Recent Advances in Indirect Drive ICF Target Physics

Presentation to
20th IAEA Fusion Energy Conference

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Outline

- 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

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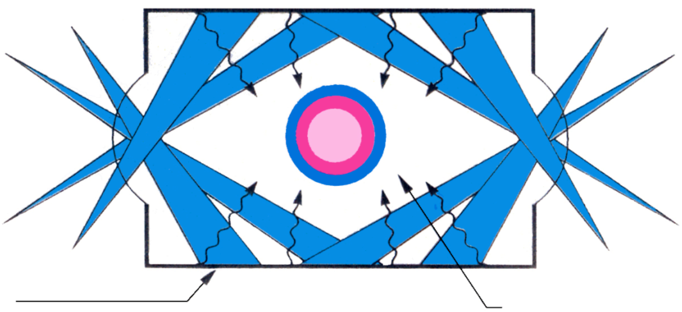
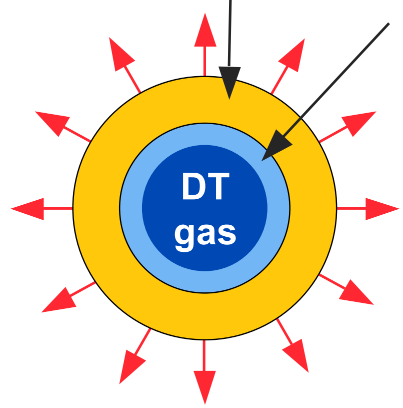
Indirect Drive

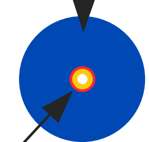


Direct Drive

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



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



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

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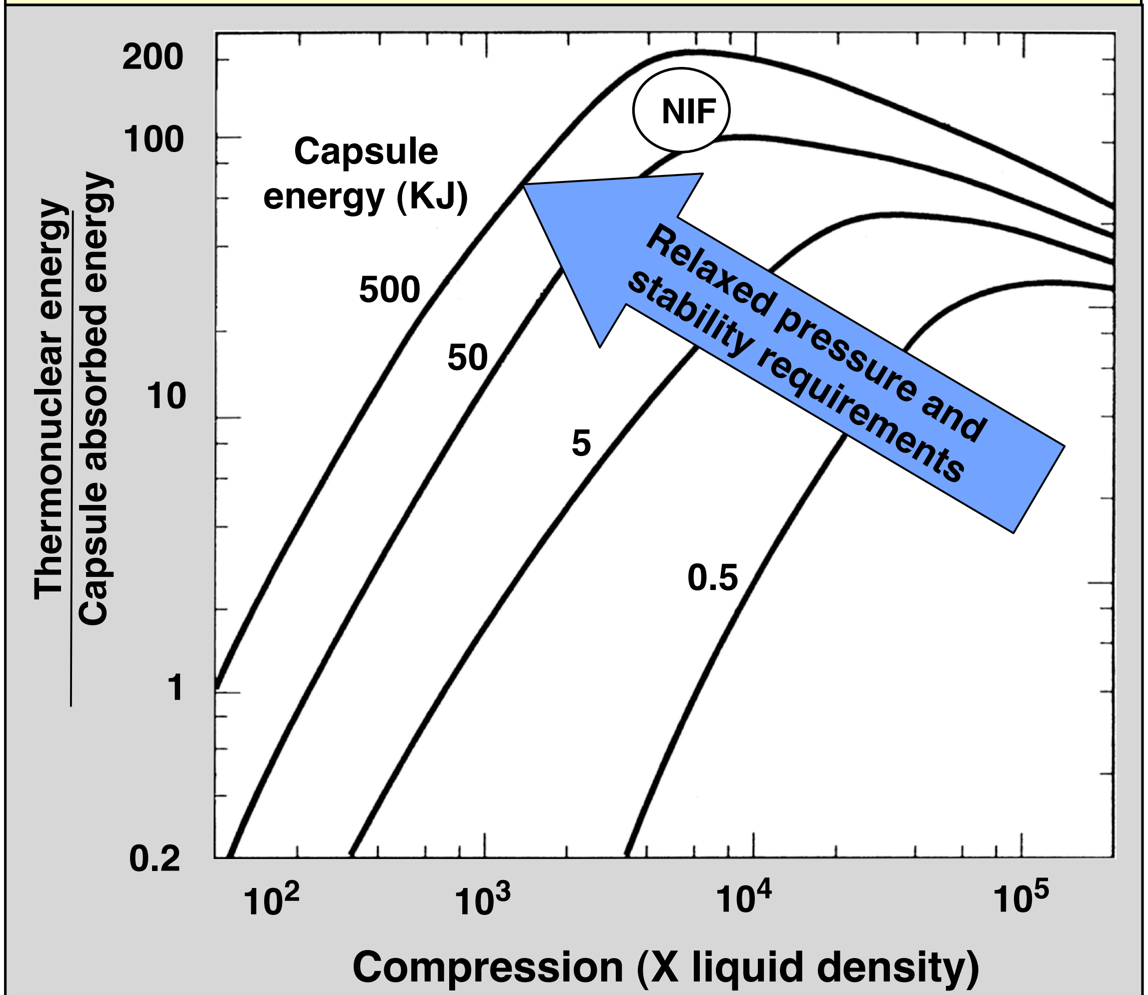
Capsule energy gain plotted versus compression



- **Pressure is limited to P(Max)~100 Mbar by Laser Plasma Interaction (LPI) effects**
- **Given the pressure limits, hydrodynamic instabilities limit implosion velocities to**

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

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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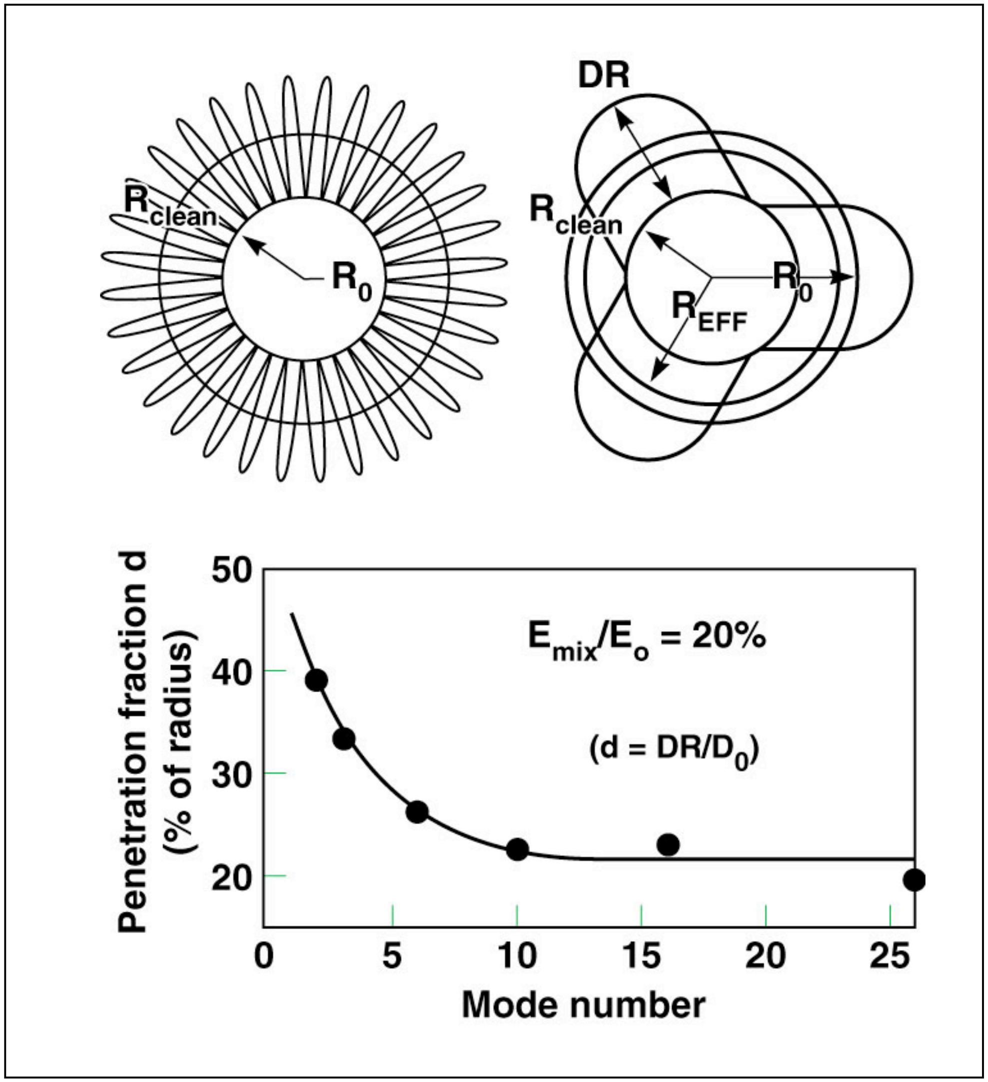

- Long Wavelength Perturbations
  - Hohlraum asymmetry
  - Pointing errors
  - Power Imbalance
  - Capsule misplacement in chamber
- Short Wavelength Perturbations
  - DT ice roughness
  - Ablator roughness
  - Ablator microstructure

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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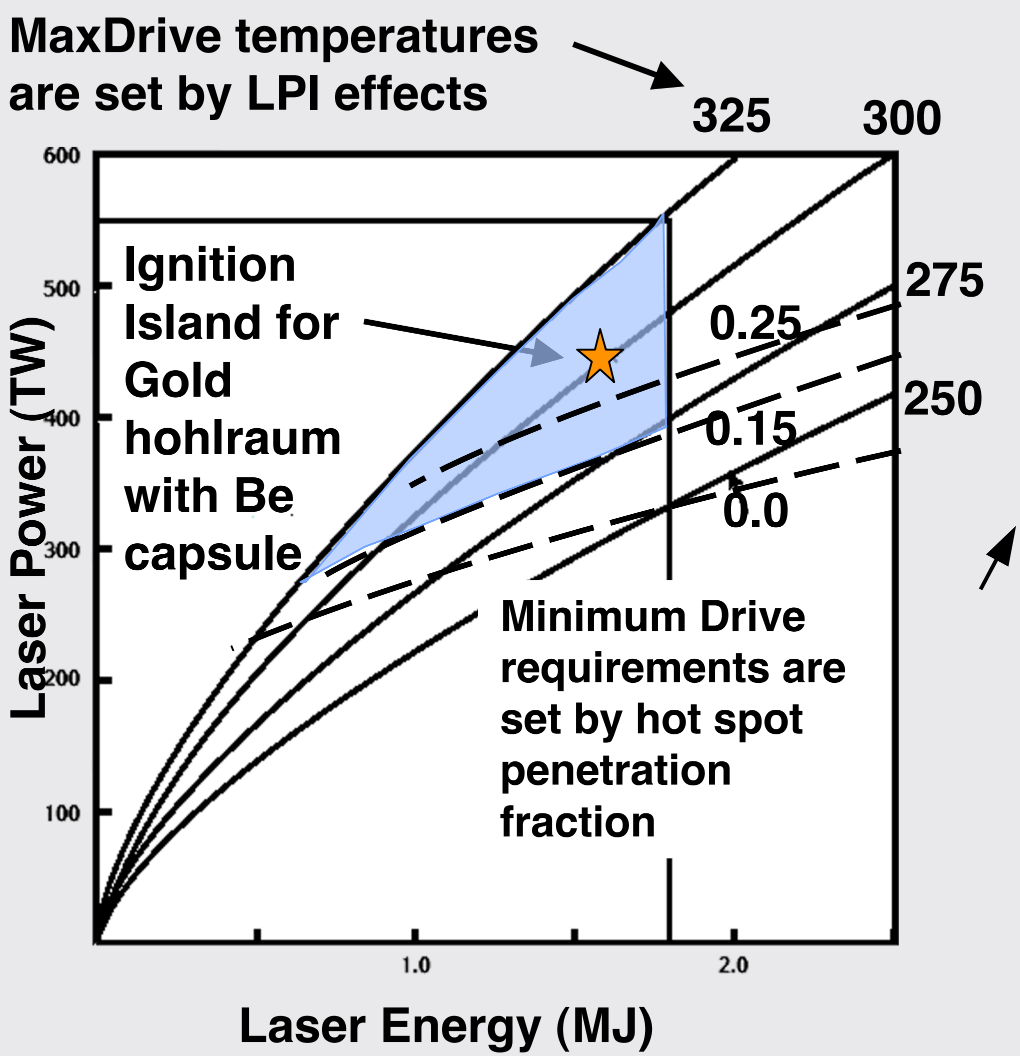

We expect ~15% hot spot penetration fraction based on detailed 2D and 3D calculations at the specified target fabrication and NIF performance levels

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

NIF Target Chamber upper hemisphere

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First four NIF beams installed on the target chamber

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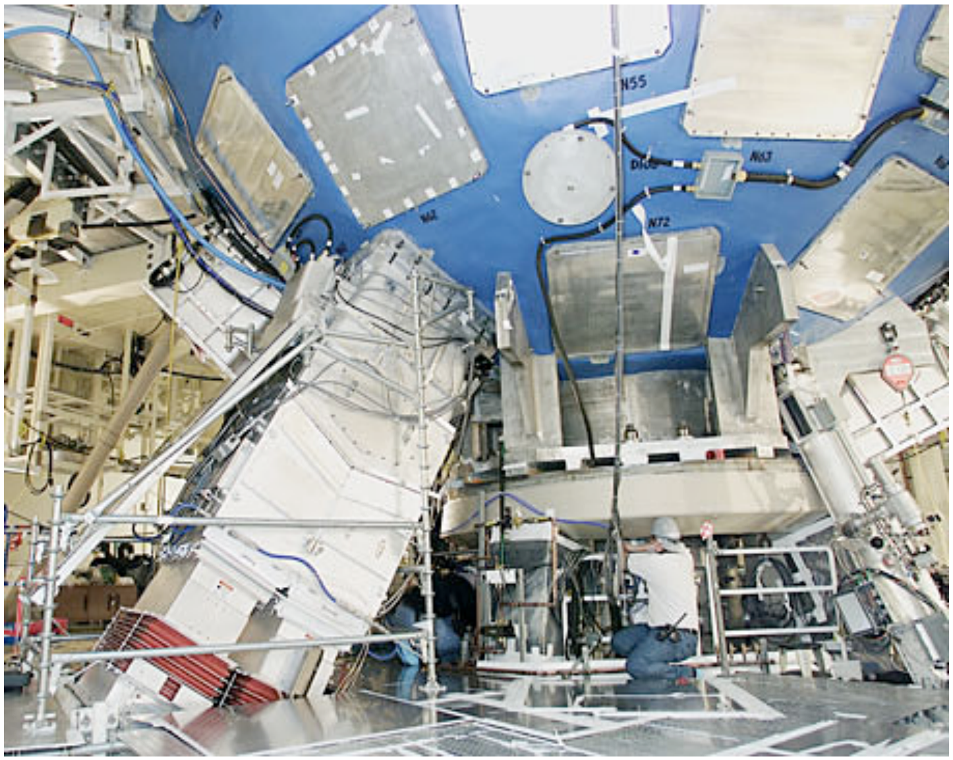
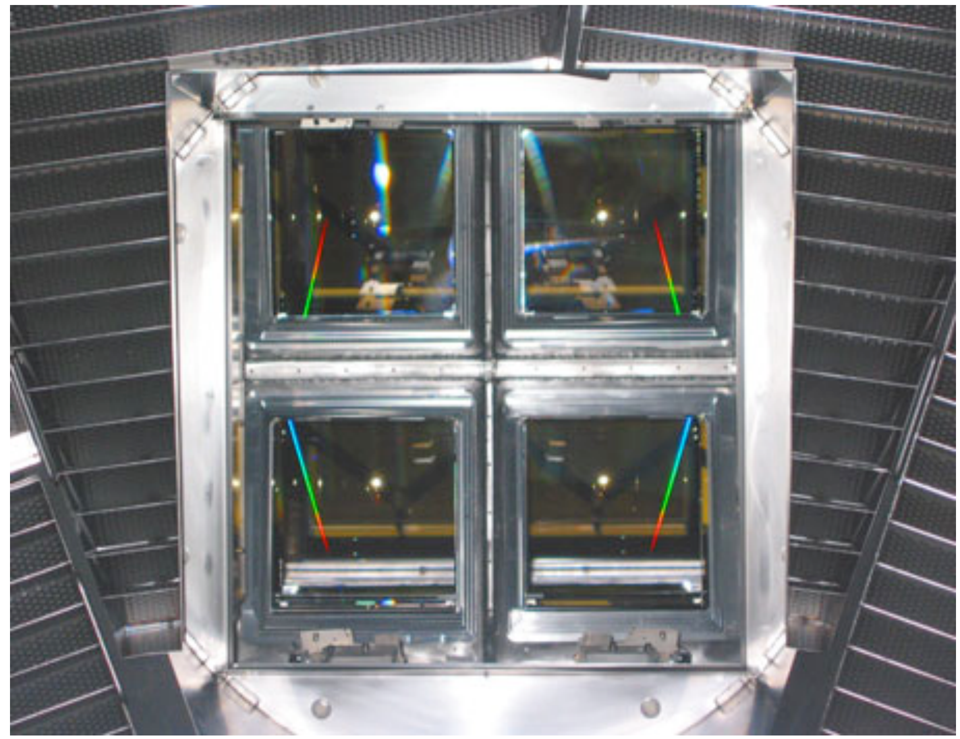
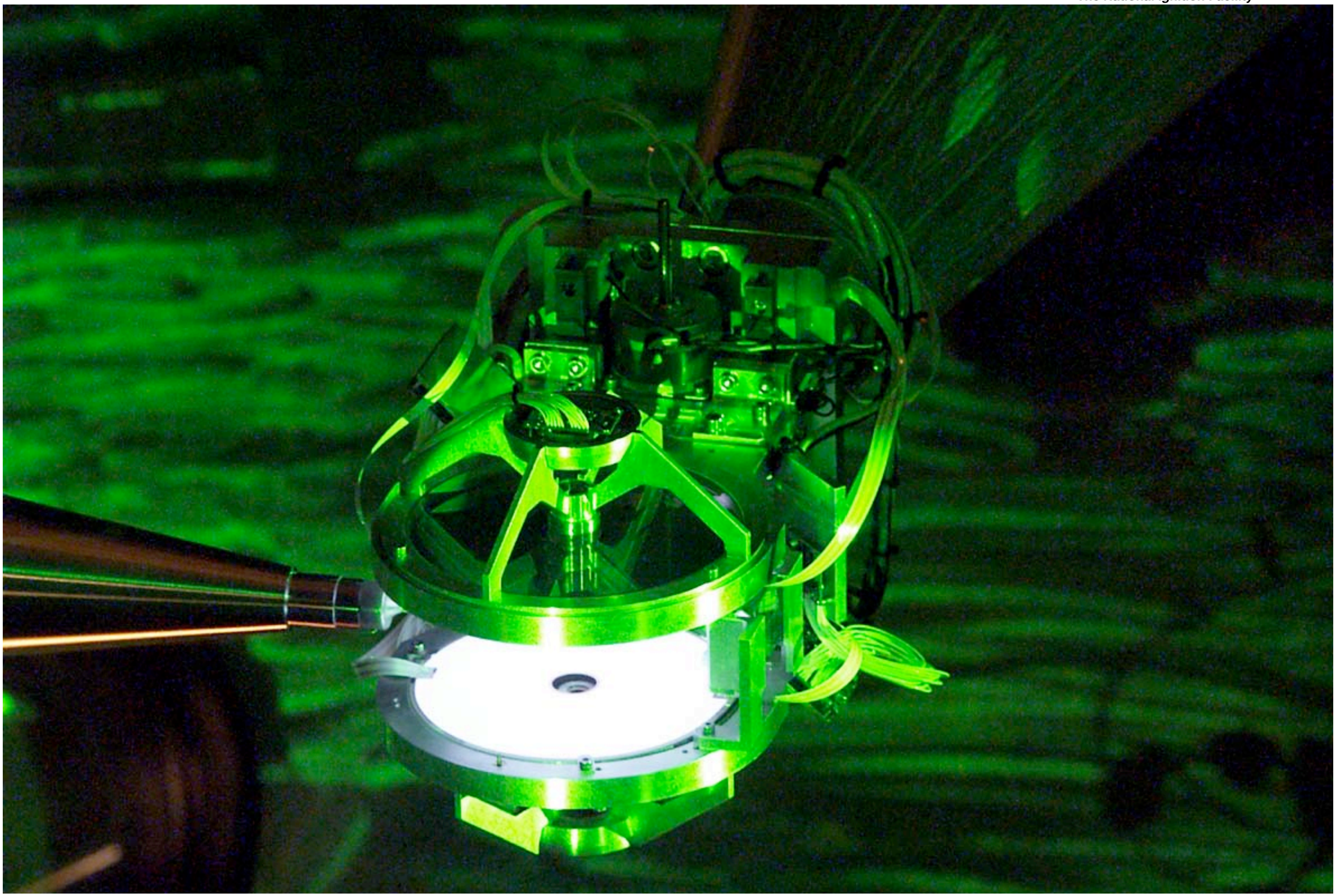




Quad 31b beamtubes and optics are installed and operational

View from inside the target chamber

Target positioner and alignment system inside target chamber



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

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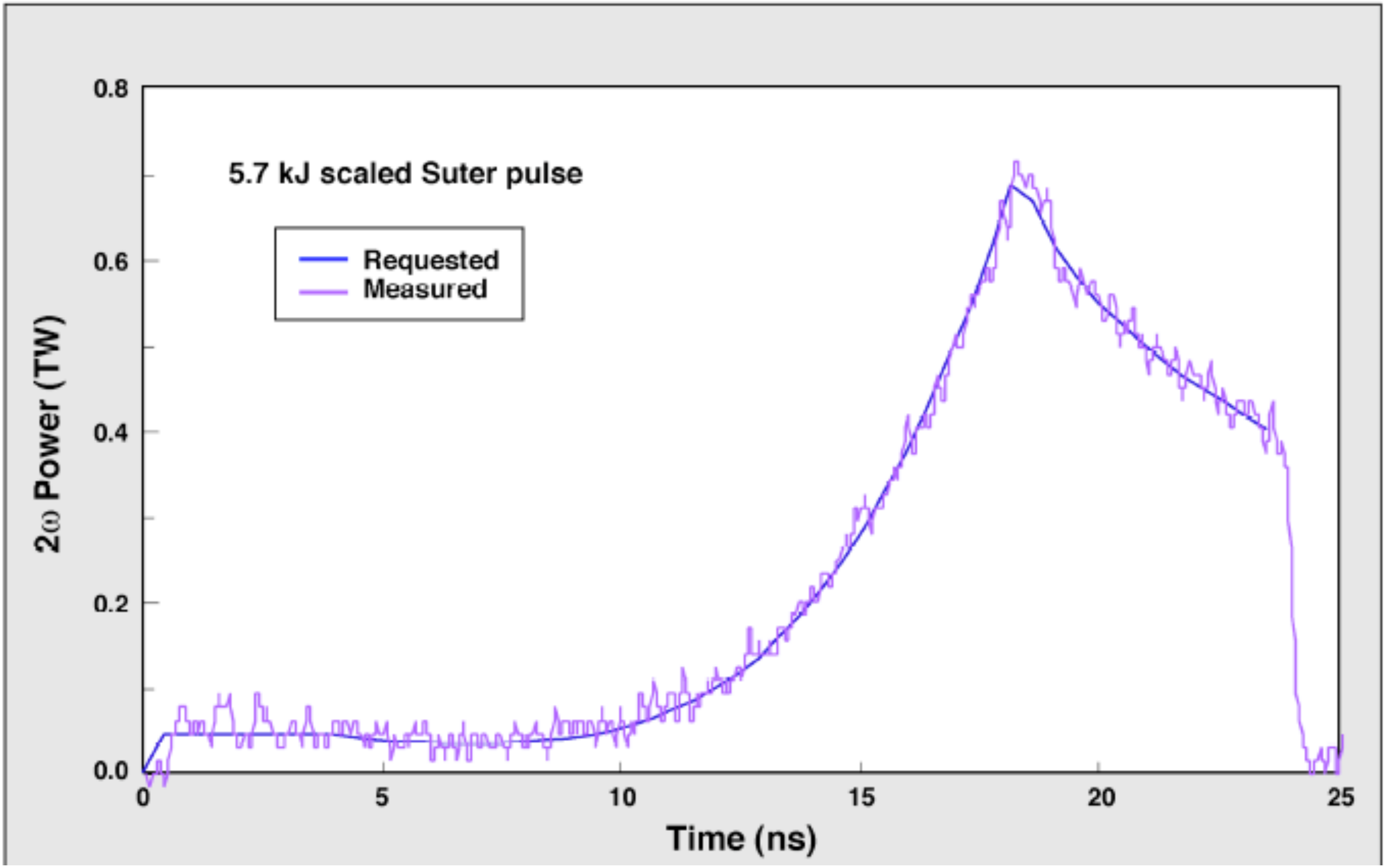

The NIF Early Light (NEL) commissioning of four laser beams has demonstrated all of NIF's primary performance criteria on a per beam basis

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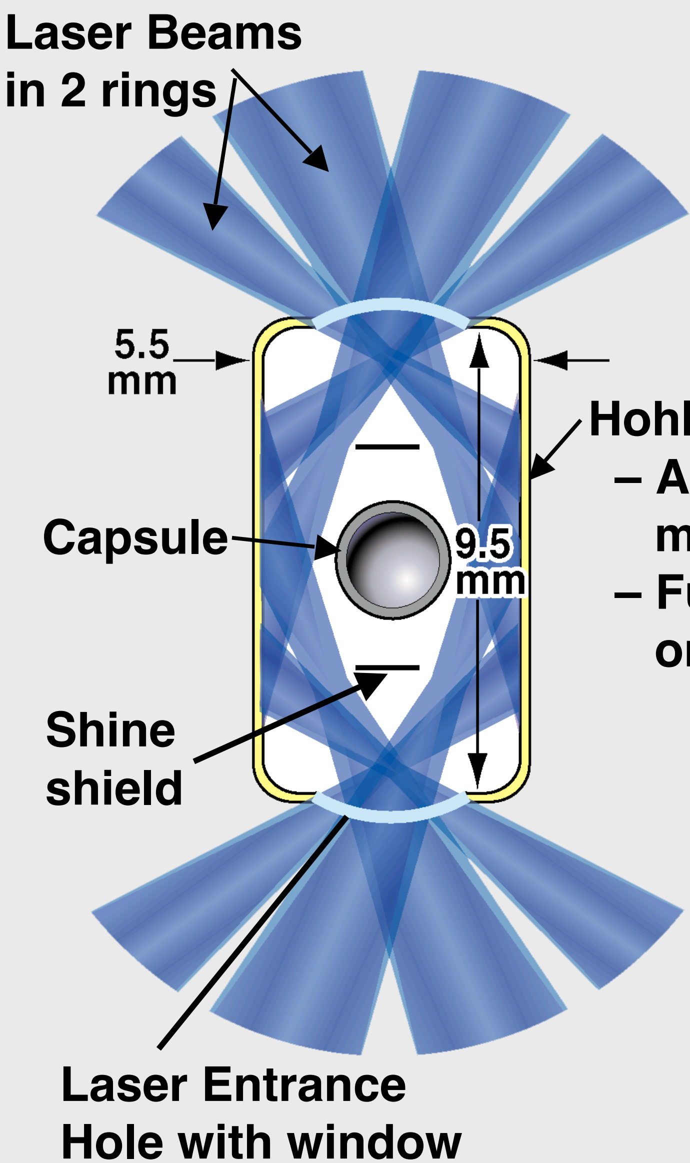
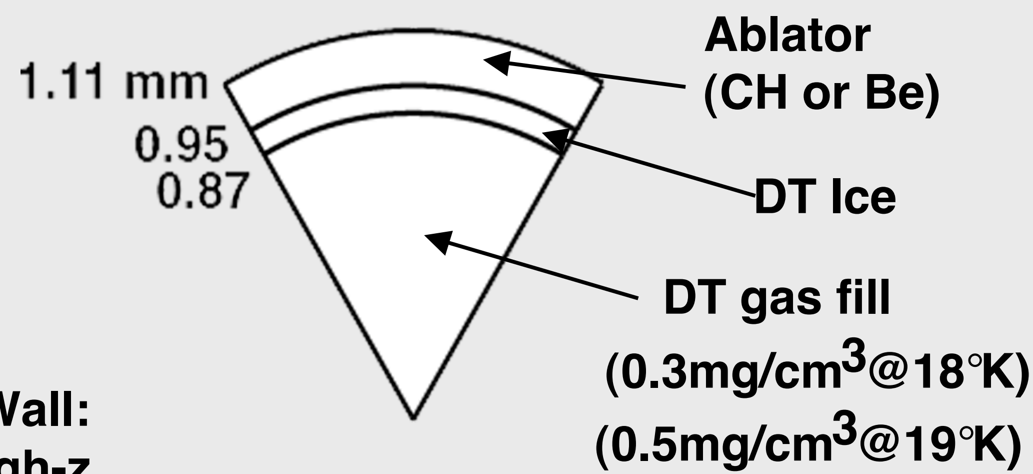
- 21 kJ of 1w light (Full NIF Equivalent = 4.0 Mjoule)
- 11 kJ of 2w light (Full NIF Equivalent = 2.2 Mjoule - non-optimal crystals)
- 10.4 kJ of 3w light (Full NIF Equivalent = 2.0 Mjoule)
- 25 ns shaped pulse
- < 5 hour shot cycle (UK funded shot rate enhancement program)
- Better than 6% beam contrast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

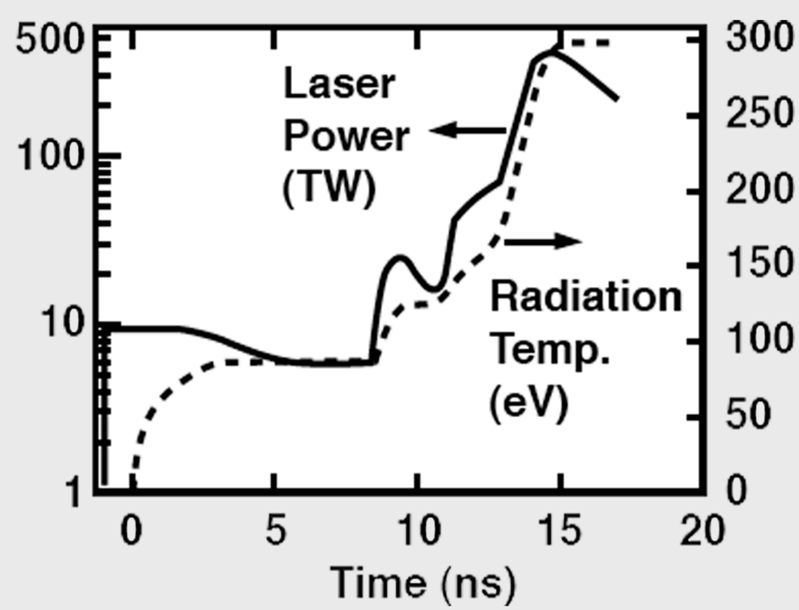
NIF Indirect Drive target schematic



Hohlraum Wall:
- Au or High-z mixture (cocktail)
- Full density or foam



Typical Pulse Shape



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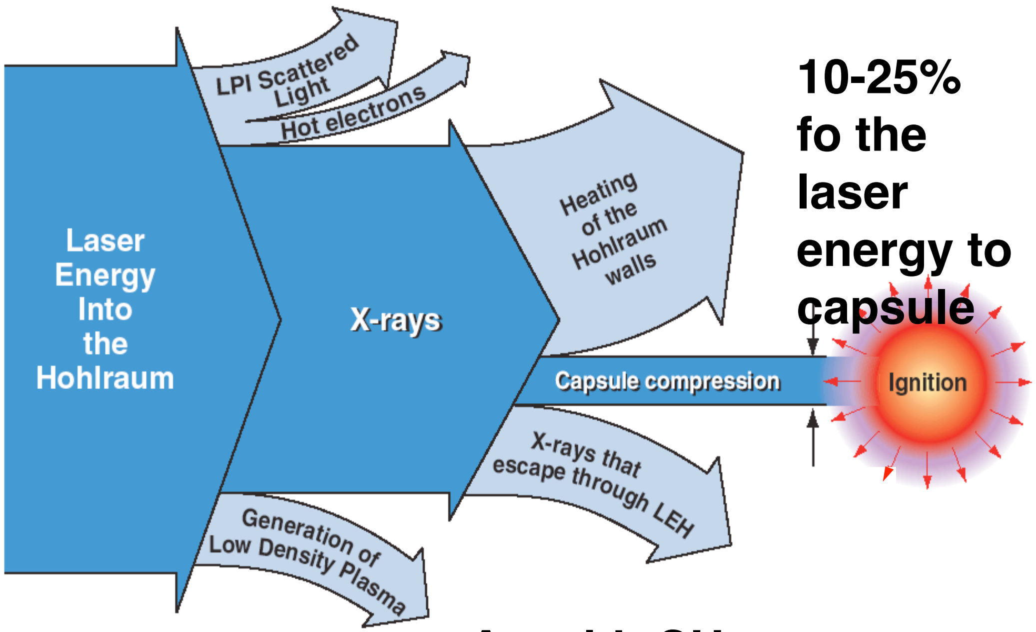
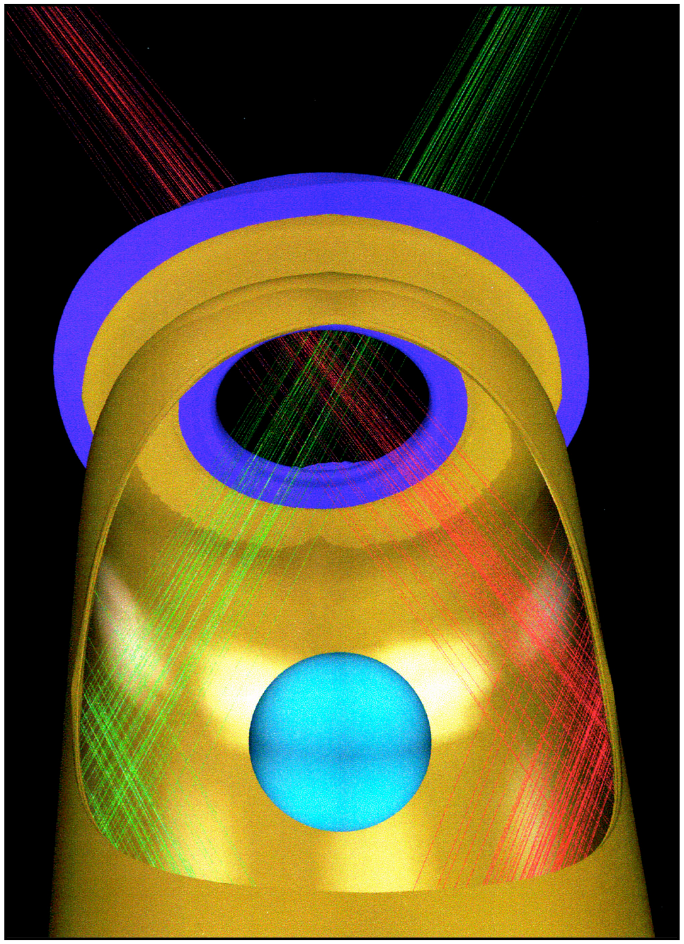
The Indirect drive ignition point design continues to evolve to optimize coupling efficiency



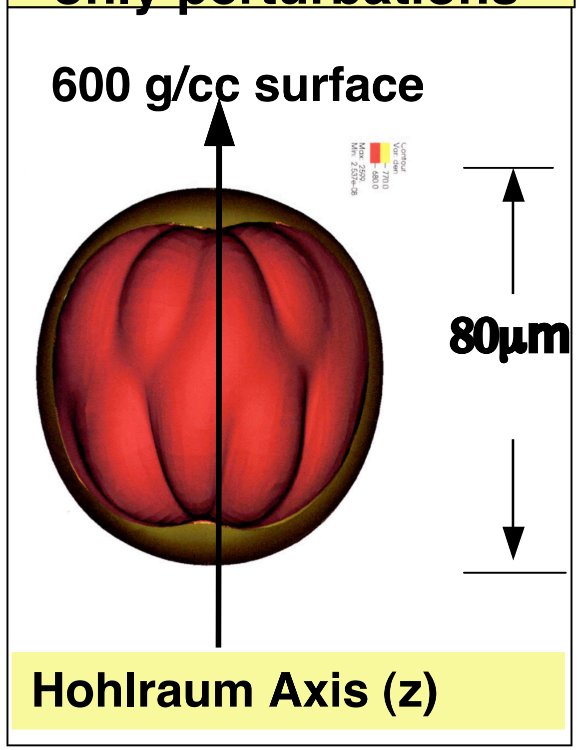
10-25% fo the laser energy to capsule

	Au with CH Capsule	Au with Be Capsule	Cocktails with Be Capsule
Laser light	1.45	1.45	1.45
(MJ) Absorbed	1.30	1.30	1.30
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%

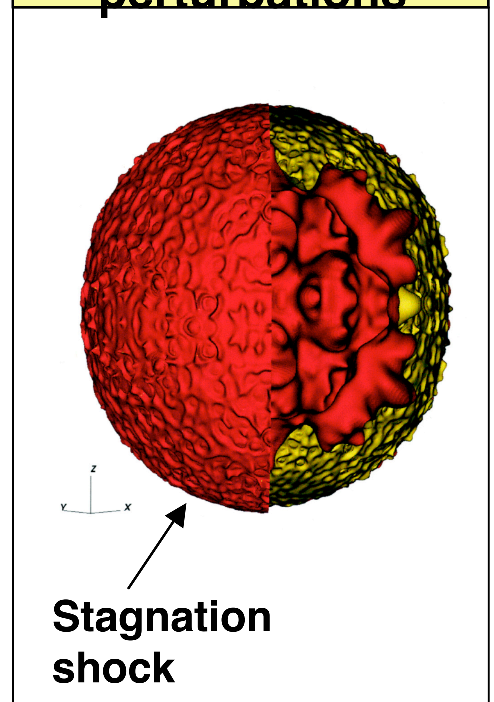
Cocktail ignition target burns with near 1D yield in 3D calculations with both asymmetry and surface roughness



Ignition - hohlraum only perturbations



Ignition - capsule and hohlraum perturbations

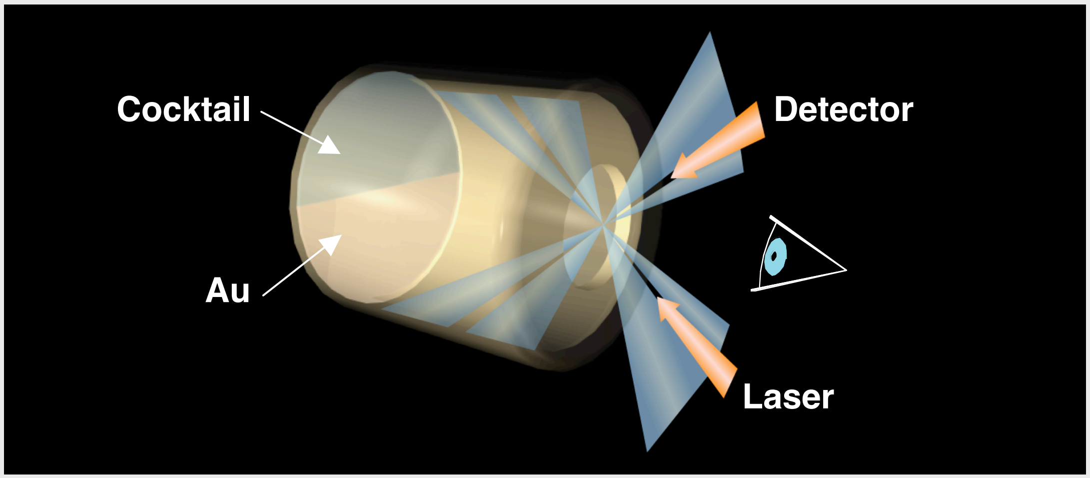


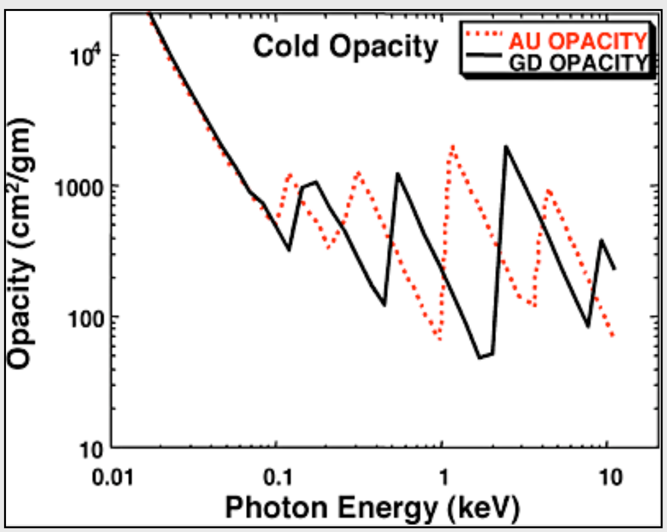
400 g/cc density isosurface

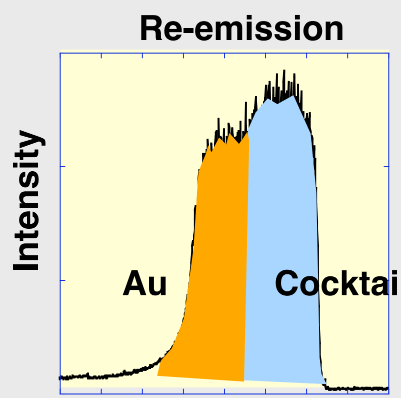
The Hydra code is used for 3D calculations on the ASCI computers

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

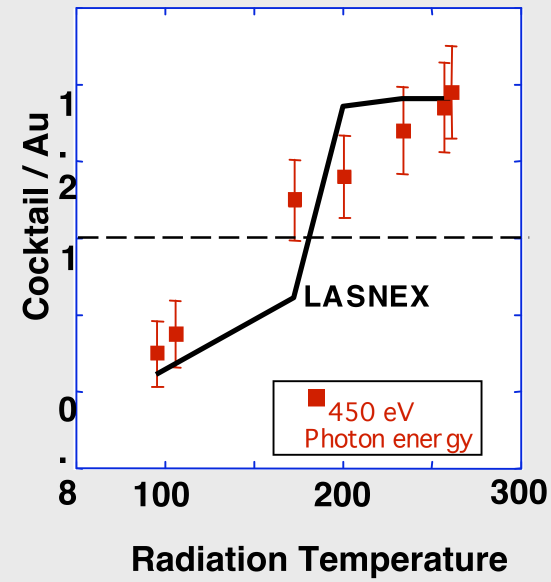
Hohlraum experiments with split back plate verify high x-ray re-emission





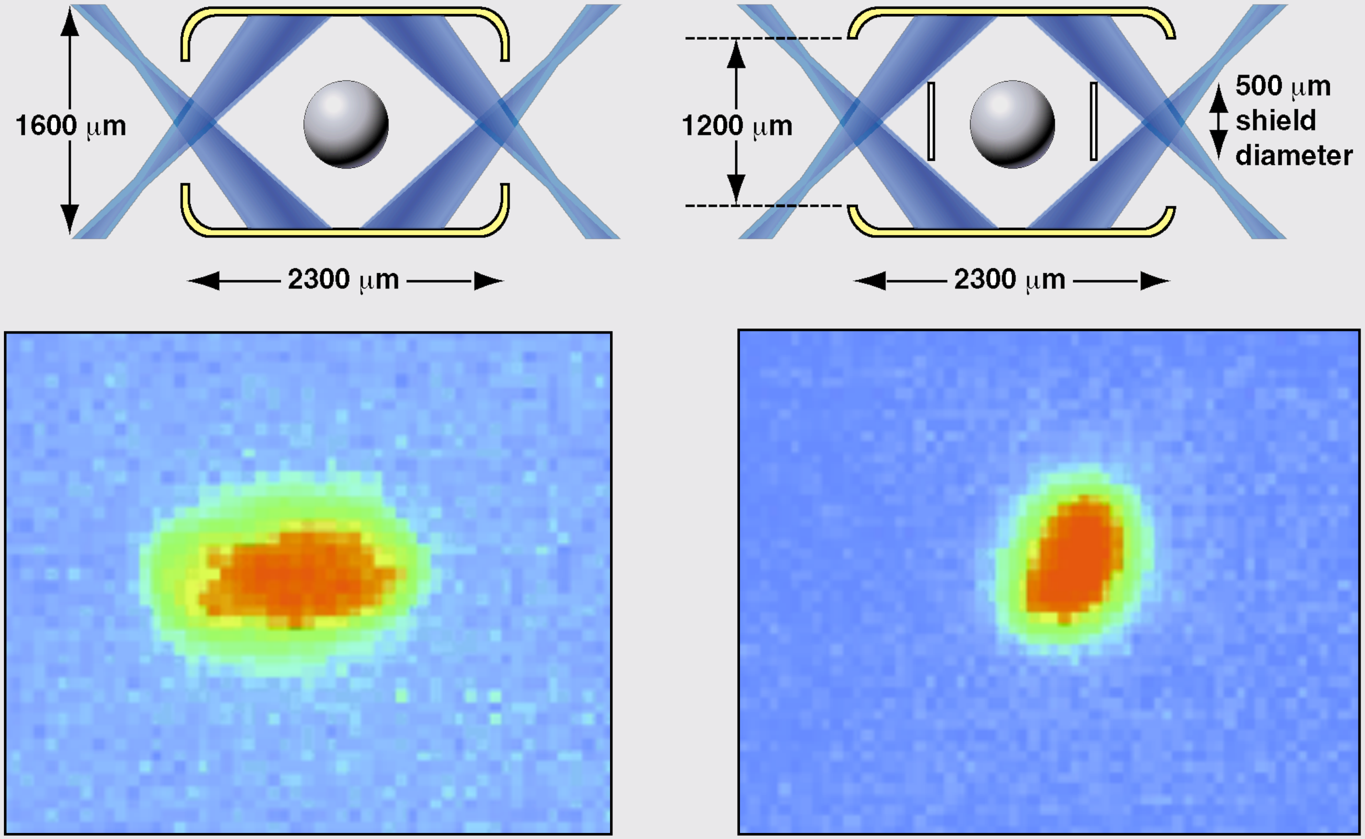


Intensity ratio of Cocktail/ Au is in agreement with LASNEX calculations



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

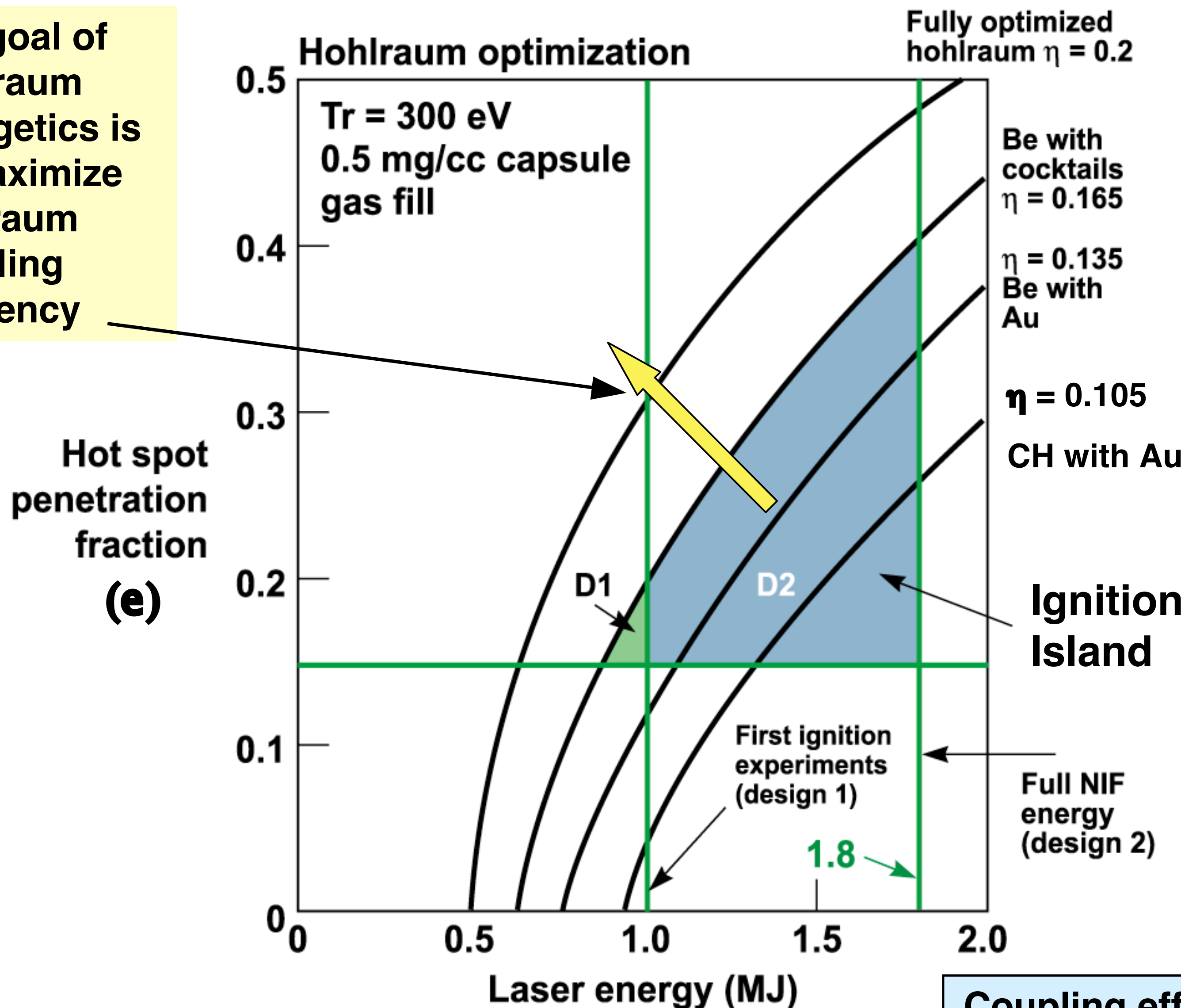


1 ns square pulse - identical pointing

- 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 Hohlraum Energetics is to maximize hohlraum coupling efficiency



Coupling efficiency = $\eta_{abs}\eta_H$

η_{abs} = 1 - backscattered fraction

η_H = hohlraum coupling efficiency

At 3ω, drive measurements and Lasnex simulations agree closely over >two orders of magnitude in T^4_R

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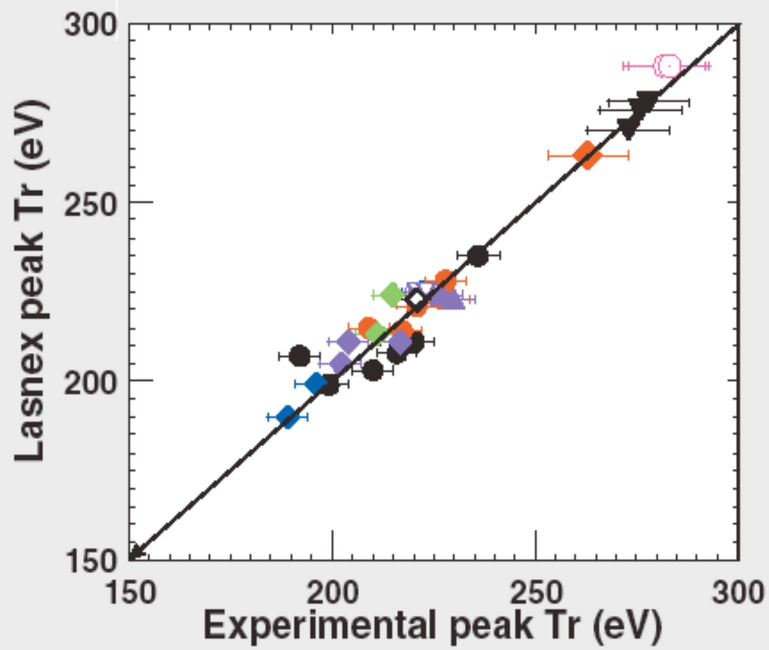
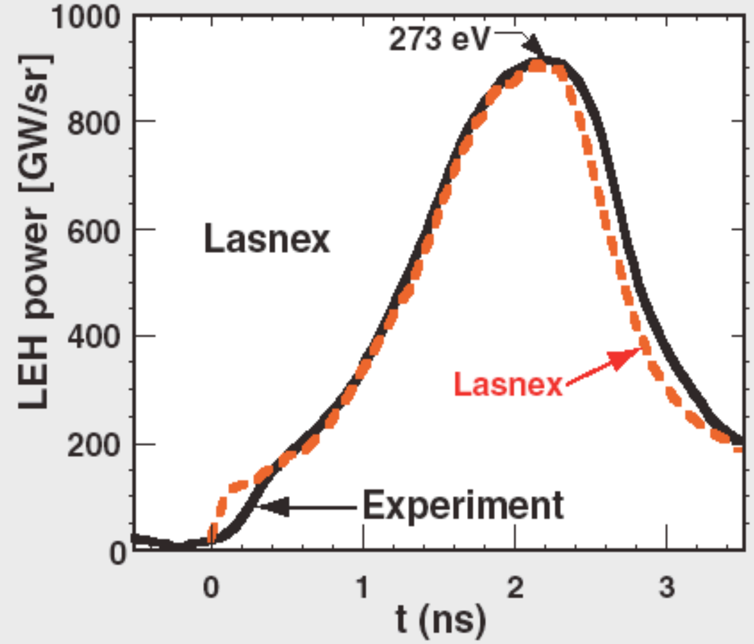
Nova and Omega Experiments





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

Lasnex can predict hohlraum drive to ±10%

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

Energetics

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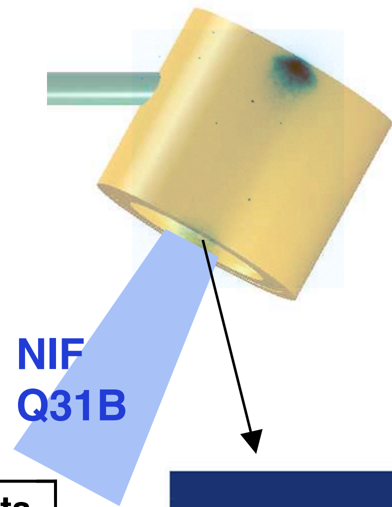
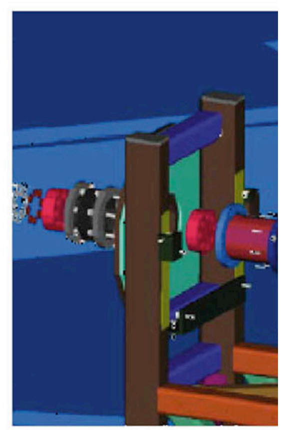
Los Alamos National Laboratory

Sandia National Laboratories

Thinwall Au Hohlraum

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

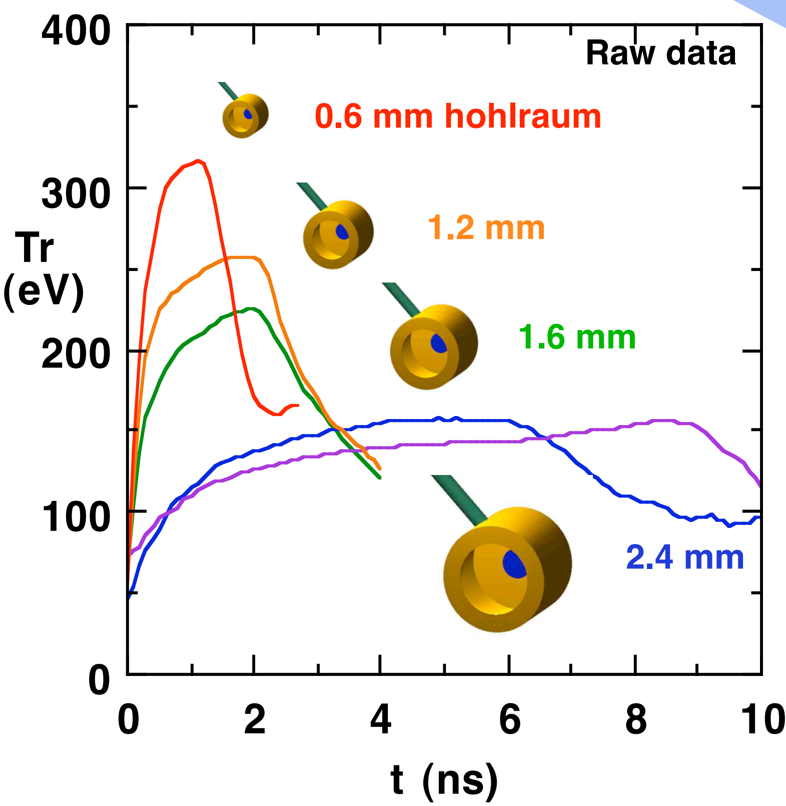




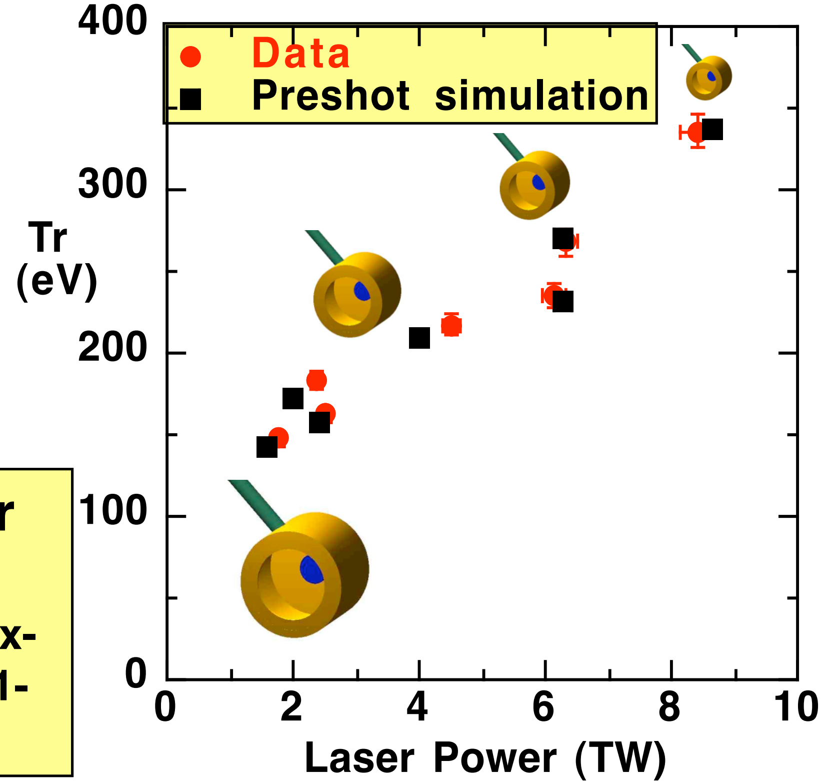
Hohlraum Tr (Dante)

18 channel soft x-ray detector (0.1-10 keV)

Hohlraum Tr vs time



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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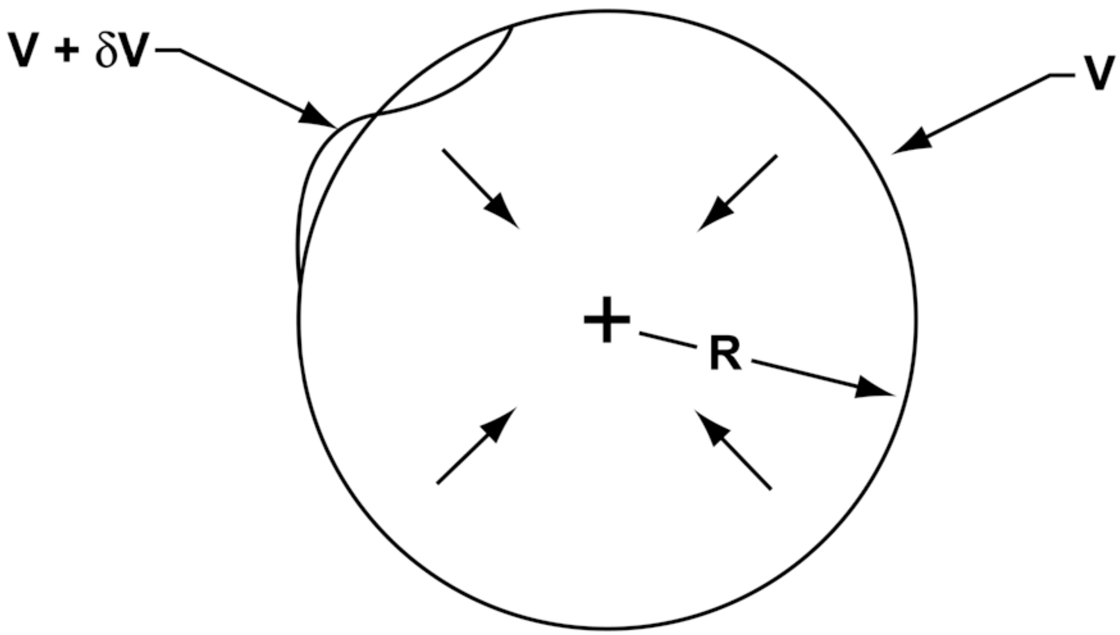
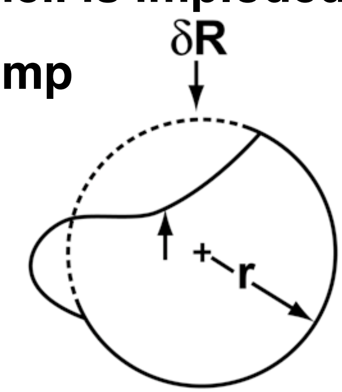
Small nonuniformity when outershell is at large radius



Becomes magnified when shell is imploded to a very small radius

Lower peak compression, temp
Lower r R



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

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

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

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

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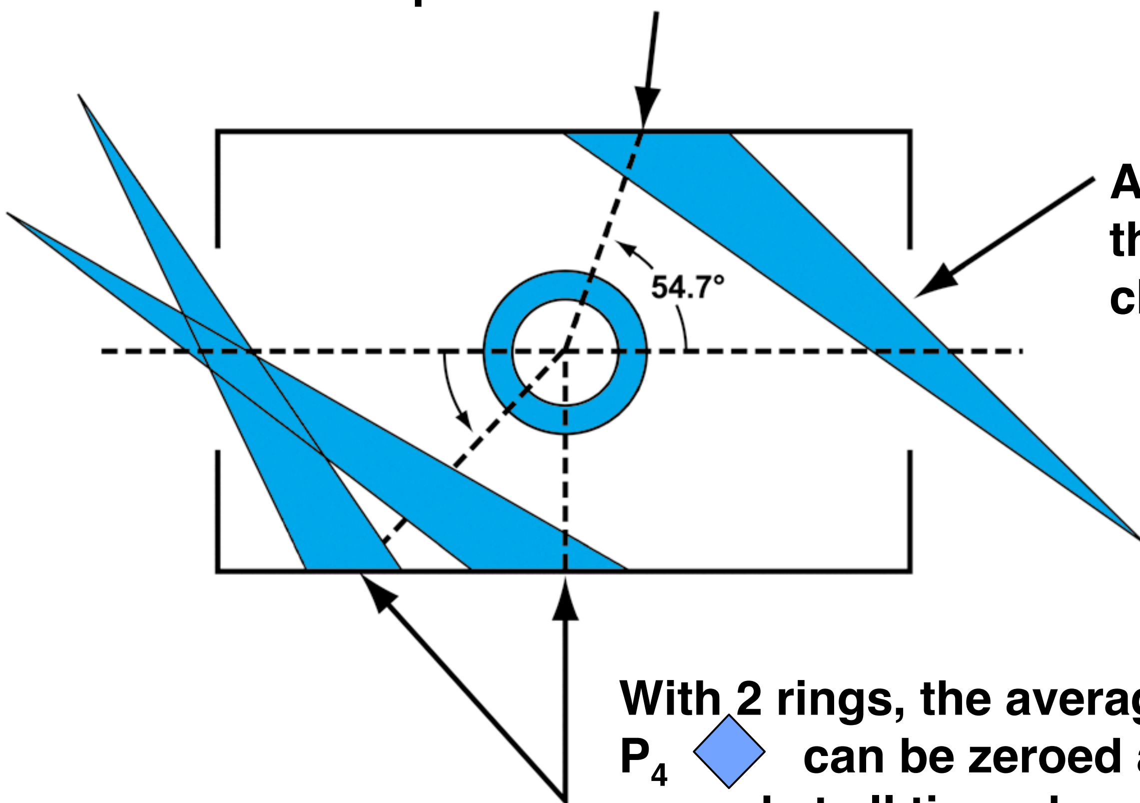
Plasma motion moves the beam position near the wall

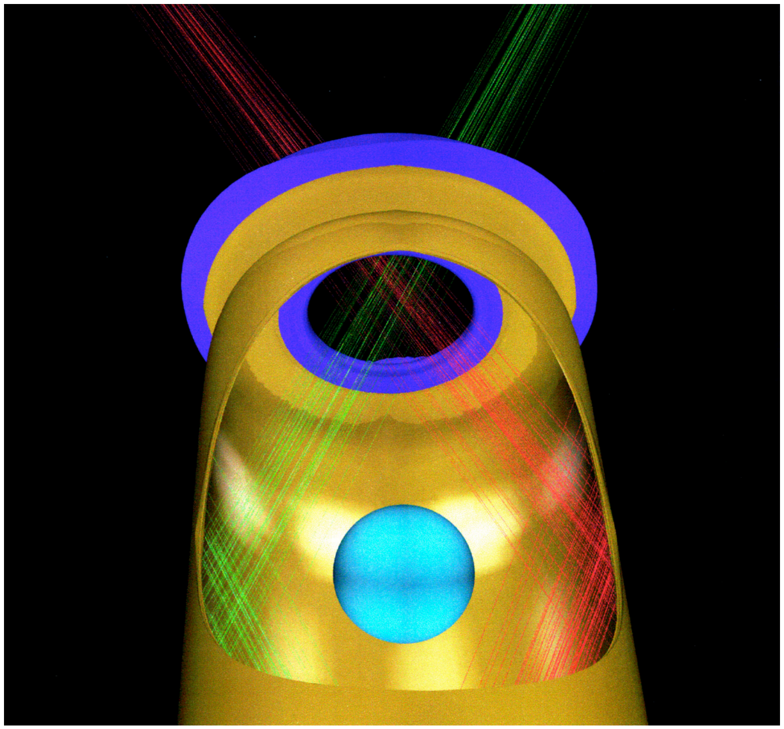


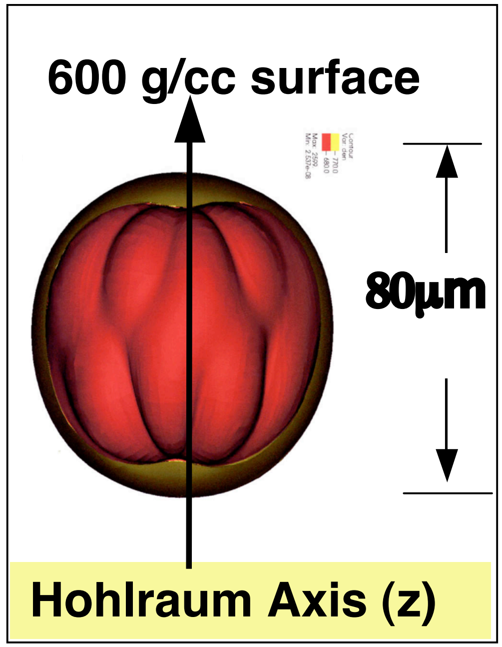
As the wall heats up the effect of the hole changes in time

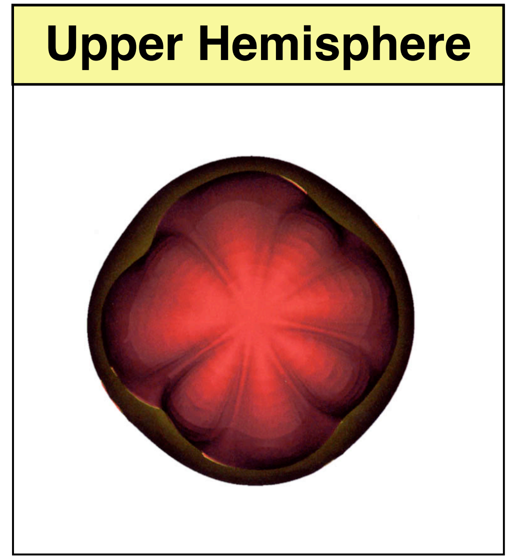
With 2 rings, the average P_2 and P_4 can be zeroed and P_2 can be zeroed at all times by adjusting the beam balance

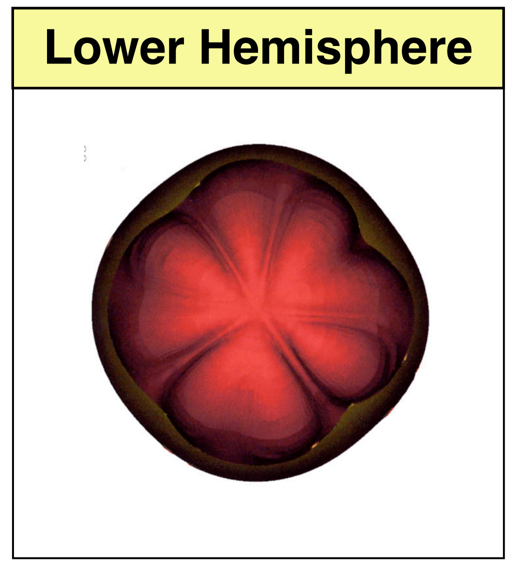
Optimization of symmetry will require close coordination of detailed design calculations and precision experimental measurements

Be capsule fuel region at ignition









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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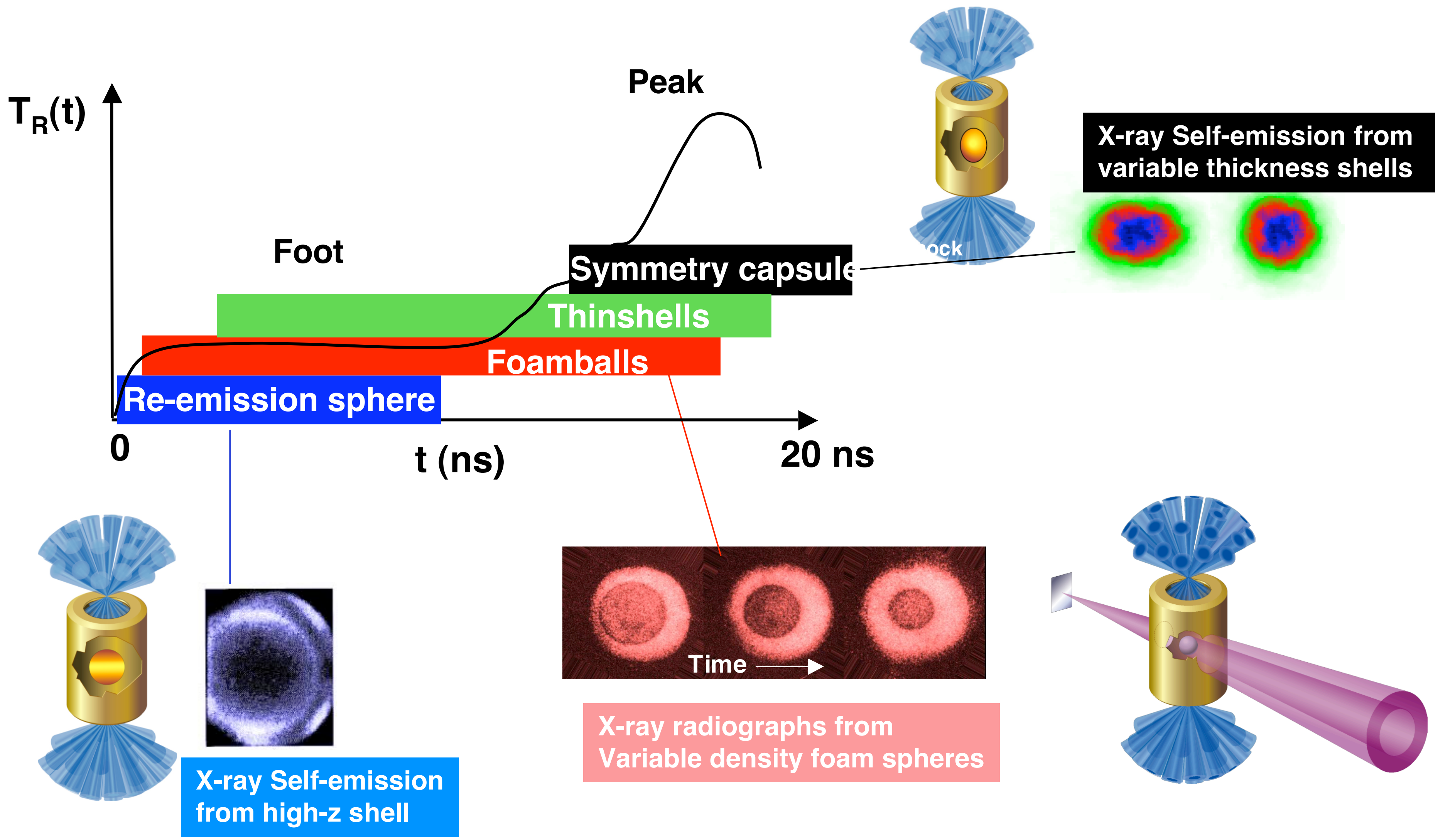

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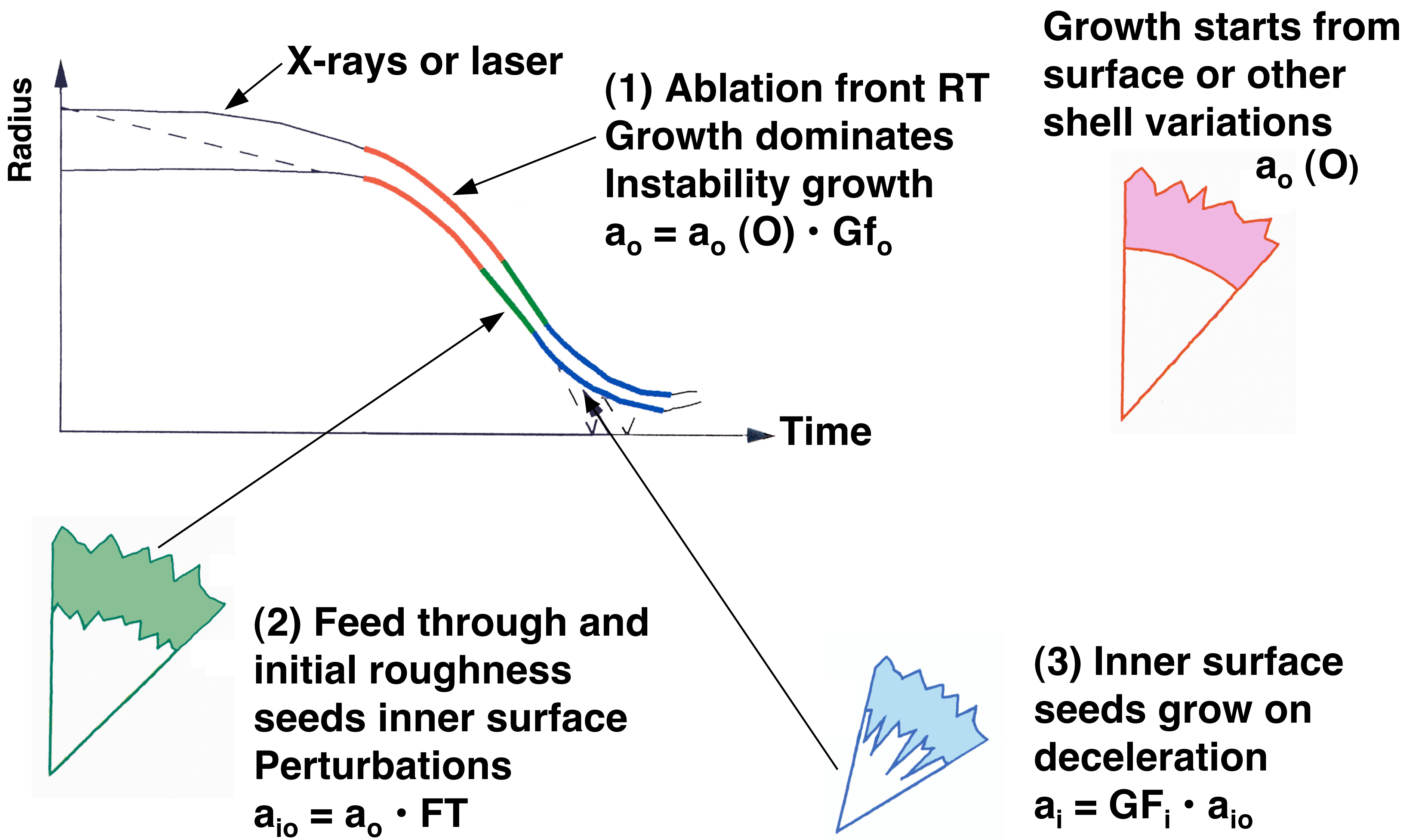
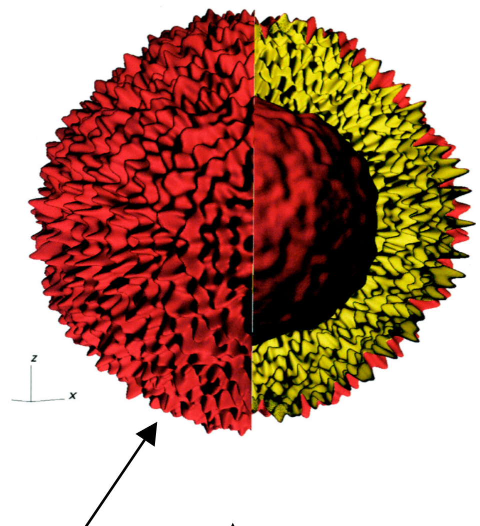
The ablation front hydrodynamic instability can destroy an imploding shell



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

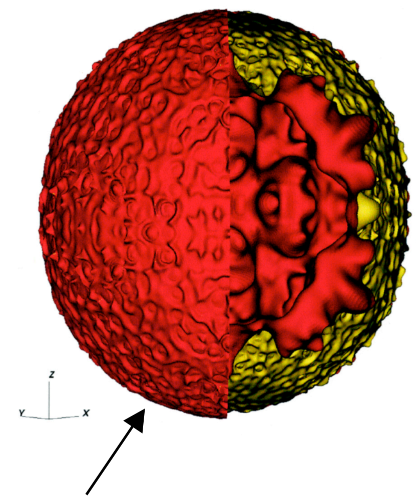
- Capsule simulations have asymmetry and fabrication perturbations
- 3D asymmetry inferred from integrated hohlraum simulation
- Nominal "at spec" perturbations on ice and ablator in low, intermediate, and high modes
- Gave 21 MJ (90% of 1D calculation)

140 ps before ignition time



60 g/cc density isosurface

Ignition time



400 g/cc density isosurface (different scale)

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

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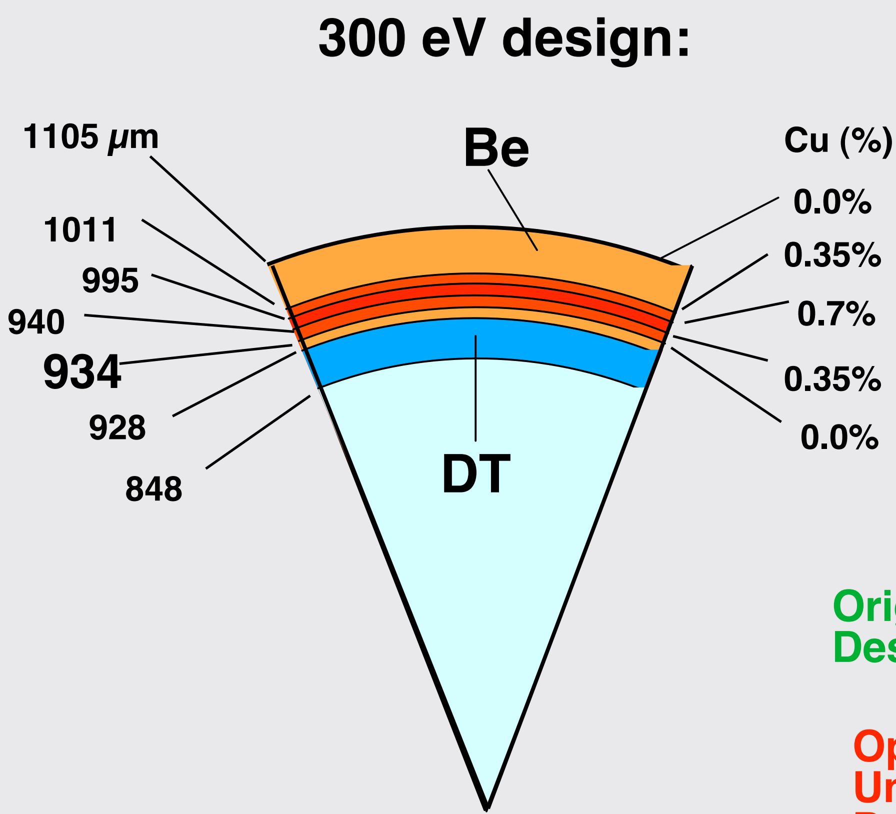
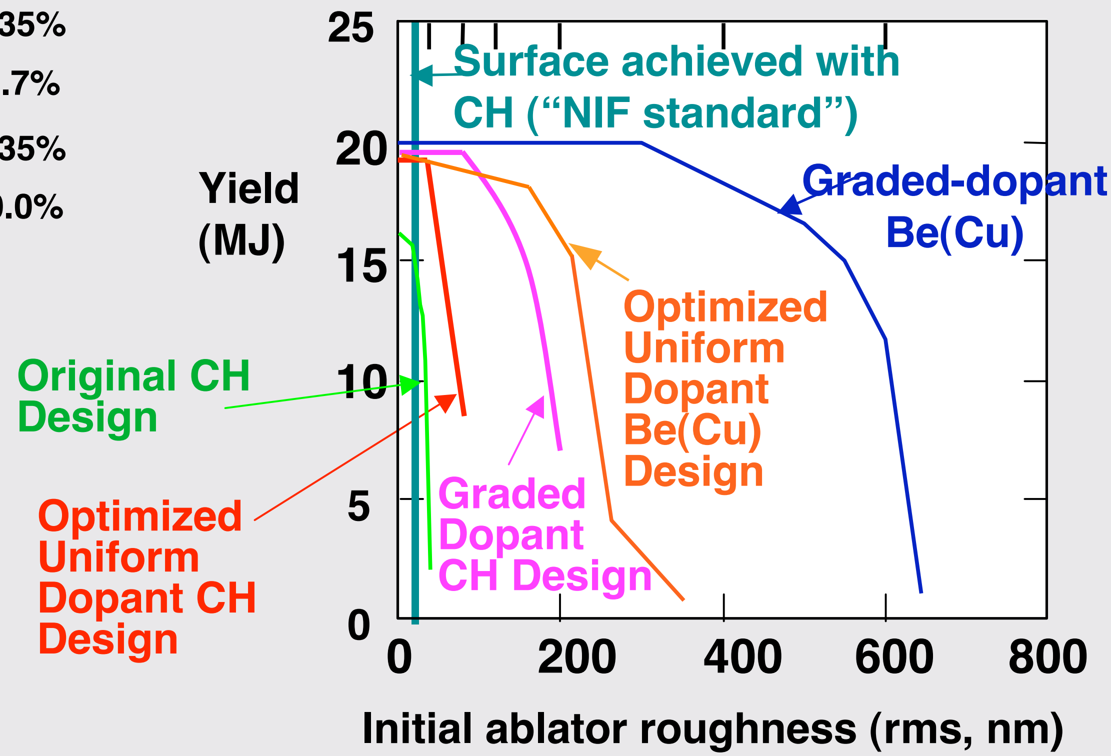


The graded doped Be capsule can tolerate 60x the NIF standard



Tolerance to ice roughness is also better (5 μm compared to 1 μm)

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

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

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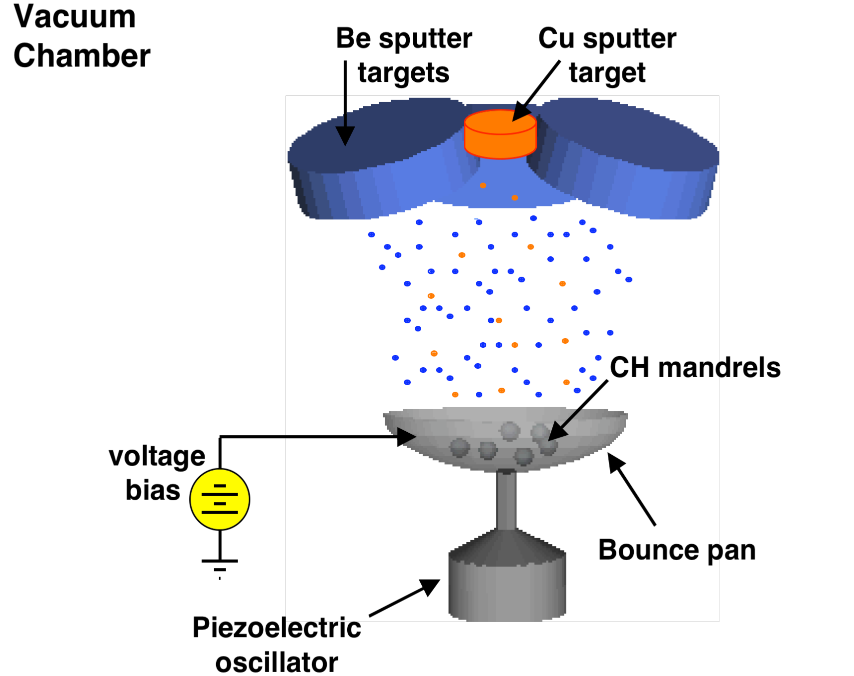
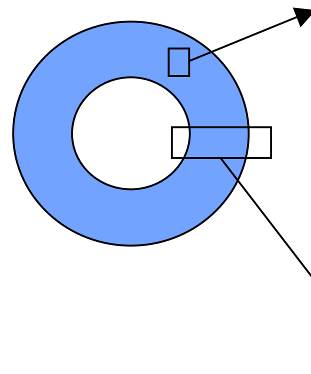
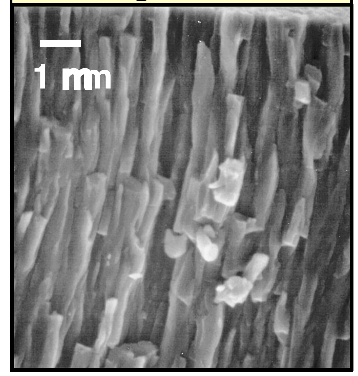
Sputter deposition on CH mandrels



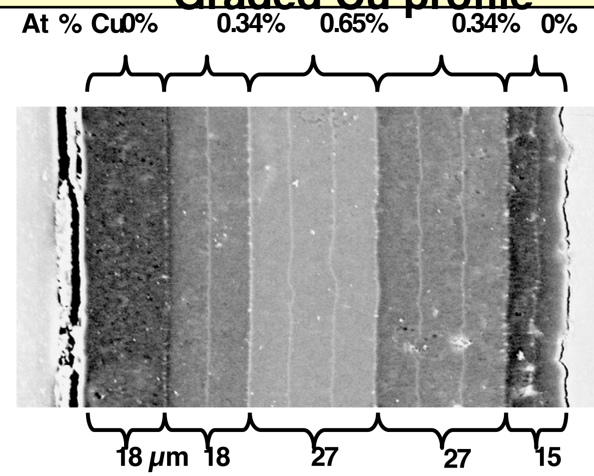


Sub-micron grains



High mode morphology

Graded Cu profile



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

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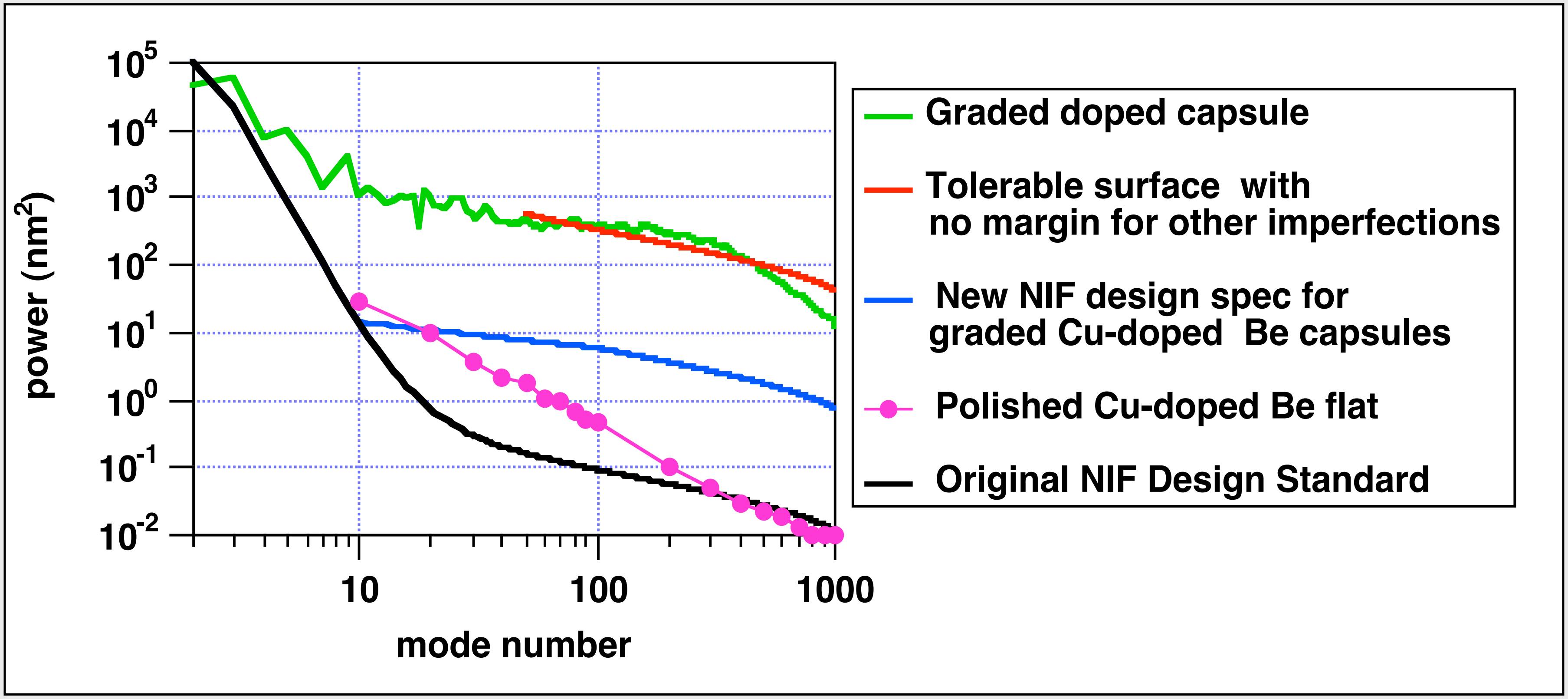

- We plan to investigate use of ion bombardment and other methods as means to improve surface finish and coating density
- In FY05 LANL will study shell polishing

Be is non-permeable, and requires a fill hole through the ~100-μm-thick ablator for filling

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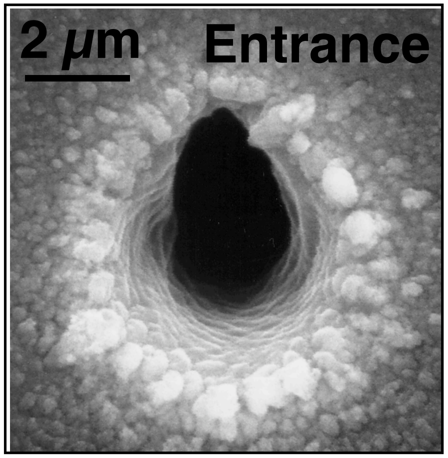
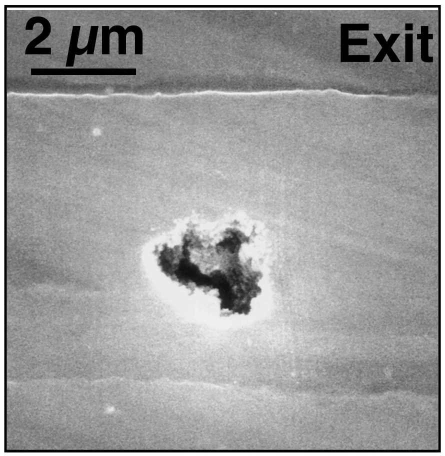
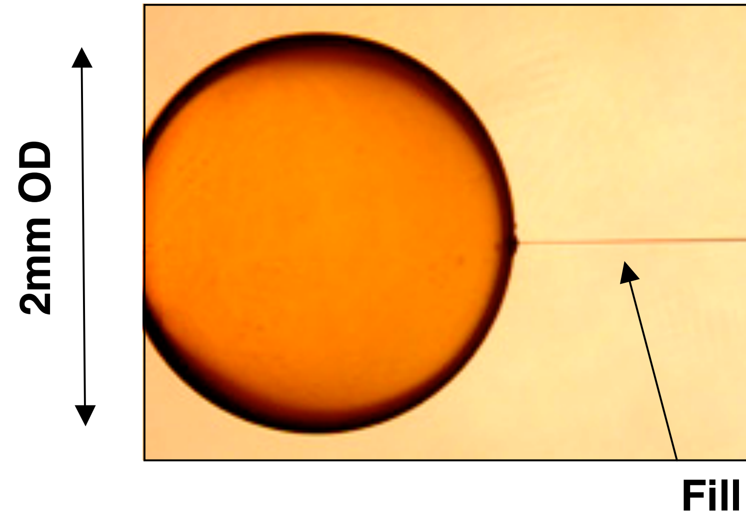
Laser:
Ti:sapphire
405 nm, <1 μJ,
120 fs, 3.5 kHz
drilling time: ~40 sec

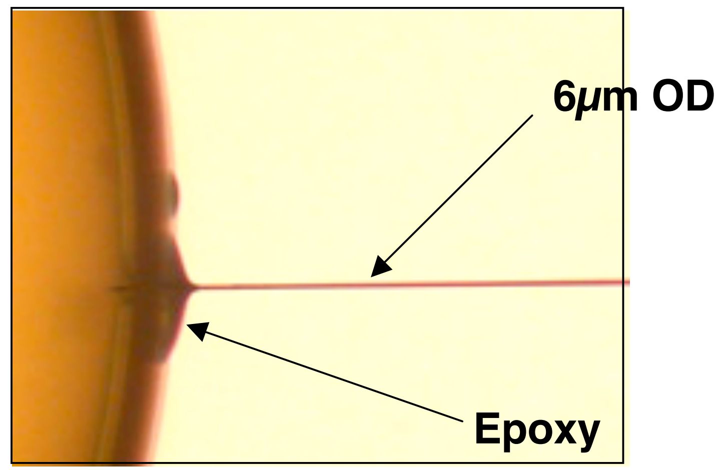




- Two routes to filling beryllium capsules
  - Fill Tube
  - Drill, Fill and Plug (Strong Capsules)

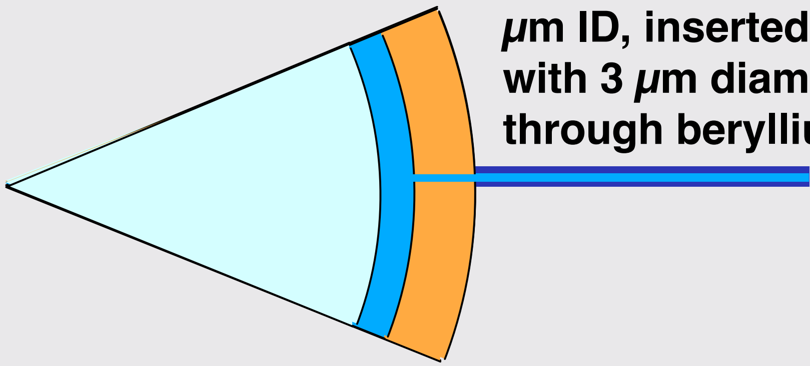
Fill Tube





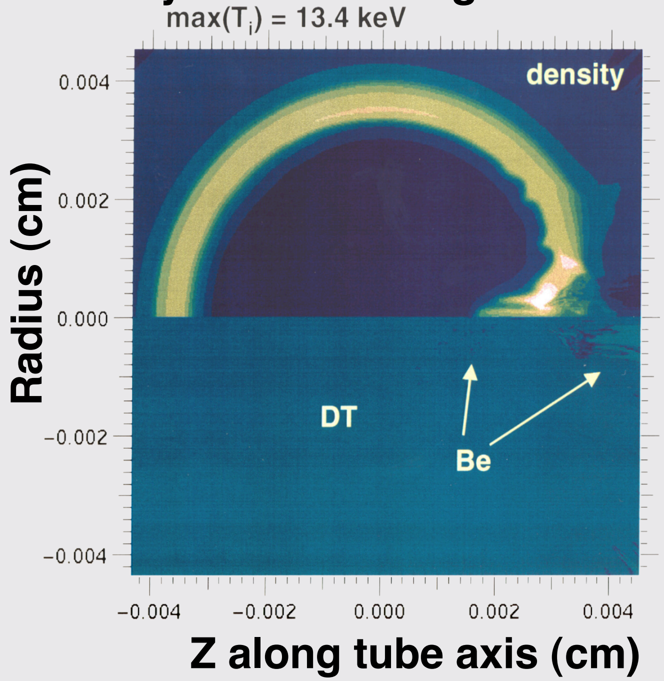
Current effort:
minimizing the glue joint

Simulations indicate that a 10 μm tube with a 3 μm hole has an acceptable impact on the implosion



Glass tube, 10 μm OD, 3 μm ID, inserted 20 μm, with 3 μm diameter hole through beryllium ablator

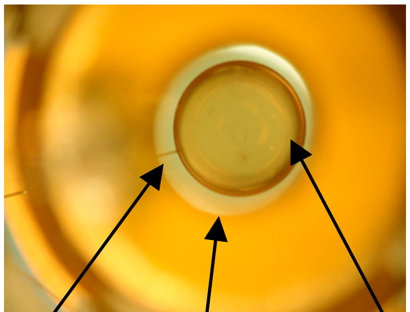
Density contours at ignition time



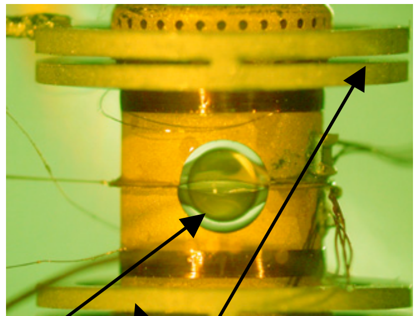
- **Uniformly doped Be(Cu) capsule**
- **Calculation ignites and burns to same yield as 1D clean -- 21.7 MJ**
- **Simulations in progress with graded-doped capsule, larger hole**

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

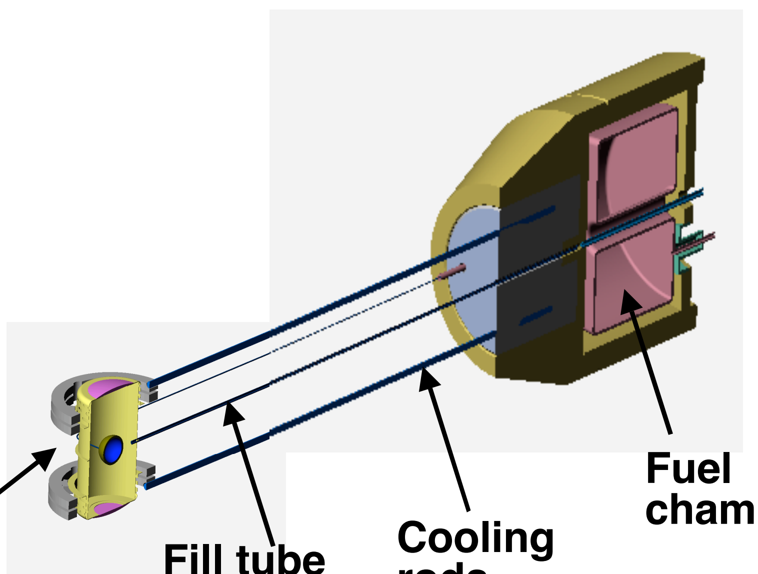
View of 2mm shell through laser entrance hole

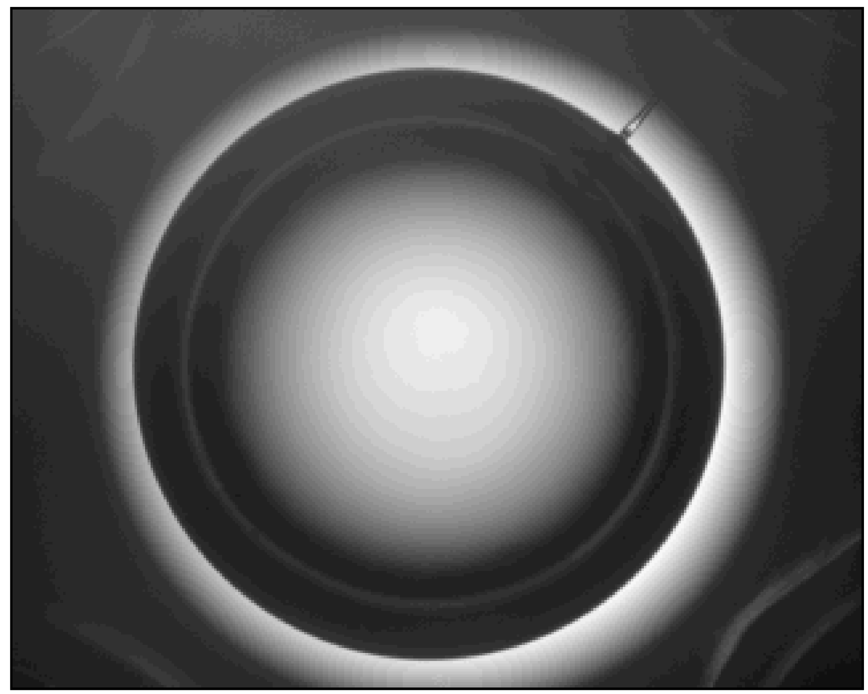


View of 2mm shell through side hole



- **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

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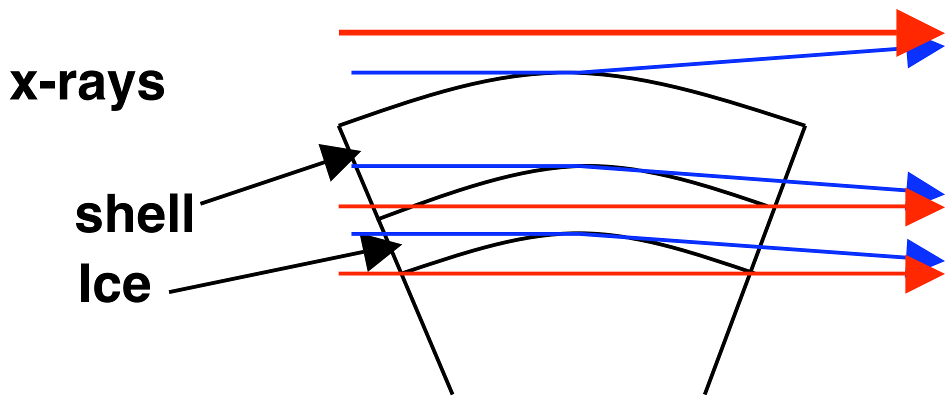
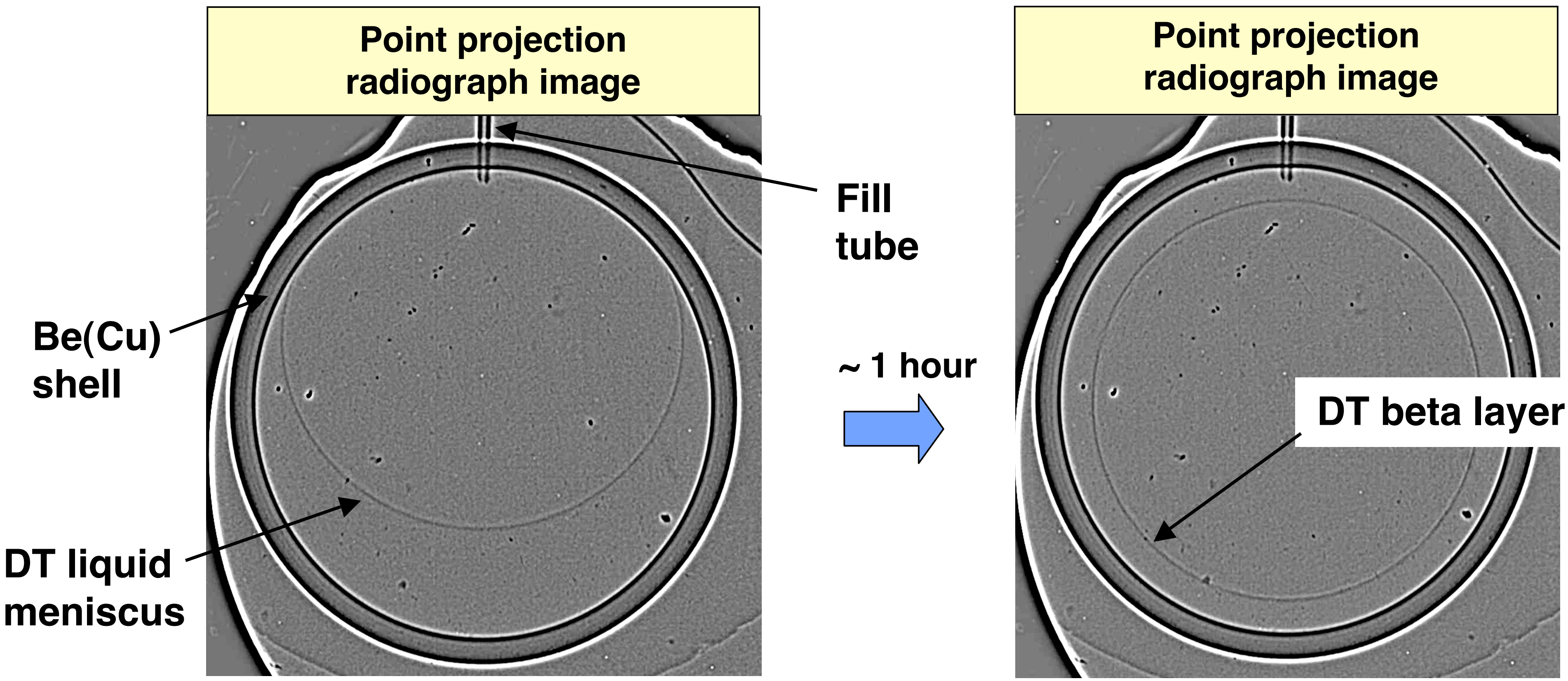


- Rays tangent to surface are slightly deflected
- Other rays are very nearly un-deflected
- This method is many times more sensitive than absorption



The best cryo layers are formed near the triple point

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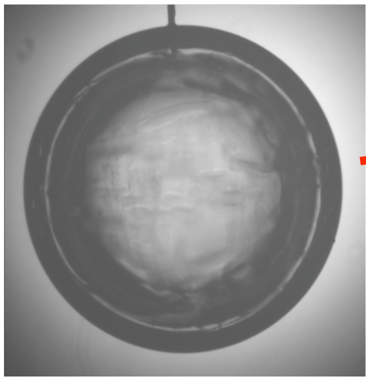
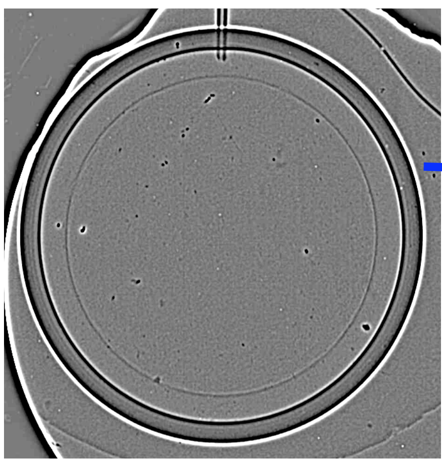
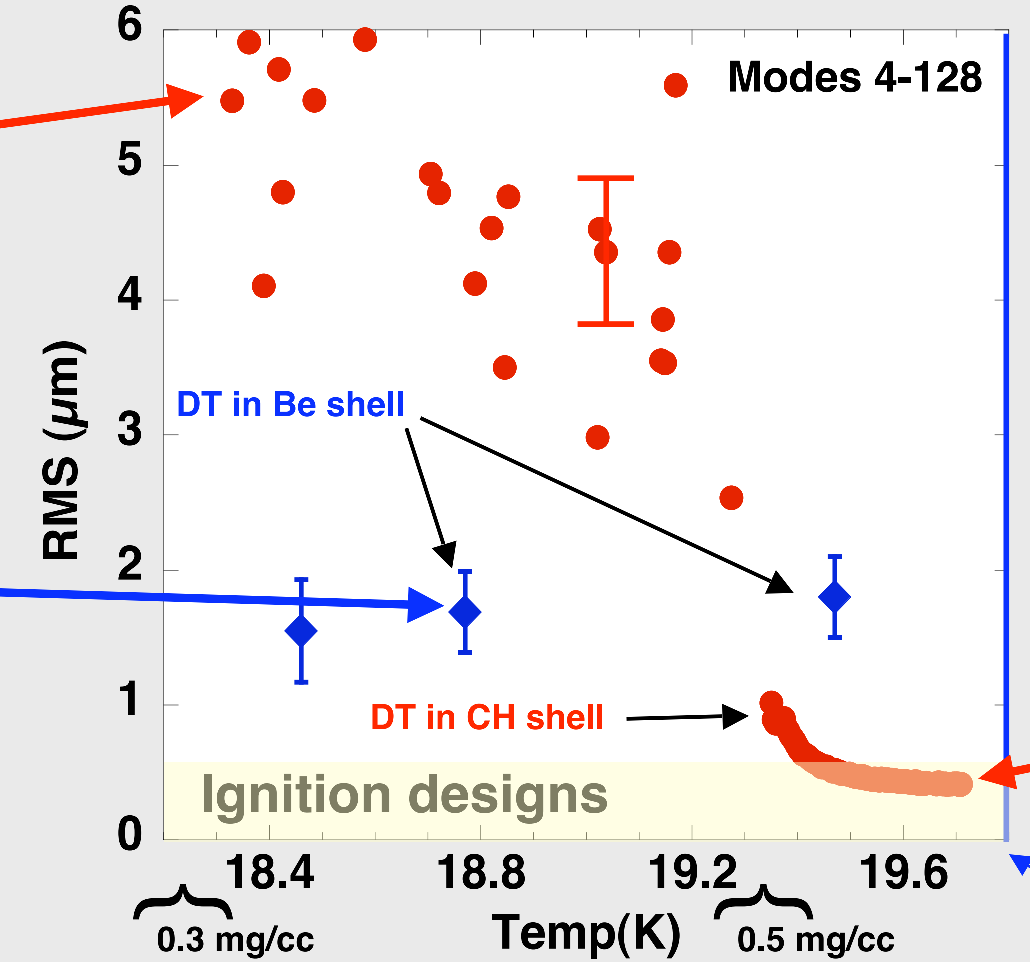
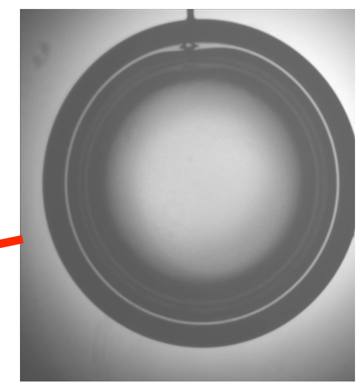
Layer smoothness appears to degrade at temperatures less than 0.5 K below the triple point





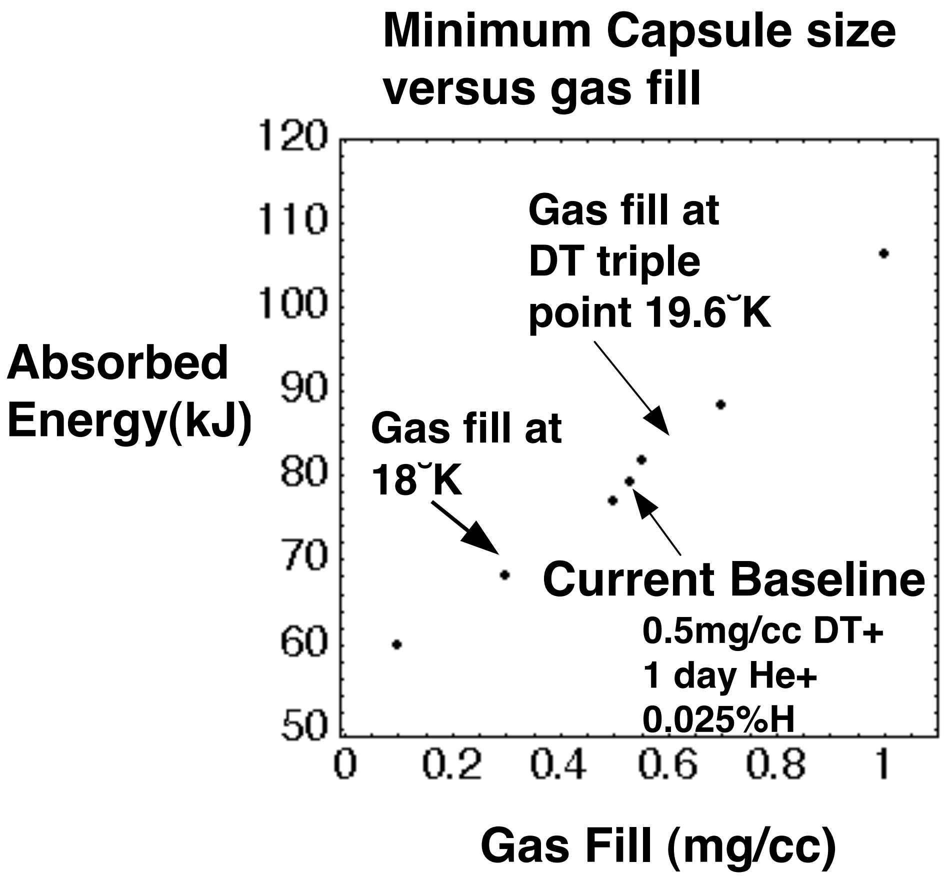




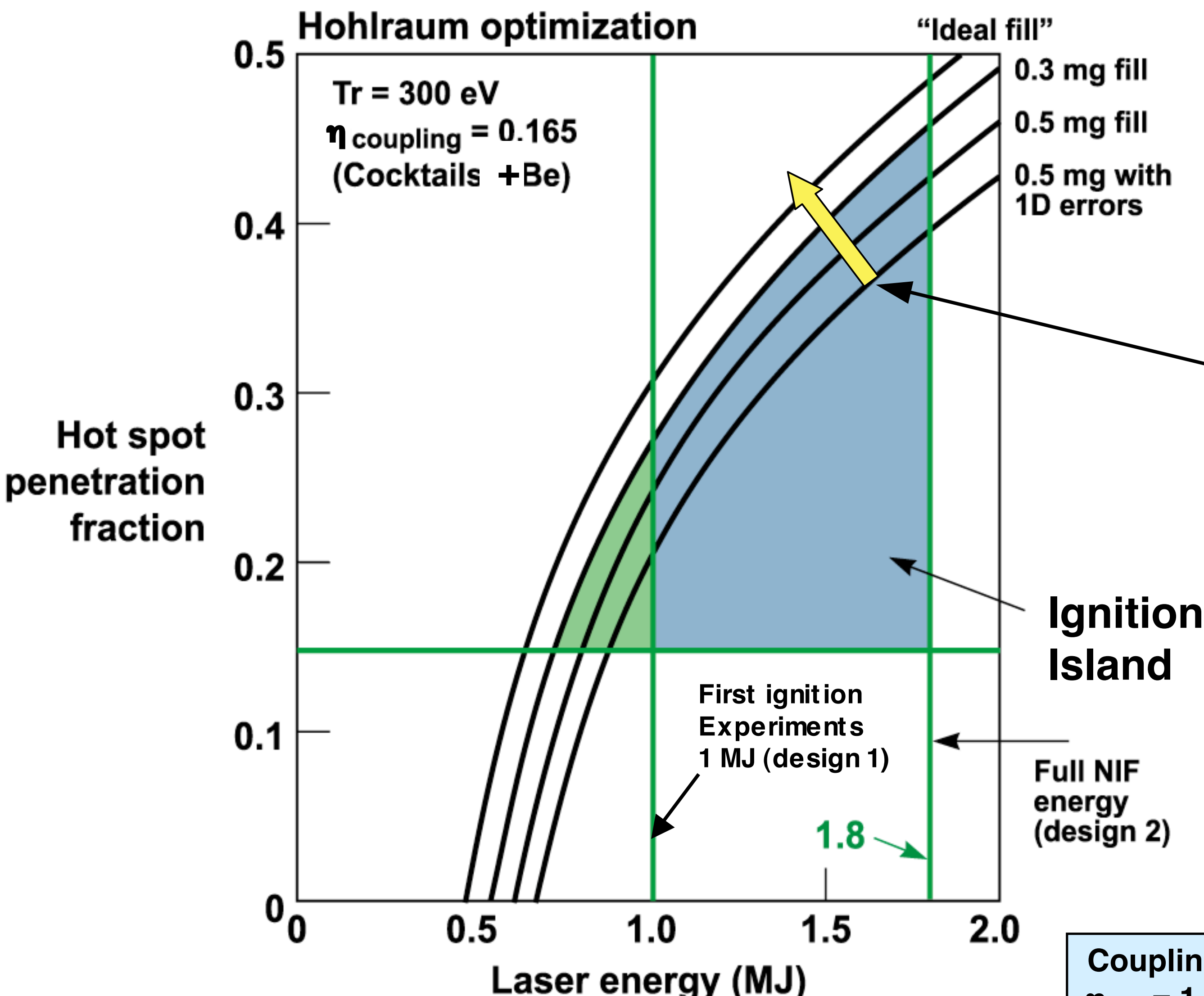
DT triple point

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

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



The ignition island is increased by improving target fabrication



The goal of target fabrication and the implosion dynamics campaign is to achieve capsule performance which is near the ideal limit

Coupling efficiency = $\eta_{abs}\eta_H$
η_{abs} = 1 - backscattered fraction
η_H = hohlraum coupling efficiency

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

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

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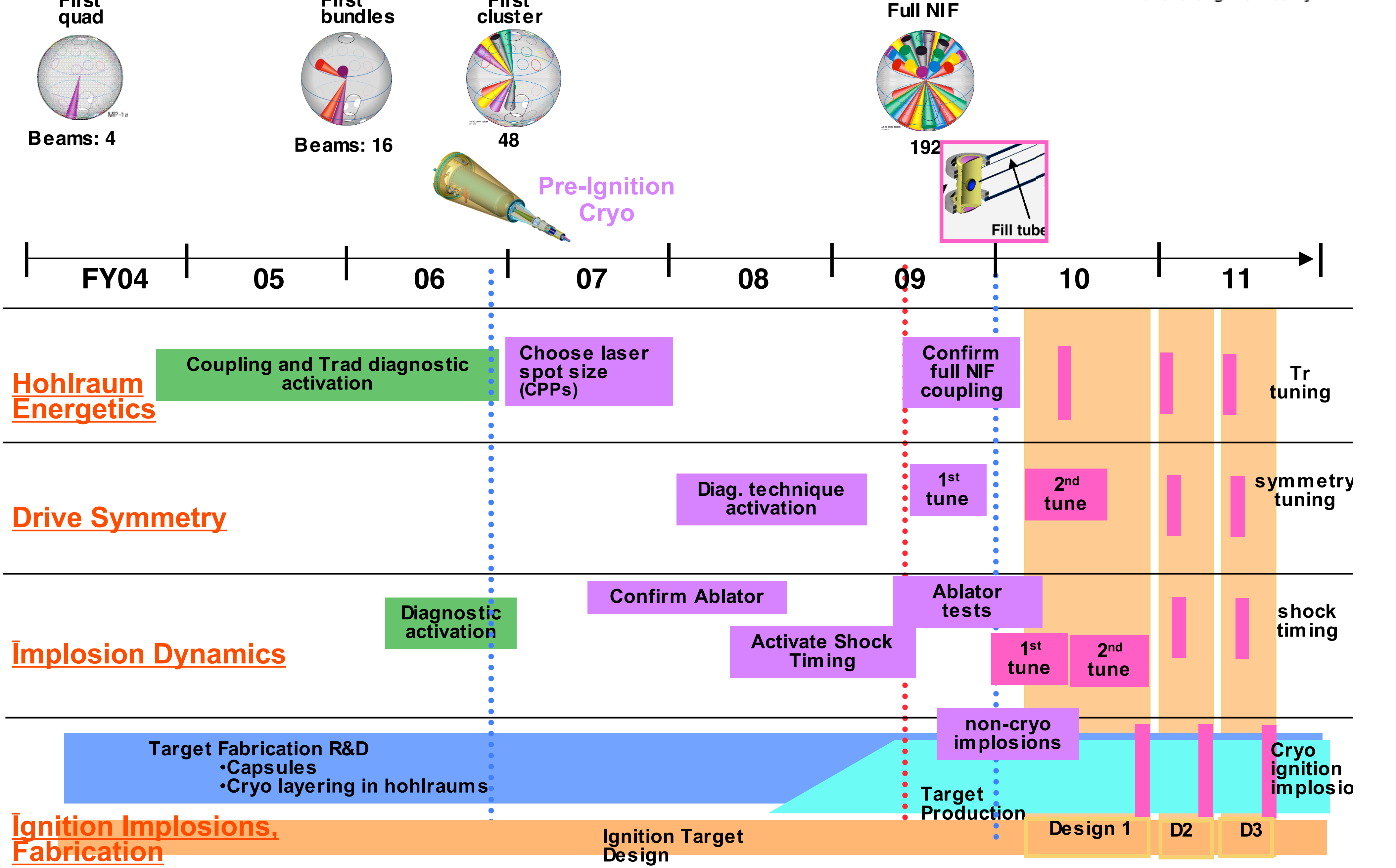

Summary/Conclusions

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- 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