Observation of ion wave decay products of Langmuir waves generated by stimulated Raman scattering in ignition scale plasmas

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Thomson scattering has been used to measure the time resolved spectrum of ion wave decay products from two instabilities which can limit the growth of stimulated Raman scattering (SRS). This experiment detected ion wave decay products far above the thermal level and demonstrates that SRS produced Langmuir waves undergo the Langmuir decay instability in ignition relevant plasmas. Product waves of the electromagnetic decay instability were not detected. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1590317]

Langmuir wave growth and saturation in plasmas is of great importance to inertial confinement fusion (ICF) applications, where Langmuir waves can reflect large fractions of the incident laser energy via stimulated Raman scattering, or SRS.[1] In SRS, the incident laser wave resonantly drives a Langmuir wave and a scattered electromagnetic wave.[2] Understanding the mechanisms which govern reflectivity under the conditions of ignition experiments is critical to allow scaling to fusion reactors.[1]

Recent studies have suggested the importance of Langmuir wave decays to SRS. Theoretical treatments have shown that strongly driven SRS can be affected by Langmuir wave decays and collapse.[3–6] Experimental studies of SRS in large scale plasmas have found reflectivities that scale weakly with plasma properties.[7–10] These experiments have shown that SRS can be limited by nonlinear saturation of the SRS Langmuir wave,[11] and that the saturation amplitude is dependent on the ion acoustic wave damping rate in the plasma.[8,9] Two processes in which the Langmuir wave decays into an ion wave and a third wave are likely candidates to explain this behavior. In the Langmuir decay instability (LDI), the third wave is a Langmuir wave. This process has been suggested as the likely SRS saturation mechanism by many analytic and numerical studies,[3–6] and decay products of LDI have been detected in small scale plasmas.[12–14] In the electromagnetic decay instability (EDI), the third wave is an electromagnetic wave. This instability has a lower threshold than LDI, and also a weaker growth rate.[15]

In this Brief Communication, we present the first demonstration that SRS-produced Langmuir waves decay by the LDI process in ignition-relevant plasmas. We performed Thomson scattering experiments in which the geometry was sensitive to the ion wave products of either the LDI or the EDI process, and observed ion waves only for the LDI case. Ion waves produced by these decay processes have unique $\overline{k}$ and ω so the $\overline{k}$ resolved Thomson measurements can identify the instability. Ion waves are also a clearer indication of the LDI instability than the counterpropagating Langmuir wave that has been observed in some colder plasmas.[12,13]

The experiments were performed at the Nova laser facility,[1] with the configuration shown in Fig. 1. The plasma is produced by a gas filled balloon target which is heated by eight 1 ns long unsmoothed Nova beams of 2.5 kJ each at 351 nm.[16] All beams are 1 ns in duration, with the interaction beams turning on 0.5 ns after the heaters.

Thomson scattering[17] of a 263.5 nm low energy (50 J) F/16 beam was used to detect the ion wave decay products of SRS Langmuir waves driven by a separate SRS drive beam. The coherent Thomson scattering $\overline{k}$ matching relations determine the direction of the scattered light from a given wave, and the angle at which the probe must intersect the wave. The frequency of the measured SRS was used to determine the $\overline{k}$ of the SRS Langmuir wave. Models of the decay processes[4,15] were used to predict the LDI and EDI wave k's (approximately $2.8k_{\mathrm{laser}}$ and $1.4k_{\mathrm{laser}}$, respectively, and hence to choose the drive beam location and wavelength as well as to position the collection optic. The Thomson scatter signal is focused by an F/10 Cassegrain optic onto the slit of a 1 m spectrometer coupled to a streak camera to provide time and wavelength resolution as well as spatial localization within a volume of approximately $(200\ \mu\mathrm{m})^3$. Only a wave of specific k will scatter light into the collector, so that any signal on the spectrum indicates a wave at the predicted k within a 10% tolerance set by the SRS bandwidth and F/numbers beam. The streaked spectrum was used to identify ion waves by the characteristic narrow features within approximately $\nu_{\text{ion-acoustic}} \approx 0.4$ nm of the probe beam wavelength (exact shift is influenced by flow conditions in the plasma).

For the LDI experiment, the SRS drive beam wavelength was 527 nm to allow k-matched scattering of the Thomson

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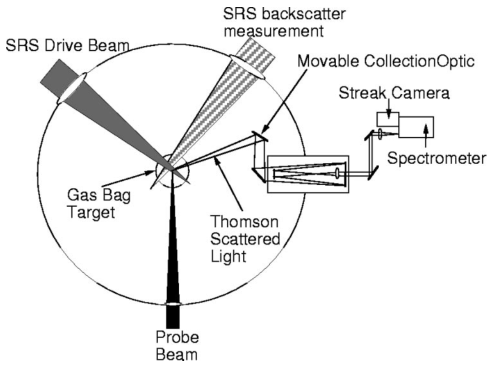

FIG. 1. Experimental configuration at the Nova facility. Eight defocused 2.5 kJ beams (not shown) were used to pre heat the gas bag target from 0 to 1 ns. Experimental beams are on from 0.5 to 1.5 ns. A 50 J probe beam at 263 nm allowed Thomson scattering measurements of ion waves driven by decay of SRS Langmuir waves from a SRS drive beam of 527 or 351 nm. Signal was detected by a streaked spectrometer with a collection optic positioned to satisfy $\bar{k}$ matching between probe, wave, and collector. A separate beam with a SRS backscatter measurement is run pointed and focused in the same way as the SRS drive beam to measure SRS in these conditions.

beam. LDI experiments with a 351 nm drive beam would require a sixth harmonic Thomson beam. For the main LDI experiments, the drive beam was a defocused 600 μm spot at the location probed by the Thomson scattering diagnostic (I_0=avg. intensity$=6\times10^{14}$ W/cm^2). A random phase plate (RPP) smoothed best focus spot of 320 μm ($I_0=2\times10^{15}$ W/cm^2) was also used. For the EDI experiment, the drive beam was a RPP smoothed best focus of 320 μm ($I_0=2\times10^{15}$ W/cm^2) at 351 nm. In order to maintain relative density at $n_e=0.10n_c$ for the LDI and EDI experiments, the gas mixture in the target was changed. For LDI experiments the gas was C_2H_6, while for EDI experiments the gas was C_5H_{12}. LASNEX 2D radiation hydrodynamic predictions of target conditions for both targets (including pointing, wavelength, and timing of the beams) show $T_e\approx2.2$ keV, and $T_i\approx0.3$–0.4 keV with a central density plateau at 10%n_c encompassing the experimental region and with slowly changing parameters until the arrival of a blast wave at about 1.4 ns.[18] X-ray spectroscopic studies and thermal Thomson scattering measurements of similar targets have confirmed the calculations.[16] Plasma conditions were chosen to be relevant to ignition experiment conditions, where it is expected that a submicron (526 nm or 351 nm) laser will encounter a mm scale, few-keV plasma of about 10%n_c,[1,7] with SRS reflectivity of the order of a percent of the incident power and exhibiting a weak or nonlinearly saturated dependence on the incident intensity.

It has been verified experimentally that SRS reflectivity under both conditions exhibits weak intensity dependence consistent with nonlinear saturation and percent level reflectivity (below), making the conditions for the LDI and EDI experiments as similar as possible given the $\bar{k}$ matching constraints. Laser plasma parameters such as volume averaged electron $v^2_{\rm osc}$ and $k\lambda_{\rm Debye}$ are also comparable for the 6×10^{14} W/cm^2 intensity at 527 nm and the 2×10^{15} W/cm^2 intensity at 351 nm. Both the RPP smoothed and unsmoothed beams used have a statistical speckle distribution of the incident intensity.[19] The only difference found in simulations between the unsmoothed and RPP smoothed beams is the speckle size, which should have a weaker effect on SRS than statistical properties we are holding constant. The main results are not affected by any possible differences because both the intensity scaling experiments which indicate SRS nonlinearity and the Thomson scattering experiments that detect nonthermal ion waves were conducted with defocused beams without RPPs.

To establish the properties of the SRS Langmuir wave, a separate diagnostic beam with an SRS backscatter measurement station was run with the same timing, focus, and intensity as the drive beam. This beam was pointed at the same target radius to encounter similar plasma conditions in the spherically symmetric plasma as the drive beam but not intersect it. SRS from Nova gasbag targets has not been found to be highly pointing sensitive, so that the SRS of this beam will be close to that of the SRS drive beam. This allowed measurement of SRS under the same conditions as the decay measurements.

The SRS measurement from the SRS diagnostic beam during the LDI measurement is shown in Fig. 2. The scattered light observed at 815 nm is SRS from a plasma density of approximately 9%n_c at 2.2 keV. The narrow feature ($\delta\lambda\approx25$ nm) at this wavelength is consistent with the formation of a plateau at 9%–10%n_c and $T=2.2$ keV that encompasses the Thomson scattering volume, as predicted by LASNEX simulations. This feature peaks in the 1.2–1.5 ns period, with a smaller level of activity (less than 50% of peak) early in the pulse. The broad and larger signals at shorter wavelengths are due to SRS in the low density halo plasma outside the Thomson scattering volume and formed by blow off around the gas bag. The power scattered in the 815 nm feature was $\approx$0.6% (time averaged) of the incident power, and this reflectivity varied less than 25% as the drive beam's intensity was varied by a factor of 2 (by changing the laser energy while focal position was kept constant). The spectrum features and the peaking of SRS reflectivity from 9%n_c between 1.2 and 1.5 ns were consistent over three shots. Such a weak dependence on intensity is not consistent with a linear

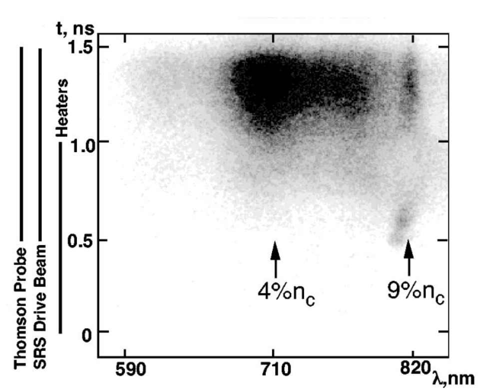

FIG. 2. SRS backscatter data from the LDI experiment. The narrow feature at 815 nm indicates scattering from a plasma at approximately 9% critical and 2.2 keV, which is the density in the Thomson scattering volume. The broad spectrum at shorter wavelength is SRS scatter from the blow off plasma around the target and outside the Thomson scattering volume. Beam timing is drawn on the left-hand side.

three wave process, and is consistent with models of Langmuir wave saturation.[3–6]

The LDI ion wave Thomson scattering spectrum is displayed in Fig. 3(a), showing a narrow, bright signal within a nm of the Thomson beam wavelength from ≈ 1.2 to 1.5 ns, the same time when the 815 nm SRS feature in Fig. 2 is strong. Drive beam intensity was 6×10^{14} W/cm^2 at 527 nm. The Thomson scatter spectrometer imaged the region $r=700\pm100$ μm from the gas bag center on the side closer to the drive beam entrance. The presence of a narrow signal far above the thermal level indicates a strongly driven wave at the predicted LDI $\bar{k}$. The main signal is a redshifted line with two bursts in time at around 1.2 and 1.5 ns. There is an interuption of this signal and a feature close to unshifted between 1.3 and 1.4 ns, which is about when the blast wave crosses the scattering volume. These lines are within $\nu_{\text{ion-acoustic}}\approx 0.4$ nm of 263.5 nm, consistent with scattering from an ion wave with the predicted LDI wave number in these plasma conditions. The absolute frequency of the lines may be shifted by flow velocities in the plasma. Similar signals and shifts have been observed for other ion waves in Thomson scattering experiments on similar targets.[20] Simulations also show that during the late time interval when SRS is observed ($t=1.2$–1.5 ns), rapidly varying sonic flows exist in the vicinity of $r=700$ μm with gradient scale lengths of 100–300 μm which will shift the ion wave frequencies in the scattering volume sufficiently that the frequency of the scattered light is difficult to predict. However, the observation of narrow lines within 1 nm Thomson beam wavelength indicates scattering from ion waves which have the $\bar{k}$ predicted for LDI.

Other features of the Thomson scattering spectrum are also consistent with LDI activity. The ion wave scattering occurs only when SRS backscatter from the density at the scattering volume ($9\% n_c$ or 815 nm) is large, i.e., 1.2–1.5 ns. The signal is not present when the SRS drive beam is not fired [Fig. 3(b)]. Models indicate that SRS can fluctuate in small regions of the beam while the spatially integrated reflectivity fluctuates much less,[4] consistent with both the localized Thomson scattering measurements and the SRS reflectivity which integrates over the whole beam path. Similar Thomson scattering results were obtained on three shots with the same drive beam set up. The peak Thomson scattering signal is at least a factor of 10^3 in intensity above the thermal scattering level in these plasmas, showing that LDI is occurring at rates that drive the ion wave far above thermal levels when SRS reflectivity is large and does not vary linearly with drive beam intensity, which is the primary result of this paper. In addition, the LDI ion waves occur in conditions similar to those where this and previous[11] experiments have shown that the SRS Langmuir wave was nonlinearly saturated and are consistent with LDI saturating SRS.

The measurement of LDI ion waves was repeated at a radius of 400 ± 100 μm with an increased intensity of 2×10^{15} W/cm^2 produced with the reduced spot size of a focused, RPP smoothed beam. No activity was observed in spite of the fact that the intensities were higher than the experiments at $r=700\pm100$ μm, consistent with LDI being most active in the outer region of the gas bag. This is also consistent with previous measurements and recent simulations by the F3D code which suggest that SRS occurs primarily in the outer region[21,22] and with the model of strongly damped Langmuir waves which shows that scattered waves grow in the direction toward the incident beam.

These experiments were repeated for the EDI ion wave using a 351 nm SRS drive beam with an intensity of 2×10^{15} W/cm^2. SRS reflectivity under these conditions has been studied previously and exhibits similar reflectivity and saturated intensity scaling to that found here for the LDI conditions.[11] Pointing was varied from $r=700\pm100$ μm from the gas bag center on the side closer to the beam entrance to $r=400\pm100$ μm away from the beam entrance. No ion waves above thermal level were detected in any of the EDI cases studied. The sensitivity of the detector was roughly the same as that in the LDI case for measurements at the location where LDI was detected, and should have detected a signal $\approx\frac{1}{1000}$ of the LDI signal. At other locations, due to different filtration and stray light, the sensitivity was sufficient to have detected a signal $\approx\frac{1}{10}$ of the LDI signal. The absence of EDI waves suggests that EDI is not playing a role in saturating SRS in these experiments. The lack of scattering at the angle corresponding to the EDI wave number is also consistent with the detected LDI waves being localized in wave number, as expected, and not part of a broad spectrum of turbulence as could be produced by other processes.

The data have been used together with analytical formulas to make simple limiting estimates of the possible effect of the LDI process on SRS in these experiments. The amplitude of the driven ion wave was estimated using the collective Thomson scatter equation,

$$\left(\frac{\delta n}{n}\right)^2 \approx 16\,\frac{P_{\text{scattered}}}{P_{\text{inc.}}}\left(\frac{n_c}{n}\right)^2 \frac{1}{k^2 L_s L_c F} \tag{1}$$

following Ref. 23, where $P_{\text{scat,inc}}$ are the scattered and incident powers, respectively, n, n_c are the electron density and the critical density, k is the wave number of the incident

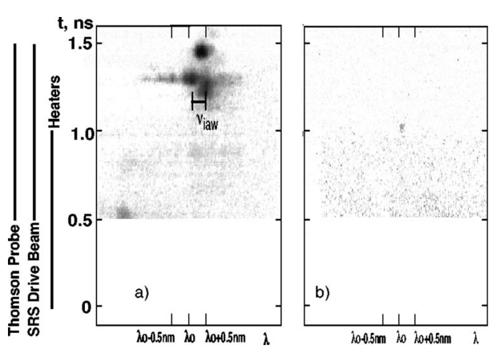

FIG. 3. Thomson scatter data showing (a) LDI ion wave spectrum with drive beam on; (b) spectrum with drive beam off. The presence only in the driven case of strong signal indicates the presence of a strongly driven wave at the $\bar{k}$ of LDI. The presence of narrow features within $\nu_{\text{ion-acoustic}}\approx 0.4$ nm of λ_0 indicates this signal is an ion wave. Absolute wavelength may be shifted by flows in the plasma. The signal is present only when the drive beam is on and only from 1.2 to 1.5 ns when SRS from the density at the scattering volume (9% critical, 815 nm) is high, indicating it is driven by SRS from that density and consistent with LDI activity. Beam timing is drawn on the left-hand side.

beam, L_s is the length of the scattering volume, L_c is the smaller of the coherence length of the wave or the speckle size (4 μm), $\delta n/n$ is the electron density perturbation amplitude of the ion acoustic wave, and F is the volume fraction that is SRS active. We can estimate an upper limit to F by requiring that the SRS gain calculated for our conditions is sufficient for the instability to grow from noise in the active regions. The SRS gain in the present case is $G^0_{\mathrm{SRS}} \approx 2.5(I/I_0)$ (weak damping limit), where I_0 is the average intensity in the laser spot, so that for SRS to be active $I/I_0 \geqslant 4$ is needed and hence for a speckle distribution $F \leqslant 0.02$.[19] We then obtain $(\delta n/n)^2 \geqslant 1\times 10^{-5}$ as the lower bound on the density fluctuation associated with the LDI ion wave. This result depends inversely on the coherence length of the wave which is assumed no shorter than a speckle size. A very incoherent wave, as can be produced in strong turbulence, would have a still higher amplitude.

Solution of the coupled mode equations in 1D (as appropriate for backscatter) yields the ion wave amplitude needed to effectively double the damping rate of the incident Langmuir wave, and thereby make the wave response significantly nonlinear,[24]

$$(\delta n_i/n_{0i})^2 = 4\nu_L/\omega_p, \tag{2}$$

where $\delta n_i/n_{0i}$ is the density perturbation amplitude of the ion acoustic wave, and ν_L is the Langmuir wave damping rate. Damping for a Maxwellian distribution is dominated by Landau damping. Many mechanisms may distort the electron distribution and reduce damping in these plasmas, including trapping of particles when the waves have large amplitudes,[11] and nonlocal heat transport. Super-Gaussian distributions produced by intense inverse bremsstrahlung heating by the laser have recently been shown to dramatically reduce the damping rate of the Langmuir wave,[25] potentially to the collisional value. The ion wave amplitude to saturate SRS is then between $(\delta n_i/n_{0i})^2 = 0.02$ using Landau damping and $(\delta n_i/n_{0i})^2 = 2\times 10^{-6}$ using electron collisional damping. Hence if damping rates are reduced significantly from Maxwellian Landau levels, the observed Thomson signals may be compatible with ion waves large enough to saturate SRS. Recent simulations have also observed LDI activity above the thermal level both with the experimental parameters and also at slightly lower $k\lambda_d$.[26] The level of LDI in these simulations is about 10% of the main SRS Langmuir wave. This was interpreted as too low to saturate the SRS, compatible with the estimate above for near Maxwellian plasmas.

In summary, Thomson scattering measurements in a large scale plasma have detected ion waves far above the thermal level which are identified by their wave vector, spectral structure, and correlation with SRS activity as decay products of the Langmuir decay instability driven by SRS produced Langmuir waves. SRS from the density at the Thomson scattering volume displayed weak intensity scaling compatible with nonlinear saturation and was of percent level reflectivity. The electromagnetic decay instability was not observed in similar experiments. These measurements are the first demonstration that SRS produced Langmuir waves undergo Langmuir decay under the conditions expected in ignition experiments.

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