Contrast enhancements to petawatt lasers using short pulse optical parametric amplifiers and frequency doubling

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This paper describes the integration of a short pulse optical parametric amplifier into the chirped pulse amplification beam lines of the Orion laser facility. This enables Orion to generate petawatt laser pulses at 1054 nm with a nanosecond contrast of $>10^{10}$. By combining this with frequency-doubling post compression, we can generate 100 J, 500 fs laser pulses with a nanosecond contrast calculated to be $\sim10^{18}$.

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1. Introduction

The Orion laser is a facility for performing high-energy density plasma physics experiments [1]. Many of the experiments that are performed, or are planned to be performed, on Orion require conditions that simultaneously achieve high temperature and density in the plasma. To realize this, chirped pulse amplification (CPA) beam lines with extremely high temporal contrast are required. Orion has two CPA beam lines, each delivering 500 J in 500 fs (1 petawatt) focused to a $<10 \mu m$ diameter focal spot.

The CPA beam lines consist of a common mode-locked oscillator, which generates an 80 MHz chain of 160 fs, 3 nJ pulses. A single pulse is selected by a Pockels cell and polarizer then split between the two beam lines. On each beam line, the pulses are stretched to 6 ns using an Offner triplet stretcher and amplified to $\sim100$ mJ using a three-stage lithium tri-borate (LBO) optical parametric amplifier (OPA) [2]. The output from the OPA is spatially shaped then amplified by four-passed mixed glass (Nd:silicate and Nd:phosphate) rod amplifiers, followed by a series of Nd:phosphate disc amplifiers of increasing aperture. The beam is expanded to 600 mm diameter before being compressed by two 1480 mm$^{-1}$ gold diffraction gratings and focused onto the target using an F/3 off axis parabola. Wavefront correction is achieved using an adaptive optics system to achieve a peak intensity of $10^{21}$ W cm$^{-2}$.

When operating in the first harmonic, the beam lines have a nanosecond contrast of $\sim10^7$ (measured after the compressors), the dominant contribution coming from amplified noise in the nanosecond optical parametric preamplifier stages. In order to achieve higher contrast, Orion was designed with the option to frequency double one of the beam lines at a reduced aperture, generating a 100 J, 500 fs laser pulse with a nanosecond contrast of $10^{14}$ [3]. This has proved highly successful [4] but is inefficient, delivering only 20% of the energy to target that is possible from the first harmonic.

A wide range of methods are used to improve the temporal contrast of petawatt-class high-energy lasers. These operate by either generating a clean, high-power seed pulse or by cleaning the pulse just prior to target.

Clean, high-power seed pulses are often generated using a double CPA system [5] where a low-power
seed pulse is stretched, amplified, and compressed then put through a nonlinear filter before being stretched and amplified again. Many Ti:sapphire, sub-100-fs systems use double CPA with nonlinear filters based on XPW [6] or saturable absorption [7], but these are unsuitable for systems which operate at 1054 nm with pulse durations over ~100 fs. Low gain OPA [8] and short pulse optical parametric amplification (discussed later) have both been used on lasers operating at 1054 nm with pulse durations from 100 s of femtoseconds to a few picoseconds.

Other methods of contrast enhancement rely on nonlinear interactions just prior to focusing onto the target such as frequency doubling [3] or the use of single- or double-plasma mirrors [9]. Contrasts of $10^{19}$ have been reported for a 6 fs pulse using a combination of XPW and plasma mirrors [10].

Short pulse optical parametric amplification is a technique that has been recently developed to enhance the temporal contrast of CPA lasers. This process was developed for use on OMEGA EP [11], and variants of the technique have since been implemented on Vulcan [12] and PHELIX [13]. Here the output from a modelocked oscillator is split into two beams: one is amplified directly using a regenerative amplifier, frequency doubled then used as a pump for an optical parametric amplifier; the other beam is stretched to a few picoseconds to match the duration of the pump beam and amplified in the optical parametric amplifier. The amplified pulses are fed into the main nanosecond stretcher then optical parametric amplifier and the beam lines. By increasing the signal-to-noise ratio in the nanosecond OPA, the nanosecond contrast is increased [7]. A similar scheme, though using full CPA to create more energetic pump beams, also has been reported [14].

We have designed and built a compact, modular, short pulse optical parametric amplifier (SPOPA) and installed it into the front end of the Orion CPA beam lines (between the mode-locked oscillator and Offner triplet stretcher), without significantly disrupting the front-end architecture (Fig. 1). The contrast improvements in the first harmonic have been characterized and calculated for the second harmonic, giving a contrast of $\sim 10^{18}$ when the two systems are used together.

2. Short Pulse Optical Parametric Amplifier

The SPOPA consists of a series of coupled subsytems: pulse selector, regenerative amplifier, stretcher, delay lines, optical parametric amplifier, and diagnostics (Figs. 1 and 2).

The SPOPA is seeded using a Spectra Physics Tsunami modelocked oscillator, which produces an 80 MHz chain of 3 nJ, 160 fs pulses centered at 1054 nm. A series of Pockels cells and polarizers are used to select two pulses, 300 ns apart, from the pulse chain. The first pulse is passed through a Faraday rotator, half-wave plate (HWP), and a 3:2 Galilean telescope before being injected into the regenerative amplifier. The second pulse is launched directly into the stretcher.
A. Regenerative Amplifier

The regenerative amplifier uses a single 1200 mm lens and irises located at the cavity end mirrors to form a 1400 mm long linear cavity. A Northrop Grumman Cutting Edge Optronics RBA35 CW diode pumped amplifier containing an 83 × 3 mm Nd:YLF rod, located in the converging beam, provides a single pass gain of up to 1.6. The pulse is trapped inside the cavity using a quarter-wave plate and a KDP Pockels cell running in quarter-wave mode.

The bandwidth of the laser pulse evolves as it passes through many round trips of the amplifier. On the first few passes, the bandwidth rapidly narrows from 18 to ~1 nm due to gain narrowing in the Nd:YLF rod. When the amplifier reaches saturation, the pulse is intense enough to generate a small amount of self phase modulation in the Pockels cell, broadening the bandwidth to 1.5 nm. We did not observe any deleterious effects on the pump beam such as temporal breakup or spectral modulations due to this broadening. The output pulse is 4 ps duration with an energy of 1 mJ and a ±1% RMS energy stability.

The amplifier will run stably from single shot to 400 Hz but is currently run at 10 Hz to best synchronize with the Orion master timing system.

On exiting the amplifier, the beam is sent back through the Galilean telescope located at the input expanding it to 2.4 mm FWHM. It is then passed through the Faraday rotator and HWP before being reflected off a polarizer.

The beam is frequency doubled using an 8 mm thick LBO crystal cut for type I frequency doubling at 1053 nm. Conversion efficiencies of ~50% are achieved while running the conversion process at saturation to aid energy stability. The beam is passed along a delay line consisting of a series of dichroic mirrors, which reject any residual first harmonic light before being sent to the OPA.

Operation of the amplifier is monitored using a photodiode to view the cavity build up, a camera to capture the spatial mode, and an energy meter after the frequency conversion stage.

B. Stretcher

A second pulse is selected from the pulse chain 300 ns after the first is sent to the regenerative amplifier. This pulse is stretched using a double-passed folded Martinez stretcher [15]. The stretcher uses a 1480 mm−1 grating with a 47.9 deg incidence angle to best match the main nanosecond stretchers and compressors. The stretcher is vertically multiplexed and is double-passed using a porro prism retro reflector to spatially separate the input and output beams. The lens and fold mirror are located on a common translation stage to allow the stretched pulse duration to be easily controlled.

A double-passed delay line is mounted on the same translation stage as the stretcher components such that the time of flight through the stretcher to the OPA is kept constant. This allows the stretcher to be detuned and the OPA optimized without having to manually resynchronize the signal and pump pulses.

The stretcher is set to ~1 ps to obtain maximum gain from the optical parametric amplifier while maintaining sufficient bandwidth to seed the nanosecond OPAs.

The output beam of the stretcher is imaged into the OPA crystal through the back of a dichroic mirror giving a 1.2 mm FWHM beam.

C. Optical Parametric Amplifier

The OPA is a 25 mm LBO crystal cut for type I frequency doubling at 1053 nm and is wedged to prevent backreflections. A small noncollinear angle is introduced between the pump and signal beams to aid separation of the idler. Beam sizes are chosen such that the pump beam overfills the signal beam (2.4 and 1.2 mm FWHM beam diameters, respectively) to minimize the effect of any beam drift through the day and improve output stability [Figs. 3(a) and 3(b)].

Gains of greater than 10^5 are realized, providing output energies of ~30 μJ with a total energy extraction of ~10%. The spectral profile of the amplified beam is controlled by varying the stretch of the seed pulse with respect to the pump pulse duration.

The Orion nanosecond stretcher and OPA are designed with a spectral hard clip at 1048–1062 nm, which matches the gain bandwidth of the Nd:glass amplifiers in the main beam lines. To ensure that the most energy is available over that spectral range, we temporally overfill the pump pulse with the seed. By running the OPA in back conversion, we generate a flattened Gaussian spectrum set to match the stretcher hard clip (Fig. 4).

Fig. 3. (a) Pump beam spatial profile. (b) OPA output spatial profile.
3. Beam Line Integration

The SPOPA is integrated into our short pulse beam lines by rerouting the beam after the short pulse oscillator through the SPOPA and back to the main beam lines (see Fig. 1). The nanosecond stretchers are retuned to take into account the additional stretch from the SPOPA.

The Orion nanosecond OPA [2] is a three-stage all LBO system where each stage is imaged onto the next to maintain beam quality and allow spatial filtering between stages. A common pump beam is split into three by a series of half-wave plates and polarizers, allowing the energy delivered to each stage to be set independently. Stage 1 of the OPA is overfilled by the seed beam, causing the output to adopt the spatial profile of the pump.

The original design intent was to use the SPOPA to replace the gain from the first stage of the OPA and therefore remove the greatest source of parametric fluorescence in the system. On installation it was found that, when run in this mode, a substantial amount of fluorescence was generated by Stage 2 of the OPA. This was because the seed energy to Stage 2 coming from the SPOPA was only about 2% of that previously delivered from the nanojoule pulses that had been amplified in Stage 1. This causes the gain from Stage 2 to rise (previously, it was run in a heavily saturated regime) to the point where fluorescence was no longer suppressed. To mitigate this, the energy balance between the first two stages was systematically optimized to reduce the parametric fluorescence while maintaining beam quality and output energy. A spatial filter with low angular acceptance, located between the two stages, is used to suppress fluorescence from the first amplifier stage, which would steal gain from the later stages, affect stability, and cause modulations in the near field.

The OPAs are set up such that they will run in either a high- or low-contrast mode. This is achieved by enabling or disabling the SPOPA pump laser thus changing the seed energy into the nanosecond OPA from under a nanojoule to around a microjoule. The energy balance in the nanosecond OPA is then optimized to achieve stable high-energy output (Table 1).

4. Contrast Enhancement

Contrast measurements were taken using a two photodiode technique on a series of full energy target shots. Here the pulse is split and sent to two photodiodes. One is heavily attenuated and used to measure the main pulse. The other sees any structure proceeding the pulse before it is saturated. The contrast is calculated from the attenuation and the impulse response of the photodiode.

When originally commissioned, the Orion CPA beam lines had a nanosecond contrast of $\sim 10^7$. The main laser pulse was preceded by a 3 ns pedestal generated from fluorescence in the optical parametric amplifier. Once the SPOPA was installed, but not energized, the contrast was reduced by over an order of magnitude due to the lower seed energy at the input to the nanosecond OPA caused by the additional passive losses within the SPOPA (primarily the stretcher). With the SPOPA activated, the contrast is enhanced by $>10^4$ to at least $10^{10}$, our current measurement limit (Fig. 5).

The picosecond contrast of the system was measured at the compressed output of the nanosecond OPA using a scanning third-order cross-correlator (a Sequoia from Amplitude Technologies). These measurements (Fig. 6) were performed with the SPOPA running and are compared with measurements taken prior to the installation of the SPOPA. They demonstrate that, with the SPOPA running, the contrast is $>10^9$ (the measurement limit of the device) an enhancement of $>10^4$ at $>100$ ps before the pulse. Discrete prepulses located before the main pulse are due to reflections inside the diagnostics.

5. Frequency Conversion

Orion uses frequency-doubling post compression as an additional method of enhancing the contrast on one of its short pulse beams [3]. The system is designed such that the main laser pulse converts in the saturated regime with high conversion efficiency.
The pedestal, or any discrete prepulses, being many orders of magnitude less intense, operate in the low-conversion regime. Their converted intensity varies quadratically with the input intensity; hence, they are suppressed.

On Orion, the beam is first reduced in size using a segmented glass apodiser, which reduces the beam size from 600 to 300 mm diameter. The beam is then passed off a 1053 nm high reflector (HR) mirror then through a 320 mm diameter, 3 mm thick KDP crystal cut for type I frequency doubling. This is followed by a series of three dichroic mirrors, which are HR at 527 nm and high transmission (HT) at 1053 nm. The beam is then focused onto a target using an f/6 parabola, which is also HR at 527 nm and HT and 1053 nm. All of the dichroic mirrors and the parabola have a 1053 nm reflectivity of 1%.

Using the beam line in its original state (with a contrast of $\sim 10^7$), we have measured contrasts of $10^{14}$ at the second harmonic [3]. This measurement was performed at the very edge of our diagnostic capability, and several optics were damaged in the process of taking it.

By running the beam line with the SPOPA activated and the frequency doubler installed, the contrast is enhanced still further. For the measured first harmonic contrast of $10^{10}$, we expect a second harmonic contrast of $10^{19}$–$10^{20}$. Unfortunately, the four mirrors used for harmonic separation in our system only realize an attenuation of $10^8$ of the first harmonic light. This results in more residual first harmonic light from the pedestal reaching the target than is converted to the second harmonic.

A simple model (Fig. 7) has been developed to calculate the achievable contrast on target after frequency doubling for a beam with a given first harmonic contrast. This calculates the expected variation in the amount of second harmonic light (the dotted line in Fig. 7) reaching target for a given first harmonic contrast and compares it with the residual first harmonic light reflected by the dichroic mirrors (the dashed line in Fig. 7). The contrast realized at target (the solid line in Fig. 7) is the greater of these. It can be seen that, with a first harmonic contrast less than $10^{-9}$, more residual first harmonic light will reach the target than is converted to the second harmonic.

Using this model, we calculate that, for a shot fired with the SPOPA running and passed through the frequency doubler, we should achieve a contrast of $10^{18}$ on target, assuming a contrast of $\sim 10^{19}$ in the first harmonic. This is equivalent to a prepulse intensity on target of $\sim 100$ W cm$^{-2}$ and would give an energy contrast of $\sim 10^{14}$ (assuming the measured 3 ns duration pedestal and 500 fs main pulse). This means that the pedestal would contain an energy of, at most, a few picojoules.

6. Conclusions
The nanosecond temporal contrast of the Orion laser has been enhanced by installing a SPOPA at the start of the beam lines. This enables us to generate a petawatt laser pulse with a nanosecond temporal contrast of $>10^{10}$. The layout of the existing front-end was disrupted only slightly, resulting in system implementation with minimal downtime. In addition, by frequency doubling the beam line post
compression, we can produce a 200 TW pulse at 527 nm with an estimated contrast of $>10^{18}$.

References


