Achievement of Core Conditions for Alpha Heating in Direct-Drive Inertial Confinement Fusion

Simulation of 77068

Time-integrated x-ray image of the hot spot

Experiment

Simulation

50 μm

58th Annual Meeting of the American Physical Society
Division of Plasma Physics
San Jose, CA
31 October–4 November 2016
Summary

OMEGA implosions hydro-scaled to the National Ignition Facility (NIF) would produce comparable alpha heating but with several times more fusion energy compared to indirect drive*

- Using hydrodynamic simulations, we reconstruct the experimentally observed conditions of the core

- Followed by a volumetric scaling of the core to a 1.9-MJ driver with the same illumination configuration and laser-target coupling; the only assumption is that the implosion hydrodynamic efficiency† is unchanged at higher energies

- We find that correcting the low-mode asymmetries can take these implosions to the burning plasma regime

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† Fraction of laser energy converted to kinetic energy of imploding shell
Collaborators


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Laboratory for Laser Energetics

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D. Shvarts
University of Michigan
Translating direct-drive hot-spot pressures to ignition and alpha-heating metrics

\[ \chi_{\text{no } \alpha} \approx (\rho R_{\text{no } \alpha})^{0.61} \left( \frac{0.12 Y_{\text{no } \alpha}^{16}}{M_{\text{stag}}^{\text{DT}}} \right)^{0.34} \]

- Measurable no-\( \alpha \) implosion-performance metric, relevant for sub-ignition scales where alpha heating is insignificant

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\( \alpha \) heating > PdV hot spot

\[ \chi_{\text{no } \alpha} \]

\( X \)

\( Y_{\alpha}/Y_{\text{no } \alpha} \)

\[ 0.0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0 \quad 1.2 \]

\[ 0 \quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \]

OMEGA 77068
56 Gbar
26 kJ

Equivalent 77068
56 Gbar
1.9 MJ

100 Gbar \( \bullet 1.9 \) MJ
\( (\chi = 0.95, Y_{\text{amp}} = 40) \)

90 Gbar \( \bullet 1.9 \) MJ

80 Gbar

1.9 MJ
Alpha-heating yield-extrapolation technique has been developed for direct drive

- Direct-drive implosions have repeatedly demonstrated hot-spot pressures in excess of 50 Gbar*
- For the best performing shot

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Yield</td>
<td>$5.3 \times 10^{13} \pm 5%$</td>
</tr>
<tr>
<td>$T_i$ (keV)</td>
<td>$3.6 \pm 0.3$</td>
</tr>
<tr>
<td>$\rho R$ (g/cm$^2$)</td>
<td>$0.196 \pm 0.018$</td>
</tr>
<tr>
<td>Stagnating mass ($\mu g$)</td>
<td>11.5</td>
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• Hydrodynamic scaling of the core

$E_L = \left( \frac{E_{\text{NIF}}}{E_\Omega} \right) \approx 73 \times$

$P \approx 56 \text{ Gbar}$

$26 \text{ kJ}$

$E \sim \tau \sim \rho R \sim E_L^{1/3} \approx 4 \times$

$\chi_{\text{no } \alpha} \sim E_L^{0.35}$

$P_{\text{no } \alpha} \approx 56 \text{ Gbar}$

$T_{\text{no } \alpha} \sim E_L^{0.06} \approx 1.3 \times$

$\text{1.9 MJ}$

$\chi_{\text{no } \alpha} \approx 0.61$

OMEGA shot 77068

OMEGA shot 77068 at 1.9 MJ

$\chi_{\text{no } \alpha} \approx 0.138$
Alpha-heating yield-extrapolation technique has been developed for direct drive

- Direct-drive implosions have repeatedly demonstrated hot-spot pressures in excess of 50 Gbar\(^*\)
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- Hydrodynamic scaling of the core

\[ E_L = \left( \frac{E_{\text{NIF}}}{E_{\Omega}} \right) \approx 73 \times \]

1.9 MJ

\( \dot{Y}_{\text{amp}} \approx 2.1 \)

\[ \dot{Y}_{\text{amp}} = \frac{Y_{\alpha}}{Y_{\text{no } \alpha}} \approx \left( \frac{1 - \chi_{\text{no } \alpha}}{0.96} \right)^{-0.75} \]

26 kJ

\( P \approx 56 \text{ Gbar} \)

\( \chi_{\text{no } \alpha} \approx 0.138 \)

\( \chi_{\text{no } \alpha} \approx 0.61 \)

\( \text{OMEGA shot 77068 at 1.9 MJ} \)

\( \text{OMEGA shot 77068} \)

The radiation–hydrodynamic code *DEC2D* is used to simulate the deceleration phase of implosions.

The radiation–hydrodynamic code *DEC2D* is used to simulate the deceleration phase of implosions. The in-flight target 77068 is modeled using the LILAC† code, while the stagnation phase is simulated using *DEC2D*.* The pulse shape of Target 77068 (26.18 kJ) is shown, with a peak power of 380 km/s. The combination for intermediate modes is given as:

\[ \Delta V_1[\ell = 2] + \Delta V_2[\text{intermediate modes}] \]

* K. M. Woo et al., TO5.00015, this conference.
Reconstruction of the deceleration phase: using a combination of low modes ($\ell \sim 2$) to degrade the hot-spot pressure with a spectrum of intermediate modes to retain a 1-D-like hot-spot volume.

Graphs showing the ratio $P/P_{1-D}$ and $V/V_{1-D}$ as a function of YOC (Yield Overlap Criterion). The graph on the left shows the data for 77068 with low modes corrected, which can produce 80-Gbar pressure. The graph on the right includes data points from experiments and various theoretical models, such as $\ell = 2$, Intermediate modes, and a combination model.
Reconstruction of the deceleration phase: to match experimental observables of the core

\[ r(nm) \]
\[ \rho (g/cm^3) \]
\[ z(nm) \]

Time-integrated x-ray image of the hot spot

Experiment
Simulation

Lineout

\[ E_L \ 26.18 \ kJ \]

<table>
<thead>
<tr>
<th>( E_L ) 26.18 kJ</th>
<th>Experiment</th>
<th>1-D simulation</th>
<th>2-D simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield ( 5.3 \times 10^{13} (\pm 5%) )</td>
<td>( 5.3 \times 10^{13} )</td>
<td>( 1.7 \times 10^{14} )</td>
<td>( 5.3 \times 10^{13} )</td>
</tr>
<tr>
<td>( P ) (Gbar)</td>
<td>56 (±7)</td>
<td>97</td>
<td>56</td>
</tr>
<tr>
<td>( T_i ) (keV)</td>
<td>3.6 (±0.3)</td>
<td>3.82</td>
<td>3.7</td>
</tr>
<tr>
<td>( R_{hs} ) (( \mu )m)</td>
<td>22 (±1)</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>( \tau ) (ps)</td>
<td>66 (±10)</td>
<td>61</td>
<td>54</td>
</tr>
<tr>
<td>( \rho R ) (g/cm(^2))</td>
<td>0.196 (±0.018)</td>
<td>0.211</td>
<td>0.194</td>
</tr>
</tbody>
</table>

OMEGA shot 77068
\[ \chi_{no} \alpha \approx 0.138 \]

R. Betti et al., POS.00008, this conference.
Extrapolating OMEGA results to hydro-equivalent targets driven by 1.9-MJ symmetric illumination leads to 125 kJ of fusion yield.

<table>
<thead>
<tr>
<th>Shot 77068</th>
<th>OMEGA 26.18 kJ</th>
<th>1.9 MJ without $\alpha$ heating</th>
<th>1.9 MJ with $\alpha$ heating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>$5.3 \times 10^{13}$</td>
<td>$2.25 \times 10^{16}$</td>
<td>$4.45 \times 10^{16}$</td>
</tr>
<tr>
<td>$P^*$ (Gbar)</td>
<td>56</td>
<td>56</td>
<td>79</td>
</tr>
<tr>
<td>$T_i$ (keV)</td>
<td>3.7</td>
<td>4.7</td>
<td>5.1</td>
</tr>
<tr>
<td>$R_{hs} (\mu m)$</td>
<td>22</td>
<td>92.3</td>
<td>92.5</td>
</tr>
<tr>
<td>$\tau$ (ps)</td>
<td>54</td>
<td>215</td>
<td>193</td>
</tr>
<tr>
<td>$\rho R$ (g/cm$^2$)</td>
<td>0.194</td>
<td>0.83</td>
<td>0.81</td>
</tr>
</tbody>
</table>

OMEGA shot 77068 at 1.9 MJ

$\chi_{no \alpha} \approx 0.61$

$Y_{amp} = 2$
Correcting the low-mode asymmetries can take direct drive to the burning plasma regime

Extrapolated to 1.9 MJ: Yield = 300 kJ; $\dot{Y}_{\text{amp}} \approx 3$.
Summary/Conclusions

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