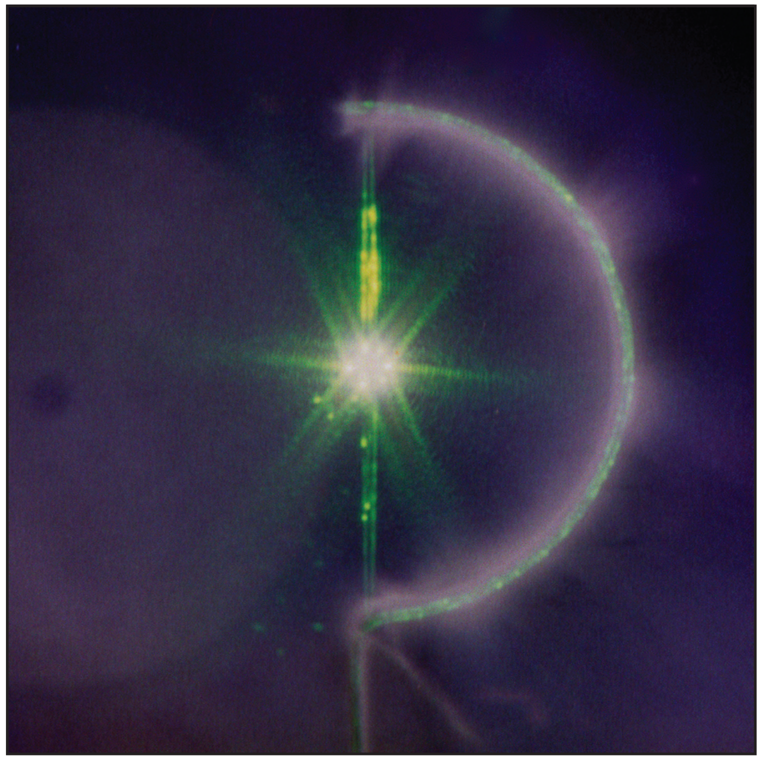
Overview of Inertial Fusion Research in the United States

Shot 44848



Cryogenic-DT-capsule implosion on OMEGA

T. Craig Sangster
University of Rochester
Laboratory for Laser Energetics

21st IAEA Fusion Energy Conference
Chengdu, China
16–21 October 2006

Acknowledgements

R. L. McCrory, V. N. Goncharov, D. R. Harding, S. J. Loucks,
P. W. McKenty, D. D. Meyerhofer, S. Skupsky, and B. Yaakobi

Laboratory for Laser Energetics, University of Rochester, Rochester, NY

B. MacGowan, L. J. Atherton, J. D. Lindl, and E. I. Moses

Lawrence Livermore National Laboratory, Livermore, CA

J. L. Porter, M. E. Cuneo, and M. K. Matzen

Sandia National Laboratories, Albuquerque, NM

C. W. Barnes, J. C. Fernandez, and D. C. Wilson

Los Alamos National Laboratory, Los Alamos, NM

J. D. Kilkenny, A. Nikroo, and H. Wilken

General Atomics, San Diego, CA

B. G. Logan and S. Yu

Lawrence Berkeley National Laboratory, Berkeley, CA

R. Petrasso

Massachusetts Institute for Technology

J. D. Sethian and S. Obenschain

Naval Research Laboratory, Washington, DC

Summary

The U.S. IFE program is based on a near-term ignition/gain demonstration and long-term technology development

UR LLE

- The National Ignition Campaign will lead to ignition on the National Ignition Facility (NIF) shortly after the facility is completed.
- Key science questions relevant to ignition are being experimentally verified on the OMEGA laser at LLE and the Z/ZR facility at SNL.
- LLE has imploded direct-drive ignition-scaled targets that meet the ignition specification for inner ice smoothness.
- Longer-term research programs are developing the key technologies to drive IFE (e.g., repetitive rate, chamber design, target injection, etc.).
- Fast ignition is being pursued as an ignition alternative and a lower-cost route to IFE.

The future of IFE requires a successful demonstration of ignition on the NIF

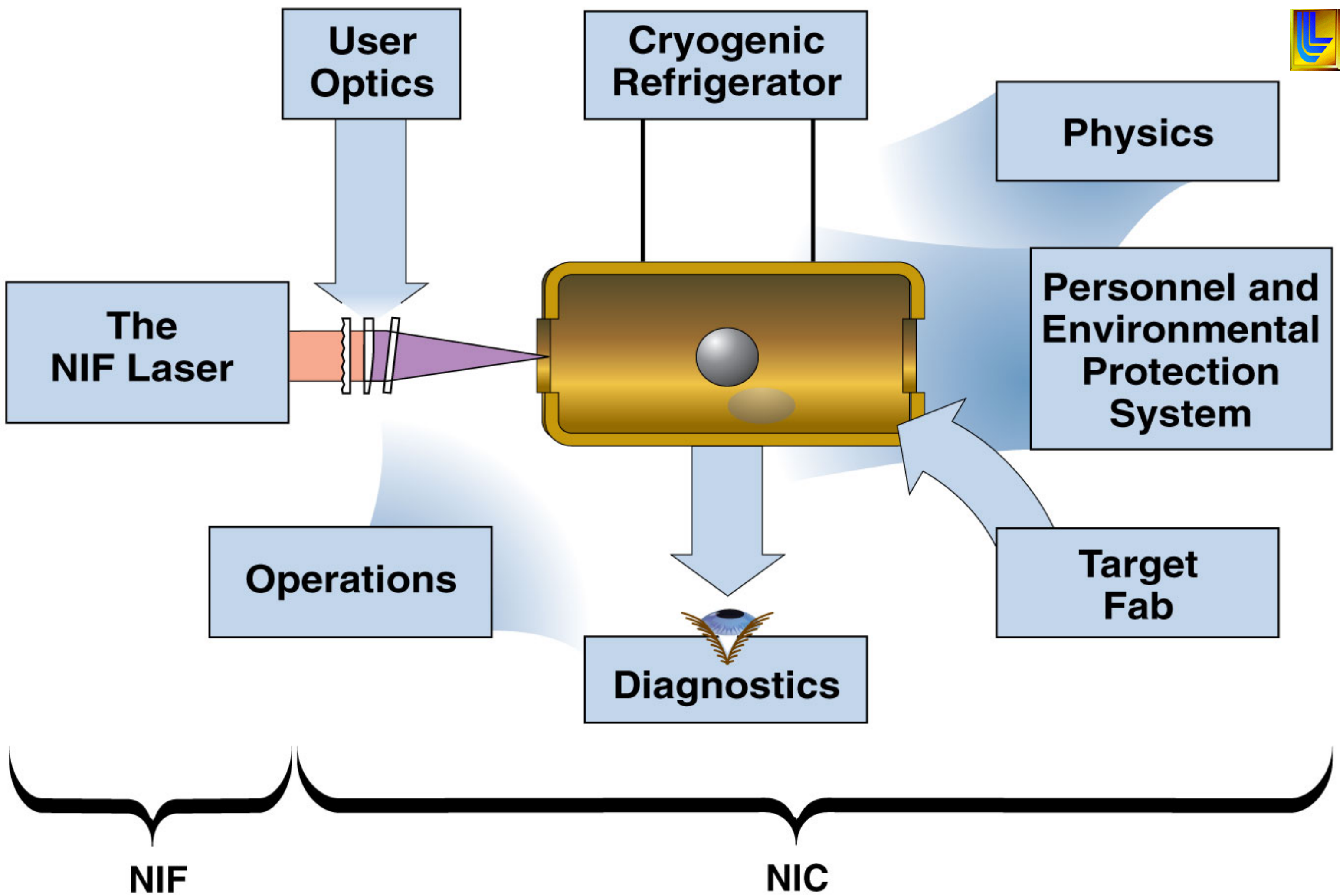
- The National Ignition Campaign
- Ignition-quality DT targets
- Target physics with cryogenic DT implosions
- IFE technology development
- Fast ignition

The National Ignition Campaign is a comprehensive effort to deliver ignition and gain on the National Ignition Facility

Each institution has clearly defined roles and responsibilities

E15184

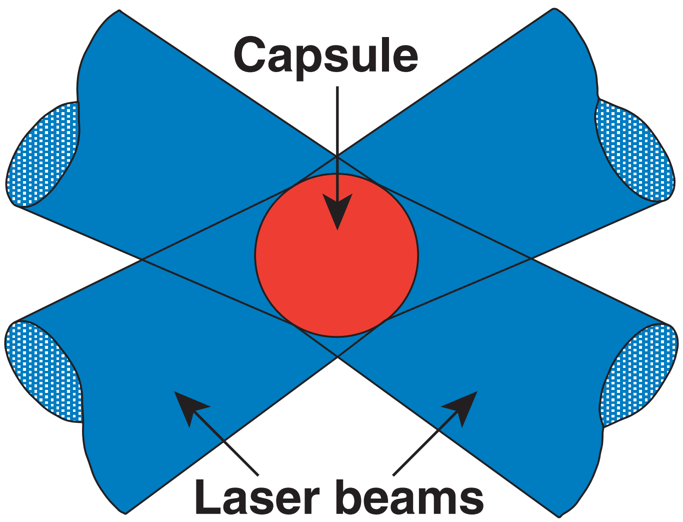
The major elements of the NIC have been defined



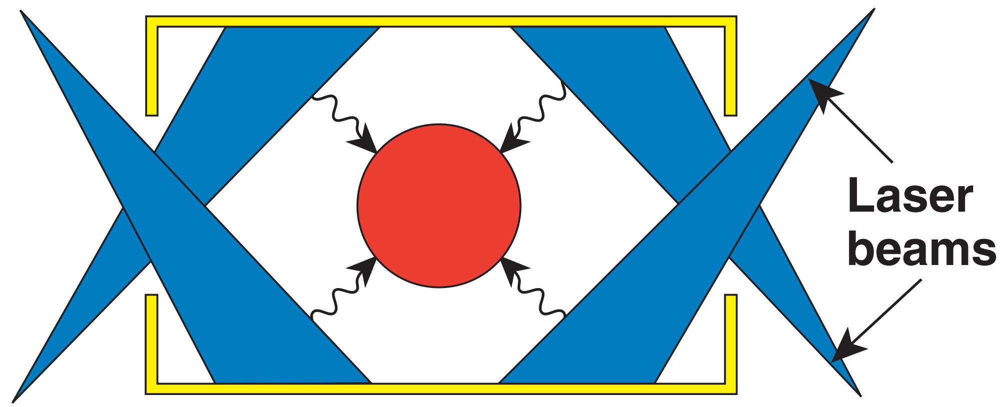
NIF-0606-12269r1
11EIM/fm
E15185

Direct-drive and x-ray-drive targets are being developed for ignition and gain on the NIF

Direct-drive target



Indirect-drive target



Hohlraum using
a cylindrical high-Z case

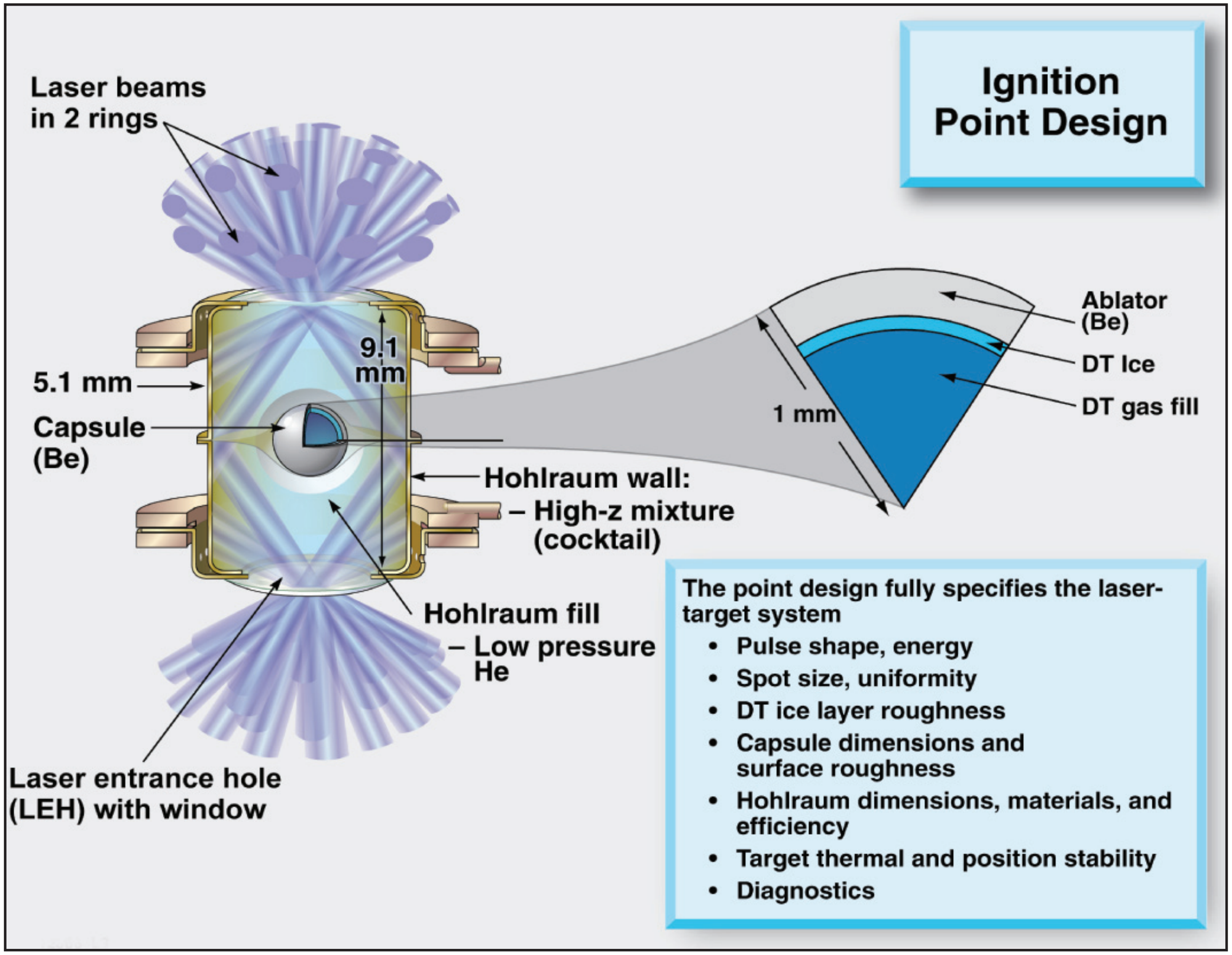
Key issues:

- Energy coupling
- Drive uniformity
- Hydrodynamic instablities

Due to much better energy coupling, direct drive is the baseline approach for laser-based inertial fusion energy

E15187

The indirect-drive ignition-point design is based on many years of experimental and theoretical work*



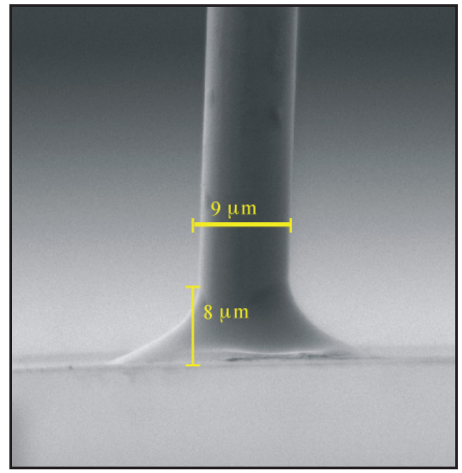
* S. W. Haan *et al.*, Nucl. Fus. 44, S171 (2004);
S. W. Haan *et al.*, Phys. Plasmas 12, 056316 (2005);
S. W. Haan *et al.*, Fus. Sci. Tech. 49, 553 (2006).

The challenge now is to fabricate the indirect-drive point-design target to specifications

Polished Be capsule

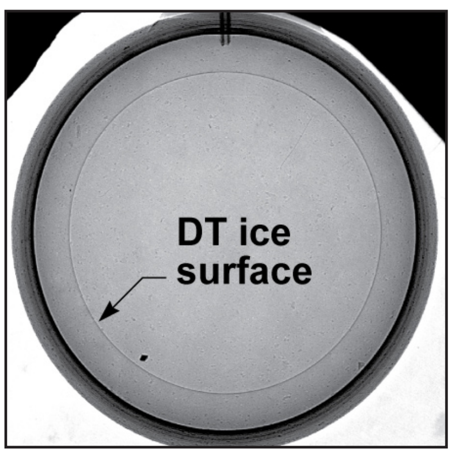
Outer surface finish is close to specifications.

Fill tube



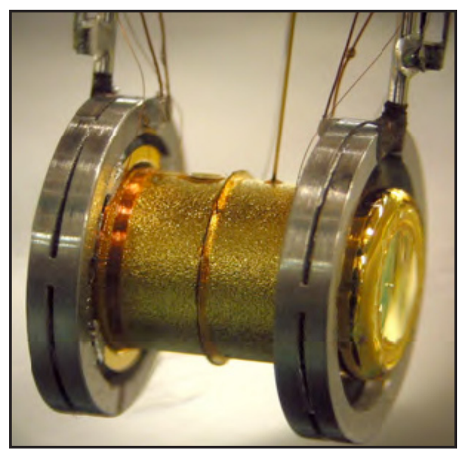
Minimal impact on performance.

DT layer in Be capsule



Ice-surface smoothness is close to specification.

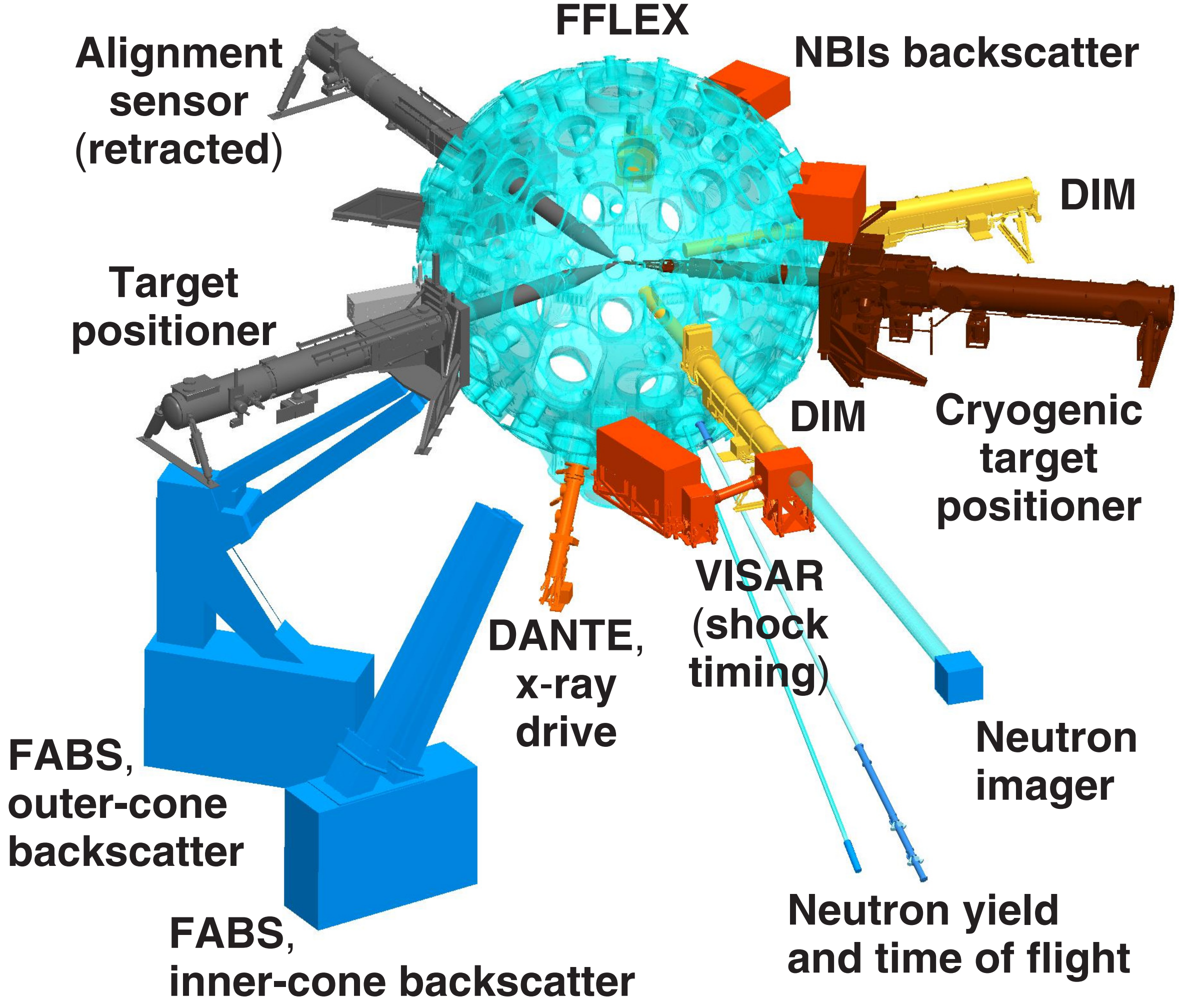
Cryogenic hohlraum



Low-mode isotherm control demonstrated.

E15030a

New ignition diagnostics and cryogenic systems will be in place for the 2009, 2010 ignition campaign



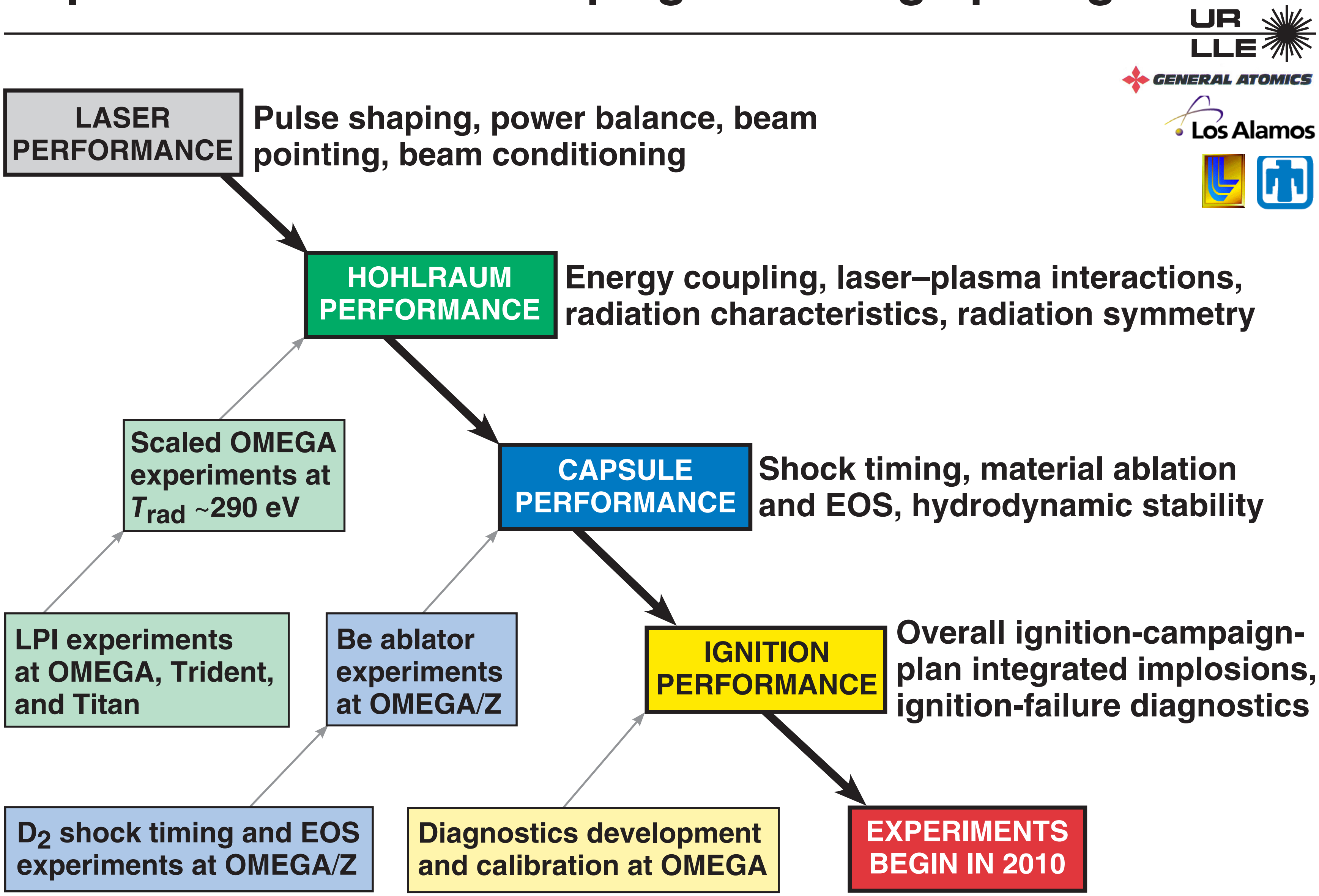
Also:

- Nuclear activation
- Magnetic-recoil spectroscopy
- γ/n bang time

Most of the non-ignition diagnostics were operational during the 2003 NIF early-light campaign.

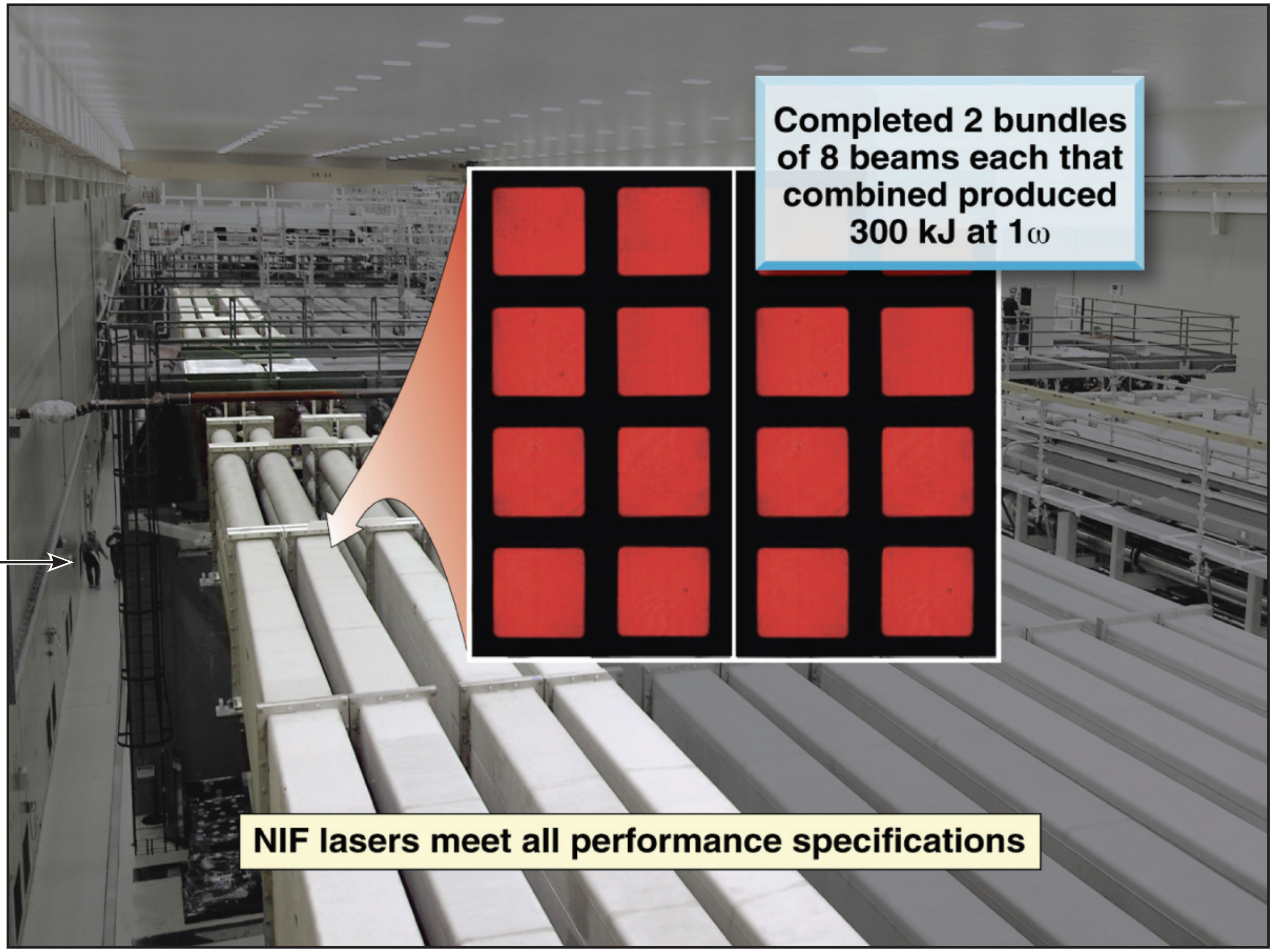
E15054a

Four integrated experiment teams are developing the requirements for the campaigns leading up to ignition



E15188

Construction of the NIF is on schedule to be completed in 2009 with target experiments to begin in 2008

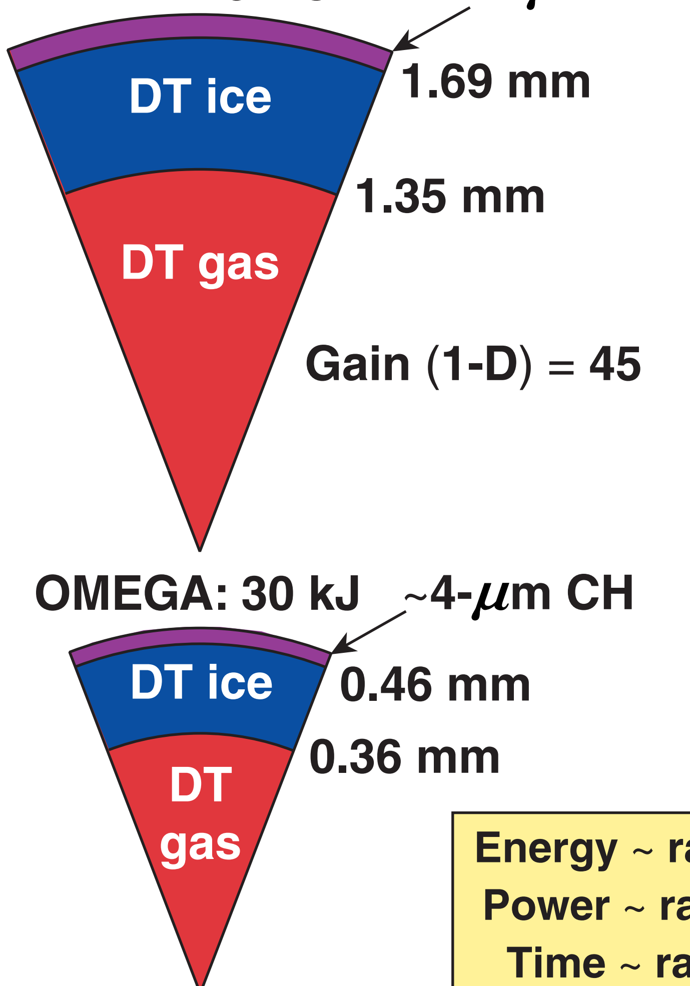


Scale

The future of IFE requires a successful demonstration of ignition on the NIF

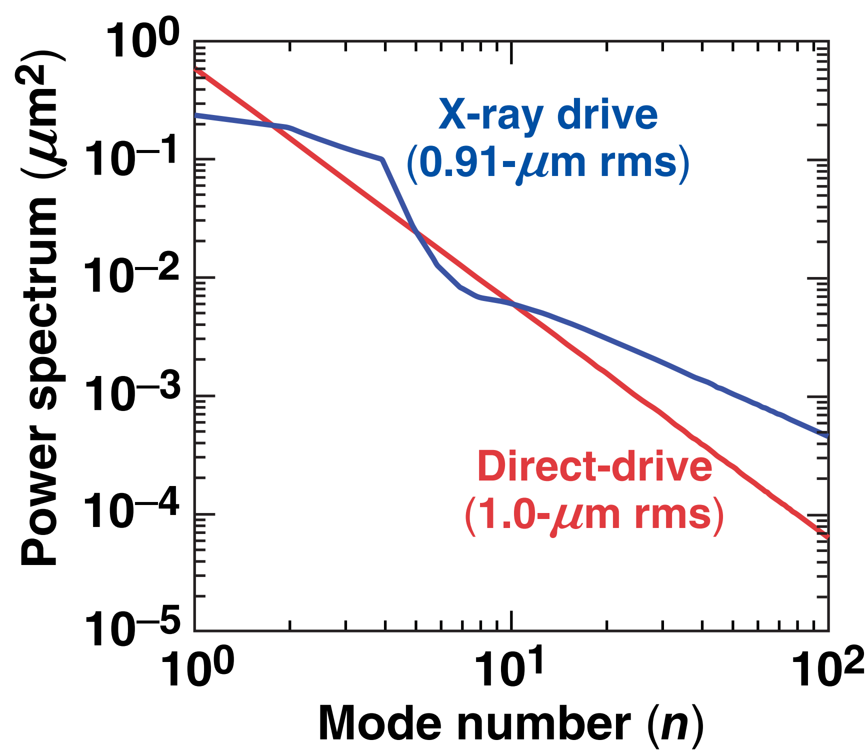
- The National Ignition Campaign
- Ignition-quality DT targets
- Target physics with cryogenic DT implosions
- IFE technology development
- Fast ignition

Scaled-ignition implosions will validate much of the capsule physics required for ignition



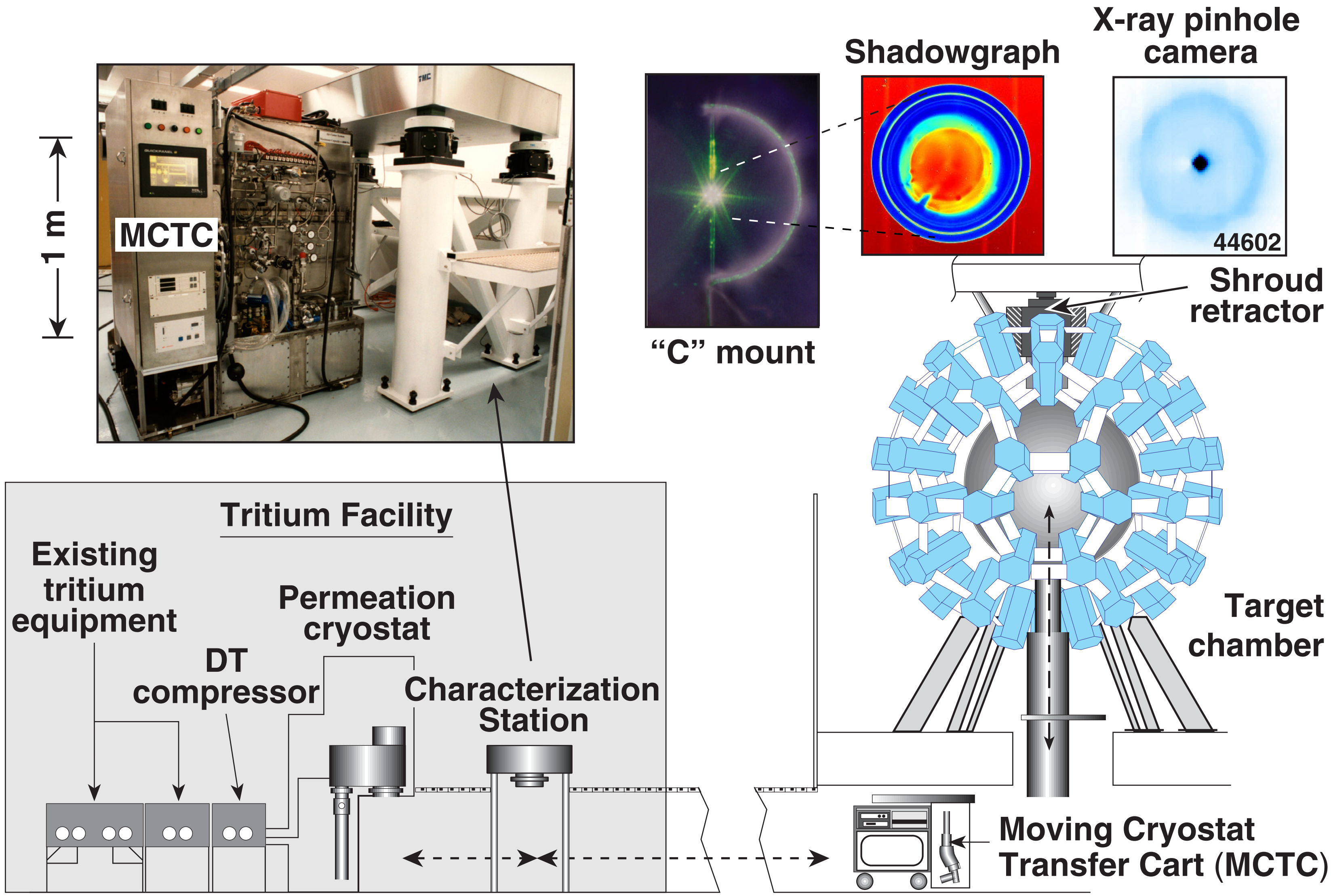
Energy ~ radius^3
Power ~ radius^2
Time ~ radius

The inner-ice-smoothness requirements are similar for direct- and x-ray-drive ignition



E15190

LLE typically implodes two to four cryogenic capsules per day, two days per month (DT and D_2)

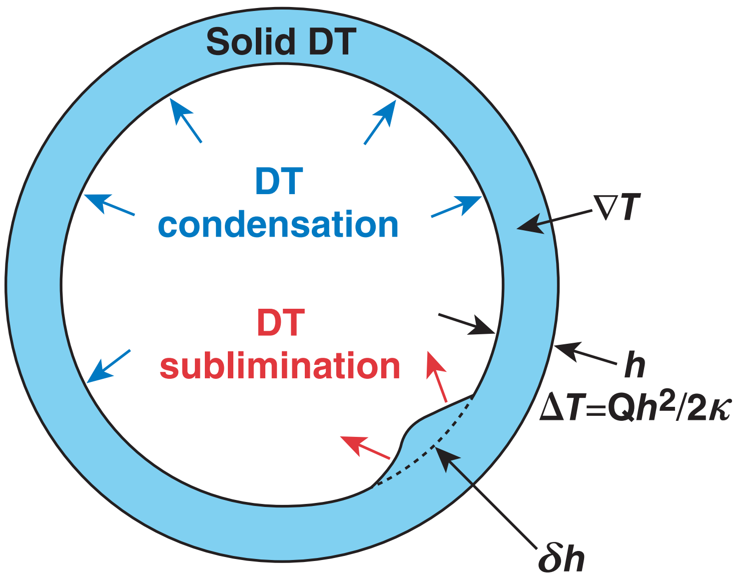


E12062g

A spherically symmetric temperature gradient across the DT (or D_2) ice is required to form a uniform layer

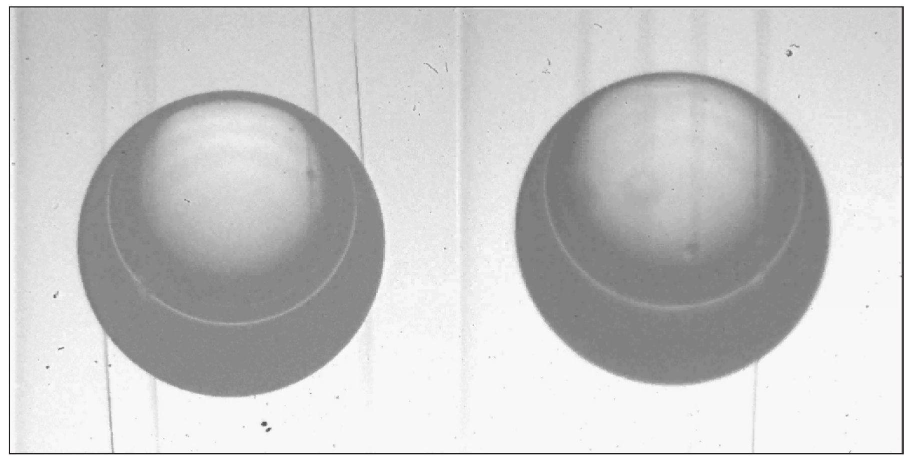
UR LLE

β-layering[1] causes the bump height to decrease as DT sublimes from the warmer region and re-deposits on the colder (thinner) surface.



The temperature gradient can also be established by heating externally (IR radiation).[2]

Gradual solidification virtually eliminates high-spatial-frequency surface roughness.



***X*-view camera** **_Y_-view camera**

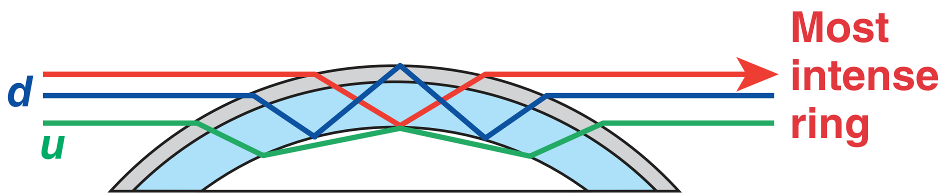
(Time lapse ~1 h)

Thermal gradients can be controlled to mK precision

E15072a

[1]J. K. Hoffer and L. R. Foreman, Phys. Rev. Lett. 60, 1310 (1988).
[2]G. W. Collins *et al.*, J. Vac. Sci. Technol. A 14, 2897 (1996).

For transparent ablators, the smoothness of the inner ice surface is measured using optical shadowgraphy



Refracted light creates a bright ring in a backlit image

Bright ring encodes radial position of the ice.

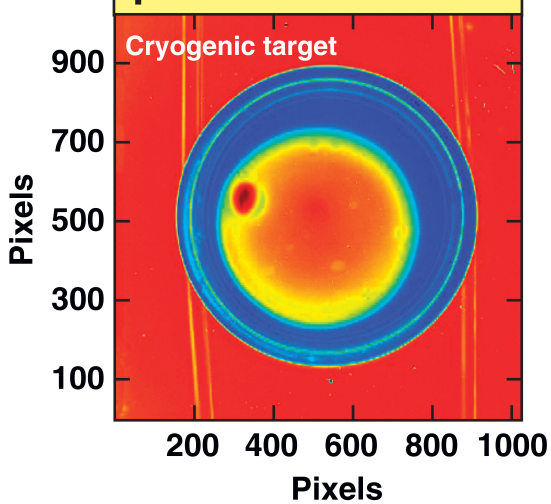
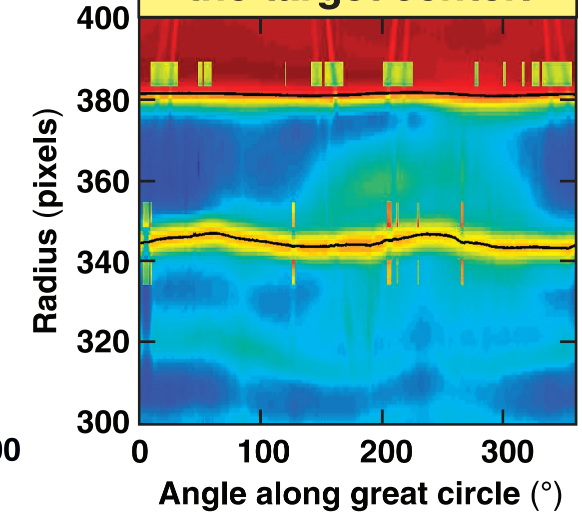
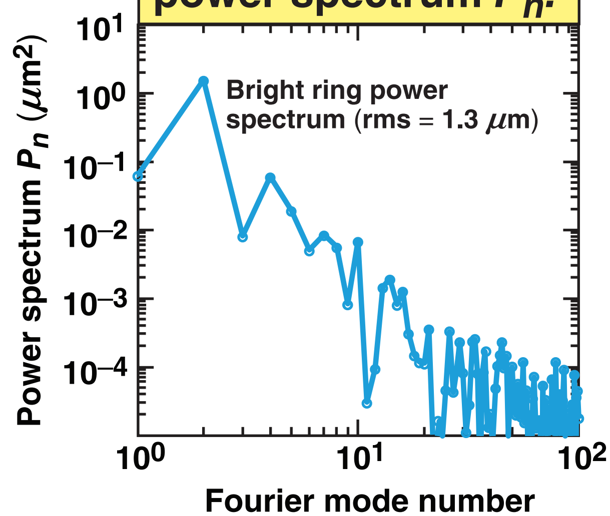


Image is unwrapped around the target center.

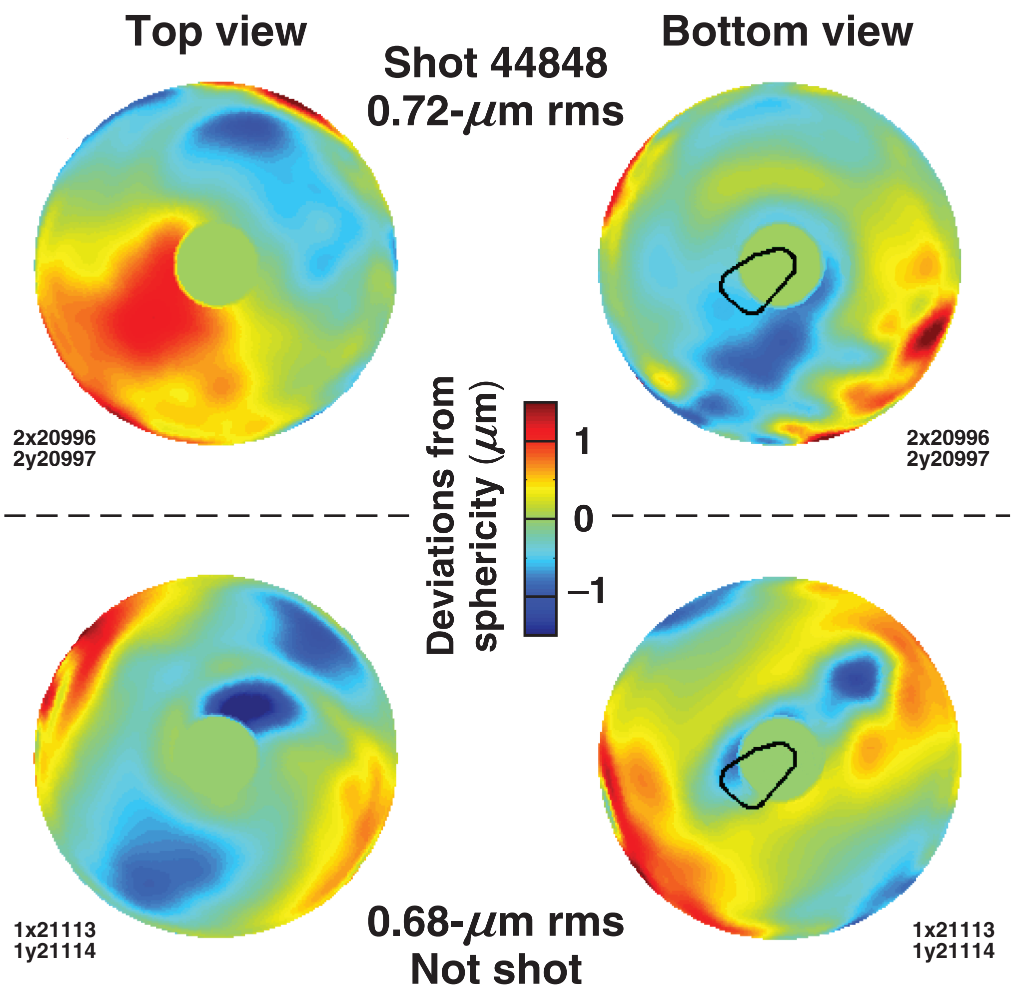


$R(\theta)$ is analyzed to get the Fourier power spectrum P_n.

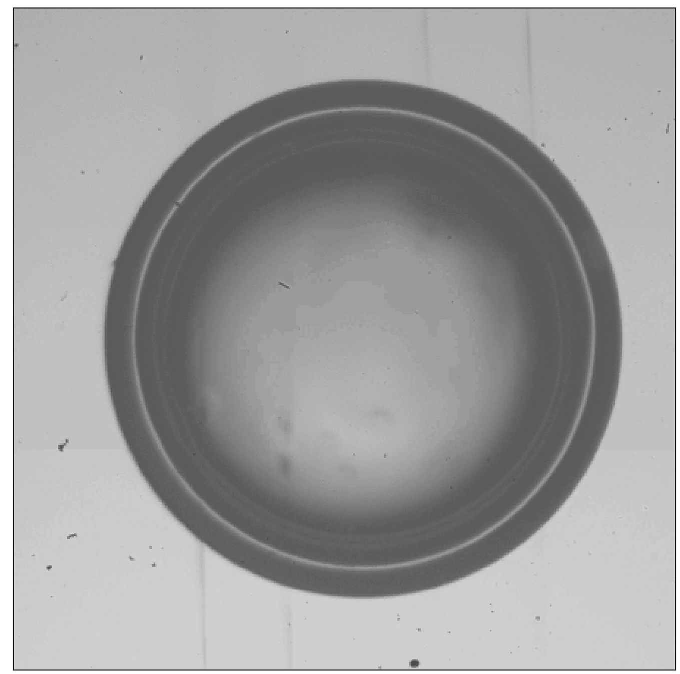


E15042a

A 3-D representation of the inner ice surface can be constructed from multiple views



Target for shot 44848



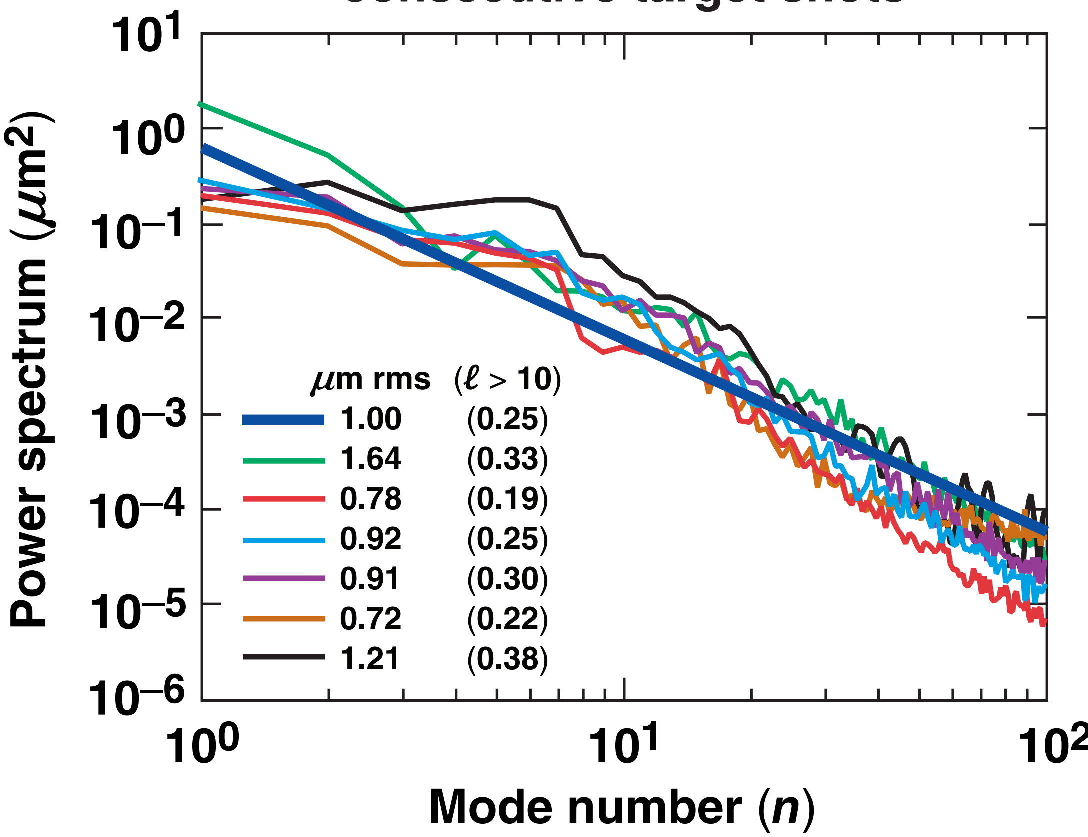
Full azimuthal rotation

T2270c

More than half of the DT capsules created to date have produced layers with sub-1-μm-rms roughness

UR LLE

The best layers for six consecutive target shots

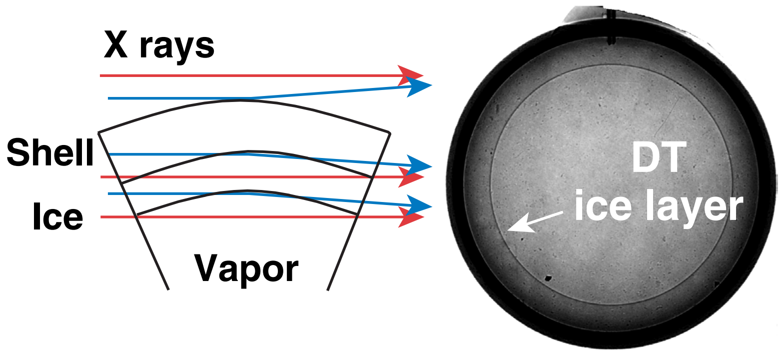


- High-mode ($n > 20$) roughness is minimal for "single crystal" layers
- Low-mode roughness ($n < 6$) is due to asymmetries in the triple point isotherm
- Mid-mode roughness ($6 < n < 20$) is likely related to outer-surface features (glue for silks)

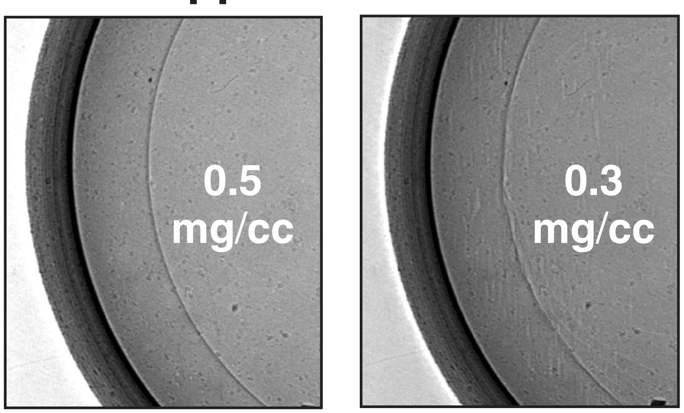
E15043a

DT layers in Be shells at 0.3 mg/cc meet the NIF smoothness standard for modes ≥10

X-ray-phase contrast imaging*

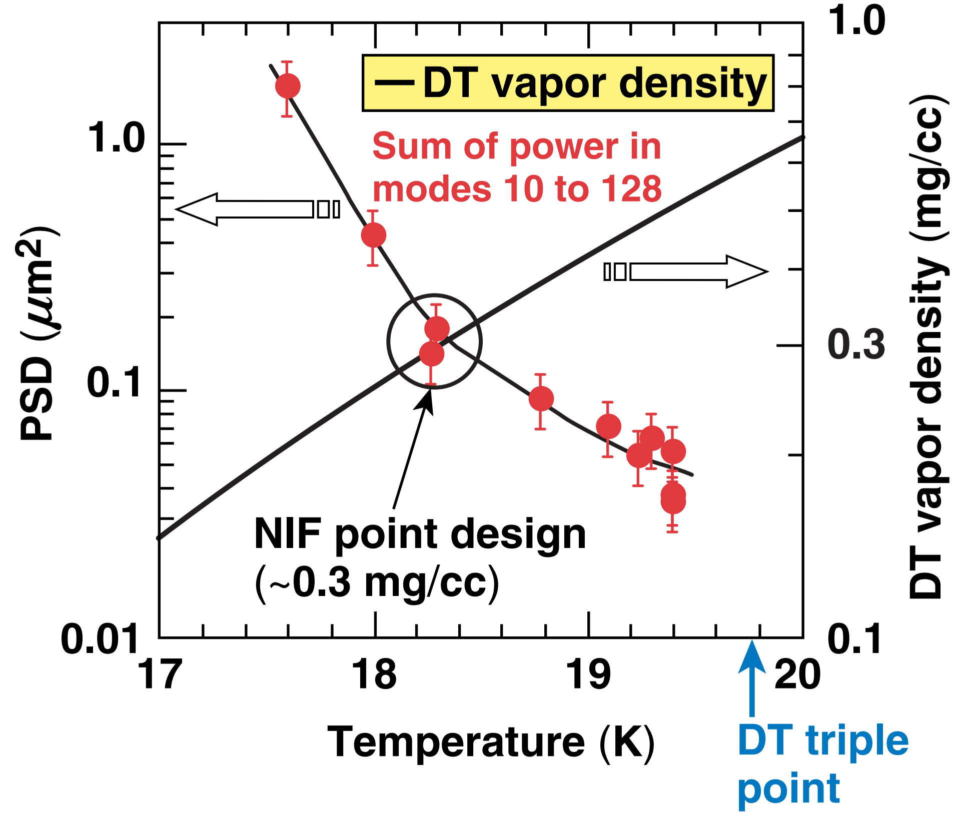


Higher-mode roughness is apparent at 18.3 K



T = 19.3 K T = 18.3 K

X-ray ignition-point design requires the temperature of the ice to be ~18.3 K



- Modes 1 to 3 add about 2 μm to the rms value.

*D. S. Montgomery *et al.*, Rev. Sci. Instrum. 75, 3986 (2004),
B. J. Kozioziemski *et al.*, J. Appl. Phys. 97, 063103 (2005).

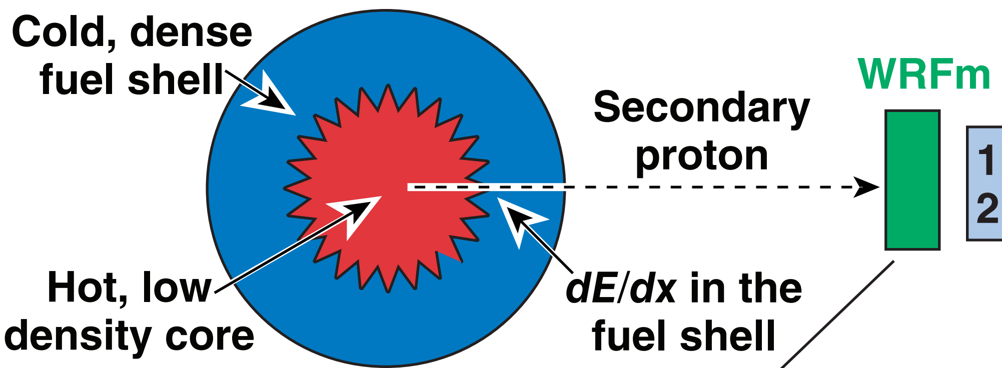
E15045a

The future of IFE requires a successful demonstration of ignition on the NIF

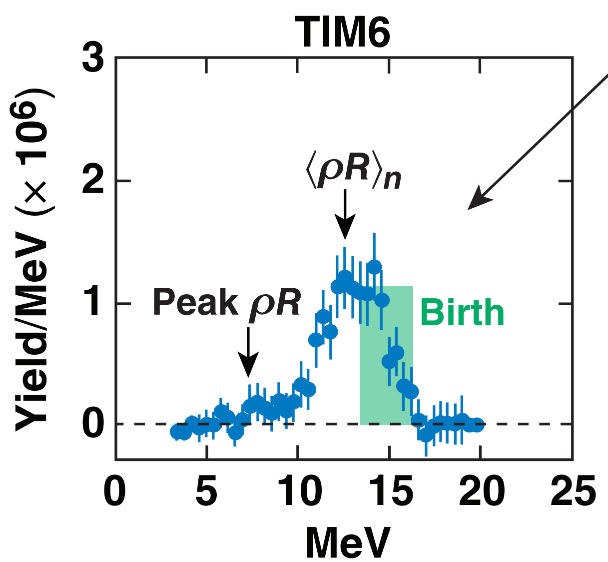
- The National Ignition Campaign
- Ignition-quality DT targets
- Target physics with cryogenic DT implosions
- IFE technology development
- Fast ignition

E15183b

The neutron averaged areal density $\langle \rho R \rangle_n$ is greater than 100 mg/cm^2 for cryogenic D_2 implosions



1. D + D → ^{3}He (0.7 MeV) + p
2. ^{3}He + D → p (12.5–17.4 MeV) + ^{4}He



- *dE*/*dx* corresponds to $\langle \rho R \rangle_n$ ~ 100 to 110 mg/cm^2 over several lines-of-sight
- Low-energy tail suggests peak ρR approaches 200 mg/cm^2

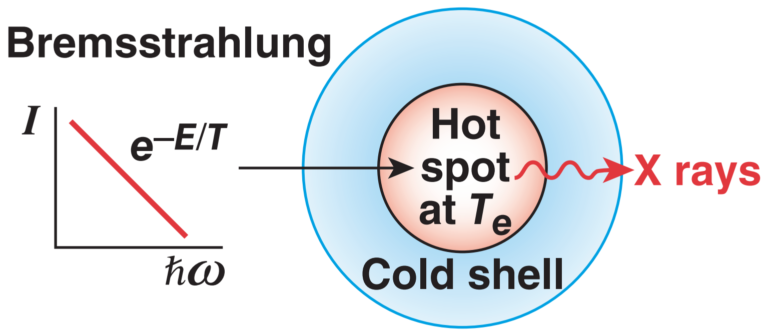
Further analysis is underway to infer a $\rho R(t)$ by convolving the neutron emission rate with the measured proton spectrum*

E15270

*V. A. Smalyuk *et al.*, Phys. Rev. Lett. 90, 135002 (2003).

The peak areal density ρR_{peak} may be inferred by using core self emission to backlight the fuel shell

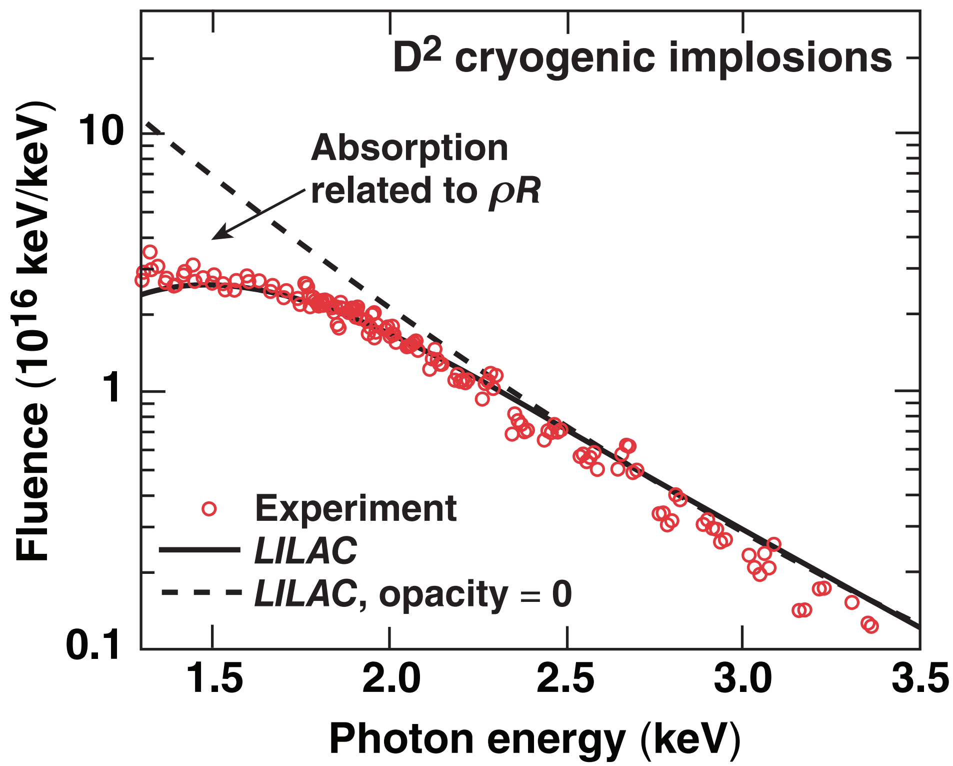
Emitted x-ray spectrum is the product of a source term and an attenuation term:



- Spect = $(e^{-E/kT_{hot}}) \times (e^{-\mu \rho R_{shell}})$, where μ is the mass attenuation coefficient and is proportional to ρ

The fuel–shell attenuation is proportional to $\rho^2 R$

1-D simulations can be used to estimate ρ and suggest the ρR_{peak} could be as high as 180 to 190 mg/cm^2



2-D simulations are expected shortly to confirm fuel density estimates

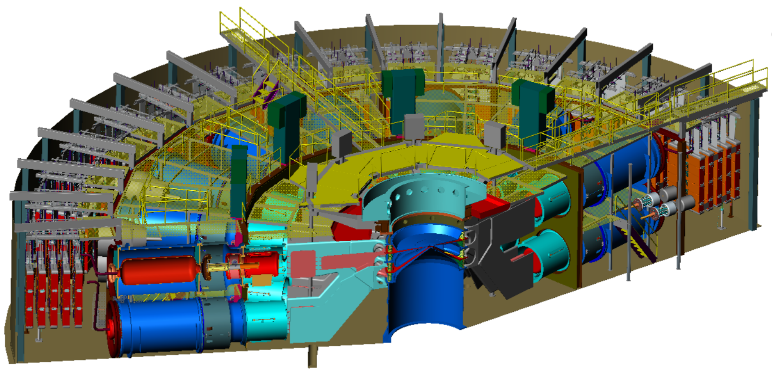
E15271

The future of IFE requires a successful demonstration of ignition on the NIF

- The National Ignition Campaign
- Ignition-quality DT targets
- Target physics with cryogenic DT implosions
- IFE technology development
- Fast ignition

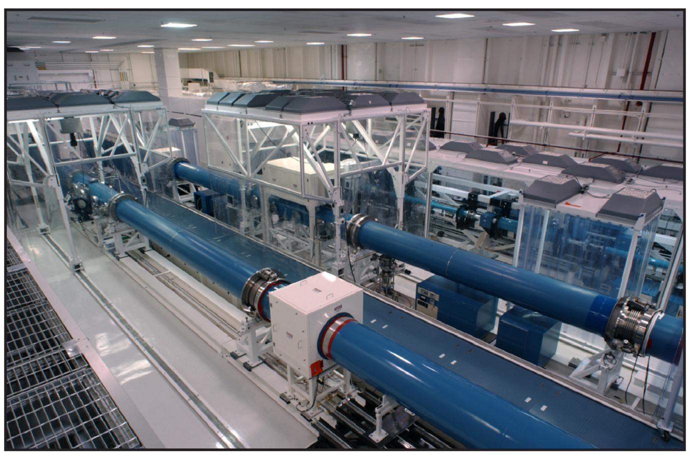
E15183c

Major upgrades of Z and Z-beamlet are underway



The ZR project is upgrading the performance of Sandia's "Z"-pinch facility

- current increased from 19 MA to 26 MA
- 2× increase in diagnostic access
- 2× increase in shot-rate capability
- 100- to 200-ns pulses for ICF/Z-pinches
- 100- to 300-ns pulses for EOS experiments



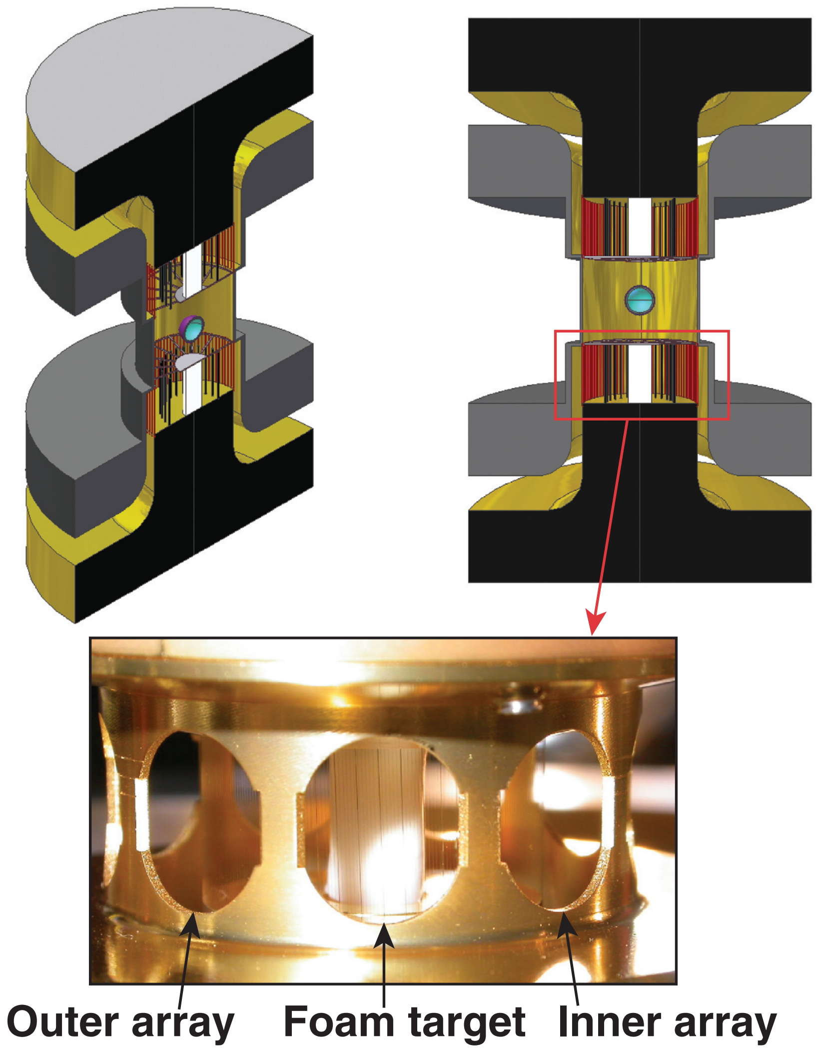
The Z-Petawatt project is upgrading the capability of Sandia's Z-Beamlet laser facility

- power increased from 2 TW to 4 PW
- x-ray-backlighter energies to 40 keV
- integrated fast-ignition experiments with peak deuterium fuel $\rho R \sim 0.8$ g/cm^2

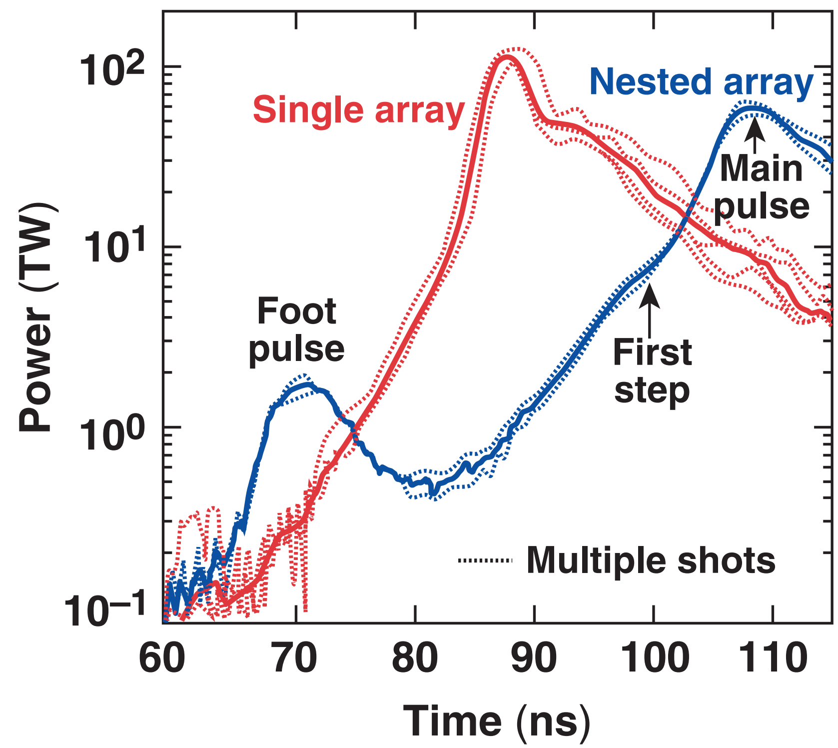
The upgraded Z and Z-Petawatt facilities will begin operation in 2007.

E15192

Nested-wire arrays show reproducible and tunable radiation pulse shapes*



Pulse produces a yield of 900 MJ when scaled to peak T_{rad} of 223 eV



*M. E. Cuneo *et al.*, Phys. Rev. Lett 95, 185001 (2005), M. E. Cuneo *et. al.*, Phys. Plasmas 13, 056318 (2006).

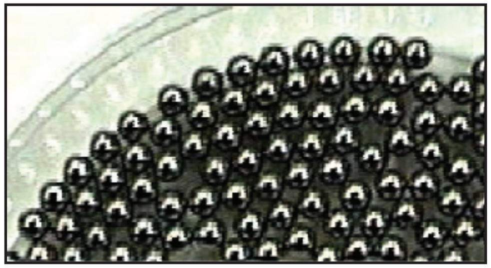
E15193

The HAPL program is developing the science and technology for an attractive fusion-power plant

UR LLE
GENERAL ATOMICS
NRL

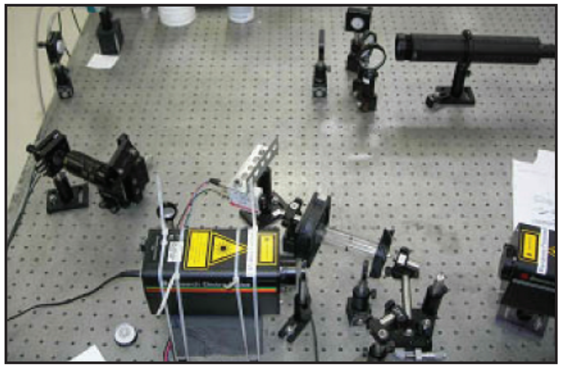
Target Fabrication: gas-tight foam capsules meet specifications

4 mm



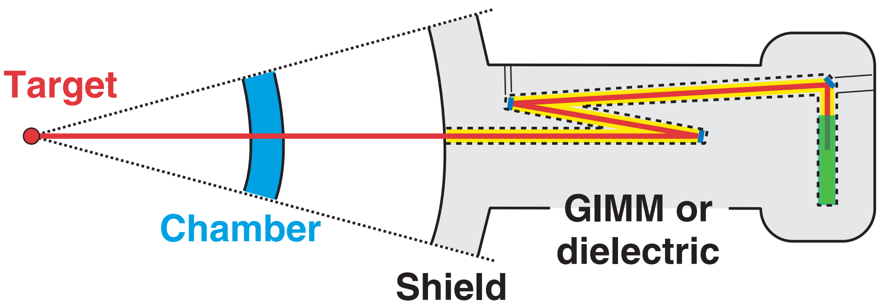
Au/Pd coated shells

Target Tracking: successful demonstration of inflight tracking

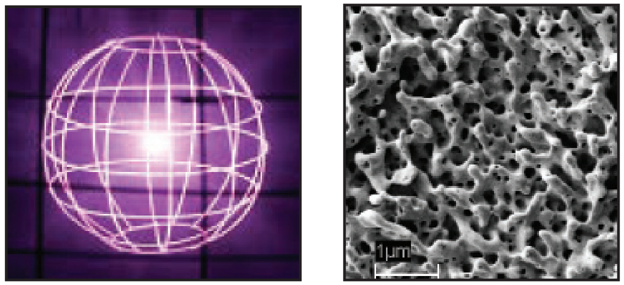


Mirror-steering test using target glint

Final Optic Train: grazing-incidence metal mirror and a dielectric final optic



Reaction Chamber Technology: develop first wall resistant to ions



Wisconsin He-implantation experiment

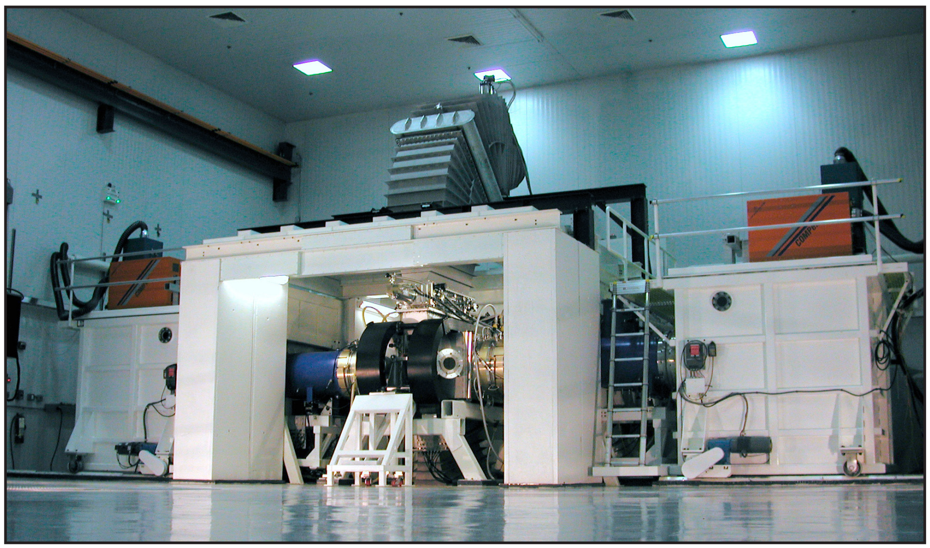
- Developing "magnetic-intervention" concept to keep ions off wall altogether and a FLIBE-inspired blanket based on Pb-Li

E15195

Both prototype driver lasers have run at power-plant repetitive rates (5 to 10 Hz) for more than 10,000 shots

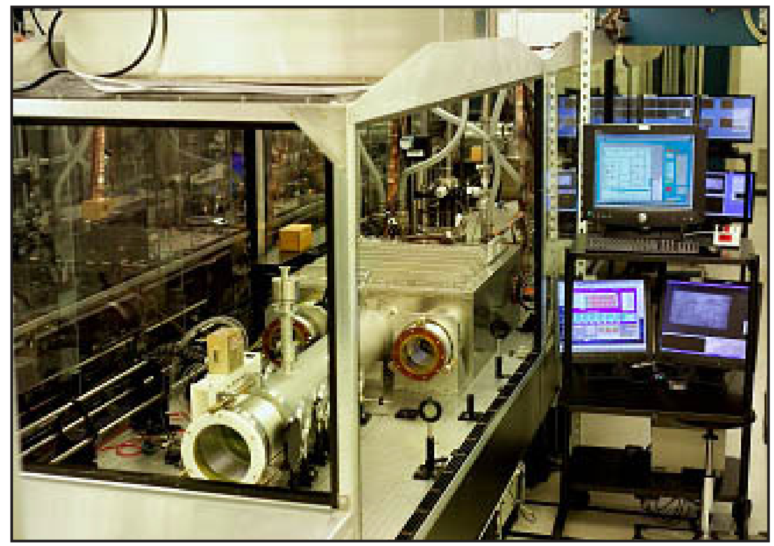
UR LLE NRL

Electra Krypton Fluoride Laser (Naval Research Laboratory)



300 to 700 J at 248 nm
120-ns pulse
1 to 5 Hz
25 k shots continuous at 2.5 Hz

Mercury Diode Pumped Solid-State Laser (LLNL)



55 J at 1051 nm*
15-ns pulse
10 Hz
100 k shots continuous at 10 Hz

*Recently demonstrated 73% conversion at 2ω

The heavy-ion fusion program has clear near- and long-term objectives

UR LLE

Top-level scientific question fundamental to both high-energy-density physics and heavy-ion fusion:

"How can heavy ion beams be compressed to the intensities required for creating high-energy-density matter and fusion energy?"

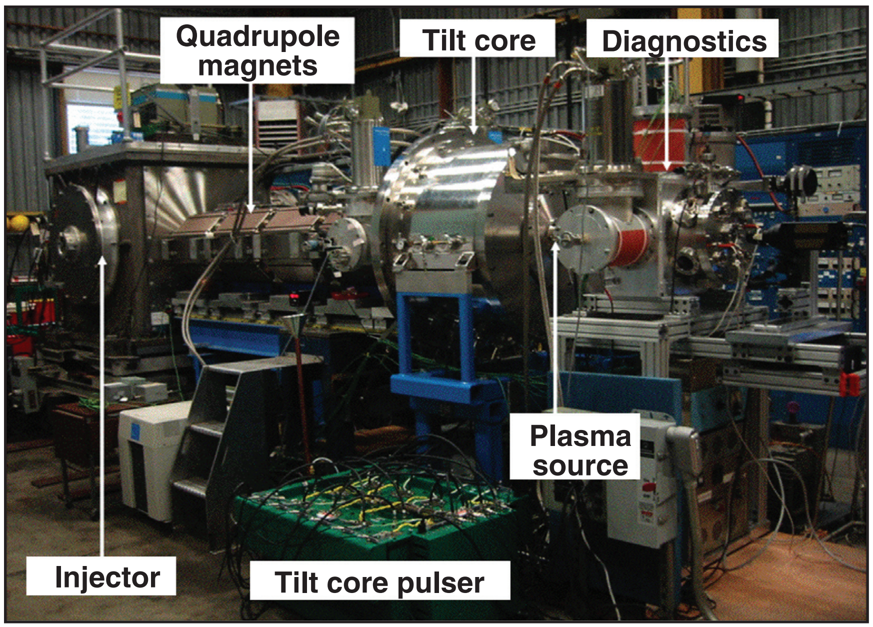
- **Challenge 1:** Understand limits to compression of neutralized beams
  - Excellent progress (>50× longitudinal; >200× transverse)
- **Challenge 2:** Integrated compression, acceleration, and focusing sufficient to reach 1 eV in targets
- **Challenge 3:** Ion-based HEDP user facility for target physics
  - DOE mission need 12-1-05
  - May prototype approach to HIF

Advances in the last two years will enable the first heavy-ion-beam–target interaction experiments to begin in 2008.

E15196

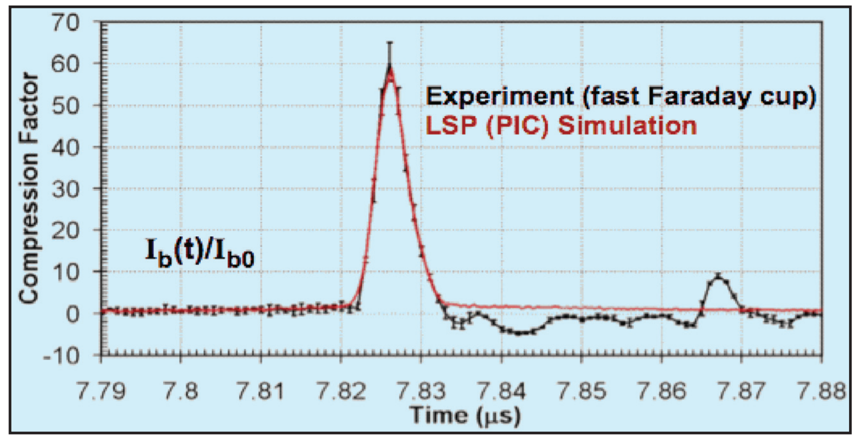
Longitudinal-bunch compression in the neutralized-drift-compression experiment (NDCX) exceeds 50×

Induction core imposes a head-to-tail velocity ramp



- Beam compresses in neutralizing plasma to minimize space charge

A 200-ns, 300-keV K+ ion beam is compressed to a few nanoseconds



- Simulations are in good agreement with this data

Pulses are now short enough (few nanoseconds) for target experiments.

The future of IFE requires a successful demonstration of ignition on the NIF

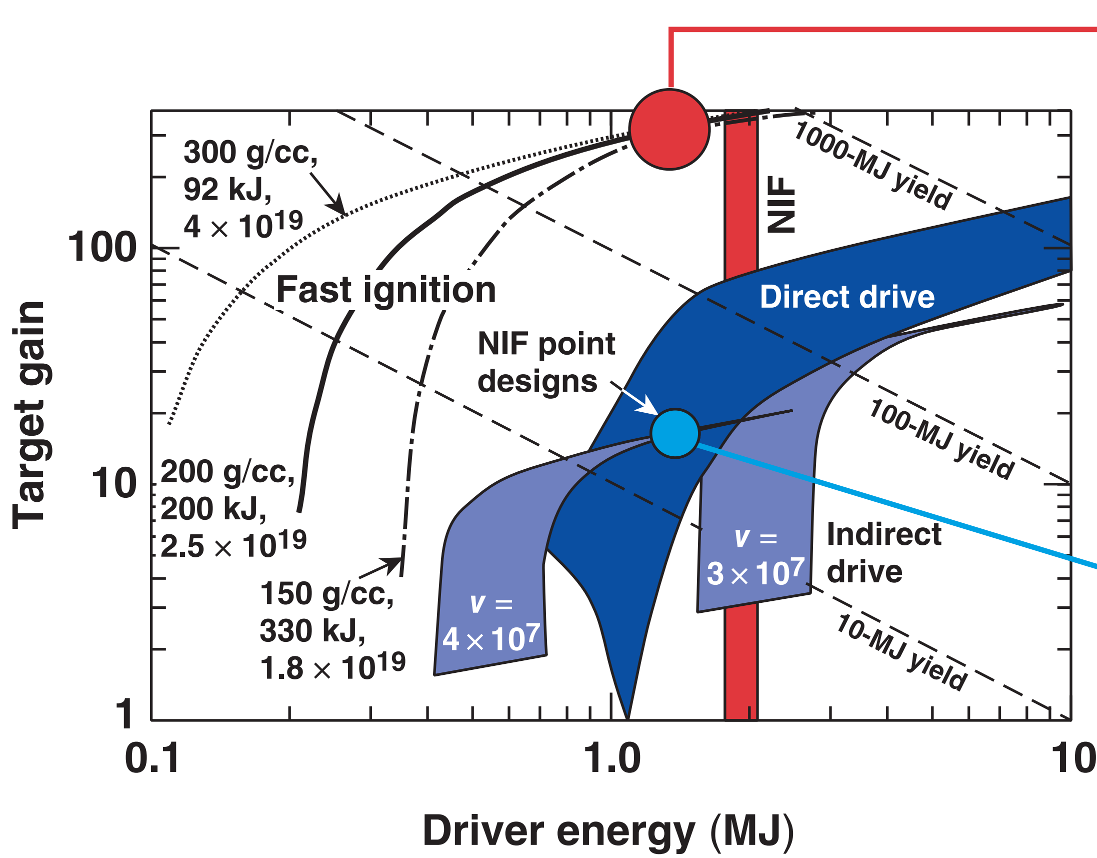
UR LLE

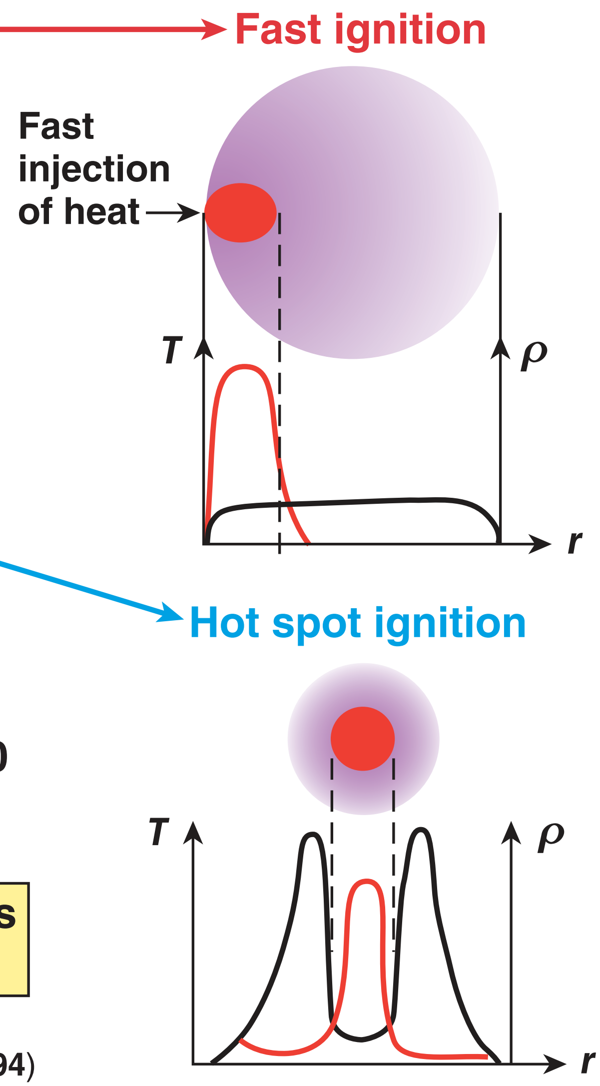
- The National Ignition Campaign
- Ignition-quality DT targets
- Target physics with cryogenic DT implosions
- IFE technology development
- Fast ignition

See IF/1-2Ra, A. J. MacKinnon
for more details on fast ignition

E15183d

Ignition could be achieved at lower drive energies with fast ignition*





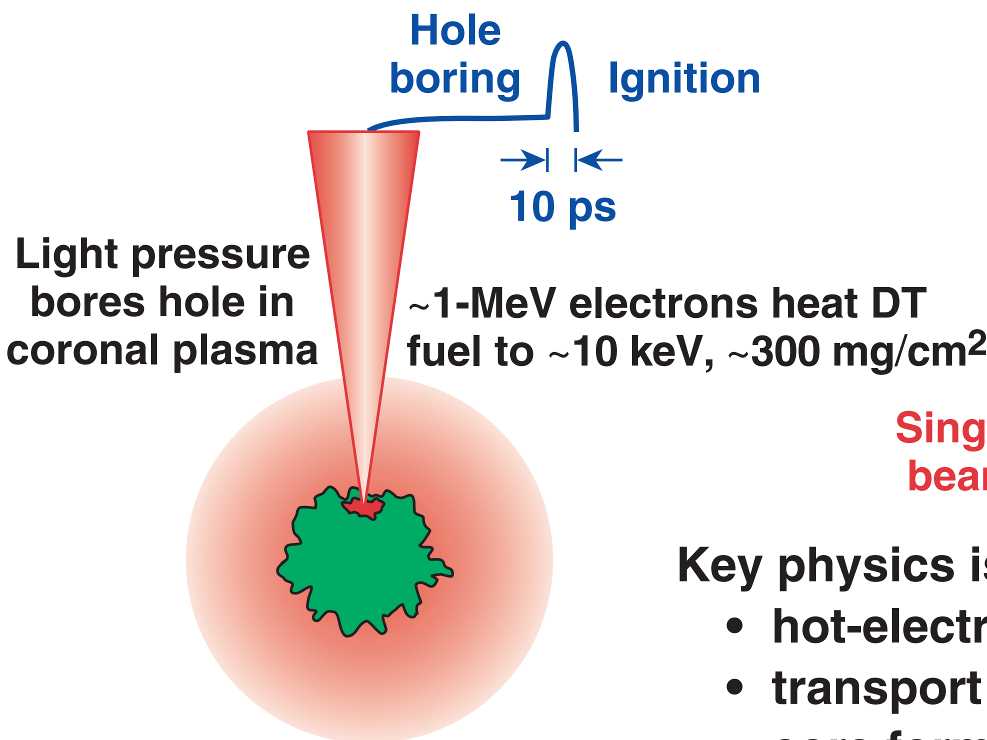
Fast ignition takes advantage of recent developments in high-energy, short-pulse laser systems

E15198

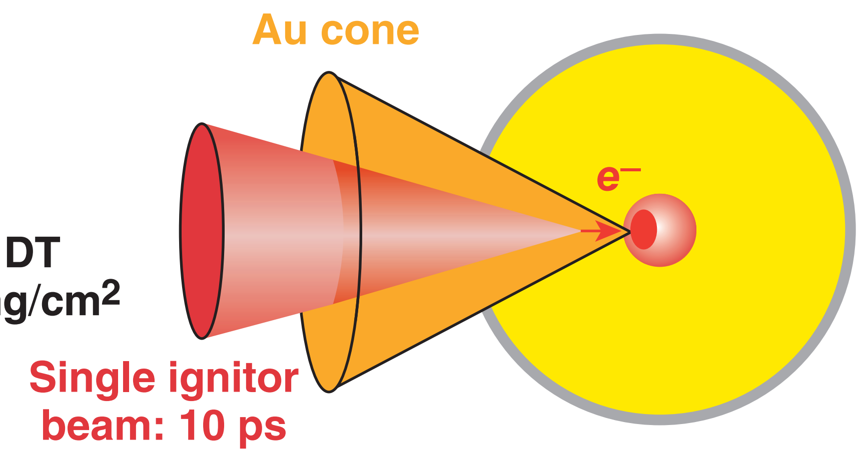
*M. Tabak *et al.*, Phys. Plasmas 1, 1626 (1994)

Two concepts have been developed to produce the heating beams close to the compressed core

Channeling Concept[1]



Cone-Focused Concept[2]



Key physics issues

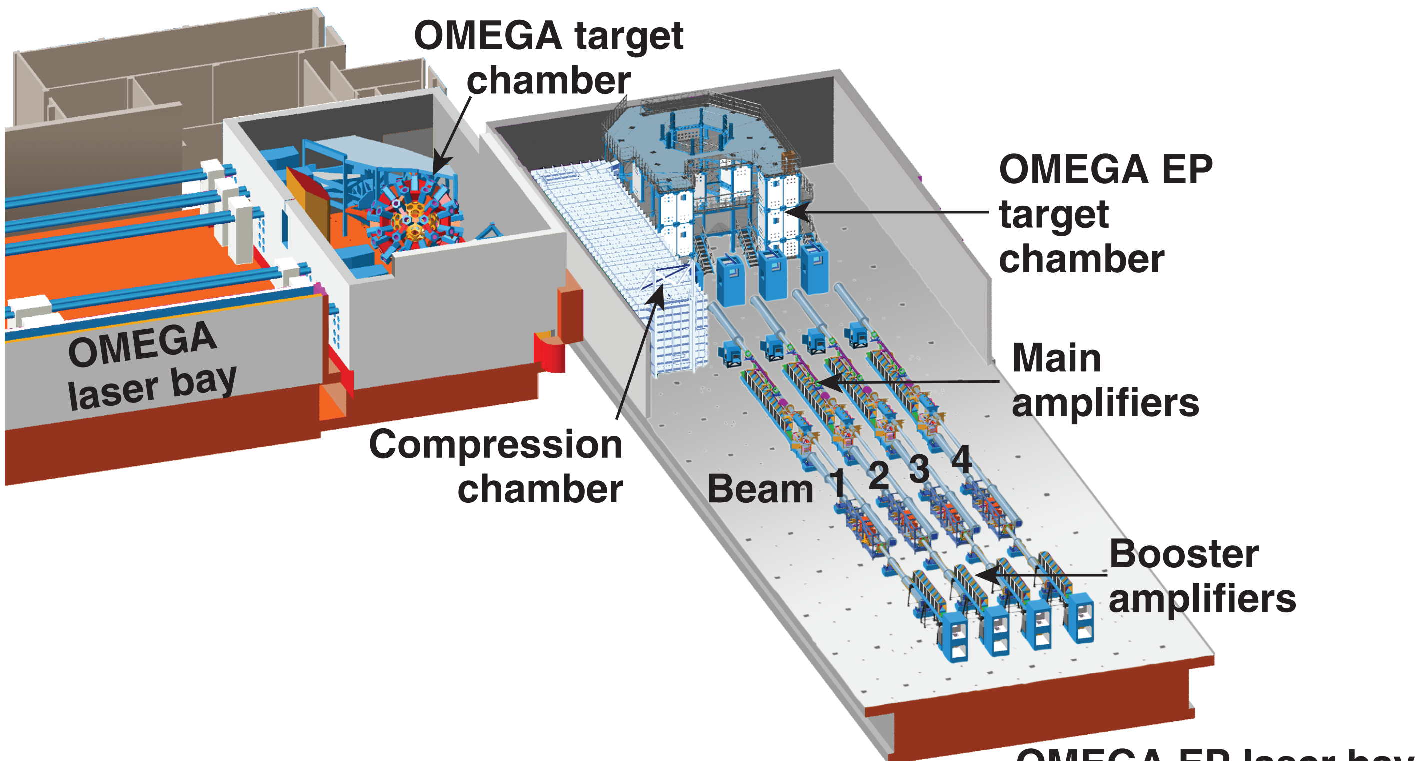
- hot-electron production
- transport to the core
- core formation

Integrated experiments would require compression and heating within a single facility.

[1]M. Tabak *et al.*, Phys. Plasmas 1, 1626 (1994),
[2]R. Kodama, Nature 418, 933 (2002).

E11710k

OMEGA EP will begin target-physics experiments in 2008



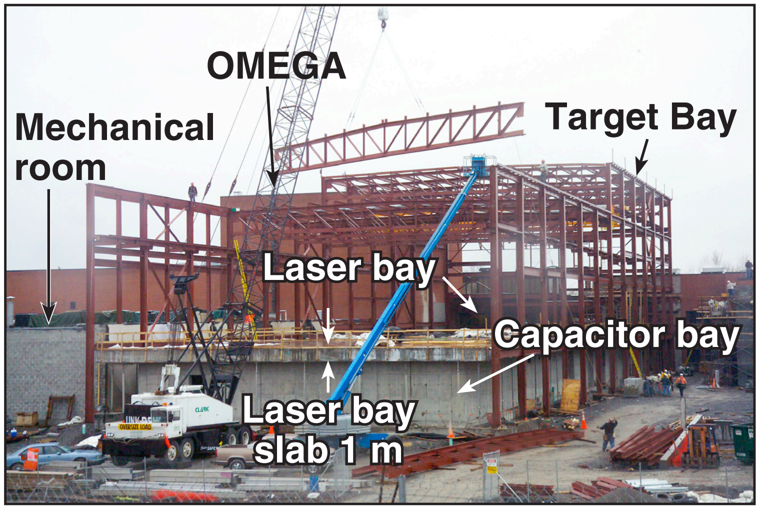
Performance capabilities	Short-pulse Beam 1	Short-pulse Beam 2	Long pulse (any beam)	
Pulse width	1 to 100 ps	1 to 100 ps	1 ns	10 ns
Energy on target (kJ)	2.6 kJ, 10 to 100 ps grating limited <10 ps	2.6 kJ, 80- to 100-ps beam combiner limited <80 ps	2.5	6.5
Intensity (W/cm^2)	3×10^{20}	$\sim 2 \times 10^{18}$	3×10^{16}	8×10^{15}
Focusing (diam)	>80% in 20 μm	>80% in 40 μm	>80% in 100 μm	

G6957k

The OMEGA EP building was completed in February 2005

UR LLE

April 2004



January 2005

OMEGA EP Laser Bay

E13574e

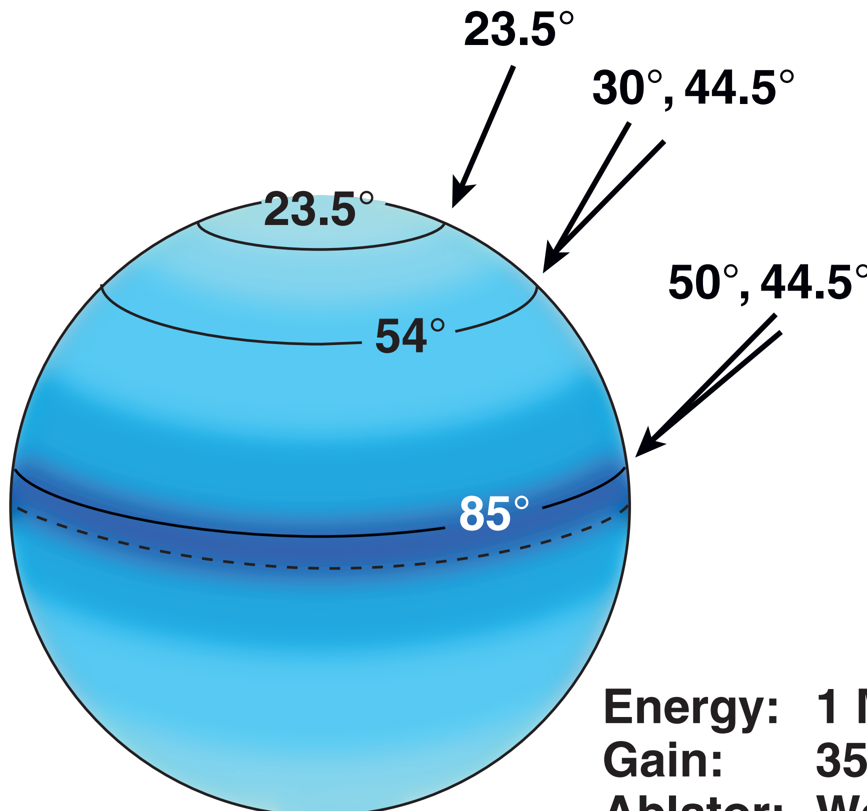
Summary/Conclusions

The U.S. IFE program is based on a near-term ignition/gain demonstration and long-term technology development

- The National Ignition Campaign will lead to ignition on the National Ignition Facility (NIF) shortly after the facility is completed.
- Key science questions relevant to ignition are being experimentally verified on the OMEGA laser at LLE and the Z/ZR facility at SNL.
- LLE has imploded direct-drive ignition-scaled targets that meet the ignition specification for inner ice smoothness.
- Longer-term research programs are developing the key technologies to drive IFE (e.g., repetitive rate, chamber design, target injection, etc.).
- Fast ignition is being pursued as an ignition alternative and a lower-cost route to IFE.

Initial direct-drive-ignition experiments will require a polar illumination geometry

Polar direct drive (PDD)



Energy: 1 MJ
Gain: 35
Ablator: Wetted foam

The required intensity variations on target can be achieved through a combination of spot shape, pulse shape, and beam pointing.

E15199