Amplification of short laser pulses by Stimulated Brillouin Backscattering

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Introduction

In search for novel techniques for amplifying laser light to ever higher intensities, plasma amplification is being investigated by several groups, including the IZEST C^3 project [1]. A plasma-based approach benefits from the fact 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 the pump pulse (ω_0, k_0) is so intense that the plasma response is determined by the pump pulse. For this to happen, the pump must fulfill the threshold condition $(v_\text{o}/v_\text{e})^2 = 4k_0 c_\text{s}\omega_0/\omega_{pe}^2$. Here, $v_\text{o} = eE/(\omega_0 m_e)$ is the electron quiver velocity in the laser electric field E, $v_\text{e} = \sqrt{kT_e/m_e}$ the electron thermal velocity, $c_\text{s} = \sqrt{ZkT_e/m_i}$ 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,

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

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.

Then, 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 $\omega_{pe} = \sqrt{4\pi Z^2 n_i e^2/m_i}$ is the ion plasma frequency so that the growth rate is $\gamma_{sc} = \Im(\omega_{sc})$ [4]. Advantages of amplification by sc-SBS compared to SRS are: 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.

Previous experiments

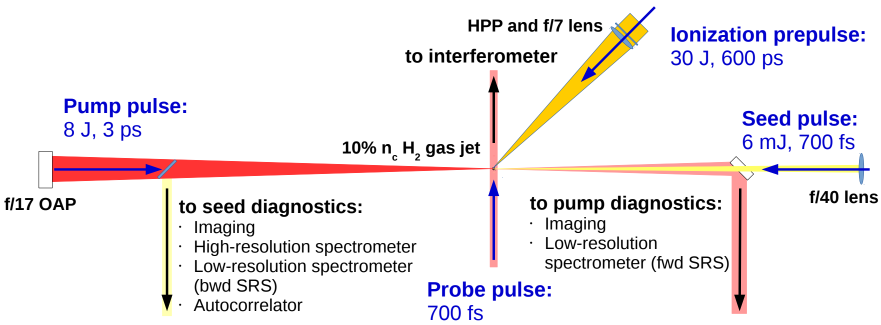

Figure 1: *Schematic setup of the 2013 experiment on SBS amplification at LULI.*

In the last experiments, the interaction between pump and seed was studied in a counterpropagating setup (Fig. 1) at the ELFIE laser facility at LULI (λ = 1057 nm). The target was a preformed plasma, created using a long (ns) high energy laser pulse in order to create a plasma having an electron temperature of $T_e \approx 200$ eV and an electron density of $n_e \approx 0.1\, n_c$. Characterization of the plasma density by transverse interferometry did not allow to find the maximum density (a part of the interferogram was not accessible due to refraction of the probe), but the highest density observed can be given as a a lower limit for the plasma density: 10^{18} cm$^{-3}/p_{bar}$ where p_{bar} is the nozzle backing pressure in bar (“meas.” in Fig. 2).

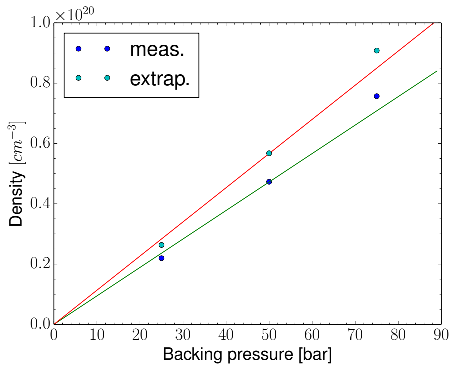

Figure 2: *Measured (blue circles) and extrapolated (green circles) on-shot plasma electron density from interferometry. Lines are linear fits.*

With these values and a pump intensity of 5×10^{15} W/cm^2, the criterion in Eq. (1) is satisfied. The highest density observed can also be used to extrapolate the plasma density at the center of the gas jet using the values from ex-situ tomography, which yields 1.2×10^{18} cm$^{-3}/p_{bar}$ (“extrap.” in Fig. 2). This is 60 % of the expected value for full ionization, and we assume that we are close to the targeted values of up to $n_e \approx 0.1\, n_c$.

In this beamtime, absolute amplification could be obtained [5]. These results are given in a companion contribution (Poster P2.224).

Planned experiment: SBS amplification of high intensity pulses

For future applications in the context of the C^3 scheme, it is planned to use the Brillouin backscattering process to amplify seed pulses up to intensities in the order of magnitude of $10^{18}\ \frac{\mathrm{W}}{\mathrm{cm}^2}$. As has been shown theoretically [6], amplification can be obtained even for seed pulses that are more intense than the pump pulse.

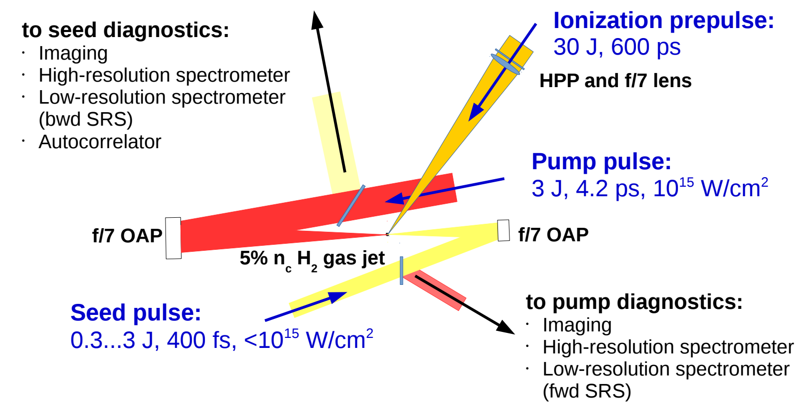

Figure 3: *Schematic setup of the planned experiment on SBS amplification at high seed intensities at the ELFIE laser facility at LULI.*

Therefore, we plan to study the process with an initial seed intensity as high as the pump intensity, mimicking a pulse that has already undergone some amplification (Fig. 3). A 3 J pump beam will counterpropagate against a 0.3 . . . 3 J seed. Being confocal with the same f number to maximize the overlap, the beams will be defocused to obtain different combinations of the intensities and spot sizes.

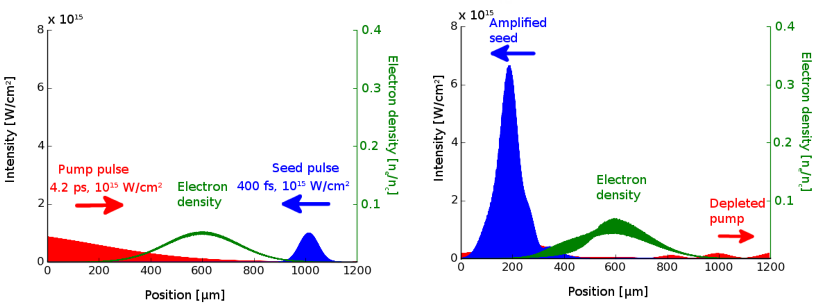

Figure 4: *1D 3V PIC simulation for a high intensity seed.*

The parameter space is limited by a maximum spot size of 90 μm (in order not to reduce the pump intensity below $10^{15}\ \frac{\text{W}}{\text{cm}^2}$) and a maximum seed intensity of $1 \times 10^{16}\ \frac{\text{W}}{\text{cm}^2}$ still with some defocus (60 μm spot size). This will allow us to study both the influence of the intensity and the spot size on the process.

The experiment is supported by simulations done by our group using the SMILEI PIC code. As shown in Fig. 4, the seed is amplified at high intensities and remains short.

Planned experiment: SBS amplification of ultrashort pulses

So far, SBS amplification has not been investigated experimentally for seed pulse durations $\tau_s < 400$ fs. This regime, however, is particularly interesting because the highest output intensities are easiest to achieve with shortest pulses as energy is limited. Furthermore, very short seed pulses are less subject to wavebreaking in the plasma [4]. On the other hand, the growth rate of sc-SBS limits amplification to a timescale $1/\gamma_{sc} = 215$ fs (for $1 \times 10^{16}\ \frac{\text{W}}{\text{cm}^2}$ pump). This will be investigated in an experiment (Fig. 5) at the ARCTURUS Ti:Sapphire laser facility (Düsseldorf, Germany). Initial seed durations down to 30 fs will allow us to verify up to which duration an initial seed remains short. A pump intensity up to $10^{16}\ \frac{\text{W}}{\text{cm}^2}$ (limited by the available energy) allows to remain in the strong coupling regime in spite of the shorter wavelength ($\lambda = 800$ nm). The diagnostics will be similar to those used in the previous experiments. In addition, they will include a SPIDER to obtain information on the spectral phase of the amplified seed.

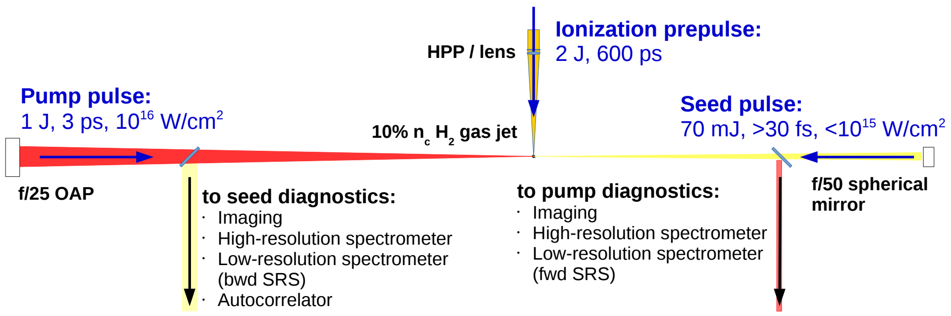

Figure 5: *Schematic setup of the planned experiment on SBS amplification of ultrashort pulses.*

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