Ultrahigh contrast from a frequency-doubled chirped-pulse-amplification beamline

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This paper describes frequency-doubled operation of a high-energy chirped-pulse-amplification beamline. Efficient type-I second-harmonic generation was achieved using a 3 mm thick 320 mm aperture KDP crystal. Shots were fired at a range of energies achieving more than 100 J in a subpicosecond, 527 nm laser pulse with a power contrast of $10^{14}$.

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1. Introduction

The Orion laser [1] is an entirely new facility for performing high energy density plasma physics experiments. Orion consists of two synchronized lasers: 10 “long-pulse” beamlines generate a total of 5 kJ at 351 nm in a 100 ps–5 ns temporally shaped pulse [2]. Two short-pulse beamlines each produce ~500 J in 0.5 ps, one petawatt, at 1054 nm.

The short-pulse beamlines are seeded by a mode-locked oscillator producing 150 fs, 3 nJ pulses centered at 1054 nm. These pulses have a positive chirp imposed upon them by an Offner triplet stretcher [3] increasing their duration to 6 ns. A single output pulse is selected by a Pockels cell and amplified using an optical parametric amplifier (OPA) pumped by a commercial pump laser. The OPA produces a 180 mJ (1.5% RMS), 18 nm bandwidth pulse with a super-Gaussian temporal and spatial profile [4]. The OPA output pulses are spatially shaped to a 30th power super Gaussian profile and then amplified by four-passed Nd:glass (Nd:silicate and Nd:phosphate) rod amplifiers followed by a series of Nd:phosphate disk amplifiers of increasing aperture. The amplified pulse is then expanded to 600 mm diameter and compressed to 500 fs using a pair of gold diffraction gratings before being focused onto a target with an $f/3$ off-axis parabola. Wavefront correction is achieved with a closed-loop adaptive-optics system.

One characteristic of chirped-pulse-amplification (CPA) beamlines, such as those on Orion, is that the compressed pulse sits on top of a pedestal formed by parametric fluorescence from the OPA preamplifier. This pedestal has a characteristic temporal profile linked to the pump pulse duration and any spectral effects in the beamline (gain narrowing and spectral clips in the compressor). Prepulses can also be present. These may be generated by badly suppressed pulses from the master oscillator, spurious reflections from the beamline, or spectral clipping on the compressor gratings. If the main laser pulse sits on top of a pedestal or is preceded by low-intensity pulses, preplasmas can be formed, which can adversely affect interactions between the main laser pulse and target [5].

Various methods of improving the temporal contrast of CPA lasers have been implemented in other facilities:
Double chirped-pulse amplification [6] (DCPA), where a preamplified pulse is compressed, passed through some nonlinear filter, restretched, and then sent to the main amplifier chain, is used extensively in small-scale, high-repetition-rate systems. Cross-polarized wave (XPW) generation [7,8] and low-gain optical parametric amplification [9] have both been used as nonlinear filters in systems operating in a similar regime to Orion. DCPA has the disadvantage that it is inherently inefficient due to the losses in the nonlinear processes and the additional compressor and stretcher.

OMEGA MTW [10] and Vulcan PW [11] both use the same technique to reduce the energy within their fluorescence pedestal; here the seed pulse is amplified in a picosecond OPA prior to the main stretcher. This reduces the gain required from the nanosecond OPA and hence increases the nanosecond signal-to-noise ratio by the same amount. The pedestal remains at the same level, albeit for a few picoseconds in front of the pulse.

The pulse can also be cleaned after amplification and compression either by the use of a plasma mirror [12] or, as is reported here, by frequency conversion. Previous investigations of type-I frequency doubling of femtosecond and picosecond laser pulses from Nd:glass [13–17] and Ti:sapphire [18,19] lasers have been performed at smaller apertures, lower energies, and/or lower intensities than are demonstrated here.

Type-I doubling is chosen to simplify implementation, as it produces a beam polarized along one of the principal axes of the target plane, and therefore avoids the use of large-aperture waveplates post compression. It also removes the need to compensate for the temporal walk off between the e and o rays, which is present in type-II doubling [13]. Frequency doubling the beamline has allowed us to provide a facility to study laser–matter interactions in a new regime [20] and improve the temporal contrast ratio of the compressed pulse by a factor of 10⁶ leading to a power contrast of 10⁹⁴.

2. Crystal Selection

A spatially and temporally resolved code has been developed to model the performance of our short-pulse beamlines [21]. This code includes a functionality to simulate the performance of potassium dihydrogen phosphate (KDP) for doubling the laser pulses post compression. The code was used to simulate the frequency conversion of the beamline operating at nominal maximum fluence for a range of crystal thicknesses and pulse durations (set by simulated detuning of the stretcher) shown in Fig. 1. A 3 mm crystal was chosen as the best option for delivering maximum energy to the target for pulse durations of 0.5–5 ps with a bias toward the shorter pulses that will be used most often.

3. Experimental

Frequency doubling is achieved at a large aperture using a 320 mm diameter, 3 mm thick KDP crystal [supplied by Gooch and Housego (Ohio)] cut for type-I phase matching with its surface at 41° to normal such that phase matching occurs with the beam at normal incidence to the face. The crystal is the largest high-aspect-ratio KDP crystal available with suitable transmitted wavefront properties. The crystal is solgel coated to achieve optimal transmission, being antireflection coated at 1054 nm on the incident face, with the exit face similarly coated for 527 and 1054 nm.

The doubling crystal and associated optics are inserted between the compressor and target chambers as shown in Fig. 2(a). The entire beamline from the compressor input onwards is enclosed in a single vacuum volume to avoid the deleterious effect of passing the compressed pulse through a vacuum window. In order to enhance operational efficiency, all of the optics required for frequency-doubled operation of the beamline except for the parabola are contained within a single, isolatable chamber.

After compression, the beam is passed to the chamber [Fig. 2(b)], where the 600 mm diameter beam is apodized to 300 mm, matching the aperture of the doubling crystal. The apodizer is centered on the region of highest intensity of the (laterally dispersed) beam achieving a transmission of ∼30%. The apodizer is formed by four segmented quadrants of absorbing glass. Each is aligned such that any reflections are dumped into the compressor vessel walls while ensuring that no caustics hit the diffraction gratings. A solid metal block is placed behind the absorbing glass to prevent any transmitted first-harmonic light from reaching the target.

After apodization, the beam is reflected off a 1054 nm highly reflective (HR) mirror, and passes through the doubling crystal, and then off three dichroic mirrors, which are HR at 527 nm and highly transmissive (HT) at 1054 nm. The beam then leaves the chamber and reflects off two further mirrors, which are specified to be HR at both 527 and 1054 nm. Focus onto the target is realized with an f/6 off-axis parabola, which is also designed to be HR at 527 nm and HT at 1054 nm. Each dichroic

Fig. 1. Model predictions for second-harmonic output energy at different input pulse lengths; the simulated input energy is 150 J.
mirror reduces the reflected power of the fundamental by \( \sim 2 \) orders of magnitude, achieving a total extinction ratio of \( \sim 10^8 \).

The majority of the unconverted, 1054 nm portion of the pulse passes through the back of the first turning mirror and is dumped into a slab of absorbing glass, which is angled to avoid back reflections. Leakage through the back of the second turning mirror is reduced in size with a Galilean telescope and used for diagnostics on the 527 nm beam. On the diagnostics table the 527 nm pulse is separated from any residual 1054 nm light by a series of dichroic mirrors that are HR at 527 nm and HT at 1054 nm. In order to prevent any scattered 1054 nm light from reaching the diagnostics, BG39 cutoff filters, which transmit 527 nm light and block 1054 nm, are placed in front of each diagnostic. The beam is split between three diagnostics stations: a near-field camera that is used to monitor the spatial profile of the beam and look for any localized deleterious nonlinear effects, a pyroelectric energy meter, and a contrast measurement station.

The contrast measurement station consists of two photodiodes: one is heavily attenuated such that it can measure the main laser pulse. The other is used to observe any low-intensity prepulses or structure present before the main pulse. The contrast of this structure can be calculated from the duration of the main pulse (measured in the first harmonic), the impulse response of the photodiode, and the attenuation of the unsaturated photodiode.

The system is aligned using a 532 nm CW laser launched through the back of the first mirror in the frequency conversion chamber shown in Fig. 2(b). Colinearity and cofocusing between the alignment beam and the main beam are set initially using an insertable subaperture spherical mirror. This is then optimized by viewing pulses from the OPA (which are sufficiently intense to achieve low levels of frequency conversion) and the (attenuated) CW beam on a camera that images target chamber center from the far side of the focal plane.

The crystal was angle tuned for optimal frequency conversion in situ using the doubled OPA light. The tuning curve was found to be broad enough to allow us to detune the crystal in its slow axis by 1 mrad such that any back reflections were stopped by the pinhole in Orion’s final spatial filter. While it is known that the sensitivity of second-harmonic power to angle increases at higher intensities due to \( \chi^{(3)} \) effects within the doubling crystal [22], we found that the angular variation in conversion efficiency even at high intensities was small enough that the 1 mrad detuning had no ill effects.

Transition between operation at 527 and 1054 nm is achieved by the removal or replacement of the beam apodizer and two turning mirrors.

4. System Operation

Full system shots were fired at progressively increasing energies with a 0.5 ps pulse duration. The system was then run for several months to generate high-contrast laser pulses for an experiment to study ionization potentials in hot dense plasmas [23]. In this period the energy was set to meet the demands of the experiment. Energy conversion efficiencies of up to 75% were achieved [once the transmission of the apodizer is taken into account Fig. 3(a)] generating 527 nm laser pulses of up to 100 J (Fig. 4). The conversion efficiencies are consistent with those seen in our previous work using 2 mm thick crystals [17] and those by others using 4 mm thick crystals [13–16] at similar intensities. While our modeling captured enough of the relevant physics to specify

Fig. 3. The first-harmonic beam (a) is apodized and frequency doubled to produce a 300 mm diameter 527 nm beam (b).
the doubling crystal, any effects not included (such as \(\chi^{(3)}\) effects \([22]\), local variations in beam intensity or wavefront and imperfections in the crystal) will have all contributed to the lower-than-calculated conversion efficiencies.

A CCD camera imaging target chamber center is used to observe focused frequency-doubled OPA pulses. This shows, in Fig. 5(a), a \(\sim10\ \mu\text{m}\) diameter near-diffraction-limited focal spot. By comparing this with the instrument-limited, \(15\ \mu\text{m}\) diameter x-ray spot generated by a full energy system shot shown in Fig. 5(b) (measured using an x-ray pinhole camera with a \(10\ \mu\text{m}\) pinhole), we can see this is directly indicative of the focal spot achieved on a full target shot giving an intensity on target of \(\sim10^{20}\ \text{W cm}^{-2}\).

It is interesting to note that we have not encountered any of the deleterious effects on the focal spot observed by Neely \textit{et al.} \([14,16]\), who used a 4 mm thick crystal KDP crystal at comparable intensities. We also do not observe any localized structure or beam break-up effects due to nonlinear effects in our doubling crystal or diffraction from the hard clip on the apodizer as shown in Fig. 3(b).

5. Contrast Enhancement

Measurements taken using a two-photodiode pre-pulse monitor on the compressed first-harmonic beam show that the beamline has a 3 ns pedestal of \(10^{-8}\) the intensity of the main pulse (Fig. 6). This pedestal is due to parametric fluorescence in our OPA and is comparable with those seen at other Nd:Glass petawatt laser facilities \([9,10]\). Similar measurements taken after frequency conversion can be seen in Fig. 6 and indicate that the pedestal has been reduced to \(10^{-14}\). In both measurements, biased silicon photodiodes (Newport 818-21A) were used; this made the 527 nm measurement \(\sim5\) times more sensitive than the 1054 nm due to the greater responsivity at this wavelength. To reach this dynamic range the photodiodes required extensive baffling, spectral filtering, and shielding to prevent any stray reflections or scattered light within the diagnostics enclosure swamping the signal. Two artifacts from scattered light within the diagnostics station, indicated in Fig. 7, proved impossible to remove.

Fig. 4. Second-harmonic energy and conversion efficiency as measured for a range of input energies over several months of operation.

Fig. 5. The low-intensity optical focal spot (a) from the doubled OPA is consistent with the x-ray spot and (b) generated by a full energy (85 J on target) shot.

Fig. 6. Contrast enhancement by frequency doubling the beamline.

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entirely. These measurements were all performed with no protection in front of the photodiodes (water cells, etc.), which shortened their life significantly.

6. Conclusions
We have integrated a large-aperture type-I frequency-doubling system into one of the petawatt beamlines on the Orion laser facility. Second-harmonic, 0.5 ps laser pulses are generated at up to 100 J, ~0.2 PW; this is, to our knowledge, the most powerful frequency-doubled beamline to be reported. The beamline is well optimized with target intensities of ~10^{20} W cm^{-2} being achieved with a power contrast of 10^{14}. The beamline is now routinely run in the second harmonic providing a high-contrast ultrahigh-intensity facility for performing plasma physics experiments.

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References