Direct-Drive Inertial Confinement Fusion Research at the Laboratory for Laser Energetics: Charting the Path to Thermonuclear Ignition

National Ignition Facility (NIF)
1.8 MJ
192 beams

OMEGA
30 kJ
60 beams

240 ft

Relative size

R. L. McCrory, S. P. Regan
University of Rochester
Laboratory for Laser Energetics

20th IAEA Fusion Energy Conference
Vilamoura, Portugal
1–6 November 2004
Collaborators


Laboratory for Laser Energetics, University of Rochester
250 East River Road, Rochester, NY 14623-1299

C. K. Li, R. D. Petrasso, F. H. Séguin, and J. A. Frenje
Plasma Science and Fusion Center, MIT
Boston, MA, USA

S. Paladino, C. Freeman, and K. Fletcher
State University of New York at Geneseo
Geneseo, NY, USA
Summary

Significant theoretical and experimental progress continues to be made at LLE – charting the path to ignition with direct-drive ICF

• Ignition target designs are being validated on OMEGA with scaled implosions of cryogenic D2/DT targets.

• Symmetric direct drive on the National Ignition Facility (NIF) is predicted to achieve high-gain (~40).

• Direct drive targets are predicted to ignite on the NIF while it is in x-ray-drive configuration with polar direct drive (PDD).

• Fully integrated fast-ignition (FI) experiments will begin on OMEGA with the completion of the high energy petawatt (HEPW) upgrade – OMEGA EP.

Prospects for thermonuclear ignition with direct drive on the NIF are extremely promising.
Outline

• Direct-drive inertial confinement fusion (ICF)
• OMEGA
• Symmetric illumination direct-drive ignition designs
• Polar direct drive
• Fast ignition research
Ablation is used to generate the extreme pressures required to compress a fusion capsule to ignition conditions.

“Hot-spot” ignition requires the core temperature to be at least 10 keV and the core fuel areal density to exceed ~300 mg/cm².
The OMEGA laser is the most powerful UV laser for fusion research in the world.

- 60 beams
- >30 kJ UV on target
- 1%–2% irradiation nonuniformity
- Flexible pulse shaping
- Short shot cycle (1 h)
OMEGA creates extreme states of matter with high reproducibility

- Compressed pressures of 5−10 Gbar
- DT neutron yields of $10^{14}$
- Peak ion temperatures of $\sim 20$ keV
OMEGA cryogenic targets are energy scaled from the NIF symmetric direct-drive point design.

NIF: 1.5 MJ
- DT ice: ~3 μm CH, 1.69 mm
- DT gas: 1.35 mm

Gain (1-D) = 45

OMEGA: 30 kJ
- D₂ ice: ~4 μm CH, 0.46 mm
- D₂ gas: 0.36 mm

Energy ~ radius³; power ~ radius²; time ~ radius

Initial cryogenic DT implosions are expected in spring 2005.
Perturbation seeds from four sources early in the implosion determine the final capsule performance.
A global nonuniformity budget for the direct-drive point design can be formed by scaling gain with \( \bar{\sigma} \).

- The NIF gain* and OMEGA yield can be related by
  \[
  \bar{\sigma}^2 = 0.06 \sigma_{\ell < 10}^2 + \sigma_{\ell \geq 10}^2; 
  \]
  \( \sigma_{\ell} \) = rms amplitudes at the end of the acc. phase.

Laser imprint

Shell stability and compressibility depend on the adiabat

- Minimum energy required for ignition: $E_{\text{min}} \sim \alpha^{1.88}$
- Rayleigh–Taylor instability growth $\gamma = \alpha_{\text{RT}}(\text{kg})^{1/2} - \beta_{\text{RT}}kV_a$

$\alpha = P/P_{\text{Fermi}}$

$V_a \sim \alpha^{3/5}$

Adiabat shaping is achieved using a high intensity picket laser pulse.

$1\text{M. Herrmann et al., Phys. Plasmas 8, 2296 (2001).}$

$2\text{R. Betti et al., Phys. Plasmas 9, 2277 (2000).}$
Measured radiographs show significant imprint reduction with picket pulses.


- Measurements at 100 µm distance traveled.
Optical-depth modulations are significantly reduced at shorter wavelengths using a picket pulse.
Adiabat shaping is a very powerful technique to reduce the growth of hydrodynamic instabilities.

\[ \alpha = 2 \]

CH

D\(_2\) ice

D\(_2\) gas

5 \(\mu\)m

80 \(\mu\)m

345 \(\mu\)m

\[ \bar{\sigma} > 10 \mu m \]

\[ \bar{\sigma} = 1.12 \mu m \]

Imprint simulations

*ORCHID*: \( \ell = 2\text{–}200\), DPP + PS, 1-THz SSD

Power (TW)

Time (ns)

\( \rho \) (g/cc)

4.20

0.10

0 100 200 300

0 100 200 300

0 100 200 300
Direct-drive target stability is dramatically improved when adiabat shaping is applied.

The benefit of pickets has been confirmed in NRL and LLNL simulations.
Reduction of the on-target laser irradiation nonuniformity on OMEGA dramatically improved implosion performance

- Far field intensity envelope: $I(r) \propto \exp\left[-\left(\frac{r}{\delta}\right)^n\right]$

- New phase plate design $n = 4.1$ (SG4)

- Old phase plate design $n = 2.2$ (SG3)
Submicron rms ice layers were demonstrated; the smoothest layers were confined to localized regions of the target.

- 24 views every 15° in “x” and “y”
- 0.8 to 1.4 µm over 1/4 of target’s surface
2-D DRACO demonstrates good agreement in predicting target performance for shot 35713 ($\alpha \sim 4$)

### OMEGA Implosions

**DRACO 2-D density near peak burn, shot 35713**

$\alpha \sim 4$, 17.5 kJ

<table>
<thead>
<tr>
<th></th>
<th>Expt</th>
<th>1-D</th>
<th>2-D</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y_{1n}$</td>
<td>$1.61 \times 10^{10}$</td>
<td>$9.90 \times 10^{10}$</td>
<td>$1.81 \times 10^{10}$</td>
</tr>
<tr>
<td>$Y_{2n}$</td>
<td>$2.55 \times 10^{8}$</td>
<td>$1.70 \times 10^{9}$</td>
<td>$2.78 \times 10^{8}$</td>
</tr>
<tr>
<td>$&lt;\rho R&gt;$ (mg/cm²)</td>
<td>88</td>
<td>117</td>
<td>133</td>
</tr>
<tr>
<td>$T_{\text{ion}}$ (keV)</td>
<td>3.0</td>
<td>1.9</td>
<td>1.70</td>
</tr>
</tbody>
</table>
A stability analysis* of the $\alpha = 4$ design defines the ignition-scaling performance window for cryogenic implosions.

- The NIF gain and OMEGA yield can be related by
  \[ \sigma^2 = 0.06 \sigma^2_{\ell<10} + \sigma^2_{\ell\geq10}, \]
  where the $\sigma^2_{\ell}$'s are the rms amplitudes at the end of the acceleration phase*.

---

Hydrodynamic simulations are consistent with implosion data over a wide range of ice roughness and target offset.
**Polar Direct Drive**

Direct drive can achieve ignition while the NIF is in the x-ray-drive configuration.

- **Standard pointing with x-ray-drive configuration**
  - 23.5° 30° 45° 50° 75°

- **Repointing for PDD**
  - 23.5° 30° 45° 50° 75°

- **2-D hydrodynamic simulations**
  - Gain = 10
  - \(\rho \text{ (g/cc)}\)
  - \(z \text{ (µm)}\)

- Polar direct drive (PDD) is based on the optimization of phase-plate design, beam pointing, and pulse shaping.
2-D hydrocode simulations track the measured target nonuniformity for initial PDD experiments on OMEGA

- The NIF PDD configuration with 48 quads has been approximated by repointing 40 beams for implosions on OMEGA.
A complementary approach to hot-spot ignition, namely fast ignition is an active area of research at LLE.

**Fast Ignition**

Low-density central spot ignites a high-density cold shell

\[ \rho T_{\text{hot}} \approx \rho T_{\text{cold}} \text{ (isobaric)} \]

Fast-heated side spot ignites a high-density fuel ball

\[ \rho_{\text{hot}} \approx \rho_{\text{cold}} \text{ (isochoric)} \]
Ignition could be achieved at lower drive energies with fast ignition.
The two viable fast-ignition concepts share fundamental issues: hot-electron production and transport to the core.

**Channeling concept**
- Light pressure bores hole in coronal plasma.
- Ignition:
  - Hole boring
  - 2.6 kJ, 10 ps
  - ~1-MeV electrons heat DT fuel to ~10 keV, ~300 g/cc.

**Cone-focused concept**
- Au cone
- Single ignitor beam: 2.6 kJ in 10 ps
- e−
Fast ignition with cryogenic fuel will be conducted on OMEGA with the high energy petawatt OMEGA EP.

<table>
<thead>
<tr>
<th>Short-pulse performance</th>
<th>Short-pulse beam 1</th>
<th>Short-pulse beam 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short pulse (IR)</td>
<td>1 to 100 ps</td>
<td>35 to 100 ps</td>
</tr>
<tr>
<td>IR energy on-target (kJ)</td>
<td>2.6</td>
<td>2.6</td>
</tr>
<tr>
<td>Intensity (W/cm²)</td>
<td>$6 \times 10^{20}$</td>
<td>$\sim 4 \times 10^{18}$</td>
</tr>
</tbody>
</table>

OMEGA EP will be completed in FY07.
Significant theoretical and experimental progress continues to be made at LLE – charting the path to ignition with direct-drive ICF

- Ignition target designs are being validated on OMEGA with scaled implosions of cryogenic D2/DT targets.

- Symmetric direct drive on the National Ignition Facility (NIF) is predicted to achieve high-gain (~40).

- Direct drive targets are predicted to ignite on the NIF while it is in x-ray-drive configuration with polar direct drive (PDD).

- Fully integrated fast-ignition (FI) experiments will begin on OMEGA with the completion of the high energy petawatt (HEPW) upgrade – OMEGA EP.

Prospects for thermonuclear ignition with direct drive on the NIF are extremely promising.
Gas-tight fast-ignition targets were developed for fuel-assembly experiments

- 870-µm OD shell
- 24-µm wall
- ~10 atm D$_2$ or D$_3$He fill
- 35° half-angle gold cone
- Backlighting
  - 35 beams, 12 kJ, 1 ns on target
  - 15 beams, 6 kJ, 1 ns on backlighter
- Areal-density measurements
  - 55 beams, 22 kJ, 1 ns on target
The backlit framing-camera images show the core assembly and cone reaction in great detail.

Shot 32381, V backlighter, 
$D_2$ fill, yield $= 6 \times 10^6$, 
$\rho R \sim 60 \text{ mg/cm}^2$ ($D^3\text{He}$ proton dE/dx)