Progress in Cryogenic Target Implosions on OMEGA

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Abstract. Cryogenic deuterium–tritium targets are imploded on the OMEGA Laser System in a direct-drive configuration. Areal densities of approximately 200 mg/cm² have been measured with implosion velocities of $3 \times 10^7$ cm/s. These implosions are used to study the dynamics of cryogenic target compression and to develop areal-density diagnostics that will be used as part of the ignition campaign on the National Ignition Facility.

1. Introduction

Most inertial confinement fusion (ICF) ignition target designs rely on the high compression of a spherical shell of deuterium–tritium (DT) ice surrounded by an ablator, commonly referred to as “hot-spot” ignition [1,2]. If the appropriate compressed-target conditions are created, a central low-density region with an ion temperature of 5 to 10 keV and an areal density of 0.2 to 0.4 g/cm² surrounded by a cold compressed shell with an areal density of 1 to 3 g/cm², the $\alpha$-particle heating from the DT reactions will lead to a thermonuclear instability, known as ignition, that will produce significant fusion output. The capsule can be driven with x rays generated within a hohlraum (indirect drive) [2] or directly by a laser system (direct drive) [3]. The initial ICF ignition experiments on the National Ignition Facility (NIF) will use indirect drive to compress a Cu-doped Be or Ge-doped CH ablator surrounding a DT-ice shell [4].

Cryogenic DT target implosions are carried out on the 60-beam OMEGA Laser System [5]. Direct-drive illumination is used on OMEGA because it can couple significantly more energy to the compressed capsule than indirect drive, making it possible to achieve higher areal densities with ignition-relevant implosion velocities.

Current cryogenic target implosions on OMEGA have implosion velocities of $3 \times 10^7$ cm/s and produce total areal densities of ~200 mg/cm² and neutron-averaged ion temperatures in excess of 2 keV. They provide the only current opportunity to study the dynamics of hot-spot formation and to develop the techniques that will be used to diagnose the areal density of ignition experiments on the NIF. This article is divided into four sections. Section 2 describes some of the diagnostic
development being carried out and Sec. 3 describes progress in understanding the performance of cryogenic target experiments with ignition-relevant implosion velocities. The article is summarized in Sec. 4.

2. Measuring the areal density in cryogenic-DT implosions

A traditional technique to determine the areal density of compressed DT targets is measuring the knock-on deuteron (triton) spectrum [3,6]. The 14.1-MeV neutrons that are produced in the DT–fusion reaction collide with ions in the compressed shell, giving them MeV energies. As the energetic ions pass through the remaining fuel, they are slowed down by Coulomb scattering. The areal density of the compressed target is inferred from the resulting energy spectrum. When the areal density of the target exceeds approximately 150 mg/cm², the knock-on spectrum becomes insensitive to the areal density (saturation) and the knock-on particles can no longer be used to measure the areal density of the target.

New diagnostic techniques are being developed to measure areal densities of 200 mg/cm² and higher to understand the OMEGA cryogenic experiments and for the ignition campaigns on the NIF. There are two basic ways to diagnose high areal densities [7]: externally backlight the implosion using a high-energy petawatt laser system such as OMEGA EP [8] or the Advanced Radiographic Capability (ARC) for the NIF [9], or use “self-backlighting” by the 14.1-MeV neutrons produced in the hot spot. The use of the knock-on spectra at lower areal densities is an example of this type of “self-backlighting.” Figure 1 shows a schematic of the various ways that the neutrons can be used for “self-backlighting.” The neutrons can collide with the compressed-shell materials, reducing their energy so that the down-scattered neutron energy spectrum is determined by the areal density of the compressed fuel. The same collisions can produce neutrons with energies greater than 14.1 MeV through the collisional acceleration of D or T ions followed by a subsequent “in-flight” DT–fusion (tertiary) reaction [10]. A measurement of the neutron-energy spectrum, or a portion of it, makes it possible to determine the target areal density.

Figure 1. Various collisional processes undergone by the 14.1-MeV neutrons from the hot spot that make it possible to infer the areal density of the compressed shell.

Diagnostic techniques to measure the neutron energy spectrum and, therefore, infer the target areal density are being developed on OMEGA by LLE and MIT [6,11–14]. These include the use of gated neutron time-of-flight detectors (nTOF’s), 12C activation to measure the tertiary neutron yield, and the magnetic recoil spectrometer (MRS) [11–14]. On OMEGA, the tertiary yield is proportional to \((\rho R)^2\) while at higher areal densities it is proportional to \(\rho R\). The basic principle of the MRS is that the neutrons emitted from the target interact with a CH or CD foil. Nearly head-on collisions produce H or D ions that are subsequently analyzed with a magnetic spectrometer. Since the neutron collisions with H or D are understood kinematically, a measurement of the H or D spectrum, along with the instrumental response, allows the neutron spectrum to be inferred. In the following section, initial data from the MRS will be used to infer the areal density of OMEGA cryogenic-DT target implosions.
3. Performance of cryogenic-DT implosions

In results from cryogenic implosions on the OMEGA Laser System reported previously, areal densities of ~200 mg/cm² were measured with implosion velocities of $2.2 \times 10^7$ cm/s [15,16]. While this was an important step toward ignition-scaled implosions on OMEGA, the velocity was too low ($2.2 \times 10^7$ cm/s) to allow scaling to ignition implosions on the NIF. It was found that the continuous pulse shapes (that were scaled from the NIF direct-drive baseline target design [17]) were very sensitive to the details of the pulse shape, producing two shock waves propagating through the target rather than the desired shock wave followed by a compression wave [18]. The baseline direct-drive-target design was changed to one that produces a series of four shock waves that are timed appropriately to produce the desired compressed-target conditions. A representative pulse shape is shown in Fig. 2. This “triple-picket” pulse shape produces a shock-wave structure that is similar to that used for the initial indirect-drive implosions planned for the NIF [4]. The advantage of this pulse shape is that the timing and energy of the pickets can be easily experimentally tuned to optimize target performance. The picket timing/energy has been tuned using direct measurements of the shock timing in “key-hole” targets [19]. The implosion velocity is $3 \times 10^7$ cm/s with an adiabat of 2, where the adiabat $\alpha$ is the ratio of the shell pressure to the Fermi-degenerate pressure at the same density. The target was driven with the pulse shape shown in Fig. 2 with a total on-target energy of 23 kJ. The peak intensity was $8 \times 10^{14}$ W/cm². The beams were smoothed with distributed phase plates [20] and polarization smoothing [21].

A second requirement for cryogenic target implosions is that the target nonuniformity be small enough to achieve ignition-relevant performance. Figure 3 shows a shadowgraphic image of a DT target used to study hot-spot formation. The target is a 5-μm-thick CH shell containing a 65-μm-thick DT-ice layer. The inner-ice-surface roughness is 1.8-μm rms, slightly above the ignition design requirement [17].

![Figure 2](image2.jpg)

**Figure 2.** Laser pulse shape (per beam) used in the current OMEGA cryogenic target implosions.

![Figure 3](image3.jpg)

**Figure 3.** Shadowgraph of a stalk-mounted cryogenic-DT capsule used for these experiments with an inner-ice roughness of 1.8-μm rms.

The areal density of the compressed shell was inferred from the MRS data. Figure 4 shows the deuteron spectrum measured by the MRS, generated by collisions of the neutrons leaving the target with a diagnostic CD foil. The blue line is a fit to the data that is generated by taking test neutron spectra and convolving them with the MRS instrumental response. In this case, the inferred areal density was $179\pm34$ mg/cm². The knock-on deuteron spectra measured from two other directions were saturated. This is consistent with this areal density.
An ion temperature of 2.2±0.5 keV was inferred using the nTOF detector [22,23]. The total neutron yield was $3.4 \times 10^{12}$, approximately 5% of that predicted by 1-D simulations.

4. Summary

Figure 5 compares the new data obtained with the triple-picket-pulse shape to that obtained previously with a continuous pulse shape having a peak intensity of $5 \times 10^{14}$ W/cm² [15,16]. The data points are plotted versus their neutron-averaged ion-temperature and areal density. This provides a Lawson-like criterion to determine the scaling to ignition [24,25]. The blue line represents a 1-D marginal ignition threshold and the yellow shaded region is where ignition and gain would be obtained. The black line represents a set of hydrodynamically equivalent designs (varying laser energy) that have a velocity of $4 \times 10^7$ cm/s using a continuous pulse shape. The yellow point shows the NIF baseline point design [17] scaled to OMEGA energies.
gain would be obtained. The black line represents a set of hydrodynamically equivalent designs (varying laser energy) that have a velocity of $4 \times 10^7$ cm/s using a continuous pulse shape. The yellow point shows the NIF continuous pulse-shape point design [17] scaled to OMEGA energies.

The areal density measured with the triple picket pulse is similar to that of the continuous pulse shape while the triple picket design has a higher implosion velocity and a higher ion temperature, moving toward the line that is hydrodynamically scaled from the direct-drive-ignition point design for the NIF [17].

In summary, progress continues in understanding cryogenic-DT implosions on OMEGA and developing areal-density diagnostics that will be used for the ignition campaign on the NIF. A new triple-picket-pulse shape makes it possible to experimentally tune the multiple shock waves and to develop high-velocity ($>3 \times 10^7$ cm/s) implosions for OMEGA cryogenic target experiments in the near future.

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