Novel Hot-Spot–Ignition Designs for Inertial Confinement Fusion with Liquid Deuterium–Tritium Spheres

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A new class of ignition designs is proposed for inertial confinement fusion (ICF) experiments. These designs are based on the hot-spot–ignition approach, but instead of conventional targets that are comprised of spherical shells with thin frozen deuterium–tritium (DT) layers, a liquid DT sphere inside a wetted-foam shell is used, and the lower-density central region and higher-density shell are created dynamically by appropriately shaping the laser pulse. These offer several advantages, including simplicity in target production (suitable for mass production for inertial fusion energy), absence of the fill tube (leading to a more-symmetric implosion), and lower sensitivity to both laser imprint and physics uncertainty in shock interaction with the ice–vapor interface. The design evolution starts by launching an ~1-Mbar shock into a homogeneous DT sphere. After bouncing from the center, the reflected shock reaches the outer surface of the sphere and the shocked material starts to expand outward until its pressure drops below the ablation pressure. At this point, an adjustment shock is launched inward by supporting ablation pressure.

This shock compresses the ablator and fuel, forming a shell. The shell is then accelerated and compressed by appropriately shaping the drive laser pulse, similar to the conventional thin-shell, hot-spot designs. This summary demonstrates the feasibility of the new concept using hydrodynamic simulations and discusses the advantages and disadvantages of the concept compared with more-traditional ICF designs.

The thin-shell cryogenic targets currently used in ICF ignition experiments have several disadvantages: First, fabrication of highly uniform frozen DT layers is time consuming and, in some cases, not reproducible. The layer must be sufficiently uniform to prevent seeding the Rayleigh–Taylor (RT) instability[1] developed during shell acceleration.[2] Even though the beta-layering technique[3] optimized over the last decade has produced smoothness that meets the uniformity specification, the layering process is still time consuming, and different engineering features (such as fill tubes, stalks, and characterization windows in the hohlraum) affect the ice-layer uniformity and lead to degradation in target performance. Second, the physics of relatively strong shocks (a few megabars) interacting with solid material (ablator and DT ice) is not well known. For example, the material phase transition behind the shock could lead to chunks of different phases being present in the shocked ablator and fuel, which contributes to the nonuniformity seeding at the ablator–ice interface and the inner surface of the shell as the first shock breaks out of the shell and material starts to accelerate, forming rarefaction or release. In addition, the physics of spallation or jetting of material from the inner ice surface after shock breakout of the shell is also not well understood and its effect on target performance remains uncertain. Third, laser imprint plays a critical role in determining the nonuniformity seeding in the laser-direct-drive designs.[4,5] Prior to establishing a conduction zone (a region between where the laser energy is deposited and the ablation front) sufficiently large to smooth out the most-damaging modes (typically, these include mode numbers $\ell > 10$), the nonuniformities seeded by laser beam speckles imprint on the target surface.[6] These amplify due to RT instability during acceleration that starts soon after the first shock breaks out of the shell.

Most of these shortcomings can be addressed by imploding liquid DT spheres. These spheres do not require fuel layering, do not have solid–gas interfaces, and have low acceleration during shock propagation through the sphere, preventing significant amplification of early laser imprint. Homogeneous DT spheres have been considered in the past for the volume-ignition approach.[7]

Volume ignition relies mainly on minimizing radiation losses. Such designs require either high-Z shells to trap radiation in the fuel or a large, optically thick fuel mass. The radiation trapping scheme has received a lot of attention in recent publications,[8–10] but the neutron yields predicted in the volume-ignition ICF approach do not significantly exceed gain ~1 (see Ref. 11). In addition, such designs require complex targets with multiple shells and buffer layers to mitigate hydrodynamic instability growth.

To illustrate the concept of dynamic shell formation, we consider a 100-μm-thick, 2400-μm-OD CH shell filled with DT fuel at the triple point with a mass density of $\rho = 0.25$ g/cm^3. This target is driven by a laser pulse with a constant-in-time power of $P_\mathrm{L} = 1$ TW, which corresponds to an on-target overlap incident intensity of $I \simeq 5.5 \times 10^{12}$ W/cm^2. Although the laser wavelength $\lambda_\mathrm{L} = 351$ nm is used in this example, any other laser frequencies will work for the dynamic shell formation since no significant laser–plasma interaction issues are expected at such low overlap intensities. According to 1-D simulations using the hydrodynamic code *LILAC*,[12] the ablation pressure corresponding to these drive conditions is $P_\mathrm{a} = 2$ Mbar. A sequence of hydrodynamic profiles is shown in Figs. 1(a)–1(c). A snapshot of the shell prior to being accelerated is shown in Fig. 2. Next, shell acceleration and fuel compression proceed similarly to the conventional hot-spot designs. An example of the ignition pulse shape is shown in Fig. 3: the total pulse energy is 1.15 MJ. The acceleration part of the pulse has a continuous, 25-ns rise from 0.3 TW to 250 TW. The design reaches $v_\mathrm{imp} = 3.5 \times 10^7$ cm/s, and, when alpha deposition is not included in the calculation, the peak areal density reaches $\rho R_\mathrm{peak} \simeq 2$ g/cm^2 and the peak neutron-average pressure is 220 Gbar. When alpha deposition is included, the target ignites and gives a 1-D gain = 75.

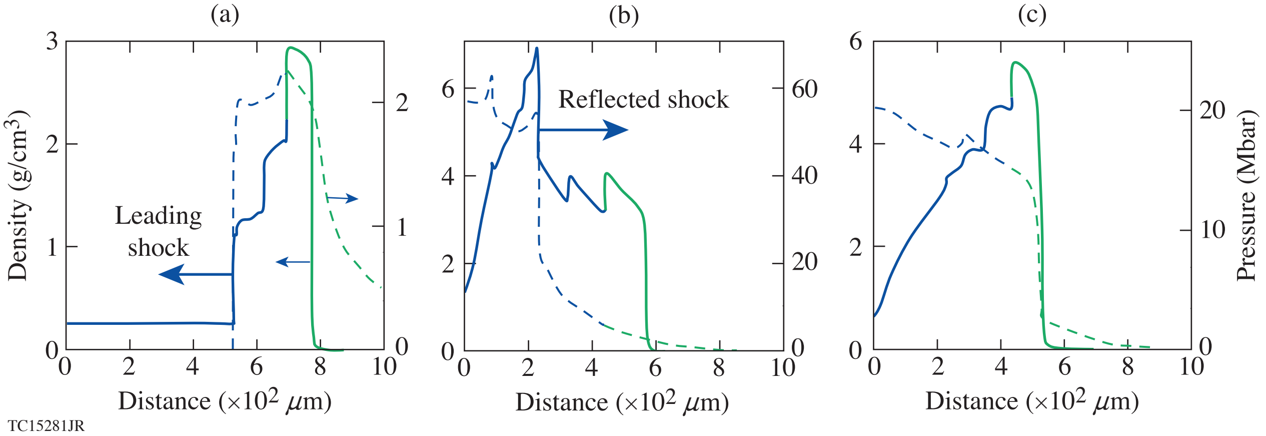

Figure 1
Snapshots of density (solid lines) and pressure (dashed lines) profiles at (a) $t = 35$ ns, (b) $t = 51$ ns, and (c) $t = 61$ ns.

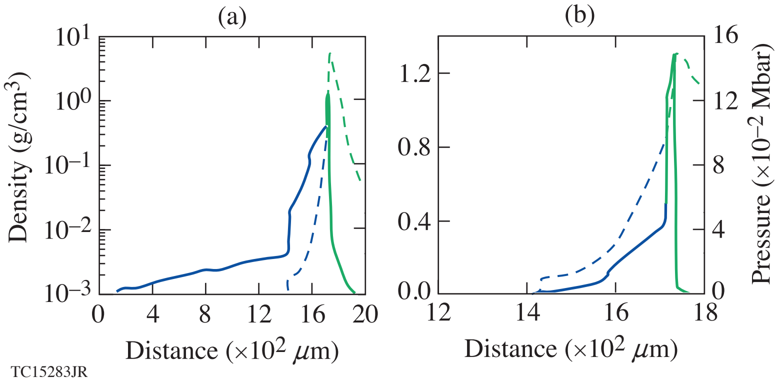

Figure 2
Dynamically formed shell profiles [(a) linear and (b) logarithmic density scales, respectively] at $t = 180$ ns for the pulse shown in Fig. 3.

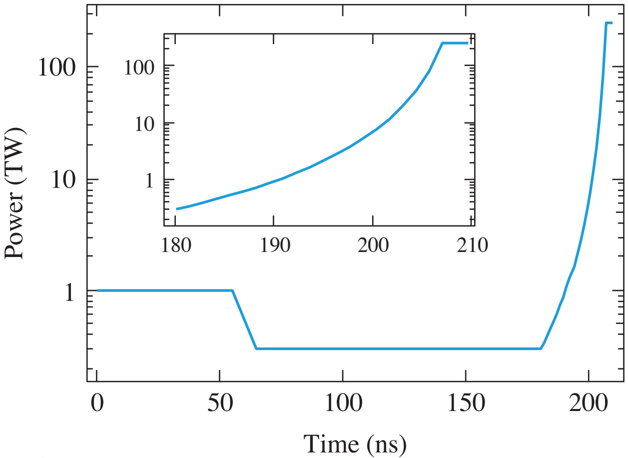

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Figure 3
Pulse shape for the E_L = 1.15-MJ ignition dynamic-shell design. The inset shows the main drive pulse.

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