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New Issues on Stimulated Brillouin Scattering in a Laser-Produced Plasma

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Abstract. — Good agreement between Stimulated Brillouin Scattering (SBS) measurements and the convective theory of SBS in randomly distributed speckles has been achieved thanks to recent progress in both the experimental and the theoretical parts. Modification of SBS in presence of a secondary interaction beam demonstrates the sensitivity of SBS to initial ion density fluctuations in the plasma.

Stimulated Brillouin Scattering (SBS) is a parametric instability which occurs during the propagation of a laser beam through a plasma where ion density fluctuations are present [1, 2]. This instability is of crucial importance in Inertial Confinement Fusion (ICF) because it can induce significant losses of the incident laser energy and spoil the illumination symmetry which is required to reach a good implosion efficiency of the pellet. SBS is the resonant decay of the incident electromagnetic wave into a scattered electromagnetic wave and an Ion Acoustic Wave (IAW). It results from a feedback loop by which the beating of the incident and scattered electromagnetic waves matches the frequency and wavenumber of the IAW. If the local laser intensity is above a threshold, which is determined by wave damping and plasma gradients, the amplitudes of the plasma and scattered waves grow exponentially on time scales of 0.1 to 10 ps until saturation [3]

SBS has been extensively studied in the past twenty years, both experimentally and theoretically, but it is only very recently that good agreement between SBS convective theory and measurements could be achieved. A crucial improvement of the experiments has been the direct measurement of the plasma waves using Thomson scattering of a short wavelength probe beam [4], and the use of well-characterized plasma conditions and laser intensity distribution in the focal volume. In this paper, we present recent SBS measurements in a preformed underdense plasma in a single beam irradiation as well as the modification of the SBS behavior in the case of multiple beam irradiation. Interpretation of the single beam results has been

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done using convective theory of SBS in randomly distributed speckles, including diffraction and inhomogeneity effects. Randomly distributed speckles correspond to the laser intensity distribution in the focal volume which is produced by the combination of a Random Phase Plate (RPP) and a focal lens. Modification of the single beam SBS in the presence of a second interaction beam, even at low intensity, demonstrates the importance of nonlinear effects when wide spectrum of IAWs is excited in a plasma.

The experiments have been performed using the six-beam laser facility of the Laboratoire pour l'Utilisation des Lasers Intenses (LULI), to produce the interaction between a $1.053 \mu\text{m}$ pump and a well-characterized preformed plasma. The plasma was produced by two opposite $0.53 \mu\text{m}$ beams, irradiating a mass limited free-standing CH foil of $450 \mu\text{m}$ diameter and $1.5 \mu\text{m}$ thickness, at time $t = 0$ (peak of the pulse). The interaction beam was focused with f/6 lenses through a random phase plate [5] (RPP) of 2 mm square elements, at time $t = 1.72 \text{ ns}$. An RPP is a transparent substrate with a random pattern of phase elements that introduce a phase shift of π in the incident light. The far-field intensity distribution of an RPP consists of an overall envelope determined by an individual phase plate element. Within this envelope there is a fine-scale speckle structure due to the interferences between different phase element contributions. This technics produces spatial smoothing of the laser beam, creating a well-characterized laser focal spot which is nearly independent of the particular aberrations of the initial laser beam. The focal spot diameter was $320 \mu\text{m}$ FWHM, with focal depth of 1.5 mm. The maximum average intensity in the focal volume of the main interaction beam was $I_{\text{pump}} = 10^{14} \text{ W cm}^{-2}$. A second interaction beam, incident at 22.5° from the first one had been used for the second part of this experiment. All its parameters were the same as the ones of the first interaction beam, with the exception of its intensity which was kept at a lower level.

At the time of interaction the plasma had a parabolic density profile along the laser axis, with a characteristic length of 1 mm. The electron density at the peak of the plasma profile evolved from $0.25 n_c$ to $0.08 n_c$, from the beginning to the end of the interaction beam (where $n_c = 1.1 \times 10^{21} \text{ cm}^{-3}$ is the critical electron density for $\lambda_0 = 1.05 \mu\text{m}$ light). The electron temperature (T_e) of the plasma, obtained by Thomson scattering of an UV probe beam in the absence of interaction beam, was between 0.4 and 0.5 keV. Both the ion acoustic and the electromagnetic waves produced by the SBS decay were diagnosed [6]. Thomson scattering of a 351 nm probe beam was used to measure the ion fluctuations level associated with SBS as a function of space and time. The backscattered light into the focusing optics of the interaction beam ($\delta\Omega = 0.045 \text{ sr}$) was spectrally resolved as a function of time, and absolute reflectivities were measured.

Figure 1 shows the temporal evolution of the SBS intensity as well as the Thomson scattered intensity from the corresponding IAWs, with respect to the laser pulse. We observed good agreement between the two diagnostics which indicates that the SBS electromagnetic wave was not strongly perturbed during its propagation through the plasma. Typical SBS reflectivities and average density fluctuations level were 2–6% and $\sim 5 \times 10^{-4}$ respectively. The duration of the SBS instability is shorter than the laser pulse, with a full width at half maximum of $\sim 300 \text{ ps}$ and its maximum at $\sim 120 \text{ ps}$ before the maximum of the interaction pulse. The temporal behavior of SBS can be explained by the evolution of the SBS gain using linear theory. Using 2D hydrodynamics simulations for density, temperature and velocity evolutions, we have calculated the convective SBS gain (G_{SBS}) using the Rosenbluth formula [7]. The expression of the amplitude gain is:

$$G_{\text{SBS}} \approx 0.092 \frac{I_{14} \frac{n_e}{n_c} \lambda_{\mu\text{m}} L_u}{T_e \left| \frac{L_u}{L_n} \frac{n_e}{n_c} \left(1 - \frac{u}{c_s} \right) - 2 \left(1 - \frac{n_e}{n_c} \right) \right|}$$

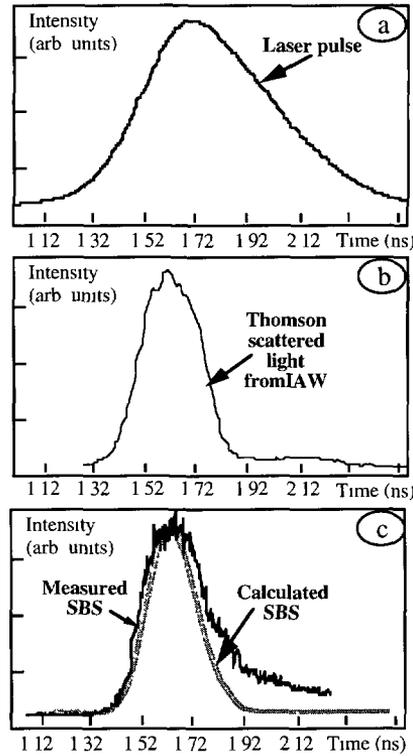


Fig. 1. — Temporal evolution of the SBS instability: a) laser pulse. b) intensity of Thomson scattered light from ion acoustic waves associated with SBS; c) intensity of stimulated Brillouin light. The gray line in Figure 1c is the calculated SBS intensity for a laser intensity of $0.8 \times 10^{14} \text{ W cm}^{-2}$, from the modeling.

where I_{14} is the laser intensity in units of $10^{14} \text{ W cm}^{-2}$, n_e/n_c is the ratio between the electron density and critical density, $\lambda_{\mu\text{m}}$ is the laser wavelength in μm , T_e is the electron temperature in keV, u is the flow velocity, c_s is the sound speed, $L_n = n_e \left(\frac{dn_e}{dz} \right)^{-1}$ and $L_u = c_s \left(\frac{du}{dz} \right)^{-1}$ are the density and velocity gradient scale lengths, respectively. Figure 2 shows the evolution of the SBS gain as a function of time for the parameters of the experiment. The temporal increase of the SBS gain follows the laser intensity, while the drop of the SBS gain is due to a combination of reduction of the electron density due to plasma expansion and increase of temperature due to plasma heating by the interaction beam.

Calculation of SBS reflectivities [8] has been done using the theory of convective amplification of SBS in an inhomogeneous plasma [9] which is applied to an individual speckle to calculate the SBS reflectivity and amplitude of the IAW. SBS is assumed to start from the thermal noise level of IAW fluctuations and, due to the plasma flow velocity gradient, each particular three wave interaction extends over a distance L_a which is short compared to the Rayleigh length L_R of the speckle. The reflectivity for an individual speckle is a microscopic quantity. In order to relate it to observations we calculate the average macroscopic reflectivity $\langle R \rangle$ by averaging the SBS emission from an individual speckle over the probability distribution of speckles with different intensities [10]. The total reflectivity is then calculated by integration of $\langle R \rangle$ along

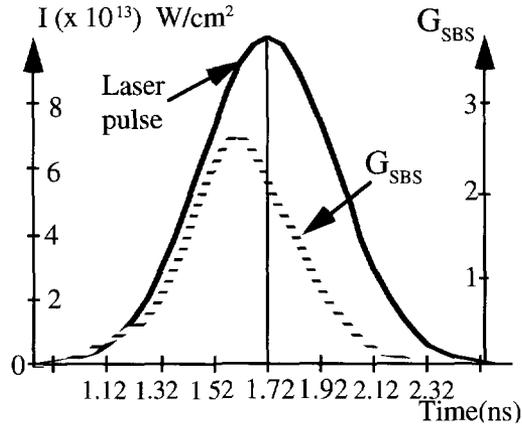


Fig 2. — Temporal evolution of the convective SBS gain including the evolution of the plasma parameters and laser intensity

the laser ray trajectories taking into account the plasma density and laser intensity profiles. The gray curve in Figure 1c is the calculated SBS intensity, for an incident laser intensity of $0.8 \times 10^{14} \text{ W cm}^{-2}$. It shows very good agreement with the measured SBS intensity. This comparison is within an error bar of 50 ps. The calculated reflectivity of 2% also agrees well with the measurements. The calculated and measured levels of density fluctuations associated with SBS agree within a factor of two. It is interesting to notice that, as the SBS gain calculated for the average laser intensity is fairly small, $\langle G \rangle \sim 3$, the major contribution to the SBS reflectivity comes from speckles with local intensities ~ 4 times above average, corresponding to local gain of about 12. In such conditions the pump depletion occurs inside a speckle, which defines the local SBS reflectivity. However, because of the small number of these high intensity hot spots, the observed overall SBS reflectivity is still low.

Important modification of the SBS reflectivity has been observed when adding a second interaction beam, even at low intensity. Figure 3 shows the decrease of the SBS reflectivity in the backward direction, with respect to the first interaction beam, when increasing the intensity of the second interaction beam. The levels of the ion acoustic fluctuations associated with SBS have been observed to decrease as well with increasing intensities of the second interaction beam. This is the first evidence that levels of IAW from SBS, as well as level of the SBS reflectivity, can be reduced as a consequence of introducing a second interaction beam. A possible explanation for this effect is the presence of IAW driven by the secondary beam, either in backscatter or side scatter, which are seen by the main beam as long wavelength ion waves. It has been observed in the theory and numerical simulations [11] that long wavelength ion fluctuations produce a nonlinear inhibition of SBS by introducing an additional phase detuning and damping for the resonant IAW. Another effect that can be responsible for the backward SBS reduction is the energy exchange between two interacting laser beams [12]. The recent theoretical analysis of the mutual interaction of two laser beams in a plasma [13, 14] demonstrates possibility of a significant energy transfer from high to low intensity laser beam. Reference [13] also demonstrates the reduction of the backward SBS and the excitation of another parametric instability, double SBS, in the bisectoral direction between two beams.

In conclusion, we have presented SBS results based on both the scattered electromagnetic and the ion acoustic waves produced in the decay. Many observed features can be explained by the theory of convective amplification of SBS in an inhomogeneous plasma, assuming that SBS

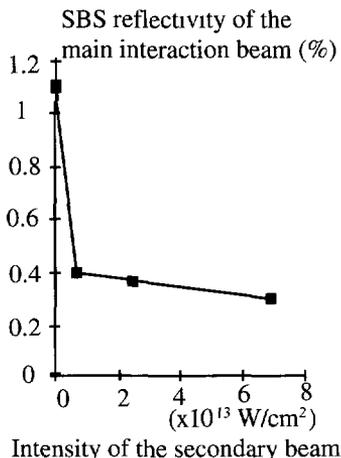


Fig. 3. — Modification of the SBS reflectivity of the main interaction beam as a function of the intensity of the secondary interaction beam

occurs in randomly distributed speckles. This hypothesis naturally combines pump depletion effects within a speckle, with relatively minor SBS reflectivity of the whole interaction beam. The modification of SBS in the presence of a second interaction beam shows the sensitivity of stimulated Brillouin scattering to the initial conditions at the point of departure. The IAW fluctuations can reduce or modify SBS depending on their spectral characteristics with respect to the ones associated with the one beam driven SBS. A detailed characterization of the ion fluctuations and turbulence is then essential, besides the plasma conditions, in order to model the overall evolution of the instability.

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