Evidence that Stimulated Raman Scattering in Laser-Produced Plasmas is an Absolute Instability

R. P. Drake, E. A. Williams, P. E. Young, Kent Estabrook, and W. L. Kruer
Lawrence Livermore National Laboratory, Livermore, California 94550

H. A. Baldis
National Research Council, Ottawa, Ontario, Canada K1A 0R6

and

T. W. Johnston
Institut National de la Recherche Scientifique–Energie, Varennes, Quebec, Canada J0L 2P0
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We report a sequence of experiments in which 3-μm-thick CH foils were irradiated by one arm of the Nova laser with square pulses of 0.35-μm light. The laser intensity, pulse duration, and spot size were varied to produce plasmas in which the dependence of stimulated Raman scattering (SRS) on laser intensity and on density-gradient scale length could be independently evaluated. The traditional, convective-amplifier model of SRS fails, by many orders of magnitude, to explain either the magnitude or the scaling of these data. We suggest that SRS is absolutely unstable in these plasmas.

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In order for laser fusion to succeed, it is important to minimize the effects of stimulated Raman scattering (SRS) in the laser-produced plasma. SRS is a three-wave, parametric instability in which the laser-light wave (the pump) decays into an electron-plasma wave (epw) and a scattered-light wave (slw)[1]. The instability is dangerous to fusion because the slw reduces the fusion efficiency by carrying energy away from the target, and because the epw, which propagates into the target, produces hot electrons that preheat the fuel and thereby reduce the fusion gain. Up to 10% of the pump has been observed to be scattered by SRS,[2] and hot-electron levels of several percent have been attributed to it.[3] It is clearly important to understand and control SRS.

In this paper, we report the results of experiments that exploited the independent control of laser energy, pulse duration, and spot size allowed by the Nova laser facility[4] to vary independently the average laser intensity, I_L, and the density-gradient scale length, $L=n(dn/dx)^{-1}$, of the target plasma. We report the dependence of the SRS-light intensity on each of these two important variables. We show that the traditional, convective model[1] of SRS does not fit these data and suggest that SRS in these plasmas is instead an absolute instability.

We begin by recalling that the usual model for SRS from densities of interest here (those below $0.25n_c$, where n_c is the critical density of the pump) is the Rosenbluth convective amplifier (CA) for a linearly inhomogeneous phase mismatch[5] of the three waves. Let the subscripts 0, SRS, and epw correspond to the pump, the slw, and the epw, respectively. In a medium with a nearly uniform pump of wavelength λ_0, and in which the phase mismatch wave vector $\Delta\mathbf{k}=\mathbf{k}_0-\mathbf{k}_{\rm SRS}-\mathbf{k}_{\rm epw}$ varies as $\Delta k_x=\kappa' x$, where x is the distance along the density gradient, the spatial amplification (for negligible damping) of a noise wave with intensity $I_{\rm noise}$ is given by

$$I_{\rm SRS}=I_{\rm noise}\exp(2\pi\gamma_0^2/\kappa' v_{\rm SRS}v_{\rm epw}). \qquad (1)$$

Here the components of the group velocity along x are $v_{\rm SRS}$ and $v_{\rm epw}$, and γ_0 is the growth rate in a homogeneous medium. Upon evaluation,[6] the argument of the exponential is proportional to $I_L L\lambda_0$, and depends weakly on the electron temperature (T_e) and on the density (n). It also depends strongly on the scattered angle for angles far from backscatter, which are not relevant here.

A number of experiments[6] have compared observations of SRS to the nominal thresholds (defined[1] as a gain of $e^{2\pi}$) or to more detailed applications of the CA theory. In various cases, the absolute amplitudes, the time-resolved spectra, the angular distribution of the SRS light, and the scaling of the SRS amplitude with intensity have been in conflict with this theory. The comparisons with theory are complicated by the presence of local regions of greater intensity (hot spots) in the laser beams used for these experiments. Hot spots increase the argument of the exponential in Eq. (1), but effectively decrease $I_{\rm noise}$ because their area is smaller than that of the laser spot. As a result, SRS may be observed at a lower I_L and may increase more rapidly with I_L than Eq. (1) suggests. Even so, the large differences between the data and the CA model have stimulated the search for alternatives.

Some researchers have proposed mechanisms that increase the noise source or enhance the gain for convective SRS. Simon and co-workers[7] have suggested that the noise may be increased when energetic beams of electrons, produced near $0.25n_c$, cause Landau growth of the plasma waves at lower densities. Barr, Boyd, and

Coutts and Liu and Tripathi have shown[8] that, under certain conditions, filaments may enhance the SRS gain. These developments would allow one to observe more SRS at lower I_L than Eq. (1) suggests, but do not alter the essential expectation of a low noise level and a sharp increase of I_{SRS} over some small range of I_L and L. The observations discussed next are very difficult to reconcile with the CA model, even with allowance for these additional enhancements.

The experiments used one arm of the Nova[4] laser at the Lawrence Livermore National Laboratory to irradiate 3-μm-thick CH foils with 0.35-μm light, in temporally flat (to $\pm 20\%$) pulses with 100-ps rise and fall times. We systematically increased I_L from 1.6×10^{13} to 4×10^{15} W/cm^2. By decreasing the pulse length from 4.4 to 1 ns, increasing the energy on target from 0.6 to 2.1 kJ, and decreasing the laser spot from 1100 to 250 μm, we produced these intensities and maintained planar plasmas. In each case, the target burned through and expanded so that the maximum n was below $0.1n_c$ by the end of the laser pulse.[9] Note that this experiment is quite different from the usual experiment with Gaussian laser pulses of fixed duration, in which I_L and the density profile cannot be independently varied.

Two diagnostics produced the results discussed here. First, a streak camera, coupled to a spectrometer, measured the time-resolved spectrum of the SRS light. Second, absolutely calibrated photodiodes[3] allowed absolute calibration of the time-resolved data. Figure 1 shows time-resolved SRS data. Before the target burns through, the observed SRS spectrum extends over more than 200 nm of wavelength. As the maximum density of the target, n_m, decreases after the target burns through, the maximum wavelength decreases with time.[9] The short-wavelength boundary of the spectrum, produced by Landau damping,[10] corresponds to a density of $0.06n_c$ and to a T_e of about 1 keV.

These data allow two comparisons that show the difficulties of the CA model. First, one can examine the dependence of I_{SRS} on L at constant I_L. As the plasma expands, the value of L at any given density n increases with time t, approaching infinity as n_m drops close to n. Figure 2(a) shows this behavior for one specific case. Simulations calculated that this target would burn through earlier than was observed,[9] and correspondingly find L to be a factor of 1.3 larger, at 200 ps, than Fig. 2(a) shows. This discrepancy is within the $\pm 50\%$ uncertainty we assign to L and does not alter the conclusions that follow. Because I_L was constant, the time dependence of the I_{SRS} corresponds to the variation with L at constant I_L.

Figure 2(b) shows an example of I_{SRS} vs t at a given density. Data from other values of n and I_L show similar behavior, with a delayed onset at lower I_L. Figure 2(b) also shows a curve that is 10^5 times I_{SRS} as determined from Eq. (1), for a thermal noise source of 8×10^4 W/(sr

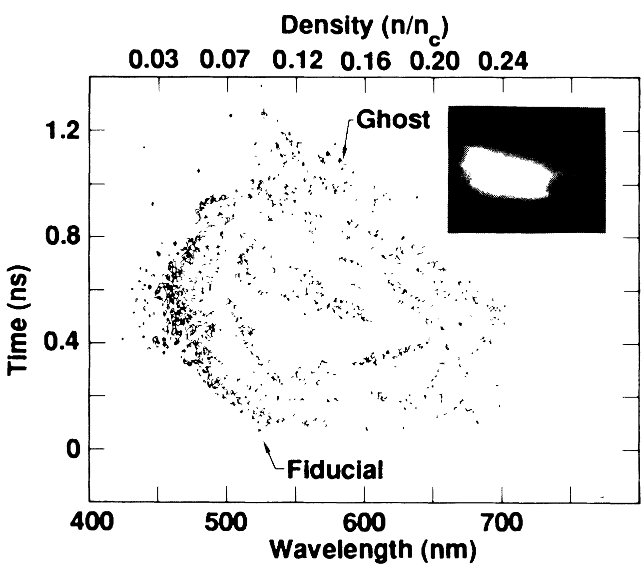

FIG. 1. A contour plot and (inset) a photograph of the time-resolved Raman spectrum from an experiment with a laser intensity of 3.5×10^{15} W/cm^2, and a 1-ns laser pulse. The contours correspond to factor-of-2 variations in I_{SRS}. The correspondence of scattered-light wavelength to electron density is indicated above the figure. The instrument was located 163° from $\mathbf{k}_0$ and 38° from the plane of polarization. A timing and wavelength fiducial, at 530 nm, is labeled. The very weak emission after 1 ns is due to an instrumental ghost.

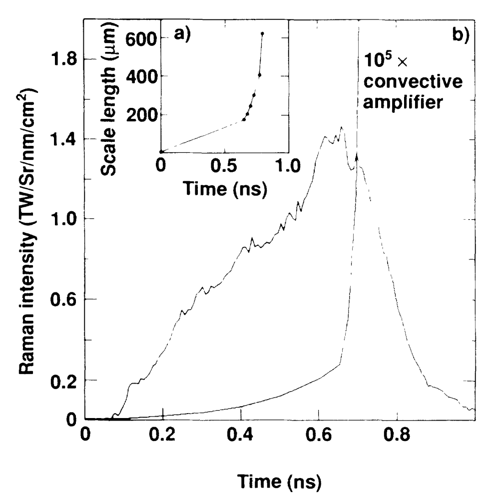

FIG. 2. The increase of L at $0.11n_c$ and I_{SRS} from $0.11n_c$ with time, at constant laser intensity, for the data shown in Fig. 1. (a) L was assumed to increase linearly with time until the maximum density reached $0.25n_c$, after which the SRS data determined (Ref. 9) n_m and a Gaussian profile was assumed to infer L. These simple assumptions lead to an absolute uncertainty in L of $\pm 50\%$ and a relative uncertainty of 20%. (b) I_{SRS} as measured and as calculated with Eq. (1), for a wavelength of 540 nm (a density of $0.11n_c$). The origin corresponds, within ± 50 ps, to the time when I_L was 0.1 times its average value.

nm cm^2). By 200 ps into the laser pulse, while L is still small, the observed I_{SRS} is more than 6 orders of magnitude above the prediction of Eq. (1). No mechanism yet suggested can produce a "noise" source large enough to explain this observation, and the argument of the exponential in Eq. (1) is 14 times too small to produce the observed I_{SRS}. After onset, I_{SRS} never increased more than about factor of 10 for the rest of the laser pulse. This corresponds roughly to the increase in the volume within which SRS could occur, and suggests that the average epw amplitude is roughly constant.

The second comparison one can make to evaluate the CA model is to examine the dependance of I_{SRS} on I_L at constant L and n. To do this, one chooses the time for each experiment when L has the desired value at the desired n and one evaluates I_{SRS} from n at that time. We determined L on the basis of n_m, assuming the density profile to be Gaussian and the radial flow of plasma to be small. Detailed calculations[9] indicate that this procedure gives the correct value of L at the maximum I_L but underestimates L by a factor of 2 at the minimum I_L (which is 300 times smaller).

Figure 3 shows this comparison. At laser intensities of about 10^{14} W/cm^2, I_{SRS} is more than 5 orders of magnitude above the thermal level, and the argument of the exponential in Eq. (1) is about 50 times too small to explain the observation. The onset of SRS occurs at an I_L that is about 2 orders of magnitude below that required by Eq. (1) (if not more—we note that collisional damping may reduce I_{SRS} at laser intensities below 5×10^{13} W/cm^2). While hot spots, enhanced noise, and filaments can make up some of this difference, they cannot very credibly make up all of it. In addition, I_{SRS} increases only linearly or slightly faster with I_L. This remarkable result suggests that the scattering volume and the epw amplitude have nearly saturated by the time the average laser intensity is only 10^{14} W/cm^2.

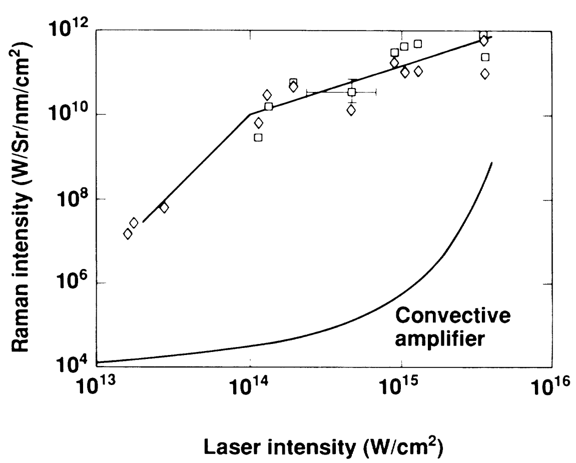

FIG. 3. I_{SRS} for wavelengths of 540 and 500 nm, corresponding to densities of $0.11n_c$ and $0.075n_c$, at times when the maximum density is $0.15n_c$ and $0.11n_c$, respectively. The corresponding scale lengths, L, are 370 and 450 μm. Typical absolute uncertainties are indicated. The labeled curve shows I_{SRS} as calculated from Eq. (1) for a 520-nm wavelength and $L=410$ μm, with a thermal noise source.

Three features of the data lead us to suggest that the SRS instability is absolutely unstable throughout these plasmas, and not just at the density maximum: (1) Convective amplification, even with hot spots, is too weak to explain the data; (2) the amplitude of the plasma waves is apparently saturated, even at low values of I_L or L; and (3) the SRS from the density maximum is not substantially more intense than that from other densities. A number of mechanisms might contribute to absolute instability: First, even small ripples can upset the delicate feedback that prevents absolute instability on the ideal, linear ramp.[11] Second, SRS may become absolute as a consequence of long-wavelength turbulence[12] or via an accumulation of effects from random ripples (Anderson localization).[13] Third, the SRS instability will be absolute at any density maxima and minima that exist in the plasma.[1,5,14] In the actual plasma (as opposed to the coupled-mode models), the plasma structures could correspond to long-wavelength turbulence, ripples, cavitons, or filaments. Such structures probably do and will exist because most present and planned experiments use strongly modulated laser beams. In addition, Brillouin scattering is a possible source of ripples or turbulence, and Brillouin backscatter was measured to be present throughout these experiments. However, we have found no correlations in the data that would indicate that Brillouin scattering contributes to the SRS. Even with the assumption that the SRS instability is absolute, the hot spots probably play a role at short L or low I_L, because some Rosenbluth gain is necessary for the instability to exceed threshold. The key difference with respect to the CA model is that the CA model requires much more Rosenbluth gain in the hot spots to produce substantial scattering.

Because such mechanisms of absolute instability are inherently local, many scattering sites must contribute to produce significant total scattering and the apparently smooth time-resolved spectrum shown in Fig. 1. We now investigate this possibility. To produce smooth results with about 100 resolution elements, one needs roughly 1000 sources, which implies a source spacing of a few times 10 μm. Since 10% density fluctuations over distances of a few microns can scatter 10% of the local laser power, a total scattering area of about 10% of the total irradiated area could scatter 1% of the total laser power. These numbers are plausible, and so this order-or-magnitude argument shows that many local, absolutely unstable scattering sites might have produced the observed SRS.

In summary, this sequence of experiments studied independently the dependence of the SRS intensity on density-gradient scale length and laser intensity. The traditional, convective-amplifier model of SRS quite dramatically fails to explain these data. We have suggested that the SRS instability is, in fact, absolutely unstable in these plasmas and have argued that this hypothesis is plausible. Further work can attempt to fit the observed scalings with specific absolute models, and can explore how variations in the properties of the laser beam may affect SRS. If this effort succeeds, one will then be able to predict the SRS efficiency for proposed high-gain, laser-fusion experiments.

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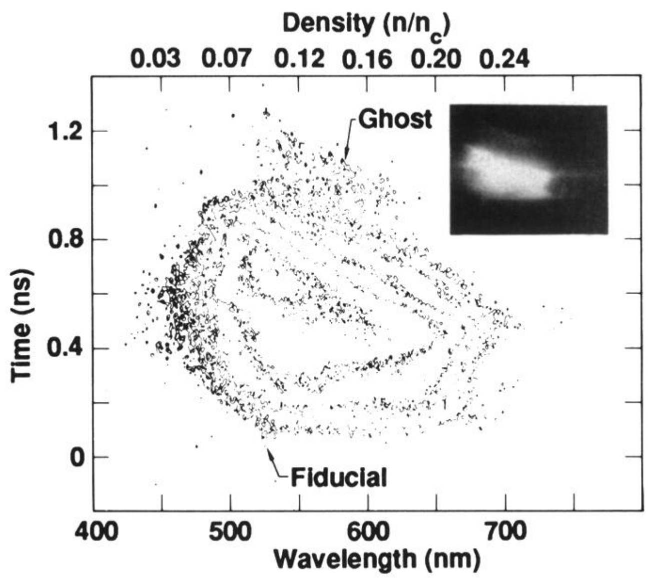

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