Development of Petawatt Laser Amplification Systems at the Central Laser Facility

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ABSTRACT

We describe two development projects: Astra-Gemini: a Petawatt class system based Ti: Sapphire amplifiers and a 10 PW upgrade for the Vulcan laser. The design concepts, features of the optical design of amplifiers and compressors are presented. Radial delay compensation techniques used for a 3-x beam expander are discussed.

Keywords: Chirped pulse amplification, optical parametric amplification, radial delay, grating compressor

1. INTRODUCTION

Recent developments in ultrahigh intensity physics and further development of the chirped pulse amplification technique have brought a great interest to the development of Petawatt (PW) class amplification systems. Most of the development approaches are based on the chirped pulse amplification[1] (CPA) and subsequent compression[2] of the pulses. Among the designs of the amplification systems there are the systems based on active laser media such as Nd:glass[3], Ti: Sapphire[4] or on the optical parametric chirped pulsed amplification (OPCPA) in non-linear crystals[5,6]. The development of the Petawatt class amplification system based on Ti: Sapphire have become possible after a series of successful developments of CPA systems[7,8]. During this activity several main issues of the high-power amplification were resolved such as the gain narrowing and the spectral shift in the Ti:Sapphire amplifiers as well as an ability to control and to compensate the spectral phase of the pulses to provide an effective pulse compression. As the result of the CPA system development the peak power level of 100 TW[8] has become limited only by the size of the crystal. Recent progress in the growth of the large aperture Ti:Sapphire crystals has increased the level of achievable ultra-high peak power with the existing techniques and technologies. Despite the recent progress in the technologies of growth of the large Ti:Sapphire crystals they are still limited in sizes and expensive to manufacture. Application of the OPCPA technique for the high power pulse amplification [5,6,] is considered as a good alterna

tive or counterpart for the laser active media amplifiers due to the availability of the large size non-linear crystals (KDP or DKDP), broad spectral gain provided by these crystals and the high energy achievable with this technique[6].

There are two major high power laser development projects at the Central Laser Facility (CLF): the Astra-Gemini laser system and the first phase of the Vulcan 10 PW project. The Astra-Gemini laser system is a dual-beam PW CPA Ti: Sapphire laser system which is being built as an upgrade to the existing Astra laser. The 10 PW project is an OPCPA upgrade of the Vulcan high power laser system.

2. ASTRA GEMINI: A DUAL BEAM PETAWATT TI:SAPPHIRE SYSTEM

The Astra-Gemini laser system as an upgrade of the existing Astra laser facility to a PW class system is based on the dual beam concept and CPA amplification in the Ti:Sapphire crystal. One of the goals of the system is to provide extremely high intensity (~10^{22} W/cm^2) on target with two independently configurable beams. Each beam will be amplified up to 25 J before compression to deliver 0.5 PW in 30 fs on target. The dual beam nature of the system not only enables new types of experiments with two intense beams but also fully exploits the availability of medium sized optical elements such as mirrors, Ti:Sapphire crystals, compressor gratings and pump lasers.

2.1 Laser design

The Astra Gemini laser area was specially designed and built within an existing building together with the new target area. The amplification system is located in the new laser area with space of 200 m^2. The target area is confined within a

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concrete bunker with 1 metre thick walls which were designed to provide the effective shielding for the penetrating radiation. The bunker walls are producing a solid support for the floor of the laser hall. The schematics of the layout of the Gemini amplification system in the laser area is presented in Figure 1.

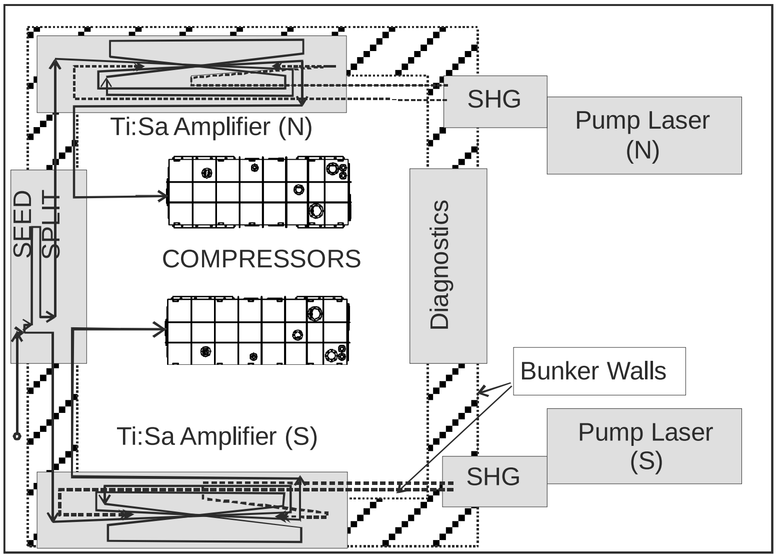

Fig.1. Schematic layout of the Gemini laser amplification system. Each Ti:Sapphire (Ti:Sa) amplifier is pumped with two beams at the second harmonic frequency of the Nd:glass pump lasers. The seed beam comes from the lower level. The compressed beams are sent down into the interaction chamber. Interaction chamber is on the lower level and it is surrounded by the bunker.

The two amplified beams will be sent down into the interaction chamber, which is underneath the compressors, to provide an efficient experimental access to the chamber. Amplification of the beams occurs in the two separate Ti: Sapphire (Ti:Sa) amplifiers pumped by their pump lasers with second harmonic generation (SHG) stages. The seed beam is uncompressed pulse coming from existing Astra laser from a lower level. The seed beam is split in two on the first table where a variable delay between the pulses can be introduced.

The seed beam is a chirped pulse amplified in the Astra system up to the level of 1.5 J. The pulse length of the seed pulses is 1ns which is twice as long as the current stretched Astra laser pulse due to additional electro-optical switch at the stretcher stage which provides the second double path through the stretcher. The switching allows us to keep the B-integral at an acceptable level in the Gemini amplifiers and to keep our existing pulse compressors in the current Astra target areas without rebuilding them and disrupting their operation. The seed beam is delivered to the Gemini area by an optical system containing a series of image relay telescopes and beam switching elements to distribute the pulses from Astra between the existing Astra Target Area 2 and the Gemini area. The optical system is described in section 2.2 of the paper.

The seed beam is expanded to ~50 mm beam diameter before it is amplified in 4-pass Ti:Sa amplifiers. The amplifiers are using Ti:Sapphire crystals of 90 mm in diameter and 25 mm in length. The crystals are held in cells with an index matching liquid with an absorbing dye in solution. The beam in the amplifiers is image-relayed by 3 vacuum relay telescopes with spatial filters in the middle (see Figure 2). Each Ti:Sa crystal is pumped from both sides by two green beams from frequency converted output of the Nd:glass pump laser system supplied by the Quantel laser company. Each of the two pump lasers delivers 52 J (26 J x 2) in two beams 45 mm in diameter at 527 nm at a maximum repetition rate of 3 shots per minute. A beam homogenising system is used for each pump beam to produce a pumped region in the crystal with a smooth top-hat profile and 50 mm in diameter. The absorption of the crystals was chosen to be at the level of 90 % to minimize the losses due to amplified spontaneous emission (A.S.E.) and parasitic transverse lasing. Pump radiation transmitted through the crystal is redirected by mirrors back into the crystal to increase pumping efficiency. The theoretically estimated output of the amplifier at 52 J pump should provide slightly more than 25 J of uncompressed radiation. The output of the amplifier is then expanded to 150 mm in diameter and the 150 mm beam is compressed in the grating compressors with an estimated throughput of 60%, giving an output of 15 J.

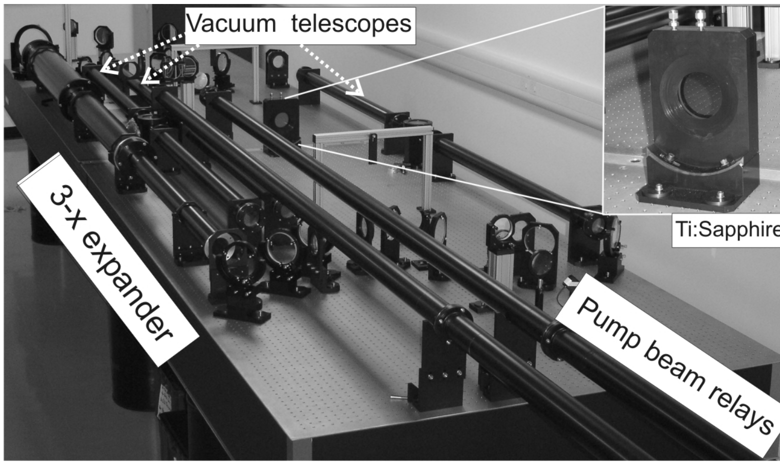

Figure 2. The photo of Ti:Sapphire amplifier (N) with insert of the close view of Ti:Sapphire crystal in the cell. There are three vacuum relay telescopes with spatial filters in middle, two pipes for the pump beams and 3-x vacuum expander.

2.2 Optical system design.

One of the features of the Astra-Gemini system is a long distance between the laser areas. The beam has to propagate about 40 meters before it reaches the first amplifier in the Gemini area. Overall the total beam path length is estimated as 85 m between the last amplifier of the Astra system and the first diffraction grating of the Gemini vacuum compressor. To overcome diffraction losses in the propagation of a top-hat beam profile the optical beam transport (OBT) system has been designed with image relay properties. The OBT system consists of a sequence of six vacuum telescopes with refractive optics. The beam after the final Astra amplifier is expanded from ∅18 mm to ∅31 mm in the first vacuum telescope. At this point there is a beam switch that can direct the pulses to either the Astra target area or the Gemini area. The intermediate expansion to a beam size of ∅31 mm allows the switching to be done where a lower intensity of the amplified pulse can be easily handled with smaller size optics and with a smaller contribution to the cumulative phase of the pulse due to the intensity dependent refractive index: the break-up integral or B-integral. In the path to Gemini the beam is expanded further to ∅50 mm in the 18 metre vacuum telescope. Then there are three image relay vacuum telescopes set within the four-pass Ti:Sapphire amplifier. The final telescope expands the beam from ∅50 mm to ∅150 mm before the grating compressor.

The design of our OBT system has taken into account the feature of refractive optical elements: the relative optical delay between different part of the beam propagating through a lens system. It is well known[10] that the difference between of group and phase velocity in a lens material could cause a substantial delay between different parts of the beam and increase duration of ultrashort pulse:

Radial delay dependence T(r) of a plano-convex lens can described by the formula 1, where r is a radius from the centre

$$T(r) = \frac{r^2\left(\lambda \cdot \left(\frac{dn}{d\lambda}\right)\right)}{2 \cdot c \cdot R} \qquad (1)$$

of the lens, c is the speed of light , R the radius of curvature of the lens surface and **(λ*dn/dλ)** gives the dispersion of the lens material with refractive index **n(λ)**. **T(r)** expresses the relative delay of the central part of the beam to that at the distance r from the centre. The 18 m long telescope with two lenses of BK7 produces the total radial delay of the central part ~(-)4.7 fs at 800nm for the beam expanded from 31 mm to 50 mm in diameter. Lenses with chromatic aberrations are acceptable for the beam transport system only with large F-numbers. Large beam diameters and short focal lenses require chromatically compensated lenses or specially designed compensator of the radial delay. We are using two element achromatic lenses with 2 m focal lens in the three image relay telescopes at the amplification stages.

Radial delay can be also estimated from a derivative of chromatic focal shift available from Zemax analysis tools. The estimation from the focal shift could be done using variation of the formula (2)[10]:

$$T(r) = \frac{\lambda \cdot r^2}{2 \cdot c} \cdot \left(\frac{d}{d\lambda} \left(\frac{1}{f(\lambda)} \right) \right) \qquad (2)$$

The equation 2 was useful for the estimation of the radial beam delay of a multi-element optical system where the beam diameter changes within the system. The technique of minimizing the chromatic shift has been used in the design of the final 3-x telescope. The amplified beams after the Gemini amplifiers have to be expanded to 150 mm before the compressors to prevent damage to the diffraction gratings. The expanders could be built using large aperture doublet achromat lenses, but they would be very expensive, so an unconventional alternative approach was adopted. The idea is to use a singlet lens at the output, plus an input lens combination with opposite dispersion to make the expander as a whole achromatic. A singlet fused silica lens (f=3 m) was chosen as the output element of the expander. The maximum relative delay for this lens reaches 86.9fs for the 150 mm beam diameter. The input lens was designed as a doublet with dispersion opposite to the dispersion of the silica singlet. It was found that a combination of CaF_2 and N-SF8 glass can compensate the dispersion of the silica singlet and make the system achromatic. A consequence of this approach is that the expansion factor varies slightly with wavelength, but we believe this will not affect the performance significantly. It was found that the fine tuning of the doublet made of CaF_2 and N-SF8 glasses can provide compensation of residual dispersion from the singlet lenses used elsewhere in the OBT system. Figure.2 shows the eventual chromatic shift of the whole system. The parabolic shape dependence of the chromatic focal shift centered close to 800 nm wavelength can be achieved instead of a slope type dependence which could be observed before the final telescope (dashed curved in Fig.3). The total uncompensated shift for the 50mm beam at 796 nm could be estimated from this data as 9 fs. The compensated chromatic shift for the whole system gives 0.37 fs relative delay at the same wavelength but for 150mm diameter beam.

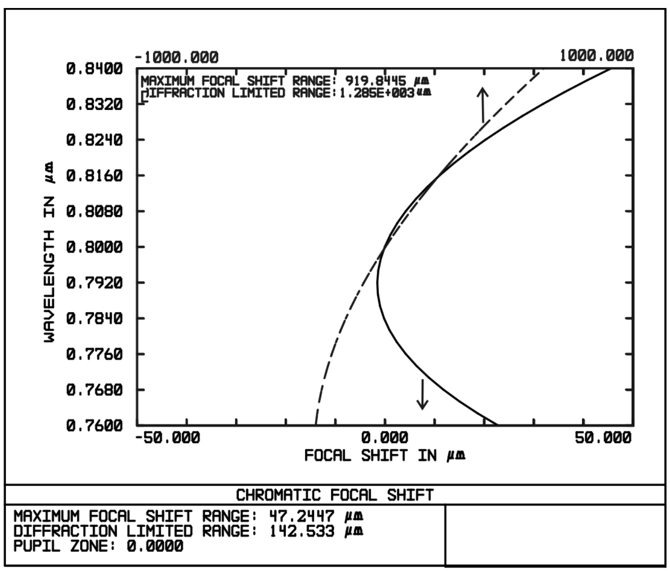

Figure 3. Chromatic focal shift of the total optical beam transport system after 3-x telescope measured at the focus of paraxial 1 meter lens (solid line). The dashed line represents the chromatic focal shift dependence of the beam passed through the whole system before 3-x telescope.

The all refractive design of the high power amplification system requires special attention to the value of B-integral due to substantial thickness of the optical material in the system. Theoretical estimation of the B-integral at 26.7 J output energy gives a value of 0.2π, which is considered as a tolerable amount for such a system.

2.3. Pulse compression design.

The Astra Gemini pulse compressor (Figure 4) is based on two gold coated reflective gratings arranged in a double pass configuration with the dispersion in the vertical direction. To allow the gratings to handle the energy from the amplifiers, the beam size will be expanded to 150 mm before the compressor. The gratings have 1480 lines/mm, and the sizes are G1: 320x205 mm and G2: 265x420 mm. The width of G1 in the non-dispersive direction is chosen to accommodate the input and output beams on the grating surface without overlap. The input beam is reflected by G1 and G2 to the back reflective mirror. The return beam is reflected at an angle of about 2 degrees from the input beam, and thus returns to the folding mirrors which direct it towards the output mirror. The output mirror reflects the compressed output beam vertically down into the target chamber in the room below. This design leaves room for a polarizer between the folding mirrors for a later upgrade of the facility that will allow experiments with counter-propagating pulses. There is an option to re-stretch the pulse to 300 ps by moving grating G1 further away from G2.

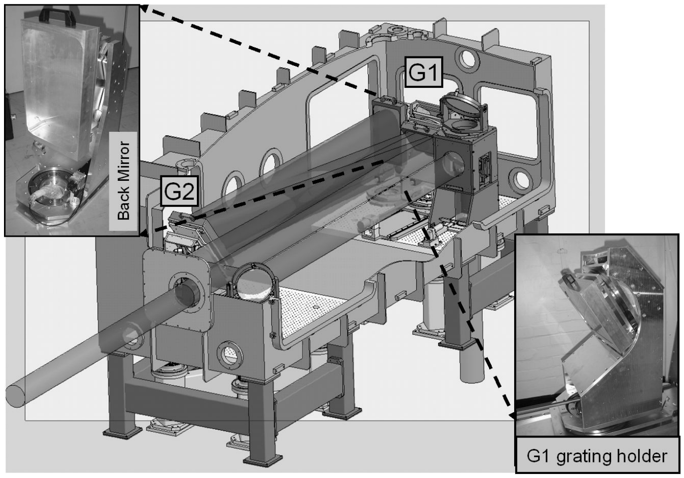

Figure 4. Schematics of the compressor chamber CAD drawing with the photos of the holders of G1 grating and the back reflective mirror.

There will be windows for input and output beams and for diagnostics output, plus a CW alignment beam that will be injected through output mirror from above. There will be an RF plasma cleaning device around the gratings. Overall separation between the gratings is 2200mm.

Compression of a chirped pulse has to take into account an additional dispersion of the material in the amplifier chain. The material dispersion between the stretcher and compressor could be compensated by the grating separation in the compressor and it creates a mismatch for the third and higher orders dispersion. Although the third order dispersion can be compensated by the change of angle of incidence on the grating there is no practical approach to compensate the higher order terms of the spectral phase. We estimated the residual spectral phase error in a compressed pulse passed through 266 mm of sapphire and several achromat lenses (130 mm of BaLF4 and 114 mm of LF4). The residual phase error for the third order dispersion (TOD) and the fourth order dispersion (FOD) were estimated as: TOD=18700 fs^3 FOD= -754000fs^4. The estimated values of TOD and FOD errors would prevent the compression of the pulse down to 30 fs, but the values are correctable with an acousto-optic programmable dispersive filter (AOPDF) such as Dazzler. The results of the compressor modeling have shown that the compressor designed for the Astra Gemini project, in combination with the AOPDF, will be able to compensate high order spectral phase errors and produce a flat output spectral phase.

3. DEVELOPMENT TOWARDS 10 PW OPCPA FACILITY ON VULCAN.

The VULCAN glass laser system at the CLF has led the world in high power, high intensity laser matter interaction science for many years. This has been made possible by a series of “step-jumps” in laser technology. The recent OPCPA developments[6,9] at the CLF have shown the prospective way towards multi-petawatt pulsed intensity. A new project to upgrade Vulcan has started recently at the CLF. The upgrade will establish a 10 PW interaction facility on Vulcan and will be based on OPCPA technology. A schematic of the proposed concept of 10PW system is shown in Fig.5.

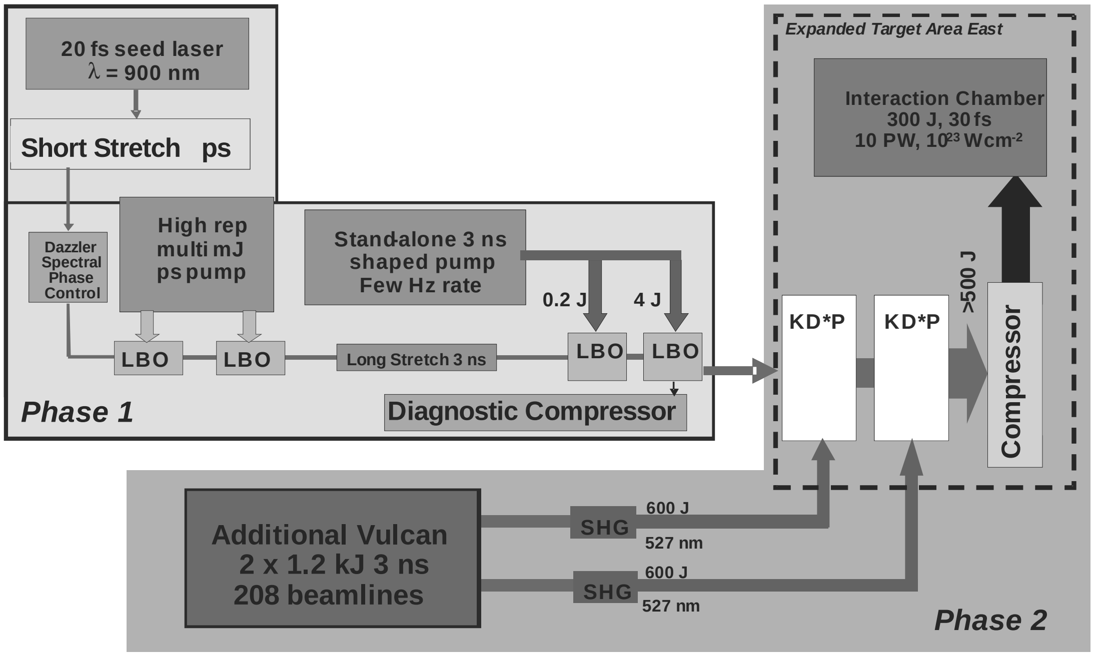

Figure 5. Schematics of the concept of the 10 PW OPCPA project.

The 10PW project is divided into two phases. The first phase, of duration two years, is intended to produce a very high contrast, medium energy pulse suitable for amplification to high energy. The first phase is currently at the experimental stage of the front-end development. The first phase will build a high repetition rate driver system capable of generating up to 100TW at Hz repetition rates. This system would provide an important target irradiation facility in its own right but perhaps more crucially would be able to address and resolve all the remaining technical design questions associated with the full 10PW scheme. In order to do this it is necessary to amplify up to the joule level in the OPCPA system and to be able to operate at Hz repetition rates. With such a system it will be possible to: optimise the contrast ratio in low aspect ratio OPAs; demonstrate the full gain bandwidth capability and gain of these smaller OPAs; develop the control of spectral phase sufficient to achieve recompressed pulse durations of 30fs or less. The scheme is based on the final optical parametric amplifiers (OPA) using deuterated KDP which has the important advantage over the previously used KDP[9] in that it can operate non-collinear with a broader gain bandwidth at a signal wavelength less than degeneracy. The optimum centre wavelength is 900nm for which the available gain bandwidth is close to 200nm. One benefit of the shorter wavelength in addition to higher OPA efficiency is the availability of oscillators with sub 30 fs pulse duration. The shorter wavelength also gives larger gain bandwidth at larger non-colinear angles for both BBO and LBO, either of which can be used for the OPAs in the initial stage of the proposed programme. In both cases bandwidths in excess of 200 nm are available.

In order to achieve the pulse contrast required for some experiments with ultra-high intensity pulses, an active control stage is included to greatly reduce the background level from the early OPAs. The oscillator pulse is amplified to the mJ level at a modest stretch of a few ps and recompressed. The recompressed stage will be used to increase the contrast of the pulses by using one of the available techniques. The resulting 'clean' pulse can then be stretched to the full extent of 1-2ns for amplification in the main OPA chain before final re-compression. Efficient re-compression to close to the original pulse duration will be achieved using a Dazzler or similar device to control the spectral phase variation. Preliminary modelling of this system Indicates that an input 20fs pulse at the nJ level can be amplified in LBO up to 1J with minimal spectral narrowing using a 4J pump pulse at 532 nm and that this pulse can be compressed to 25fs.

In the subsequent phase of this scheme two beamlines of 1.2kJ energy apiece would be constructed to pump the final KD*P crystals. The second phase of the project will require further development of the Vulcan beam lines, building new level for the final OPCPA stages and vacuum compressor. The existing TA East will be developed into a new multi Petawatt user facility with new interaction chamber.

4. RECENT PROGRESS AND SUMMARY.

The development projects on the PW laser system at the CLF are in different stages. The first phase of 10PW upgrade for Vulcan is in the first experimental stage of the two year project. The Astra-Gemini project is coming to the final stage of the three year project. The first experimental measurements of gain and gain distribution in the Ti:Sa amplifiers have shown encouraging results. The pump lasers are delivering more than 26 J of energy in each of the 4 pump beams at the repetition rate of 1 shot every 20 seconds. The gain distribution in Ti:Sa amplifiers has been tested with index matching liquid around the crystal and the liquid has shown a good suppression of the transverse A.S.E. which is responsible for the losses in the gain at high pump energy. The measurements of the small signal gain have shown the predicted gain which is necessary to achieve the expected 25 J of the uncompressed output pulse.

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