Amplifier design for the Astra Gemini project

K G Ertel, C J Hooker, J L Collier

Central Laser Facility, CCLRC Rutherford Appleton Laboratory, Chilton, Didcot, Oxon., OX11 0QX, UK

Main contact email address: *k.ertel@rl.ac.uk*

Introduction

The Astra Gemini upgrade incorporates two identical large aperture multipass titanium-sapphire (Ti:Sa) amplifiers which are operated in parallel. The pulses from the current Astra system at around 1.5 J will be split equally and amplified to an energy of 25 J each. Compression to 30 fs and an expected compressor throughput efficiency of 60 % will result in two 0.5 PW beams on target. Each amplifier will be pumped by two commercially supplied Nd:glass lasers, each delivering at least 52 J at 527 nm.

Basic Layout

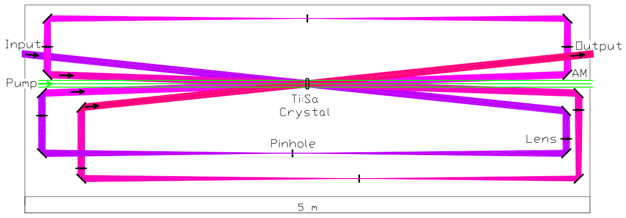

Figure 1. Layout of Gemini Ti:Sa amplifier. **AM**: adaptive mirror.

A sketch of the layout is shown in Figure 1. The design incorporates vacuum spatial filtering and image-relaying of the crystal plane onto itself after each pass. The layout is chosen such that all passes have the same round trip length and hence lenses of equal focal lengths can be used for exact image relaying after each pass. The lenses need to be achromatic in order to avoid pulse front distortion. The pump beams will come in at a slight angle from above and terminate (or will be retro-reflected, see below) at a level below the signal beams. One of the turning mirrors in the amplifier, probably immediately after the second pass of the crystal, will be an adaptive optic to correct errors in the phase front. The wavefront sensor will be placed at the output of the amplifier.

Calculation of Gain

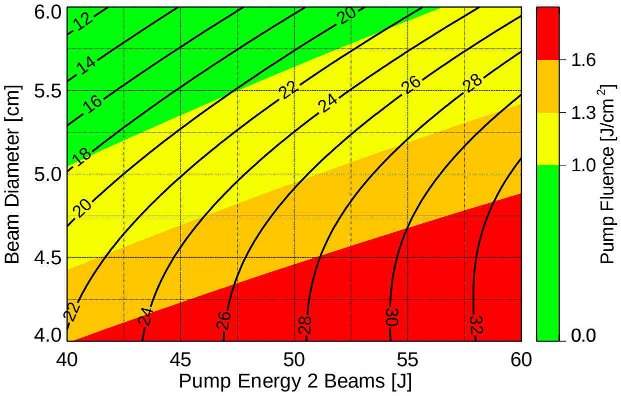

Figure 2. Predicted amplifier output energy as a function of pump energy and beam diameter. Contour lines indicate output energy, colour map indicates pump fluence. Other parameters explained in text.

Figure 2 shows a graph of the predicted output energy. The parameters used for the calculation were: pump light absorption 99 %, pumping efficiency 90 % (accounting for ASE and other losses), input energy 0.75 J, four passes, losses for each pass 3%. It can be seen that at a beam diameter of 5 cm for both pump and signal beams and at a combined pump energy of 52 J the predicted output energy is 26 J which is just above the target value of 25 J. Increasing the fluence level or adding another pass would not have a significant effect in this configuration since the system already operates close to complete saturation. If the input energy should however fall below the expected value of 0.75 J, the implementation of such measures will be beneficial.

Parasitic Lasing

Parasitic oscillations are a significant problem for large aperture laser amplifiers as there are optical paths within the laser medium with a very high gain-length product. Only a very small fraction of spontaneously emitted light needs to be reflected at the crystal surface in order to start parasitic oscillations along such paths. In our case, the gain coefficient is highest just beneath the surface of the laser crystal and the highest gain is experienced by photons crossing the whole diameter of the pumped region. Reducing this transverse gain can be achieved by lowering the doping concentration of the crystal. In order to maintain a high pump light absorption and hence a high longitudinal gain the crystal either needs to be made thicker or the unabsorbed pump light needs to be sent back through the crystal in a second pass. The double-pass pump approach enables the use of thinner crystals giving the advantages of lower cost and reduced dispersion and non-linear effects.

Figure 3 shows a comparison between a highly doped crystal showing a 99 % pump absorption in a single pass and a lower doped crystal with 99 % absorption in two passes (90% single-pass absorption). What is shown is the gain coefficient along the optical axis, calculated for a 25 mm thick crystal, for 5 cm pump beam diameter and 52 J combined pump energy. In the double pass configuration, the gain is more evenly distributed and hence much lower at the crystal surface. The transverse gain across the surface amounts to 810 for the single-pass case and to 58 for the double-pass case which is a reduction by a factor of 14. Increasing the pump energy to 75 J and the beam diameter to 6 cm (which is planned for a future upgrade of the system) would even raise this factor to 24 and the transverse gain to as much as 3100 in the single-pass configuration.

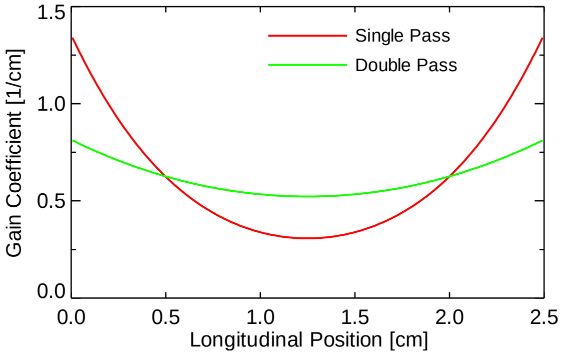

Figure 3. Gain coefficient along the optical axis of a laser crystal in single-pass and double-pass pump configuration.

Crystals with lower doping levels are rather easier to grow, and tend to suffer fewer optical imperfections, which are additional advantages. Nevertheless it will be important to minimise the feedback of ASE from the cylinder face of the crystal. Leaving the surface in a fine-ground state will eliminate specular reflections, and an index-matched absorbing material around the crystal will minimise scattered light. There are several high-index liquids that are a good match for sapphire (n = 1.76) and may be suitable; the possibility of dissolving an absorbing dye in one of these will be investigated. Figure 4 shows an exploded view of the proposed design of the crystal holder. The crystal is supported from below, and its faces are sealed against the holder by O-rings, so the entire cylinder face is immersed in the liquid. The cell allows the liquid to be circulated for cooling if required. The curved blue strip is an absorbing insert, which will be unnecessary if the absorber is dissolved in the liquid.

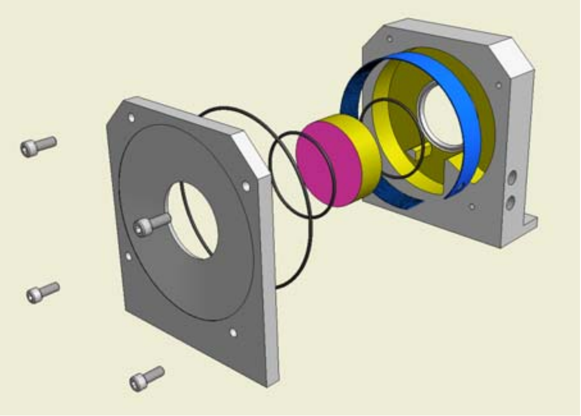

Figure 4. Design of the crystal holder. For explanation see text.

Thermal Lensing

The amplifiers will be operated at a maximum repetition rate of one shot per minute. The average thermal power dissipated inside the crystal is then about 0.5 W. This low figure and the large volume of the pump region already suggest that thermal effects will be of no great concern. This is confirmed by a numerical calculation of the radial temperature distribution inside the crystal. Figure 5 shows the results of this calculation obtained for a 9 cm-diameter crystal with a diameter of the pumped region of 5 cm, a crystal thickness of 25 mm and a dissipated thermal energy of 30 J. What is shown is the equilibrium radial temperature profile immediately before a shot. The following pump pulse only adds a top-hat temperature distribution which does not contribute to the thermal lens and which does not change until long after the amplification has taken place. The focal length of the resulting thermal lens that is inferred from the temperature distribution by fitting it with a second-order polynomial is 44 km. The thermal equilibrium is reached after just 3 shots and for earlier shots the focal length is even longer.

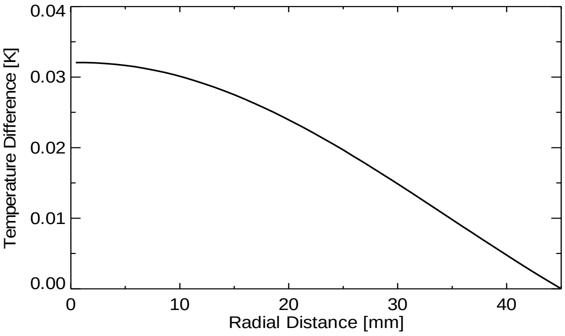

Figure 5. Equilibrium radial temperature distribution inside the amplifier crystal immediately before a pump pulse.

Amplifier Modelling using MIRO

The MIRO software package provided by the French nuclear energy agency CEA is a powerful tool for 4D-modelling of laser amplifiers. Physical phenomena which are taken into account include diffraction and non-linear phase modulation. At this stage of the design process MIRO is most useful for calculating B-integral as it accounts for the fact that the intensity is not constant inside the gain material. For the configuration described so far the B-integral value accumulated inside the amplifier was calculated to be 0.73. For the calculation the duration of the input pulse was 1.06 ns and the 6 achromatic lenses and another such lens at the amplifier output (not shown in Figure 1) were each assumed to contain 1 cm of F2 and 1 cm of SK2 glass. The empirical formula given in reference 1) was used for calculating the nonlinear refractive indices of these glasses. Furthermore it was assumed that there will be a 1 cm thick fused-silica vacuum window in addition to each lens. The calculated value for B-integral is rather high and ways to reduce it will need to be explored. It may be possible to use thinner elements for both the lenses and the windows. Alternatively, abandoning the spatial filter after the 3rd pass would reduce B-integral by a value of 0.21, and replacing the lens after the amplifier with a parabolic mirror would reduce it by a value of 0.12.

At a later stage when e.g. the intensity distribution of the pump lasers or the wave front error of the optical elements is known, MIRO will be used for making detailed predictions of the generated pulses, both for optimizing the design and for day-to-day operations.

References

1. N L Boling, A J Glass, and A Owyoung,
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