Direct-drive implosion physics: Results from OMEGA and the National Ignition Facility

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Abstract. Direct-drive–implosion experiments from both OMEGA and the National Ignition Facility (NIF) are critical to gain confidence in ignition predictions on the NIF. Adequate performance of hydrodynamically scaled 1.8-MJ ignition designs must be obtained on OMEGA at 26 kJ. Implosions on the NIF must be used to identify and mitigate the effect of laser–plasma interactions (LPI's) on hydrodynamic parameters at the NIF scale. Results from spherically driven OMEGA cryogenic implosion experiments are described. Mitigation of nonuniformity sources and cross-beam energy transfer (CBET) is important for improving target performance on OMEGA. Initial polar–driven implosion experiments on the NIF have provided valuable measurements of trajectory and symmetry. Simulations that include the effect of CBET more closely reproduce the observed velocity.

1. Introduction

In the direct-drive approach to hot-spot ignition, nominally identical laser beams irradiate a capsule containing a layer of cryogenic deuterium–tritium (DT), driving the shell inward like a rocket [1]. The converging shell performs PdV work on the hot spot, raising the temperature. If a sufficient number of alpha particles from the DT-fusion reaction are produced and the hot spot has sufficient areal density ($\sim$300 mg/cm^2 at a temperature $\sim$5 keV), the alpha particles deposit their energy, further raising the temperature and increasing the number of DT neutrons produced. Ignition is said to occur when the energy produced in the 14.1-MeV neutrons is greater than the laser energy used to irradiate the target.

One-dimensional (1-D) target designs are characterized by the fuel adiabat α (the ratio of the pressure to the Thomas–Fermi pressure at peak shell density), implosion velocity V_{imp} (the peak mass-averaged shell velocity), and ablation pressure P_{a}. The ignition threshold factor $\mathrm{ITF}_{1\text{-}D}$ [2], defined as the ratio of the shell's kinetic energy to the minimum energy for ignition [3], scales as $\mathrm{ITF}_{1-D} = E_K \big/ \min\left(E_{\mathrm{ign}}\right) \sim \left[P_a(I)\right]^{0.8} V_{\mathrm{imp}}^7 \big/ I\alpha$, where I is the on-target intensity. Designs that

successfully ignite in multidimensional hydrodynamic simulations typically have ITF_{1-D} values between 3 and 5 [2].

2. Results from OMEGA implosions

The OMEGA [4] laser is used to study direct-drive–implosion physics with the goal of developing and validating the models required to predict ignition. In order to be ignition relevant, cryogenic implosions on OMEGA are scaled [5] from ignition designs [6] for the NIF [7]. A typical OMEGA cryogenic implosion has a diameter of 860 μm with an ~3-ns-long shaped laser pulse at 26 kJ of laser energy. Three pickets that set the adiabat profile in the shell precede a main pulse [figure 1(a)].

Implosion energetics must be accurately modeled to simulate and predict performance. OMEGA implosions indicate that it is necessary to include the effect of nonlocal heat transport of the deposited laser energy [8] and CBET [9] to reproduce the observables related to energetics—time-resolved scattered light, trajectory, and timing of the neutron-production histories (figure 1) [9]. Nonlocal heat transport is important because of the finite mean free path of the energetic coronal electrons from the tail of their distribution. As figure 1(a) indicates, including only nonlocal transport significantly underestimates the time-resolved scattered light. Simulations, including the effect of CBET and nonlocal transport, reproduce the time-resolved scattered light very well. The trajectory [figure 1(b)] is inferred from gated framing camera images of self-emission, which peaks just outside the ablation surface [10]. Again, excellent agreement with the inferred trajectory and neutron rate timing is obtained when both CBET and nonlocal transport are included in the simulation.
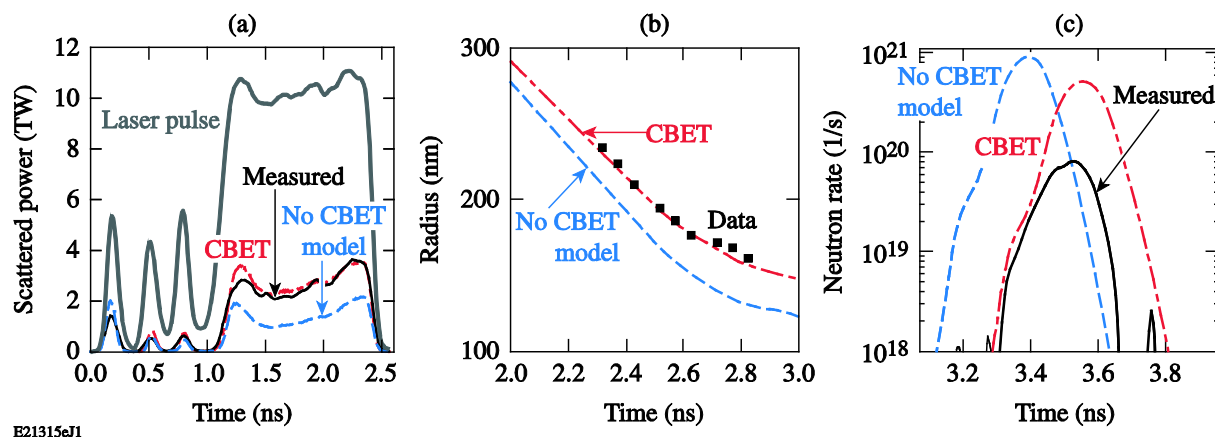

Figure 1. (a) Scattered light, measured laser pulse (gray); (b) trajectory of the ablation surface inferred from x-ray emission images; (c) neutron rate. Measured (black), collisional absorption with nonlocal heat conduction (dashed), collisional absorption with the effect of CBET and nonlocal heat conduction (dashed–dotted).

The triple-picket laser pulse shape has been shown to achieve high, nearly 1-D areal density in cryogenic implosions [6]. Relative to the simulation that includes only collisional absorption as the mechanism of energy deposition, the inclusion of CBET effects reduces ablation pressure by nearly 40% in OMEGA implosions and implosion velocity by nearly 15%. This can reduce ITF_{1-D} by nearly a factor of 10. Options for improving ITF_{1-D} include reducing the adiabat, increasing the implosion velocity by reducing shell mass or mitigating CBET, improving ablation pressure by mitigating CBET, and increasing the intensity on target.

OMEGA cryogenic implosions have been performed for a range of implosion velocities and adiabats. The adiabat is varied by primarily varying the energy in the first picket. The timing between pickets is varied to optimize the adiabat profile in the shell. Different implosion velocities are obtained by varying the shell and ablator mass. The measured yields increase with implosion velocity

(figure 2), consistent with simulation, indicating that higher nonuniformity growth rates related to the higher implosion velocity do not overwhelm the 1-D effect of implosion velocity on the temperature. A fit to the data in figure 2(a) reveals, however, that while simulated yields scale as V_{imp}^6, measured yields scale as V_{imp}^5 suggesting that nonuniformities do compromise the yield.

Two-dimensional (2-D) simulations using the hydrodynamic code *DRACO* [11] have been performed for a range of cryogenic implosions [12]. These simulations include short-wavelength nonuniformities from laser imprint due to single-beam uniformity ($\ell \leq 150$) and the effect of beam smoothing through smoothing by spectral dispersion (SSD) [13], longer wavelength nonuniformities ($\ell \leq 10$) including the roughness of the inner ice layer, and beam imbalances such as mistiming and power imbalance. For the moderate adiabat ($\alpha \sim 4$) implosions, these simulations reproduce all the observables well (simulated yield is within 75% of the measured value, whereas ion temperature, burn width, hot-spot size, and areal density are within 90% of the measured values), indicating that these implosions are adequately understood. For lower-adiabat implosions, such as $\alpha = 2$, the simulations do not reproduce many of the observables including areal density and hot-spot radius. Areal density, in particular, is compromised at lower adiabats; for example, at $\alpha = 2$ the measured areal density is ~35% of the simulated value (figure 3). The decrease in areal density is correlated with increased x-ray emission from the core relative to spherically symmetric simulations, suggesting the mixing of ablator carbon into the hot spot [14]. The role of outer-surface defects has been investigated as a possible source of this degradation [15]. These simulations indicate that defects smaller than 1 μm in height can significantly compromise performance. Other possible sources of areal density degradation being investigated include higher levels of single-beam nonuniformity, void formation at the ice–ablator interface during the cooling process, early-time laser shinethrough, etc. Ongoing identification and mitigation of these sources of nonuniformity are expected to improve cryogenic target performance on OMEGA.
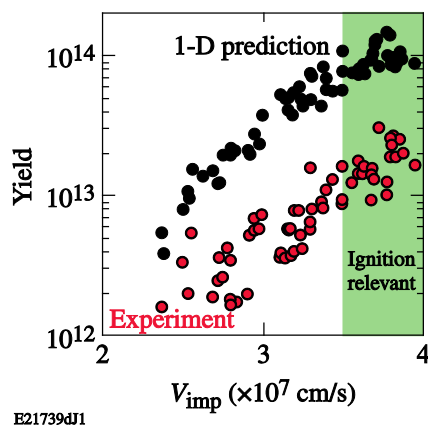

Figure 2. Measured yields (gray) and simulated yields (black) from cryogenic DT OMEGA implosions versus implosion velocity. Each point represents a single OMEGA shot with simulated values of adiabat between 2 and 5.
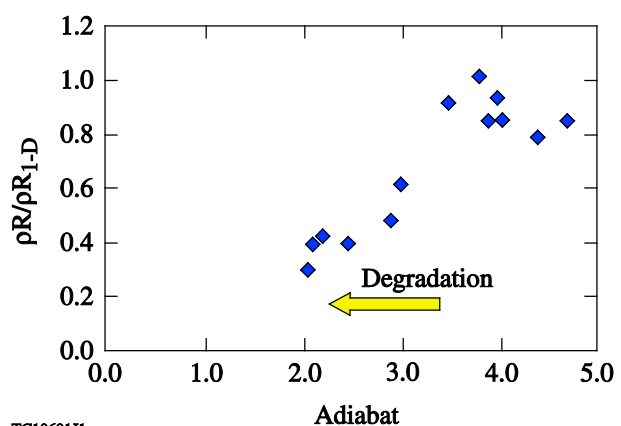
Figure 3. Ratio of measured areal density to simulated areal density versus the adiabat.

To improve ITF$_{1-D}$ requires a further decrease in adiabat beyond the typical values in current implosions. Given current sources of performance degradation, it is less likely that lower adiabats than 2 can lead to high-performing implosions.

Increasing ablation pressure and implosion velocity by mitigating the effect of CBET is necessary to improve OMEGA target performance and improve ITF$_{1-D}$. Targets with mid-Z ablators, such as Si, have been shown to mitigate the effect of CBET [16]. CBET results in the transfer of laser energy

from the incoming rays to the outgoing rays mediated by ion-acoustic waves near the quarter-critical surface in the corona. The thickness of the layer is chosen such that Si stays at the quarter-critical region of the corona when the CBET gain is expected to be the highest, i.e., during the main drive of the pulse. With a higher average charge than CH, the temperature at the quarter-critical surface is larger with the mid-Z layer. Since the CBET gain scales inversely as the temperature [9], a Si layer reduces the extent of CBET.

Cryogenic targets with multiple layers will be investigated on OMEGA. The layers from the outside are an outer doped-plastic layer (to reduce imprint [17], thereby permitting more-stable implosions at a higher implosion velocity); a thin Si layer (<1 μm); a Be layer, with an inner cryogenic DT layer. Beryllium (Be) offers a higher ablation pressure than the historically used plastic (CH) ablator [16]. Simulations indicate that the combination of Be and a mid-Z material (Si) increases ablation pressure by 15% and velocity by nearly 5% through a better choice of ablator material and by mitigating CBET in the Si.

Other ways to mitigate CBET include modifications to the laser. The use of smaller phase plates during the main pulse reduces beam overlap and therefore the interactions of rays that result in the greatest CBET transfer. Improved target performance in room-temperature implosions has been demonstrated with this concept [18]. Further development involves using "zooming" phase plates [19]. There the beam size matches the target radius initially in the implosion and is reduced later during the main pulse, permitting reduced initial nonuniformity seeds while mitigating CBET later in the implosion. The use of different wavelengths on different beams causing the greatest overlap will also be investigated.

3. Results from NIF implosions

OMEGA implosion performance cannot be simply extrapolated to NIF scales because of the different density scale lengths in the corona (~150 μm for OMEGA-scale 26-kJ implosions compared to ~600 μm for the ignition-scale implosion at 1.8 MJ). Most laser–plasma interactions scale with increasing coronal density scale lengths.

Room-temperature experiments are being conducted in the polar-drive (PD) configuration [20] on the NIF to validate models and identify and mitigate the effect of LPI on implosions. Ideally, direct drive requires spherical drive with beams arranged symmetrically around the target chamber, like the OMEGA geometry; on the NIF, however, beams are arranged axisymmetrically. Simulations indicate that the reduced irradiation at the equator can be corrected by a combination of beam repointing, where beams at higher latitudes are repointed toward the equator, an optimal choice of pulse shapes for the different rings, and custom beam profiles. Ongoing experiments [21] use the existing NIF phase plates, defocused to improve low-order uniformity. These are not optimal, however, for PD and offer limited freedom in design. These experiments are intended to identify and demonstrate mitigation of LPI effects on gross hydrodynamic parameters, such as symmetry and implosion velocity, and not to achieve high-performance direct-drive implosions.

The target is an 80-μm-thick CH shell driven with an $\alpha \sim 3$ pulse shape comprising a low-intensity foot rising to a flat-top pulse. The average intensity at the initial target radius is ~4×10^{14} W/cm^2. The hydrodynamic code *DRACO* has been modified to include a model of CBET [22] based on the formulation of Randall *et al.* [23]. Preliminary simulations with this model indicate that CBET can have an observable effect on inferred velocity and shape. As the contour plot of the instantaneous deposited laser energy (figure 4) indicates, significant energy is transferred out of the equator into the outgoing rays of beams from the other rings relative to a simulation that includes only collisional absorption. This results in an overall reduction of time-integrated absorbed energy from 90% to 68% . The drive near the equator is also reduced, leading to a more-oblate shape.

The trajectory of the ablation surface is inferred from the time-resolved x-ray framing camera images [9]. The peak of the emission is identified using the method of matched filters and averaged in
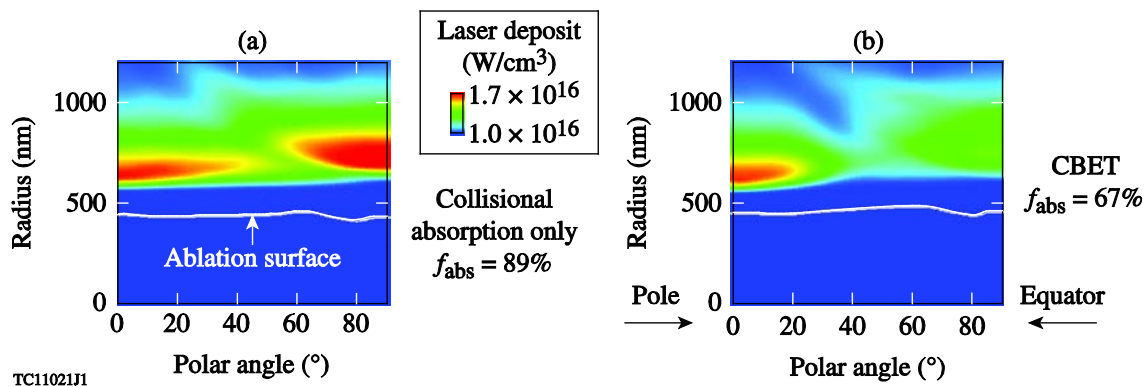
Figure 4. Contour plot of instantaneous laser energy deposited versus radius of the target and polar angle (a) with only collisional absorption and (b) with the inclusion of the CBET model.

angle to obtain an average radius versus time. This method has provided an important measurement for validating laser deposition and heat conduction models on OMEGA, as shown in figure 1(b). Simulations indicate that implosions at this intensity are relatively insensitive to the model of heat conduction, making this an ideal test for the CBET model. The images, including the effect of the pinhole used in the experiment, and the experimental gate width are created from the *DRACO* simulation using the code *Spect3D* [24]. The same procedure used to extract trajectories from the data is used on the simulated images. The velocity of the ablation surface inferred from the trajectories is shown in figure 5. Better agreement with experiment is obtained when CBET is included in the simulation (figure 5). The resulting difference between simulation and experiment may be due to the uncertainties in the beam profiles used in the simulation, the relatively lower resolution of the quarter-critical surface in the simulation, the effect of short-wavelength nonuniformity growth that could potentially decouple the ablation surface from the center of mass (an effect not included in the simulation), or limitations in the modeling (for example, an ion-acoustic wave damping coefficient is currently parameterized by a single value of 0.2; larger values indicate greater damping). These sources are currently being investigated.
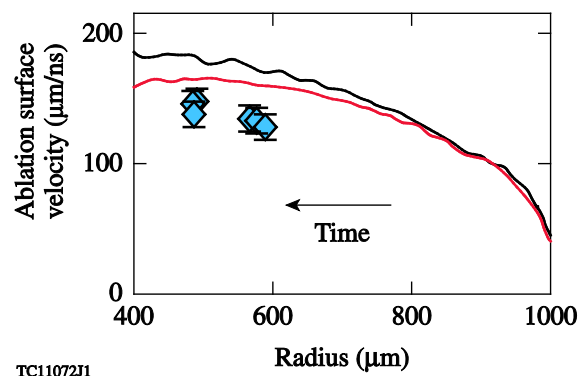

Figure 5. Inferred ablation surface velocity versus the radius of the peak emission region. Symbols: measured; black curve: simulated with only collisional absorption; gray curve: simulated with the CBET model.

4. Summary

Results from direct-drive OMEGA cryogenic implosions show that implosion energetics can be reproduced well using models of CBET and nonlocal heat conduction. Yields and ion temperatures from cryogenic implosions scale with implosion velocity, indicating that nonuniformity does not

overwhelm the increase in these values from higher implosion velocity. Moderate-adiabat ($\alpha \sim 4$) target performance can be described well using two-dimensional simulations that include single-beam nonuniformity, beam imbalances, and inner ice roughness. Lower-adiabat performance cannot be explained with these sources of nonuniformity, indicating that other sources need to be accounted for. Candidates such as outer surface defects, void formation at the ice–ablator interface during the cryogenic process, and possible underestimation of laser imprint seeds are being investigated. Mitigating CBET is also important for improving cryogenic target performance.

Implosions on the NIF with the existing x-ray drive configuration are performed to study symmetry, velocity, and preheat. Simulations with the newly developed CBET model in *DRACO* indicate that velocity is significantly influenced by CBET. Future PD implosions on the NIF will be used to validate the CBET model and study various ways of mitigating CBET, including mid-*Z* layers and different wavelengths on the inner and outer cones.

Acknowledgements

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