Direct Drive and Alternate Approaches for Laser Inertial Confinement Fusion (ICF)

OMEGA target shot

Plasma channel from EP beam

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Direct-drive ignition is the main thrust in LLE fusion research activities

- Fusion research at LLE is focused on building the foundations for a direct-drive–ignition demonstration at the National Ignition Facility (NIF)
- LLE is interested in the fusion-energy applications of inertial confinement fusion (ICF), but it is currently concentrating its efforts on demonstrating thermonuclear ignition of DT fuel
- Producing a burning plasma in the laboratory for the first time
  - is a grand scientific challenge ("a star on earth")
  - has great scientific value in astrophysics, nuclear, and plasma physics
  - has important implications for national security (Stockpile Stewardship)
  - represents the fundamental block of fusion-energy development by showing that fusion has the potential to be a viable energy source
Direct- and indirect-drive ICF aim to ignite a DT plasma by imploding capsules with on-target applied pressures of $\sim 100$ Mbar

- More energy coupled to the target
- Less-uniform driver

- Less energy coupled to the target
- More-uniform driver
NIF is currently configured in a polar-drive setting for indirect-drive ignition; this is *not* an optimal configuration for direct drive that requires spherical illumination.

- The National Ignition Facility (NIF) at LLNL delivers ~2-MJ UV light at ~500 TW
Polar-drive–ignition experiments on the NIF requires beam repointing and upgrades to the laser system.

The laser technology required for polar-drive ignition on the NIF using a NIF PAM is being demonstrated on OMEGA EP.
OMEGA is currently the premiere facility for direct-drive experiments; it is coupled to a high-power, short-pulse laser (OMEGA EP) to explore advanced ignition and radiography.

The OMEGA laser at the University of Rochester’s Laboratory for Laser Energetics (LLE) delivers ~30-kJ UV light at ~30 TW.

The OMEGA EP laser delivers ~2-kJ IR light in 10 ps (~2 PW) and 20-kJ light in UV-ns pulses.
The NIF is currently pursuing indirect-drive ignition; to assess the prospects for direct-drive ignition, OMEGA results are scaled to NIF energies.
Hydro-equivalent ignition on OMEGA
Like in Magnetic Confinement Fusion, the Lawson criterion determines the ICF ignition condition. In ICF, ignition occurs in the central hot spot.

\[ \chi \approx \frac{3P}{2\tau} \]

\[ \chi \equiv \frac{P\tau}{24\langle \sigma v \rangle \varepsilon_{\alpha} / T^2} \]

Ignition parameter \( \rightarrow \) \( \chi > 1 \)

**Ignition condition**

**LLNL Performance Parameter**

\[ ITF\chi \approx \chi^3 \]

*B. K. Spears et al., Phys. Plasmas 19, 056316 (2012).*
ICF implosions cannot achieve ~10-keV temperatures through compression alone

- High $T$ requires high implosion velocity $V_i$
- High $V_i$ requires thin shells
- Thin shells break up in flight because of hydrodynamic instabilities

**Imploding shell**

$T \sim V_i$

ICF must ignite at ~5 keV, requiring $V \sim 400$ km/s and $P\tau > 25$ atm s.
The Lawson plot shows the performance of fusion devices with respect to thermonuclear ignition (not fusion energy).

\[ \langle P \rangle / E \] (atm × s)

\[ \langle T \rangle \] (keV)

- Ignition
- FRC
- Spheromak
- RFP
- ST
- Stellarator
- Tokamak
- Tokamak
- Tokamak
- Tokamak
- Laser DD
- Laser ID


Hydrodynamic similarity provides a tool for estimating the energy scaling of implosion performance

- Scaling of ignition parameter ($\chi > 1$ for ignition)
  \[ \chi \approx \chi_{\text{ref}} \left( V_i, \alpha, I_{\text{laser}} \right) \left( \frac{\sigma_{\text{rms}}}{R_{\text{target}}} \right) \left( \frac{E_{\text{laser}}}{E_{\text{laser}}^{\text{ref}}} \right)^{0.4} \]
  
  $V_i =$ shell implosion velocity, $\alpha =$ shell entropy ($\sim P / \rho^{5/3}$),
  $I_L =$ laser intensity, $\sigma_{\text{rms}} =$ amplitude of nonuniformities, $R_t =$ target radius

- Expect improvement in relative nonuniformities on the NIF as a result of larger hot-spot size, more beams, and equal ice roughness
  
  \[ \chi_{\text{NIF}} \approx \chi_{\Omega} \left( V_i, \alpha, I_{\text{laser}} \right) 2^{0.34} \left( \frac{E_{\text{laser}}^{\text{NIF}}}{E_{\text{laser}}^{\Omega}} \right)^{0.4} \]
  
  Energy scaling $\rightarrow$
  
  \[ \text{ITFx}_{\text{NIF}} \approx 2 \times \text{ITFx}_{\Omega} \times \left( \frac{E_{\text{laser}}^{\text{NIF}}}{E_{\text{laser}}^{\Omega}} \right)^{1.28} \]
Targets and laser pulses are designed for OMEGA to reproduce direct-drive NIF hydrodynamics.

OMEGA 26 kJ

\[ R_{\text{target}} \sim E_{\text{laser}}^{1/3} \]
\[ P_{\text{laser}} \sim E_{\text{laser}}^{2/3} \]
\[ \text{Time} \sim E_{\text{laser}}^{1/3} \]

Direct-drive NIF 1.8 MJ

3.6 mm

Power (TW)

Time (ns)

Power (TW)

Time (ns)
Hydro-equivalent ignition at 26 kJ on OMEGA requires an \( \sim 1.7 \times \) improvement in areal density and \( \sim 2 \times \) improvement in neutron yield

- \( \chi = 0.16 \) is required for hydro-equivalent ignition on OMEGA

\[
\chi \approx \left( \frac{\rho R_{\text{g/cm}^2}}{n_0} \right)^{0.61} \left( \frac{0.24 Y_n^{16}}{M_{\text{DT}}^{\text{mg}}} \right)^{0.34}
\]

- \( \rho R \) is the areal density, \( Y_n \) is the neutron yield, and \( M_{\text{DT}} \) is the DT fuel mass

- Current OMEGA experiments: \( M_{\text{DT}} = 0.02 \text{ mg} \), \( \rho R \approx 0.18 \text{ g/cm}^2 \), \( Y_n \approx 2 \times 10^{13} \) \( \rightarrow \chi = 0.09 \)

- Required for hydro-equivalent ignition: \( M_{\text{DT}} = 0.02 \text{ mg} \), \( \rho R \approx 0.3 \text{ g/cm}^2 \), \( Y_n \approx 4 \times 10^{13} \) \( \rightarrow \chi = 0.17 \)
OMEGA performance can be scaled up to NIF energies and spherically symmetric drive. The extrapolated ITFx for direct drive on NIF is about $0.18 \rightarrow \chi \approx 0.56$

- This is a purely hydrodynamic scaling
- It does not include laser–plasma instability effects
- It does not include the polar-drive configuration of the NIF
- Given the large extrapolation and limited physics, this result should be considered as a rough estimate

*T. C. Sangster et al., “Improving Cryogenic DT Implosion Performance on OMEGA”, to be published in Physics of Plasmas.*
What is limiting the performance of OMEGA implosions?
Isolated defects on the shell surface of cryogenic DT targets severely limits the implosion performance

- Isolated surface debris on the target appear to be limiting the implosion performance
  - a significant engineering effort is underway to remove the defects
  - a 2011 shot series showed improved yields when fewer defects were present
The Tritium Fill System hydrogen permeator will remove all non-hydrogen contaminants in the LLE DT fuel supply.

First use will be for 19 February cryo targets.
The performance of direct-drive capsules is further degraded by cross-beam energy transfer (CBET)

- CBET involves electromagnetic (EM)-seeded, low-gain stimulated Brillouin scattering
- EM seed is provided by edge-beam light
- Center-beam light transfers some of its energy to outgoing light*
- The transferred light bypasses the highest absorption region near the critical surface*

CBET reduces laser absorption and hydrodynamic efficiency.**

Several options to mitigate the effects of CBET are currently under investigation.

- **Two-state laser beam zooming**

- **Other possible solutions**
  - stacked laser pulse: 96 beams with large focal spot $R_{\text{beam}} = R_{\text{target}}$ followed by 96 beams zoomed at $R_{\text{beam}} = 0.5 R_{\text{target}}$
  - moderate-Z ablators like carbon or saran (CHCl) or glass
Demonstrating hydro-equivalent ignition on OMEGA is a major step forward but does not resolve all the uncertainties about achieving ignition on the NIF.

<table>
<thead>
<tr>
<th>Non-hydrodynamic physics that does not scale</th>
<th>OMEGA</th>
<th>NIF</th>
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<tr>
<td>Laser-energy collisional absorption</td>
<td>Less</td>
<td>Better</td>
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<td>Laser–plasma instabilities and hot-electron preheat</td>
<td>Less</td>
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<td>Cross-beam energy transfer</td>
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Alternate direct-drive–ignition schemes
Shock ignition is a promising alternative to conventional direct-drive implosions

The shock beams are tightly focused on target

2-D simulations of the shock-ignition target designs for the NIF in polar drive predict ignition with Gain = 52 at 750 kJ of laser energy (no CBET included)
Research in high-intensity laser–plasma interaction provides the basis for fusion applications of high-power lasers (fast ignition).

Light pressure creates a channel in the coronal plasma. Light from ~1-MeV electrons heats the DT fuel to ~10 keV, ~300 mg/cm².

**Channeling concept**
- Hole boring
- Ignition
- 10 ps
- ~1-MeV electrons heat DT fuel to ~10 keV, ~300 mg/cm²

**Cone-focused concept**
- Au cone
- Single ignitor beam: 10 ps

**Plasma channel from OMEGA EP beam (4ω probe)**

**Graph:**
- Neutron yield ($\times10^7$) vs. OMEGA EP arrival time (ns)
- Neutron yield peaks around 3.6 ns.
Summary/Conclusions

Steady progress continues to be made in direct-drive ignition; ignition-scalable performance on OMEGA is within reach

- Current cryogenic implosions on the OMEGA laser do not yet scale to ignition on the NIF
- Hydro-equivalent ignition on OMEGA requires improvements in areal density (~1.7×) and neutron yields (~2×)
- Causes for implosion-performance degradation have been identified (isolated defects and cross-beam energy transfer) and are being addressed
- Shock ignition is a promising path to direct-drive ignition and ignition designs for the NIF have been developed and simulated
- High-power lasers provide additional ignition options (fast ignition)