The 1-D Cryogenic Implosion Campaign on OMEGA

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YieldExp (×10\(^{14}\))

1.4
1.2
1.0
0.8
0.6
0.4
0.2

4.5 \times 10^{13} \left(\frac{V_{\text{LILAC}}}{400}\right)^4 \left(\frac{M_{\text{LILAC}}}{0.01}\right)^{0.8} \left(\frac{T_{\text{min}}}{T_{\text{max}}}\right)

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Summary

High-adiabat ($\alpha \approx 6$ to $7$) implosions achieved the highest fusion yields of $1.4 \times 10^{14}$ on OMEGA with high predictability using a statistical mapping model.

- The ongoing 1-D campaign is building an experimental database of high-adiabat, low-convergence implosions ($\text{CR}^* \sim 12$ to $14$).
- The highest fusion yield of $1.4 \times 10^{14}$ (tripled in the past year) is achieved by increasing the target outer diameter and reducing the DT ice thickness.
- Based on these recent results, a roadmap is being developed to find the optimum target and laser pulse.

*CR: convergence ratio
Collaborators


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Laboratory for Laser Energetics

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Plasma Science and Fusion Center
Massachusetts Institute of Technology
The 1-D Campaign Implosions
The 1-D Campaign developed a database of more-predictable, lower-convergence, high-adiabat implosions.
Systematic hydro-stability, convergence, shock-timing, and preheat tests are conducted to assess degradation mechanisms and proximity to stability cliffs.

- **Shock-timing test**
  - Time (ns): 0, 1, 2, 3
  - Power (TW): 0, 5, 10, 15, 20

- **SSD* on/off (RT** test**)**
  - Time (ns): 0, 1, 2, 3
  - Power (TW): 0, 5, 10, 15, 20

- **Convergence test**
  - CR = 12
  - CR = 16
  - Time (ns): 0, 1, 2
  - Power (TW): 0, 10, 20

- **Hot electrons on/off**
  - Time (ns): 0, 1, 2, 3
  - Power (TW): 0, 5, 10, 15, 20

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*SSD: smoothing by spectral dispersion
**RT: Rayleigh–Taylor
To date, high-adiabat, low-convergence implosions achieved the highest fusion yields on OMEGA with areal densities up to ~65% of the highest compression shots.

[LILAC* is the LLE 1-D hydrodynamics code]
As expected, the main dependence of the yield is on the implosion velocity. Calculated $V_{imp}$ (km/s) 

YieldExp ($\times 10^{14}$) 

OMEGA implosions are testing the IFAR\(^*\) limits.

*IFAR: in-flight aspect ratio
The Statistical Mapping Model as a Predictive Tool

V. Gopalaswamy and R. Betti, CO8.00010, this conference.
A reliable predictive capability is required to find the optimum implosion.

- Conventional predictive capability is based on using simulations to design future experiments.
- Despite advances in simulations, codes are still not predictive enough to enable quick progress in improving implosion performance.

### Target specifications

**Implosion experiments**

- Yield
- Laser pulse
- Good predictive capability
- Limited predictive capability

**Optimum implosion**

- Implosion performance figure of merit
- Lawson parameter $\chi^*$
- Experimental ignition threshold factor (ITFx)**

ITFx and $\chi$ scale with

$$\rho R^2 \times \frac{\text{yield}}{\text{mass (DT)}}$$

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By assuming that the 1-D codes do not accurately reproduce the 1-D implosion dynamics, we look for statistical correlations between experimental and simulated data.

Instead of comparing each simulated parameter with its measured value, we map each measurement onto all simulated parameters through nonlinear correlations.

New predictive capability (also valid for 3-D systematic nonuniformities)

Example: \( \text{Yield}^{\text{Exp}} = F(V_{\text{LILAC}}^{\text{imp}}, \rho R_{\text{LILAC}}^{\text{imp}}, T_{i}^{\text{LILAC}}, \tau^{\text{LILAC}}, \ldots) \)
The combination of 1-D simulations and mapping relations provides a predictive capability as long as its validity can be extrapolated.
The higher yields were achieved through CD ablators, thinner ice, 40/60 DT mixture, modified pulse shapes, and larger diameter shells.

\[ Y = 3.2 \times 10^{13} \]
\[ \rho R = 126 \text{ mg/cm}^2 \]
\[ T_i = 2.6 \text{ keV} \]

\[ Y = 1.2 \text{ to } 1.4 \times 10^{14} \]
\[ \rho R = 110 \text{ to } 130 \text{ mg/cm}^2 \]
\[ T_i = 4.3 \text{ to } 4.6 \text{ keV} \]
Systematic changes to the target specifications and laser pulse resulted in the expected increase in yield.

\[
\Delta_D = 42 \text{ \(\mu\text{m}\)} \\
\Delta_D = 48 \text{ \(\mu\text{m}\)} \\
\text{Outer diameter (OD) = 870 \(\mu\text{m}\)} \\
\text{Sequential shot number} \\
\text{Measured yield} \\
\text{Prediction from mapping}
\]

Four shot days (Feb. to July 2017)

\[4.3 \times 10^{13} \left( \frac{V_{\text{LILAC}}}{400} \right)^{4.2} \left( \frac{M_{\text{LILAC}}}{0.01} \right)^{0.65}\]
In the last two shot days (ten shots), an \(\sim 20\%\) yield variability is observed between repeats and also between the measured yield and prediction of mapping model. Large temperature asymmetries suggest nonsystematic distortions possibly caused by the large DT ice rms (\(\sim 1.5 \mu m\)) or target offsets.
What are the Results Telling Us?
Hydro stability SSD on/off tests show modest degradation in performance but no proximity to a stability cliff
Including lower-adiabat implosions shows the yield increase from convergence is less than 1-D predictions while the areal density scales as 1-D.

In experiments, a higher CR leads to a very modest increase in yield.

\[ \rho R (\text{MRS}^*) \begin{align*}
100 \left( \frac{\text{CR}_{\text{Exp}}}{13} \right)^{1.5}
\end{align*} \]

Neutron yield: experiment versus LILAC param +CR^{Exp}

\[ 4 \times 10^{13} \left( \frac{V_{\text{LILAC}}^{\text{imp}}}{400} \right)^{4} \left( \frac{M_{\text{stag}}^{\text{lilac}}}{0.01} \right)^{0.7} \left( \frac{\text{CR}_{\text{Exp}}}{11} \right)^{0.5} \]

\[ \text{1-D theory} \]

\[ \text{CR}^{2} \]

\[ \text{1-D theory} \]

\[ \text{CR}^{10} \]

\[ \text{CR}^{17} \]

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\[ \text{1-D theory} \]

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\[ \text{CR}^{13} \]

\[ \text{1-D theory} \]
The shape of the hot-spot self-emission profile is used as a measure of proximity to 1-D behavior; the 1-D Campaign targets are more “1-D” than high-CR targets.

2-D DRACO simulations*

Core self-emission lineouts

Normalized intensity

 normalized intensity

 Radius (μm)

87256: $Y = 10^{14}$
$\rho R = 130 \text{ mg/cm}^2$

77070: $Y = 3.9 \times 10^{13}$
$\rho R = 225 \text{ mg/cm}^2$

GMXI**

GMXI** lineouts

Arbitrary units

 Radius (μm)

87256
$SG_{exp}^{fit} = 3.1$

77070
$SG_{exp}^{fit} = 2.1$

† GMXI: gated monochromatic x-ray imager
OMEGA Roadmap and Extrapolation to NIF* Laser Energies
A systematic approach is being used to find the optimum implosion on OMEGA

Hydro-stability or laser-energy boundary

Optimum implosion

Larger yield by increasing OD, better coupling, larger $V_{imp}$, larger IFAR

Velocity campaign

Increase DT thickness

Tuning campaign

increase $\rho R$

October 3 shots: as predicted $Y = 1.4 \times 10^{14}$, $\rho R = 110$ to 130 mg/cm$^2$

April 4 shots: as predicted $Y = 7.8 \times 10^{13}$, $\rho R = 110$ mg/cm$^2$
OMEGA highest-yield shots extrapolate to fusion yields $\gtrsim 230$ kJ at 1.9 MJ of symmetric illumination

1-D profiles from OMEGA/NIF-symmetric used in the extrapolation

- $\rho$ (OMEGA)
- $\rho$ (NIF)
- $P$ (OMEGA)
- $P$ (NIF)

Hydro-equivalent extrapolation*

$V_{\text{imp}} = \text{const}, \alpha = \text{const}, \text{mass} \sim \text{volume} \sim E_L$

Direct drive NIF 1.9 MJ

Hydrodynamic scaling

<table>
<thead>
<tr>
<th>Shot 87026</th>
<th>$T_i$ (keV)</th>
<th>$R_{17}$ (µm)</th>
<th>$\tau$ (ps)</th>
<th>$\langle P \rangle$ (Gbar)</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>4.08</td>
<td>34.5</td>
<td>79</td>
<td>40</td>
<td>$1.1 \times 10^{14}$</td>
</tr>
<tr>
<td>Simulation (degraded** in 2-D to YOC† = 0.75)</td>
<td>4.01</td>
<td>34.0</td>
<td>74</td>
<td>43</td>
<td>$1.1 \times 10^{14}$</td>
</tr>
<tr>
<td>1.9-MJ extrapolation</td>
<td>5.3 4.9 no $\alpha$</td>
<td>143</td>
<td>300</td>
<td>51</td>
<td>$8.2 \times 10^{16}$ 230 kJ</td>
</tr>
</tbody>
</table>

† YOC: yield-over-clean
Summary/Conclusions

High-adiabat ($\alpha \approx 6$ to 7) implosions achieved the highest fusion yields of $1.4 \times 10^{14}$ on OMEGA with high predictability using a statistical mapping model.

- The ongoing 1-D campaign is building an experimental database of high-adiabat, low-convergence implosions (CR* $\approx$ 12 to 14).
- By mapping the experimental results onto the simulation database, an accurate predictive tool is developed that enables the design of targets with improved performance.
- The highest fusion yield of $1.4 \times 10^{14}$ is achieved by increasing the target outer diameter and reducing the DT ice thickness.
- Based on these recent results, a roadmap is being developed to find the optimum target and laser pulse.
- Hydro-equivalent extrapolation to 1.9 MJ symmetric illumination shows fusion yields $\geq 230$ kJ for best performing implosions.

*CR: convergence ratio
Backup
The time history of the hot-spot radius $R_{17\%}$ monitors deviations from 1-D behavior

- Low modes ($\ell \sim 2$) increase the hot-spot size
- Intermediate modes ($\ell \sim 10$) decrease the size

The time history of the hot-spot radius reveals which modes are dominant.

* A. Bose, R. Betti, and D. Shvarts, JO7.00007, this conference.
The hydrodynamic scaling holds in three dimensions

- **In-flight scaling:**  
  \[ R \sim E^{1/3}_L \]  
  \[ P_L \sim E^{2/3}_L \]  
  \[ \tau_{\text{pulse}} \sim E^{1/3}_L \]  
  \[ V_{\text{imp}} \sim \text{const} \]  
  \[ \alpha \sim \text{const} \]  
  RT growth factors \( \sim \text{const} \)

- **Stagnation scaling:**  
  \[ P \sim \text{const} \]  
  \[ T \sim R^{0.2} \]  
  \[ \tau_{\text{burn}} \sim R \]  
  \[ \rho R_{\text{tot}} \sim R \]  
  \[ V_{hs} \sim R^3 \]

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\[ \rho \text{ (g/cm}^2\text{)} \]

\( Y_{\text{on} \alpha} \sim E^{1.45}_L \)

\[ \chi_{\text{no} \alpha} \sim E^{0.35}_L \]

\[ Y_{\alpha} \approx \frac{1}{(1 - 1.04 \chi_{\text{no} \alpha})^{0.75}} \]

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A. Bose et al., Phys. Plasmas 22, 072702 (2015);  
The hydro-equivalent extrapolation uses the results of 1-D simulations combined with 2-D degradation to match the experimental observables.

The yield predictive capability of the mapping relations applies over a wide range of extrapolations.
The yield’s unique dependence on 1-D simulated parameters persists in 3-D as long as the 3-D dynamics are affected by dominant systematic nonuniformities.

\[ Y_{\text{exp}} = Y_{1-D} \text{ (1-D parameters)} \cdot YOC \text{ (distortion)} \]

- \( Y_{\text{exp}} = Y_{1-D} \) (1-D parameters) YOC (distortion)
- \( A_0 \) = initial nonuniformities (target and/or laser)
- \( f \) (1-D) = amplifications of distortion caused by implosion (RT, RM*, BP**)
- \( YOC = YOC[\tilde{A}_0^{\text{systematic}} f_s (1-D) + \tilde{A}_0^{\text{random}} f_r (1-D)] \)
- If systematic nonuniformities are dominant: \( \tilde{A}_0^{\text{systematic}} \gg \tilde{A}_0^{\text{random}} \)
- \( Y_{\text{exp}} = Y_{1-D} \) (1-D parameters) YOC \( [\tilde{A}_0^{\text{systematic}} f_s (1-D \text{ parameters})] \)
- If \( \tilde{A}_0^{\text{systematic}} = \) constant, the yield depends only on 1-D parameters even in distorted implosions

For 1-D implosions or 3-D with dominant systematic nonuniformities

*RM: Richtmyer–Meshkov
**BP: Bell–Plesset
A convergence test on the thin 42-µm ice targets did not show proximity to stability cliffs for low and mid modes.

Higher-CR targets performed better than low-CR targets at the same predicted velocity.
Simulated trajectories compare favorably with experimental measurements.