Nonlinear Laser–Plasma Coupling Caused by Two-Plasmon Decay and Cross-Beam Energy Transfer

A. V. MAXIMOV, D. TURNBULL, D. H. EDGELL, R. K. FOLLETT, H. WEN, J. P. PALASTRO and D. H. FROULA

University of Rochester, Laboratory for Laser Energetics

Abstract

- In the plasmas of the direct-drive approach to inertial confinement fusion (ICF), there are two main laser–plasma instabilities (LPI's) that strongly affect the coupling of laser light power to the plasma corona: two-plasmon decay (TPD) that is localized in the plasma region near the quarter-critical density for the laser light, and cross-beam energy transfer (CBET) that favors the plasma region where the plasma flow is close to Mach-1 magnitude*
- In the ICF implosions on the OMEGA Laser System, both TPD and CBET are driven by a large number of overlapping laser beams, and the regions close to the quarter-critical density and close to Mach-1 flow can overlap
- We analyze the interplay between TPD and CBET in the plasma region near the quarter-critical density for conditions relevant to direct-drive implosions on OMEGA. Three-dimensional simulations of nonlinear laser–plasma interactions driven by the realistic intensity profiles of OMEGA laser beams have been performed using the laser-plasma simulation environment (*LPSE*)**

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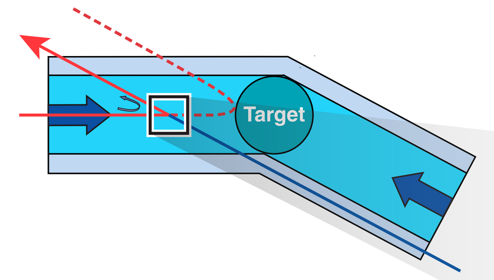
*J. F. Myatt *et al*., Phys. Plasmas 21, 055501 (2014).
**D. Turnbull *et al*., Phys. Rev. Lett. 124, 185001 (2020).

TC16144

CBET is the redistribution of laser power between different laser beams due to scattering via ion-acoustic waves



CBET gain

$$\frac{\partial G}{\partial l} = \frac{\omega_0^2}{2c^2 n_c} \mathrm{Re}\left\{ \frac{n_e k_s^2 c_s^2 I_0}{2\nu_i \omega_s + i\left[(\omega_s - k_s U_0)^2 - k_s^2 c_s^2\right]} \frac{1}{2k_0} \right\}$$

$$I_0 \frac{|E|^2}{4\pi n_c T_e}$$

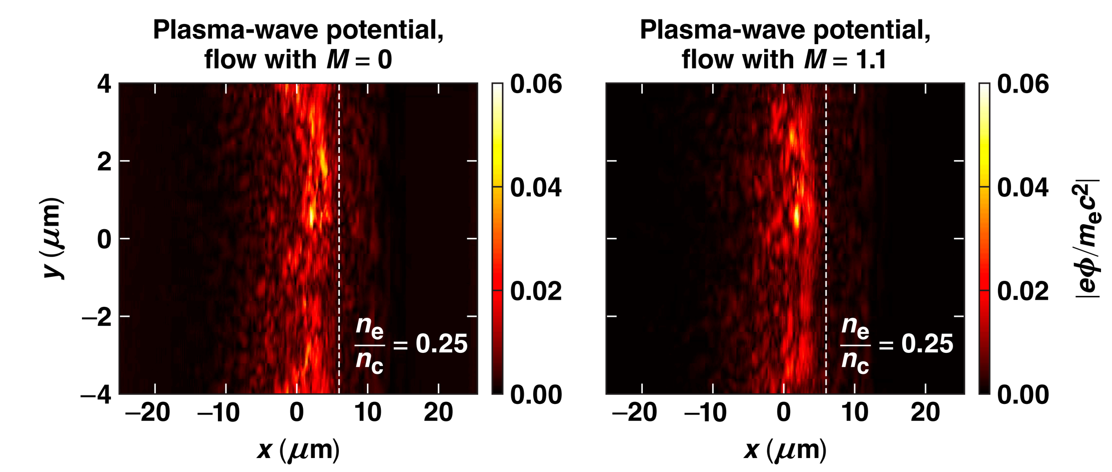
- CBET* reduces the energy of center-beam light and increases the energy of outgoing edge-beam light
- Most favorable conditions for CBET are in the region where the flow velocity is near $M = 1$

CBET is strongest near the Mach-1 flow region

*I. V. Igumenshchev *et al*., Phys. Plasmas 19, 056314 (2012).

TC13941a

In *LPSE* simulations with changing flow velocity, the intensity of plasma waves depends on the flow value



$I_{av} = 4.8 \times 10^{14}$ W/cm² $\eta = 1.4$

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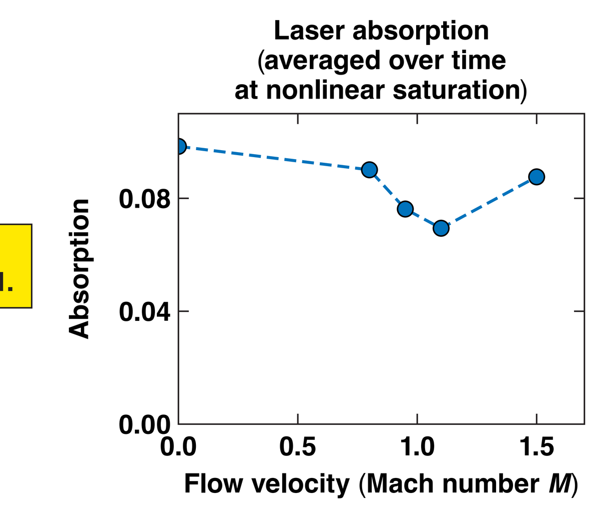
In *LPSE* simulations with changing flow velocity, the largest reduction of nonlinear TPD is found in the case of flow velocity close to Mach 1

CBET is strongest at flow velocity close to Mach 1.



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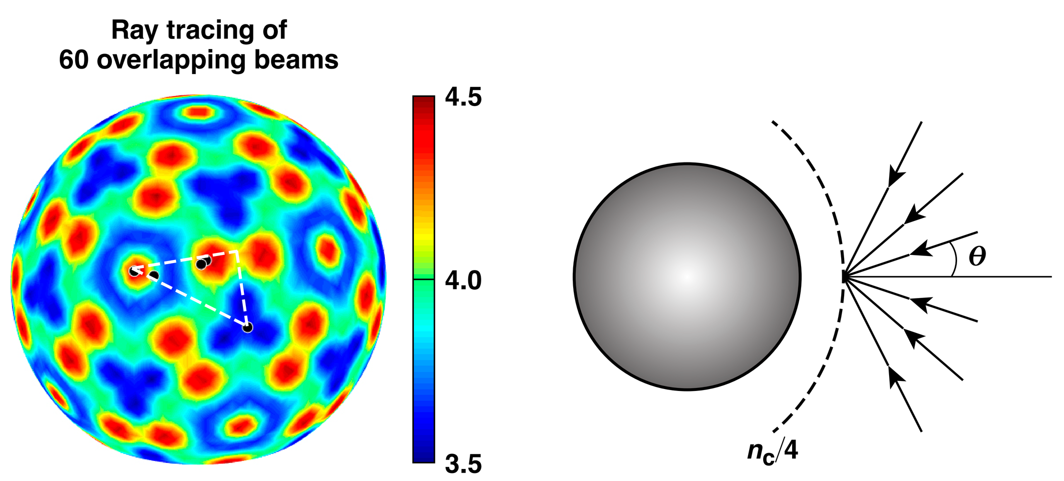
The modeling of LPI has been performed for a particular region of OMEGA plasmas, where the laser-intensity profile is determined by the overlap of multiple laser beams



$I_{av} = 4 \times 10^{14}$ W/cm²

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LPSE can model nonlinear LPI including TPD and CBET

- The model describes the evolution of laser light (enveloped near frequency ω_0), plasma-wave field (near ω_p), and ion-acoustic perturbation δN

Laser light

$$i\frac{\partial V_0}{\partial t} + i\gamma_0 \circ V_0 + \frac{c^2}{2\omega_0}\nabla^2 V_0 + \frac{\omega_0^2 - \omega_p^2(1 + N_0 + \delta N)}{2\omega_0} V_0 = \frac{i\omega_p}{4\omega_0}\left[(\nabla \cdot V_p)V_p\right]_T \cdot e^{-i\delta\omega t}$$

Plasma wave

$$i\frac{\partial V_p}{\partial t} + i\gamma_p \circ V_p + \frac{3V_{Te}^2 c^2}{2\omega_1}\nabla^2 V_p + \frac{\omega_p(1 + N_0 + \delta N)}{2} v_p = \frac{1}{\omega_p}\left[\nabla(v_p^* \cdot v_0) - (\nabla \cdot V_p^*)V_0\right] \cdot e^{i\delta\omega t}$$

Ion acoustic

$$\frac{\partial^2 \delta N}{\partial \tau^2} + 2\gamma_{ia} \times \frac{\partial \delta N}{\partial \tau} - \frac{c^2}{2\omega_0} c_s^2 \nabla^2 \delta N = \frac{1}{16\pi n_0 m_i}\nabla^2\left[|E_p|^2 + \frac{n_0}{n_c}|E_0|^2\right]$$

where $V_j = \frac{ieE_j}{m_e \omega_j}(j = 0, p)$, $\frac{\partial}{\partial \tau} = \frac{\partial}{\partial t} + U_0 \times \nabla$,

U_0: flow; N_0: background density profile; $\delta\omega = \omega_0 - 2\omega_p$: frequency mismatch

It is possible to study the relative importance of different wave-coupling processes.

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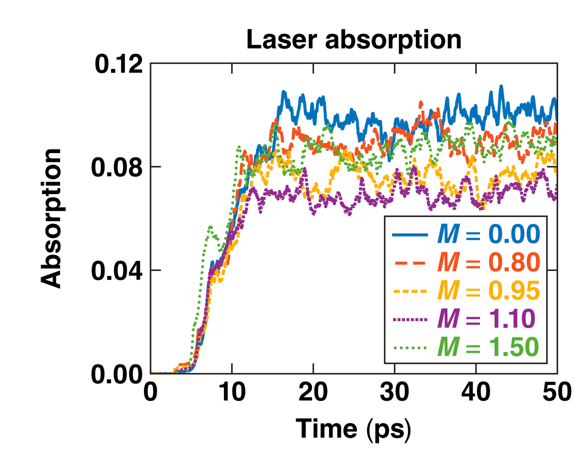
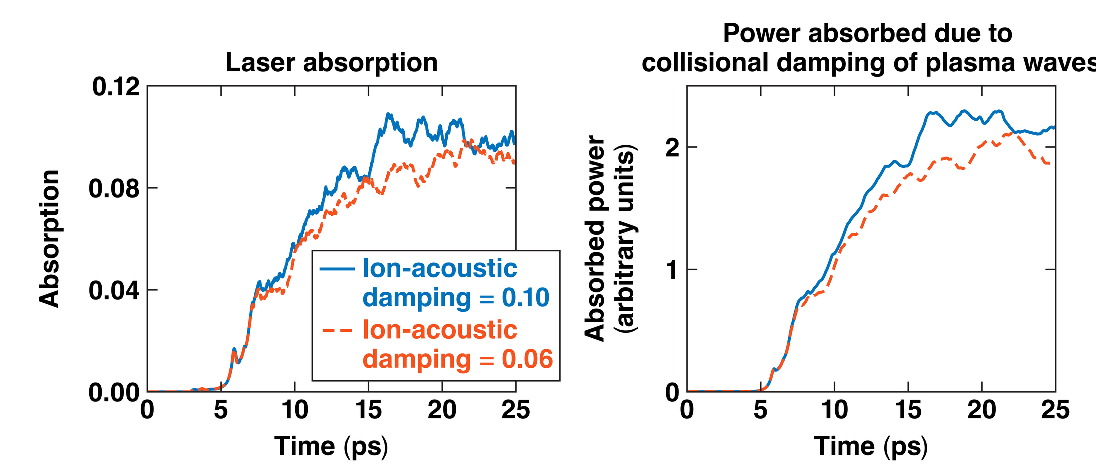
In *LPSE* simulations with changing flow velocity, the nonlinear stage of TPD depends on the flow value

Absorption of laser light due to nonlinear TPD is an important effect for laser–plasma coupling.



TC16148

In *LPSE* simulations with changing ion-acoustic damping, nonlinear stage of TPD depends moderately on the ion-acoustic damping



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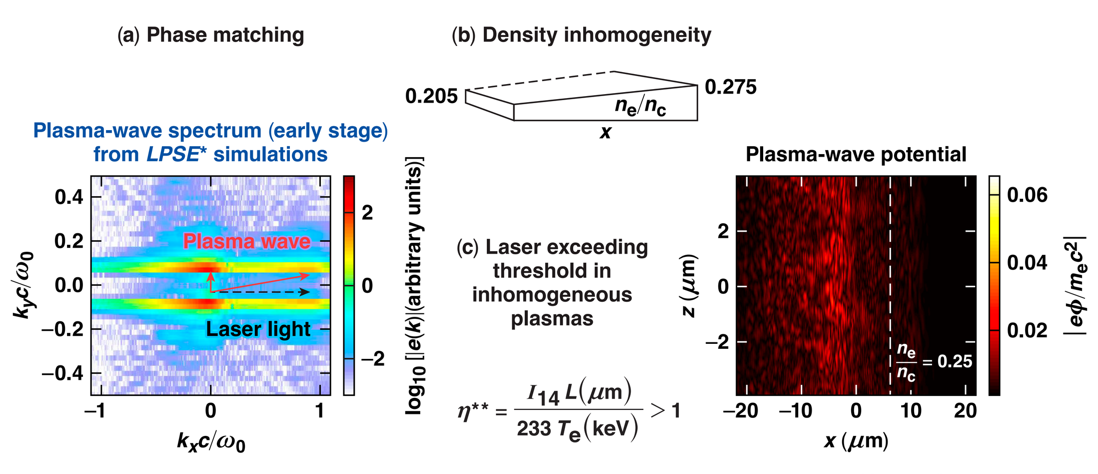
TPD is the decay of incident laser light into two plasma waves near the quarter-critical surface, leading to the formation of the region of incoherent plasma waves

The absolute TPD instability requires:



$$\eta^{**} = \frac{I_{14} L(\mu m)}{233\, T_e(\mathrm{keV})} > 1$$

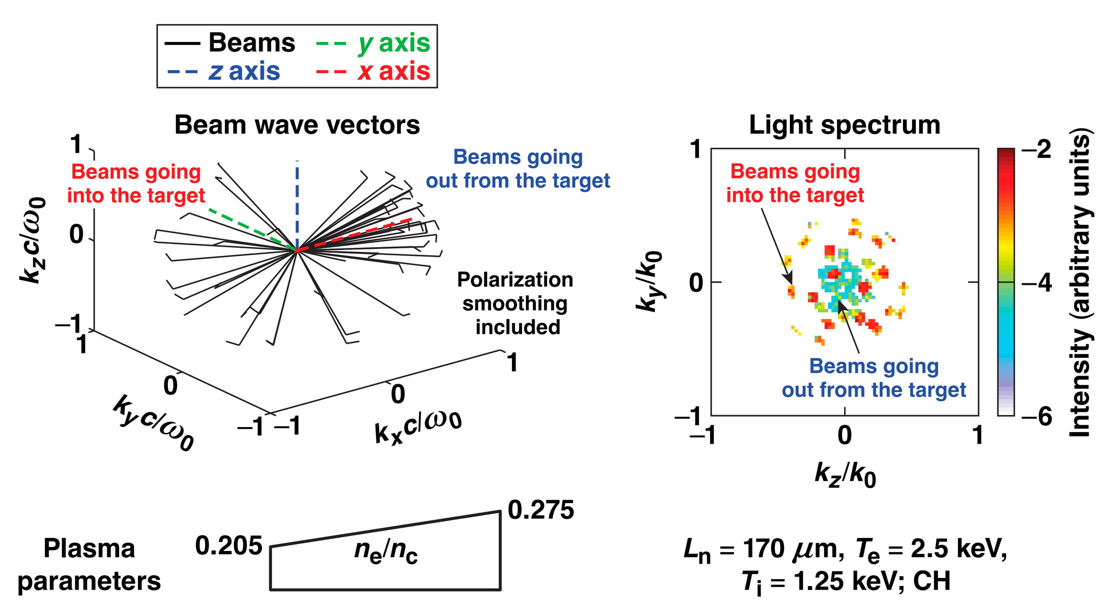
$I = 5 \times 10^{14}$ W/cm²

In ICF experiments on OMEGA, the threshold for instability is well exceeded.

*J. F. Myatt *et al*., Phys. Plasmas 24, 056308 (2017). **A. Simon *et al*., Phys. Fluids 26, 3107 (1983).

TC15937a

All OMEGA laser beams are included in the laser-intensity profile in a particular region near quarter-critical density

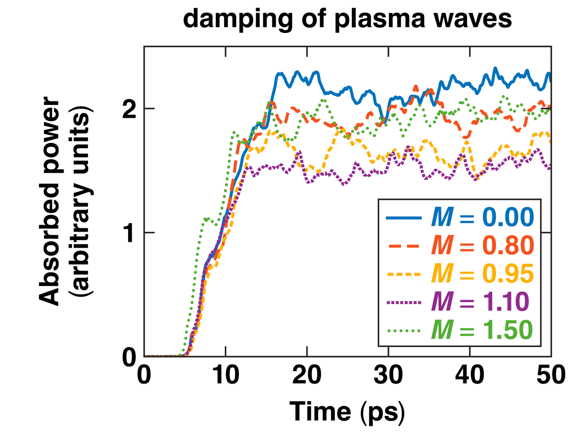


$L_n = 170\ \mu m$, $T_e = 2.5$ keV, $T_i = 1.25$ keV; CH

TC16146

In *LPSE* simulations with changing flow velocity, the coupling of laser power to plasma depends on the flow value

Collisional absorption of plasma waves is the main mechanism coupling the laser power to plasma near the quarter-critical density.



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Conclusions

In the plasmas of direct-drive ICF, the reduction of TPD instability due to plasma flow is observed

- In direct-drive ICF plasmas, two LPI processes (CBET and TPD) have the largest influence on the coupling of laser power to plasmas, and these two processes coexist in the plasma region near the quarter-critical density
- Three-dimensional modeling with the *LPSE* platform has confirmed that plasma flow can limit the growth of TPD and increase CBET for the conditions relevant to the experiments on the OMEGA Laser System at the Laboratory for Laser Energetics
- The intensity of plasma waves in TPD can be reduced by up to one third if the plasma flow is close to the Mach-1 value near the quarter-critical density

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