Experimental Investigation of Fuel–Pusher Mix in Direct-Drive Implosions on OMEGA

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Summary

The RT instability in its highly nonlinear, turbulent stage causes atomic-scale mixing of the shell material with the fuel in the compressed core of direct-drive ICF targets.

- Fuel–pusher mix was diagnosed with x-ray spectroscopy, charged-particle spectroscopy, and core x-ray imaging.¹
- Laser imprint and shell thickness were varied to change the feedthrough level of perturbations from the ablation surface to the inner surface of the shell.
- The mass density of plastic shell material (pusher) mixed with the hydrogen isotope fuel in the outer core is shown to depend on the calculated levels of feedthrough.

Spherical plastic shell targets were imploded with a 23-kJ, 1-ns square laser pulse.

Predicted convergence ratios ranged from 13 to 15.

Laser irradiation with 1-THz SSD, PS, and on-target beam-to-beam power imbalance < 5% rms.

Gas fills:
1. 15 atm DT
2. 15 atm DD
3. 15 atm DD and 0.054 atm Ar
A charged-particle spectrometer is used to record the knock-on-deuteron spectrum for fuel-\(\rho R\) measurements\(^1\)

\[ n + D \rightarrow n' + D' \]

number of \(D' \propto \langle \rho R \rangle Y_n \)

The seed of the deceleration-phase RT instability is calculated with a postprocessor to a 1-D hydrocode.*

Growth factor of RT instability during deceleration phase is predicted to be comparable for 20- and 24-μm shells.

Rayleigh–Taylor growth:

\[ GF = e^{\gamma t}, \text{ where } \gamma t = \sqrt{\frac{A_T 2 \ell}{R} \frac{gt^2}{2}} \]
Streaked x-ray spectroscopy is used to measure time-dependent Ar K-shell spectral line shapes

- Absolute timing of peak x-ray signal is established with a slower streak camera.
Time history of emissivity-averaged core $n_e$ and $T_e$ is inferred from the Ar $K$-shell spectroscopy.

- Significant changes in the Ar $K$-shell emission spectrum occur during the implosion.
- Peak neutron production is measured $\sim 170 \text{ ps} \pm 100 \text{ ps}$ before peak x-ray production.
- *LILAC* simulations indicate that peak neutron production occurs at the same time as peak emissivity-averaged $T_e$. 

![Graph showing time history of $n_e$ and $T_e$](image)
Spectroscopic results are compared with nuclear measurements of $\rho_f R$ and x-ray core images to estimate the amount of fuel-pusher mix.

- The $\rho_f R$ measurement is obtained from knock-on deuteron spectra recorded on similar implosions with a DT fill gas.
  \[ \rho_f R \text{ (knock-ons)} = 15 \text{ mg/cm}^2 \]

- The radius of the imploding core at peak neutron production estimated from $M_f = \frac{4}{3} \pi \rho_f R^2$ is consistent with the radius estimated from gated x-ray images ($R_{x\text{-ray}} = 38 \pm 5 \mu m$)
  \[ R = 42 \mu m \]

- $\rho_f = 3.6 (\pm 1) \text{ g/cm}^3$

Time-resolved x-ray spectroscopy
\[ n_e = n_{e(D)} + n_{e(Ar)} + n_{e(CH)} \]
DD(15)CH[20] implosion with full-beam-smoothing has an estimated core mass composition in the mix region of $\sim1/2$ deuterium and $\sim1/2$ CH

\[
DD(15), \text{Ar}(0.054), \text{CH}[20] \\
\ne(CH) = n_e - n_e(D) - n_e(Ar)
\]

<table>
<thead>
<tr>
<th>$n_e$</th>
<th>$2.2 \times 10^{24}$ cm(^{-3}) (averaged over 170-ps neutron burn width)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_e$</td>
<td>1.9 keV (averaged over 170-ps neutron burn width)</td>
</tr>
<tr>
<td>$n_e(D)$</td>
<td>$1.1 \times 10^{24}$ cm(^{-3})</td>
</tr>
<tr>
<td>$n_e(Ar)$</td>
<td>$3.3 \times 10^{22}$ cm(^{-3})</td>
</tr>
<tr>
<td>$n_e(CH)$</td>
<td>$1.1 \times 10^{24}$ cm(^{-3})</td>
</tr>
<tr>
<td>$\rho_{CH}$</td>
<td>$3.4 \pm 1.2$ g/cm(^3)</td>
</tr>
<tr>
<td>$\rho_f$</td>
<td>$3.6 \pm 1.0$ g/cm(^3)</td>
</tr>
</tbody>
</table>

- **Pressure** (electron + ion) $\sim 11$ Gbars
- **Because the diagnostic spectral lines are sensitive only to the** $n_e$ **within approximately a Debye length of the Ar radiator, the shell material must mix with the Ar-doped fuel on the atomic scale.**
Fuel–pusher mix depends on hydrodynamic stability of implosion

\[ n_e = n_e(D) + n_e(Ar) + n_e(CH) \]

\[ \rho_{CH} \text{ in mix region} \]

Calculated feed through rms for \( \ell > 10 \) (\( \mu \text{m} \))
Summary/Conclusion

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