Exploring Pathways to Hydro-Equivalent Ignition on the OMEGA Laser

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There are plausible scenarios based on current OMEGA experiments for hydro-scaled ignition at 2 to 6 MJ of symmetric illumination

- A physics-based mapping model used to predict OMEGA implosion performance can identify possible paths to hydro-scaled ignition at multi-MJ of symmetric illumination

- At least three factors can augment implosion performance in hydroscaled targets
  - a faster-than-hydro-scaling dependence on size
  - larger OD targets to improve the energy coupling
  - zooming the laser after the picket

- Combining these three effects, there is a plausible path to hydro-scaled ignition at ~2 to 3 MJ of symmetric illumination (assuming LPI degradation remains at the levels of OMEGA)

- Lowering the adiabat below $\alpha \sim 4$ would greatly improve performance but is not assumed here
Collaborators

V. Gopalaswamy, J. P. Knauer, A. Lees, D. Patel, C. A. Thomas, and W. Theobald

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The best-performing OMEGA implosion achieved a normalized Lawson triple product $\chi \approx 0.174 \pm 0.01$, hydroscaled to $\chi \approx 0.74$ for ~2 MJ of laser energy.

<table>
<thead>
<tr>
<th>Shot</th>
<th>Yield</th>
<th>$\rho R$ (mg/cm)</th>
<th>$T_i$ (keV)</th>
<th>$x$-ray GMXI $R$ ($\mu$m)</th>
<th>$\tau_{BW}$ (ps)</th>
<th>$P$ (Gbar)</th>
<th>$\alpha$</th>
<th>CR $R_l/R_{GMXI}$</th>
<th>$E_L$ (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>96806</td>
<td>$1.6 \pm 0.1 \times 10^{14}$</td>
<td>160±12 (3 LOS)</td>
<td>4.42±0.3</td>
<td>26.5±1</td>
<td>67±8</td>
<td>65±10</td>
<td>4.2</td>
<td>18</td>
<td>27.25</td>
</tr>
</tbody>
</table>

- **Normalized Lawson parameter**

  $$\chi \equiv \rho R_g^{0.61} \left( \frac{0.12 Y_{16}}{M_{mg}} \right)^{0.34}$$

  $$\chi_{OMEGA} \equiv 0.174 \pm 0.01$$

- **Hydro scaling to MJ’s of laser energy**

  $$\chi = \frac{P_T}{(P_T)_{ign}(T)} \tau \sim R \sim E_L^{1/3}$$

**Hydro-equivalent ignition (definition)**

$$\chi_{MJ} \equiv \chi_{OMEGA} \left[ \frac{E_L(MJ)}{E_L^{OMEGA}} \right]^{1/3} \Rightarrow 1$$

<table>
<thead>
<tr>
<th>$E_L$</th>
<th>2 MJ</th>
<th>2.5 MJ</th>
<th>3 MJ</th>
<th>6 MJ</th>
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<tbody>
<tr>
<td>$\chi$</td>
<td>0.74</td>
<td>0.8</td>
<td>0.84</td>
<td><strong>1.04</strong></td>
</tr>
</tbody>
</table>

LOS: line of sight
Laser pulse shapes hydro scaled up to 2.5 MJ of laser energy are below the 500-TW limit.
The mapping model* is a useful tool to uncover trends in the experimental database and identify degradation mechanisms**

\[
\text{Yield}_{\text{exp}} \approx \text{Yield}_{\text{sim}}^{1-D} \cdot \text{YOC}_{\text{hydro}}(\alpha, \text{IFAR}, \text{CR}) \cdot \text{YOC}_{\text{He}^3} \cdot \text{YOC}_{\beta} \cdot \text{YOC}_{\text{res}}
\]

- \( \text{YOC}_{\text{hydro}} \) = degradation from hydro instabilities, shock mistiming, 1-D physics inaccuracies
- \( \text{YOC}_{\text{He}^3} \) = degradation from T decay, \( \text{He}^3 \) contamination, ablator damage from \( \beta \) decay
- \( \text{YOC}_{\beta} \) = degradation from target offset and laser mispointing
- \( \text{YOC}_{\text{beam}} \) = degradation from finite beam size
- \( \text{YOC}_{\text{res}} \) = residual size scaling

\[
\approx \rho R_{\text{sim}}^{1-D} \cdot \rho \text{RoC}_{\text{hydro}}(\text{IFAR}, \text{CR}) \cdot \rho \text{RoC}_{\text{He}^3} \cdot \rho \text{RoC}_{\beta} \cdot \rho \text{RoC}_{\text{res}}
\]
Dedicated hydro-scaled experiments* on OMEGA seem to indicate that the areal density scales faster than predicted by hydro scaling.

\[ P = 52 \pm 9 \text{ Gbar} \]

\[ P = 65 \pm 10 \text{ Gbar} \]

\[ \rho \text{RoC} = \frac{\rho_{\text{exp}}}{\rho_{\text{sim}}^{1-D}} \]

\[ \langle \rho \text{RoC} \rangle = 0.83 \]

\[ \langle \rho \text{RoC} \rangle = 0.69 \]

* C. A. Thomas et al., O09.00010, this conference.
W. Theobald et al., B09.000012, this conference.
Both the OMEGA implosion database and dedicated hydro-scaled experiments exhibit a size dependence of the fusion yield faster than hydro scaling.

\[ \text{Yield}_{\text{exp}} \approx \text{Yield}_{\text{sim}}^{1-D} \text{YOC}_{\text{hydro}}(\alpha, \text{IFAR, CR}) \]\n
\[ \text{YOC}_{\text{He}^3} = 1.0 \text{YOC}_{\text{YOC}} \text{YOC}_{\text{res}}. \]

1-D code hydro scaling

Scale invariant

Residual scaling

\[ \text{YOC}_{\text{res}} \sim R^{1.04 \pm 0.2}. \]

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C. A. Thomas et al., O09.00010, this conference.
W. Theobald et al., B009.00012, this conference.
The faster-than-hydroscaling size scaling could be sufficient for hydro-equivalent ignition at 3 MJ of symmetric illumination

- Possible causes of residual scaling: defects, kinetic effects, radiation preheat, stalk, hot-electron preheat
- Since the origin of this residual size scaling is currently unknown, it is not possible to determine the extent of its validity; a reasonable extrapolation of this residual size scale for another 20%

\[ \chi \equiv \rho R^{0.61} \left( \frac{0.12 Y_{16}^{\text{stag}}}{M_{\text{mg}}} \right)^{0.34} \left( \frac{E_l}{E_{\text{OMEGA}}} \right)^{1/3} \]

- Hydro-scaled experiments
- \( \langle \text{YOC} \rangle = 0.43 \)
- \( \text{YOC} \sim R^{0.85} \)
- \( \langle \text{YOC} \rangle = 0.36 \)

\[ \chi = (1.2 \times \rho R)^{0.61} \left( \frac{0.12 Y_{16} \times 1.2}{M_{\text{mg}}} \right)^{0.34} \left( \frac{E_l}{E_{\text{OMEGA}}} \right)^{1/3} \]

- \( 1.2 \times R \Rightarrow 1.7 \times E_{\text{L}}^{\text{OMEGA}} = 47 \) J
- \( 1.2 \times R \Rightarrow \text{YOC} = 0.52 \) \( \rho \text{RoC} = 1 \) 

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<tr>
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<tr>
<td>( \chi ) without residual scaling</td>
<td>0.74</td>
<td>0.8</td>
<td>0.84</td>
<td>1.04</td>
</tr>
<tr>
<td>( \chi ) with residual scaling</td>
<td>0.87</td>
<td>0.94</td>
<td>( \boxed{1.0} )</td>
<td>1.25</td>
</tr>
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</table>

Exceeds OMEGA laser energy

Limit?

TC15859a
Another path to hydro-equivalent ignition is to improve the performance of OMEGA implosions beyond shot 96086: larger shells lead to higher yields.

\[
\text{Yield}_{\text{exp}} \approx \text{Yield}_{\text{sim}}^{1-D} \text{YOC}_{\text{hydro}}(\alpha, \text{IFAR, CR}) \text{YOC}_{\text{He}^3} \text{YOC}_{\text{He}} \text{YOC}_{\text{res}}
\]

1-D simulated yield increases at larger OD due to better energy coupling. Larger OD's and \(V_{\text{imp}}\) lead to larger IFAR compensated by higher adiabat.

Assuming yield \(2 \times 10^{14}\) and same \(\rho R\):

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<tr>
<td>(\chi) without residual scaling</td>
<td>0.79</td>
<td>0.85</td>
<td>0.90</td>
<td>1.14</td>
</tr>
<tr>
<td>(\chi) with residual scaling</td>
<td>0.94</td>
<td>1.0</td>
<td>1.07</td>
<td>1.35</td>
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For \(1010\) OD, \(\alpha = 4.7\), \(V_I = 521\) km/s.

For \(1016\) OD, \(\alpha = 4.9\), \(V_I = 485\) km/s.

For \(1018\) OD, \(\alpha = 5.3\), \(V_I = 503\) km/s.

1060 OD, \(\alpha = 4.2\), \(V_I = 450\) km/s.

Yield corrected for fill age and \(T_i\) asymmetries (\(\ell = 1\)).
Another path to hydro-equivalent ignition is to improve the performance of OMEGA implosions beyond shot 96086: Zooming phase plates lead to higher yields.

\[ \text{Yield}_{\text{exp}} \approx \text{Yield}_{\text{sim}}^{1-D} \times \text{YOC}_{\text{hydro}}(\alpha, \text{IFAR, CR}) \times \text{YOC}_{\text{He}}^{3} \times \text{YOC}_{\text{YOC}}^{YOC} = \text{YOC}_{\text{YOC}}^{R_{b}, R_{t}} \times \text{YOC}_{\text{res}} \]

Large loss of yields comes from finite beam size i.e., ratio \( R_{\text{beam}} / R_{\text{target}} \)

3-D ASTER* simulations:** about 50% of the yield loss comes from nonuniformities seeded during the picket (0.8\times smaller beam size is required in ASTER for yield degradation)

\[ \text{YOC}_{\text{beam}} = \left( \frac{R_{b}}{R_{t}} \right)^{3.4} = 0.5 \text{ for 1010 \( \mu \)m OD} \]

Zooming after picket (i.e., YOC up 50%)

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</tr>
</thead>
<tbody>
<tr>
<td>( \chi ) without residual scaling and 1.5\times yield</td>
<td>0.90</td>
<td>0.97</td>
<td>1.0</td>
<td>1.3</td>
</tr>
<tr>
<td>( \chi ) with res scaling and 1.5\times yield</td>
<td>1.07</td>
<td>1.16</td>
<td>1.23</td>
<td>1.55</td>
</tr>
</tbody>
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** V. Gopalaswamy et al., GO10.00002, this conference.
Summary/Conclusions

There are plausible scenarios based on current OMEGA experiments for hydro-scaled ignition at 2 to 6 MJ of symmetric illumination

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