# Anomalous Absorption by the Two-Plasmon–Decay Instability

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Radiation-hydrodynamic simulations of directly driven fusion experiments at the Omega Laser Facility accurately predict absorption when targets are driven at low overlapped laser intensity. Discrepancies appear at increased intensity, however, with higher-than-expected laser absorption on target. Strong correlations with signatures of the two-plasmon–decay (TPD) instability—including half-harmonic and hard x-ray emission—indicate that TPD is responsible for this anomalous absorption. Scattered-light data suggest that up to ~30% of the laser power reaching quarter-critical density can be absorbed locally when the TPD threshold is exceeded. A scaling of absorption versus TPD threshold parameter was empirically determined and validated using the laser-plasma simulation environment (*LPSE*) code.

The coupling of the laser to directly driven inertial confinement fusion targets is arguably the most fundamental ingredient of such implosions, necessitating accurate models that capture all of the primary laser-absorption processes. In radiation-hydrodynamic simulations (i.e., using the *LILAC* code), the recent transition from a flux-limited thermal transport model to a more-physical nonlocal model revealed significant errors in predicted laser absorption, with more light scattered from the target than expected. This led to the realization that resonant amplification of unabsorbed light leaving the target (i.e., cross-beam energy transfer, or CBET) significantly degrades the laser coupling. Simulation fidelity was improved by the addition of an in-line model describing the instability. This model, however, ostensibly overcompensates—increasing scattered light and reducing shell velocity beyond the level suggested by measurements.

One of the critically important laser–plasma instabilities in OMEGA-scale direct-drive implosions is the TPD instability,[1] in which an incident photon decays into two electron plasma waves near the quarter-critical density surface $n_c/4$. Here, we show that the discrepancy between predicted and observed scattered light is a signature of anomalous absorption of laser light due to the excitation of TPD. Over a wide range of laser intensities spanning the typical design space of implosions on OMEGA, the time-dependent absorption difference is shown to be strongly correlated with the time history of TPD activity, which was diagnosed using half-harmonic emission. The data suggest that ~15% to 20% of the laser light reaching $n_c/4$ is typically absorbed when TPD is active, which significantly modifies the coronal plasma energetics of implosions on OMEGA.

The basic mechanism is as follows: The incident lasers transfer energy to the coronal plasma through electron–ion collisions. Between approximately 10% and 50% of the critical density, the incident light is also coupled to the outgoing light by CBET. When the ingoing rays reach their turning point, the photons that have not yet been absorbed get reflected. Upon re-entering the CBET-active region, this outgoing light becomes the seed that is amplified by CBET. When some fraction of the incident laser light is absorbed near $n_c/4$ due to TPD, the power at every point thereafter will be reduced by approximately that fraction, including the net power out.

Figure 1(a) shows the total incident laser power for six different implosions along with the scattered light predicted by *LILAC* (using the nonlocal and CBET models) and the measured scattered light. The time-integrated coupling percentage is included for both the simulations and the experiments, with differences as large as 8% (shot 76824). Also noted is the average quarter-critical overlapped intensity during the peak according to *LILAC* (ranging from $I_{14}$ = 2.5 to 4.1 in units of $10^{14}$ W/cm$^2$) and the associated vacuum hard-sphere intensities (6.0 to 10.7). The examples shown are emblematic of the systematic trends evident in the broader absorption database. At low overlapped intensity (e.g., shot 75043), there is excellent agreement between predicted and observed scattered light. At higher quarter-critical intensity, however, they tend to diverge at some point during peak power.

In search of qualitative correlation between the apparent error in scattered light and TPD, the time-resolved difference between the predicted and observed scattered light was plotted [see Fig. 1(b)] against the time history of half-harmonic emission—a spectral doublet centered around 702 nm that is known to be a signature of TPD.[1] The agreement in terms of onset, timing, and overall shape is generally remarkable.

Assuming the decrease in total scattered power is dominated by the reduction of the unabsorbed light seed, the ratio of scattered power with TPD (i.e., the experimental result) to scattered power without TPD (i.e., the simulated result) is a direct measurement of the transmission $T$ past $n_c/4$, and absorption is simply $A_{n_c/4} = 1 - T$ [Fig. 1(c)]. Typical incident power levels yield absorption in the range of 10% to 25%. Such levels are consistent with the conclusions drawn from electron-temperature measurements of the quarter-critical region based on half-harmonic emission.[2]

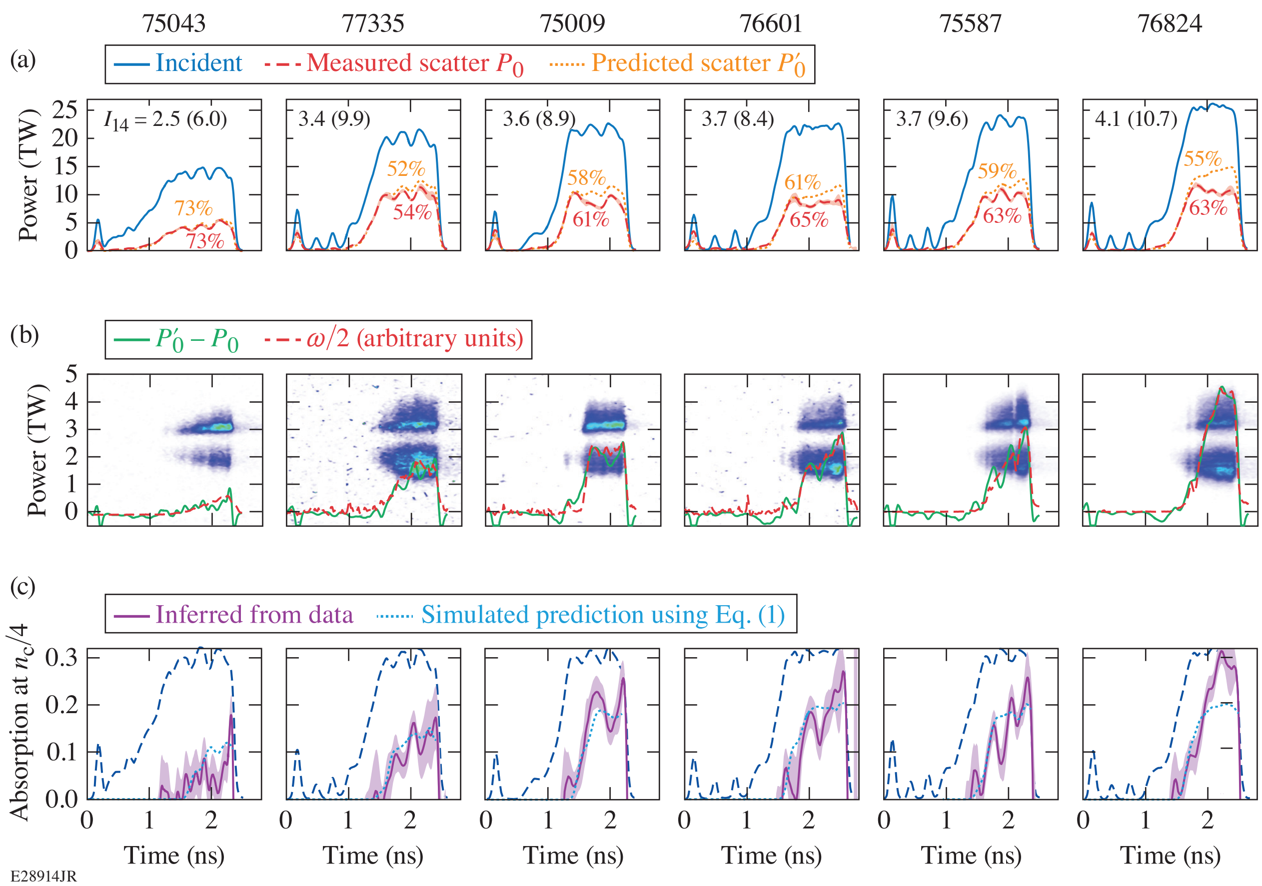


Figure 1
Use of scattered light data to infer anomalous absorption due to TPD. (a) From left to right, peak power increases along with overlapped intensity at quarter-critical density. During peak power, scattered-light data are increasingly divergent from the simulated predictions as quarter-critical intensity increases. (b) The difference between predicted and observed scattered light correlates extremely well with half-harmonic emission, indicating the discrepancy is associated with TPD. (c) Assuming that anomalous absorption by TPD primarily reduces the unabsorbed light seed for CBET, absorption at $n_c/4$ due to TPD is typically found to be in the range of ~10% to 25%. The absorption time dependence can be predicted inline using parameters in *LILAC* along with Eq. (1).

It would be useful to have an in-line model for enhanced TPD absorption that does not rely on experimental measurements *a posteriori*; inferring an appropriate scaling for such a reduced model is a main goal of this work. TPD activity has previously been shown to scale with the Simon threshold parameter $\eta = I_{14}L/(233\ T_e)$, with the density gradient scale length $L$ in $\mu$m, electron temperature $T_e$ in keV, and laser intensity specified at $n_c/4$. For each of the shots in Fig. 1 (highlighted in blue) as well as 11 other shots from the same 2014–2015 time period, $\eta(t)$ was extracted from the *LILAC* simulations and plotted against the inferred absorption. Figure 2 shows the inferred scaling of anomalous TPD absorption versus TPD threshold parameter. Above a threshold at $\eta = 0.71$, the data are well fit by the power law

$$A_{n_c/4} = 0.248 - 0.061\,\eta^{-4}. \tag{1}$$

Convolving the simulated Simon threshold parameter with an appropriate response function and then applying the above scaling yields an estimated absorption using the code parameters for direct comparison to the data on an individual shot. The results, included in Fig. 1(c), generally track the data well. This should, therefore, be a good starting point for a reduced model that can be included inline in radiation-hydrodynamic simulations.

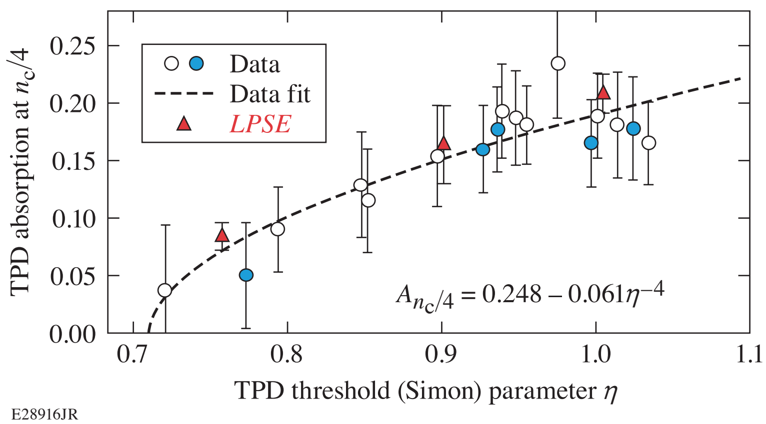


Figure 2
A trend of inferred absorption versus the Simon threshold parameter extracted from simulations is found using the average values from a wide range of shots with differing drive conditions. Typically, conditions during peak power are ~20% to 30% above the TPD threshold, resulting in ~15% to 20% local absorption at $n_c/4$. Two-dimensional *LPSE* simulations accurately reproduce both the threshold and the scaling above threshold.

To validate the empirical scaling, 2-D simulations were run using *LPSE*. Notably, a new pump-depletion model was used that self-consistently evolves the electromagnetic field of the laser as power is pumped into electron plasma waves. Figure 2 shows that *LPSE*'s predictions for TPD absorption are in very good agreement with the data. The use of a speckled beam was found to be essential in reproducing both the threshold and the scaling above threshold because individual intense speckles become unstable below $\eta = 1$, while other parts of the beam remain below threshold. Critically, the simulations found that 5× to 8.3× more power is dissipated by collisional (rather than Landau) damping, which explains why such large laser absorption does not result in undue levels of hot electrons—most of the power is thermalized around $n_c/4$.

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1. W. Seka *et al.*, Phys. Plasmas **16**, 052701 (2009).

2. W. Seka *et al.*, Phys. Rev. Lett. **112**, 145001 (2014).