Saturation of Raman instability in gas jet plasma in LULI 2000 laser experiments

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Abstract. This paper presents results obtained in an experiment performed at the LULI 2000 laser facility where we measured saturated Stimulated Raman Scattering (SRS) in a supersonic gas jet of ethylene (C2H4). Our conditions correspond to the following parameters: kEPWλD = [0.2-0.3], Te = [0-1] keV and ne = [1.2-10] % of critical density at 526 nm. The laser was smoothed with a random phase plate and had a maximal average intensity of 1.2x1015 W/cm² in the focal spot.

1. Introduction
The Raman instability is a three wave coupling which appears in laser plasma interaction physics, in particular in the field of inertial confinement fusion [1]. Controlling its linear and nonlinear behaviour is an important issue in this field. In case of high laser intensity, long plasma, high electronic density, or low electronic temperature the SRS instability can be saturated, that is to say that the SRS backscattered intensity no more increases exponentially with the incident laser intensity. Various saturation processes have been identified during experiments or in simulations. A key parameter in these processes is the damping of the electron plasma wave (EPW) [2] which is correlated to the value of kEPWλD, where λD represents the electron Debye length and kEPW the wavenumber of the EPW. The experiment was designed to study the saturation of the Raman instability at 526 nm, for moderate intensity (I_MAX ≈ 1.2x1015 W/cm²) and intermediate kEPWλD value (kEPWλD = [0.2-0.3]) with a final objective of comparing the saturation level of the SRS at 526 and 351 nm. This kEPWλD regime has already been investigated at lower intensity, with a 1.054 µm beam, using exploding foil plasma which exhibits a different electronic density [3, 4]. In our experiment, we used gas jet plasma, which allows a control of the maximum electronic density of the plasma which increases with the jet pressure. The experiment is described, the experimental plasma conditions are given and preliminary results are presented and discussed.

2. Description of the experiment
The experiment was performed using the two kilojoule-beams of the LULI 2000 laser facility. The two 1.053 µm laser beams were separated by an angle of 45°, doubled in frequency and could reach 350 J at 0.526 µm in a 1.5 ns flat topped pulse. The first beam was used to create the plasma whereas the second beam was used to interact with the plasma. The creation beam was focused to a circular focal spot using an f/4 plan-convex lens and a random phase plate (RPP) with 2 mm approximately square elements. The interaction beam was RPP smoothed with 4 mm square elements, corrected with an adaptive optics operated in the laser bay, and focused with an f/4 lens. We calculated for the creation beam a best focus FWHM (full width half maximum) of 260 µm, and for the interaction beam a FWHM of 130 µm. The interaction beam reached an intensity of 1.2x10\(^{15}\) W/cm\(^2\) at maximum energy. The delay between the two beams was 1.5 ns so that at the end of the creation beam pulse, the interaction beam was fired.

A high quality beam splitter was placed in the beam path of the interaction laser to sample both the incident beam energy and the light reflected from laser-plasma instabilities. The backscattered light was collected in the incident beam aperture, was collimated by a mirror and relayed to a series of diagnostics. We used a spectrometer coupled to an optical streak camera with electronic readout to measure the time-resolved spectra from SRS and Stimulated Brillouin Scattering (SBS). For SRS (respectively for SBS), the measurements were done in a range of \(\lambda = 500–900\) nm (respectively \(\lambda = 522–530\) nm) and during 5 ns with spectral and temporal resolutions of 10 nm and 200 ps (respectively 0.1 nm and 200 ps). A S1 (respectively S20) photodiode filtered to suppress the SBS and let the SRS pass (respectively suppress the SRS and let the SBS pass) was used to measure the entire SRS (respectively the entire SBS) backscattered energy. Photodiodes were absolutely calibrated and their signals were recorded on fast transient digitizers. Configuration of the experiment and laser characteristics are summarized in Fig. 1.

### Table 1: electronic temperature (\(T_e\)), electronic density divided by critical density calculated at 526 nm (\(n_e/n_c\)) assuming that the jet is fully ionized, and corresponding wavenumber of the EPW \((k_{EPW})\) driven by the SRS times the electron Debye length \((\lambda_D)\) as a function of the pressure at the entrance of the target.

| Pressure (bar) | 12 | 22 | 30 | 35 | 50 |
|---------------|----|----|----|----|----|
| \(T_e\) (eV)  | 250| 350| 420| 500| 600|
| \(n_e/n_c\)   | 1.2| 3.1| 4.2| 6.1| 10 |
| \(k_{EPW}\)   | 0.3| 0.27| 0.24| 0.22| 0.22|

Figure 1: experimental set-up for the LULI 2000 experiment.

### 3. Description of the plasma.

The target was a supersonic gas jet of ethylene (C\(_2\)H\(_4\)). The jet was circular with 2 mm of diameter. The two laser beams were focused 1 mm upon the nozzle and crossed in the front part of the jet so that the interaction beam did not pass through non ionised gas before reaching the plasma as shown in Fig. 1. Due to the angle between the two beams, the length of interaction was 280 µm. We have characterised the atomic density of the gas jet, by using an interferometer technique [6], as a function of the pressure put at the entrance of the nozzle. Fig 2a) and 2b) present the electronic density divided by the critical density calculated at 526 nm (\(n_e/n_c\)) of the jet, assuming that the jet is fully ionised, obtained at 1 mm above the nozzle for different backing pressure. Fig. 2a) shows the dependence of...
ne/nc as a function of the pressure. Fig. 2b) shows the transverse profile: we observed that the jet was almost homogeneous over a circular area of about 2.1 mm of diameter. Simulations with the hydrodynamic code FCI2 showed that the electronic temperature (T_e) was approximately constant and did not vary significantly during the interaction pulse. So, assuming that the plasma was stationary, we deduced T_e of the plasma from the SBS spectral shifts. In Table 1, we summarize the plasma characteristics for each pressure used in our experiment. We notice that T_e was higher when ne/nc was higher, as expected from the collisional absorption.

4. Experimental results

The Raman backscattered spectra analysis indicates that for each pressure, ne/nc which corresponds to the fully ionised gas was actually present in the plasma and corresponded to the maximum ne/nc over which the instability occurred. A typical SRS spectrum measured for a backing pressure of 35 bars at the maximal laser intensity of I = 1.2x10^15 W/cm² is shown in Fig. 3a). The corresponding time integrated spectrum is plotted in Fig. 3b). We notice that the maximal backscattered wavelength appearing in Fig. 3a) and 3b) is 710 nm which corresponds to a value of ne/nc = 6%. This value is similar to the electronic density measured by interferometry, assuming that the gas jet is fully ionised. The Raman spectra were relatively narrow, so we deduce that the plasma was fairly homogeneous. The maximal backscattered wavelength in the SRS backscattering spectrum decreases in time. This has been interpreted as due to a decrease of the plasma density because of the plasma expansion. During the interaction, the value of the short wavelength cut-off decreases slightly, indicating that the electron temperature slightly goes down.

For this intermediate pressure condition and from the backscattered wavelengths, we calculate that the SRS occurs for ne/nc ranging from 4% to 6%. Assuming that T_e = 450 eV, we calculate that the laser intensity is above the absolute instability threshold intensity for a homogeneous media [1]. At 750 ps, the SRS backscattering drops off. There are two possible explanations for this: (i) the density of the plasma is too small to provide conditions for an absolute instability, (ii) the density profile becomes too sharp and the plasma is not enough homogeneous.

To study the effect of the laser intensity, it was varied from 0.5x10^14 to 1.2x10^15 W/cm² in gas jets at 35 and 50 bars which corresponded to initial densities of 6% and 10% of critical respectively. For both pressures, the SRS backscattering level increased linearly with the laser intensity demonstrating the saturation of the instability. Indeed, if in the growing regime, we could expect an exponential growth instead of linear. We found a saturation level of [10-20] % at 35 bars and [15-30] % at 50 bars. Then we studied the saturation of the SRS as a function of the electronic density of the plasma. The intensity of the laser beam was adjusted to a value around 1.2x10^15 W/cm² and the density of the
plasma was changed by modifying the backing pressure. We measured with photodiodes SRS and SBS energies for pressure of [12, 22, 30, 35, 50] bars. Results show that the instantaneous SRS intensity at the beginning of the interaction increases with the density approximately linearly. Such behaviour of the saturated SRS reflectivity with plasma density is consistent with saturation due to coupling of the EPWs with ion acoustic wave dynamics.

5. Summary
We have presented experiments in gas jets of different pressures, at 0.536 µm. Maximal electron densities of the plasma were in a range of n_e/n_ec = [1.2-10], electronic temperature extends from 300 eV to 650 eV and k_EPWλ_D values extends from 0.2 to 0.3. We have observed the saturation of the SRS at 35 and 50 bars. We have measured a linear dependence of the SRS backscattered maximum reflectivity with the electronic density of the plasma for a laser intensity of I = 1.2x10^{15} W/cm². A first interpretation of SRS spectra has been proposed. Further investigations are in progress with the hydrodynamic code FCI2 and SRS gain calculation with the PIRANAH post processor.

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