump comes on before the grating chamber turbo pump. Residual gas analysis showed that water is a primary contaminant. This is removed by cooling a thin walled metal tube of surface area 0.05 m^2 to liquid nitrogen temperatures after a pressure of 0.1 mbar has been attained. This cold finger is located in the target chamber and is replaced on each cycle.

A gate valve [22] containing a 100 mm diameter plane parallel BK7 window is located between the grating chamber and target chamber. This enables an alignment beam to propagate through the grating compressor and onto the chamber optics whilst the target chamber is at atmospheric pressure.

The complete system has been installed and commissioned satisfactorily and operational experience to date shows that the system meets its design requirements. Typical pump down and let up curves are shown in figure 17. The actual pump down curve agrees very closely to that predicted by the computer simulations. Tests have also shown that the vacuum isolation of the grating and turning mirror ensure that between air and vacuum the interaction beam suffers less than 0.1 mrad deflection.

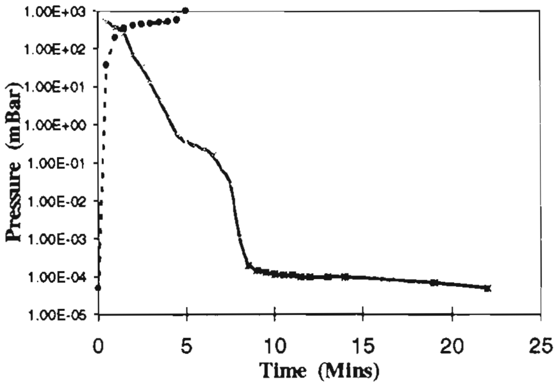


Fig 17. Typical pump down and let up curves

9. Target area commissioning

Target Area West has been reconfigured to work with all eight of the Vulcan laser beams. This consists of the two Chirped Pulse Amplified (CPA) lines (beams 7 and 8) and six 108 mm diameter long pulse lines (beams 1-6). The area is organised to provide maximum flexibility and chamber access whilst optimising experimental choice and maintaining a safe working environment. All Vulcan laser beams enter through the North TAW wall. The two CPA beams are brought in through 280 mm diameter 25 mm thick AR coated windows located in the western corner of the north wall at a height of 1.3 m above floor level. The six long pulse beams enter through 145 mm diameter 15 mm thick AR coated windows located on the centre of the north wall on a three level system.

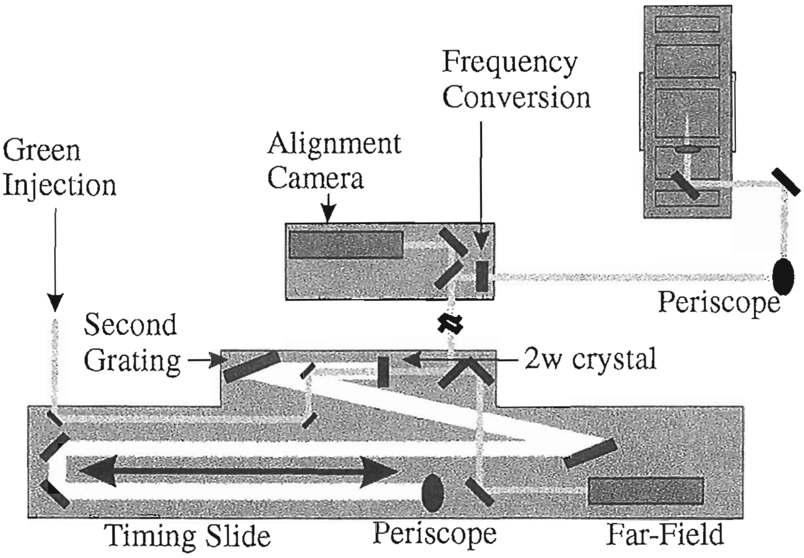


Figure 18. Schematic layout showing beam line 7 the secondary CPA line used for optical probing.

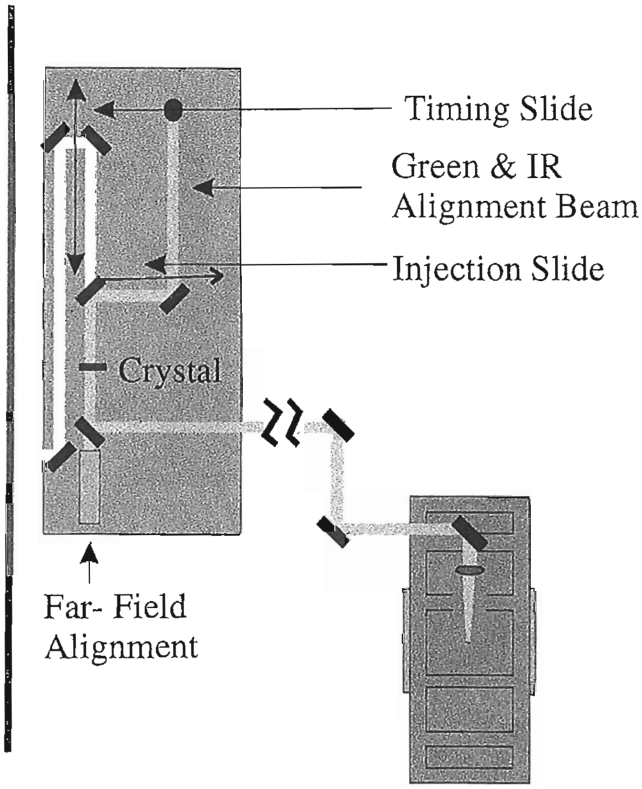


Figure 19. Layout showing beam 3 a long pulse beam line

The secondary 150 x 89 mm CPA beam line (beam 7) is primarily intended for plasma diagnostic uses requiring a few mJ to J of energy. To maintain experimental flexibility, the recompression gratings for this line will be mounted in air on a single level table. The beam will be transported and frequency doubled, quadrupled or Raman frequency shifted [23] before entering the vacuum chamber through a thin glass window. After entering the area beam 7 is reflected onto the lower level of the CPA bench where two recompression gratings, a 4 m timing slide and alignment systems are situated, as shown in figure 18. A linear injection slide is used to inject the same 150 mW CW alignment beam [24] as beam 8 into this line as required. When frequency doubling, quadrupling or shifting techniques are employed, space has been left on the lower level for additional injection and pointing system to be installed.

Beam lines 1-6 all have similar configurations to beam line 3 as shown in figure 19. The pointing systems, timing slides, frequency doubling crystals and alignment systems for all six beams are situated on the two three level tables located beside the North wall of the target area. The beams can be used at either the fundamental or frequency doubled wavelength and can be injected into the main chamber using external plinths to accommodate the required experimental geometry.

9.1 CPA diagnostics

After leaving the second grating the beam is steered with a 98 % efficiency 45 degree mirror into the interaction chamber and the 2 % leakage used for diagnostic purposes. The 2 % leakage from the final turning mirror which injects the CPA beam into the main chamber is fed through a 30 mm thick window onto two turning mirrors and then into the diagnostics chain.

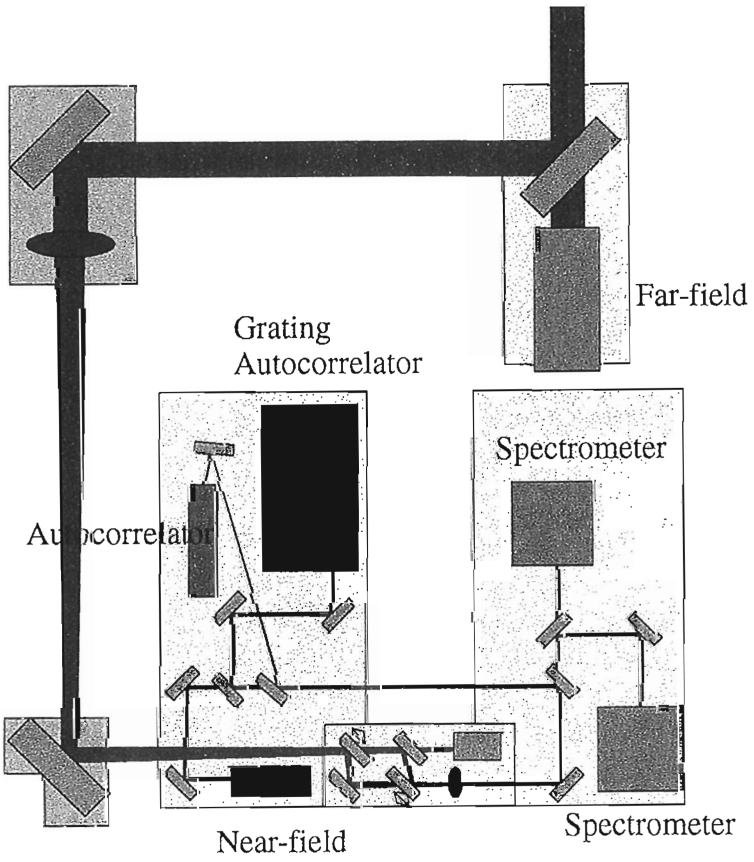


Fig 20. Diagnostic set-up in TAW.

A commercial 250 mm aperture Schmidt Cassegrain telescope [25] monitors the 0.2 % leakage through the first turning mirror to ensure that the pointing direction of the beam onto the gratings and between them is always maintained. This is essential during all grating tuning and optic replacement operations. After the turning mirrors, the beam is spatially demagnified by a factor of 6.7 using a Gallilean telescope consisting of a 4 m positive lens and a 0.6 m negative lens. Between low and full energy shots, a 75 mm uncoated front surface mirror and a 50 mm 25 % reflective mirror are injected into the telescope in such a manner that the path between the elements of the telescope is unchanged. These mirrors are used to control the intensity into the negative element of the telescope, avoiding B-integral effects causing any measurable pulse degradation. The beam from the telescope is then fed into two diagnostics tables where near field, far-field, spectrum and pulse duration are measured on every shot.

9.2 CPA Optimisation

The reduction in pulse length and increase in grating size for the Phase 1 PW upgrade requires more stringent recompression grating alignment tolerances. New alignment techniques must be considered to minimise beam shear, pedestal and pulse lengthening effects. After surveying the gratings into position, optical alignment using the zero and first order reflection from the grating surface of a near diffraction limited convergent visible laser beam was employed to set the grating surfaces and grooves in the vertical plane. Then, the grating surfaces were set parallel to each other in the horizontal plane at an input angle matched to the stretcher using precision surveying. A low energy 3-4 nm broad bandwidth beam was then injected into the grating recompression pair and their alignment adjusted to obtain a minimum far-field spot size, giving an alignment parallelism accuracy of 0.4 mrad. After the recompression gratings were aligned, tuning to obtain the shortest possible CPA pulse was initially carried out using an optical streak camera. The autocorrelators were then used to fine tune this and the results are shown in figure 21.

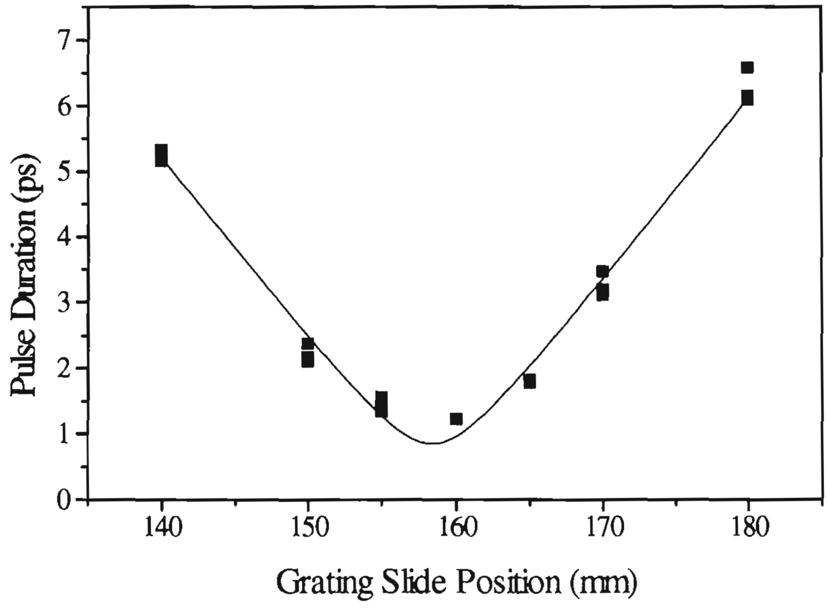


Figure 21. Grating tuning curve

To avoid beam shear and pulse lengthening effects which will become critical in the future when the pulse length is reduced from its present value of ~1 ps to less than 400 fs, the grating surfaces must be set more accurately to within 50 μrad parallelism. It is intended that orthogonally sampling autocorrelators will be used to set the grating parallelism to better than 0.05 mrad which corresponds to optimum system performance [26].

Once compressed the CPA beam is transported to target and focused using only dielectric coated reflective optics to minimise B-integral and maintain focusability. Point foci are generated using: a 0.6 m focal length Off Axis Parabola [27] for ultra-high intensity interactions ($>10^{19}$ Wcm^{-2}); a 3 m focal length for long focal length gas target interactions; and a 0.225 m focal length On Axis Parabola for interactions in excess of 10^{20} Wcm^{-2}.

10. Diagnostics

10.1 Sub-picosecond streak camera

One of the key components of the Phase I PetaWatt upgrade was an ultra-high resolution streak camera. This is an essential diagnostic in the monitoring of compressed pulse duration's and in the diagnosing of laser / target interactions. The device purchased is a state of the art Hamamatsu 200 fs resolution streak camera (FESCA-200, C6138). The camera is fitted with an S1 streak tube giving measurement sensitivity from the ultra-violet through to the near infrared. The streak camera comes complete with a digital readout system which is connected through to a PC via a Frame-Grabber board. The whole system is controlled through Windows based software [28].

10.2 A multi-channel soft X-ray flat-field spectrometer

The development of a three channel soft X-ray spectrometer which was specifically designed to resolve the angular intensity distribution of laser generated high harmonics [29]. On VULCAN significant advances have been made recently in the production of coherent soft X-ray sources from CPA driven laser matter interactions including: high harmonic production from solid and gaseous interactions and collisionally pumped soft X-ray lasers. Grazing incidence spectrometers based on flat-field aperiodic gratings [30] have been the primary soft X-ray diagnostic. To increase sensitivity and provide a high signal to noise ratio a collection mirror is used to image the source onto the detector plane. Of particular interest to recent experiments has been measuring the brightness of each source which requires a calibrated throughput and angular resolution. This section details the design of such an instrument with a total wavelength coverage of 4 - 100 nm.

The spectrometer is based around a Hitachi [31] aperiodic 1200 l/mm flat-field concave grating. To obtain maximum detection sensitivity it is necessary to simultaneously obtain optimum spatial and spectral resolution. Spatial resolution was obtained using a set of collection mirrors located between the source and the grating. Each imaging mirror's surface is orthogonal to the grating surface, thus, the spatial imaging properties of the mirrors and spectral imaging/ dispersion of the grating can be considered separately.

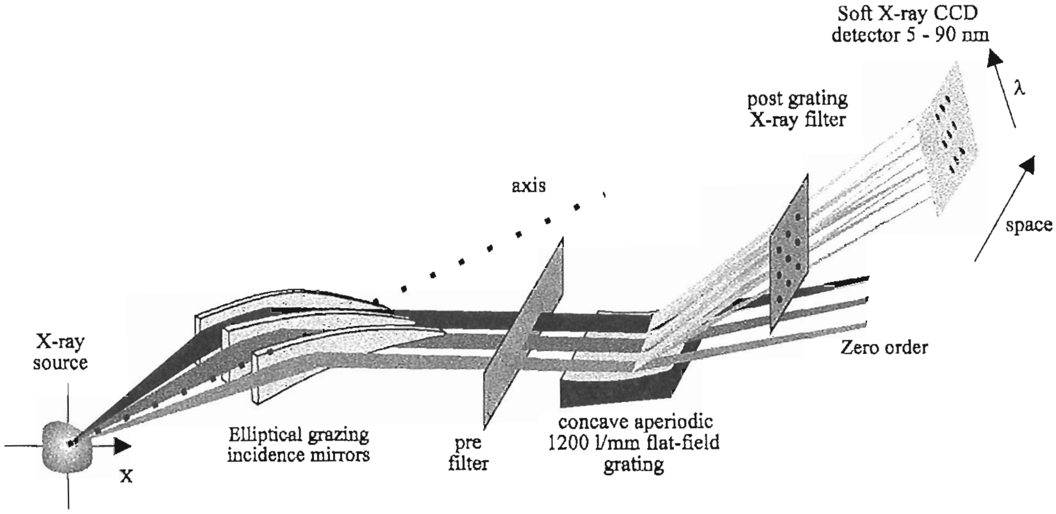


Figure 22. Schematic layout showing the triple mirror collection optics and flat-field spectrometer design

The final instrument essentially consists of four parts, a collection and imaging system, a diffraction grating, a back thinned CCD detector [32] and a light tight housing and associated filters as shown in figure 22. The spectrometer uses a Micro-channel plate (MCP) detector with a resolution of ≈ 200 μm.

The imaging optics consists of three 300 nm gold over-coated 1 mm thick, 160 mm long BK7 glass mirrors of RMS surface roughness < 1 nm, orientated to focus in a direction perpendicular to the dispersion direction of the grating. Their effect is to produce three rows of dispersed images of the harmonic source on the detector plane, each corresponding to a different angular channel. An operational requirement of the system was that the collection optics operated at a source to image plane distance of 0.7 m, have no parts closer than ~0.1 m to the source and subtended a large angle ~ 100 mrad with minimum obscuration. It was considered that a tapered mirror which can be bent into an elliptical profile through the application of a bending moment was the optimum design giving maximum flexibility.

The imaging flat-field spectrometer was designed to provide high detection sensitivity, an absolute throughput efficiency, ease of use and reliability. The design adopted eliminates any narrow apertures which is normally the case in a soft X-ray spectrometer. Instead, the source is imaged directly onto the detector plane. This makes the design highly efficient, much easier to align and use than standard spectrometers and also ensures that the instrument can be set-up in a reproducible manner on different experiments. This provides the users with comparable data on different experiments and has been highly successful even producing data on the first shot.

10.3 Phase front monitor

The wavefront uniformity of the VULCAN Nd:glass laser system is important because it not only affects the focusability of the beam but also limits the shortest pulse duration achievable. The wavefront quality has been directly measured using a radial-shear single-shot interferometer [33,34] developed for the Phase 1 PetaWatt Upgrade. This is shown schematically in Fig 23.

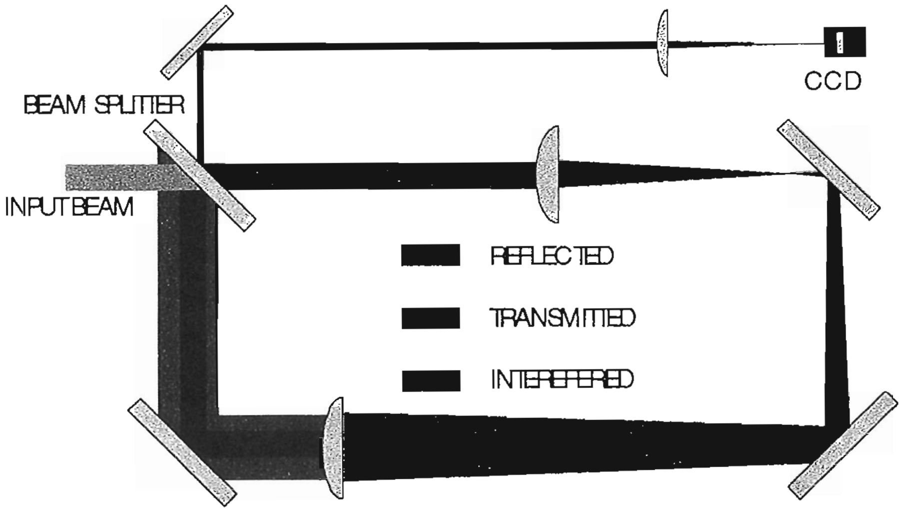


Figure 23. Radial Shear Interferometer

High contrast fringe patterns are produced by the interference of two beams which are propagated clockwise and anticlockwise through the device. The input laser beam is split at the beam splitter which transmits 90% of the light and reflects 10%. The transmitted beam is expanded in diameter by a factor of three, while the reflected beam is reduced in diameter by a factor of three. When the expanded beam passes through the beam splitter for the second time only 90% of it is transmitted and similarly 10% of the compressed beam is reflected. This results in equal intensity in the two interfering beams. Interference takes place on the beam splitter between the whole spatial extent of the compressed beam and a small fraction of the expanded beam. The wavefront errors are sufficiently small in the input beam to assume that over this small fraction of the expanded beam there is a flat wavefront. Special care is taken in the design so that the beam splitter is imaged back onto itself and this coupled with the equal intensity in each beam ensures a 100% fringe visibility.

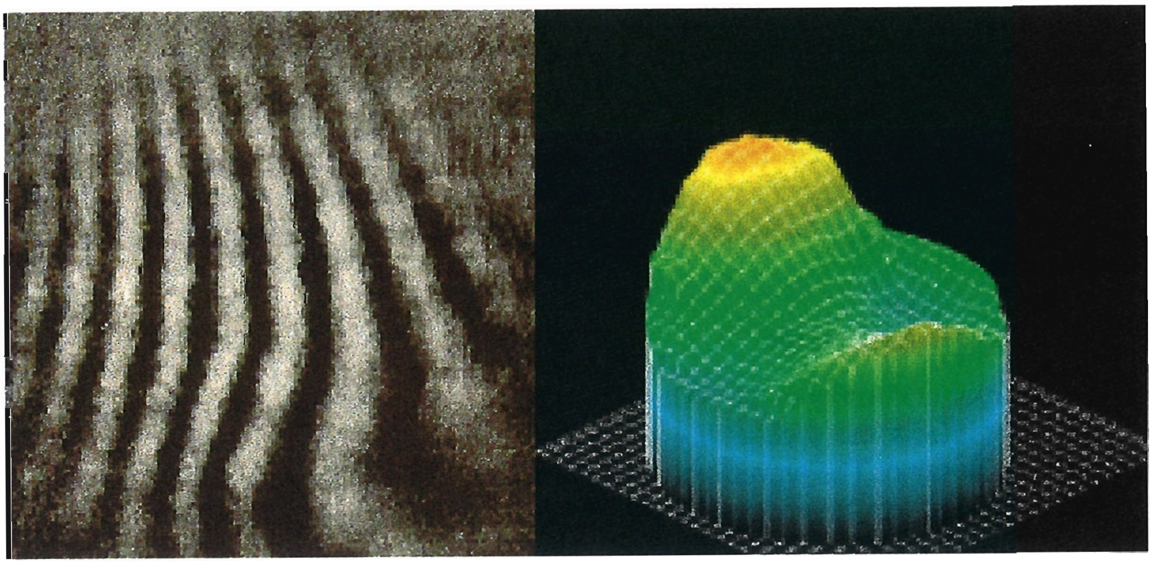


Figure 24. An Interferogram and OPD plot of the VULCAN output wavefront quality

The interference pattern is imaged onto a CCD camera with a typical output as shown in Figure 24(a). The fringe pattern is then processed to reconstruct the wavefront. The corresponding wavefront error map generated from the fringe pattern is illustrated in Figure 24(b).

The reconstructed wavefront can be further processed to extract information about the nature of the wavefront distortion. This information allows us to breakdown the complex shape of the wavefront into combinations of the classically known aberrations that can arise in optical systems and those that can be attributed to non classical optics such as turbulence and thermal distortion. For example, the saddle shape of the wavefront in Figure 24(b) shows that the dominant aberration is an astigmatism. More detailed study over the long term and 'on the shot' analysis will allow us to pinpoint the source of the aberrations and devise static and dynamic schemes to correct them.

10.4 An elegant single-shot Auto-correlator

A new design of an optical pulse autocorrelator is presented having a novel uni-axial design offering a number of distinct improvements over traditional designs [8]. The principal benefits are the extreme simplicity of alignment and operation coupled with a substantial reduction in size and component cost. The basic design is almost non-dispersive and thus suitable for use with ultra-fast pulses in addition to being virtually insensitive to wavelength (mixing crystal excepted). Fixed and equal group delay in each arm and a fixed, unchangeable calibration are additional features.

As in other autocorrelator devices the technique consists of splitting an input beam into two and then recombining them in a non linear crystal. The non linear crystal is used to produce a Sum Frequency Signal from the two split beams when a pulse is present. Traditional techniques generally use a 50% reflectivity mirror for the splitting process to generate the two arms from the input beam, thereby forcing a bi-axial design. Often the bi-axial design becomes a tri-axial design deriving from the need to carefully match the optical path length of the two arms. The multi-axial design of these types of autocorrelator generally lead to difficulty of alignment, especially when pulses are only available on a minute by minute basis as found in larger laser systems.

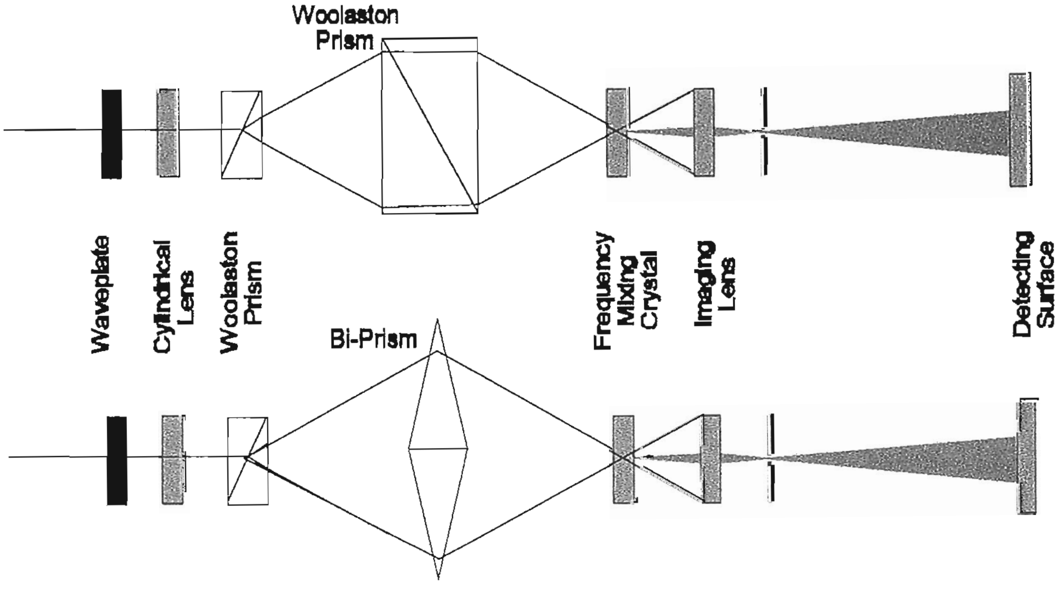


Figure 25. The basic auto-correlator designs.

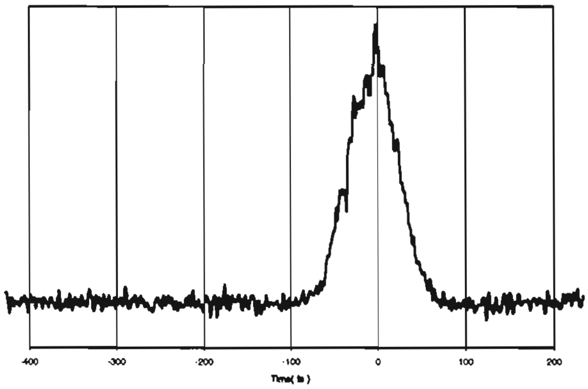


Figure 26. Autocorrelator output

The basic design is presented in Figure 25. The input beam, which should have a uniform and constant spatial profile over the input aperture of the system enters via a wave-plate, used to control the splitting ratio of the two arms. The auto-correlation however is relatively insensitive to this ratio since it derives from the product and not the ratio. Following passage through a cylindrical lens, whose focal plane is coincident with the frequency mixing crystal, the beam is split into two using a Wollaston Prism (a birefringent device that splits an unpolarised input beam into two orthogonally polarised output beams that propagate at two virtually equal angles symmetrically about the input beam direction). The two diverging beams are then forced to converge by one of two means. Either the two beams are incident on a second Wollaston Prism that has its internal interface angle specifically cut such that the diverging beams are made to converge with a given convergence angle or by use of a symmetric bi-prism. The auto-correlation, is then imaged onto a detecting surface such as a CCD camera or linear CCD array in a standard way, utilising a pinhole to prevent residual fundamental or unwanted second harmonic signals reaching the detecting surface. Figure 26 shows the output of the device for 120 fs pulse train at 1053 nm. The device has also been tested with a single 150 fs pulse at 768 nm.

One of the important benefits of the basic design is that the group delay is equal in both arms. This clearly simplifies the alignment since the two pulses from each arm are guaranteed to overlap in time at the crossing point. Additionally, the absolute calibration of the device (fs / mm) is also fixed and not adjustable by the user. Calibration of the imaging system is easily achieved by inserting a glass etalon of known thickness into one of the arms of the device thereby providing an exactly known group delay to that arm. Figure 27 shows a photograph of the autocorrelator.

10.4(i) Long Pulse-length Extension

The minimum pulse length resolvable is limited by material dispersion and the maximum pulse length by the aperture of the device and the crossover angle. The maximum pulse length resolvable can however be significantly increased with the small modification to the device. This is important especially when tuning the compression gratings as the starting pulse length is likely to be in excess of a picosecond. This is achieved at the expense of an increase in dispersion and thus a corresponding increase in the minimum pulse length resolvable. Injection is by means of a diffraction grating which imposes a temporal shear across the beam which the dove prism inverts in one arm only. The glass block in the other arm compensates for the group delay.

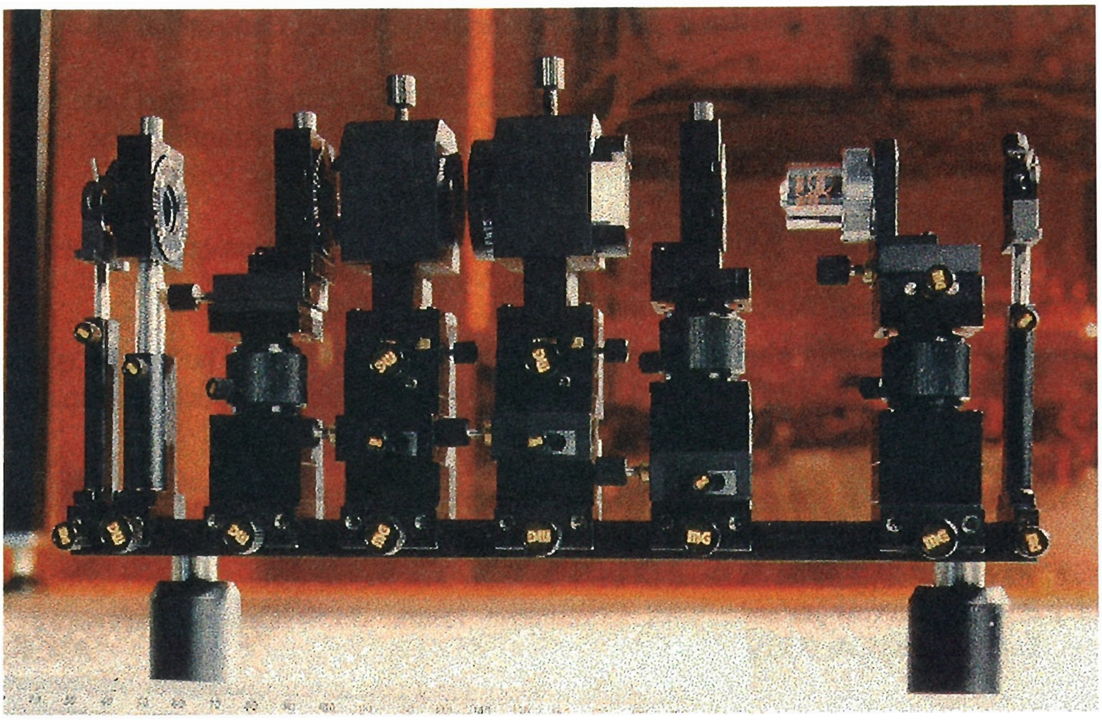


Figure 27. Photograph of the autocorrelator illustrating its compact nature.

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Appendix I

Phase I Petawatt Grant Management Committee

Dr CB Edwards (Chair)

Prof. MH Key / Prof. H Hutchinson (Director CLF)

Mr CN Danson (Project Manager)

Mr BE Wyborn (CLF Chief Engineer)

Dr IN Ross (CLF R+D group)

Prof. S Rose (CLF Theory)

Dr J Collier (Secretary)

Dr P Thompson (AWE plc.)

Dr J Wark (Oxford University "User Representative")

Appendix II

VULCAN CPA Upgrade: Target Area Specification

PA Norreys.

Introduction.

An important sequel to the recent Review of the CLF was the award of a substantial EPSRC grant to upgrade VULCAN CPA. The upgrade will provide the following output pulse specification:

Pulse duration : 350fsec. Energy on target: 100 J at 1micron. Beam quality: x4 diffraction limit.

The grant includes funds to reconfigure the target area and build a dedicated target chamber and these will be installed in about one year's time. The aim of the design is to provide for the best use of all the Vulcan beams in TAW.

The chamber will need to be designed to accommodate a possible Phase II upgrade (presently unfunded) based on the use of 200 mm disc amplifiers which has the following outline specification:

Number of beams: 1, Pulse duration 400 - 500 fsec, wavelength 527 and 1053nm, energy on target 400 - 500 J, peak power 1PW, beam quality x6 diffraction limit.

The University User community was approached to provide details of the types of experimental configurations that will be required over the next five year time period. The responses to this request for information has been collated below, and a number of schematic outlines of the target area and chamber, based on this survey, are enclosed.

User community questionnaire response.

(i) Fast Ignitor studies.

An important topic of current interest is the so called Fast Ignitor concept, where energetic electrons are generated at the critical density surface of an already compressed high density plasma. These electrons travel through the compressed material, losing energy as they do so. This energy is transferred to the plasma as heat, and the idea is to heat the compressed material to igntion temperatures before it has time to diassemble. The requirement in this work is for the 6 beams of VULCAN to be configured in both cylindrical and spherical geometries, with the CPA beam timed to coincide at the peak of the compression.

(ii) Beatwave, wakefield and harmonic generation studies.

Another area of great interest at the moment is the generation of large amplitude plasma wave formation by wakefield and beatwave interactions and the acceleration of electrons to very high velocities by particle - wave processes. The requirement in this case is for co-propagating infra-rad CPA beam and a green long pulse 108mm beam for Thompson scattering measurements. Future experiments may require very long focal length (f/50 - f/100) CPA optics, which are also a requirement for future gas harmonic generation experiments. Intensity dependent damage thresholds on the dielecric coatings limit the CPA beam to the same output aperture size as the input beam, i.e. telescoping the beam to a smaller diameter is not an option.

(iii) Collisional and Recombination X-ray Laser Studies.

The H - like recombination x-ray laser can be scaled to the water window using the output of the phase II upgrade and will require irradiation of fibre targets using the 20cm CPA beam. In collisional x-ray laser studies, the requirement will be for the 6 beams to be used to generate a line focus plasma, and the CPA beam to be used in a travelling wave excitation mode. The wavefront displacement required by the travelling wave mode will be implemented in the oscillator room, and will not require large area optics in the target area.

To produce high gain in travelling wave collisional excitation, it is necessary to rapidly ionise the material to the Ne-like or Ni-like ionisation stage while maintaining a low ion temperature. Hence the CPA beam should heat the plasma medium to > 1keV. To get an idea of the intensity required, MEDUSA code was run for the case of 1.3psec FWHM CPA beam sitting on top of a 130 psec FWHM pedastal at 10^{-6} intensity level interacting with a CH target. 20% resonance absorption is assumed with a flux limit of f=0.1. Figure 1 shows that to generate electron temperatures of ≥ 1.0 keV in the coronal plasma, an intensity of 5×10^{15} $\mathrm{Wcm^{-2}}$ is required. If the line focus width is set at 50μm, then a 1cm length of line focus is required for a 100J/350 fsec pulse. Lateral transport of energy will reduce the achievable electron temperature, but this may be off-set by higher absorption of laser energy. Thus a line focus length of upto 2.0 cm will be required for this set of experimental conditions, and in all likelihood, a shorter line focus will be needed.

(iv) Interaction Studies.

To provide a long scalelength plasma with reasonable density gradients, it is necessary to use double sided irradiation (4 or 6 of the 108 beams) with the CPA beam interacting from a single side. Access ports should be as large as possible, and an access to the chamber should be made as simple as possible.

Schematic outlines of T.A.West configurations and target chamber specification.

The outline plan of Target Area West, shown in Figures (2) - (5), have been made with the idea of minimising the turn-around time required to reconfigure the target area between different experimental configurations. These outlines have the following features:

1 Decouping of grating chamber from interaction chamber, so that the beam can be introduced into the target chamber from different directions in the various experimental configurations

2 The removal of the three level tables and their replacement with a compact space frame around the chamber.

3. The introduction of timing slides to all 108 beams in TAWest. Gross timing differences between the CPA beam and the 108's will be catered for in the laser room by the operations team.

4. The chamber should have a ring structure, similar to TA East or TA Titania and be sufficiently large to accomodate 208mm diameter beam envisaged in the Phase II upgrade with the required reflecting optics.

5. The optics inside the target chamber and grating chamber should be vacuum isolated.

Figure 2. Line focus configurations.

The CPA beam is steered from the grating chamber into the target chamber directly onto the off axis parabolic mirror. The beam tube diameter must be sufficient to accomodate changes in line focus lengths from 5mm - 2.0 cm. The 108 beams are directed onto 'ears' attached to the chamber. Using f/5 focusing optics will increase the separation of the off axis spherical mirrors from the target plane and allow all 6 beams to be employed.

Figure 3. 'Cluster' arrangement.

Four of the 108's (the top and bottom beamlines 1,2,5,6) are directed into the chamber in opposite pairs by mirrors attached to a space frame around the chamber. The CPA beam is directed onto a turning mirrror in the target chamber that steers the beam onto the off axis parabola. The OAP is arranged so that the focusing axis of the parabola is orthogonal to the target, and parallel to the 108mm heating beams. The 108mm beam 3 on the horizontal plane can be directed to co-propagate with the CPA beam.

Figure 4. Long focal length off axis parabola arrangement

An extension tube is attached to the grating chamber and the beam is steered so that it enters the target chamber along the south - north direction. A co-propagating 108mm beam is injected into the beamline via the turning mirror. The beams are steered onto an OAP located a maximum of 6 m from the centre of the target chamber, which (with the phase II upgrade) will yield a maximum f/50 focusing arrangement.

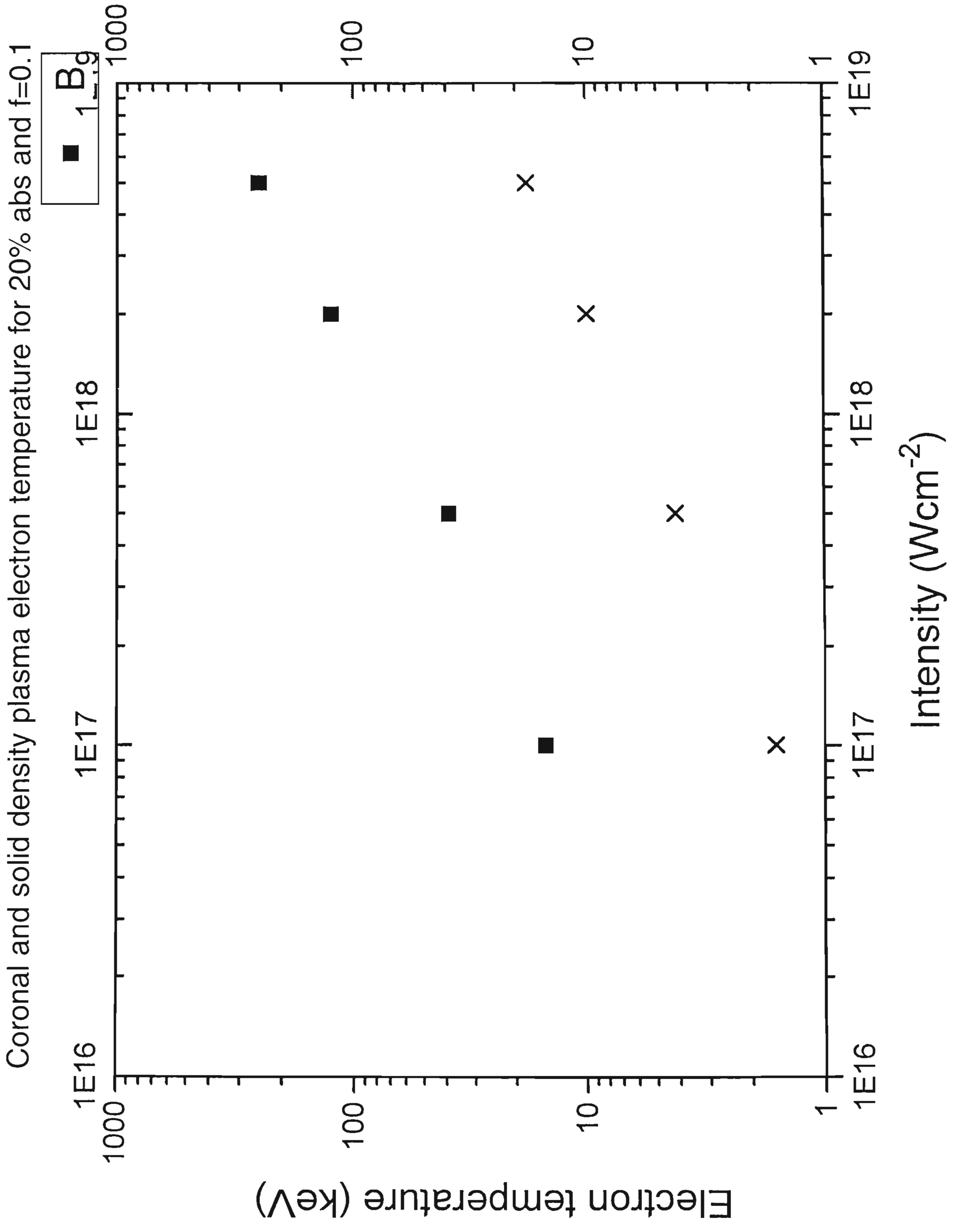
Figure 5. Spherical compression geometry.

The upper and lower 108mm beams are directed into the chamber at 45° in opposite pairs by the space frame. The CPA beam is steered onto a turning mirror and then onto the OAP. The two horizontal beams are directed as shown into the chamber in the north-south and south north directions, as illustrated.

Engineering considerations.

The cluster arrangement in figure (3) requires the 108mm heating beams to be as close to the horizontal plane as possible, given the constraint of employing them with a 20.8cm f/4 off axis parabolic mirror. On the other hand the spherical compression requires the beams to be at 45° in opposing pairs. The design of the space frame and the entrance ports will need to take these constraints into account.

6.



Coronal and solid density plasma electron temperature for 20% abs and f=0.1

Fig. (2) Line Focus Arrangement

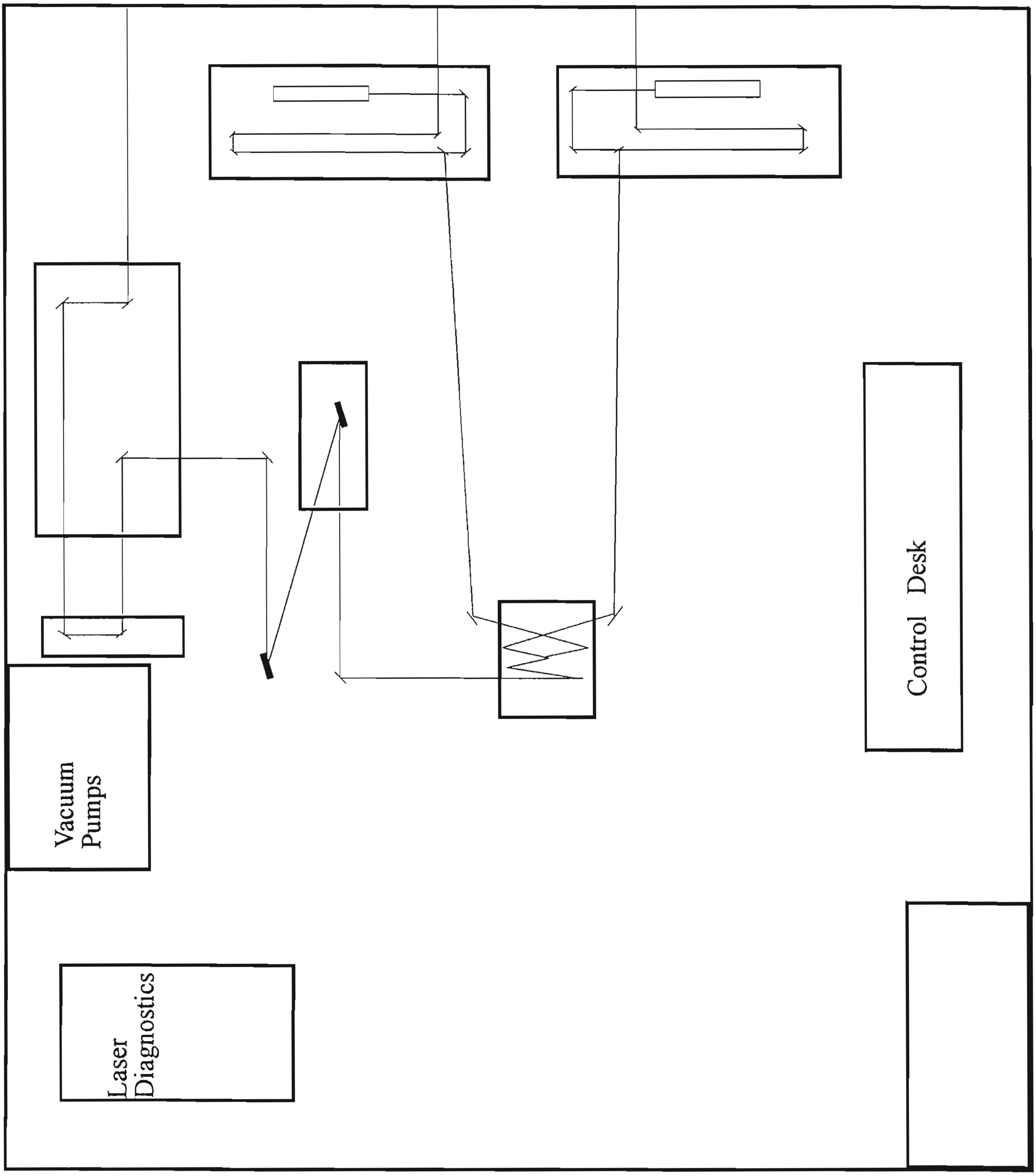


Fig. (3) “Cluster” Arrangement

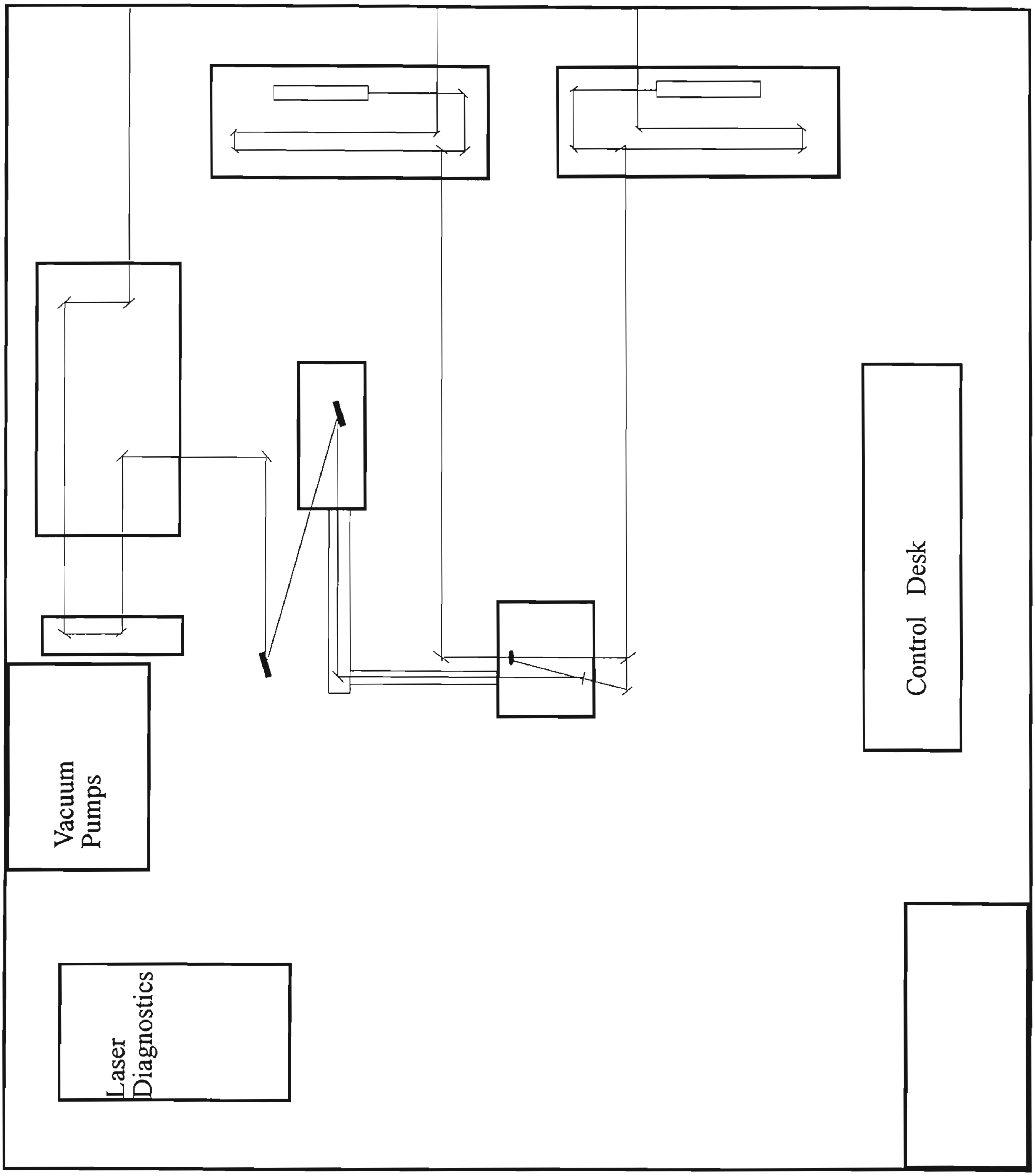


Fig. (4) Long Focal Length Arrangement

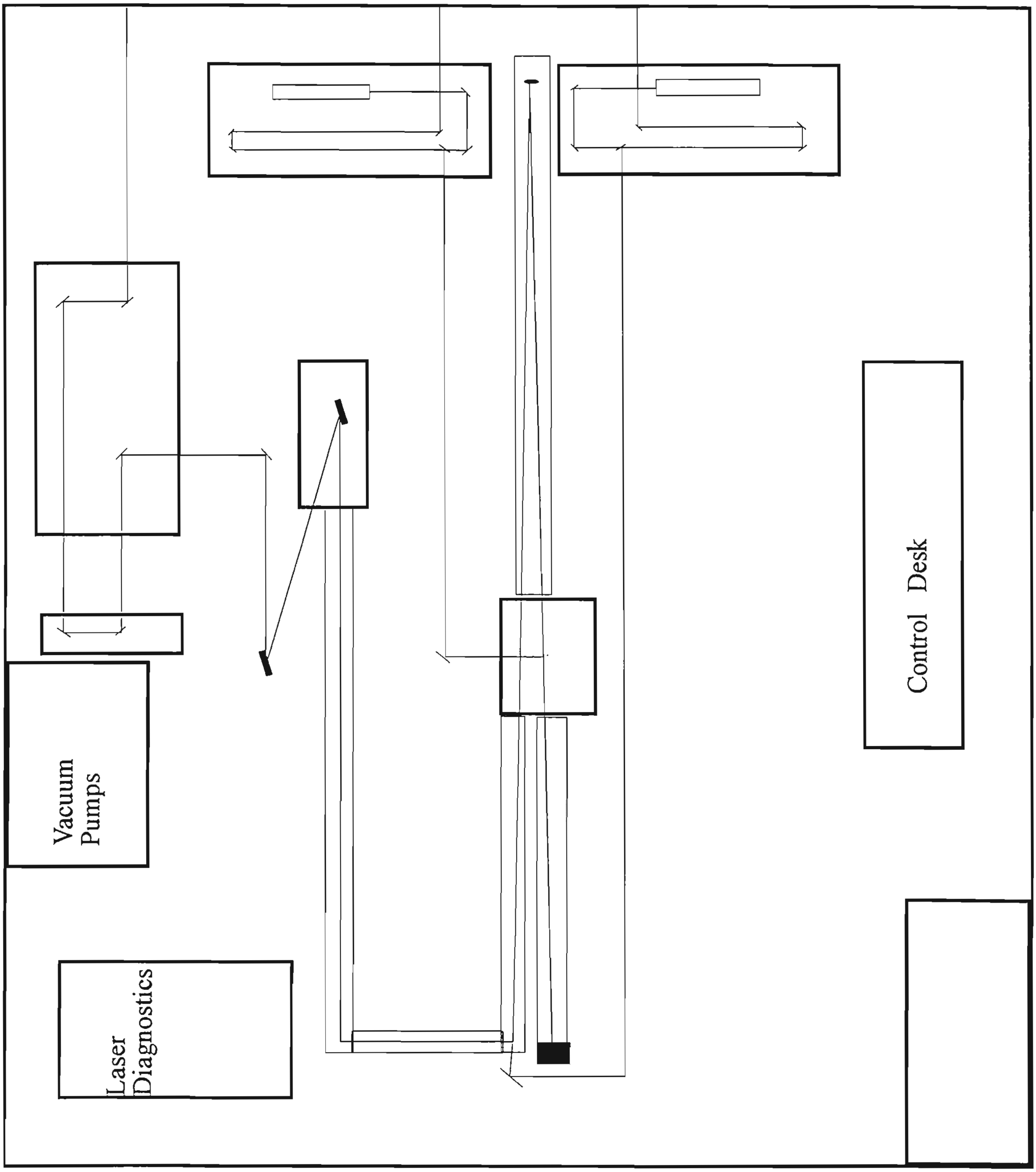
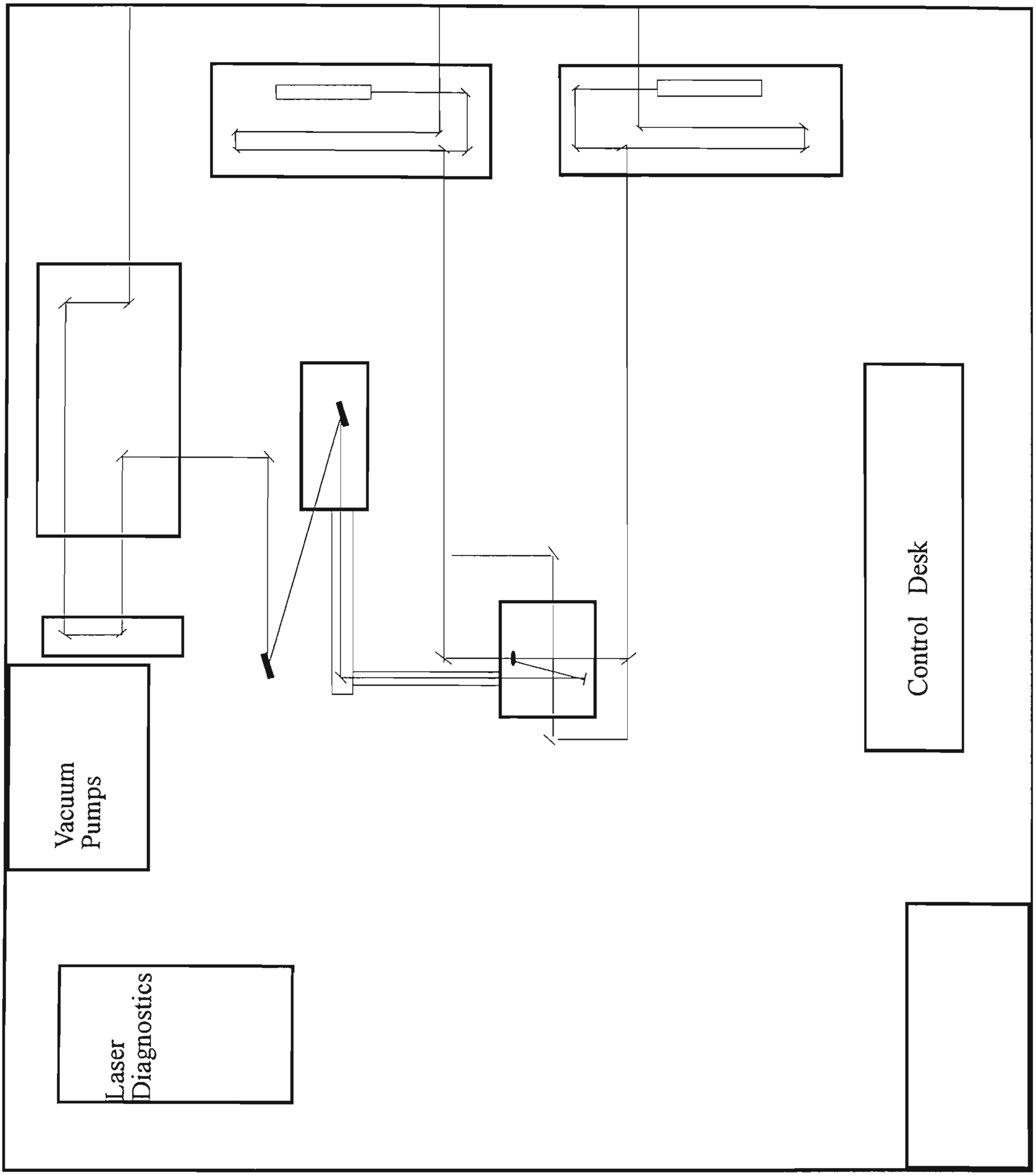


Fig. (5) Spherical Irradiation Configuration



Appendix III

Publications Arising

(i) Refereed Publications

D Neely, D Chambers, C Danson, P Norreys, S Preston, F Quinn, M Roper, J Wark and M Zepf. "A Multi-Channel Soft X-ray/VUV Spectrometer Development." In Preparation for Rev Sci Inst.

J Collier, C Johnson, C Mistry and CN Danson. "An elegant single shot auto-correlator for ultra-short pulse measurement." In preparation.

CN Danson, LJ Barzanti, A Damerell, CB Edwards, MHR Hutchinson, MH Key, D Neely, PA Norreys, DA Pepler, IN Ross, PF Taday, WT Toner, M Trentelman, FN Walsh, TB Winstone and RWW Wyatt. "Well Characterised 10^{19} Wcm^{-2} Operation of a high power Nd:glass laser." Accepted by J of Mod Opt.

M Trentelman, IN Ross and CN Danson. "The effects of using finite size compression gratings in a large aperture chirped pulse amplification laser system." Applied Optics, Vol.36, No.36, 9348-9358, 20 Dec 1997.

IN Ross, M Trentelman and CN Danson. "Optimisation of a Chirped Pulse Amplification Neodymium Glass Laser." Applied Optics, Vol.36, No.33, 8567-8573, 20 Nov 1997.

(ii) Conference Proceedings

D Neely, R Allott, C Clayton, AE Dangor, CN Danson, J Collier, CB Edwards, MHR Hutchinson, A Modena, Z Najmudin, P Norreys, DA Pepler, IN Ross, M Trentelman, FN Walsh, TB Winstone, E Wolfrum and M Zepf. "The Development of Pulse Diagnostics for Ultra-high Power Laser/Plasma Interactions." *Proceedings of the International Conference on Superstrong Fields in Plasmas, Villa Monastero, Varenna, Italy, Aug 27 - Sept 2, 1997*

CB Edwards, CN Danson, MHR Hutchinson, D Neely, BE Wyborn. "200TW upgrade of the Vulcan Nd:glass laser facility." *Proceedings of the International Conference on Superstrong Fields in Plasmas, Villa Monastero, Varenna, Italy, Aug 27 - Sept 2, 1997*

CN Danson, S Angood, L Barzanti, N Bradwell, J Collier, A Damerell, CB Edwards, C Johnson, MH Key, D Neely, M Nightingale, DA Pepler, DA Rodkiss, IN Ross, P Ryves, N Thompson, M Trentelman, FN Walsh, E Wolfrum and RWW Wyatt. "Design and Characterisation of the VULCAN Nd:glass Laser to give focused intensities of $>10^{19}$ W cm^{-2}." SPIE Proceedings of the 2nd Annual International Conference on Solid State Lasers for Application to Inertial Confinement Fusion (ICF). Paris, France, October 22-25, 1996

C Danson, L Barzanti, N Bradwell, J Collier, A Damerell, C Edwards, C Johnson, M Key, D Neely, M Nightingale, D Pepler, I Ross, P Ryves, C Stephens, N Thompson, M Trentelman, F Walsh, E Wolfrum and R Wyatt. "Characterisation of the VULCAN Nd:glass laser for multi-TW operation." Proceedings of the 24th ECLIM, Madrid, Spain.

CB Edwards, L Barzanti, CN Danson, MH Key, D Neely, P Norreys, DA Pepler, WT Toner, TB Winstone, FN Walsh, MHR Hutchinson, IP Mercer, D Wilson and F Zhou. "Optimisation of system design and performance to generate > 10^{20} Wcm^{-2}." Proceedings of the Conference on the Generation, Amplification and Measurement of Ultrashort laser pulses II, SPIE Vol 2377, p 260-268 (1995)

(iii) Conference Presentations

IOP Applied Optics and Opto-Electronics, Brighton, UK, March 16-19 1998

C Hernandez-Gomez, J Collier, CN Danson, CB Edwards, S Hawkes, DA Pepler, IN Ross and TB Winstone. "Interferometric Measurement and Analysis of the Wavefront Quality of the VULCAN Laser Facility"

R Allott, S Angood, C Beckwith, G Booth, J Collier, CN Danson, A Damerell, CB Edwards, J Ellwood, P Exley, P Flintoff, J Govans, S Hancock, P Hatton, S Hawkes, D Hitchcock, MHR Hutchinson, MH Key*, C Hernandez-Gomez, J Leach, W Lester, D Neely, P Norreys, M Notley, D Pepler, C Reason, DA Rodkiss, M Stainsby, M Trentelman, J Walczak, T Winstone, R Wyatt and B Wyborn. "10^{20} Wcm^{-2} to Target with the Upgraded Vulcan Laser System"

IOP National Quantum Electronics Conference (QE13), University of Wales, Cardiff, September 8-11, 1997

C Danson, S Angood, L Barzanti, J Collier, A Damerell, C Edwards, S Hancock, P Hatton, H Hutchinson, M Key, W Lester, C McCoard, D Neely, D Pepler, C Reason, D Rodkiss, I Ross, W Toner, M Trentelman, F Walsh, T Winstone, E Wolfrum, R Wyatt and B Wyborn. "VULCAN: A Unique System Delivering 250 TW and Focused to give Intensities of 10^{20} Wcm^{-2}."

D Neely, M Trentelman, CN Danson, C Beckwith, CL McCoard, JL Collier, CB Edwards, DA Pepler, M Stainsby and FN Walsh. "Frequency Doubling of Picosecond Pulses on the Vulcan Large Aperture CPA Laser System."

J Collier, DA Pepler, CN Danson, IN Ross, CB Edwards, TB Winstone, J Ellwood, P Exley, D Hitchcock, C Beckwith, M Stainsby, C McCoard, D Neely, R Allott and M Trentelman. "The Vulcan Laser System 250 TW Upgrade - Ultra High Power Pulse Diagnostics."

International Conference on Superstrong Fields in Plasmas, Villa Monastero, Varenna, Italy, Aug 27 - Sept 2, 1997

D Neely, R Allott, C Clayton, AE Dangor, CN Danson, J Collier, CB Edwards, MHR Hutchinson, A Modena, Z Najmudin, P Norreys, DA Pepler, IN Ross, M Trentelman, F Walsh, T Winstone, E Wolfrum and M Zepf. "The Development of Pulse Diagnostics for Ultra-high Power Laser/Plasma Interactions."

CB Edwards, CN Danson, MHR Hutchinson, D Neely, BE Wyborn. "200TW upgrade of the Vulcan Nd:glass laser facility"

24th Annual UK IOP Plasma Physics Conference, University of Leeds, March 24-27, 1997

C Danson, S Angood, L Barzanti, J Collier, A Damerell, C Edwards, S Hancock, P Hatton, H Hutchinson, M Key, W Lester, C McCoard, D Neely, P Norreys, DA Pepler, C Reason, D Rodkiss, I Ross, W Toner, M Trentelman, F Walsh, T Winstone, E Wolfrum, R Wyatt and B Wyborn. "The VULCAN Nd:Glass Laser: A Unique System to give Focused Intensities of up to 10^{20} Wcm^{-2} for Laser/Plasma Interaction Studies."

D Neely, P Norreys, A Damerell, R Parker and C Danson. "A high efficiency soft X-ray and optical spectrometer."

IOP Half-Day Technical Meeting, Advances in Solid State Lasers, London, November 20, 1996

CN Danson, S Angood, L Barzanti, N Bradwell, J Collier, A Damerell, CB Edwards, C Johnson, MH Key, D Neely, M Nightingale, DA Pepler, DA Rodkiss, IN Ross, P Ryves, N Thompson, M Trentelman, FN Walsh, E Wolfrum and RWW Wyatt. "VULCAN: an ultra-high intensity Nd:glass laser interaction facility."

2nd Annual International Conference on Solid State Lasers for Application to Inertial Confinement Fusion (ICF). Paris, France, October 22-25, 1996

CN Danson, S Angood, L Barzanti, N Bradwell, J Collier, A Damerell, CB Edwards, C Johnson, MH Key, D Neely, M Nightingale, DA Pepler, DA Rodkiss, IN Ross, P Ryves, N Thompson, M Trentelman, FN Walsh, E Wolfrum and RWW Wyatt. "Design and Characterisation of the VULCAN Nd:glass Laser to give focused intensities of $>10^{19}$ W cm^{-2}."

24th ECLIM, Madrid, Spain, June 3-7, 1996

C Danson, L Barzanti, N Bradwell, J Collier, C Edwards, C Johnson, M Key, D Neely, M Nightingale, D Pepler, I Ross, P Ryves, N Thompson, M Trentelman, F Walsh and R Wyatt. "Characterisation of the VULCAN Nd:glass laser for multi-TW operation."

IOP Plasma Physics Conference, Crieff, Scotland, 1-4 April 1996.

FN Walsh, N Bradwell, CN Danson, LJ Barzanti, J Collier, A Damerell, CB Edwards, P Fews, C Johnson, MH Key, D Neely, PA Norreys, DA Pepler, P Ryves, C Stephens, M Nightingale, N Thompson, M Trentelman, E Wolfrum and R Wyatt. "Characterisation of the VULCAN ultra-high power CPA laser/plasma interaction facility giving intensities to target of 10^{19} Wcm^{-2}."

FN Walsh, S Angood, CN Danson, LJ Barzanti, J Collier, A Damerell, CB Edwards, MH Key, D Neely, PA Norreys, DA Pepler, D Rodkiss, IN Ross, M Trentelman, E Wolfrum and R Wyatt. "Progress towards 10^{20} Wcm^{-2} on VULCAN."

Appendix IV

User Experiments using the upgraded TAW interaction area

GR/L11946 Prof. C Lewis, Queens University Belfast
X-ray laser experiment

During this travelling wave CPA X-ray laser experiment transient gain in Ni-like ions was studied for the first time. Saturation was achieved in both Ni-like Sn and Ne-like Ge. Gain was also measured at shorter wavelengths with the observation of lasing in Ni-like Sm. Optimisation of the CPA system resulted in a significantly shorter pulse than previously achieved.

GR/K15367 Dr J Wark, Oxford University
Spectroscopy studies

The experiment investigated radiation transport in an expanding radially symmetric laser produced plasma. Very strong velocity gradients are present which influence the radiation transport and result in a complex distortion of the emitted line-shapes. These were recorded in high resolution both spectrally and spatially using a vertical dispersion crystal spectrometer. An excellent data set was produced which allows a novel method for testing radiation transport codes and escape factors since actual line-shapes are compared, not just absolute intensities. The experiment utilised six 250J, 1nsec beams in line focus geometry.

GR/L04436 Prof. O Willi, Imperial College
Ultra-short pulse propagation

The experiment investigated the propagation of an ultra-short CPA pulse through a pre-formed plasma and short pulse propagation through capillary tubes to simulate plasma channelling. A 4th harmonic CPA probe beamline was constructed to provide optical probing of the pre-formed plasma allowing significant improvement in resolution and image quality compared to previous experiments. A good data set was produced providing new insights into capillary beam propagation which is presently being analysed.

GR/K93815 Dr P Norreys, RAL
Solid target interactions

This experiment utilised the ultra-high intensities achievable in the new interaction facility and yielded a number of novel results. These include measurements of the rear surface plasma expansion by optical shadowgraphy, indicating collimation of the fast electron flow through the solid density material. Initial indications that the 100th harmonic of the laser frequency has been observed, non-linear Thomson scattering from plasma waves at the quarter critical density region and direct measurements of the electron velocity distribution. Analysis of the results is in progress and a number of high level publications are anticipated.