NIF Target Design and Fabrication

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This is the work of many people…..

- **LLNL**

Craig Alford
Suhas Bhandarkar
Steve Buckley
Beth Dzenitis
Steve Haan (and other designers)
Mike Johnson
Jeff Klingmann
Bernie Kozioziemski
Steve Letts
Evan Mapoles
Rick Montesanti
John Moody
Jack Reynolds
Jim Sater
Rich Seugling
Masaru Takagi
and others…

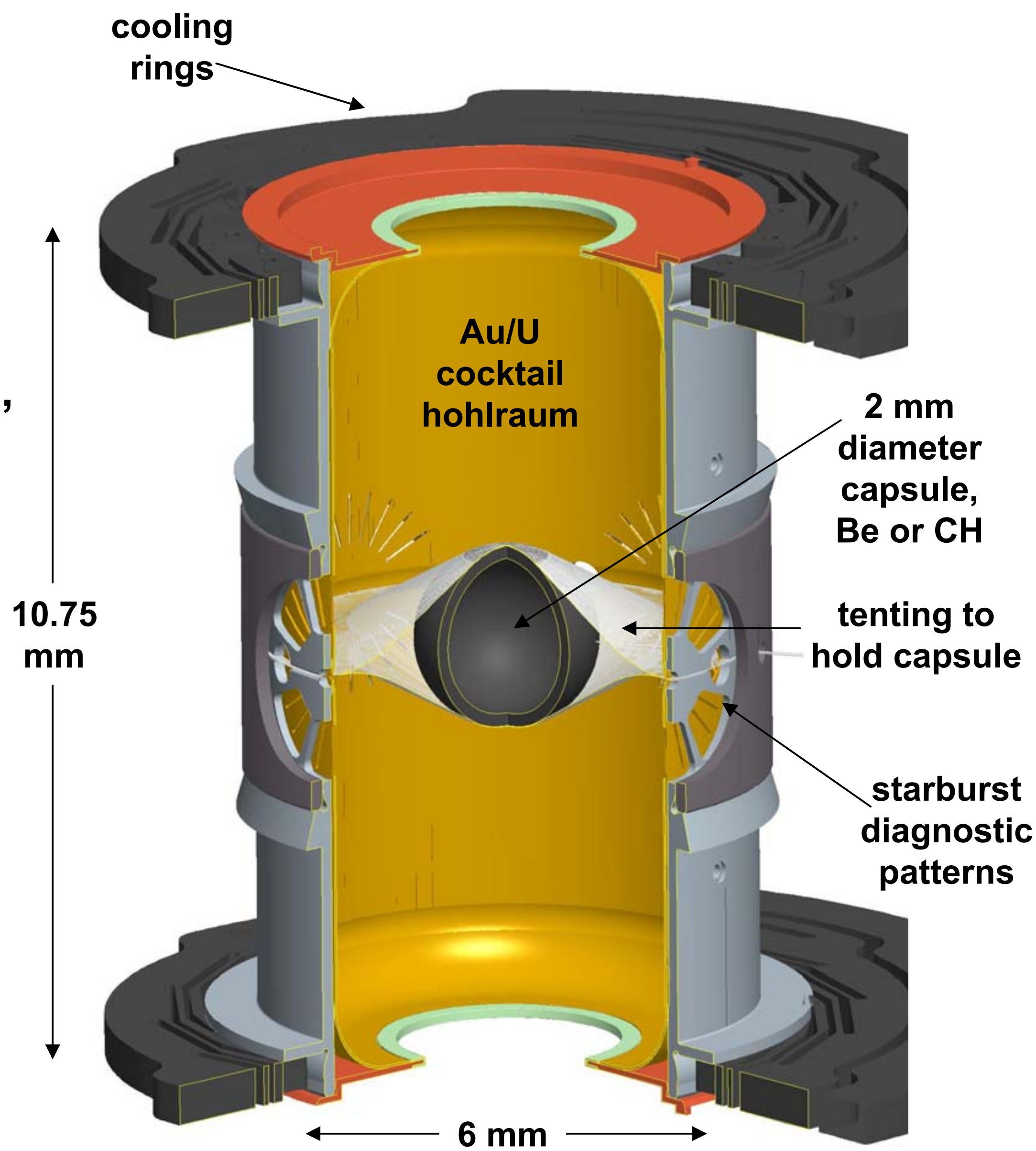
- **General Atomics**

Abbas Nikroo
Ethan Alger
Jay Crippen
Sam Eddinger
Andrew Forsman
Haibo Huang
Erik Lundgren
Kari Moreno
Richard Stephens
Don Wall
Jason Wall
Heather Wilkens
Hongwei Xu
Kelly Youngblood
Zabrina Zimmer
and others…

- Plus folks at LANL and LLE…..

The design for the NIF ignition target is very demanding

- The current point design is for a graded Cu-doped Be capsule layered with solid DT at 18.3 K in a cocktail hohlraum.
- There are very stringent requirements on all surfaces, as well as material homogeneity.
- Precision assembly is critical.
- There are in addition rigorous requirements for laser performance, power balance, pulse shaping, beam quality, and beam pointing.



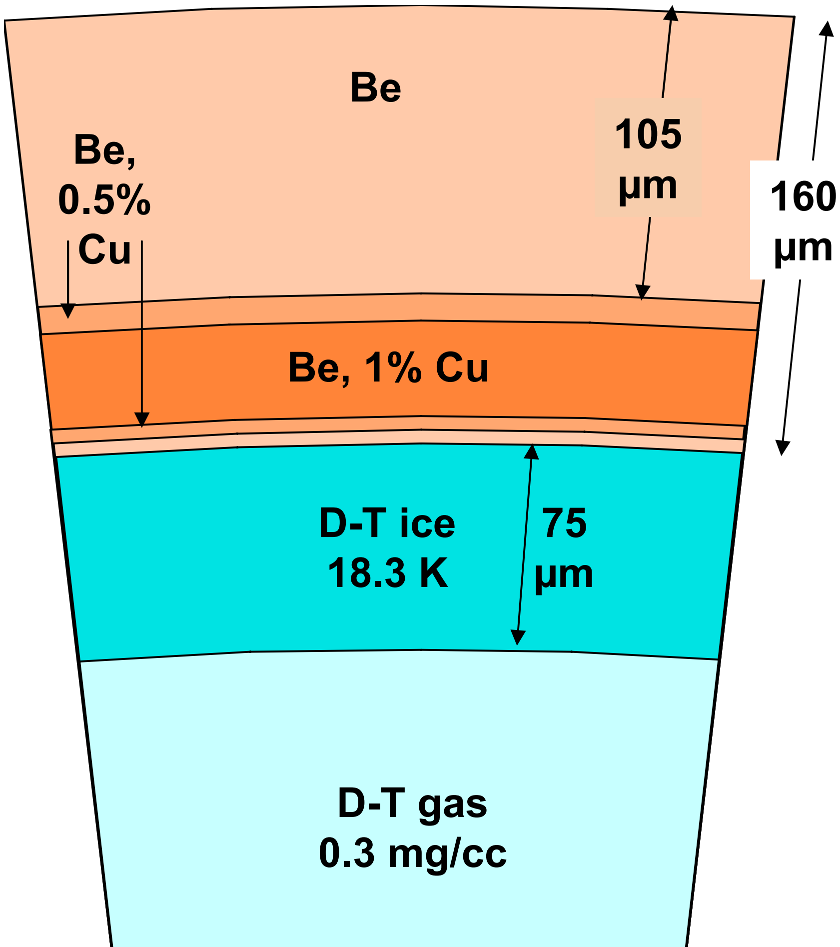
Outline

- Capsule fabrication and characterization
- Cryo layer formation and characterization
- Hohlraum fabrication
- Status of the National Ignition Facility

Polished Be capsule

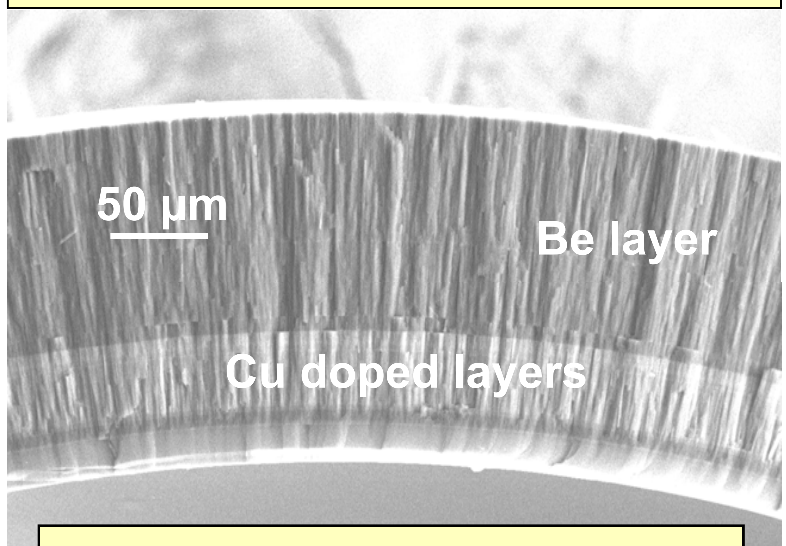
Be capsule with bonded fill tube

The current lead capsule design is Be with a graded Cu dopant



See H. W. Xu, *et al*., *Fusion Sci. Technol*. **51**, 547 (2007) **for details.**

Controlled Columnar Structure



Full thickness Cu doped Be shell

- **There are tight specifications on the composition as well as the allowable surface roughness at all interfaces.**
- **A "similar" Ge-graded CH capsule serves as a back-up.** K. C. Chen, *et al*., *Fusion Sci. Technol*. **49**, 750 (2006).

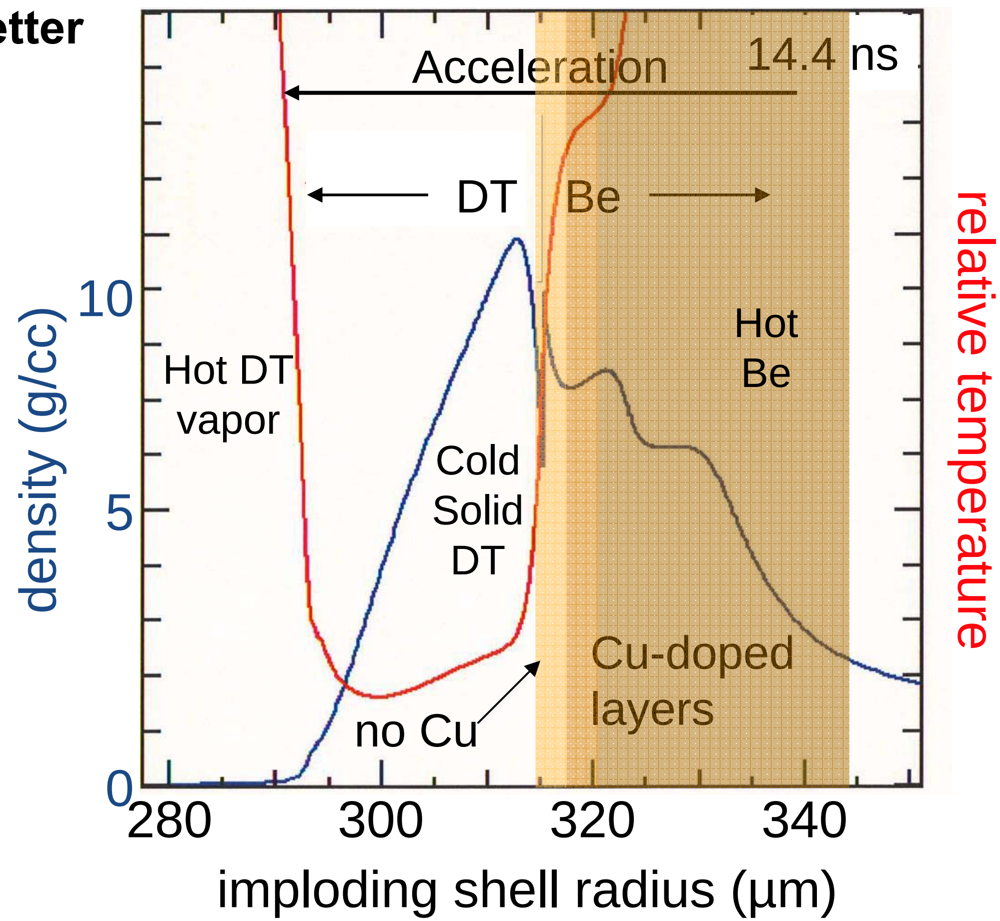
Several layers of varying Cu-dopant provide control over the temperature, hence density, in the shell

- The Be absorbs more x-rays than the relatively transparent DT, which can result in a large and unstable density gradient at the interface.

- The Cu-doped layers are even better absorbers.

- Because the inner layers have less or no Cu, they absorb x-rays less, thus are cooler and kept at higher density, a better match for the cold compressed solid DT

- Specification of Cu-doped layers allows one to control the density profile at the interface and reduce the instability.



Cu-doped Be capsules are made by sputtering Be and Cu on to plastic mandrels

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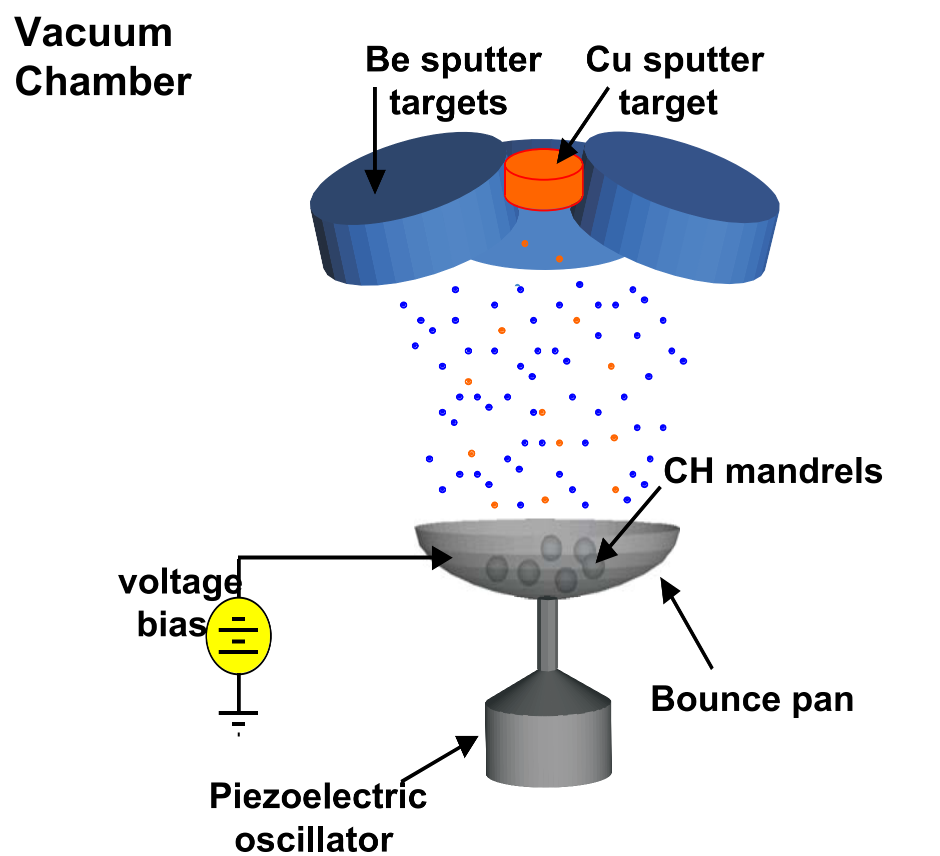
Sputter deposition on CH mandrels



- **CH mandrels are produced by the PaMS/GDP process, see** B. W. McQuillan, *et al., Fusion Technol*. **31**, 381 (1997)**.**
- **Variation in the power to the Cu sputter target allows us to precisely control the Cu concentration in the deposited material.**
- **The coating rate is from 0.25 to 0.5 µm/h, thus requiring several weeks to coat a batch of 10 to 20 shells to full thickness**

Non-destructive dimensional and dopant concentration measurements are made with quantitative contact radiography

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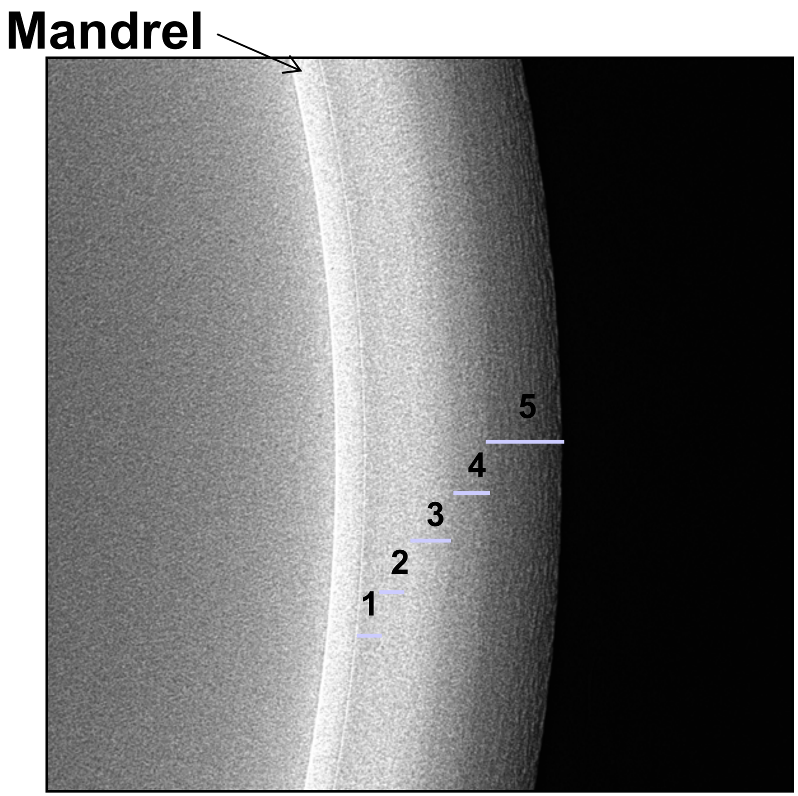
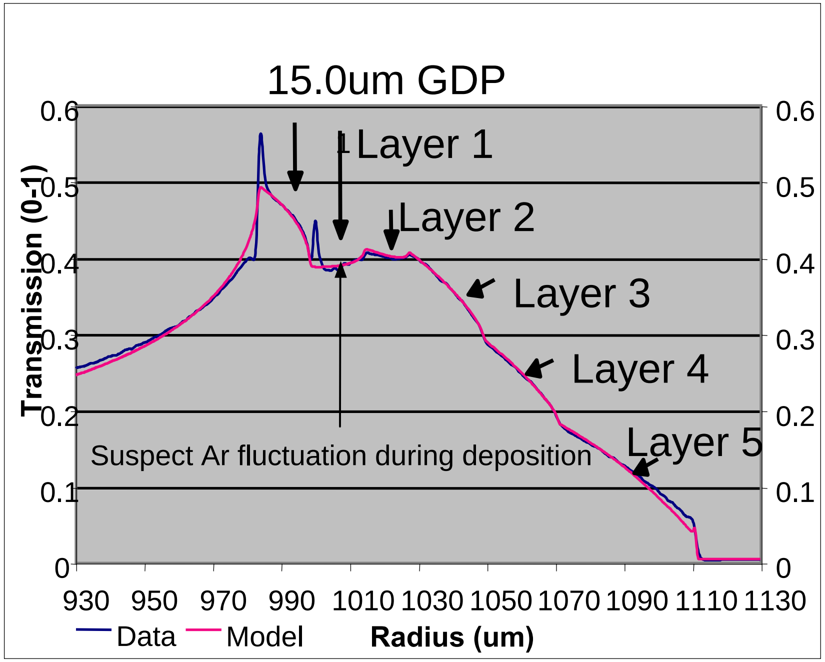




- **Film model developed**
- **2K x 2K pixel digitization of film allows**
  - **Sub micron dimensional resolution**
  - **6 orders of magnitude of dynamic range; ~0.05 at% Cu concentration measurement**
- **See** H. Huang, *et al., Fusion Sci. Technol*. **51**, 530 (2007).

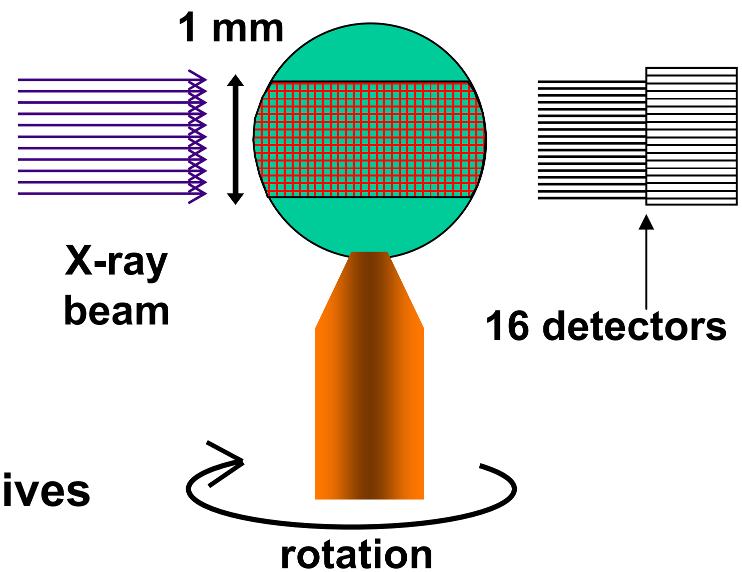
Precision radiography measures the bulk properties of shells

- NIF capsule design specification require x-ray optical depth uniformity of 1 part in 10^4 at mode 25 (120 μm lateral)

- X-rays pass through 2 shell walls, $T=T_0 e^{-\mu x}$, μx is the optical depth

- Shell rotates (1 rpm), data taken at every 0.1°, data interleaved to eliminate long term drift

- 16 detectors in two columns - a second measurement after a 90° rotation of shell gives 97.5% coverage



- System counts every x-ray photon, thus noise ~ 1/sqrt(counts)

- Measurement time has been reduced to less than a day

- **See** S. A. Eddinger, *et al*., *Fusion Sci. Technol*. **51**, 525 (2007).

Current precision radiography indicates shells meet 10^{-4} optical depth uniformity specification

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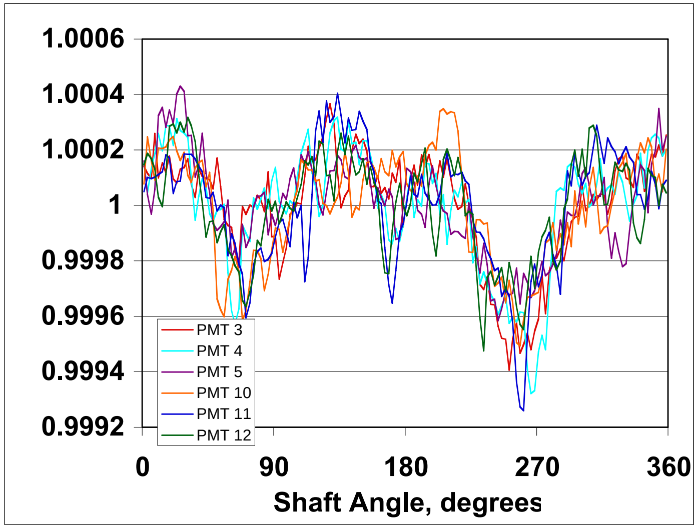
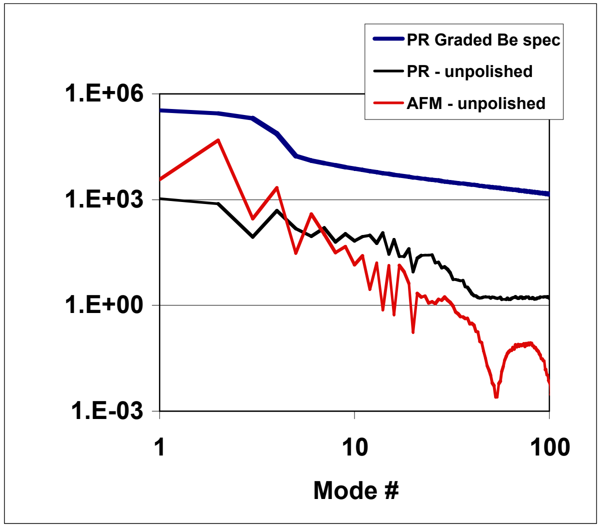
- For graded Be:Cu three factors can lead to OD variations
  - Inside or outside surface roughness
  - Roughness at Cu doped interfaces
  - Void agglomeration



X-ray transmission vs angle

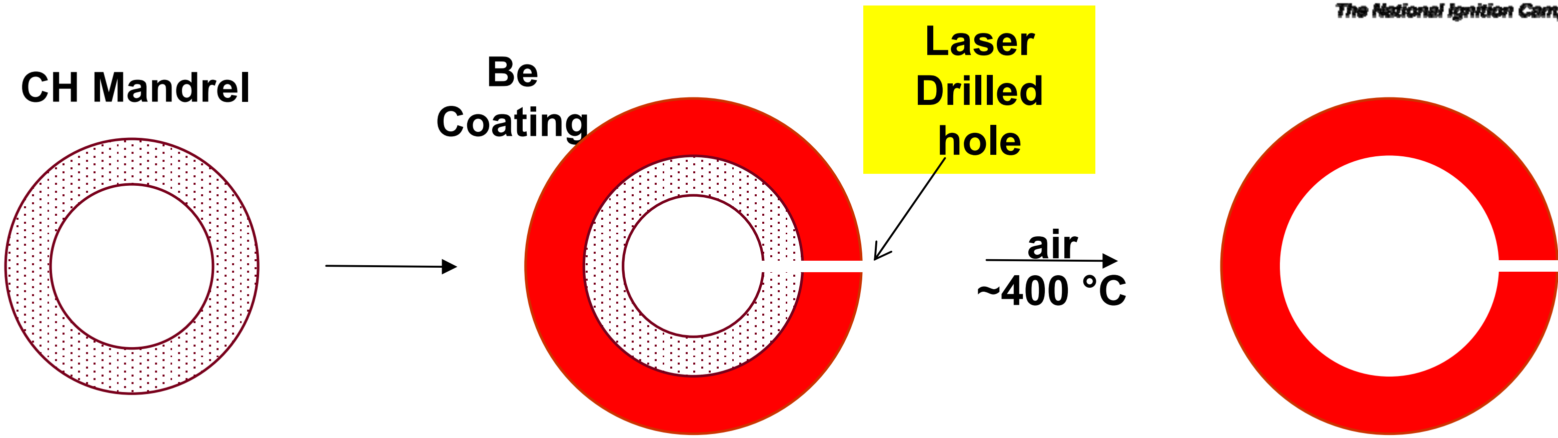
- All of these conditions will lead to instability growth during the implosion.

- Currently produced shells meet the 10^{-4} specification



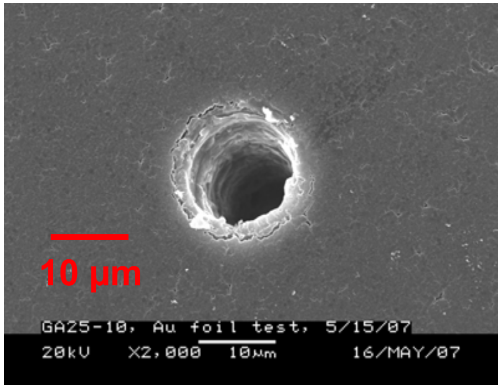
Graded doped Be:Cu shell

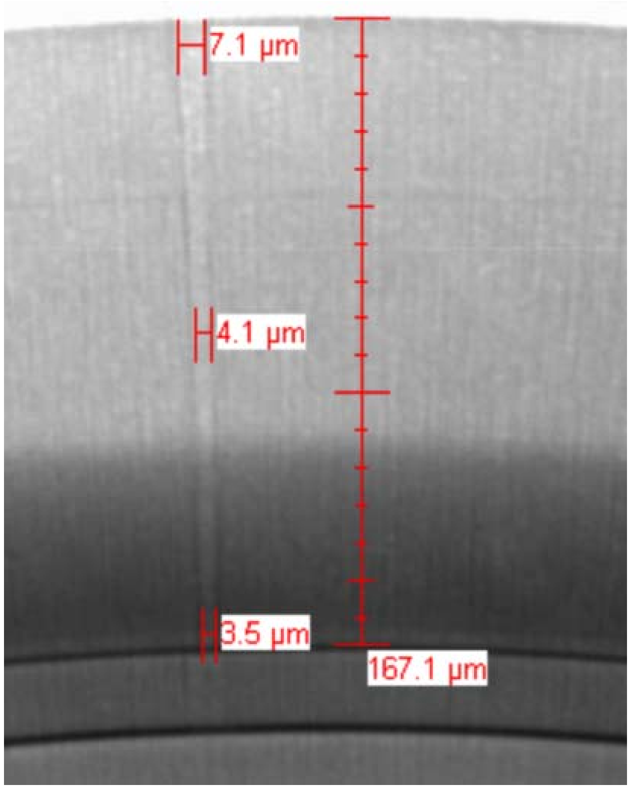
Removal of the plastic mandrel is done thermally after a small diameter fill hole is laser drilled



- **Laser drilling is done with a double pulse technique developed at General Atomics (**A. Forsman, *et al*., *J. Appl. Phys*. **98**, 033302 (2005))

- **Nd-YAG laser, λ = 532 nm, 4 ns laser pulses in double pulse technique**

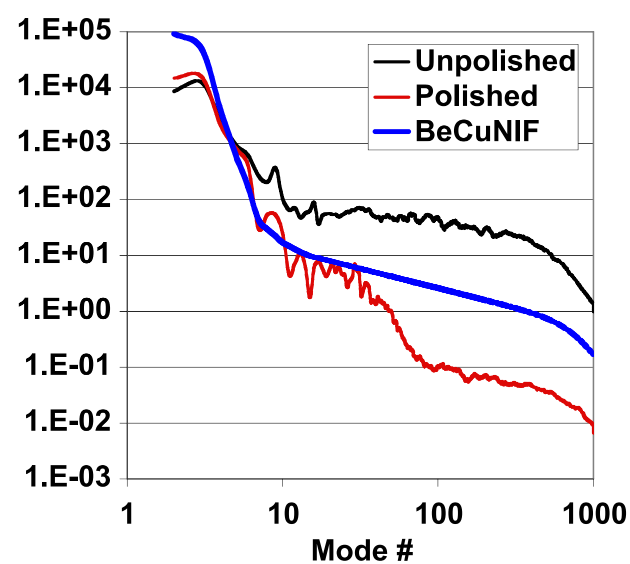




The Be capsule is mechanically polished to meet surface finish specifications

Unpolished and polished Be shells

Polished Be vs spec



- **Polishing reduces the high mode roughness to well below the required specification, and has no effect on the low mode symmetry**

- **The low mode asymmetry is set by the mandrel, excellent CH mandrels are available.** A. Nikroo, *et al*., *Fusion Sci. Technol*. **45**, 165 (2004)**.**

Spherical Interferometry allows surface mapping of the outside and inside of shells

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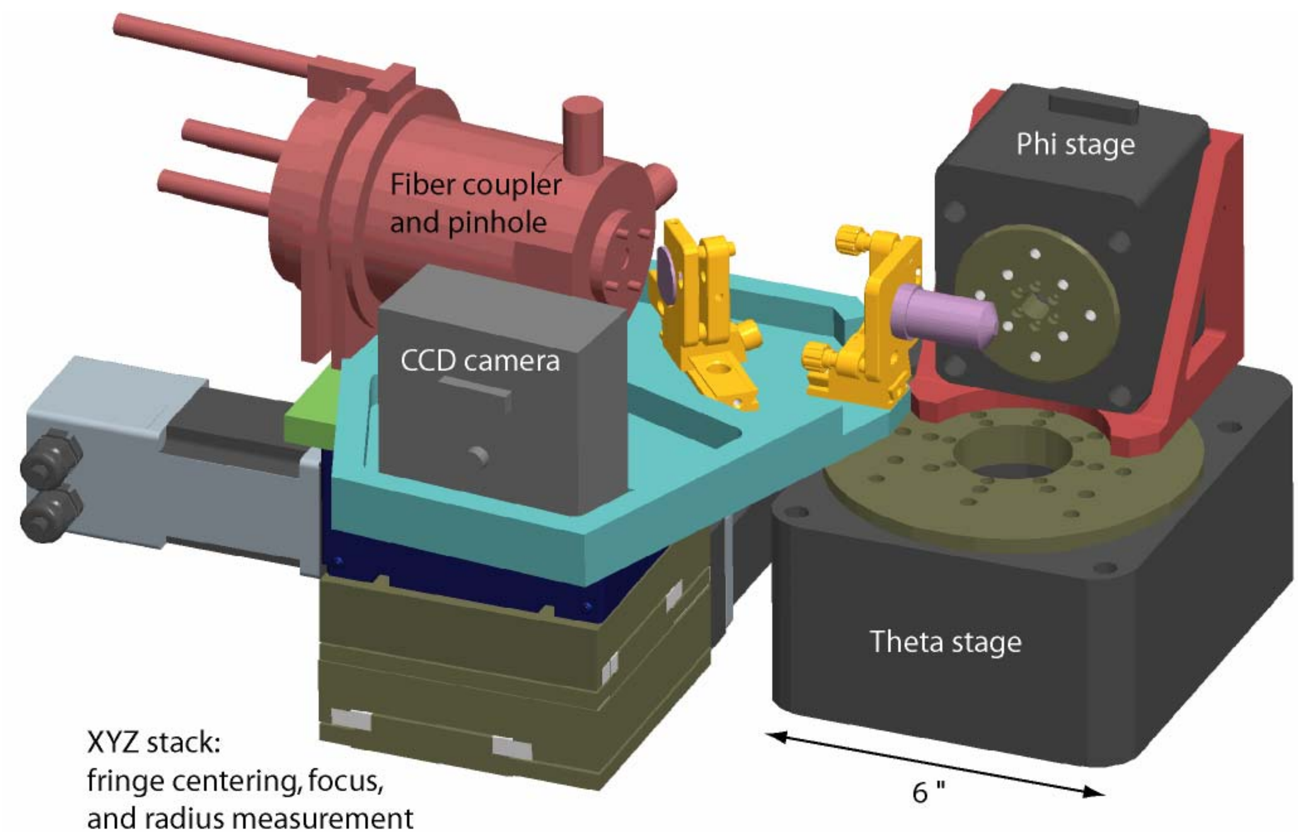
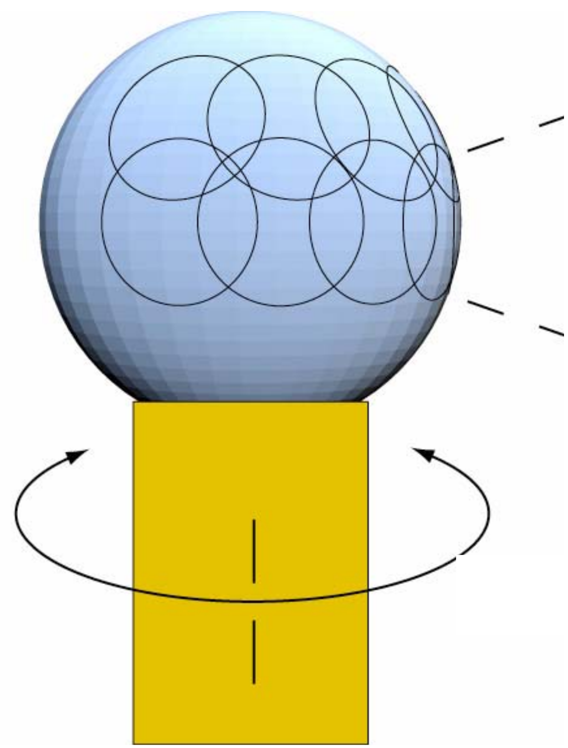
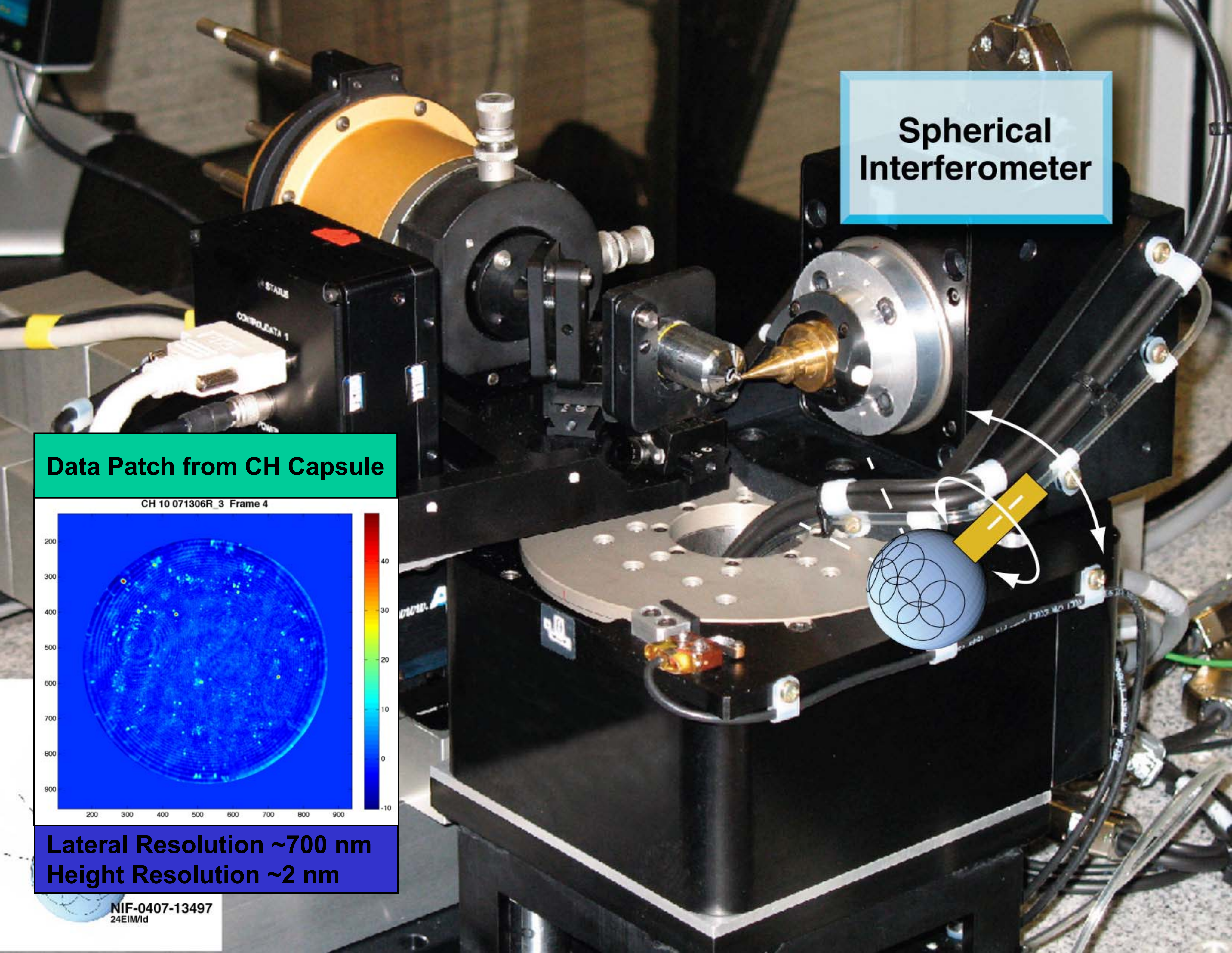
- Phase sensitive diffractive interferometry (PSDI) has been adapted to provide complete mapping of exterior capsules surface

- Best tool to quantify isolated defects






Spherical Interferometer
Data Patch from CH Capsule
CH 10 071306R_3 Frame 4
Lateral Resolution ~700 nm
Height Resolution ~2 nm
NIF-0407-13497
24EIM/ld

Inner surface of full thickness shells meets the NIF specification

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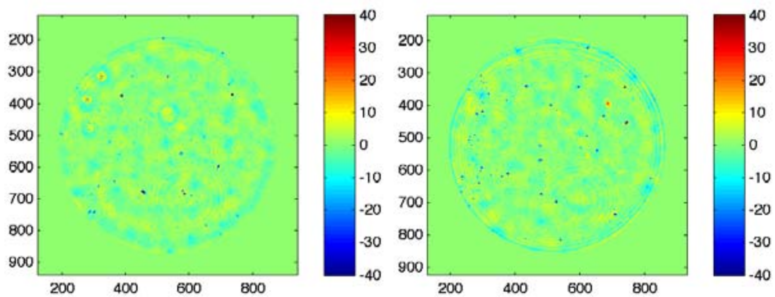
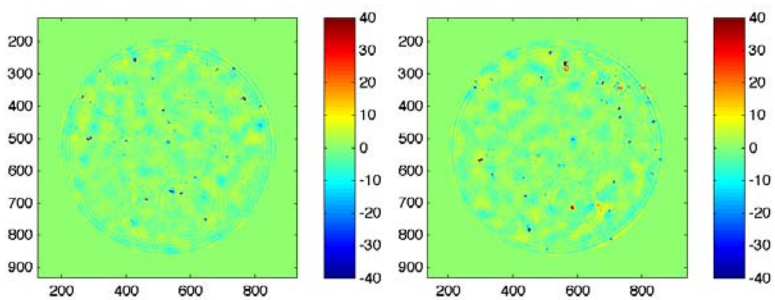
- The spherical interferometer can also look at the interior (concave) surface quality

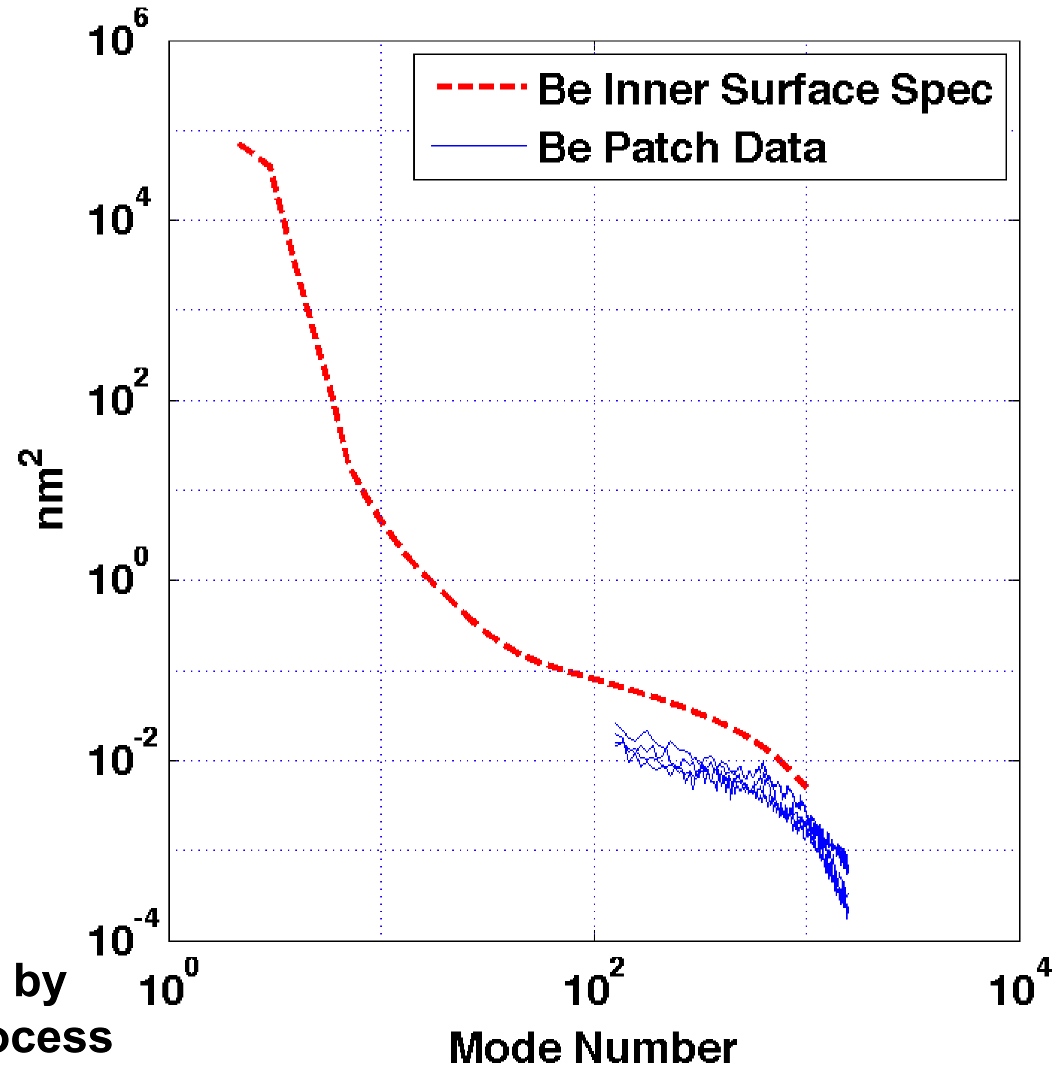


PSDI Patch scans ~ 500 μm dia



- Destructive test

- Inner surface quality determined by the mandrel and its removal process



Precise polyimide fill tubes are fabricated with a custom micro-heater

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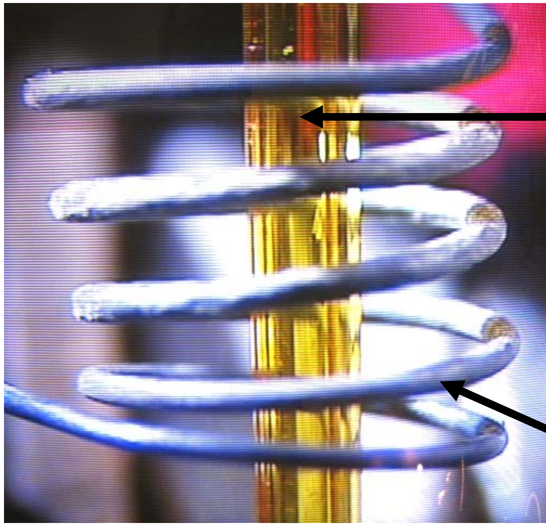
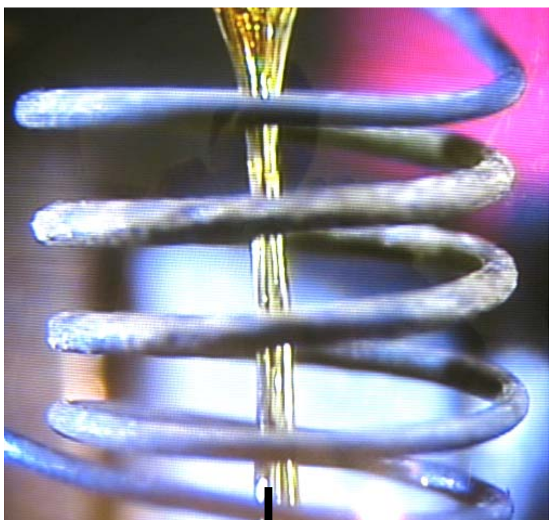
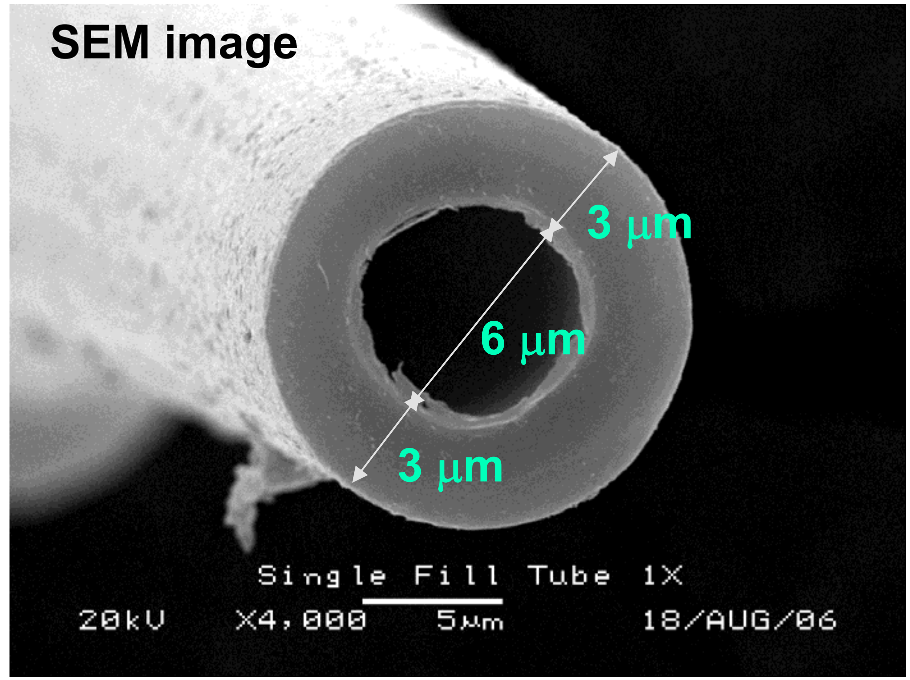


Polyimide tube
OD 230 μm
ID 150 μm

heating coil



pulling weight

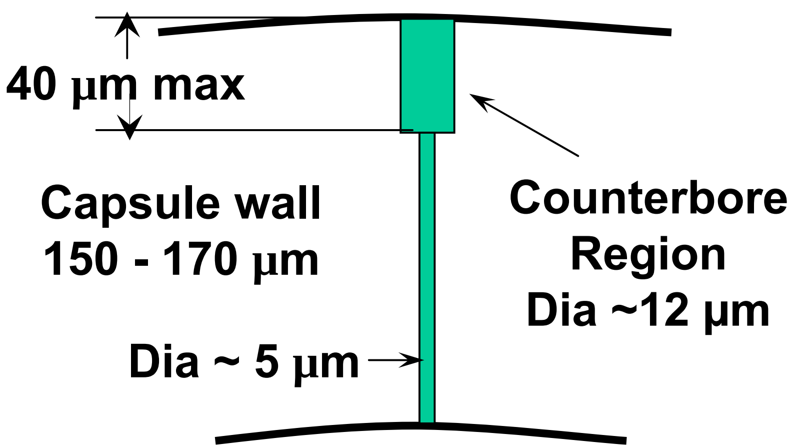


- A special thermoplastic polyimide tube is used
- Tips are laser etched to produce flat ends
- Tubes 1-2 mm long with 10-12 μm OD tips are repeatedly fabricated

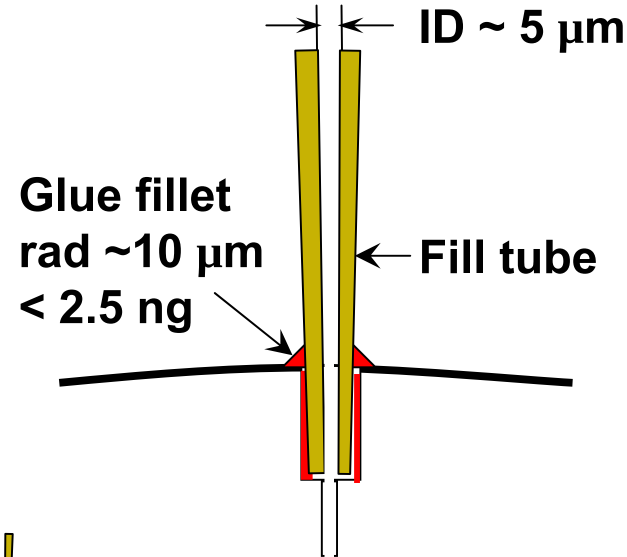
M. Takagi, *et al*., *Fusion Sci Technol*. **51**, 638 (2007).

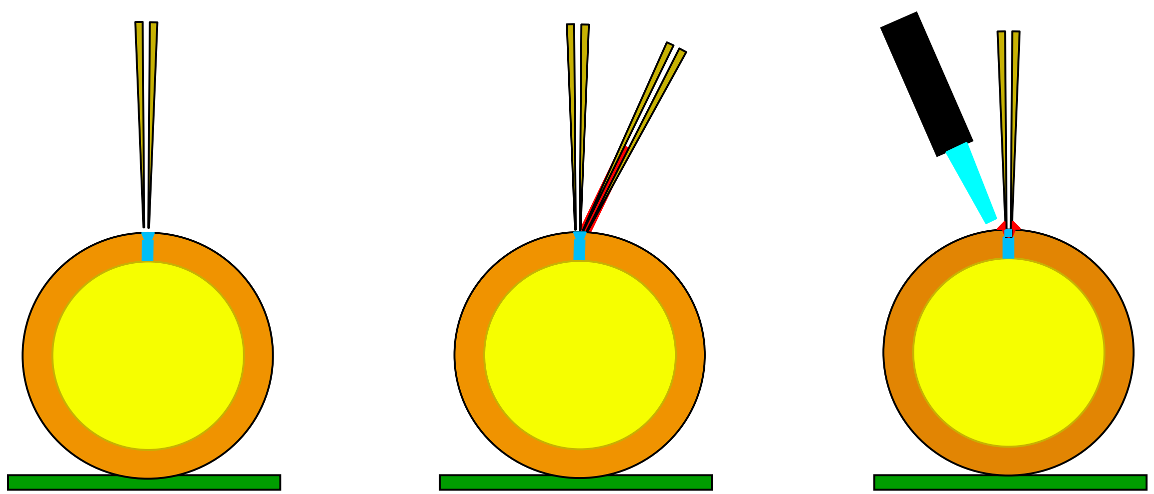
Specifications and requirements for fill tube assembly are tight.

- Fill hole configuration



- Attached fill tube

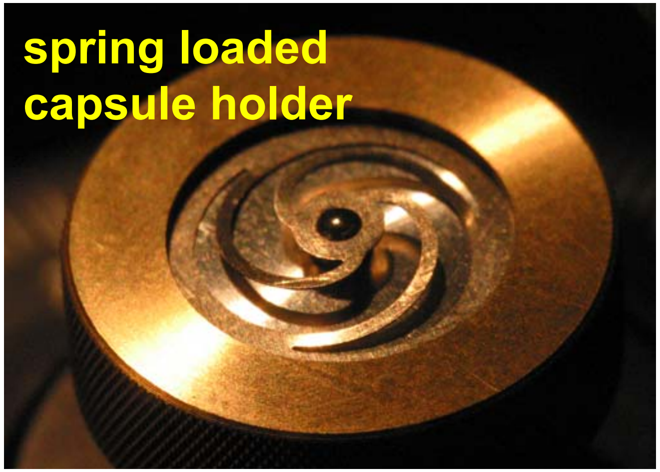


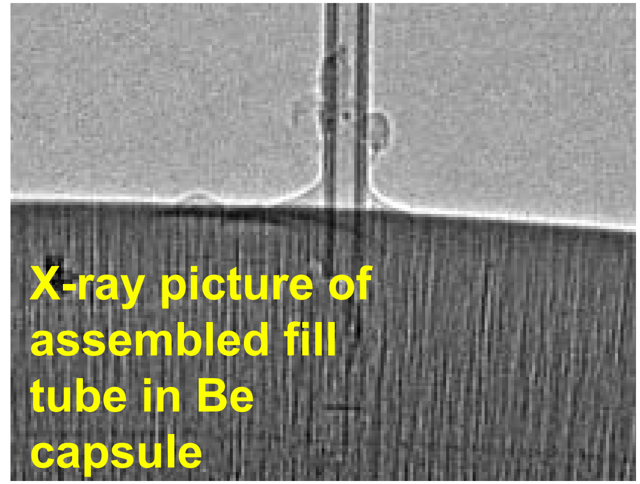


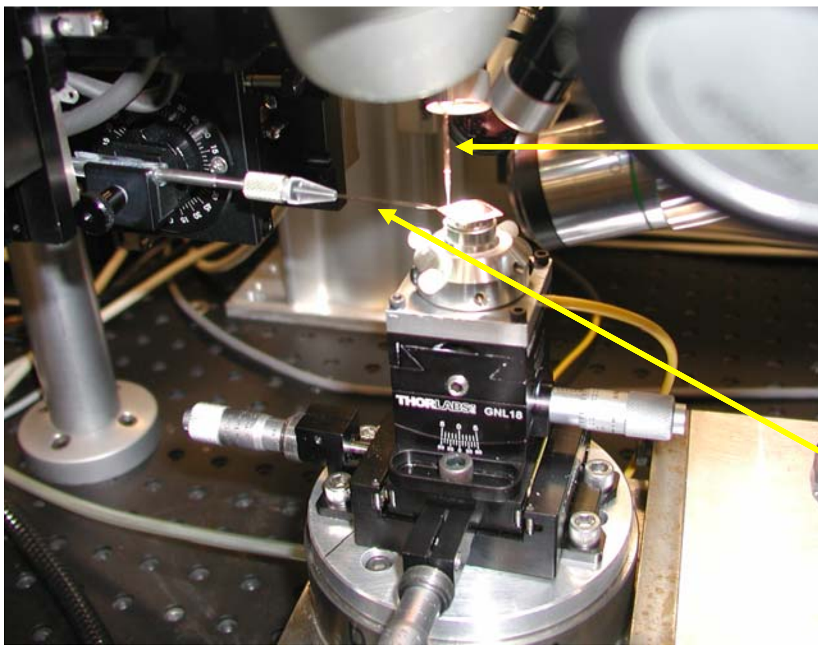
- Insert fill tube
- Apply epoxy
- Cure with UV

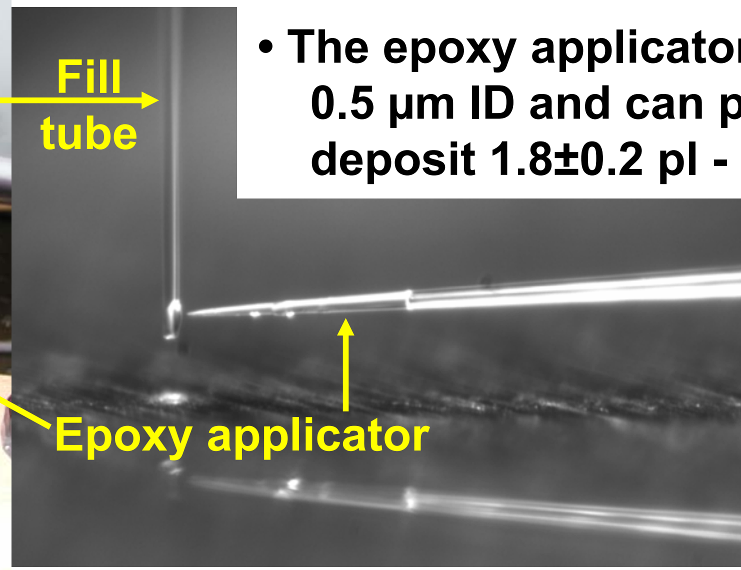
- Attachment must be gas tight and strong while not blocking the through-hole

Precision assembly has been developed to meet our needs



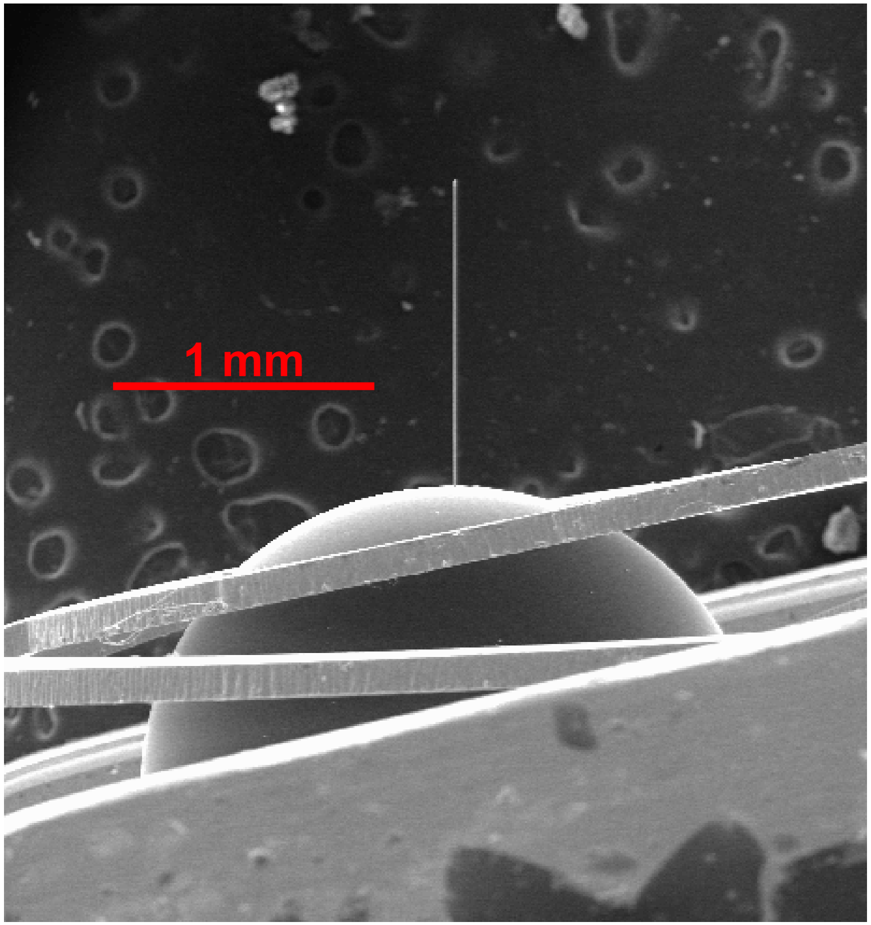


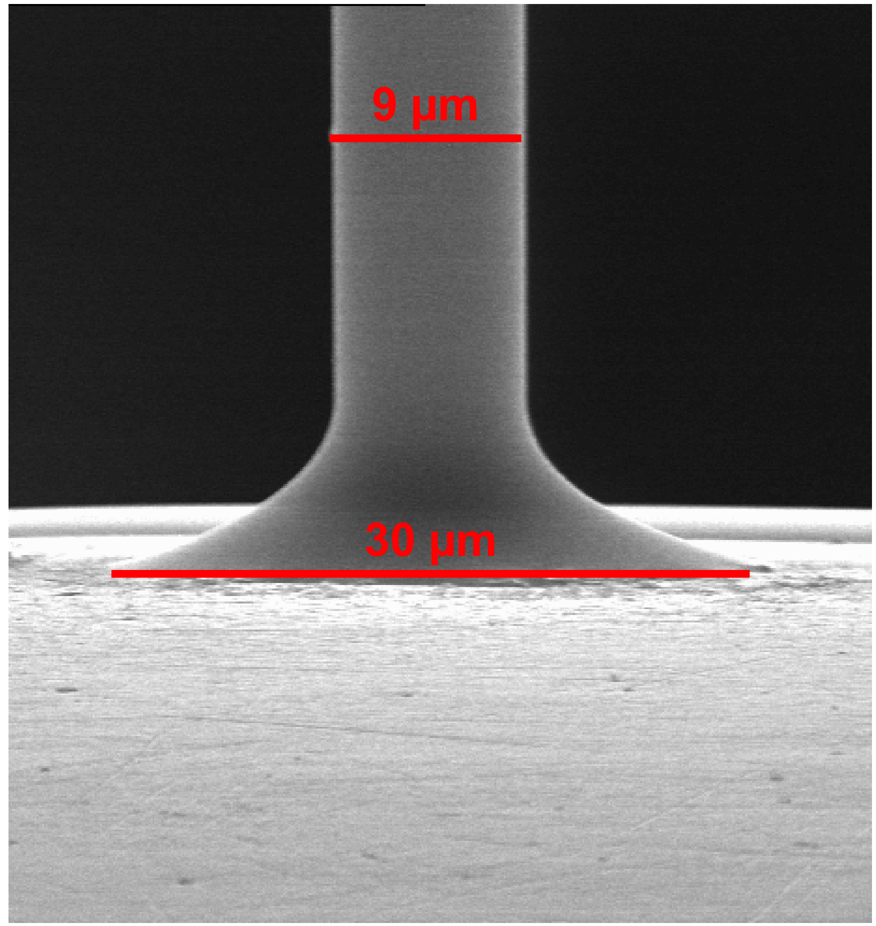




- The epoxy applicator has a 0.5 µm ID and can precisely deposit 1.8±0.2 pl - about 2 ng.

SEM images of a fill tube in a polished Be capsule





Capsule fabrication is in good shape

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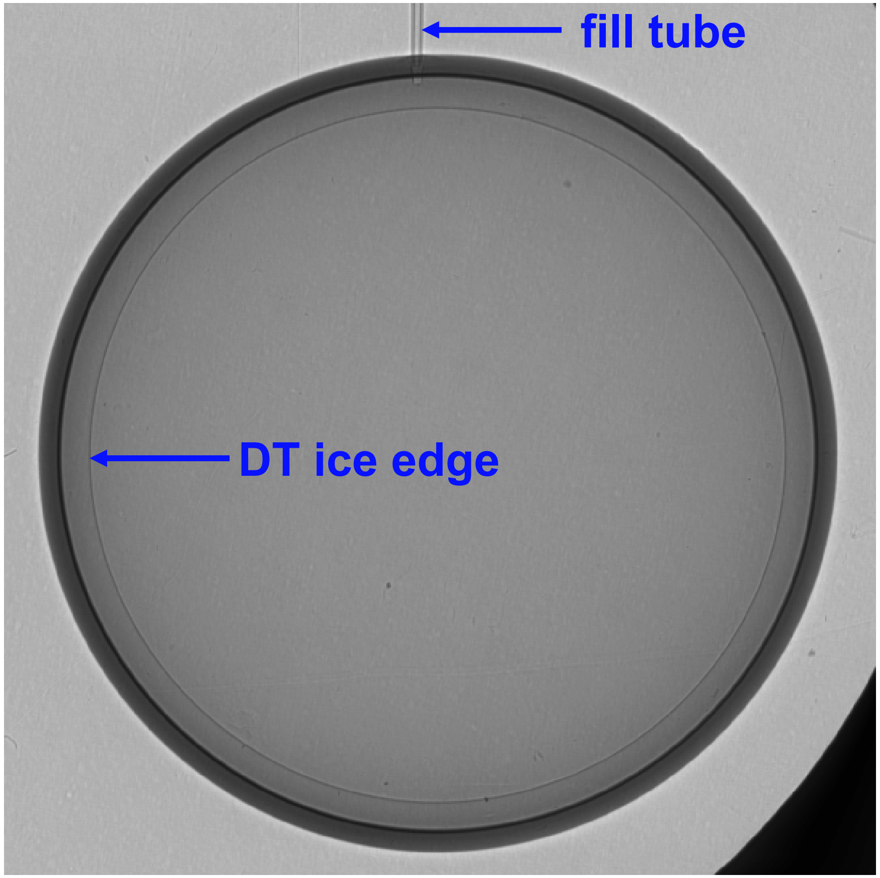
- Graded Cu-doped Be capsules are produced that meet design specifications
  - Graded Ge-doped CH capsule that meet design specifications can also be fabricated
- Capsule fill hole drilling, fill tube manufacture and attachment has been demonstrated
- Effort is now focused on precision assembly of the delicate capsule and fill tube parts into hohlraums

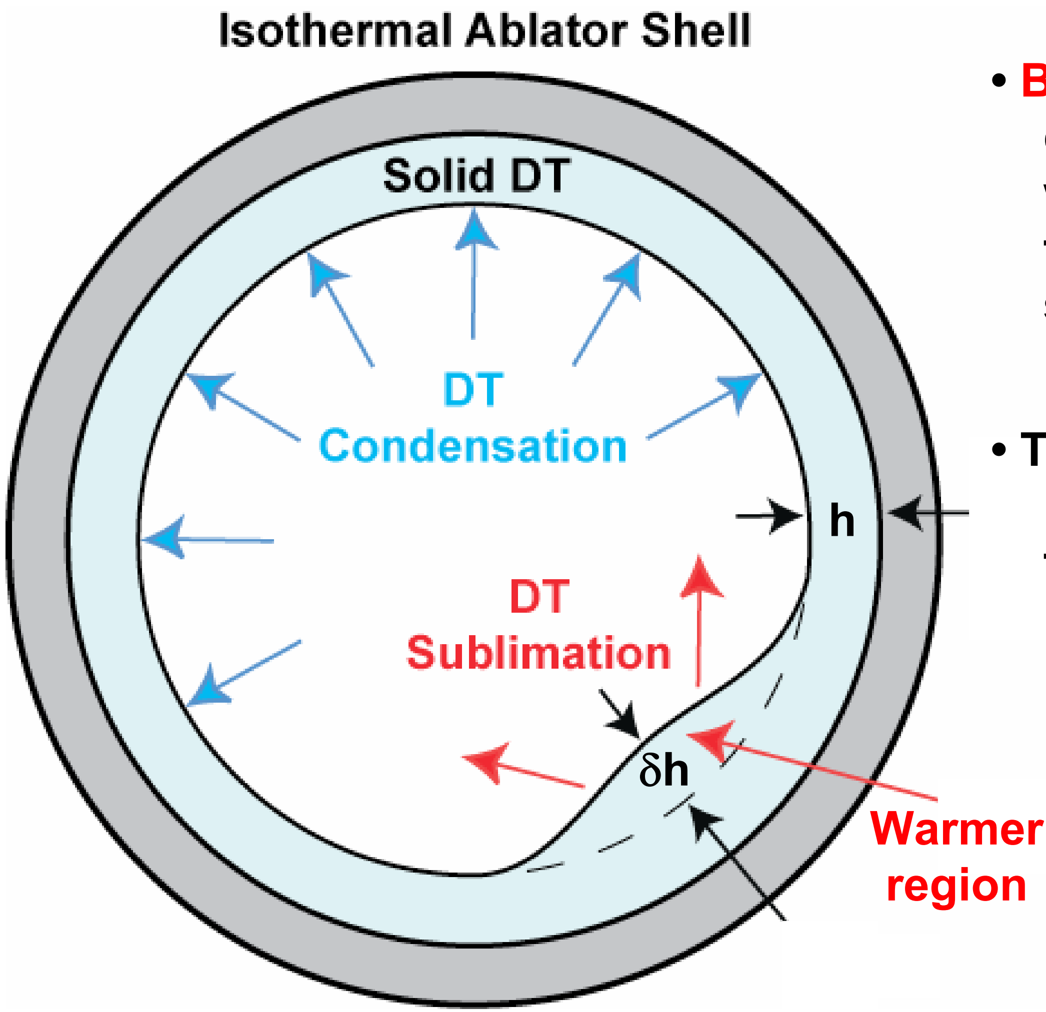
Outline

- Capsule fabrication and characterization
- Cryo layer formation and characterization
- Hohlraum fabrication
- Status of the National Ignition Facility



X-ray phase contrast image of a DT layer inside a 2 mm diameter Be shell

Spherical layers of solid D-T form naturally in an isothermal environment due to self-heating



- **Beta-layering* causes the bump height to decrease as D-T sublimes from the warmer region (due to beta-decay of tritium) and condenses on colder surfaces. Time constant ~30 min.**

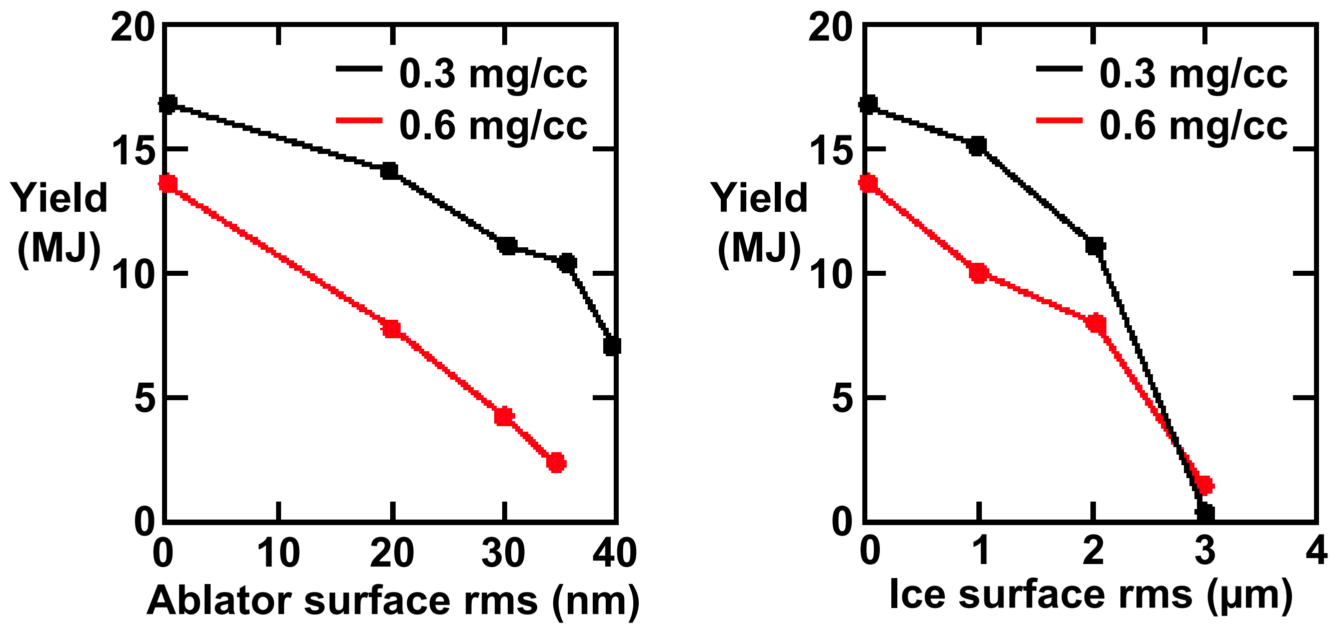
- **The key design requirements are that the internal ice layer be smooth AND that the internal DT vapor density be no more than 0.3 mg/cm^3, reached at 1.5 K below the triple point.**

- **The best layers are made near the triple point, lowering the temperature tends to roughen the layer.**

*J. K. Hoffer and L. R. Foreman, *Phys. Rev. Lett.* **60**, 1310 (1988).

It is important to keep the inner gas density low to decrease the work of compression and increase the convergence.

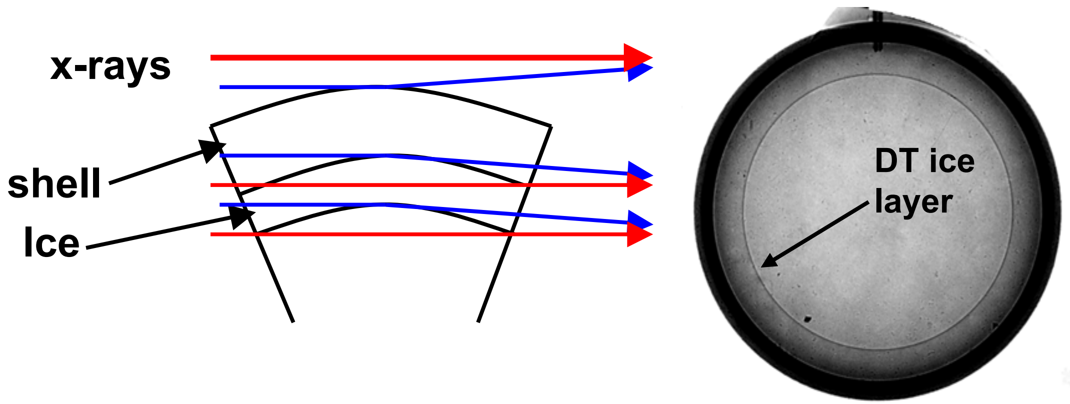
- The inner gas density is controlled by the DT ice temperature
- There is an increase in margin/performance with the decreased DT vapor density



(example taken from a previous polyimide capsule design)

Ice roughness is characterized with both x-rays and visible light.

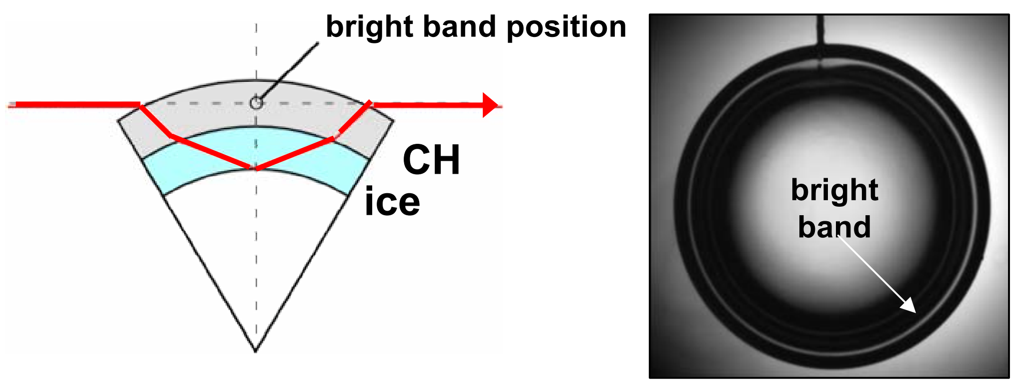
X-ray phase contrast



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

- All shell materials
- 1-D (quantitative)
- 2-D (qualitative, but quantitative with multiple 1-D images)
- Slow (~ 5 min)

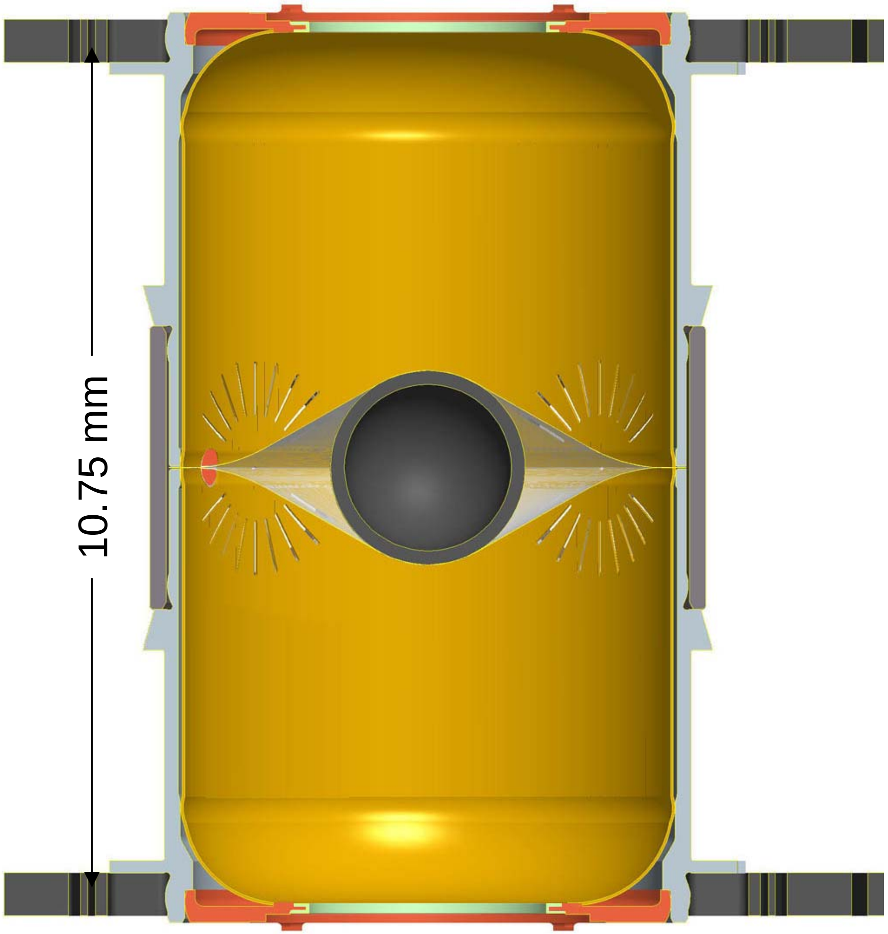
Optical shadowgraphy

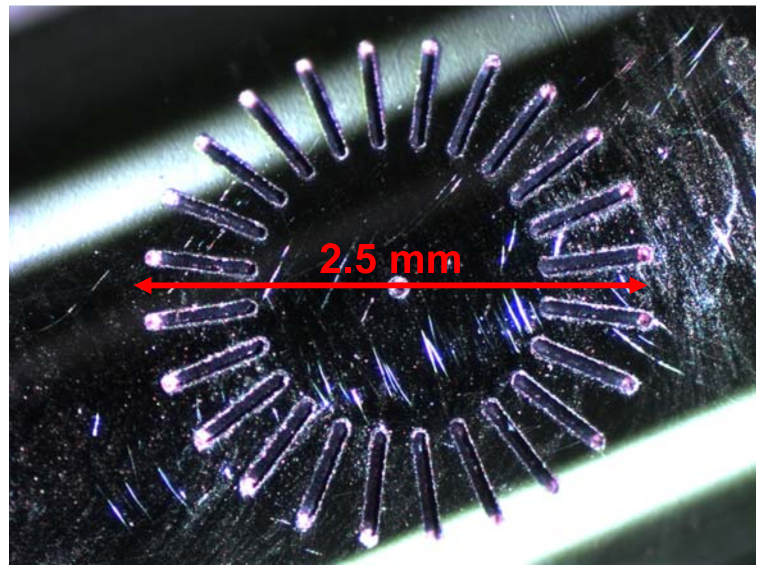


- Transparent shells only
- 1-D (quantitative)
- 2-D (qualitative)
- Fast (sub 1 sec)

- X-ray or optical backlighting through the LEH and side provides D-T fuel layer characterization of equatorial and axial modes
- Measuring local defects below ~ 2 μm is difficult

Four “starburst” patterns are created at the hohlraum mid-plane to allow for axial characterization





From either an X-ray phase contrast or shadowography image the mode spectrum of the ice/vapor interface can be determined.

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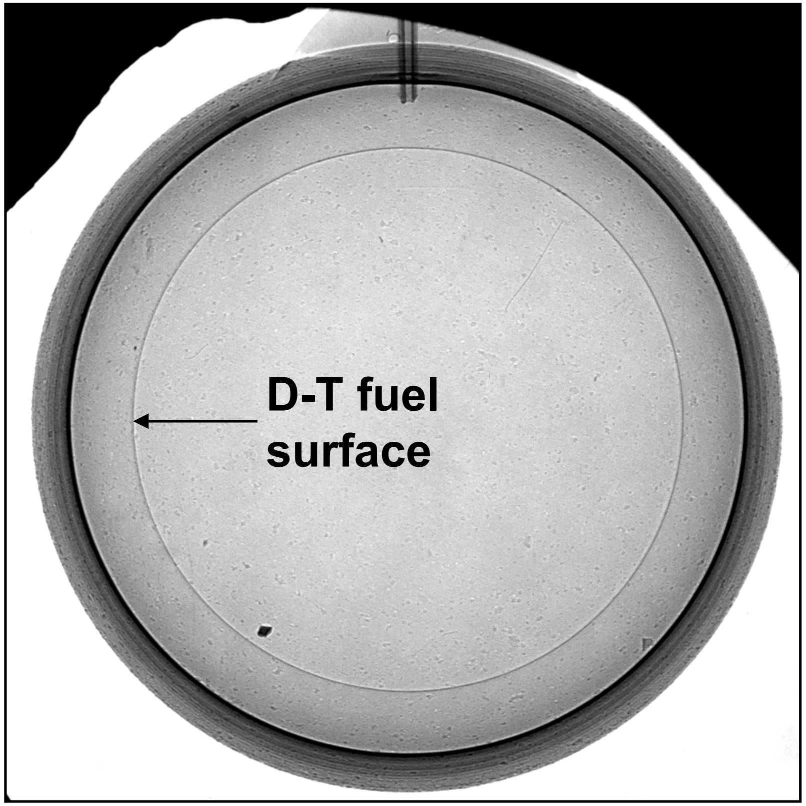
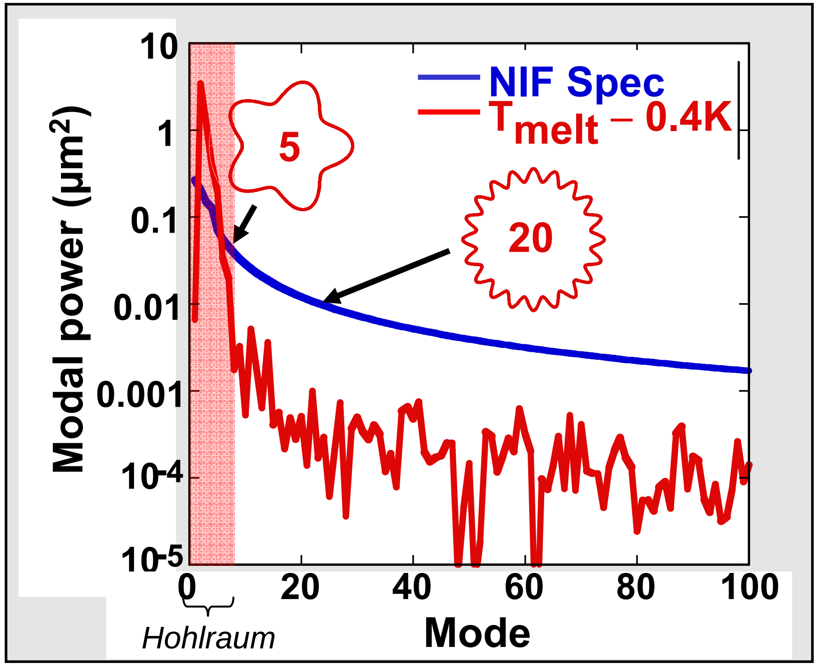
X-ray phase contrast image



Smooth D-T Layer in a Be Shell

Layer analysis

Mode spectrum



X-ray phase contrast has sufficient accuracy for D-T characterization

- **Reliable information out to ~mode 80 can be obtained.**

Slow cooling to 18.3 K to reduce the internal gas density leads to cracks in the D-T ice layer.

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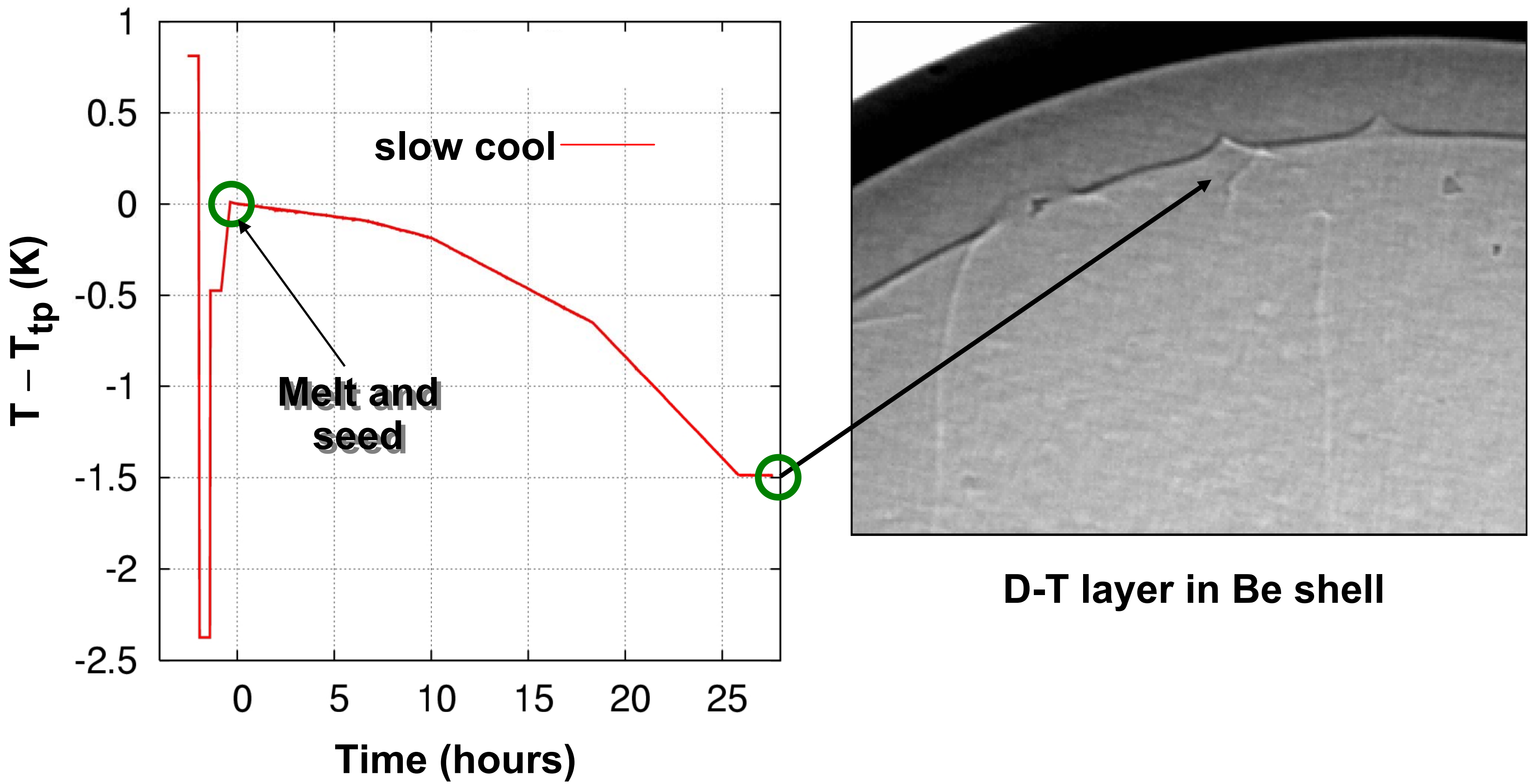
- **Typical slow cool procedure:**
  - Form layer at ~0.1 K below triple point
  - Slowly cool over ~25 hours to 1.5 K below triple point
  - Layer develops cracks and roughens



D-T layer in Be shell

We are exploring a "rapid quench" method of D-T ice layer formation introduced at CEA*

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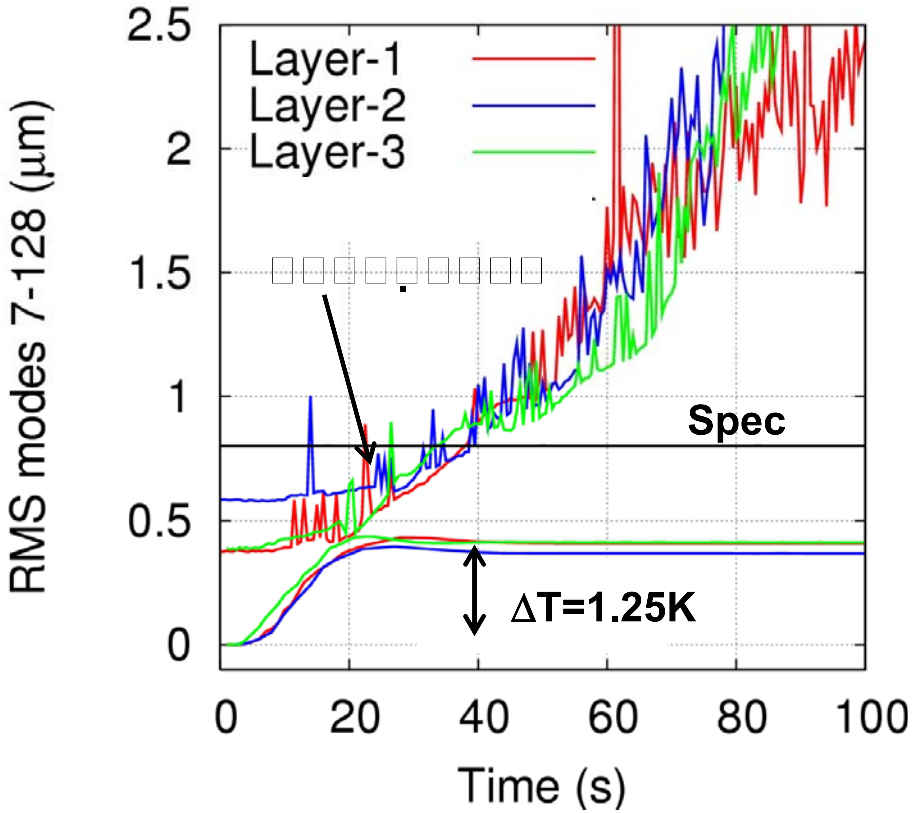
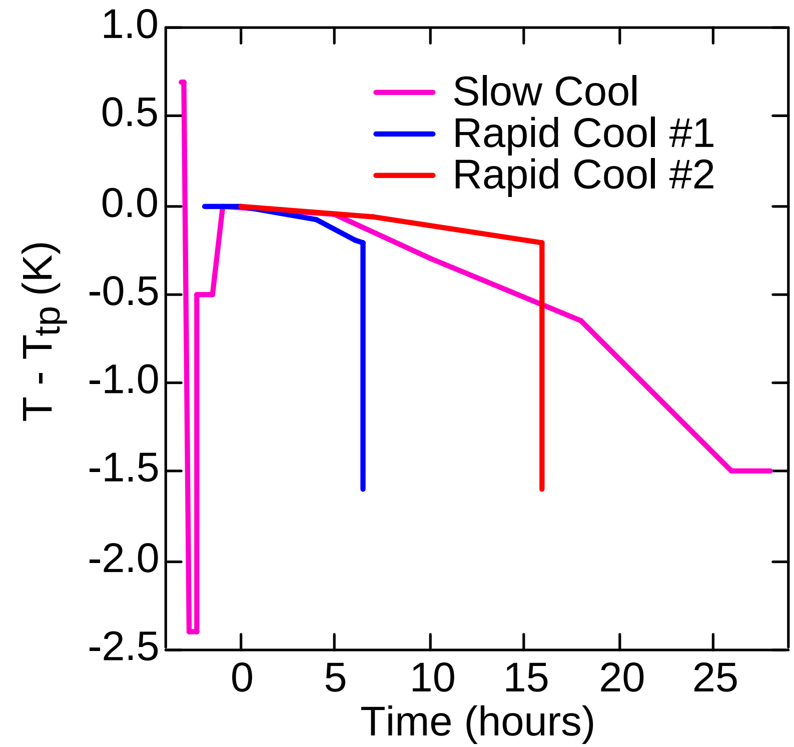
- Form layer near triple point
- Characterize layer pre-quench
- Cool rapidly for ~20 seconds
- Fire laser before roughness develops





- D-T roughness begins to increase as soon as temperature falls, but increase is small during cooling phase
- Layer is much smoother than typical slow cool to T_m- 1.5 K

* M. Martin, *et al., Fusion Sci. Technol.* **51**, 747 (2007); **49**, 600 (2006).

Rapid cooling shows promise for producing layers with with improved surface finish at 18.3 K

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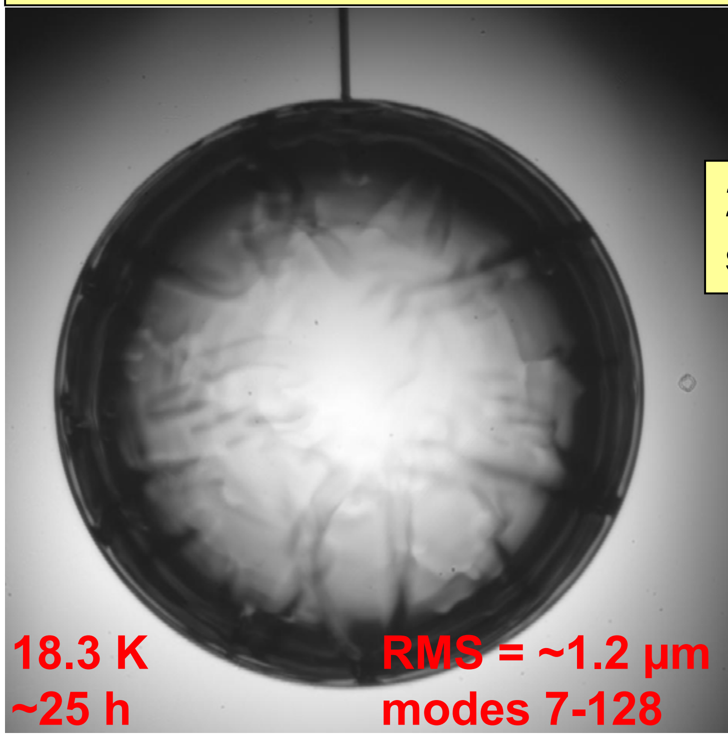
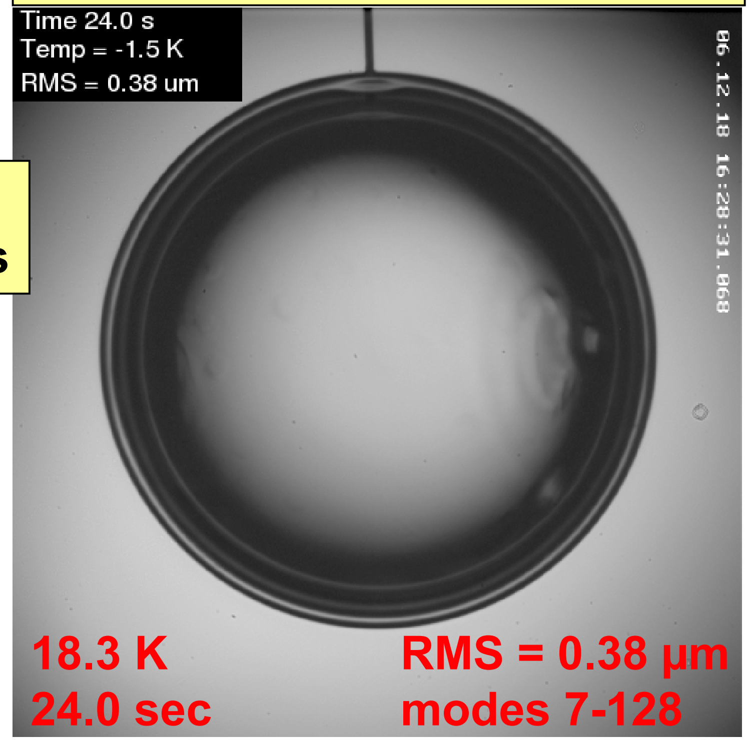
Slow cooled layer in CH



2 mm shells

Rapid cooled layer in CH



- NIF cryogenic target fielding system will support rapid cooling
- Calculations show that a cool down of 1.5 K in a NIF hohlraum is feasible in 1-3 seconds

The cryo picture is optimistic

- Characterization techniques are mature for Be and CH capsules
- Very smooth layers can be made at 0.5 K below the triple point
- Rapid cool techniques show promise in reducing the ice/vapor temperature further while maintaining a sufficiently smooth ice surface

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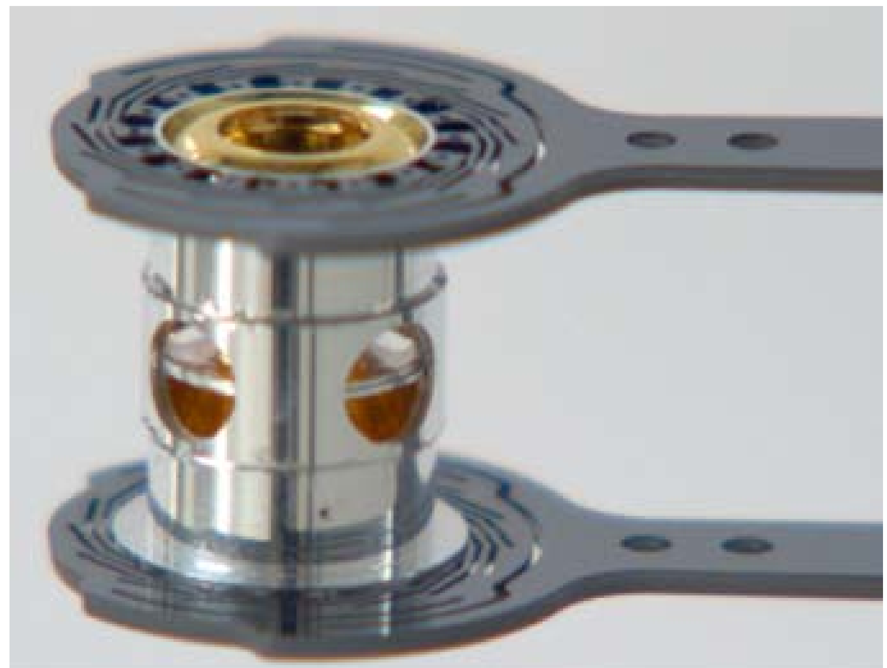
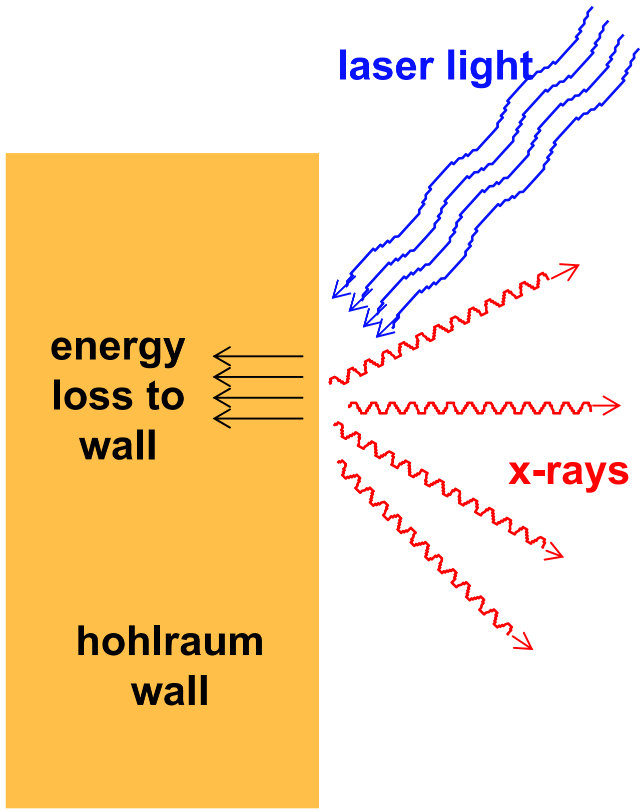
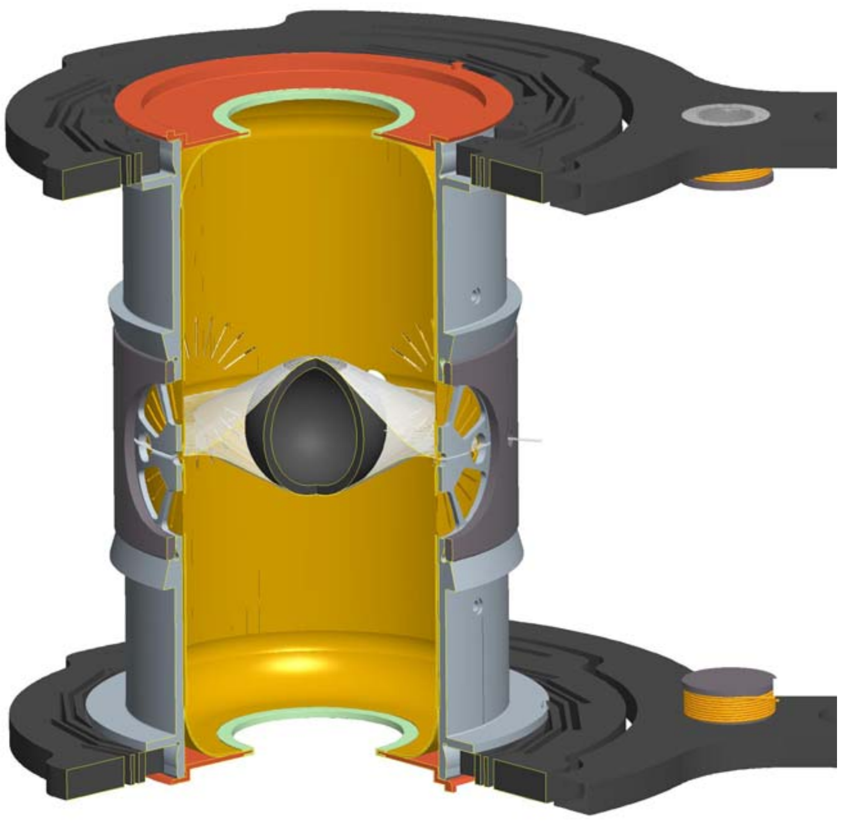


Hohlraums convert laser light to x-rays to drive the capsule





- Energy loss to the wall needs to be minimized

The NIF target design calls for a "cocktail" hohlraum to minimize these losses

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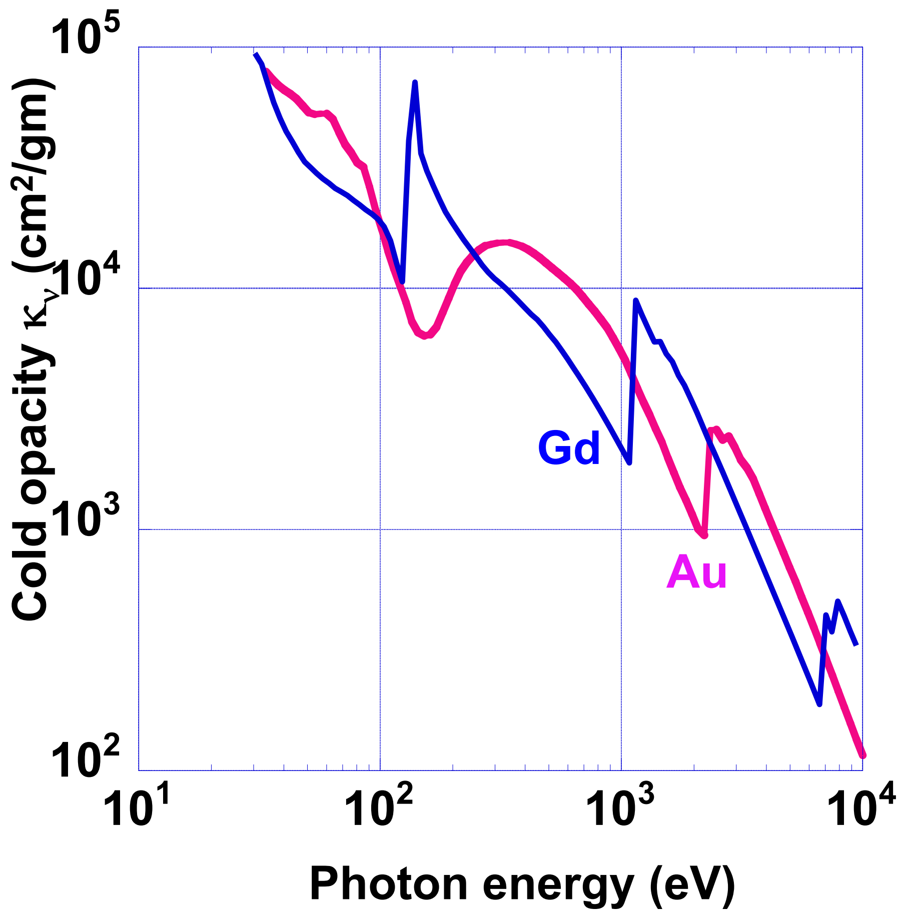
- By combining materials the composite can have a higher net opacity than the individual constituents
- A higher hohlraum wall opacity means more x-ray re-emission and thus a higher drive
- Uranium also fills in the gold opacity gaps

- Example of Gold and Gadolinium

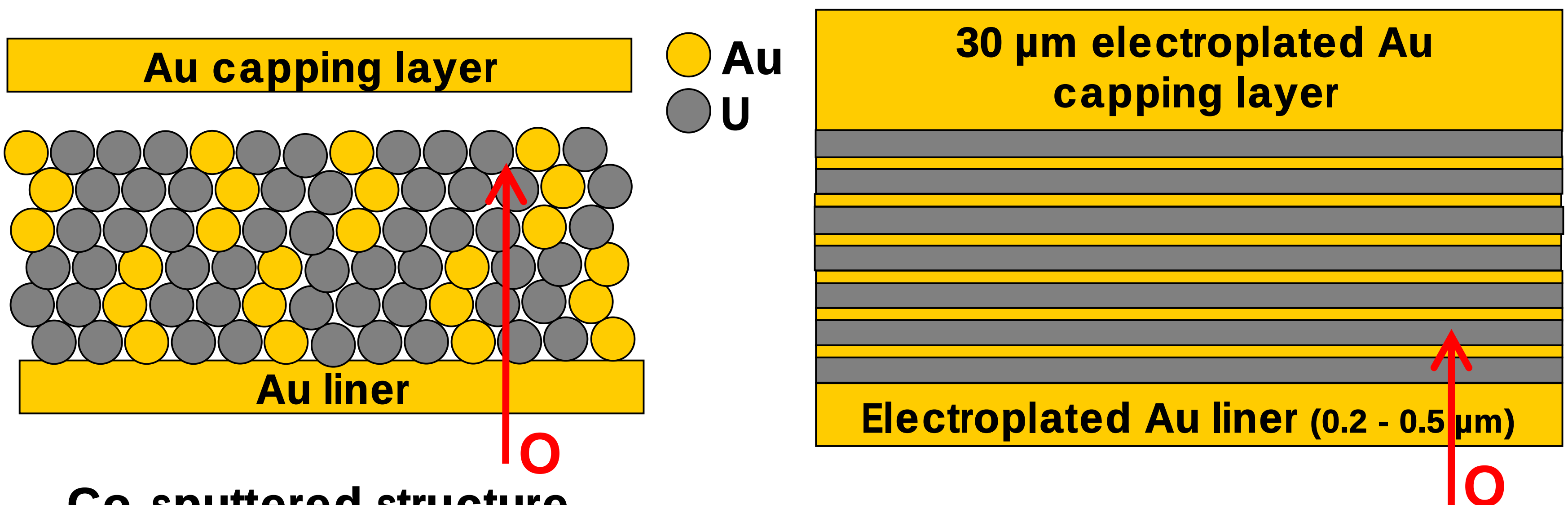


Keeping uranium from oxidizing during the hohlraum fabrication has been a challenge

- The presence of oxygen in the hohlraum wall both cancels the efficiency gain and leads to physical failure

- A dense, multi-layered structure is used to retard oxygen permeation

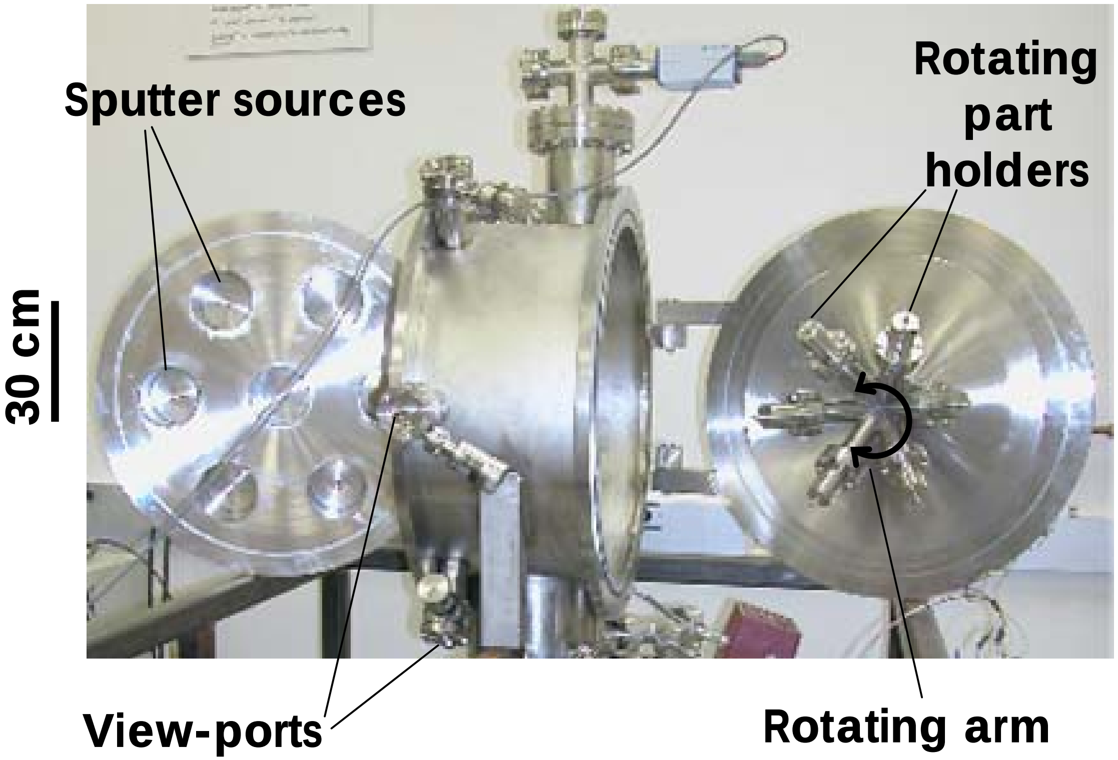
- The NIF hohlraum cocktail is composed of 185 - 30 nm U and 8 nm Au layers

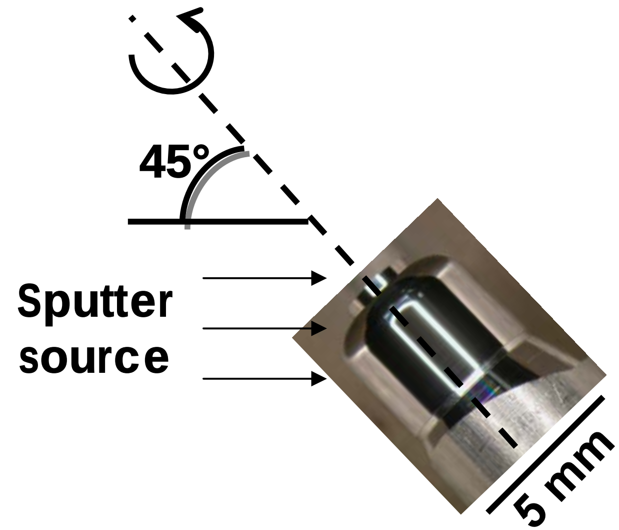


Co-sputtered structure

Multi-layered structure

The multi-layers are made by rotating the substrate between separate U and Au sputter sources





Rotating mandrel onto which material is sputtered

Oxygen mitigation:
- Base pressure - high 10^{-8} Torr
- Monitor chamber with residual gas analyzer

The fabrication takes several individual coating steps

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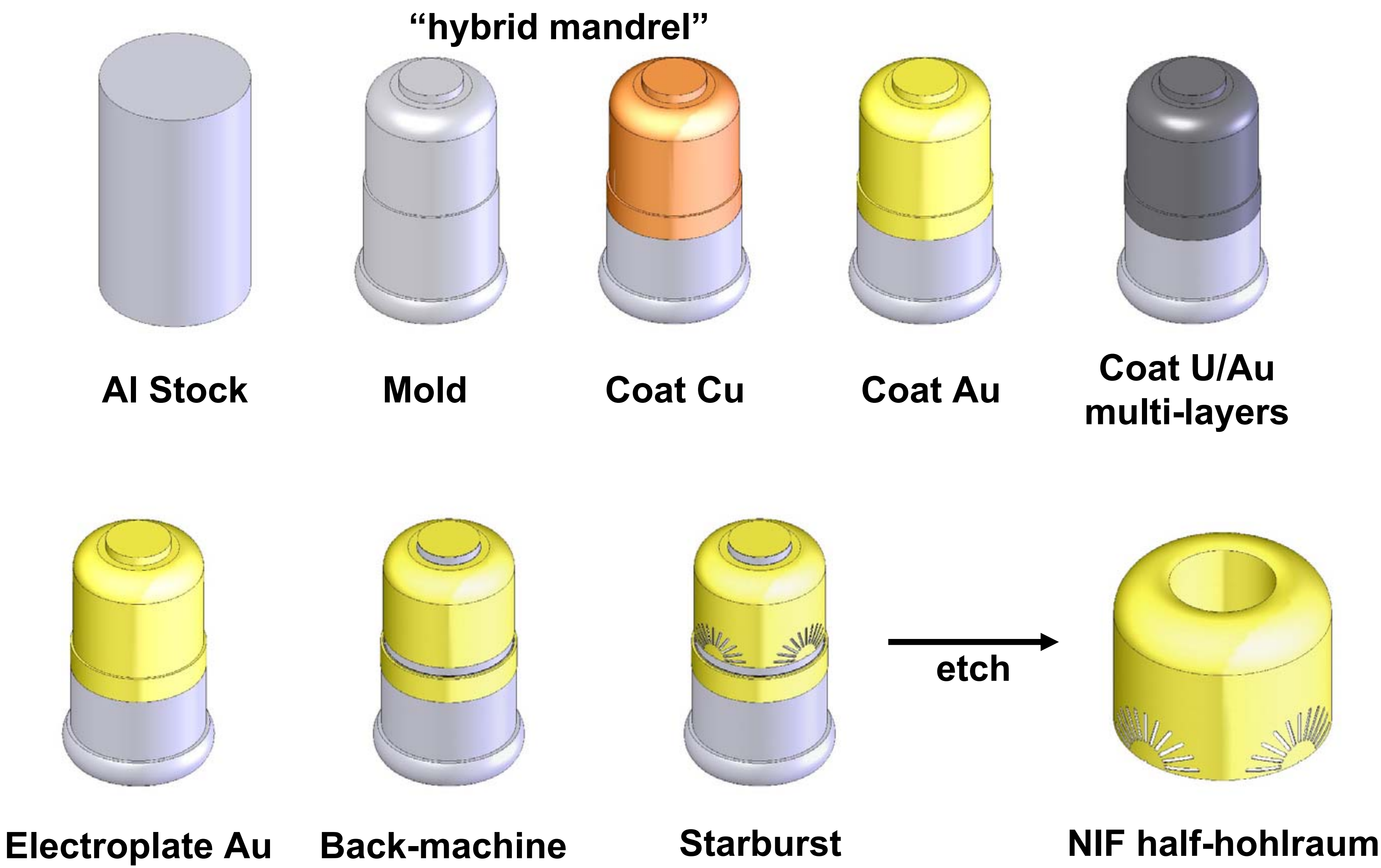
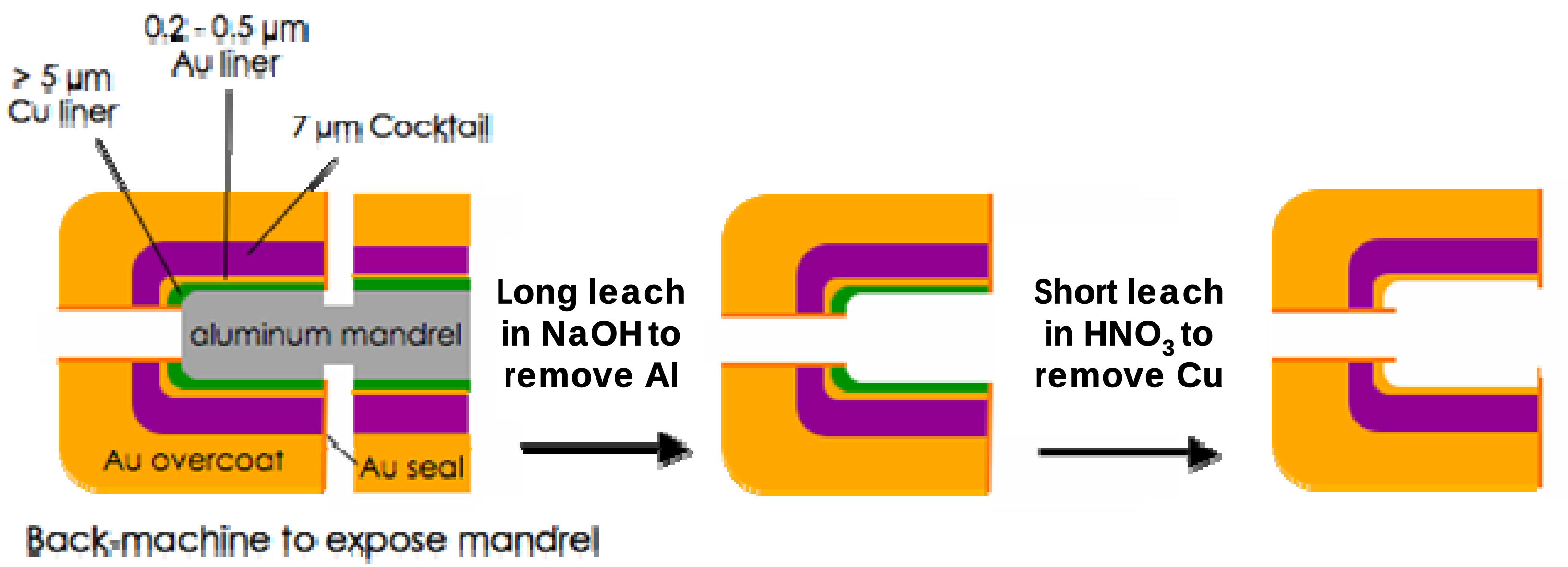


Using a hybrid mandrel allows survival of cocktail hohlraum during leaching

- Leach on full metal mandrels was unsuccessful
  - Al mandrel - NaOH leach (damage to U by oxidation)
  - Cu mandrel - HNO_3 leach (damage to U by disintegration)

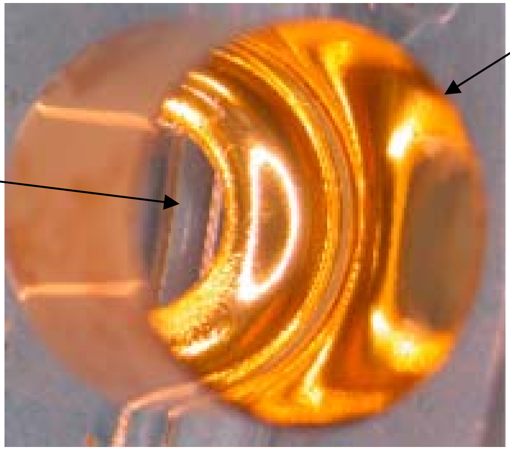
- ≥ 5 μm-thick Cu "tube" protects cocktail during leach in NaOH



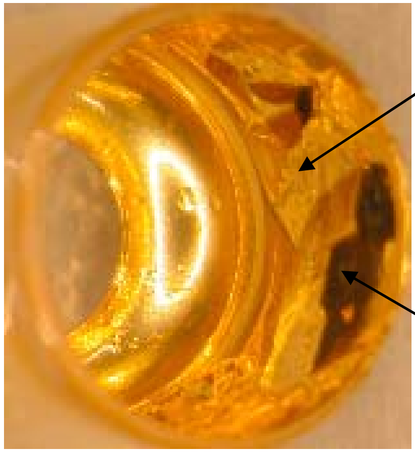
Short leach in nitric acid results in parts that show no immediate visible signs of damage

- Watching under a microscope, part is removed from HNO_3 as soon as the Cu is leached away, typically about 3 minutes

- Damage may still initiate through edges exposed by back-machining and possibly through the Au liner



Pristine NIF-scale cocktail hohlraum half



Example of failure during HNO_3 leach

- A 2-4 week lifetime is required for assembly, currently more than half meet this goal

Significant progress has been made producing NIF hohlraums

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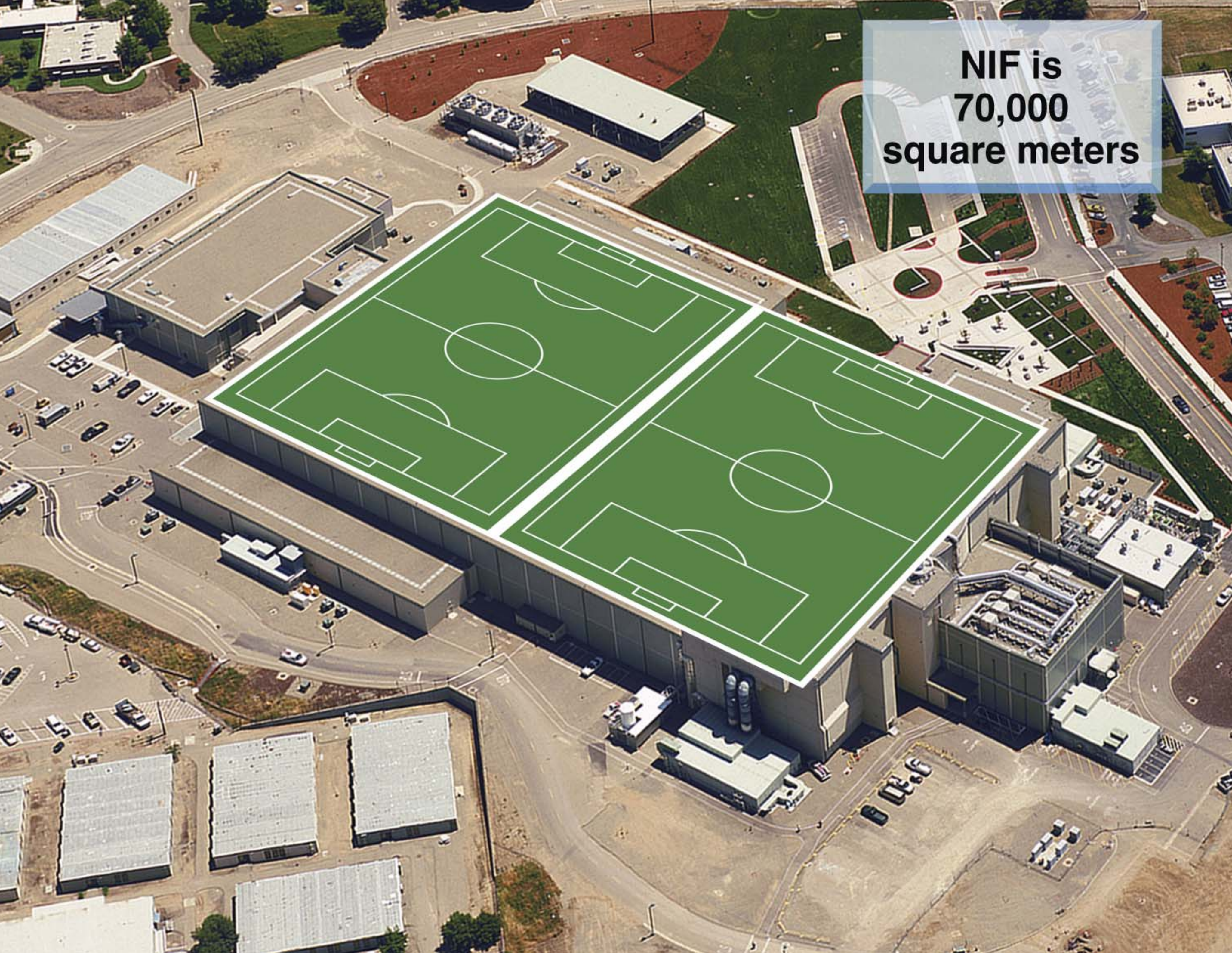
- We've demonstrated that cocktail hohlraum halves with sufficient shelf-life (> 4 weeks) can be fabricated.
  - An increase in production capabilities is planned to produce the 4-6 halves per day needed for shots starting in late 2008.
- A more thorough understanding of the oxidative degradation mechanisms is being pursued in order to further increase the components shelf-life.
- As noted earlier, effort is now being focused on precision assembly of the delicate capsule and fill tube parts into hohlraums

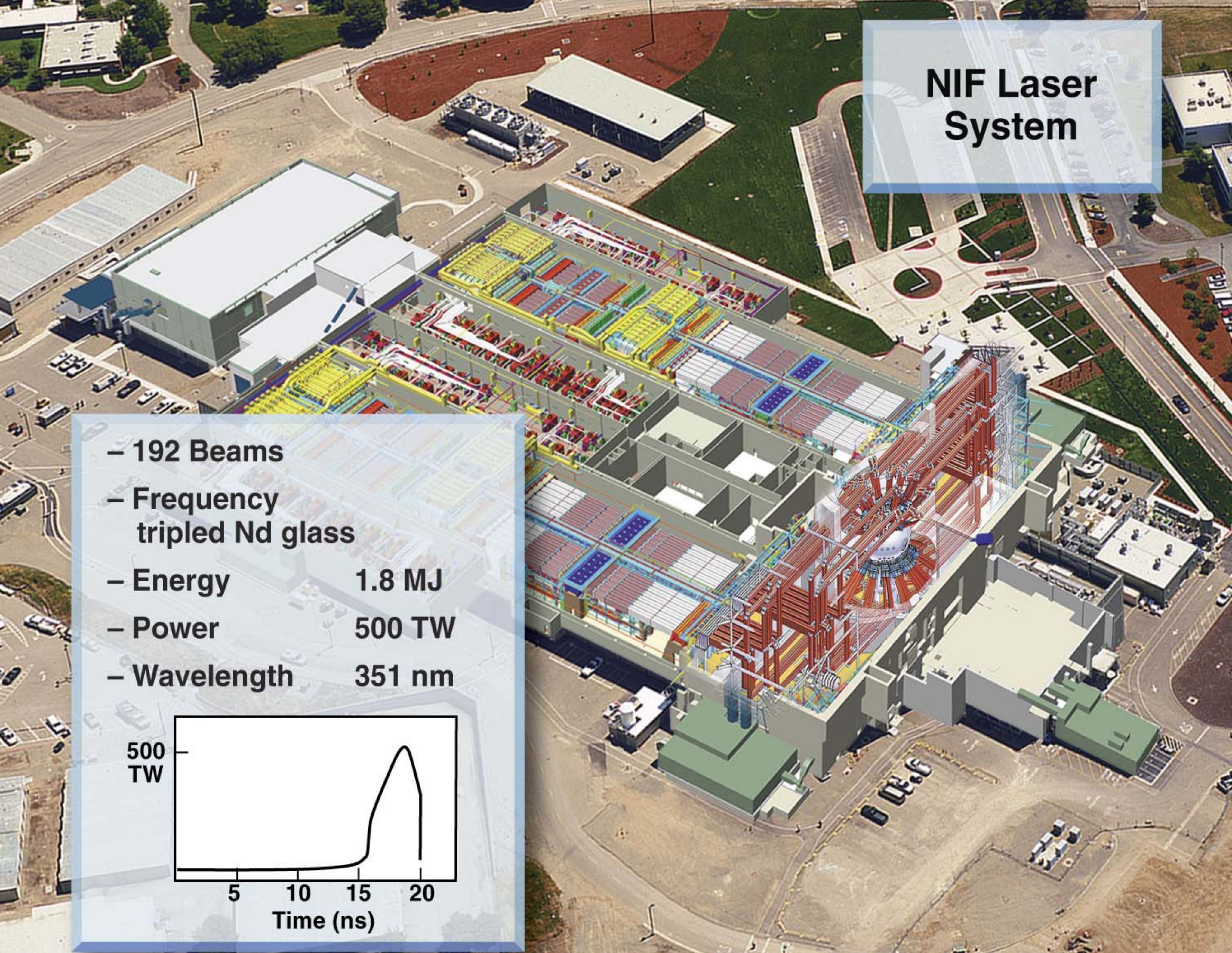
Outline

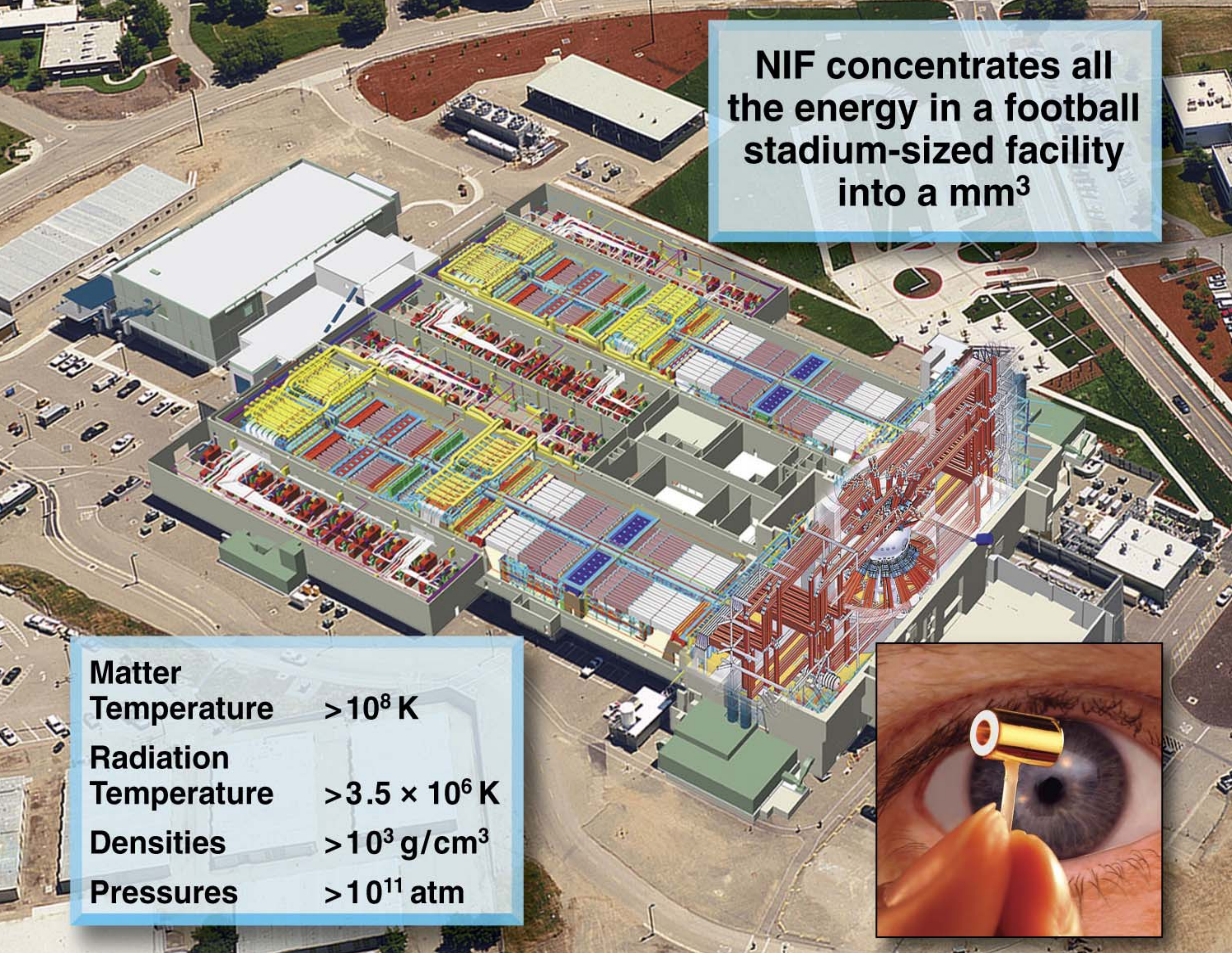
- Capsule fabrication and characterization
- Cryo layer formation and characterization
- Hohlraum fabrication
- Status of the National Ignition Facility


San Francisco
(45 mi.)
Lawrence Livermore National Laboratory
National Ignition Facility

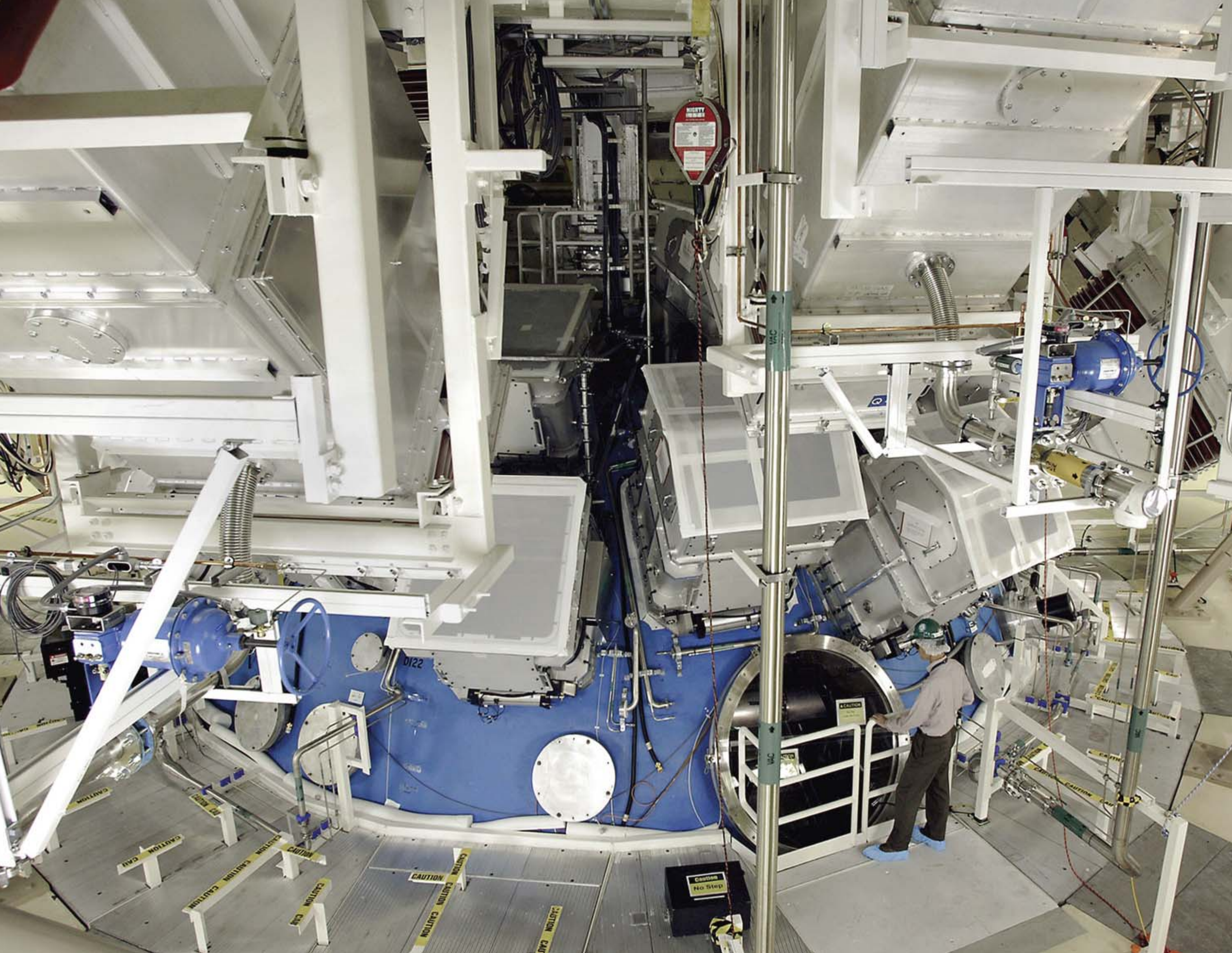

National
Ignition
Facility


NIF is
70,000
square meters

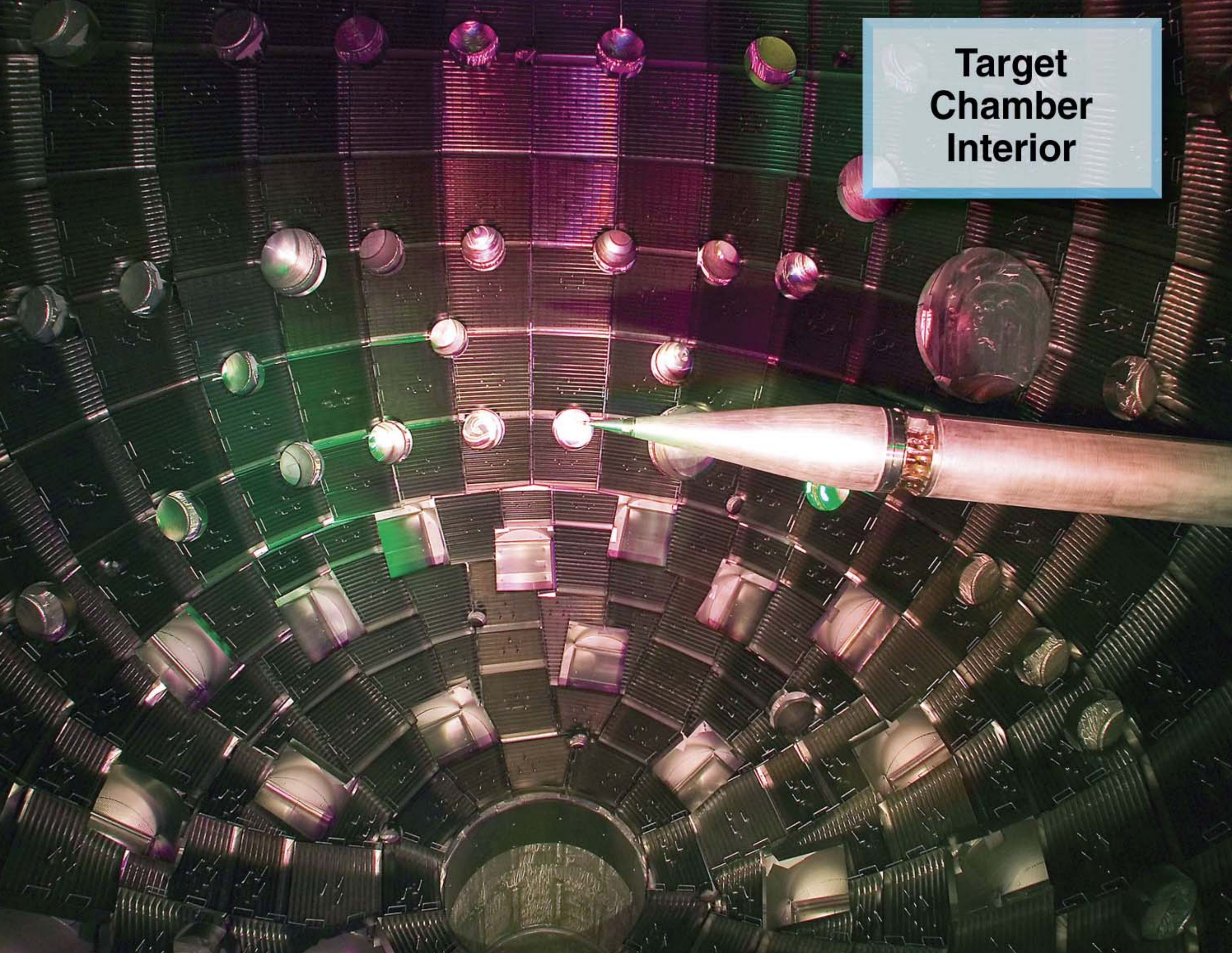

NIF Laser System
– 192 Beams
– Frequency tripled Nd glass
– Energy 1.8 MJ
– Power 500 TW
– Wavelength 351 nm
500 TW
5
10
15
20
Time (ns)


NIF concentrates all the energy in a football stadium-sized facility into a mm³
Matter Temperature >10⁸ K
Radiation Temperature >3.5 × 10⁶ K
Densities >10³ g/cm³
Pressures >10¹¹ atm

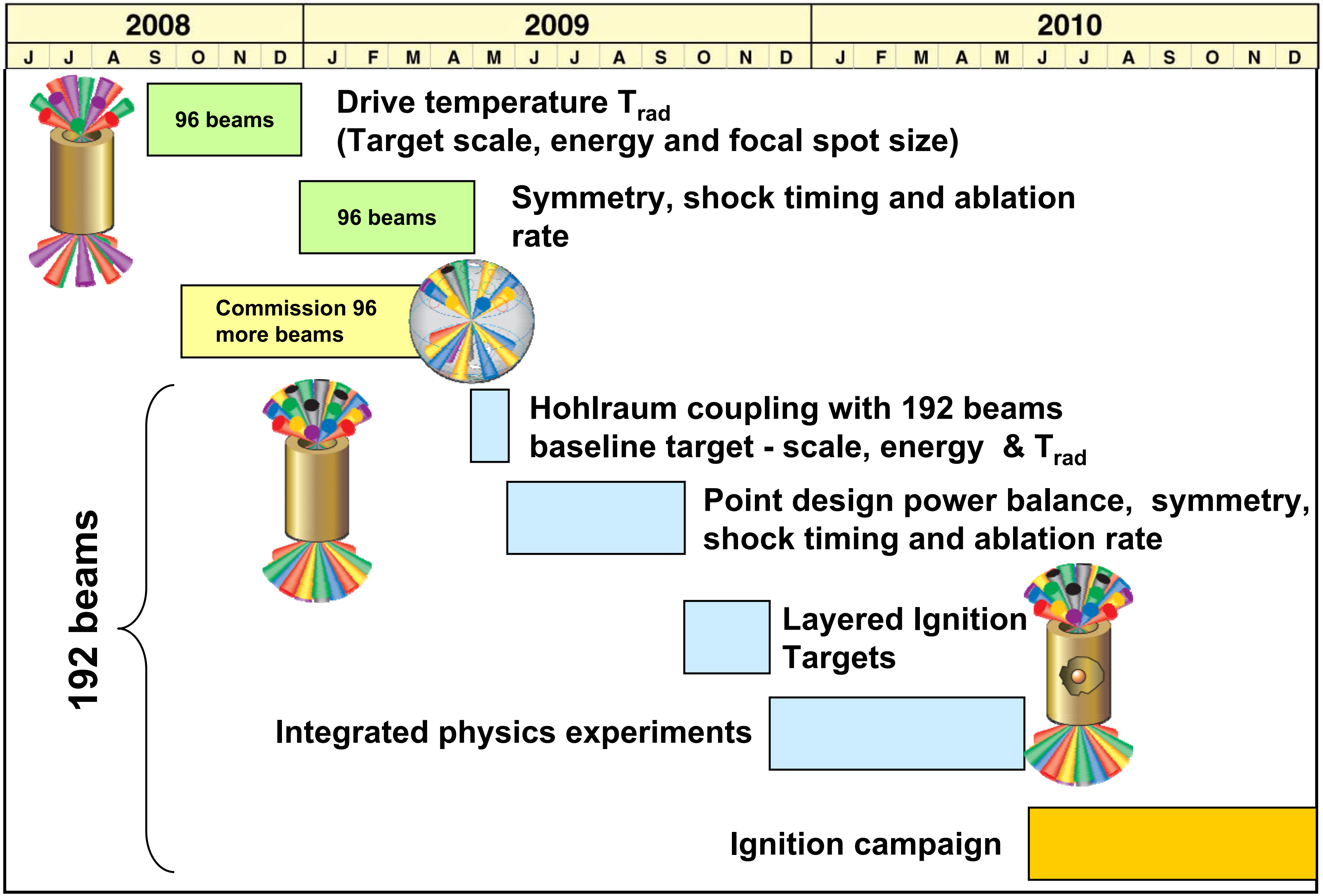

Target
Chamber



CAUTION
Caution
No Step
VAC
D122


Target
Chamber
Interior

The National Ignition Campaign is focused on preparing for the first ignition expts in 2010

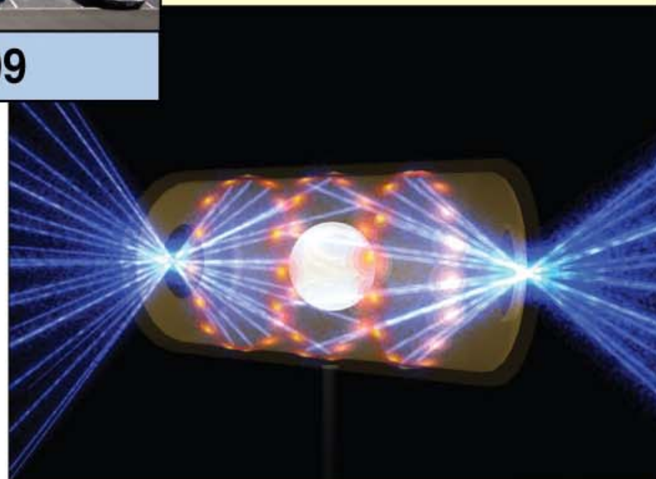


NIF Master Strategy

NIF Project

Completion in 2009

National Ignition Campaign



2006—2012

National User Facility

2009—2030

NIF-0506-12063r9_L1
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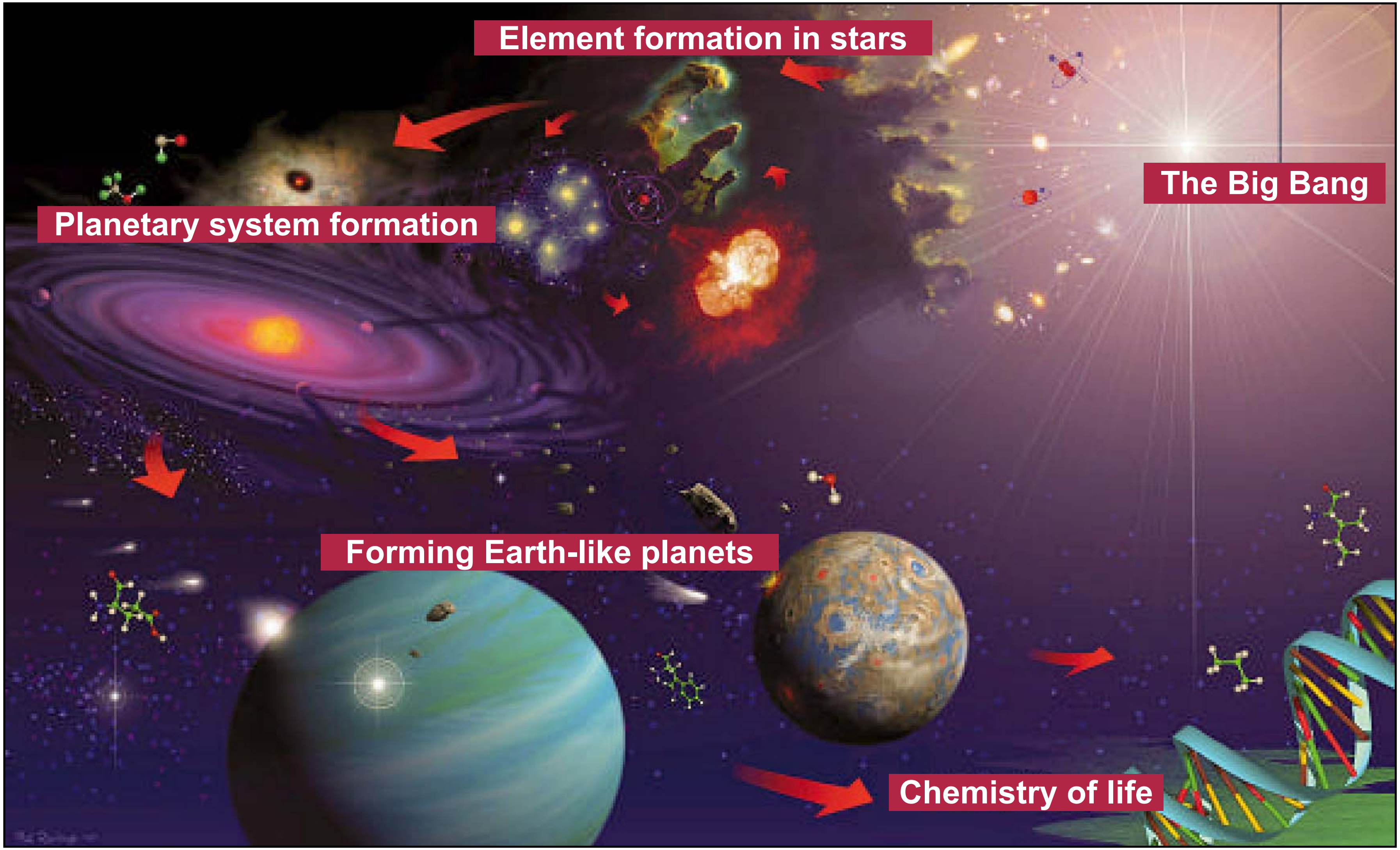
Our vision: open NIF to the outside scientific community to pursue frontier high energy density laboratory science

The National Ignition Campaign

The physics of the universe…



National Ignition Facility

~~Three~~ Two Years to a New Age for Science


NIF-0506-12035
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Robert Cook