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Two-color terawatt laser system for high-intensity laser-plasma experiments

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Abstract: We report a two-color terawatt laser system for use in controlling laser-plasma instabilities. The system includes a commercial 45 TW Ti:Sapphire laser system at 800 nm, temporally synchronized with a 1 TW CPA Raman-Ti:Sapphire hybrid laser centered at 873nm that we designed and built to complement the 800 nm system. The two-color system will be used to seed, enhance, suppress, or otherwise control a variety of instabilities which arise in laser-plasma interactions.

Keywords: Raman scattering, CPRA, seeded instability, laser-plasma interaction

INTRODUCTION

There are a variety of instabilities which arise from laser-plasma interactions. Some of these can be detrimental to particle acceleration—as when relativistic self-focusing [1-2] and forward Raman scattering combine to produce significant axial and transverse structures in the laser beam [3], thereby preventing the stable propagation of the beam over distances necessary for effective particle acceleration. On the other hand, relativistic self-focusing does allow a laser pulse to achieve smaller spot sizes and thus higher intensities than could be achieved by simpler focusing optics such as mirrors or lenses [2], and thus can be highly beneficial to particle acceleration when properly controlled. Kalmykov *et al*. recently proposed that relativistic self-focusing could be controlled [4-5] by using a two-color laser pulse to generate (via electron density perturbation) a periodic index grating, or beat-wave, in the plasma which can either cause focusing ($\Omega > \omega_{pe}$) or defocusing ($\Omega \leq \omega_{pe}$) depending on whether the difference Ω between the two laser frequencies exceeds or falls short of the electron plasma frequency ω_{pe} [6].

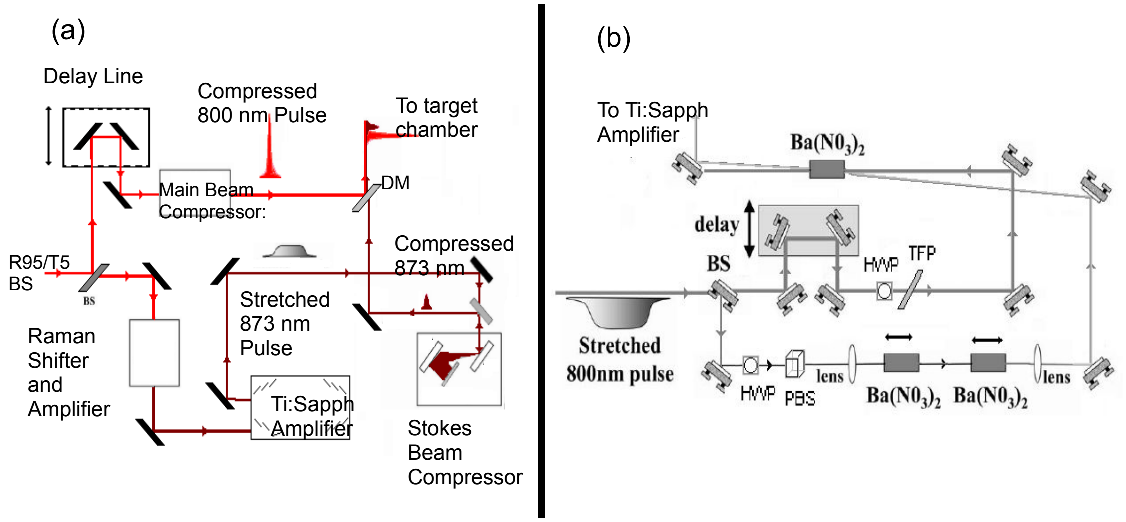

Figure 1. (a) The basic overview of the secondary pulse's generation, amplification, and compression, and its subsequent recombination with the primary pulse. (b) A more detailed diagram of the first two stages--shifting via spontaneous Raman scattering and amplification via SRS and 4WM--of this Raman generation process.

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This proposal requires the use of a two-color terawatt system in which the second color is down-shifted in frequency by ~ ω_{pe} from the first. For a plasma density of $n_e = 1.22 \times 10^{19}$ cm^{-3}, this corresponds to a primary pulse centered at 800 nm (e.*g.* a Ti:Sapphire pulse) and a secondary at 873 nm. Both colors need powers ~TW so that the primary pulse power is overcritical and the secondary pulse modulates the combined pulse field sufficiently to create the density grating.

Here we describe the University of Texas two-color terawatt (UT^3) system in which the primary pulse is derived from a commercial THALES Ti:Sapphire laser system with nominal pulse parameters 1 J energy, 30 fs pulse duration, 800 nm center wavelength. We then designed, built, and demonstrated a chirped-pulse Raman amplifier (CPRA) to provide the secondary pulse without compromising the properties of the primary pulse. We split off ~ 5% of the energy of the pre-compressed primary beam, shifted this to 873 nm via stimulated Raman scattering, amplified the first Stokes wave in an externally-pumped Ti:Sapph amplifier, then compressed this pulse to a bandwidth-limited, ~Gaussian pulse of duration ~75 fs. CPRA systems had previously been demonstrated by Zhavoronkov *et al*. [7], achieving 0.08 mJ, 190 fs secondary pulses, and more recently by Grigsby *et al.* [8], achieving 3 mJ, 110 fs pulses of high focusability. Our system builds on the work of Grigsby *et al.* to achieve first Stokes energies of >300 mJ (uncompressed), with broader bandwidth and hence shorter compressed pulse durations than in previous work.

SYSTEM DESIGN AND RESULTS

Our Raman system is designed in four stages: seeding, stimulated Raman amplification, Ti:Sapphire amplification, and compression. Figure 1 shows the set-up of our system, along with detail of the first two stages.

To drive the CPRA, we split ~50 mJ, or about 5%, of the 500 ps pre-compressed primary

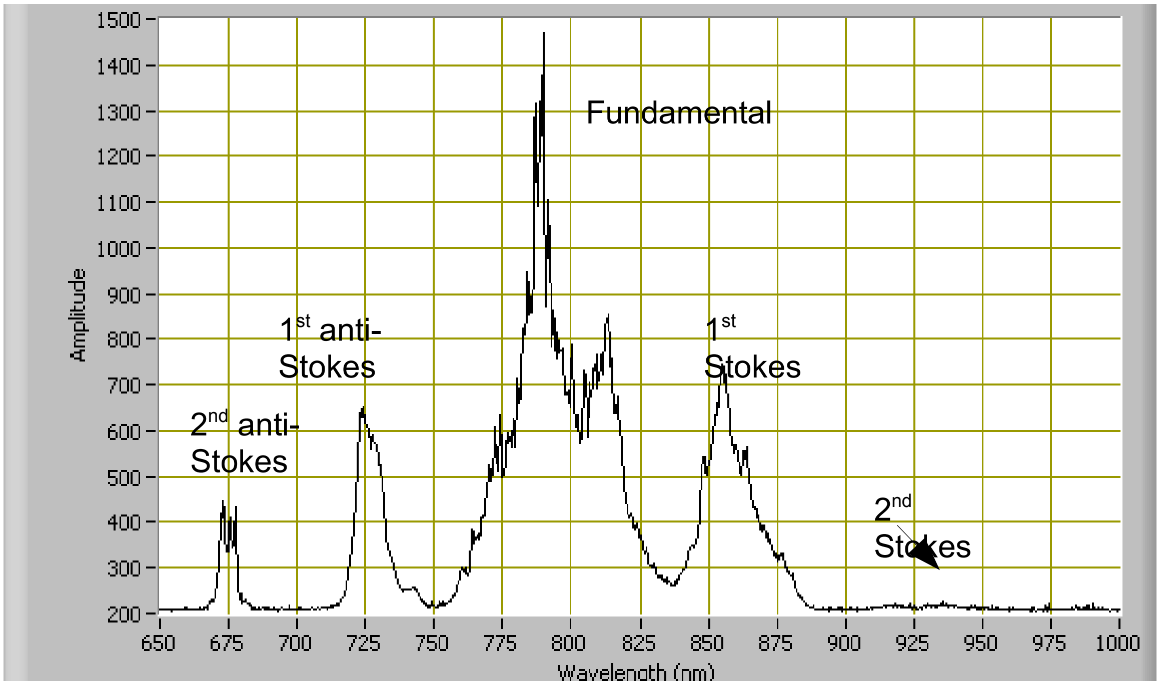

Figure 2. The spectrum of the lower order modes in the Raman cascade, from the 2nd anti-Stokes to the 2nd Stokes. The fundamental beam was initially centered at 790 nm and hence all wavelengths are shifted by ~10 nm to the blue from their expected positions, so that 1st Stokes is centered at 860 nm rather than 873 nm. The spectra are obtained via a fiber spectrometer, which is is moved to collect data from each mode individually; these are then added together to produce the "cascade spectrum" in the figure. Therefore, the spectrum shown is not for one single shot, but rather for several shots averaged together. It is also notable that not all orders have the same spectral bandwidth, nor do they each have the same energy: some of the orders will be more preferentially amplified than others due to phase-matching considerations, and furthermore the lower orders will achieve higher energies before the higher orders.

800 nm pulse, the remainder of which was compressed to ~25 fs and sent to the target chamber. We generated the secondary pulse in three stages. In the first stage, we split ~2.5 mJ from the 50 mJ incoming pulse, and focused it with an f/100 lens into a tandem pair of barium nitrate crystals, which have a Raman-active vibrational mode centered at 1047 cm^{-1} that shifted it from 800nm to 873 nm via stimulated Raman scattering (SRS), yielding a ~ 0.1 mJ first Stokes "seed" pulse. We found empirically that a pair of crystals placed at different locations in the focus of the drive pulse yields a superior seed pulse compared to the single crystal used in previous work [7, 8]. For optimum performance, we placed the first seed crystal before the focus of the drive beam, the second with its back surface at focus, yielding higher first Stokes energy (~0.1 mJ vs. ~0.01 mJ) and broader spectrum than when only one crystal is used. This seed pulse was then sent to the second stage, where it underwent additional SRS and other higher-order four-wave mixing processes pumped by the remainder of the 50 mJ pulse. The result was a Raman cascade from which we selected the first-Stokes' wave, now amplified to ~1.5 mJ. The spectrum of part of the Raman cascade after one pass through the second stage crystal is shown in Figure 2. Each mode order of the cascade (*e.g*. fundamental, 1st Stokes, 2nd Stokes, 1st anti-Stokes, 2nd anti-Stokes) is spatially separated according to the phase-matching conditions imposed by four-wave mixing [8]. The 1st Stokes mode is further amplified, but higher-order modes of this cascade could be compressed and used as probe pulses [9].

In the third stage, the 1.5 mJ first Stokes' wave was sent to a 6-pass "bowtie" Ti:Sapphire amplifier, which was externally pumped by a 1.15 J, frequency-doubled Nd:YAG laser with a top-hat transverse mode profile. Here it was amplified by a factor of 100 to 200. Figure 3 shows far field modes through each of the first three stages. The fundamental beam is nearly Gaussian when it arrives at the first barium nitrate crystal (Fig. 3a); the seed mode (Fig. 3b) is cleaned up in the second-stage barium nitrate crystal due to a phase averaging effect (Fig 3c), and ultimately has a nearly Gaussian profile after third-stage amplification in the Ti:Sapphire crystal (Fig. 3d). The amplified 873 nm pulse is then resized and compressed using a pair of 1200 lines/mm grating. Figure 4a shows the spectrum of the incoming fundamental beam alongside spectra of the fully-amplified 873 nm beam. The bandwidth of the latter ranges from 10-20 nm (FWHM), and the peak wavelength from 870 to 880 nm. This first Stokes beam is thus sometimes redshifted slightly. This redshift is due to the leading edge of our pulse depleting the Raman gain in the system. Our pulses are positively chirped, so the leading edge of the pulse is red compared to the trailing edge. The spectrum of the fundamental beam changes little from shot-to-shot, although its mode and energy fluctuate. Fluctuations in the spectra—profile, bandwidth, and center—for the 1st Stokes beam are more pronounced, since they depend nonlinearly on the fundamental beam's intensity.

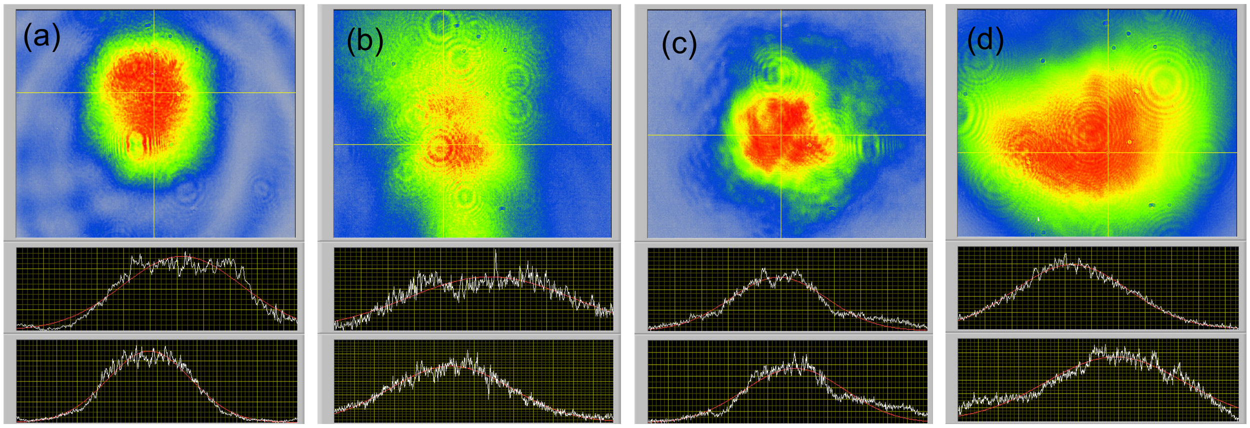

Figure 3. Evolution of the farfield mode through the first three stages of the Raman CPA system. From left to right, this is the mode of the 800 nm fundamental beam (a) as used to pump the amplifier crystal in the second stage. The Raman signal used to seed this second stage (e.g. the signal out of the first stage) is somewhat bi-modal (b), but the beam undergoes some cleanup after one pass through the amplifier crystal in the second stage (c), and is further cleaned up (and also shaped) in the Ti:Sapphire crystal after 6 passes (d). The total energy in (d) is 105 mJ. Below each ccd image are the horizontal (upper) and vertical (lower) line-outs (white) along with a Gaussian fit (red).

These fluctuations in the Raman spectra result in some fluctuations in the compressed pulse's duration (Fig. 4b). We therefore observed some pulses as sort as 60 fs, though a typical duration was closer to 75-80 fs. The bandwidth limited duration for a pulse centered at 873 nm with a FWHM bandwidth of 15 nm is 74.3 fs, so these pulses are compressed to near the bandwidth limit for a Gaussian pulse. These pulses then re-combine via transmission through a magnesium-fluoride-based dichroic mirror (reflects at 800 nm, transmits at 873 nm) with the fundamental pulses. The resulting combined pulse pair will have two spectrally distinct colors, each having a power of > 1TW.

TWO PROPOSED EXPERIMENTS

There are two planned experiments which will utilize this two color laser system. The first is a seeded version of the relativistic cross-phase modulation experiment conducted by Chen *et al* [10]. In Chen's experiment, a 1053 nm laser of 400 fs duration was focused to a spot size of 12 microns FWHM (containing 60% of the energy); the beam's power was varied from 0.4 TW to 2.4 TW, giving an intensity of 2.4 x 10^{17} to 1.3 x 10^{18} W cm^{-2}. At the lowest intensity, a Raman-shifted peak appears in the spectrum (centered near 900 nm); this peak is then broadened when the laser power (and hence intensity) is increased, and then develops modulated sidebands. The power and spot size (and hence the intensity) used by Chen for this experiment are realizable with our Raman beam. We therefore will use the 873 nm beam as the pump in this experiment, and the 800 nm beam (after attenuation) as a seed. Chen *et al.* note that the modulated signal which they observe is asymmetric due to the group-velocity walkoff between their Raman pulse and their fundamental pulse, and also because more energy resides in the front part of the Raman pulse, which outruns the fundamental in the plasma due to its anomalous dispersion. Our pulses will have a smaller group velocity walkoff, and moreover the seed pulse (800 nm) has a more symmetric energy distribution than their Raman pulse. Therefore, we should expect to eliminate some of the asymmetry which arose in Chen's experiment.

The second experiment which we will undertake is the suppression or enhancement of relativistic self-focusing (RSF). It is well-known [11] that a beam which exceed the critical power, $P>P_{cr}=16.2\ (\omega_l/\omega_{pe})^2$ GW, self-focusing will overcome diffraction and the beam will focus. However, when a second color is present in the laser, this self-focusing effect can be enhanced or suppressed [12-13] by over-detuning (suppress) or under-detuning (enhance) the lasers' frequencies with respect to the plasma frequency. The frequency difference between the Fundamental and Raman beams is resonant with a plasma of density 1.2 x 10^{19} cm^{-3}. In essence, the second color sets up a transverse electron density profile variation which can counter-act the effects of RSF. The bi-color pulses should therefore by dynamically guided as a result of the combined effect of electromagnetic cascading, resonant self-modulation, and beat-wave-driven electron density perturbations.

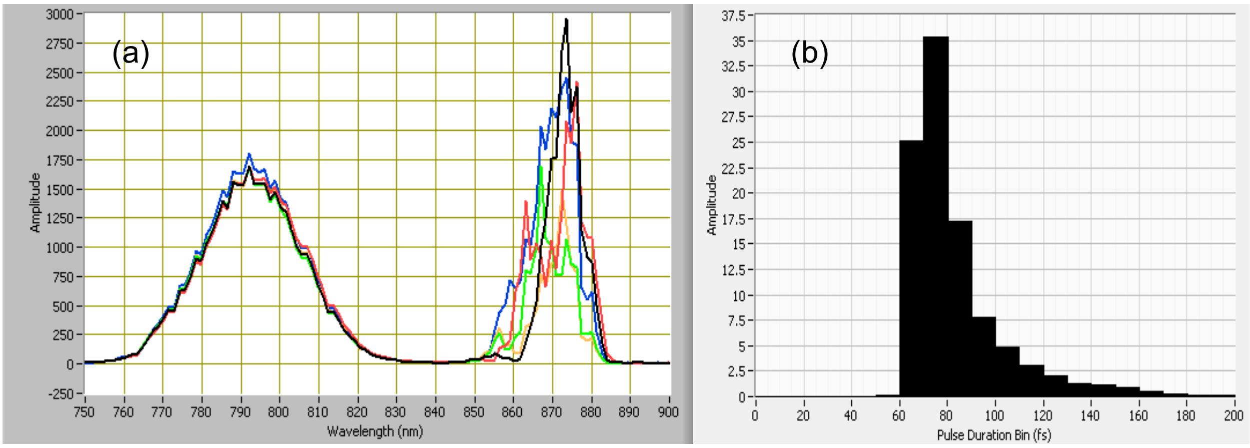

Figure 4. (a) The spectra of the main laser (left, centered at ~793 nm) and the Raman laser (right, centered at ~873 nm) for 5 different shots. Each fundamental-Raman pair was taken simultaneously via a two-channel spectrometer. Very small variations in the specta of teh fundamental spectra do not correspond to similarly small changes in the Raman spectra. (b) These fluctuations in Raman spectra in turn lead to fluctuations in pulse duration, giving some shots as short as 60 fs, and some shiots exceed 120 fs.

CONCLUSION

We have built a two-color terawatt laser system using a Raman shifting and amplification process. The second color requires only a fraction of the energy of the main laser system, thus leaving the performance of the primary (commercial) laser unaffected. By using a two stage Raman shifter and amplifier supplemented by a multi-pass Ti:Sapph amplifier system, we have achieved a Raman beam of much greater energy, broader bandwidth, and shorter duration than previously reported. The Raman beam's mode is moreover of similar quality to the primary laser system's mode. The two can therefore be matched for co-propagation in two-color laser-plasma experiments. This new laser system will allow us to perform several unique experiments which utilize the two-color properties of our pulses.

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