Direct Observation of Stimulated-Brillouin-Scattering Detuning by a Velocity Gradient

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We report the first direct evidence of detuning of stimulated Brillouin scattering (SBS) by a velocity gradient, which was achieved by directly measuring the frequency shift of the SBS-driven acoustic wave relative to the local resonant acoustic frequency. We show that in the expanding part of the plasma, ion-acoustic waves are driven off resonance which leads to the saturation of the SBS instability. These measurements are well reproduced by fluid simulations that include the measured flow.

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Stimulated Brillouin scattering (SBS) is the result of the resonant ponderomotive coupling of an incident light wave, a reflected light wave, and an ion-acoustic wave. In principle, this process could result in the reflection of a large fraction of the incident energy for inertial confinement fusion (ICF) targets. In order to minimize this energy loss, a good understanding of mechanisms that could limit SBS is important. In many targets, a velocity gradient within the expanding plasma provides such a mechanism; the frequency of the local acoustic waves is Doppler shifted, therefore, detuning the three-wave resonant process [1].

In this Letter, we present the first direct measurement of SBS detuning by a velocity gradient. A novel use of two Thomson-scattering (TS) diagnostics has allowed us to directly measure the frequency and amplitude of the ion-acoustic wave responsible for SBS as a function of space. This is the first measurement that spatially resolves both the frequency and the amplitude of the ion-acoustic waves directly responsible for SBS. These measurements link the saturation of the SBS instability to the frequency detuning from an expanding plasma. We have independently measured the ion-acoustic frequency and the frequency of the driven acoustic wave at various positions in the plasma. Therefore, by comparing the local ion-acoustic frequency with the local frequency of the driven acoustic wave we have measured the actual detuning of the SBS instability. The measured electron temperature, velocity gradient, and electron density have been included in fluid simulations which clearly support the measured SBS detuning by a velocity gradient.

The experiments used a three-beam configuration at the Trident Laser Facility [2]. The Be plasmas were produced by a heater beam with 180 J of 2ω ($\lambda = 527$ nm) laser light in a 1.2-ns-long square pulse, focused normal to the target surface using an $f/6$ lens and a strip line random phase plate (RPP) [Fig. 1(c)]. This produced a line focus with an intensity of 10^{14} W cm^{-2} and an initial 1000 μm $\times$ 100 μm Be plasma [3]. An interaction beam (50 J, 2ω, 1.2-ns-long square pulse) was aligned $x = 400$ μm from the target surface and was focused to a 60 μm diameter spot, resulting in an intensity of 1.5×10^{15} W cm^{-2}. The interaction beam was used to drive SBS which excites ion-acoustic waves with wave vector $\mathbf{k}_{\|} = 2\mathbf{k}_o$ copropagating in the direction of the interaction beam. The backscattered SBS light was collected and collimated by the focusing lens of the interaction beam. A fraction of the backscattered light was focused on a fast photodiode and two, 1/4-meter stimulated Raman scattering (SRS) and 1-meter SBS, spectrometers. The SRS and SBS spectra were measured with a respective resolution of 0.5 nm and 0.45 Å. The absolute SBS energy was measured with a diode [4].

The third laser beam, 3ω ($\lambda = 3513$ Å), was used as a TS probe beam. The probe beam and TS collection optics define a volume (70 μm $\times$ 70 μm $\times$ 60 μm) located at the center of the chamber. Light scattered from the TS volume was imaged onto two separate TS spectrometers. The interaction beam is focused in the middle of this volume. The first TS diagnostic probes ion-acoustic

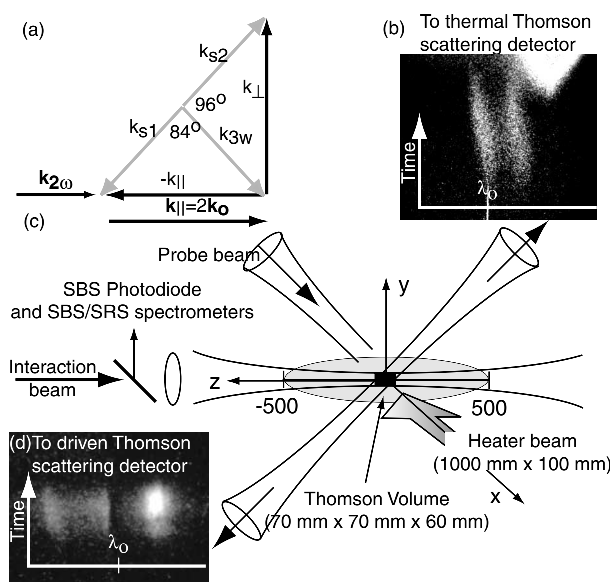

FIG. 1. (a) A diagram detailing the ion-acoustic wave vectors probed is shown. (b) A thermal TS spectrum ($k_\perp$) and (d) a driven TS spectrum ($k_{\|}$) are shown. (c) The experimental setup is shown.

fluctuations [Fig. 1(b)] propagating perpendicular to the interaction beam ($\mathbf{k} = \mathbf{k}_\perp$) and allows us to independently measure the electron temperature, T_e. The geometry [Fig. 1(a)] of the second TS diagnostic was chosen to measure light scattered from SBS-driven ion-acoustic waves [Fig. 1(d)] that are excited by the SBS instability ($\mathbf{k} = \mathbf{k}_\|$) [5].

The interaction beam was timed to turn on 1.0 ns after the heater beam. The 180 ps Gaussian Thomson probe beam was turned on 400 ps after the interaction beam near the peak of the backscattered SBS light.

The plasma has been well characterized; Fig. 2(a) shows a constant electron temperature profile [$T_e(x = 400\ \mu\text{m}) = 450$ eV] along the interaction beam axis. The location of the TS volume and the focus of the interaction beam remained at target chamber center throughout the experiment; the target (and the heater beam) was moved to probe different positions in the plasma parallel to, and 400 μm from, the surface of the target. The electron density [$n_e(x = 400\ \mu\text{m}) = 1 \times 10^{20}\ \text{cm}^{-3}$] was measured using the SRS spectrum [4]. The ion temperature [$T_i(x = 300\ \mu\text{m}) = 250$ eV] was previously reported in Ref. [5].

Figure 2(b) shows a TS spectrum taken from the streak data in Fig. 1(b). Two peaks corresponding to ion-acoustic fluctuations propagating along the direction of $\mathbf{k}_\perp$ are evident. The separation between the intensity peaks in the TS spectra is sensitive only to the electron temperature; therefore, fitting the data using a standard theoretical form factor and the parameters of the plasma gives the electron temperature, $T_e(x = 400\ \mu\text{m}) = 450$ eV [6]. The measured peaks are broadened by velocity gradients perpendicular to the interaction beam. This broadening is to be expected as the initial plasma length is only $y = 100\ \mu$m in the perpendicular direction. The measured width of the peaks ($\delta\lambda$) gives an estimated velocity range $\frac{\delta v}{v}(\propto \frac{\delta\lambda}{\lambda}) = 0.5$ within the TS volume. The instrument function of the spectrometer was measured to be 0.2 Å.

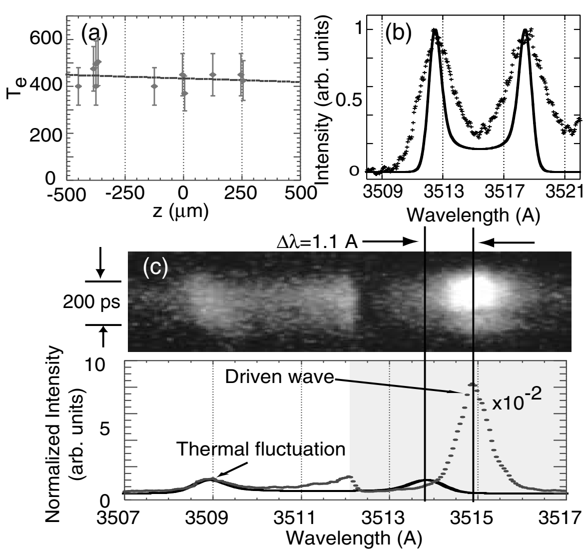

FIG. 2. (a) A constant electron temperature, $T_e = 450$ eV, is measured along the interaction beam axis. The Be is fully ionized ($Z = 4$). (b) Representative TS spectra taken from the spectrum in Fig. 1(b) (points) probing ion-acoustic fluctuations along ($\mathbf{k}_\perp$); the theoretical form factor is fit (line). (c) TS data are shown collected by the diagnostic observing ion-acoustic waves propagating parallel to the interaction beam ($\mathbf{k}_\|$). The spectrum (points) is shown below averaged over 50 ps. The theoretical form factor (solid line) is fit to the blueshifted light using a velocity flow $\frac{v}{v_{th}} = 0.7$ and the electron temperature measured with the first TS diagnostic ($T_e = 450$ eV). The shaded region was optically filtered by $\times 100$.

The blueshifted intensity peak in the spectra measured by the second TS diagnostic is a direct measure of the local resonant frequency of the ion-acoustic waves in the laboratory frame ($-\mathbf{k}_\|$). The frequency of the scattered light in the laboratory frame is shifted from the laser frequency in two ways: by the frequency of the probed ion-acoustic wave ($\omega = c_s k_\|$ where c_s is the sound speed which is a function of the electron temperature), and by the overall flow, $\mathbf{u}_f$, of the plasma relative to the frame of the laboratory (Doppler shift $\mathbf{k}_\| \cdot \mathbf{u}_f$) which leads to a wavelength shift in the Thomson-scattered light given by

$$\Delta\lambda = \frac{\lambda_{3\omega}^2}{2\pi c}\mathbf{k}_\| \cdot (\mathbf{c}_s + \mathbf{u}_f).$$

Since the electron temperature is known, the plasma flow parallel to the z axis is determined from the local frequency shift between the frequency of the TS probe ($\lambda_{3\omega} = 3513$ Å) and the blueshifted intensity peak, as shown in Fig. 2(c). Note that the use of two TS diagnostics is necessary as the SBS-driven acoustic wave is not always at the local resonant ion-acoustic frequency. This is evident in Fig. 2(c), where the redshifted intensity peak and the corresponding resonant intensity peak are offset by 1.1 Å.

Figure 3(d) shows the plasma flow along the z axis measured from the frequency of the local resonant ion-acoustic fluctuations ($-\mathbf{k}_\|$). A 200 μm velocity plateau is measured in the center of the plasma; a Mach 1 flow was measured in the front edge of the plasma. One can directly observe the effect of the velocity gradient on SBS from the frequency mismatch between the measured frequency of the SBS-driven acoustic wave, and the measured frequency of the local resonant waves.

Figure 3(a)–3(c) shows spectra for representative data shots at three positions in the plasma; the frequency of the driven ion-acoustic wave remains unchanged ($\lambda = 3515$ Å) while the frequency of the local thermal ion-acoustic waves ($-\mathbf{k}_\|$) increases as one moves from the plateau to the front of the plasma (this increase is a direct effect of the plasma flow as the electron temperature is constant). SBS light is scattered from the velocity plateau where large resonant acoustic waves grow exponentially [shaded region, Fig. 4(c)]. The light scattered from the plateau and the incident light create a constant ponderomotive force with a constant frequency profile in the

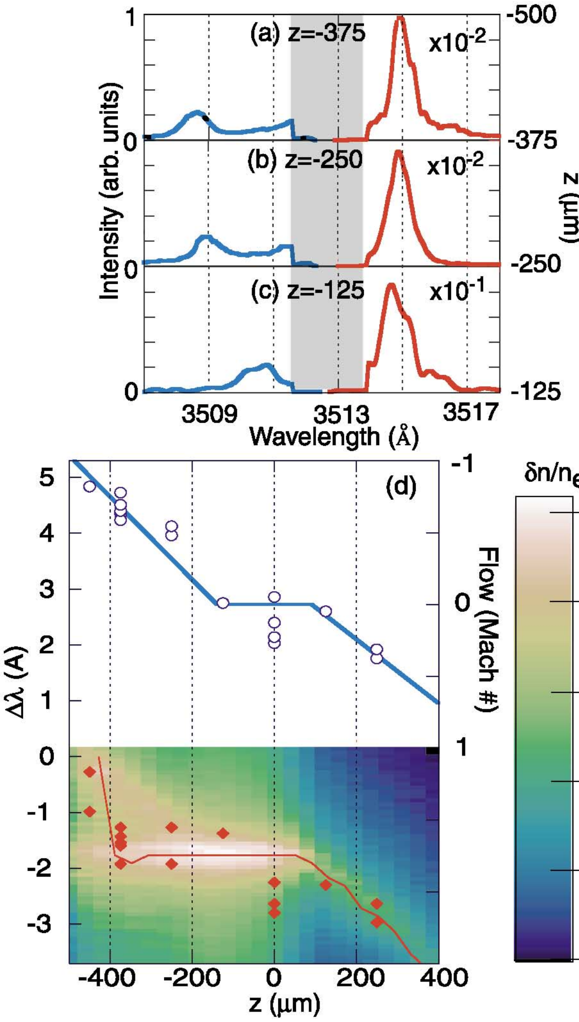

FIG. 3 (color). TS spectra at (a) $z = -375$ μm, (b) $z = -250$ μm, and (c) $z = -125$ μm are shown. The increasing shift of the thermal peak (blue peaks) indicates a velocity flow. One can see that the frequency of the SBS-driven ion-acoustic wave remains unchanged (red peaks). The shaded area has been filtered by a factor of 10. (d) The wavelength shift for the two peaks are plotted for every TS spectra obtained. The wavelength shift of the redshifted peaks (red points) reveals off-resonant ion-acoustic waves in the front of the plasma. A pF3d simulation is shown (color) where large acoustic waves are driven in the plateau region and the frequency of the driven acoustic waves remain constant in the front of the plasma (red line).

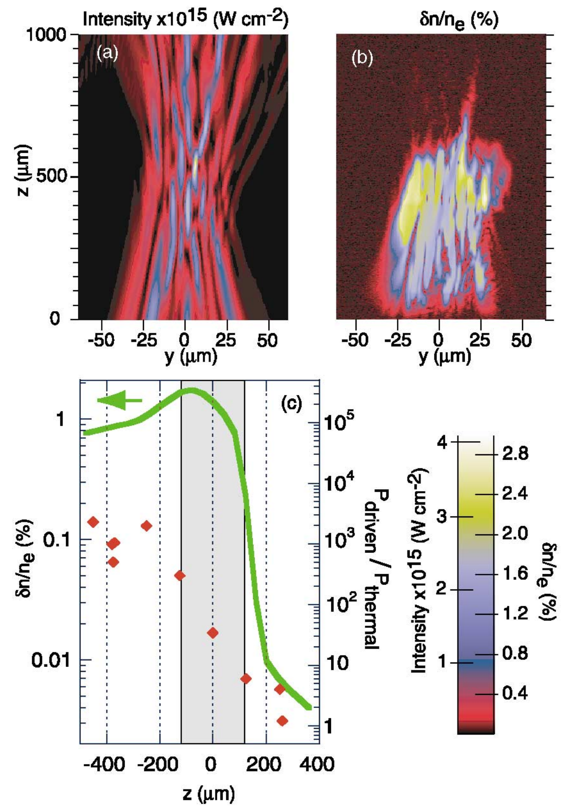

FIG. 4 (color). (a) The intensity of the interaction beam is plotted 70 ps into the pF3d simulation. (b) The ion-acoustic waves are large in the front of the plasma. (c) The measured amplitude of the excited ion-acoustic wave (diamonds) is plotted as a function of the position along the interaction beam. The amplitude profile given by pF3d is also plotted (solid). The shaded region represents the velocity plateau.

front of the plasma. This constant frequency ponderomotive force drives nonresonant acoustic waves as the velocity gradient shifts the resonant frequency.

The experiment was simulated in 2D using pF3d [7]. A $f/6$ RPP beam with a best focus of 60 μm and an average vacuum intensity of 10^{15} W cm^{-2} was propagated through a 1 mm slab of plasma ($T_e = 450$ eV, $n_e = 1 \times 10^{20}$ cm^{-3}). A Mach 2 transverse flow (lateral expansion of the target) and the measured velocity profile along the propagation axis shown in Fig. 3(d) were included.

Figure 4(a) shows a plot of the interaction beam 70 ps into the simulation. Intensity of the most intense speckles is around 4×10^{15} W cm^{-2}. A linear nonlocal heat transport model was used. The maximum local temperature fluctuation observed was $\frac{\Delta T}{T} \approx 30\%$ in the most intense speckles. The transverse flow suppressed most of the filamentation and the simulations show little beam bending.

Figure 4(b) and the solid line in Fig. 4(c) show that large ion-acoustic waves are driven by SBS only in the front half of the plasma [8]. The velocity gradient in the back of the plasma prevents any significant SBS growth. The plateau in the middle provides a resonant region where SBS drives ion-acoustic waves exponentially to large amplitude. In the front of the plasma, the strong velocity gradient prevents SBS growth at the local resonant frequency, but the reflected light coming from the plateau and the incoming light provide a constant frequency ponderomotive force that drives nonresonant acoustic waves as seen between $z = -200$ μm and $z = -400$ μm in Fig. 3. As one moves away from the plateau and towards the front of the plasma, the acoustic wave amplitude slightly decreases as the ponderomotive driver is increasingly off-resonance [Fig. 4(c)]. This effect of detuning SBS by a velocity gradient is further verified by postprocessing the simulation providing a measure of the local frequency of the driven ion-acoustic waves. This agrees well with the experimentally measured frequencies, as shown in Fig. 3(d); off-resonant driven ion-acoustic waves are evident in the front part of the plasma.

While the amplitude of driven acoustic waves ($\frac{\delta n}{n_e}$) is readily obtained from simulations, it has to be calculated from the intensity peaks in the TS spectra. This is done by comparing the scattered power from thermal fluctuations [i.e., the power scattered into the left intensity peak in Fig. 2(c)], with the power scattered by the driven acoustic wave (Bragg scattering) which gives the ratio [4]

$$\frac{P_{\text{driven}}}{P_{\text{thermal}}} = n_e \lambda_{3\omega}^2 \Delta\Omega_{\text{exp}} L_c \left(\frac{\delta n}{n_e}\right)^2, \quad (1)$$

where $\delta n/n_e$ is the amplitude of the acoustic wave, L_c is its correlation length along the direction of the 3ω probe beam, and $\Delta\Omega_{\text{exp}}$ is the solid angle of the collection optics (an $f/5$ lens). L_c can be estimated by the transverse size of speckles generated by the interaction beam $f_{2\omega}\lambda_{2\omega}$.

Figure 4(c) shows that the estimation of $\delta n/n_e$ from Eq. (1) reproduces the overall spatial shape predicted by pF3d, but the absolute amplitude is smaller by almost an order of magnitude. Various factors can explain this discrepancy. For instance, any misalignment of the optics, an overestimation of L_c, or enhanced thermal fluctuations would lead to an underestimation of the acoustic wave amplitude. Assuming the latter, we have verified that increasing the amplitude of the thermal noise source used both in the TS calculations and in the SBS simulations by an order of magnitude gives a good agreement between the measured and simulated wave amplitude and spatial profiles. A study of the amplitude of the thermal noise in laser plasmas needs to be completed to investigate the discrepancies in the calculated wave amplitudes seen in this and other studies [9].

A peak SBS reflectivity of 6% was measured. The SBS spectrum (Fig. 5) confirms our analysis of the effect of the velocity gradient on SBS. The frequency of the peak intensity corresponds to the resonant acoustic frequency in the velocity plateau. The spectrum has a tail towards the fundamental frequency that corresponds to light scattered from the flow propagating towards the detector. There is a sharp cutoff towards higher wavelengths indicating that there is no scattering coming from the back of the plasma where the velocity flow is propagating away from the detector. This is consistent with the fact that we measure very small ion-acoustic waves in the back portion of the plasma [Fig. 4(c)]. Overall, the SBS spectrum is characteristic of the central plateau, while the expanding plasma only slightly modifies its shape.

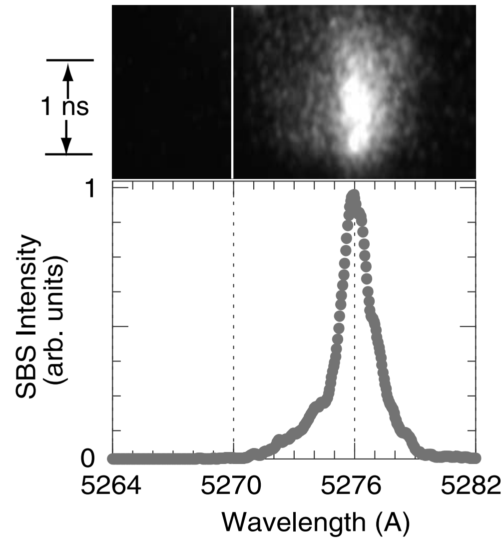

FIG. 5. Ths SBS spectra are plotted as a function of intensity. The peak intensity corresponds to light scattered from the velocity plateau; a tail towards the fundamental frequency corresponds to light scattered from ion-acoustic waves in the front of the plasma.

In summary, we have presented the first direct measurement of SBS detuning by a velocity gradient. We studied an expanding plasma with a central velocity plateau. The frequency mismatch between the frequency of the SBS-driven ion-acoustic wave and the local resonant frequency (as measured from thermal waves) was mapped throughout the plasma. It was found that acoustic waves in the flow are driven off-resonance by the ponderomotive force with a beat frequency created by the incoming light and the light reflected from the plateau. This detuning inhibits further SBS growth in the expanding plasma. These findings are important to many laser-plasma experiments and occur in various ICF direct-drive [10] and indirect-drive targets [9].

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