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Observation of Saturation of Energy Transfer between Copropagating Beams in a Flowing Plasma

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Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94551

W. Seka
Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14627
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Experiments demonstrate energy and power transfer between copropagating, same frequency, beams crossing at a small angle in a plasma with a Mach 1 flow. The process is interpreted as amplification of the low intensity probe beam by the stimulated scatter of the high intensity pump beam. The observed probe amplification increases slowly with pump intensity and decreases with probe intensity, indicative of saturation limiting the energy and power transfer due to ion-wave nonlinearities and localized pump depletion. The results are consistent with numerical modeling including ion-wave nonlinearities.

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Energy and power transfer between laser beams that intersect in a plasma [1,2] is of interest for a number of reasons, including its effect on power deposition spatial profiles in indirect drive inertial confinement fusion experiments [3,4], its use as a tool for studying plasma wave nonlinearity [5,6] and wave-wave interaction [7], and its potential for manipulating light at high intensity [8,9]. The underlying process is seeded stimulated scattering in which a wave propagating in a plasma is driven resonantly by the beating of the two beams. When the plasma conditions are such that the beam frequency and wave number are resonant with a plasma mode, the wave grows large and scatters substantial energy from one beam to the other, resulting in amplification (or depletion) of the beam. Previous experiments on energy transfer by stimulation of ion waves in high temperature plasmas [2,4] have raised the possibility of energy transfer between beams in indirect drive ignition experiments, which could affect the target radiation symmetry necessary for implosion and ignition [3,10]. More recently experiments in denser, colder plasmas have shown that the side scatter of one beam can be amplified by the presence of a second [11,12].

In this Letter we report the first observation of energy transfer between copropagating beams in a plasma with a Mach 1 flow and show that the dependence of the energy transfer on both pump and probe beam intensities is saturated by the nonlinear response of the ion-wave and localized pump depletion. Modeling including the nonlinear frequency shift of the ion wave is consistent with the observations in this case. This is the first study of energy transfer between beams that are crossing at small copropagation angles, and small values of the ion-wave **k** vector, in a flowing plasma. It is also the first demonstration that energy transfer can be saturated when only a small fraction of the beam energy is transferred.

The experiments were performed on the Omega laser system [13] with two high intensity beams ($I \leq 7 \times 10^{14}$ W/cm^2, $\lambda = 351$ nm) crossing in a flowing preformed plasma. The plasma is created by heating an exploding CH_2 foil with near normally incident heater beams. The foil has transverse dimensions of 750 μm $\times$ 1000 μm and the heater beams are pointed at the centroid and defocused to produce roughly circular spots with 500–600 μm diam. The heater beams produce a total power of $\sim$1.1 TW in a 2 ns square pulse. The plasma is formed by burning through the high density material which expands primarily in one dimension and is heated until $t = 2$ ns at which time a fairly high and uniform density region is formed in which the flow velocity increases from zero at the initial foil position to Mach 1 at a position $\sim$350 μm above the initial foil position. Simulations of the plasma formation and heating have been performed using Lasnex [14] for two different initial foil thicknesses (10 and 8 μm). The simulations show that at the end of the heater pulses the plasma density is 6.4% (3%) of the critical density, and the temperature is 1.4 keV (1.5 keV). In both cases the plasma flow velocity at this time is outward at Mach 1.1 (0.9) at the point where the beams cross. Two interactions beams are crossed at the Mach $\sim$1 point each with a 1 ns square, 0.5 TW pulse timed to arrive at the crossing point between 1.5 and 2.5 ns after the heating begins. The interaction beams are focused and pointed to cross at 25° from parallel at a point 350 μm above the center of the foil and centered in a heated foil area as shown in Fig. 1. The focal spot sizes of the interaction beams are limited to 240 μm (FWHM) by using distributed phase plates (DPP) in each beam line, so that the peak intensity can be a maximum of 7×10^{14} W/cm^2. The interaction beams are set at different intensities, with the lower intensity beam designated as the probe, and the higher intensity beam designated as

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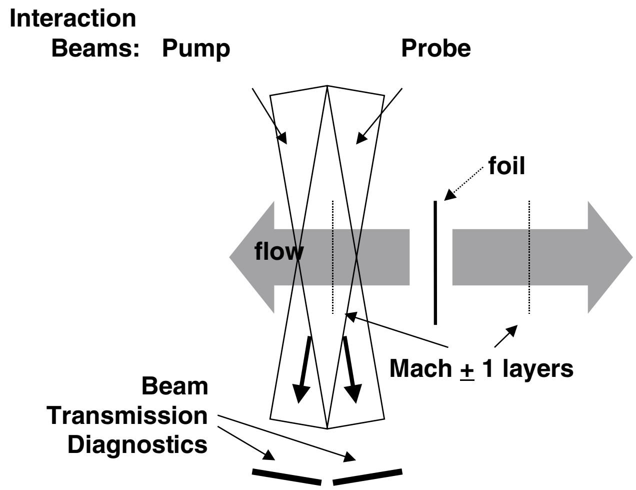

FIG. 1. Experiments to detect energy exchange between two crossing laser beams produced by interaction in a plasma with a Mach 1 flow use the geometry shown. The energy is transferred by scattering by the ion wave driven in the beam crossing volume with the direction of the transfer determined by the flow. Experiments with reversed flow (on the opposite side) or with a single beam are compared with the type shown to determine beam amplification in the presence of plasma absorption.

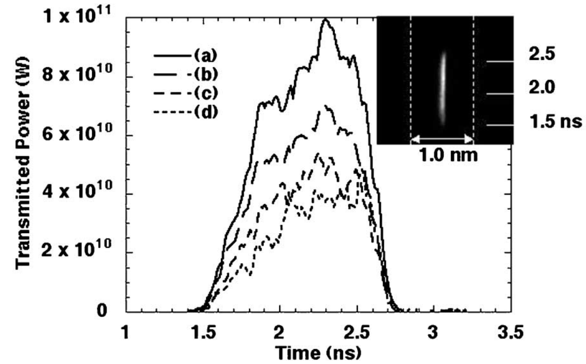

FIG. 2. The measured transmitted power of the probe beam is shown for four different cases: (a) a Mach 1 flow is present and directed to transfer energy to the probe beam (Mach +1) and the pump beam intensity is 7.1×10^{14} W/cm^2, (b) same as (a) but with a pump intensity of 3.9×10^{14} W/cm^2, (c) same as (a) but with the pump beam off, (d) same as (b) but with the flow direction reversed (Mach -1). Enhancement of the transmission with increasing pump intensity in the Mach $+1$ case demonstrates the energy transfer effect. The transmitted spectrum is narrow as shown in the inset.

the pump. The pump beam provides the high intensity necessary to drive stimulated Brillouin scattering (SBS) in these plasma conditions, while the probe is a seed for the pump's SBS forward scatter to grow from. The product of the pump and probe amplitudes provide the "beat" ponderomotive force that drives the ion waves responsible for scattering energy from beam to beam. The time resolved transmitted spectrum of each of the two beams is measured by collection of the light on the far side of the target over the entire f-cone of the undeflected beam ($f/6.6$) using the focusing optics of an opposed beam line that is not activated.

Energy transfer between the two interaction beams can occur when the ponderomotive force produced by the beating of the two beams with identical frequencies has a wave vector ($\mathbf{k}$) that is resonant with a stationary ion acoustic wave ($\omega = 0$) in a plasma with a Mach > 1 flow. The energy transfer is demonstrated in these experiments by comparing the transmitted power and energy of the beams for three different cases: the case where the Mach 1 flow is directed to produce a resonance for ion waves that scatter energy from the pump to the probe ("Mach $+1$"), the case with oppositely directed flows of the same magnitude ("Mach -1"), and the case where the pump beam is off ("pump off"). The transmitted power waveform of the probe beam for each of these three cases and for a plasma density of 6.4% of critical, pump beam intensity of 3.9×10^{14} W/cm^2 and 7.1×10^{14} W/cm^2 and a probe intensity of 1.2×10^{14} W/cm^2 is shown in Fig. 2. The Mach $+1$ cases are seen to have the highest probe beam transmission throughout the pulse due to the energy transfer, while the pump off and Mach -1 cases are lower with the Mach -1 case being only slightly less than the pump off case. The transmitted spectrum is found at all times to be quite narrow, unshifted, and close to the incident wavelength ($\Delta\lambda \lesssim 0.1$ nm) as shown in the inset in Fig. 2. The spectrally integrated transmitted power of both probe and pump beams is found in all cases to rise quickly between 1.5 and 2 ns, due to the decreasing inverse bremsstrahlung absorption in the heating plasma. To determine if any of the pump beam energy was refracted or scattered into the probe beam transmission detector an experiment was also done with the probe beam off in which negligible energy appeared in the probe transmission. The observation of a probe transmission in the Mach $+1$ cases that is above the pump off and Mach -1 cases and the supporting experiments are the first demonstration that energy and power transfer occur between nearly copropagating beams of the same frequency in a plasma with a Mach 1 flow. The observation of a slightly reduced transmission of the Mach -1 case relative to the pump off case is consistent with energy transfer in the opposite direction (probe to pump) with a Mach -1 flow. The amplification of the probe beam is determined by integrating the transmission waveforms shown in Fig. 2 over the time period of the experiment and taking the ratio of the Mach $+1$ case to the pump off case or alternately to the Mach -1 case. The amplification of the probe relative to the pump off case is determined from a series of experiments with both 6.4% critical density plasma and 3% critical density plasma, in which the pump beam intensity is as shown in Fig. 3. The amplification rises slowly with pump intensity for both plasma densities. The error bars in Fig. 3 are determined from the observed shot to shot fluctuation in transmitted power under similar conditions. The

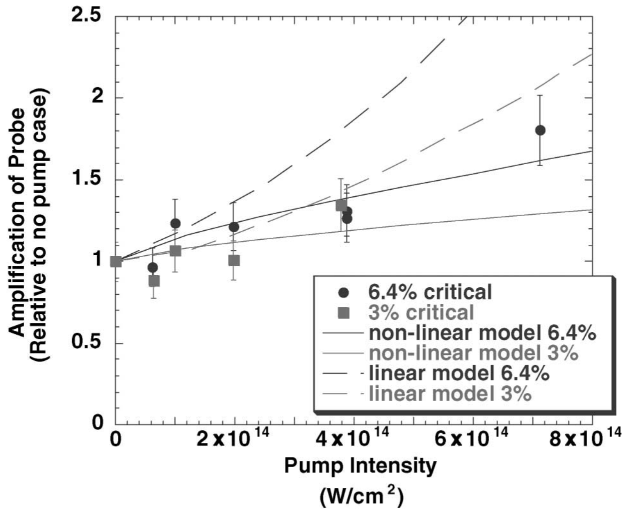

FIG. 3. The time-averaged amplification of the 1.2×10^{14} W/cm^2 probe beam in the Mach +1 case above the value it has in the pump off case is shown for two different target plasma conditions, and several different pump beam intensities. The observed scaling with pump intensity is weak compared to the linear model discussed in the text.

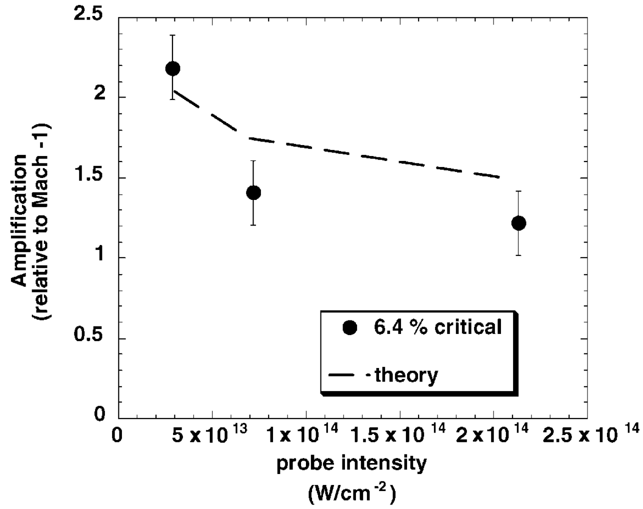

FIG. 4. The time-averaged amplification of the probe beam in the Mach +1 case compared to the Mach −1 case for the case of 6.4% critical plasma density and pump beam intensity of 7.1×10^{14} W/cm^2 is shown for different probe beam intensities. The reduction of amplification with probe intensity is a possible signature of ion-wave saturation as discussed in the text.

observed dependence of the amplification on the pump intensity is not consistent with linear three wave theory, which predicts an exponential dependence of the amplification on pump intensity, but is in agreement with models including ion-wave nonlinearity as shown in the figure.

To further investigate the source of the nonlinearity apparent in Fig. 3 experiments were performed with the beams crossing at the Mach +1 point and the probe beam intensity varying over an order of magnitude (2.0×10^{13} W/cm^2 to 2.2×10^{14} W/cm^2) and the heater beam conditions similar to that of Fig. 2. The probe beam intensity is sufficiently low that it is unlikely to have a significant nonlinear effect on the plasma by itself (such as by plasma heating), but when beating with the pump beam can produce a large enough ponderomotive force to drive the ion-wave response into a nonlinear regime. In this series of experiments a transmission measurement was also performed with the beams pointed at Mach −1, a pump intensity of 7.0×10^{14} W/cm^2, and a probe intensity of 1.0×10^{14} W/cm^2. The percent transmission measured with the beams pointed at the Mach +1 point was normalized to the percent transmission measured in the Mach −1 experiment (at 1.0×10^{14} W/cm^2) to determine the amplification plotted in Fig. 4. This comparison is appropriate for determining the amplification due to energy transfer, because the beams fractional attenuation in the absence of a high intensity crossing beam was measured using the pump beam during the experiments shown in Fig. 3 and was found to be independent of pump intensity up to $\sim 2.2 \times 10^{14}$ W/cm^2, as is expected for inverse bremstrahlung absorption and scattering from plasma fluctuations. At or above this intensity the transmission fraction dropped which indicated a 30% (upward) correction to the amplification measured at the highest intensity shown in Fig. 4. The drop in single beam transmission at high intensity is presumably due to beam spray, which has been observed previously [15] and which can deflect a larger fraction of the transmitted energy out of the detecter cone at high intensity. SBS and stimulated Raman scattering backscatter are not likely important since they have been found to be low under conditions similar to these [7]. The amplifications of the probe beam shown in Fig. 4 are produced by energy transfer and are clearly dependent on probe beam intensity which is qualitatively consistent with nonlinear saturation of the ion wave, and, in the case where energy transfer occurs in very localized regions, with pump depletion in those regions. (Depletion of the whole pump beam cross section cannot explain the observed nonlinearity when only a few percent of the pump energy is transferred to the probe.) A model of the nonlinear ion-wave response to the applied ponderomotive force is also shown in Fig. 4. The dependence of the amplification on probe intensity shown in Fig. 4 cannot be explained by heating of the plasma by the probe beam, primarily because the probe beam intensity is several times lower than the pump intensity and provides little additional heating.

For comparison with the measurements two theoretical models have been developed. The first, "linear," theory treats the beat ion waves in a linearized manner but includes some effects of the beam geometry and plasma flow profile. The second, "nonlinear," theory limits the growth of the ion-wave amplitude by inclusion of a nonlinear frequency shift [16,17] but collapses the beam geometry and plasma profile effects into a single effective interaction length consistent with the first model. The linear theory is derived from a quasineutral fluid plasma model coupled to a light model by the beat ponderomotive force. The response of the ion acoustic wave to this force was derived from fluid plasma equations that were linearized about a self-similar rarefaction solution, with parameters chosen to match the experiment. Transverse refraction of the probe beam was included. The equation for the energy transfer from pump to probe was numerically integrated along the probe rays across an assumed Gaussian profile of the pump beam. This neglects any effects of internal beam structure of the beams created by the phase plates, diffraction effects, and localized pump depletion. Whole beam pump depletion is accounted for by iteration. The pump and probe intensities at the interaction region boundary are reduced to agree with the experimental absorptions. The amplification predicted by this theory for the limit of low probe beam intensity is shown for the 3% and 6.4% critical density case in Fig. 3 (labeled linear).

The nonlinear ion-wave model incorporates the nonlinear shift in the ion acoustic frequency due to ion trapping and the concomitant relaxation of ion Landau damping [6,17]. This model consists of the steady-state coupled mode equations for the pump, probe, and ion-wave amplitudes in a one-dimensional homogeneous slab of plasma. The ion-wave advection is neglected (i.e., strong damping approximation), but an amplitude-dependent frequency shift is included. An analytical solution has been obtained for energy transfer from the pump to the probe in the limit that pump depletion is negligible, which is the case in these experiments (excluding possible pump depletion in intense speckles). All of the plasma and crossing-beam inhomogeneities and geometrical limiting factors are absorbed into an effective interaction length, and it is assumed that the interaction is occurring at the Mach 1 layer. The model illustrates how the frequency shift effectively detunes the SBS resonant interaction and limits the energy transfer of the crossing beams. With a residual ion-wave dissipation rate equal to 1.5% of the acoustic frequency (due to electron Landau damping and ion collisions), nonlinear frequency shift scaled to the acoustic frequency equal to $-0.5(\delta n_e/n_e)^{1/2}$ [16,17], pump and probe beam intensities decreased to 70% of incident for $n_e/n_c = 0.064$ and to 93% for $n_e/n_c = 0.03$ to model collisional absorption, and an effective interaction length of 75 μm, we obtain the nonlinear theoretical predictions shown as curves in Figs. 3 and 4 (labeled nonlinear). The interaction length is similar to what is determined from the amplification in the 2D linear model and the formula for the spatial SBS growth rate. This nonlinear model compares closely with the observed dependence on pump and probe intensities. The trapping model suggests that the peak ion-wave amplitudes produce electron density perturbations in the range of a couple of percent. The divergence of the linear gain prediction and the data in Fig. 3 and the good agreement of the data with the nonlinear ion-wave model in Figs. 3 and 4 support the hypothesis that the energy transfer observed in these experiments may be saturated by an ion-wave trapping nonlinearity.

In conclusion, we have demonstrated for the first time the resonant energy transfer between copropagating beams in a plasma with a transverse Mach 1 flow. At fixed pump intensity the probe amplification drops with increasing probe intensity faster than was obtained from a smooth beam model whose only nonlinearity was whole beam pump depletion, suggesting that saturation of the resonant ion wave and pump depletion from very localized interaction regions were saturating the energy transfer. A simple model including the effect of detuning by ion-trapping-induced frequency shifts better reproduced the scaling of amplification with both probe and pump beam intensity and indicates that ion trapping is a candidate mechanism for the saturation.

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