Progress in Direct-Drive Inertial Confinement Fusion

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Summary

The Laboratory for Laser Energetics is making significant progress in direct-drive ICF research

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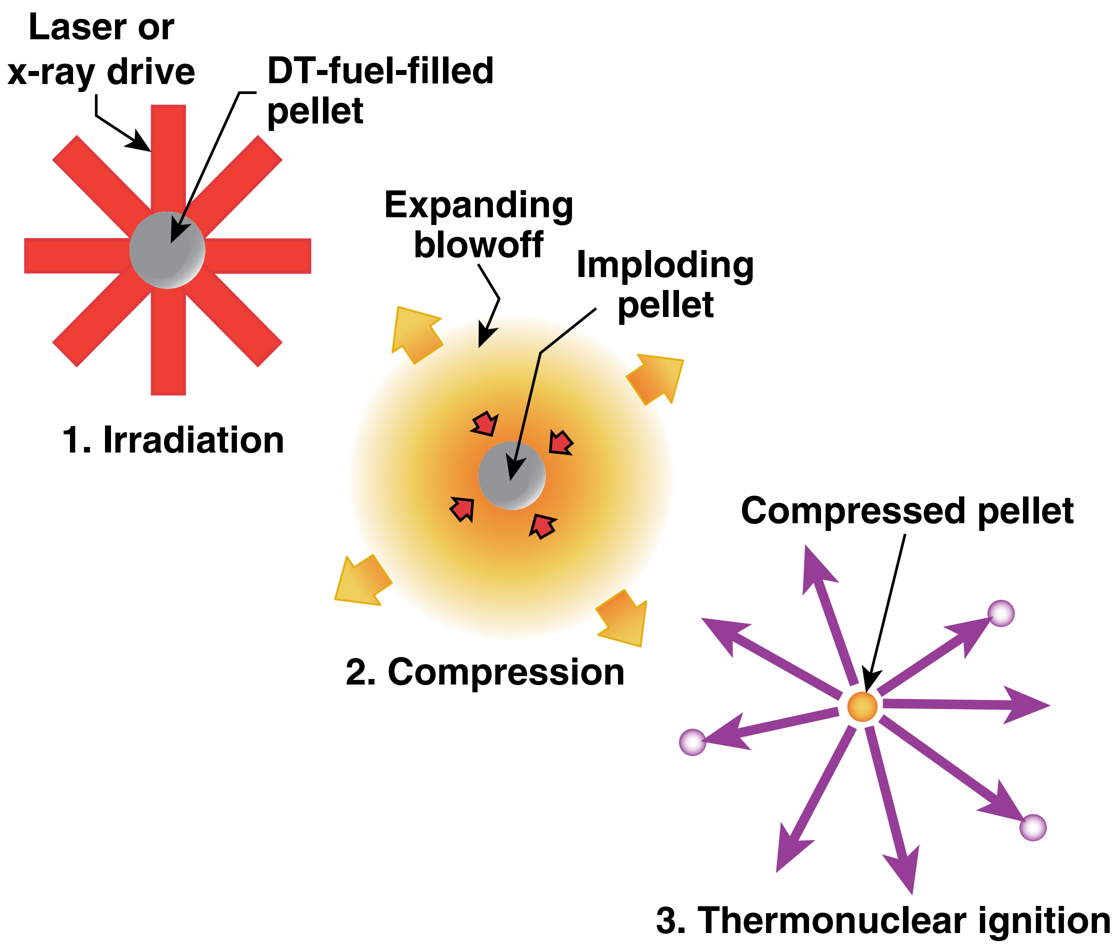
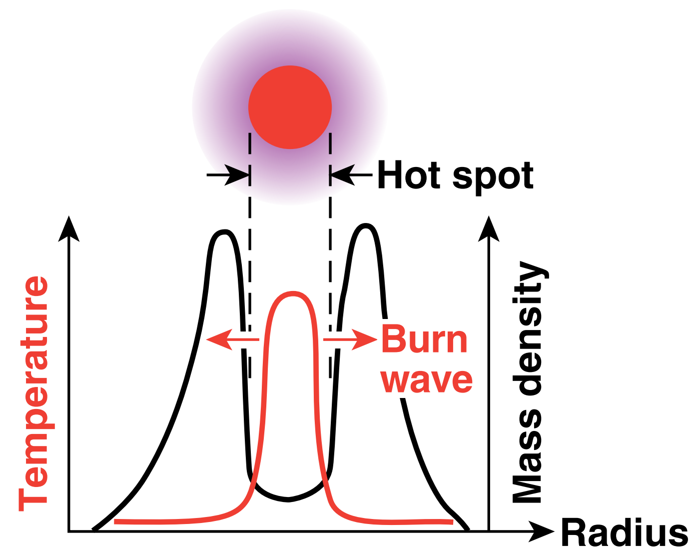
- LLE is the lead laboratory for the exploration of direct-drive inertial confinement fusion (ICF).
- The implosion of thick cryogenic DT target shells is required for both direct- and indirect-drive ICF.
- Recent implosions of direct-drive cryogenic targets on OMEGA have produced areal densities in excess of 200 mg/cm^2 and compressed D_2 densities of ~100 g/cm^3.
- The polar-direct-drive (PDD) concept will allow direct-drive-ignition experiments while the National Ignition Facility (NIF) is configured for indirect-drive experiments.
- Direct-drive ICF and high-energy-density physics are strong attractors of high-quality graduate students.

The prospects for direct-drive ignition on the National Ignition Facility appear favorable.

Ablation is used to generate the extreme pressures required to compress a fusion capsule to ignition conditions

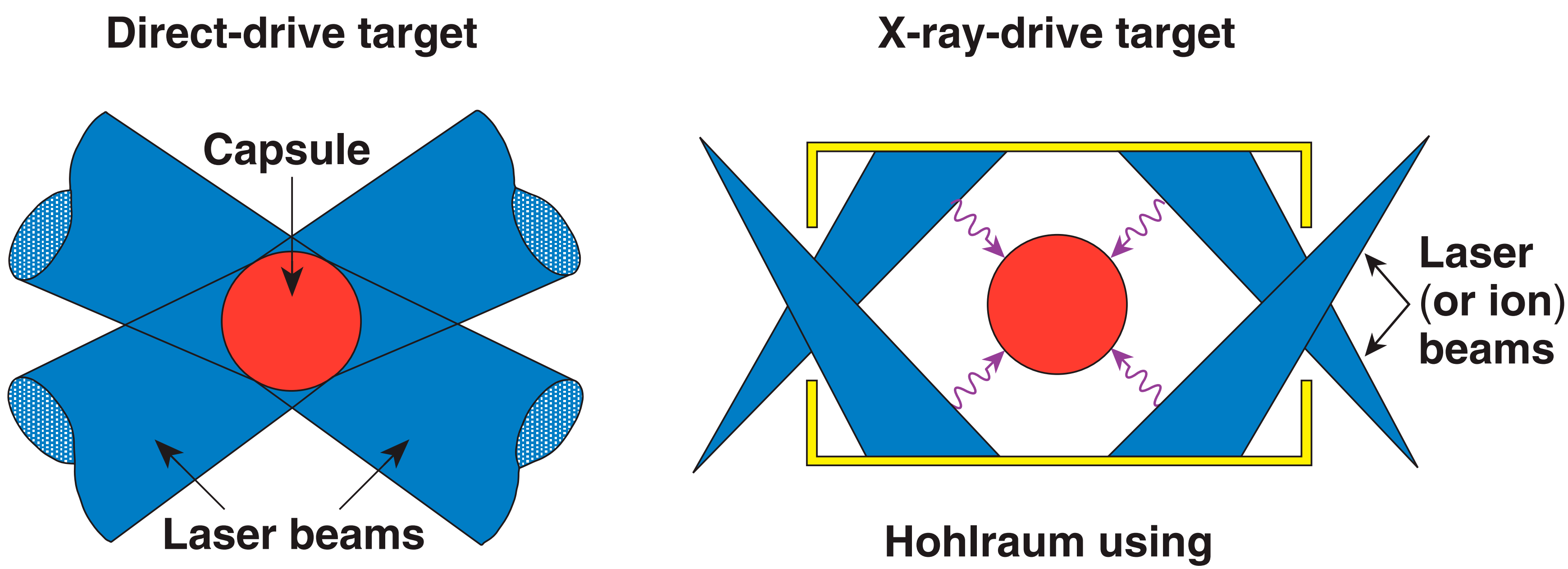




$$\text{Gain, } G = \frac{\text{Fusion energy out}}{\text{Laser energy in}}$$

"Hot-spot" ignition requires the core temperature to be at least 10 keV and the core fuel areal density to exceed ~300 mg/cm^2.

ICF implosions are carried out with both direct drive and x-ray drive



Hohlraum using
a cylindrical high-*Z* case

Key physics issues are common to both

- Energy coupling
- Drive uniformity
- Hydrodynamic instabilities

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The alpha particles are confined by assembling a sufficiently dense fuel

- The 3.5-MeV alpha particles must pass through sufficient areal density to be stopped (transferring their energy to the background plasma);

$$\rho R \geq 0.3 \text{ g/cm}^2.$$

- For solid-density DT ($\rho \sim 0.25$ g/cm^3), this requires a length of ~1 cm.
- Compression is used to increase the density 1000× to reduce the scale to ~10 μm.
- A "hot spot" with temperature of 5 ~ 10 keV and $\rho R \sim 0.3$ g/cm^2 starts the ignition process.

This is not sufficient for efficient gain.

Optimizing ignition conditions requires the use of cryogenic targets

- The target should burn as much of the DT fuel as possible.
- The burnup fraction depends on the areal density (ρR).

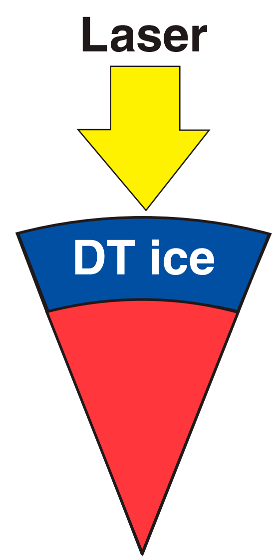
$$f_b = \frac{\rho R}{\rho R + \beta(T)},\ \beta(T) = 5.5 \sim 6.5\ \text{g/cm}^2 \text{ for optimal burn conditions}$$

$$\rho R \gtrsim 3\ \text{g/cm}^2 \text{ for } f_b > \frac{1}{3}$$

- The DT target mass for $f_b > \frac{1}{3}$ depends on the areal density and the target density.

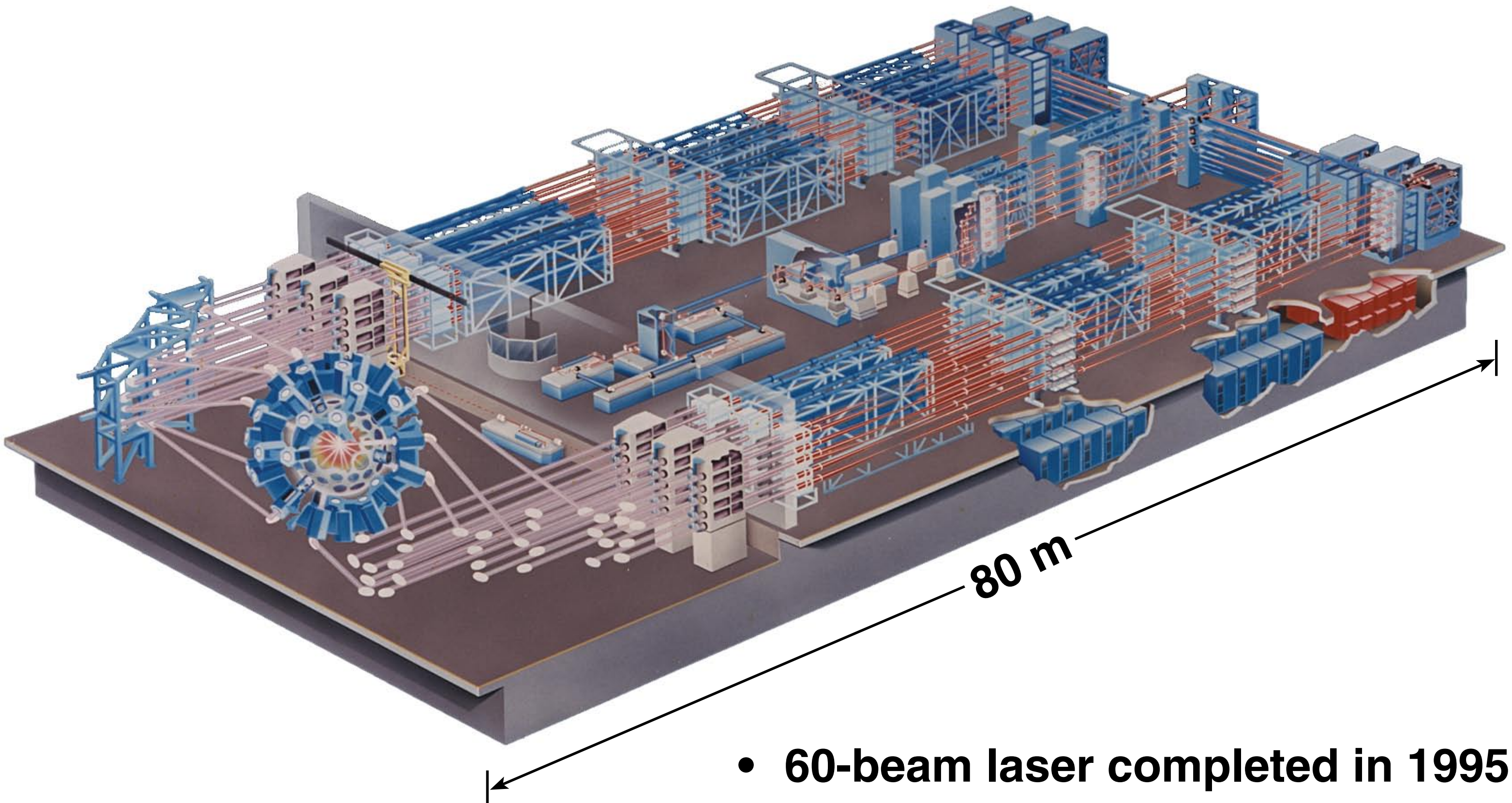
$$m = \frac{4\pi}{3}\frac{(\rho R)^3}{\rho^2}$$

- Compression to $\rho \gg \rho_{\text{solid}}$ reduces the total yield while optimizing the target efficiency.



The implosion of cryogenic (solid DT) spherical shells yields high compression and maximizes the energy efficiency.

The OMEGA laser is designed to achieve high uniformity with flexible pulse-shaping capability



- 60-beam laser completed in 1995
- >30-kJ UV on target
- 1% to 2% irradiation nonuniformity
- Flexible pulse shaping
- Short shot cycle (1 h)

OMEGA produces ~1500 target shots per year.

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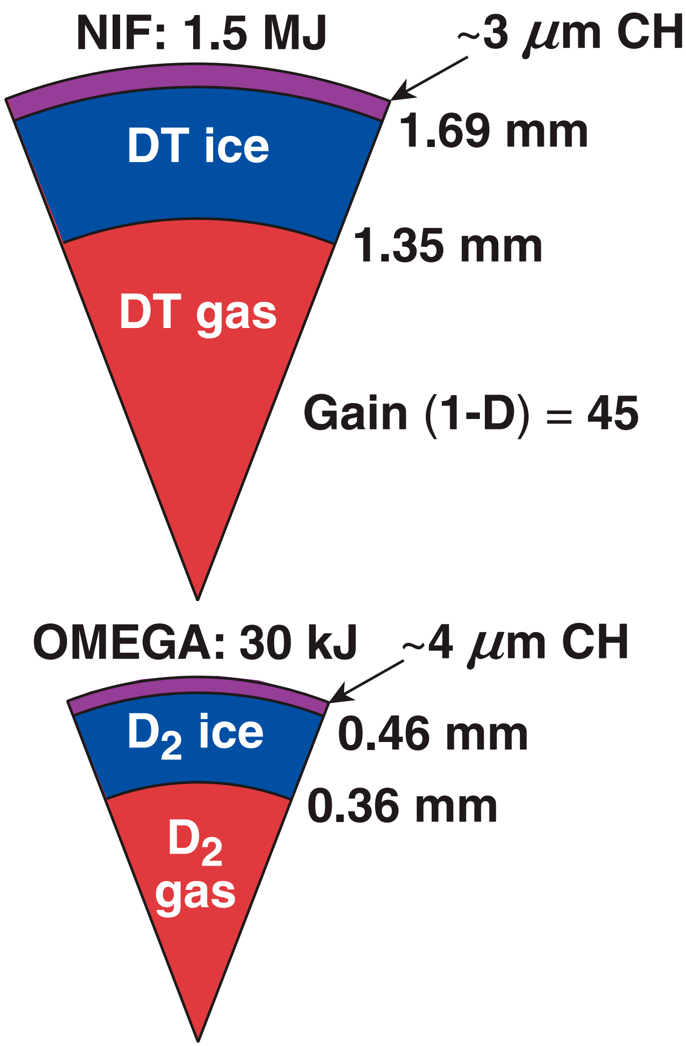
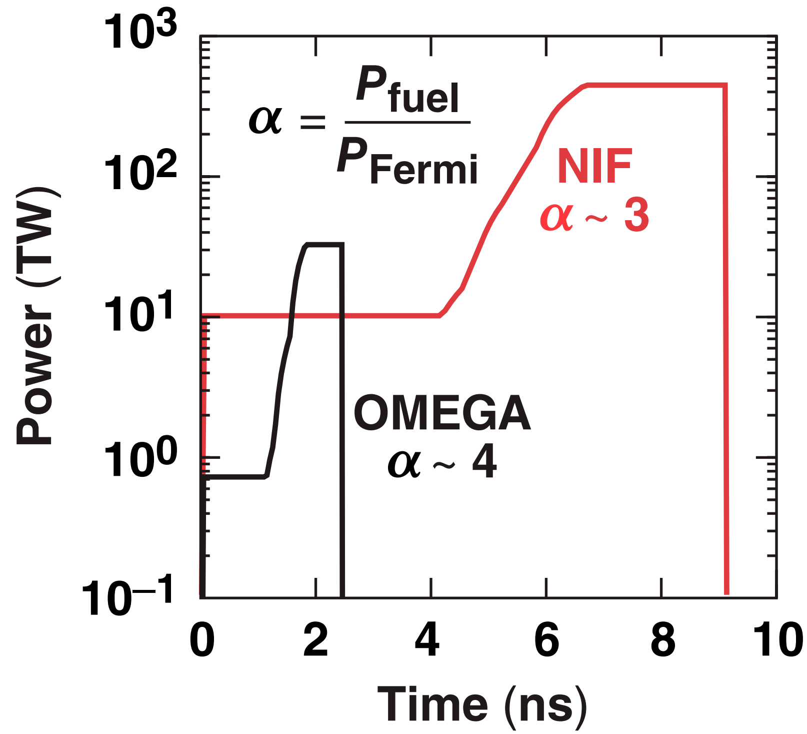
OMEGA cryogenic targets are energy scaled from the NIF symmetric direct-drive point design



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



β-layering provides a smooth inner layer.

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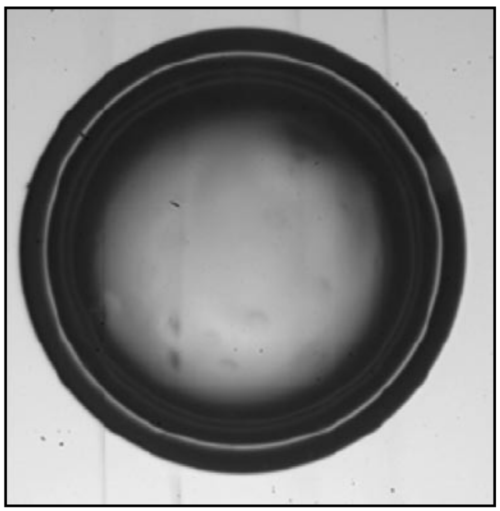
Ignition (both IDI and DDI) requires cryogenic DT targets

- β-layered 50:50 DT cyrogenic targets have measured ice-roughness nonuniformities <1-μm rms, meeting the NIF IDI and DDI specifications.
- Thick (>tens of microns) DT ice layers are required for ignition.



Shadowgraph image of a cryogenic DT target (~100-μm thick layer)

Ice surface roughness: 0.47-μm rms in a single view

LLE has performed the only laboratory implosions of thick-layer cryogenic targets.

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A cryogenic D_2 implosion on OMEGA produced an areal density of 202±7 mg/cm^2

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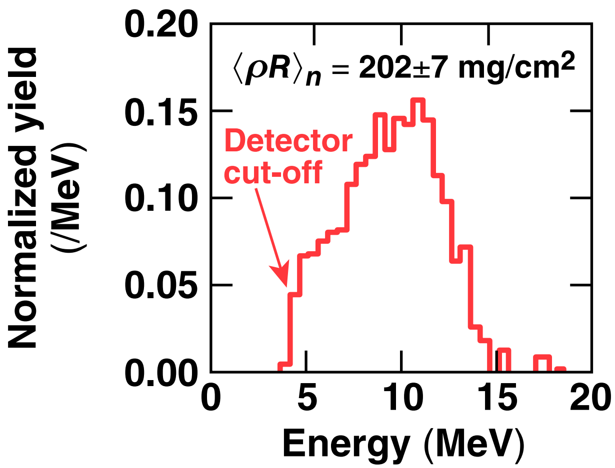
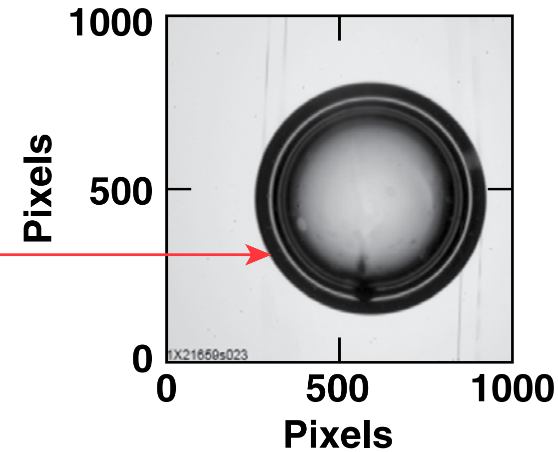
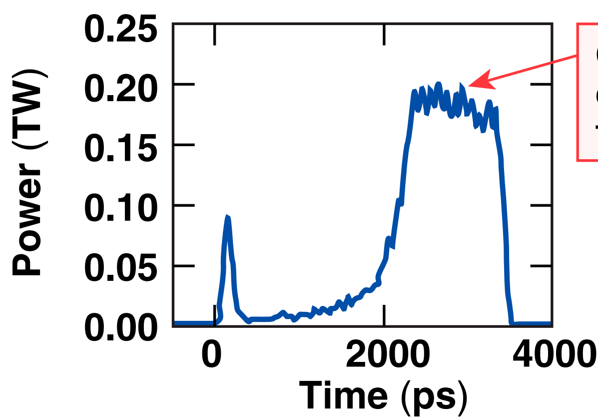
Secondary D^3He proton spectrum



Shadowgraph of target

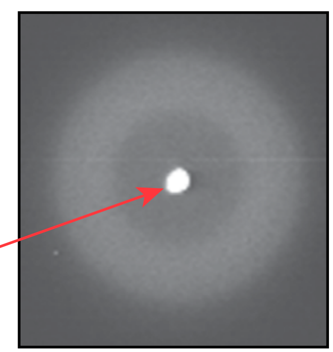


To achieve high density, the inner ice surface must be very smooth: ~2-μm rms or better



OMEGA routinely produces the complex pulse shapes needed to reach high fuel densities

X-ray pinhole camera



Fuel density reaches ~100 g/cc (500× liquid density); more than adequate for ignition on the NIF

These are, by far, the highest areal densities measured in ignition-relevant laboratory implosions — very important for direct- and indirect-drive ignition.

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Polar Direct Drive

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

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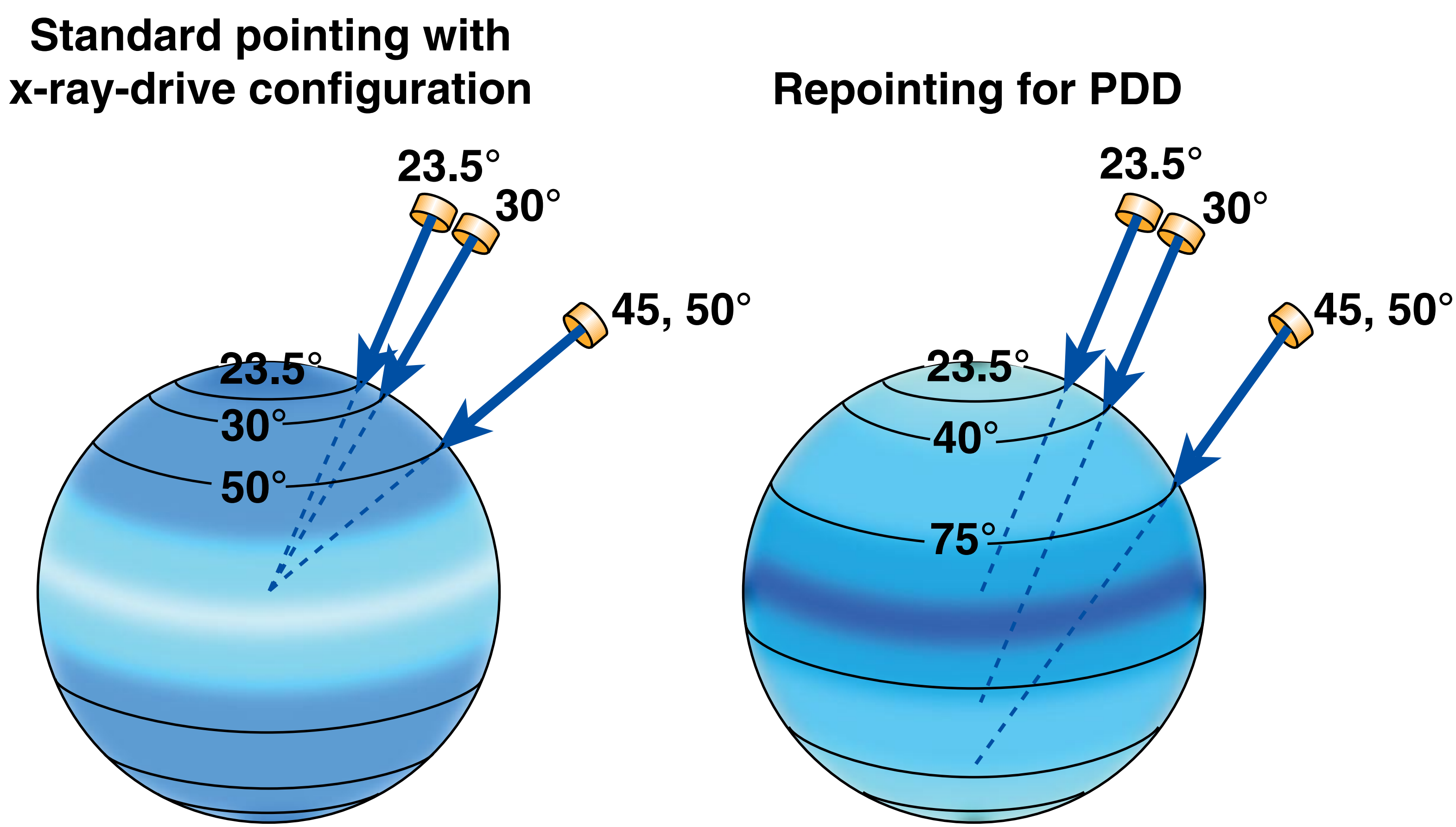

- Polar direct drive (PDD) is based on the optimization of phase-plate design, beam pointing, and pulse shaping.

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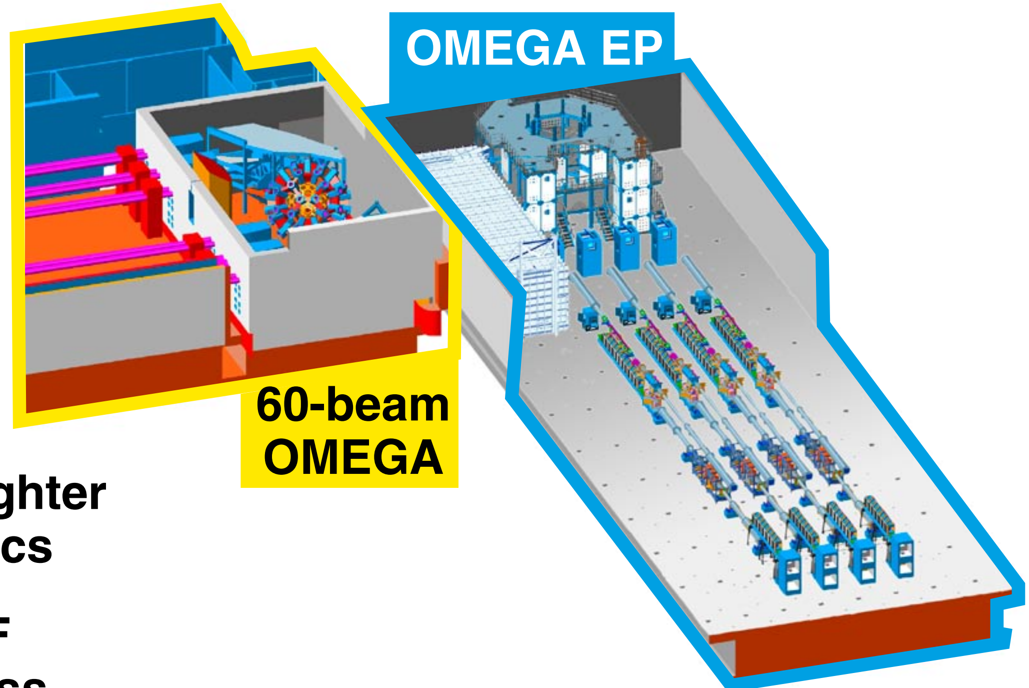
OMEGA EP will be completed in April 2008

- There are five primary missions.

  1. Extend HED research capabilities with high-energy and high-brightness backlighting
  2. Perform integrated advanced-ignition experiments
  3. Develop advanced backlighter techniques for HED physics
  4. Staging facility for the NIF to improve its effectiveness
  5. Conduct ultrahigh-intensity laser–matter interactions research



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Short-pulse OMEGA EP beams can be directed either to OMEGA or to the new OMEGA EP target chamber

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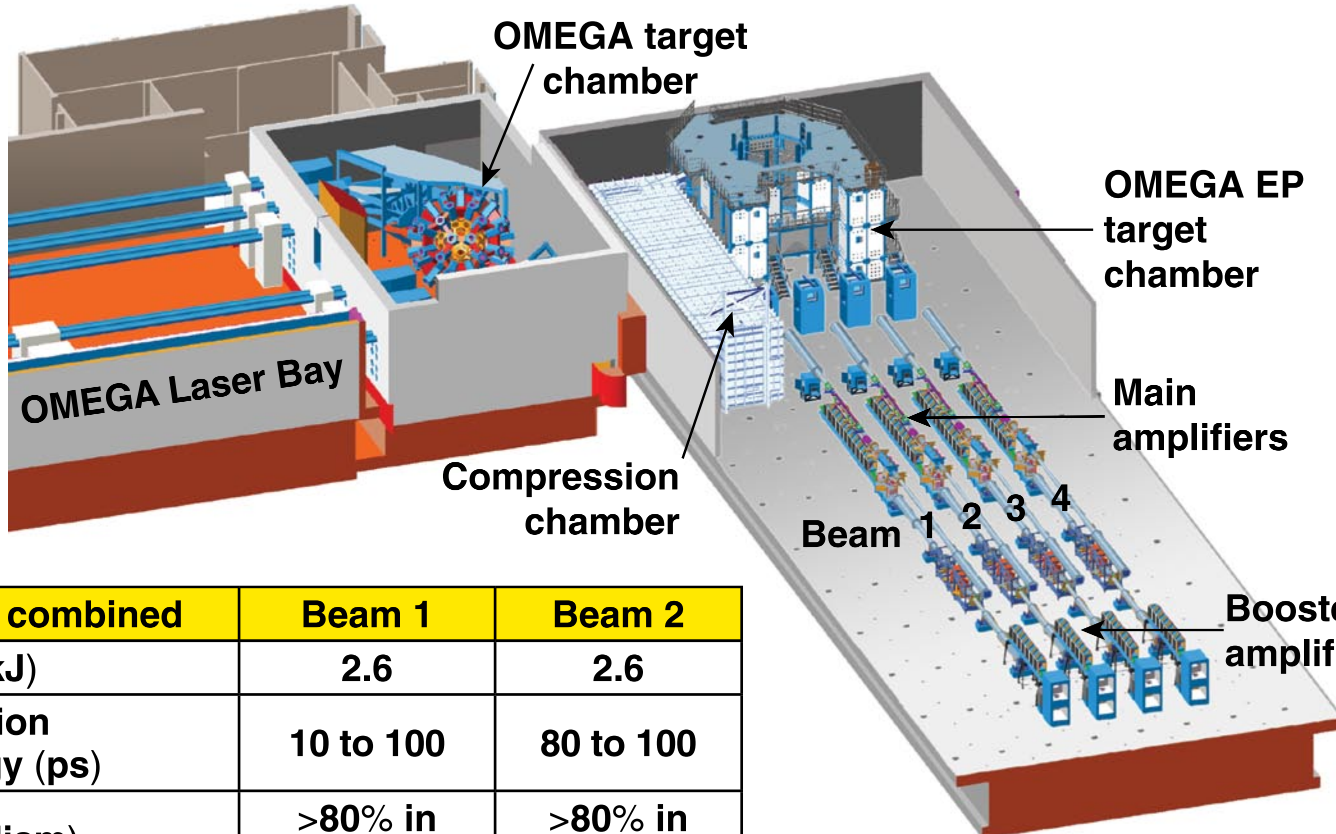

Short pulse combined	Beam 1	Beam 2
IR energy (kJ)	2.6	2.6
Pulse duration at full energy (ps)	10 to 100	80 to 100
Focusing (diam)	>80% in 20 μm	>80% in 40 μm
Intensity (W/cm^2)	3×10^{20}	2×10^{18}

- 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

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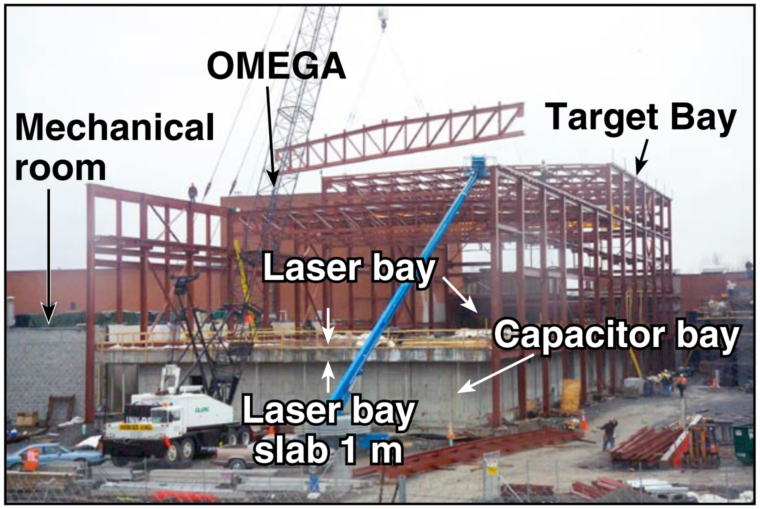
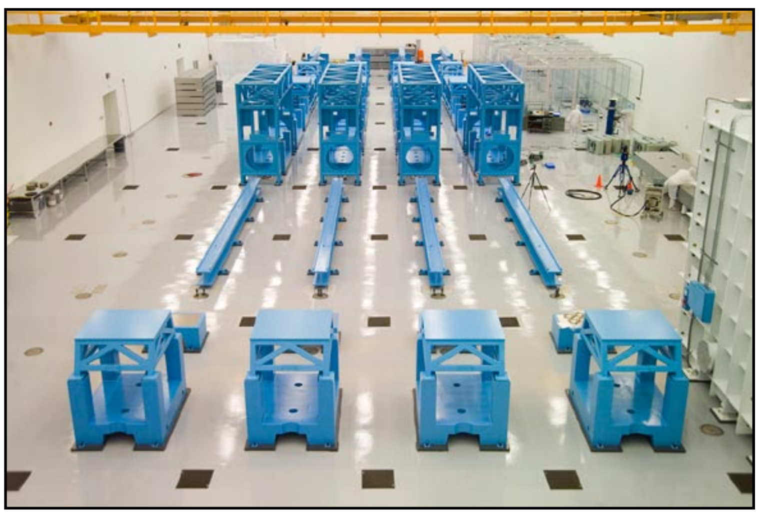
OMEGA EP construction is progressing on schedule

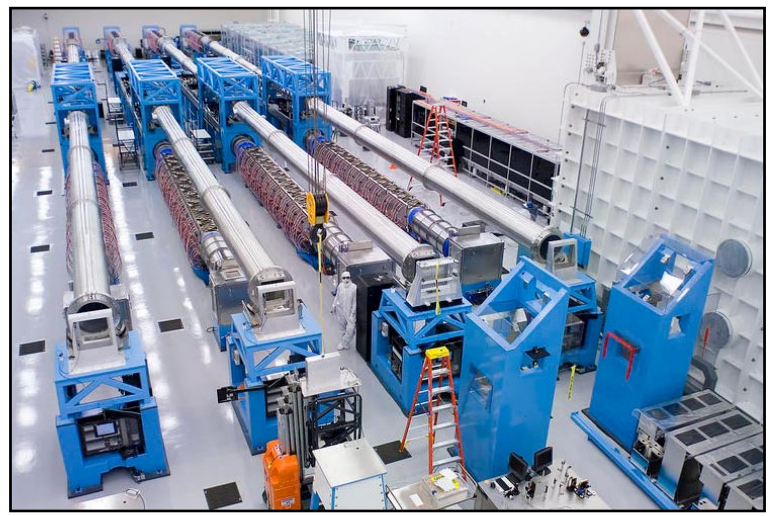
April 2004



January 2005



January 2006



May 2007

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One of LLE's primary missions continues to be the education and training of students

- 24 collaborating faculty members from five departments.
- 57 graduate students are currently pursuing Ph.D.'s.
- 161 students have completed Ph.D. degrees since LLE's founding.
- 31 Ph.D. students are directly funded by LLE through the Horton Fellowship Program.
- 41 undergraduate students are currently employed at LLE.
- LLE operates a summer research program for high school students (13 students in 2006).

University users will have access to OMEGA/OMEGA EP through the existing National Laser Users' Facility (NLUF)

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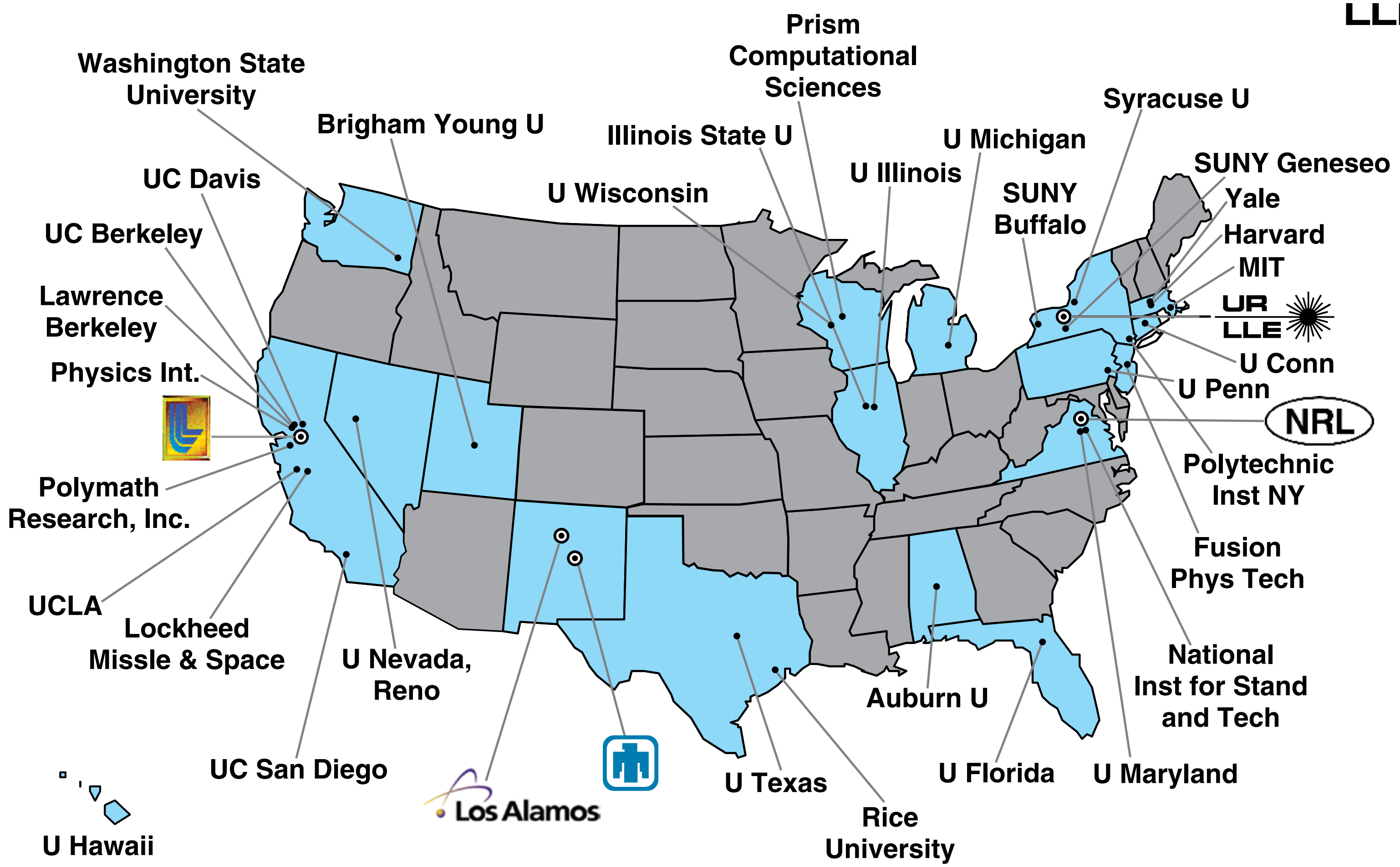
- 15% of OMEGA/OMEGA EP shots will be available for university/ industry users through the NLUF program.
- A wide HED physics regime will be available.
- It is anticipated that the completion of OMEGA EP will significantly increase the demand for NLUF access.

LLE's National Laser Users' Facility (begun in 1979) is NNSA's window to university researchers



- 278 proposals
- 143 approved
- >90 Ph.D. students

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