High Yields in Direct-Drive Inertial Confinement Fusion Using Thin-Ice DT Liner Targets

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Achieving the thermonuclear instability known as “ignition” in inertial confinement fusion implosions requires high levels of compression and large fusion yields.[1] This summary centers around a new target design—the thin-ice DT liner—that is intended to greatly increase neutron yields from direct-drive implosions on OMEGA.

Nominal OMEGA cryogenic implosions are able to produce implosion velocities v_{imp} within the range of 350 to 450 km/s, which generate ion temperatures ~5 keV when the deuterium–tritium (DT) shell stagnates at the target center.[2] The implosion velocity can be increased to over 650 km/s by driving large-outer-diam targets (~1010 μm) with thinner DT ice layers (~34 μm), with the target in Fig. 1(a) serving as an example. The implosion velocity scales as

$$v_{\text{imp}} \propto \sqrt{\frac{P_{\text{a}}}{\rho_0}\left(\frac{R_0}{\Delta_0}\right)}, \tag{1}$$

where P_{a} is the ablation pressure, ρ_0 is the initial density of the shell, R_0 is the initial shell radius, and Δ_0 is the initial shell thickness.[3] Therefore, large initial aspect ratios (R_0/Δ_0) allow DT liners to be imploded quickly without increasing laser intensity, which is preferred since intensities above 10^{15} W/cm^2 excite deleterious laser–plasma interactions that reduce laser absorption and limit compression.[4]

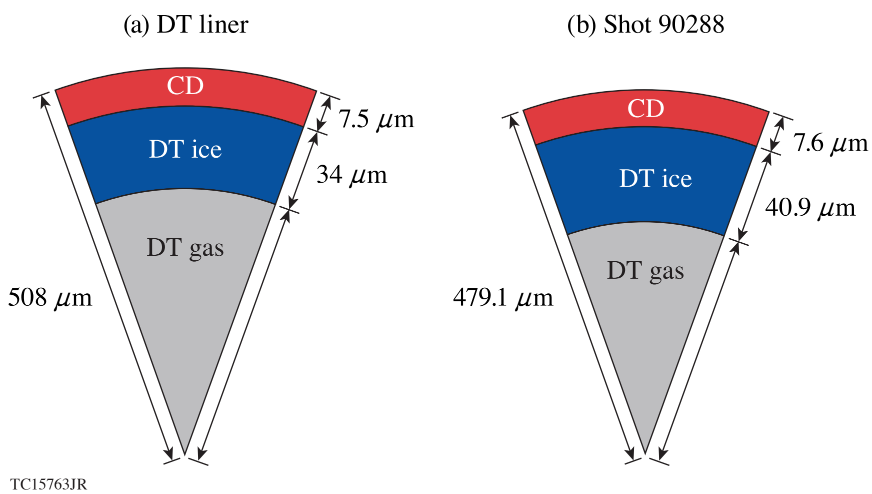

Figure 1
A target geometry comparison between (a) a thin-ice DT liner and (b) the capsule of shot 90288, a more-conventional direct-drive target. Note that the DT liner is 6% larger in diameter, yet, its fuel layer is 17% thinner, which raises v_{imp} according to Eq. (1).

One-dimensional simulations of DT liners exhibit neutron-averaged ion temperatures just below 9 keV and core temperatures up to 14 keV. These elevated temperatures greatly augment the fusion reaction rate, which leads directly to an increase in fusion yield. Statistical models predict DT liner yields to exceed 3.5×10^{14} fusion reactions when driven with ~30 kJ of 351-nm laser light.

Historically, thin and fast implosions are degraded by hydrodynamic instabilities that jeopardize the integrity of the shell during the acceleration phase of the implosion.[5] Furthermore, the instabilities that grow while the shell accelerates can feed through the shell to its inner surface and perturb it. During deceleration, the inner shell surface is unstable and the seeded perturbations are free to grow, which leads to reduced temperatures and pressures in the stagnating fusion fuel. The designs of this work promote stability during shell acceleration by raising the laser power early in the pulse, as shown in Fig. 2. This causes strong shock waves to travel through the shell, creating entropy and density profiles that are conducive for ablative stabilization of the in-flight shell.[6] In fact, strong ablative stabilization results in a 25% decrease in the cutoff wave number of DT liners compared to shot 90288, a previous high-performing implosion performed on OMEGA. Due to the high temperature of the hot spot and low density of the confining shell, DT liners benefit greatly from ablative stabilization during deceleration as well.[7] The temporally shaped pulses presented in this work demonstrate cutoffs in the unstable spectrum at lower modes than nominal implosions; they cut off at $\ell \approx 35$ for DT liners compared to a cutoff at $\ell \approx 45$ for shot 90288. The square pulse shape produces a more-extreme spectrum than the temporally shaped laser pulses; it has its cutoff mode number at $\ell \approx 15$, corresponding to greatly improved deceleration phase stability.

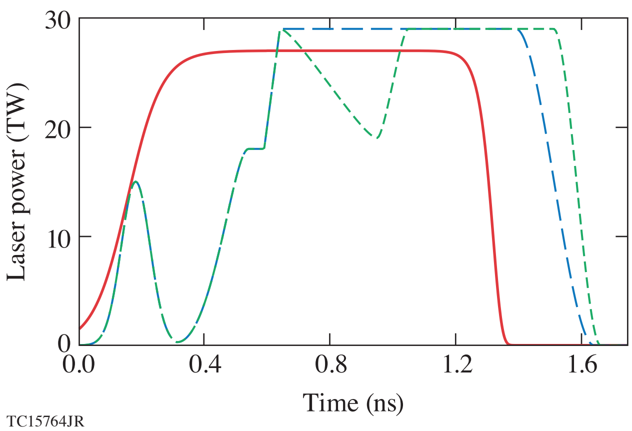

Figure 2
The laser pulse shapes used to irradiate the target described in Fig. 1(a). The laser energy of the square (solid red curve), flattop (long dashed blue curve), and double-spike (short dashed green curve) pulses is 31 kJ each.

Simulations of thin-ice DT liners show them to possess unique properties apart from their ability to produce high yields. For instance, higher mass ablation at the hot spot/cold shell interface during deceleration leads to a substantial accumulation of mass in the hot spot. At the time of peak neutron-production rate (the bang time), roughly 60% of the total areal density comes from the hot-spot plasma, with the remaining 40% provided by the cold tamping shell. In contrast, for high-convergence implosions such as shot 90288, only ~40% of the total areal density comes from the hot spot. The cold shell accounts for the remaining 60%.

The distinction between hot spot and cold shell vanishes as the in-flight shell entropy is increased, a regime easily accessed by using square pulses. Instead of two distinct regions at bang time, the unablated mass is nearly constant density and the temperature gradient becomes smoother, with temperatures above 6 keV persisting up to 25 μm from the target center. Implosions of this kind resemble those of volume ignition designs, in which all of the unablated mass acts as a hot spot.

An additional consequence of the thin ice layer in DT liner targets is that by starting with less ice at the beginning of the implosion, most of the fuel mass (up to 70% in the reported designs) has been ablated by bang time. This allows the return shock rebounding off the target origin to pass through almost all of the final fuel mass. Since most of the piston-like compression work is done by the shocked portion of the shell, DT liners act as efficient pistons with very little residual kinetic energy in the unshocked "free-fall" portion of the shell.[8]

The designs for thin-ice DT liner targets show that fusion energies above 1 kJ can be attained with only ~30 kJ of laser energy. If validated experimentally, this would be the first demonstration of capsule gain for an implosion on the 60-beam OMEGA laser, with capsule gain defined as the ratio of fusion energy yield to in-flight shell kinetic energy. Realizing the record yields that DT liners are predicted to produce will help LLE shot designers find an optimum between the high-yield, low-convergence DT liners and more-conventional designs that have greater areal densities but lower yields.

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