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Stimulated Brillouin scattering with a 1 ps laser pulse in a preformed underdense plasma

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An experimental study of stimulated Brillouin scattering (SBS) with a 1 ps laser pulse in a large underdense preformed plasma is presented. It is shown that the SBS reflectivity increases from 10^{-4} to 10^{-1} as the intensity of the interaction beam rises from 5×10^{14} to 10^{16} W/cm^2; for intensities between 10^{16} and 10^{17} W/cm^2, a saturation level at 10% is experimentally established. This experimental result is compared with theoretical estimates of time-integrated SBS reflectivity in the transient phase of the so-called modified decay regime. The latter results are seen to be consistent with the experimental data provided that there exists a nonthermal noise in the plasma depending on the laser intensity.

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Stimulated Brillouin scattering (SBS) is a parametric instability in which an incident light wave resonantly decays into a scattered light wave and an ion acoustic wave (IAW) [1]. This instability can grow over a large volume of plasma, whenever the inequality $n/n_c < 1$ is satisfied; here n and n_c denote the electron and critical density, respectively. Since SBS has a great potential for scattering and redistributing the incident light energy, it is an important issue for inertial confinement fusion (ICF).

The SBS instability has been extensively studied for many years both theoretically [2] and experimentally [3]. So far the experimental studies were performed with nanosecond laser pulses [3,4]. Under such experimental conditions the instability already reaches a highly nonlinear saturated state for most of the pulse duration, which makes it very difficult to identify and study the physical processes in play. A different approach for studying SBS consists in using a short laser pulse as a pump. For most plasma conditions and laser intensities of interest, the SBS growth time is of the order of a picosecond: the use of a picosecond duration laser pump allows one to study SBS at a stage where the nonlinear saturation has not yet been reached, thus permitting a more direct and easier comparison with theoretical works. Moreover, studying SBS with a short laser pulse has the advantage of minimizing the effects of the hydrodynamic evolution of the plasma: the different scale lengths and the expansion velocity changing on slow hydrodynamic time scales can be regarded as frozen on the short pulse duration time scale.

Until now very few experimental works on SBS with short laser pulses in a preformed plasma have been published. The first reported experiment was performed with a 10 ps, 1.06 μm laser pulse [5,6]. It showed that the time integrated SBS reflectivity rose from 10^4 to 10^{-2} as the incident laser intensity was raised from 7×10^{13} W/cm^2 to 2×10^{15} W/cm^2. This work has originated both analytical and numerical studies [6,7] which have revealed a strong discrepancy between theory and experiment, especially at low laser intensities. In this paper, we present an experimental study of SBS produced by the interaction of a 1 ps laser pulse with a large preformed plasma free of critical density. The experimental results are compared with theoretical estimates of time-integrated SBS reflectivity. The latter results are seen to be consistent with the experimental data provided that the instability is assumed to grow from an effective noise depending on the laser intensity like I^α with $1 < \alpha < 2$.

The experiment was performed at Commissariat à l'Energie Atomique (CEA), Centre d'Etudes de Limeil-Valenton (CEL-V) using the P102 picosecond Nd-glass laser system, extensively described in Ref. [8]. The concept of this ultraintense and ultrashort laser is based on the chirped pulse amplification (CPA) technique [9]. For this experiment, a polarizing filter split the chirped laser beam into two beams: the first one was used to perform the plasma; the second one was used for the interaction with the underdense plasma. This configuration makes it possible to study the interaction over a large range of laser intensities with the same plasma conditions. The experimental setup is sketched in Fig. 1.

The first beam, or creation beam, 300 ps full width at half maximum (FWHM), was focused by a $f/5$ lens ($f = 450$ mm) at 45° to the target plane onto a thin plastic foil (CH) at the fundamental frequency of the Nd-glass laser (1.064 μm). A 2 mm cell random phase plate (RPP) was added to smooth the focal spot. The focal spot size was 250×350 μm^2. The energy of the creation beam was maintained at 3 J, yielding an average intensity of 1.5×10^{13} W/cm^2. The target thickness (100 nm) and the time delay Δt between the creation beam and the interac-

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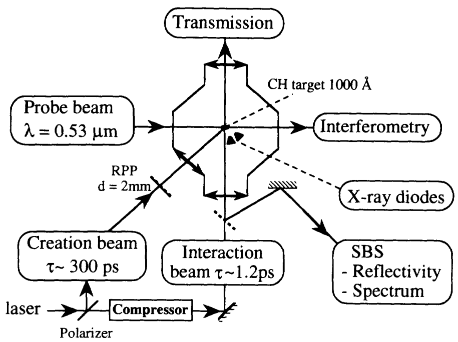

FIG. 1. Experimental setup.

tion beam ($\Delta t = 1.2$ ns) were chosen to obtain a subtenth critical plasma during the interaction, according to the mass ablated formula [10] and the London-Rosen model [11]. The density and the temperature profiles just before the arrival of the ps pulse were estimated from one dimensional (1D) hydrodynamic simulations (FILM) [12]. One obtained a 1 mm FWHM Gaussian electron density profile with a maximum of $(0.03\text{–}0.05)n_c$ and an electron (ion) temperature around 100 eV (60 eV).

Two diagnostics, optical interferometry and x-ray diodes, were used to characterize the preformed plasma. The interferometry was performed using a 0.53 μm probe of 20 ps duration and a Wollaston type interferometer. It probed the plasma 25 ps before the interaction pulse arrival, giving an electron plasma density between 4% and 5% of critical density. Time-integrated measurements made with x-ray diodes for shots without the interaction beam give an electron temperature of 100 eV just before the interaction. These values are in good agreement with the predictions of the 1D simulations.

The second beam, or interaction beam, was focused with a $f/9$ lens ($f = 645$ mm) in a direction perpendicular to the initial target plane, onto a smaller focal spot (1600 μm^2) [13]. The pulse duration was 1.2 ps FWHM at 1.064 μm, as measured with a single-shot autocorrelator. A pedestal of 100 ps duration preceded the picosecond pulse; the intensity peak-to-background contrast ratio was measured to be $10^4 : 1$. The spectral width of the picosecond pulse was typically 2 nm FWHM. The energy of the interaction beam on target was varied from 10 mJ to 3 J by locating optical-quality attenuators in the beam (cf. Fig. 1).

The backscattered light was collected through the focusing lens of aperture $\Delta\Omega = 0.02$ sr and analyzed with two separate diagnostics. The first consisted of a fast S1 photodiode adequately filtered; the rise time (300 ps) was limited by the bandwidth of the oscilloscope which was sufficient to clearly separate the signals originating from the nanosecond and picosecond laser pulses. The second diagnostic was a spectrometer (5×10^{-3} nm resolution) in combination with a charge coupled device (CCD) camera; because of the weak sensitivity of the CCD camera, the spectra were recorded only at laser intensities above 10^{16} W/cm^2. The transmitted light was measured through a lens identical to the focusing lens and was imaged onto a second fast S1 photodiode.

The main result concerns the time-integrated SBS reflectivity as a function of the laser intensity and is presented in Fig. 2. This reflectivity is the ratio of the SBS energy backscattered through the focusing lens to the incident laser energy. Two remarkable features are observed: (i) the SBS reflectivity sharply increases from below 10^{-4} to 10^{-1}, as the incident laser intensity is raised from 5×10^{14} W/cm^2 to 10^{16} W/cm^2; (ii) the reflectivity clearly reaches a plateau at 10^{-1} for intensities between 10^{16} W/cm^2 and 2×10^{17} W/cm^2. These results are in sharp contrast with those in Refs. [5,6] in which the reflectivity was observed to gently increase with the laser intensity without reaching any plateau. It is experimental evidence of SBS reflectivity saturation for picosecond laser pulses.

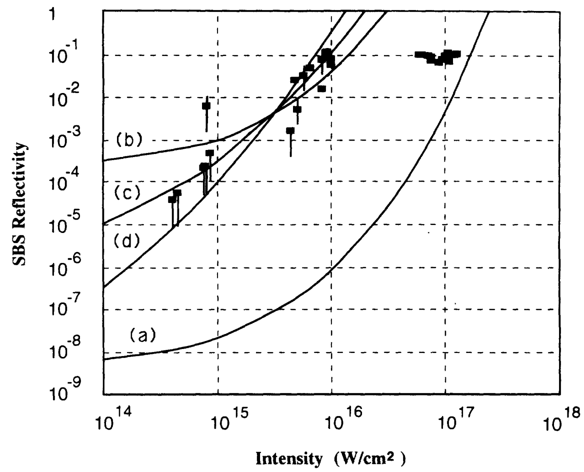

FIG. 2. Time-integrated SBS reflectivity, as a function of the laser intensity. The squares represent the experimental data and the solid lines represent the theoretical curves calculated for different noises (in terms of Thomson reflectivity R^{Thom}): curve (a) $R^{\text{Thom}} = R^{\text{Thom}}_{\text{Therm}} = 7.02 \times 10^{-9}$, curve ($b$) $R^{\text{Thom}} = 3.32 \times 10^{-4}$, curve ($c$) $R^{\text{Thom}} = 1.03 \times 10^{-5} I_{14}$ and curve (d) $R^{\text{Thom}} = 3.20 \times 10^{-7} I_{14}^2$. The parameters are $L = 600$ μm, $T_e = 0.1$ keV, $T_i = 0.06$ keV, and $n_e/n_c = 0.04$.

The spectrum of the incident pulse is shown in Fig. 3(a). Figure 3(b) displays a typical SBS spectrum for a 10^{17} W/cm^2 intensity shot. The spectra generally exhibit a redshifted emission. The mean wavelength shift, measured as the distance between the peaks of the incident and scattered spectra, remains around 1 nm and exhibits no clear dependence on the laser intensity. On the other hand, the width of these spectra weakly increases with the laser intensity, from 2–2.5 nm FWHM at 10^{16} W/cm^2

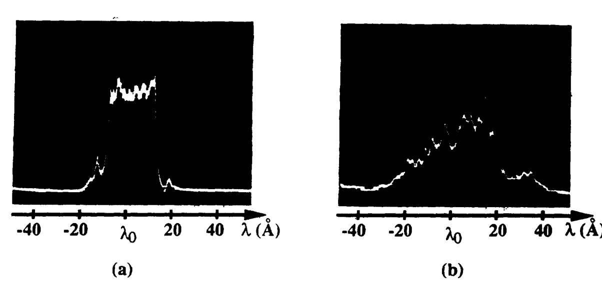

FIG. 3. Incident (a) and reflected (b) spectra for a laser intensity of 10^{17} W/cm^2.

to 2.5–3 nm FWHM at 10^{17} W/cm^2.

From the dependence of the transmitted light upon the incident laser intensity, it can be seen that the transmission rate increases from a few percent at 5×10^{14} W/cm^2 to about 20% at 10^{17} W/cm^2. The transmission rate for thicker 200 nm CH foil plasma remains below 3%, even at high laser intensity. The increase of the transmission rate with the laser energy is consistent with the heating of the plasma by the interaction beam; however, a quantitative estimate of this heating on a picosecond time scale and for high intensities is not straightforward and is beyond the scope of this paper.

Measurements of SBS reflectivity as displayed in Fig. 2 strongly suggest that the SBS *nonlinear* saturation only starts playing a significant role for pump intensities above 10^{16} W/cm^2. For lower intensities one can ignore the pump depletion and the IAW nonlinearity so that the reflectivity should in principle be predicted from theoretical estimates based upon the *linear* theory of SBS. In the following, we will restrict ourselves to the comparison between experimental and theoretical results within the validity domain of the linear theory $I_0 \leq 10^{16}$ W/cm^2 only.

In its simplest form [7] this theory is characterized by the three following features: (i) a 1D model is used in which the waves propagate in an underdense homogeneous preformed plasma of finite length L; (ii) the incident pulse of peak intensity $I_{\max}$ and characteristic duration t_p is replaced by a square pulse of intensity I_0 and duration t_p, where I_0 is determined so that the total energy is identical to the incident energy ; (iii) the parametric growth from IAW noise is solved in terms of fluctuating initial conditions, boundary conditions, and source terms.

It is worth noticing that, unlike the case of the experiment reported in Refs. [5,6] the SBS growth rate γ can be *greater* than the IAW frequency ω_s so that the time envelope approximation for the SBS driven IAW fails within the validity domain of the linear theory itself. One has therefore to compute the reflectivity either in the standard decay regime, defined by $\gamma \ll \omega_s$, or in the modified decay regime, defined by $\gamma \gg \omega_s$, depending upon the intensity of the pump wave. The detailed calculations of the time evolution of the reflectivity as given by this theory are beyond the scope of this paper [14] and we will only consider the time-integrated reflectivity to be compared with the experimental results of Fig. 2.

We have numerically observed that the theoretical time-integrated reflectivity R does not depend strongly on the electron temperature, electron density, and interaction length. It is therefore reasonable to use typical values, namely, $T_e = 0.1$ keV, $T_i = 0.06$ keV, $n/n_c = 0.04$, and $L = 600$ μm (corresponding to the Rayleigh length of the irradiation optics) for modeling this experiment. The remaining parameters are $Z = 5.29$, $A = 6.55$, and $\lambda_0 = 1.06$ μm. Figure 2, curve (a), shows the theoretical curve assuming that SBS grows from the *thermal* level; the squares represent the experimental data. One can observe that the theoretical prediction is lower by several orders of magnitude than the experimental results.

There is no easy explanation for this dramatic discrepancy between theory and experiment (we have checked that varying the plasma parameters within a realistic range cannot account for the several orders of magnitude difference). Possible causes are (i) SBS in the pedestal, (ii) hot spots in the laser beam, and (iii) SBS growth from a nonthermal noise.

(i) We have checked that, for our experimental conditions, the SBS reflectivity *in the pedestal* is always less than the Thomson reflectivity *in the principal pulse.* It follows that the SBS reflectivity in the pedestal cannot significantly enhance the reflectivity in the principal pulse.

(ii) Hot spots could exist due to either the quality of the laser beam [13] or the filamentation instabilities which can develop in an underdense plasma. Using standard expressions for the ponderomotive and thermal filamentation growth rates, one finds that the gain factors for these two instabilities cannot be very large compared to unity in the regime $I_0 \leq 10^{16}$ W/cm^2 so that filamentation is very unlikely to be present and to play a significant role in this experiment. On the contrary, hot spots associated with a nonuniform laser intensity distribution could be an important issue for what concerns the relevance of our comparison between theory and experiment. These hot spots might lead to a large reflectivity in the low flux regime provided that the laser intensity probability distribution is non-negligible over an intensity range of more than one order of magnitude above the mean value. One cannot *a priori* reject such an intensity distribution until the histogram of the laser intensity is available. Consequently, it will be of great interest for future short pulse experiments to measure this histogram.

(iii) Curve (b), Fig. 2, shows the SBS reflectivity calculated from an enhanced nonthermal noise corresponding to an effective Thomson reflectivity of 3.32×10^{-4}. The latter value has been obtained as the best fit from the least square method and corresponds to an enhancement of four orders of magnitude relative to thermal noise. Such a translation of the theoretical curve might represent some residual enhanced IAW's remaining from the preforming pulse after the 1.2 ns delay. It can be seen that this curve does not fit the experimental data so that some other mechanisms for the nonthermal noise generation should be invoked. Curves (c) and (d), Fig. 2, show the SBS reflectivity calculated from an enhanced nonthermal noise corresponding to an effective Thomson reflectivity given by $\eta_1 I_{14}$ and $\eta_2 I_{14}^2$, respectively, with $\eta_1 = 1.03 \times 10^{-5}$ and $\eta_2 = 3.20 \times 10^{-7}$ and where I_{14} denotes the laser intensity in units of 10^{14} W cm^{-2}. In this case, the theoretical curves are seen to fit the experimental results far better than in the previous one. Accordingly, one is led to the hypothesis that the thermal Thomson reflectivity should be replaced by an effective one proportional to I^α with $1 < \alpha < 2$. It follows in particular that the enhanced nonthermal noise originates from the interaction beam and not only from the creation beam.

A possible explanation for the fact that the effective Thomson reflectivity depends on the laser intensity is the coupling between SBS and stimulated Raman scattering (SRS) [15]. Although SRS develops from a noise level lower than that of SBS by a factor ω_s/ω_{pe}, it has a larger growth rate; the SRS driven electron plasma waves (EPW's) can then give rise to either parametric decay or modulational instabilities [16] which lead to cascading and/or collapse. These nonlinear processes may generate IAW turbulence characterized by an anomalous IAW noise from which SBS could in turn develop.

For a 1 ps laser pulse duration, a scenario involving *parametric decay* of the SRS driven EPW has to be ruled out: numerical simulations in the low intensity regime [17] have indeed shown that, in this case, it takes a few tens of picoseconds for these processes to occur. On the other hand, one finds that, for the physical parameters of Fig. 2, the growth rates of SRS (for $I \geq 10^{15}$ W cm^{-2}) and of the modulational instability are both greater than 10 ps^{-1}, which is consistent with a 1 ps laser pulse. One may therefore conjecture that the effective IAW noise from which SBS grows is generated by the *modulational instability* of the SRS driven EPW. Numerically checking the latter conjecture is currently in progress.

To summarize, we have presented an experimental study of SBS with a 1 ps laser pulse in a large underdense preformed plasma. The theoretical reflectivity is seen to be consistent with the experimental data provided that the noise is assumed to depend on the laser intensity like I^α with $1 < \alpha < 2$. We conjecture that this intensity dependent noise originates from the SBS-SRS coupling through the modulational instability of the SRS driven EPW. Simultaneous measurements of SBS and SRS reflectivities as well as Thomson scattering probing of EPW and IAW noise levels would be of great interest in order to check the actual importance of SRS-SBS coupling in 1 ps laser pulse experiments.

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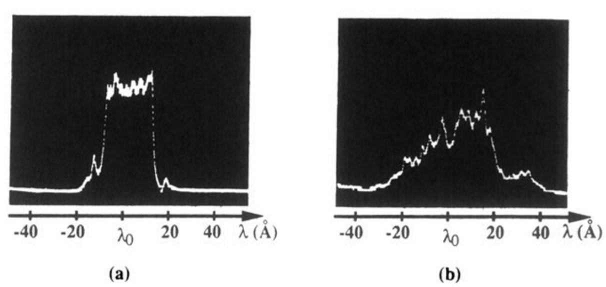

FIG. 3. Incident (a) and reflected (b) spectra for a laser intensity of 10^{17} W/cm^2.