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Progress in direct-drive inertial confinement fusion research at the laboratory for laser energetics

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Abstract. Direct-drive inertial confinement fusion (ICF) is expected to demonstrate high gain on the National Ignition Facility (NIF) in the next decade and is a leading candidate for inertial fusion energy production. The demonstration of high areal densities in hydrodynamically scaled cryogenic DT or D_2 implosions with neutron yields that are a significant fraction of the "clean" 1-D predictions will validate the ignition-equivalent direct-drive target performance on the OMEGA laser at the Laboratory for Laser Energetics (LLE). This paper highlights the recent experimental and theoretical progress leading toward achieving this validation in the next few years. The NIF will initially be configured for X-ray drive and with no beams placed at the target equator to provide a symmetric irradiation of a direct-drive capsule. LLE is developing the "polar-direct-drive" (PDD) approach that repoints beams toward the target equator. Initial 2-D simulations have shown ignition. A unique "Saturn-like" plastic ring around the equator refracts the laser light incident near the equator toward the target, improving the drive uniformity. LLE is currently constructing the multibeam, 2.6-kJ/beam, petawatt laser system OMEGA EP. Integrated fast-ignition experiments, combining the OMEGA EP and OMEGA Laser Systems, will begin in FY08.

PACS. 52.57.-z Laser inertial confinement – 52.50.Jm Plasma production and heating by laser beams – 52.57.Fg Implosion symmetry and hydrodynamic instability

1 Introduction

Direct-drive inertial confinement fusion (ICF) offers the potential for higher gain implosions than X-ray drive and is a leading candidate for an inertial fusion energy power plant [1]. The achievement of thermonuclear ignition and high gain in the laboratory with direct-drive inertial confinement fusion (ICF) requires a physical understanding of the entire implosion process. Significant theoretical and experimental progress continues to be made at the University of Rochester's Laboratory for Laser Energetics (LLE). This paper provides an update on direct-drive ICF research at LLE [2].

LLE's direct-drive ICF ignition target designs for the National Ignition Facility (NIF), or other megajoule-class lasers, rely on hot-spot ignition [3] where a cryogenic target with a spherical DT-ice layer, within or without a foam matrix, enclosed by a thin plastic shell will be directly irradiated with ∼1.5 MJ of laser energy [4]. During an implosion, the main fuel (DT-ice) layer compresses the residual DT gas, forming a central hot spot. A thermonuclear burn wave is predicted to propagate through the main fuel layer when the hot spot's fuel areal density reaches ~ 0.3 g/cm^2 with a temperature of ∼10 keV [3]. High-gain (∼35) ignition with the symmetric baseline direct-drive target design is likely on the National Ignition Facility (NIF) based upon 2-D hydrodynamic simulations [4,5]. The NIF is a 1.8-MJ, 351-nm, 192-beam laser system [6] under construction at Lawrence Livermore National Laboratory.

The path to ignition is being explored with hydrodynamically scaled, direct-drive implosion experiments on

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the 60-beam, 30-kJ OMEGA Laser System [7]. These experiments are validating the hydrodynamic codes used to design high-gain, cryogenic DT ignition targets. Targets are imploded to investigate the key target-physics issues of energy coupling, hydrodynamic instabilities, and implosion symmetry. The performance of imploding cryogenic D_2 capsules on OMEGA [5,8] is close to the predictions of the 2-D hydrodynamic code *DRACO* [9]. This research gives high confidence that direct-drive implosions will ignite on the NIF when it is configured for symmetric illumination.

The NIF will be initially configured for X-ray drive, with no equatorial beams to symmetrically irradiate a direct-drive target. Although the implementation of the direct-drive beam configuration is not currently scheduled until at least 2014, prospects for direct-drive ignition on the NIF while it is in its X-ray-drive irradiation configuration are favorable with the development of polar direct drive (PDD) [10]. The PDD approach is based on the optimization of phase-plate design, beam pointing, and pulse shaping to provide uniform drive with nonsymmetric beam locations. Initial 2-D simulations of the PDD target design have shown ignition with gain close to those of symmetric illumination [11]. Recently, a novel PDD concept has been developed: the addition of a CH ring around the equator to refract laser light toward the equator as the target implodes [12]. This concept has the potential to improve the on-target uniformity throughout the implosion. PDD simulations are being validated by experiments on OMEGA [13].

Fast ignition (FI) [14] is a complementary approach to central hot-spot ignition and an active area of research at LLE. In this concept, a target is compressed without the formation of a central hot spot. At peak compression, a high-energy petawatt (HEPW) laser provides the "spark" energy to begin the ignition process. An HEPW capability is being constructed at LLE adjacent to the existing OMEGA compression facility. The OMEGA EP (Extended Performance) laser will add two short-pulse (∼10-ps-duration), 2.6-kJ beams to the OMEGA Laser System to study FI physics with focused intensities up to 6×10^{20} W/cm^2 for experiments beginning in 2008. Direct-drive fuel-assembly experiments with FI cone targets are currently being carried out on OMEGA, and a substantial fraction of the predicted core areal density has been measured [14,15].

This paper presents highlights from the direct-drive target physics program at LLE. A general description of direct-drive ICF is given in Section 2. Symmetric direct-drive research on OMEGA and the predicted performance of LLE's baseline direct-drive target design for the NIF are presented in Section 3. PDD for the NIF and PDD experiments on OMEGA are discussed in Section 4. A brief description of the OMEGA EP is given in Section 5, along with the results from FI fuel-assembly experiments and integrated simulations of future OMEGA/OMEGA EP experiments. The conclusions are presented in Section 6.

2 Direct-drive inertial confinement fusion

A direct-drive implosion is driven by the ablation of material from the outer surface of a spherical shell containing thermonuclear fuel with intense laser beams [3,4]. The ablated shell mass forms a coronal plasma that surrounds the target and accelerates the shell inward via the rocket effect [3]. Since ICF target acceleration and subsequent deceleration occur while hot, low-density plasma pushes against (accelerates/decelerates) a cold, high-density plasma, the target implosion is unstable to Rayleigh–Taylor instability (RTI) [3–5,17]. The implosion can be divided into four stages: shock generation, acceleration phase, deceleration phase, and peak compression. Perturbation seeds early in the implosion from single-beam laser nonuniformities (imprint), laser drive asymmetry, and the outer/inner-shell-surface roughnesses determine the final capsule performance. The unstable RTI growth is controlled by reducing the seeds (e.g., laser imprint and target-surface roughness) and the growth rates of the dominant modes. These perturbations feed through the shell during the acceleration phase and seed the RTI of the deceleration phase at the inner shell surface [18]. When the higher-density shell converges toward the target center and is decelerated by the lower-density hot-spot plasma, the RTI mixes shell material into the hot spot (i.e., shell mix) [19].

Laser imprint levels are reduced by creating a uniform laser irradiation of the target. High-compression, direct-drive experiments require an ∼1% rms level of on-target laser irradiation nonuniformity averaged over a few hundred picoseconds [20]. This is accomplished on the OMEGA Laser System using two-dimensional smoothing by spectral dispersion (2-D SSD) [21–23], distributed phase plates (DPP's) [24,25], polarization smoothing (PS) using birefringent wedges [26,27], and multiple-beam overlap [28]. These techniques have been demonstrated on OMEGA [29] and are directly applicable to direct-drive ignition target designs planned for the NIF [4,5]. The on-target uniformity continues to improve. The beam-to-beam power imbalance of the 60 OMEGA beams with a shaped laser pulse (averaged over 300 ps) is ∼4% over much of the pulse, meeting the OMEGA requirements.

Recently, the laser irradiation nonuniformity was reduced on OMEGA with a new distributed phase plate [30]. The envelope of the single-beam, far-field intensity has a super-Gaussian shape $I(r) \propto \exp\left[-\left(r/\delta\right)^n\right]$, where r is the radius of the beam, δ is the $1/e$ half-width, and n is the super-Gaussian order. The new SG4 DPP with $n = 4.1$ and $\delta = 357$ μm produces a more azimuthally symmetric far field and replaced the SG3 DPP with $n = 2.3$ and $\delta = 308$ μm. The low-ℓ-mode ($3 < \ell < 8$) nonuniformity level was significantly reduced, as were selected modes in the intermediate range ($10 < \ell < 80$) [30]. The effects of the low- and intermediate-ℓ-mode nonuniformities on the target performance of high-adiabat, deuterium-filled plastic-shell implosions were investigated [30]. Implosions are categorized by the adiabat α or isentrope parameter of the shell, defined as the ratio of the shell pressure to the Fermi-degenerate pressure [3]. Target performance is

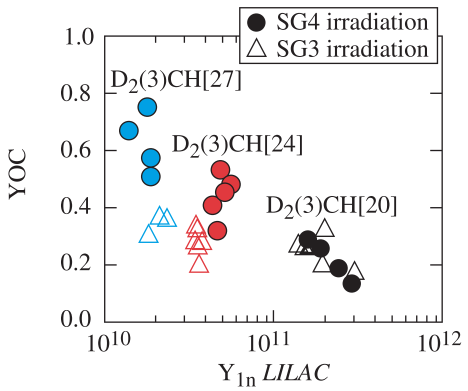

Fig. 1. Measured neutron yield normalized to the 1-D predicted neutron yield versus predicted neutron yield for 20-, 24-, and 27-μm-thick CH targets filled with 3-atm D_2 gas. The solid circles were obtained using the newer SG4 DPP's while the open triangles were obtained with the SG3 DPP's.

quantified by the ratio of measured primary neutron yield to 1-D predicted yield, the yield over clean (YOC). Figure 1 shows that the YOC for 3-atm, deuterium-filled, high-adiabat ($\alpha \sim 5$), plastic-shell implosions with 27-μm-thick shells increased by almost a factor of 2 with the reduced nonuniformity, while the YOC for the 20-μm-thick shells remained unchanged. The target performance of the more unstable, thinner-shell target is less sensitive to the reduced long-wavelength nonuniformities because it is dominated by the very short-wavelength, single-beam-irradiation nonuniformities [9]. In contrast, the thicker-shell target is less susceptible to the laser imprint from the high-ℓ modes and more sensitive to the reduction in the low- and intermediate-ℓ-mode nonuniformities [9]. These targets have a 1-D predicted convergence ratio of 35.

Ongoing research is refining the understanding of laser coupling and thermal transport [31]. While absorption and bang-time measurements have been in good agreement with simulations for cryogenic target implosions, there have been some discrepancies for low-adiabat ($\alpha < 3$) CH targets. Such discrepancies are due to limited applicability of the flux-limited Spitzer thermal transport model [32] used in hydrocodes. In the model, the heat flux is proportional to the temperature gradient $\mathbf{q}_{\rm SH} = \kappa - \boldsymbol{\nabla}{\rm T}$. In the region where $\mathbf{q}_{\rm SH} > f\mathbf{q}_{\rm FS}$, the heat flux is calculated as a fraction f of its free-streaming value $q_{\rm FS} = nTv_t$, where κ is the heat conductivity, T is the electron temperature, $v_T = \sqrt{(T/m)}$, and n is the electron density. The coefficient f is commonly referred to as the "flux limiter". In addition to discrepancies in laser absorption, the constant flux limiter is in contradiction with the implosion measurements of dual-shock timing and ablative Richtmyer–Meshkov instability (RMI) growth in CH targets. A new nonlocal thermal transport model has been developed. It leads to a "time-dependent" effective flux limiter that appears to resolve these discrepancies [31,33]. The electron distribution function is modeled with a simplified Boltzmann equation and limits the heat penetration depth to the electron deposition range. The thermal transport is then calculated by taking the third moment

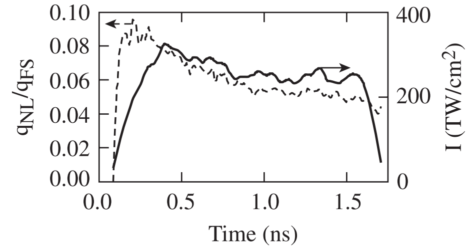

Fig. 2. Effective flux limiter ($q_{\rm NL}/q_{\rm FS}$) (dashed) versus time of a 1.5-ns laser pulse (solid) incident on a CH target.

of the distribution function in velocity space. This has the effect of producing a time varying "effective flux limiter" ($q_{\rm NL}/q_{\rm FS}$), plotted in Figure 2 for a 1.5-ns square laser pulse. A comparison of the predicted shock velocity evolution and optical depth modulation in an RMI experiment using the nonlocal model in a 1-D simulation is shown in Figure 3, with good agreement between theory and experiment observed. A similar simulation with a constant flux limit of 0.06 disagrees with the experimental observations.

3 Symmetric illumination direct-drive ignition

Ignition target designs are being validated with implosions on OMEGA [7]. Cryogenic and plastic/foam (surrogate cryogenic) targets that are hydrodynamically scaled from ignition target designs (laser energy $\sim$ target radius^3, laser power $\sim$ target radius^2, and time $\sim$ target radius) are imploded to investigate energy coupling, hydrodynamic instabilities, and implosion symmetry [5,34–36].

Routine cryogenic target implosions on OMEGA have required significant engineering and development [37]. Cryogenic implosions have been carried out on OMEGA for the last three years. Significant obstacles have been overcome, including cryogenic target transport, target survival, target layer survival, and target vibration at shot time. In a cryogenic target, perturbations of the inner ice surface seed RTI by both feedout during the acceleration phase and directly seeding the deceleration phase. Extensive research and development have produced inner ice-layer roughnesses [36,38] approaching the 1-μm rms requirement for ignition targets. The outer CH roughness is approximately an order of magnitude lower.

The effects of laser irradiation nonuniformities and target-surface roughness on implosion performance are modeled with the 2-D hydrodynamic codes *ORCHID* or *DRACO* [9]. The performance of imploded cryogenic D_2 capsules on OMEGA is close to the prediction of the 2-D hydrodynamic code *DRACO* [5,8] with yields a factor 2$\sim$4 of those required to validate direct-drive ignition predictions [4,5]. The highest average measured $\rho R \sim 100$ mg/cm^2 is $\sim$60% of 1-D predictions and very close to 2-D predictions [8]. Figure 4 shows the measured areal densities compared to 1-D simulations for various implosion adiabats (α = fuel pressure/Fermi-degenerate pressure). The current results are within a factor of $\sim$2 of achieving the NIF requirements on OMEGA. The

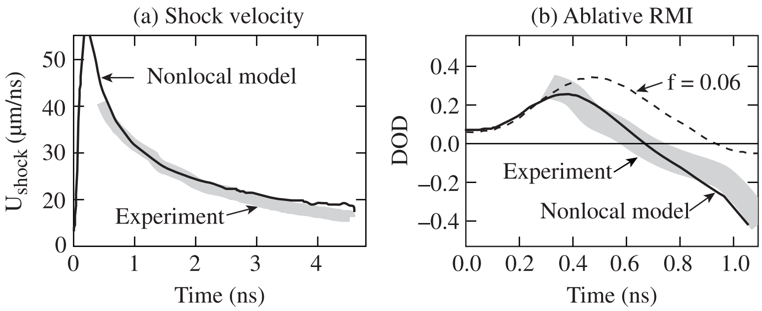

Fig. 3. (a) A comparison of measured and calculated shock velocity using the nonlinear heat flux for a 100-ps laser pulse incident on a CH target. (b) A comparison of the measured and calculated optical-depth modulation in an RMI experiment using the nonlinear heat flux. The result of a constant flux limiter ($f = 0.06$) is shown for comparison.

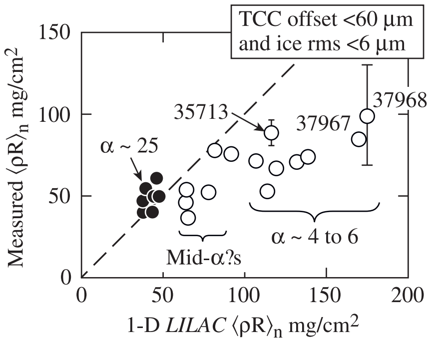

Fig. 4. Measured versus 1-D simulated areal densities for different cryogenic D_2 implosions (adiabats).

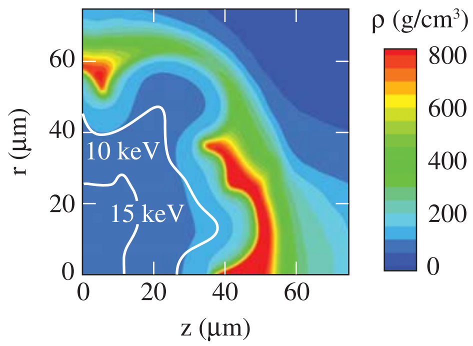

Fig. 5. 2-D temperature and density contours for a 2-D simulation of a PDD implosion on the NIF, near peak compression, using perfect single-beam nonuniformity. The predicted gain is 35 for a 1-MJ drive pulse.

dominant source of degradation at high predicted areal densities appears to be the inner ice-layer roughness. The hot-spot n_e and T_e profiles of an imploded cryogenic D_2 target have been inferred with gated X-ray core images and secondary neutron measurements. They are close to 1-D predictions with an inferred isobaric core pressure is ~5 Gbar [39].

The path to ignition involves DT cryogenic implosions. To this end, the D_2 Fill/Transfer Station (FTS) is presently being upgraded to provide concurrent DT and D_2 cryogenic operations on OMEGA. Initial cryogenic DT implosions are expected in 2006.

4 Polar direct drive on the NIF and OMEGA

Prospects for direct-drive ignition on the NIF while it is configured in its X-ray-drive irradiation configuration are favorable with polar direct drive (PDD) [10]. The PDD approach is based on optimizing the phase-plate design, beam pointing, and pulse shaping to minimize the spherical drive nonuniformity on an ignition capsule for the nonsymmetric illumination configuration of the NIF in its indirect-drive configuration. The baseline PDD design uses a scaled version of a NIF high-performance, wetted-foam, direct-drive target design. Initial 2-D simulations of the PDD target design predict ignition with gains similar to symmetric illumination [11,40]. Figure 5 shows the 2-D temperature and density contours for a 2-D simulation of a PDD implosion on the NIF, near peak compression, using perfect single-beam nonuniformity. The predicted gain is 35 for a 1-MJ drive pulse.

The development of the "Saturn" ring target [12] provides a complementary PDD approach. In this case, a plastic ring at the equator refracts laser light to the target equator during the implosion, improving the drive symmetry. Recent results have shown that Saturn target implosions with 40 laser beams in the PDD configuration at full energy have produced 75% of the neutron yield of a symmetrically illuminated (60-beam) implosion with each beam at 2/3 of the full energy [40].

5 Fast-ignition research on OMEGA/OMEGA EP

The fast-ignition (FI) concept for ICF [14] is an active area of research at LLE. Higher gains are predicted with FI than with hot-spot ignition. A high-energy petawatt (HEPW) capability is being constructed at LLE next to the existing 60-beam OMEGA Facility. The OMEGA EP (Extended Performance) laser will add two short-pulse (10- to ~100-ps), 2.6-kJ beams to the OMEGA Laser System to study FI physics with focused intensities up to 6×10^{20} W/cm^2. The HEPW beams will be integrated into the OMEGA compression facility for experiments beginning in 2008. OMEGA EP will also have two dedicated, long-pulse beams (6.5 kJ$_{UV}$/beam in 10 ns) for performing high energy density physics experiments in a separate target chamber [41]. In addition, one or both of the HEPW beams can operate in long pulse mode.

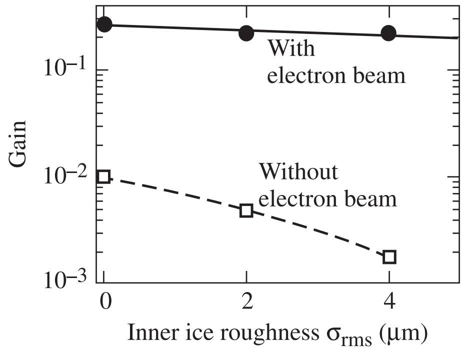

Fig. 6. The target gain, with and without the HEPW-generated electron beam, is plotted as a function of inner-ice-surface roughness, with the current low-order OMEGA illumination nonuniformity included, for a standard OMEGA cryogenic target.

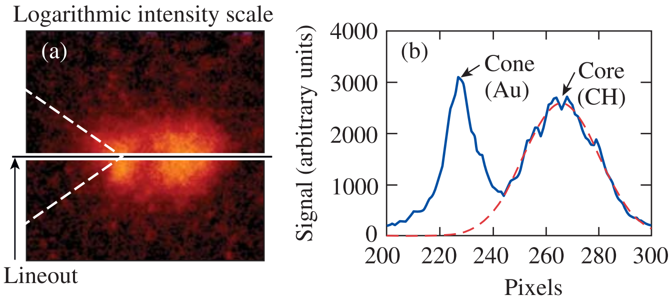

Fig. 7. Evaluation of cone-in-shell material mixing on surrogate implosions on OMEGA. X-ray self-emission from a cone-in-shell implosion (a) with a lineout shown in (b). The clear separation of the Au and CH emission shows that little Au is mixed into the compressed core of the implosion.

Experiments designed to validate fast ignition will be performed with scaled cryogenic capsules. A high-density fuel configuration will be assembled with the OMEGA compression facility, and OMEGA EP will produce suprathermal electrons via high-intensity laser–plasma interaction to heat the core. LLE is performing integrated 2-D simulations of combined OMEGA/OMEGA EP integrated fast-ignition experiments to be performed when OMEGA EP is completed. The modeling assumes that the high-energy electrons have a distribution function given by Wilks et al. [42] The electrons are propagated into the compressed core on straight-line trajectories and slowed using a recent stopping formula [43]. In the simulations, the energy (2.6 kJ) and pulse duration (10 ps) are kept constant while the beam radius determines the peak intensity. The self-consistent electron beam energy distribution is determined from the instantaneous intensity. Figure 6 shows the effect of target nonuniformities with and without the HEPW-generated electron beam. A cryogenic target is driven by a low-adiabat pulse. The target gain is plotted as a function of inner-ice-surface roughness with the current low-order OMEGA illumination nonuniformity included. For the case where the electron beam is included, the gain is essentially independent of target nonuniformity; without the electron beam, the gain drops by a factor of 5 as the ice roughness is increased from 0 to 4 μm rms. The neutron yield is $\sim 10^{14}$ without the HEPW laser beam, increasing to $\sim 3 \times 10^{15}$ for an optimally timed HEPW laser beam. If alpha transport and heating are not included, the predicted yield decreases. The decrease of gain with increasing ice nonuniformity is due to cooling of the central hot spot. When the electron beam is applied, the high and low density regions along its path are heated to almost the same final temperature, independent of initial temperature, leading to constant yields.

Surrogate direct-drive, fuel-assembly implosions with FI cone targets have been performed on OMEGA with a substantial fraction of the predicted core areal density measured. Gas-tight FI targets with a Au cone developed for fuel-assembly experiments were imploded on OMEGA [15]. Figure 7a shows the X-ray self-emission from a cone-in-shell implosion on OMEGA. The lineout in Figure 7b shows two distinct peaks, one from the gold emission from the entrained material and a second from the fuel-assembly-driven hot spot. The clear distinction between the two peaks provides an estimate that less than 0.01% of Au is mixed into the core material [15]. This result is extremely encouraging for the cone-in-shell fast-ignition concept.

6 Conclusions

The achievement of thermonuclear ignition with direct drive on the NIF, or any other megajoule-class laser system, is extremely promising. Significant experimental and theoretical progress has been achieved by LLE's direct-drive ICF program, charting the path to ignition. High-performance layered deuterium cryogenic targets are imploded on OMEGA to validate the hydrodynamic codes used to design direct-drive ignition targets. Initial cryogenic DT implosions are expected on OMEGA in 2006. Symmetric direct drive on the NIF is predicted to achieve high gain ($\sim$35) with adiabat shaping. Prospects for direct drive on the NIF while it is in its X-ray-drive irradiation configuration are also extremely favorable with polar direct drive. Initial 2-D simulations of the PDD target design have shown ignition with similar gains. Fully integrated fast-ignition experiments will begin on the OMEGA compression facility once the high-energy petawatt upgrade — OMEGA EP — is completed in 2007.

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