Cross-Beam Energy Transfer Saturation by Ion Heating

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Cross-beam energy transfer (CBET) saturation by ion heating was measured in a gas-jet plasma characterized using Thomson scattering. A wavelength-tunable UV probe laser beam interacted with four intense UV pump beams to drive large-amplitude ion-acoustic waves. For the highest-intensity interactions, the power transferred to the probe laser dropped, demonstrating ion-acoustic–wave saturation. Over this time, the ion temperature was measured to increase by a factor of 7 during the 500-ps interaction. Particle-in-cell simulations show ion trapping and subsequent ion heating consistent with measurements. Linear kinetic CBET models were found to agree well with the observed energy transfer when the measured plasma conditions were used.

In laser-driven inertial confinement fusion (ICF), high-intensity lasers are used to drive capsules that reach pressure and temperature conditions required for nuclear fusion.[1] This requires multiple overlapping laser beams to propagate through plasmas surrounding the fusion capsule. The plasma mediates energy transfer between the laser beams, which can disrupt the energy coupling and/or cause irradiation nonuniformity.[2,3] To account for this CBET, linear models have been implemented in the hydrodynamic codes used to simulate ICF experiments.[4,5] The ability to predict this transfer of energy is critical to the success of all laser-driven ICF concepts.

The experiment was performed on the OMEGA laser–plasma interaction platform. Figure 1 illustrates the experimental configuration that consisted of a gas-jet system that produced a gas plume, which was heated by nine 500-ps-long UV beams. The target gas was a mixture of 45% nitrogen and 55% hydrogen to approximately reproduce the ion-acoustic wave damping from typical ICF experiments. The probe beam used the tunable OMEGA port 9 (TOP9) laser, which was wavelength tunable over ~3 nm around the pump beams' wavelength of 351.11 nm. The resonant wavelength of the probe beam (351.40 nm) was used for all experiments and was determined by maximizing the energy transfer while scanning its wavelength. The four CBET pump beams used half-wave plates to align their linear polarizations to the probe beam's polarization and had single-beam averaged intensities of $\sim 7 \times 10^{14}$ W/cm^2. The power in the probe beam was measured before and after the CBET interaction using the transmitted beam diagnostic (TBD). The time-resolved plasma conditions were measured using the streaked Thomson-scattering system.

Shots were performed for a range of incident probe-beam intensities, and time-resolved measurements of the plasma conditions and outgoing probe intensity were made. Figure 2 shows the amplification of the probe beam due to CBET at four initial probe intensities. Although the ion-acoustic wave (IAW) amplitudes are expected to increase with increasing probe intensity, linear CBET theory predicts a constant P/P_0 (pump depletion was negligible in the experiment by design). The fact that the power ratio P/P_0 decreases with increasing probe intensity with minimal pump depletion suggests nonlinear saturation. Furthermore, every probe-beam intensity greater than 0.1×10^{14} W/cm^2 exhibits a strong time-dependent reduction in amplification. For the three highest initial probe-beam intensities, the amplification started high (~1000 ps) but decreased over time before plateauing toward the end of the pump pulse (~1300 ps).

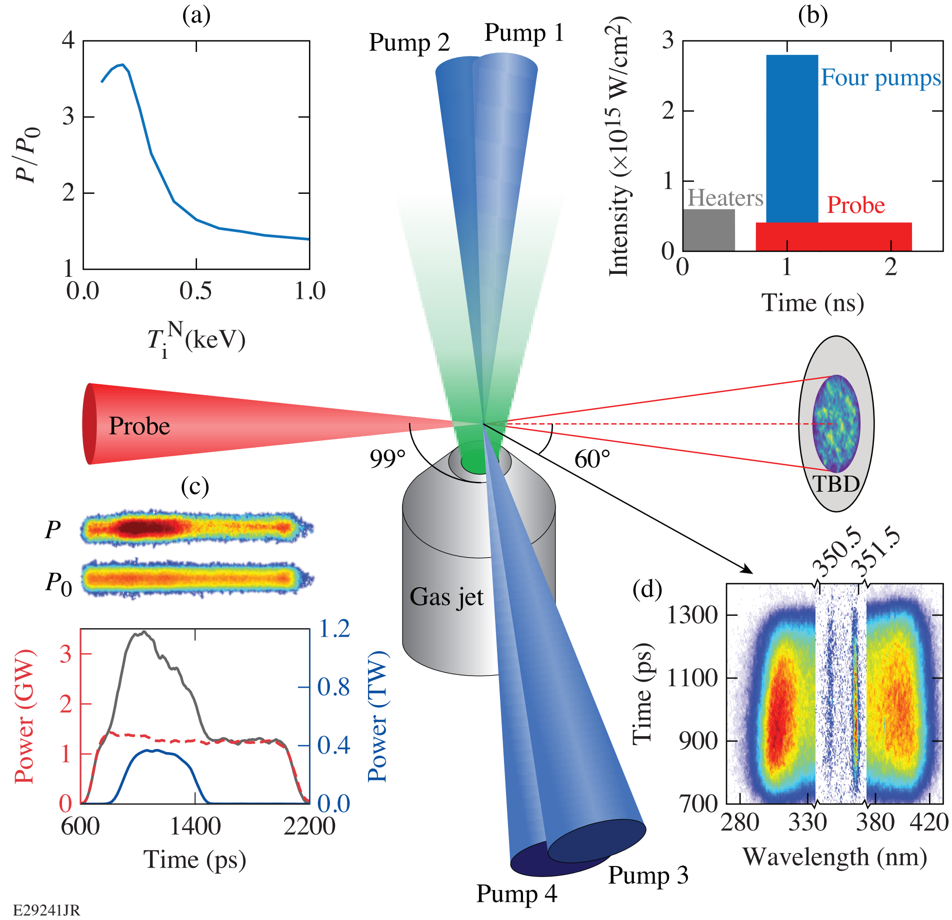

Figure 1
(a) The ratio of the output power (P) to the incident power (P_0) of the probe beam was calculated using a linear kinetic CBET model for the conditions of these experiments over a range of nitrogen ion temperatures. (b) The laser intensity, pulse shapes, and beam timings for each of the beam groups. (c) TBD data showing the input- (dashed red curve) and output- (solid black curve) probe and pump (solid blue curve) powers. (d) Time-resolved Thomson-scattering data showing the electron plasma wave and ion-acoustic wave spectra of a pump beam with minimal ion heating.

The plasma conditions measured using Thomson scattering revealed ion heating due to CBET in the high-intensity probe-beam shots ($I_0 > 0.1 \times 10^{14}$ W/cm^2). Kinetic linear theory predictions of CBET were in excellent agreement with the measured energy transfer when these increased ion temperatures were considered. As the ions were heated, the IAW dispersion evolved along a new branch with increased frequency at the wave number determined by the beam crossing angle. Because the driving frequency was fixed, the driven IAW was no longer at a resonant frequency, which increased the wave damping and saturated CBET.

Simulations of the high-intensity CBET interaction using the code VPIC were performed and found to qualitatively reproduce the measured energy transfer and ion heating. These simulations showed that at high probe-beam intensities, the large driven IAW's trapped and accelerated ions to the wave's phase velocity. The trapped ions were then detrapped through ion–ion collisions on short time scales (~10 ps), which resulted in bulk ion heating on ~100-ps time scales.

Although significant nonlinear CBET physics is occurring at the high probe-beam intensities, it is interesting that the linear CBET theory reproduces the measured results when accounting for the instantaneous plasma conditions. The plasma conditions are affected by CBET, however, suggesting that feedback from laser–plasma instabilities on hydrodynamics must be accounted for in modeling to accurately predict the energy transfer.[5]

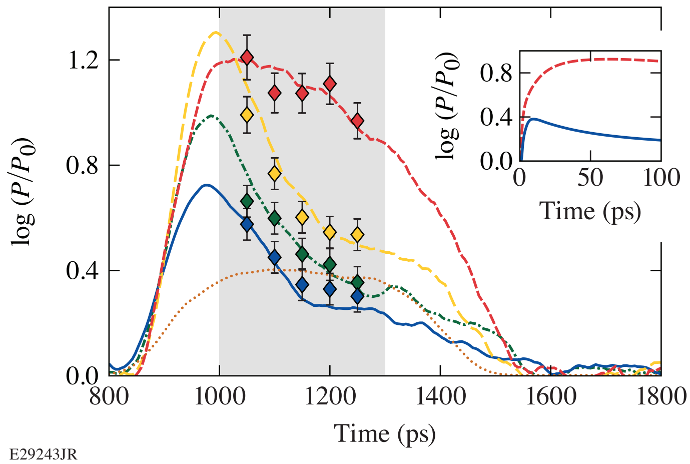

Figure 2
The power transferred into the probe beam for four different initial probe-beam intensities [0.1×10^{14} W/cm^2 (dashed red curve), 0.9×10^{14} W/cm^2 (dashed yellow curve), 2.0×10^{14} W/cm^2 (dashed–dotted green curve), 4.1×10^{14} W/cm^2 (solid blue curve)], and the corresponding calculated power transfer using linear kinetic theory for the measured plasma conditions (diamonds). The pulse shape of the pump beams is overlayed for reference (dotted orange curve). The inset shows VPIC simulated probe beam amplification corresponding to the lowest (dashed red curve) and highest (solid blue curve) experiment probe intensities.

This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003856, the University of Rochester, and the New York State Energy Research and Development Authority.

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