ICF and IFE Research at the Laboratory for Laser Energetics

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Summary
The Laboratory for Laser Energetics is validating concepts for ICF ignition

- The baseline direct-drive ignition target for the NIF is a thick cryogenic DT shell enclosed by a thin plastic shell.
- DT ice layer roughness <1-\(\mu\)m rms are routinely achieved.
- Ignition-scaled cryogenic D\(_2\) and DT implosions are underway.
- Polar direct-drive (PDD) will allow direct-drive ignition experiments while NIF is configured for indirect drive.
- A new high-energy petawatt laser system—OMEGA EP—is under construction at LLE (completion April 2008).
- Integrated fast-ignition experiments will begin in 2009.
- National Ignition Campaign (NIC) success is a prerequisite for Inertial Fusion Energy (IFE).

ICF physics validation is required for IFE.
The NIF symmetric direct-drive point design is a thick DT-ice layer enclosed by a thin CH shell.

Energy: 1.5 MJ
Absorption fraction: 63%
Gain \( \frac{\text{fusion energy out}}{\text{laser energy in}} \): 45
OMEGA cryogenic targets are energy scaled from the NIF symmetric direct-drive point design.

NIF: 1.5 MJ
- DT ice: 1.69 mm
- DT gas: 1.35 mm

Gain (1-D) = 45

OMEGA: 30 kJ
- DT ice: 0.46 mm
- DT gas: 0.36 mm

Energy ~ radius^3
Power ~ radius^2
Time ~ radius

\[ \alpha = \frac{P_{\text{fuel}}}{P_{\text{Fermi}}} \]

NIF \( \alpha \sim 3 \)

OMEGA \( \alpha \sim 4 \)

Time (ns)

Power (TW)
A reliable cryogenic fuel system is required for IFE

- Target positioning accuracy is challenging with cryogenic targets.
\textbf{$\beta$-layered 50:50 DT cryogenic targets have been imploded on OMEGA}

- $\beta$-layered 50:50 DT cryogenic targets have ice roughness nonuniformity $<1$-$\mu$m rms.
- Progress in IR layering of $D_2$ cryogenic targets have led to ice roughness nonuniformity $<2$-$\mu$m rms.
- Diagnostics show that the ice uniformity is maintained at shot time.
- DT and $D_2$ implosions allow different diagnostics to interrogate target performance and improve hydrodynamic simulations.
- Peak areal densities are approaching 150 mg/cm$^2$.

Cryogenic target implosions on OMEGA will validate direct-drive target physics and numerical simulations.
We have produced four DT (45:55) ice layers with an ice roughness less than 1-\(\mu\)m rms for all modes, in three separate capsules.
The cryogenic DT layer roughness exceed the NIF direct-drive ignition specification

Formed from a single crystal; 0.47-μm rms in a single view
Both x-ray and neutron spectroscopy can be used to measure the ICF target core conditions\(^1\)

- The self-emission spectrum at peak compression is exponential given by the electron temperature filtered by the areal density of the compressed shell.

- The emergent x-ray spectrum diagnoses the inner hot-spot electron temperature \(kT_e\) and shell areal density \(\rho R_{\text{shell}}\):

\[
e^{-\mu \rho R_{\text{shell}}} e^{-E/kT_{\text{hot}}}
\]

\[
\mu(E, \rho, T) = \frac{0.44 \rho_{\text{shell}}}{(E/\text{keV})^{3/2} (kT_{\text{shell}}/\text{keV})^{1/2}}
\]

where \(\mu(E)\) is the mass absorption coefficient.

X-ray spectra from DT cryo shots are compared to 1-D simulations to infer the areal density

- There is evidence that the compressed fuel is being preheated during the laser pulse.

The estimated areal density is 140 mg/cm².
The Lawson criterion is estimated from the areal density and disassembly time

- The disassembly time is \(~100\) ps.
- The density is given by the areal density divided by the calculated shell thickness at peak compression.

\[ \rho = \frac{\text{areal density}}{\text{calculated shell thickness at peak compression}} \]

- The Lawson criterion is \(6 \sim 12 \times 10^{20} \text{ s/m}^3\).
- The \(n_e \tau T\) is \(3 \sim 20 \times 10^{20} \text{ s keV/m}^3\) depending on whether the hot spot or shell temperature is used.

Fuel thickness from x-ray data and simulations: \(\Delta R < 50 \mu\text{m}\)

Mass density \(\rho = 25\) to \(50 \text{ g/cm}^3\)
Polar direct drive (PDD) can achieve ignition while the NIF is in the x-ray-drive configuration.

X-ray-drive configuration

Repointing for polar direct drive*

Direct-drive configuration

*Pointing for standard PDD
The latest NIF-scale PDD simulations ignite and achieve significant gain

Cryogenic DT wetted CH foam

<table>
<thead>
<tr>
<th>Simulation type</th>
<th>Incident energy</th>
<th>Absorbed energy</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>LILAC (1-D)</td>
<td>1.0 MJ</td>
<td>0.87 MJ</td>
<td>33</td>
</tr>
<tr>
<td>DRACO (2-D) PDD</td>
<td>1.3 MJ</td>
<td>1.0 MJ</td>
<td>20</td>
</tr>
</tbody>
</table>
Direct-drive-ignition scaled performance will be validated over the next two years

- DT(50%), low $V_i$, high $\rho R$
- Ongoing $D_2$ operations
- DT(50%), validate ignition scale performance
- DT(50%), set smoothing requirements and begin PDD campaign
- Foam shell implosions ($D_2$)
- Routine 1-$\mu$m rms $D_2$ layer quality
- Further target R&D including fill tubes
- Routine TCC offsets of $\sim$10 to 15 $\mu$m

June 06  June 07  June 08
Nuclear diagnostics are being developed for the NIF on high-yield OMEGA experiments.

- In 2005, the suite of the NIF nuclear diagnostics was defined:
  - PROTEX: primary DT neutron yield
  - neutron time of flight (nTOF): D₂, DT yield, Tᵢ, ρR
  - neutron activation diagnostic (NAD): DT yield, ρR
  - bang time/reaction history diagnostic
  - magnetic recoil spectrometer: ρR, DT yield, Tᵢ
  - neutron imaging system

A multilab effort to specify system design requirements (SDR), and develop and integrate diagnostics on the NIF is in progress.
The neutron activation diagnostic (NAD) will measure primary and tertiary neutron yields on OMEGA and the NIF.

- NAD will consist of copper and carbon activation.
- Copper activation* will measure the primary DT neutron yield.
  \[
  ^{63}\text{Cu} \ (n,2n) \ ^{62}\text{Cu} \quad E_n > 10.9 \text{ MeV}
  \]
  \[
  ^{62}\text{Cu} \rightarrow ^{62}\text{Ni} + e^+ \quad (T_{1/2} = 9.8 \text{ min})
  \]
  \[
  e^+ + e^- \rightarrow 2\gamma \quad (0.511 \text{ MeV})
  \]
- Carbon activation** will measure the tertiary neutron yield.
  \[
  ^{12}\text{C} \ (n, 2n) \ ^{11}\text{Cu} \quad E_n > 22 \text{ MeV}
  \]
  \[
  ^{11}\text{C} \rightarrow ^{11}\text{B} + e^+ \quad (T_{1/2} = 20.39 \text{ min})
  \]
  \[
  e^+ + e^- \rightarrow 2\gamma \quad (0.511 \text{ MeV})
  \]
- Cu and C activations will use very similar counting systems and the same retraction system.

*R. A. Lerche et al., LLNL 1976 Annual Report
CEA developed penumbral- and ring-aperture neutron imaging on OMEGA

Penumbral aperture and ring aperture center at 260 mm from TCC

The ring aperture combines a penumbral aperture with a biconical plug to produce a continuous assembly of 8-mm-diam neutron pinholes distributed along a ring and aimed at the target.

Image recording system at 8 m

DT(15)CH[15]

\[ Y_n = 3.2 \times 10^{13} \]

SNR = 44

\[ \Delta s \approx 20 \, \mu m \]

\[ 300 \, \mu m \]

D\textsubscript{2} cryogenic target

\[ Y_n = 2.6 \times 10^{11} \]

SNR = 13

\[ \Delta s = 50 \, \mu m \]

\[ 300 \, \mu m \]

L. Disdier et al., RSI 75, 2134 (2004).
The OMEGA EP laser system will be used to backlight cryogenic implosions and study fast ignition.

<table>
<thead>
<tr>
<th>Short pulse combined</th>
<th>Beam 1</th>
<th>Beam 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR energy (kJ)</td>
<td>2.6</td>
<td>2.6</td>
</tr>
<tr>
<td>Pulse duration at full energy (ps)</td>
<td>10 to 100</td>
<td>80 to 100</td>
</tr>
<tr>
<td>Focusing (diam)</td>
<td>&gt;80% in 20 μm</td>
<td>&gt;80% in 40 μm</td>
</tr>
<tr>
<td>Intensity (W/cm²)</td>
<td>$3 \times 10^{20}$</td>
<td>$2 \times 10^{18}$</td>
</tr>
</tbody>
</table>

- Each beam duration can be as short as 1 ps at reduced energy (grating damage and B-integral)
- Beam 2 can produce 2.6 kJ in 10 ps when propagating on a separate path

OMEGA EP will be completed in FY08.
OMEGA EP is progressing on schedule

OMEGA EP Building  
(completed in February 2005)

OMEGA EP Laser Bay  
(Sept. 2006)
Fast Ignition

OMEGA EP will test two concepts for fast ignition; two techniques have been developed to reduce the distance that an electron beam must traverse.

Channeling Concept
- Channeling 100-ps pulse
- Light pressure creates a channel in the coronal plasma
- \( \sim 1\text{-MeV electrons heat DT fuel to } \sim 10\text{ keV, } \sim 300\text{ mg/cm}^2 \)

Cone-Focused Concept
- Igniting 10-ps pulse
- Au cone
- Single ignitor beam: 10 ps

Integrated cryogenic fast-ignition experiments will begin in FY09
Streaked optical pyrometry (SOP) is used to observe the cone filling with plasma.
The $70^\circ$ cone shows a clean shock-breakout signal at the tip of the cone.

- Shot 38548, 1-ns pulse, 18 kJ, 48 beams, 24-$\mu$m CH shell
Low-adiabat, low-$V_i$ experiments with CH targets are used to study fast-ignition fuel assemblies

$\alpha \approx 1.3, V_i \approx 2 \times 10^7 \text{ cm/s}$
The measured areal densities ($\rho R$) are the largest ever for laser-driven implosions.

<table>
<thead>
<tr>
<th>Areal densities</th>
<th>$\rho R$ (g/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle \rho R \rangle_p$ experiment DD fill, 25, 33 atm</td>
<td>0.13</td>
</tr>
<tr>
<td>$\langle \rho R \rangle_p$ experiment DHe₃ fill, 25, 33 atm</td>
<td>0.14</td>
</tr>
<tr>
<td>$\langle \rho R \rangle_n$ simulation averaged over NTD</td>
<td>0.145</td>
</tr>
<tr>
<td>$\langle \rho R \rangle_{max}$ simulation</td>
<td>0.28</td>
</tr>
</tbody>
</table>

X-ray image shows uniform core.
Summary/Conclusions

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