Nonlinear Ion-Wave Development and Saturation of Stimulated Brillouin Scattering

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The growth of ion waves at a wave number of $2k_{\text{pump}}$ has been studied in a CO_2-laser–plasma interaction, by use of Thomson scattering. Time- and wave-number–resolved spectra have been obtained. Harmonic generation has been observed in the ion-wave spectrum. Saturation of the reflectivity is also observed. These results are consistent with nonlinearities in the ion wave affecting both the damping and the interaction length.

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The phenomenon of stimulated Brillouin scattering (SBS) is by now well established in the study of laser-plasma interactions.[1] The scattering is a parametric instability where an ingoing electromagnetic wave of wave number k_{pump} resonantly drives a backscattered electromagnetic wave at k_{pump} and a forward-traveling ion wave at $2k_{\text{pump}}$. The instability occurs because of a feedback loop: The pondermotive force generated by the superposition of the ingoing and scattered electromagnetic waves is of the appropriate phase to drive an ion-acoustic wave at $2k_{\text{pump}}$, which itself in turn scatters the ingoing electromagnetic wave more strongly. SBS has been held responsible for the reflection of a large fraction of the incident laser light in the corona of the target (i.e., the region of plasma where $n_e \leq n_c$, the critical density).[2] Most theories predict the fraction of reflected light to be large, far larger than many experimental observations suggest,[3] although the range of saturated reflectivities is wide.[2,3] Variations from the theories are most often explained in terms of the nonlinear behavior of large-amplitude ion waves[3,4] (ion trapping, for example), or by strong linear Landau damping produced by ion heating.[5]

In this paper we present direct experimental evidence of nonlinearities in the development of ion waves driven by SBS. In particular, harmonic generation has been observed to occur at large ion-wave amplitudes. This behavior is consistent with the theory of long-wavelength, dispersive ion waves.[6] At high pump intensities, a rapidly varying (< 100 psec period), 100% modulation of the wave at $2k_{\text{pump}}$ is also observed. The results can be interpreted, in terms of nonlinear theories of ion wave propagation, to explain the saturation which has also been observed in the plasma reflectivity at high laser energies.

The experiments were performed with a CO_2 laser ($\lesssim 40$ J, 1 nsec), interacting with a well-characterized carbon plasma which was preformed by a Nd-doped yttrium aluminum garnet laser (4 J, 30 nsec). The plasma temperature $T_e \simeq T_i \lesssim 100$ eV, electron density $n_e \simeq (0.1-0.2)n_c$ for these experiments ($Z \sim 3-4$), and the density scale length along the axis $(n^{-1}\, dn/dx)^{-1} \simeq 300$ μm. The critical density n_c is the cutoff plasma density for the electromagnetic wave (10^{19} cm^{-3} for $\lambda = 10.6$ μm). The CO_2 laser light was incident perpendicular to the plasma axis, as in previous experiments,[7] and focused to a spot of diameter $d \lesssim 200$ μm.

Thomson scattering was performed by using a 3 nsec, 50-mJ probe pulse at $\lambda_{\text{probe}} = 0.53$ μm, focused to a spot size of dimension $2a_0 \simeq 100$ μm. A streak camera was used to resolve the scattered spectrum with a resolution in time ~ 30 psec.[8] To look for ion-acoustic waves of wave number $2k_{\text{pump}}$ in a direction along k_{pump}, the input and collection optics for the scattering were positioned as shown in Fig. 1 (the subscript "pump" refers to the CO_2 laser). The usual way a Thomson scattering experiment is performed is that the light collected from a small region of the plasma illuminated by the probe is reimaged at the detector (after being spectrally resolved). In this experiment, the collection optics for the scattered light was modified, to enable the distribution of intensities in k space (where $k_w \lambda_D \ll 1$) to be measured. This can be done when the scattering angle θ is small, as there is a one-to-one relationship between k_w and θ: $\theta = 2\sin^{-1}(k_w/2k_{\text{probe}})$. Consequently, resolution in k space is achieved by imaging the distribution of scattered light across the collection lens inside the target chamber onto the entrance slit of the streak camera. With a range of scattering angles in this experiment from 3° to 16°, a range of wave numbers from $\sim 6\times10^3$ cm^{-1} to $\sim 4\times10^4$ cm^{-1} ($\sim k_{\text{pump}}$ to $6k_{\text{pump}}$) could be covered simultaneously (Fig. 1). A grating spectrograph was used to isolate scattered light near the probe frequency (i.e., light scattered from low-fre-

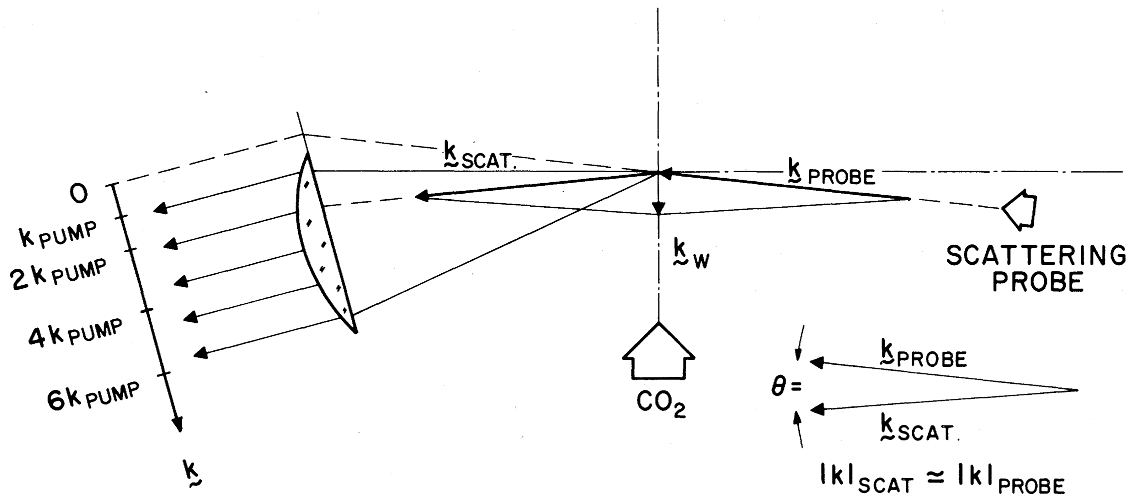

FIG. 1. Diagram of the scattering geometry inside the target chamber. The plasma wave vectors k_w are parallel to the CO_2 wave vector k_{pump}. The range of scattering angles encompassed by the collection optics permits a range of k vectors to be scanned from $\sim k_{\text{pump}}$ to $\sim 6k_{\text{pump}}$. At $k_w = 2k_{\text{pump}}$ (appropriate for SBS), the scattering angle is 5.8° when $\lambda_{\text{probe}} = 0.53\ \mu\text{m}$. At $n_e \sim 0.2n_c$, this angle is reduced to 5.2°.

quency ion waves).

Experimental observations of 0.53-μm light scattered from the plasma produced by the Nd-doped yttrium aluminum garnet laser showed a broad, uniform spread across the k spectrum, as expected from a thermal plasma. But when the CO_2 laser was focused into the plasma, the nature of the spectrum changed (Fig. 2). At low energies, a well defined line at $k_w \simeq 2k_{\text{pump}}$ was seen [Fig. 2(a)]. As the energy increased, a second line appeared, at $4k_{\text{pump}}$ [Fig. 2(b)]. Finally, if the line at $2k_{\text{pump}}$ was streaked by use of the full temporal dispersion of the camera, a rapid time modulation in the ion wave amplitude was seen [Fig. 2(c)].

The harmonic generation seen in Fig. 2(b) is a well-known feature of ion waves at levels $\tilde{n}/n_e \sim (k_w \lambda_D)^2$; however, we believe this to be the first direct observation of it in ion waves driven by SBS. The second unique result is that of the time modulation of the ion wave amplitude [Fig. 2(c)]. Observations at different CO_2 energies showed that the modulation period (averaged over several periods) decreased as the laser energy

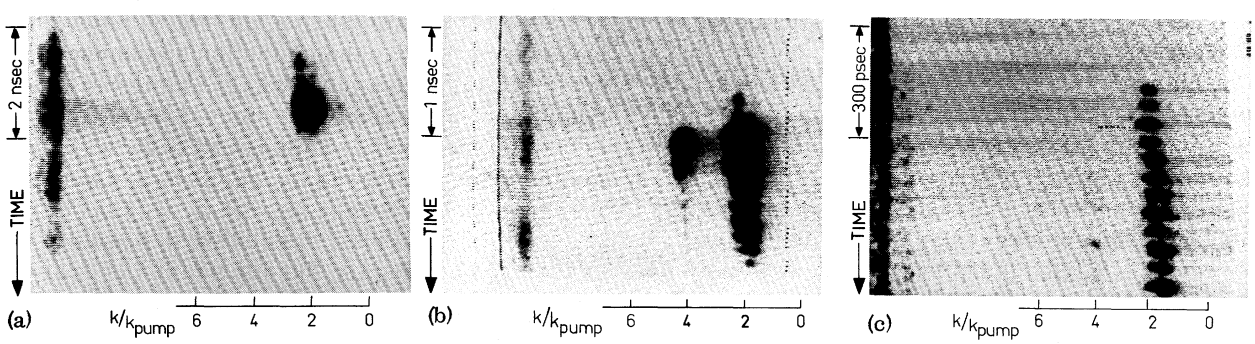

FIG. 2. k-resolved streak records of light scattered from ion-acoustic fluctuations. A monitor trace is shown at the left of each record (see Refs. 7 and 8 for details). Numbers shown along the k axis are in terms of k_{pump}. Incident CO_2 energies for each shot are (a) 3.5 J, (b) 9.5 J, and (c) 26 J. Note different sweep speeds on each record. Also, signal intensities have been attenuated (by different amounts) to give unsaturated images. The modulation seen in (c) is unrelated to any modulation in the probe or the CO_2. The picture in (b) was obtained with relatively less attenuation of the scattered light and so shows the presence of the harmonic at $4k_{\text{pump}}$ more clearly than the streak record in (c). Typically, the ratio of intensities in the first and second harmonic varied up to a maximum ~50%.

increased, from 100–150 psec at 10 J incident to ~50 psec at 25 J incident. The latter figure is close to the ion-acoustic period ($2\pi/\omega$) of the wave but longer than the homogeneous growth rate in the absence of damping for an ion wave driven by SBS at these intensities (~2–5 psec). The modulation is at least qualitatively similar to behavior seen in computer simulations of the Brillouin instability.[9] In the simulations, the periodic behavior seems to be due to catastrophic quenching of the ion wave as it reaches a wave-breaking amplitude.

The peak scattered power around $\lambda_{probe} = 0.53$ μm, measured on different shots as a function of the CO_2 laser energy, is plotted in Fig. 3. The normalized scattered power, and thus the fluctuating density in the ion wave at $2k_{pump}$, saturates when the CO_2 energy exceeds 10 J. To complement this scattering data at 0.53 μm, the energy back-reflected from the plasma at 10.6 μm was measured by a calibrated Au:Ge detector, as a function of incident CO_2 energy. The results showed a strong saturation of the plasma reflectivity at a level (~6–10)%, for CO_2 energies ranging from 10 to 30 J (the reflectivity increased with CO_2 energy below this range). Thus, independent measurements at two different wavelengths, 0.53 μm (as a probe) and 10.6 μm (as a pump), show a saturation in the percentage of radiation scattered from the large-amplitude ion waves in the plasma, at sufficiently high CO_2 energies. As well, the time-resolved ion-wave

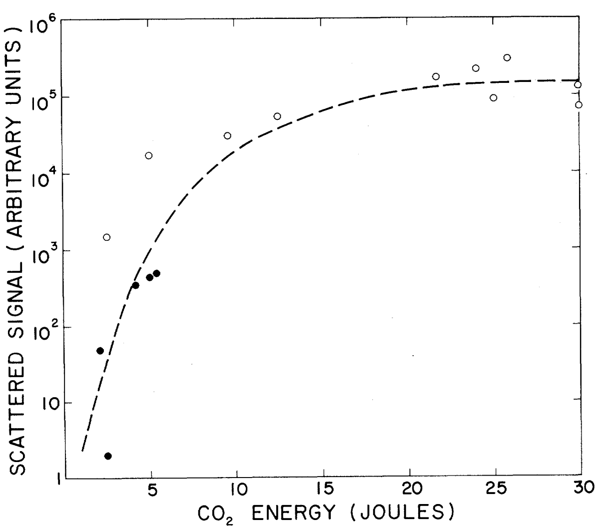

FIG. 3. Variation of signal at 0.53 μm scattered from ion waves as a function of CO_2 energy. The black points are those for which no harmonic was seen. The open points represent data for which a harmonic was seen.

behavior at high CO_2 energies [Fig. 2(c)] indicates a rapid quenching of the wave growth which, it is reasonable to assume, is associated with the saturation.

An analysis of the scattering data at 0.53 μm yields an estimate of the fluctuating ion wave density: $\tilde{n}/n \simeq (15 \pm 5)\%$. This result was obtained in two ways: first, by comparing the enhanced level of scattering from the coherent wave[10] $[P_s/P_0 = \frac{1}{4}\tilde{n}^2 r_0^2 \lambda_{probe}^2 \langle d \rangle^2]$ to the thermal level of scattering, which yielded $\tilde{n}/n \sim (10–15)\%$; and second, by normalizing the fluctuation level in Fig. 3 at which harmonic generation occurs to the theoretical result of Dawson *et al.*: $\tilde{n}/n_e \sim (k_w \lambda_D)^2$ (=0.7% here). This gave a saturated wave amplitude ~(20–24)%. In the application of the coherent-wave formula, it has been assumed that the ion wave is uniform in amplitude across d, the CO_2 focal spot.

If a wave amplitude $\tilde{n}/n_e \sim (10–20)\%$ is used in the expression quoted by Kruer[11] for the plasma reflectivity at 10.6 μm,

$$R = \tanh^2\left[\frac{\pi}{2}\,\frac{\tilde{n}}{n_e}\,\frac{n_e}{n_c}\,\frac{L}{\lambda_{pump}}\left(1 - \frac{n_e}{n_c}\right)^{-1/2}\right],$$

good agreement with the experimental result is obtained only if L, the interaction length, is ~30–60 μm. This is much less than the density scale length (< 300 μm). Some aspects of the data presented in Fig. 3 support the conclusion that L is this small. At low laser energies, the spread in points is large, but the scatter is reduced markedly at high energies. This is quite consistent with scattering from a convectively unstable ion wave for which the gain length at low CO_2 energies is greater than $2a_0$ (100 μm), and becomes less than $2a_0$ as the CO_2 energy, and amplitude of the driven ion wave, increases.

Our experimental observations show that the ion wave driven by SBS has reached large amplitude at saturation (~20%) and that the interaction length L has become considerably shorter than the plasma scale length. The saturation of the reflectivity at 10.6 μm seems to be mainly due to the latter result: For example, if L were 100 μm and $\tilde{n}/n_e = 20\%$, the reflectivity would be close to 100%. The shortening of L should not be due to hydrodynamic effects because the observed saturation occurs early in the history of the driven ion wave.

On the other hand, a shortening in the interaction length and a saturated wave amplitude $\ll 100\%$ are quite consistent with a dramatic increase in the wave damping, or alternatively with a dephasing of the ion wave from the pondermotive force which drives it.[4] Both effects are expected once the large-amplitude ion waves become nonlinear.[6,12] Such nonlinearity has been seen here in the generation of harmonics [Fig. 2(b)], and in the rapid periodic quenching of the ion wave [Fig. 2(c)]. Although the modulations are similar to those seen in computer simulations,[9] they are quantitatively different, in that the density fluctuations observed here are $\lesssim 20\%$, rather than $\sim 100\%$ in the simulations. This difference may be attributable to differing parameter ranges either of $(k_w \lambda_D)^2$ (which determines when harmonic generation will occur) or of ZT_e/T_i (which determines the level at which ion trapping should begin[12]). Our results indicate that when such nonlinearities in ion-wave behavior do occur, they affect both the damping of the wave and the interaction length. Therefore, their effect on the reflectivity of the backscattered light may be more dramatic than previously supposed.

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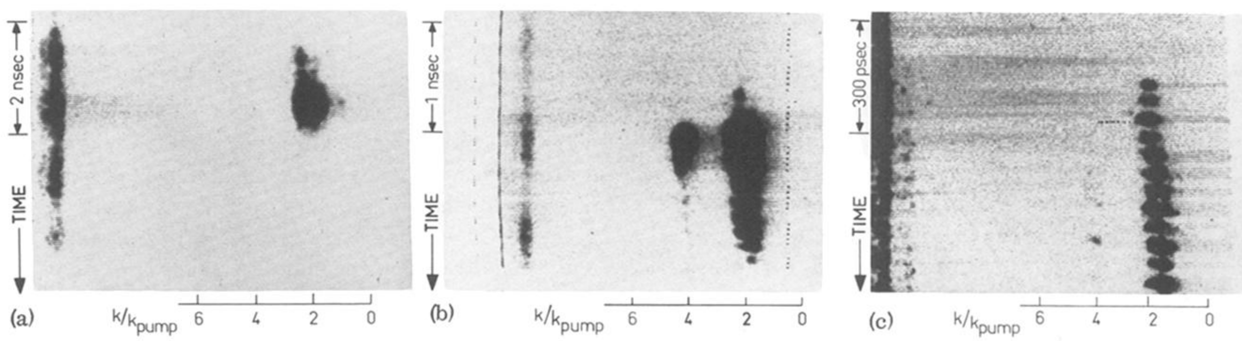

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