# The Vulcan 10 PW project

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## Introduction

This projects aim is to upgrade the Vulcan high power laser located at the Central Laser Facility (CLF), to beyond the 10 PW power level ($10^{16}$ W) and provide focused intensities of greater than $10^{23}$ $Wcm^{-2}$ to its international user community [1]. The project was divided in two phases. Phase 1 of 2 year duration, started in December 2006. A proposal for phase 2 has been submitted and reviewed. The start date of phase 2 is still under discussions. We report here on the overall progress made during the first phase. There were essentially three key areas to address as part of phase 1:

- A novel "front end" system has been developed for the overall project and its performance has been verified with respect to key indicators such as wavelength, energy, bandwidth, pulselength, contrast etc.
- There has been a significant reduction in the risk associated with several key technical elements of the project, particularly the large aperture diffraction gratings and laser amplifiers Several outstanding risks remain but at a level that we judge is acceptable to be addressed as part of Phase 2.
- In consultation with our user community, an optimised design for Phase 2 has been developed, including radioprotection and a cost established to an adequate level of confidence.

## 10 PW front end

A key objective of Phase I was to develop a new front end that delivers pulses with energies of up to 1 Joule with sufficient bandwidth to support a pulse with a maximum duration of 30 fs. The contrast of these pulses should be at least $10^7$ when measured at 5 ps and $10^{11}$ when measured at 5 ns.

The work on the Front End started by generating a novel broadband seed at 900 nm [2]. An important element of the design is the bandwidth we have chosen to use. To achieve the 30 fs pulse length specification, approximately 50 nm of bandwidth is required to achieve close to its transform limit. The Optical parametric Chirp Pulse Amplification (OPCPA) design is theoretically capable of supporting a bandwidth of more than 150 nm, which offers the potential of eventually exceeding the 10 PW specifications. An alternative view is that it also gives contingency on the basic power specification. We have therefore elected to

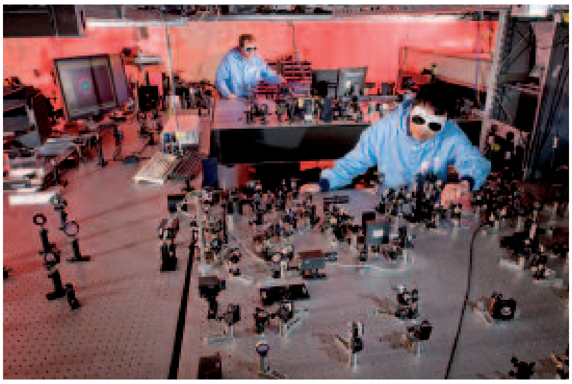

**Figure 1. Area photograph of the 10 PW Front End.**

develop this high (150 nm) bandwidth version and the overall design is now based on this approach.

The 910 nm seed currently generated with the chirped scheme has a bandwidth of 165 nm and energy of 40 µJ per pulse. This seed is then stretched to 1.87 ns FWHM and amplified in two LBO crystals [3-4] pumped by a commercial temporally shaped pump laser. The design of the Joule stage in terms of contrast, gains and energy were based on a millijoule of seed energy at the input. As the input seed energy is currently limited to 1~ µJ due to stretcher inefficiencies, additional gain over that originally anticipated has been provided in the first stage by placing two crystals consecutively. In this way the un-depleted pump energy from the first crystal is recycled to extract gain from the second one. The Stage 1 crystals have gains of ~400 each and the 2nd stage a gain of ~40. In using this scheme the output energy achieved so far is >15 mJ for stages 1 and 2 and 0.4 J for stage 3. Figure 1 shows a photograph of the Front End.

To achieve the contrast specification of the Front End it is necessary to increase the output pulse energy of the mJ-stage OPA on ps time scale significantly from its current ~40 µJ to ~1 mJ. This will allow the first stage to operate with a single crystal as originally designed. The output energy of the mJ stages is currently limited by the output power of the existing commercial Compact Pro amplifier, giving only ~1.8 mJ at 800 nm. Therefore a boost Ti:Sa amplifier has been designed and developed to increase the pump pulse energy to ~30 mJ at 800 nm [5]. This IR pulse will be then frequency

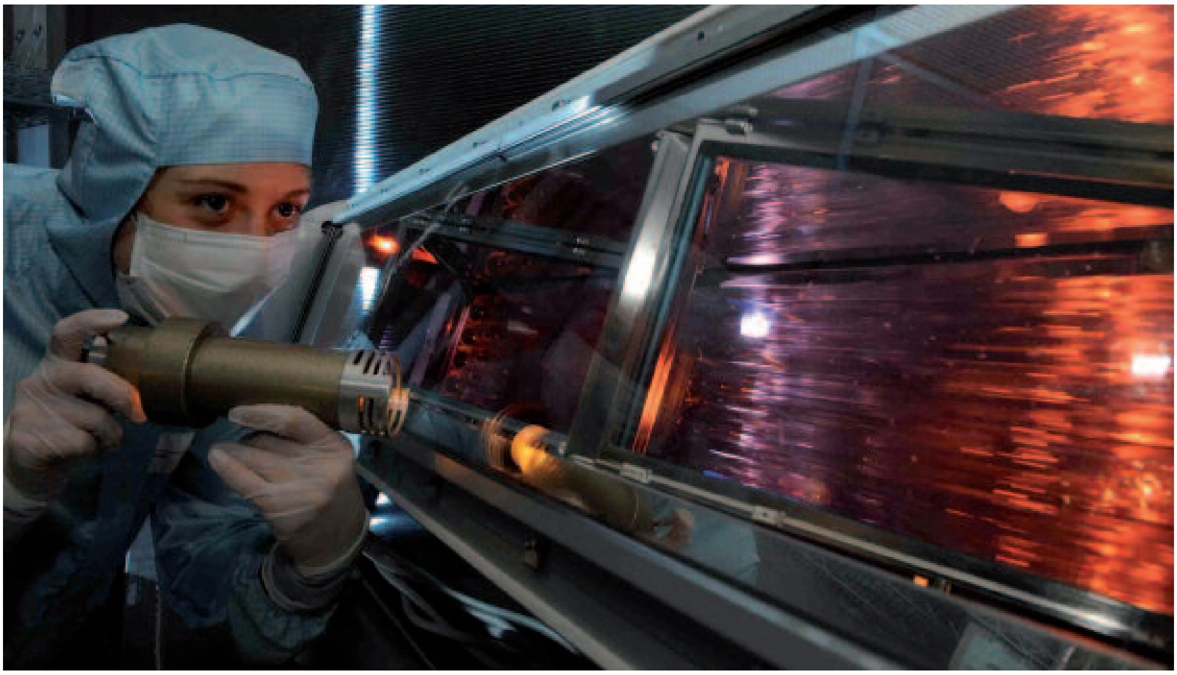

**Figure 2. Photograph of the 150 mm square slab amplifier.**

doubled using a thin BBO crystal to generate the required blue pump pulse of ~4.5 mJ that will be used to pump 3rd and possible 4th mJ-stage OPA to produce a 1 mJ ps pulse while retaining the full bandwidth.

## Laser technology

Two of the risk areas for phase 2 that we have been addressing in phase 1 are the grating and laser amplifiers.

***Diffraction gratings:*** The highest technical risk relates to the availability of the large aperture diffraction gratings required for the compressor. These compressor gratings need a line density of between 900 l/mm and 1200 l/mm. Calculations performed indicate that the optimum line density for the gratings of the large aperture compressor for the bandwidth we intend to use is 900 l/mm. These low line density gratings are not readily available at the large aperture required from any manufacturer.

To mitigate this risk we approached several large grating manufacturers. After initial negotiations with a number of companies we placed two design study contracts with Lawrence Livermore National Laboratory (LLNL) and with Plymouth Grating Laboratory (PGL) to investigate the theoretical performance over a large bandwidth of gold and dielectric gratings at 900-1100 l/mm, and to establish the feasibility of having these manufactured at large diameter apertures. It is worth noting that these two grating manufacturers operate with radically different manufacturing techniques. In addition we theoretically modelled the performance of the gratings under different configurations to establish the optimum geometrical configuration to use in the compressor.

The LLNL report concluded that gold over coated master gratings were needed to cover the 800 to 1000 nm bandwidth at TM ( or ‘p’) polarisation and that a line density of 1100 l/mm or greater was required for >90% theoretical Diffraction Efficiency. The LLNL report did not consider TE or “s” polarization. The PGL report showed that good performance with efficiency of >90% for s-polarisation, with good response across the full bandwidth range was possible for gold gratings at lower line densities, and particularly 900 l/mm. Following these studies a second contract was placed with PGL to actually manufacture small grating samples in order for us to test their performance.

The gratings samples were tested at the configurations that they would be used and the results qualitatively (and in parts quantitatively) agreed with the theoretical calculations. Although the efficiency is good across the bandwidth range it is still 90% or less [6].

The second part of the grating test was to check damage threshold of these grating samples to ensure we can determine the beam size that we would have to operate them at. The initial damage test of these gratings was performed on the Astra laser and confirmed expectations [7]. Also, different dielectric coatings and silver coatings of mirrors were tested to determine the damage threshold of each of these coatings. These combined results have provided us with the initial beam size of full energy 10 PW and have enabled some cost reducing measures in terms of beam transport to be developed for the project.

These damage tests were repeated in an ISO laser damage test facility in Lithuania by the Vilnius University Laser Research Centre to double check the damage thresholds of each coating. The initial tests conducted on two grating samples in both gold and silver demonstrates a laser damage threshold after 10,000 shots of 43 mJ/cm$^2$ for the gold gratings. For the silver grating two kids of laser induced damage thresholds were observed Catastrophic LIDT at 94 mJ/cm$^2$, and non catastrophic LIDT at 25 mJ/cm$^2$. Tests were carried out using an 800 nm central wavelength and a 44 fs pulselength, with the grating at Littrow angle and an ‘s’ polarisation beam incident.

***Laser Amplifiers:*** The current Vulcan laser is composed of a series of small aperture rod amplifiers and large aperture circular disc amplifiers. The laser chain would need to be upgraded to deliver the required 1.2 kJ at 1053 nm to pump the large aperture OPCPA stages in Phase 2. To provide an optimised geometry for the OPCPA amplification and particularly pulse compression, square pump beams are required. This means that Phase 2 will require laser amplifiers with square slabs (as opposed to the current elliptical ones) which is a new type of technology to the one currently being used in Vulcan. In addition, there is a very limited supply of the gain medium Nd:glass that the slabs are made of, square or otherwise. As part of phase one therefore, we investigated the possibility of using existing so called 460 mm half discs supplied by the US Department of Energy from the closure of the Nova Laser System. This had the additional attraction of minimising the cost of the new amplifiers required for Phase 2. The initial test was to build a 150 square slab amplifier by cutting some of the 460 discs in half. Following negotiations with LLNL (who own the cladding patent), a specialist optical company (Zygo Corp, USA) successfully cut the existing 460 half discs into 150 mm square amplifier slabs and re-clad them using this proprietary technique. The new mechanics for the amplifier were manufactured and assembled. The redesigned square amplifier has required several modifications to fit together to a suitable level so that a complete amplifier can be assembled in suitably clean conditions. The new completed amplifier received the standard 10 flashlamp firings to provide sufficient evidence of flashlamp integrity. There was a delay in the delivery of Brewster windows, therefore a sub aperture 120 mm diameter window has been installed at each end to provide a suitable sub aperture testing window. The new amplifier is shown in Figure 2. These discs have a doping of $2.5 \times 10^{11}$ Nd ions per cc, which is a similar level to the doping of the discs within Vulcan. Discs cut from this material should have similar gain to the existing amplifier discs in Vulcan. To confirm the gain of the new amplifier we plan to conduct gain tests in the next few weeks. The repetition rate of Vulcan will be quadrupled to four shots an hour in the new 10 PW facility, to extend the potential for a broad range of experimental set-ups. This will require a set of tests to investigate the aberrations in the beam produced by the disc amplifiers when fired at a higher rep rate.

## Facility design

Another central objective of Phase I was to explore the different options to build Phase 2 and develop the facility design to a point that it could be adequately costed.

A significant extension to the Vulcan building infrastructure is required in order accommodate the large amount of new equipment. Vulcan is however “land locked” and opportunities for expansion in any direction are quite limited, as the current building could only be extended to the south and west. A design optimisation process was followed therefore, balancing the requirements of the project, the user community, the surrounding RAL departments etc with the physical constraints of the location in consultation with the RAL Estates Management Division.

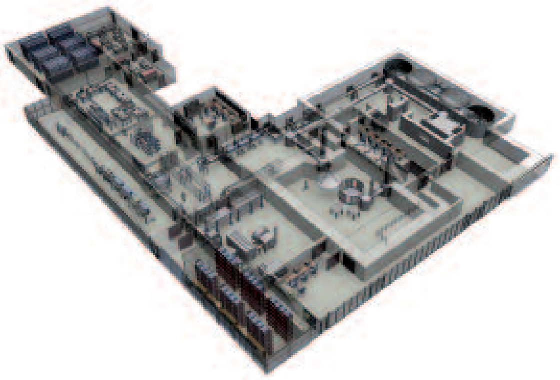

**Figure 3. Schematic of the ground floor of the new proposed extended building.**

The proposed new building requires the existing building to be extended on the South and West sides and a second floor built above the current Target Area West (TAW) and Target Area East (TAE), the ground floor is shown in Figure 3. The upper floor would then house the additional laser chain, OPCPA amplifiers and compressor. The existing Target Area Petawatt (TAP) would be enhanced to become a combined 1+10 PW area; TAP would also require a small extension to the south for radiological protection reasons. TAE would be transformed to become a dedicated High Intensity 10 PW area and we would maintain TAW as the third operating area only until the first of these 10 PW areas were fully established and operating. As part of the facility specification for Phase 2 we have conducted initial designs for the whole of the facility. The different areas that had to be considered in addition to the building were the laser amplifier chain, the OPCPA amplification stages, the compressor, the beam propagation, possible beam combinations and the target areas.

The laser chain and OPCPA stages have been designed and modelled to a level that ensures that the design meet the technical specifications required to deliver 300 J in 30 fs. The laser chain required to pump the OPCPA stages will be a combination of the existing chain and a new set of amplifiers. The additional laser amplifier chain has been designed using a minimum number of amplifiers in a double pass configuration using angular multiplexing. The compressor design is based on a single pass four grating scheme as shown in figure 4.

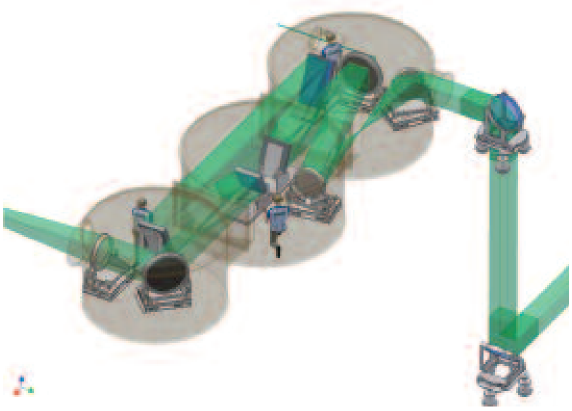

**Figure 4. Schematic of the 10 PW compressor.**

Its design was dependant on the gratings available and a design has been produced based on the parameters obtained through the grating studies as explained above. Once the beam is compressed it needs to be transported to the target areas. A design has also been developed for the beam propagation from the compressor to the new combined 10 PW + 1 PW TAP area (TAP10) and the new 10 PW High Intensity area, including a beam demagnification from a 600 mm diameter beam to 450 mm diameter beam, based on the results from the damage test of currently available coatings. In terms of the combined TAP10 target area significant design work has been conducted to define the different experimental configurations available with long and short focal length parabolas. In the HIA area a design has been made for the new chamber & transport for high yield experiments.

Both areas HIA and TAP10 will be shielded appropriately to provide adequate radiation protection TAP10 will be built first and will operate for a year in the different configurations. The HIA, delivering the highest intensities will follow 12 months later, replacing the current Target Area East, and will incorporate a new heavily shielded roof and walls.

## References


1. C. Hernandez-Gomez *et al.*, The Vulcan 10 PW OPCPA project, CLF Annual Report 2006-2007.
2. Y. Tang *et al.*, *Optics letters*, Vol 33, No 20 (2008).
3. A. Lyachev *et al.*, *"Development of the Joule level amplification stage for the Phase 1 of the Vulcan 10 PW OPCPA project"*, CLF Annual Report 2007-2008.
4. A. Lyachev *et al.*, *"Front End10 PW Front-End Characterization"*, CLF Annual Report 2007-2008.
5. Y. Tang *et al.*, *"High performance Ti:Sa amplifier for 10PW front-end system"*, CLF Annual Report 2007-2008.
6. A. Lyachev *et al.*, CLF Annual Report 2007-2008.
7. M. Streeter *et al.*, *"Damage testing of reflective coatings in Astra TA2"*, CLF Annual Report 2007-2008.