Amplification of ultrashort laser pulses by Stimulated Brillouin Backscattering in the Strong Coupling Regime

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Introduction

In order to amplify laser light to ever higher intensities, novel techniques are widely investigated. In this context, plasma amplification is subject to research of several groups, including the IZEST C^3 project [1]. A plasma-based approach has the advantage that a plasma can sustain much higher intensities than a solid state amplifier. In a plasma, energy can be transferred from one laser pulse (pump) to another (seed), either via a high-frequency plasma electron wave (stimulated Raman backscattering, SRS [2]) or by a low-frequency ion acoustic wave (stimulated Brillouin backscattering, SBS [3]). Especially, the strong coupling regime of SBS (sc-SBS) is of interest since seed pulses much shorter than the ion acoustic timescale $\frac{\lambda}{c_s} \approx 10$ ps can be amplified.

The strong coupling regime is reached when the pump pulse (ω_0, k_0) is so intense that it determines the plasma response. For this to happen, the pump must fulfill the threshold condition $(v_\mathrm{o}/v_\mathrm{e})^2 = 4k_0 c_\mathrm{s}\omega_0/\omega_{pe}^2$. Here, $v_\mathrm{o} = eE/(\omega_0 m_e)$ is the electron quiver velocity in the laser electric field E, $v_\mathrm{e} = \sqrt{kT_e/m_e}$ the electron thermal velocity, $c_\mathrm{s} = \sqrt{ZkT_e/m_i}$ the ion sound velocity, and $\omega_{pe} = \sqrt{4\pi n_e e^2/m_e}$ is the electron plasma frequency. In more practical units, the minimum pump intensity is given by

$$I_{14}\lambda_{\mu m}^2 = 0.11\ T_{\text{keV}}^{3/2} \sqrt{\frac{Z}{A}\frac{n_\text{c}}{n_\text{e}}} \sqrt{1-\frac{n_\text{e}}{n_\text{c}}}, \tag{1}$$

where I_{14} is the intensity in $10^{14}\,\frac{W}{cm^2}$, $\lambda_{\mu m}$ is the pump wavelength in μm, T_{keV} is the electron temperature in keV, Z is the charge number, $A = m_i/m_e$ is the mass number, and n_e is given in units of the critical density $n_c = \omega^2\varepsilon_0 m_e/e^2$. Therefore, this regime is attained at high pump intensities, high plasma electron densities, and low plasma electron temperatures.

Under this condition, the plasma wave is not a natural eigenmode of the plasma determined by the ion acoustic frequency but a quasi-mode with the dispersion relation $\omega_{sc} = (1+i\sqrt{3})/2\left(k_0^2 v_{osc}^2 \omega_{pi}^2/\omega_0\right)^{1/3}$ where $\omega_{pi} = \sqrt{4\pi Z^2 n_i e^2/m_i}$ is the ion plasma frequency. In practical units, it is

$$\frac{\omega_{sc}}{\omega_0} = 1.71 \times 10^{-3}(1-i\sqrt{3})\left[\frac{Z}{A}\frac{n_e}{n_c}\left(1-\frac{n_e}{n_c}\right)I_{14}\lambda_{\mu m}^2\right]^{1/3} \tag{2}$$

Then, the growth rate is $\gamma_{sc} = \Im(\omega_{sc})$ [4]. Compared to amplification by SRS, sc-SBS has several advantages: The interaction length can be short, full pump depletion can be attained, pump and seed can have the same frequency, and the process is less sensitive to density inhomogeneities.

Amplification by sc-SBS has already been studied by our workgroup, at the ELFIE laser facility at LULI (Palaiseau, France) [5, 6]. The highest amplification so far could be reached using a setup with counterpropagating pump and seed pulses in a preformed plasma. The target plasma was created by ionizing a Hydrogen supersonic gas jet using a 600ps, 30 J prepulse. The plasma had an electron temperature of $T_e \approx 200$ eV and an electron density of $n_e \approx 0.1\,n_c$. Pump and seed pulses were at 1058 nm wavelength with 6 nm bandwidth. The 4 mJ, 0.7 ps seed pulse was focused to an intensity of 3×10^{13} W/cm^2. The 6 J, 4 ps pump pulse was focused to an intensity of 2×10^{15} W/cm^2. The gain, defined as the energy of the outgoing pulse divided by the energy of the incoming pulse, was a factor of 4 in this experiment. The growth of the seed was efficient enough to deplete the pump, thus occurring in the self-similar regime, which is a signature of efficient amplification [6].

Experiment on SBS amplification of ultrashort pulses

In a recent beamtime at the ARCTURUS Ti:sapphire laser facility (ILPP, Düsseldorf), amplification was investigated for pulse durations of tens of femtoseconds. This regime is particularly interesting in view of the intended application, i. e. the amplification of the shortest and most intense possible pulses. It was the first experiment on amplification by sc-SBS for seed pulse durations $\tau_s < 400$ fs. Since the characteristic timescale is $1/\gamma_{sc} \approx 200$ fs (for $1\times 10^{16}\ \frac{\text{W}}{\text{cm}^2}$ pump), it was also the first experiment for pulses shorter than $1/\gamma_{sc}$.

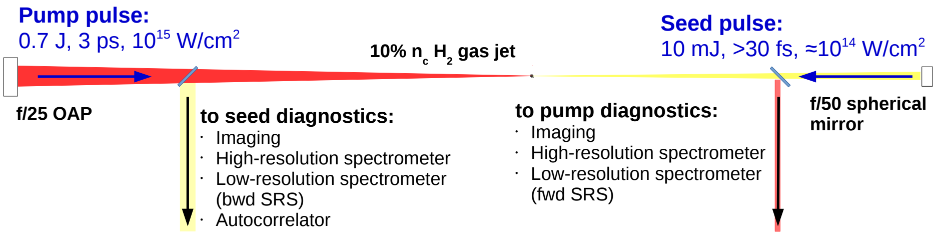

Figure 1: *Schematic setup of the experiment on SBS amplification of ultrashort pulses at ARCTURUS.*

Figure 1 shows the experimental setup. The 6 mJ seed had initial durations between 30 fs and 300 fs, leading to intensities of $2 \times 10^{13} \ldots 4 \times 10^{14}$ W/cm^2. The 700 mJ pump was chirped to obtain a duration of 3 ps. It was focused by an $f/25$ off-axis parabola (OAP) to an intensity of $1 \times 10^{15}\ \frac{\text{W}}{\text{cm}^2}$. This allowed to be in the strong coupling regime in spite of the shorter wavelength ($\lambda = 800$ nm).

Pre-ionization with a separate prepulse was not possible. Therefore, the pump pulse was relied upon to ionize the plasma. Since it was chirped, a time-resolved measurement of its intensity could be done using a spectrometer. As shown in Fig. 2, the leading flank of the pump ionized the plasma but did not depose much energy into it as the plasma density was still building up. The remainder of the pulse was then attenuated by inverse bremsstrahlung absorption. This did not preclude amplification over the spectral bandwidth of pump and seed pulses, but the growth rates were limited.

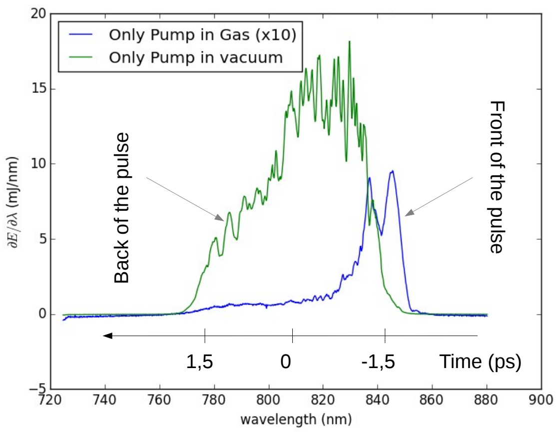

Figure 2: *Spectrum of the pump beam.*

The amplification of the pulse was measured using absolutely calibrated charge-coupled device (CCD) cameras. At the same time, an autocorrelator measurement allowed to prove that the outgoing signal was still shorter than 1 ps. Spontaneous Brillouin backscattering, growing from noise, could therefore be ruled out. No amplification was observed when the polarization of pump and seed was at 90°. Therefore, the gain can be attributed to amplification of the seed by sc-SBS.

Since amplification is possible only where the pulses overlap temporally, scanning over the delay between pump and seed allows to find a point of optimal amplification. Figure 3 shows the gain of a 30 fs seed pulse depending on the pump-seed delay. The maximum gain is 1.4 for the shortest pulses. Gains as high as in the previous experiment could not be observed. We attribute this in part to lower growth rates due to the attenuated pump pulse. Data are still subject to analysis.

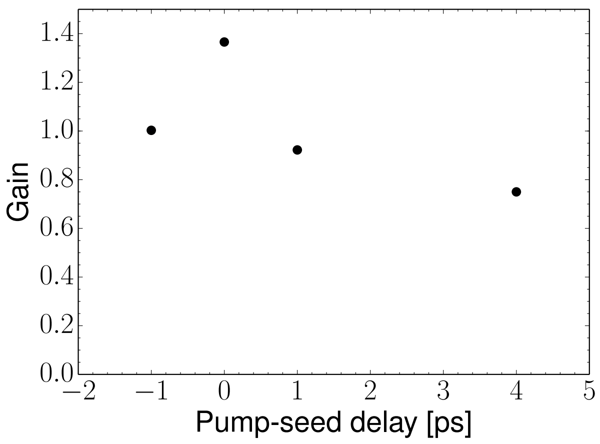

Figure 3: *Amplification depending on the pump-seed delay.*

Prospects

In an upcoming beamtime, an improved setup (Fig. 4) is planned: The plasma will be formed by a 20 ps, 1 J prepulse, focused using an $f/6$ OAP in a defocused configuration. Its intensity will be $\approx 10^{14}$ W/cm^2, optimized to generate a plasma with a density (10^{20} cm^{-3}) and temperature (180 eV), comparable to the one obtained in the ELFIE beamtime.

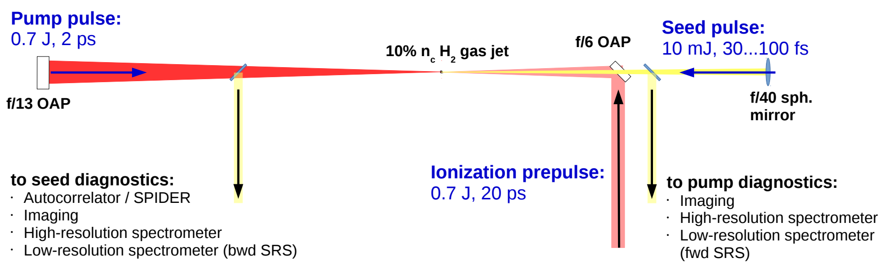

Figure 4: *Schematic setup of the upcoming ARCTURUS experiment.*

With these improved plasma parameters, we aim at obtaining a higher gain than in the previous experiment. Use of the SPIDER diagnostic will allow to account for the spectral phase of the amplified pulses. Optimized gas jet targets will allow to verify whether concurrent Raman backscattering can be mitigated by using a ramped density profile, as predicted by simulations [7].

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