Nonlinear Transmission of Laser Light Through Coronal Plasma due to Self-Induced Incoherence

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The success of direct laser-driven inertial confinement fusion (ICF) relies critically on the efficient coupling of laser light to plasma. At ignition scale, the absolute stimulated Raman scattering (SRS) instability can severely inhibit this coupling by redirecting and strongly depleting laser light. This summary describes a new dynamic saturation regime of the absolute SRS instability. The saturation occurs when spatiotemporal fluctuations in the ion-acoustic density detune the instability resonance. The dynamic saturation mitigates the strong depletion of laser light and enhances its transmission through the instability region, explaining the coupling of laser light to ICF targets at higher plasma densities.

While still in the research stage, controlled fusion could deliver an almost endless supply of power with relatively low environmental impact and a nearly inexhaustible reserve of fuel. As evidenced by active research programs throughout the world, the realization of such a technology would have lasting impact both geopolitically and for the health of our planet. In the direct-drive ICF approach, an ensemble of laser beams symmetrically illuminates a cryogenic target containing thermonuclear fuel.[1] The illumination ionizes and heats the outer shell of the target, creating a pressure that drives inward fuel compression and outward mass ejection. The mass ejection creates a region of low-density plasma, or corona, that plays a critical role in direct-drive ICF: coupling of laser light to the corona determines the strength of the ablation pressure and, ultimately, the implosion performance.[1]

Achieving efficient coupling of laser energy to the fusion target is arguably the most essential component of direct-drive ICF. A high ablation pressure requires the transmission of laser light to deep within the corona, where collisions can efficiently convert electromagnetic energy to plasma thermal energy. To get there, however, the laser light must propagate through the outer corona, where it can drive a number of parametric instabilities. In their nonlinear stage, these instabilities can redirect the incident light into unwanted directions and repartition the light energy into plasma waves. These waves can subsequently undergo local collisional damping, in which case the energy is deposited too far from the ablation surface, or collisionless damping, which creates nonthermal electrons that can preheat the fuel and reduce its compressibility.[1] In either case, the premature depletion of laser energy in this region presents a significant challenge for direct-drive ICF.

Within the U.S., the primary direct-drive program has been centered around LLE's OMEGA laser. Compared to the National Ignition Facility (NIF), the high repetition rate of OMEGA serves as an ideal platform for studying the underlying physics of direct drive. However, due to its limited laser pulse energy (30 kJ), the OMEGA laser cannot create the conditions required for a burning fusion plasma. As a result, the focus has turned to direct-drive implosions on the NIF. With its larger laser energy (>1 MJ), the NIF can drive larger capsules, which changes the characteristics of the plasma, e.g., the corona has a longer scale length and higher electron temperature. As a result, absolute SRS becomes the dominate instability[2] in contrast to OMEGA experiments in which two-plasmon decay (TPD) dominates.

In SRS, an incident laser light wave decays into a scattered Raman light wave and an electron plasma wave. In a region near the quarter-critical plasma density n_c, determined by the frequency of the laser, the SRS decay waves can grow exponentially in time as an absolute instability until they nonlinearly saturate. Recent planar-target experiments on the NIF that emulated the plasma corona of an ignition-scale direct-drive implosion showed a clear SRS feature originating from close to the quarter-critical density and no clear evidence of TPD.[2] The observations confirmed theoretical estimates that, because of the large density scale lengths in the plasma corona (of the order of few hundred microns), the threshold for absolute SRS would be exceeded. Those same estimates also suggest that the instability would strongly deplete the laser light, preventing significant transmission deep into the corona. The hydrodynamic evolution of the target was consistent, however, with the efficient conversion of laser energy into plasma thermal energy.[2] As a result, a critical question emerges: How can the laser light propagate through the absolute instability region with a high transmission rate?

The discovery of a dynamic saturation regime of the absolute SRS instability due to self-induced incoherence answers this question. As the incident light propagates through the instability region, it drives a primary SRS decay that initially depletes the laser intensity. The electron plasma waves resulting from the SRS decay then undergo a secondary instability that drives a broad spectrum of low-frequency density perturbations. The instability saturates when the density perturbations reach a high enough level to detune the primary SRS resonance, establishing a dynamic balance between the transmitted and scattered laser light. This dynamic, incoherent saturation mitigates depletion and facilitates the transmission of the laser light through the instability region, explaining how light can penetrate deep into the corona to efficiently drive ICF implosions.

To investigate the saturation of absolute SRS in the regime relevant to direct-drive implosions at the NIF scale, the laser-plasma simulation environment (*LPSE*)[3] was employed. *LPSE* applies a fluid plasma model to describe the evolution of the four waves (light, Raman, electron plasma, and ion acoustic) and the couplings between them. The simulations were performed in two spatial dimensions with *s*-polarized light. The laser light was normally incident on a plasma with linear gradient $n = n_\mathrm{c}\left(1 + x/L\right)/4$, where L is the density scale length at the quarter-critical density. The plasma parameters are as follows: laser wavelength = 0.351 μm; density scale length = 500 μm; electron temperature = 4 keV; ion temperature = 4 keV; ion charge $Z = 3.5$; ion atomic number = $2Z$; and density range from 0.21 to 0.265 n_c. At these conditions, the threshold for TPD is more than 3× higher than the threshold for absolute SRS.

Figure 1 illustrates the nonlinear saturation of absolute SRS for laser light with an incident intensity of 2×10^{14} W/cm^2 (approximately 3× greater than the theoretical instability threshold at these parameters, 6×10^{13} W/cm^2). Early in time, the laser light propagates through the plasma without scattering but undergoes a small amount of collisional absorption, about 2%; shortly thereafter, the absolute instability develops. By 5.4 ps, the instability has strongly depleted the pump [Fig. 1(a)], and the Raman light [Fig. 1(c)] has grown to an amplitude comparable to the laser light. This pump depletion stage quickly gives way, 3 ps later, to a dynamic saturation stage in which the amplitudes of both the laser and Raman light become nonstationary and spatially incoherent [Figs. 1(b) and 1(d), respectively].

Figure 2 displays the scaling of the transmission, in both the pump depletion (red circles) and dynamic saturation (blue circles) stages, as a function of laser intensity. At intensities below the absolute SRS threshold (6×10^{13} W/cm^2), the transmission is reduced by about 2% due to inverse bremsstrahlung absorption. Above the threshold, the dynamic saturation increases the transmission well above the levels determined by pump depletion alone.

The enhanced transmission explains why the temperature inferred in ignition-scale experiments agrees with radiation-hydrodynamic simulations that do not include a model for absolute SRS.[2] For example, if the intensity reaching the absorption surface was reduced by a factor of 2 due to pump depletion, radiation-hydrodynamic simulations would predict a 30% lower electron temperature.

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.

1. R. S. Craxton *et al*., Phys. Plasmas **22**, 110501 (2015).
2. M. J. Rosenberg *et al*., Phys. Rev. Lett. **120**, 055001 (2018).
3. J. F. Myatt *et al*., Phys. Plasmas **24**, 056308 (2017).

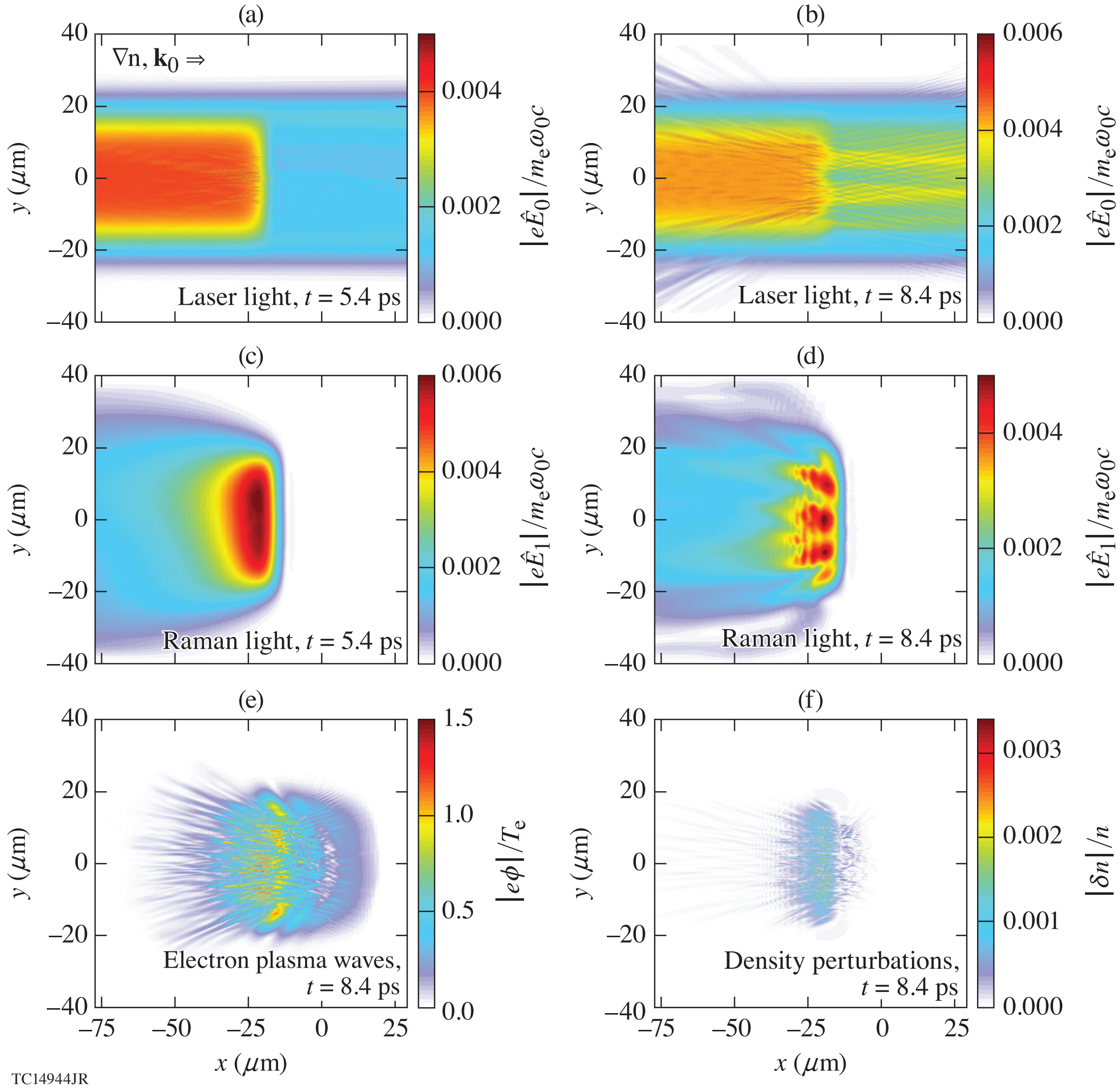

Figure 1
The amplitudes of laser and Raman light waves [(a) and (c), respectively] at 5.4 ps and [(b) and (d), respectively] 8.4 ps. (e) The amplitudes of plasma waves (in terms of wave potential energy normalized to temperature) and (f) low-frequency density perturbations at 8.4 ps.

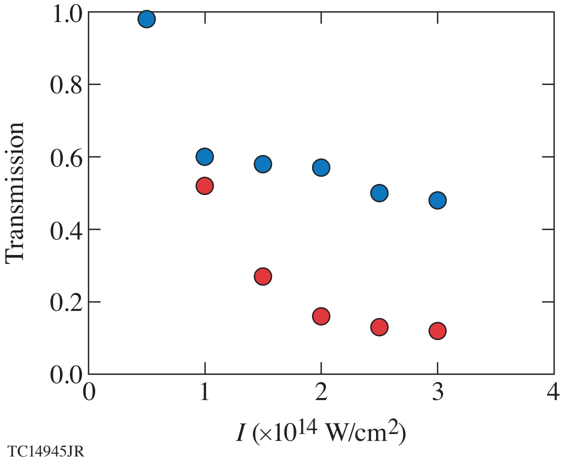

Figure 2
The scaling of light transmission at the end of the pump depletion stage (red circles) and during the dynamic saturation stage (blue circles) as a function of the incident laser intensity.