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Amplification of light in a plasma by stimulated ion acoustic waves driven by multiple crossing pump beams

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Experiments demonstrate the amplification of 351 nm laser light in a hot dense plasma similar to those in inertial confinement fusion ignition experiments. A seed beam interacts with one or two counter-propagating pump beams, each with an intensity of 1.2×10^{15} W/cm^2 at 351 nm, crossing the seed at 24.8° at the position where the flow is Mach 1, allowing resonant stimulation of ion acoustic waves. Results show that the energy and power transferred to the seed are increased with two pumps beyond the level that occurs with a single pump, demonstrating that, under conditions similar to ignition experiments where each beam has a low gain exponent, the total scatter produced by the multiple beams can be significantly larger than that of the individual beams. It is further demonstrated that the amplification is greatly reduced when the pump polarization is orthogonal to the seed, as expected from models of stimulated scatter.

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To ignite fusion reactions with intense laser beams by the indirect drive approach [1] multiple pump beams must transit plasma in the interior of a hohlraum cavity in order to reach the high density material at the wall where they convert efficiently to x-rays to drive an implosion of the fuel. The overall efficiency of this process has long been known to be influenced by the stimulated laser backscatter [2] produced by the pump beams in the plasma (see Refs. [3–9] and references therein). In addition, the symmetry of the deposited energy is influenced by the transfer of forward going energy between the beams that cross and produce plasma waves [10–13]. As a result, targets designed for ignition experiments at the National Ignition Facility (NIF) have been significantly constrained by an analysis of the backscatter that would be produced if each beam interacted independently with the plasma to produce both ion acoustic and Langmuir waves [9,14]. A parallel effort has optimized the wavelength of the incident beams to control the transfer forward power between the beams as they interact with each other via ion acoustic waves in the plasma [11–13]. In addition, experiments have shown that weak laser light, intersecting a single, counter-propagating pump beam can be amplified by ion acoustic waves [15] or Langmuir waves [16,17], but with gain exponents limited to $\lesssim 1$ by strong wave damping or nonlinear saturation of the waves. In a similar effort studying ignition by direct drive, observations were consistent with amplification of scattered light by an incident cone of multiple pump beams, but in the geometry studied [18,19] the light amplification effect could not be separated from the previously observed effect of ion wave seeding [20]. The ion waves produced by crossing laser beams may also be important because their effect on stimulated Raman scatter (SRS) has been documented [21]. Most recently, an analysis of the effect of the multiple pump beams intersecting the light backscattered from the interior of ignition targets has shown that, even when the linear gain exponent of each pump beam is $\ll 1$, the combined effect of up to 23 crossing pumps can amplify both Brillouin and Raman scatter by 10 to 100 fold if the waves remain linear [22,23] and if the individual pumps can all amplify the same light wave.

In this paper we report the demonstration that light is amplified by more than one counter-propagating pump beam in an under-dense plasma, producing total scatter that is enhanced above both the original light seed and the light scattered by a single pump and seed combination. Furthermore, this multi-pump amplification of scatter occurs with beam and plasma conditions similar to what are expected in ignition targets. In ignition experiments scattered light crosses many pump beams, each of which amplify the light by interaction with a separate plasma wave to produce a low linear gain exponent. The scattered light in this case is expected to experience a combined effect much greater than would be produced by each individual pump. This experiment uses an axisymmetric plasma with an axially directed seed beam that is crossed by two different pump beams at the same polar angle but different azimuthal angles, so that each seed-pump pair is simultaneously resonant for Brillouin scattering, but produces a different ion acoustic wave, as shown in Fig. 1(a). In this geometry the sharing of ion waves cannot produce amplification of the seed beam as has been observed in other geometries [18]. This demonstration is the basis for an emerging model of the effect of multibeam amplification of scatter on the coupling in ignition targets [22,23].

The experiments were carried out at the Omega laser facility [24] with exploding foil plasmas preheated by 28 351-nm heater beams with a total of 4.2 kJ of energy in a 1.5 ns flat-in-time pulse incident from both sides of an initially 3-μm-thick CH foil target, as also shown schematically in Fig. 1(a). The f/6.6 heater beams are unsmoothed, pointed together on the surface of the foil and focused 3.9 mm past their initial position, so that the full width at half maximum (FWHM) of the intensity profile transverse to the direction of propagation is 590 μm. The plasma conditions are simulated in two dimensions (2D) with the HYDRA code [25], which predicts the plasma density, temperature and flow conditions

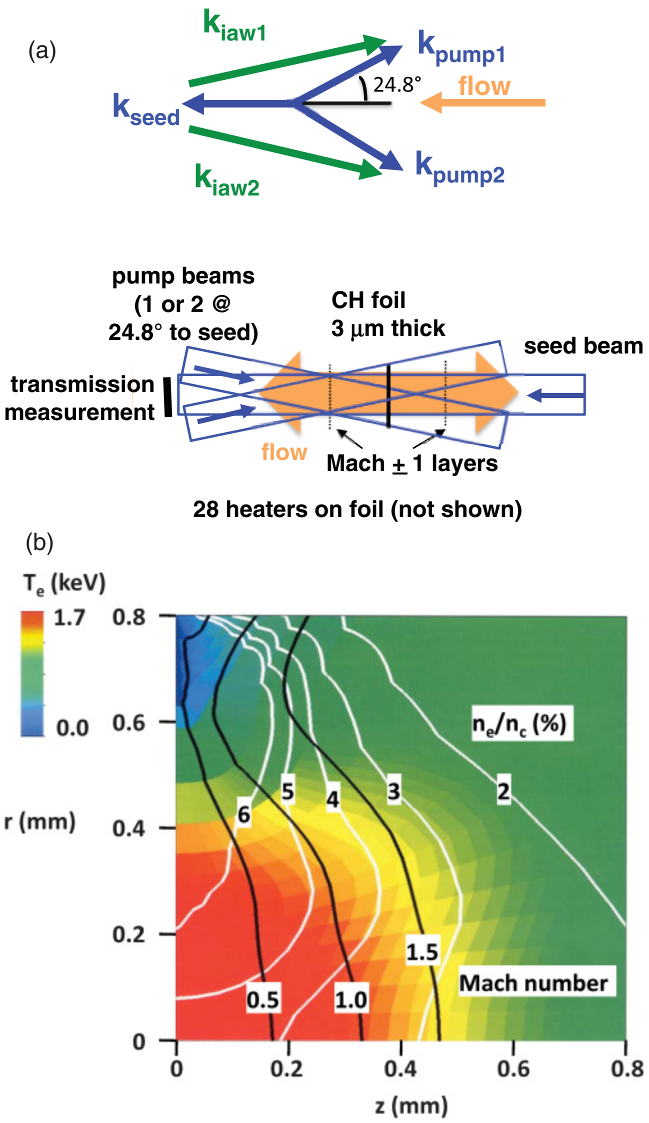

FIG. 1. (Color) (a) Geometry of experiment to allow amplification of a seed beam by up to two pump beams in resonance with ion acoustic waves in a plasma with a sonic flow. The k matching diagram shows that an axial flow near Mach 1 will allow resonance of the seed with both pumps when all electromagnetic wavenumbers are equal, and the experimental geometry shows how this is achieved with a preheated exploding foil plasma. (b) Plasma profiles from 2D simulations for the CH foil targets at 1.4 ns after the heater beams turn on, which show that the Mach +1 flow needed for resonant amplification of a beam of the same frequency as the pump is produced near the point of intersection of the pump and seed at $z = 330$ μm. Here, z is both the direction normal to the foil and the axis of the seed in Fig. 1(a).

shown for $t = 1.4$ ns in Fig. 1(b). A seed beam of 351 nm light is propagated down the axis of the foil plasma with its best focus placed beyond the foil to produce a spot diameter of 165 μm FWHM in the interaction region, with incident energies of 4.2, 16, and 48 J, also in a 1.5 ns pulse. The f/6.6 seed beam is delayed 0.5 ns with respect to the heater beams. The transmission of the seed is measured by a streaked spectrometer and a calorimeter with an acceptance cone of f/6.6. The time-resolved spectrum of the transmitted light is seen to be initially redshifted relative to the incident wavelength, with the magnitude of the redshift decreasing markedly after $t \sim 1.0$ ns, as shown in the inset to Fig. 2. The expected variation in the transmitted seed wavelength caused by the time variation of the plasma density is observed primarily when the plasma density is high at early time, with little variation in wavelength occurring after 1.0 ns where the amplification is studied. The fraction of transmitted energy was measured with the calorimeter in three different "seed only" experiments with energies ranging from 4.2 to 48 J and found to be nearly constant, at 0.645 ± 0.035 for three shots, and compares with the simulated value of 0.78. The spectrally integrated power is obtained by normalizing the streaked spectra to the fraction of transmitted energy as measured by the calorimeter on each shot. For the seed only data the transmitted power fraction waveform is averaged over the three measurements to improve its accuracy. The seed only power then determined for the 15 J incident case is shown in Fig. 2 to increase in time due to a reduction in inverse bremsstrahlung absorption as the plasma heats and expands, reaching a maximum near the end of the heater pulse.

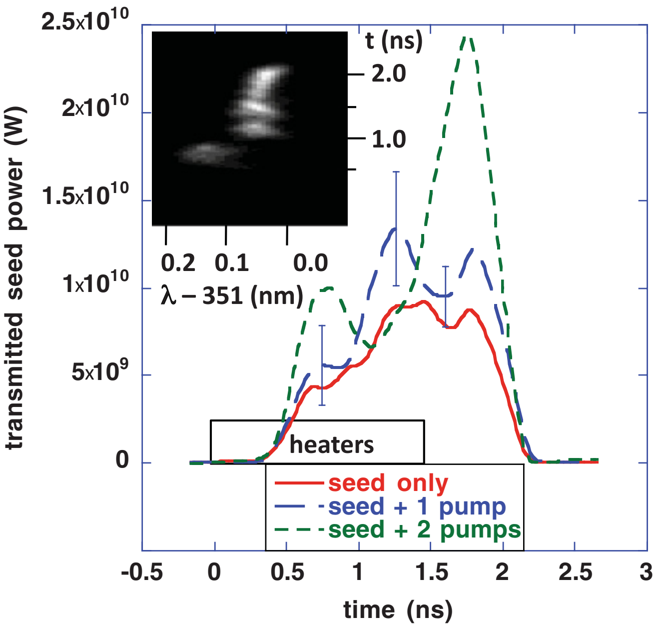

FIG. 2. (Color) Time resolved transmitted spectra for an experiment with a 15 J seed and no pumps, and the transmitted power waveforms obtained from it and from experiments with one and two pump beams, showing enhanced power for both experiments with pumps, with the transmission increasing with number of pump beams, as discussed in the text.

The seed beam transmission is observed to be resonantly amplified by both one and two crossing pump beams, each with 375 J of 351 nm light in a 1.5 ns flat pulse timed to arrive with the seed, and incident 24.8° from counter-propagation with the seed. The pumps have the same polar angle with respect to the seed but are incident at azimuthal angles that differ by 120°. The pumps are also smoothed with distributed phase plates (DPP) that produce a best focus spot of 165 μm FWHM at the point where the beams cross the seed beam axis, which is 300 μm above the initial surface of the foil. The two pumps each have their polarization aligned to within $<23°$ of the seed polarization so that the dot product of the seed and pump vectors is similar, $\gtrsim 0.92$ and 0.98 in each case. The pointing was chosen to allow a Mach +1 flow directed toward the pump to be centered in the crossing volume at 1.4 ns to produce resonant amplification. The Mach −1 layer on the opposing side can produce a similar deamplification of the seed if there is also a pump crossing it. At 1.4 ns the Mach −1 layer has moved just outside the beam-crossing volume, as shown in Fig. 1, so the integrated seed amplification across the profile is expected to be maximized [15,26]. The Mach +1 amplification is expected to be the dominant effect of the pump on the seed transmission since simulations also show minimal plasma heating by the pump so that changes in the seed absorption rate associated with the heating are unimportant. Furthermore, the additional energy that would appear in the seed transmission diagnostic due to the pump and heater beams scattering in a manner independent of any interactions with the seed was measured in an experiment in which both pump and heater beams were turned on and the seed was off. In this case the transmission detector received only $\lesssim 0.12$ J. This energy and the fraction of it that is produced by a single pump beam have negligible effect on the transmission measurements when the seed is present for all the cases studied. In the experiment with pumps and heaters, only the backscatter toward one of the pumps was measured to be 0.9 J of stimulated Brillouin scatter (SBS) and $\lesssim 9$ J of SRS (or $\lesssim 2.4\%$ of the incident pump energy collected in the 400–700 nm range). Furthermore, the scatter was similar or less in all of the experiments which had the diagnosed pump beam on. The energy detected in the pump backscatter detector was also more than an order of magnitude less in all cases when the diagnosed pump beam was off. As a result of these measurements it can be concluded that the incident pump intensities are not significantly affected by backscatter in these experiments. In addition, the transmission measurements are not significantly affected by backscatter because when the seed beam is off the SBS scatter into the pump and seed detectors is still much less than the seed energy so that any variation of this scatter is a small effect on the measured seed transmission. The effect that the pump beams that are resonant for SBS amplification have on the transmitted seed power is then determined by comparison of the transmitted seed power in an experiment with no pumps with that in experiments with one and two pumps, as shown in Fig. 2. The seed transmission, with 15 J in the incident pulse, is measured in the "one pump" case in two different and identical experiments, each using a different pump beam, and shows that both the similarity of the two pump beams and the reproducibility of the measurement produce transmitted energy fractions within 8% in these cases. The difference in the power waveforms in these two experiments is also used to determine the error bars shown in Fig. 2. The average of the transmitted powers in these two experiments increases significantly above the "no pump" case and is also shown in Fig. 2. The increase is especially clear near 1.4 ns when the effect is expected to be maximum, and where the difference between the "no pump" and average "one pump" waveforms is clearly larger than the difference in the two identical "one pump" experiments, as is indicated by the error bars on the "one pump" waveform. The variability observed in the transmitted seed power in the "one pump" case may be due to hydrodynamic variation in the plasma flow, and to the statistical realization of the speckle structure in the beams, both of which vary from shot to shot. The former would cause the resonance location to move in the interaction volume while the latter would cause different overlapped intensity profiles, producing different gain rates along ray paths. In addition, there is also evidence of amplification near the beginning and end of the seed pulse but its significance relative to the "no pump" case is less. This could be an artifact of the greater variability in the pulse shape at the beginning and end of the incident pulse. Next, both pump beams were used, each crossing the seed at the same point and with the same incident energy, pulse shape, and timing. The most important result is that the transmitted seed power in the "two pump" case has a maximum much greater than either the "one pump" or "no pump" cases, clearly demonstrating that the total induced scatter is increasing as the number of crossing pump beams is increased. In fact, the ratio of the peak power in the "two pump" case to the "no pump" power at the same time gives a peak amplification by a factor of 2.9 with two pumps, whereas the same comparison for the "one pump" case shows a peak amplification factor of 1.6. For comparison, the gain exponent calculated from integrating along the axis of the simulated 2D profiles is 0.87 for a single pump with a uniform intensity profile propagating in a straight line though the plasma. The reduction by a factor of 0.6 of the exponent in the experiment is likely due to the three-dimensional (3D) nature of the resonance layer and beam crossing volume as well as possible nonlinear wave saturation mechanisms. It is also noteworthy that, in this case, the effect on the amplification of adding a second crossing pump beam at an angle to drive a different ion wave is very similar to what would be expected if the energy of the second pump was added to the first pump and a single ion wave was driven, consistent with expectations from linear models. The position of the maximum in the "two pump" case is delayed relative to the "one pump" case. This might be due to small variations in the flow profile in the interaction volume, and the location of the resonance associated with it. It may also possibly be due to nonlinear frequency shifts in the ion wave resonance when both waves are present.

The dependence of the observed amplification on the number of pump beams and on the intensity of the seed beam was studied in a series of experiments with zero, one, and two pump beams. We show consistency between these experiments by integrating over the pulse shown in Fig. 2 and considering the time integrated energy and energy amplification factor, as shown in Figs. 3 and 4. Figure 3 shows that the transmitted energy is enhanced in all cases with pump beams present relative to the case with no pump beam, and the enhancement exhibits a weak dependence on seed energy as is expected for a linear response of the ion acoustic waves to the ponderomotive force. In addition we observed the energy amplification factor to scale close to exponentially with the number of pump beams, as also expected for a linear wave response and shown as a line in Fig. 4. That the lowest seed energy measurement of the energy amplification factor with two pumps appears to be low and just outside the error bars of the others may not be statistically significant in such a large group of data points, but it could also represent a weaker ion wave response at low drive in these conditions. These data demonstrate that both

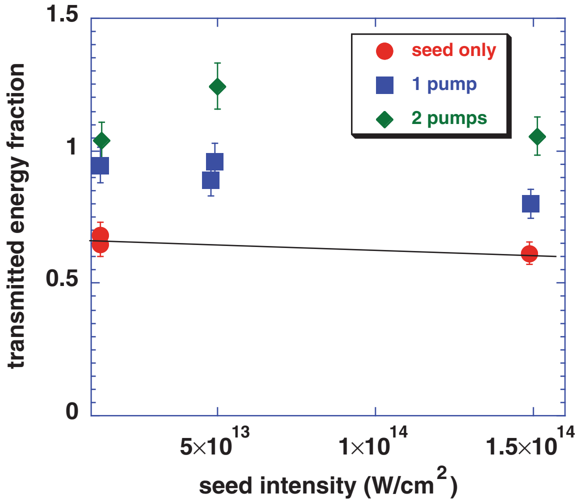

FIG. 3. (Color) Plots of transmitted energy obtained in experiments with 1 and 2 pump beams and in "seed only" experiments, similar to Fig. 2 but with seed energy varying from 4.2 to 47 J, showing that the energy amplification factor is weakly dependent on seed energy.

scattered power and energy increase as the number of resonant crossing pump beams is increased, consistent with the model of stimulated scattering from multiple laser beams that we are now employing for ignition target designs [22,23].

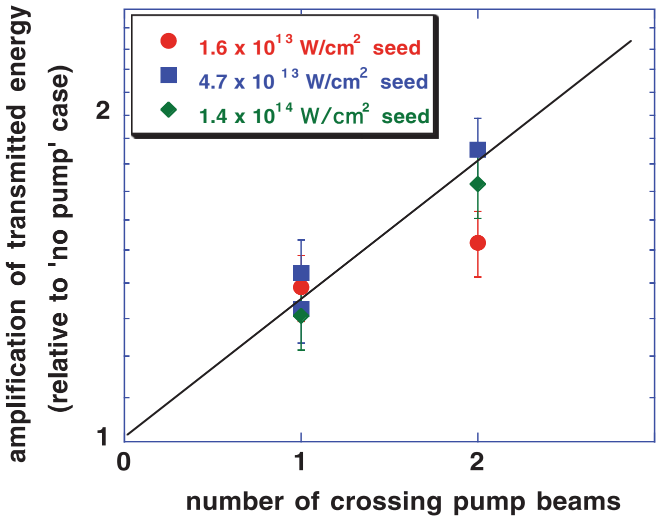

FIG. 4. (Color) Plot of energy amplification factor or transmitted energy normalized to that with no pump beams vs the number of pump beams, showing an increase withthe number of pumps in all cases.

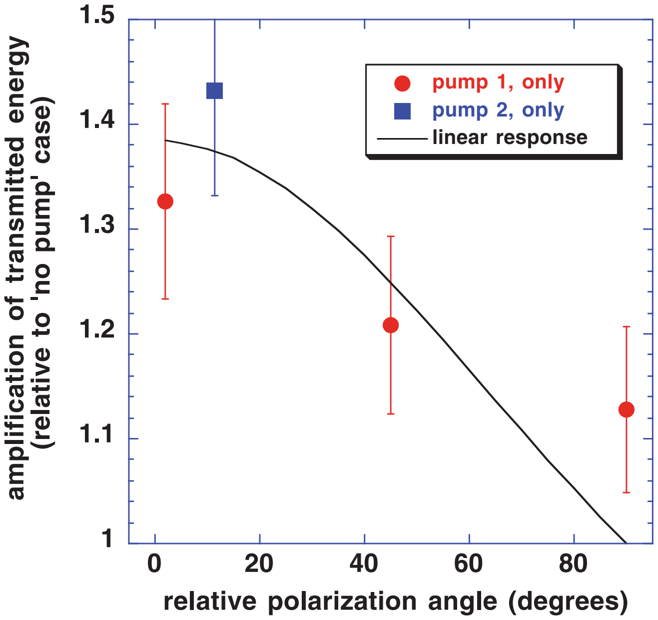

FIG. 5. (Color) Plot of the energy amplification factor from experiments where the pump polarization is rotated relative to the 15 J seed, showing that the amplification factor is primarily determined by the component of the pump field aligned to the seed field, and that each of the pumps produce similar factors when best aligned to the seed.

A separate set of experiments demonstrated the dependence of the "one pump" amplification factor on the relative polarization of the pump and seed. This confirms that the observed energy amplification factor was due to a coherent interaction of the pump and seed and not due to the hydrodynamic modification of the plasma by the pump beam. For these experiments, a half-wave plate in the path of one of the incident pump beams was rotated to produce both a 45° and a 90° angle between pump and seed fields for comparison with the 0° case. With 15 J of incident seed energy, the energy amplification factor relative to the "no pump" case was seen to decrease as the angle between the pump and seed fields was increased to 90°. This follows expectations for a linear wave responding to the ponderomotive force produced by the dot product of the two fields, as shown in Fig. 5. The fact that the amplification factor decreases to close to unity when the polarizations are orthogonal is consistent with the effect being primarily due to the stimulated growth of ion waves rather than plasma heating by the pump. The dependence on the polarization direction of the pump beam cannot be explained by the pumps' individual level of backscatter having a dependence on direction due to its polarization since the total 0.9 J of scatter into the incident beam cone of the pump is small compared to the increased seed energy observed in Fig. 5. In addition, the dependence of the seed transmission outside of the cone of the incident seed was measured with a near backscatter image [27] which showed that the transmitted light intensity dropped rapidly as the angle away from the incident cone increased by a few degrees, indicating the light collected within the cone does not have a significant contribution from scatter from other beams over a broad range of angles. Moreover, a similar rapid decrease of the light with angle outside the cone of the seed was also observed in the shot with the pump off, confirming that there is little angular spray of the seed produced by the effect of the pump on the plasma, and suggesting that filamentation of the pump beam does not affect the measured seed transmission significantly. This demonstrates that ion wave energy transfer between beams can be controlled with beam polarization.

In conclusion, we have demonstrated that the amplification of light propagating in a plasma with multiple crossing pump beams driving ion acoustic waves is a cumulative process, with each pump beam causing additional scattering. In the case studied, the observations are consistent with a linear wave response leading to the approximate addition of the gain exponents of each of the pump beams. That these effects occur under conditions similar to what is expected in ignition experiments confirms models of stimulated scattering from multiple crossing beams.

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