Three-Dimensional Hydrodynamic Simulations of OMEGA implosions

OMEGA direct-drive cryogenic target

Shape of hot spot at peak neutron production

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

Consistent interpretation of OMEGA direct-drive implosions indicates significant effects of large-scale asymmetries

- Several x-ray and neutron-based observations show the presence of large-scale asymmetries in direct-drive cryogenic and room-temperature OMEGA implosions.
- Three-dimensional \textit{ASTER} simulations using measured low-\(\ell\)-mode seeds reproduce these observations.
- Simulations indicate that asymmetries resulting from measured target offset, beam-to-beam power imbalance, and ice-shell nonuniformities reduce the stagnation pressure by 40%.

Three-dimensional simulations are essential to guide physics campaigns and engineering advancements on the OMEGA laser.

Collaborators


University of Rochester
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• Introduction
• Measured evidences of large-scale asymmetries
• 3-D hydrodynamic codes at LLE
• *ASTER* simulations of drive asymmetry in room-temperature OMEGA implosions
• Simulations of a cryogenic OMEGA implosion
• Path forward
Direct drive requires a factor of 3 lower hot-spot pressure for ignition than indirect drive

\[ \text{Direct-drive ignition: } CR > 22 \text{ and } P_{hs} > 120 \text{ Gbar} \]

\[ \text{Indirect-drive ignition: } CR = 30 \text{ to } 40 \text{ and } P_{hs} > 350 \text{ Gbar} \]

- Pressure threshold for ignition

\[ P_{th} \sim 1/\sqrt{E_{hs}} \]

**Figure:**
- **Hot-spot energy** \( E_{hs} \) (kJ)
- **Pressure threshold** \( P_{th} \) (Gbar)

**Graph:**
- **Indirect drive**
  - Required: \( P_{hs} = 350 \text{ to } 400 \text{ Gbar} \)
- **Direct drive**
  - Required: 140 Gbar
  - Achieved: 56\(\pm\)7 Gbar (~40% of \( P_{th} \))

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*CR: convergence ratio
OMEGA cryogenic implosions are hydrodynamically scaled from NIF-scale ignition designs.

1.5-MJ, spherically symmetric direct-drive design

- \( V_{\text{imp}} = 3.8 \) to \( 4 \times 10^7 \) cm/s
- Adiabat \( \alpha = 1.6 \) to 3
- IFAR\(_{2/3} = 20 \) to 25
- CR = 20 to 23

26- to 29-kJ OMEGA cryogenic design

Adiabat and IFAR are controlled by pulse shaping

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

Adiabat

\[ \alpha = P/P_{\text{Fermi}} \]

IFAR = shell radius/shell thickness

ifAR: in-flight aspect ratio
Achieving $P_{hs} \sim P_{th}$ requires understanding and mitigating various sources of performance degradation in OMEGA implosions

1-D physics

- Uncertainties in equation of state (EOS)
  - strongly coupled plasma
  - shell release

- Hydrodynamic efficiency
  - effect of cross-beam energy transfer (CBET)
  - heat transport

- Preheat
  - radiation from hot corona
  - energy particles as a result of laser–plasma interactions (LPI)

- Small-scale mix
  - laser imprint
  - target defects

- Large-scale asymmetries

J. P. Knauer et al., NO5.00008, this conference.

P. B. Radha et al., NO5.00005; J. A. Marozas et al., NO5.00009, this conference.

A. K. Davis et al., NO8.00007, this conference.

A. R. Christopherson et al., NO5.00007, this conference.

J. A. Delettrez et al., UO9.00015, this conference.

D. T. Michel et al., TO5.00006; S. X. Hu et al., JO5.00001; A. Shvydky et al., JO5.00003, this conference.

S. P. Regan et al., TO5.00004, this conference.

This talk; K. S. Anderson et al., NO5.00011; K. M. Woo et al., TO5.00015, this conference.

K. M. Woo et al., TO5.00015, this conference.
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Measurements show large-scale asymmetries in OMEGA implosions

Target asymmetry during laser drive

Time-resolved x-ray self-emission imaging ($h\nu > 1$ keV)

Evolution of mode-2 amplitude

\[ R_{\text{shell}} \text{ (\textmu m)} \]

\[ t \text{ (ns)} \]

\[ \text{Mode-2 amplitude} \% \]

\[ t \text{ (ns)} \]

\[ \text{0} \quad 1 \quad 2 \quad 3 \]

\[ \text{Mode-2 amplitude} \% \]

\[ 0 \quad 1 \quad 2 \quad 2.0 \quad 2.5 \quad 3.0 \]

\[ \text{Evolution of mode-2 amplitude} \]

\[ \text{Time-resolved x-ray self-emission imaging} \]

\[ \text{Projection of the ablation surface} \]

\[ \text{Target} \]

\[ \text{Plasma corona} \]

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*D. T. Michel et al., Rev. Sci. Instrum. 83, 10E530 (2012).*
Measurements show large-scale asymmetries in OMEGA implosions

Asymmetry of dense shells before stagnation

Time-resolved x-ray backlighting of cryogenic implosions ($h\nu \sim 1.9$ keV)


t_{\text{bang}} \sim 100$ ps

C. Stoeckl, Ni2.00004, this conference (invited).
Measurements show large-scale asymmetries in OMEGA implosions

Implosion asymmetry near bang time*

D$_2$-filled Ti-doped plastic shell target

Time-resolved $T_i$ He-$\beta$ emission image (~5.5 keV)

*R. Shah et al., G05.00001, this conference.
Measurements show large-scale asymmetries in OMEGA implosions

Time-integrated and time-resolved x-ray imaging of hot spot

GMXI (4 to 8 keV)*

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GMXI: gated monochromatic x-ray imager
Measurements show large-scale asymmetries in OMEGA implosions

Directional variation of neutron data

\[ \langle T_i \rangle_n \text{ includes the flow effect}^* \]

\[ \langle T_i \rangle_n = T_i + \frac{2}{3} m_i V_f^2 \]

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Two 3-D codes are being used in LLE to simulate direct-drive (DD) implosions

HYDRA†
- Established inertial confinement fusion (ICF) and high-energy-density physics (HEDP) community code
- DD-relevant physics packages under development
  - nonlocal heat transport
  - noise-free 3-D ray trace for laser deposition
  - CBET

ASTER‡
- Eulerian code optimized for DD implosions
- Uses simplified models for
  - heat transport (flux-limited Spitzer)
  - 3-D ray trace with CBET (spherically symmetric corona)
- Used to interpret and guide DD implosion experiments on OMEGA

K. S. Anderson et al., NO5.00011, this conference.
A. Shvydky et al., JO5.00003, this conference.
Measured sources of nonuniformity are used as input to ASTER

- Exact illumination nonuniformities on target are not well known

TCC: target chamber center
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Measured mode 2 from drive asymmetry is modeled well in simulations

- Room-temperature implosions
  - no ice-shell nonuniformity
  - no offset (<5 µm)

Self-emission images at $t = 2.7$ ns

![Self-emission image](image1)

Simulations

Evolution of mode-2 amplitude

- Phase of mode 2 does not change in time but is different in experiment and simulations (will be addressed later)
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Cryogenic implosions are simulated assuming all known sources of large-scale implosion asymmetry

Included (measured) sources
- Beam overlap
- 4-μm (±3-μm) target offset
- Ice thickness ±2 μm (bottom thinner)
- Beam-to-beam power variation (power history)
- Beam mispointing (σ_{rms} = 8.4 μm)

\[ \alpha = 3.2, \text{ IFAR} \approx 24 \]

\[ E_L = 26 \text{ kJ} \]

\[ P_{hs} = 56\pm7 \text{ Gbar} \]

\[ P. W. McKenty et al., TO5.00011, this conference. \]
\[ D. Cao et al., TO5.00012, this conference. \]
\[ K. S. Anderson et al., NO5.00011, this conference. \]
Large-scale asymmetry in the implosion core causes deformation and displacement of the hot spot

Three-dimensional view of the hot spot (surface $T_i = 1$ keV) at peak neutron production

Beam overlap only (YOU = 95%)  All asymmetry sources (YOU = 39%)

YOU: yield-over-uniform
Simulations accurately predict reduction in implosion performance

Performance reduction is caused by

- Excessive heat losses by the hot spot
  \[ \langle T_i \rangle_n = 3.39/3.03 \text{ keV (1-D/3-D)} \]
- Under compression of the hot spot

<table>
<thead>
<tr>
<th>Summary of performance</th>
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<tbody>
<tr>
<td></td>
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<tr>
<td>Neutron yield</td>
</tr>
<tr>
<td>( P_{hs} ) (relative to 1-D)</td>
</tr>
</tbody>
</table>

Target at peak neutron production, \( t = 2.664 \text{ ns} \)

Meridional cut views at \( \phi = 83^\circ \)
Increase of the residual kinetic energy in asymmetric implosions results in under-compression of the hot spot

Simulated energy balance* in shot 77066

\[ E_{\text{kin}} \text{ (1-D)} = 0.07 \text{ kJ (6%)} \]
\[ E_{\text{kin}} \text{ (3-D)} = 0.22 \text{ kJ (18%)} \]
\[ \Delta E_{\text{kin}} \approx 0.15 \text{ kJ (12%)} \]

*Energies are integrated over the center volume of \( R = 200 \mu m \)
Simulations of shot 77066 reproduce the magnitude of asymmetric plasma flow in the hot spot but not directionality.

- Diagnostic is being developed to measure on-target drive asymmetries.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Experiment</th>
<th>Simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ($\theta = 85^\circ$)</td>
<td>3.6±0.2</td>
<td>3.9</td>
</tr>
<tr>
<td>2 ($\theta = 88^\circ$)</td>
<td>3.8±0.2</td>
<td>3.5</td>
</tr>
<tr>
<td>3 ($\theta = 61^\circ$)</td>
<td>3.2±0.2</td>
<td>4.4</td>
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</tbody>
</table>

$\Delta T_i \approx 0.6$ keV  $\Delta T_i = 0.9$ keV
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A better understanding of the role of large-scale asymmetries in OMEGA implosions is required

- Are large-scale modes the only source of target degradation for mid- and high-adiabat implosions?
  - 1-D physics
  - small-scale mix
- What is the main source for large-scale modes?
  - ice/ablator-shell asymmetry
  - uncertainty in beam balance/pointing/timing
  - uncertainty in target positioning
- Can we better measure actual laser nonuniformities on a target?
Engineering advancements and physics campaigns are planned to improve implosion performance on OMEGA

<table>
<thead>
<tr>
<th>Target quality</th>
<th>Illumination uniformity</th>
<th>Coupling</th>
<th>1-D physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>-- fill-tube cryogenic system for nonpermeable ablatorss</td>
<td>-- reconstruction and correction of in-flight shell shapes</td>
<td>-- R75 design*</td>
<td>-- 1-D cryo campaign***</td>
</tr>
<tr>
<td>-- clean environment</td>
<td>-- campaign for measuring and improving beam balance</td>
<td>-- 61st-beam project with a tunable $\lambda$**</td>
<td>-- shell release†</td>
</tr>
<tr>
<td>-- polystyrene shells</td>
<td>-- individual beam-profile measurements</td>
<td>-- tricolor OMEGA upgrade</td>
<td>-- shell thickness‡</td>
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<td></td>
<td></td>
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<td>-- CH/DT interface</td>
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<td></td>
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<td>-- shock timing</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>-- conduction zone††</td>
</tr>
</tbody>
</table>

*V. N. Goncharov et al., TO5.00003, this conference.
**D. H. Froula et al., UO8.00008, this conference.
***R. Betti et al., PO5.00008, this conference.
†J. P. Knauer et al., NO5.00008, this conference.
‡D. T. Michel et al., TO5.00006, this conference.
††A. K. Davis et al., NO8.00007, this conference.
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*I. V. Igumenshchev et al., Phys. Plasmas 23, 052702 (2016).*