

Laser–plasma interaction in direct-drive inertial confinement fusion

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Abstract. Hot electrons generated by the two-plasmon–decay instability in direct-drive targets are a preheat concern. A mitigation strategy that employs a layered ablator [V. N. Goncharov *et al.*, Phys. Plasmas **21**, 056315 (2014)] has been investigated both numerically and experimentally. The numerical simulations described here predict reduced hot-electron production compared with similar targets using either a solid CH or Be ablator. These findings are shown to be consistent with experimental observations

1. Introduction

Of the many challenges facing laser-driven inertial confinement fusion (ICF) [1, 2], controlling the impact of laser–plasma interactions [3] has shown itself to be one of the most difficult and uncertain. In the direct-drive approach [4, 5] the collective interaction of multiple beams [6] leads to two important instabilities: multiple-beam two-plasmon decay (TPD) [7, 8] and cross-beam energy transfer (CBET) [9, 10, 11]. Two-plasmon decay has the potential to create enough hot electrons to preheat the cold fuel, while CBET reduces the efficiency of laser coupling, i.e., an $\approx 30\%$ loss of drive energy on OMEGA.

While TPD is known to be active in spherical implosions on OMEGA [12, 13], the preheat associated with the instability is not currently thought to be sufficient to impair target performance [14]. It has the potential to become so when CBET is mitigated since the mitigation of CBET will increase the laser intensity at the quarter-critical density (the active region for TPD) by as much as a factor of two. Beam zooming is planned as a mitigation strategy for CBET [15, 16]. Two-plasmon–decay preheat may be detrimental at the longer plasma scale lengths obtainable in NIF-scale implosions [17] that are required for ignition.

For these reasons it is important to understand the effectiveness of mitigation strategies for TPD. The strategy described here employs a mid-Z (silicon) layer buried within the ablator. The effectiveness of the mid-Z layer can arise because of hydrodynamic effects (higher coronal temperature and shorter density scale length) and/or collisional effects that modify the plasmon physics [18, 19]



2. Simulating TPD with LPSE

Each of three targets was simulated with the 1-D hydrodynamics code LILAC [20] to obtain hydrodynamic variables as a function of time. These simulations incorporated the effects of CBET using a ray-based in-line model [10]. The targets corresponded to those shot in a recent OMEGA experimental campaign (shots 77388, 77391, and 77392). A schematic of a multilayer target is shown in Fig. 1. In the other two targets, the ablator was either solid CH (shot 77388) or solid beryllium (shot 77391).

The predicted coronal temperature, at a radius corresponding to the quarter-critical density, is shown for the three target designs as a function of time in Fig. 2. Notice that the coronal temperature in the multiple-ablator design is higher, particularly when the Si layer is present at the quarter-critical surface (shaded region in the figure). The increased temperature combined with a shorter density scale length (not shown) in these targets corresponds to a reduced TPD threshold factor [13] (shown in green). This suggests that TPD should be below threshold for the multiple-ablator experiment.

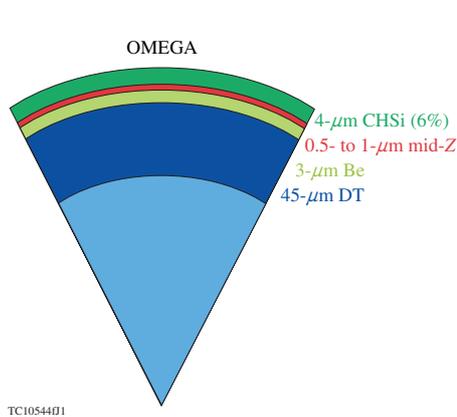


Figure 1. Schematic for a multi-ablator target design. The purpose of the thin Si layer is to mitigate the two-plasmon-decay (TPD) instability.

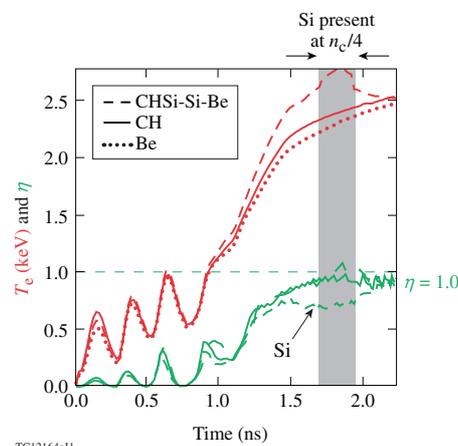


Figure 2. Quarter-critical temperature and empirical TPD threshold factor for three ablator designs, as simulated by LILAC.

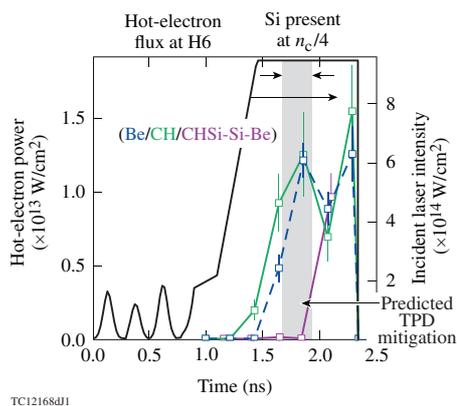
While the TPD threshold factor $\eta = I_{14}L_{\mu\text{m}}/(230 T_{e,\text{keV}})$ is based on the instability threshold for a single plane wave [21, 22], its application to spherical implosion experiments (substituting total overlapped intensity) is empirical. It is therefore of interest to compute the effects on the modified target hydrodynamics on TPD hot-electron production using a physical model that takes into account the details of the multiple-beam irradiation on the threshold and nonlinear evolution, including hot-electron production.

The LPSE code (laser plasma simulation environment) does this by combining a physical model of TPD with an established model of plasma-wave turbulence [23, 24] in three spatial dimensions. The incident laser light in the simulations reflects the actual illumination — i.e., it takes into account the angles of the overlapping beams and beam smoothing. Kinetic effects and hot-electron production are incorporated in a way that has similarities with the quasi-linear model described in Ref. [18]. Instead of solving a quasi-linear diffusion equation to evolve the spatially averaged distribution function, however, electron particle trajectories are numerically integrated in the electrostatic field using a novel algorithm that exploits hardware (GPU) acceleration.

The LPSE model takes advantage of the separation between the hydrodynamic and plasma-wave time scales. The duration of the ~ 2 -ns implosion is sampled at several points in time and

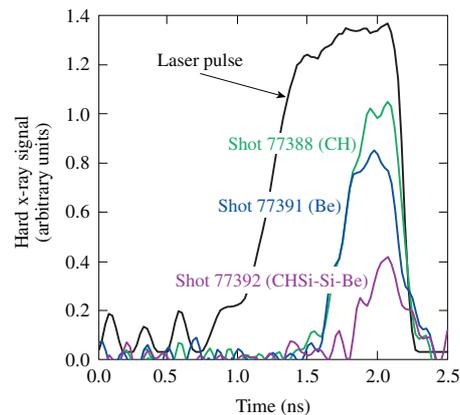
the hydrodynamics are imported into LPSE. These variables are then “frozen” over the duration of the LPSE simulation (with the exception of density profile modification), which is performed over a time sufficient to obtain a statistical steady state for the hot-electron production (typically ~ 20 ps). The volume of the calculation does not include the whole $n_c/4$ surface but only a small ($30 \times 30 \times 70\text{-}\mu\text{m}^3$) fraction of it. This is therefore a local analysis in the neighborhood straddling a point (r, θ, ϕ) on the surface. Several angular locations are simulated, confirming that electrons are preferentially generated at hex centers [25].

Figure 3 shows the simulated hot-electron production as a function of time (each marker corresponds to a sample time) for three simulated implosions.



TC12168dJ1

Figure 3. Hot-electron production as simulated by LPSE for three targets with different ablator types.



TC12168dJ2

Figure 4. Measured hard x-ray yield from the three corresponding implosion experiments.

The simulation results for the CH ablator, shown in green in Fig. 3, compare well with experimental results (Fig. 4). The error bars in hot electron fraction reflect fluctuations about the statistical steady state seen in the simulations. Uncertainties in the hydrodynamic conditions are not accounted for. While the comparison is complicated because the experiment measured hard x rays (in the approximate range of 40-80 keV) and not hot-electron power, a good agreement is observed between the time of onset. This suggests that the LPSE model makes a good prediction for the threshold. The Be simulation is predicted to be very similar to CH (blue markers). Again, the experimental x-ray signatures for Be and CH are very close. For all cases, the simulated hot electron temperatures are close to those observed experimentally (30-40 keV).

Importantly, the simulations confirm the mitigating effect of the Si layer. Very few hot electrons are predicted to occur while the Si is present at the $n_c/4$ surface (magenta points). Hot electrons are produced at later times and at a level that is similar to the other ablaters. Experimentally, the late onset is similar to the predictions, but the mitigating effect appears to be even stronger than predicted by LPSE. This may be due to mixing of the Si layer.

3. Summary

Simulations of TPD mitigation experiments using the LPI code LPSE confirm the effectiveness of buried mid-Z layers. Furthermore, several aspects of these simulations are consistent with experimental observations. It remains to be seen how effective this strategy will be at the ignition scale when the instability is anticipated to be more strongly driven.

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