Measurement of Absolute Growth Rates and Saturation Phenomena for Stimulated Brillouin Scattering in a CO_2-Laser–Irradiated Plasma

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Growth rates and saturation of stimulated Brillouin scattering in a CO_2-laser–irradiated plasma are investigated by picosecond Thomson scattering of ruby laser light and backscatter spectroscopy. The temporal growth rates are found to be consistent with theoretical predictions. The ion acoustic waves saturate at a fluctuation amplitude of $<20\%$ and subsequently show a modulated temporal behavior, as well as sidebands in the backscatter spectra consistent with saturation by strong ion trapping.

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Stimulated Brillouin scattering (SBS) is believed to be a potentially dangerous loss mechanism in proposed laser fusion schemes. In recent CO_2-laser experiments, optical-probe-laser Thomson scattering has been used to investigate the temporal and spatial behavior of SBS.[1–3] Other experiments at 1.06 μm (Ref. 4) and 10.6 μm (Refs. 5 and 6) have examined the temporal development of SBS backscattered radiation. Theory[7] predicts that at least for small damping of the electromagnetic (incident and scattered) and ion waves, the ion fluctuation amplitude initially should grow absolutely. Measurements of absolute growth have not been reported previously either because of limited temporal resolution or because heavy damping limited the growth to the convective regime. In this Letter we report first measurements of the absolute growth of SBS ion waves in CO_2-laser–plasma interactions using probe ruby-laser Thomson scattering. The results support previous theoretical predictions.[7] In addition, we would like to report on experimental evidence for dominant saturation by ion trapping obtained consistently from Thomson-scattering measurements and measurements of the backscatter spectra.

The experiments were performed with a CO_2-laser that produces 2-ns FWHM, 1.2-ns rise-time pulses of ≤ 12 J focused to a measured Gaussian $1/e$ radius of ~ 50 μm. The target consists of a pulsed supersonic N_2 jet, ~ 1.5 mm thick, which flows from a two-dimensional Laval nozzle into a 5-Torr He background.[8] The plasma evolution has been investigated previously.[9] Single-shot backscatter spectra were obtained with a 0.5-m spectrometer–image-dissector[10] combination and a Cu:Ge detector. The combined detector–gigahertz-oscilloscope rise time permitted some temporal resolution of the spectra.

The Thomson-scattering arrangement is shown in Fig. 1. A cylindrical lens focuses a 6-ns ruby pulse to a line (~ 1 mm high, ~ 5 mm long) in the interaction region. Scattered ruby light is imaged onto the slit of a picosecond streak camera (Hamamatsu Temporal Disperser C1370-01/III Analyzer System) by means of two 30-cm focal-length lenses. The streak records are digitized and stored on tape for computer analysis. Two sets of scattering experiments were performed. In the arrangement of Fig. 1, a strip just in front of the first lens is imaged onto the slit in order to study the k spectrum of the SBS ion waves. Detected are waves in the approximate range $k_0 \leq k \leq 4k_0$ ($k_0 = k_{CO_2}$), which is limited by the target-chamber port and the cone angle of the SBS ion waves (assumed to be limited to within the $\sim f/7$-focused CO_2-laser beam). In a second set of experiments the second lens was repositioned to image the interaction region onto the slit in order to study the spatial evolution of the instability. An 11-nm bandpass interference filter for 694.3 nm in the scattering beam removes broadband plasma light and scatter from possible electron plasma waves. Part of the incident ruby beam is focused, after suitable delay, onto a single-mode optical fiber placed in contact with the slit to provide a fiducial mark on the streak record. The absolute intensity response of the system was calibrated by scattering ruby light off a Mylar sheet located at the interaction region. The ratio of this

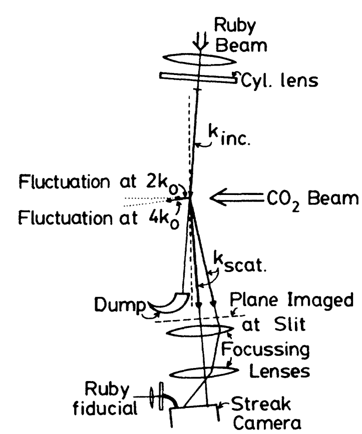

FIG. 1. The Thomson-scattering optics used for measuring the k spectrum of the SBS-excited plasma waves. A similar arrangement was used to study the spatial behavior of the SBS interaction region.

scattered-to-incident intensity was measured separately with a fast photodiode. The linearity of the streak camera–TV monitor combination at 694.3 nm was measured with the aid of a calibrated neutral-density step wedge placed at the uniformly illuminated slit. The response is linear over a dynamic range of 80–100. The reported results were obtained in this range.

The plasma first appears in two regions, at the front and rear N_2-He jet interfaces. Subsequently the development of the rear plasma stops except for a slow expansion. The front plasma rapidly extends into the He background. Peak densities $\leq 0.4n_c$ ($n_c = 10^{19}$ cm^{-3}) are measured near the initial plasma location. Breakdown in the background gas leads to the formation of a long–scale-length plasma ranging in density from $0.05n_c$ to $0.2n_c$ as shown in Fig. 2(a). This indicates that this plasma is composed of a $\sim$2:1 mixture of He to N ions. The N_2 contamination of the background gas arises from the $\sim$10-ms operation of the jet prior to the laser pulse. Spatially resolved Thomson-scattering measurements indicate that SBS is located in this plasma as demonstrated in Fig. 2(b). The enhanced scatter starts before the peak of the CO_2-laser pulse and grows rapidly to extend over regions of the order of 1 mm. Approximately 0.5 ns later, a second separated region of scatter appears in front of the first and later becomes the major source of SBS. The discrepancy in extension between the scattering regions in Fig. 2(b) and the plasma in Fig. 2(a) probably arises from shot-to-shot variations.

During the initial phase of the laser pulse, the plasma is expected to have a high electron temperature.[9] However, the ion temperature should remain low because of the long ($\sim$300-ns) electron-ion equilibration time. Therefore, there should be low damping of the ion-acoustic and electromagnetic waves which should permit absolute growth of SBS. The growth rate γ of the ion-acoustic amplitude was determined by measurement of the growth of the Thomson-scattered intensity I_s. Since $I_s \propto (\delta n/n)^2$, γ of the ion fluctuations is one-half that of I_s. The growth of both the spatially (at a given position) and wave-number resolved [within the range $(2.0 \pm 0.05)k_0$] Thomson scattering was measured. The inset in Fig. 3 shows a typical example. The points in this semilog graph are well fitted by a straight line indicating, indeed, exponential growth. The rates from both sets of measurements are plotted in Fig. 3. The good agreement between the two sets indicates that the same growth occurred in the entire interaction region as expected for an absolute instability.

For an infinite homogeneous plasma, SBS should grow at a rate γ_0, which may be calculated analytically for cases of strong or weak coupling[7,11] or may be obtained from a numerical solution of the plasma dispersion relation [Eq. (16) in Ref. 11] for cases of intermediate laser intensity. In a finite interaction region of length l, growth at γ_0 persists only for a time $\sim l/V_-$ after which the growth rate gradually de-

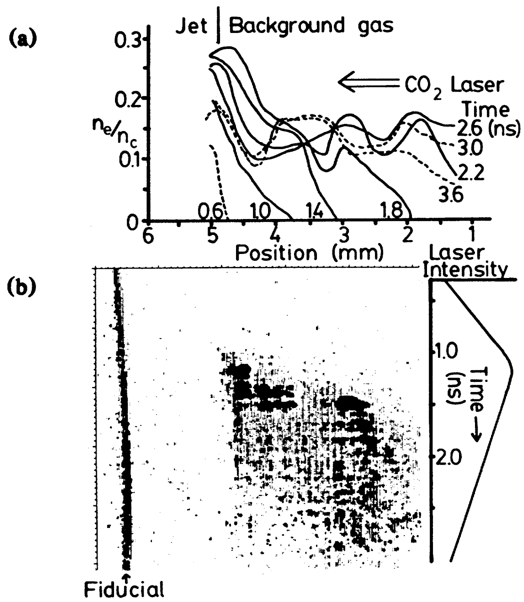

FIG. 2. (a) The plasma density in the SBS interaction region as a function of position and time. (b) An example of a spatially resolved streak record showing the development of the SBS interaction region.

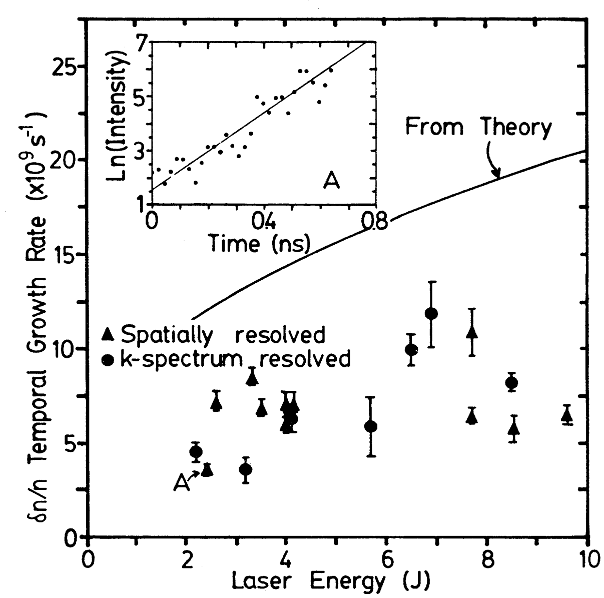

FIG. 3. The measured growth rate of the ion waves as a function of laser energy. The solid curve shows the theoretical growth rate as calculated from Eq. (1). Inset: typical measurement of scattered intensity vs time (for point A).

creases until a time l/V_{ia} when the growth rate becomes[7,12]

$$\gamma = 2\gamma_0 (V_{ia}/V_-)^{1/2}. \quad (1)$$

Here V_{ia} and V_- are the group velocities of the ion-acoustic and scattered waves, respectively. We have calculated γ_0 for a He-N_2 plasma of our conditions by solving Eq. (16) of Ref. 11 generalized for two ion species,[13] and we have then determined γ from Eq. (1). The result is indicated by the solid curve in Fig. 3. The measurements are obtained for $l/V_- << t << l/V_{ia}$, but appear to be in reasonable agreement with this curve. Some of the discrepancy is probably due to overestimation of the incident intensity and hence γ_0 by use of the peak CO_2 intensity since SBS usually began during the rise of the laser pulse. For intensities well above threshold, γ_0 depends very weakly on T_e/T_i, and so higher ion temperature should not strongly affect γ_0.[13]

Kroll[12] predicts that between times l/V_- and l/V_{ia} (as in the present experiment), the instability should exhibit a transient behavior with the amplitudes increasing exponentially with the square root of time. Such behavior was not seen either in the present experiment or in a previous microwave experiment[14] where good agreement was observed between the measured growth rate and that predicted by Eq. (1).

A typical k-resolved streak record is shown in Fig. 4. As expected for SBS, the dominant scattering comes from fluctuations with $k \simeq 2k_0$, though some harmonic generation is apparent. Harmonic generation[16] and wave steepening are expected to occur if $\delta n/n \geq (k\lambda_D)^2$. For our conditions of $n_e \simeq 0.1 n_c$ and $T_e \geq 300$ eV, $(2k_0\lambda_D)^2 \simeq 0.2$, which is much smaller than the measured peak value $\delta n/n \simeq 0.17$. However, the observed scattered intensity at $4k_0$ was only $\sim \frac{1}{200}$ of that at $2k_0$. Therefore, the $4k_0$ fluctuation amplitude was $< 10\%$ of that at $2k_0$, ruling out strong harmonic generation and subsequent wave breaking as a possible saturation mechanism for SBS.[1]

A strong periodic modulation, often approaching 100%, was observed in the amplitude of the ion waves. Some temporal variation is expected as a result of variation in the ruby-laser intensity, but this is usually smaller and exhibits little periodicity as seen on the fiducial. The measured modulation period (uncertainty $\pm 30\%$) is plotted in Fig. 5 as function of laser energy. We propose that the modulation is caused by the bounce period of ions trapped in the wave potential. Similar modulations have been seen in the case of electron trapping by electron plasma waves.[17] The bounce period can be calculated on the assumption that the ions oscillate harmonically in the potential of the ion wave:

$$\tau_B = \lambda_{ia}\left(\frac{m_i}{Ze\phi}\right)^{1/2} = \lambda_{ia}\left(\frac{m_i}{Zk_B T_e}\right)^{1/2}\left(\frac{\delta n}{n}\right)^{-1/2}, \quad (2)$$

where we used the relation $e\phi/k_B T_e \simeq \delta n/n$. Here m_i is the ion mass, Z the ion charge, and ϕ the wave potential. Using our measurements of the peak ion wave amplitude as function of laser energy, we have estimated τ_B from Eq. (2). The results are indicated in Fig. 5 by the shaded band. The agreement with the measured values is quite good.

Additional evidence for strong ion trapping is found in the SBS backscattered spectrum. The trapped-ion bouncing is expected to generate sidebands separated from the ion acoustic frequency by the bounce frequency.[6] These sidebands have previously been seen for large-amplitude electron waves[17] and recently in SBS backscattered spectra.[6] Three spectral peaks with

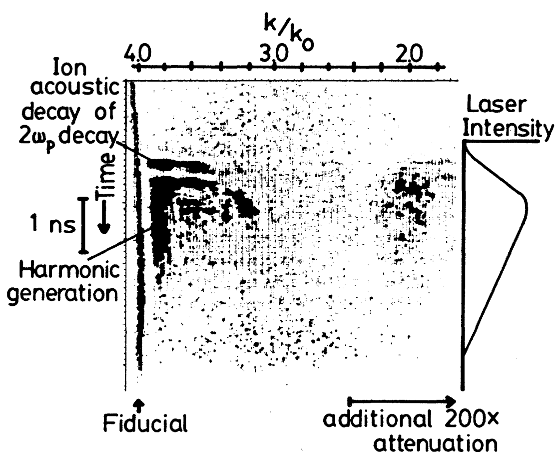

FIG. 4. An example of a k-resolved streak record showing scatter from SBS fluctuations with $k \sim 2k_0$ and $k \sim 4k_0$. The other features are discussed in Ref. 15.

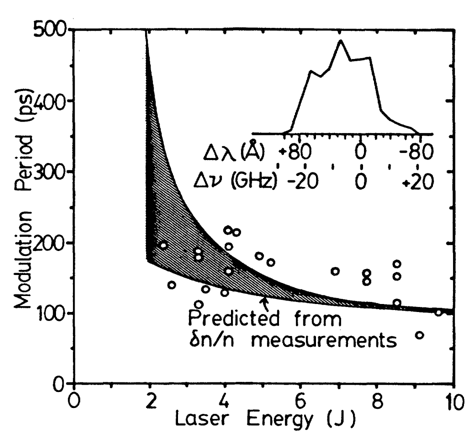

FIG. 5. A plot of the measured and predicted ion acoustic wave fluctuation periods as a function of laser energy. Inset: A typical backscatter spectrum. The instrument FWHM $\simeq 7$ GHz.

average shifts from the $P(20)$-CO_2 line of 7 ± 6 Å (-1.9 ± 1.6 GHz), 33 ± 6 Å (-8.8 ± 1.6 GHz), and 61 ± 6 Å (-16.3 ± 1.6 GHz) are observed in our spectra. The relative intensities of the peaks varied considerably from shot to shot and even during a shot. A sample spectrum is in the inset of Fig. 5. The spectrum shows evidence of all three peaks, while the other spectra show two peaks separated in time. The second type with large enough temporal separation to be detected with the image dissector was only observed at higher laser powers. We interpret the spectra as follows: The central peak (shift = 33 Å) is dominant in cases with little ion trapping and is due to the SBS-driven ion wave. This requires a plasma blowoff velocity towards the laser of $\gtrsim 10^5$ m/s. The other two peaks arise, in cases of strong trapping, from scattering off the associated sidebands. Since the trapping is likely to change during a shot, it is not unreasonable to expect a complicated behavior of the spectra. Handke, Rizvi, and Kronast[6] have also seen changes in their spectra, which they interpret as evidence for changes in the distribution function near the wave velocity. For 6 J at which most spectra were obtained and with use of Eq. (2), the two sidebands are expected to be separated by 14–17 GHz, in good agreement with the observed separation of 14.4 ± 2.3 GHz. This supports our hypothesis that ion trapping is significant in our experiment. Estimates of the SBS reflectivity limited by strong linear damping[18] give values $\geqslant 20\%$, much larger than the observed reflectivity saturation at $\sim 10\%$. Therefore, because of the evidence for strong ion trapping, as well as evidence against alternative mechanisms, we conclude that ion trapping was the dominant cause for saturation of SBS in our experiment.

We have shown that SBS grows as an absolute instability in our plasma at rates well predicted by theory. The ion waves saturate early in the laser pulse at peak $\delta n/n < 20\%$ and exhibit an intensity-dependent modulation as well as production of sidebands. These effects are consistent with strong ion trapping.

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