Demonstrating Ignition Hydrodynamic Equivalence in Cryogenic DT Implosions on OMEGA

\[ \text{Yield} \times 10^7 \text{ cm/s} \]

\[ V_{\text{imp}} (\times 10^7 \text{ cm/s}) \]

\[ \rho R/\rho R_{1-D} \]

Ignition hydro-equivalent

Improved nonuniformity seeds

Current stability boundary

\[ \rho R/\rho R_{1-D} > 0.95 \]

\[ \rho R/\rho R_{1-D} < 0.90 \]

\[ \rho R/\rho R_{1-D} > 0.85 \]

\[ \rho R/\rho R_{1-D} < 0.80 \]

\[ \rho R/\rho R_{1-D} > 0.75 \]

\[ \rho R/\rho R_{1-D} < 0.70 \]

\[ \rho R/\rho R_{1-D} > 0.65 \]

\[ \rho R/\rho R_{1-D} < 0.60 \]

\[ \rho R/\rho R_{1-D} > 0.55 \]

\[ \rho R/\rho R_{1-D} < 0.50 \]

\[ \rho R/\rho R_{1-D} > 0.45 \]

\[ \rho R/\rho R_{1-D} < 0.40 \]

Data

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Summary

The performance degradation of OMEGA cryogenic implosions is understood in terms of unshocked shell mass at stagnation

- Yields in excess of $3.4 \times 10^{13}$ [yield-over-clean (YOC) $\sim 35\%$] and ion temperatures up to 4 keV were measured in cryogenic implosions with $V_{imp} \sim 3.8 \times 10^7$ cm/s
- Performance degradation in moderate-adiabat ($\alpha \sim 4$) implosions is fully understood by 2-D DRACO simulations
- Shells in lower-adiabat implosions ($\alpha \sim 2.5$) break up during acceleration, leading to an increased hot-spot mass and reduced convergence
- The unshocked mass at peak compression determines the impact of the ablator mix

Improving shell stability and mitigating cross-beam energy transfer (CBET) are required to demonstrate ignition hydrodynamic scaling on OMEGA.
Collaborators


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Direct-drive target performance is optimized by varying implosion velocity, in-flight aspect ratio (IFAR), fuel adiabat, and ablator material.

- $V_{\text{imp}}$ and IFAR are controlled by varying the ablator (7.5 to 12 μm) and fuel thickness (40 to 66 μm).

Adiabat
\[ \alpha = \frac{P}{P_{\text{Fermi}}} \]

IFAR = shell radius/shell thickness
One-dimensional dynamics are verified using self-emission, bang time, and scattered-light measurements

![Graphs showing neutron production and scattered light](image)

Target Performance

Target yield has a strong dependence on implosion velocity.
The maximum hot-spot pressure can be estimated using the measured neutron production rate

\[
\frac{dN}{dt} \sim n^2 \langle \sigma \nu \rangle V_{hs} \sim p_{hs}^2 V_{hs} T^{2.5}
\]

\[
p_{hs} V_{hs}^{5/3} = \text{const}
\]

\[
\frac{dN}{dt} \sim p_{hs}^{7/5} T^{2.5}
\]

\[
p_{exp} \sim p_{sim} \left( \frac{T_{exp}}{T_{sim}} \right)^{-1.8} \left( \frac{\dot{N}_{exp}}{\dot{N}_{sim}} \right)^{0.7}
\]
Pressures up to $\sim 40$ Gbar are inferred in $\alpha \sim 4$ implosions.
Pressure is significantly reduced in low-adiabat ($\alpha < 2.5$) implosions.

**Target Performance**

$P_{\text{max}} = 150 \text{ Gbar}$

$\langle P \rangle_n = 110 \text{ Gbar}$

$P_{\text{max}} = 23 \text{ Gbar}$

$\langle P \rangle_n = 15 \text{ Gbar}$

Inferred from data

Shot 69236, $\alpha = 2.1$
The highest hot-spot pressure is achieved for $\alpha \sim 4$ implosions at IFAR $\sim 22$
Two-dimensional simulations for $\alpha \gtrsim 4$ implosions reproduce measured stagnation quantities

- Sources of nonuniformity included in simulation: laser imprint, ice roughness, power imbalance, and beam mistiming

### Simulation vs. Experiment

<table>
<thead>
<tr>
<th></th>
<th>Simulation</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>$3.9 \times 10^{13}$</td>
<td>$3.0 \times 10^{13}$</td>
</tr>
<tr>
<td>$T_i$</td>
<td>3.7 keV</td>
<td>3.6 keV</td>
</tr>
<tr>
<td>$\rho R$</td>
<td>0.18 g/cm$^2$</td>
<td>0.17 g/cm$^2$</td>
</tr>
<tr>
<td>$R_{17}$</td>
<td>24.4 $\mu$m</td>
<td>25.2 $\mu$m</td>
</tr>
<tr>
<td>$P_{hs}$</td>
<td>32 Gbar</td>
<td>30 Gbar</td>
</tr>
</tbody>
</table>

Shell instability is the main candidate for performance degradation in low-adiabat implosions

- Simulations* include \(~100\) surface features, size: \(5\) to \(20\) \(\mu\)m in diameter, \(0.5\) to \(1.0\) \(\mu\)m in depth

The main goal of these simulations is to identify a possible hydrodynamic scenario that explains the observations.

Hydrodynamic simulations including local defects match the evolution of hot-spot pressure and neutron rate.

Shot 66613, $\alpha = 2$

1-D simulations

2-D simulations

Inferred from data using neutron-rate ratio

Pressure (Gbar) vs. Time (ns)

Neutron rate (s$^{-1}$) $\times 10^{21}$ vs. Time (ns)
Excessive vapor mass leads to a larger hot-spot radius at stagnation

![Graph showing Nominal vapor mass, Beginning of shell deceleration, and Stagnation with plots of Density (g/cm³), Pressure (Gbar), and Radius (μm) over different ranges.]
Excessive vapor mass leads to a larger hot-spot radius at stagnation

- Fuel contamination and ablator-to-vapor mix contribute to larger vapor mass
Excessive vapor mass leads to a larger hot-spot radius at stagnation

- Fuel contamination and ablator-to-vapor mix contribute to larger vapor mass

Larger vapor mass leads to stronger shell deceleration

A shell with more vapor mass stagnates at a larger radius

\[ \rho R \sim \frac{\rho R_{\text{max}}}{\sqrt{1 + \frac{m_{\text{vapor}}}{m_{\text{norm}}}}} \]

\[ P_{\text{hs}} \sim \frac{P_{\text{max}}}{\left(1 + \frac{m_{\text{vapor}}}{m_{\text{norm}}}\right)^{0.8}} \]

- For OMEGA targets: \( m_{\text{norm}} = 0.1 \ \mu g \)
- Vapor mass increases to 2 \( \mu g \) because of mix in \( \alpha < 2.5 \) implosions
Degradation Mechanisms

Reduced shell density contributes to degradation in hot-spot compression

Pressure gradient stops the shell

Nominal shell density

$\rho_{\text{shell}} \sim \rho_{\text{shell}} v^2$

$P_{\text{shock}} \sim \rho_{\text{shell}} v^2$
Reduction in shell density contributes to degradation in hot-spot compression. Shell decompression caused by instability growth at ablation front or preheat. Pressure gradient stops the shell.
Reduced shell density contributes to degradation in hot-spot compression

Pressure gradient stops the shell

Shell decompression caused by instability growth at ablation front or preheat

For smaller $P_{\text{shock}}$, lower $P_{\text{hs}}$ stops the shell $\rightarrow$ larger stagnation hot-spot radius.
Degradation Mechanisms

Target compression degradation caused by ablation-front mix depends on the fraction of shell mass overtaken by the shock at bang time.

![Diagram of shock wave propagation](image-url)
Degradation Mechanisms

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Target compression degradation caused by ablation-front mix depends on the fraction of shell mass overtaken by the shock at bang time

\[
P_{hs} \sim R_{hs}^{-5}
\]

\[
M_s(t_{stag}) \leq M_{shell}
\]

\[
\frac{d\nu_{hs}}{dt} \sim \frac{R_{hs}^2 (P_{hs} - P_{shock})}{M_{shock}(t)}
\]

\[
\nu_{hs}(t_{stag}) = 0
\]
Degradation Mechanisms

Target compression degradation caused by ablation-front mix depends on the fraction of shell mass overtaken by the shock at bang time (continued)

Outgoing shock

Mix region

Pressure

Target performance is not degraded if $M_{mix} < M_{shell} - M_{shock}(t_{stag}) = M_{unshocked}$. 

$P_{hs}$

$P_{shock}$

$R_{hs}$

$\rho$

$M_{shock}$

$M_{mix}$

$M_{shell}$

$M_{unshocked}$
Degradation Mechanisms

Shocked-shell fraction at stagnation depends on implosion velocity, adiabat, and drive pressure

\[ \frac{M_{\text{shock}}}{M_{\text{shell}}} \sim \frac{V_{\text{imp}}^{4/3}}{\alpha^{2/5} P_a^{4/15}} \]
Degradation Mechanisms

Shocked-shell fraction at stagnation depends on implosion velocity, adiabat, and drive pressure

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Degradation Mechanisms

Shocked-shell fraction at stagnation depends on implosion velocity, adiabat, and drive pressure.

More unshocked mass, less sensitivity to Rayleigh–Taylor (RT) mix at ablation front.
Reduction in peak areal density and pressure depends on the mass of the mix region relative to the unshocked mass.
Degradation Mechanisms

Target compression degradation is a strong function of unshocked mass at peak neutron production.

\[ M_{\text{shell}} = 30 \mu g \]

\[ M_{\text{shell}} = 16 \mu g \]

\[ \rho R_{\text{exp}} / \rho R_{1-D} \]

Unshocked mass (\(\mu g\))

Adiabat

\[ M_{\text{shell}} = 16 \mu g \]
Degradation Mechanisms

Amount of RT mix at the ablation front can be inferred from the stability boundary

8 $\mu g$ of shell is mixed at the ablation front because of a RT growth
Degradation Mechanisms

Significant mix of the ablator material into the hot-spot limits performance of $\alpha < 2.5$ implosions

Mitigating CBET* allows the shell and unshocked masses to be increased

Mitigating CBET* allows the shell and unshocked masses to increase

Using smaller beams at the main drive reduces CBET

*Nominal beam, no CBET

Nominal beam

\[ D_{\text{beam}} = 0.85 \, D_{\text{target}} \]

Mitigating CBET makes it possible to drive more massive targets at a higher adiabat.
Mitigating CBET is required to demonstrate ignition hydrodynamic scaling on OMEGA.

- Ignition hydrodynamic-equivalent OMEGA implosions require $t_R \sim 300$ mg/cm$^2$ and $V_{imp} \sim 3.7 \times 10^7$ cm/s
The performance degradation of OMEGA cryogenic implosions is understood in terms of unshocked shell mass at stagnation

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