Progress in Direct-Drive Inertial Confinement Fusion Research
at the Laboratory for Laser Energetics

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Abstract: Significant theoretical and experimental progress toward the validation of direct-drive inertial confinement fusion (ICF) has been made at the Laboratory for Laser Energetics (LLE). Direct-drive ICF offers the potential for high-gain implosions and is a leading candidate for an inertial fusion energy power plant. LLE's base-line direct-drive ignition design for the National Ignition Facility (NIF) is an "all-DT" design that has a 1-D gain of ~45 (~30 when two-dimensional calculations are performed). The "all-DT target" consists of a thin (~3 μm) plastic shell enclosing a thick (~330 μm) DT-ice layer. Recent calculations show that targets composed of foam shells, wicked with DT, can potentially achieve 1-D gains ~100 at NIF energy levels (~1.5 MJ). The addition of a "picket" pulse to the beginning of the all-DT pulse shape reduces the target sensitivity to laser nonuniformities, increasing the potentially achievable gains. LLE experiments are conducted on the OMEGA 60-beam, 30-kJ, UV laser system. Beam smoothing includes 1-THz, 2-D SSD and polarization smoothing. Ignition-scaled cryogenic D_2 and plastic-shell spherical targets and a comprehensive suite of x-ray, nuclear, charged-particle, and optical diagnostics are used to understand the characteristics of the implosions. Recent cryogenic D_2 implosions with high adiabat ($\alpha \sim 25$) perform as predicted by one-dimensional (perfectly symmetric) simulations. Moderate-convergence-ratio (CR ~ 15), high-adiabat ($\alpha \sim 25$), warm-capsule (surrogates for cryogenic capsules) implosions produce >30% of the 1-D predicted neutron yield and nearly 100% of the predicted fuel and shell areal densities. From a combination of x-ray, nuclear, and particle spectroscopy, a "Lawson" fusion parameter ($n_i T_i \tau_i$) of ~7×10^{20} m$^{-3} \cdot$ s $\cdot$ keV was measured, the highest directly measured in inertial confinement fusion experiments to date. Estimates from cryogenic target performance give similar Lawson conditions. Future cryogenic target experiments will use "picket" pulse shapes to further validate direct-drive target performance. DT-fuel cryogenic implosions will be performed on OMEGA in the next two years.

1. Introduction

Significant theoretical and experimental progress has been demonstrated toward the validation of the direct-drive inertial confinement fusion (ICF) [1] concept at the University of Rochester's Laboratory for Laser Energetics (LLE). Direct-drive ICF offers the potential for higher gain than the indirect-drive approach. LLE's work gives increased confidence in the achievement of direct-drive ignition on the National Ignition Facility (NIF) [2,3] and suggests that direct-drive ICF is a viable candidate for an inertial fusion energy (IFE) power plant.

LLE's target physics research program combines all aspects of direct-drive ICF including early-time phenomena such as plasma formation and laser beam imprinting, Rayleigh–Taylor (RT) growth during the acceleration and deceleration phases, pusher–fuel mix at peak burn, and shock timing and coalescence. Key results of LLE's direct-drive ICF research include data from

cryogenic and surrogate (warm) capsule implosions and the results of design work on advanced capsules containing cryogenic DT-filled foams that may attain capsule gains of ~100 on the NIF.

A typical direct-drive ICF ignition target consists of a cryogenic target with a spherical DT-ice layer enclosed by a thin plastic shell. The 60-beam, 30-kJ OMEGA laser system has been used to implode both cryogenic and gas-filled (surrogate-cryogenic) plastic targets. Section 2 describes studies of surrogate target implosions. Results of cryogenic target experiments are described in Sec. 3, and advanced concepts to increase the target gain and stability are described in Sec. 4.

2. Surrogate Target Implosions

Implosions of surrogate targets on the OMEGA laser are important in developing an understanding of the physics of capsule implosions in the absence of the technological complications arising from fielding cryogenic-fuel capsules. The implosions are extremely well diagnosed and highly reproducible. This allows a wide variety of similar shell types and fill gases to be used in conjunction with a comprehensive suite of diagnostics to create a complete picture of the implosion.

ICF implosions are susceptible to the RT instability, which can lead to fuel–shell mixing and breakup of the target. Recent improvements in the irradiation uniformity have significantly increased the performance of gas-filled plastic-shell implosions [1]. Single-beam nonuniformity of 3% (averaged over 300 ps) was achieved with the full implementation of 1-THz bandwidth, 2-D smoothing by spectral dispersion (SSD), and polarization smoothing (PS) with birefringent wedges [4]. This corresponds to an on-target nonuniformity of less than 1% rms due to beam overlap. The beam-to-beam power imbalance has been reduced to below 5% rms. Moderate-convergence-ratio targets (CR ~ 15) produce ~30% of the neutron yield predicted by one-dimensional (1-D) hydrodynamic simulations and nearly 100% of their predicted fuel and shell areal densities. At predicted convergence ratios close to 40, the primary neutron yield is ~20% of the 1-D prediction. The moderate-convergence-ratio targets driven with a 1-ns square pulse have acceleration-phase stability characteristics similar to ignition-scaled cryogenic implosions.

In one series of experiments, CH polymer shells with an interior layer of CD and filled with ^{3}He were used to investigate fuel–shell mix as shown in Fig. 1 [5]. Neutron detectors, charged-particle spectrometers (CPS), and wedge-range-filter spectrometers (WRF) [6] were used to measure the D^{3}He fusion neutron and proton spectra from these implosions as a function of CD layer position. A relatively small fusion yield was produced when the CD layer was offset by 1 μm from the inside of the CH shell. Higher fusion yields were obtained when the CD layer was placed in the inner surface of the shell, adjacent to the ^{3}He. The yield is significantly higher than predicted for a clean (no mix) implosion, suggesting that it is due to compression-phase mix between the CD layer and the interior He gas. The fusion yield increases with decreasing fill pressure, suggesting that more-severe fuel–shell mix occurs in the higher-convergence-ratio, more-unstable implosions.

A second experiment designed to study fuel–pusher mix was conducted using Ar-doped, deuterium-filled CH shells [7]. The density of the shell material mixed into the outer core of the plastic shell was estimated using time-resolved x-ray spectroscopy, nuclear measurements, and core x-ray imaging. Electron densities of ~5×10^{24} cm^{-3} and electron temperatures of ~2.5 keV were measured for 3-atm-deuterium-filled capsules as seen in Fig. 2. Higher-fill-pressure (15 atm), lower-convergence-ratio targets (CR ~ 15), have lower peak densities and electron temperatures (Fig. 3). When the x-ray data are integrated with core fuel-areal-density measurements and gated x-ray images, the composition of the compressed core may be determined as shown in Table I. For the CR ~ 15 capsules, this procedure results in an estimated mass
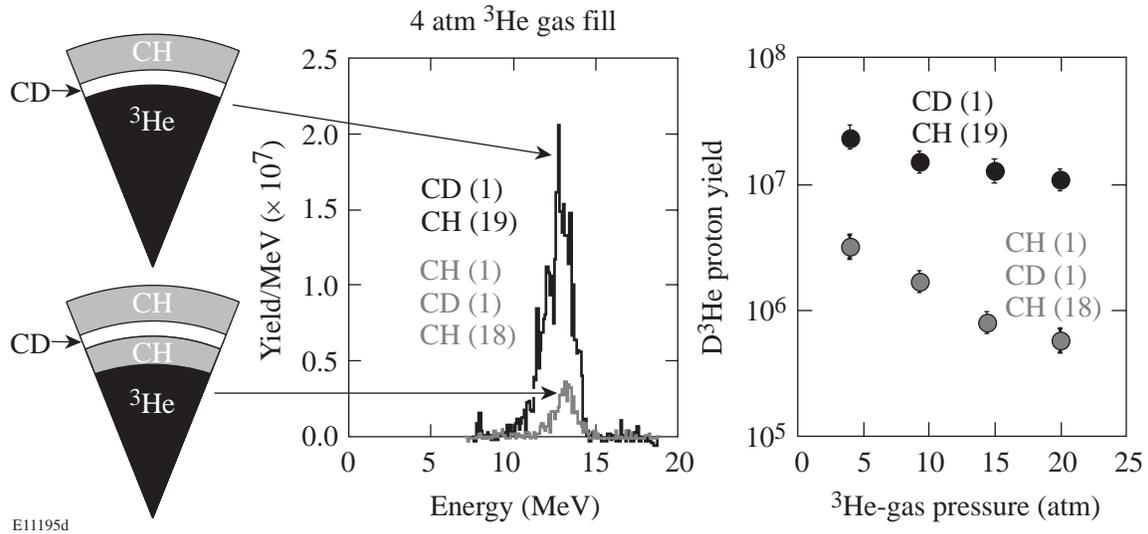
FIG. 1. *Proton yield and spectrum as measured with an array of WRF spectrometers in implosions of*
^{3}He-filled (4 to 20 atm) CH shells containing a 1-μm-thick layer of CD. On targets with a CD layer
located 1 μm away from the gas, the D^{3}He proton yield is less than one-tenth that of the targets with the
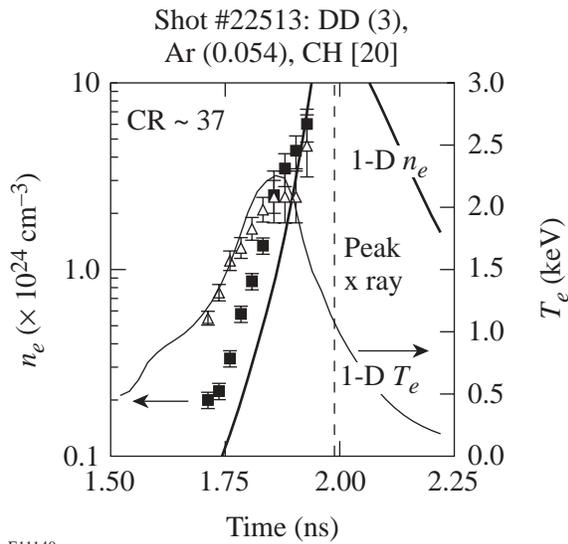*CD layer adjacent to the ^{3}He gas.*

FIG. 2. *Electron density and temperature as*
functions of time during the implosion of a
20-μm-thick CH shell filled with 3 atm of D_2
and 0.054 atm of Ar. The triangles (electron
temperature) and squares (electron density)
indicate the experimental measurements inferred
from time-resolved Ar spectroscopy; the solid
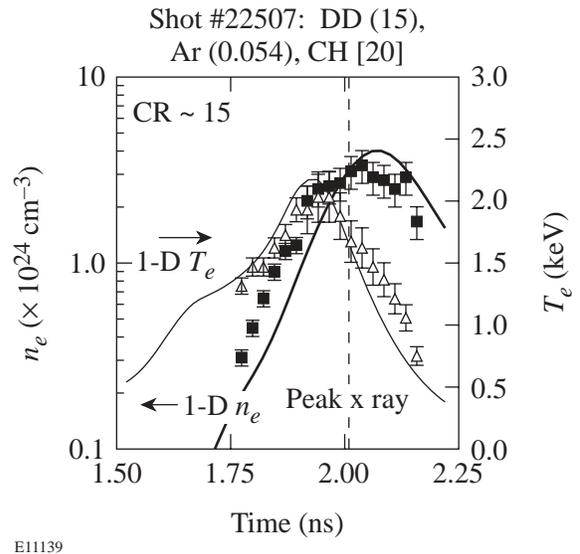*lines represent the 1-D hydrodynamic code*
predictions.

FIG. 3. *Electron density and temperature as*
functions of time during the implosion of a
20-μm-thick CH shell filled with 15 atm of D_2
and 0.054 atm of Ar. The data for both Figs. 2
and 3 were obtained using a spectrally resolved
x-ray streak camera.

composition in the mix region of ~1/2 deuterium and 1/2 CH. The increased electron density due to the mixed material can be clearly seen in the higher measured electron density compared to the predicted (1-D) value.

The electron temperature is ~1.9 keV averaged over the duration of the 170-ps neutron burn width. This results in a total (electron and ion) pressure of ~11 Gbars and an $n\tau T$ product of $7 \times 10^{20} \, \text{m}^{-3} \cdot \text{s} \cdot \text{keV}$. This is the highest Lawson fusion parameter directly measured in inertial fusion experiments and is comparable to the highest-performance Tokamak experiments [8].

A self-consistent analytical model was developed that produces an experimentally constrained set of core properties for the CR ~ 15 implosions [1,9]. As shown in Table II, the model reproduces most of the experimental observables including fuel areal density, neutron rate, burn width, ion temperatures, secondary particle ratios, and fusion yields. A different model of the structure of the compressed core parameters [5] reaches similar conclusions about the amount of mix in these implosions.

TABLE I: Core parameters estimated for Ar-doped, D_2-filled CH shell implosions.

DD (15), Ar (0.054), CH [20]	
$n_e(\text{CH}) = n_e - n_e(\text{D}) - n_e(\text{Ar})$	
n_e	$2.2 \times 10^{24} \, \text{cm}^{-3}$ (averaged over 170-ps neutron burnwidth)
T_e	1.9 keV (averaged over 170-ps neutron burnwidth)
N_e (D)	$1.1 \times 10^{24} \, \text{cm}^{-3}$
N_e (Ar)	$3.3 \times 10^{22} \, \text{cm}^{-3}$
N_e (CH)	$1.1 \times 10^{24} \, \text{cm}^{-3}$
ρ_{CH}	3.4 ($\pm$1.2) g/cm^3
ρ_f	3.6 ($\pm$1.0) g/cm^3

TABLE II: Comparison of experimentally measured implosion observables to the analytical model results of Ref. [9].

Parameter	Measurement	Model (% of experiment)
Fuel ρR (mg/cm^2)	15±3	100
Peak neutron production rate (s^{-1})	$(9\pm2) \times 10^{20}$	120
Burnwidth (ps)	170±20	94
T_{ion} (D$_2$) (keV)	3.7±0.5	90
Secondary neutron ratio	$(2.1 \pm 0.4) \times 10^{-3}$	90
Secondary proton ratio	$(1.8\pm0.3) \times 10^{-3}$	100
D^{3}He proton yield	$(1.0\pm0.2) \times 10^7$	100
D$_2$ neutron yield	$(4.5\pm1.5) \times 10^8$	135
T_{ion} (CD) (keV)	1.7±0.5	110

3. Cryogenic Fuel-Layer Capsule Implosions

A multi-year science and engineering effort implemented a reliable and precise cryogenic target experimental capability on the 60-beam OMEGA laser system. The original 24-beam OMEGA cryogenic system was capable of forming thin (~ a few micron thick) DT-ice layers in thin glass shells [10,11]. The new Cryogenic Handling System forms ~100-μm-thick DT layers in very thin (a few microns) polymer shells [12].

The target adiabat α, where α is the ratio of the pressure to the Fermi-degenerate pressures is varied in OMEGA cryogenic target implosions. The adiabat determines the RT stability of the target, with higher α leading to a more stable implosion, but lower predicted ignition gains. The results of the initial D_2 cryogenic target implosions with high adiabat ($\alpha \sim 25$) were impressive [13]. Recent results include primary neutron yields of ~1.3×10^{11}, up to 100% of those predicted by clean, one-dimensional simulations, and areal densities of ~61 mg/cm^2, comparable to, or even exceeding, the predicted values (Fig. 4). While these targets are predicted to be more stable than the targets required for ignition, they provide optimism about ignition target performance as the capability for manufacturing high-quality cryogenic targets continues to improve. Recent experiments with lower-adiabat ignition-scaled pulses ($\alpha \sim 4$–5) with stability characteristics similar to those of the base-line NIF direct-drive pulses have produced primary neutron yields ~19% of clean, 1-D predictions and areal densities up to 80 mg/cm^2.
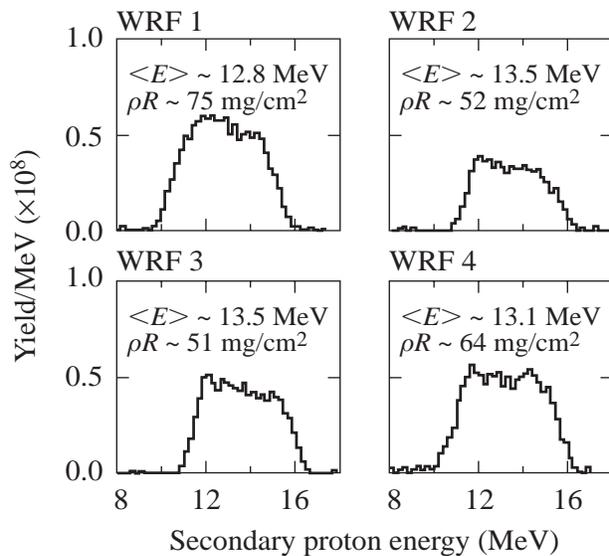

FIG. 4. Secondary proton spectra measured with four WRF spectrometers on a high-adiabat cryogenic target shot (28900). The average areal density estimated by these spectra is ~61±11 mg/cm^2. One-dimensional hydrocode predictions of the capsule areal density for this shot were 45 mg/cm^2.

4. Advanced Direct-Drive Target Concepts

LLE's base-line direct-drive ignition design for the National Ignition Facility (NIF) is an $\alpha = 3$, all-DT design (a spherical DT-ice layer enclosed within a thin CH shell), which has been theoretically shown to be sufficiently stable and to have a 1-D gain of ~45 at a drive energy of ~1.5 MJ [3]. This gain is reduced to ~30 when the 2-D effects of the anticipated levels of laser and target nonuniformities are included. Recent work has led to a target design comprised of a spherical foam shell wicked with DT. The advantage of this "wetted-foam" design over the "all-DT" target is the presence of a relatively higher-Z material (CH) in the laser deposition region, resulting in increased laser absorption. For the NIF designs, the laser absorption increases from 60% absorption in DT to 85% in the wetted foam. The increased absorbed laser energy allows the capsules to contain an increased amount of fuel. The wetted-foam targets are thicker and less sensitive to the acceleration-phase RT instability and have higher target gain. The principal

result of the initial design work is that the wetted-foam designs achieve target gains approaching 100 (see Fig. 5). Detailed two-dimensional hydrodynamic simulations are in progress.

To improve the stability aspects of high-performance capsules, advanced targets using an initial intensity spike to shape the adiabat inside the shell are being developed (see Fig. 6). This places the outer regions of the shell on a higher adiabat, reducing the seeds and growth rate of the RT instability, while maintaining the low adiabat in the main fuel region, preserving the target gain. Initial adiabat-shaping experiments conducted with warm CH shells show a dramatic improvement in target performance (Fig. 7) [14].
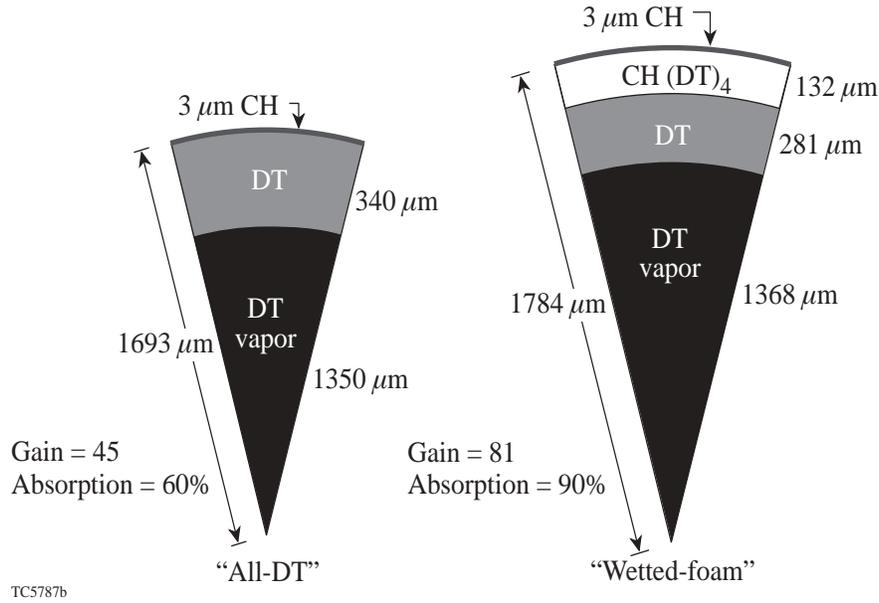

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FIG. 5.   *Schematic representation of a base-line NIF direct-drive target (all-DT) compared to the "wetted-foam design."*
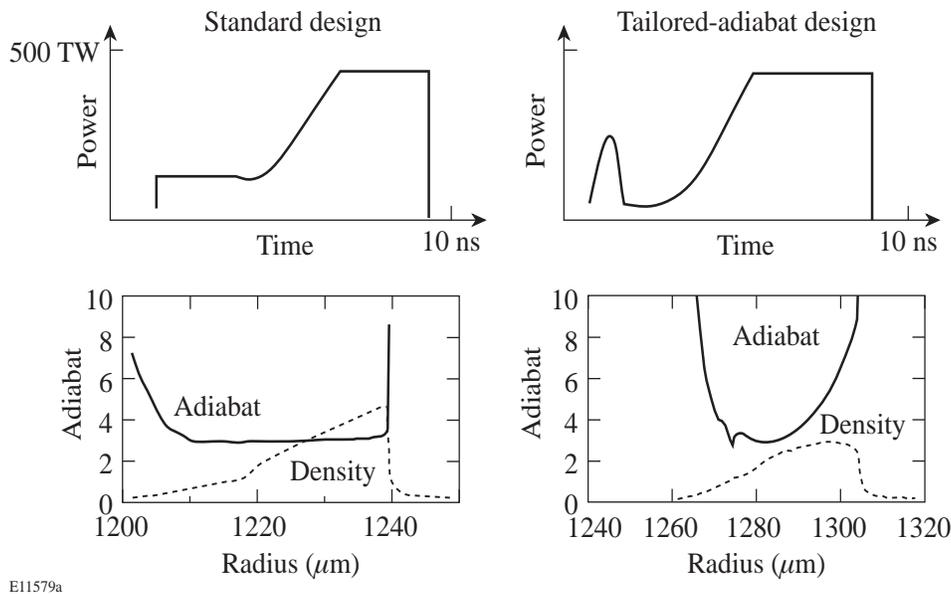

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FIG. 6. *Illustrations graphically demonstrating the effect of an intensity spike on the capsule implosion. The intensity spike at the leading edge of the slowly rising pulse raises the adiabat during the critical acceleration phase of the implosion for improved hydrodynamic stability but maintains a relatively low adiabat at the fuel–shell interface until late in the implosion to maximize the efficiency of the implosion.*
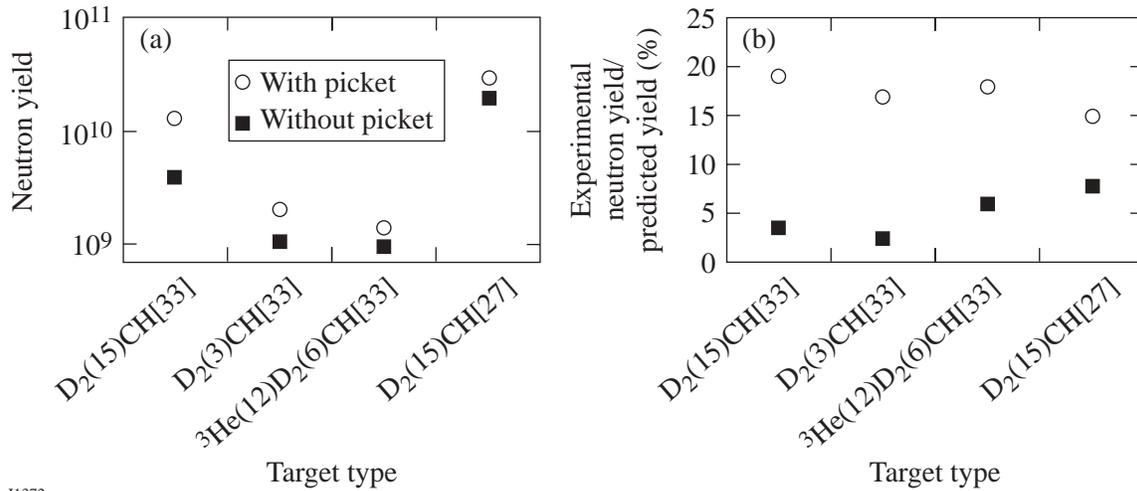
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FIG. 7. Results from experiments to investigate the effect of an intensity spike (picket fence) on the leading edge of the pulse. (a) The absolute value of the neutron yield from D_2- and D_2-^{3}He-filled CH shell implosions driven with nearly identical energy and similar pulse shapes except for a leading-edge picket. The shots with a picket pulse resulted in ~2-times-higher yield. (b) The ratio of experimental neutron yield over that calculated using a 1-D hydrodynamic code assuming a clean no-mix implosion. The numbers in parentheses correspond to the pressure of the fill, and the numbers in square brackets correspond to the CH-shell thickness in microns. Thicker shells generally are more stable and less prone to breakup and mix than very thin shells.

5. Prospects for Direct-Drive Experiments on the NIF

The successful demonstration of high-quality cryogenic capsule implosion experiments on OMEGA is a prerequisite for the implementation of direct drive on the NIF. While aspects of the NIF system are designed "not to preclude" the direct-drive option, the full implementation of direct-drive moving beams to the equatorial positions to symmetrically irradiate capsules may be expensive, in both funds and time. An alternative option currently being investigated is the use of the base-line (indirect-drive) irradiation configuration for direct-drive experiments. This may be possible by repointing some of the beams to obtain an irradiation pattern similar to the original 24-beam OMEGA. The penalty with asymmetric illumination may be mitigated by the clever use of phase-plate design, beam pointing, pulse shaping, and ice layer/capsule shimming.

6. Conclusion

In conclusion, the experimental and theoretical progress achieved by LLE's direct-drive ICF program increases the confidence in the achievement of direct-drive ignition on the NIF. LLE's research covers all aspects of direct-drive inertial fusion. Cryogenic and surrogate-cryogenic (warm) implosions have increased the understanding of direct-drive capsule physics, and recent cryogenic target results are very encouraging. Advanced target designs using wetted foams may allow significantly higher gains than the base-line NIF direct-drive targets. Picket-fence, adiabat-shaping pulses may control the pusher adiabat to mitigate the deleterious effects of hydrodynamic instabilities while still keeping the efficiency associated with low-adiabat pulses.

References

[1]   MEYERHOFER, D.D., et al., "Core performance and mix in direct-drive spherical implosions with high uniformity", Phys. Plasmas **8** (2001) 2251–2256.

[2]   McCRORY, R.L., et al., "OMEGA ICF experiments and preparations for direct drive on NIF", Nucl. Fusion **41** (2001) 1413–1422.

[3]   McKENTY, P.W., et al., "Analysis of a direct-drive ignition capsule designed for the National Ignition Facility", Phys. Plasmas **8** (2001) 2315–2322.

[4]   REGAN, S.P., et al., "Experimental investigation of smoothing by spectral dispersion", J. Opt. Soc. Am. B **17** (2000) 1483–1489.

[5]   LI, C.K., et al., "Effects of fuel-shell mix upon direct-drive, spherical implosions on OMEGA", Phys. Rev. Lett. **89** (2002) 165002.

[6]   SÉGUIN, F.H., et al., "Spectrometry of charged particles from inertial-confinement-fusion plasmas", to be published in Rev. Sci. Instrum. (2 December 2002).

[7]   REGAN, S.P., et al., "Shell mix in compressed core of spherical implosions", Phys. Rev. Lett. **89** (2002) 085003.

[8]   HAWRYLUK, R.J., et al., "Fusion plasma experiments on TFTR: A 20 year retrospective", Phys. Plasmas **5** (1998) 1577–1589.

[9]   RADHA, P.B., et al., "Inference of mix in direct-drive implosions on OMEGA", Phys. Plasmas **9** (2002) 2208–2213.

[10]   McCRORY, R.L., et al., "Laser-driven implosion of thermonuclear fuel to 20 to 40 g cm^{-3}", Nature **335** (1988) 225–230.

[11]   MARSHALL, F.J., et al., "Cryogenic-laser-fusion target implosion studies performed with the OMEGA UV-laser system", Phys. Rev. A **40** (1989) 2547–2557.

[12]   BESENBRUCH, G.E., et al., "Design and testing cryogenic target systems", in *Inertial Fusion Sciences and Applications 99*, LABAUNE, C., HOGAN, W.J., TANAKA, K. (Eds.), Elsevier, Paris (2000) 921–926.

[13]   STOECKL, C., et al., "First results from cryogenic target implosions on OMEGA", Phys. Plasmas **9** (2002) 2195–2201.

[14]   KNAUER, J.P., et al., "Improved performance of direct-drive implosions with a laser-shaped adiabat", submitted to Phys. Rev. Lett.