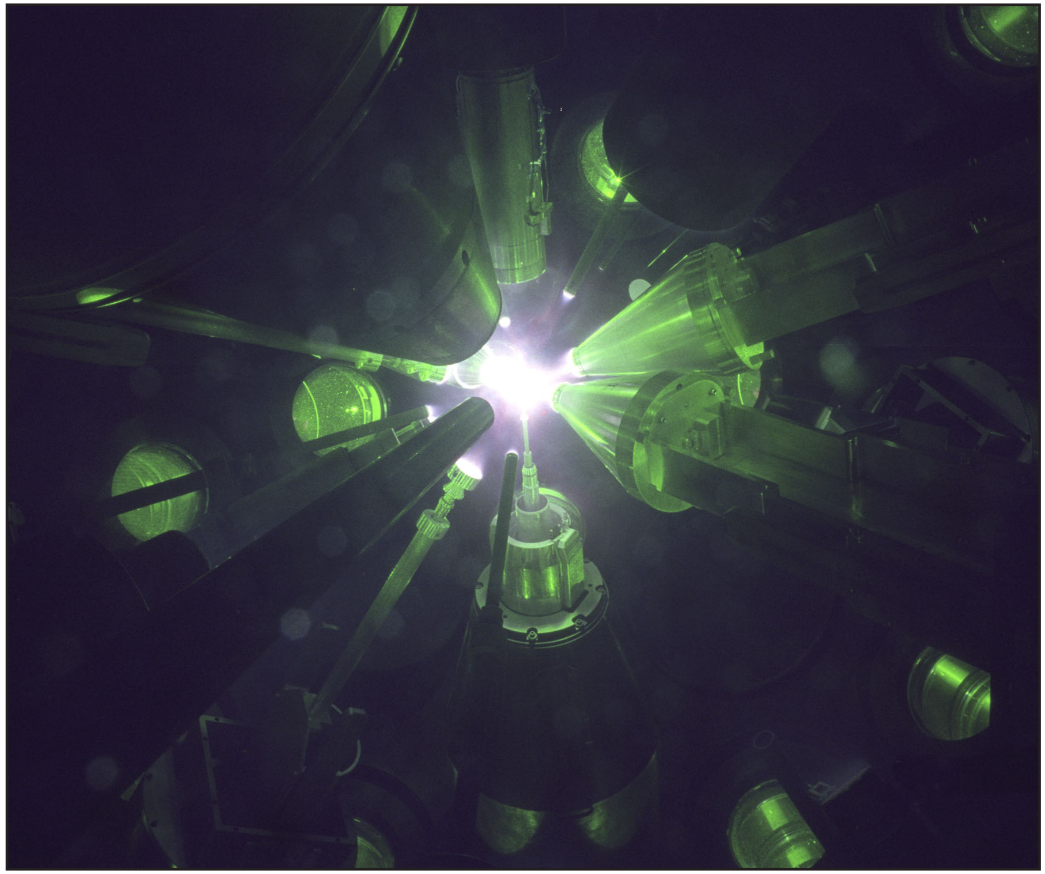
Cryogenic DT and D_2 Targets for Inertial Confinement Fusion



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Summary

Ignition-scaled cryogenic DT capsules are being imploded on the OMEGA Laser System

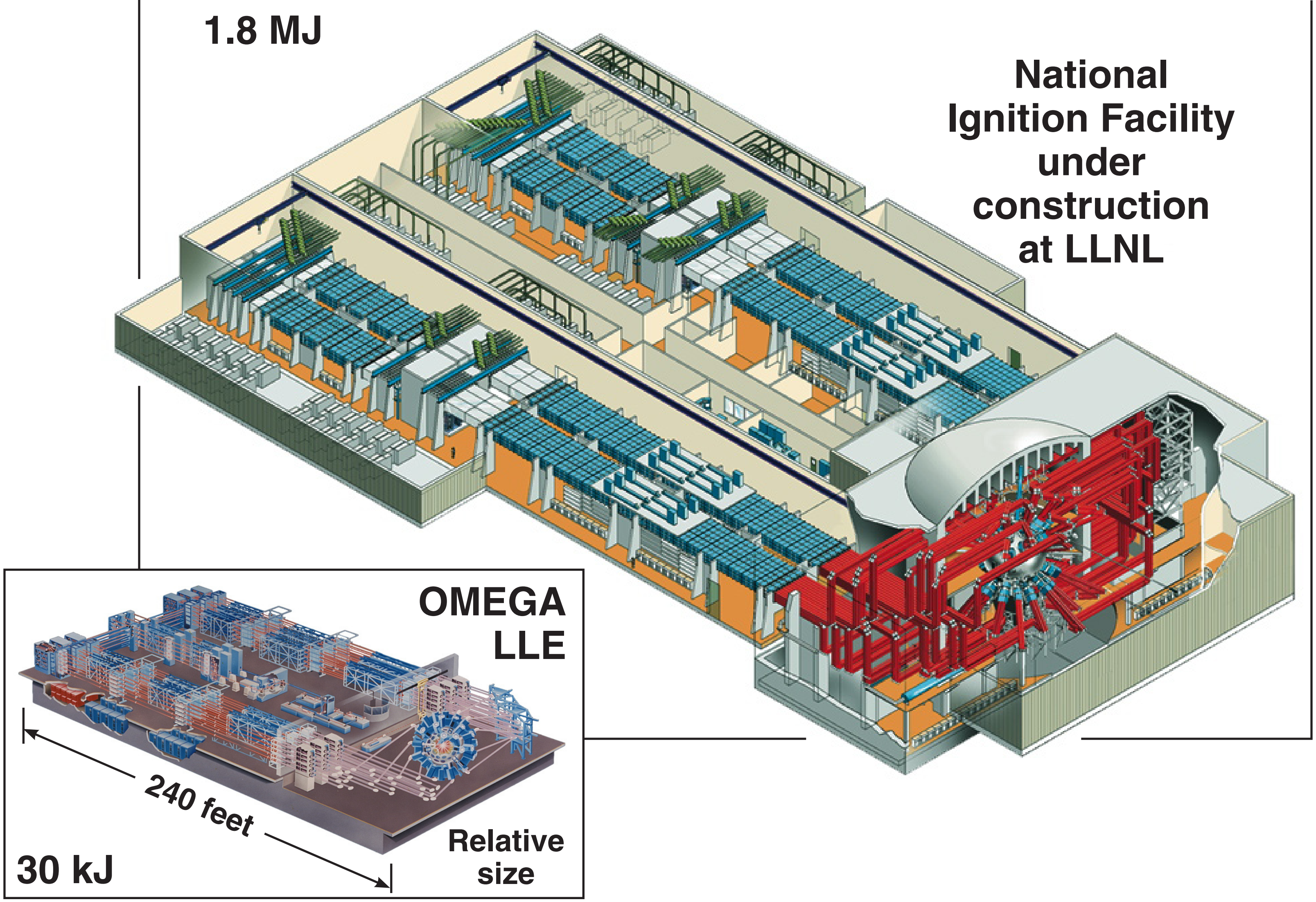
- The success of the cryogenic target handling system at LLE is the culmination of three decades of research and development.
- Since 2001, 118 cryogenic D_2 and 15 cryogenic DT capsules have been imploded on the OMEGA laser.
- β-layering produces inner-ice smoothness well below the ~1-μm-rms (all modes) requirement for direct- and indirect-drive ignition.
- IR layering of D_2 targets produces similar results.
- The NIF cryogenic target development program has produced and characterized ignition-quality ice layers in Be shells.

Peak fuel areal densities approaching 200 mg/cm^2 have been achieved in both D_2 and DT implosions.

E15028

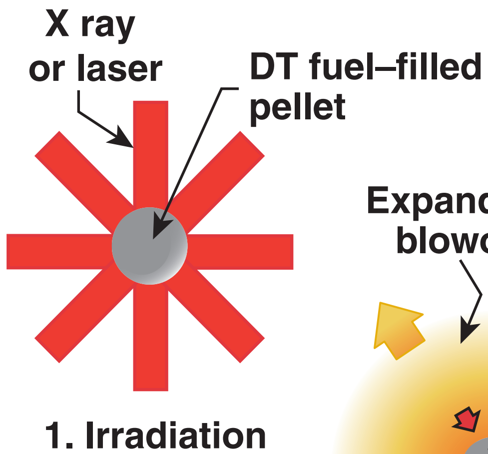
A goal of ICF research is to demonstrate ignition and burn at the lowest possible incident energy

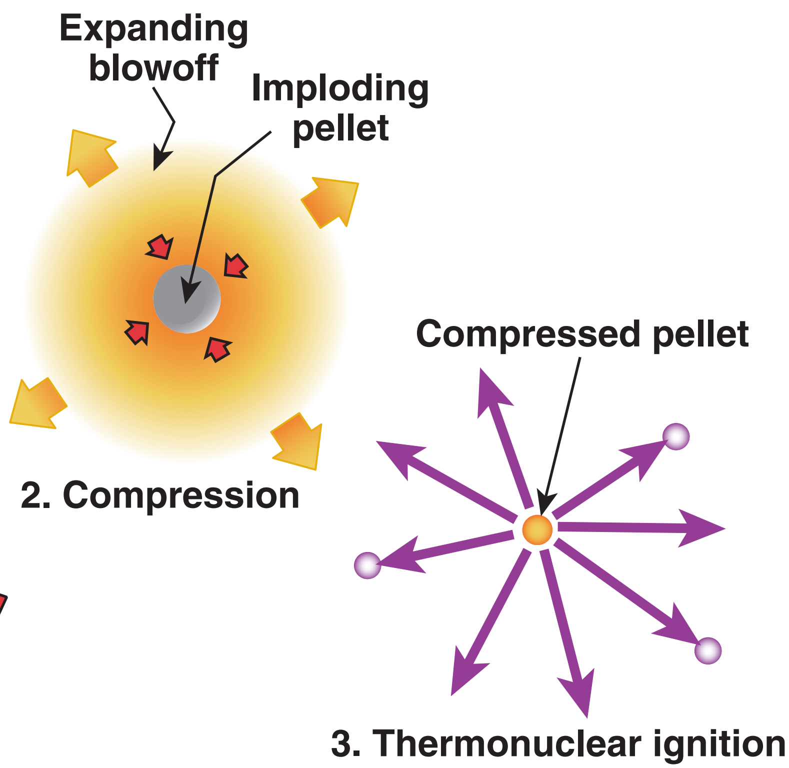
LANL · UR LLE · NIF The National Ignition Facility

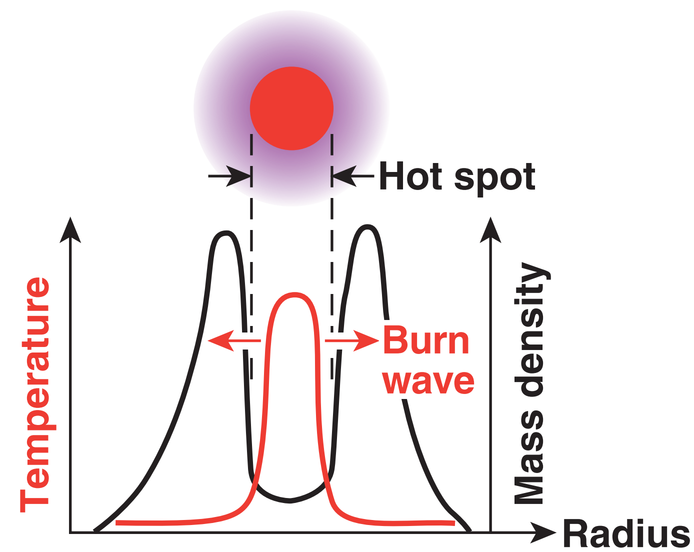


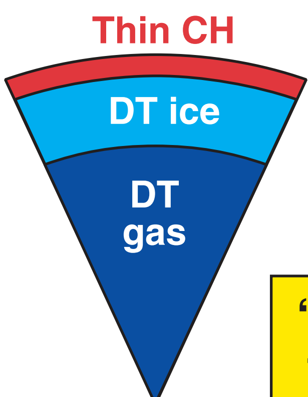
TC4680j

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







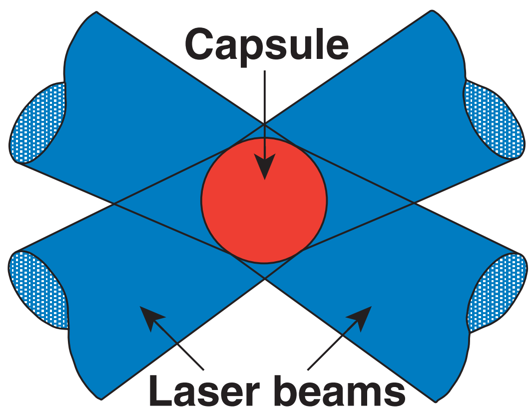


"Hot-spot" ignition requires the core temperature to be at least 10 keV and the core fuel areal density to exceed ~300 mg/cm^2.

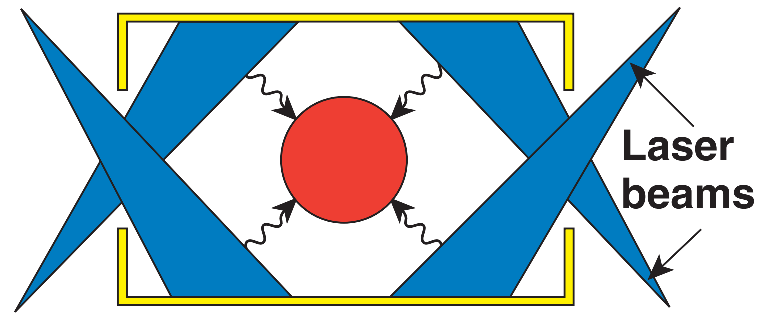
The basic capsule design and fabrication tolerances are similar for both direct- and x-ray-drive ignition

UR LLE

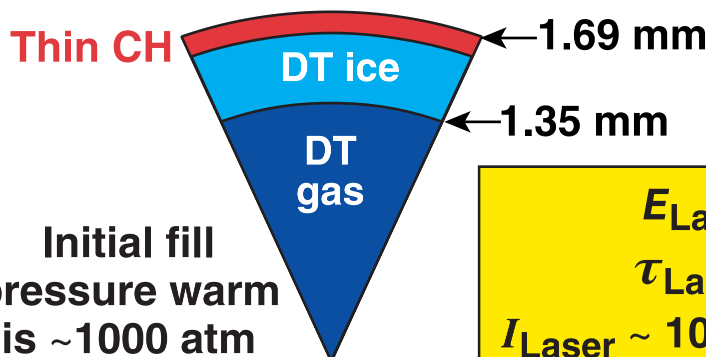
Direct-drive target



X-ray-drive target



Hohlraum using
a cylindrical high-*Z* case



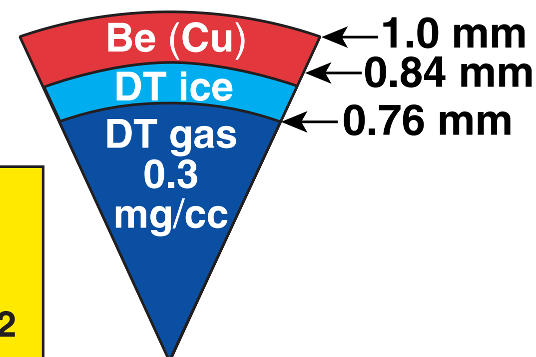
E_{Laser} ~ 1 MJ

τ_{Laser} ~ 10 ns

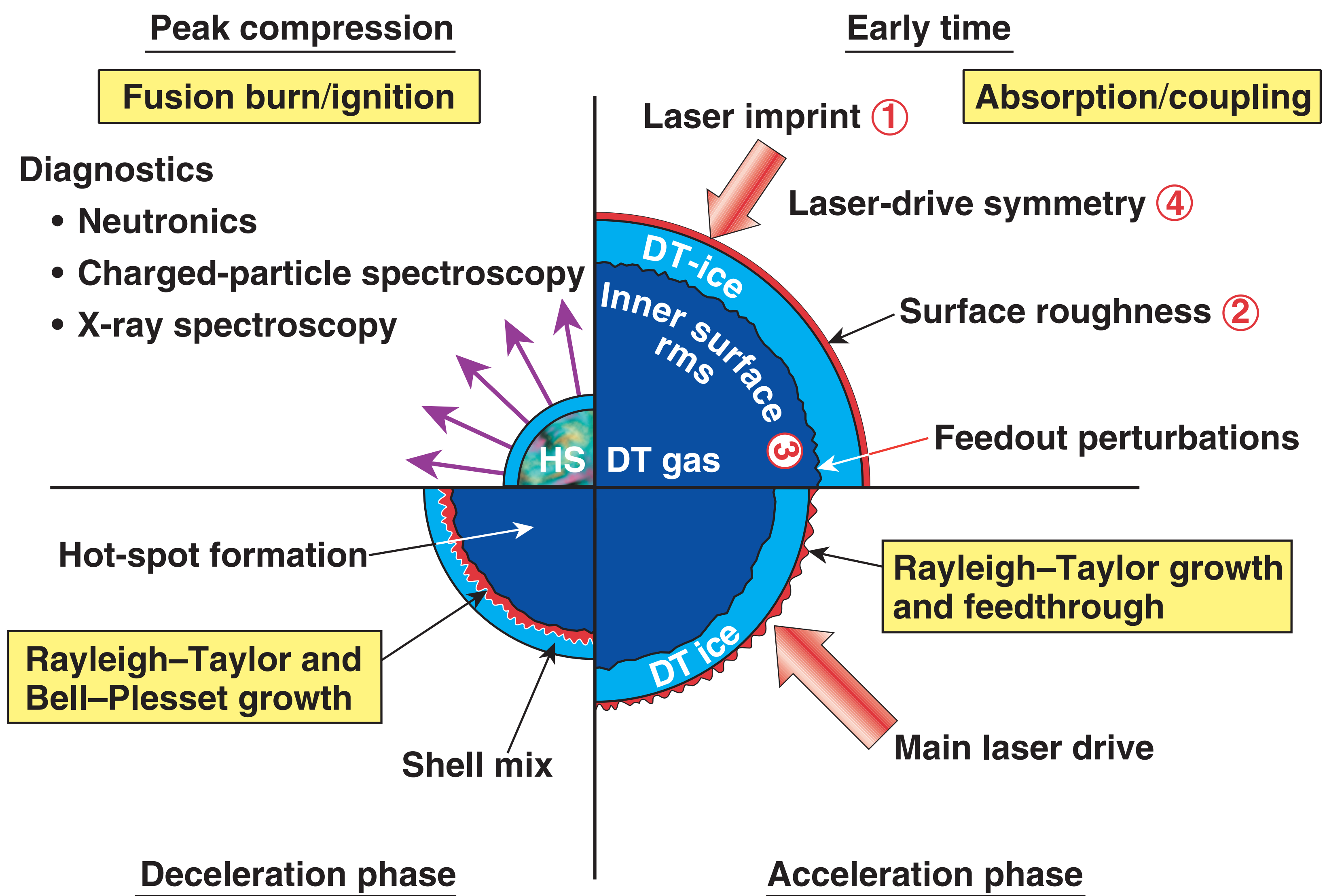
I_{Laser} ~ 10^{13} to 10^{15} W/cm^2

λ_{Laser} = 351 nm

Gain = $E_{TN}/E_L \gtrsim 10$

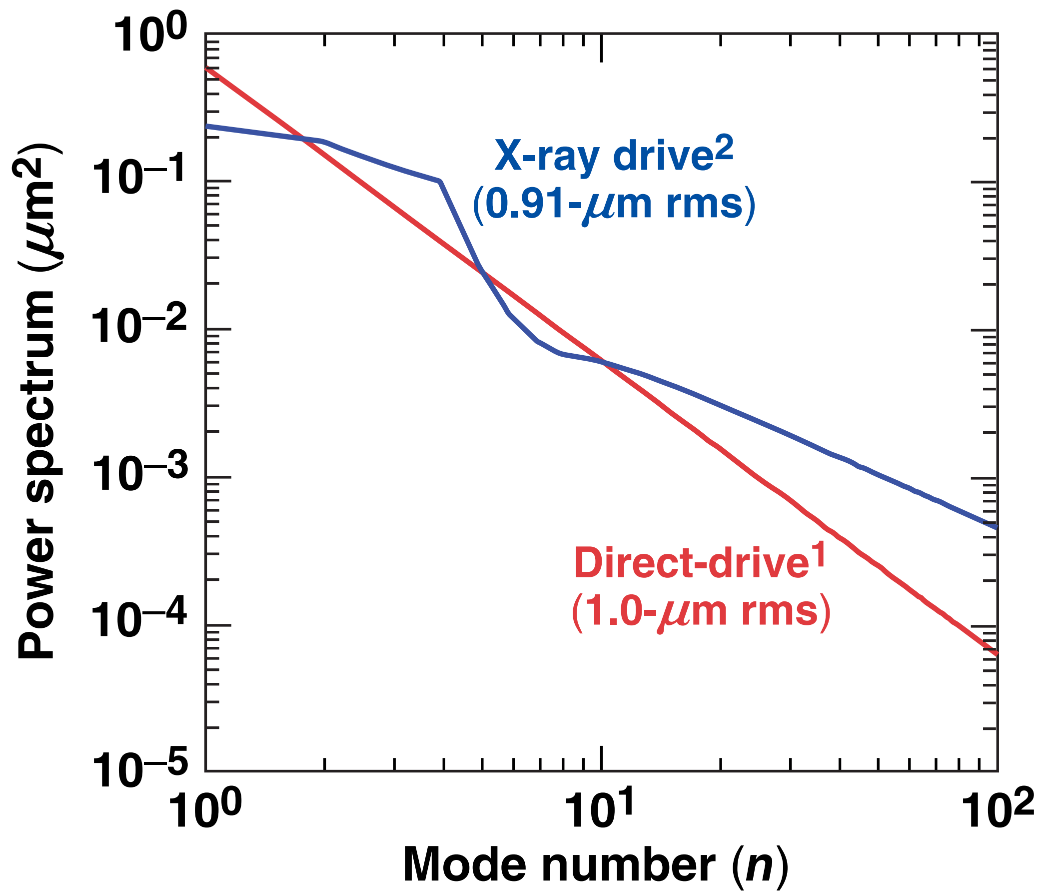


Perturbation seeds early in the implosion determine the final capsule performance



E12130c

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



- These requirements are based on detailed multi-dimensional simulations of the implosion performance[1,2]

[1]P. W. McKenty *et al.*, Phys. Plasmas 8, 2315 (2001).
[2]J. D. Lindl *et al.*, Phys. Plasmas 11, 339 (2004).

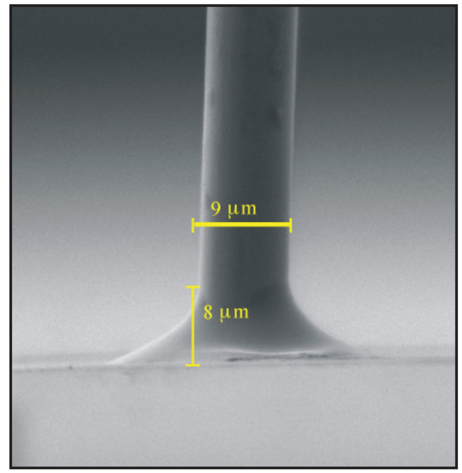
E15190a

The challenge for ignition on the NIF is to fabricate the x-ray-drive point design target to specifications

Polished Be capsule

Outer-surface finish is close to specifications.

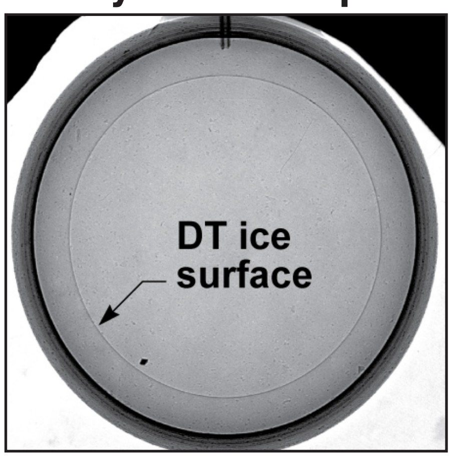
Fill tube



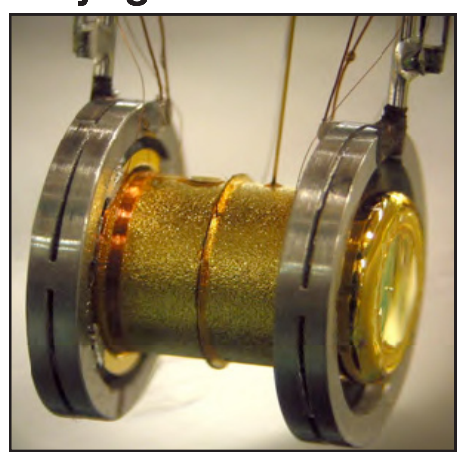
Minimal impact on performance.

DT layer in Be capsule

Ice-surface smoothness is close to specification.



Cryogenic hohlraum



Low-mode isotherm control demonstrated.

Outline

- Brief history
- Making a smooth D_2/DT ice layer
- Characterizing the layer smoothness
- Imploding the target
- Results of recent cryogenic DT implosions on OMEGA

Inertial confinement fusion ignition and gain is made possible by two technological breakthroughs

1. β-layering of the DT fuel

2. Inner-ice-surface characterization using optical shadowgraphy (transparent ablators) and x-ray phase-contrast imaging (opaque ablators).

E15071

Cryogenic target development evolved rapidly following pioneering research at KMS, Illinois, LLNL, LANL, and LLE

KMS shoots thin cryo DT-glass shells using point-contact conduction cooling ($Y_n \sim 10^{6-7}$) (Henderson & Johnson, 1977)

Illinois/KMS use cold He gas to fast refreeze thin DT layers for improved layer uniformity (Kim & Reiger, 1980)

1977 → 1979 → 1980

KMS uses a fast shroud-retraction scheme to expose target at shot time (Mulsinski *et al.*, 1979)

Cryogenic target development evolved rapidly following pioneering research at KMS, Illinois, LLNL, LANL, and LLE

UR LLE

1977

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1982

Holographic interferometry used to characterize layers in thin DT glass (Bernat, 1982)

1983

Irradiation uniformity important for target performance (LLE report, 1983)

1987

OMEGA-24 beam implodes thin DT-glass shells (fast refreeze); system based on KMS concepts including retractable shroud and He thermal exchange gas (1987)

β-layering proposed by KMS for inertial fusion targets (Martin, Simms, & Jabobs, 1988)

1988

β-layering demonstrated at LANL (Hoffer & Foreman, 1988)

E15032-2

Cryogenic target development evolved rapidly following pioneering research at KMS, Illinois, LLNL, LANL, and LLE

UR LLE

1977 → 1979 → 1980 → 1982

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β-layering demonstrated at LANL (Hoffer & Foreman, 1988)

β-layering work…

1996

Enhanced IR layering for D_2 fuel demonstrated at LLNL (Collins *et al.*, 1996)

1999

Design of OMEGA-60 CTHS complete for ignition-scaled D_2 and DT (1999)

~2-μm-rms DT layers demonstrated in 1-mm-CH shells at LLNL (Sater *et al.*, 1999)

Cryogenic target development evolved rapidly following pioneering research at KMS, Illinois, LLNL, LANL, and LLE

UR LLE

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β-layering work…

1996 — Enhanced IR layering for D_2 fuel demonstrated at LLNL (Collins *et al.*, 1996)

1999 — Design of OMEGA-60 CTHS complete for ignition-scaled D_2 and DT (1999)

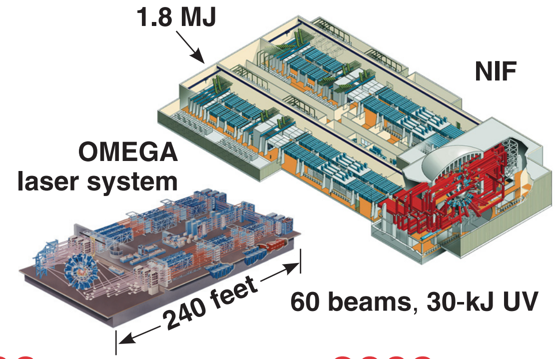
~2-μm-rms DT layers demonstrated in 1-mm-CH shells at LLNL (Sater *et al.*, 1999)

2001 — D_2 production implosions begin on OMEGA using IR and shadowgraphy (2001)

2004 — Phase-contrast imaging demonstrated for thick Be ablators at LANL (Montgomery *et al.*, 2004)

2006 — Sub 1-μm-rms DT and sub 2-μm-rms D_2 layers imploded on OMEGA (2006)

2009 — Fill-tube based system cryogenic target system ready for ignition (2009)

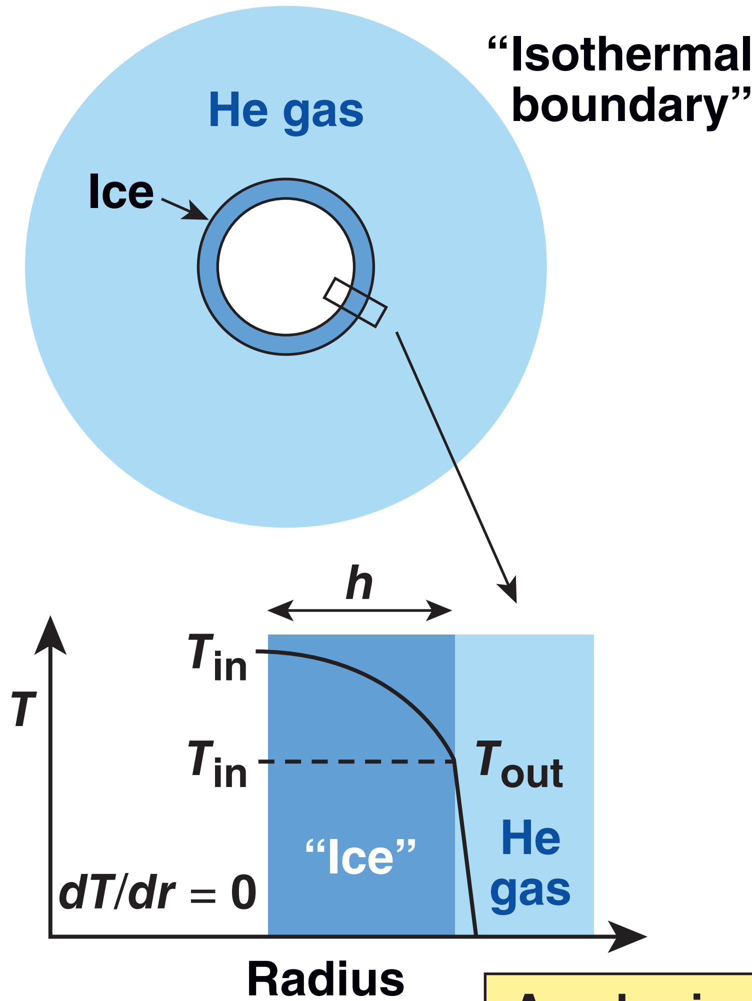


E15032-4

Outline

- Brief history
- Making a smooth D_2/DT ice layer
- Characterizing the layer smoothness
- Imploding the target
- Results of recent cryogenic DT implosions on OMEGA

The first step in DT/D_2 layering is to establish an isothermal temperature near the triple point on the capsule surface



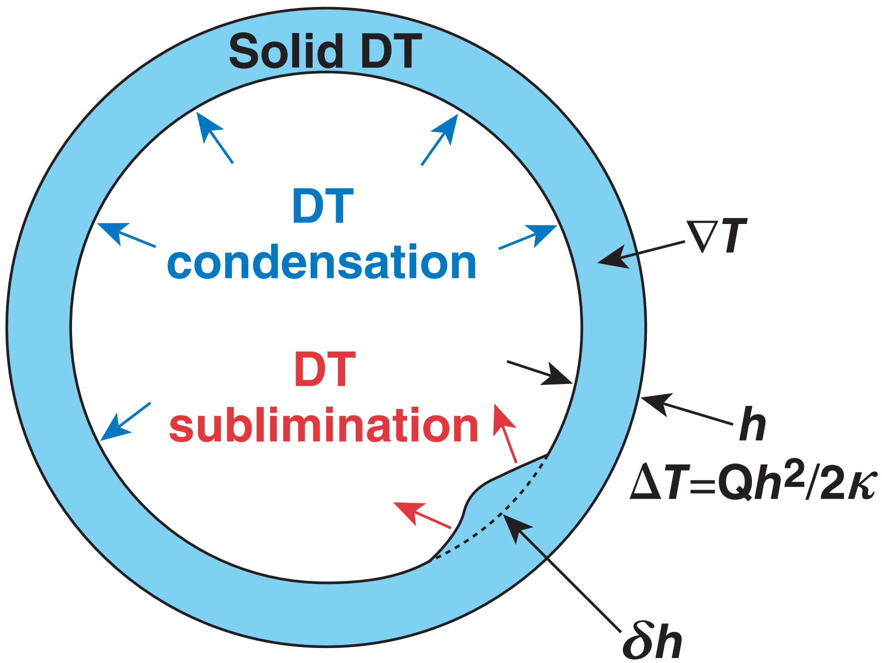
- Low-pressure He gas is used to exchange heat with an external "isothermal boundary."
- *dT/dr* across the ice becomes positive by depositing heat, Q, directly into the bulk ice.
- If *dT/dr* across the ice is > 0, thicker (warmer) regions sublimate and deposit on thinner (cooler) regions.

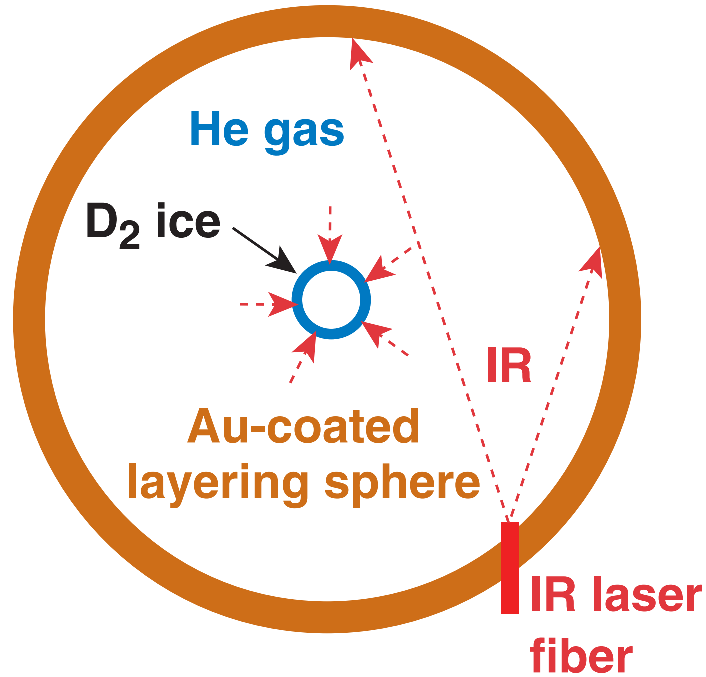
$$C_v dT/dt + \nabla(\kappa_{ice}\nabla T) = Q = -\kappa_{He} dT/dr$$

$$T_{in} = T_{out} + Qh^2/2\kappa_{ice} \text{ (typically <1 mK)}$$

A spherically symmetric temperature gradient across the DT or D_2 ice will form a uniform ice layer.

Heat can be deposited into the bulk ice by the radioactive decay of tritium[1] or absorption of IR radiation[2]





For β-layering,[1] the recoil e^- from the radioactive decay of the tritium deposits heat into the bulk DT ice

For IR-layering,[2] infrared light ($\lambda \sim 3\ \mu$m) preferentially deposits heat into the bulk D_2 (or DT) ice

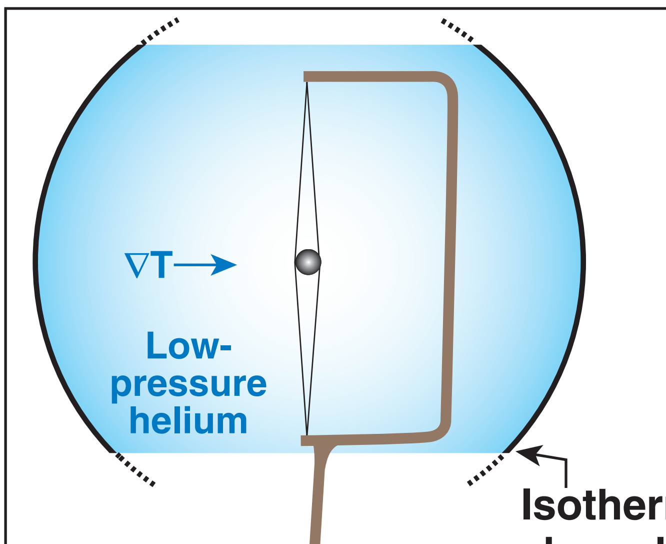
E15072

[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).

Physically mounting the capsule affects the low-mode symmetry of the isotherm

A robust mechanical support is required to ensure target survival and precision alignment.

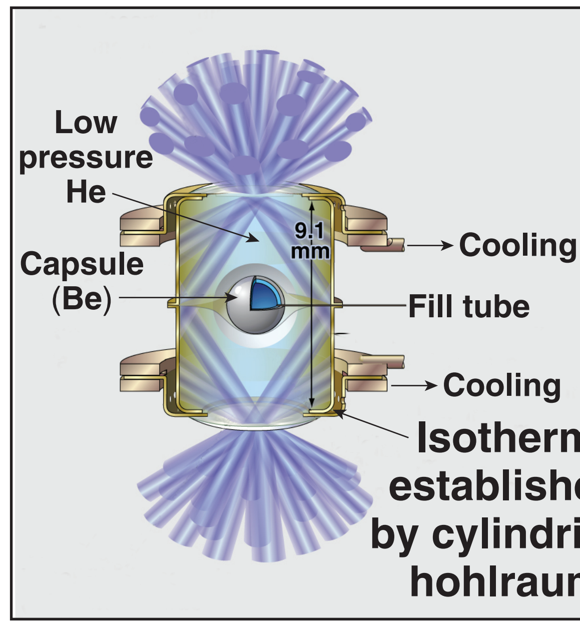
Direct-drive target



Isotherm established by spherical cavity

IR illumination imposes low-mode asymmetry by preferentially heating the target structures

Indirect-drive target



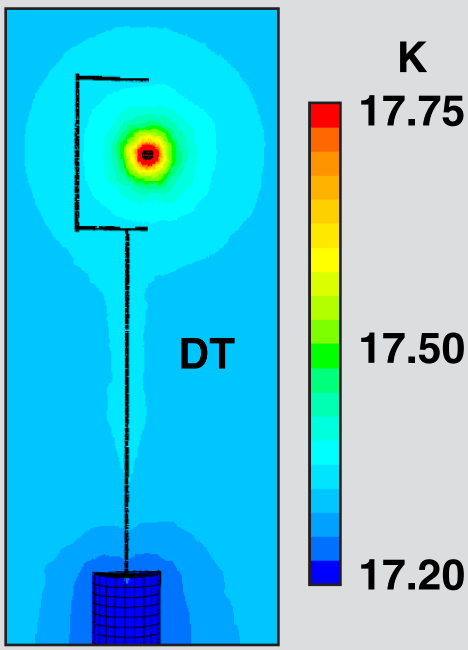
Low-mode thermal symmetry must be actively controlled in a hohlraum

E15035

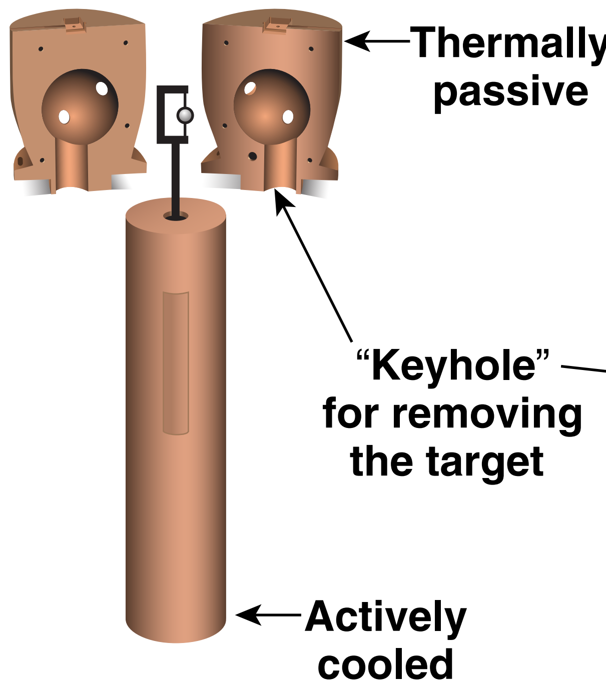
Direct Drive

A 3-D model is essential to understand the trade-offs between structural integrity and thermal uniformity

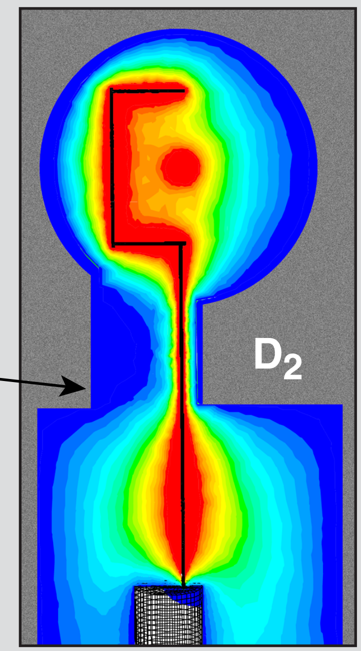
Thermal gradients set by layering sphere and exchange gas



Layering sphere for direct drive



Thermal gradients set by IR absorption in target materials

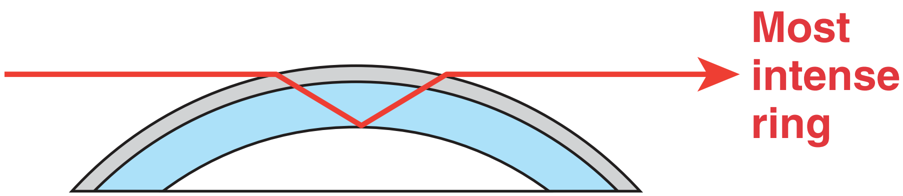


For direct-drive targets, thermal symmetry is achieved with clever design rather than active controls

E15036

Direct Drive

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



Light reflected off the inner surface creates a bright ring in a backlit image.

Bright ring encodes radial position of the ice.

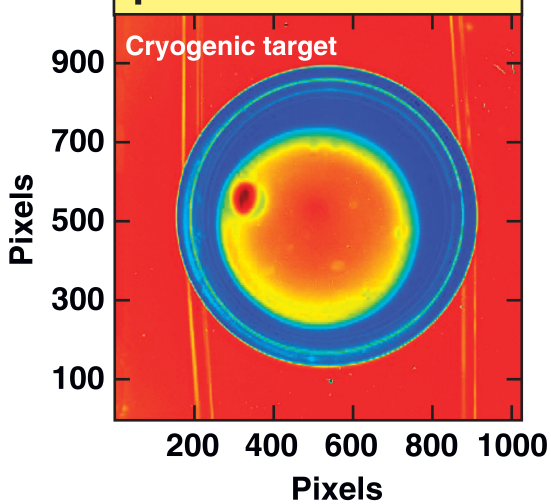
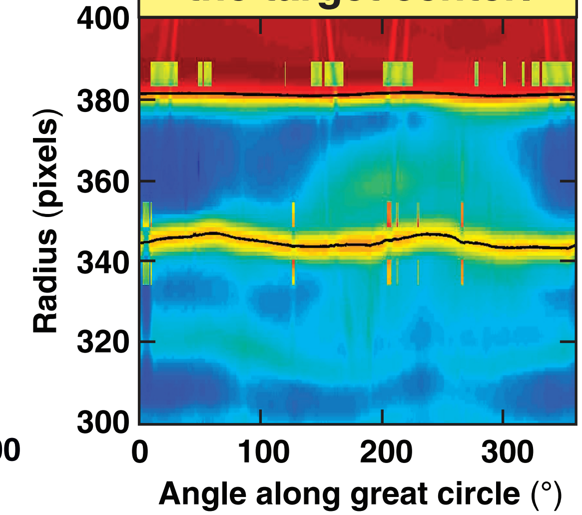
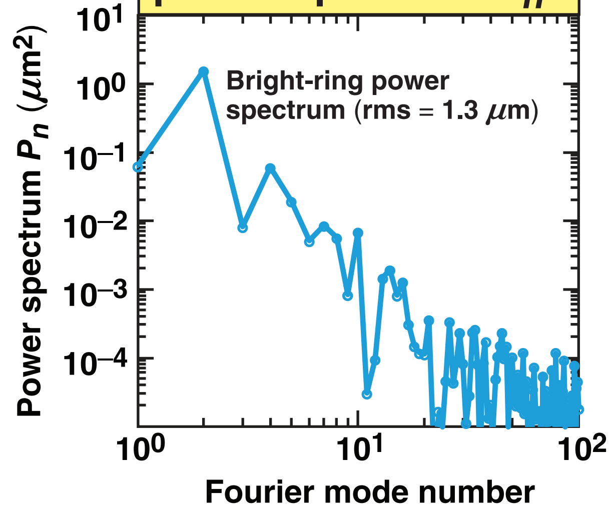


Image is unwrapped around the target center.



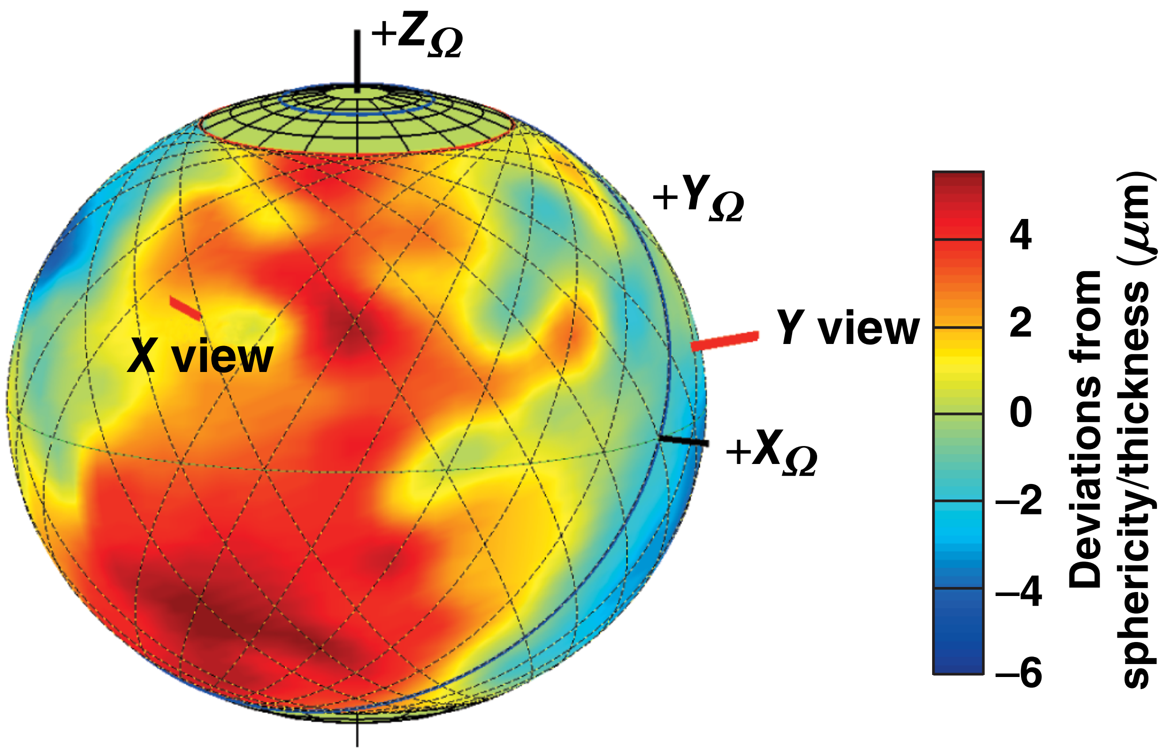
$R(\theta)$ is analyzed to get the Fourier power spectrum P_n.



D. H. Edgell, session JO2.00004

Direct Drive

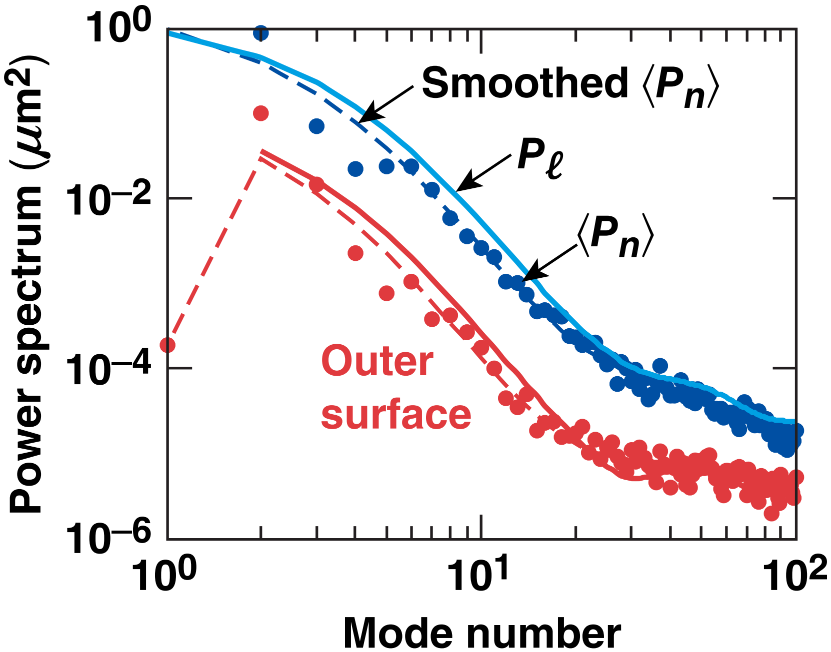
A 3-D representation of the inner ice surface can be constructed from multiple views (typically 48)



Structures in the ice correlate with known asymmetries in the thermal environment and are consistent over repeated layering/melting cycles.

E12255g

For input to simulations, the Legendre modes can be mapped from the average Fourier components*



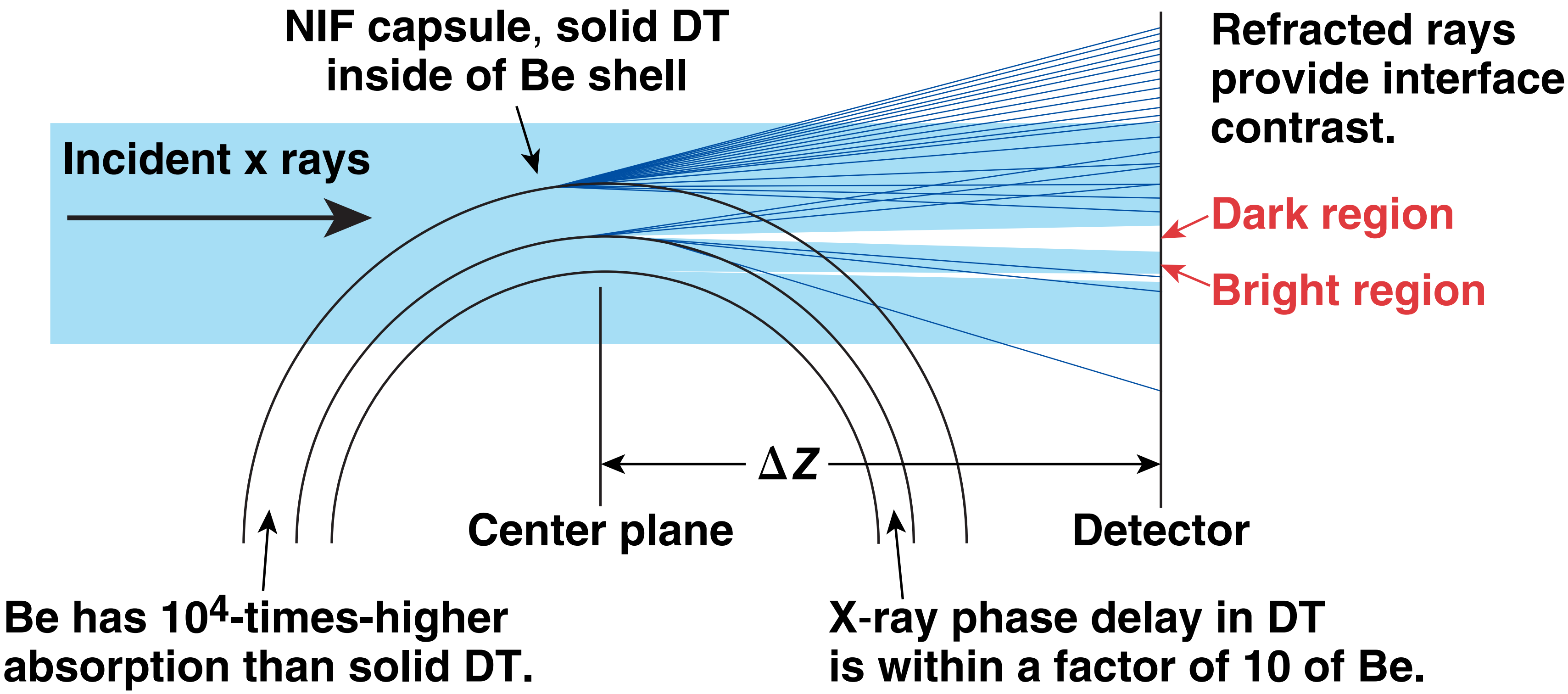
- A direct fit to the 3-D surface can be used for $\ell \lesssim 12$
- 2-D Fourier components $\langle P_n \rangle$ are averaged over many great circles
- Smoothed $\langle P_n \rangle$ to improve mapping behavior
- $P_\ell = \sum_{n=\ell,\ell+2,\ldots}^{\infty} a_{\ell n} \langle P_n \rangle$
- Assumes isotropic distribution of perturbations

A more-accurate spectrum is produced by starting with a large number of independent views.

E15038

*S. Pollaine and S. Hatchett, Nucl. Fusion 44, 117 (2004).

X-ray-phase contrast imaging* is used to characterize the ice in opaque shells (e.g., Be, C, and foam)



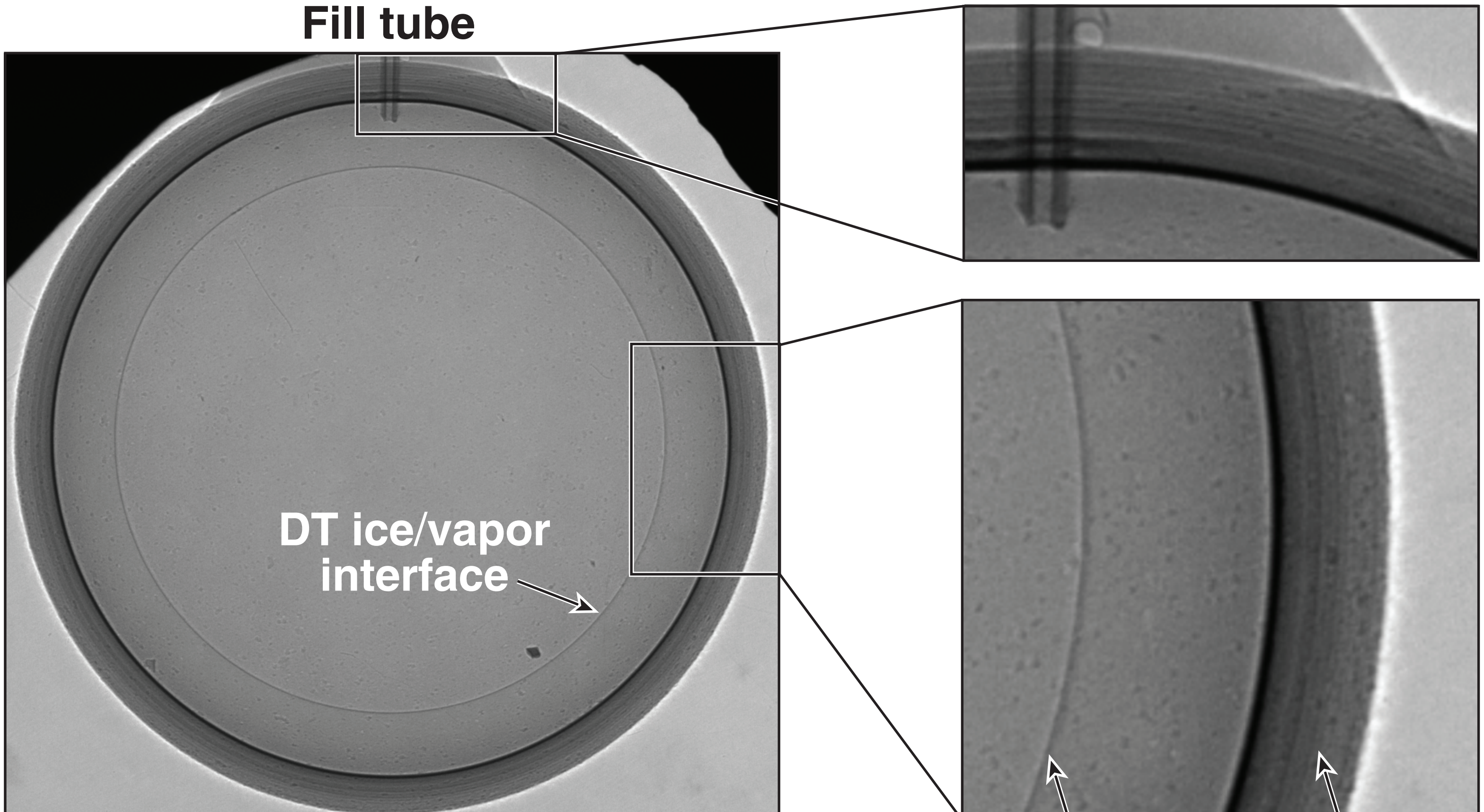
Need sufficient spatial coherence (plane wave or point source) to obtain good contrast for a given imaging configuration.

E15039

*D. S. Montgomery, *et al.*, Rev. Sci. Instrum. 75, 3986 (2004).

X-Ray Drive

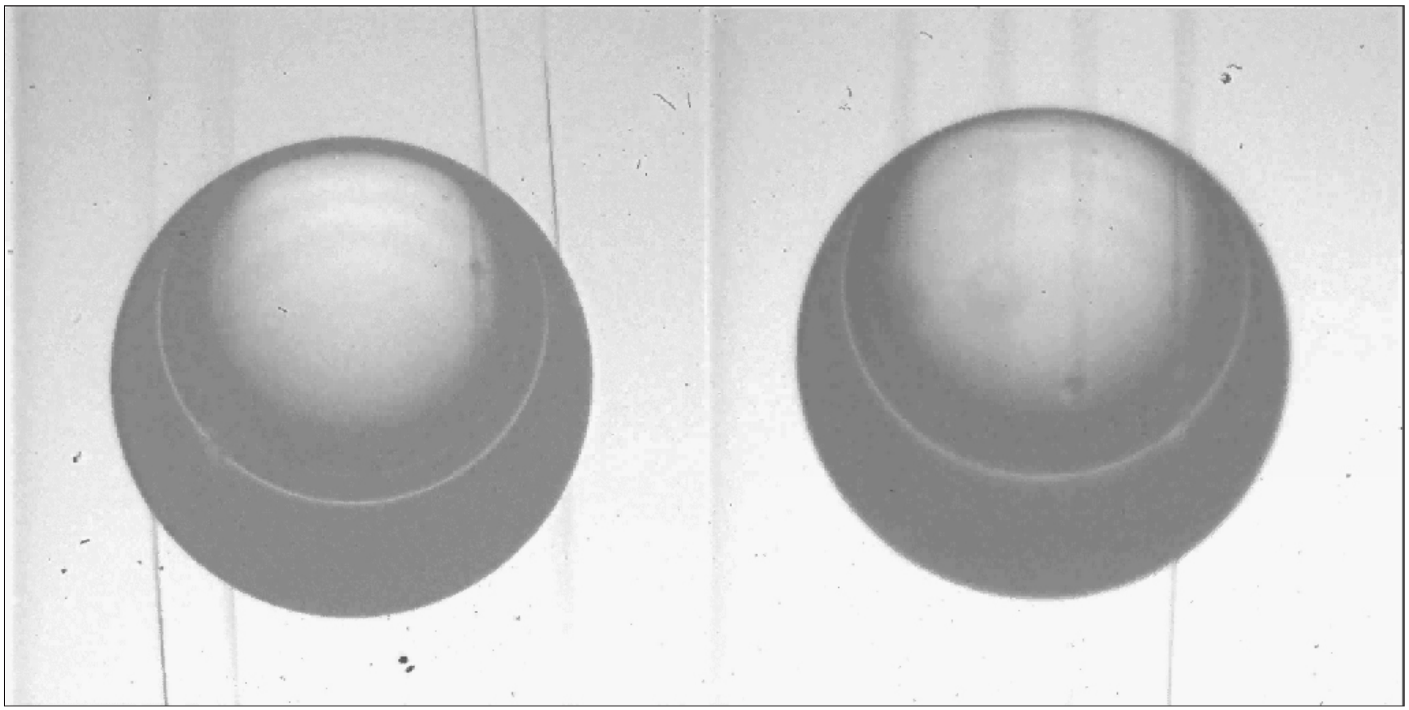
X-ray-phase contrast images reveal detailed structures in Be(Cu) DT cryogenic capsules



The surface ring is analyzed for the Fourier components using a process similar to that used with shadowgraphy.

E15040

Gradual solidification virtually eliminates high-spatial-frequency surface roughness

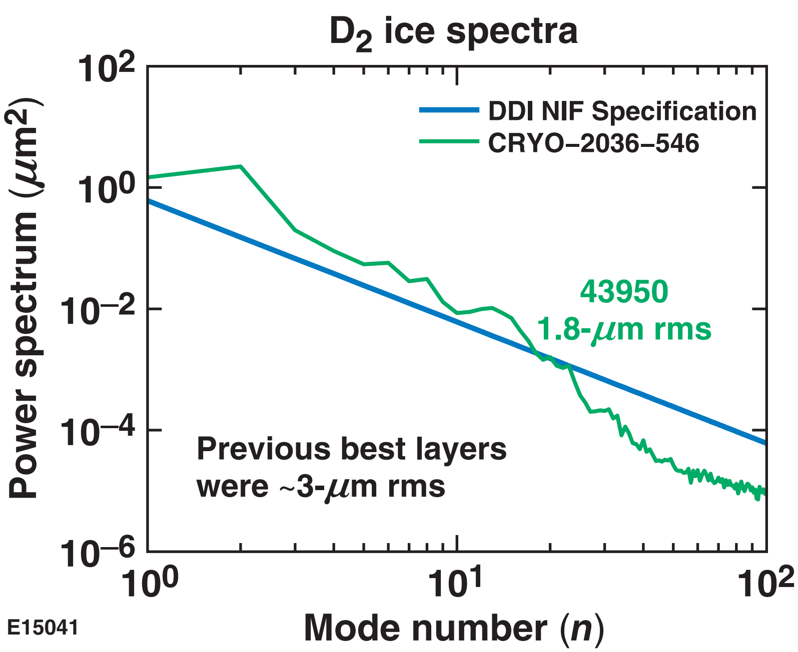


"Single-crystal" ice layers grown at the triple point require temperature control to mK precision

E15338

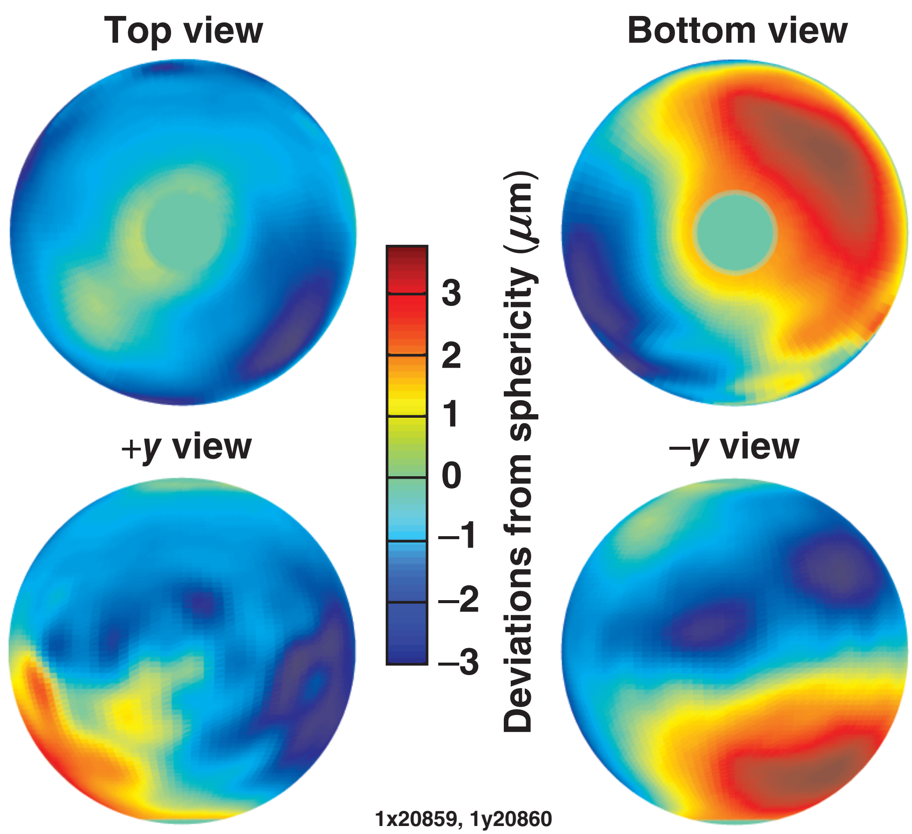
3-D thermal modeling led to a significant improvement in ice smoothness for D_2 capsules (IR layering)

- Layering-sphere upgrades based on thermal modeling
  - Increased the exchange-gas pressure
  - Added a diffuser to the IR laser-fiber input
  - Modified the mount structures to minimize IR absorption (e.g., Au coating)



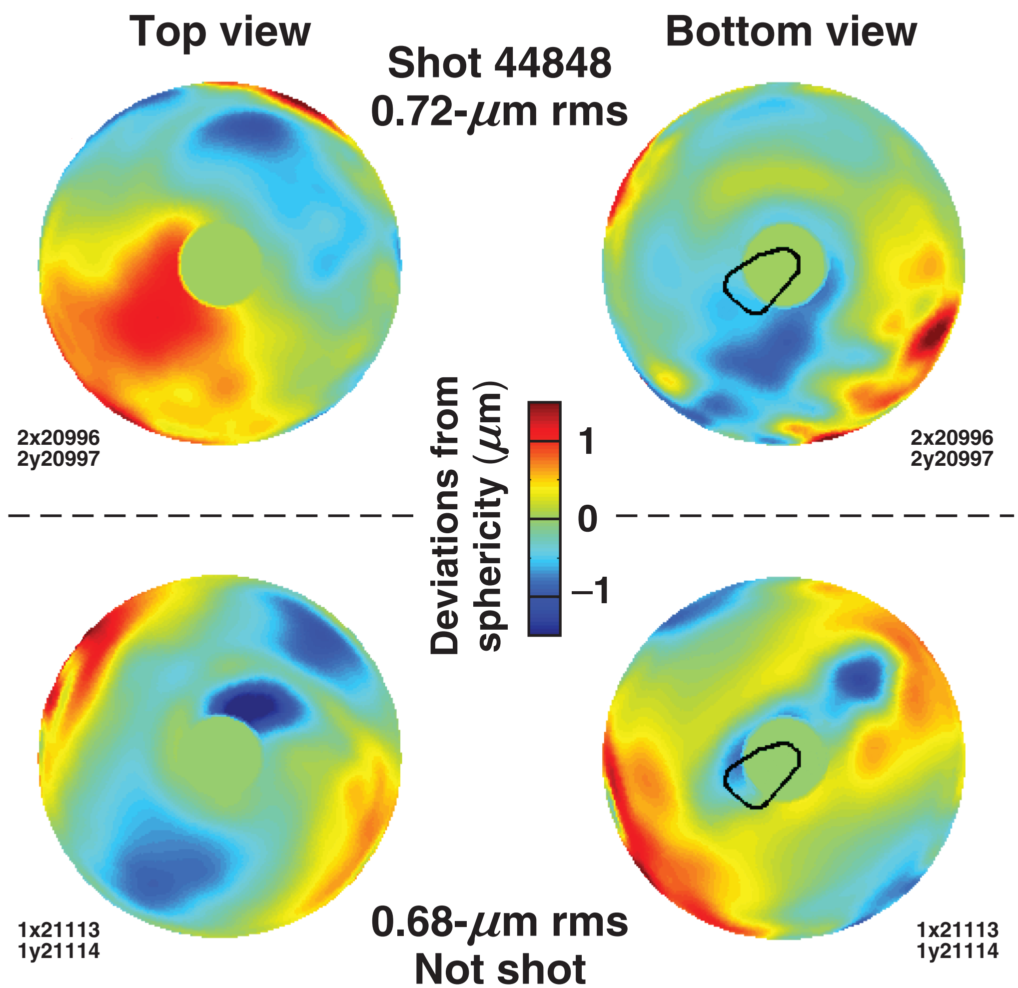
E15041

Shot 43950: 1.8-μm-rms D_2 capsule

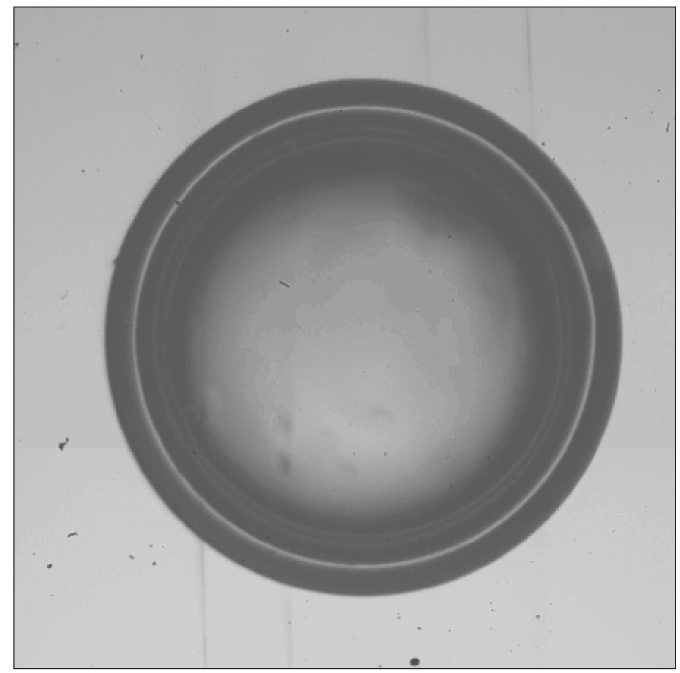


1x20859, 1y20860

Several DT (45:55) targets with an ice roughness of $\lesssim$1-μm rms for all modes have been imploded on OMEGA



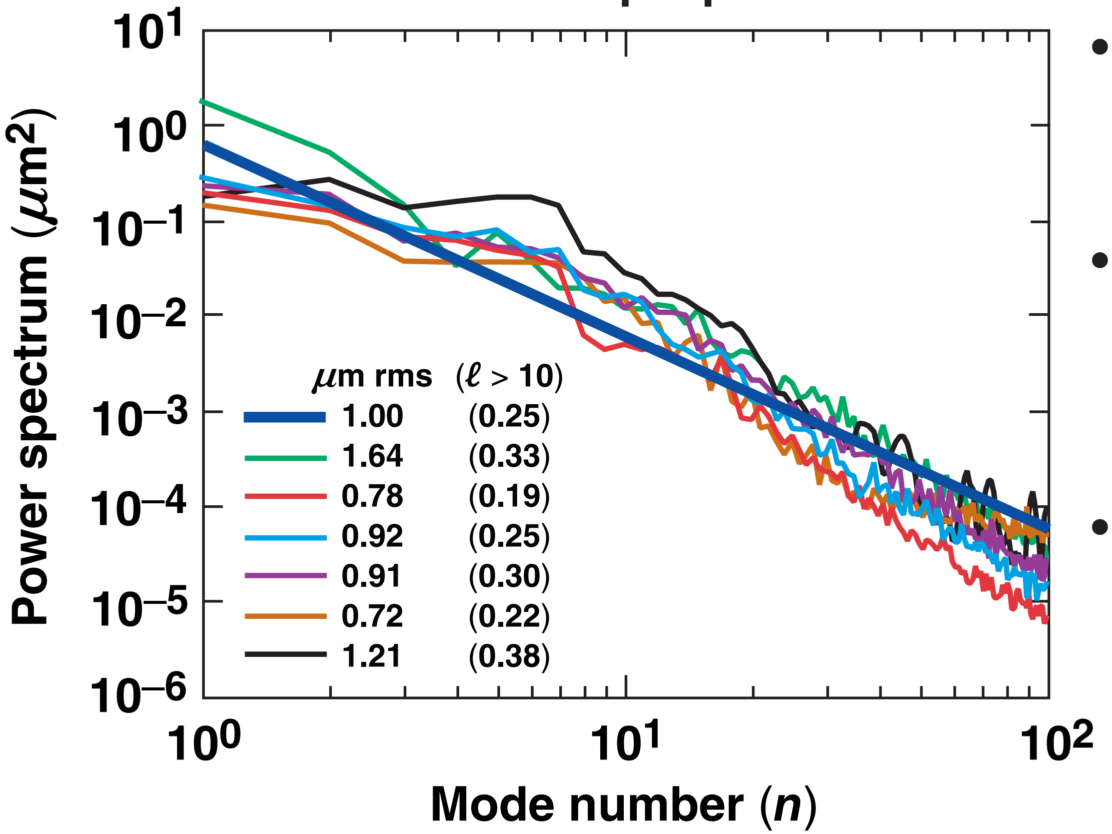
Target for shot 44848



Full azimuthal rotation

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

The best layers achieved at the triple point

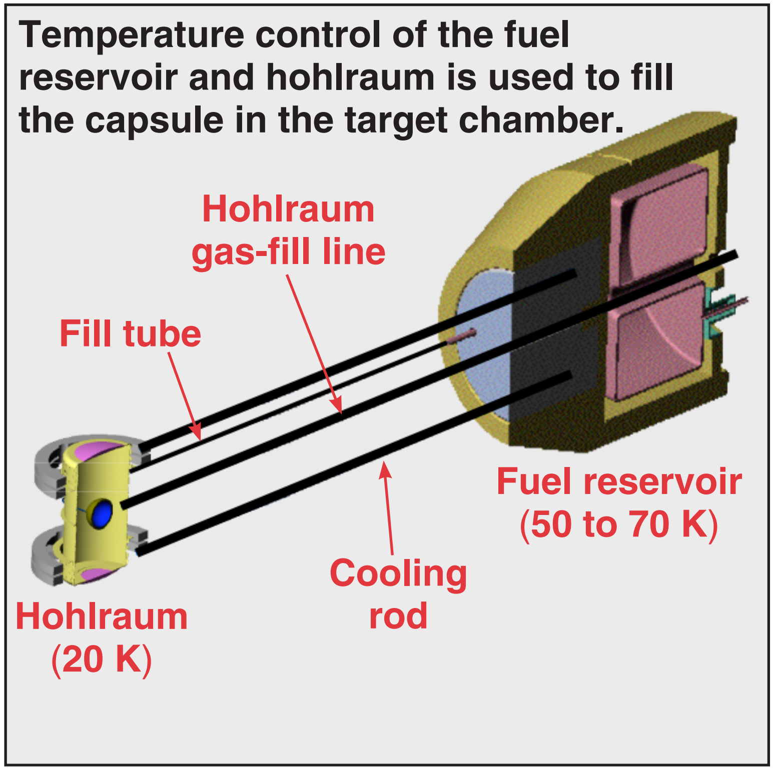


- High-mode ($n > 20$) roughness is minimal for "single crystal" layers
- Low-mode roughness ($n < 6$) is due to asymmetries in the triple point isotherm
- Mid-mode roughness ($6 < n < 20$) is likely related to outer-surface features (glue for silks)*

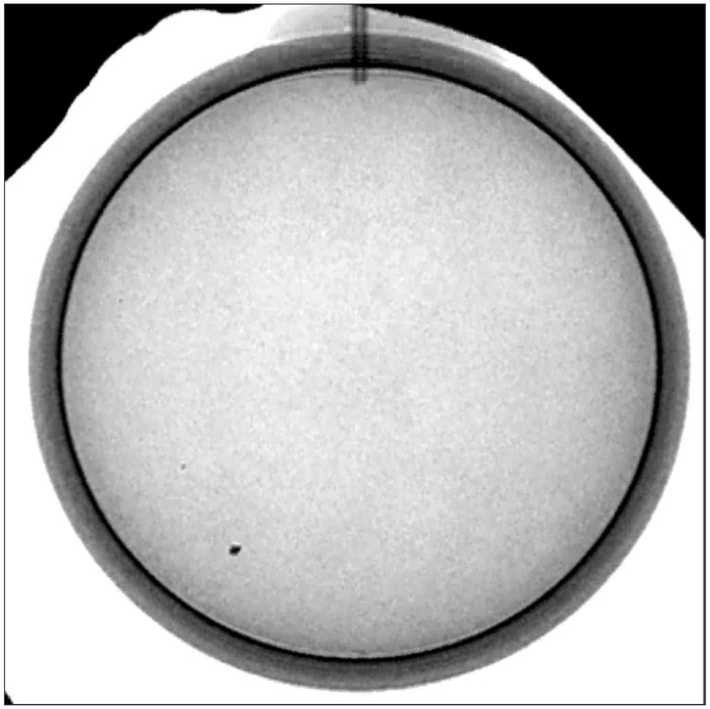
*D. H. Edgell, session JO2.00004

On the NIF, DT will be introduced into the Be(Cu) shell through a fill tube

Self-filling target concept



DT liquid in shell



Fill time is <30 min.

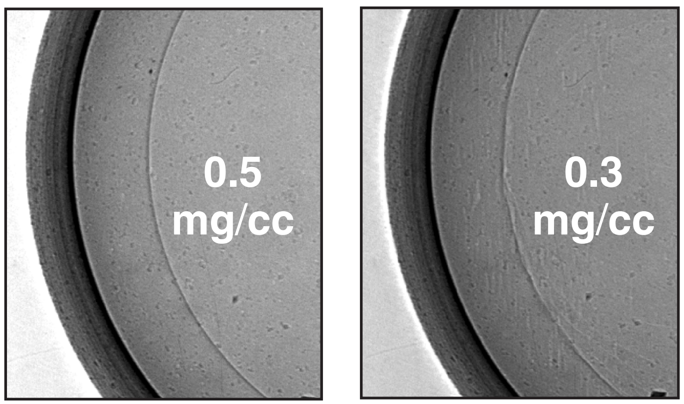
Ice-layer thickness can be controlled with high accuracy.

X-Ray Drive

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

UR LLE NIC The National Ignition Campaign

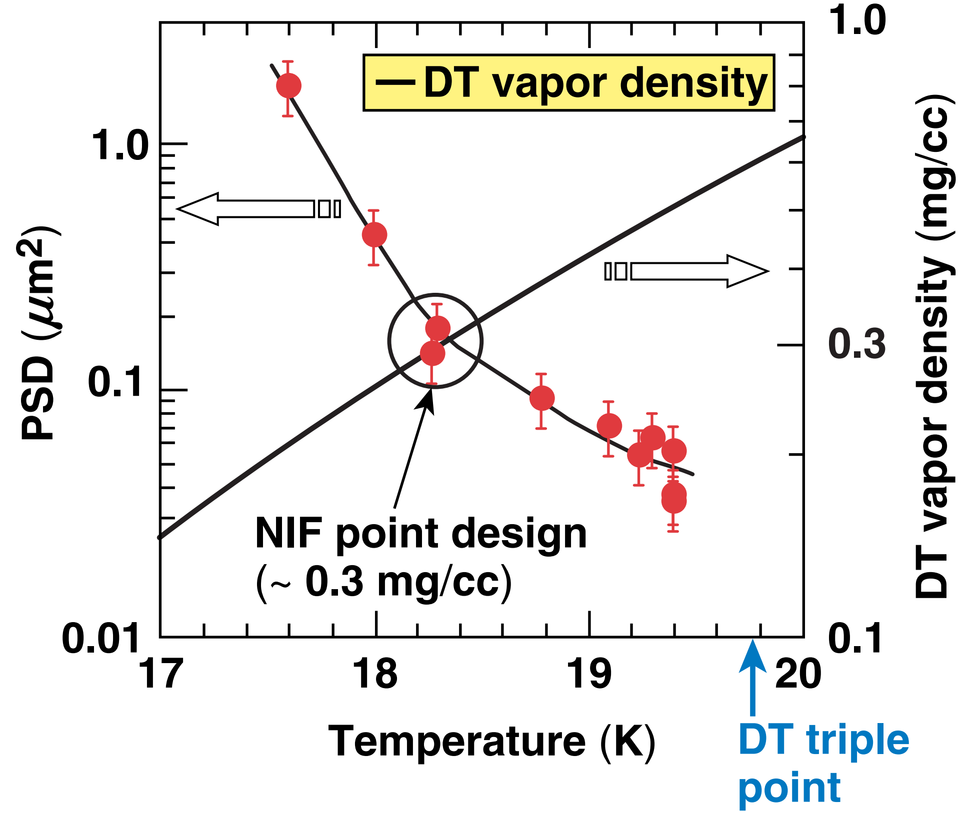
DT layers in Be shell



T = 19.3 K *T* = 18.3 K

The layer roughens in the mid-modes as the shell contracts below the triple point

Sum of power in modes 10 to 128

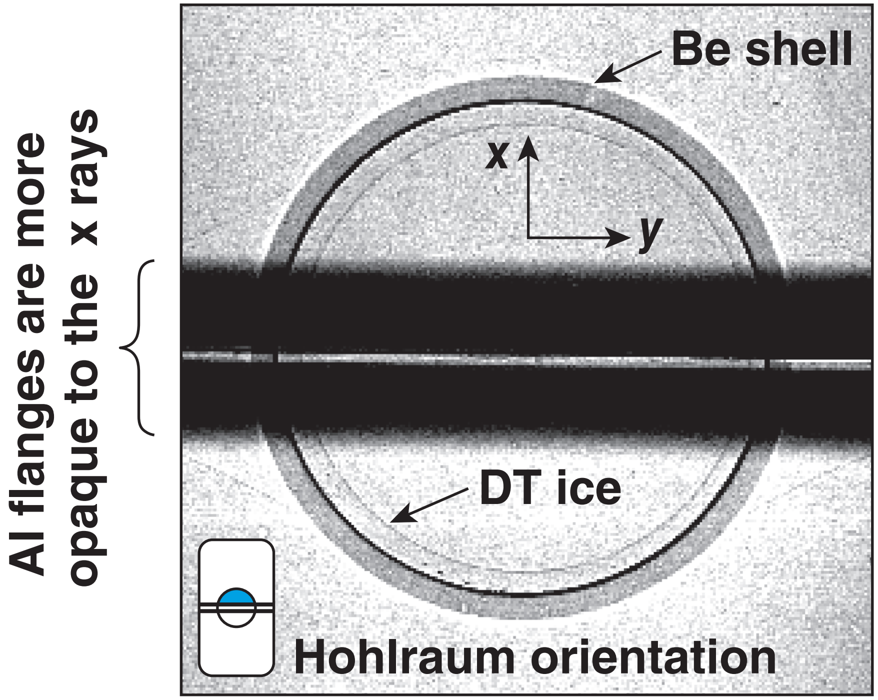


- Modes 1 to 3 add about 2 μm to the rms value

E15045

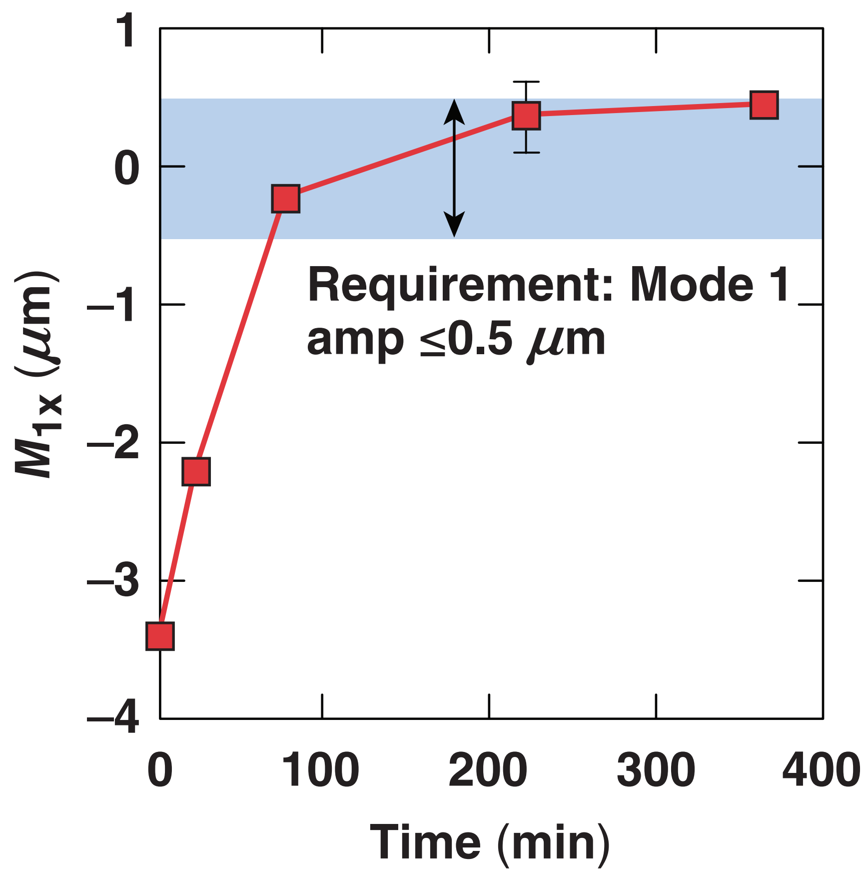
LLNL has successfully shimmed the axial P1 mode in an aluminum hohlraum

Capsule—ice view through side of hohlraum



Be shell in an Al hohlraum

Axial P1 mode meets the ignition requirement

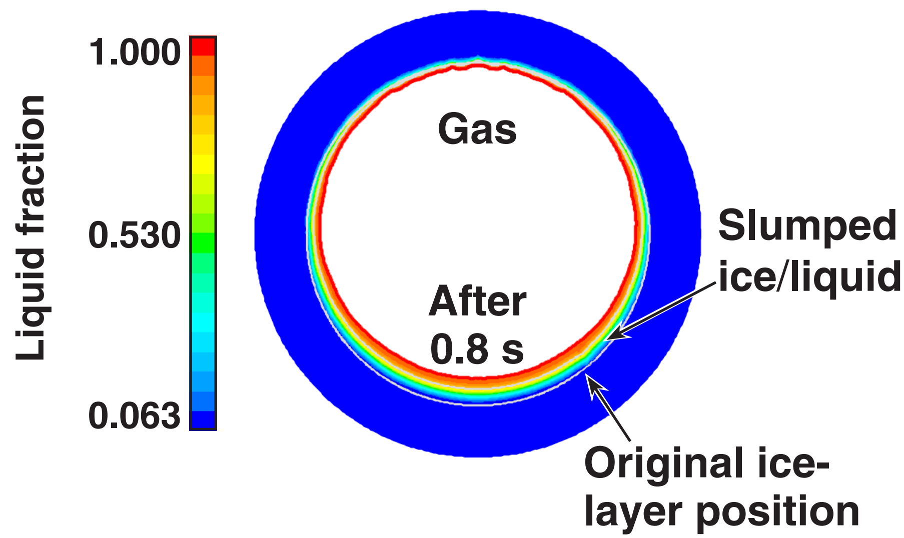


Outline

- Brief history
- Making a smooth D_2/DT ice layer
- Characterizing the layer smoothness
- Imploding the target
- Results of recent cryogenic DT implosions on OMEGA

Excessive exposure to ambient chamber radiation at shot time will significantly affect the layer quality

2-D axisymmetric model includes solid-to-gas and solid-to-liquid phase changes



<u>After 0.8 s</u>

OMEGA DT target: rms ~ 10 μm

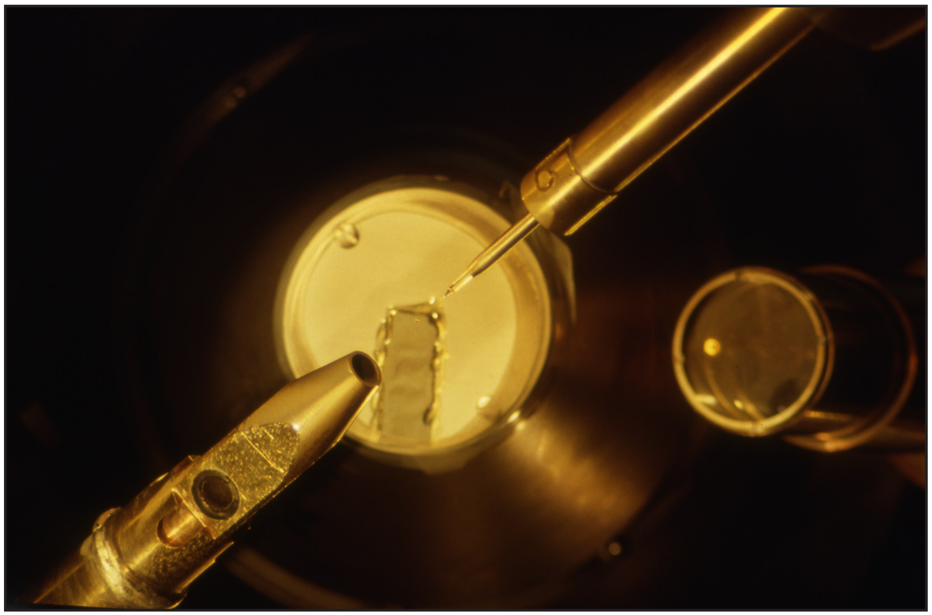
NIF DT target: rms ~ 12 μm

The modeling indicates that exposure times of less than 100 ms are required to preserve the layer for direct drive.

The rapid removal of a thermally passive shroud meets the requirements for exposure time and thermal uniformity

UR LLE

OMEGA-24 shroud and target assembly (1987–1988)



Based on original KMS concept[1]

- Opposed port shroud retractor using a linear induction motor (~10-ms exposure to chamber)
- Insertion/retraction mechanisms decoupled from the target chamber
- He gas cooling for high-uniformity, fast-refreeze, thin-DT-glass-shell targets (5-μm-thick DT and 3- to 7-μm-thick glass)
- Interferometric layer characterization

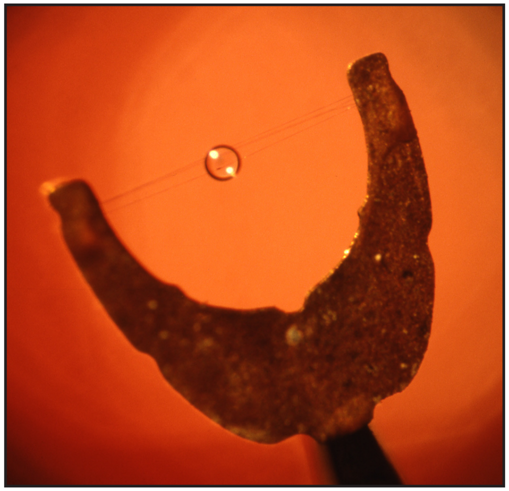
E15049

[1] D. L. Musinski *et al.*, Appl. Phys. Lett. 34, 300 (1979).

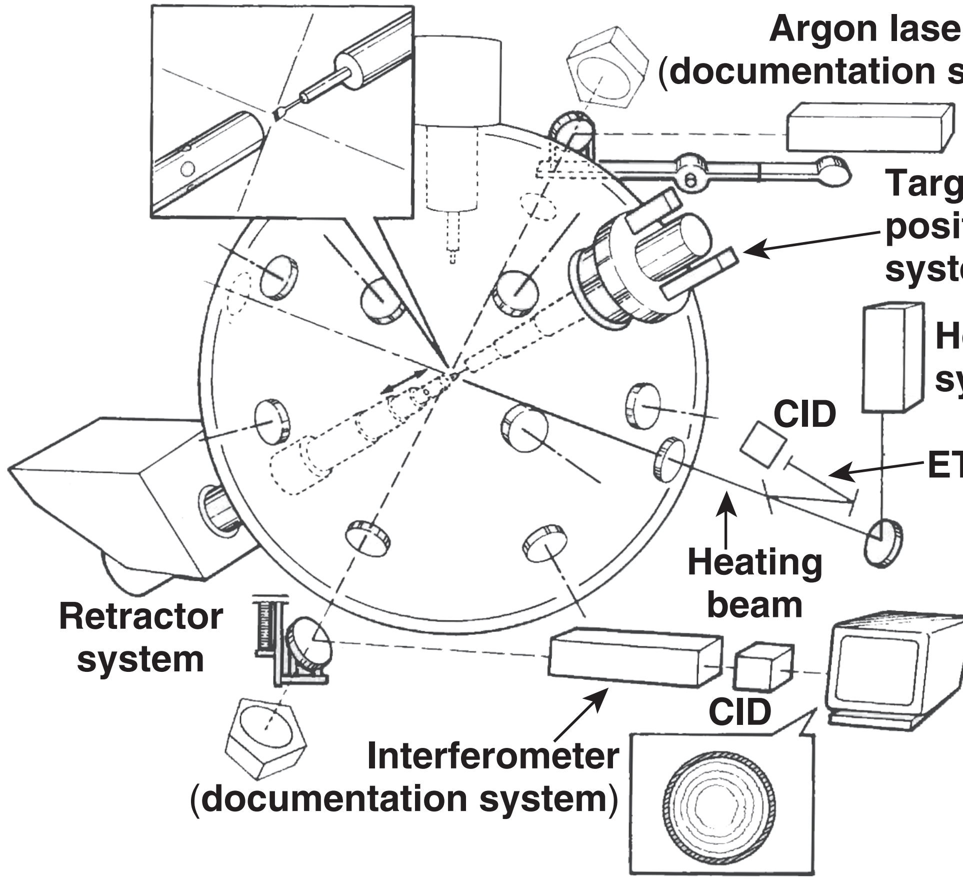
Direct Drive

The OMEGA-24 CTHS performed over 100 cryogenic DT target shots and produced 200× DT liquid density[1]

“Horseshoe” target



3 to 7-μm SiO_2 shells with 5-μm-thick DT layer



This system did not scale to the recently developed ignition-relevant target designs (e.g., thick DT layers and CH ablators).

E15051

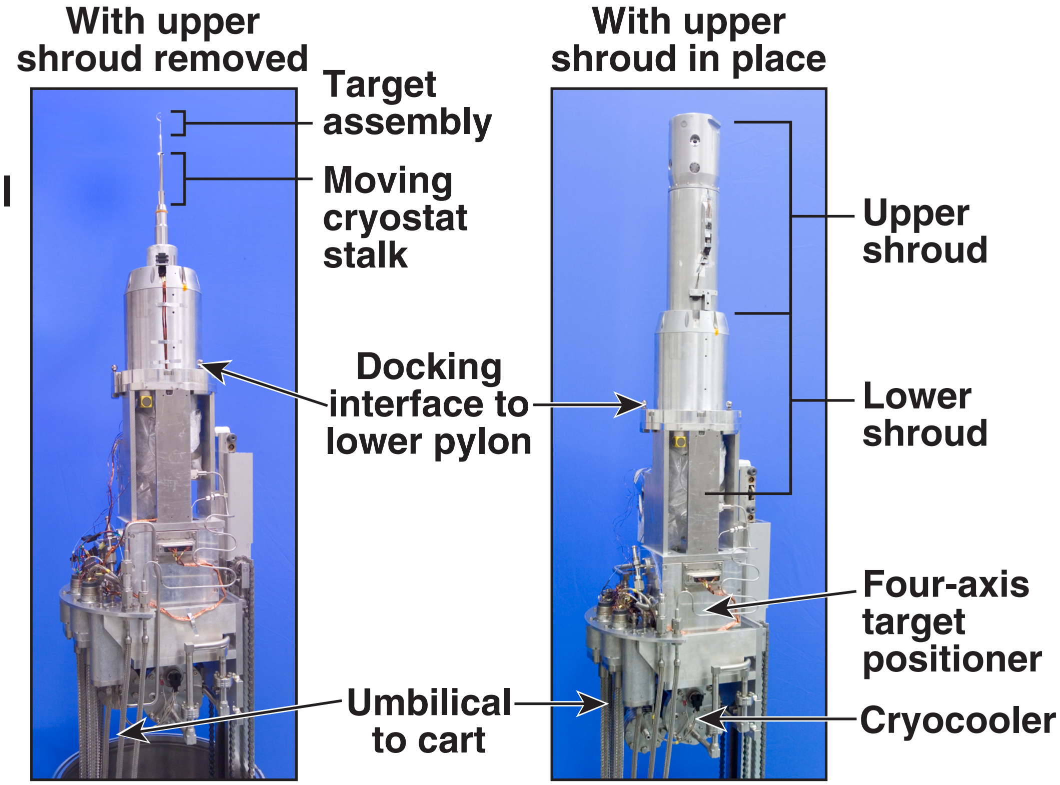
[1]R. L. McCrory *et al.*, Nature 335, 225 (1988).

The conceptual design of the OMEGA-60 CTHS has roots in the earlier systems

New requirements included:

- high-pressure permeation fill
- up to 100-μm-thick ice
- fill 12 targets per week
- IR-enhanced layering for D_2
- optical characterization
- moving cryostat
- alignment to 5 μm relative to TCC
- exposure time <100 ms
- vertical shroud pull

OMEGA-60 shroud, moving cryostat, and layering sphere



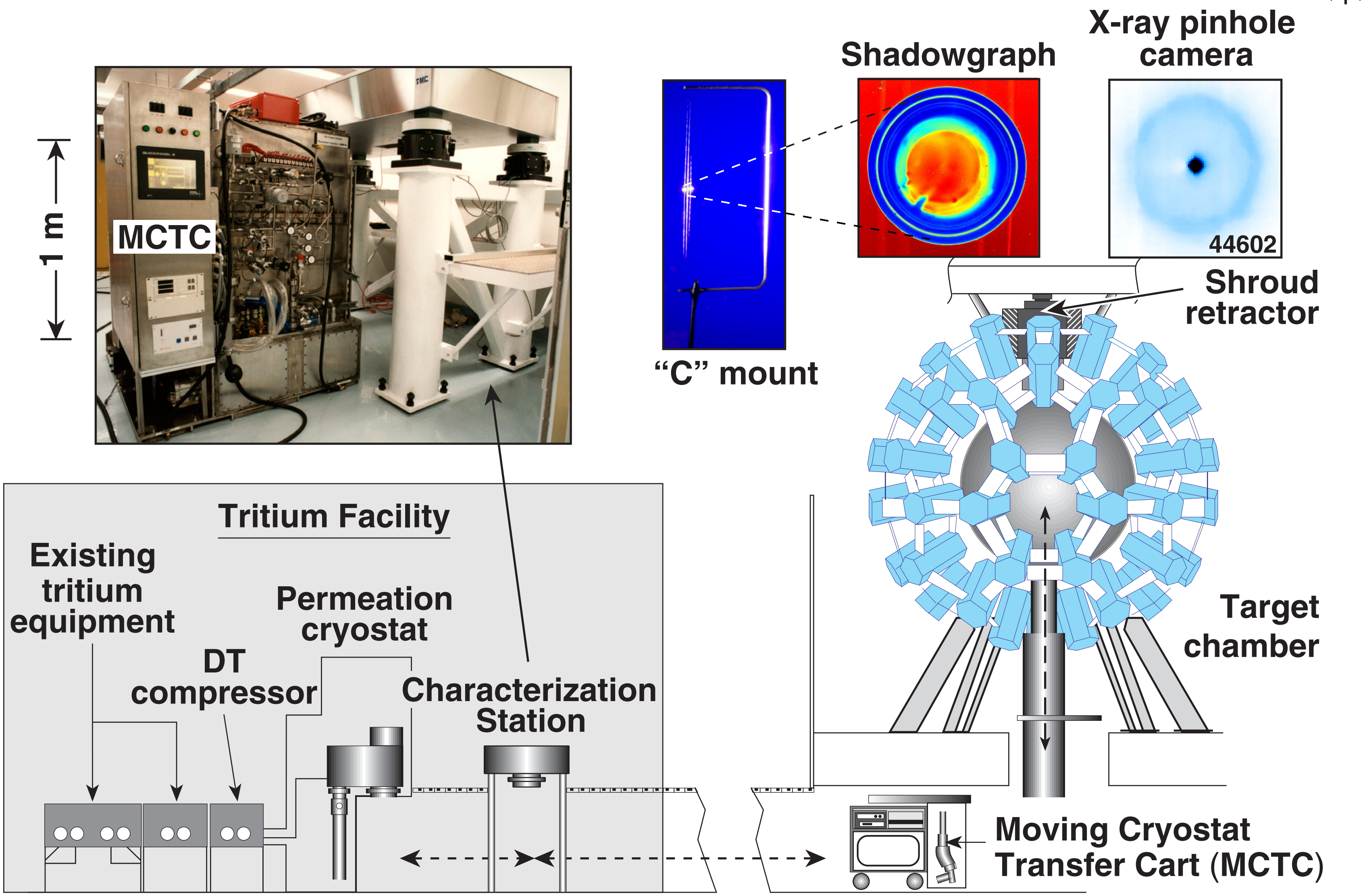
Cryostat assembly is for target positioning and life support.

Design was started in 1992 at General Atomics and was completed in 1999; first cryogenic D_2 implosion in 2000!

Direct Drive

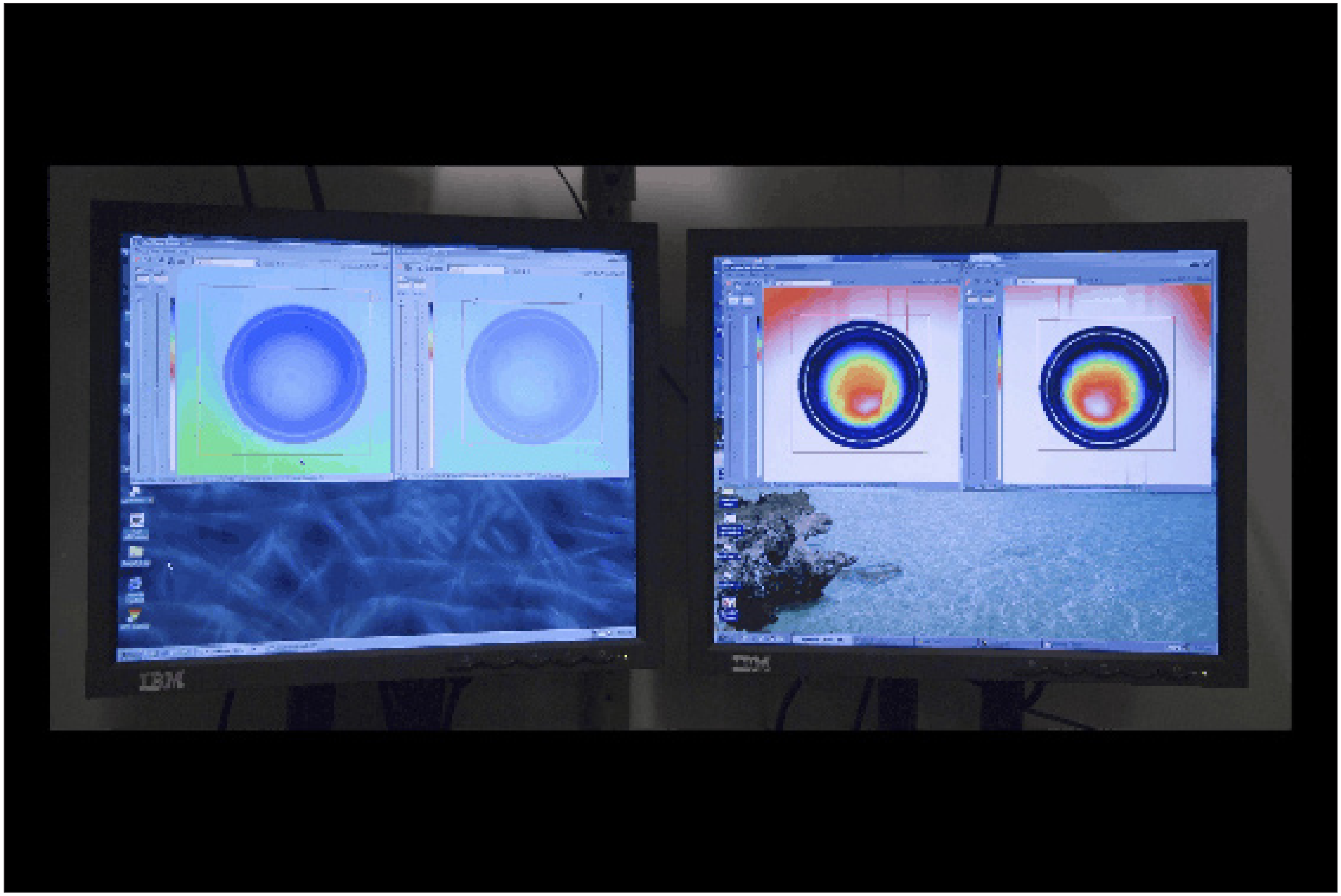
LLE typically implodes 2 to 4 cryogenic capsules per day, two days per month (DT and D_2)

UR LLE



E12062f

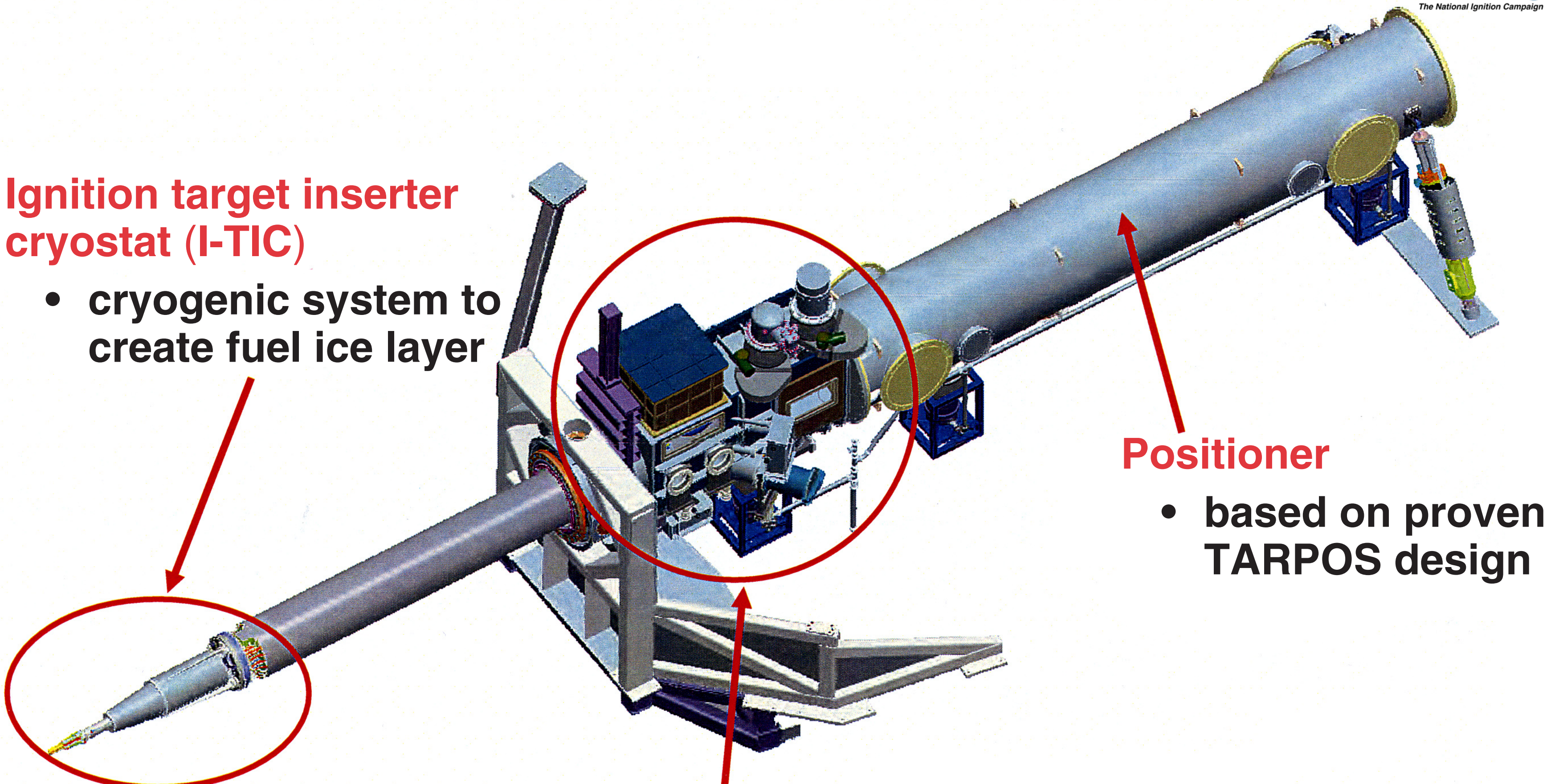
The key to the sucess of the OMEGA-60 CTHS is the moving cryostat



X-Ray Drive

On the NIF, cryogenic DT targets will be filled and characterized on the chamber

UR LLE
NIC The National Ignition Campaign



Ignition target inserter cryostat (I-TIC)

- cryogenic system to create fuel ice layer

Positioner

- based on proven TARPOS design

Load, layer and characterization system (LLCS)

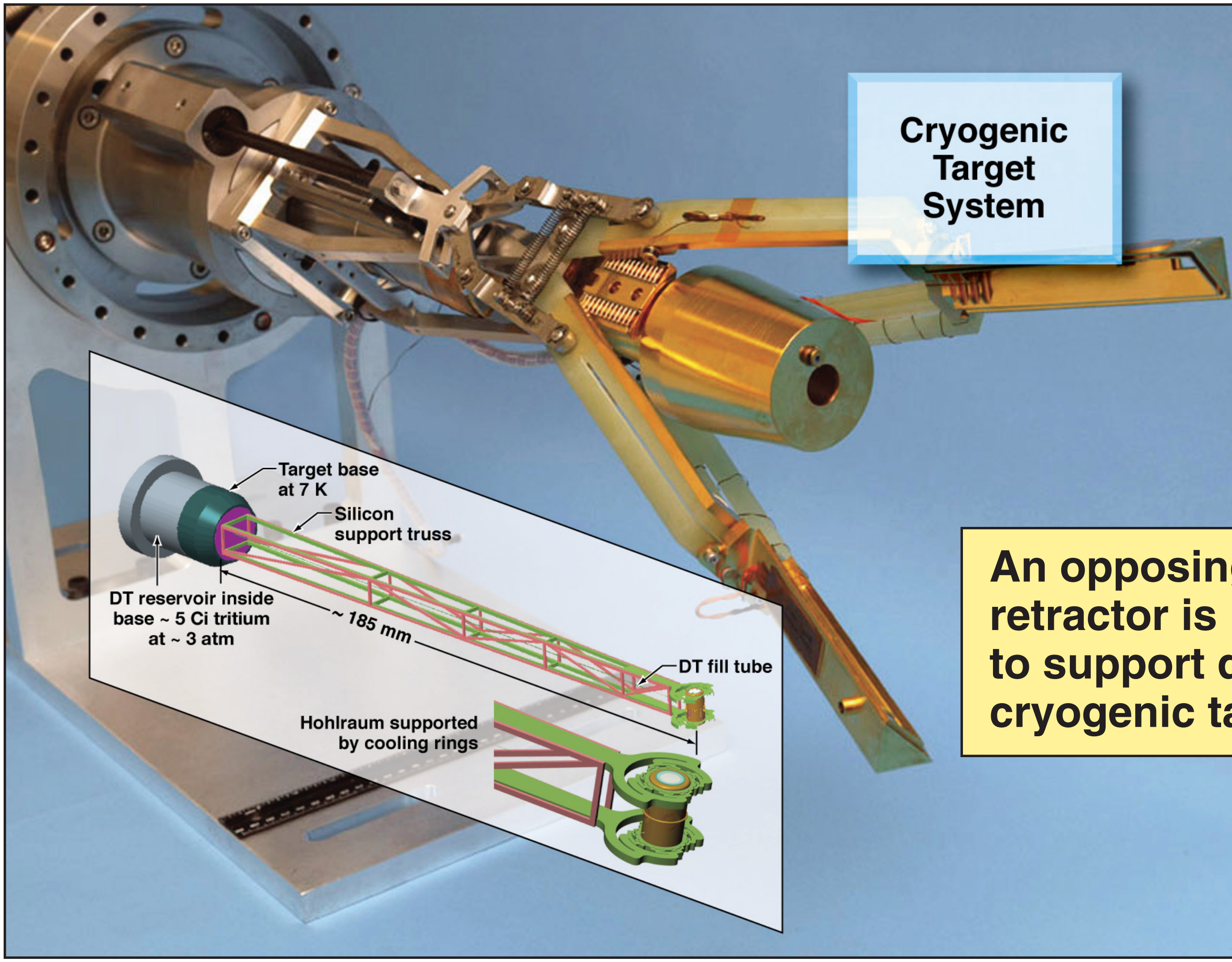
- target loading glovebox
- x-ray imaging for fuel-ice-layer characterization

E15054

X-Ray Drive

Cryogenic hohlraum targets on the NIF will be fielded using a "clam-shell" retractor

UR LLE
NIC The National Ignition Campaign



An opposing port shroud retractor is being designed to support direct-drive cryogenic targets.

E15055

Outline

- Brief history
- Making a smooth D_2/DT ice layer
- Characterizing the layer smoothness
- Imploding the target
- Results of recent cryogenic DT implosions on OMEGA

Direct Drive

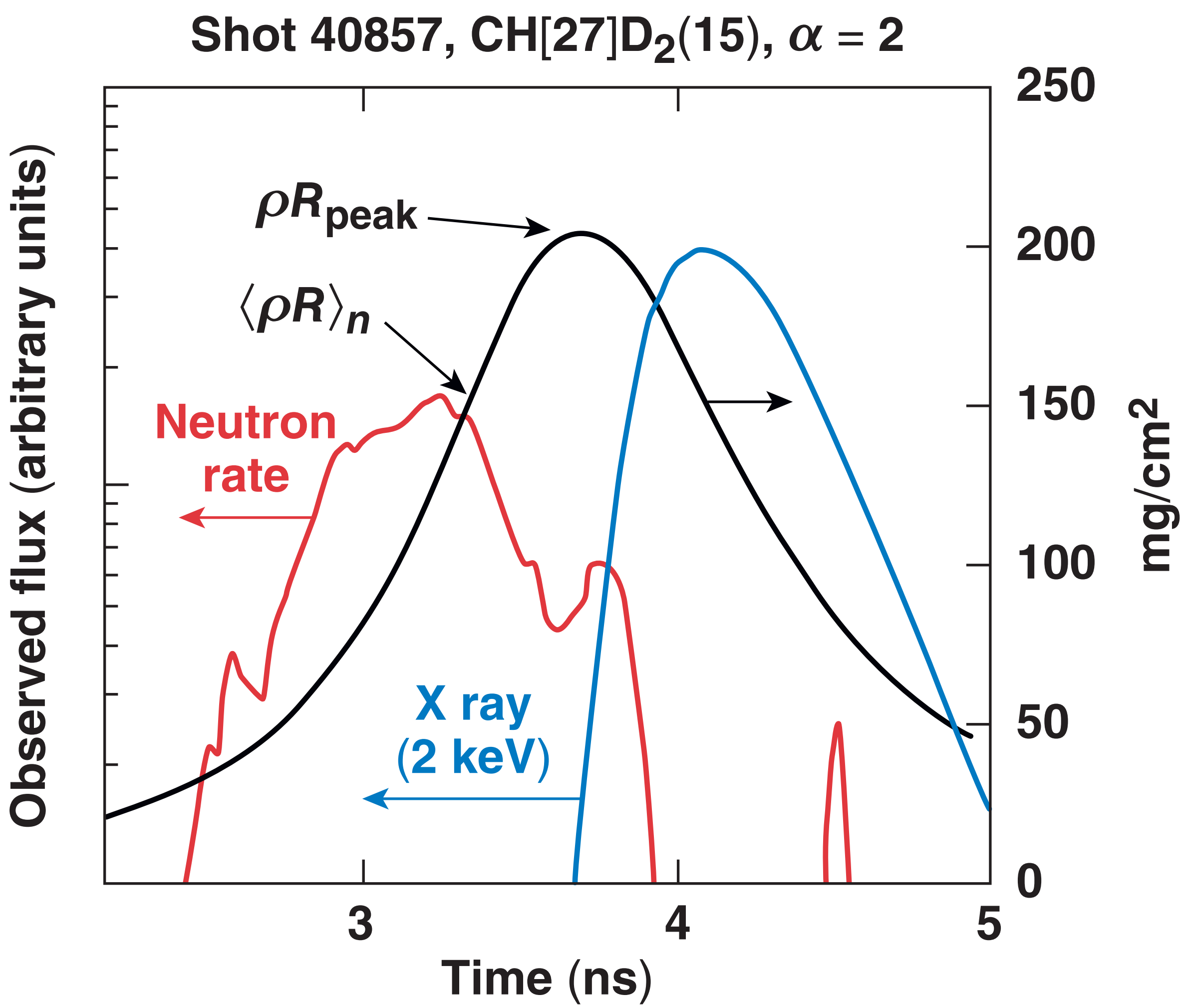
Hot-spot physics can be done on OMEGA with ignition-quality ice

- Fuel assembly (areal density)/convergence
  - P. B. Radha, GO2.00008
  - J. A. Frenje, GO2.00009 and JO2.00003
  - D. D. Meyerhofer, ZO1.00001
- Core temperature
- Yields
  - V. Yu. Glebov, GO2.00011
- Laser-energy coupling
  - W. Seka, ZO1.00002
  - I. V. Igumenshchev, ZO1.00013
  - V. N. Goncharov, ZO1.00012
  - S. P. Regan, ZO1.00005
- Performance sensitivity to single beam smoothing
- Performance sensitivity to adiabat shaping
  - P. W. McKenty, VO2.00002
- Performance sensitivity to shell stability (adiabat)

15 DT implosions and 118 D_2 implosions have been performed on OMEGA

E15056

The areal density increases significantly during the fusion burn

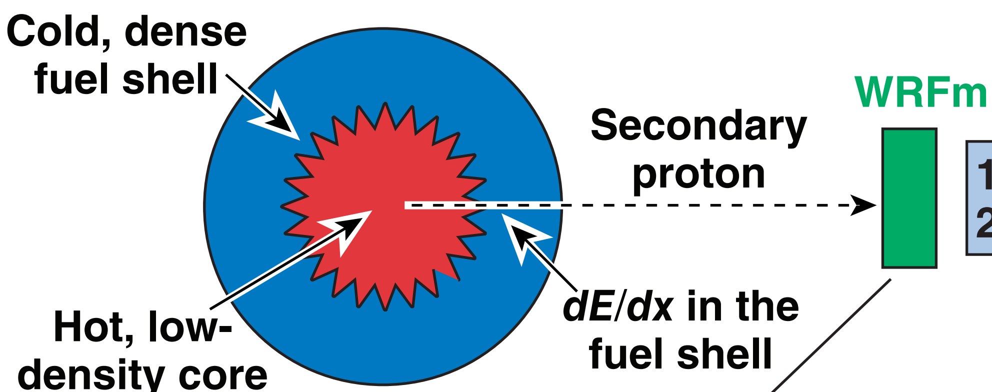


E15340

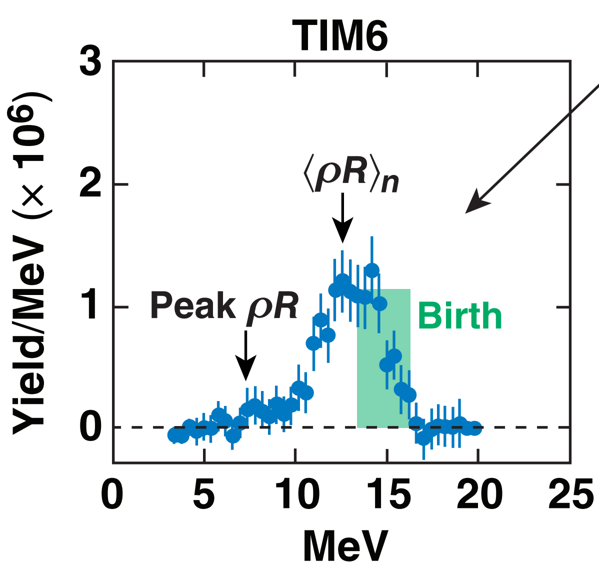
See P. B. Radha, G02.00008

Direct Drive

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



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



- *dE*/*dx* corresponds to $\langle \rho R \rangle_n \sim$ 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*

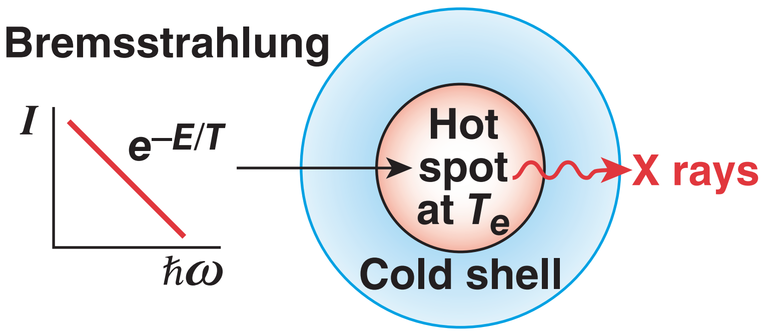
E15270a

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

Direct Drive

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

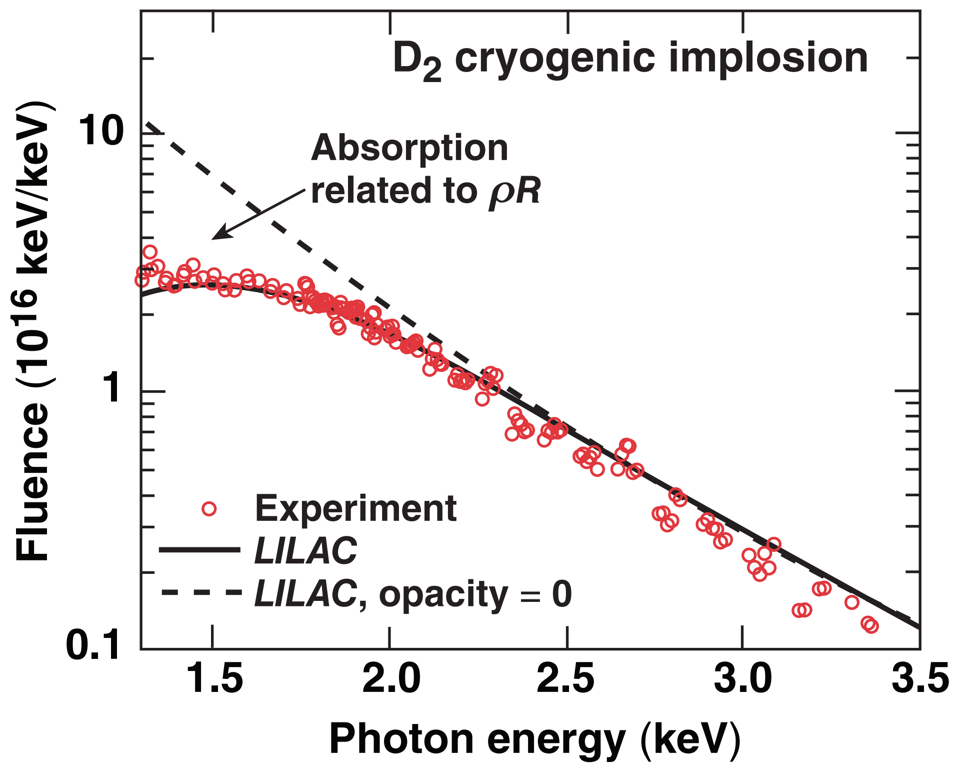
Emitted x-ray spectrum is the product of a source term and an attenuation term



- 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

E15271a

Summary/Conclusions

Ignition-scaled cryogenic DT capsules are being imploded on the OMEGA Laser System

UR LLE

- The success of the cryogenic target handling system at LLE is the culmination of three decades of research and development.
- Since 2001, 118 cryogenic D_2 and 15 cryogenic DT capsules have been imploded on the OMEGA laser.
- β-layering produces inner-ice smoothness well below the ~1-μm-rms (all modes) requirement for direct- and indirect-drive ignition.
- IR layering of D_2 targets produces similar results.
- The NIF cryogenic target development program has produced and characterized ignition-quality ice layers in Be shells.

Peak fuel areal densities approaching 200 mg/cm^2 have been achieved in both D_2 and DT implosions.