

Toward Exawatt lasers: amplification and compression of short laser pulses in plasma

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Abstract: Raman amplification of short laser pulses in plasma is a promising scheme for reaching extreme laser powers. This talk reviews recent progress in development of a plasma amplifier with ns pump pulses.

Keywords: Raman backscattering, plasma, laser

1. INTRODUCTION

Raman amplification in a plasma was proposed a decade ago for short laser pulses to reach ultrahigh laser powers well above that currently available by CPA (chirped pulse amplification) laser systems [1][2]. This Raman scheme utilizes plasma as the gain medium to overcome the limit imposed by the damage threshold of solid-state optics. The amplification of short laser pulses is achieved by energy transfer from a long pump pulse through a three-wave interaction with a plasma wave when the frequency difference of the pump and the seed matches the plasma frequency. Since the first experimental demonstration of Raman amplification in a plasma [3], there has been a growing interest in developing a plasma amplifier and compressor for short laser pulses in both theoretical [4-6] and experimental [7-13] studies. Recent experiments have demonstrated pump depletion accompanied with compression of the amplified pulse [9]. The interaction length has been extended by double-pass (~4mm) [11] or waveguiding (~9mm) [12] to reach higher output energy, making the plasma amplifier close to a practical device.

At present most experimental efforts involve μJ seed pulses and picosecond, mJ pump pulses. To approach the ultimate goal of petawatt-exawatt laser powers, it is necessary to scale up the Raman scheme to ns pump pulses that are available at kJ energy level in large laser systems. A recent experiment with a ns pump showed an amplification of ~ 25 , however with substantial attenuation of the seed pulse by the plasma (transmission $\sim 20\%$) [13]. As discussed in [13], ns pump pulses present more challenges in the Raman scheme. Due to the longer interaction time with the plasma, ns pumps are more susceptible to instabilities, such as Raman scattering

growing from thermal noise which competes with the seed pulse, and filamentation instability which causes beam spray and degrades the optical quality of the amplified pulse. The heating of the plasma by the ns-long pump will also lead to Landau damping of the plasma wave.

In this talk, I'll present recent results from ns-pulse experiments performed at Lawrence Livermore National Laboratory [14][15]. A high-quality amplified pulse has been observed when the pump intensity is kept below the threshold of filamentation instability. Although the heating of plasma by the ns pump pulse results in strong Landau damping of the plasma wave, an output energy of 13mJ has been achieved in a plasma $< 3\text{mm}$ long. This is, to the best of our knowledge, the highest output energy from Raman amplification in plasma up to now. Further improvement of the plasma amplifier by overcoming the saturation due to plasma wave nonlinearities will also be discussed.

2. EXPERIMENTAL RESULTS

An experiment was carried out at Jupiter Laser Facility (JLF) at LLNL to study the beam quality of the output pulse of Raman amplification in plasma. The 1ns Janus laser was employed as the pump pulse, and the near-counter-propagating seed pulse was created by wavelength-shifting the 5ps COMET laser pulse in a N_2O Raman gas cell. By measuring angular profiles of the output beam at three pump intensities, it is found that the beam quality deteriorates as the pump intensity increases. At $I_{\text{pump}} = 0.8 \times 10^{14} \text{ W/cm}^2$, the transmitted seed pulse has a similar profile to that of the incident one, while as the I_{pump} increases to $2.4 \times 10^{14} \text{ W/cm}^2$, the profile is completely flattened and the transmission drops down to less than 10%. The onset intensity of the beam spray is consistent with filamentation instability [16]. Therefore, the pump intensity needs to be kept below $1.5 \times 10^{14} \text{ W/cm}^2$ to maintain good focusability of amplified pulses in our experimental conditions.

The second experiment was focused on the scaling of amplification. The beam profiles of the amplified pulse (pump+seed), the seed pulse itself (seed only) and the thermal Raman (pump only) obtained by a calibrated photoarray are shown in Fig. 1(a). The intensities of the pump and the seed

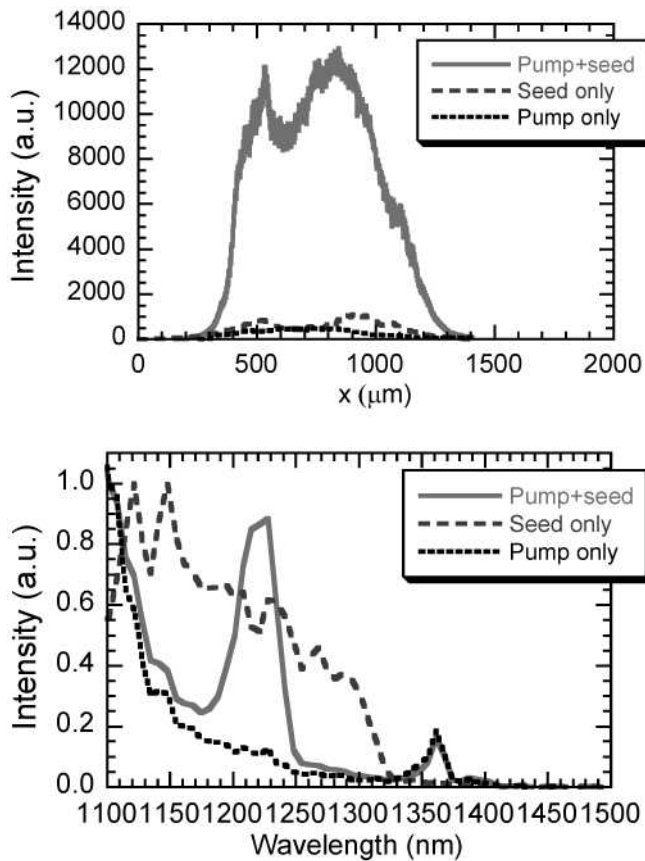


Fig. 1 (a) output beam profiles and (b) normalized spectra.

were 1.5×10^{14} W/cm² and 8.5×10^{10} W/cm², respectively. The thermal Raman was slightly weaker than the seed pulse. When the pump and the seed were both present, the output beam showed enhancement with a profile similar to that of the input seed, demonstrating that the optical quality of the pulse was maintained through Raman amplification in the plasma. The spectra of the amplified pulse, the seed and the thermal Raman are shown in Fig. 1(b). A resonant peak is clearly seen at 1220nm with a FWHM \sim 40nm, which is much narrower than the seed spectrum. Therefore, only a small portion of the seed pulse was amplified. The amplification refers to the energy ratio of pump+seed to seed-only with this bandwidth.

The amplification as a function of pump and seed intensities was also studied. The amplification levels off as the pump intensity rises above 1.2×10^{14} W/cm², in good

agreement with the onset of beam spray due to filamentation. At a pump intensity of 1.2×10^{14} W/cm², the output energy reaches 4.8mJ, 12.1mJ, 12.7mJ and 13.9mJ for seed energies of 0.24mJ, 1.1mJ, 1.7mJ and 6.3mJ, respectively, corresponding to amplifications of 20, 11, 7.6 and 2.2. The saturation of the amplification as the seed intensity increases is due to particle trapping in the plasma wave, which is demonstrated in particle-in-cell simulations using the fully kinetic code OSIRIS [17]. Our PIC simulations also suggest that a shorter seed pulse is desired to overcome this limit and reach pump depletion.

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