Direct-Drive Double-Shell Implosion: A Platform for Burning-Plasma Physics Studies

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Laser-driven inertial confinement fusion[1] (ICF) has been actively pursued in the laboratory for decades. The current efforts have focused mainly on the so-called "hot-spot" ignition scheme, in which a single shell containing a solid-DT (deuterium–tritium) fuel layer covered by ablator materials is driven to implode by high-energy laser beams in either an *indirect* or *direct* way. In indirect-drive ICF, the high-energy laser beams irradiate inside a hohlraum and convert the laser energy into thermal x-ray emissions that ablatively drive the capsule (placed inside the hohlraum) to implode;[2,3] while for the other scheme, the laser beams *directly* irradiate the ICF target.[4,5] For hot-spot ignition in both schemes, the single shell acts not only as the "piston" but also provides the major DT fuel for the final hot-spot formation. For the piston to have enough energy and still be compressible at stagnation, one needs to drive the single shell for a long distance (for enough acceleration) and to maintain it at a relatively low entropy state (low adiabat). Roughly speaking, for such single-shell hot-spot ignition to work at laser energies in the MJ range, the imploding DT-containing shell must have a velocity of $V_{\text{imp}} > 350$ km/s and a high convergence ratio of CR > 30 (CR = R_0/R_{hs}, with R_0 being the initial shell radius and R_{hs} the final hot-spot radius). These requirements impose formidable challenges for the central-spot–ignition scheme to reach the so-called *burning-plasma stage*,[6] in which the self-heating of plasmas by the DT-fusion–produced α particles exceeds the radiative and conduction loss.

To reach the burning-plasma stage, the single-shell hot-spot ignition in both direct-drive and indirect-drive schemes must overcome daunting challenges, especially for the current low-margin designs due to the limited laser energy. First of all, the large CR, low adiabat, and high implosion velocity demand stringent requirements on target and driver perturbations. For example, 3-D simulations of indirect-drive ICF implosions[7,8] show that the driver asymmetry and target engineering features such as fill tube and interface mixing can gradually "eat" away the design margin for burning plasma to happen. The situation is also similar for direct-drive, high-convergence ICF implosions, in which the perturbations from target imperfection and long-/short-wavelength laser nonuniformities can also significantly degrade the target performance,[9–12] due to the fact that these high-convergence, low-adiabat single-shell implosions are highly susceptible to violent Rayleigh–Taylor (RT) instability growth.[13–17] In addition, the DT layer being part or the whole of the piston requires tremendous effort to maintain its low entropy. Precisely timing several shocks[18–20] is necessary to set the shell in a designed low adiabat. Still, excessive radiation and/or superthermal electrons produced by laser–plasma instabilities, such as two-plasmon decay[21] and stimulated Raman scattering,[22] could possibly preheat the in-flight, low-temperature DT shell and render it less compressible at stagnation. All of these challenges are currently faced by the laser-drive ICF community.

Different from the above-mentioned central-spot ignition, alternative laser-fusion schemes seek to separate the hot-spot formation from the shell (piston) acceleration. Over the past two decades, some efforts in the laser-fusion community have been put into studies of these alternative schemes, including fast ignition,[23] shock ignition,[24,25] double-shell implosions,[26–31] and a triple-shell *Revolver* design,[32] just to name a few. Although these schemes have their own challenges, the separation of hot-spot formation from accelerating the piston generally relaxes the stringent requirements for the single-shell, hot-spot–ignition scheme.

Taking a double-shell implosion as an example, the outer shell (piston) can be set at a much higher adiabat so that RT instability and radiation/fast-electron preheat do not significantly affect the shell integrity as it accelerates, while an inner shell composed of high-density metal layer(s) and filled with DT gas or liquid can be volumetrically shocked/compressed and heated by an ~Gbar pressure reservoir that is created through the spherical stagnation (impact) of the outer shell upon the inner one. Given the electron-rich nature of a high-density inner shell, only a significantly low convergence ratio (CR $\le$ 10) is needed to reach a pressure of ~400 Gbar required for DT plasma burning.[31] The double-shell scheme generally trades some of the physics challenges of high-convergence (CR $\ge$ 30) single-shell implosions for the complexity of double-shell target fabrication and diagnoses.

For the past two decades, the study of double-shell implosions in both experiments and simulations has focused mainly on the indirect-drive scheme.[26–31] With a drive laser at the National Ignition Facility[33] (at an ~MJ energy level), recent 1-D simulations showed that a maximum energy of only ~10 to 15 kJ can be coupled to the kinetic motion of the inner shell,[31] even with a high-density inner-shell material like Au. The limited margin for an energetic inner shell is caused by the lower hydroefficiency in the indirect-drive scheme, in which a much thicker and massive outer shell is needed for x-ray drive. Motivated by the higher overall hydroefficiency of direct drive,[5,10] we have performed a thorough investigation on whether or not a direct-drive double-shell (D^3S) platform has its own merit to create a burning plasma in the laboratory at MJ laser energy. We found that even with the currently reduced hydrocoupling caused by cross-beam energy-transfer (CBET),[34–37] direct-drive double-shell implosions can give at least twice the kinetic energy (~30 kJ) as the indirect-drive case; such a more-energetic inner shell could provide more margin to reach the DT-plasma burning stage. In addition, we propose to use the newly invented technology of magnetron sputtering[38] to make a density-gradient inner shell of a tungsten/beryllium mixture. By varying the tungsten-to-beryllium concentration ratio, one may be able to construct an inner shell with density dropping from $\rho_0 \sim 19$ g/cm^3 (97% W + 3% Be) to $\rho_0 \sim 2.2$ g/cm^3 (1% W + 99% Be) along both inward and outward directions. The idea of using gradient-density layers, proposed earlier for single-shell ICF,[16] can help to mitigate the classical RT problem during the outer-shell collision.[39] It not only reduces the Atwood number but also increases the density scale length at the collisional surface. It can be thought of as multiple "tamper" layers used for indirect-drive double-shell designs[28,29,31] but with a gradual density variation.

In the radiation-hydrodynamic studies of direct-drive double-shell implosions presented here, we have used both the 1-D code *LILAC*[40] and the 2-D code *DRACO*[41] developed at LLE. State-of-the-art physics models, including the nonlocal thermal-transport model,[42,43] the 3-D ray tracing with CBET model,[34–37] accurate material properties such as first-principles equation of state,[44–47] first-principles opacity tables,[48,49] and the average-ion model[50] for the opacity and emissivity of the W/Be mixture, have been employed in our radiation-hydrodynamic simulations. In our D^3S designs, a 70-μm-thick beryllium outer shell is driven symmetrically by a high-adiabat ($\alpha \ge 10$), 1.9-MJ laser pulse to a peak velocity of ~240 km/s. Upon spherical impact, the outer shell transfers ~30 to 40 kJ of kinetic energy to the inner shell filled with DT gas or liquid, giving neutron-yield energies of ~6 MJ in 1-D simulations. Two-dimensional, high-mode *DRACO* simulations indicated that such high-adiabat D^3S implosions are not susceptible to laser imprint, but the long-wavelength perturbations from the laser port configuration along with CBET can be detrimental to the target performance. Nevertheless, neutron yields of ~0.3- to 1.0-MJ energies can still be obtained from our high-mode *DRACO* simulations. One example is shown in Fig. 1, where the robust α-particle bootstrap is readily reached, which could provide a viable platform for burning-plasma physics studies. Once CBET mitigation and/or more laser energy becomes available, we anticipate that breakeven or moderate energy gain might be feasible with the proposed D^3S scheme.

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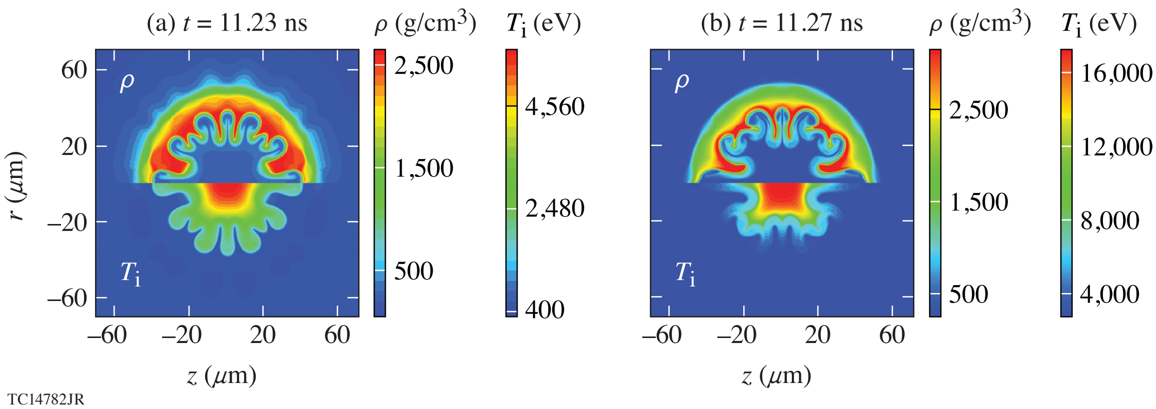

Figure 1
The density (ρ) and ion temperature (T_i) contour plots on the r,z plane during the inner-shell stagnation: (a) at the beginning of bootstrap heating (t = 11.23 ns) and (b) at the peak neutron production (t = 11.27 ns) when the burning-plasma stage is reached.

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