Exploring the Saturation Levels of Stimulated Raman Scattering in the Absolute Regime

D. T. Michel,[1,2] S. Depierreux,[2] C. Stenz,[3] V. Tassin,[2] and C. Labaune[1]
[1]*LULI, UMR 7605 CNRS-Ecole Polytechnique-CEA-Université Paris VI, 91128 Palaiseau cedex, France*
[2]*CEA DAM DIF, F- 91297 Arpajon, France*
[3]*CELIA, Université Bordeaux 1, 351 cours de la Libération, 33405 Talence cedex, France*
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This Letter reports new experimental results that evidence the transition between the absolute and convective growth of stimulated Raman scattering (SRS). Significant reflectivities were observed only when the instability grows in the absolute regime. In this case, saturation processes efficiently limit the SRS reflectivity that is shown to scale linearly with the laser intensity, and the electron density and temperature. Such a scaling agrees with the one established by T. Kolber *et al.* [Phys. Fluids B **5**, 138 (1993)] and B Bezzerides *et al.* [Phys. Rev. Lett. **70**, 2569 (1993)], from numerical simulations where the Raman saturation is due to the coupling of electron plasma waves with ion waves dynamics.

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In laser-produced plasmas, stimulated Raman scattering (SRS) is a parametric instability by which the incident laser electromagnetic wave couples with electron plasma waves (EPWs) to produce scattered electromagnetic waves [1]. Above a laser intensity threshold, which depends on plasma parameters, the three waves coupling becomes unstable with significant amplification of the daughter waves. Part of the laser energy is transferred to these waves resulting in a net energy loss for many laser applications like inertial confinement fusion (ICF) [2] or electron acceleration [3]. In particular, hot electrons accelerated by these stimulated EPWs can preheat the fusion fuel in ICF experiments with a subsequent reduction in the compression efficiency.

The two decay waves can either experience convective amplification as a function of space, or grow exponentially in time in the regime of an absolute instability. The limit between these two regimes is given by $\gamma_0{}^2 > \frac{1}{2}\,\nu_{\mathrm{EPW}}\sqrt{\frac{v_{g,\mathrm{SRS}}}{v_{g,\mathrm{EPW}}}}$ which corresponds to the absolute threshold in an homogeneous plasma, where $\gamma_0 \propto I^{1/2}$ is the homogeneous SRS growth rate, ν_{EPW} is the EPW damping rate, and $v_{g,\mathrm{SRS}}$ ($v_{g,\mathrm{EPW}}$) is the group velocity of the SRS electromagnetic wave (EPW) [1]. For a given laser intensity, the absolute threshold depends on the electron density and temperature mainly through the parameter $k\lambda_{\mathrm{De}}$ (where k is the EPW wave vector and λ_{De} is the Debye length) which governs the Landau damping rate of the EPWs. This threshold is shown in the electron temperature and density plane in Fig. 1(a).

Below the absolute threshold, the SRS growth is described by the linear gain, $G = \frac{\gamma_0^2 L}{\nu_{\mathrm{EPW}} v_{g,\mathrm{SRS}}}$, where L is the plasma length, that can be calculated by postprocessing the hydrodynamics plasma parameters. In this regime, the SRS reflectivity has been shown to be controlled by the gain as long as it remains below ~15 [4]. This strategy is presently tested in ignition experiments where large-scale, hot plasmas are produced. For convective SRS gains larger than 15, the instability is expected to saturate. Experiments performed in this regime have shown a linear scaling of the saturated SRS reflectivities as a function of the laser intensity [5]. Evidences of the nonlinear evolution of the SRS EPWs through the Langmuir decay instability (LDI) were found by the observed dependence of the saturated SRS level on the ion acoustic wave damping [6] and by the direct observation of the ion acoustic wave decay products [7]. In these experiments the linear Landau damping rate of the EPWs was so high that the LDI threshold was not expected to be reached. Reduced EPW Landau damping rates due to trapping effects and/or electron distribution function modification were proposed to explain the reduction of the LDI threshold.

Above the absolute SRS threshold, the stimulated EPWs and backscattered light wave rapidly grow in time until the EPWs reach a sufficient level for triggering nonlinear saturation mechanisms. Then, the final EPW amplitude, and the corresponding backscattering level, are determined by the saturation mechanisms. This nonlinear evolution of the EPWs is mainly governed by the parameter $k\lambda_{\mathrm{De}}$ [8]. For low $k\lambda_{\mathrm{De}}$ values, the saturation of the EPW is expected to result from fluid coupling of the EPWs with the ion

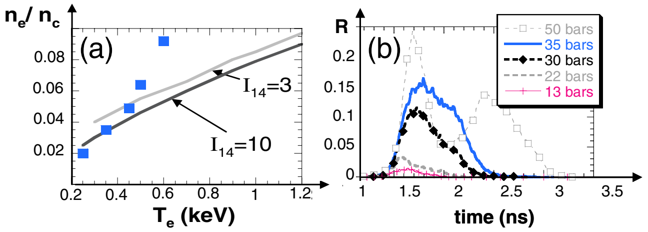

FIG. 1 (color online). (a) Absolute SRS threshold in the density and temperature plane for laser intensities $I_{14} = 3$ and 10 in units of 10^{14} W/cm^2. The absolute regime is for electron densities above the represented threshold. The blue squares show the initial parameters. (b) SRS reflectivities as function of time for the parameters of Fig. 3.

acoustic wave dynamics. For higher $k\lambda_{De}$ values, a significant amount of electrons are expected to be trapped in the stimulated EPW resulting in a modified electron distribution function that affects both the EPW Landau damping rate and frequency eventually leading to the subsequent saturation of the SRS level. Both fluid and kinetics saturation mechanisms come into play in determining the final SRS saturation level with a relative importance that depends on the laser and plasma parameters [9]. The simulations of SRS either rely on a fluid or kinetics description of the interaction. Attempts are made for including both types of effects in simulations [10]; however, the saturated SRS level is still hardly computable. Establishing and validating a scaling law for the saturated SRS reflectivity in the absolute regime is critically important to assess the reflectivity in this regime. Such a situation of SRS growing as an absolute instability is expected to occur in low temperature plasmas [see Fig. 1(a)]and could also happen in ignition scale plasmas in localized plasma regions for some times during the laser pulse due to either low electron temperature early in time, or to reduced EPW damping rate.

This Letter reports experiments which were designed to explore the saturation levels of SRS in the absolute regime. Using a fully ionized and preheated ethylene gas jet plasma, the transition between the convective and the absolute growth was observed. Significant instantaneous reflectivities were recorded only in the absolute regime. The saturation levels were measured as a function of the plasma parameters and are consistent with the scaling law established in the mid-1990s in [11,12] in the case of SRS saturated by the coupling of the EPW with the ion dynamics initiated by the Langmuir decay instability.

The experiments have been performed with the two main beams of the LULI2000 laser facility. Each beam delivers a maximum of 300 J, at 526 nm, in a 1.5 ns square pulse. The two beams were focused with $f/4.4$ corrected lenses. The experimental setup and the geometry of the beams are shown in Fig. 2(a). The plasma-producing beam irradiated a gas jet of 2 mm of diameter to preform a plasma. It was smoothed by a random phase plate producing a circular focal spot of 255 μm diameter full width at half maximum (FWHM), with a resulting averaged intensity of 2.5×10^{14} W/cm^2. At the end of this heater beam, the interaction volume was fully ionized and heated to an electron temperature of ~0.5 keV. The interaction beam was fired at this time, which corresponds to a delay of 1.5 ns with the creation beam. It was smoothed with a random phase plate producing a 130 μm focal spot (FWHM) with an average maximum intensity of 10^{15} W/cm^2. Both beams were focused 750 μm in front of the center of the gas jet, towards the interaction beam, to minimize the nonionized gas on the interaction beam path before the interaction region.

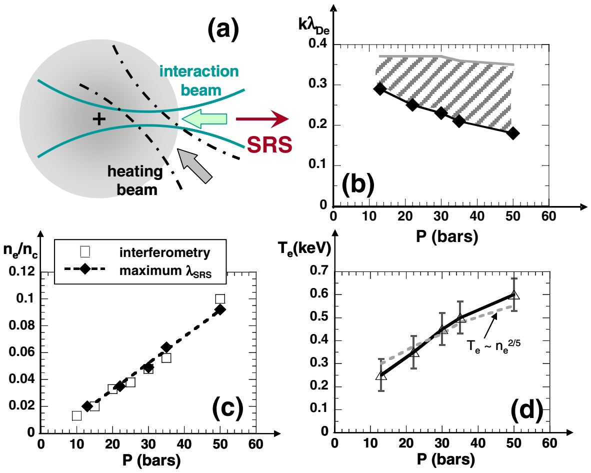

FIG. 2 (color online). (a) Geometry of the two beams inside the gas jet; (b) Range of $k\lambda_{De}$ values explored in the experiment: the black points give $k\lambda_{De}$ for the initial parameters and the shaded area indicates the domain for which significant SRS reflectivities were detected; (c) Maximum electron density present in the time-resolved SRS spectra as a function of the pressure compared with the electron density deduced from interferometry measurements of the initial neutral gas density; (d) Electron temperature as a function of the jet pressure compared with the $n_e^{2/5}$ scaling that results from reduced inverse Bremsstrahlung heating as the density decreases.

The SRS backscattered light was analyzed in two ways: (i) time-integrated SRS reflectivities were measured with absolutely calibrated fast photodiodes and (ii) time-resolved SRS spectra were recorded with an S1 streak camera coupled with a $f = 40$ cm spectrometer. The spectral and temporal resolutions of this diagnostic were, respectively, 10 nm and 250 ps. An equivalent diagnostic for the stimulated Brillouin scattering (SBS) electromagnetic wave was also setup in this experiment.

The electron density present in the ethylene (C_2H_4) gas jet was varied by adjusting the pressure at the output of the gas bottle. The initial neutral gas density was precharacterized through Mach-Zehnder interferometry measurements performed in the full range of investigated pressures. The corresponding electron densities are shown in Fig. 2(c) assuming a complete ionization of the gas. For initial pressures between 13 and 50 bars, the electron density varies from $0.02n_c$ to $0.09n_c$ where n_c is the critical density of the interaction beam. The electron temperatures during interaction were deduced from the SBS spectra assuming a stationary plasma. SBS data will be discussed in a longer paper. Typically, SBS reflectivities were in the range of 1%–5%. The electron temperatures are shown in Fig. 2(d) as a function of the gas jet pressure. The observed scaling of the electron temperature with the initial density is consistent with a reduced collisional absorption when the density decreases as predicted by a simple model [13]. The explored initial interaction conditions are represented in Fig. 1(a) and correspond to $k\lambda_{De}$ between 0.17 and 0.3, as shown in Fig. 2(b). For an interaction intensity of 10^{15} W/cm^2, the initial plasma parameters set the SRS instability above the absolute threshold at the beginning of the interaction pulse for all the investigated pressures.

The first results come from the time-resolved SRS spectra which are shown in Fig. 3 for the different pressures. The electron densities deduced from the maximum SRS wavelengths observed in the spectra are shown in Fig. 2(c). They correspond to the maximum density initially present in the plasma as given by the interferometric measurements. The width of the spectrum at any given time is small (<40 nm) for all the investigated pressures. This spectral width is associated with density variations of $\pm 0.01 n_c$ around the mean density, indicating that the interaction takes place at a well-defined electron density.

The temporal evolution of SRS reflectivities for the different initial pressures is shown in Fig. 1(b). For all the investigated pressures, except for 50 bars, the SRS signal is shorter than the interaction pulse with a duration of the SRS emission that depends on the initial density: the SRS signal is shorter when the density is lower. All these observations are consistent with the fact that SRS is observed when it grows in the absolute regime, which happens at the beginning of the laser pulse, and disappears because of the decrease of density as a function of time. This happens earlier in time in the case of low initial density. When SRS is below the absolute threshold, the SRS convective gains calculated over a speckle length do not exceed $G = 7$ whatever the pressure. Indeed, the absolute threshold for $I = 10^{15}$ W/cm^2 almost corresponds to $k\lambda_{\mathrm{De}} = 0.3$. As a result, when the instability is below the absolute threshold, the EPWs are strongly Landau damped ($k\lambda_{\mathrm{De}} > 0.3$) and the corresponding convective gain is too low for significant amplification to occur. As a consequence, the detected SRS signal ceases at the transition between absolute and convective regimes. Our observation is in agreement with a past experiment [14] investigating the short wavelength (or Landau) cutoff of the SRS spectrum where it was shown with Thomson scattering plasma characterization that the cutoff happens in the SRS spectrum when the absolute SRS threshold was no longer exceeded.

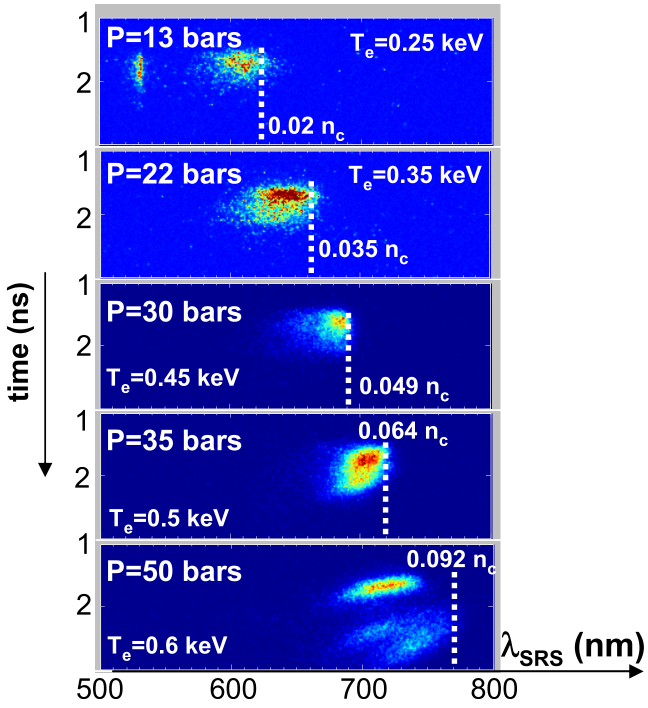

FIG. 3 (color online). Time-resolved SRS spectra measured for $P = 13$, 22, 30, 35 and 50 bars at the maximum laser intensity of 10^{15} W/cm^2. Different optical attenuators were used to record these experimental images.

These observations were used to study the SRS reflectivities as a function of the plasma parameters in the absolute regime. The SRS reflectivities, integrated over 100 ps at the beginning of the laser pulse, are plotted as a function of the laser intensity in Fig. 4(a) and show a saturation tendency. We have systematically studied the saturated SRS reflectivity as a function of the plasma density and temperature: it is almost proportional to the product $(IT_e n_e/n_c)$. These observations are consistent with the scaling law proposed in Ref. [11] where SRS saturation occurs via the LDI and associated cavitation processes.

The saturation of SRS through the coupling with ion dynamics has been the subject of numerous theoretical and numerical studies [11,12,15]. Following the results of Heikkinen and Karttunen [15], it has been first suggested that the level of density fluctuations of the SRS EPW will be limited exactly at the LDI threshold [16] resulting in a constant SRS reflectivity as soon as the LDI threshold is exceeded. This should result in a fixed saturated SRS reflectivity as the laser intensity increases in contradiction with our experimental observations [see Fig. 4(a)]. Extensive numerical studies performed in the 1990s [11,12] lead to the conclusion that the EPWs level will

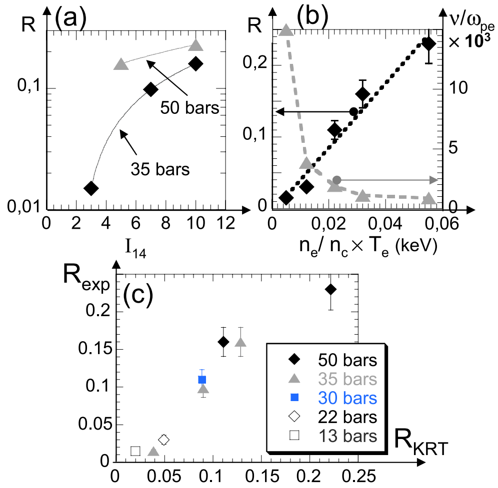

FIG. 4 (color online). (a) Maximum SRS reflectivities as a function of the laser intensity for $P = 50$ bars (▲) and $P = 35$ bars (◆); (b) Same SRS reflectivities, measured at 10^{15} W/cm^2 for the different pressures, and normalized EPW damping rate plotted as a function of the product $n_e/n_c \times T_e$; (c) Comparison between the experimental saturated SRS reflectivities (R_{exp}) with those calculated with the Kolber, Rozmus and Tikhonchuk [11] expression (R_{KRT}).

not be limited at the LDI threshold and would rather increase with the scaling $(\delta n/n_e)_{\mathrm{EPW}} = (\delta n/n_e)_{\mathrm{th,LDI}} \times (\frac{2}{3}G)^{1/2}$ where $(\frac{\delta n}{n_e})_{\mathrm{th,LDI}} = 2k\lambda_{\mathrm{De}}\sqrt{\frac{\nu_a}{\omega_a}\frac{\nu_{\mathrm{EPW}}}{\omega_{\mathrm{EPW}}}}$ is the LDI threshold. This scaling results in a linear dependence of the reflectivity on the laser intensity and no direct dependence on the EPW damping rate. Such a tendency is also observed in our experiment as shown in Fig. 4(b). For $n_e/n_c \times T_e > 0.02$ keV, the EPW damping is almost constant but the reflectivity keeps growing. The corresponding expression of the saturated SRS reflectivity is written in [11] as:

$$R_{\mathrm{KRT}} = 6.5 \times 10^{-7} T_{e,\mathrm{keV}} {\lambda_{0,\mu\mathrm{m}}}^{-1} {L_{\mu\mathrm{m}}}^{3} I_{14} \frac{\nu_a}{\omega_a} E\left(\frac{n_e}{n_c}\right) \quad (1)$$

with $E(x) = x[(1-x)^{1/2} + (1-2\sqrt{x})^{1/2}]^4 (1-2\sqrt{x})^{-1} \times (1+\sqrt{x})^{-1} \approx 12.4x$ for $x < 0.1$. Our results compare fairly well with this expression for more than one reflectivity decade as illustrated in Fig. 4(c). Here, L, the length over which SRS experiences coherent amplification is taken as the speckle length $L = 64$ μm and ν_a/ω_a, the normalized ion acoustic wave damping, is $\nu_a/\omega_a \sim 0.1$.

In [11,12], the simulations were done with interaction conditions placing the SRS instability above its absolute threshold ensuring that SRS will reach a saturated regime. They were based on the Zakharov equations that describe the coupling of the SRS EPWs with ion acoustic waves. The expression (1) for the saturated SRS reflectivity was successfully compared with numerical results in [11] where the plasma parameters correspond to $k\lambda_{\mathrm{De}}$ between 0.1 and 0.27. All these conditions are similar to the ones investigated in this Letter.

The stimulated EPWs are likely to decay through LDI in this experiment. Indeed, the LDI products have been observed in past experiments performed in close conditions at $T_e \sim 600$ eV and $n_e/n_c \sim 0.05$–0.1 [9,17]. Moreover, the density fluctuations $(\delta n/n_e)_{\mathrm{EPW}}$ associated with the stimulated EPW exceed the LDI threshold for all the parameters investigated in our experiment. The LDI threshold decreases from 2×10^{-2} to 3×10^{-3} when the pressure increases from 13 to 50 bars. The density fluctuations $(\delta n/n_e)_{\mathrm{EPW}}$ are estimated from the Bragg diffusion law $R = \frac{\pi^2}{4}(\frac{\delta n}{n_e})^2_{\mathrm{EPW}}(\frac{n_e}{n_c})^2(\frac{L}{\lambda_0})^2(1-2\sqrt{\frac{n_e}{n_c}})^{-1}$ that describes the coherent scattering of the SRS light off the stimulated EPW with a constant fluctuation level $(\delta n/n_e)_{\mathrm{EPW}}$. At 10^{15} W/cm^2, $(\delta n/n_e)_{\mathrm{EPW}} \approx 2.5 \times 10^{-2}$ for all the pressures and at 3×10^{14} W/cm^2 for 35 bars, $(\delta n/n_e)_{\mathrm{EPW}} = 7 \times 10^{-3}$ so that the fluctuations levels $(\delta n/n_e)_{\mathrm{EPW}}$ are above the LDI threshold.

Finally, our experimental reflectivities are well reproduced by the numerical scaling law (1) based on Zakharov simulations established for laser and plasma conditions similar to the experimental ones. Even if the LDI threshold is exceeded in our experiment, the coupling with the ion acoustic wave dynamics was not expected to fully control the saturated SRS reflectivity. Indeed, recent studies have demonstrated from particles in cell simulations that kinetics effects come into play for $k\lambda_{\mathrm{De}}$ values as low as 0.15 [18,19]. However, our experimental observations tend to indicate that in spite of the kinetic effects that are likely to occur in our conditions when $k\lambda_{\mathrm{De}} > 0.2$, the final backscattering level is well reproduced by the scaling law (1).

In conclusion, we have demonstrated an experimental scaling law for saturated SRS reflectivities in the absolute regime. This law is in agreement with theoretical modeling in which the main saturation mechanism is due to the coupling of electron plasma waves with ion waves dynamics.

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