Stimulated Brillouin backscattering from underdense expanding plasmas in a regime of strong filamentation

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Stimulated Brillouin backscattering (B-SBS) from delayed interaction with a preformed, long scale-length expanding plasma was experimentally investigated in a regime favorable to strong self-focusing (SF) and filamentation. An extremely low backscattering reflectivity (of the order of 10^{-4}) was measured and anomalous time-resolved spectra were observed. Spectral and temporal features of the reflectivity suggest a strong effect of SF on B-SBS: In the early phase of the interaction SF lowers the B-SBS threshold and possibly leads to rapid saturation, while in the late phase there is a substantial decoupling of the SBS active regions from the plasma bulk due to their motion towards the laser beam. This motion is attributed to a moving focus effect driven by ponderomotive SF. [S1063-651X(99)00601-7]

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I. INTRODUCTION

Stimulated Brillouin scattering (SBS) is currently a major topic in laser-plasma interaction research, since it is widely recognized that a control and, possibly, the suppression of SBS are of crucial importance in laser-driven inertial confinement fusion (ICF) [1]. The elementary SBS process is the decay of an electromagnetic (EM) wave into an ion-acoustic wave (IAW) and a second EM wave, which propagates preferentially in the direction opposite to the incident one. In principle, the SBS parametric instability may grow to high levels in an underdense plasma resulting in a large amount of backscattered laser radiation. Theoretical investigations have shown that SBS generation in ''realistic'' conditions of interaction of focused laser beams with underdense, inhomogeneous plasmas is a complex process. It depends on various factors such as, for example, the interplay with laser self-focusing (SF) and other parametric instabilities and hot spot collective effects.

Experiments on delayed interaction with preformed, long-scale-length plasmas (see [2], and references therein) have evidenced a number of features which are not always satisfactorily explained, including localization of SBS emitting regions, large spectral width, and low reflectivity. On the other hand, it was recently suggested by Drake [3] that, according to some significant experiments, the importance of SBS as a detrimental factor in ICF is actually overestimated. The effort towards the control of SBS could therefore be reduced, with consequent beneficial effects in the development of next generation ICF facilities, such as the U.S. National Ignition Facility (NIF). However, the verification of this assumption requires a very detailed and critical analysis of experimental results, since the complexity of the interaction scenario could make traditional diagnostics less useful, and measurable quantities ambiguous, including intensity thresholds, spectrum, or backward reflectivity.

As an example of such a case we mention the effects of the interplay between self-focusing or filamentation instability (FI) and SBS. It was previously proven that the onset of FI provides an effective threshold to SBS, whose level can be consequently reduced by use of beam smoothing techniques [4]. Experiments using diagnostics such as time-resolved imaging [5] or Thomson scattering [6] showed a speckle or filamentary structure of SBS emitting regions. Theoretically, it was suggested that the rapid evolution of filaments may strongly influence the temporal evolution of SBS, the amount and direction of the scattered light [7,8]. In a recent theoretical study a quasistatic unified treatment of SF and SBS was developed showing in particular that the SBS reflectivity is dramatically enhanced in hot spots containing a laser power beyond the FI threshold [9]. However, rapid saturation can be produced by flow profile modifications inside the hot spots [10]. Very recently, kinetic effects in intense hot spots were suggested to affect significantly SBS [11]. Therefore, in a regime of strong SF many effects may influence the level and features of SBS, but a detailed picture of their relative weight, as well as a definitive estimate of the importance of detrimental effects of B-SBS, is still lacking.

In this paper we describe measurements of stimulated Brillouin backscattering (B-SBS) from the interaction of a laser pulse with a preformed, inhomogeneous plasma in conditions favorable to SF: in particular, a high f number ($F=15$) focusing optics and an IR wavelength ($\lambda=1.064\ \mu$m) for the interaction pulse were used. The experiment was designed to investigate the propagation of a laser pulse in a long-scale-length plasma, with the simultaneous use of several diagnostics including probe interferometry, x-ray time-resolved spectroscopy, second-harmonic

(SH) emission, and B-SBS. A substantial effort has been devoted to the production and characterization of the preformed plasma to obtain well-known and reproducible interaction conditions [12]. Significant anomalous features were found in the experimental SBS data: the time-resolved B-SBS spectral reflectivity was found to change dramatically in time, showing a first sharp, broadband peak followed by a weaker narrow-band emission shifting regularly in time to the blue side of the spectrum, with a second, less intense peak at later times. The overall SBS reflectivity was extremely low (10^{-4}). These features were weakly dependent upon the laser intensity which was varied by a factor of 20 over the set of experimental data shots. The early backscattering peak suggests rapid saturation of B-SBS due to SF in hot spots. By comparison of B-SBS spectral data with optical and x-ray diagnostics we found that the large spectral width of the first peak cannot be explained in terms of Doppler shift from a large plasma region. Also nonlinear optical effects, such as self-phase modulation due to further plasma ionization during the interaction, cannot account for the observed spectral width of the early spectrum. Late spectral features are consistent with a supersonic motion of the B-SBS emitting region towards the laser, which is attributed to a backward ''moving focus'' process, leading to decoupling of the interaction beam from the region of maximum SBS gain. The speed and direction of the ''moving focus'' are in good agreement with the nonlinear theory of dynamical SF [13]. The set of experimental results support a scenario in which SBS evolution is driven by SF dynamics, which, as discussed below, is responsible for keeping the time-integrated backscattering reflectivity very low.

II. EXPERIMENTAL SETUP AND PLASMA CHARACTERIZATION

The plasma was preformed by laser heating of thin Al foil targets using four synchronized 600 ps duration, 1.053 μm wavelength laser beams of the Vulcan laser. The beams were focused with $F/10$ optics and superimposed in pairs on each side of the target in a 600 μm diameter focal spot to provide a total intensity up to 1.2×10^{14} W cm^{-2}. The targets consisted of 0.5 μm thick, 400 μm diameter Al dots coated on a thin 0.1 μm plastic stripes. Two-dimensional electron density maps were obtained by interferometry [12,14], using a 100 ps, frequency-doubled (0.53 μm) probe beam set to propagate in the direction perpendicular to the main longitudinal target axis. Consequently, the interferometry channel also gave time-integrated images of side-emitted second-harmonic (SH) light. The electron temperature was monitored by means of time-resolved x-ray spectroscopy [12]. A 600 ps, 1.053 μm interaction pulse, incident along the main longitudinal target axis, was delayed by 2.5 ns with respect to the peak of the heating pulses. A more detailed description of the experimental setup can be found in [12].

The longitudinal electron density profile, i.e., the electron density profile along the main target axis, at the time of interaction (2.5 ns after the peak of the heating laser pulses) is shown in Fig. 1 ($N=n_e/n_c$, $n_c=1.1\times 10^{21}$ cm^{-3} being the critical density for Nd laser light) . At this time the electron temperature (T_e) was 450 ± 50 eV. Figure 1 also shows the profile of the longitudinal flow velocity (v_x) in units of

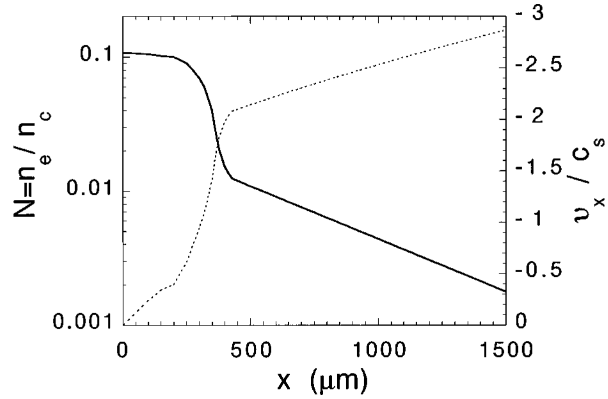

FIG. 1. Longitudinal density profile obtained from interferometry (thick line), in units of the critical density $n_c=10^{21}$ cm^{-3}, and self-consistent longitudinal velocity profile (dashed), in units of the sound velocity c_s, with the assumption of isothermal plasma and steady-state planar hydrodynamical expansion (see text). The initial target position is at $x=0$.

the sound velocity $c_s=\sqrt{ZT_e/M}$, estimated from the density profile assuming a steady-state planar hydrodynamical expansion ($v_x\partial_x v_x=-\partial_x N/N$); Z is the average ionization degree and M the ion mass. For an Al plasma with $T_e=450$ eV and $Z=11$ we find $c_s=1.3\times 10^7$ cm s^{-1}.

The interaction beam was focused by an $F/15$ optics, either in a 150 μm circular spot with an approximately Gaussian intensity profile (tight focus), or in an elongated 150 μm$\times$300 μm spot (line focus) obtained by tilting the focusing lens. The focal depth was about 1.5 mm in a vacuum, ensuring that the intensity was almost constant over the whole longitudinal extent of the plasma. The focal spot size was definitely smaller than the plasma transverse scale length (400 μm) to avoid refraction effects at the boundaries of the plasma. The intensity of the interaction pulse (I_L) was varied in the range $7\times 10^{13}-6\times 10^{14}$ W cm^{-2} in the line focus case and in the range $1.5\times 10^{14}-1.2\times 10^{15}$ W cm^{-2} in the case of tight focus. The far-field image of the beam transverse profile showed intensity modulations with a contrast up to 50% and a typical scale length of approximately one-tenth of the spot size.

Experimental data were also obtained using smoothing techniques such as random phase plates (RPP) and smoothing by spectral dispersion (SSD). However, they are not reported here since the effect of smoothing is beyond the aim of the present paper. We only mention that, in the case of RPP, the need of a spot width less than the plasma transverse extent posed limitations on the size of their structure, such that both the spot and the speckles size were not largely different from those obtained without the use of RPPs; consistently, a preliminary analysis of the backscattering data with RPP smoothing did not evidence substantial differences with the data reported in this paper.

In order to investigate B-SBS, the backscattered light was collected in the solid angle of the $F/15$ focusing lens. A calibrated diode was used for energy measurements and a $\frac{1}{2}$-m spectrometer coupled to an IR streak-camera was used for time-resolved spectroscopy. The time and spectral resolutions were 100 ps and 1 Å, respectively.

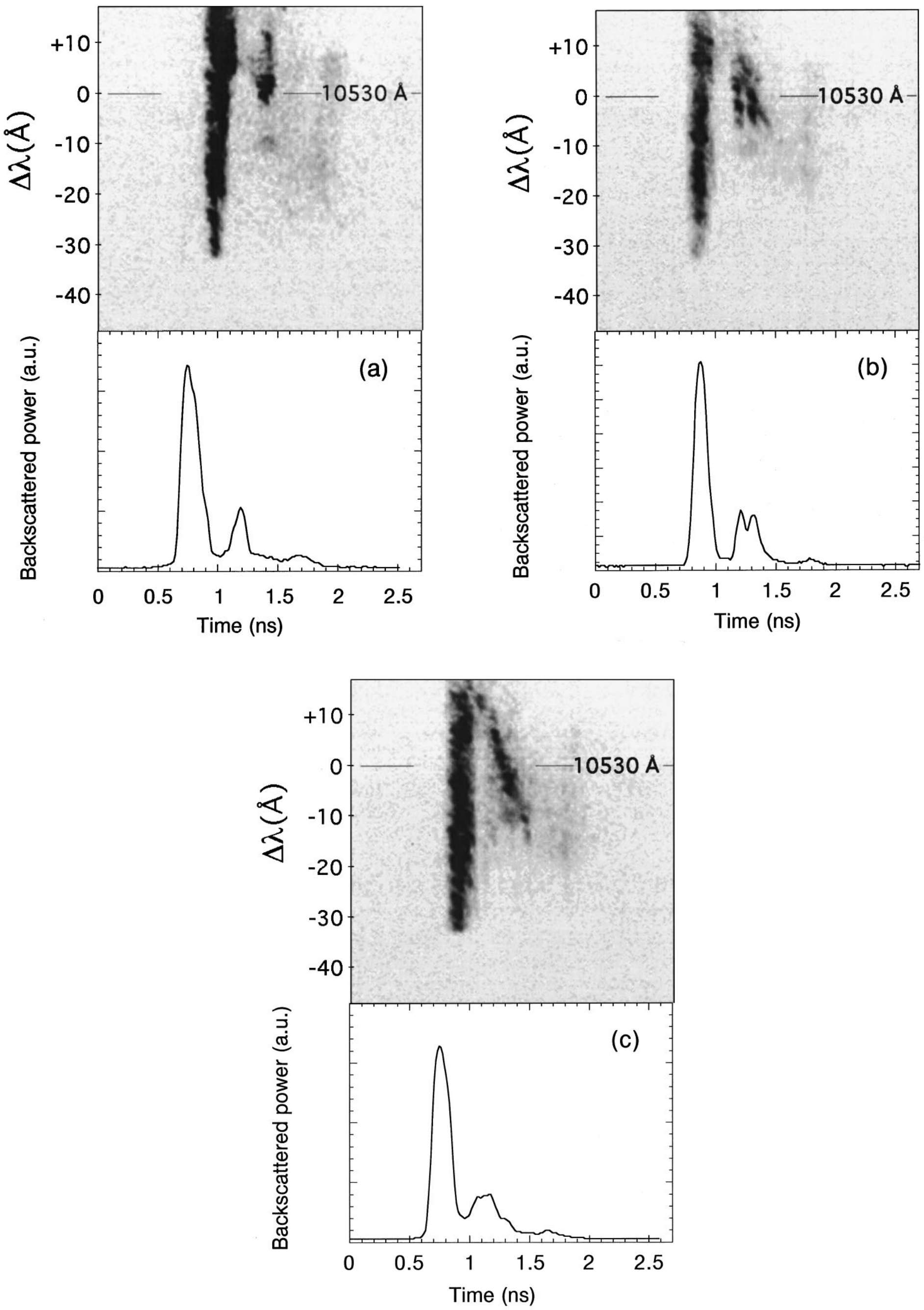

FIG. 2. Time-resolved spectra (top frames) and time histories (bottom frames) of backscattered light from interaction with the preformed plasma, obtained in the ''line focus'' configuration for three different intensities of the interaction pulse: 7×10^{13} W cm^{-2} (a), 3.3×10^{14} W cm^{-2} (b), 5×10^{14} W cm^{-2} (c). The temporal histories are obtained by integration over the full wavelength range of the spectra.

III. EXPERIMENTAL RESULTS

Figure 2 shows three representative time-resolved B-SBS spectra from the interaction with the preformed Al plasma, taken in the line focus configuration at intensities $I_L=7.0\times10^{13}$ W cm^{-2} (a), $I_L=3.3\times10^{14}$ W cm^{-2} (b), and $I_L=5.0\times10^{14}$ W cm^{-2} (c), respectively. In the bottom frames the backscattering histories, obtained by integration along the wavelength axis, are reported. The spectra show a first broadband peak, extending from -30 Å to $+15$ Å with respect to the laser wavelength and having an instrument-limited duration of about 120 ps; this early part is rather independent of the laser intensity. At later times the spectra show a weaker, narrow-band emission whose frequency changes in time; it is characterized by a secondary peak occurring about 500 ps after the first peak, centered approximately around the unperturbed laser wavelength. A third weak maximum is also apparent at about 1 ns after the first peak. In the spectrum at higher intensity, Fig. 2(c), the narrow-band emission is clearly seen to shift in time regularly from the red side of the spectrum at $+15$ Å to the blue side at -10 Å, with a typical drift rate of about 40 Å/ns.

Figure 3 shows a spectrum taken in the tight focus configuration for $I_L=1.2\times10^{15}$ W cm^{-2}. This spectrum is very similar to the ones of Fig. 2 obtained with the line focus at

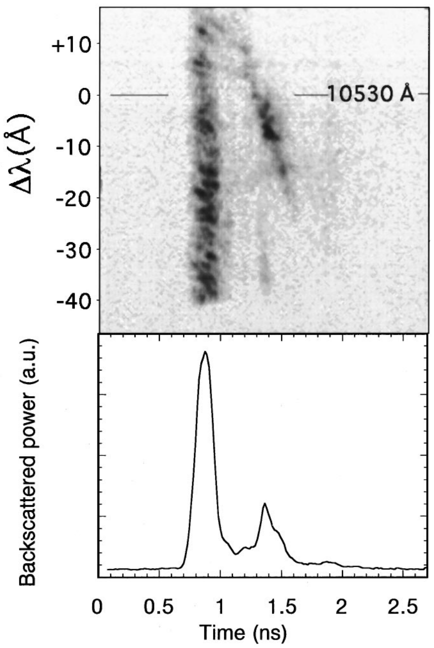

FIG. 3. Time-resolved spectrum (top frame) and temporal history (bottom frame) of backscattered light from interaction with the preformed plasma, obtained in the ''tight focus'' configuration for an interaction pulse intensity of 1.2×10^{15} W cm^{-2}.

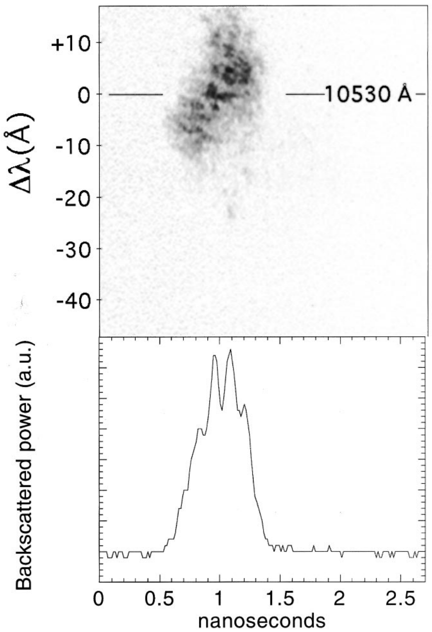

FIG. 4. Time-resolved spectrum (top frame) and temporal history (bottom frame) of backscattered light from interaction with the solid target (no preformed plasma) for an interaction pulse intensity of 1.2×10^{15} W cm^{-2}.

lower intensities. In this shot, the detection level was kept well below saturation in order to investigate the presence of spectral modulations in the early broadband emission which shows a spectral periodicity of roughly 2 Å.

The time-integrated backscattering reflectivity, measured in the same conditions as those of Figs. 2 and 3, was found to be extremely low and weakly increasing with laser intensity, ranging from 0.8×10^{-4} for $I_L=7\times10^{13}$ W cm^{-2} (line focus) to 1.1×10^{-4} for $I_L=1.2\times10^{15}$ W cm^{-2} (tight focus). We notice that the early reflectivity is much higher than the time-integrated one. In addition, due to the limited temporal resolution, it may be even higher.

Both spectral features and reflectivity data are completely different from those taken in some reference shots where the interaction beam was focused directly on the solid target, without preforming the plasma. Figure 4 shows one spectrum obtained in these conditions at an intensity $I_L=5\times10^{14}$ W cm^{-2}. In these shots the backscattering reflectivity ranged between 1×10^{-2} and 2×10^{-2}. The spectra are similar to those previously obtained in the same experimental conditions [2,15] suggesting that parametric instabilities occurring at or near the $n_c/4$ layer, like two-plasmon decay, may influence significantly SBS enhancing ion density fluctuations. These phenomena do not take place, however, in the case of the preformed plasma since at the interaction time the plasma density is well below $n_c/4$. The following discussion will be limited to the spectra of backscattering from preformed plasmas, which are less standard and require a more involved interpretation.

IV. DISCUSSION

For the sake of clarity we split our discussion in three subsections. First we discuss the early backscattering emission, which we attribute to the arising phase of SF and its nascent effect on SBS. Second, we discuss the large spectral width associated with the early phase, pointing out that it cannot be interpreted in terms of Doppler shift by the flow of the B-SBS active region. Finally, we discuss the late B-SBS features showing that they are consistent with a backward motion of the B-SBS region due to a supersonic moving focus process.

Early backscattering history and reflectivity

The early part of the backscattered radiation is the one that gives the major contribution to the total B-SBS reflectivity. The backscattering intensity rises up rapidly before the peak of the pulse and in a time shorter than the temporal resolution (100 ps); moreover, the early temporal history is quite independent of the laser intensity. This suggests that the backscattering threshold is lower than the lower bound of the investigated intensity range (7×10^{13} W cm^{-2}), and that backscattering saturates very rapidly as the threshold is exceeded.

Because of the convective nature of the SBS instability, its onset and saturation are generally correlated with the extent of the SBS active region, which in an inhomogeneous, flowing plasma is determined by the density and flow velocity profiles. For nonuniform laser irradiation, hot spot driven collective effects are also important in determining the total SBS yield. A criterion for nonlinear saturation of SBS in the case of a hot spot distribution corresponding to an RPP-smoothed beam is that the gain factor $G>1$ [16]. To evaluate G in our experimental conditions we may use the Rosenbluth formula obtained from linear convective theory [17]:

$$G=\frac{\pi(v_q/v_{\mathrm{th}})^2N(1-N)^{1/2}L_v}{2\lambda_L|N(L_v/L_n)(1-v_x)-2(1-N)|}, \qquad (1)$$

where L_n, L_v are the scale lengths of density and flow velocity, respectively, and v_q and v_{th} are the quiver and the thermal velocities. According to Eq. (1), the maximum B-SBS gain is expected in the plasma bulk, because of the higher density and the very large density scale length $L_n \gg L_v$. Since $N \ll 1$, in the plasma bulk of our experimental plasma G might be roughly estimated as

$$G \approx \frac{\pi T(v_q/v_{th})^2 N L_v}{4\lambda_L} \approx 0.9 I_{13} \tag{2}$$

with I_{13} the intensity in units of 10^{13} W cm^{-2}; in the calculation we assumed $N=0.1$, $L_v=500$ μm, and $T_e=450$ eV; from the density profile we also calculated $T=0.7$ as the fraction of laser intensity that reaches the bulk of the plasma, taking collisional absorption into account. Therefore, according to the criterion given above, one may expect from Eq. (2) that for an intensity of a few times 10^{13} W cm^{-2} B-SBS enters a nonlinear saturation regime because of the strong SBS reflectivity in the most intense hot spots. However, this explanation does not fit well with the extremely low backscattering reflectivity. Theoretical models [16] predict reflectivities almost two orders of magnitude larger than our observations; similar values are also obtained in experiments designed to test the SBS statistical theory, as will be discussed in Sec. V. Nevertheless, if we assume that the early reflectivity might approach values of a few percent, the actual duration of the first peak (masked by the limited temporal resolution in our spectra) has to be a few tens of ps. We point out that these estimates refer to B-SBS into the cone of the $F=15$ focusing lens. As will be discussed below, a relevant part of the light scattered by SBS processes might fall outside this narrow cone, because of the onset of FI.

It is interesting to note that the interferograms reported in [12], and in particular the SH radiation emitted sidewards (which, as discussed below, provide a reliable diagnostic for the localization of the SBS active regions) showed that the interaction beyond the density maximum was much weaker than in the plasma front side. The pump depletion in the low-density plasma blow-off by either B-SBS or collisional absorption ($\approx 30\%$) is unable to fully account for this effect.

According to the analysis above, it is apparent that the B-SBS reflectivity, the duration of the first intense B-SBS burst, and the localization of the interaction region cannot be fully explained by ''pure'' B-SBS models in an underdense plasma irradiated by nonuniform laser light. Indeed, the onset of SF in laser hot spots is likely to play an important role in determining such anomalous B-SBS features. To estimate the importance of self-focusing in our plasma conditions, we use the nonlinear theory of Ref. [13]. For a ''Gaussian'' hot spot, the nonlinear threshold condition for ponderomotive filamentation is

$$2.5\times 10^{-3} F^2 N \lambda_{\mu m}^2 I_{13}/T_{keV} > 1 \tag{3}$$

while the threshold for thermal filamentation is obtained from Eq. (3) multipying the left-hand side by the factor

$$g \approx 2\times 10^{-2}\left(\frac{Z^2 F N \ln\Lambda}{\lambda_{\mu m} T_{keV}^2}\right)^{2/3}. \tag{4}$$

Taking $F=15$, $N=0.1$, $\ln\Lambda=10$, and $Z=10$, we obtain $g=8$ in the plasma bulk. Therefore the SF threshold has to be evaluated in the thermal regime; using Eqs. (3) and (4) we find that the threshold is exceeded if the intensity is above 10^{13} W cm^{-2}. In our experimental conditions, the most important parameter in keeping the SF threshold low is the f number. Therefore competition between SF and SBS has to be expected. As pointed out in [13], laser spots undergoing SF are likely to enter the ponderomotive regime as their radii decrease; as shown in Sec. IV C, late spectral features suggest that late SF might be in the ponderomotive rather than the thermal regime.

The early SF has an effect on nascent SBS [9,18] and may account for the sudden rise of the backscattered light. However, while the same effect is also expected to lead to a dramatic increase of the B-SBS yield, the reflectivity is very low. This might be due to the fact that the interaction region is decoupled from the denser plasma bulk where the SBS gain is expected to be maximum, as suggested by interferograms and SH images [12]. Indeed, rapid SF may lead to a local increase of the effective f number, making the waist of the focal spot move backwards. In the discussion of late backscattering in Sec. IV C, it will be suggested that the process is dynamical; the laser focus drifts backwards shifting the interaction region in the plasma blow-off, where the SBS gain is very low. Concerning the early phase, we further note that, in a regime of very strong SF, SBS could be effectively quenched rather than enhanced [7,8,18], due, for example, to the effects of density depletion or flow fluctuations. We also point out that the onset of SF may already leave the ''total'' SBS rate unchanged, but may strongly reduce the amount of backscattered light collected into the small aperture of the $F=15$ focusing lens, since diffraction is enhanced into filaments leading to an increased spread of the laser wave vector, and thus B-SBS light would tend to fall outside the lens cone. A further contribution to this effect may come from lateral deflection of filaments induced, for example, by the plasma flow in the direction transverse to the laser beam axis [19]. However, filament deflection should be weak in our case since the spot of the interaction beam is less than the plasma transverse dimension, and thus the flow velocity is mainly longitudinal.

B. Early broad spectra

The spectral width of the early backscattering cannot be fully explained in terms of the linear theory of B-SBS in an inhomogeneous flowing plasma. The linear B-SBS shift from the plasma layer with flow velocity v_x (in Mach number units) is given by

$$\Delta\lambda/\lambda = (2c_s/c)(1+v_x), \tag{5}$$

where the second term accounts for the Doppler shift due to the flow velocity of the emitting region. Thus, from the knowledge of the flow velocity profile, the measurement of the spectral shift can be used to localize the B-SBS sources in the plasma. However, applying this analysis to the velocity profile of Fig. 1, the early backscattering bandwidth corresponds apparently to a large plasma extent extending for more than 2 mm from $v_x \approx +0.8$ to $v_x \approx -4.7$. If we take into account the temperature increase during interaction, which is estimated from x-ray spectra to be approximately 200 eV, the B-SBS active region extends from $v_x \approx +0.65$ to $v_x \approx -3.8$. Such a large plasma region is highly unlikely to emit B-SBS radiation at a comparable intensity over its whole extent because the density drops more than two orders of magnitude from the inner to the outer velocity layer, and also the laser intensity decreases considerably. Moreover there is a clear disagreement with the SH images taken at 90°, which provide a reliable diagnostic of the localization of SBS sources [20]. These images show that the most active region is localized in the plasma front side and extends roughly 100 μm away from the layer of maximum density, where the flow is still well subsonic. Thus the early B-SBS bandwidth cannot be related to the extent of the B-SBS active region.

There is indeed a variety of effects related to the laser-plasma interaction which may shift or broaden the SBS spectrum. For example, collisional absorption could drive a redshift of SBS via the temperature rise or by the increase of the IAW frequency because of kinetic effects [11]; these latter might play a role in the present regime because of the relatively high value of $Z=13$, but the redshift turns out to be quite weak indeed. Among nonlinear optical effects which may affect the SBS spectral width, the most relevant is self-phase modulation (SPM) of an EM wave traveling in a plasma where the electron density, and thus the refractive index, change in time. The frequency of the EM wave is shifted according to the formula [21]

$$\Delta\omega/\omega = (L/2c)(1-N)^{-1/2}\partial N/\partial t, \tag{6}$$

where L is the length of the interaction region. According to Eq. (6), SPM will produce redshift (blueshift) of either the pump or the backscattered wave if the electron density decreases (increases) in time. A change in time of the plasma electron density can be induced during the interaction by two distinct effects which we discuss separately: further ionization of the plasma by the interaction beam and density evolution into filaments due to SF.

For what concerns the further ionization of the plasma due to the interaction with the delayed laser pulse, information can be acquired from time-resolved x-ray spectra. One of these spectra is shown in Fig. 5(top). This x-ray spectrum was taken simultaneously with the B-SBS spectrum of Fig. 2(c). The collisional-radiative equilibrium model adopted to extract the history of electron temperature and ionization degree from these spectra was described in Ref. [12]; the results of the analysis for this spectrum are shown in Fig. 5 (bottom). We see that due to reionization of the plasma, the electron density increases during the interaction by approximately 5% (assuming a collisional-radiative equilibrium model for the x-ray emission) in a time $\leqslant 100$ ps. Such a change in the electron density gives a blueshift of the emission as described by Eq. (6). However, considering that $\partial N/\partial t \approx 5\times10^{-2}N/(100\ \text{ps})$ even assuming an interaction length of $L=1500\ \mu$m corresponding to the focal depth in a vacuum (much larger than the effective length of the SBS active region), we obtain $\Delta\lambda/\lambda = -\Delta\omega/\omega \approx -1.2\times10^{-4}$, which is still too small to account for the observed B-SBS spectral width. The observed ionization time scale is of the order of the inverse of the rate of collisional ionization of

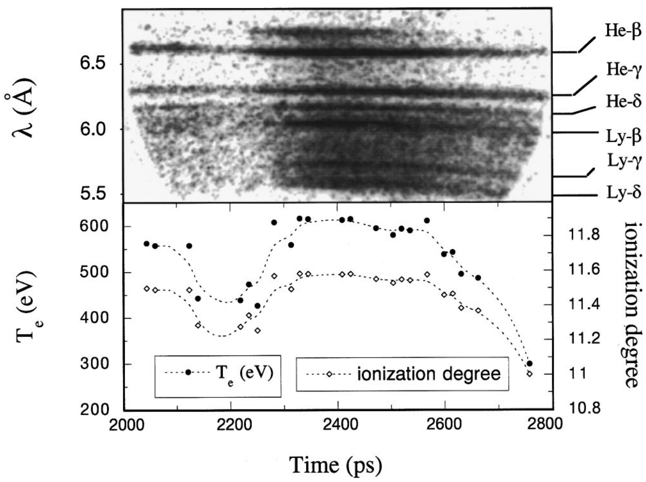

FIG. 5. Top frame: x-ray time-resolved spectrum obtained simultaneously with the spectrum of Fig. 2(c). Bottom frame: electron temperature and ionization degree as a function of the time from the peak of the plasma heating laser pulses, as obtained from x-ray line ratios in the CRE approximation (see text). In this plot the peak of the interaction pulse reaching the plasma is located at 2.5 ns.

Al XI ions to Al XII ions; the plasma ionizes during interaction due to the temperature increase in the interaction region, while rapid ionization processes, such as multiphoton or tunneling ionization, are not important at these intensities for $Z>10$.

If, consistently with the discussion of Sec. IV A, we assume that B-SBS takes place inside the hot spots undergoing SF, Eq. (6) can be used to estimate the effects of the density variations inside the filament [22,23]. Since the onset of SF leads to density depletion, a redshift of the emission is expected during the initial development of filaments. The time scale may be roughly estimated as the typical hot spot radius, $F\lambda$, divided by the sound velocity: we obtain a time of 100 ps. For a filament length of order $F^2\lambda$ and a density variation of 50% we find $\Delta\lambda/\lambda = -\Delta\omega/\omega \approx 1.5\times10^{-4}$, showing that SPM due to SF may only weakly affect the red part of the early spectrum. Indeed, a large blueshift could be generated if one assumes that most of B-SBS originates from intense hot spots which are unstable and undergo supersonic collapse. In this case, the relative variation of N might be positive and of the order of unity on a time scale of a few tens of ps, giving, according to Eq. (6), the correct order of magnitude for the observed blueshift. A qualitatively similar argument has been recently invoked to explain the blueshift of transmitted light in the regime of relativistic filamentation [24]. It is questionable whether the spectral modulations observed inside the broad early spectrum (particularly evident in the spectrum of Fig. 3, because of the appropriate choice of filters) may be due to SPM. For the spectrum in Fig. 3, as well as for similar spectra, roughly $10-20$ periods are observed; this corresponds [23] to a source term duration of the order of 20 ps, which might be consistent with the picture of supersonic collapse.

A more detailed and quantitative investigation of spectral SBS modifications would require numerical simulations of the same experimental conditions. In general, when B-SBS originates from filaments in a strongly nonlinear regime, we may expect that there are fast and relevant variations of plasma density and flow velocity which may strongly broaden the B-SBS spectrum. Computation of synthetic B-SBS spectra in numerical simulations accounting self-consistently for SBS and SF would help to identify the related physical mechanisms.

C. Late backscattering features

As pointed out in Sec. IV B, during the first intense temporal burst, B-SBS emission is likely to be in a strongly nonlinear regime where the anomalous broadening is due to mechanisms possibly related with the evolution of SF. Within a time of 100 ps or less, backscattering features are completely different: the B-SBS emission intensity drops dramatically, becomes narrow-band, and shifts rather regularly in time from the red to the blue side of the spectrum. In this section we will show that the spectral features and the low intensity of late backscattering are consistent with a supersonic backward motion of the B-SBS active region, due to a moving focus process driven by ponderomotive SF.

The low intensity of B-SBS after the first broadband peak gives us confidence in unfolding the late spectrum in terms of linear B-SBS shift, Eq. (5). From the comparison of the instantaneous width of the late SBS spectrum with the velocity profile in Fig. 1 we obtain a spatial width of about 200 μm for the SBS active region, very similar to the value measured independently by sideward SH emission; we note that this value is much less than the vacuum focal depth, a typical signature of the onset of SF. The spectral drift towards the blue side shows that the B-SBS active region moves backward at a supersonic speed, starting from the subsonic region ($|v_x|<1$) with redshift, crossing the Mach surface ($|v_x|=1$) with zero shift, and finally moving into the supersonic region ($|v_x|>1$) with blueshift. We attribute this motion to a ''moving focus'' process driven by the dynamical development of SF. As the nonuniform laser beam is focused into the preformed plasma with a large f number, a cooperative action of whole-beam SF and FI is expected. This action first leads to a spatial backshift of the beam waist and a decrease of the longitudinal size of the focal region, influencing the early features of interaction and backscattering as discussed in the preceding section. Then, due to the progressive density depletion along the beam axis by the action of additive thermal and ponderomotive forces, each laser spot experiences the action of a converging plasma lens whose refractive power increases in time, resulting in a spatial backshift of the focal region. This backward motion decouples the active region from the plasma bulk leading to a very rapid drop in the temporal reflectivity. On the other hand it is reasonable to assume that this supersonic motion may keep the instantaneous B-SBS level low and well below saturation. Thus this picture is consistent with a very low SBS yield, with respect to what can be estimated, for example, using convective, steady-state SBS theory to evaluate the gain factor as given by Eq. (1) corresponding to the density and velocity profile of Fig. 1. It also qualitatively accounts for the observation that late B-SBS emission appears more sensitive to the laser intensity than the early emission.

An estimate of the moving focus speed can be obtained comparing the instantaneous spectral shift with the initial, unperturbed profiles of density and velocity of Fig. 1. This comparison gives a moving focus velocity $v_{\mathrm{MF}}=8c_s$, for $c_s=1.3\times10^7$ cm/s. This evaluation does not account for the local temperature increase due to collisional absorption and the local density and flow perturbations which can be produced by strong SF and, therefore, it should be considered as an order-of-magnitude estimate. However, it shows that the moving focus speed is highly supersonic.

It is also important to note that the secondary maximum in the temporal reflectivity is observed close to the time for which the spectral shift is zero, i.e., when the active region crosses the Mach surface where a resonance in B-SBS gain is expected under quite general conditions. This is an indication, independent of the knowledge of the actual density and velocity profiles, that the late backscattering history must be associated with a supersonic motion of the B-SBS active region.

A supersonic ''moving focus'' in the backward direction has been predicted by the nonlinear theory of ponderomotive SF of Ref. [13]. In the ponderomotive regime the focal region is predicted to move backward with a typical supersonic speed of the order of $v_{\mathrm{MF}}\approx Fc_s$, which is consistent with our experimental data. We note that the effect of the moving focus becomes important during the laser pulse because of the large value of the f number. Moreover, Ref. [13] also predicts that the dependence of v_{MF} upon the laser power is relatively weak, and is expected to be proportional to the square root of the power in the spot. This result accounts for the little difference in the B-SBS spectra observed in our experiment by varying the laser intensity. It also suggests that the drift velocity is weakly dependent upon the hot spot statistics, consistent with the little differences observed between the data obtained in the line focus or tight focus configurations, or in the few data taken with RPP smoothing.

We point out that our physical picture of late backscattering identifies the B-SBS active region with the moving focus whose features are in good agreement with the nonlinear theory of ponderomotive SF [13], where, however, self-consistent SBS is neglected. On the other hand, since the level of B-SBS is very low, it is reasonable to assume that B-SBS has to follow the evolution of SF. This picture agrees with previously reported numerical simulations [8], where a backward supersonic motion of the B-SBS active regions due to dynamical ponderomotive SF was also found. These simulations of single hot-spot behavior in an initially homogenous plasma show that the long-time development of the spatial patterns of the laser intensity and the SBS active regions may be quite complex. This evolution may lead to the generation of a complicated pattern of ''SBS-active islands,'' where SBS is alternatively activated by the local intensity increase or quenched due to dephasing and decrease of the gain length, and is characterized by a burstlike emission at later times. Our experimental results suggest a similar B-SBS and SF dynamical interplay; in particular, a third weak B-SBS burst is visible in the spectra as in the case of Fig. 2. Additional complexity, however, may arise from the inhomogeneity and the flow velocity of the preformed plasma. Another difference from the simulations of Ref. [8] is that thermal rather than ponderomotive forces, seem to be dominant at the initial stage of SF (thus also determining its threshold) in our experiment.

Our final point concerns the energy balance, to which B-SBS in the solid angle of the focusing lens clearly gives a negligible contribution. SBS at different angles was not measured; however, in conditions of strong SF, more precisely when the size of the interaction region becomes smaller than the SBS growth length, numerical simulations [7] show that an important fraction of the laser energy is scattered sidewards; in particular, the level of energy backscattered in the narrow focusing angle is expected to decrease strongly, as already suggested in Sec. IV A.

V. COMPARISON WITH OTHER EXPERIMENTS

In order to make a proper comparison with other experiments, we observe that our experimental results are strongly determined by the relatively high value of the *f* number *F* of the focusing optics, which is a crucial parameter for both nonlinear SBS saturation due to collective hot spot effects [17] and the nature (thermal or ponderomotive) of the FI regime [13]. Low values of *F* quench FI and the propagation of the laser beam can be enhanced by ponderomotive channeling [25]. Increasing values of *F* lead to a stronger role of hot spot collective effects, and also to conditions more favorable to SF.

Drake *et al.* [26] performed a detailed quantitative study of B-SBS using 0.53 μm light with $F=8.3$, proving the onset and saturation of B-SBS over a large plasma region due to hot spot collective effects; they also pointed out that thermal FI might have affected long-term SBS to some extent, without changing its features dramatically. The reflectivity reached values up to 15%, much higher than that we observed in our experimental conditions of strong filamentation.

A speckle or filamentary structure of SBS sources was found in the experiments described in [5,6]. Afshar-Rad *et al.* [5], using 0.53 μm light with $F=10$, found that SBS was localized in small-scale filaments in a longitudinally homogeneous plasma; the filaments scale length and the FI intensity threshold were in good agreement with ponderomotive SF theory. The backscattering reflectivity was of the order of 10^{-2}, much higher than that observed in our experiment. We attribute this difference to the fact that the plasma is longitudinally inhomogeneous and expanding towards the laser in our case, thus the motion of the B-SBS active region towards the low-density plasma blow-off results in a much lower SBS gain.

Labaune *et al.* [6], using 0.53 μm light and $F=6$ optics, have observed that SBS emission at different angles originates from different regions of a flowing plasma and, in particular, from the front side, resulting in a completely blueshifted backscattering spectrum due to the Doppler effect from the flowing plasma. Strong pump depletion by B-SBS in the laser hot spots was suggested to explain this effect. As discussed in Sec. IV A, in our case this explanation does not fit well with the very low backscattering reflectivity and the localization of side SH emission; our data suggest that early SF rather than pump depletion leads to the localization of B-SBS in the front side of the plasma.

Watt *et al.* [27] performed a systematic study of the dependence of SBS upon *F*. They found that large values of *F* lead to a lower intensity threshold and to a rapid saturation of the B-SBS reflectivity with the laser intensity, up to values of approximately 1%. The authors also point out that filamentation was not expected to give a dominant contribution in their experiment, and that experiments in a regime of strong FI remained to be done. Our data add a piece of information to the study of this regime.

The most recent experiment brought to our attention is that of Chirokikh *et al.* [2], where SBS in long-scale-length plasmas with 1.054 μm light and optics with $F=3.6$ was investigated. In the same work the experimental results are compared with a detailed calculation of the SBS reflectivity in a flowing plasma, accounting for statistical effects but neglecting SF. Despite the noticeable differences with the regime of our experiment, it is interesting to note that the calculation of Ref. [2] is, to our knowledge, the only one that predicts, for similar preformed plasma conditions, reflectivity values as low as those we observed. However, Chirokikh *et al.* report a much higher reflectivity ($\approx 2\%$), which is in contrast with the predictions of their simulations.

Finally, it is interesting to discuss to what extent our experimental results contribute to the question raised by Drake [3] in regard to the poor agreement with theory and the actual relevance of SBS in laser fusion schemes. Concerning the first issue, Drake points out that in many experiments the SBS spectral width is quite broad giving rise to ambiguity in its interpretation. We actually found the SBS spectrum in the early phase hard to be explained in terms of a simple linear theory. The explanation of the spectral width and the strong blueshift remain open issues, possibly related to the strong effect of rapid SF on SBS. However, concerning the late, weaker spectral features, we found that the explanation of the B-SBS spectrum in terms of simple Doppler shift leads to an interpretation of late backscattering in terms of a moving focus effect, which is in reasonable agreement with existing theories and simulation [8,12] and may also account for the very low reflectivity.

Concerning the second issue raised in Ref. [3], i.e., the SBS contribution to the energy balance, the amount of total backscattered energy we measured in the solid angle of the f/15 focusing lens is negligible with respect to the incident interaction energy. However, our physical picture indicates that this very low level of reflectivity (comparable to that detected using SSD smoothing, see [5]) is not a signature of efficient propagation of the laser pulse through the plasma, since dynamical SF decouples the focal region from the plasma bulk. Finally, concerning the relevance of SBS to ICF schemes, we may say that, in our experimental conditions, SBS is not an instability of ''primary importance,'' since its features appear to be dominated by the dynamic evolution of SF. Therefore, the goal of SBS control basically reduces to the issue of SF suppression; to this aim, spatial and temporal beam smoothing techniques [4] retain their value. It is also important to notice that a correct evaluation of SBS yield in a strong filamentary regime requires taking into account the side-wards SBS contribution to the energy balance.

VI. CONCLUSIONS

We studied stimulated Brillouin backscattering from the interaction of a laser pulse with a long-scale-length, expanding plasma. The preformed plasma was carefully characterized in terms of density and temperature to obtain reproducible interaction conditions. The interaction was strongly qualified by the large f number of the focusing optics. Our experimental results, including very low backscattered energy and spectral anomalies, show a strong effect of dynamical self-focusing on B-SBS. In the early phase the onset of SF strongly influences the rise, saturation, and spatial location of the B-SBS active region. The early spectral features, tentatively interpreted as due to self-phase modulation effects, also suggest strong SF effects and possibly filament collapse. The late part of B-SBS time-resolved spectra provides evidence of a supersonic backward motion of the SBS active plasma region, which is attributed to a moving focus effect in good qualitative agreement with existing theories and simulations. To our knowledge, no strong evidence of this moving focus effect has been discussed so far in the literature. The extremely low reflectivity, measured as the ratio of the light backscattered into the focusing cone, was mainly accounted by the decoupling of the B-SBS active region from the plasma bulk and the enhanced spread of the wave vectors of the scattered waves, both effects being due to strong SF. Comparison with other experiments demonstrates the key role played by the long f number of the focusing lens used in our experiment. With respect to previously reported experiments, our data add a piece of information on the SBS features in a regime where the SBS instability is dominated by SF.

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