Observation of the Nonlinear Saturation of Langmuir Waves Driven by Ponderomotive Force in a Large Scale Plasma

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We report the observation of nonlinear saturation of Langmuir waves produced by a probe laser beam interacting with a high intensity pumping laser beam. Amplification of the probe beam is observed and interpreted as scattering of pump energy by a Langmuir wave that is produced by the beating of the two beams. It is found that, as the probe beam amplitude is increased, the scattering and Langmuir wave amplitude do not increase proportionally, demonstrating that the wave is nonlinearly saturated consistent with saturation by secondary-ion-wave instabilities.

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The scattering of laser energy by large amplitude Langmuir waves has long been recognized as an important loss mechanism in laser driven inertial confinement fusion research [1]. The Langmuir waves are driven to large amplitude by the three wave process of stimulated Raman scattering (SRS). At moderate laser intensities the three wave process can be limited simply by a "convective saturation" which results from the propagation of energy out of the interaction volume by one or both of the decay waves. When the convective saturation level is sufficiently high, as in large scale plasmas, the stimulated Langmuir waves can be saturated at much lower amplitude by nonlinear processes, such as secondary stimulation of ion acoustic and other waves [2–6]. Previous experiments have found the products of secondary mechanisms that could cause wave saturation [7–9]. Experiments have also shown that Langmuir waves and ion waves anticorrelate in time suggesting that they are nonlinearly coupled [10–13]. More recent experiments have shown that, under conditions similar to what is expected in ignition experiments, the SRS reflectivity is dependent on the damping rate of the ion acoustic wave [14–16] consistent with saturation by secondary decay. Further, it has been shown that the scattered SRS spectrum has both a shape [17] and magnitude [14] that is consistent with Langmuir wave saturation by a secondary decay involving ion waves. These observations suggest that the Langmuir wave response to the ponderomotive force may be nonlinear. However, there has as yet been no direct observation of this nonlinear response. The potential to observe the Langmuir wave response has been shown by theoretical [18,19] and experimental [13,20–22] studies, in which Langmuir waves and their secondary decay products [23] have been generated by the beating of two laser beams of different frequency. A parallel line of experimentation has used beating laser beams to study the ion wave response [24,25].

In this Letter we report the first demonstration of the nonlinear saturation of Langmuir waves driven by ponderomotive force under conditions relevant to indirect drive ignition experiments. The Langmuir waves are driven by the beating of two intersecting laser beams with widely separated frequencies. Scattering of energy from the high frequency beam to the low frequency beam provides a measure of the wave amplitude, while adjustment of the intensity of the low frequency beam allows the ponderomotive force to be varied. The amplitude of the Langmuir wave is thus found to be very weakly dependent on the ponderomotive drive when the drive is large, as expected by secondary decay models [2–6]. The experiments are done in low Z plasmas which have electron temperatures, densities, and scale lengths similar to what is expected in indirect drive ignition experiments [26,27].

The experiments were performed at the ten beam Nova facility using eight of the beams (1 ns pulse length, 0.35 μm wavelength) to preheat a gas-filled balloon target to form a nearly uniform plasma of 2 mm diam [14]. The remaining two beams (see Fig. 1) are brought to focus at the same point ($r = 400\ \mu$m) where the plasma is expected to be most uniform and are chosen to cross 25° away from antiparallel, approximating the geometry of SRS backscatter [27]. The "pump" beam is $f/4.3$ with 2.5 kJ of energy at 351 nm wavelength in a 1 ns square pulse that is delayed 0.5 ns with respect to the heaters. The use of a random phase plate (RPP) on the pump beam limits the spot size to 320 μm FWHM at best focus. The "probe" beam has a wavelength of 527 nm with a variable energy (100 J to 1 kJ) in a 2 ns pulse that is turned on simultaneously with the heaters. The RPP on the probe limits the spot size to 350 μm. As a result, the region of overlap of the two beams is a parallelogram 800 μm on each side with an acute interior angle of 25° (see Fig. 1). The timing of the two beams allows the interaction to

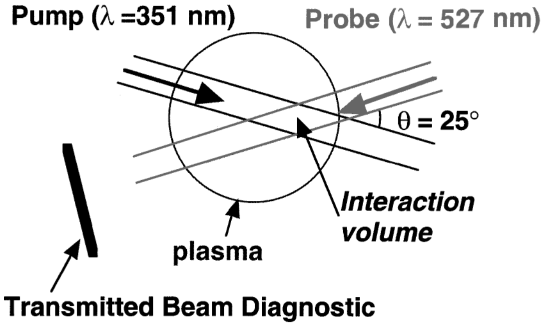

FIG. 1. Geometry of the crossing beam experiment showing a short wavelength, a high intensity pump beam, and a long wavelength probe beam intersecting in gas target plasma. The time history of the probe beam transmission is measured.

occur during the 0.5 to 1.5 ns period. During the first half of this period ($\Delta\tau = 0.5$ to 1.0 ns) the plasma is heated and the plasma density is nearly constant in time, while during the second half the plasma is cooling by radiation and expansion and the plasma density is decaying in time.

The plasma density is controlled using three carbonous fill gases that are mixed in various percentages which, together with small variations in the fill pressure, provide an initial density variable between 5.6% and 8.2% of the critical density for 351 nm light (n_{c0}) which brackets the Langmuir wave resonance for the experimental setup described below. The target is filled to between 730 and 800 Torr with a mixture of the following gases: C_3H_8, C_5H_{12}, and CH_4, and with a 1% Ar impurity to allow for spectral analysis [26]. The plasma density from 0.5 to 1.0 ns ($\Delta\tau$) is very close to the initial density as expected from LASNEX simulations [27] and confirmed by measurements of the peak wavelength of SRS back [27] and forward [28] scattering. The electron temperature T_e is determined from x-ray spectral measurements from the interaction region ($r = 400$ μm) and is found to increase to a maximum of ~2.6 keV at 1.0 ns, in reasonable agreement with LASNEX simulations [26].

The primary observable in this experiment is the measurement of the transmitted probe beam power through the plasma with a time resolution of ~150 ps [28]. As shown in Fig. 2, the transmitted probe beam power in the presence of the pump beam (pump-on) is substantially enhanced compared to experiments without the pump (pump-off) when the initial plasma density was in the vicinity of $n_0/n_c = 7.1\%$, indicating that significant energy is transferred from the pump beam. The amplification of the probe beam can be defined as the ratio of the pump-on to pump-off signals, and is shown in Fig. 2 to rise quickly during the first 0.2 ns after the pump turns on, limited by detector rise time, followed by a slower variation until ~1.2 ns when there is a rapid drop due to changing plasma conditions detuning the resonance. The transmitted probe power in the absence of a pump beam (pump-off) was only weakly sensitive to the changes in density. The observed attenuation of the transmitted beam in the pump-off case is determined primarily by inverse bremsstrahlung absorption and is also affected by scattering, as described in Ref. [28].

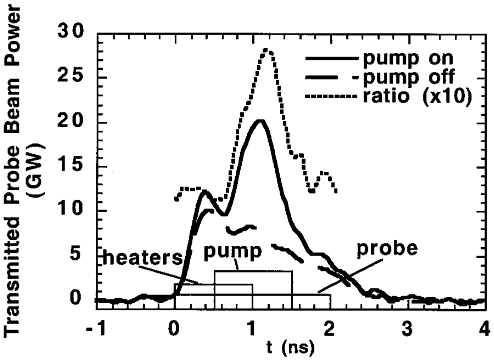

FIG. 2. Measurement of power transmitted through the plasma by the probe beam for the cases with and without a pump beam. The amplification shown is the ratio of the two measurements. The transmission of the probe beam is enhanced by a factor of ≥2 during the time period that the pump is on, indicating that a large amplitude Langmuir wave is being stimulated and scattering substantial energy.

The behavior of the transmitted signal (see Fig. 3) is consistent with a steady state interaction of the two beams with a Langmuir wave in the plasma which results in the unstable growth of the probe by the decay of the pump. The interaction is found to be strongly resonant with plasma density as observed in the plot of the amplification, averaged over $\Delta\tau$, versus n_0 shown in Fig. 3. In order to show that the observations are consistent with stimulation of Langmuir waves, the three wave amplification rate for SRS has been calculated [26,29] using the plasma density and temperature profiles that are predicted by the LASNEX simulation code and consistent with the plasma characterization measurements described above, and is integrated over the probe beam trajectory, averaged over $\Delta\tau$, and plotted for comparison with the measurements in

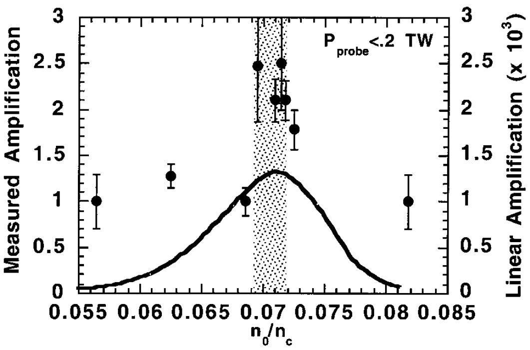

FIG. 3. The amplification measured during the 0.5 to 1.0 ns time period is shown as a function of the initial plasma density for the case of low probe intensity. A maximum is observed at $n_0/n_{c0} = (7.1 \pm 0.15)\%$ (shaded) consistent with the location of the linear Langmuir wave resonance calculated with simulated plasma profiles.

Fig. 3. The maximum measured amplifications occur at a density that is close to the maximum of the calculation as expected. The peak amplification measured is much less than the linear theory which is consistent with nonlinear saturation. Further quantitative comparison of the experimental signal levels to the predictions is not practical because the linear response of a Maxwellian plasma to the ponderomotive force produced by the incident beams is sufficient so that the wave amplitude predicted by linear theory within 1 μm of the incident edge of the intersection volume $(\delta n_0/n)^2$ is 1 to 2 orders of magnitude greater than the threshold for nonlinear trapping [30], $(\delta n_{\text{tr}}/n)^2 \sim 1 \times 10^{-5}$ for the plasma conditions and intensities used in these experiments. Particle trapping can reduce the level of damping, and produce narrower Langmuir wave resonances and larger amplitudes than linear theory predicts [30–32]. When the amplitudes reach still higher levels, secondary decay processes may enhance the damping and reduce the wave amplitudes [2–6].

The time history of the amplification observed during $\Delta\tau$ in Fig. 2 can be interpreted as the time history of the scattering wave amplitude during a period when the plasma electron density is nearly constant and the electron temperature is changing slowly, and is consistent with either a linearly or nonlinearly saturated state with a weakly varying saturation level. This weak variation in the scattering is consistent with mild detuning of the three wave resonance by the simulated 14% temporal variation of the temperature during this period. At later times, simulations indicate that the linear resonance is detuned by the rapidly dropping plasma density, consistent with the stronger temporal variation observed.

Figure 4 shows that above a probe power of 200 GW, the transmitted power no longer continues to increase with the laser power, demonstrating the nonlinearly saturated response of the Langmuir wave to the ponderomotive force produced by the beating of the two laser beams that is the primary result of this Letter. The transmission diagnostic itself demonstrates linearity up to an order of magnitude higher transmitted power [28]. The power scattered from the pump beam is determined as the difference between the transmitted probe power in the pump-on and pump-off cases, again averaging over $\Delta\tau$, and is plotted versus the incident probe power with the pump power constant in Fig. 4. For probe powers below 200 GW, the scattered power is not significantly different than the linear scaling represented by the solid line in Fig. 4, while for probe powers greater than 200 GW the scattered power clearly falls below the linear scaling demonstrating nonlinear saturation. The scattered power is corrected for absorption between the point of scattering (where the center of the beams cross) and the outer edge of the plasma. The nonlinear saturation observed in the scattered power in Fig. 4 indicates a nonlinear Langmuir wave response because the power scattered by the Langmuir wave is proportional to the square of its amplitude, δn^2, and the probe power is proportional to the square of the ponderomotive force driving the Langmuir wave.

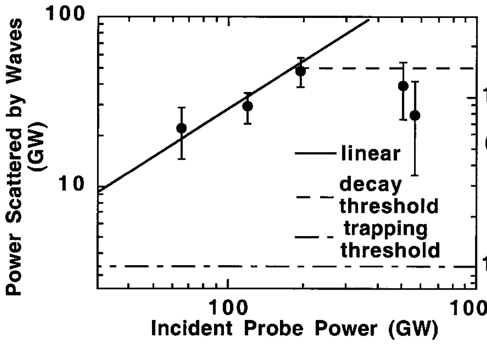

FIG. 4. The additional power scattered into the probe when the pump beam is present and the density is resonant is plotted vs the incident probe power. The data at low power are best fit to a linear scaling of Langmuir wave amplitude with ponderomotive force (solid line). The data at high probe power fall below the linear scaling showing nonlinear saturation. The scattered power is interpreted as Langmuir wave amplitude and compared with the threshold of trapping and secondary decay instabilities (dashed lines) as discussed in the text.

Finally, we will show that the observed transmitted light levels are consistent with saturation of the Langmuir waves by secondary decays, as suggested by analysis of backscatter measurements from ignition relevant plasmas [14,15]. The possible decay processes include the electromagnetic decay instability (EDI) and the Langmuir wave decay instability (LDI). The Langmuir wave amplitude estimated from the fraction of power that it scatters from the pump beam (F) is compared to the minimum or threshold amplitude necessary for these processes to occur. A 1D Bragg wave scattering model for a homogeneous beam [14,33] shows the relationship between F and the wave amplitude $(\delta n/n)$ averaged over the interaction volume and the 0.5 to 1.0 ns time period in terms of the normalized plasma density, the incident beam wave number, and two characteristic lengths: the system size (L), and the correlation length of the Langmuir waves $(\Delta k)^{-1}$,

$$F \sim \frac{1}{4}\left(\frac{n}{n_{c0}}\right)^2 k_0^2 L (\Delta k)^{-1} \left(\frac{\delta n}{n}\right)^2 . \tag{1}$$

As an estimate of the Langmuir wave correlation length we use the correlation length of the driving ponderomotive force produced by the two $f/4.3$ beams. The width of the spectrum of $k_z = (\mathbf{k}_1 - \mathbf{k}_2) \cdot \hat{\mathbf{z}}$ is the speckle length projected into the axis of the probe beam (z); using this width of the k_z spectrum of the incident beams we find $\Delta k \sim 1.2 \times 10^6\ \text{m}^{-1}$. From this length and the experimental plasma parameters in Eq. (1), the averaged amplitude of the scattered Langmuir wave is estimated from the measurements F, as shown on the right axis in Fig. 4. F is calculated using the pump beam power that is determined from the incident power and a correction for inverse bremsstrahlung between the plasma edge and the point at which the center of the two beams cross. The results are compared with the threshold for the secondary decay instability shown as dashed lines in Fig. 4. The peak $\delta n/n$ in the interaction volume may be much greater than the measured average value shown. The threshold is determined by the damping rates of both the secondary decay products and can be written in terms of the Langmuir wave amplitude as

$$\left(\frac{\delta n}{n}\right) = 4k_L\lambda_D\left(\frac{\nu_{\mathrm{ia}}}{\omega_{\mathrm{ia}}}\right)^{1/2}\left(\frac{\nu_3}{\omega_3}\right)^{1/2}, \qquad (2)$$

where k_L is the wave number of the primary Langmuir wave that is driven by the beating of the two beams, λ_D is the Debye length, ω_{ia} and ν_{ia} are the real and imaginary parts of the frequency of the ion acoustic decay product ($\nu_{\mathrm{ia}}/\omega_{\mathrm{ia}} \sim 0.2$ [34] for a $T_{\mathrm{ion}}/T_e \sim 0.15$ as determined by simulations for this case), and ω_3 and ν_3 represent the frequency of the third wave. When the instability is EDI (LDI) the third wave is an electromagnetic wave (Langmuir wave) [6], and ω_3 and ν_3 are approximately the plasma frequency and the inverse bremsstrahlung absorption (electron Landau damping) rate. Analysis of the non-Maxwellian electron velocity distribution produced by collisional absorption of the beams, nonlinear Landau damping of the Langmuir waves, or nonlocal heat transport [35] has shown that the electron Landau damping rate may be much lower than in a Maxwellian plasma and, in a laser hot spot, the damping rate could be reduced by an order of magnitude or more, approaching the collisional damping rate as a lower limit. The threshold given by Eq. (2) is evaluated with ω_3 and ν_3 equal to the plasma frequency and the collisional damping rate corresponding to EDI or LDI in a non-Maxwellian plasma and compares well with the estimates of average saturated wave amplitude as shown in Fig. 4.

In conclusion, we have demonstrated that the response of Langmuir waves to ponderomotive force is nonlinearly saturated under conditions relevant to indirect drive inertial confinement fusion.

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