

Cryogenic target-implosion experiments on OMEGA

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Abstract. The University of Rochester's Laboratory for Laser Energetics has been imploding thick cryogenic targets for six years. Improvements in the Cryogenic Target Handling System and the ability to accurately design laser pulse shapes that properly time shocks and minimize electron preheat, produced high fuel areal densities in deuterium cryogenic targets (202 ± 7 mg/cm²). The areal density was inferred from the energy loss of secondary protons in the fuel (D₂) shell. Targets were driven on a low final adiabat ($\alpha = 2$) employing techniques to radially grade the adiabat (the highest adiabat at the ablation surface). The ice layer meets the target-design toughness specification for DT ice of 1- μ m rms (all modes), while D₂ ice layers average 3.0- μ m-rms roughness. The implosion experiments and the improvements in the quality and understanding of cryogenic targets are presented.

1. Introduction

Inertial confinement fusion (ICF) ignition designs require the implosion of targets with thick cryogenic DT layers [1]. Targets imploded on OMEGA [2] are energy scaled from National Ignition Facility (NIF) ignition targets. The key physics issues are expected to be the same. This work shows that a high-fuel-area density can be achieved at peak compression that would, once a temperature of ~ 10 keV is achieved, lead to NIF ignition. Calculations indicate that the areal density depends primarily on the laser energy and the fuel adiabat (the ratio of the shell pressure to the Fermi-degenerate pressure) [3]. The sensitivity of the measured areal density to the target adiabat is studied. The intensity of the laser was varied from 0.2 to 1.5×10^{15} W/cm² and the measured areal density is sensitive to changes in the adiabat caused by (1) shock heating and (2) preheat of the fuel by radiation or suprathermal electrons [4].

The performance of the Cryogenic Target Handling System (CTHS) controls the quality of the implosion. The influence of the CTHS on the availability and quality of targets, and the commonality of the cryogenic target science to indirect-drive ICF make these results essential to the national ICF program.

2. The direct-drive-target design

The OMEGA ignition-scaled target is a spherical shell with a thin-wall hydrocarbon ablator containing a thick (70- to 95- μm) DT cryogenic layer [5] (Fig. 1). The implosion velocity at an intensity of $9 \times 10^{14} \text{ W/cm}^2$ is $2.8 \times 10^7 \text{ cm/s}$. D_2 cryogenic targets provide accurate areal density measurements from the neutron-averaged secondary proton spectrum obtained at the 10^{10} to 10^{11} neutron yield levels [6].

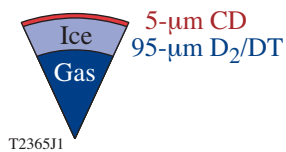


Figure 1. The OMEGA-scaled, direct-drive cryogenic target.

3. The CTHS

Cryogenic D_2 (DT) experiments began in 2001 (2006) and 162 [36 (45% D, 55% T)] targets have been imploded. Targets are permeation filled over a three-day-production cycle. The OMEGA CTHS functions as designed as measured by production times and safety performance. The two remaining areas where its performance affects the experimental campaigns are: (1) the position of the target relative to the focus of the laser beams at the moment of implosion and (2) the smoothness of the D_2 ice layer. Cryogenic DT targets meet the ice-layer smoothness target-design specifications.

3.1 Target position

When the thermal shroud is removed to expose the target for implosion, a small mechanical impulse is imparted to the target assembly that does not damp before the target is imploded. This motion results in the target being displaced from the optimal position. Improvements to the system have reduced the target offset to its current median value of 25 μm . The calculated effect of a 25- μm offset is to halve the neutron yield but not affect the areal density.

3.2 Cryogenic target ice roughness

Targets with DT ice meet the ice-roughness specification of 1.0- μm rms. Targets containing only deuterium ice possess a median roughness of 3.0 μm , ranging from 1.3 to 7.0 μm [7]. The ice roughness is measured using optical shadowgraphy, [8]. A Fourier cosine-power spectrum to the great circle defining the gas-ice interface gives a single 2-D ice-roughness distribution [Fig. 2(a)]. Rotating the target in 15° increments and acquiring multiple images allows a 3-D surface to be constructed [Fig. 2(b)]. Spherical harmonics ($Y_{\ell m}$) are calculated from the measured radial position of the ice-gas interface to quantify the roughness of the lower mode number (<15) [7]. Higher mode numbers are determined by averaging the Fourier power spectra [9], with a representative power spectrum shown in Fig. 2(c).

The roughness of the ice layer is affected: the quality of the ice crystal that forms during the “layering” process [10] and external thermal perturbations imprinted into the ice. Cooling the target through the triple point (0.001 K/min) allows a single seed crystal to nucleate at the top of the target from which the ice crystal propagates. The ice smoothness that results from repeatedly melting and reforming defect-free ice crystals is reproducible with the variation in the resulting ice roughness of less than 0.3 μm .

All thermal perturbations to DT targets have been eliminated. The smoothest DT targets have an rms roughness of 0.5 to 0.6 μm for the first 100 modes. The median ice-roughness value for all DT targets is 1.0 μm . D_2 targets are affected by the external heat source (IR light at the D_2 absorption wavelength, 3.16 μm) [11] that is needed to produce a thermal gradient for layering. The infrared light is absorbed by the target support affecting the ice roughness [12]. The heat deposited in the support has been minimized, reducing the thermal imprint so that the smoothest D_2 ice layer possessed an rms roughness of 1.3 μm . This process is not currently sufficiently repeatable.

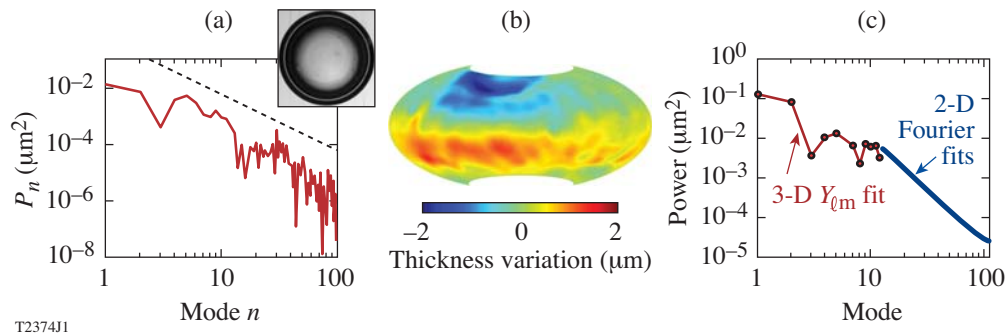


Figure 2. (a) Shadowgraph of a cryogenic target with a 95- μm DT ice layer and a 2-D roughness spectra for the ice surface (dashed line—ice-roughness specification). (b) A 3-D surface map displayed as an Aitoff projection. (c) The power spectrum used to describe the surface.

The quality of the ice layer is evaluated 0.05 s before a cryogenic target implosion from a single 2-D image of the ice layer. The gas density is determined by a combination of experiments and calculations. The calculated time-dependent response of the target duplicates the observed melting behavior and allows the response of the target over short, non-observable time increments to be estimated [12]. Experiments and calculations show the target melts within 10 s; extrapolating the behavior to shorter times shows that the pressure in the gas void begins to rise rapidly after 0.4 s. The rapid shroud retraction employed on OMEGA reduces the exposure time to <0.2 s.

Future cryogenic experiments will require targets with an internal wetted-foam wall. A transparent DT ice layer (91 μm) in a foam wall target (5- μm CD ablator, 65- μm foam wall—120 mg/cm^2) with a roughness of 1.5- μm rms has been observed.

4. Experimental implosion results

The fuel areal density at peak compression depends primarily on the energy of the laser and the adiabat of the fuel [3]. The fuel areal density is measured in a series of cryogenic target implosions with varying laser intensity on target (0.2 to $1.0 \times 10^{15} \text{ W}/\text{cm}^2$) and laser pulse shape, which determines the fuel adiabat. The neutron-averaged areal density was inferred from the energy loss of secondary protons produced in the core [6]. Five independent measurements of the secondary proton spectrum were made for each shot. The thickness of the plastic ablator was varied between 5 and 10 μm , and noncryogenic targets with thicker, mass-equivalent plastic ablators were imploded for comparison with cryogenic performance.

An areal density of $202 \pm 7 \text{ mg}/\text{cm}^2$ was obtained with the laser pulse shown in Fig. 3. The averaged secondary proton spectrum (Fig. 4) is overlaid with the spectrum predicted by a 1-D simulation (*LILAC*) weighted according to the experimentally measured neutron burn profile [13] showing close agreement (1-D simulation predicted areal density was 224 mg/cm^2). The D_2 neutron yield was 7.7×10^9 neutrons. The target possessed a 10- μm CD ablator, 95 μm of D_2 ice, an ice roughness of 2.3 μm , and was offset from the optimal position by only 19 μm . A second target (same ablator and ice

thickness, 2.7- μm ice roughness, and 24- μm target offset), was imploded with a laser pulse where the timing between the picket and the compression pulse was decreased by 200 ps relative to the first implosion. The averaged areal density decreased (as expected) to $182 \pm 7 \text{ mg/cm}^2$ (1-D predicted areal density was 192 mg/cm^2).

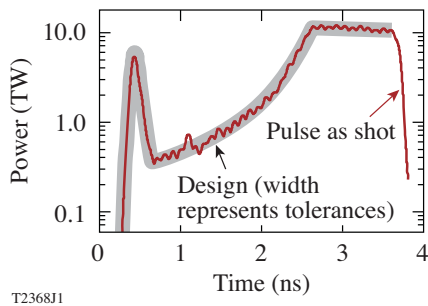


Figure 3. The laser pulse shape (solid red line) used to achieve the high-areal-density value (202 mg/cm^2) is shown. The outline surrounding the shape represents the tolerance for the design.

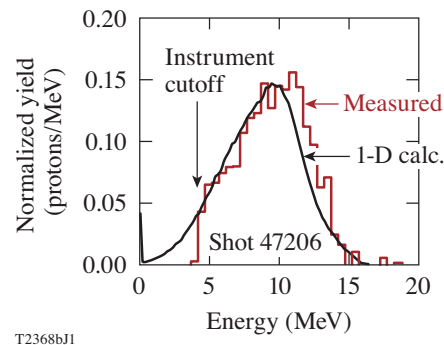


Figure 4. Secondary D^3He spectrum consistent with an areal density of $202 \pm 7 \text{ mg/cm}^2$.

5. Summary

These results show that ignition-relevant fuel areal densities can be achieved using cryogenic target implosions. The infrastructure needed to conduct cryogenic experiments is operational and the target quality is acceptable. Future experiments will be carried out with higher implosion velocities (minimum of $3.5 \times 10^7 \text{ cm/s}$) using thinner cryogenic shells and higher laser intensities.

Acknowledgment

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