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STIMULATED RAMAN SCATTER FROM LASER-PRODUCED PLASMAS: MERELY NONLINEAR OR ALSO CHAOTIC?

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Stimulated Raman scattering from laser-produced plasmas: merely nonlinear or also chaotic?

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ABSTRACT

Stimulated Raman scattering in plasmas is a three-wave instability with important practical consequences for laser fusion. Most studies of this process to date have focussed on its threshold. Even the linear-theory threshold poses interesting problems; and observed thresholds have been difficult to interpret. However, with increasing evidence that this instability often becomes absolute, it has become appropriate to examine saturation mechanisms as well. A number of such mechanisms are discussed here, one of which has been reported to have a chaotic regime.

1. Introduction

Stimulated Raman scattering (SRS) occurs in many media, including plasmas. Any Raman process produces a scattered electromagnetic wave by the interaction of a driving electromagnetic wave with an electrostatic wave whose frequency is characteristic of the medium. Such a process is stimulated when the three waves interact so as to produce gain in time and/or space. The present discussion will focus exclusively on SRS in plasmas.[1,2] In this case, the driving electromagnetic wave (the "pump") is most often produced by a laser, and the electrostatic wave is an electron-plasma wave. In many such cases, and in all the examples discussed herein, the plasma is produced by a laser as well. SRS in plasmas is an important process that can be a rich subject for nonlinear studies.

SRS is important because of its effects. SRS has two important adverse effects for laser fusion,[3] as illustrated in fig. 1. First, the scattered-light wave carries away energy, thereby reducing the efficiency of the target. Second, the electron-plasma wave accelerates electrons to high energies, which enables them to penetrate the fusion capsule and heat the fusion fuel before it is compressed. This reduces the gain of the target. As a result, one needs to understand SRS well enough to control it by proper choice of laser and target. Beyond laser fusion, SRS has other potential applications: to particle acceleration for current drive[4] in tokamaks, to particle acceleration as a component of an accelerator system, and to the production of broadband light.

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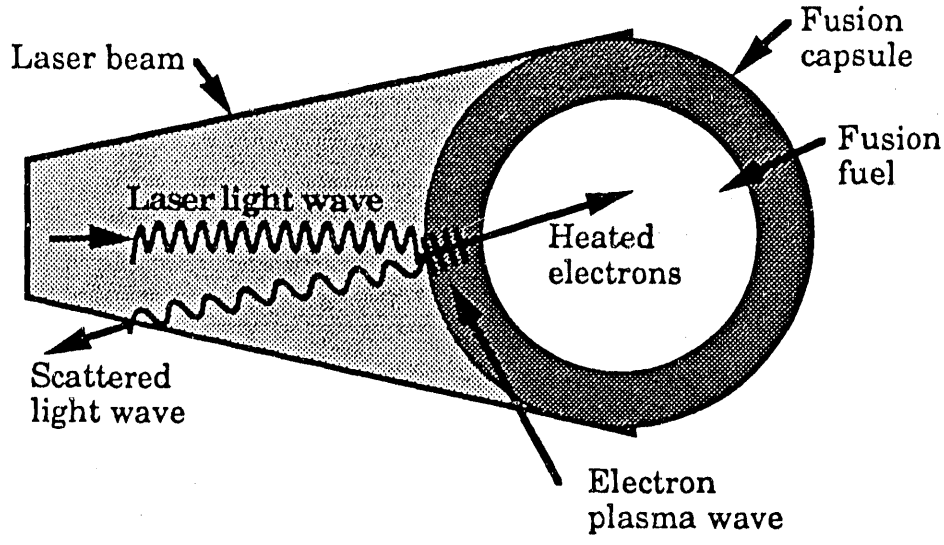

Figure 1. Stimulated Raman scattering can occur in the plasma at the surface of a laser-fusion capsule, by the decay of the laser-light wave into a scattered-light wave and an electron-plasma wave. The adverse effects are discussed in the text.

SRS is of value for nonlinear studies because of its simplicity. Three waves with simple dispersion relations are involved,[2] and the frequencies of the two decay waves are closely tied to the electron density. In a non-magnetized plasma the pump, scattered-light wave, and plasma wave have frequencies and wavevectors designated by w_o, $\mathbf{k}_o$, ω_s, $\mathbf{k}_s$, and w_{epw}, $\mathbf{k}_{epw}$, respectively. These quantities must satisfy the matching relations

$$\omega_o = \omega_s + \omega_{epw} \quad \text{and} \quad \mathbf{k}_o = \mathbf{k}_s + \mathbf{k}_{epw}\,, \tag{1}$$

and the dispersion relations

$$\begin{aligned} \omega_o^2 &= \omega_{pe}^2 + c^2k_o^2\,, \\ \omega_s^2 &= \omega_{pe}^2 + c^2k_s^2\,, \text{ and} \\ \omega_{epw}^2 &= \omega_{pe}^2 + 3v_{th}^2k_{epw}^2\,. \end{aligned} \tag{2}$$

Here ω_{pe} is the plasma frequency, c is the speed of light, and v_{th} is the thermal speed of the electrons, given by $(T_e/m)^{1/2}$, in which T_e and m are the electron temperature and the electron mass. The connection to the plasma density is through ω_{pe}^2, which equals $4\pi ne^2/m$, in which n is the electron density and e is the electronic charge.

As the intensity of the pump increases and the damping of the decay waves decreases, SRS should develop from a linear regime with small wave amplitudes, through nonlinear regimes with more complex behavior, to a turbulent and/or chaotic regime in which the decay waves drive other

decays and are coupled to the motion of the ions in the plasma as well. Because one can in principle choose the pump strength and the wave damping, by choice of laser and target, experiments should eventually be able to study each of these regimes and the transition from one to the next.

SRS was initially difficult to detect because it was hard to produce sufficiently large, warm, dense plasmas using small lasers.[5,6] However, once lasers became available with ≥ 100 J of energy at wavelengths ≤ 1300 nm, it became easy to produce and study SRS.[7,8] And once lasers with energies ≥ 2 kJ were developed, levels of SRS in excess of 10% were readily observed.[9,10]

The spectrum of the scattered-light intensity has proven to be complex and interesting, as the example shown in fig. 2 illustrates, and has provided the focus for a large number of experimental and theoretical studies during the past decade.[12,13] SRS provides one major advantage for experimental studies: longer scattered-light wavelengths come from higher densities, up to a limit of twice the laser wavelength, $2\lambda_0$, which comes from quarter-critical density, $n_c/4$. (The critical density, n_c, is the density at which $\omega_{pe} = \omega_0$.) As in the case of fig. 2, the observed spectra often do not extend to $2\lambda_0$; and the spectra show a short-wavelength limit that is caused by increased Landau damping of the electron-plasma wave at low density. In addition, because fig. 2 is from an experiment in which the maximum density of the plasma decreased with time, the spectrum shows a decreasing maximum wavelength toward the end of the laser pulse.

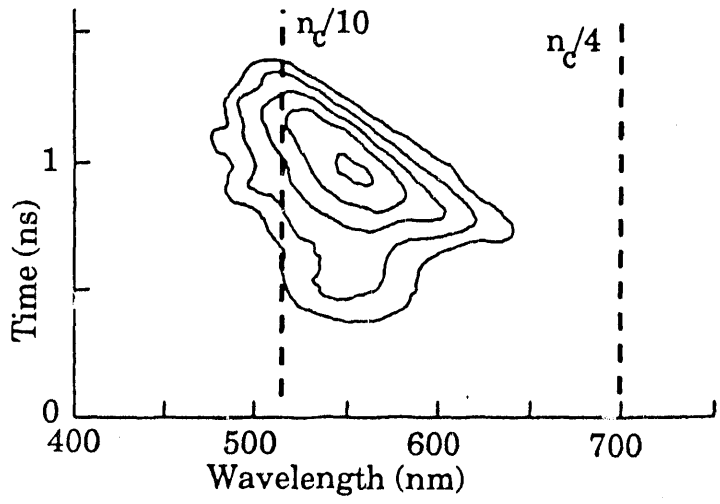

Figure 2. One example of a time-resolved spectrum, in the form of a contour plot showing how the spectral intensity of the observed scattering depends on the scattered wavelength and the time. The contours show factor-of-two changes in the spectral intensity. In this experiment[11] a 3 μm thick CH target was irradiated by a 1.3 ns, constant-intensity pulse of 350 nm light at an intensity of 1.3×10^{15} W/cm^2.

2. Experiments *versus* Linear Theory

The linear theory of SRS has been the subject of numerous theoretical studies. Such treatments often consider Maxwell's equations for the electromagnetic waves and the simple fluid equations for the electron-plasma wave, keeping only linear terms in the decay-wave amplitudes. For example, one can relate the vector potentials for the pump and the scattered-light wave, $\mathbf{A}_L$ and $\mathbf{A}_s$, respectively, to the amplitude of the electron-plasma wave, $\delta n/n$. This yields

$$\left(\frac{\partial^2}{\partial t^2} + 2\,\Gamma_s \frac{\partial}{\partial t} - c^2\nabla^2 + \omega_{pe}^2\right)\mathbf{A}_s = -\,\omega_{pe}^2\left(\frac{\delta n}{n}\right)\mathbf{A}_L \quad \text{, and} \tag{3}$$

$$\left(\frac{\partial^2}{\partial t^2} + 2\,\Gamma_{epw}\frac{\partial}{\partial t} - 3\,v_{th}^2\nabla^2 + \omega_{pe}^2\right)\frac{\delta n}{n} = \left(\frac{e}{m\,c}\right)^2\nabla^2\left(\mathbf{A}_L\cdot\mathbf{A}_s\right) \quad . \tag{4}$$

Here the amplitude-damping rates of the scattered-light and the electron-plasma waves are given by Γ_s and Γ_{epw}, respectively. Collisions damp the scattered-light wave while both collisions and Landau damping damp the electron-plasma wave.[14] Eqs. 3 and 4 are often reduced to linear, partial-differential equations by the WKB method. They have been analyzed using a wide variety of assumptions regarding the spatial properties of the plasma and the pump, some of which will be mentioned below.

The simplest solution of Eqs. 3 and 4 is found by assuming the plasma and the pump to be homogeneous and very large. In this case the damping threshold for SRS is found to be

$$\gamma_0^2 / \left(\Gamma_s\,\Gamma_{epw}\right) > 1 \quad , \tag{5}$$

where γ_0, which equals $(1/4)k_0 v_0 \omega_{pe}/(\omega_s \omega_{epw})^{1/2}$, is the homogeneous growth rate, in which v_0 is the oscillating velocity of the electron in the field of the pump. This threshold has been observed[14] by producing very large, warm plasmas and irradiating them at low intensities, as fig. 3 illustrates. Fig. 3a shows the ratio on the left-hand-side of Eq. 5, as calculated for the experiment whose observed spectrum is shown in fig. 3b. The detailed physics in the actual plasma of the experiment is somewhat more complex than this agreement with such a simple model suggests, but nonetheless the homogeneous-plasma, damping threshold holds very well for this and for numerous other experiments.

In contrast to the results of experiments with large plasmas and strong damping, the results of experiments with weak damping and moderate density-gradient scale lengths have proven quite difficult to

interpret in terms of linear theory. The simplest theoretical result concerns a linear density profile with specific boundary conditions,[1,15] in which case SRS is a convective instability with finite gain in steady state. There is some evidence for such convective SRS in experiments using special laser techniques to produce a very smooth plasma.[16] However, other experiments have always observed SRS long before the laser intensity and density-gradient scale length were large enough to provide the necessary convective gain.[17] And many theoretical studies have shown that SRS can easily become an absolute instability as the result of turbulence,[18] boundary conditions,[19] local maxima,[15] or profile curvature.[20]

These issues motivated a specific experiment in which the laser intensity and the density-gradient scale length were varied over a wide range.[21] This experiment observed scattered light with a spectral intensity many orders of magnitude above thermal levels under conditions when the convective gain was as low as $e^{0.2}$, which supported the suggestion that SRS was absolutely unstable in the plasmas studied. In addition, the hypothesis that SRS is absolutely unstable allows a consistent explanation of the otherwise confusing trends in the observed total SRS from a number of experiments.[10] At this point the evidence that some mechanism has produced absolute growth of SRS in most of the experiments to date is fairly convincing, although more dramatic alternative models remain possible.[22]

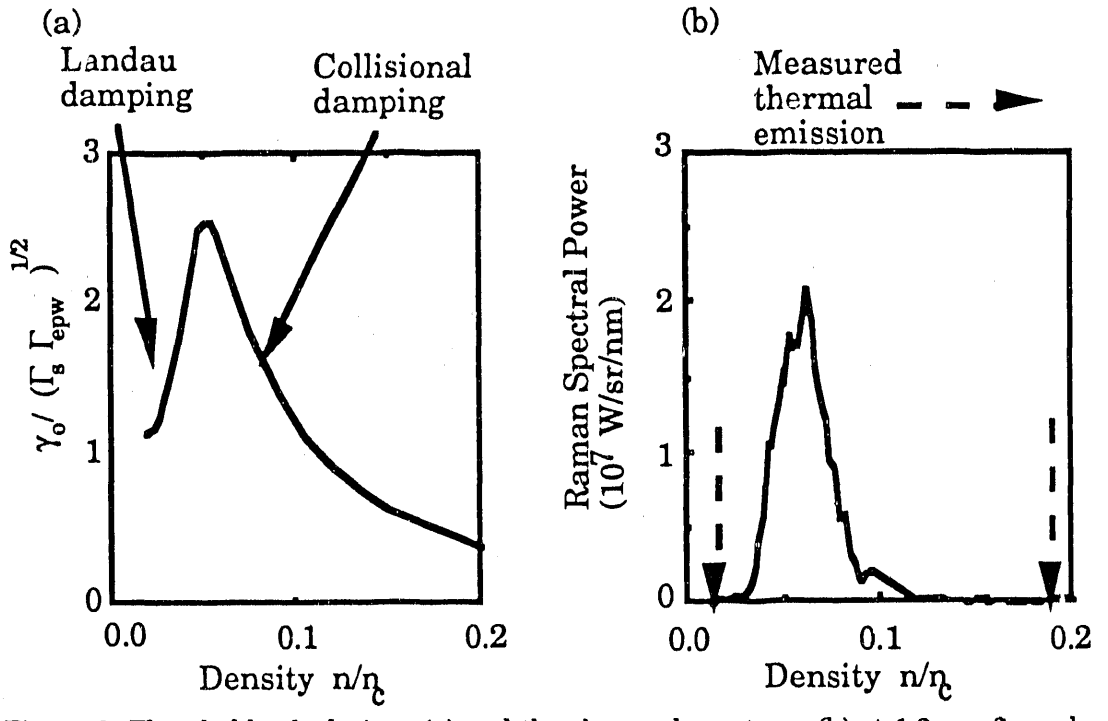

Figure 3. Threshold calculations (a) and the observed spectrum (b) at 1.3 ns after a laser has begun to irradiate a 3 μm thick CH target with 350 nm light at a constant intensity of 3×10^{13} W/cm^2.

3. Saturation Mechanisms

The linear theory of SRS has proven to be a rich and complex field, because of the many possible properties of the plasma and the pump. Much less work has been done on saturation mechanisms than on linear theory, and very few comparisons with experiment have been made. Nonetheless, since it is likely that the observed SRS is produced by an absolute instability, the observed levels and spectrum of SRS are likely to be determined by the physics of saturation. We will focus on electron-plasma-wave saturation effects here, because these are likely to become important before the scattered-light wave saturates or the pump depletes.

On the one hand, SRS can in principle saturate through the action of the electron-plasma wave on the electron distribution function. The simplest such saturation mechanism is wavebreaking, in which the amplitude of the plasma wave becomes large enough to accelerate electrons to the phase velocity of the wave in one period.[2] This mechanism typically requires fluctuation amplitudes that are a small multiple of 10% to be effective. A related saturation mechanism is electron-tail formation, in which the plasma wave heats some of the electrons, forming a "tail" on the electron velocity distribution. This tail increases the Landau damping of the plasma wave, and a self-consistent state is reached when the plasma-wave amplitude becomes large enough maintain the required density of heated electrons. Ion-tail formation by stimulated Brillouin scattering has very successfully explained its saturation behavior in some experiments.[2] However, because of the small mass of the electron, large fluctuation amplitudes are necessary to produce a dense enough electron tail to reach steady state for SRS. Both electron-tail formation and wave breaking can be seen in appropriate plasma simulations.

On the other hand, SRS can saturate through the coupling of the electron plasma wave to the ions in the plasma. One of the simplest such mechanisms, and a likely first step in several more complex saturation mechanisms, is the Langmuir decay instability. In this process, the electron-plasma wave decays into an ion-acoustic wave and an oppositely-directed electron-plasma wave of slightly smaller frequency and wavenumber. The threshold fluctuation amplitude for the Langmuir decay instability, in a homogeneous plasma, is

$$\left(\frac{\delta n}{n}\right) = 2\, k_{epw}\lambda_D \left(\frac{\Gamma_{epw}}{\omega_{pe}}\right)^{1/2} \left(\frac{\Gamma_{ia}}{\omega_{ia}}\right)^{1/2} , \qquad (6)$$

in which Γ_{ia} and ω_{ia} are the damping rate and frequency of the driven ion-acoustic wave, and λ_D is the Debye length. Even when the normalized damping rates in Eq. 6 are quite large (~ 0.1), the threshold $\delta n/n$ for Langmuir decay is only a few percent. And in some experiments, at some

densities, the normalized damping rates are quite small (~0.001), implying a very low threshold for Langmuir decay. The Langmuir decay process may be the first step in a weakly-turbulent cascade, and this may lead to strong turbulence and to caviton formation, depending upon the damping of the waves and the strength of the pump. In addition, if plasma waves having a range of wavevectors are driven by SRS, such waves may couple to produce driven ion modes, as has been seen in simulations of two-plasmon decay.[23] But whatever the specific mechanism, it appears likely that SRS will saturate by coupling to the ions, rather than modification of the electron-distribution function.

4. A Chaotic Regime ??

Saturation of SRS by the Langmuir decay instability has been considered in one theoretical paper,[24] which did not consider any further complications and did not compare its results to those of experiment. These authors worked with the system of five differential equations describing the behavior of the three waves involved in SRS and the two additional waves involved in the Langmuir decay. They analyzed this system in terms of the normalized damping of the electron-plasma wave, β, given by

$$\beta = \left(\frac{\Gamma_{epw}}{\gamma_o}\right)\left(\frac{v_{th}}{c}\right)^{-1}\left[\frac{4}{3}\left(\frac{k_s}{k_{epw}}\right)\left(\frac{\omega_{pe}}{\omega_s}\right)\left(\frac{\omega_{pe}}{\omega_{epw}}\right)\right]^{1/2} . \qquad (7)$$

Except near $n_c/4$, where k_s becomes small, the only component of β which varies substantially with electron density is Γ_{epw}/γ_o. Three regimes were identified. In the first regime, the damping is strong ($\beta > 2$), so that Eq. 6 is not satisfied for typical values of the plasma conditions and ion-wave damping and Langmuir decay does not occur. In this regime, SRS may or may not be above threshold. In the second regime the damping is moderate ($2 > \beta > 0.2$), Langmuir decay does occur, and a steady, SRS reflectivity results. The reflectivity is smaller than it would be in the absence of Langmuir decay. In the third regime the damping is small ($\beta < 0.2$) and the reflectivity appears to be chaotic and to have a reduced average value. However, either multi-dimensional effects[25] or the development of a cascade[26] may prevent the development of chaos in this case.

Comparison of the parameters of this model to the conditions of experiments shows that all three of these regimes are reached in experiments that study SRS, and sometimes even in the same experiment, as figure 4 illustrates. Experiments access such a large range of predicted behavior because of the large variation of Landau damping. At very low densities, corresponding to small scattered-light wavelengths, the phase velocity of the electron-plasma wave is small and Landau damping is large

(~ 0.1 ω_{pe}). As density increases, the Landau damping of the plasma wave that participates in SRS decreases several orders of magnitude, until Γ_{epw} is determined by collisional damping as the density approaches quarter critical. If the level of collisional damping is small enough relative to the pump strength, then the experiment reaches the weak-damping, and possibly chaotic, regime.

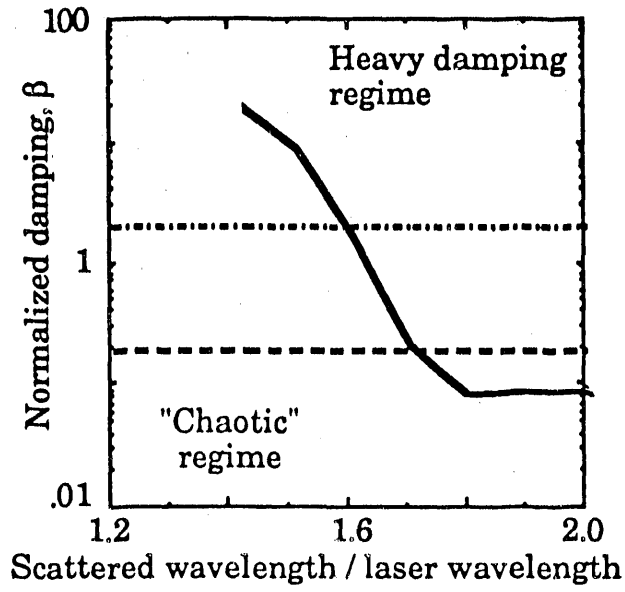

Figure 4. The dependence of the normalized damping parameter on the scattered-light wavelength produced by SRS is shown for an experiment in which a CH target is irradiated with 527 nm light at an intensity of 1.3 x 10^{15} W/cm^2. The curve corresponds to densities from about 0.08 n_c to 0.25 n_c.

The remarkable aspect of this comparison is that the observed spectra show very little emission at the wavelengths that correspond to this weak-damping regime, and show the strongest emission when the damping is relatively large. For example, the spectrum of fig. 2 shows little emission near 700 nm, corresponding to densities where the electron-plasma wave is weakly damped, and shows stronger emission at shorter wavelengths, corresponding to lower densities where the damping is larger. This suggest that ion-wave decay, and/or more complicated saturation mechanisms involving ion motion, may be responsible for the observed shape of the Raman spectrum. We are now exploring this possibility.

5. Conclusion

SRS is a fascinating yet tractable physical process that to date has yielded many interesting results. The linear damping thresholds have been verified but the effects of inhomogeneity have yet to be clearly

established by experiment. And the potential of SRS as a nonlinear playground has barely begun to be exploited. The ability to vary the pump strength, damping rates, and plasma properties over a very wide range should allow future experiments to systematically access conditions that are predicted to exhibit various nonlinear effects. The ability to probe the electrostatic waves by means of Thomson scattering should allow one to follow the first phases of the onset of turbulence and may allow one to find a chaotic regime.

With regard to laser fusion in particular, experiments have clearly shown that SRS is sensitive to damping. In all cases, the homogeneous-plasma, damping threshold is a good guide to the occurrence of SRS in large plasmas. Thus, laser fusion systems can control SRS, at minimum, by keeping it below this threshold. Ongoing, current work suggests that the SRS reflectivity may also be low from plasmas in a turbulent or chaotic regime. This may open up new options for laser-fusion target design. In addition, SRS has been shown to be sensitive to laser-beam coherence, although this has not been our focus here. Control of the laser-beam coherence, and in particular the production of induced incoherence, offer further possibilities for control.

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