Compressor design for the Astra Gemini project

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The Astra Gemini project is intended to enhance the existing Astra Ti:sapphire laser system to the Petawatt level, by adding two large aperture Ti:sapphire amplifiers, two double-pass grating compressors and a new interaction facility. The compressors are required to compress high energy pulses (up to 15 J at 800 nm central wavelength) with a beam diameter of 150 mm and a stretched pulse duration of 1.06 ns produced by a double pass of the existing Astra stretcher [1,2)]. This paper presents the technical design of the vacuum grating compressors and the results of theoretical estimations of spectral phase errors between stretcher and compressor.

The Astra Gemini compressor will be based on two gold coated reflective gratings (G2, G2) arranged in a double pass configuration, (Figure 1a). The input beam coming from the right will be diffracted by grating G1 towards G2 and by G2 towards the back reflecting mirror (RM). On the return path the compressed beam is displaced laterally, and is redirected by folding mirrors M1-M2 toward output mirror M3. M3 reflects the compressed output beam vertically down into the target chamber in the room below. The mirrors M1-M3 should be 235 mm in diameter. The current design leaves room for a polariser between M2 and M3 for a later upgrade of the facility that will allow experiments with counter-propagating pulses. There will be an option for re-stretching the pulse to 300 ps by moving the G1 grating further apart.

The vacuum chamber for the compressor (Figure 1b) will be constructed of welded steel with reinforcing ribs, nickel plated to minimise outgassing. The interior will be accessible via two ports at each end, large enough to allow breadboards and other hardware to be moved into the chamber, and positioned to optimise access to the optics. There will be windows for input and output beams and for diagnostics output, plus a CW alignment beam that will be injected through M3 from above. There will be an RF plasma cleaning device around the gratings. The optics breadboards will have a separate support from the compressor chamber to minimise vibration noise transfer.

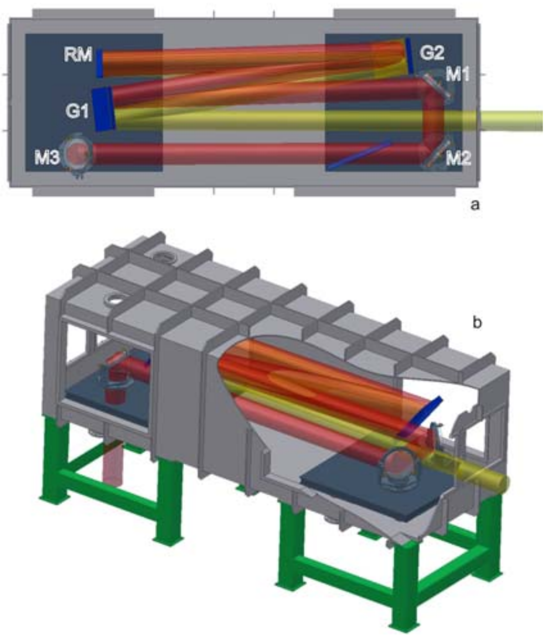

Figure 1. Design drawing of the compressor: a- a plan view; b- in the vacuum chamber.

The diffraction gratings were chosen to have the same line density as in the stretcher: 1480 lines/mm. The sizes of the gratings were selected according to the parameters of the expanded amplified beam diameter of 150mm: grating1 (G1)-320x205 mm and G2-265x420 mm. The size of G1 in the non-dispersive direction is wider (320 mm) than the beam size in order to accommodate both the input and output beams on the grating surface without spatial overlap. The separation between the beams should reduce thermal loading on the grating surface to extend the lifetime of the grating. The design with different positions of the input and output reflections at G1 also helps to separate the input and output beams at a reasonable distance within the vacuum chamber (Figure 1). The beam separation can be achieved by using different off-plane angles in the first and second path through the compressor. At a slant distance (Lc) between gratings G1 and G2 of around 2200 mm the angles were taken as 5.3 and 3.3 degree for the input and output beam directions, respectively.

The main goal of theoretical optimisation of the compressor is to find the parameters for the grating separation and incident angles on the gratings to compensate all orders of the spectral phase introduced by the stretcher and by the dispersion of refractive material in the laser chain. Such compensation would provide the shortest pulse after compression. The compressor optimisation has been done using both Zemax software and analytical formulae for coefficients of the spectral phase up to the fourth order to optimise the spectral dependence of the group delay for the output pulse to a desired slope. A stretcher-compressor pair with identical grating groove densities, incidence angles and separations would be perfectly matched. However, the dispersion of the material in the laser chain between the stretcher and compressor has to be compensated by a change in separation of the compressor gratings, and this creates a mismatch for third and higher order phase coefficients. The third-order phase error can be compensated by a change of incidence angle on the gratings, but once this is done there

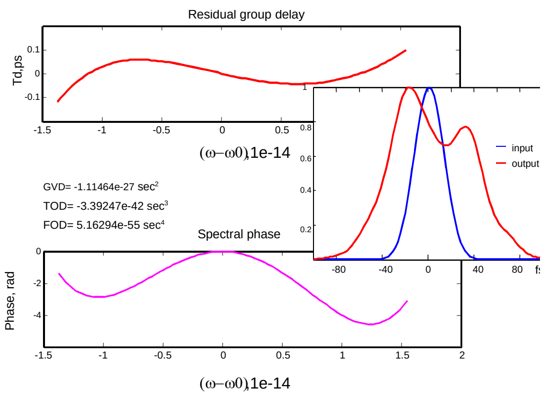

Figure 2. Estimated spectral dependence of residual group delay (upper plot), spectral phase dependence (lower) in the vicinity of central frequency ω_0 (λ_0=800nm) and corresponding shape of distorted output pulse (red in the insert) for a 30 fs input pulse (inset) passed through stretcher, material and an optimised compressor.

are no more adjustable parameters, so some additional control of the spectral phase coefficients is needed. This control can be achieved with an acousto-optic programmable dispersive filter (AOPDF)[3)] - Dazzler™. Without a Dazzler, stretched 30 fs pulses at 800 nm passed through 266 mm of sapphire and several achromatic lenses (130 mm of BaLF4 and 114 mm of LF4) would acquire some higher order spectral phase distortions which would prevent complete compression of the pulse. An example of the output pulse shape as well as residual group delay dependence and dependence of the spectral phase on angular frequency around central frequency ω_0 (λ_0=800nm) are presented in Figure 2. The dependences presented in Figure 2 were calculated with parameters of the above materials and the following parameters of the stretcher: length Ls=2200 mm, incident angle βs=36.3^0, off-plane angle αs=3^0; and the compressor: Lc= 2220.11 mm, βc=36.587^0 and αc= 3.3/5.3^0. If only the grating separation and the incident angle were changed, the higher-order dispersion coefficients would remain uncompensated and the output pulse would be nearly 3 times longer than the input (see insert in Figure 2). This clearly shows the necessity of an AOPDF to control dispersion.

To achieve effective compensation of the spectral phase errors with an AOPDF over a wide (100 nm) spectral range some phase matching conditions have to be fulfilled[3)]. The group delay (GD) over 100 nm spectral range should not be longer than 3 ps although the group delay in the AOPDF crystal (TeO_2) itself exceeds this value (Figure 3a). The GD in the 25 mm long TeO_2 crystal is 3.69 ps per 100nm at 800 nm which is larger than the GD that can be compensated by the AOPDF (Dazzler). The total GD (ΔT_g) of the whole CPA system including the stretcher-material, AOPDF material and compressor of ΔT_g=2.8 ps over 100 nm was achieved by optimising the compressor length and the incident angle to values of Lc=2228.5 mm and βc= 36.62^0. The sign of the GD slope was chosen the same as for the TeO_2 crystal. It makes smaller another important parameter of the GD slope range, which can be described as a ratio of a maximum value of the slope to its minimum value, and is limited to ~3 by the Dazzler. The maximum and minimum absolute values of the slope *((abs*($\Delta T_g/\Delta\lambda$*))* were: ~49.2 ps/µm and 20 ps/µm , respectively, giving a slope range of ~2.46. In combination these measures should permit effective operation of the Dazzler for dispersion control of the pulses.

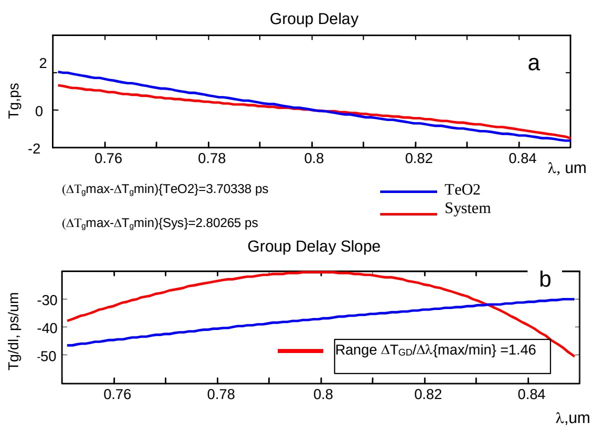

Figure 3. Wavelength dependences of the group delays (a) and the group delay slopes $\Delta T_g/\Delta\lambda$ (b) for the whole CPA system (red) and TeO_2 crystal (blue).

An example of the RF signal generated by the Dazzler software is shown in Figure 4. The presented RF signal (Figure 4, lower right) was generated to compensate high order dispersion coefficients of the spectral phase estimated from the group delay of an optical pulse passed through the whole CPA system (Figure 3a, red line). The following values of higher order phase coefficients or (phase) derivatives, as seen on the Dazzler control board (Figure 4, upper left), were used: f_2 (GVD)=-7006 fs2; f_3 (TOD)=18669 fs3; f_4 (FOD)=-754422 fs^4. The GVD, TOD and FOD are the group velocity dispersion, third order and fourth order dispersion coefficients, respectively. The RF signal has a smooth double peak shape and duration within an appropriate time window of ~3 ps. The amplitude modulation of the signal is also generated by the Dazzler software, in order to control the shape of the Dazzler output spectrum (Figure 4, lower left graph). This reduces spectral narrowing due to gain pulling during amplification in the Ti:Sapphire.

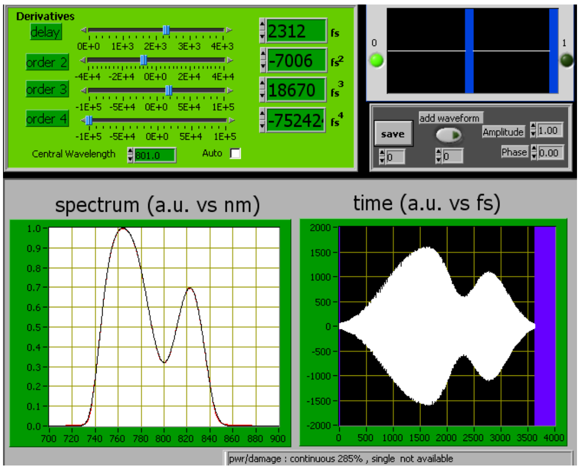

Figure 4. Screenshot with part of the Dazzler software control panel: upper left - dial for inputs of the high order dispersion coefficients; lower left- an expected spectral amplitude graph of the output spectrum; lower right - temporal shape of the RF signal generated by the Dazzler with estimated input phase parameters.

The results of the compressor modelling 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. This will ensure that the output pulses are fully compressed and reach the design pulse duration of 30 femtoseconds. Further design of the grating holders is to be complete soon.

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