# Time-Resolved Thomson-Scattering Measurements of Ion Fluctuations Driven by Stimulated Brillouin Scattering

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Thomson-scattering measurements of ion fluctuations driven by stimulated Brillouin scattering in a $CO_2$-laser–plasma interaction experiment are reported. It is found that the ion fluctuations correspond to a heavily damped, convective model of the Brillouin instability. The dominant $2k_0$ wave number ($k_0$ is the $CO_2$-laser wave number) for the ion fluctuations is confirmed, with no evidence for harmonic generation. Growth and decay times of the ion fluctuations were found to be relatively long, ~150–700 ps, consistent with heavy wave damping.

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The interaction of intense laser radiation with plasma can generate parametric instabilities in which the incident electromagnetic wave decays into electrostatic and electromagnetic waves. These instabilities are of considerable interest (a) in their own right, (b) for determining turbulence levels and modifications to plasma transport properties, and (c) particularly for their importance in laser fusion due to possible detrimental effects of either poor laser-target coupling or target preheat. Stimulated Brillouin scattering (SBS) is one such parametric instability where the incoming laser radiation may be converted into scattered electromagnetic and ion-acoustic waves with a resultant low net energy deposition to the plasma. While considerable progress has been made in identifying features of SBS, much work remains to be done to understand completely temporal and spatial growth, saturation, and decay of the Brillouin instability in order to reduce or eliminate it in long-pulse laser-target interaction.

In this Letter we report on ruby-laser Thomson-scattering measurements of SBS-induced ion fluctuations which have been made to determine three key features: (a) wave-number spectra, (b) spatial extent, and (c) growth rates of ion-acoustic waves driven by SBS in a $CO_2$-laser–plasma interaction experiment. Thomson scattering offers a particularly powerful technique for directly probing the ion fluctuation level ($\delta n$) to correlate with calculated theoretical values and, moreover, it permits higher temporal resolution than that accessible through monitoring 10-$\mu$m backscattered light. Previous work on Thomson scattering in our laboratory has been limited to ~2-ns time resolution with a photomultiplier. We note, however, that such time-integrated measurements do provide useful average $\delta n$ values. Currently, a high-speed streak camera with 1 to 100-ns full streak and 1% temporal resolution has enabled detailed measurements of induced ion fluctuations in the $CO_2$-laser–plasma interaction region. Importantly, the saturated behavior of the fluctuations plus general growth and decay features are identified in time-resolved experiments.

The experimental apparatus consisted of a pulsed supersonic oxygen gas jet target[1] irradiated by a focused 40-ns gain-switched transversely excited atmospheric $CO_2$ laser pulse. The focused $CO_2$ laser beam, with intensities $\leq 6\times 10^{12}$ W cm$^{-2}$ in a 100-$\mu$m focal spot, ionized the oxygen target, and then provided the electromagnetic pump wave for generating SBS in the expanding plasma. Note that for our experimental times of interest, $\gtrsim 5$ ns following gas breakdown, asymptotic expansion gave relatively quiescent plasma conditions for the laser-plasma interaction. The time evolution of the density profile was followed by using ruby-laser interferometry which showed plasma densities of $(3-4)\times 10^{18}$ cm$^{-3}$ and density gradient scale lengths of 600 $\mu$m at the time of peak Brillouin scattering. Electron temperature was determined from absorbing-foil/scintillator x-ray measurements, yielding $T_e \sim 150$ eV.

The incident ruby-laser direction and collection optics for the Thomson-scattered light were arranged to probe selectively the ion fluctuations associated with SBS backscattering (the case of maximum growth). From frequency and wave-number matching of the pump $(\omega_0, \vec{k}_0)$, scattered $(\omega_-, \vec{k}_-)$, and ion-acoustic waves $(\omega_s, \vec{k}_s)$ in SBS, i.e., $\omega_0 = \omega_- + \omega_s$, $\vec{k}_0 = \vec{k}_- + \vec{k}_s$, where $\omega_s \ll \omega_0, \omega_-$, we find $k_s = 2k_0$ for backscattering. Consequently, with respect to the ruby-laser scattering geometry illustrated in Fig. 1, the scattering angle $\theta$

 

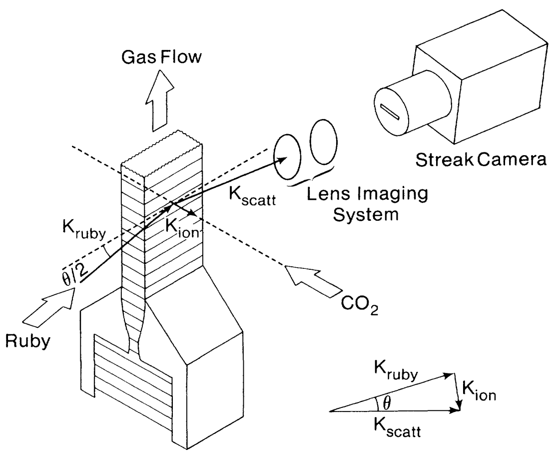


FIG. 1. Ruby-laser scattering geometry for probing ion fluctuations induced by SBS in $CO_2$-laser–irradiated $O_2$ gas jet target (neutral gas flow dimensions > 1 mm thick × 1 cm wide). The streak camera slit was oriented to probe spatial or $k$ spectra along the $CO_2$ pump direction.

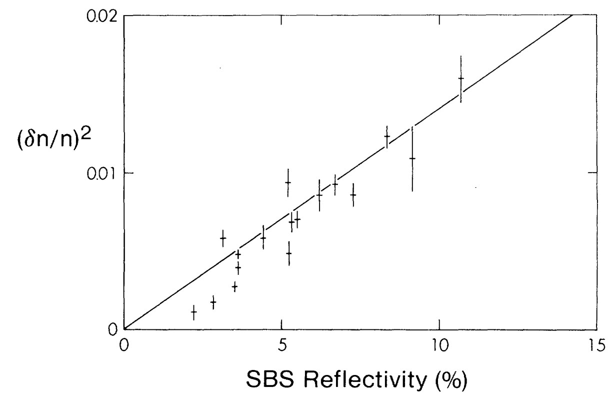


FIG. 2. Ion fluctuation $(\delta n/n)^2$ as a function of SBS reflectivity, $R$, for nominal $CO_2$-laser pump intensity $\sim 3\times 10^{12}$ W cm$^{-2}$. The theoretically predicted result for wave damping $\gamma_s/\omega_s = 0.3$ and plasma conditions $n_e = 0.3n_c$ and $T_e = 150$ eV is indicated with a solid line. SBS reflectivity is observed to saturate at $\simeq 15\%$–$20\%$ for $I \geq 6\times 10^{12}$ W/cm$^2$.

was chosen to include the wave number $k = 2(\omega_{0R}/c)\sin\frac{1}{2}\theta = k_s$, where $\omega_{0R}$ is the ruby-laser frequency. The $Q$-spoiled ruby-laser probe used for this study provided an 8 MW, 20-ns light pulse which was focused to a spot 150–300 $\mu$m (depending on focusing lens). This dimension was greater than the SBS interaction length and so only spatially averaged fluctuations are reported for the photomultiplier measurements. Scattered light levels were sufficiently large that considerable attenuation was necessary to give linear response of either photomultiplier or streak camera detection.

We first discuss time-integrated measurements of the ion fluctuations obtained by using a photomultiplier for detection of the Thomson-scattered ruby light. The $2k_0$ ion fluctuation level, $\delta n/n$, was determined for an unattenuated, but shot-to-shot varying, $CO_2$ laser intensity ($I_{\text{average}} \sim 3\times 10^{12}$ W cm$^{-2}$) and varying Brillouin reflectivity $R$. Calibration of the optical system was made by using a black-body radiation source. Results are summarized in Fig. 2 which clearly show that $(\delta n/n)^2$ was linearly related to the Brillouin reflectivity as expected for small $R$. It should be mentioned that the large ion fluctuations result in scattered light levels several orders of magnitude higher than that expected for scattering from thermal fluctuations (enhancements as large as $10^6$ have been observed).

It is instructive to compare our experimental results with those calculated theoretically. In steady state we find from Drake[2]

$$\frac{\delta n}{n} = \frac{-k^2}{8\pi n m\omega_0^2}\frac{\chi_e\chi_i}{1+\chi_e+\chi_i}\vec{E}_0\cdot\vec{E},$$

$$\vec{E}_0 = \vec{E}_0\cos(\vec{k}_0\cdot r - \omega_0 t),$$

which reduces to $\delta n/n = \frac{1}{2}(V_0/V_e)^2(\omega_s/2\gamma_s)\sqrt{R}$, where $V_0$ is the electron quiver velocity in the pump field $(eE_0/m\omega_0)$, $V_e$ is the electron thermal velocity, and $\gamma_s$ $(\omega_s)$ is the damping coefficient (frequency) of the ion sound waves.

Assuming strong ion wave damping, which is substantiated for our case by the spectral width of the backscattered 10-$\mu$m radiation[1] and temporal data (to be discussed later), we have plotted the theoretical dependence of $\delta n/n$ for varying $\gamma_s/\omega_s$ and our best estimates of experimental plasma parameters. From this analysis, we infer an effective damping $\gamma_s/\omega_s \sim 0.3$ as seen by the agreement between theory and experiment in Fig. 2. Effects of nonlinear modifications to the susceptibility terms have been ignored in this simple treatment. Even so, the salient feature that $\delta n/n$ varies as $\sqrt{R}$ is demonstrated, which is consistent with heavily damped convective growth of ion waves and Brillouin backscatter.

In the second experiment, the effective interaction length in the plasma was determined directly with use of the streak camera. One can first crudely estimate the interaction length from the Bragg reflectivity relation (which assumes coherent waves over the interaction length, $L$). If $\delta n/n$ is not self-consistently solved for through the coupled equations describing the Brillouin instability, but rather is taken to have a given value (such as estimated from steady-state ion heating or ion trapping), this reduced description simply yields,[3] for small $R$,

$$R = \left(\frac{\pi}{2}\right)^2 \left(\frac{n}{n_c}\right)^2 \left(\frac{\delta n}{n}\right)^2 \left(\frac{L}{\lambda_0}\right)^2 \left(1 - \frac{n}{n_c}\right)^{-1/2},$$

where $\lambda_0$ is the free-space wavelength of the pump and $n/n_c$ is the plasma electron density normalized to critical density ($n_c = 10^{19}$ cm$^{-3}$ for 10.6 $\mu$m). This implies, for our experimental parameters, $L/\lambda_0 \sim 6$ which is much smaller than the density gradient scale length. On the other hand, interaction-length calculations based on variations of the pump intensity through the $f/2$ focusing optics and consequently the SBS gain through the unstable region indicate $L/\lambda_0 \sim 11$.

Experimentally, a direct measurement of $L$ was obtained by imaging the Thomson-scattering region onto the streak-camera slit with a magnifying relay lens system. The measured scattering dimension was found to be $80 \pm 20$ $\mu$m which shows in fact that the observed $L/\lambda_0$ is bracketed by the reflectivity calculation and the scale-length estimate from the pump focusing. Disagreement with both low and high estimates of $L/\lambda_0$ may be attributable to the nonuniform ion fluctuation level and the incoherent nature of the heavily damped waves. The low $L/\lambda_0$ estimate can be ascribed to the assumption of constant $\delta n/n$ through the interaction region rather than accounting for convective growth from noise and consequently a spatially varying ion fluctuation. On the other hand, the apparent observed scattering region can be smaller than its real extent because of instrumental limitations in detecting low light scattering from diminishing ion fluctuation levels at the extremities of the interaction zone. More detailed measurements of $\delta n/n$ as a function of position could conceivably yield useful information on the instability's evolution as determined by the local ion wave damping. The spatial resolution of our present setup was inadequate for this task.

In a third experiment, we attempted to find any evidence for harmonic or subharmonic generation of the ion-acoustic fundamental at $2k_0$. With appropriate scattered-light collection optics spanning a range $\Delta k \geq 3k_0$ ($k \propto \theta$, for small $\theta$), the wave-number spectra of the ion fluctuations driven by SBS were temporally dispersed with the streak camera. Scattering corresponding to $2k_0$ ion fluctuations was confirmed, for which the predominant scattering angle was 6°– 8°. We note that for vacuum $k_0$ the scattering angle is $\theta = 7.5°$ and for $n_e/n_c = 0.3$, $\theta = 6.3°$ for a ruby-laser scattering probe. The instrumental function $\Delta k/2k_0 \sim 0.13$ was large enough to obscure any effects of $k$ broadening through ion wave broadening or sidescattering except for the broadest spectra. Significantly, no subharmonic ($k_0$) or harmonic ($4k_0$) ion fluctuations were detected for our pump levels of $\leq 6\times 10^{12}$ W cm$^{-2}$ even though saturated Brillouin backscatter levels of 15%–20% are observed. This is in sharp contrast to the result reported by Walsh and Baldis[4] where evidence for $4k_0$ was seen even for lower saturated reflectivity (6%–10%) when a short-pulse $CO_2$-laser pump was used. Higher wave damping due to significant ion heating in the longer pulse irradiation of our experiment and some influence due to lower pump intensity could explain the difference between our results and theirs. The absence of subharmonic spectra would appear to rule out secondary ion wave decay[5] as a saturation mechanism for our case. This is consistent with the heavy ion wave damping regime since decay requires $\delta n/n \gtrsim \gamma_s/\omega_s$.

Finally, we report on the temporally resolved behavior of the SBS-generated ion fluctuations as measured through Thomson scattering. Both the spatially imaged and $k$-spectrally dispersed scattered light were temporally analyzed with the streak camera. Variation in the ruby-laser output and in its timing with respect to the scattering event necessitated simultaneous monitoring of the ruby-laser and Thomson-scattered light.

Figure 3 shows typical streak-camera results of the spatially imaged scattered light which illustrate the growth and decay characteristics of SBS-induced fluctuations. The Thomson-scattered light measurements showed monotonic growth of the ion-acoustic level over periods of 150– 700 ps and decays of similar duration. The absence of exponential growth in time or rapid modulation in the scattered light is clear evidence for strong ion wave damping beginning well ahead of the peak ion-fluctuation level. This behavior prevailed over a detection dynamic range of better than $10^4$, obtained by using different neutral-density filters and streak speeds. This, in turn, implies a growth limited only by the instantaneous gain conditions determined by laser and plasma for a heavily damped convective regime. The relatively slow variation in amplitude of ion waves, even for relatively early time ($\leq$ 20 ps) after scattering is detected, may be due to a combination of effects including slow variations in

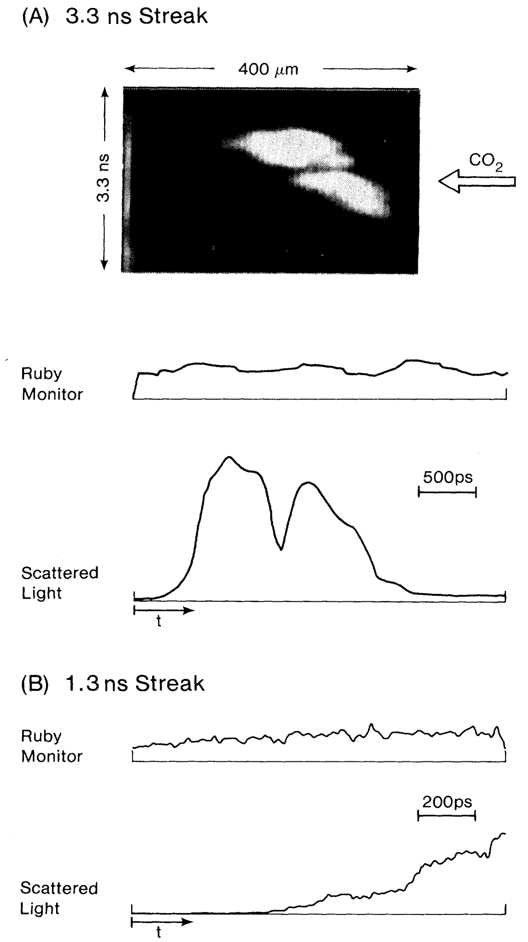


FIG. 3. Spatially imaged streaks of Thomson-scattered ruby-laser light; note the two spatially separate regions giving rise to SBS at different times. (a) 3.3-ns streak showing a typical modulation feature in ion fluctuations driven by SBS; (b) 1.3-ns streak showing the characteristic monotonic increase in Thomson-scattered light, indicating heavily damped ion waves. For $CO_2$-laser shots leading to saturated reflectivity (as detected near 10.6 $\mu$m in backscattering), we observe a constant value of ruby Thomson-scattered signal indicating saturated $(\delta n)^2$.

pump, plasma hydrodynamics, and ion heating from Brillouin scattering limiting ion wave growth.

The mechanisms responsible for disrupting Brillouin scattering, as seen in Fig. 3, are still not fully understood but may possibly be related to either ion turbulence in the plasma resulting in enhanced pump absorption and electron heating[6] or filamentation giving rise to local heating, both of which at sufficient levels could reduce Brillouin gain.

In conclusion, we have made direct measurements of the level of ion fluctuations and their temporal evolution as driven by SBS in a laser-plasma interaction experiment. Ion fluctuation levels, $\delta n/n$, show the correct functional dependence on $R$ from which an effective damping coefficient $\gamma_s/\omega_s \sim 0.3$ is inferred. The measured effective interaction length of $80 \pm 20$ $\mu$m is greater than the Bragg value but less than the optical depth which is consistent with heavily damped, convective growth of waves. The smooth temporal features of the scattered light also support the view that the ion waves are heavily damped even for early time.

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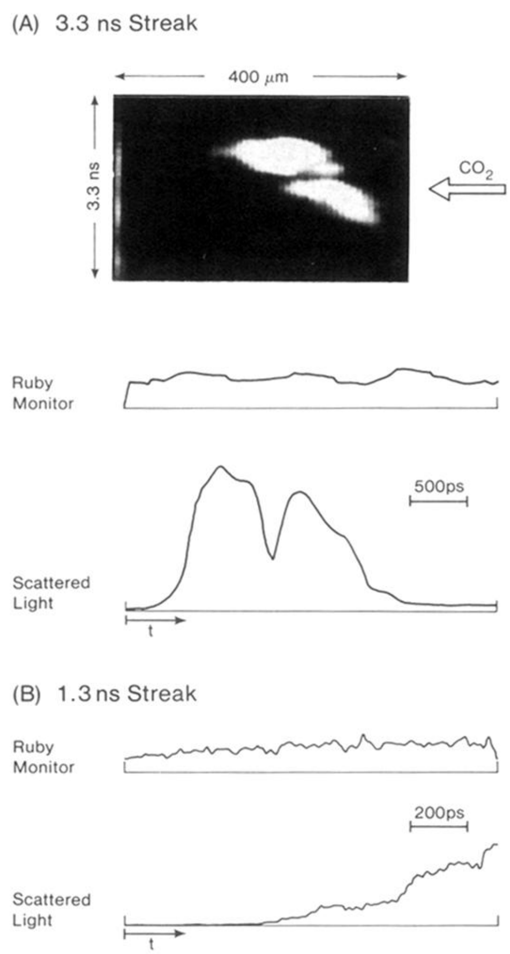


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