Onset and Saturation of the Spectral Intensity of Stimulated Brillouin Scattering in Inhomogeneous Laser-Produced Plasmas

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Measurements are reported of the spectral intensity of emissions attributed to stimulated Brillouin scattering (SBS) of 0.53 μm laser light from an inhomogeneous CH plasma, at densities of interest to laser fusion or x-ray lasers. The onset of SBS confirms recent theory, and no dependence of the saturated spectral reflectivity on density or pump strength is seen. The total reflectivity, which reaches 15%, increases with the spectral width of the SBS. These quantitative data can test theory and simulations of saturation and also have implications for the National Ignition Facility. [S0031-9007(96)00528-5]

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Stimulated Brillouin scattering (SBS) is a well-known phenomenon in any medium which sustains both electromagnetic and acoustic waves. In SBS, a resonant acoustic wave scatters an electromagnetic pump, producing a scattered-light wave. The scattered-light wave then beats with the pump so as to amplify the original acoustic wave through the nonlinear response of the medium. SBS is relevant to many applications of lasers, where it may be useful for phase conjugation or pulse modification, or may be detrimental. Intense SBS can deplete the laser power, can damage laser (or x-ray laser) optics, and in plasmas can heat the ions. The growth and saturation of SBS in plasmas [1] has proven difficult to understand in experiments to date [2,3]. In addition, this subject remains an issue for the proposed National Ignition Facility, as depletion or even redirection of the laser power can prevent ignition. The present work reports, for inhomogeneous plasmas, the first confirmation of the onset of SBS predicted by recent theory [4] and also reports the first data regarding the scaling of the saturated spectral intensity (as opposed to total reflectivity) of SBS from a large, inhomogeneous, flowing plasma.

The present work addresses two specific issues. The first is the scaling of the SBS onset. While experiments have long attributed the observed scattered light with small frequency shifts to SBS, these experiments have faced many obstacles and have for the most part been inconclusive [2,5,6]. There are many potential sources of signal at such frequencies, and few experiments have observed the onset of SBS as an additional confirmation. Recent progress has included observations of the spatial profile of the acoustic waves near threshold [7] and of the scaling of the SBS onset in homogeneous plasmas [8,9]. We report here the first confirmation of the theory [4] in an inhomogeneous plasma.

The second issue is the saturation behavior. Existing nonlinear theory has proven sufficient to explain, principally through ion trapping, the saturation of SBS in experiments using infrared (CO_2) lasers or microwaves as pumps [10–12]. In contrast, it has fared poorly [2,3] (predicting much-larger-than-observed saturation levels) in explaining experiments using pumps of "short" wavelength ($\leq$1.06 μm), which is the regime relevant to laser fusion and x-ray lasers. Measurements of the integrated reflectivity, often reported previously, are inadequate to test theory or simulation of saturation. They inherently convolve plasma volume and signal amplitude, since regions whose flow velocities differ significantly will contribute independently at different frequencies to the total scattering of the pump. Instead, measurements of the scaling of the SBS spectral intensity (e.g., W cm^{-2} nm^{-1}) are necessary. We provide such data here and show that they rule out some candidate saturation mechanisms.

The experiment (Fig. 1) was performed at the Trident laser facility [13]. We formed a plasma by irradiating a 6.7 μm thick, CH target with 175 $\pm$ 25 J of 527 nm laser light in a 1.3($\pm$0.1) ns full width at half maximum (FWHM) pulse of approximately constant intensity. The preforming, $f/6$, laser beam had a nominally flat-topped spatial profile and was both defocused and incident at a 60° angle to form an elliptical, 160($\pm$20) μm by 320($\pm$40) μm spot. A "pump" laser beam, of the same 527 nm wavelength and the same pulse shape, delayed

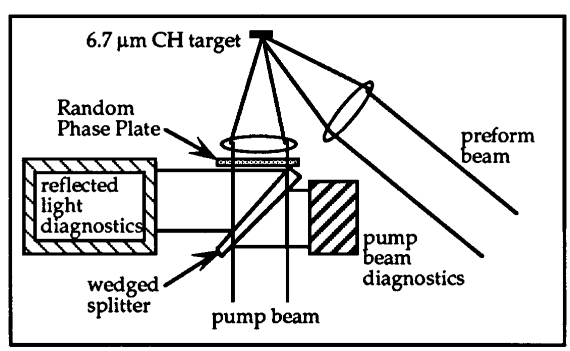

FIG. 1. Schematic of the experiment.

mechanically by 1.6 ns (to 50 ps accuracy) relative to the onset of the first beam, irradiated the plasma at normal incidence. The pump passed through a random phase plate having 6 mm hexagonal elements, and was focused onto the target using a lens of 120 cm focal length, stopped to $f/8.3$. This produced a 110 μm diam FWHM laser spot in the plasma, with the most intense speckles having an 11 μm full width (min to min) and 290 μm full length. The pump intensity, I_{pump}, quoted below is the average intensity, calculated as $I_{\text{pump}} = 0.5E_L/\tau A$, where E_L and τ are the laser energy and pulse duration, respectively, and A is the area of a 110 μm diam spot. We used whole-beam attenuators to vary E_L.

We made three measurements of the reflectivity by coupling whole-beam samples of the incident and reflected light (i) into calorimeters, (ii) into a fast photodiode, and (iii) into a fiber optic, which went to a 0.5 m Czerny-Turner spectrometer and streak camera whose output was recorded using a scientific-charge-coupled device camera. The resolution in time and wavelength was 230 ps (limited by the spectrometer) and 1 Å, respectively. We sampled the reflected light in an $f/6$ cone (in two cases we used an $f/8.3$ cone, finding no significant differences). The three reflectivity measurements typically agreed to within 20% when E_L was above 10 J so that the calorimeter obtained good signals. For each shot, we used the most accurate measurement of the reflectivity to calibrate the spectral intensity of the streaked image. The streak camera response was linear for these data. No variations in the streak-camera sensitivity in time or wavelength were identified, but such variations potentially could reach a factor of 2.

These targets are thicker than the "exploding foils" used in a number of past studies, and reviewed in [14]. They might be referred to as "ablating foil" targets. Two-dimensional, hydrodynamic simulations by the LASNEX computer code [15,16], using a flux limiter of 0.06, provided plasma parameters for the theoretical analysis. Figure 2 shows results for a 67 J pump, at 1.8 ns (200 ps after the pump onset). We found that, throughout most of the pump pulse, the pump laser is absorbed at $n \leq 0.4n_c$, where n_c is the critical density of the pump. The plasma density falls roughly exponentially to lower densities, with a characteristic scale length of 220 μm. Electron conduction carries some of the laser energy to the ablation surface, which is separated from the absorption layer by an extended ($\sim$300 μm) zone of plasma at $n \sim 0.3n_c$. Negligible laser intensity ($< 0.1\%\ I_{\text{pump}}$) penetrates through this plasma to the critical surface, and thus critical-surface phenomena cannot contribute to the results discussed below.

Both the simulations and observations of stimulated Raman scattering (SRS) indicate that the maximum density remains above $0.1n_c$ throughout the pump pulse. We observed no SRS during the growth and saturation of SBS discussed below. Near the end of the pump pulse (except at the lowest pump energies), the foil is predicted to

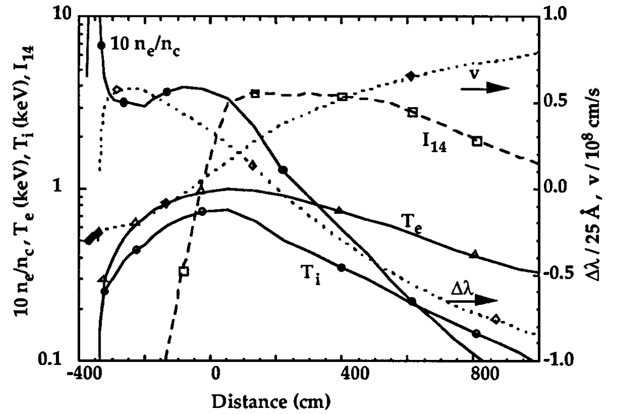

FIG. 2. Simulation results at 1.8 ns, corresponding to the conditions of Fig. 3(e). Normalizations are indicated on the axis labels, and I_{14} is the I_{pump} in units of 10^{14} W/cm^2.

burn through. The density of the extended plateau region then drops below $n_c/4$ so that SRS can be driven there. At this late time, well after the saturation of SBS, we observed SRS from $n > 0.1n_c$.

The simulations at 1.8 ns find the flow velocity, v, the velocity gradient, and the velocity scale length, $(\nabla v/c_s)^{-1}$, to be 5.5×10^7 cm/s, 7.5×10^8 s^{-1}, and 500 μm, respectively, at $n \sim 0.05n_c$. Here c_s is the sound speed. The profiles of density and velocity are insensitive to I_{pump}. In contrast, T_e at 1.8 ns increases from 400 eV with a 2 J pump to $\sim$1 keV with a 67 J pump. The half maximum of I_{pump} is at $0.35n_c$ when T_e is 1 keV and at $0.27n_c$ when T_e is 400 eV.

The observed spectra showed systematic and reproducible variations. Figure 3 shows the measured spectral intensity, I_{spect}, from six laser shots, with I_{pump} as indicated. We interpret the observed wavelength as the combination of an acoustic shift and a Doppler shift (other sources of wavelength shift are unimportant here). For example, the data of Fig. 3(f) extend from $0.23n_c$ and Mach 0.7 at +3 Å to $0.02n_c$ and Mach 2.8 at −15 Å, based on the simulations and the ion wave phase velocity in CH plasmas [17].

Figure 3(a) shows weak signals having redshifts of about 0–4 Å. We provisionally attribute these signals to Thomson scattering from the acoustic noise at comparatively high density. Such scattering should be proportional to the local laser intensity, which sufficiently explains the observed time dependence. The inferred noise spectrum is far (about 10^5 times) above thermal levels and cannot be isotropic, as no comparable, blueshifted signal is seen. (This result is not unique [2].) We would not expect to see SBS here, as the gain is small even after integrating over the distribution of laser intensities, because I_{pump} is well below the homogeneous damping threshold for convective instability [18], which is about 10^{13} W/cm^2. As I_{pump} increases above 10^{13} W/cm^2, the data show weak SBS which grows nonlinearly in time, as shown in Fig. 3(b) and at shorter wavelengths in Fig. 3(c).

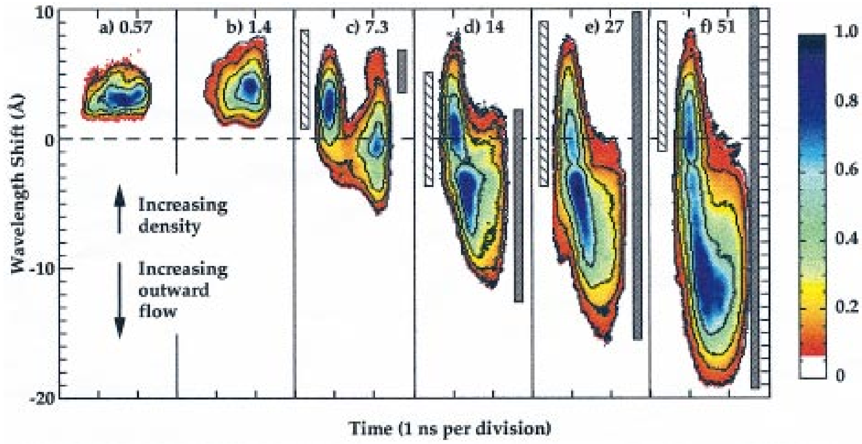

FIG. 3(color). The scattered spectral intensity, I_{spect}, is shown for six laser shots. The numbers indicate I_{pump} in units of 10^{13} W/cm^2. The contours are spaced by factors of 2 in I_{spect}, with the highest contour at 50% of the maximum in each case. The maxima, in W cm^{-1} nm^{-1}, are (a) 7.1×10^{10}, (b) 7.1×10^{11}, (c) 1.4×10^{13}, (d) 4.8×10^{13}, (e) 1.5×10^{14}, and (f) 1.8×10^{14}. The minimum in the emission at -2 Å is produced by a dead spot on the photocathode and is not real. The bars are explained in the text.

Convective amplification, limited by the gradient in flow velocity, provides a good explanation for the data of Figs. 3(c)–3(f). The theory of Ref. [4], which accounts for the distribution of intensities in the laser speckles, predicts that one should see *saturated* signals at each frequency for which I_{pump} is large enough that the convective gain of backscattered power, evaluated for an intensity I_{pump}, is approximately e^1. We used the simulation results for each case shown in Fig. 3 to evaluate the convective gain by established methods [18–20]. The shaded bars in Fig. 3 show the range of wavelengths for which the gain exceeds e^1. The data confirm the theory remarkably well both in scaling with I_{pump} and in magnitude. The present results are thus the first confirmation, in an inhomogeneous plasma, of the theory of Ref. [4]. Traditional convective theory, in contrast, would require that I_{pump} be much larger to produce saturation.

Although the interpretation just given explains the observations fairly well, it is worth asking whether this interpretation is unique. We do not believe the observed signals could be due to an absolute instability, because the damping threshold for absolute instability is above 10^{16} W/cm^2. In addition, there are good reasons, discussed above, to believe that neither critical-surface phenomena nor SRS interfere with the observed SBS. Furthermore, much of the blueshifted spectrum of Fig. 3 originates from regions where Landau damping quenches SRS.

While one cannot easily rule out any impact of two plasmon decay (TPD), any effect it might have should be localized in wavelength since TPD occurs only near $n_c/4$. As the $n_c/4$ surface is near the sonic point in the plasma, any coupling to SBS of ion waves produced in consequence of TPD [21] should alter the emission and/or the time dependence near the unshifted frequency. No such local effect is observed in the data. TPD is not predicted to exceed its damping threshold here before the gain for SBS and thermal filamentation is significant; perhaps one of these mechanisms (SBS is well known to quench SRS [22]) quenches TPD.

Thermal filamentation of the laser speckles could be playing some role here, although it is not required to explain the SBS onset. Once these speckles exceed the (nonlocal) threshold for thermal filamentation [23,24], the spatial gain for filamentation is large enough (>100 cm^{-1}) so that they should focus quite strongly. The hatched bars in Fig. 3(b) show the range of wavelengths over which the threshold for thermal filamentation (Table 1, Ref. [23]) is exceeded at a perpendicular wave number of $2\pi/5.5$ μm. The comparison suggests that thermal filamentation may explain some of the long-term saturation behavior, perhaps by rendering the beam and/or plasma unable to sustain SBS, but we leave to later work the detailed discussion of this and other long-term behavior. In contrast, the gain for ponderomotive filamentation remains small throughout.

The observed scattering also shows systematic saturation behavior. For I_{pump} above about 10^{14} W/cm^2, the signals increase rapidly to a maximum instantaneous emission, $I_{max}(\lambda)$ at each particular wavelength λ. We focus here on the behavior of $I_{max}(\lambda)$, the maximum saturated level. $I_{max}(\lambda)$ is effectively averaged over one time-resolution element of 230 ps. While the actual maximum emission might be composed of numerous, brief bursts, it is not composed of a single, intense maximum because the rise time and the FWHM of the intense emission are typically in excess of 400 ps. The most important property of $I_{max}(\lambda)$ is that the innermost contour, which encloses signals within a factor of two of the overall maximum, spans a large inferred range of density [more than a factor of 5 in Fig. 3(f)]. Moreover, the slight increase in $I_{max}(\lambda)$ with increasing blueshift (on the assumption that the instrumental response is sufficiently uniform) is consistent with the gradual decrease in the velocity gradient. The saturated amplitude of the acoustic fluctuations is thus roughly

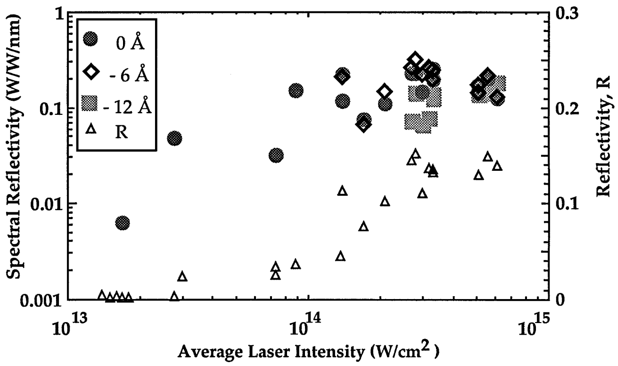

FIG. 4. The temporal maximum in the spectral reflectivity of the backscattered light is shown versus pump intensity for selected wavelengths, as indicated. The total, time-integrated reflectivity, R, is also shown.

independent of the density at which SBS is resonant. This may prove difficult to explain as saturation models typically find the normalized, rather than the absolute, fluctuation amplitude to depend weakly on density.

Figure 4 shows that the saturated spectral reflectivity, $I_{\max}(\lambda)/I_{\mathrm{pump}}$, also varies little with I_{pump}. Once signal appears at any given wavelength, $I_{\max}(\lambda)/I_{\mathrm{pump}}$ immediately approaches 15% per nm. It then increases little as I_{pump} increases several-fold. The small scattering from any given resonant volume of plasma weighs against saturation mechanisms which require large ion-wave amplitudes, including ion trapping and harmonic generation [12]. The observed scaling weighs against mechanisms that predict a dependence of reflectivity on pump intensity, such as ion tail formation. The abrupt saturation is reminiscent of the behavior of SRS [25]. However, for SRS, there is an instability of the driven Langmuir wave which provides a natural and very definite threshold for saturation. The analogous instability of the SBS ion wave [26] seems unlikely to be important here, however, as the ion-wave damping and wave number are both too large. These data thus pose a challenge to theories that seek to explain SBS saturation. We note that it requires examination of the spectral intensity to correctly identify the saturation behavior. The total reflectivity increases with the width of the saturated spectrum and thus increases steadily with I_{pump} as a larger volume of plasma is driven unstable, reaching time-integrated values of ~15% (implying instantaneous values above 50%) in some cases.

In conclusion, we have produced an inhomogeneous plasma in which the onset and saturation of SBS may be reproducibly observed, using a laser pump and plasma density in the regime of interest to x-ray lasers and laser fusion. The onset of SBS above the observed noise level is reasonably consistent with current linear theory. The spectral reflectivity of the scattering saturates at a low level that is nearly independent of pump strength or density but is nonetheless large enough to be of some concern for applications. In the context of laser fusion, recent experiments [27] have driven SBS to very high theoretical gain over a very narrow frequency range, and have observed small total reflectivities. The evidence here suggests that such experiments provide incomplete evidence regarding the level of SBS which will be driven in the National Ignition Facility. In fusion targets on this facility, the laser beams will penetrate plasma in which there is some gain for SBS across a range of flow velocities. The issue of the spectral width and corresponding total reflectivity of SBS in such plasmas remains to be addressed.

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