Beam switching and beam transport for the Astra Gemini project

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Introduction

The new amplifiers of the Astra Gemini system require as input the approximately 1.5 Joule pulses from the third amplifier of Astra. The Gemini laser area is a considerable distance from Astra, so an optical system is required to transport the beam of broadband chirped amplified pulses from one area to the other without compromising the beam or pulse quality. As described elsewhere in this report [4], the chosen route is through a trench in the floor that runs from Astra under the services area and the Gemini target area, and then up the outside of the target area wall. The beam transport system must have image relaying properties to preserve the flat-top beam profile and minimise diffraction losses, and must be essentially achromatic to minimise the variation of optical delay across the beam, which is particularly important for broadband ultrashort pulses. This paper presents a description and analysis of the beam transport optics, beam switching system and the design of some special optical components used in the system.

Beam transport system

One of the features of the optical beam transport (OBT) from Astra to Gemini is the long distance between the areas. The pulse has to propagate more than 40 metres before it reaches the first amplifier in the Gemini area. Overall the total beam path length is estimated as 85 m between the final amplifier of Astra and the first diffraction grating of the Gemini vacuum compressor. A schematic layout of the OBT system is presented in Figure 1: it consists of a sequence of vacuum telescopes with different magnifications, labelled T1, T2, etc. The beam after Astra amplifier 3 is expanded from 18 mm to 31 mm diameter in the first vacuum telescope, located in the Astra area. The output of this expander is the point where the beam can be switched between Gemini and Target Area 2. The beam sent to TA2 has to be expanded from 31 to 60 mm in another vacuum telescope. The intermediate beam size of 31 mm was a good match to the largest polarising beamsplitter cubes that were readily available (38 mm on a side).

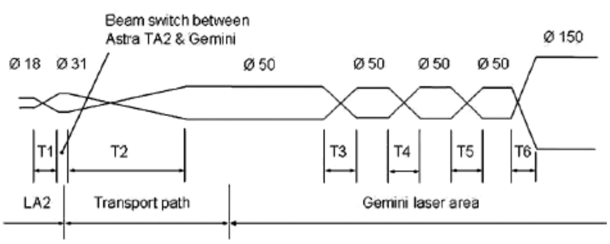

Figure 1. Schematic of the optical system that transports the beam from Astra to the Gemini pulse compressors.

The beam for Gemini is expanded to 50 mm in the next vacuum telescope, T2, which consists of two long focal length singlet lenses with an overall separation of 18 metres, and occupies the major part of the 20-metre path in the floor trench. The lenses themselves form the windows of the vacuum pipe. The next three vacuum telescopes are image relay telescopes of unit magnification set within the four-pass Ti:Sapphire amplifiers, which in effect re-image the Ti:sapphire crystal onto itself. The last telescope, T6, expands the output beam of each Gemini amplifier from 50 mm to 150 mm, before the beam is sent into the grating compressor.

Beam switching

The beam switching assembly consists of a half-wave plate and a 38mm cube polarizer, visible in the upper right of Figure 2. The 18-31 mm and 31-60 mm expander telescopes and the beam switching components are mounted on a frame above the final Astra amplifier. When the waveplate is set to give vertical polarisation, the beam is reflected by the polariser, and sent to TA2 via the 31-60 mm expander telescope. When the waveplate is set to output horizontal polarisation, the beam is transmitted through the polariser and reflected down to table level. In this path there are a second half-wave plate and cube polariser for energy control, an electro-mechanical shutter for switching a single optical pulse out of the 10 Hz pulse train, and two movable partially-reflecting mirrors (95% and 98% reflectivity) for energy mode control. In the path to TA2 there is another fast electro-mechanical shutter and a similar combination of attenuators, to ensure the energy modes in TA2 and Gemini are the same. This is important for safety reasons, as many experimenters are likely to work in both areas at different times.

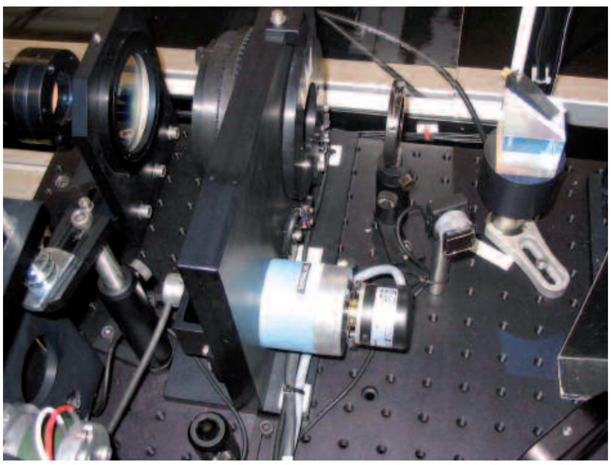

Figure 2. The optical set-up of the beam switch between TA2 and the Gemini beam line.

Pulse front delay

An essential point in the design of this optical system was to minimise the relative optical delay between different parts of the beam propagating through the lens system. It is known[1] that the difference between group and phase velocity in the lens material could cause a substantial delay between different parts of the beam, and increase the duration of the focused ultrashort pulse. The radial delay dependence $T(r)$ of a plano-convex lens can described by the formula[1] (1), where r is the radial distance from the centre of the lens, c the speed of light, R the radius of curvature of the lens surface and ($\lambda * dn/d\lambda$) the dispersion of the lens material with refractive index $n(\lambda)$. The long focal length telescope T2, consisting of two lenses made of BK7 working at an F/number of around 220, introduces a delay in its central part of around -4.7 fs at 800 nm. Lenses such as this with chromatic aberration are acceptable for the beam transport system only with large F-numbers. Large beam diameters or short focal lengths require chromatically compensated lenses.

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

The three vacuum telescopes for each amplifier stage were designed using achromatic doublet lenses with a focal length of 2 metres. A combination of SK2 and F2 glasses was chosen, which gives a reasonably small chromatic focal shift of 178 μm within the 750-850 nm spectral range. Material cost and values of n_2, the non-linear refractive index, were taken into account in choosing these glasses. The values of n_2 for SK2 and F2 were estimated according to the formula in Reference[2] as 4.63E-20 m^2/W and 9.21E-20 m^2/W, respectively. The pulse front delay between the edge and the centre of a 50 mm diameter beam was found to be -0.003 fs at 800 nm, using a variation of formula (1) for biconvex lenses.

Radial delay can also be estimated from a derivative of the chromatic focal shift which is available from Zemax analysis tools. The equation for the focal shift is[1]:

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

Equation (2) is useful for estimating the radial beam delay of a multi-element optical system where the beam diameter changes within the system. This technique of minimising the chromatic shift was used in the design of the final 3× beam expander 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 86.9 fs 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.

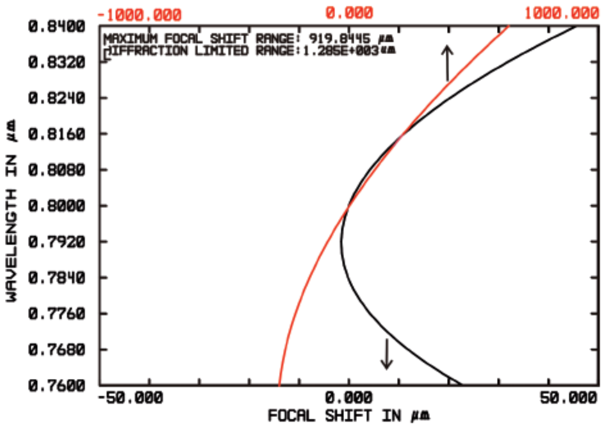

Figure 3. Comparison of focal variation of compensated (black) and uncompensated (red) beam transport systems.

Fine tuning of the input lens design was carried out to compensate residual dispersion from the singlet lenses used earlier in the OBT system. Figure 3 shows the chromatic shift of the whole system: a parabolic shape dependence of the chromatic focal shift centred close to 800 nm wavelength can be achieved (black line, lower scale) instead of a slope type dependence which could be observed before the final telescope (red curve, top scale). The total uncompensated shift for the 50 mm beam at 796 nm was evaluated from this data as 9 fs. The compensated chromatic shift for the whole system is reduced to 0.37 fs relative delay at the same wavelength, but for a 150 mm diameter beam.

When using an all-refractive design such as this, the cumulative B-integral and the total group delay need to be considered, because there is a lot of material in the system. The effect of the extra material on pulse compressibility in Gemini has been discussed earlier[3]. The effect of B-integral was calculated using the Miro code, assuming 417 mm total path length of optical materials and a single pass amplifier gain of ~4.8× with 750 mJ input energy. The calculation gave 26.9 J output energy with an accumulated B-integral of 0.2π. This value should be tolerable for high power laser operation.

Image relaying

Conservation of the beam profile along the optical system is one of the main characteristics of an image relay system. The image relay properties of the OBT system were analysed using Zemax. Figure 4 shows plots of the beam profiles at various places in the system. The analysis of the beam propagation shows that the beam profiles remain smooth flat-topped supergaussian shapes at key points of the system such as the amplifier crystals and compressor gratings.

We have presented the main design parameters of the all-refractive optical system which has been developed to deliver the output of the Astra laser to the Gemini area over a path of 40 metres. The optical system described has been implemented and most components have already been installed. Further work will include tests of the optical performance of the system and of the delay in the compressed beam.

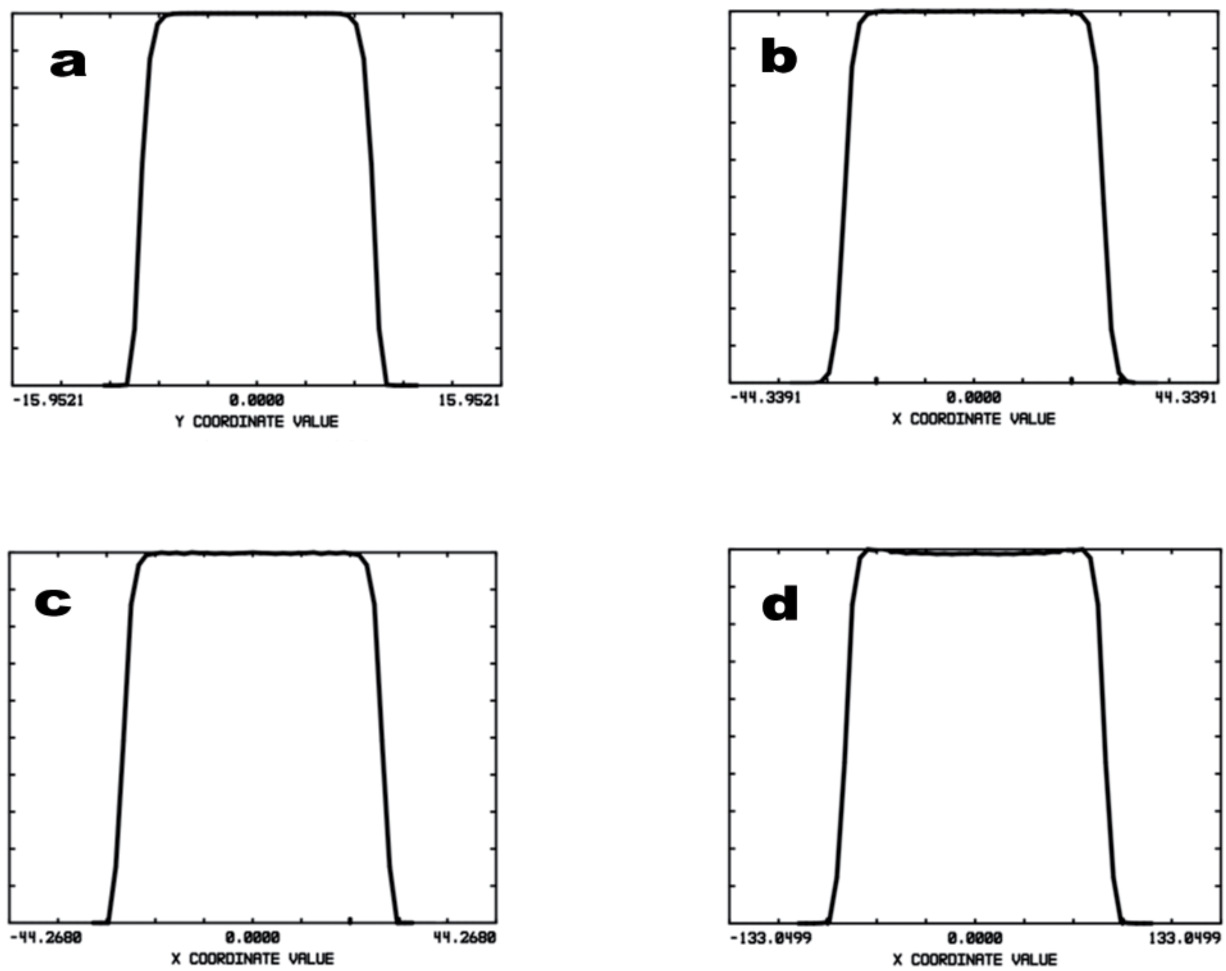

Figure 4. Beam profiles from the Zemax model of the OBT system: (a) Input (b) Amplifier 1st pass (c) Amplifier 4th pass (d) First compressor grating.

References

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4. J. L. Collier *et al., CLF Annual Report 2006/2007*.