Suppression of Stimulated Raman Scattering by the Seeding of Stimulated Brillouin Scattering in a Laser-Produced Plasma

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By seeding of an ion wave by means of optical mixing, it was possible to totally suppress stimulated Raman scattering in a laser-produced plasma. A counterpropagating seed beam with 1% of the intensity of the main beam was sufficient. A novel frequency- and wave-number–resolved image of the Thomson-scattered plasma-wave spectrum was used to shed light on the competition between stimulated Raman scattering and stimulated Brillouin scattering.

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Both stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) in laser-produced plasmas are relatively well understood theoretically. However, only in the last few years has there been an effort to understand how these instabilities interact and coexist.

Kaw, Lin, and Dawson[1] were the first to solve the dispersion relation for plasma waves in the presence of an stationary ion-density ripple. Others[2] have studied SRS in the presence of a stationary density ripple. Rozmus, Offenberger, and Fedosejevs[3] gave a treatment of the interaction between SRS and SBS, describing how the ion waves from SBS can spoil the phase-matching requirements for SRS. Bonnaud[4] and Estabrook and Kruer[5] have performed particle simulations to determine the importance of the ion mass on the development of SRS, and both observed a reduction in SRS with mobile ions. More recently, Aldrich *et al.*,[6] Rose, DuBois, and Bezzerides,[7] and Rozmus *et al.*[8] have used the Zakharov model to follow the nonlinear development of plasma waves and their subsequent collapse which can act as a seed for SBS.

The first experimental observation of competition between SRS and SBS was reported by Walsh, Villeneuve, and Baldis,[9] who saw a strong correlation between the quenching of SRS plasma waves and the initiation of SBS ion waves. The present experiment utilized the same plasma configuration with novel diagnostics to study wave harmonics, and clearly demonstrated the importance of ion waves on SRS by entirely suppressing SRS at will by means of a counterpropagating beam to seed the SBS.

In this paper we shall deal first with the observation of competition between SRS and SBS, then with the comparison of the experiment with current theories, and finally with the effect of an ion-wave seed to suppress SRS.

Five laser beams were incident on the target chamber: a glass laser to preform the plasma, a CO_2 laser to pump the instabilities, a second CO_2-laser beam to seed ion waves, a frequency-doubled green beam for Thomson scattering, and another green beam for interferometry.

The plasma was preformed from a carbon target by a 3-J, 20-ns, 1.06-μm laser pulse. The plasma density profile along the pump beam axis was approximately parabolic, with a parabolic scalelength of typically 1.5 mm. The peak density was controllable, and was usually kept below $0.05n_c$, where $n_c = 10^{19}$ cm^{-3} is the critical density for the pump laser. Thus there was no critical or quarter-critical surface present at any time.

The pump beam used to drive the instabilities was a 30-J, 1-ns, 10.6-μm pulse focused to a 150-μm-diam focal spot with an $f/10$ lens. The plasma was diagnosed by interferometry to measure the density profile, and by Thomson scattering to detect ion and plasma waves. The electron and ion temperatures, T_e and T_i, were measured by Thomson scattering during the pulse in a related experiment[10] and showed that $T_e = 50$ eV and $T_i = 35$ eV at the beginning of the pump pulse, rising to $T_e = 300$ eV and $T_i = 70$ eV by the end.

The green Thomson-scattering probe beam was incident at about 90° to the pump beam and was focused to a 4-mm by 200-μm line focus parallel to the axis of the pump beam. The scattered light was collected by an $f/1.2$ lens and passed through an interference-filter wavelength splitter to separate the unshifted light (corresponding to low-frequency ion waves) from the shifted light (corresponding to higher-frequency plasma waves). Both types of waves were imaged onto separate regions of an Imacon 500 streak camera so that their individual time histories could be determined. In addition, both components were imaged in either space or wave number onto the streak camera. In both cases the field of view was 3 mm and the angle of view corresponded to wave numbers from $1.5k_0$ to $7k_0$, where k_0 is the pump wave number in the plasma. Because of the difference in the frequencies of ion and plasma waves, the waves being detected were about 3° apart, but this was within the focal cone of the pump beam.

A second streak camera was used as a framing camera to record the wave spectra in ω-k space. This was done by imaging the k spectrum of both waves onto the entrance slit of a spectrograph which dispersed the spectrum in frequency in a direction orthogonal to that of the k spectrum, thence onto the slitless photocathode of a Hamamatsu C979 streak camera.

Figure 1 shows the time-resolved wave-number spectra from a typical shot. The plasma waves appear early in the pump pulse, last for about 50 ps, and stop abruptly. Soon thereafter the ion waves from SBS appear and continue for the rest of the pulse. The second harmonic of the ion wave at $4k_0$ was usually seen. Only in a few percent of the shots did the plasma waves recur after the SBS began.

The ω-k spectrum for the same shot is seen in Fig. 2. The pair of dark vertical lines at $\omega_p=0$ are due to stray light passing around a narrow strip of 100-times-neutral-density attenuator; the ion-wave components may be seen between the lines, but at a lower position because of the slow sweep. The plasma waves are not streaked because of their short duration and so are shown in their correct position.

The frequency of the plasma waves gives the plasma density at which the SRS is occurring to be $n/n_c=0.035$, which agrees within experimental accuracy with the peak density measured interferometrically. The harmonic at $2\omega_p$ is also a wave-number harmonic at $2k_p$, and so is well off the dispersion curve for the plasma waves. The third harmonic at $(3\omega_p, 3k_p)$ is also present but does not show well on the reproduction. Occasionally, a harmonic at (ω_p, k_p+2k_0) was observed, and was probably caused by coupling between the plasma wave and the ion wave.

Rose, DuBois, and Bezzerides[7] (RDB) have developed a model of SRS and SBS to compare with our earlier experiment.[9] Using detailed initial conditions derived from the actual plasma, such as electron and ion temperatures and realistic thermal fluctuation levels, they were able to duplicate the temporal behavior seen, namely a 30-ps burst of SRS followed by SBS. They found that as the peak density of the plasma was increased beyond $0.05n_c$ the SRS did not occur, in agreement with the experimental observation, basically because the ratio of SRS to SBS growth rates γ_R/γ_B dropped below 2.

The scenario they present is that early in the pulse both SRS and SBS are growing, but the SRS more quickly. The plasma waves localize in the SBS ion wave and grow until collapse[6,11] occurs. The density fluctuations remaining from the collapse act as an enhanced source for the SBS which then grows quickly and dominates. The effect of a stationary ion wave[2] on detuning SRS is not important because the SRS simply grows at the new matching point. What is important above $0.05n_c$ is that the SBS be growing too, so that the SRS matching condition is shifting too rapidly for growth to occur. (The Zakharov model of Rozmus *et al.*[8] in a periodic plasma predicts that below $0.08n_c$ the plasma waves grow quickly to the wave-breaking regime, but that collapse does not occur, and that the wave-number harmonics will be weaker at lower densities.)

The RDB theory agrees with the present experiment except in the nature of the k spectrum of the plasma wave. The theory predicts that, when SBS grows quickly enough, the k spectrum of the plasma waves will initially be at the usual $k_p=1.8k_0$, with wave-number harmonics at k_p+2nk_0, followed by a broad spectrum of fluctuations if Langmuir collapse occurs. However, there is no

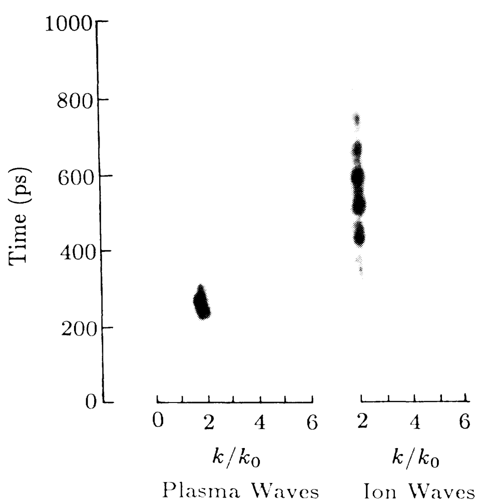

FIG. 1. Streak photograph of k spectra of ion and plasma waves. The plasma waves actually occur 66 ps earlier than shown relative to the ion waves as a result of the differing optical path lengths.

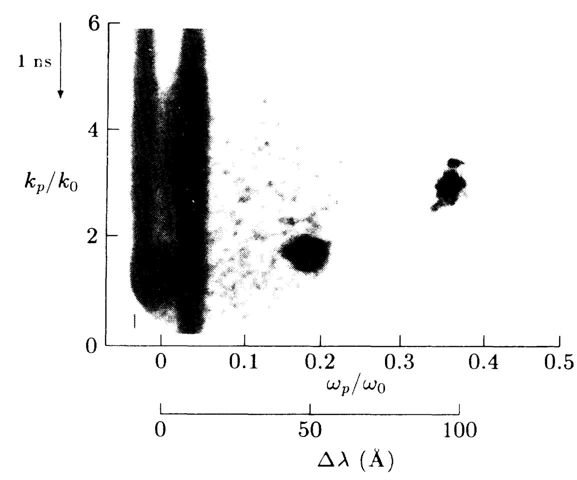

FIG. 2. An ω-k plane image of plasma waves taken simultaneously with that shown in Fig. 1. The bright features near $\omega_p=0$ are from stray probe light and ion waves. The fundamental of the plasma wave is at $k_p=1.8k_0$ and $\omega_p=0.19\omega_0$, which agrees with the SRS occurring at the peak plasma density of $0.035n_c$. The second harmonic appears to be both a frequency and wave-number harmonic. A slow sweep speed added temporal dispersion in the vertical axis as shown, which shifted the ion-wave components down but did not affect the much briefer plasma waves.

evidence of a broad spectrum of fluctuations predicted from the collapse process. In the latter case, however, it is not clear whether the very short burst ($\simeq 1$ ps) would have sufficient energy to be detectable.

Furthermore, the harmonics of the plasma wave are usually frequency and wave-number harmonics ($n\omega_p$, nk_p) rather than wave-number harmonics ($\omega_p, k_p + 2nk_0$). There are several possible explanations for this. First, we generally operated at densities somewhat below the "transition region" near $0.05n_c$ where the competition changes from SRS to SBS dominated, to avoid the random nature of the appearance of SRS. Here, the SRS develops so fast that wave steepening and breaking may occur before collapse, leading to the production of frequency harmonics.[12] Cavitons have also been observed to radiate frequency harmonics as they collapse.[13]

In all other features where the experiment can be compared with the RDB model, there is remarkable agreement. RDB have predicted that by enhancing the initial ion-wave fluctuation level so that SBS grows more quickly, it should be possible to completely suppress the SRS, and further, that perfect frequency matching in the seeding of SBS should not be necessary. They calculated that a seed intensity of 0.1% of the pump's should be sufficient to suppress the SRS.

To test this prediction, a second pump beam (the "seed" beam) was introduced into the target chamber 180° from the main pump beam. It carried 4% of the pump-beam energy, and was also focused with an $f/10$ lens to a somewhat larger focal spot, so that the seed intensity was about 1% of the pump's. These two beams drove a standing ion wave by optical mixing,[14] with $\omega_i = 0$ and $k_i = 2k_0$. Shots were taken alternately with and without the seed beam, to compare the effects.

Figure 3 shows the results of the shot immediately following that in Fig. 1, but with the seed beam. It is clear that the SRS plasma waves have been eliminated. This suppression was quite repeatable, although at very low densities ($\simeq 0.01n_c$) the seed was not strong enough to entirely suppress the SRS. (This is reasonable since γ_R/γ_B is greatest at lowest densities.) Reducing the seed intensity to 0.2% of the pump's also permitted some SRS to occur, as seen in Fig. 4, although the harmonics became purely spatial rather than temporal, indicating that the plasma waves were coupling to a higher level of ion waves than was present without the seed. This is consistent with RDB's prediction of spatial harmonics in the transition region or wherever SRS is controlled by SBS.

There appears to be no difference in the time of onset of SBS with and without the seed beam. At first this seems to run counter to the conjecture; however, it is in fact consistent: With the seed beam there is an enhanced "noise" source for the SBS to grow from, and so the SBS should grow earlier; without the seed beam the collapse of the plasma waves leaves a residue of fluctuations at $2k_0$, which also acts as a seed for the SBS, and so here too the SBS begins earlier than it would normally.

It would be interesting to speculate on the implications of these results on the often-seen "Raman gap," i.e., the lack of SRS emanating from the $(0.2-0.25)n_c$ density region in many experiments with shorter-wavelength drivers, if we assume that the lack of SRS above $0.05n_c$ in this experiment is caused by a similar process. Although their model contains many more details, RDB

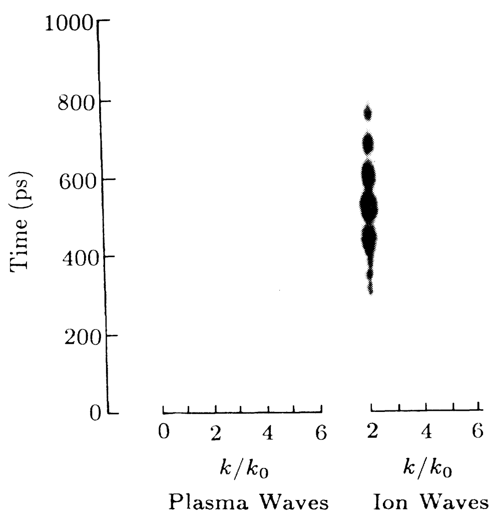

FIG. 3. Streak photograph of k spectra of ion and plasma waves, taken on the shot subsequent to that shown in Figs. 1 and 2. The 1% seed beam has completely suppressed the SRS plasma waves. The corresponding ω-k spectrum similarly showed no evidence of plasma waves.

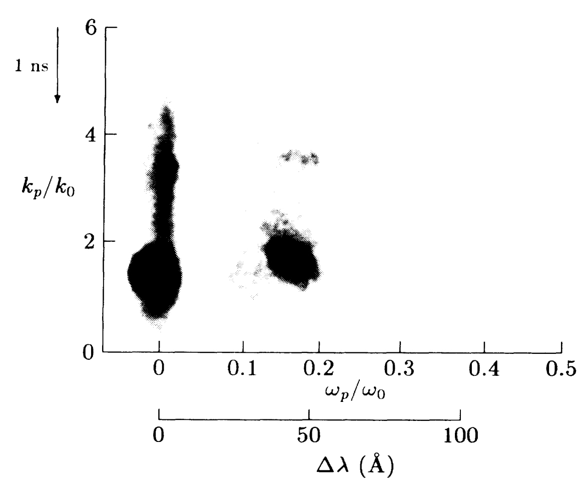

FIG. 4. An ω-k plane image of a shot with a seed beam intensity only $\simeq 0.2\%$ of the pump's. The harmonic $(\omega_p, k_p + 2k_0)$ is consistent with coupling with the stronger seeded ion waves, and the lack of frequency harmonics indicates a weaker plasma wave.

point out that the transition region between SRS and SBS domination occurs near $\gamma_R/\gamma_B = 2$. To see how this scales to other experiments, we calculate the ratio of homogeneous growth rates in the weak-coupling limit,[15]

$$\frac{\gamma_R}{\gamma_B} = 0.2KT^{1/4}\left[\frac{\omega_{pe}}{\omega_0}\left(1-\frac{\omega_{pe}}{\omega_0}\right)\right]^{-1/2},$$

where $K = (1-\omega_{pe}^2/\omega_0^2)^{1/2} + (1-2\omega_{pe}/\omega_0)^{1/2}$, and T is in electronvolts.

This function decreases with increasing density, and increases with T. We find that $\gamma_R/\gamma_B = 2$ at $n/n_c = 0.075$ for $T = 50$ eV (our case) and $n/n_c = 0.21$ for 300 eV (a typical early-time temperature for shorter-wavelength experiments). Thus the transition shifts up in density to the vicinity of the observed gap. In addition, there may be seeding of the ion wave in some experiments at higher density caused by the nearby fluctuation of the pump.

In conclusion, experimental evidence has been presented which supports the model of Rose, DuBois, and Bezzerides[7] on the competition between SRS and SBS in a laser plasma. Harmonics of the plasma waves, both temporal and spatial, were observed in agreement with the theory. A weak counterpropagating seed beam driving a standing ion wave was sufficient to dramatically suppress the SRS.

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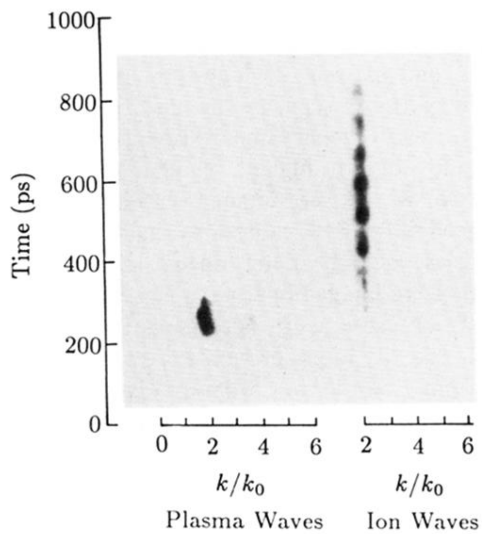

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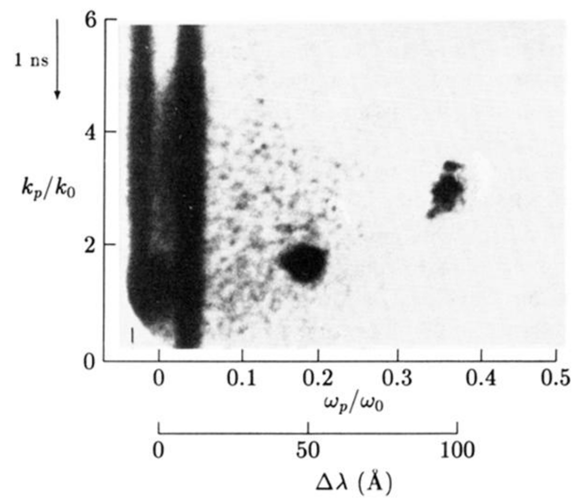

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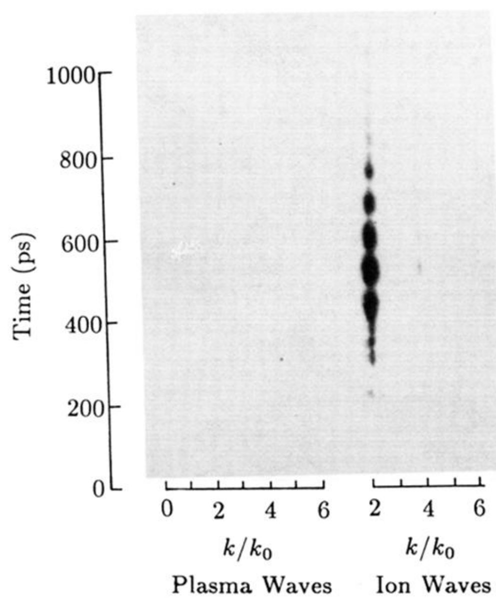

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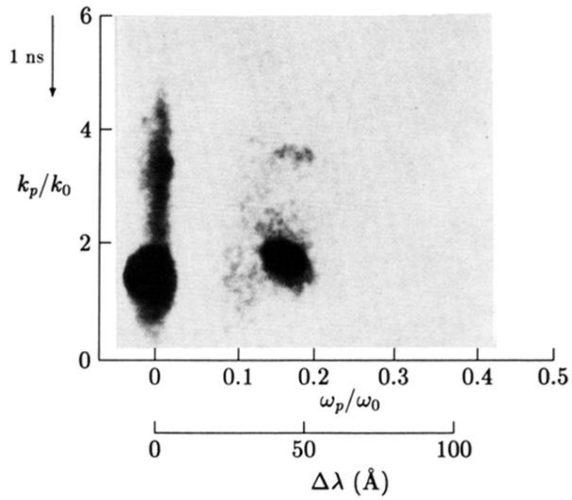

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