Design and Implementation of a Test Compressor for the Vulcan Front End

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Introduction

Vulcan [1] is a petawatt-class ultra-intense ultrafast chirped pulse amplification (CPA) [2] laser system capable of delivering sub 400fs pulses with an energy of 400J. A schematic of the petawatt beamline is shown in Figure 1: the front end consists of a Ti:Sapphire oscillator operating at 1053 nm followed by a picosecond optical parametric (OP) CPA [3, 4]; this is stretched to 4.5 ns and then subsequently a 3-stage nanosecond OPCPA delivers ~30 mJ pulses with a bandwidth over 15 nm [5] providing the seed to the power (rod/disc) amplifiers, a test compressor and diagnostics. The OPCPA stages are used to preserve the pulse bandwidth and to enhance the pulse contrast when compared to conventional (i.e. non-parametric) amplification. The last OPCPA stage is used in high saturation mode to ensure maximum power stability that, due to the nonlinear interaction between the chirped main pulse and post-pulses, can result in the generation of pre-pulses after compression. In addition, any imbalance in the high order spectral phase – particularly third-order phase due to an incorrect alignment angle of the stretcher/compressor gratings – results in poor compression of the final amplified pulses and thus a reduction in peak power. We have therefore designed and built a test compressor for use in the front end after the nanosecond OPCPA stages to monitor and optimize the spectral phase and pulse contrast, as well as providing a tool to develop pulse diagnostics suitable for Vulcan.

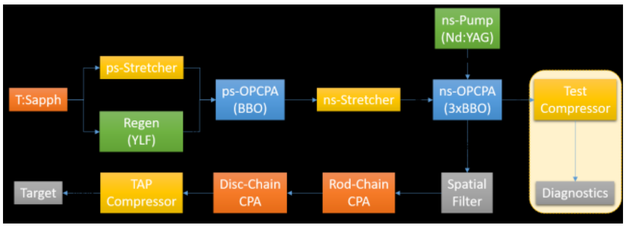

Figure 1 | Schematic of the layout of Vulcan petawatt beamline. *Top row:* front end. *Bottom row:* power amplifiers. *Far right:* new compressor and diagnostics.

Compressor Design

The chirped pulses in Vulcan have a nominal group delay dispersion (GDD) of ~300 ps/nm with a GDD variation from linear of ~4 ps/nm^2. Using gratings with a groove density of 1480l/mm at an angle of 48.7° (offset from the Littrow angle of 51.3°) requires a perpendicular grating spacing of ~2 m (13 m optical path length at the central wavelength). For the target area compressor, the damage threshold and diffraction efficiency are the most major concerns, hence a single pass configuration is used. However, for diagnostics purposes at relatively low energy (<10 mJ), the most practical considerations are the cost and physical size of the system. We therefore employed a folded quadruple pass geometry as illustrated in Figure 2. Using a double pass geometry eliminates any spatial chirp that is intrinsic to the single pass geometry used in the target area. This is required because the front end's gain bandwidth is over 15 nm, thus we can ensure that the front end is maximally optimized before injection into the power amplifiers. By quadruple passing the system, the width of the diffracted beam on the second grating is reduced by a factor of 4, significantly reducing the size, cost and mounting complexity of the grating, but at the expense of reducing the net efficiency to 10-20%.

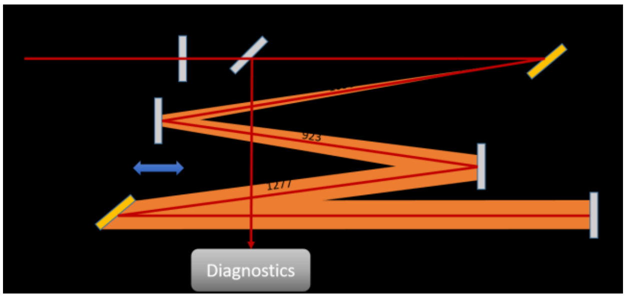

Figure 2 | Schematic of compressor layout. G: grating, FM: fold mirror, RM: retro mirror, PO: pick-off, I: iris. Dimensions in millimetres.

GDD tuning of a stretcher/compressor is achieved by changing the optical path length between the two gratings G1 and G2. We achieve this by translating the folder mirror (FM1) on a motorized linear translation stage. We chose to translate this optic for several reasons: translation of G2 is impractical due to the relatively large sized grating and optical mount; translation of G1 would result in a large lateral shift in the beams due to the long optical path length and fixed angle of incidence required to compensate third order dispersion in the nanosecond stretcher/target area compressor; the change in optical path length is approximately double for the same translation of a grating; and the angle of propagation between the two fold mirrors (FM1 & FM2) can be set almost arbitrarily (limited by the size of the optical mounts and diffracted beam width) and thus the lateral displacement of the diffracted beam is minimized. The major disadvantage is that any angular movement in the translation stage is magnified by a factor of $2^4 = 16$ due to the quadruple reflections, thus requiring higher precision stages. Translating the smaller first fold mirror (FM1) reduces the load on and thus cost of the translation stage.

Initial Setup

We used a broadband tuneable optical parametric oscillator (OPO) as an alignment laser to perform the initial setup. Using a nonlinear crystal temporarily located at the entrance to the compressor, we tuned the OPO's internal dispersion compensation to maximize the second harmonic intensity and thus ensure a near Fourier-limited pulse incident on G1.

Due to its relatively small size, G1 was mounted on two goniometers mounted perpendicularly on top of each other with their centre of rotation located at the centre of the grating, and then mounted on top of continuous rotation stage to provide full yaw, pitch and roll (rotation, tip and tilt) adjustments. G1 was first rotated normal to the incident beam and the pitch of the grating set by retro-reflecting the specular reflection. The grating was then rotated to Littrow angle and the roll set so that the first order diffraction is retro-reflected. The process was iterated a couple of times to ensure the grating pitch and roll is set (i.e. that the diffracted beam lies in the horizontal plane). Using a micrometre screw, the grating was rotated to the desired angle of incidence from normal with a precision of 1 arcminute (0.29 mrad).

The fold mirrors (FM1 & FM2) were aligned according to the design distances and angles and set to ensure reflection remains in the horizontal plane. Due to its relatively large size, G2 could not practically be mounted with continuous rotation, hence its pitch and roll were adjusted by ensuring both the specular and diffracted beams remained in the horizontal plane using a fixed height iris. G2's rotation was set approximately by measuring the angle of the diffracted beam and then fine-tuned using the procedure below to eliminate space-time coupling (spatial chirp and angular dispersion). The final retro mirror (RM1) was placed along the optical path and located after FM2 to prevent clipping the diffracted beam and aligned with a small vertical tilt so that the "retro" beam was slightly vertically displaced below the input beam at the input iris (I1).

The space time-coupling (i.e. spatial chirp and angular dispersion) of the beam exiting the compressor was minimized after the first double pass, thus ensuring correct alignment of G2 and RM1. A pick-off mirror was inserted below the compressor input beam to direct the exit beam (after the first double pass) to a more accessible location and into a 50μm diameter multimode fibre coupled spectrometer to measure the spectrum. The rotation angle of G2 was recorded and the horizontal spatial chirp was measured by scanning the fibre horizontally across the beam (for quick adjustments, the horizontal tilt of RM1 can also be used). The rotation of G2 was adjusted and recorded, then the horizontal tilt of RM1 adjusted to bring the exit beam directly below the input beam at I1 and the spatial chirp measurement repeated. This process was repeated until no spatial chirp was measured. Finally, a small retro-mirror (RM2) was inserted below the input beam for the second double pass and aligned so that the final exit beam (quadruple pass) was located slightly vertically above the input beam, and then a pick-off (PO) mirror used to send the beam to the pulse diagnostics. Figure 3 shows a photograph of the compressor setup.

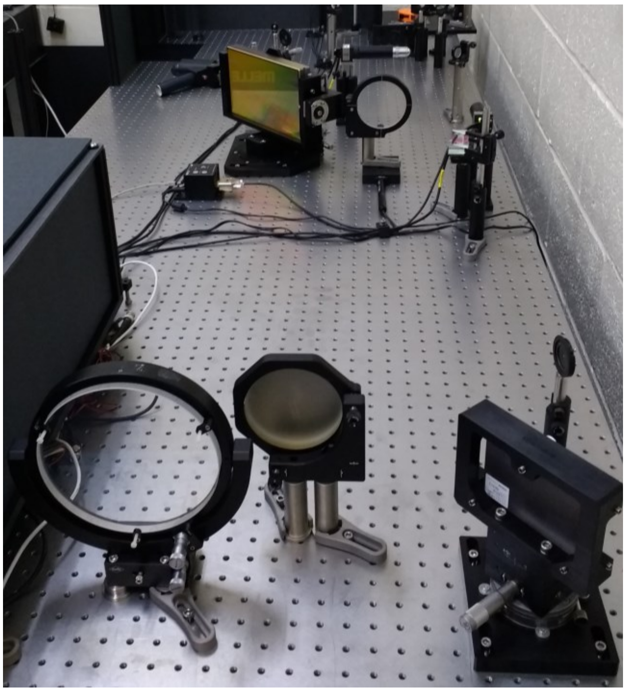

Figure 3 | Photograph of compressor setup. Beam enters from top right, G1 is located in the bottom-right, G2 top-left and RM1 bottom-left.

Chirp Calibration

Due to the relatively large sized optics, long optical path length and low repetition rate of the OPCPA, it is not practical to perform temporal diagnostics on the beam and then iterate the setup of the compressor (grating angle and separation). In addition, the temporal diagnostics have a limited window of pulse duration that can be measured, and small errors in the compressor geometry can lead to large stretch factors. Therefore we developed a simple procedure to calibrate the compressor dispersion using the OPO based on linear sonograms [6].

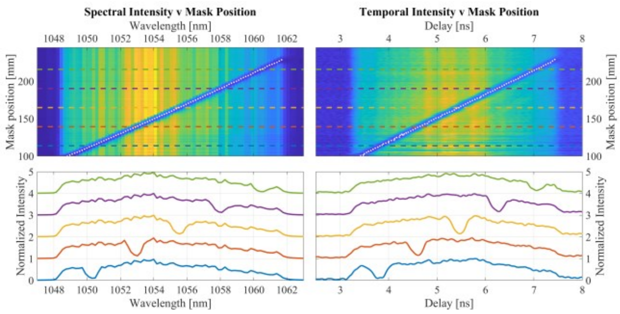

Figure 4 | Measured sonogram data (top) with marked location of intensity null (dotted white line) and corresponding lineouts (bottom) at dashed locations. Measured spectral (left) and temporal (right) intensity as function of mask position.

The exit beam (quadruple pass) was directed into a fibre-coupled spectrometer and a beamsplitter was used to send a portion of the beam to a fast photodiode. A mask was then mounted to a translation stage and inserted into the optical beam just in front of RM1 where the beam is spectrally dispersed to block a small portion of the spectrum. The spectral and temporal intensities of the beam exiting the compressor were measured simultaneously as the mask was translated across the face of the retro-mirror, thus changing the wavelength of light blocked by the mask (Figure 4). For every mask position, the wavelength and timing of the intensity null were recorded, enabling the spectrally dependent group delay (GD) of the compressor to be recovered. A quadratic fit to this curve, corresponding to a cubic fit of the compressor phase, was performed and used to estimate the grating angle and separation (Figure 5). This information was then used to rotate G1 and to reposition G2. The fold mirrors (FM1 & FM2) were also laterally displaced to minimize spectral clipping and the space-time coupling minimization routine was repeated followed by the sonogram measurements until the GD curve matched the design parameters. The GD was measured to be 320 ps/nm and the GDD measured to be 2 ps/nm^2, very close to the desired values.

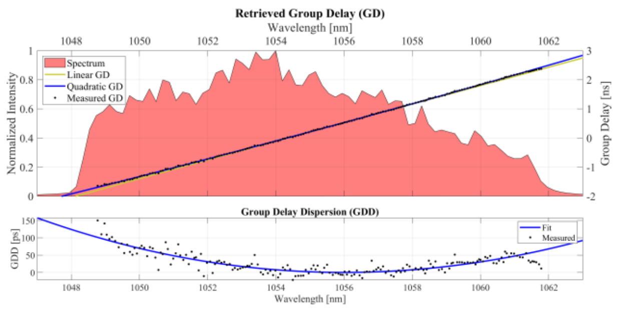

Figure 5 | *Top*: Measured spectrum (red) and retrieved group delay (black dots) with linear (yellow) and quadratic (blue) fits. *Bottom*: group delay dispersion calculated by removing the linear group delay.

Temporal Characterization

Once the chirp of the compressor was optimized to match the design parameters, we injected the output of the nanosecond OPCPA into the compressor and performed two different methods of temporal characterization on the compressed pulses. We first performed a dispersion scan (DS) [7] using a grating-based zero-dispersion delay line (ZDL); the results are plotted in Figure 6. If the pulse was optically compressed, then the second harmonic spectrum would have increased and then decreased uniformly in intensity as the grating separation of the ZDL was translated. The large slope in the spectral dependence with grating position indicated high-order dispersion.

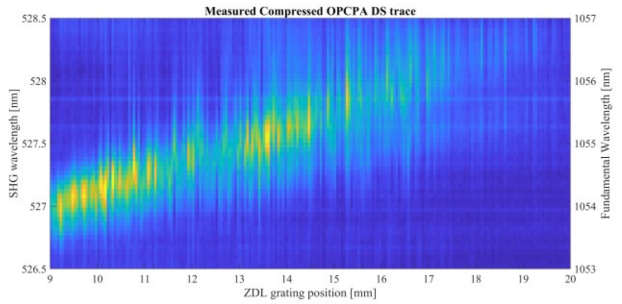

Figure 6 | Measured SHG-DS trace from compressed ns-OPCPA output before final optimization.

Several optomechanics were replaced (translation stage with less angular deviation, motorized mirror mounts), input/output beam diagnostics installed for automated beam alignment, an alignment laser installed and then the compressor setup optimized to reduce the high order dispersion. A single-shot autocorrelator [8, 9] was used to measure the pulse duration in order to reduce acquisition times – results are plotted in Figure 7.

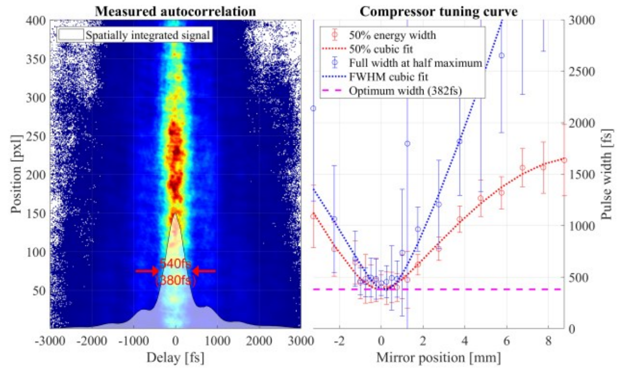

Figure 7 | *Left:* Measured single-shot autocorrelation at the optimal grating separation indicating a 50% energy pulse width of 380fs assuming a Gaussian intensity profile. *Right:* Measured pulse width as a function of grating separation (by displacement of FM1); error bars indicate standard deviation, mean and standard deviation calculated from ensemble of spatial distribution and four individual measurements.

Conclusions

We have designed, built, calibrated and tested a nanosecond test compressor for the Vulcan front end in order to compress the output of the front end for diagnostics purposes and to enable future development of advanced pulse diagnostics and optimization of the petawatt beam pulse duration on target. Whilst the compressor is not yet optimized to fully compensate higher order dispersion, the compressed pulses are less than several hundred picoseconds and thus are sufficiently compressed to enable contrast measurements of the front end to be performed. This will then enable the pulse contrast from the front end, particularly in relation to the generation of pre-pulses, to be optimized on a routine basis during user experiments.

Acknowledgements

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