Investigation of temporal properties of a cross-polarised wave generation temporal filter at the front–end of the Gemini laser system

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Introduction

The development of chirped pulse amplification (CPA) systems has changed dramatically since the invention of the grating compressor [1] and the first formulation of the CPA concept for achieving high intensity laser pulses [2]. The introduction of Ti^{3+}-doped sapphire as an active medium [3] and the later development of Kerr lens mode-locking in Ti:sapphire [4] paved the way towards present-day multi-petawatt system designs. The CPA systems today incorporate many developments to maintain the quality of amplified optical pulses. The temporal contrast and pulse duration are two of the most important parameters that allow targets, especially nanometer-thick targets, to be irradiated with extreme optical intensities. Other important techniques adopted in multi-petawatt systems are those which enhance the contrast and retain the broad spectrum of the optical pulses. Optical parametric pulse amplification (OPCPA) [5, 6] stages are often implemented in hybrid CPA systems [7, 8, 9, 10]. The other frequently adopted technique is temporal pulse cleaning based on various non-linear optical processes. One of most popular techniques is a degenerate third-order nonlinear process, involving the generation under phase-matched conditions of a new wave with a polarisation direction orthogonal to the direction of the linearly polarised incident wave [11,12]. This technique is now generally known as XPW, which is a form of acronym of the term “cross-polarized wave” [13, 14]. The XPW technique has been intensively investigated [15, 16, 17], and devices based on it are now available commercially.

Following the recent purchase [18] of such a temporal filter based on XPW, work has continued on further incorporation of the XPW system into the front end of the Gemini laser. Here we describe the design of a new structural element of the front–end system, which is referred to in the following as a temporal cleaning unit (TCU). We present and discuss the first measurements of the energy, spectrum and temporal contrast obtained from the device.

The scheme for incorporating XPW into the front end system is for the TCU to use the pulse train from the Ti:sapphire pre-amplifier (Compact Pro, Femtolasers GMBH), which supplies stretched pulses of approximately 10 ps duration at 1kHz repetition rate. After cleaning by the XPW temporal filter, the cleaned pulses are reconditioned back to their original beam parameters and re-injected into the path to the pulse stretcher and the Gemini amplifier chain.

Experimental setup

The TCU consists of a small transmission grating compressor (TGC) [18], XPW temporal filter (SourceLAB Laser Plasma Technologies [19]), a glass-block stretcher and a set of positively chirped mirrors (PCM), an acousto-optical programmable dispersion filter (AOPDF) (Dazzler, Fastlite) and a multipass Ti:sapphire booster amplifier. A schematic view of the TCU table is presented in Figure 1.

When Gemini is operating normally, the kHz beam from the pre-amplifier passes through an optical switch consisting of a fast-acting Pockels cell between two polarizers, which passes a 10Hz pulse train to the rest of the laser chain. The second polarizer is a Glan-Thomson type, and the rejected pulse train containing 99 pulses out of every 100 is redirected towards the TCU polarizer and sent into the TGC. The pulse is compressed by a double pass through the TGC and 4 reflections from negatively chirped

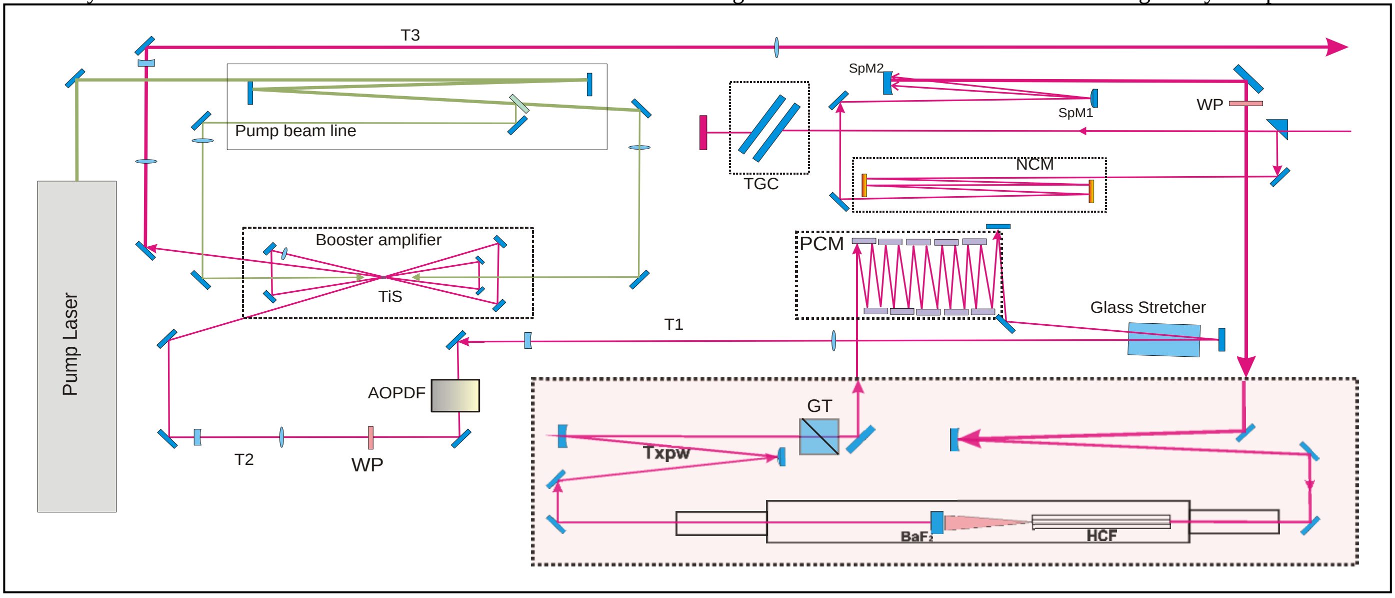

Figure 1. Schematic of the temporal cleaning unit (TCU). TCU contains a transmission grating compressor, negative chirped mirrors (NCM), expanding telescopes (SpM1/SpM2, T_{XPW}, T3). The XPW filter, marked with light pink colour, contains a hollow-core fibre (HCF), BaF_2 crystal, telescope T_{XPW} and Glan–Taylor (GT) polarizer. The XPW signal goes through a positive chirped mirror (PCM) stretcher and a glass block stretcher, the AOPDF, de-magnifying telescopes T1 and T2 and the booster amplifier. Several half-wave wave plates (WP) are used for polarization management at various places within the TCU.

mirrors (NCM) which help to compensate the accumulation of nonlinear phase from the substrates of the TGC. After the NCM compressor the beam is expanded by a Galilean-type mirror expander (SpM1/SpM2) and sent into the XPW filter. The design of the filter is described in detail in [17]. The input beam is then focused into a hollow-core fibre (HCF) which works as a spatial filter to produce a smooth beam profile for XPW generation. The BaF_2 crystal can be moved along the beam path to optimize the energy density on the crystal, in order to maximize the conversion efficiency into the XPW signal. The crystal can be rotated around the axis normal to its plane to achieve the phase matching condition for XPW generation. A reflective expanding telescope, T_{XPW}, is used to collimate and expand the output beam, to reduce the intensity level of the XPW pulse in the material of the Glan-Taylor polarizer.

In the next stage the XPW filtered signal is first stretched by 5 pairs of positively chirped mirrors [20] to further decrease the intensity of the pulse, then stretched by a double pass through a glass stretcher consisting of a 150 mm long block of SF10 glass. Following the glass block, an AOPDF (Dazzler) allows for both flexible compensation of residual spectral phase errors and modification of the spectral shape to achieve a short pulse after compression.

The beam before the Dazzler is reduced in size to a diameter of 2.7-3.1 mm and collimated by telescope T1, which has a magnification of 1/3.4. The Dazzler also functions as a pulse picker to reduce the repetition rate of the diffracted pulses to 10 Hz. The second telescope, T2, which has a magnification of 1/1.9, produces a slightly converging beam with a waist located behind the first pass through the Ti:sapphire crystal of the booster amplifier. A lens in the booster amplifier further reduces the beam divergence in the amplifier. The pulse makes 4 passes through the 6 mm Ti:Sapphire crystal of the booster, which is pumped from both sides by the second harmonic output of a Q-switched Nd:YAG laser (INDI, Spectra–Physics). The pump beam is steered onto the crystal via a 4m delay line between the laser and the imaging lens, which allows the imaging of a plane just outside the pump laser cavity to ensure good near-field quality of the pump beams.

The beam after the amplifier is expanded by telescope T3 to a diameter of ~ 3.5mm. The divergence of the beam is controlled by the telescope to be identical to the divergence of the regular input beam under normal operation of Gemini. The output from the TCU is re-injected into the normal beam path just after the fast Pockels cell of the front-end system.

Results and discussion

The performance of the TCU was tested by sending the output temporally-cleaned pulses into the Gemini amplifier chain. The pulses were stretched and amplified to the same energy as in normal operations, and the temporal contrast was measured after pulse compression in the Gemini grating compressor.

The output of the XPW temporal filter was optimized by using a dispersion scan routine with the AOPDF [18] which helps to find optimum parameters of pump pulse compression in TGC. The pump power available for the experiment was lower than the original design parameters for the XPW filter, and this was partially compensated by moving the BaF_2 crystal closer to the hollow-core fiber. The XPW signal energy was in the region of ~60 µJ, which corresponds to approximately 15 % conversion efficiency of the input pulses. The spectrum of the XPW signal (see Figure 2) was ~ 83nm, twice as wide as the input at the full width half maximum (FWHM) level and nearly double that (~ 163nm) at the 10% level.

The centroid of the XPW generated spectrum was located at 777nm, a movement of more than 15nm to the blue side of the spectrum. This spectral shift in XPW is usually explained [21,22] by the effect of the asymmetric pulse shape and a rapid change of the pulse phase. The blue spectral shift was observed [18] with a combination of the second and third order of the spectral phase of the input pulse (controlled by the AOPDF in the Compact Pro laser) at which the shortest pulse and broadest XPW spectrum were observed. The bandwidth changed significantly while the pulse was propagating through the TCU, with the main change in the spectrum occurring at the AOPDF. The width after the AOPDF was reduced to 55 nm FWHM even when the amplitude filter was set to 120 nm.

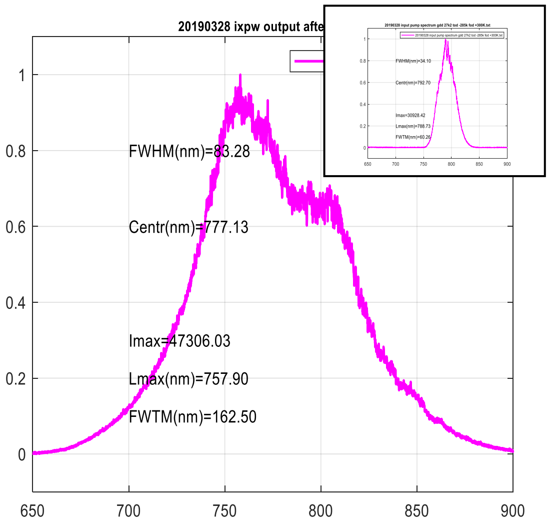

Figure 2. Output spectrum of the XPW filter with an example of the spectrum of the input pump signal after TGC (inset).

The input into the booster amplifier was at the 10 µJ level, limited by the diffraction efficiency of the AOPDF and its specifications for the intensity of the input beam [23]. The output of the booster amplifier ranged from 0.5 to 0.9 mJ. The amplification in the booster amplifier reduced the bandwidth to ~ 46nm with a red shift of the centroid of the spectrum to ~ 794 nm. Despite the reduced spectral width at FWHM, the spectrum width at the ten percent points of the spectrum still extended from 700 to 850 nm. Unfortunately, at the time these experiments were done the stretcher was slightly misaligned, resulting in a clip of the long wavelength side of the spectrum at 810 nm. Overall the spectral width achieved after the third amplifier was wider (FWHM ~36 nm) than the usual spectrum from the front end with that misalignment in the stretcher.

The temporal contrast of the pulses was measured using a third order cross-correlator, (Sequoia, Amplitude Technologies) at the end of the amplifier chain after compression in the Gemini compressor. The pulse width was minimized by adjusting the compressor length and by fine tuning the second order of the spectral phase with the AOPDF. The compressed pulse duration was in the region of 40fs. The contrast measurement scans are presented in Figure 3 below.

The first contrast measurements revealed some unexpected features of using this XPW setup. There were new pre- and post-pulses at ±26 ps delay (red and blue lines in Figure 3). The post pulse corresponds to a double reflection at the uncoated surfaces of the 2.5 mm long BaF_2 crystal in the XPWF, and this post-pulse was subsequently converted into a pre-pulse by nonlinear spectral modulation [24]. Unfortunately the BaF_2 crystal was neither antireflection coated nor made with a wedge, which would have prevented propagation of the reflected replica pulses along the beam path to the end of the laser chain. The origin of this pulse was confirmed by measuring the contrast with the booster amplifier seeded by the pump pulse for XPW, passing through all elements of the TCU but with the BaF_2 crystal removed (black line in Figure 3). The energy level of the pulse into the booster amplifier pulse was kept at the same level as it would have been with the XPW generated signal, but the pre- and post-pulses are not present.

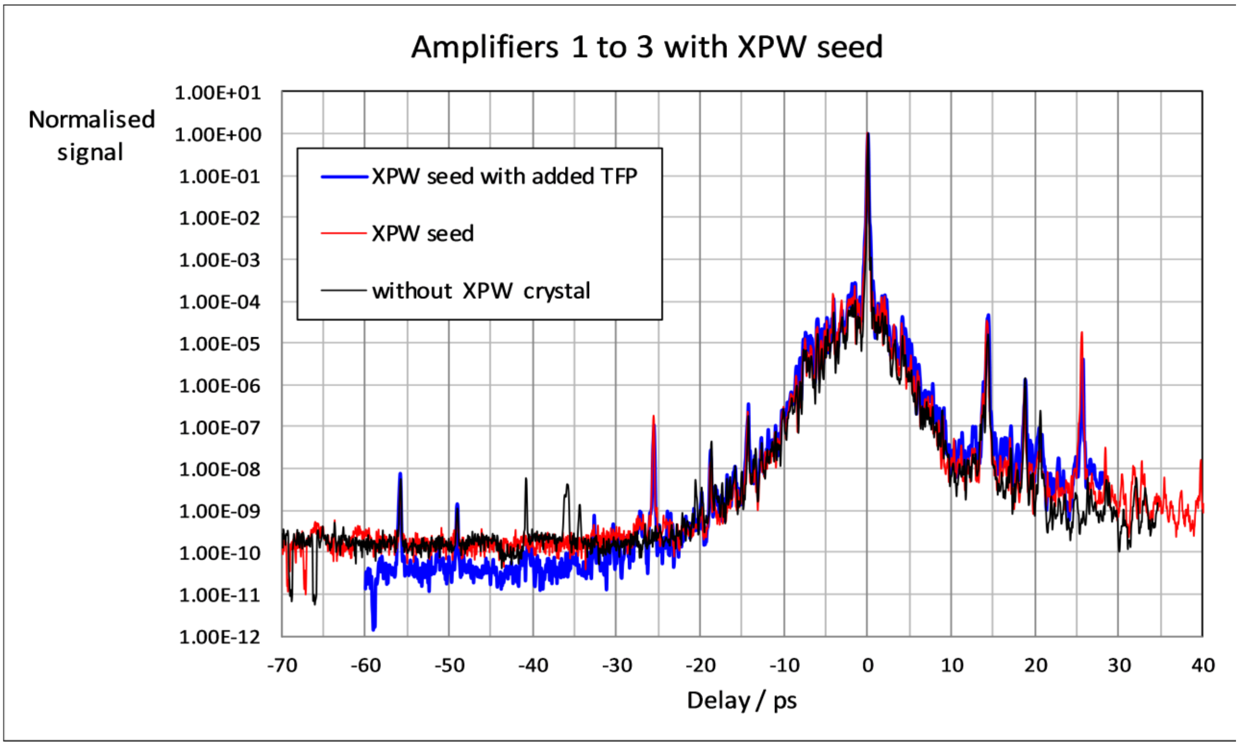

Figure 3. Traces of the temporal contrast scans of compressed pulses at the end of the Gemini laser chain. Red: with BaF_2 crystal; black: XPW seed without BaF_2 crystal; blue: XPW seed with extra thin film polarizer before XPWTF. The peaks in the red and blue traces at ±26 ps are due to the BaF_2 crystal.

At first the improvement of the contrast level with the XPW seed was marginal. It should be pointed out that the background noise, which is clearly seen to be higher than the Sequoia background level, was assigned as coming from the XPW filter. The high background noise level was first attributed to insufficient extinction ratio provided by the output GT polarizer. Despite the fact that GT polarizers with 15 mm clear aperture are commonly specified with an extinction ratio of 10^5, the ratio measured for our polarizers was only 10^3. To improve the extinction ratio of the system a thin film polarizer (TFP) was introduced in the pump beam before it entered the XPW filter. There was a small but visible reduction of the background level between -60 ps and -25 ps (blue line in Figure 3). The improvement of the contrast level with the extra polarizer indicates that the polarization purity of the seed pulse might have lessened between the first GT polarizer and the input into the XPW filter. However, the improved extinction ratio with the TFP only decreased the background by slightly less than an order of magnitude.

This result disagrees with reports of contrast improvement of more than 3 orders of magnitude achieved with XPW [13, 17]. However, those levels of improvement were obtained when the initial contrast was only 10^{-6} or 10^{-7} [17], whereas the contrast of the Gemini system without the XPW filter is significantly better (10^{-10} at -50ps). Nevertheless it was expected that the contrast improvement with the XPW filter would correspond to the polarizer extinction ratio, down to the instrument background level if the extinction ratio of the polarizers was the only significant factor. The instrument background level is visible on the contrast traces where there are dropouts of the signal line (at ~ -70ps) which were created by blocking the input beam either before the Sequoia or before the booster amplifier. This clearly indicates that the source of the background is the XPWTF seed pulse, rather than the booster amplifier.

Comparing the traces of the contrast scans with and without the XPW crystal clearly shows that there are several groups of pre-pulses: [-41ps, -36ps, -34ps], which were removed by the XPWTF. There are also pre-pulses which are generated in the optical path through the amplifier chain, which is common for both cases. The other feature of the contrast traces for pulses amplified and compressed in a CPA laser with grating stretcher-compressor combinations is a coherent pedestal [25] which is the broad feature visible on all the scans extending about 22ps on either side of the main peak. The pedestal was unaffected by the XPW filter, which is to be expected because it is understood to be generated by phase noise originating in surface irregularities of the gratings in the stretcher [25].

Conclusions

We report on the first experimental performance test of the newly built temporal cleaning unit (TCU) in combination with the amplifier chain of the Gemini laser. The main part of the TCU is a temporal filter based on XPW generation. The output of the XPWTF was stretched, amplified in a booster amplifier and then spatially modified to be injected into the chain of amplifiers at the front end of the Gemini system. The XPW seeded pulse was stretched in the grating stretcher, amplified and compressed in the Gemini compressor. The measured temporal contrast of the compressed pulse has shown some improvement in the time region which is usually attributed to a background level of amplified spontaneous emission. The temporal contrast scans have also revealed some questions about the limiting factors for the best achievable contrast with the XPWTF and whether the extinction ratio of the polarisers is the only parameter responsible for it. These questions will be investigated further during the next available experimental period. Several further stages of testing and improvement of the TCU will be required before it is commissioned for operation as a standard part of the Gemini system.

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