

# **Recent Advances in Indirect Drive ICF Target Physics**

**Presentation to  
20th IAEA Fusion Energy Conference**



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Lawrence Livermore National Laboratory**

**November 1-6, 2004**

# Outline

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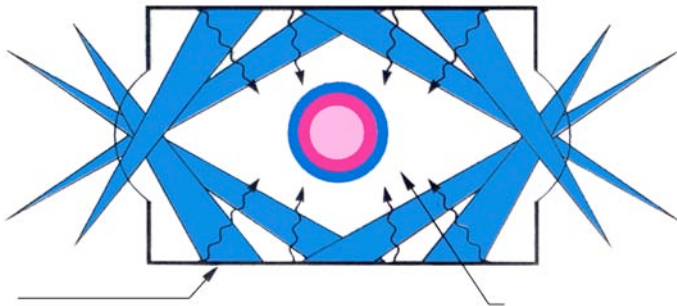


- **Ignition Introduction**
- **NIF status**
- **Target Requirements and recent advances**
  - **Energetics**
  - **Symmetry**
  - **Implosion dynamics**
  - **Target Fabrication**
- **Plan for experiments leading to first ignition target shots in 2010**

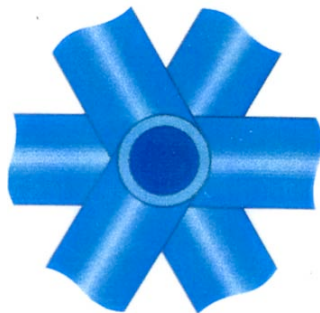


# There are two principal approaches to compression in Inertial Confinement Fusion

**Indirect Drive**

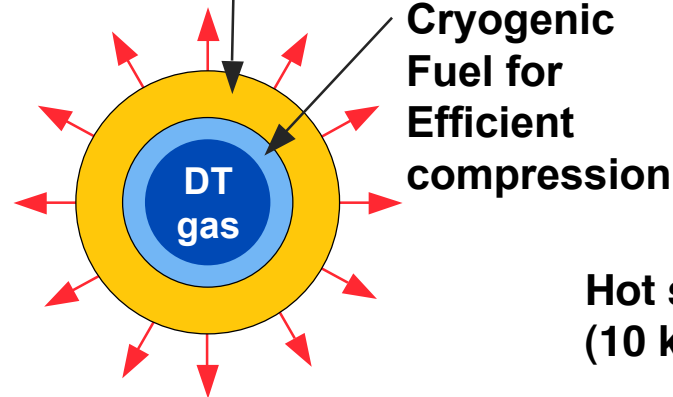


**Direct Drive**



Inertial Confinement Fusion uses direct or indirect drive to couple driver energy to the fuel capsule

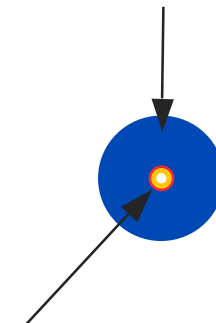
**Low-z Ablator for Efficient absorption**



Spherical ablation with pulse shaping results in a rocket-like implosion of near Fermi-degenerate fuel

**Cold, dense main fuel (200-1000 g/cm<sup>3</sup>)**

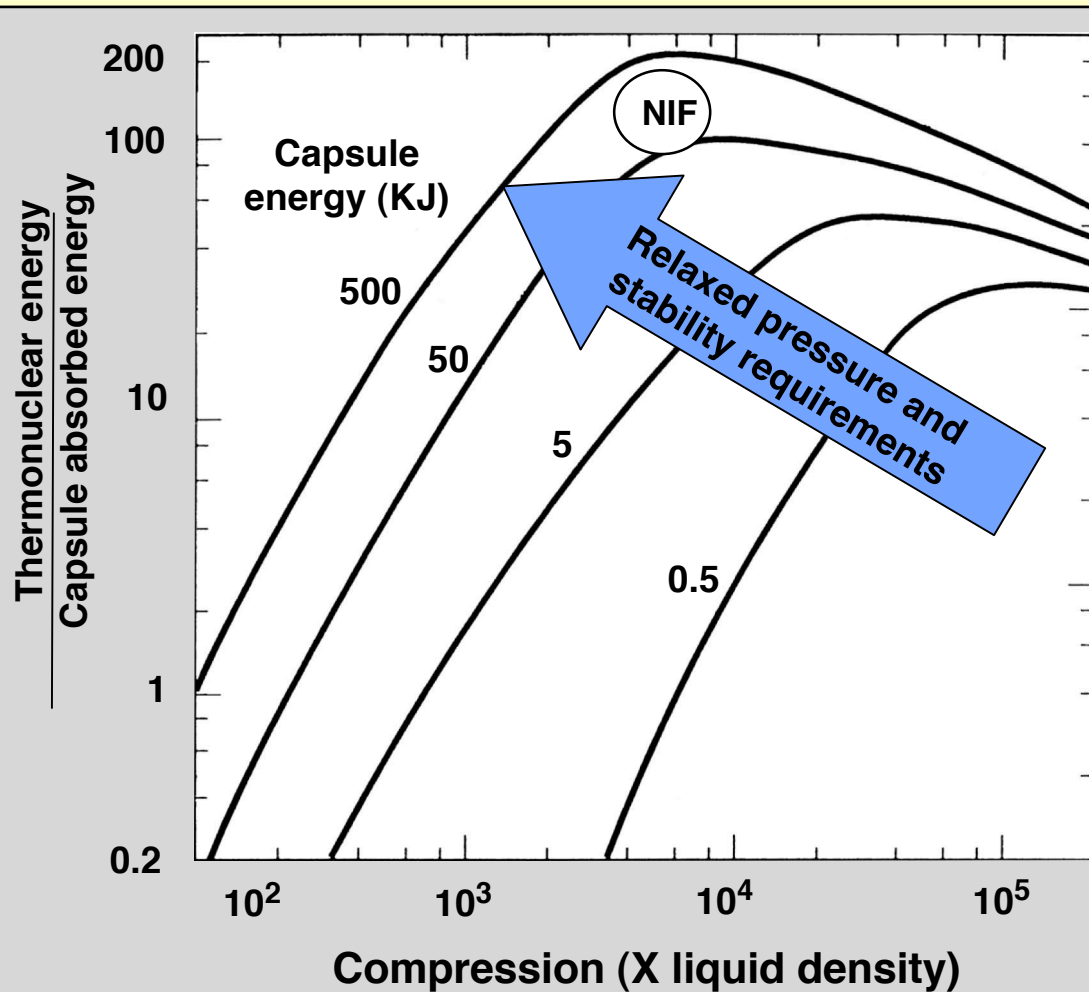
**Hot spot (10 keV)**



Spherical collapse of the shell produces a central hot spot surrounded by cold, dense main fuel

# The scale of ignition experiments is determined by the limits to compression

Capsule energy gain plotted versus compression



- Pressure is limited to  $P(\text{Max}) \sim 100$  Mbar by Laser Plasma Interaction (LPI) effects
- Given the pressure limits, hydrodynamic instabilities limit implosion velocities to

$$V_{\text{imp}} < 4 \times 10^7 \text{ cm/sec}$$

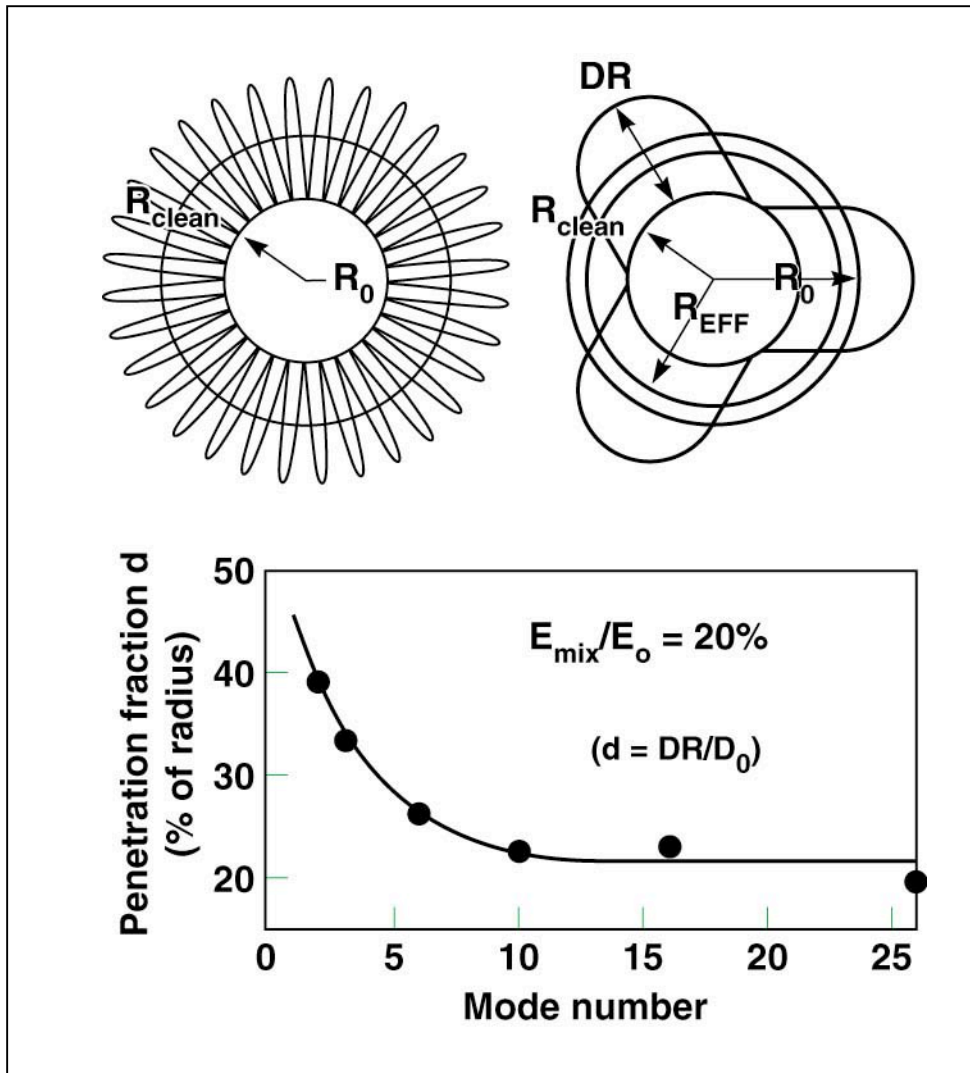
and this limits the maximum compression

- Symmetry and pulse shaping must be accurately controlled to approach the maximum compression

# The impact of most effects that degrade an implosion can be specified as a hot spot perturbation amplitude



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- Long Wavelength Perturbations
  - Hohraum asymmetry
  - Pointing errors
  - Power Imbalance
  - Capsule misplacement in chamber
- Short Wavelength Perturbations
  - DT ice roughness
  - Ablator roughness
  - Ablator microstructure

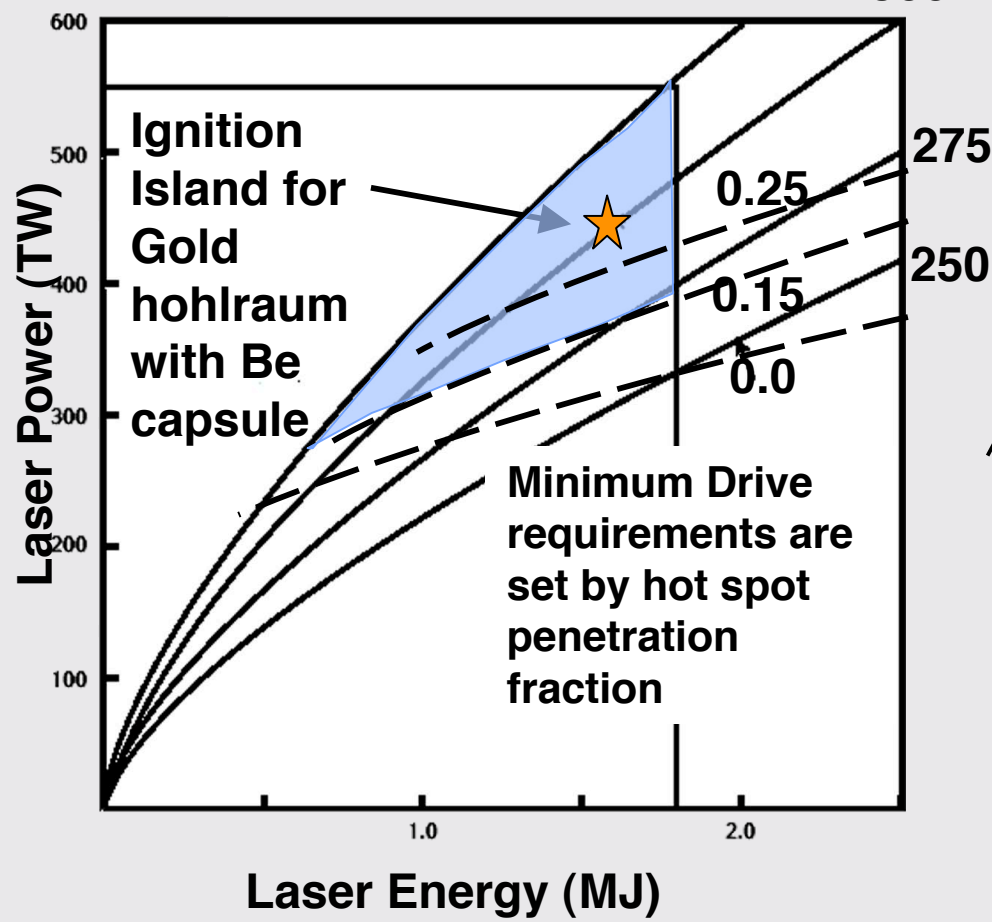
The hot spot penetration is the fraction of the hot spot perturbed by the various sources of error

# The “ignition island” size provides an integral measure of the robustness of the NIF ignition designs



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MaxDrive temperatures are set by LPI effects



We expect ~15% hot spot penetration fraction based on detailed 2D and 3D calculations at the specified target fabrication and NIF performance levels

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**The beampath infrastructure for all 192 beams is complete and the first four beams have been activated for experiments**

*NIF Project*



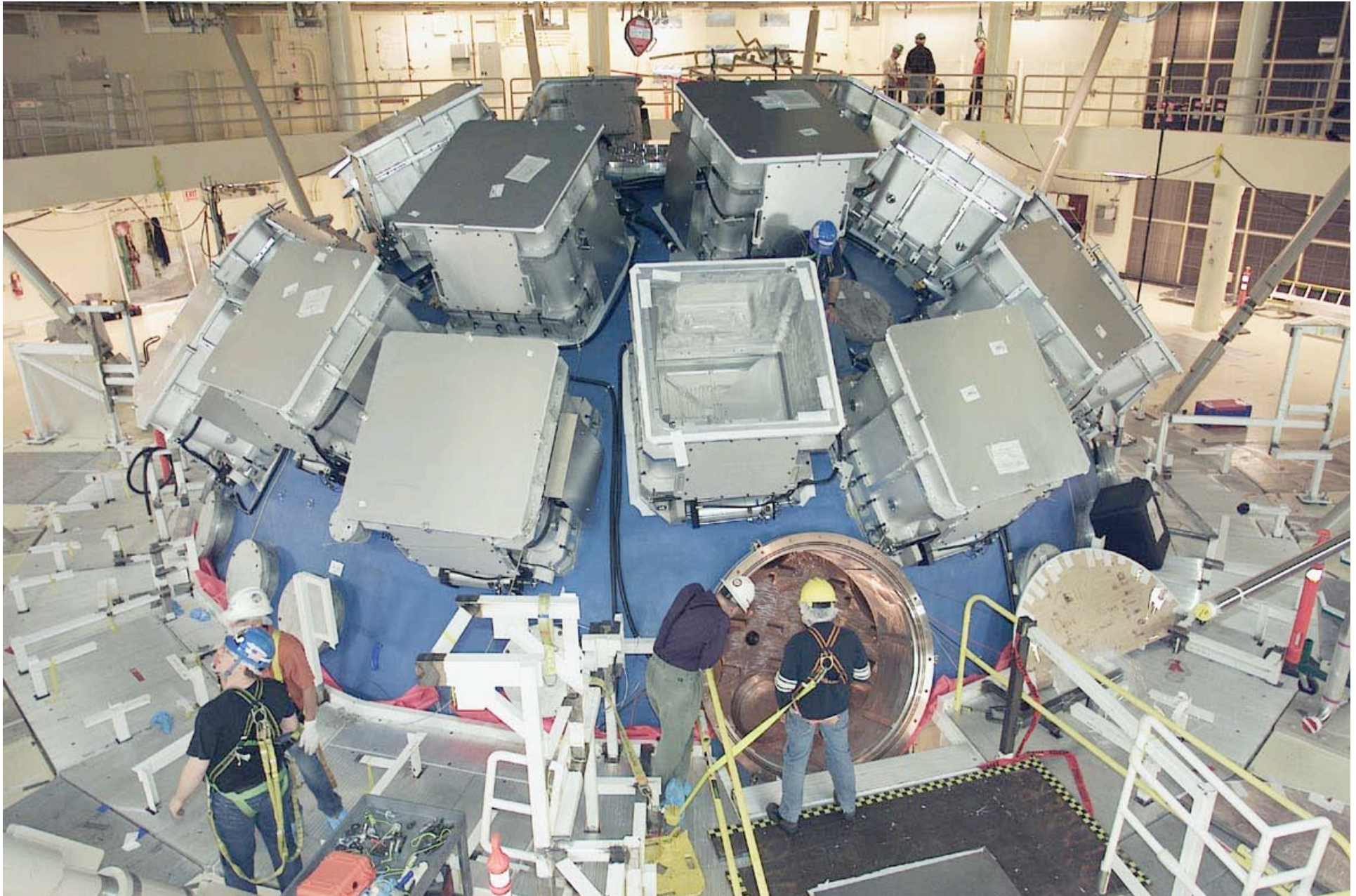
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# NIF Target Chamber upper hemisphere



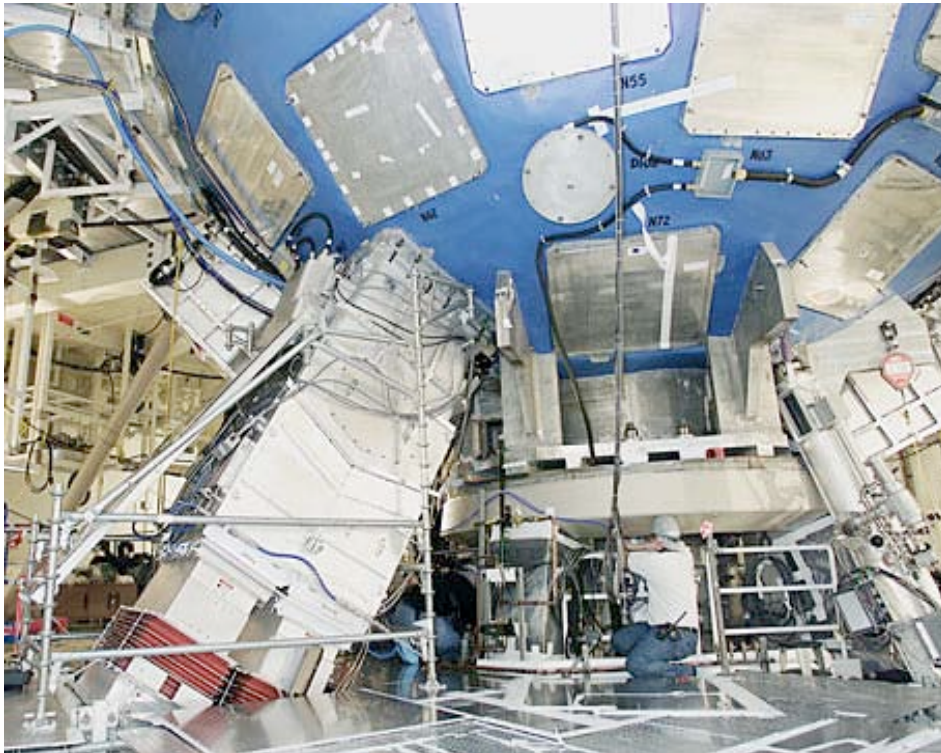
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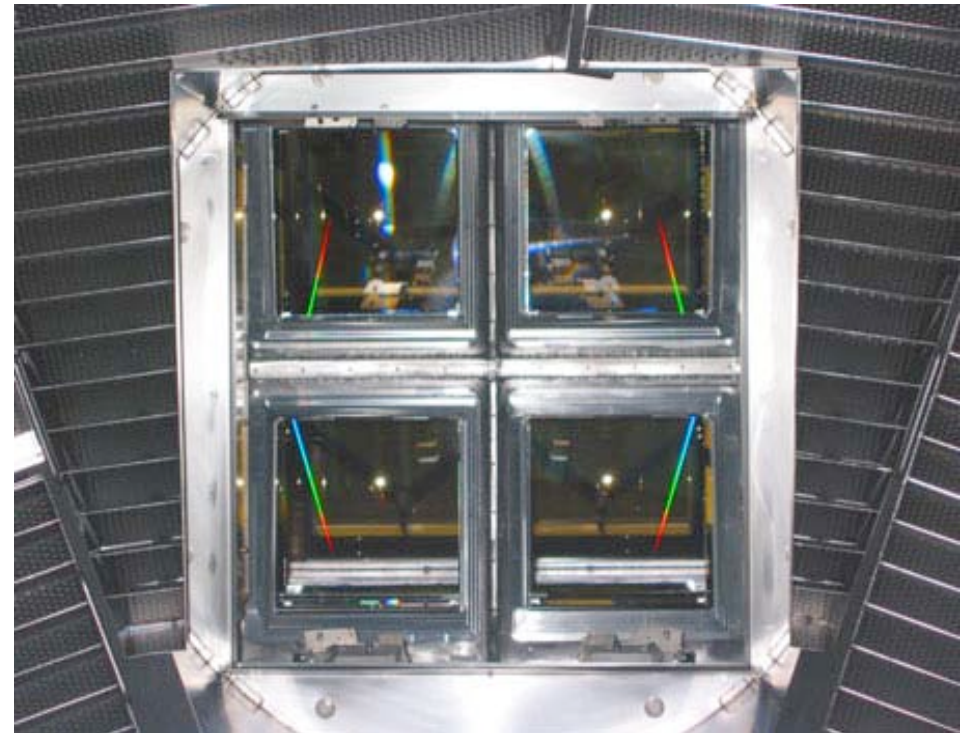
# First four NIF beams installed on the target chamber



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Quad 31b beamtubes and optics are installed and operational

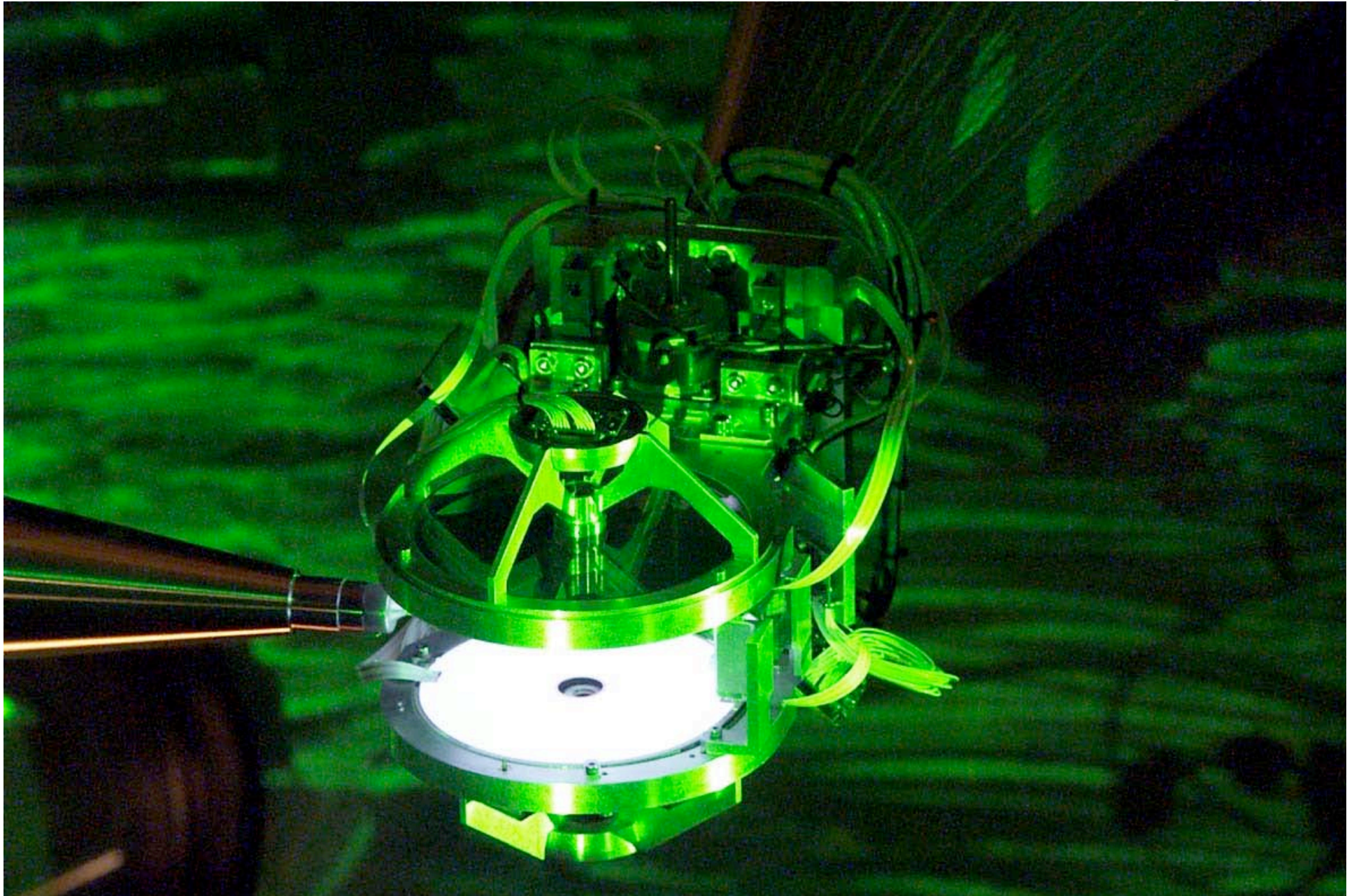


View from inside the target chamber

# Target positioner and alignment system inside target chamber



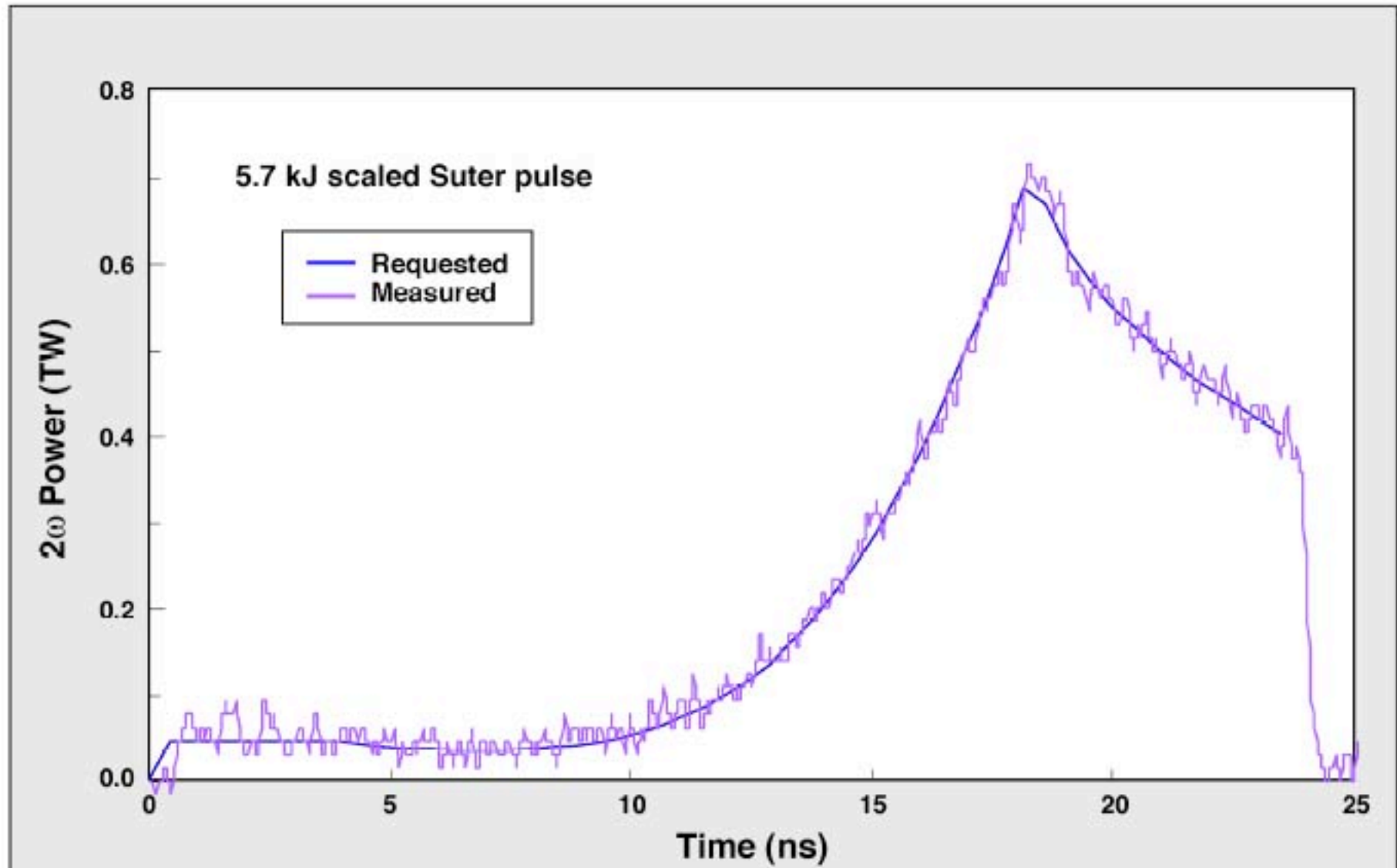
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# NIF has demonstrated the pulse shaping precision and flexibility required for Ignition experiments



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# The NIF Early Light (NEL) commissioning of four laser beams has demonstrated all of NIF's primary performance criteria on a per beam basis

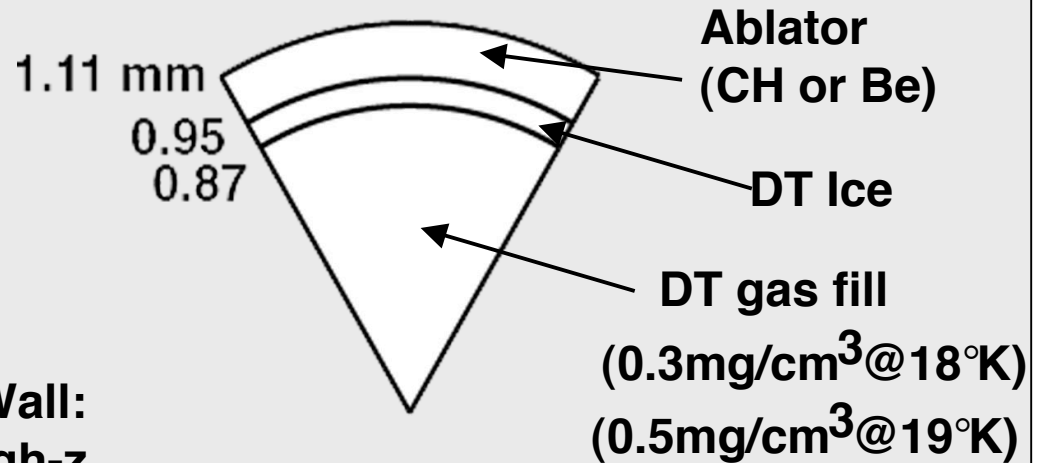
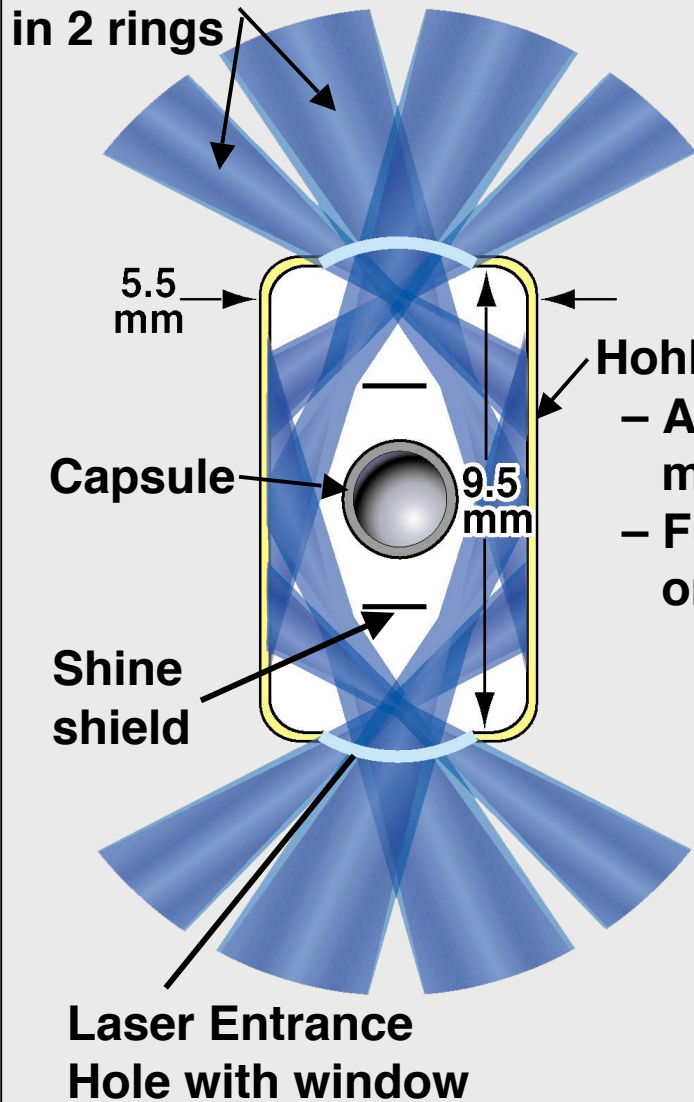
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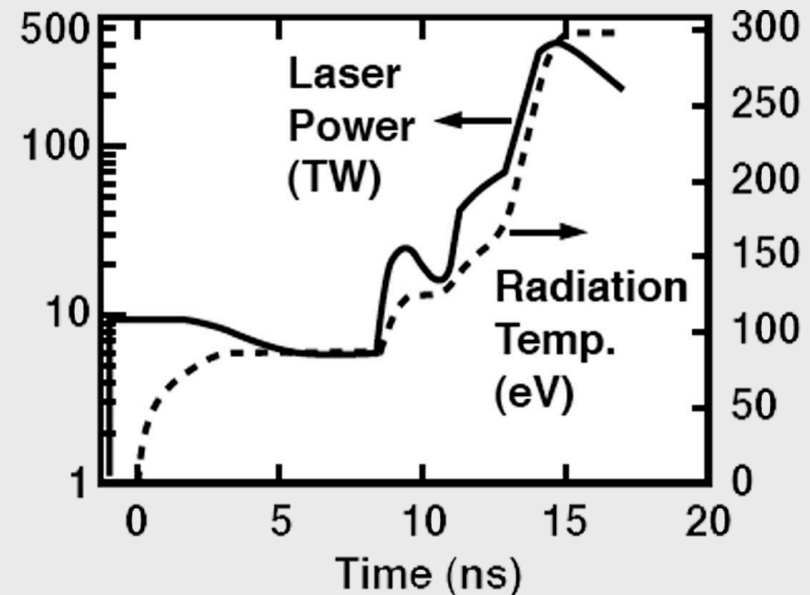
- 21 kJ of 1w light (Full NIF Equivalent = 4.0 Mjoule)
- 11 kJ of 2w light (Full NIF Equivalent = 2.2 Mjoule - non-optimal crystals)
- 10.4 kJ of 3w light (Full NIF Equivalent = 2.0 Mjoule)
- 25 ns shaped pulse
- < 5 hour shot cycle (UK funded shot rate enhancement program)
- Better than 6% beam contrast
- Better than 2% beam energy balance
- Beam relative timing to 6 ps

# NIF Indirect Drive target schematic

Laser Beams  
in 2 rings



Typical Pulse Shape



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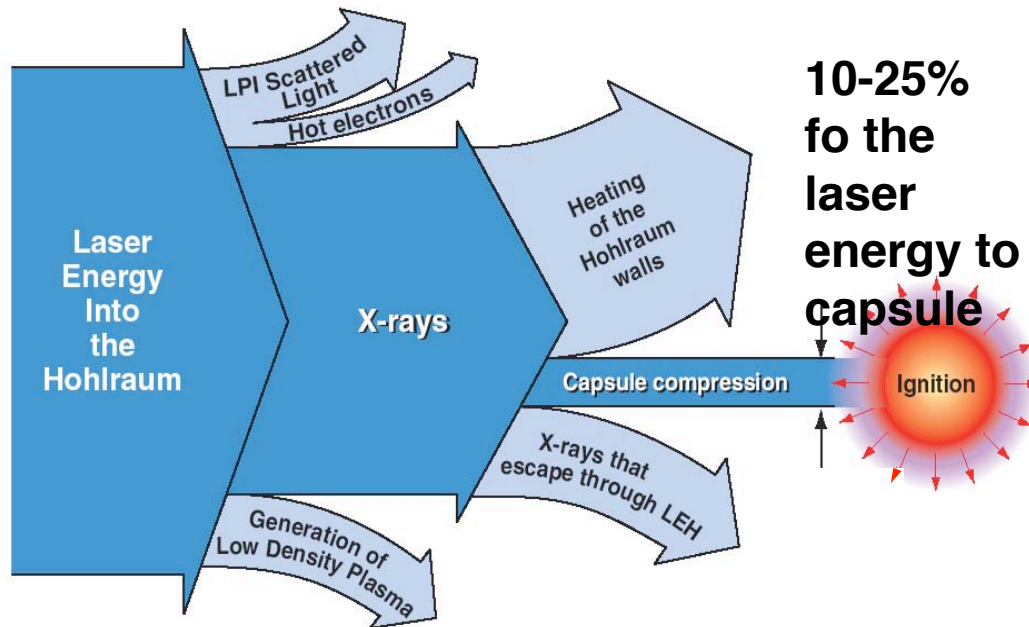




# The Indirect drive ignition point design continues to evolve to optimize coupling efficiency



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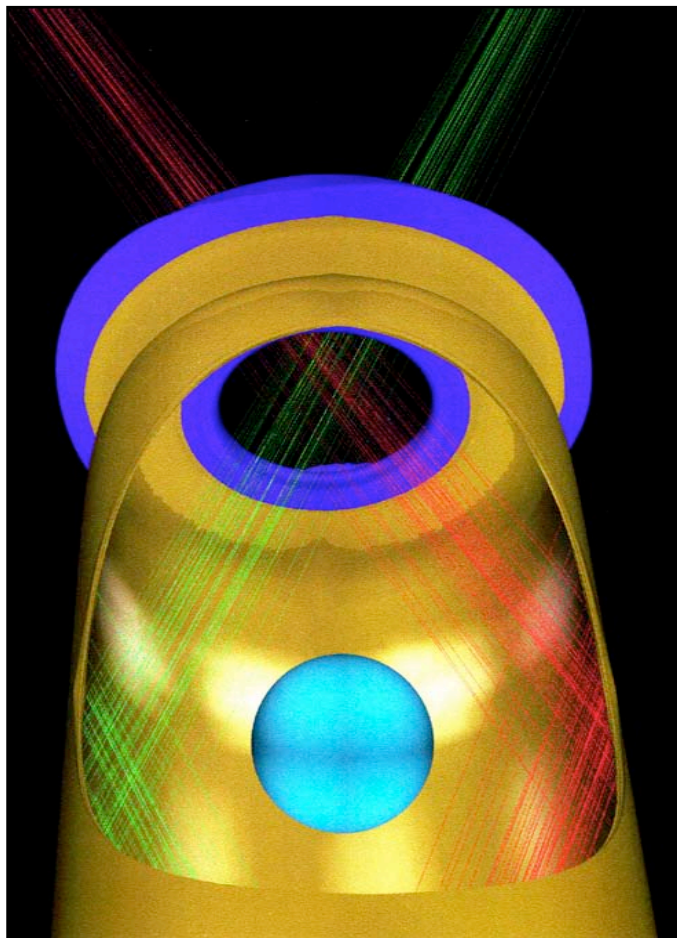


	Au with CH Capsule	Au with Be Capsule	Cocktails with Be Capsule
Laser light (MJ) Absorbed	1.45	1.45	1.45
xrays	1.10	1.10	1.10
wall loss	0.65	0.62	0.53
hole loss	0.30	0.28	0.33
capsule	0.15	0.20	0.24
efficiency (%)	10.5%	13.5%	16.5%

# Cocktail ignition target burns with near 1D yield in 3D calculations with both asymmetry and surface roughness

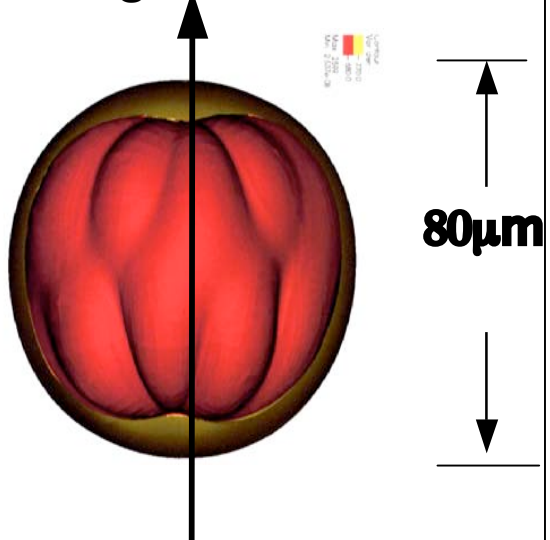


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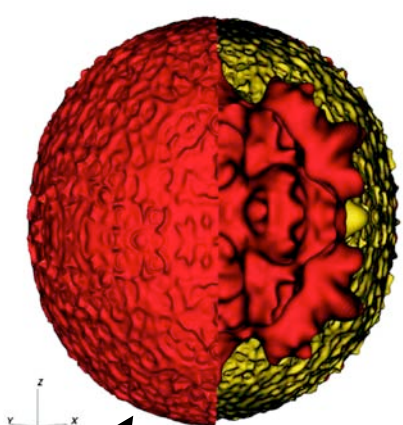
**Ignition - hohlraum only perturbations**

600 g/cc surface



Hohlraum Axis (z)

**Ignition - capsule and hohlraum perturbations**



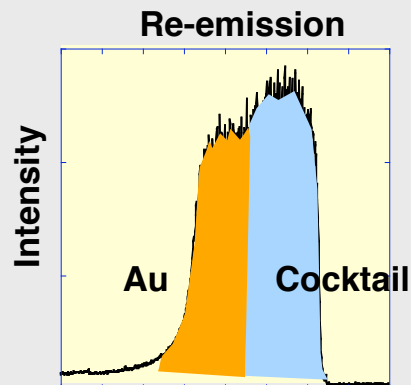
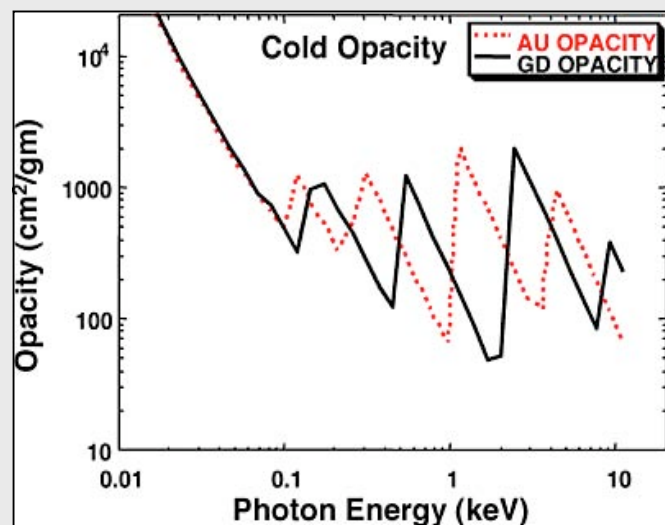
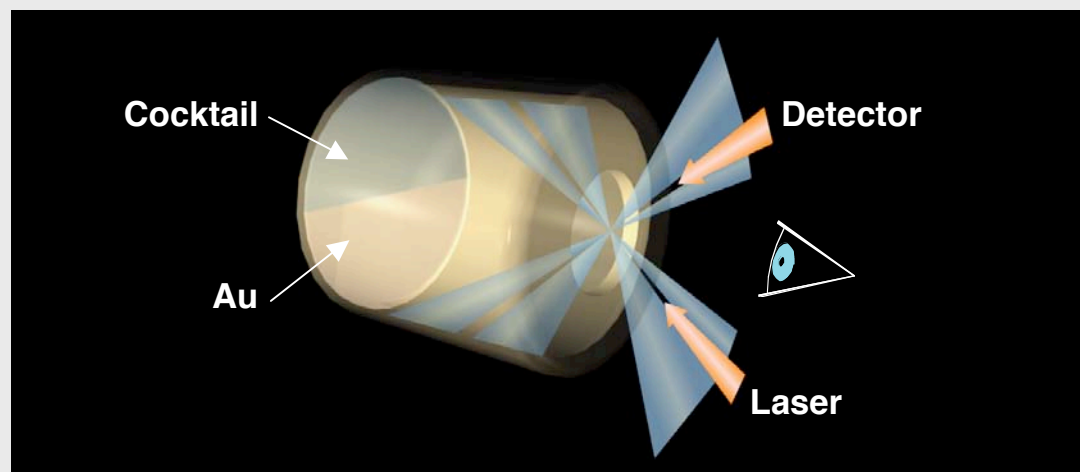
Stagnation shock

400 g/cc density isosurface

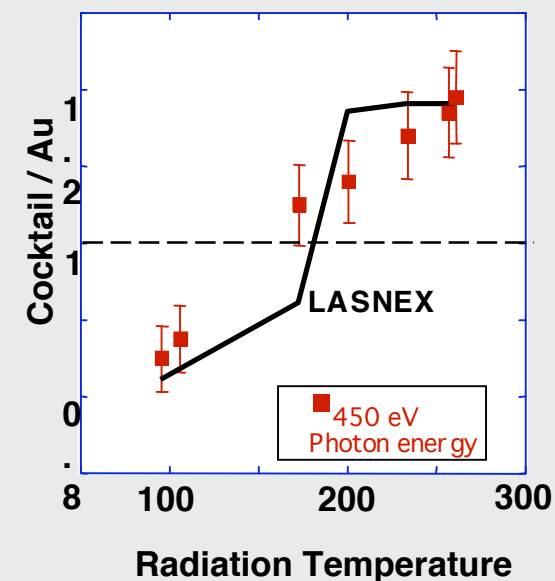
The Hydra code is used for 3D calculations on the ASCI computers

Omega experiments show larger albedo for cocktail walls made of  $((U Nb_{0.14})_{0.6}, Au_{0.2}, Dy_{0.2})$

Hohlraum experiments with split back plate verify high x-ray re-emission



Intensity ratio of Cocktail/Au is in agreement with LASNEX calculations

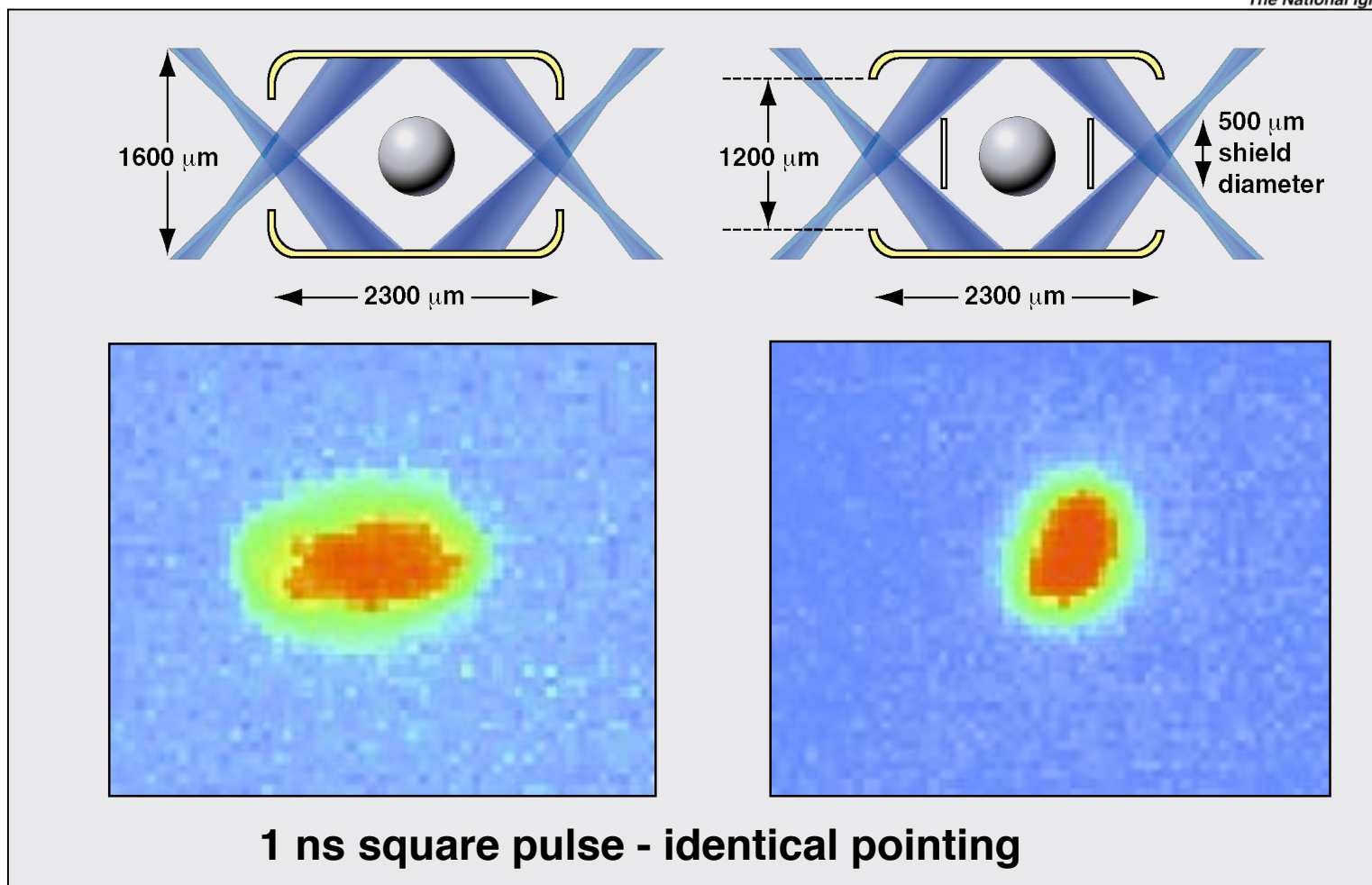


Agreement with LASNEX calculations indicate that cocktail materials may be advantageous compared to Au. Integrated hohlraum experiments with unsmoothed beams have not demonstrated higher  $T_{RAD}$  but measure higher laser backscatter

# LEH shields provided a 20% increase in capsule radiation flux at Nova and an extra symmetry tuning degree of freedom



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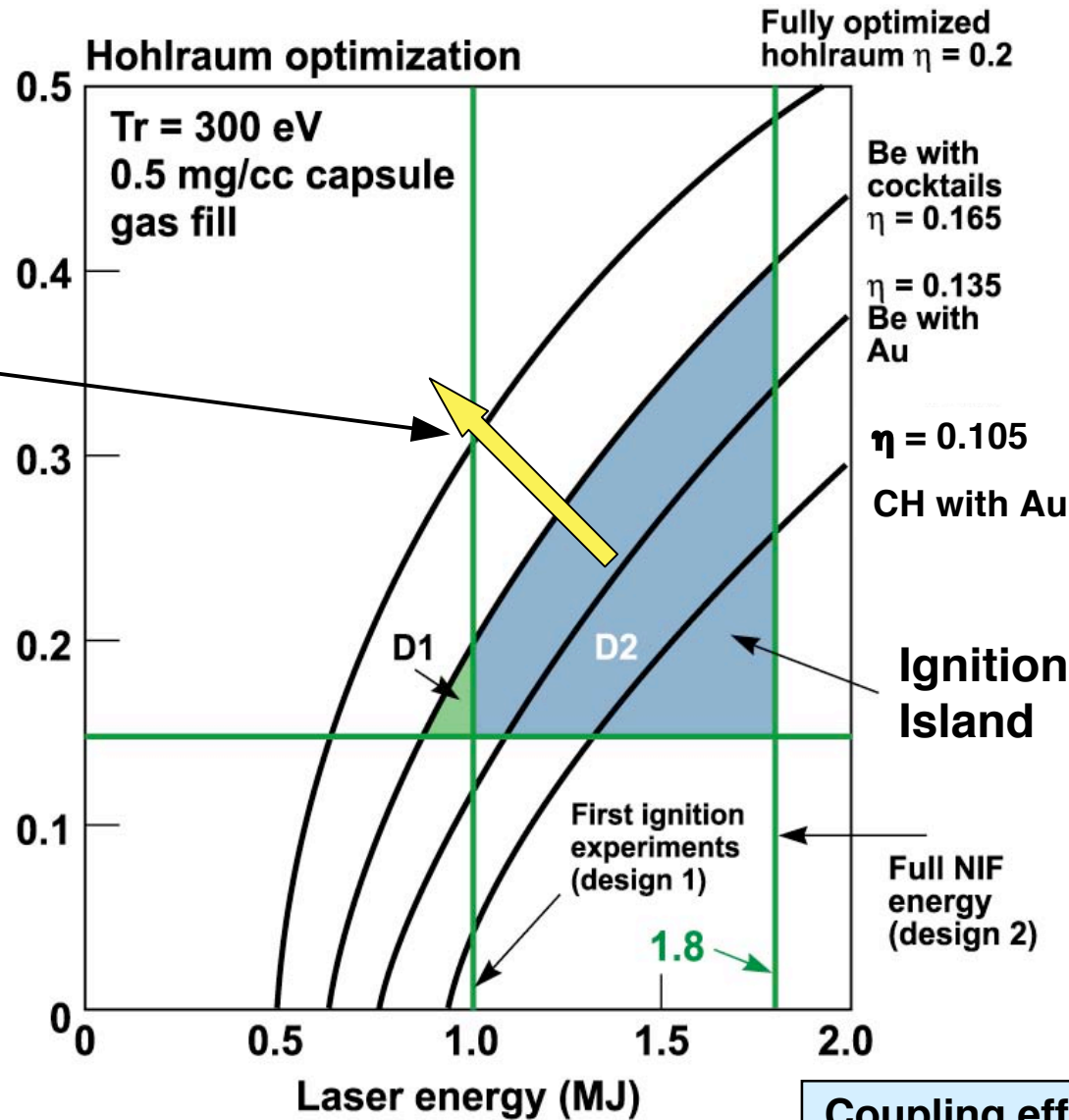


- LEH shields will be retested on Omega in NIF-like multicone geometry
- Similar advantages possible for NIF ignition hohlraums - depends on beam propagation with added plasma source

# Enhancements in hohlraum coupling efficiency expected by 2010 will substantially increase the ignition island

The goal of Hohlräum Energetics is to maximize hohlraum coupling efficiency

Hot spot penetration fraction (e)



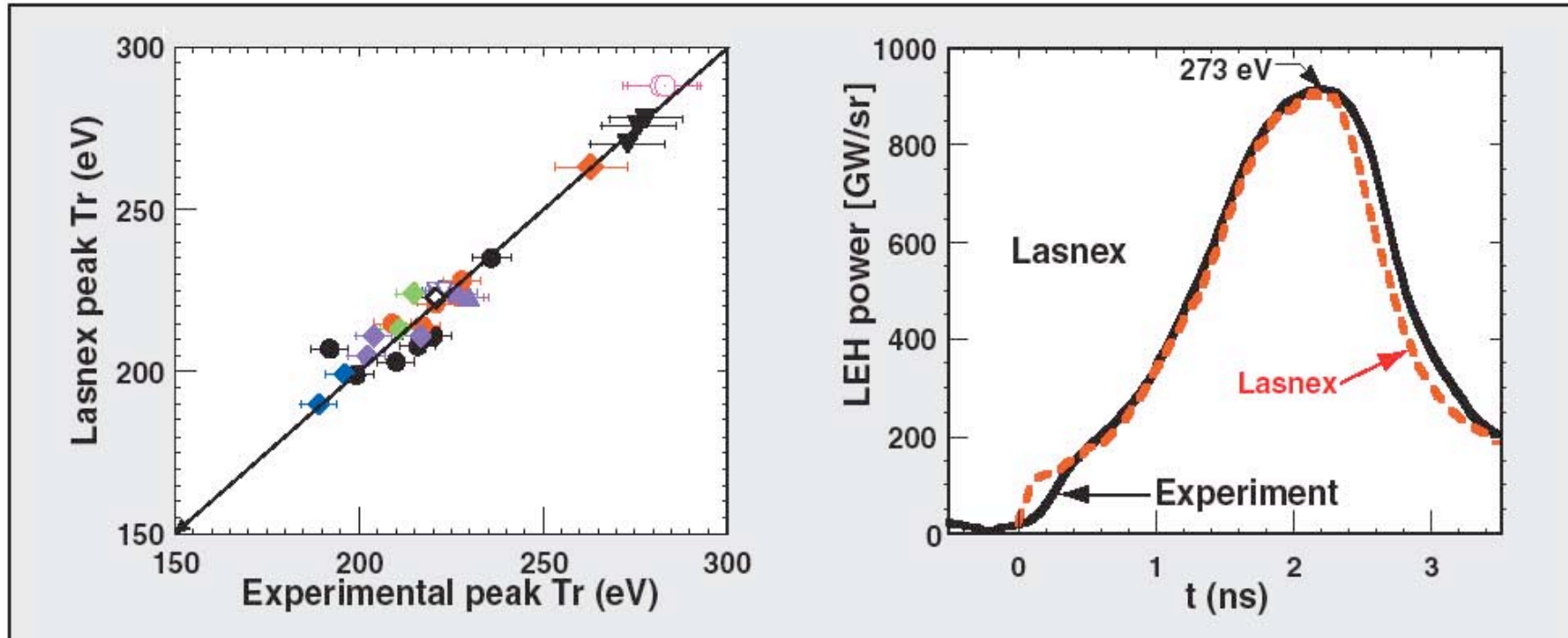
Coupling efficiency =  $h_{abs} h_H$   
 $\eta_{abs} = 1 - \text{backscattered fraction}$   
 $h_H = \text{hohlraum coupling efficiency}$

# At 3W<sub>drive</sub> measurements and Lasnex simulations agree closely over >two orders of magnitude in $T_R^4$



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## Nova and Omega Experiments



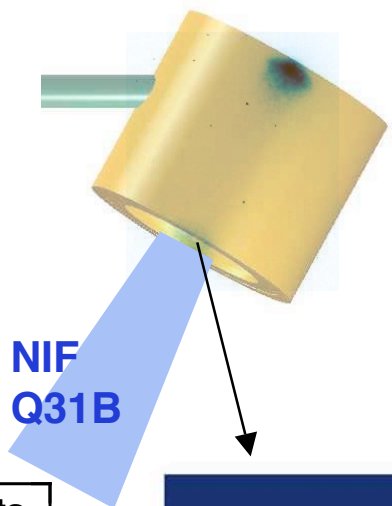
Vacuum and gas-filled hohlraums with 2.2 ns shaped pulses (3:1 and 5:1 contrast ratio)

Lasnex can predict hohlraum drive to  $\pm 10\%$

# An international team has successfully activated hohlraum diagnostics at NIF and the first hohlraum experiments are in close agreement with calculations

**Thinwall Au Hohlraum**

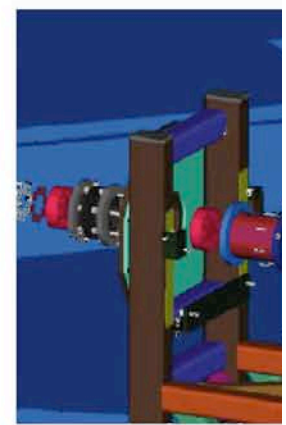
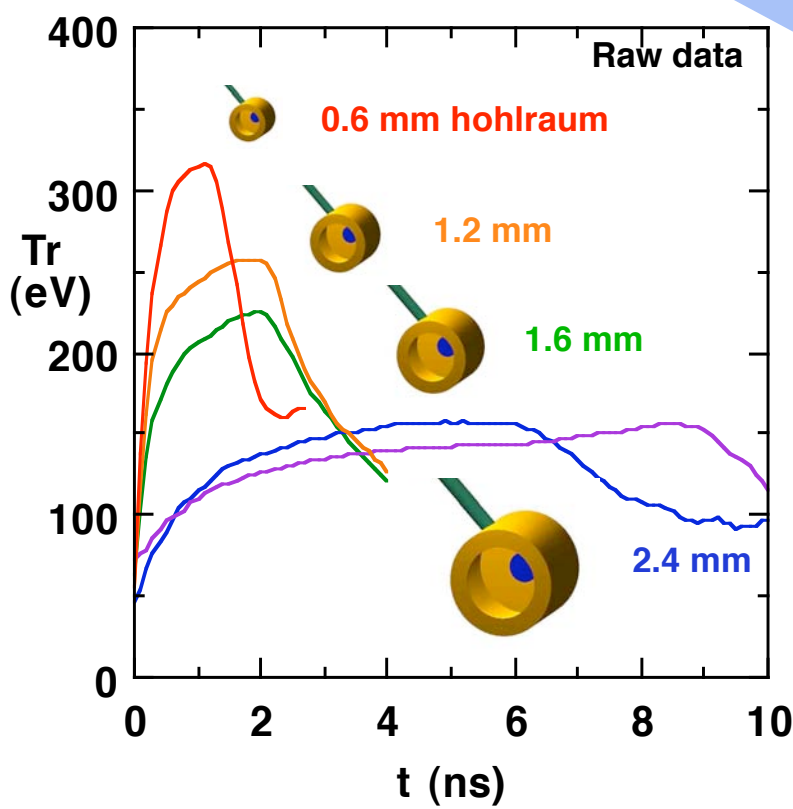
4-16 kJ, 1- 9 ns,  
 $10^{15}$ - $10^{16}$  W/cm<sup>2</sup>  
with beam  
smoothing



NIF  
Q31B

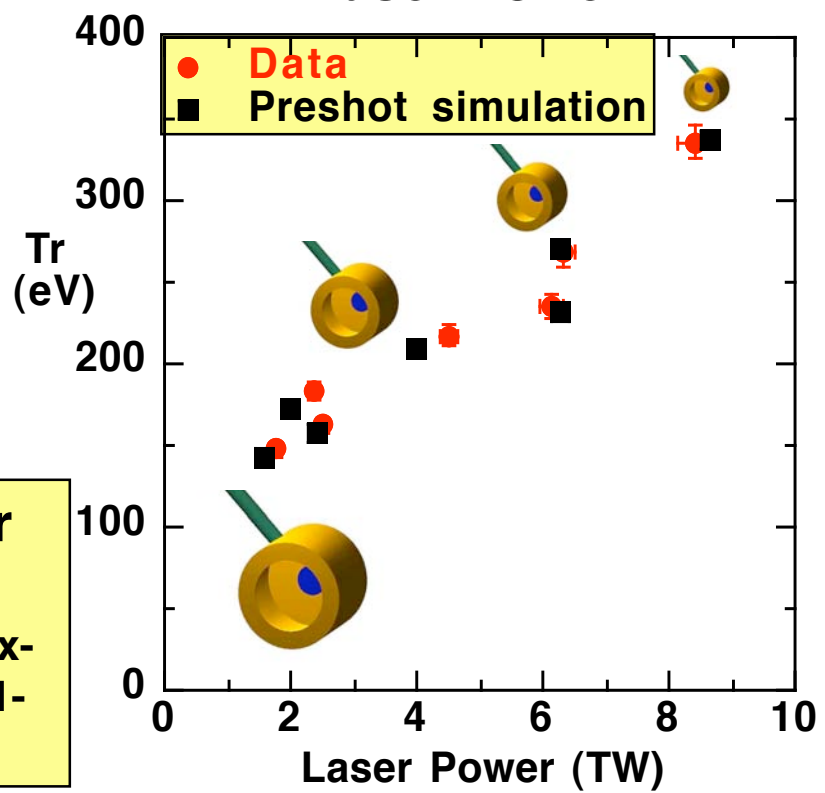


**Hohlraum Tr vs time**



**Hohlraum Tr (Dante)**  
18 channel soft x-ray detector (0.1-10 keV)

**Peak Hohlraum Tr vs Laser Power**



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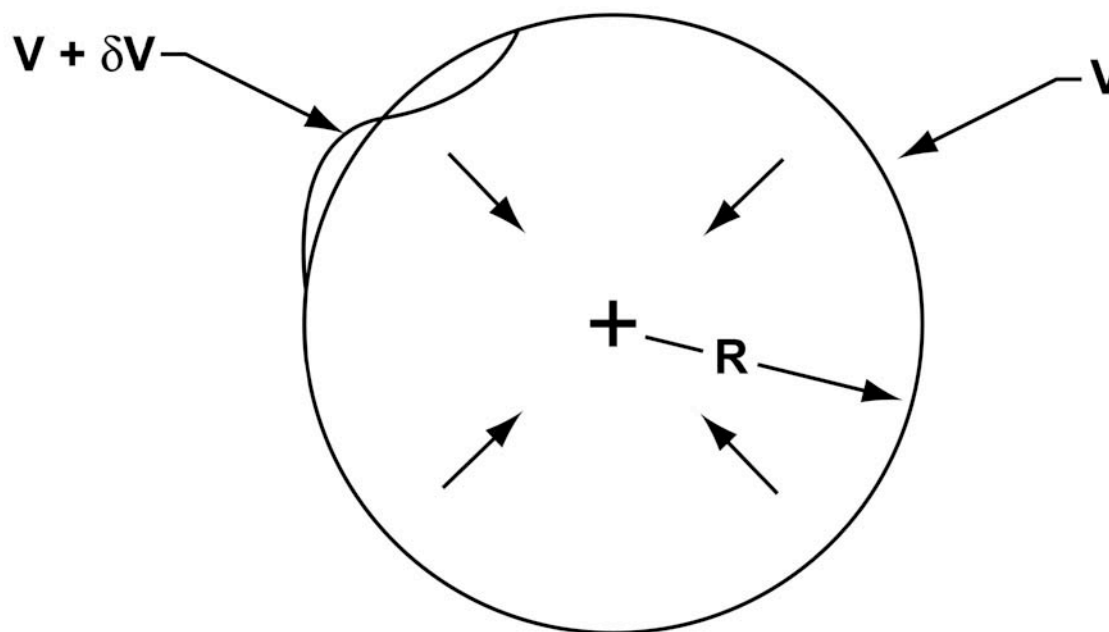


# Implosion symmetry is an important issue for high convergence ratio targets



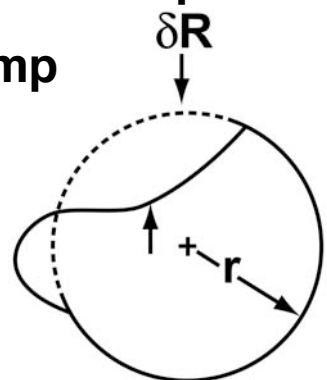
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Small nonuniformity when outershell is at large radius



Becomes magnified when shell is imploded to a very small radius

Lower peak compression, temp  
Lower  $r/R$



$$dR = (dV)t \sim dV \frac{R}{V} < 1/2 r$$

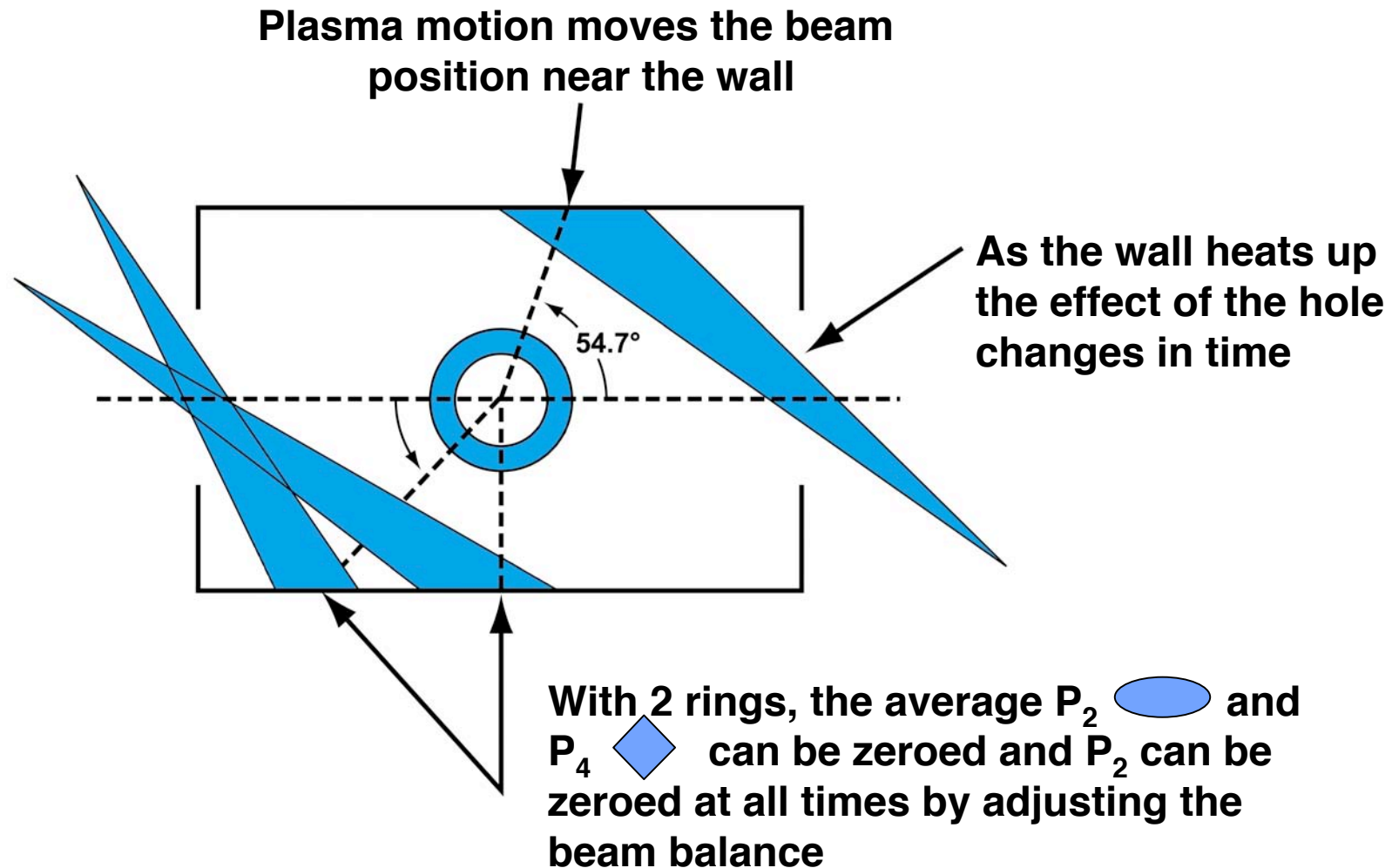
$$\frac{dR}{r} = \left( \frac{dV}{V} \right) \frac{R}{r} < 1/2$$

$$\frac{dV}{V} < 1/2 \quad \frac{r}{R} < 1/2 \text{ (conv. ratio)}^{-1}$$

# Plasma motion and the laser entrance hole (LEH) result in a time variation in capsule symmetry



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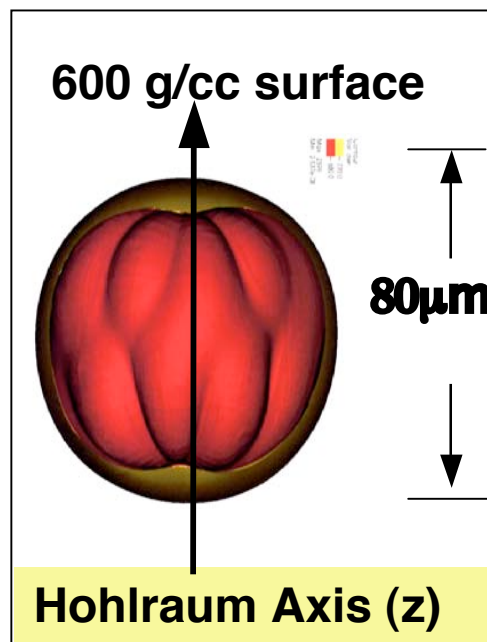
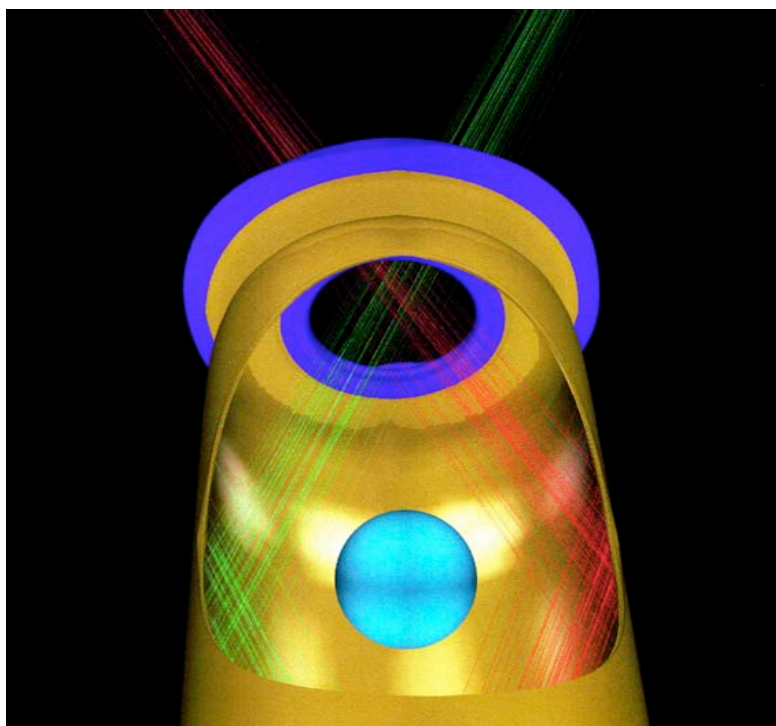


# Optimization of symmetry will require close coordination of detailed design calculations and precision experimental measurements



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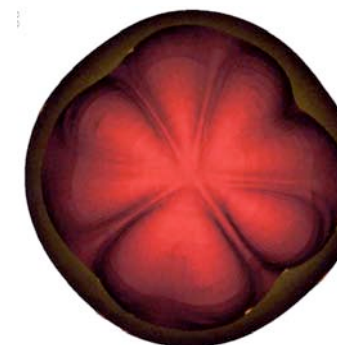
## Be capsule fuel region at ignition



### Upper Hemisphere

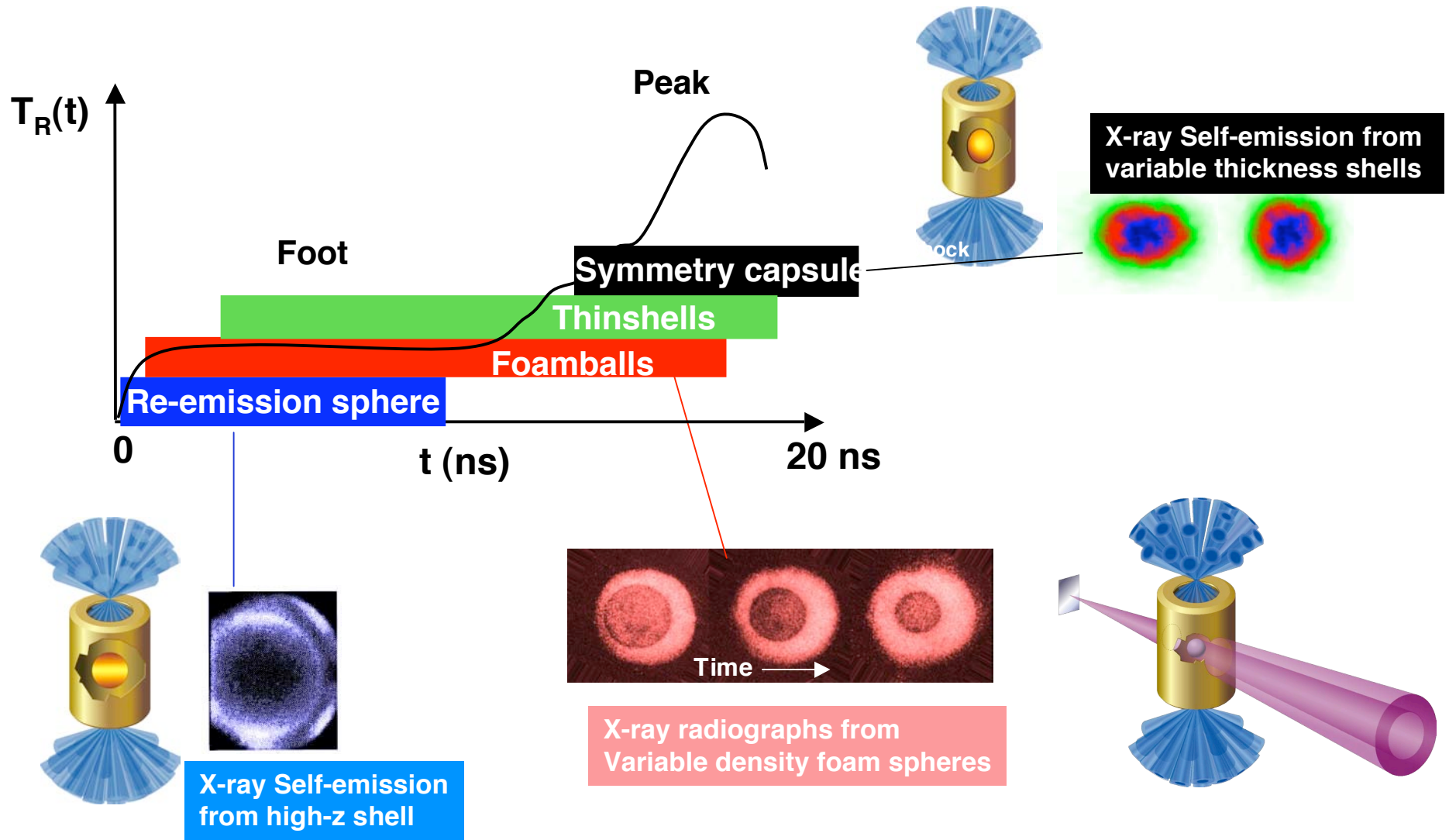


### Lower Hemisphere



The Hydra code is used for 3D calculations on the ASCI computers

# Diagnostic techniques developed at Nova and Omega will provide overlapping and complete coverage of irradiation asymmetry history on the NIF



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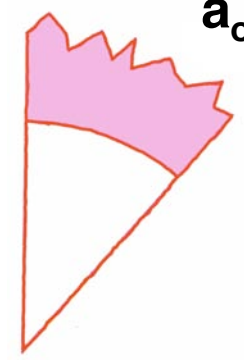
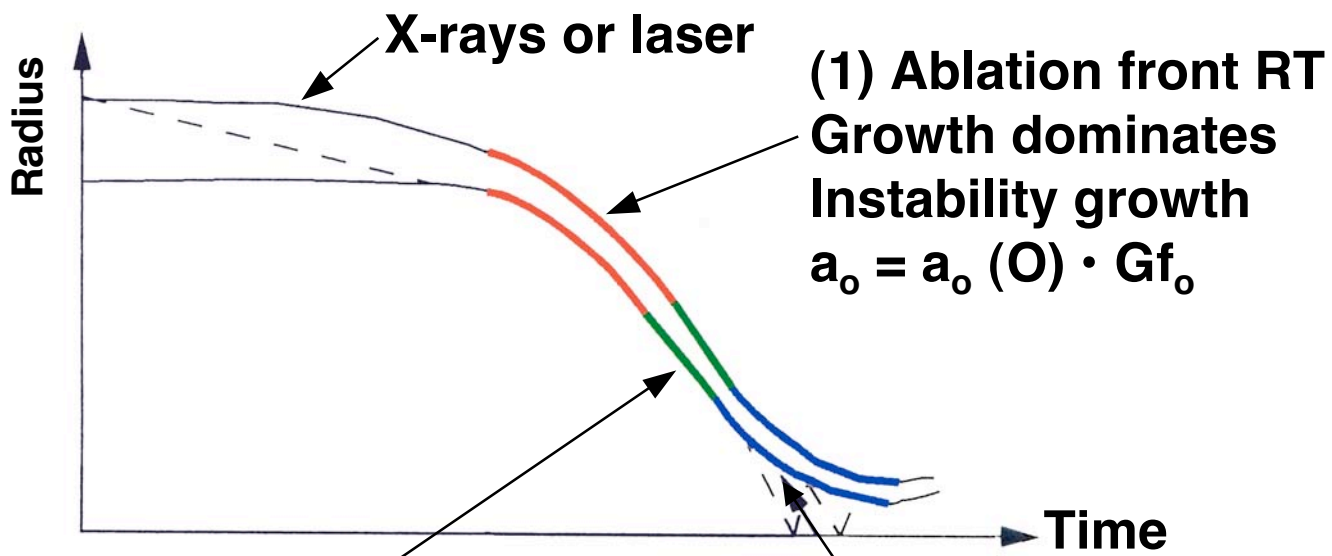
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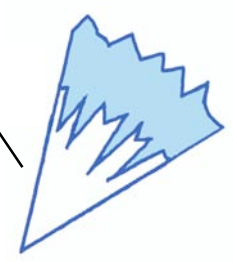
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# The ablation front hydrodynamic instability can destroy an imploding shell

Growth starts from surface or other shell variations  
 $a_o (0)$



(2) Feed through and initial roughness seeds inner surface  
 Perturbations  
 $a_{io} = a_o \cdot FT$



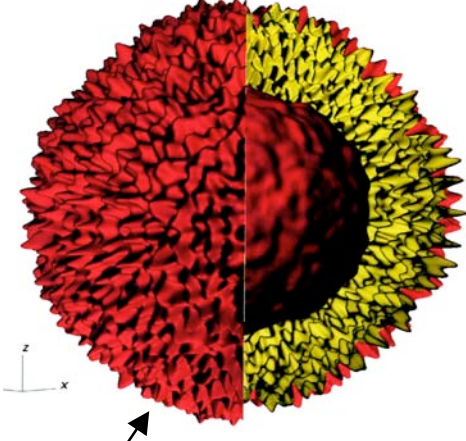
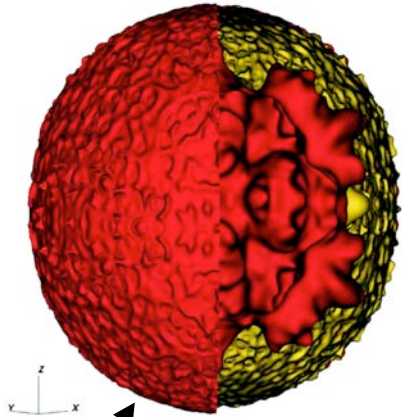
(3) Inner surface seeds grow on deceleration  
 $a_i = GF_i \cdot a_{io}$

# Recent 3D calculations (having both asymmetry and surface roughness) burn with near 1D yield



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- Capsule simulations have asymmetry and fabrication perturbations
- 3D asymmetry inferred from integrated hohlraum simulation
- Nominal “at spec” perturbations on ice and ablator in low, intermediate, and high modes
- Gave 21 MJ (90% of 1D calculation)

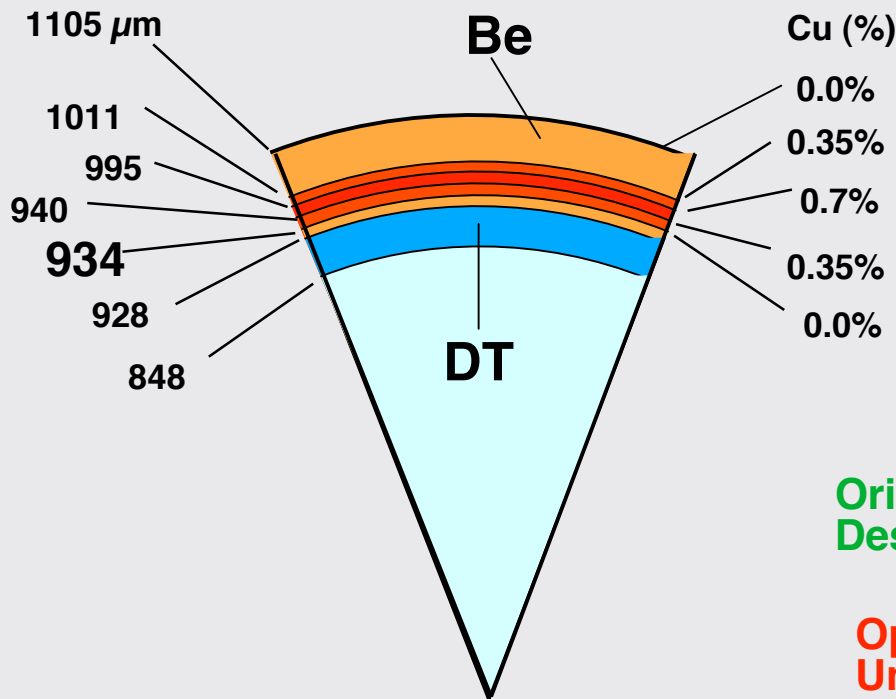
140 ps before ignition time	Ignition time
 <p data-bbox="976 1079 1438 1177">Plastic/DT interface ↑ Hohlraum axis ↓</p>	 <p data-bbox="1501 1079 1732 1177">Stagnation shock</p>
<p data-bbox="1039 1209 1396 1307">60 g/cc density isosurface</p>	<p data-bbox="1522 1209 1900 1356">400 g/cc density isosurface (different scale)</p>

# Be Capsule designs using graded dopants for pre-heat shielding have the best calculated performance

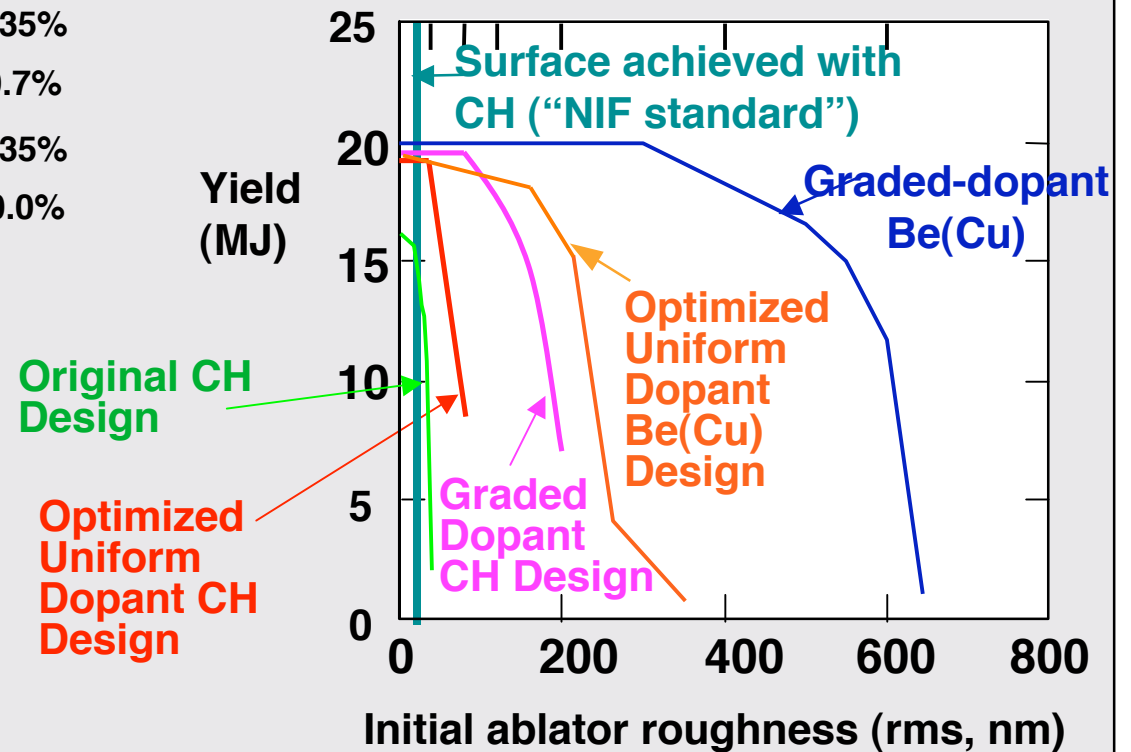


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## 300 eV design:



The graded doped Be capsule can tolerate 60x the NIF standard



Tolerance to ice roughness is also better (5  $\mu\text{m}$  compared to 1  $\mu\text{m}$ )



## Several developments have led us to adopt the current Beryllium capsule point design

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- **With given laser & hohlraum, beryllium absorbs 35% more energy than plastic**
- **Beryllium has better short wavelength stability, especially with graded dopant - an experimental program will be required to establish the acceptable level of Be microstructure**
- **Many previous difficulties in Be fabrication have been solved (filling, diagnosing layer)**
- **A staged cryo system with an initial fill tube capability (or fill and plug) for warm transport, provides the best opportunity for early ignition experiments**
- **Although, the fill tubes are a design and target fabrication complexity, current simulations and fabrication progress lead us to conclude we can make them small enough for success - an experimental program is needed to test the calculations**

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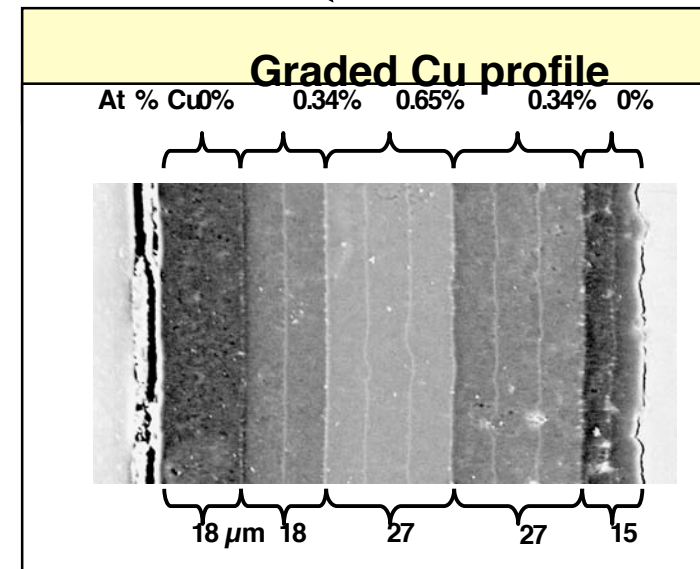
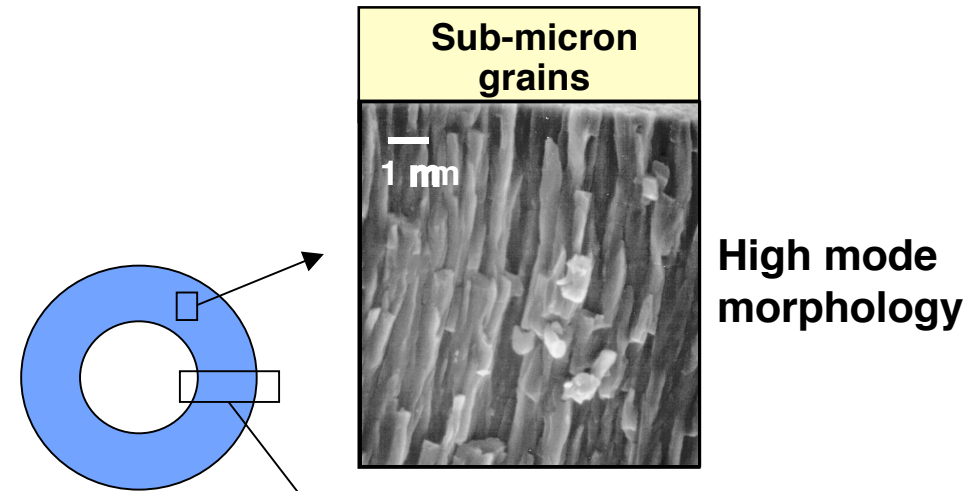
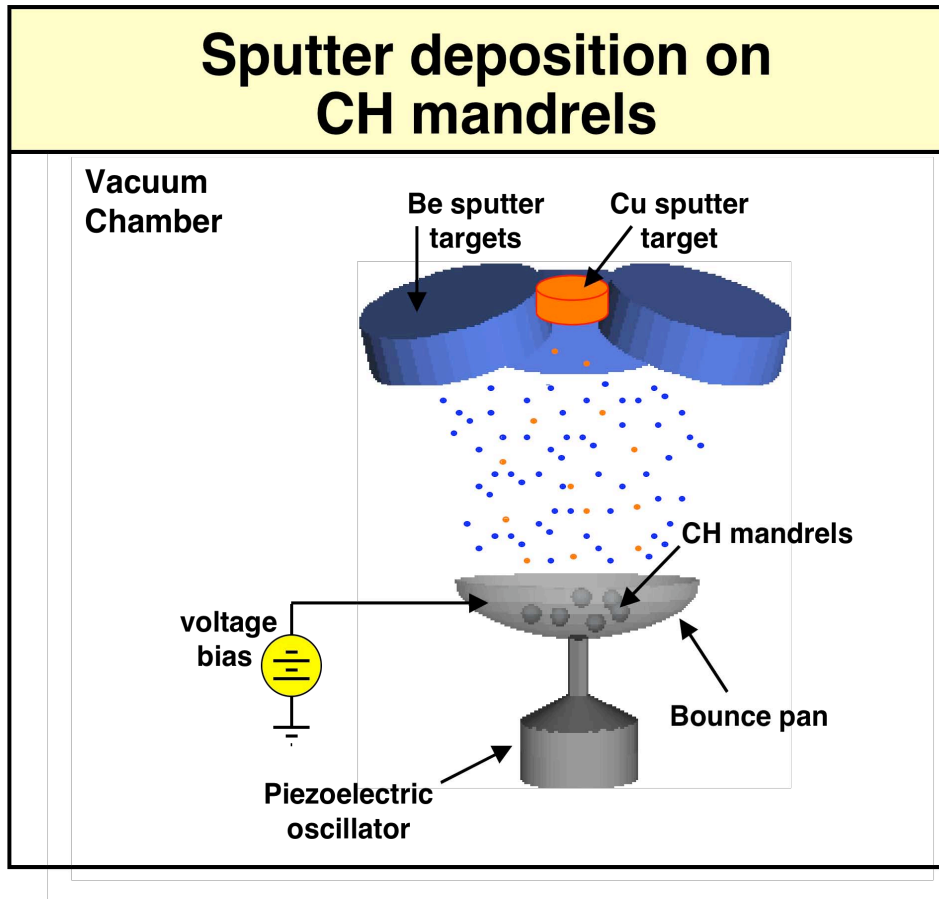
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# We have produced graded Cu-doped Be capsules at NIF-scale by sputter deposition



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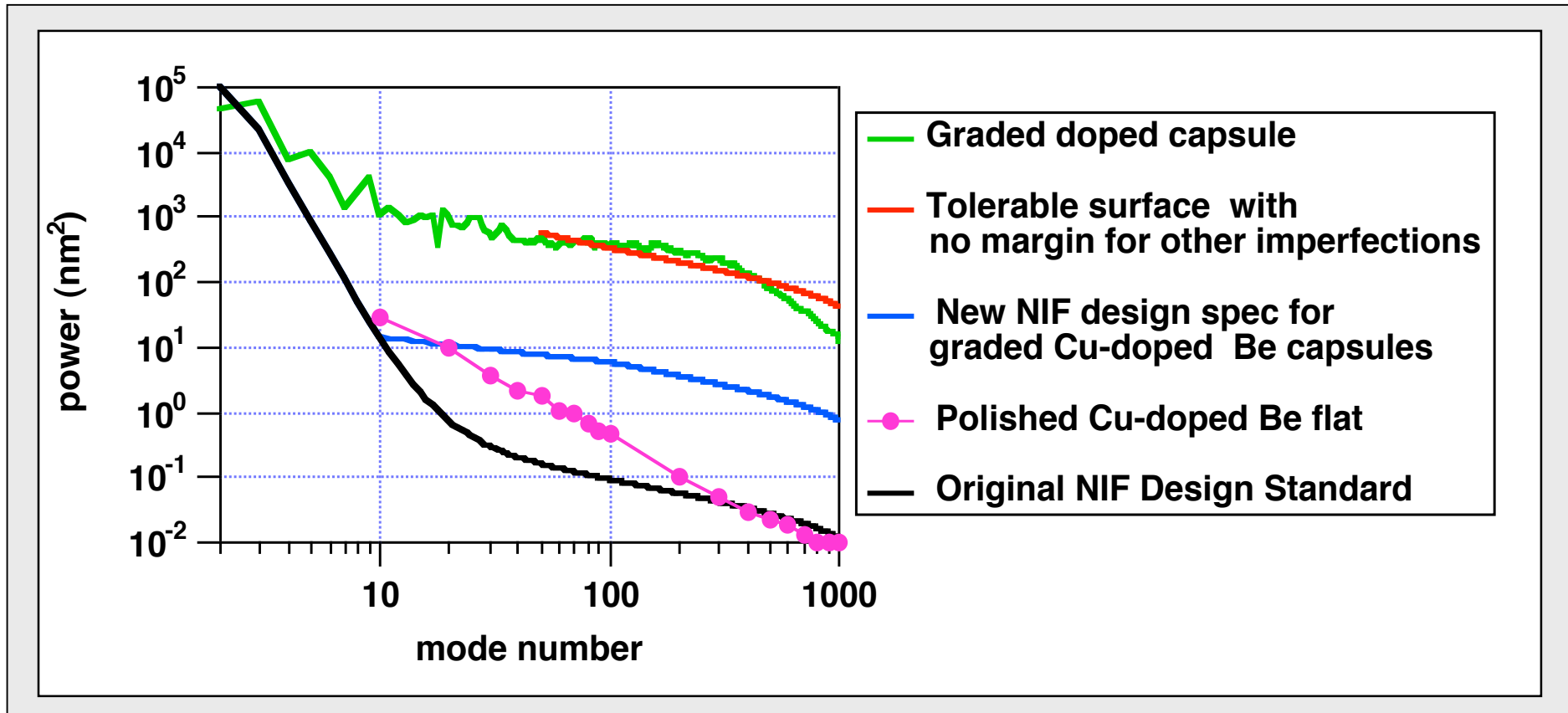


The surfaces of our first graded dopant Be capsules don't meet specifications, but improvements are planned

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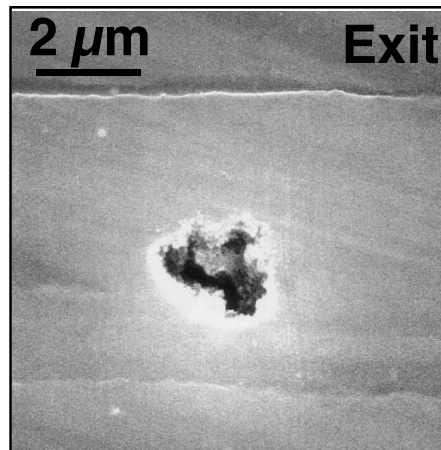
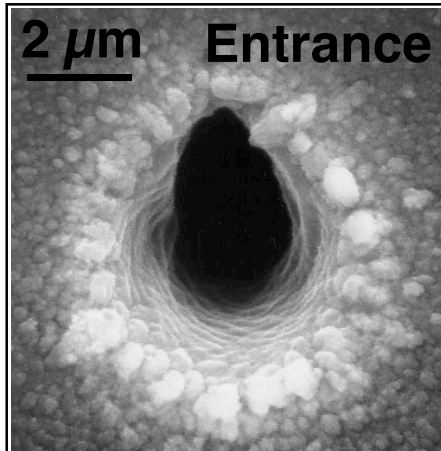
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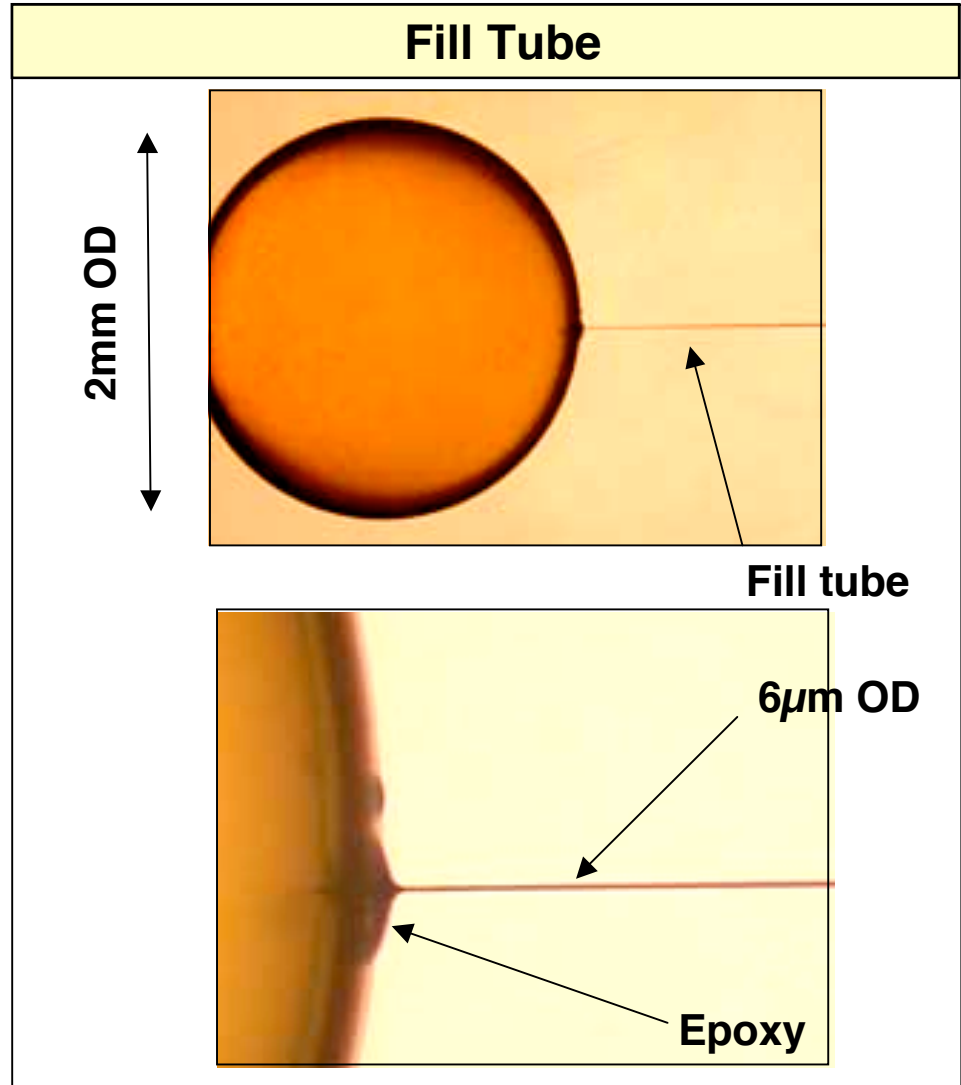
- We plan to investigate use of ion bombardment and other methods as means to improve **surface finish** and **coating density**
- In FY05 LANL will study shell polishing

# Be is non-permeable, and requires a fill hole through the $\sim 100\text{-}\mu\text{m}$ -thick ablator for filling

Laser:  
Ti:sapphire  
405 nm,  $<1\ \mu\text{J}$ ,  
120 fs, 3.5 kHz  
drilling time:  
 $\sim 40$  sec



- Two routes to filling beryllium capsules
  - Fill Tube
  - Drill, Fill and Plug (Strong Capsules)

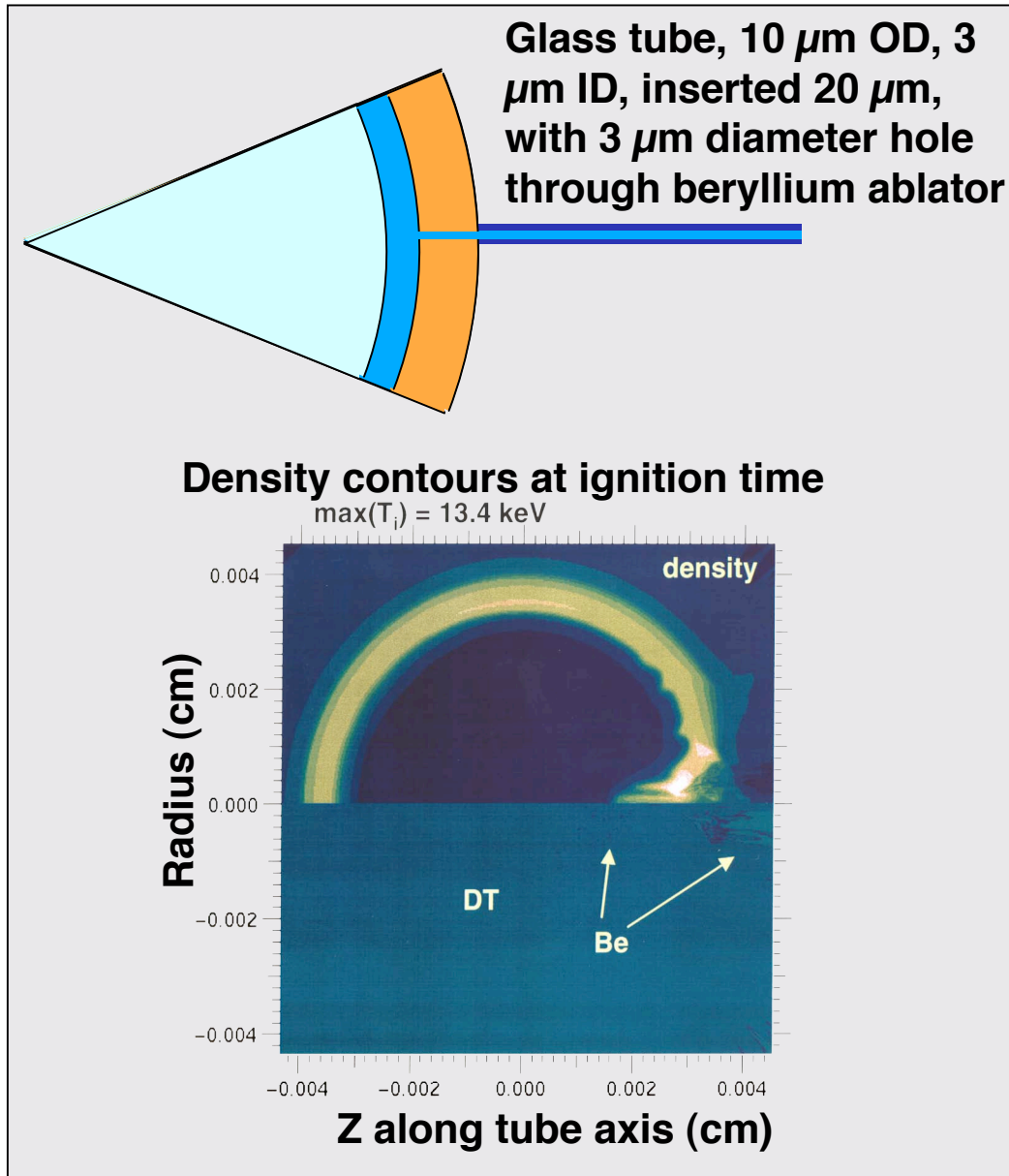


Current effort:  
minimizing the glue joint

# Simulations indicate that a 10 $\mu\text{m}$ tube with a 3 $\mu\text{m}$ hole has an acceptable impact on the implosion



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- Uniformly doped Be(Cu) capsule
- Calculation ignites and burns to same yield as 1D clean -- 21.7 MJ
- Simulations in progress with graded-doped capsule, larger hole

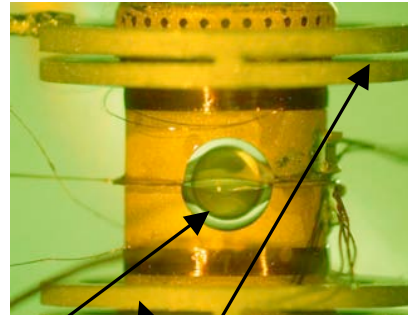
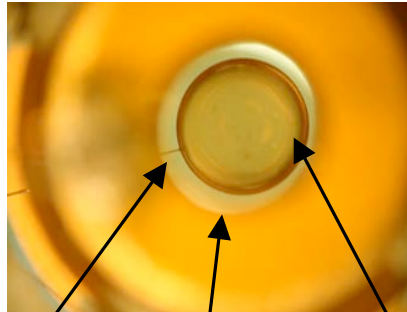
# The target is filled through the small fill-tube using a self-contained fuel reservoir



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View of 2mm shell through laser entrance hole

View of 2mm shell through side hole



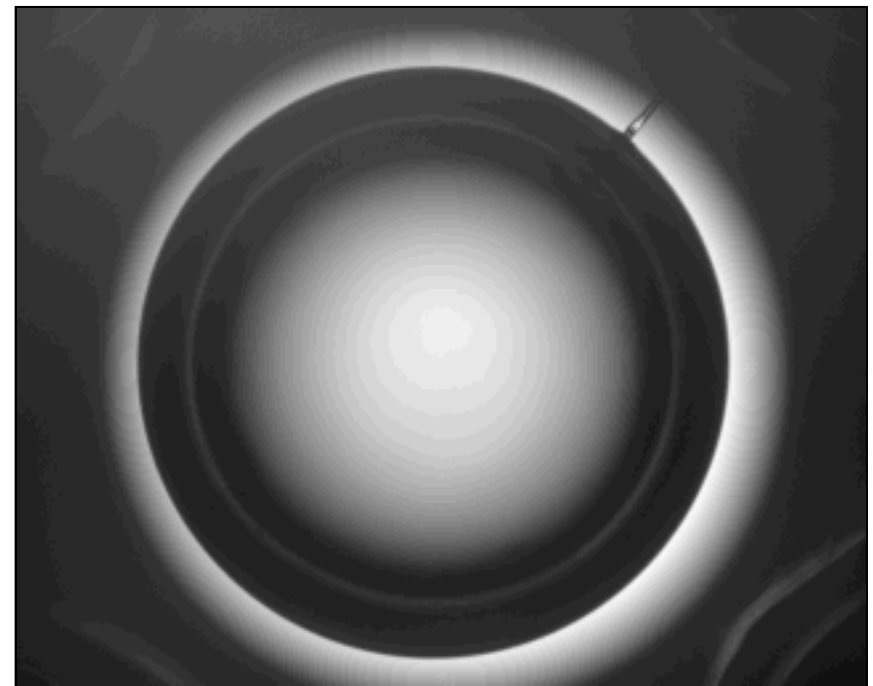
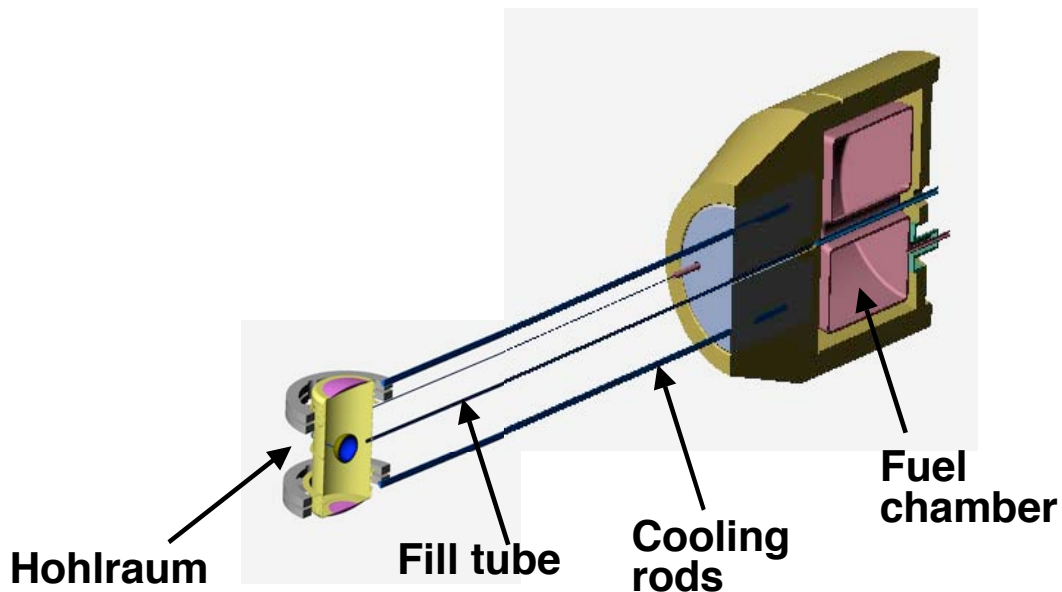
Fill tube  
8  $\mu\text{m}$  ID

Laser entrance hole

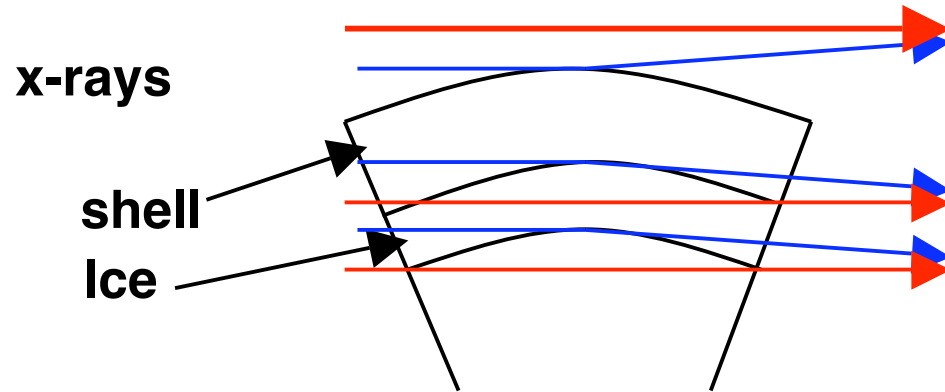
Shell

Cooling rings

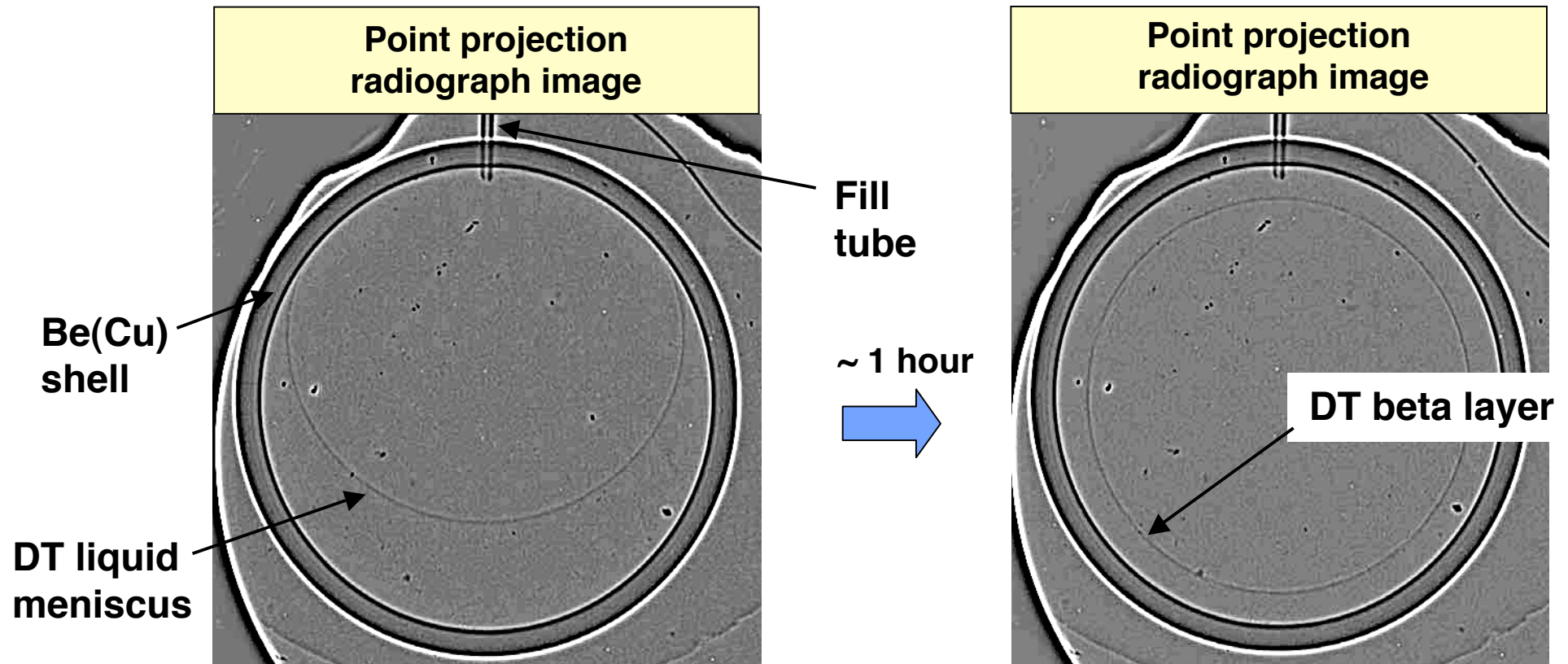
- Fuel pressure 2-3 atm
  - ~ 5 Ci DT
- Capsule filled *in target inserter* by temperature control on fuel reservoir and hohlraum



# The DT fuel layer in optically opaque beryllium has been recently characterized with x-ray refraction



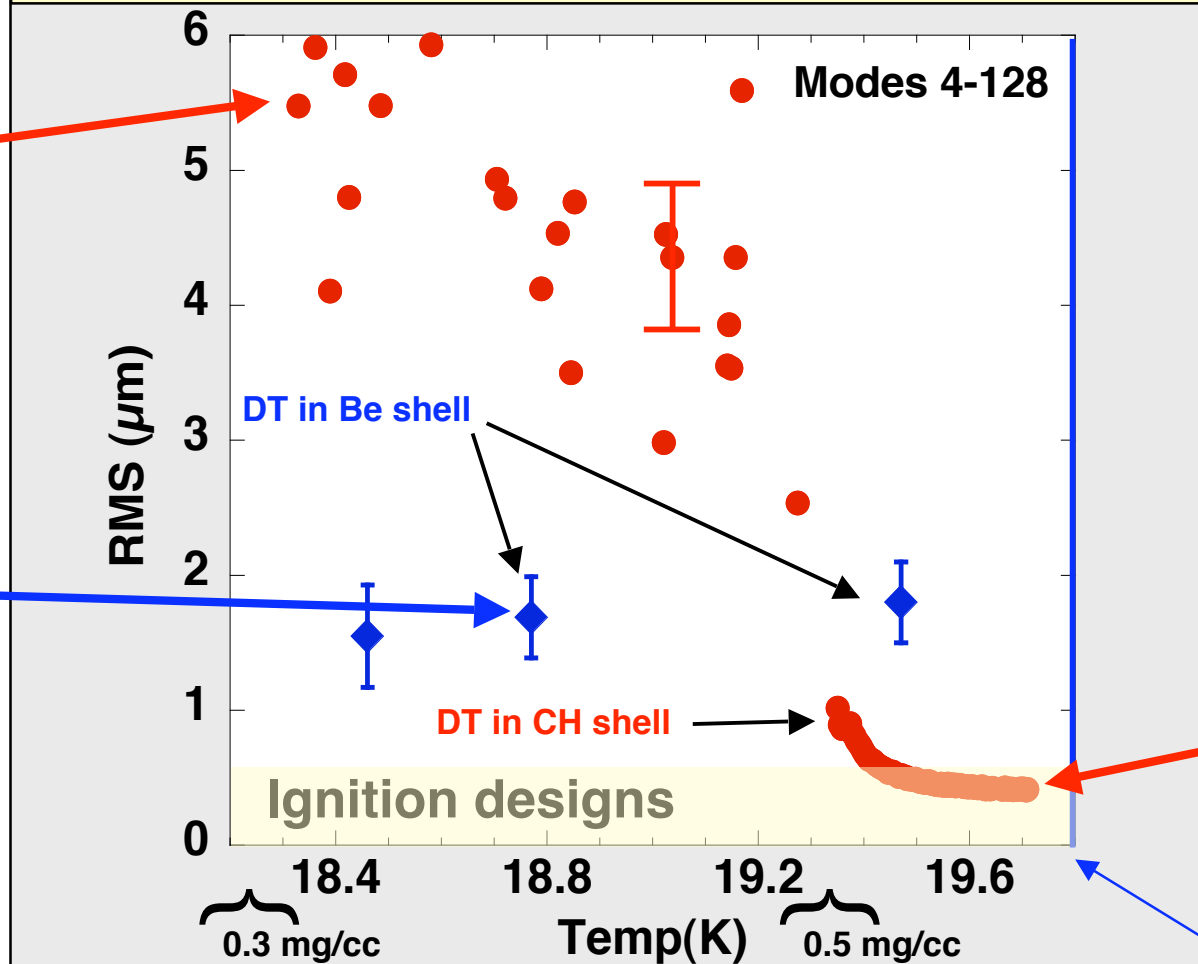
- Rays tangent to surface are slightly deflected
- Other rays are very nearly un-deflected
- This method is many times more sensitive than absorption





# The best cryo layers are formed near the triple point

Layer smoothness appears to degrade at temperatures less than 0.5 K below the triple point



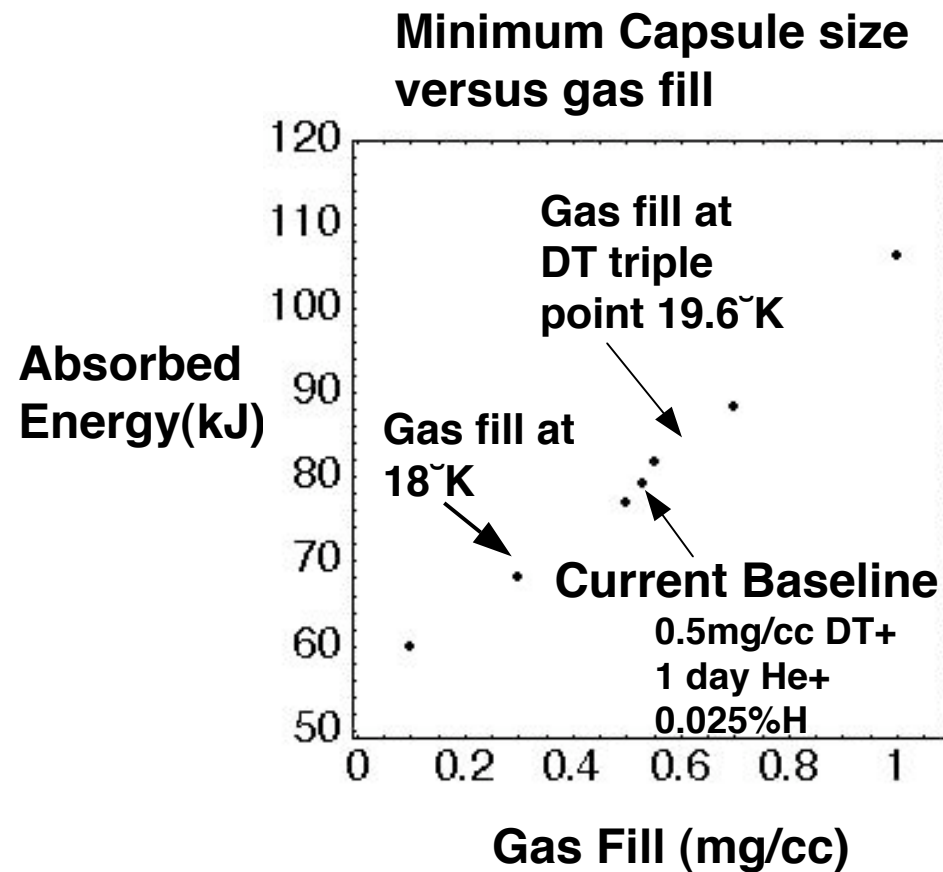
IR enhanced layering is one technique shown to keep the layer smooth at temperatures down to 1.5 K below the triple point

DT triple point

# The lower gas fill obtained with lower temperature cryo fuel layers lowers the energy required for ignition



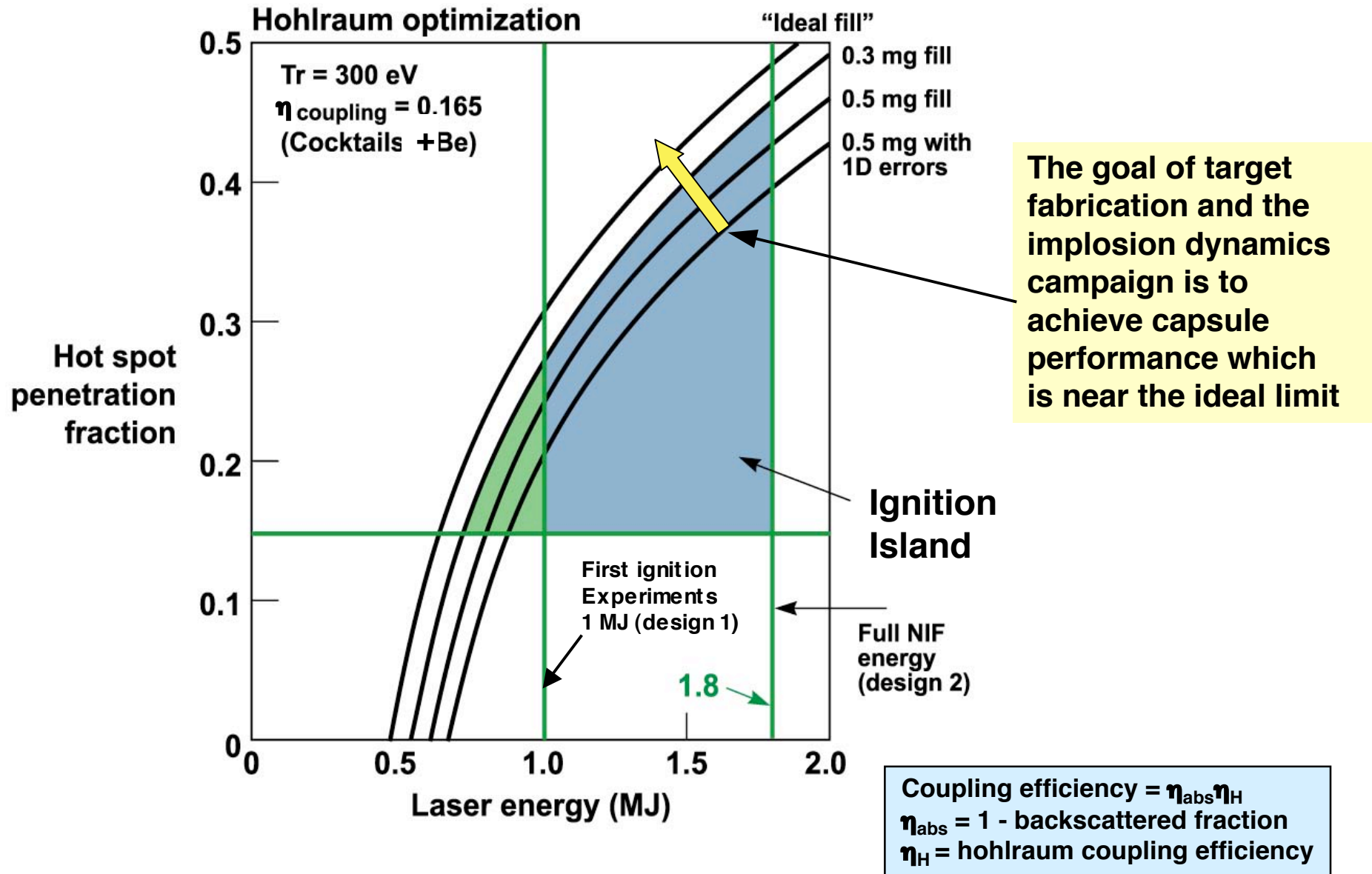
The National Ignition Facility



# The ignition island is increased by improving target fabrication



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# Outline

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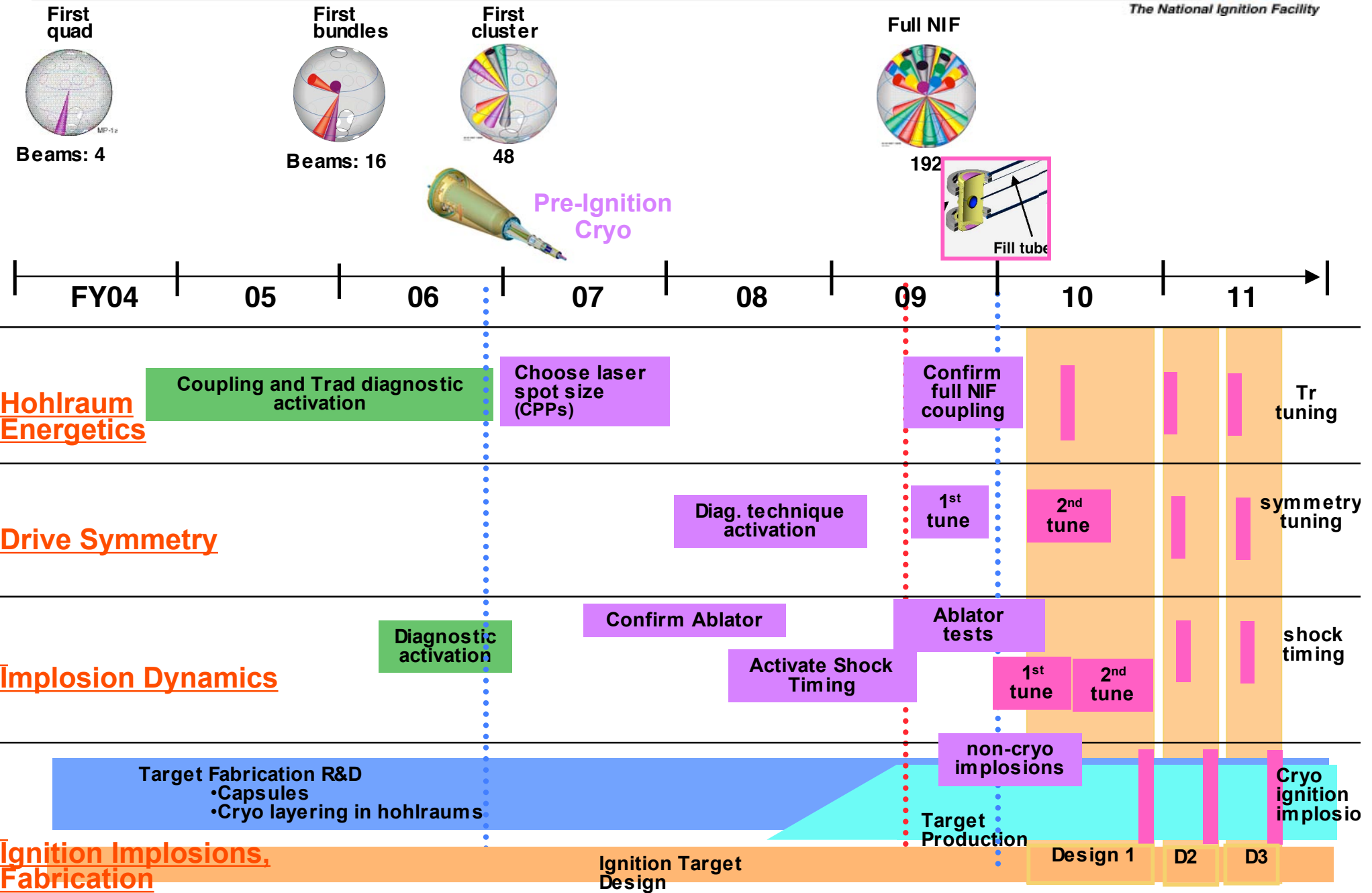
The National Ignition Facility

- Ignition Introduction
- NIF status
- Target Requirements and recent advances
  - Energetics
  - Symmetry
  - Implosion dynamics
  - Target Fabrication
- • Plan for experiments leading to first ignition target shots in 2010

# Key NIF ignition experiments begin in FY07 following first cluster completion and full system ignition experiments start in FY9-10 following project completion



The National Ignition Facility



# Summary/Conclusions

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The National Ignition Facility

- **The first 4 beams of NIF have been activated and used for initial hohlraum experiments. These beams meet all of NIF's primary performance criteria on a per beam basis. The first cluster (48 of 192 beams) will be completed late in FY06 and the full laser system will be available for experiments in FY09**
- **Numerical simulations, benchmarked by over 15,000 experiments on Nova, Omega, Z and other facilities, provide a first principles description of x-ray target performance (except for laser-plasma interactions)**
- **A Gold hohlraum with a Be capsule has substantial ignition margin at full NIF performance**
- **Significant enhancements in ignition target performance, including cocktail hohlraums and laser entrance hole shine shields, are being explored and we expect many of these to be incorporated into the baseline targets by 2010**