Fuel–Shell Interface Instability Growth Effects on the Performance of Room-Temperature Direct-Drive Implosions

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Performance degradation in direct-drive inertial confinement fusion implosions is caused by several effects, one of which is Rayleigh–Taylor (RT) instability growth during the deceleration phase. In room-temperature plastic target implosions, deceleration-phase RT growth is enhanced by the density discontinuity and finite Atwood number at the fuel–shell interface (see Fig. 1). The Atwood number $\left[A_\mathrm{T}=\left(\rho_\mathrm{shell}-\rho_\mathrm{fuel}\right)/\left(\rho_\mathrm{shell}+\rho_\mathrm{fuel}\right)\right]$ of the interface is systematically varied by altering the ratio of deuterium to tritium (D:T) within the DT gas fill. The stability of the interface is best characterized by the effective Atwood number, which is primarily determined by radiation heating of the shell. Both simulation and experimental data show that yield performance scales with the fraction of D and T present in the fuel and that the observed inferred ion-temperature asymmetry $\left(\Delta T_\mathrm{i}=T_\mathrm{i}^\mathrm{max}-T_\mathrm{i}^\mathrm{min}\right)$, which indicates the presence of long-wavelength modes, has a small sensitivity to the different D:T ratios. Three D:T ratios (10:90, 25:75, and 50:50) were chosen based on the material interface A_T to create *stable*, *neutrally stable*, and *unstable* conditions, respectively, during the deceleration phase.

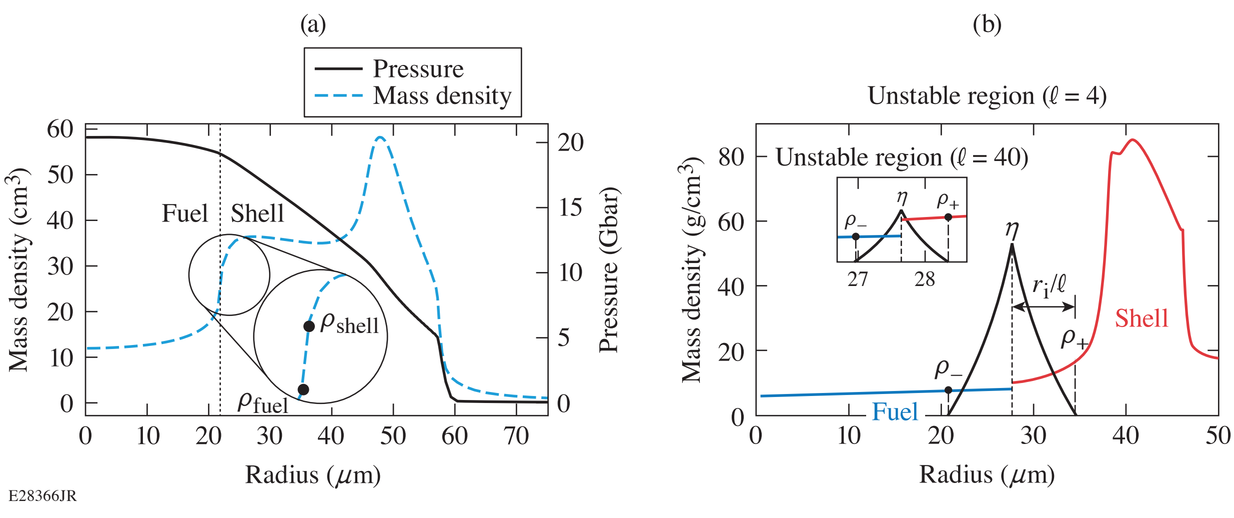

Figure 1
(a) The fuel–shell interface of room-temperature targets during the deceleration phase is classically unstable because of the jump in density. (b) Any ℓ-mode perturbations (η) present at the interface (r_i) will grow if $A_\mathrm{T}>0$. The size of the unstable region is proportional to the wavelength of the perturbation.

The fuel–shell interface Atwood number ($A_\mathrm{T,i}$) is found to be *stable* for 10:90 ($A_\mathrm{T,i}=-0.03$), *neutrally stable* for 25:75 ($A_\mathrm{T,i}\approx 0.0$), and *unstable* for 50:50 ($A_\mathrm{T,i}=0.05$) using the ideal-gas equation of state and continuity conditions for pressure and temperature across the interface:

$$\frac{\rho_{\text{shell}}}{\rho_{\text{fuel}}} = \frac{m_{\text{i}}^{\text{shell}}}{m_{\text{i}}^{\text{fuel}}} \frac{1 + Z_{\text{fuel}}}{1 + Z_{\text{shell}}}.$$

Unstable modes present at the material interface grow during the deceleration phase of the implosion. Linear stability analysis of RT instability growth in semi-infinite density profiles has shown that these unstable modes are local to the interface, and that within the linear growth regime, the size of the unstable region is proportional to the perturbation wavelength.[1] The amplitude of the perturbation is highest on the interface itself and decays exponentially as the distance from the interface increases. In spherical geometry, the velocity perturbations decay as $\left(r_{\text{i}}/r\right)^{\ell+2}$ for $r > r_{\text{i}}$ and $(r/r_{\text{i}})^{\ell-1}$ for $r < r_{\text{i}}$, according to the radial distance (r) from the material interface (r_{i}) and mode number (ℓ). The effective Atwood number,[2] defined as $A_{\text{T}} = \left(\rho^{+} - \rho^{-}\right)/\left(\rho^{+} + \rho^{-}\right)$, uses the mass density averaged over the perturbation region $\left(\pm r_{\text{i}}/\ell\right)$ rather than the fuel and shell densities at the material interface (c.f., $A_{\text{T,i}}$). Figure 1(b) illustrates mass-density profiles with unstable regions for $\ell = 4$ and $\ell = 40$ perturbations. During the deceleration phase, these unstable regions are influenced by x-ray radiation that is released in the DT fuel of the hot spot. This x-ray radiation is absorbed into the colder CH shell, causing the material to heat up and expand inward, and results in a thicker shell with increased density and A_{T} near the material interface. This radiation preheat effect is present in both D:T 10:90 and 50:50 targets and causes their respective effective Atwood numbers to be comparable across a range of unstable modes.

Small-amplitude ($k\eta < 1$), single-mode perturbations grow exponentially in time, and since the Atwood number affects the exponential growth rates, 10:90 experiences significantly smaller growth factors (by a factor of ~5) compared to 50:50. As perturbation amplitudes become nonlinear ($k\eta > 1$), the growth changes from exponential to linear in time[2,3] and the difference in the growth factors between 10:90 and 50:50 becomes much smaller (only ~20%). Perturbations must grow to significant levels and become nonlinear in order for target performance to be affected. This explains why target performance should have small sensitivity to the Atwood number variations used in the experiment described below.

Multiple targets were fabricated to meet the design specification based on the classical material interface $A_{\text{T,i}}$. Each target was designed to be 860 μm in diameter with 27-μm-thick CH shells and a DT fuel fill pressure of 10 atm. Additional targets were created and opened up to measure the actual fuel D:T ratios after fabrication. Significant levels of protium (^{1}H) were found and were much higher than the initial D:T fill ratios. The yield-over-clean ratios $\left(Y_{\text{exp}}/Y_{\text{1-D}}\right)$, which used post-shot 1-D simulations that included the measured fuel levels, were consistent across all D:T ratios (see Fig. 2). This suggests that each shot experienced

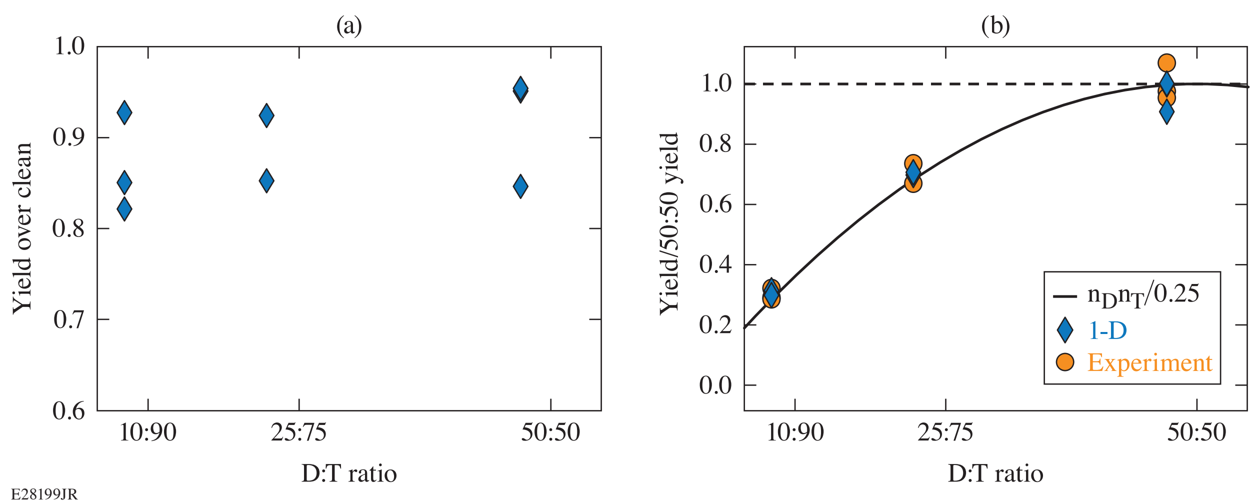

Figure 2
(a) Yield over clean $\left(Y_{\text{exp}}/Y_{\text{1-D}}\right)$ and (b) yield scaling. In (b), D:T 50:50 data points that lie above the dashed line at $y = 1.0$ indicate a higher than average yield. The solid black curve represents a simple yield scaling relation based on the DT number densities in the fuel.

the same level of asymmetry and instability growth. Additionally, the yield of each target, for both measured and simulated, scaled according to the fraction of deuterium and tritium in the fuel. Figure 2(b) illustrates the DT yield of each shot normalized to the respective (simulated or experimental) average 50:50 yield. Close clustering of the data points around the solid black curve indicates that the yield scaled according to the fuel composition.

Performance of the implosion is also assessed through inferred ion temperatures (T_{i}). These observations are taken from different lines of sight within the OMEGA target chamber. Ion temperature asymmetry $\left(\Delta T_{\mathrm{i}} = T_{\mathrm{i}}^{\mathrm{max}} - T_{\mathrm{i}}^{\mathrm{min}}\right)$, currently taken from the set of six different neutron time-of-flight (nTOF) measurements, is used to identify significant differences in T_{i} caused by velocity broadening. Large ΔT_{i} indicates that there are significant nonradial components of velocity in the hot spot near peak neutron-production time, most likely caused by instability growth and highly directional flow variance. Figure 3 shows ΔT_{i} for each D:T ratio for both simulated and experimental results. Both simulated and experimentally inferred T_{i} indicate a comparable level of asymmetry across all D:T ratios. The experimental error bars (±100 eV) arise from the noise level in the detector signal, uncertainty in the numerical fit analysis,[4] and instrument response function of each detector.

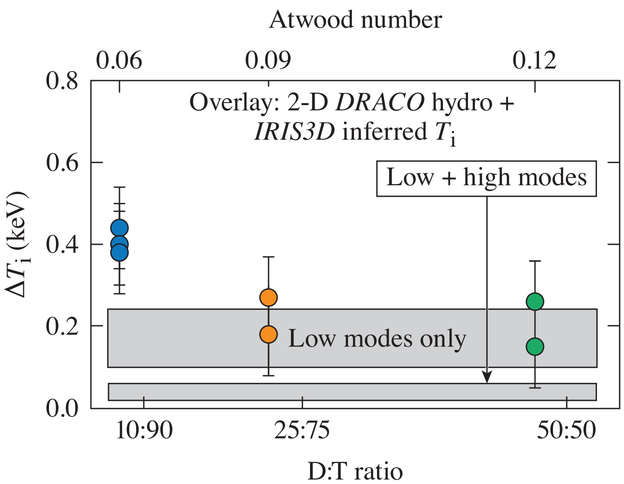

Figure 3
Inferred DT T_{i} asymmetry $\left(\Delta T_{\mathrm{i}} = T_{\mathrm{i}}^{\mathrm{max}} - T_{\mathrm{i}}^{\mathrm{min}}\right)$, as a function of the D:T ratio and estimated Atwood number. The 2-D *DRACO* simulations provided the hydrodynamics and *IRIS3D*[5] provided the synthetic neutron diagnostics.

Simulations indicate that radiation preheat in all D:T ratios cause the interface to have comparable density profiles near the fuel–shell interface, and therefore similar A_{T} and instability growth factors. While 10:90 and 50:50 experience different linear instability growth factors for small-amplitude perturbations, nonlinear perturbations that impact target performance grow at comparable rates in either D:T configuration. In both experiments and simulations, the yield of all target configurations scales according to the composition of the fuel. Significant ΔT_{i} outside measurement uncertainty requires highly directional flow variance in order for detectors to observe differences from various lines of sight. Because both 10:90 and 50:50 had similar effective Atwood numbers, the simulated deceleration RT instability growth was nearly identical for nonlinear RT growth, and there was little influence on the inferred T_{i} and ΔT_{i} by altering the D:T ratio. Measurement uncertainty and noise levels make behavior trends inconclusive, and it is likely that the hot spot is relatively insensitive to changing the D:T ratio, as simulations suggest.

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1. V. N. Goncharov, Phys. Rev. Lett. **88**, 134502 (2002).
2. V. N. Goncharov, "Self-Consistent Stability Analysis of Ablations Fronts in Inertial Confinement Fusion," Ph.D. thesis, University of Rochester, 1998.
3. U. Alon *et al*., Phys. Rev. Lett. **74**, 534 (1995).
4. R. Hatarik *et al*., J. Appl. Phys. **118**, 184502 (2015).
5. F. Weilacher, P. B. Radha, and C. J. Forrest, Phys. Plasmas **25**, 042704 (2018).