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Transmissive Grating CPA System Design for the Vulcan Laser

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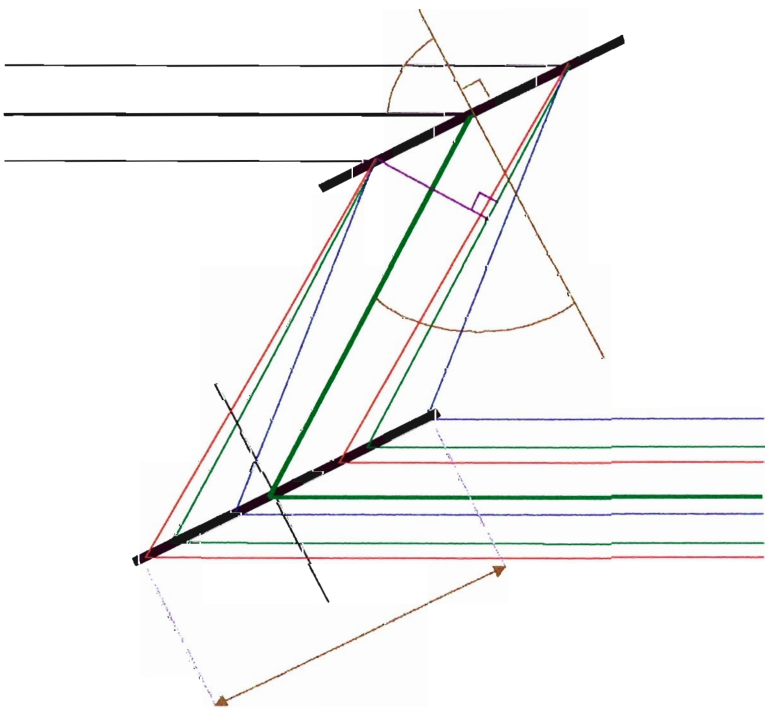
ABSTRACT

In this report the physical and spectral properties of transmissive diffraction gratings are geometrically modelled. This leads to a study of how these gratings may be used to produce a pulse compression system that will operate optimally for pulse durations between 10-300 ps. It will be shown that this system can deliver a greater amount of energy compared to a reflective grating system of similar input beam diameter. A specific system is proposed for Vulcan glass laser that will offer efficient energy delivery, and operate without the need for vacuum beam compression. Finally, an investigation is carried out into the effects of using different grating line densities to stretch a pulse than in its subsequent recompression.



CONTENTS

1 Introduction

Chirped Pulse Amplification (CPA) is essentially a method in which safe large-scale laser light amplification can be carried out. On amplification to high-energies, laser light intensity will increase such that the refractive index of the gain medium is modified. This can ultimately lead to damaging effects. One method to avoid this is to stretch out the laser pulse in time, whilst it is being amplified and then recompress it down to a short pulse just prior to using it. This reduces the laser intensity in the amplifing media and avoids much of the non-linear effects. This is routinely made possible with the use of a diffractive 'stretcher' system, which introduces a spectrally dependent delay 'chirp' into the laser pulse early in the amplification chain. Further amplification can now take place without the risk of damage to the laser gain medium. A pair of 'compressor' diffraction gratings can then be used to temporally recompress the resulting high-energy pulse, dramatically increasing the intensity of the delivered laser light.

Transmissive diffraction grating systems have several advantages over their reflective counterpart for high-energy laser pulse compression. They exhibit higher damage fluences, enabling more energy to be delivered to target for a given beam size, and can also be easily operated at the littrow angle, achieving maximum efficiency. This report will show that a transmissive CPA system can operate optimally over pulse durations between 10 ps and 300 ps. The transmissive system proposed for Vulcan discussed in this paper will be capable of delivering up to ~ 20 TW of power to target, and operate without the need for vacuum beam compression.

2 Benefits of a Transmissive Grating System

Conventional reflective CPA grating compressors are ultimately limited in their maximum energy handling abilities by the damage fluence of the grating surface. Past studies indicate that in the sub-ps to 300 ps pulse duration range, the gold-coated gratings exhibit single shot damage at ~ 0.4 J/cm^2 [3, 4, Appendix 1]. The average operational fluence limit is set to around 1/3 of the single shot damage fluence threshold for safe running. This accommodates the shot to shot variations in the energy and quality of the pulse delivered, and ensures grating lifetimes of tens of thousands of shots in normal operation.

The single shot damage fluence for fused silica is ~ 10 times that of gold in the 10 ps to 300 ps regime. This is reduced slightly if anti-reflection coatings are added to the substrate to increase the total throughput efficiency of a transmissive CPA compressor.

Figure 1 gives an indication of how the deliverable energy is restricted due to the damage limits for a Transmissive Grating CPA (TG-CPA) system compared to a similar aperture (ϕ208mm) long pulse beam line, and an equivalent reflective CPA line. The long pulse curve is derived from operational experience and will exhibit an energy limit due to the maximum possible energy being extracted from the laser gain medium (at pulses >1 ns). The central and lower sections of this curve are influenced by the B-integral damage limits for the system [1, 2, 6]. Published data tells us that the damage fluence for gold-coated reflective gratings is constant up to around 100 ps pulse duration [Appendix 1]. This explains the uniform nature of the equivalent reflective CPA beam line graph. The damage fluence threshold curve for the coated transmission optics was estimated using the same published experimental data [1, 2]. Again, the intention is to operate at approximately 1/3 of this threshold fluence. The TG-CPA plot in figure 1 indicates the damage threshold limited deliverable energy, and is independent of any beam propagation effects. Clearly, the TG-CPA line will deliver the greater amount of energy to target over a large range of pulse durations.

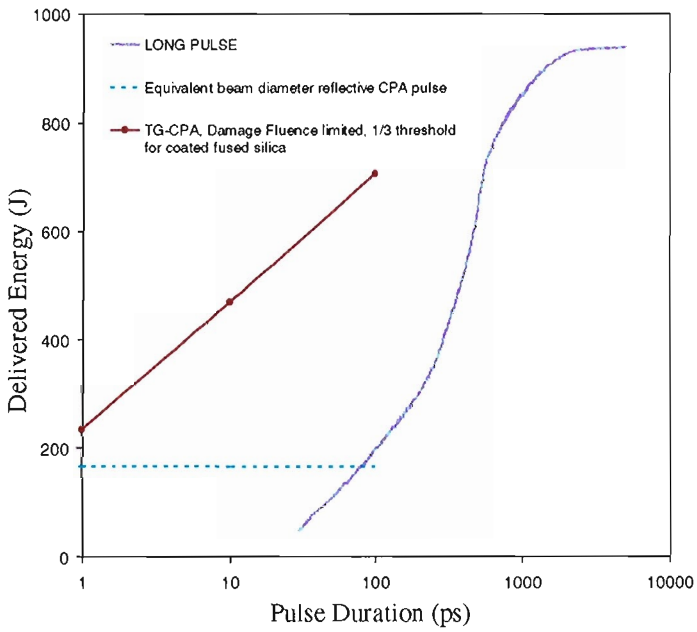


Figure 1 Deliverable energy as a function of laser pulse duration for three proposed beam lines of diameter 208 mm operating at 1053 nm.

3 General Compressor Requirements

To maintain pulse fidelity it is important for any pulse recompression system to reverse the effects of the stretcher to as large an extent as possible. It is intended that Vulcan will deliver a 600 ps, 600 J chirped pulse of 2 nm bandwidth to the "Petawatt" target area.

It is essential to select a system that will not only fulfill the scientific requirements, but also fit into the target area, be viable in an engineering sense, and remain economically viable.

The system design should contain the least possible amount of transmissive optics, keeping the B-integral to a minimum [6]. Larger B-integral leads to small scale beam break-up and self focussing which can cause optical damage. It is therefore practical to suggest that a transmissive focusing optic should be used as the target chamber vacuum window, leading the beam directly to target position. Figure 2 gives a representation of how this setup may be constructed. The transmissive gratings may simply sit on plinths with no vacuum required.

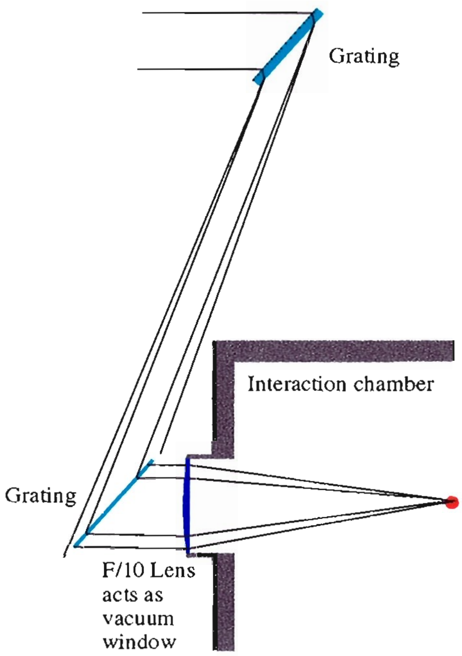


Figure 2 Target area layout diagram for the Transmissive CPA system proposed for Vulcan. Refer to figure A3 of Appendix 5 for further system layout information.

There is a large range of possible solutions for the proposed TG-CPA system. Compromises must be made between the various parameters of grating length, line density, separation and input angle such that the most sensible design is attained.

For a grating to operate at high efficiency, light should be diffracted into only one order at a time. Figure 3 shows the solution set for the existence of output diffraction orders as the input beam angle is varied as a function of grating line density for a 1053 nm beam. The region of potential high efficiency is shown in figure 3 as the white unshaded area where only the desired first order will exist. The Littrow curve shows the solution set within this parameter range along which maximum transmissive diffraction efficiency will occur in relation to the grating line density used. The maximum diffraction efficiency for a grating with a symmetrical groove profile occurs when the Bragg conditions are satisfied. The transmissive system can easily operate under this condition thus delivering the highest possible diffraction efficiencies. Ideally, the system would operate at the intersection of the littrow curve and the desired compression solution set. Figure 3 also includes various solution sets to show the line followed by a constant arbitrary compression rate (shown in orange).

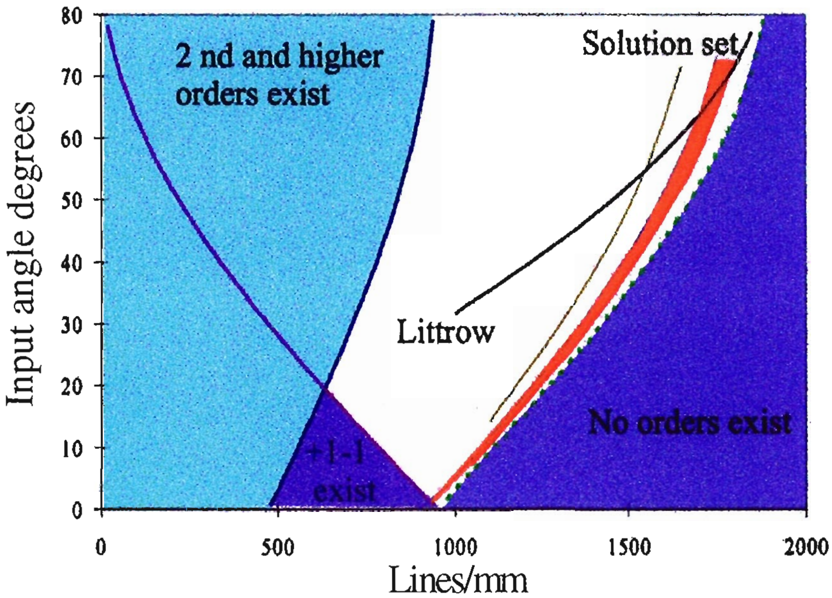


Figure 3 Available output diffraction orders as a function of beam input angle for over various grating line densities.

Higher grating line densities essentially give larger spectral dispersion. This means that the grating separation can be smaller to give the same pulse compression value. It is this increased dispersion however, along with an increased footprint due to a larger littrow input angle, that forces the grating length to increase. The length of the second grating must be sufficient enough to accommodate the footprint of a 208 mm input beam diameter at Littrow, and the spectral dispersion due to the first grating, at the line densities available. The useful standard line densities available are 1330, 1480, 1550 and 1740 lines/mm. A system that uses grating line densities under 1330 lines/mm will exhibit an excessively large grating separation, and any grating with over 1740 lines/mm becomes both expensive and difficult to produce. Table 1 shows the results of a geometrically modelled CPA compressor system to preserve the optimum compression of the 600ps chirped pulse from a matching stretcher.

Line density l/mm	Input angle degrees	Beam deviation degrees	Grating separation m	Fractional beam spread
1330	44	91	25	0.27
1480	51	78	15	0.22
1550	55	71	12	0.20
1740	66	47	5	0.17

Table 1 Geometrically modelled parameters required for a transmissive CPA system to achieve a compression of 600ps with a 2nm bandwidth, operating at the Littrow input angle, with a 208 mm diameter input beam. The extent of beam spread is indicated in the table and refers to the fraction of the output grating covered by the incident diffracted beam (of 2nm bandwidth) on the final grating divided by beam size on the incident grating.

4 Grating parallelism

It is essential to ensure parallelism between the two compression gratings to deliver optimum focusability and compressability of the output pulse. Any non-parallelism will induce a wavefront spectral divergence anomaly in the pulse due to the residual dispersion of the laser light.

The Vulcan laser system has a number of wavelengths that can be utilized to monitor grating parallelism. These wavelengths are injected into the system and the gratings optimized until any spectral dispersion between the beams is eliminated. These injected wavelengths lie at 1047 nm and 1053 nm (dichroic Nd:YLF oscillator), and 1064 nm (Nd:YAG oscillator). At a suitable incident angle onto the first grating, these wavelengths will fill or partially fill the second of the two transmissive gratings. The extent to which they fill the second grating will determine the effective aperture with which the specific wavelength is then incident onto the focusing optic. (see Figures 2 and 4). This in turn will effect the full width half maximum (FWHM) of the focal spot, and thus the accuracy of measurement. System modeling demonstrates that the 1064 nm beam will deviate from the Vulcan central wavelength of 1053 nm by such an amount as to totally miss the second grating on all four of the initially proposed grating systems. Thus, the alignment system will be limited to the use of the 'short' 1047 nm, λ_S wavelength, and the 'long' 1053 nm, λ_L wavelength of the Nd:YLF when adjusting for non-parallelism.

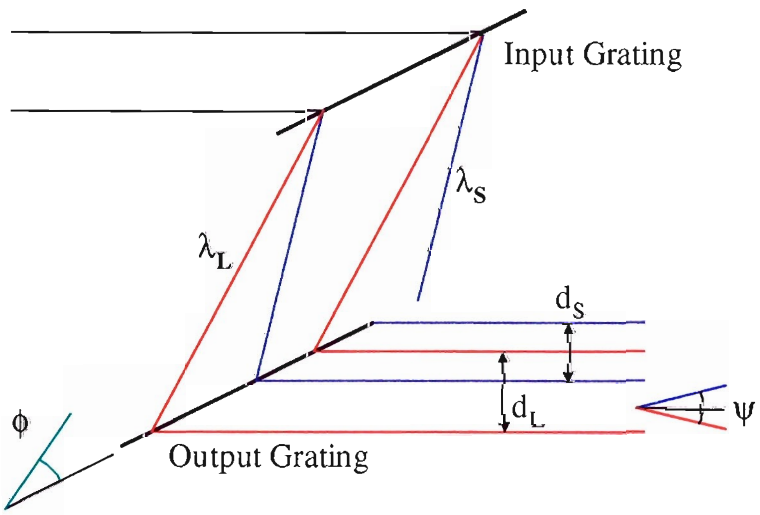


Figure 4 Extent of second transmissive grating fill at the two incremental wavelengths. ϕ represents the angular non-parallelism between the two transmissive gratings.

Calculation of the resulting FWHM for the 1053nm and 1047nm wavelengths, using their effective apertures, d_L and d_S respectively, will give an indication of how the resultant focal spot may appear. Here it is assumed that the FWHM of the far-field is a simple summation of the two component wavelength FWHM. From this, the corresponding angular resolution ψ is found. When diffraction limited, ψ can be approximated by:-

$$\Psi \approx \frac{\lambda_c(d_L + d_s)}{d_L.d_s} \qquad (1)$$

Where λ_c is the central wavelength in the grating system. Here we assume that $\lambda_S \sim \lambda_L = \lambda_c$. With further mathematical modeling it is possible to simulate the degree of non-parallelism required to produce a difference in the output angle equivalent to this angular resolution. Thus, we obtain ϕ_m which is the maximum recompression grating misalignment error that can be permitted before seriously effecting the output angular divergence, ψ and thus, intensity in the focal plane [5]. For an m times diffraction limited beam of spectral bandwidth $\Delta\lambda_B$ (using nth order of diffraction), ϕ_m can be simply approximated using the following expression:-

$$\phi m \approx \frac{m\lambda}{\Delta\lambda_B npL \tan\theta_0} \qquad (2)$$

θ_0 is the resultant output angle from the first (input) grating. L and p and represent the second (output) grating parameters of grating length (m), and grating period (lines/m) respectively.

Line density l/mm	Input grating length cm	Final grating length cm	ϕ_m mrads	ξ µrads
1330	35	48	2.01	7.3
1480	40	51	0.89	5.2
1550	43	54	0.63	4.8
1740	62	72	0.20	4.0

Table 2 Table of theoretical tolerance values in non-parallelism for each compressor grating period studied. ξ is the maximum angular divergence of the 2 nm bandwidth output beam of Vulcan after the gratings are aligned, due to residual dispersion.

The modeled data shown in Table 2 gives an indication of the tolerances associated with the setup and alignment of a transmissive compressor system, with respect to the grating line density used.

The intrinsic divergence of the Vulcan beam is ~ 20 μrads. Table 2 demonstrates that the maximum angular divergence of the 2nm bandwidth produced in alignment, ξ has a negligible effect on the overall output beam divergence.

5 Optimum Compressor Design and Geometry

The line density of the gratings will determine many of the physical characteristics of the compressor system. As the line density increases the gratings operate at larger incidence angles. Longer gratings are therefore required to accommodate the beam. However, as table 1 shows the separation between the gratings required to achieve a given pulse compression reduces as the line density increases, with the optimum efficiency being maintained. Also, the beam smoothing effect due to spectral dispersion on the second grating is largest for lower line density gratings. This can help minimize the effects of self-focusing effects in the final optics of the system.

A survey of the Vulcan upgrade target area indicates that no more than 12m is permissible between the gratings for the system to fit into the available space. The 1740 lines/mm diffraction grating compressor system requires only 5m to obtain the correct pulse compression. However, 72 cm long grating substrates are required and manufacturing efficient high line density transmission gratings is more complex. As table 1 indicates, the 1550 lines/mm grating system would satisfy the grating separation criteria (11.9 m) with the grating length of just under 54 cm [Appendix 2].

To obtain maximum recompression of the laser pulse the compressor grating setup should 'match' the stretcher configuration exactly in terms of grating line density, input angle and grating separation. This is only strictly necessary however if the shortest attainable pulse lengths are required. To operate in the desired 10-300 ps regime it is necessary to 'de-tune' the system away from maximum pulse compression. Reducing the grating separation of the compressor, or stretcher to suit can do this. It was found that it is possible to run a compressor system with differing grating periods to the stretcher. In the case of a 1480 lines/mm stretcher in conjunction with a 1550 lines/mm compressor, the recompressed pulse will exhibit a residual stretch. This non-linear anomaly will induce a maximum temporal defect of ~ 0.45 ps (see Figure 5). When operating in the 10-300 ps pulse duration range this value is essentially negligible negligible. The implication of this is of economical benefit, in that the 1480 lines/mm stretcher gratings that are already available to Vulcan can be used in conjunction with the proposed 1550 lines/mm compressor gratings.

Target Area West has an existing CPA compressor which comprises of two 1740 lines/mm reflective diffraction gratings. It is important that this system runs in coincidence with the proposed TG-CPA beam line. Figure 6 however indicates that when running a 1480 lines/mm stretcher with a 1740 lines/mm compressor, the maximum residual stretch present in the compressed pulse is ~ 2.5 ps. As the desired pulse in Target Area West is under 1 ps, this temporal defect is too large for normal operation.

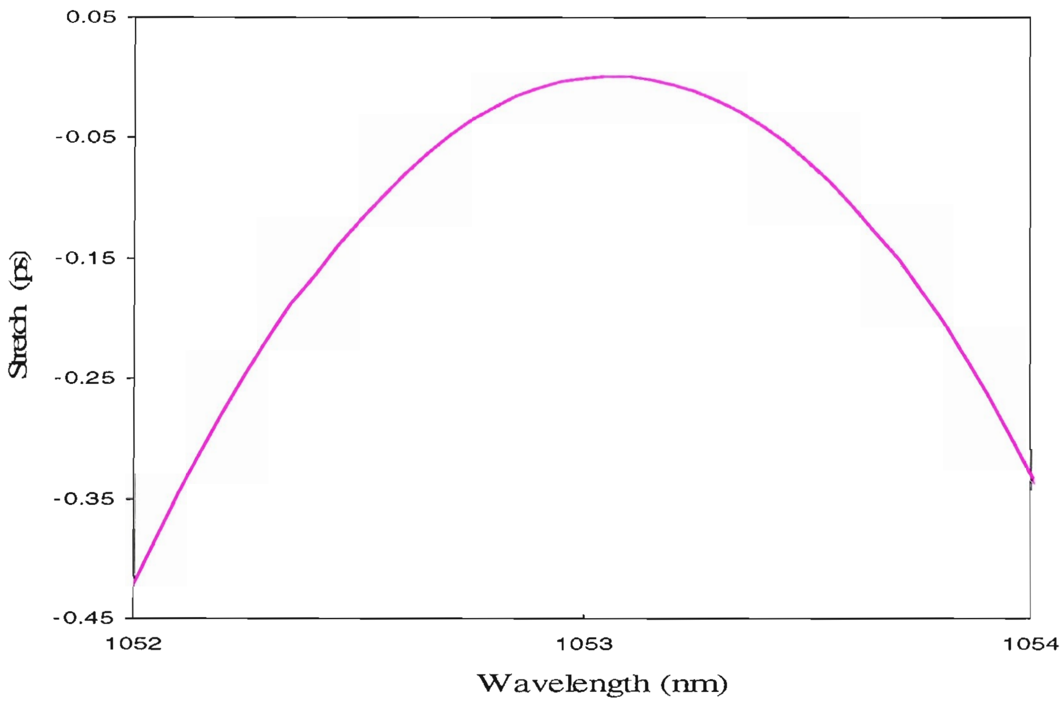


Figure 5 Graph showing the residual stretch in ps between a 1480 lines/mm stretcher (51.2 degrees incident angle, 15.20 m separation) and a 1550 lines/mm compressor (54.7 degrees incident angle, 11.78 m seperation).

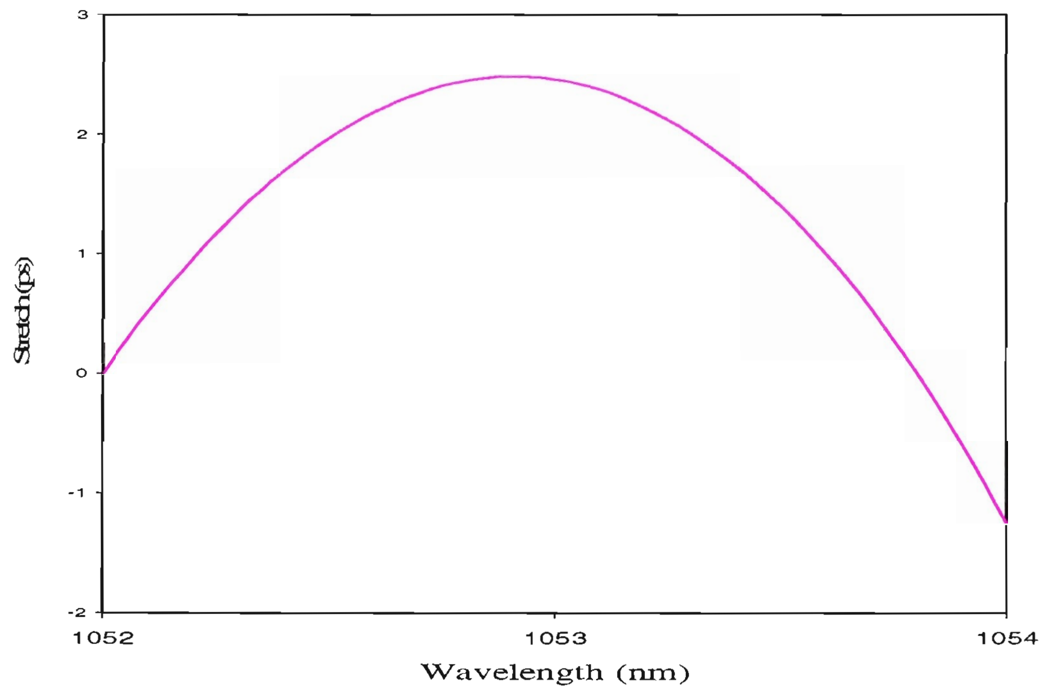


Figure 6 Graph showing the residual stretch in ps between a 1480 lines/mm stretcher (51.2 degrees incident angle, 15.20 m separation) and a 1740 lines/mm compressor (66.4 degrees incident angle, 4.49 m seperation).

5.1 Effects of B-Integral on the Compressor system

The B-integral value [6, Appendix 4] provides an indication of the extent at which intensity modulations increase non-linearly through the optical system. These modulations will ultimately determine the deliverables of any transmissive system. B-integral is dependent upon both the intensity of the pulse, and the non-linear refractive properties of the medium through which it propagates. The intensity of the pulse modulations will increase exponentially (proportionally with e^B). If these modulations become sufficiently intense, the optics that make up the system may become damaged (depending upon the damage fluence of the material used). The B-integral through a length, l of optical material is typically given by the expression:-

$$B = \frac{2\pi}{\lambda} \int_0^l \gamma I(x).dx \qquad (3)$$

Where I is the intensity of the laser pulse, and γ is the non-linear refractive index component, or the non-linear phase retardation coefficient (m^2/W). It is this component that determines the extent of self-focusing that is present as the pulse propagates. $\gamma=(n-n_0)/I$. Self focusing occurs when the refractive index, n not only has a field independent term, n_0 but also a field dependent term, n_2 [6]. We also know that $n=n_0+n_2\langle E^2\rangle$.

The grating manufacturers have indicated that, for a 1550 lines/mm grating of the dimensions specified, the fused silica substrate will be 1 cm in thickness [Appendix 2, Appendix 3]. From the efficiency data values supplied by the manufacturers, a good estimate can be formulated as to how large the B-integral in the proposed system would be (including an assumed 3 cm maximum thickness fused silica lens). Further more, an indication of deliverable energy for a constant B-integral can be studied over the range of pulse durations in question.

Using the calculated efficiency of the grating (85% into desired order), and the known incident pulse parameters of 600J in 600ps, the maximum deliverable energy for the TG-CPA system is found to be 420J (see figure 7). It is considered that the maximum B-integral which could be tolerated before optical damage due to self focusing or beam breakup in the focal plane at this energy, will limit the system to $6 < B < 12$ (damage testing will need to be conducted to verify this limitation). The operating curves (dashed curves) corresponding to B=6 and B=12 are shown on figure 7. The marked solid line on figure 7 shows the estimated damage fluence limits for the gratings. The flat portion of these lines is determined by the maximum deliverable energy of the 208 mm beam line for a 600 ps pulse. Clearly, the performance of the system will be restricted at the shorter pulse durations (<30 ps) by self-focusing damage mechanisms rather than average fluence effects.

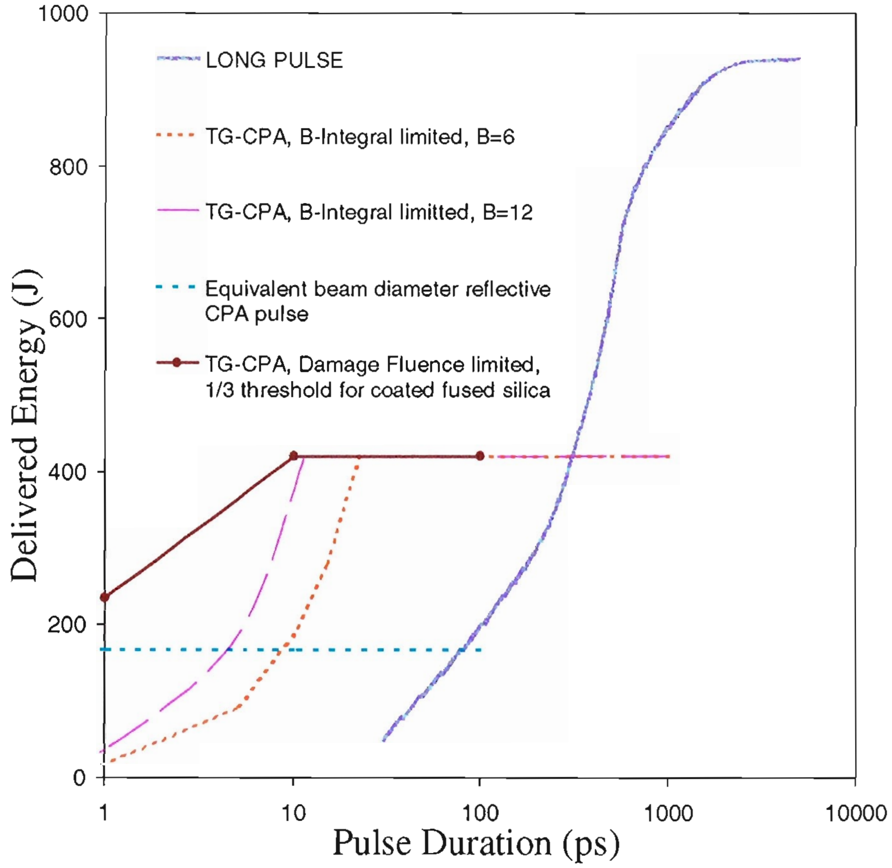


Figure 7 Deliverable energy as a function of laser pulse duration for three proposed beam lines of diameter 208 mm operating at 1053 nm. The TG-CPA plot indicates 3 variations: one theoretical damage (due to average fluence effects) threshold line, and two forecasted deliverable lines limited by damage due to self focusing at B-integrals of 6 and 12.

The systems limitations can be further illustrated when plotting the deliverable power against the desired pulse length, as shown in figure 8. It can be seen that a suitable TG-CPA system will deliver more power to target than an equivalent beam diameter reflective CPA pulse for a pulse durations larger than 10ps. At around 300ps and above, the long pulse beam lines will take over as the means for maximum deliverable power.

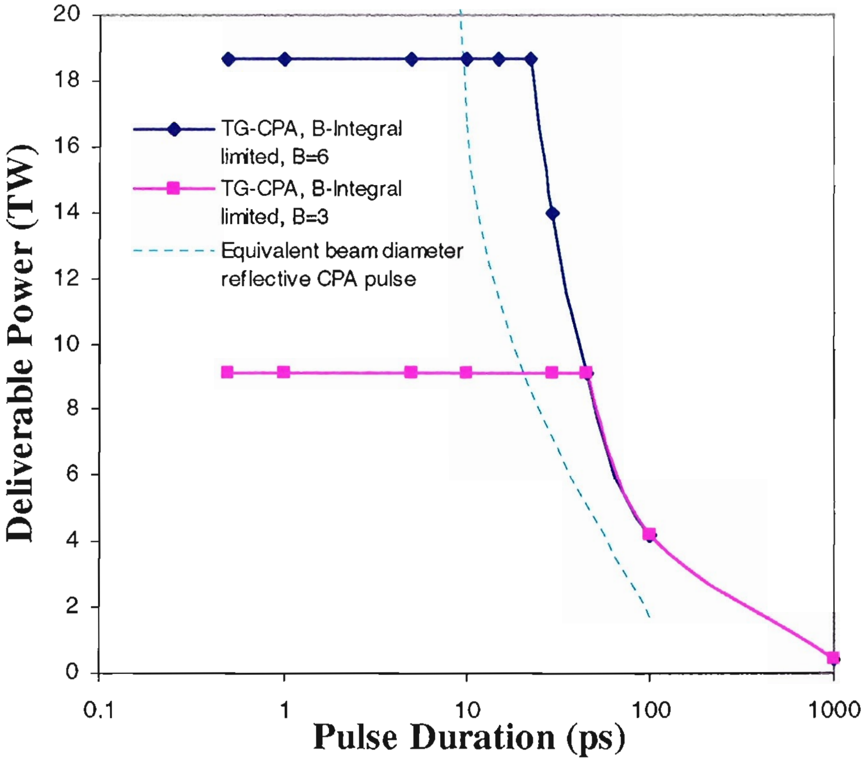


Figure 8 Deliverable power as a function of laser pulse duration for two proposed TG-CPA beam lines of diameter 208 mm operating at 1053 nm. These lines correspond to safe constant B-Integrals of 3 and 6. The dashed line indicates the deliverable power for a reflective CPA line of similar beam diameter.

6 Conclusions

A transmissive grating chirped pulse amplification system can efficiently deliver multi terrawatt beams to target, in the 10-300ps pulse duration range. The proposed design relies on compressing a pulse in air and then using the final focusing optic as the air/vacuum interface. The deliverable energy is ultimately limited by self focusing damage within the fused silica substrates of the final compressor grating and focusing optic. The maximum deliverable power at B=6 is ~ 20 TW at 20 ps and ~ 1.5 TW at 300 ps.

7 Acknowledgements

I would like to thank T. Winstone of RAL, Oxon, for the work on the transmissive grating specification [Appendix 2], P. Hatton of RAL, Oxon, for the Engineering diagrams involved [Appendix 3, Appendix 5] and R. Clarke for technical support through out the project.

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Appendix 1

Single Shot Damage Fluence

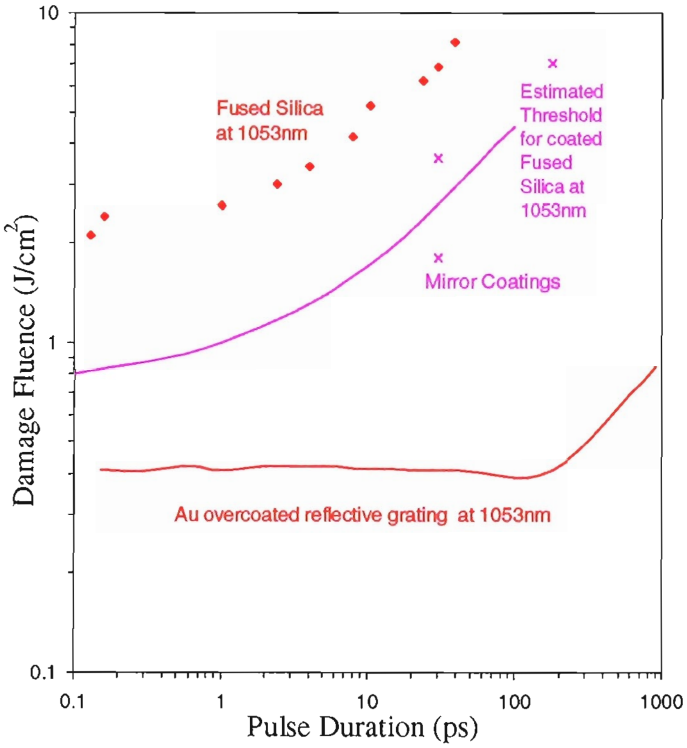


Figure A1 Damage fluences for various media as a function of pulse duration, for laser light at 1053nm wavelength (see Refs 1 and 2 for source information).

The composition of commercial metallic gratings can vary to a large extent. Generally, damage is seen to occur more readily at shorter pulse durations. Published data [4] indicates that very short pulses (<<1 ps) show negligible melting or collateral damage. This would infer that damage at these pulse durations is to ablation or vaporization of the metal grating layer. For longer pulse durations however, grating damage is seen as the temperature reaches the meting point of the metal, gold in this case of the Vulcan reflection gratings (see figure A1). The damage fluence of these gratings will fall at pulse durations <<1 ps as the boiling point of the metal is exceeded.

When converting to a fused silica transmissive grating system, it is immediately apparent that the damage fluence threshold values increase dramatically. These can be affordably lessened with the addition of AR coatings (see figure A1). The damage fluence threshold curve for the coated transmission optics was estimated using known points available through experimental testing. Again, the intention is to operate at approximately 1/3 of the threshold values.

Appendix 2
Transmissive Grating Specification

SPECIFICATION OF TRANSMISSION COMPRESSION GRATINGS :

TRANSCOMPGRAT 00-8

This specification is to be read in conjunction with RAL drawing A0-SL-3300-119.

Substrate Material Fused Silica suitable for High Power Laser use

Grating period	1550 l/mm
Substrate length	530 (+2.0, -0.0) mm
Substrate width	290 (+2.0, -0.0) mm
Maximum substrate thickness	5-10 mm
Minimum grating length	490 mm
Minimum grating width	250 mm
Input angle	54.7 degrees

Substrate parallelism To be parallel to within 20 arc seconds

Corners All corners to be chamfered 1 mm x 45 degrees

Edges All non optic edges to be fine ground

Internal Defects < 100 μm diameter.

Area of defects < 1.0 mm^2 per 100 cm^2.

Damage threshold Damage threshold to be tested on similar samples

Grating Area Grating to cover surface up to 20 (+0.0, -1.0) mm of the substrate edge.

Efficiency > 85 %

Operational wavelength 1053 nm

Diffracted phase front < $\lambda/4$ at 1053 nm

Diffracted phase front gradient < $\lambda/10$ per cm

Monochromatic beam divergence < 20 microrad at 1053 nm

Anti-reflection coating	Damage threshold to be tested. Sol-Gel coated on rear surface to be used in air.
Quantity	A matched pair of gratings is required
Mounting Bezel	To be provided by manufacturer.

Markings
The grating substrate is to be sandblasted around the edge with a unique number furnished by the Laboratory prior to polishing.

Documentation
Each grating should be supplied with 1st order interferograms, an efficiency distribution map, and a detailed map of any cosmetic defects immediately prior to packing.

Packing
Each grating should be carefully packaged such that nothing touches the grating surface. It should be placed in low dust producing materials, and this outer sealed in a polythene bag, before being placed in a box suitable both for the mode of conveyance and for storage.

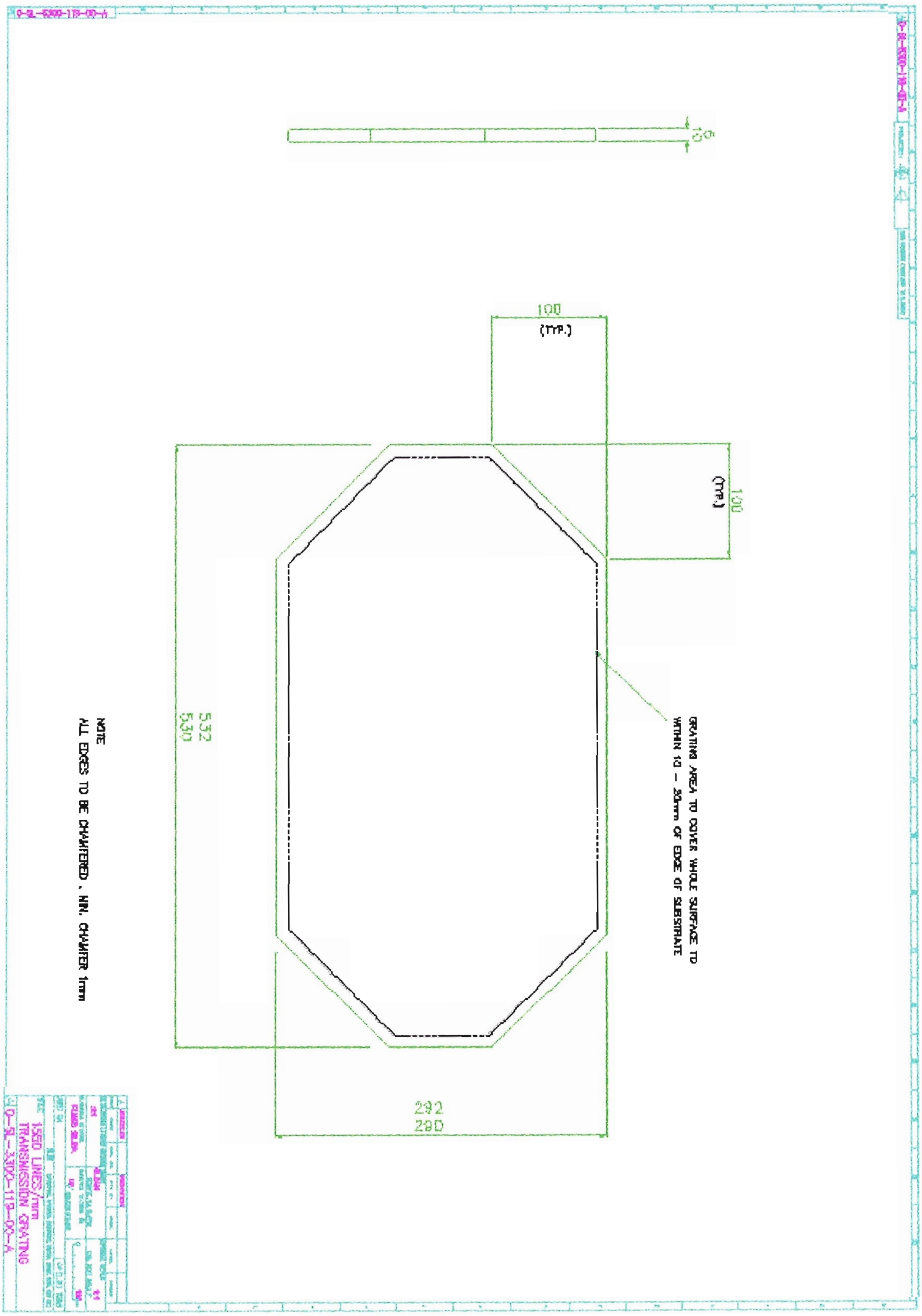
The outer packing to be marked "To be opened only in a clean room", "Only to be opened by Technical staff familiar with the contents of the package", and "FRAGILE - GLASS".

Limitations in manufacture

The fused silica transmissive diffraction gratings will be produced by the Lawrence Livermore National Laboratory, CA 94550, USA. They have indicated that the grating can be made to the dimensions specified in this report, with one exception. The maximum grating length is limited by the size of the circular plant in which the grating will be produced. This has limited the grating to a length of 53 cm rather than the 54 cm indicated, and will only be possible if the corners of the gratings are removed [Appendix 3]. The extent of overfill of the second (output) grating that this produces is negligible as the intensity drops at the wings of the beam profile.

Appendix 3

Transmissive Grating Engineering Diagram



Appendix 4
Further B-integral Theory

B-integral is essentially a phase anomaly within the normally fairly coherent laser light (units in radians). The phase anomaly occurs due to the dependence of a materials refractive index on the intensity of the electromagnetic radiation propagating through it. The refractive index value in turn will determine the phase velocity of the light, which will ultimately vary across a beam profile wherever an intensity gradient is present. A Gaussian intensity distribution over a beam cross section for example can induce an effect called self-focussing. This results in the beam being brought to a focus as light of differing intensity is refracted toward the same point within the medium. This however, may not always occur over the full beam profile. Hot spots within a near-field cause localized intensity gradients that can collapse individually, resulting in filamentation of the beam.

The B-integral value gives an indication of the accumulated phase defect that is present in an emerging beam, and can be calculated using equation (3). A B-integral of 3.142 corresponds to a non-linear phase retardation of ½ λ. When a coherent beam is brought to focus (using a focussing optic), theoretically all of the light will arrive in phase at the focal point. With the introduction of B-integral however, this will not occur completely. Thus, increasing the B-integral will reduce the quality of a resulting focus (see figure A2).

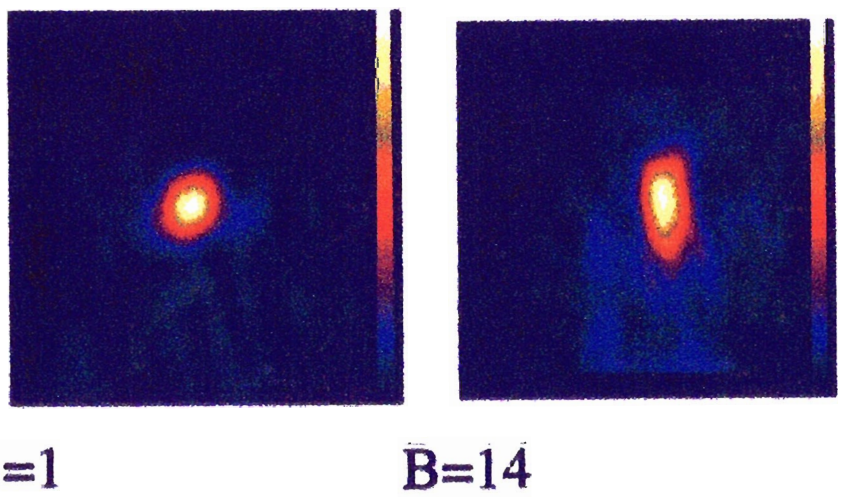


Figure A2 Two focal spot images showing degradation as the B-Integral is increased.

Appendix 5

The "Petawatt" Target Area: Schematic Diagram

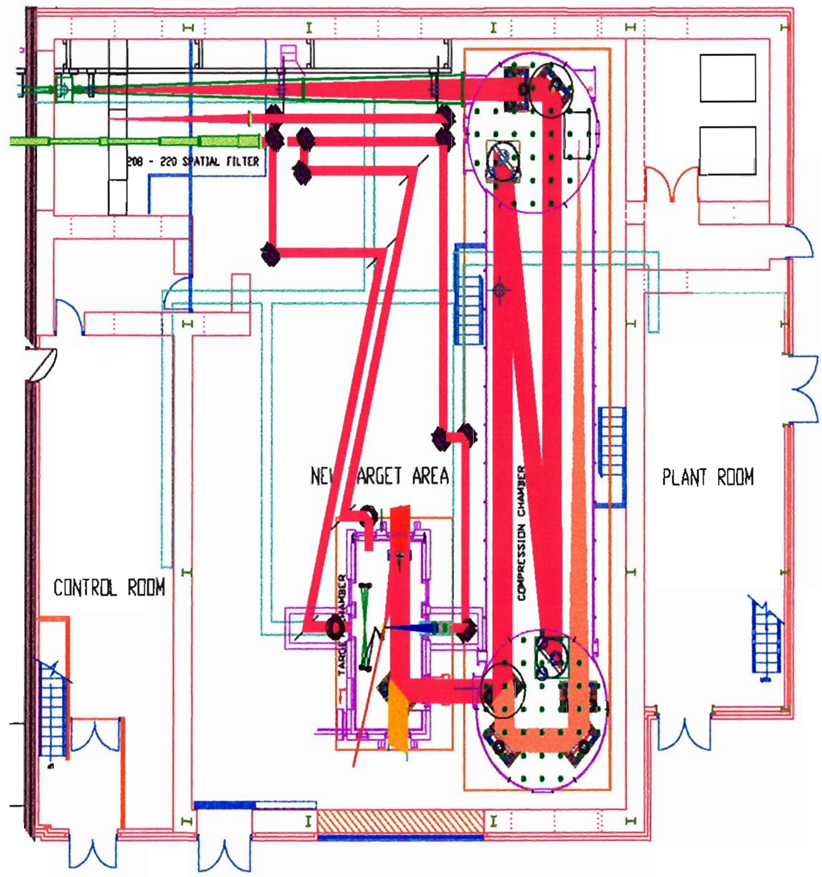


Figure A3 A schematic diagram showing the plan view of the Vulcan upgrade target area. The larger reflective CPA beam is show to the right, initially running parallel with the East wall of the target area. An example of how a TG-CPA beam line may be installed is shown by the smaller diameter beams positionaed more centrally in the diagram. A beam line similar to the one disscussed though out this report can be seen cutting across the corner of the rectangular target chamber, entering it from the right. The actual target can be located at focus, in the centre of this vacuum chamber.