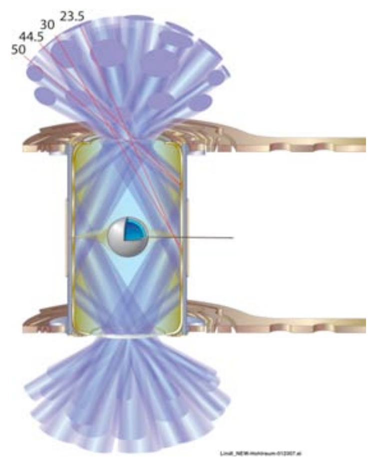
The Development of Indirect Drive ICF and the Countdown to Ignition Experiments on the NIF

Maxwell Prize Address
APS Division of Plasma Physics Meeting
November 15, 2007



John Lindl
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Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

The NIF ignition experiments will be the culmination of five decades of development which started with the invention of the laser in 1960

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- Ted Maiman demonstrated the first laser in 1960
- John Nuckolls 1972 Nature paper spelled out the essential requirements for high gain laser driven ICF
- Indirect drive experiments started at Livermore in the mid-1970's
- Dramatic advances in computations, lasers, diagnostics, and target fabrication over the past 3 decades laid the groundwork for NIF and the National Ignition Campaign (NIC)
- We are designing precision experimental campaigns for hohlraum energetics, shock strengths and times, implosion velocity and ablated mass, and symmetry, which will take 100-200 shots leading up to the first ignition attempts
- Targets near 1 MJ of laser energy have a credible chance for ignition in early NIF operations
- The initial ignition experiments only scratch the surface of NIF's potential

There are two principal approaches to compression in Inertial Confinement Fusion

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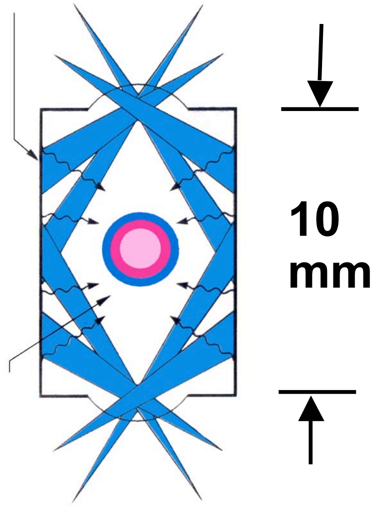
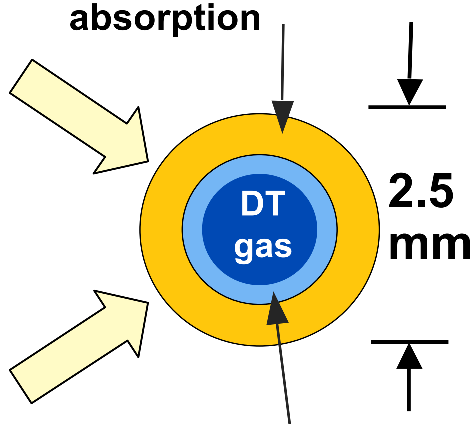
Indirect Drive

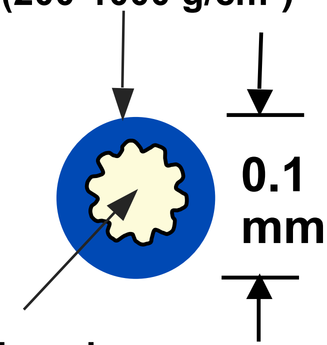


Direct Drive

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

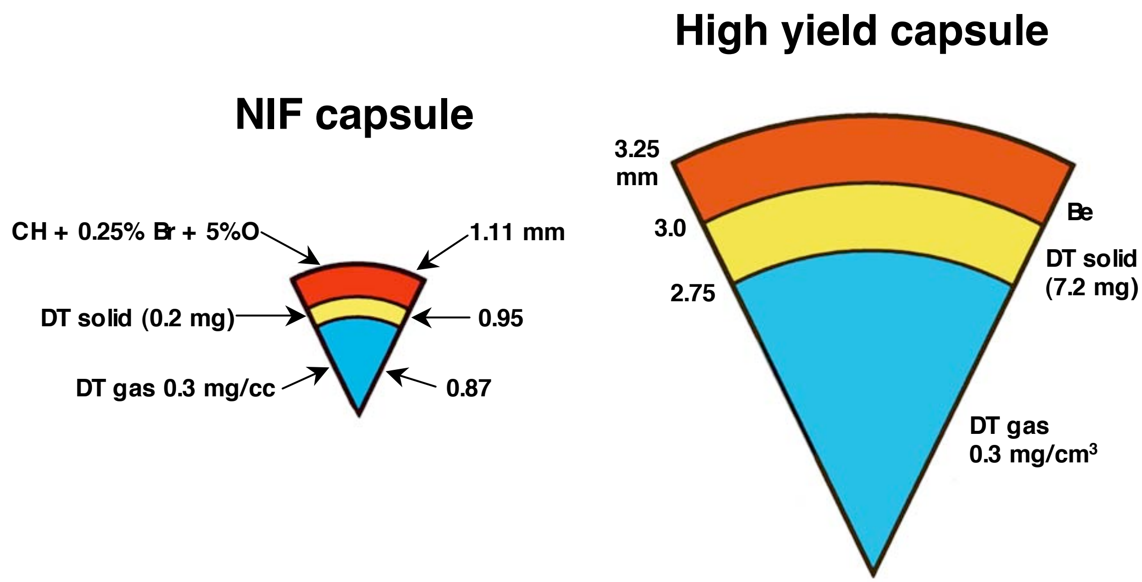


Spherical ablation with pulse shaping results in a rocket-like implosion of near Fermi-degenerate fuel



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

To illustrate the physics of ICF ignition, we compare a NIF capsule and a possible future high yield capsule



	NIF capsule	High yield capsule
Radiation temperature	= 300 eV	210 eV
Implosion velocity	= 4 x 10^7 cm/sec	3 x 10^7 cm/sec
Capsule absorbed energy	= 0.15 MJ	2.0 MJ
Capsule yield	~ 15 MJ	~ 1000 MJ

Ignition is defined as the point at which α–particle deposition sustains the burn with no additional input of energy

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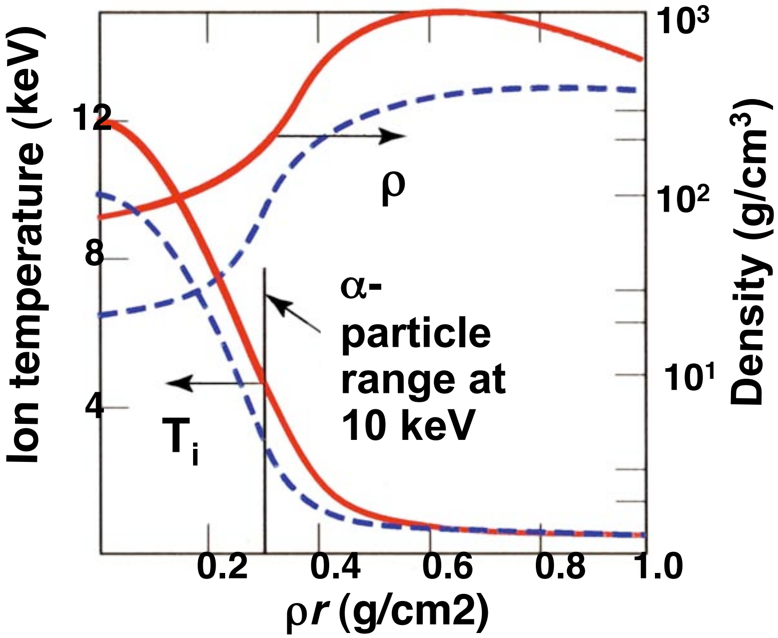
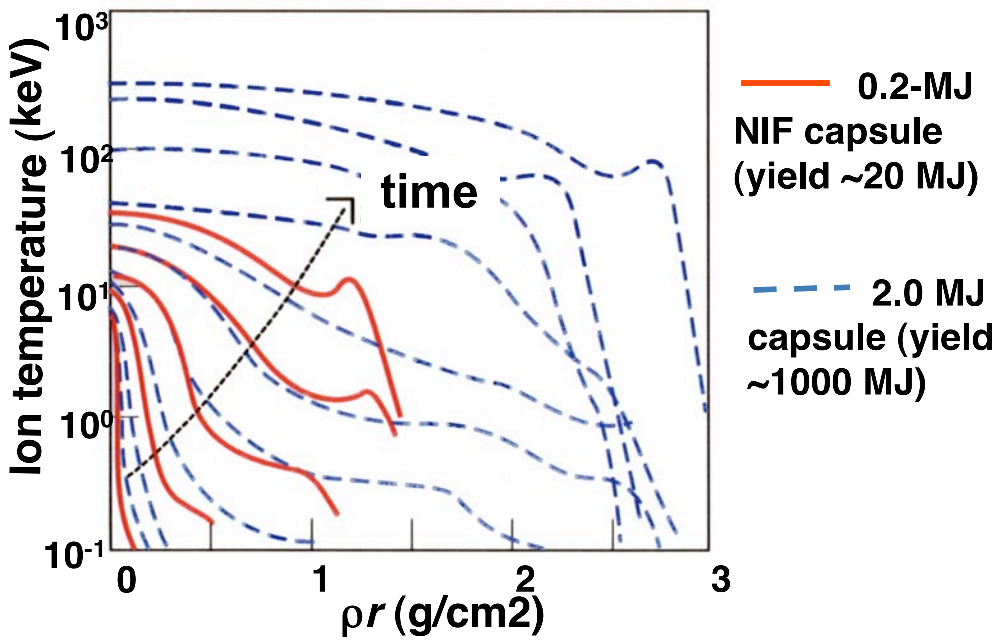
Density and temperature profiles at ignition



Burn propagation after ignition depends only on fuel ρR



- About 15 kJ of energy is coupled to the fuel for compression and ignition of the 200 kJ NIF sized target
- At 1 MJ of yield, 200 kJ of α-particle energy is coupled to the fuel and it is well into the ignition region - definition of ignition adopted by 1996 NRC review of NIF
- In ITER with a Q=10, α-deposition is twice the external power needed to sustain the plasma

Why do we believe that ignition will work on NIF?

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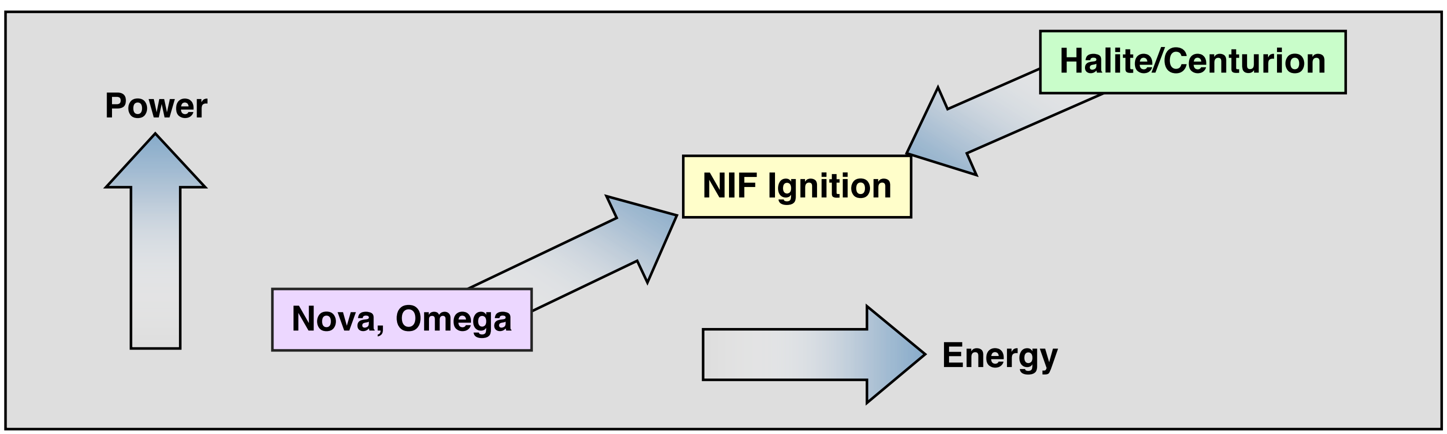
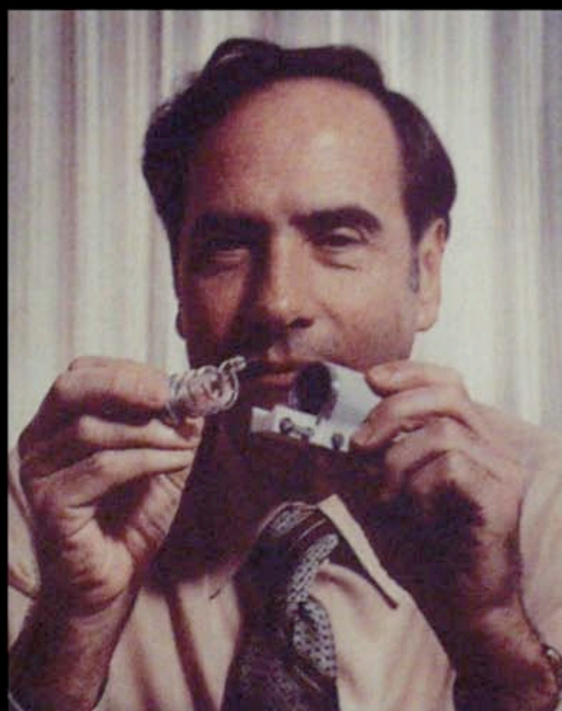
- Over 3 decades of experiments on Nova, Omega and other facilities have provided an extensive data base to develop confidence in the numerical codes

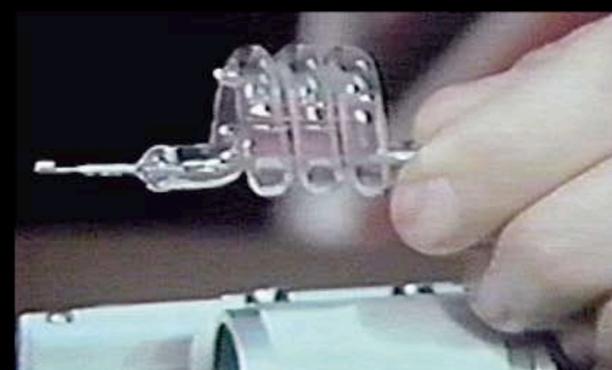
- Benchmarked numerical simulations with radiation-hydrodynamics codes provide a first principles description of x-ray target performance (Laser-plasma interactions are treated separately with codes which are now becoming predictive for NIF-relevant plasmas)

- "The Halite/Centurion experiments using nuclear explosives have demonstrated excellent performance, putting to rest fundamental questions about the basic feasibility to achieve high gain" from 1990 NRC review of ICF



The first laser was demonstrated by Theodore Maiman in Malibu, CA, in May 1960





John Nuckolls and John Emmett were central to the development of the LLNL ICF Program

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Disk Amplifier Prototype from the mid 1970's

John Emmett, who came to LLNL in 1972 was the driving force behind the development of the LLNL laser program

John Nuckolls' vision of small thermonuclear explosions, laid out in his seminal 1972 Nature paper, provided the motivation for an aggressive ICF Program

Would you hire these people?

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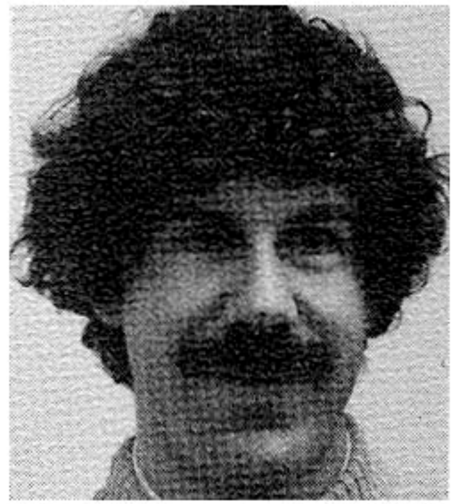
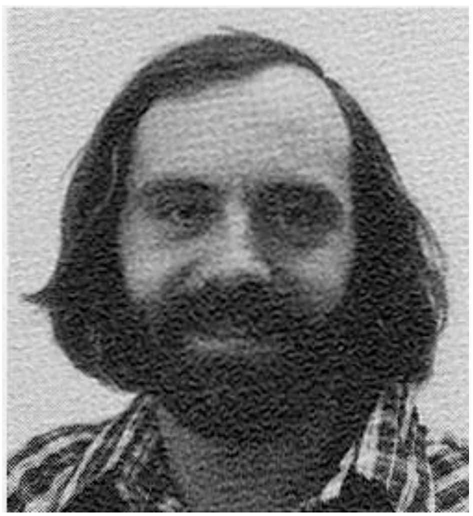
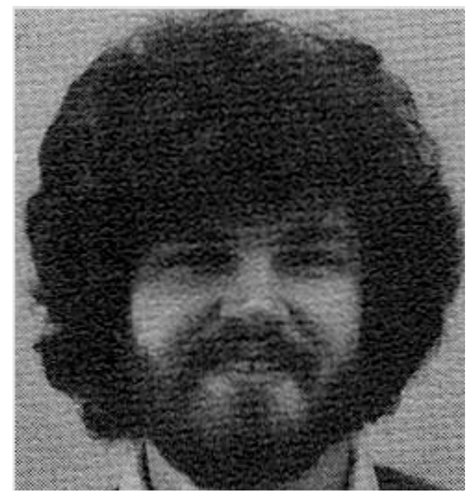
John Lindl



George Zimmerman



Mike Campbell



Laser Programs 1978 Manpower Book

Ed Moses did not come to Livermore until the 1980's but he would have fit right in during the 1970's

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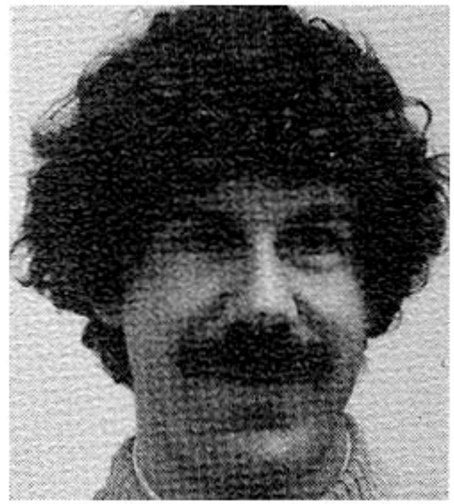
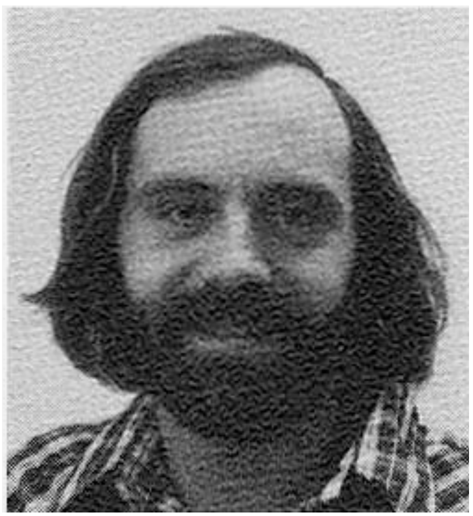
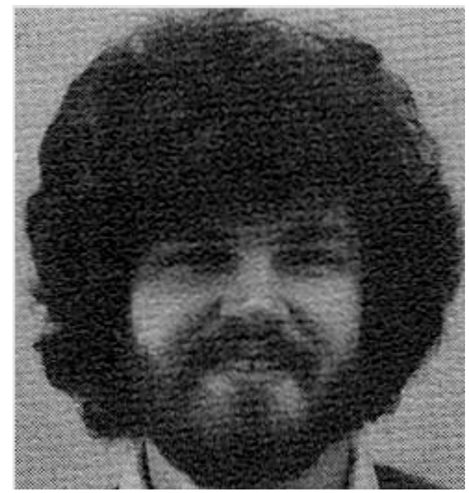
John Lindl



George Zimmerman



Mike Campbell



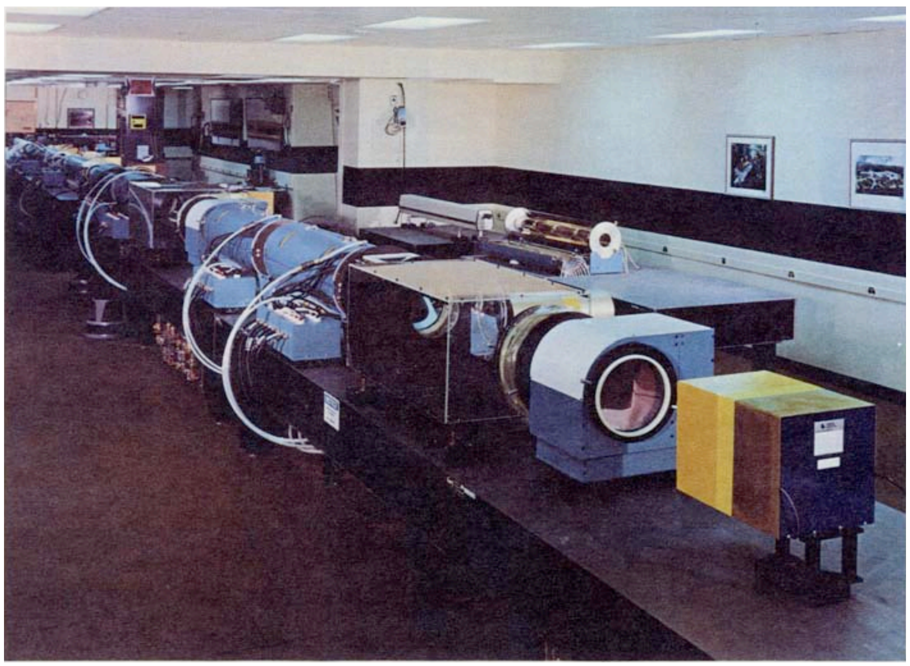
Ed Moses

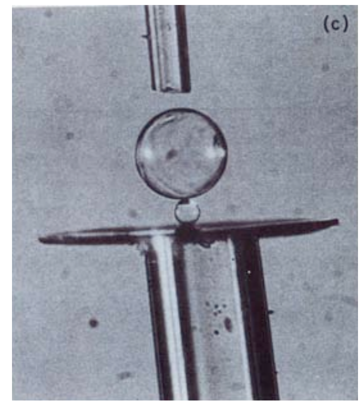
Laser Programs 1978 Manpower Book

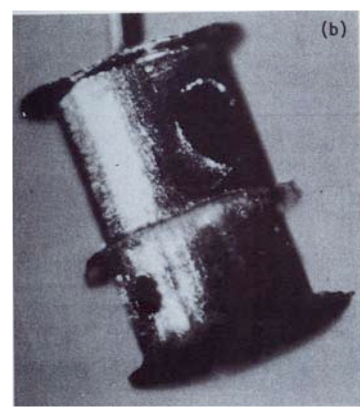
The first steps leading to indirect drive ignition with lasers took place in the mid 1970's

- **1970's: Radiation driven target designs provided a path forward for high gain ICF with relaxed laser beam quality and hydrodynamic instability compared to direct drive**

- **1976: first laser driven indirect drive experiment in 1976 on the Cyclops laser**







—Cyclops was developed as a prototype beamline for Shiva

The 20 beam 10 kJ 1.06 μm Shiva laser was a major step forward in the scale and complexity of high energy laser systems

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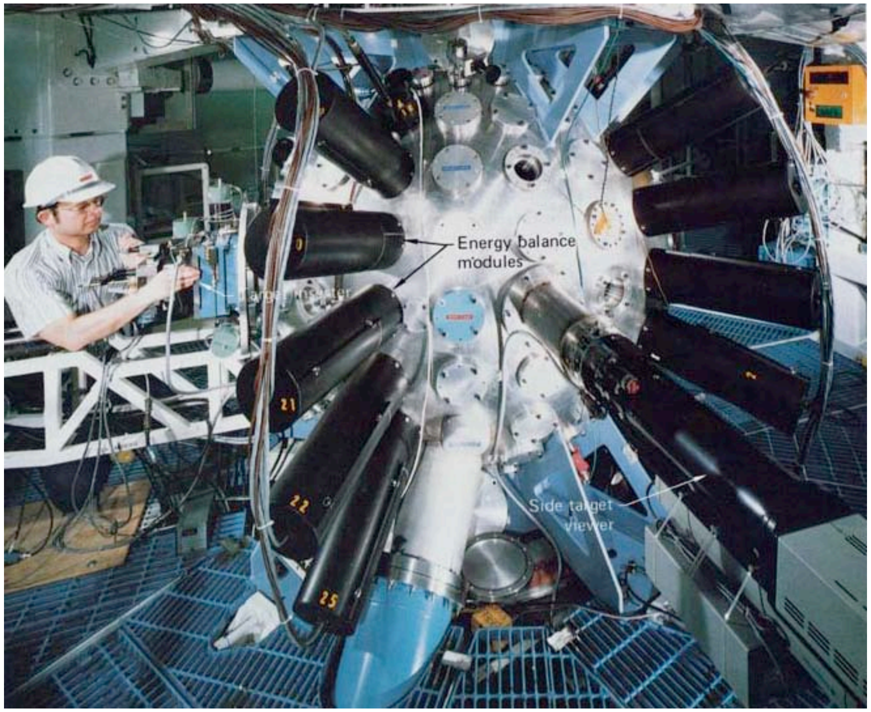
Shiva laser bay

Shiva target area



Experiments on the Argus and Shiva lasers provided key results on achievable hohlraum temperatures

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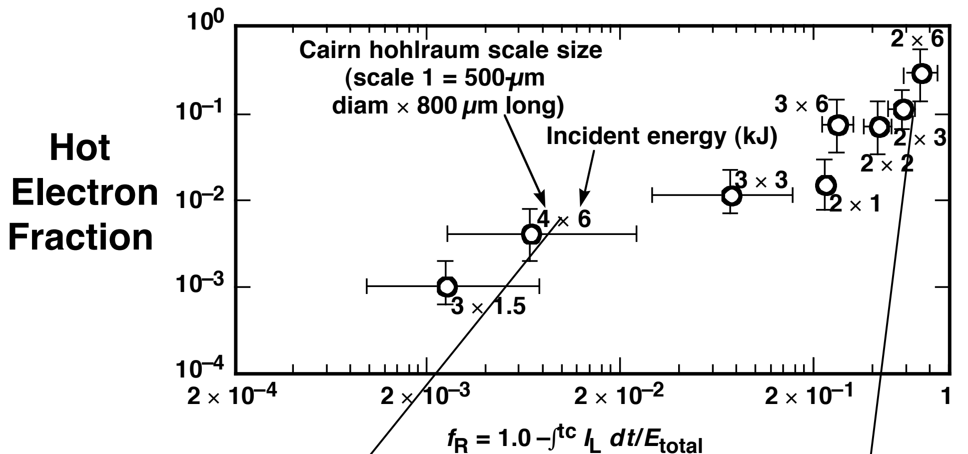
- **1979-1981: Shiva and Argus experiments show limits to radiation temperature from LPI and a path to T_R>200 eV using frequency converted light (2ω and 3ω)**

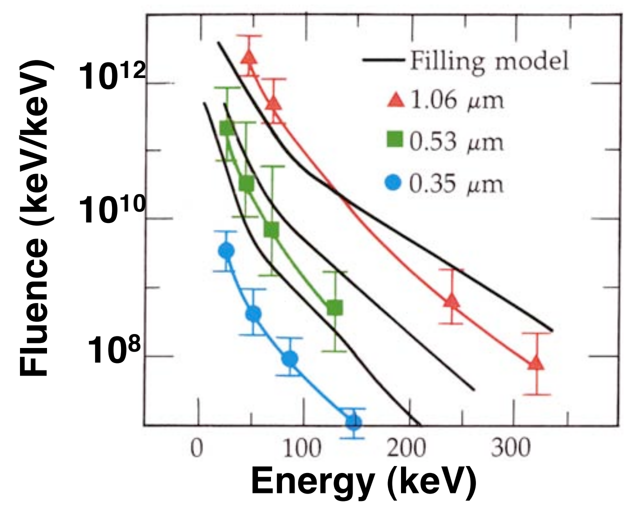
Hot electron fractions approached 50% in 1ω hohlraums on Shiva



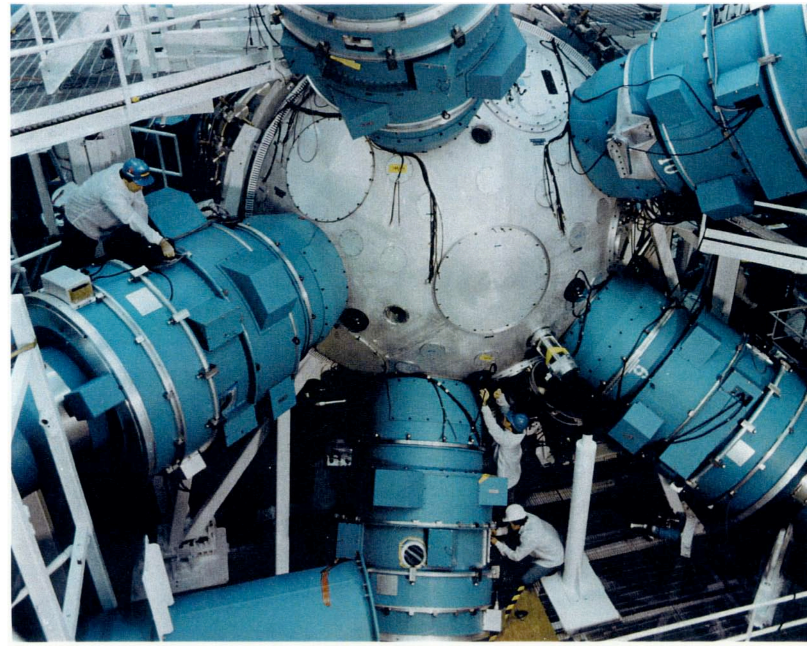
30-50% at Tr ~160-170 eV

1% at Tr = 130 eV

Shorter laser wavelengths can dramatically reduce hot electrons for a given laser energy into a hohlraum



From 1984 to 1999, the 10 beam, 30 kJ, 0.35 μm Nova laser was the central facility for indirect drive ICF



With Nova, the ICF program brought together advances in laser performance, precision diagnostics, and advanced modeling tools needed to establish the requirements for Ignition.

Plasma physics issues constrain the hohlraum temperature and hydrodynamic instabilities establish the minimum required temperature

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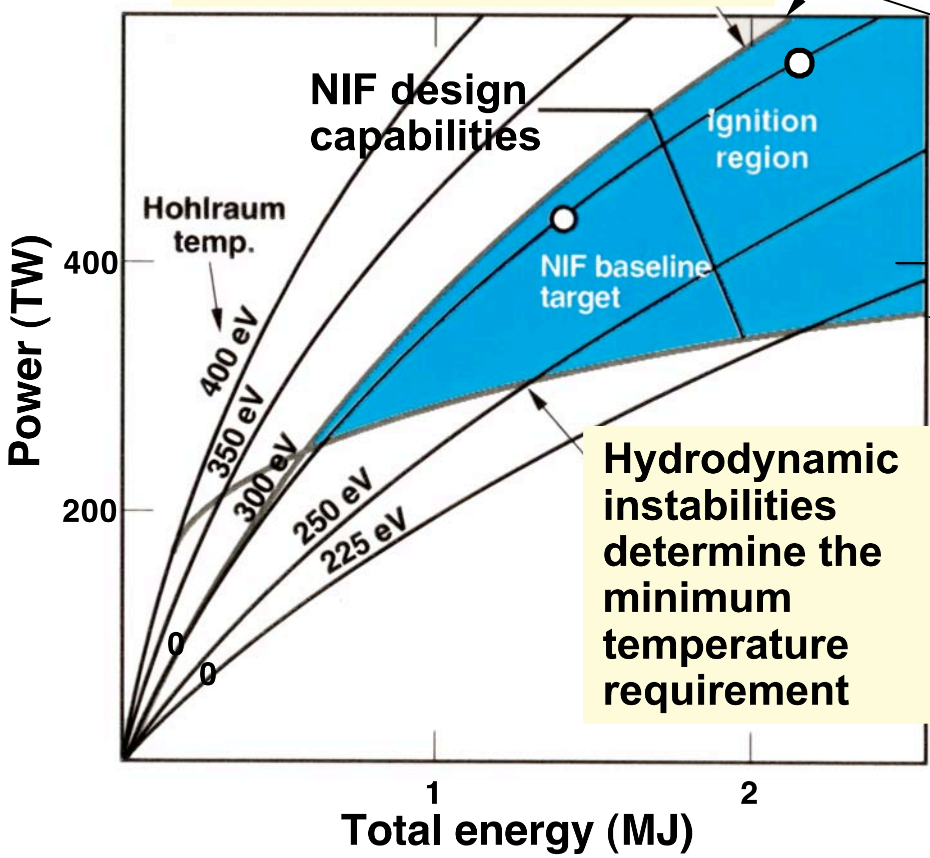
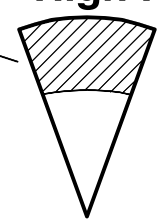
"Bird's beak" plot from 1990

Hohlraum physics acceptable below about 300 eV

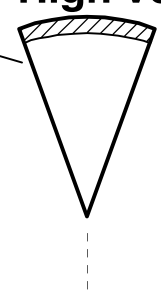


Hydrodynamic instabilities determine the minimum temperature requirement

High P_r, T_r, I_L $\Rightarrow$ plasma instabilities



High vol $\Rightarrow$ large $\frac{R_o}{R_{final}}$ $\Rightarrow$ symmetry



$\Rightarrow$ large R/DR

$\Rightarrow$ hydroinstability

Experiments on the Nova laser demonstrated key target physics results needed for ignition

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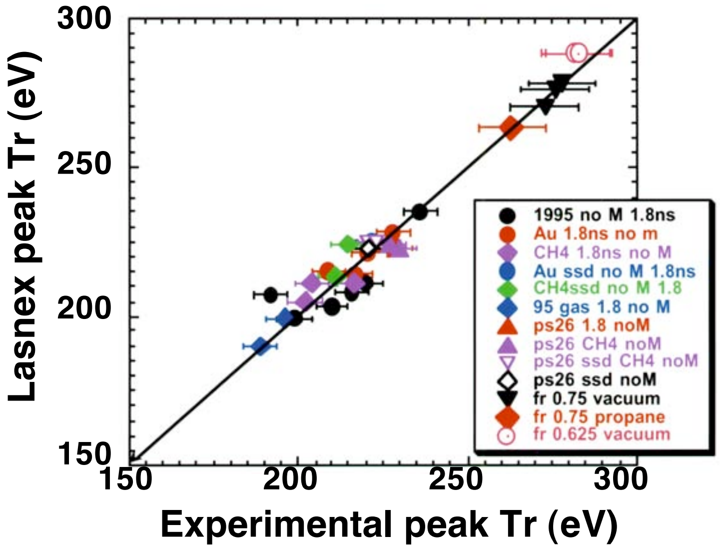
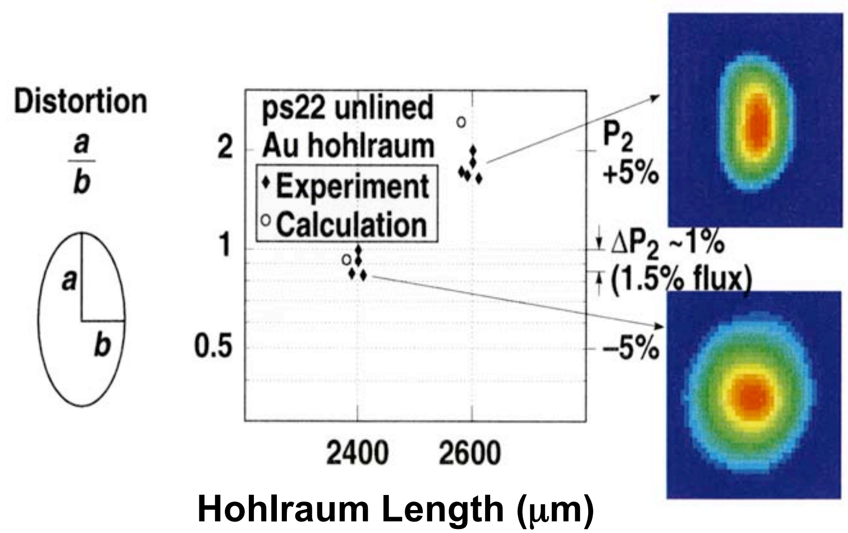
- **1985-1990: Nova experiments demonstrated key target physics requirements for laser driven high gain (pulse shaping, symmetry control, Rayleigh-Taylor stabilization by radiation ablation, T_R>200 eV with 3ω light**

- **1990: 300 eV hohlraum temperature demonstrated on Nova led to a reduced scale ignition facility from the 5-10 MJ LMF to the 1-2 MJ NIF as recommended by the 1990 NRC review of ICF**

- **1990's Demonstration of precision control of laser driven hohlraums as required for ignition (Nova Technical Contract from 1990 and 1996 NRC reviews of ICF)**

Scaling of peak drive temperature





Advanced diagnostics have been central to measuring the phenomena critical to understanding NIF

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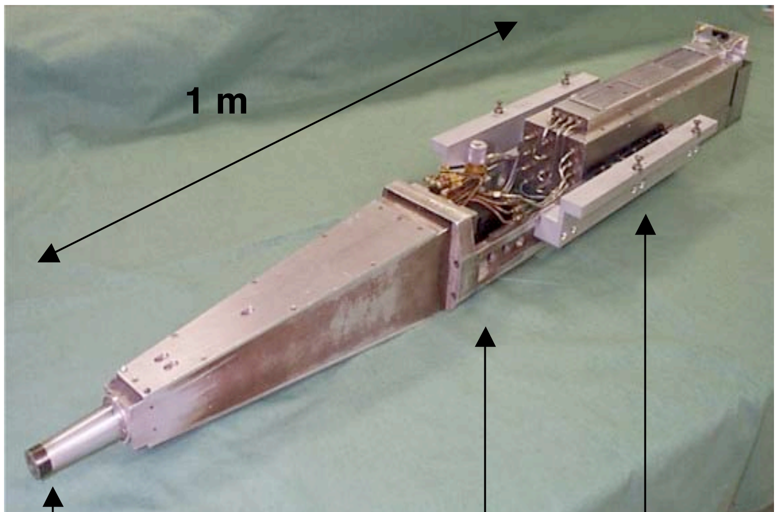
Gated MCP x-ray imager

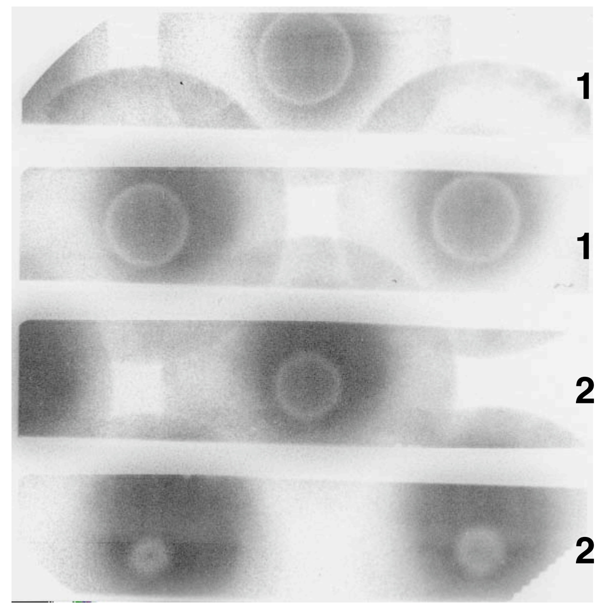


Pinholes

MCP +
film pack

Gating
electronics

Sequence of x-ray backlit images of imploding capsule



time

300 μm

1.6 ns

1.9 ns

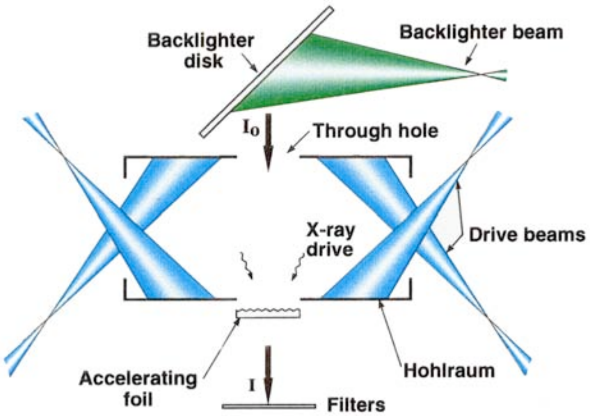
2.2 ns

2.5 ns

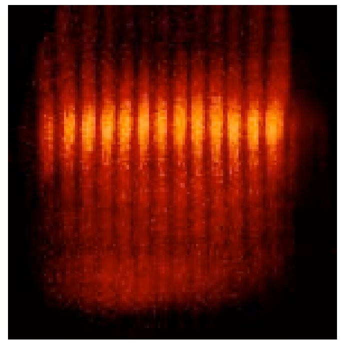
time

MCP gated imagers were operated between 100 eV and 10 keV with 5-50 μm, 30 -300 ps resolution

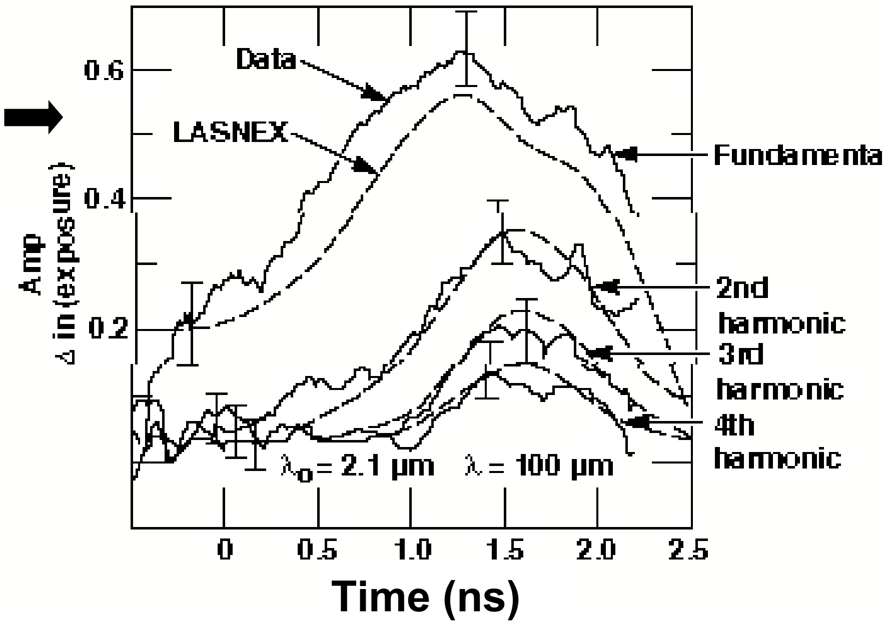
The measured growth of ablative hydrodynamic instabilities in ICF agrees with numerical models

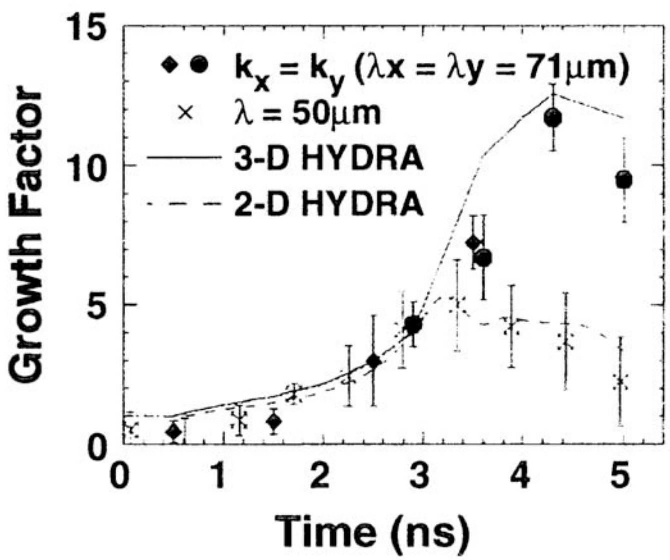


Face-on: Streaked



Growth of Harmonics vs time





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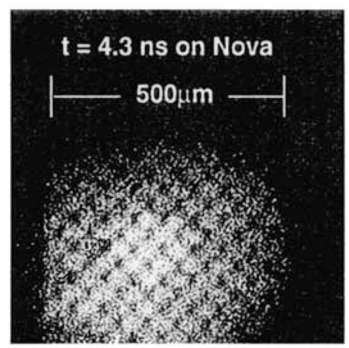
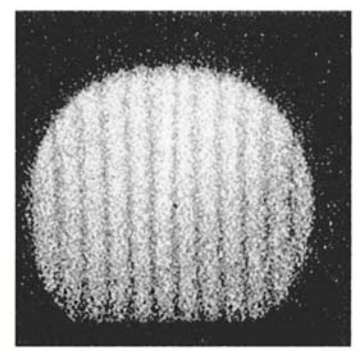
3-D



2-D



Recently, we have been able to produce well characterized NIF-like plasmas on the Omega laser

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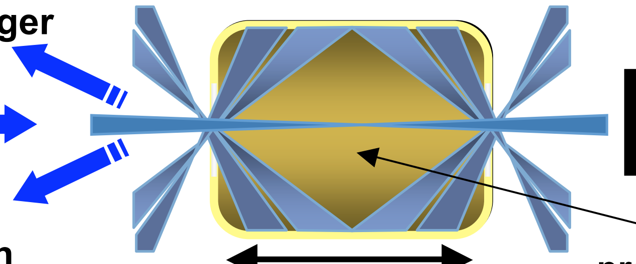
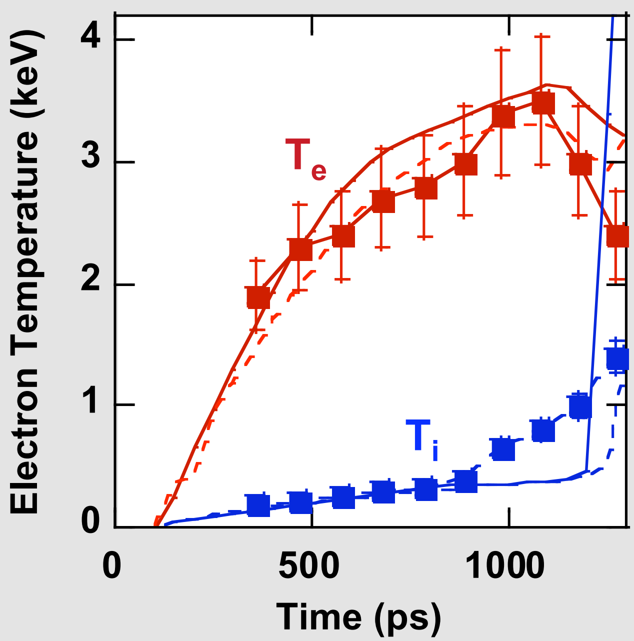
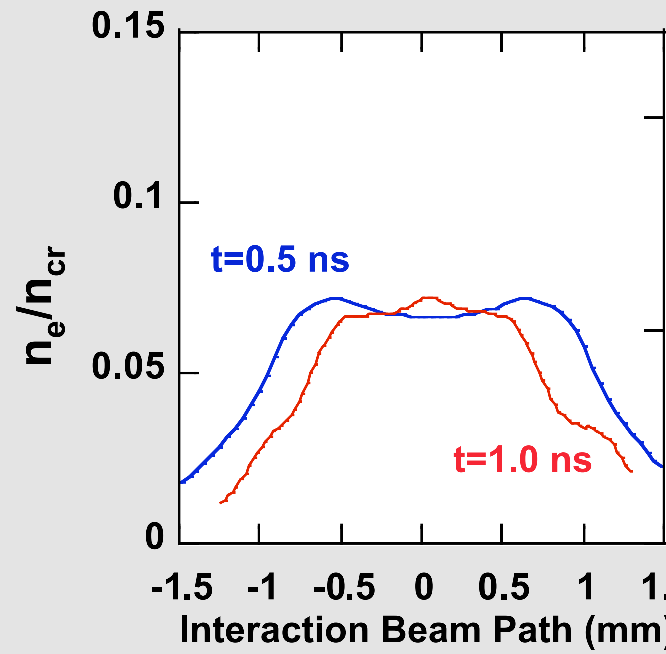


Plasma temperatures measured with Thomson scattering agree well with simulations



A uniform 6%n_{cr} plateau is produced between 0.5 and 1.0 ns



Froula *et al.*, Phys. Plasmas 13(5) (2006)

Calculations of these Omega experiments provide evidence of a significant step towards meeting the grand-challenge of predictive modeling of LPI with pf3d

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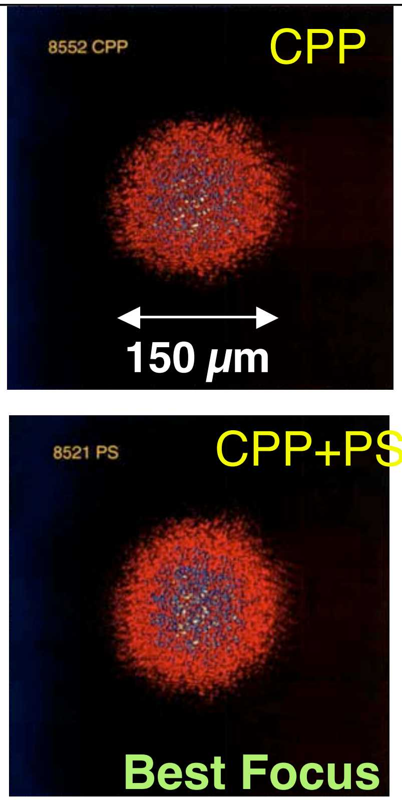

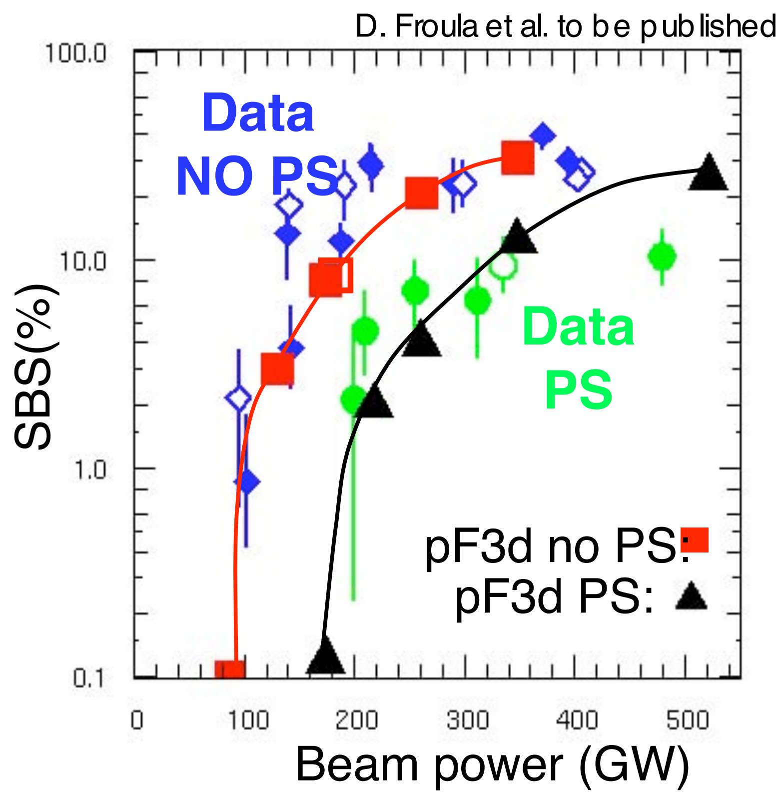

Divol TI1-5
Thursday

Froula NO6-13
Wednesday

- **PS instantly reduces the contrast, suppressing the amplification from intense speckles**

- **The pF3D calculations took about 1 million CPU hours**

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

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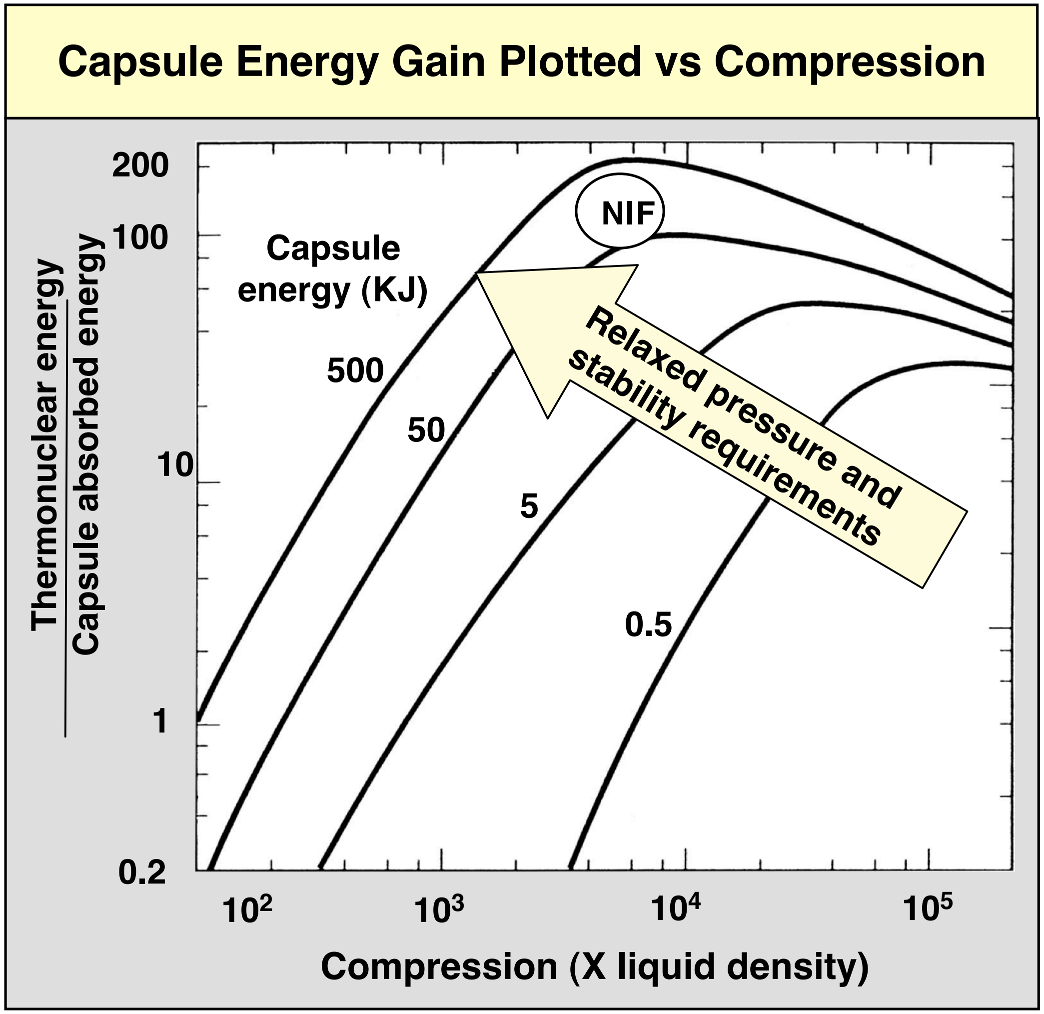
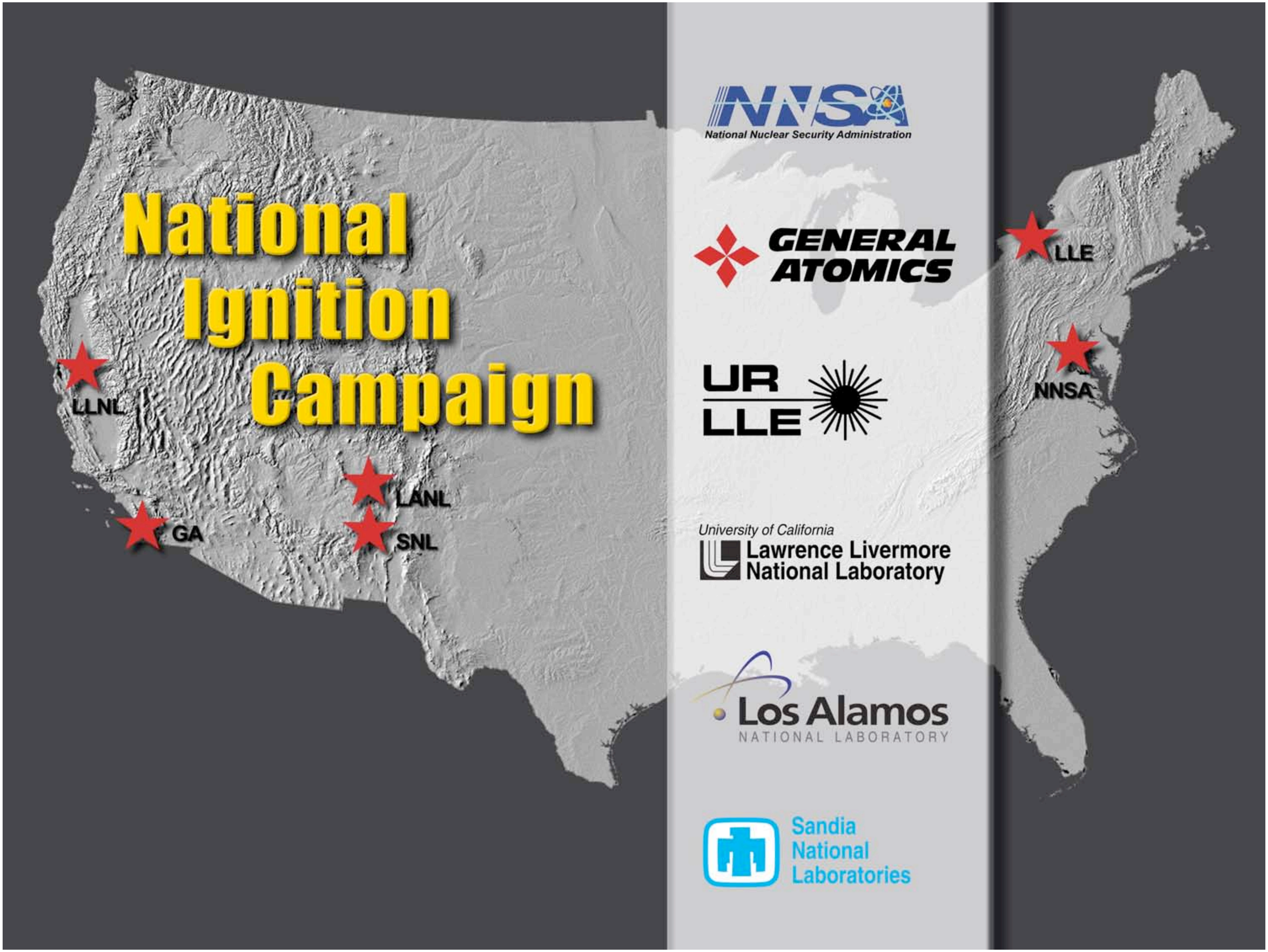


- Pressure is limited to P(Max)~100 Mbar by Laser Plasma Interaction (LPI) effects
- Given the pressure limits, hydrodynamic instabilities limit implosion velocities to

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

and this limits the maximum compression

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



National Ignition Campaign
LLNL
GA
LANL
SNL
LLE
NNSA
NNSA
National Nuclear Security Administration
GENERAL ATOMICS
UR LLE
University of California
Lawrence Livermore National Laboratory
Los Alamos
NATIONAL LABORATORY
Sandia National Laboratories

NIF will provide a qualitative advance in ICF capability with >50X more energy and far greater precision and flexibilty than any previous high energy laser facility

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NIF is a 192 beam laser organized into “clusters”, “bundles” and “quads”

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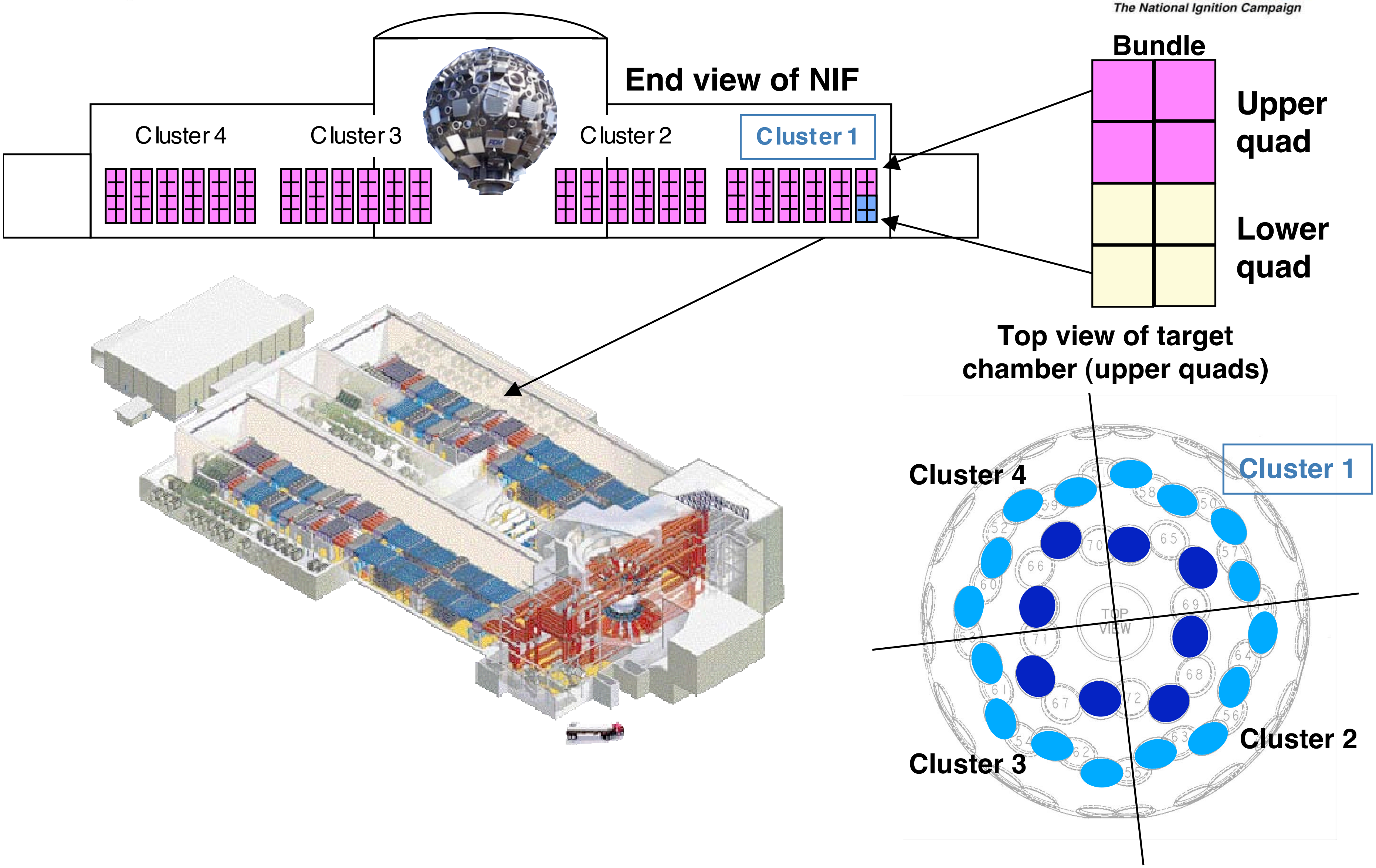

The NIF Project is over 94% complete and 15 of the 24 1 μm laser bundles (120 beams) have been performance qualified

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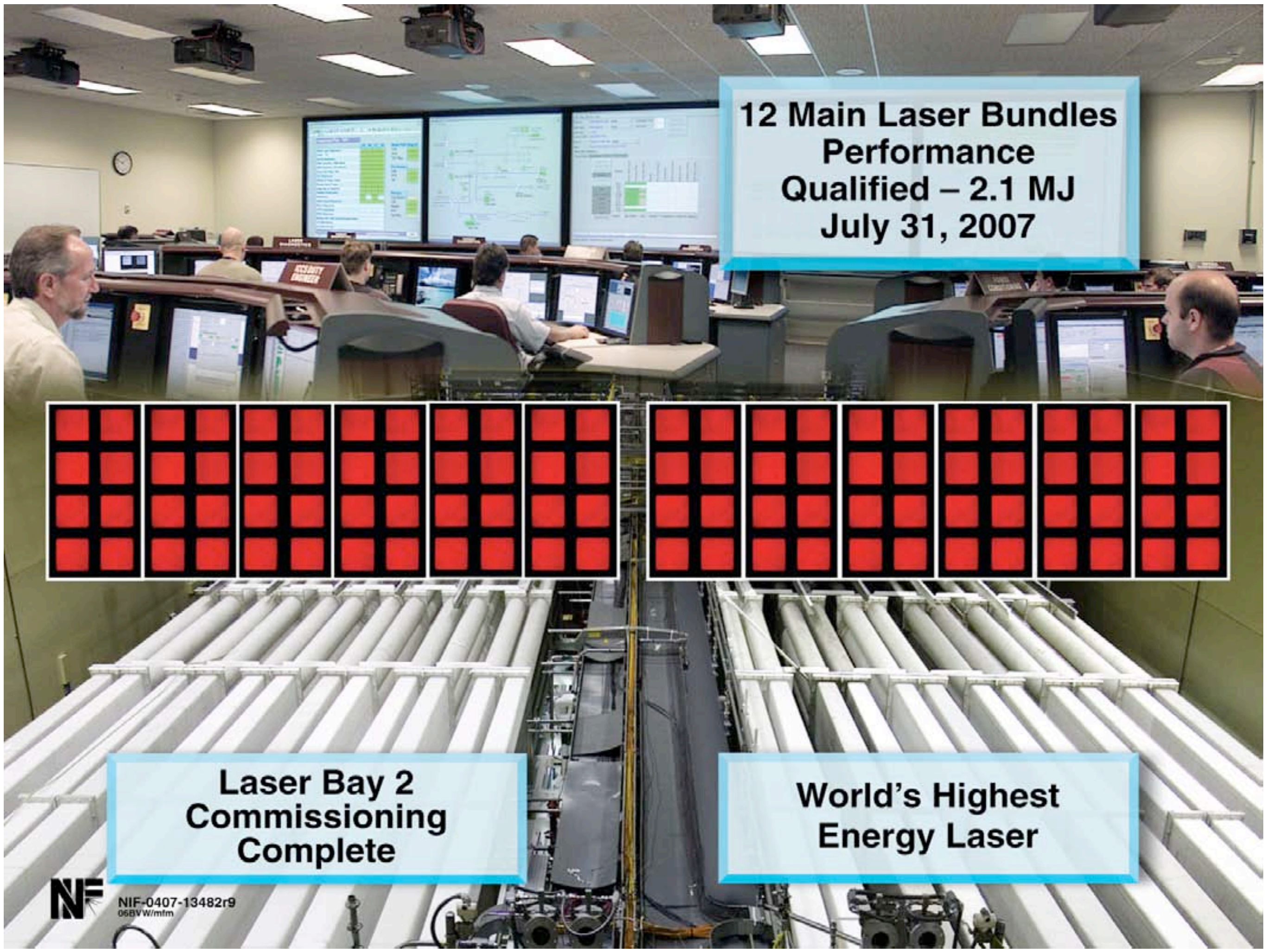

1.8 MJ NIC ignition point design, energy, power, pulse shape & beam smoothing were achieved simultaneously (single beam)

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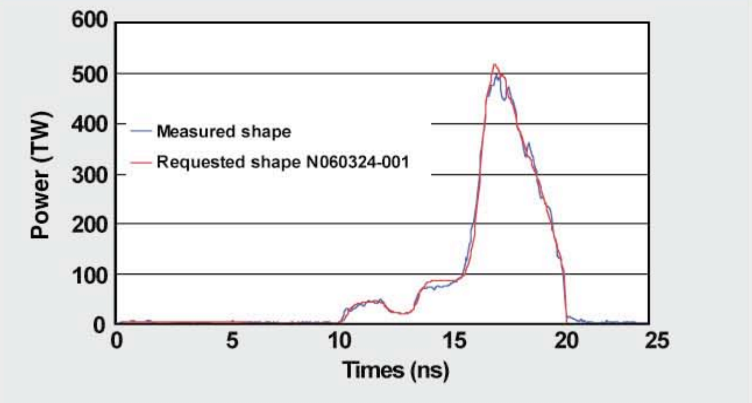
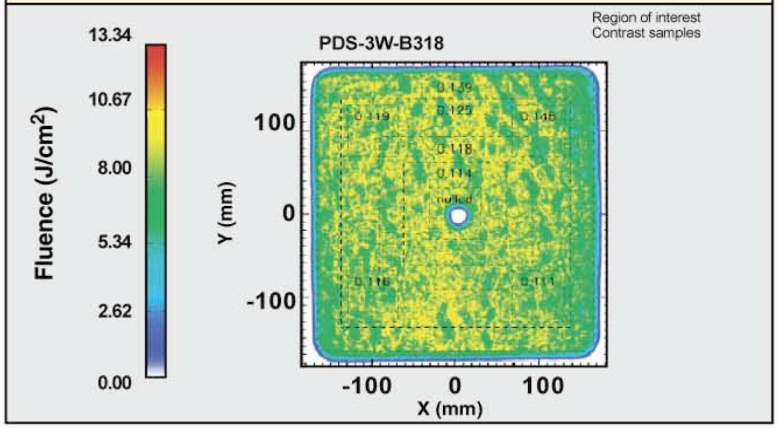
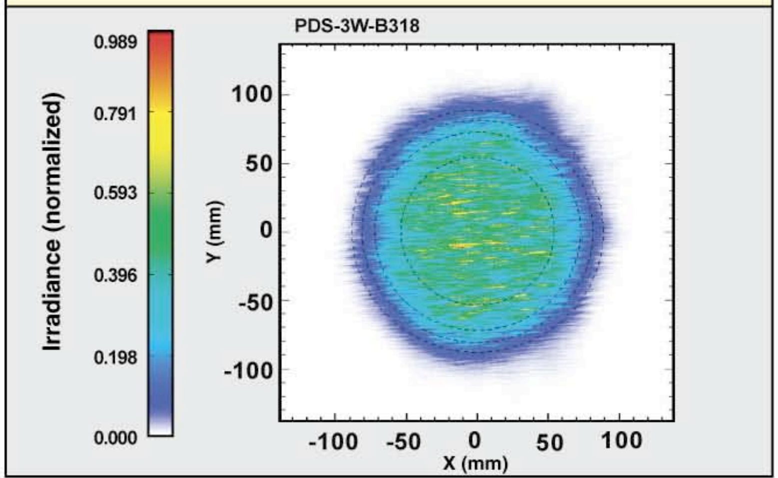
3ω Pulse Shape (500 TW)



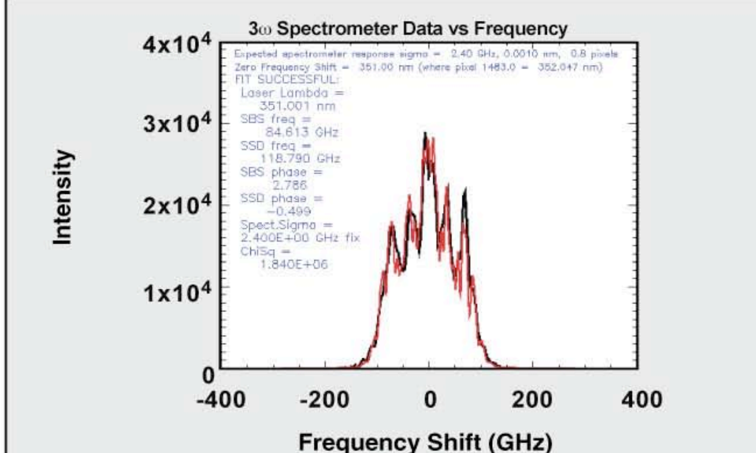
3ω Field Profile (CR = 12.5%)



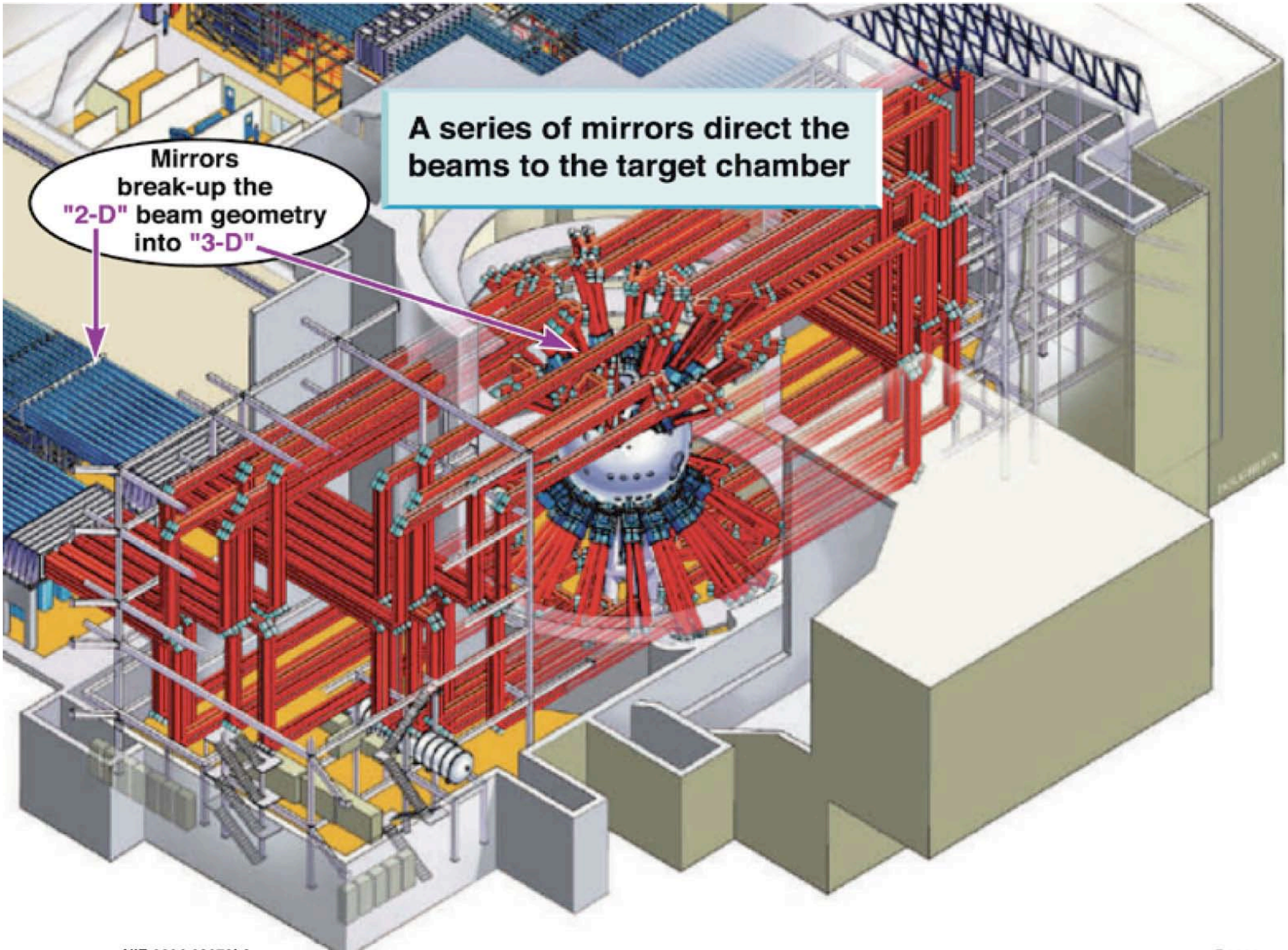
3ω Focal Spot (1.3 × 1.2 mm²)



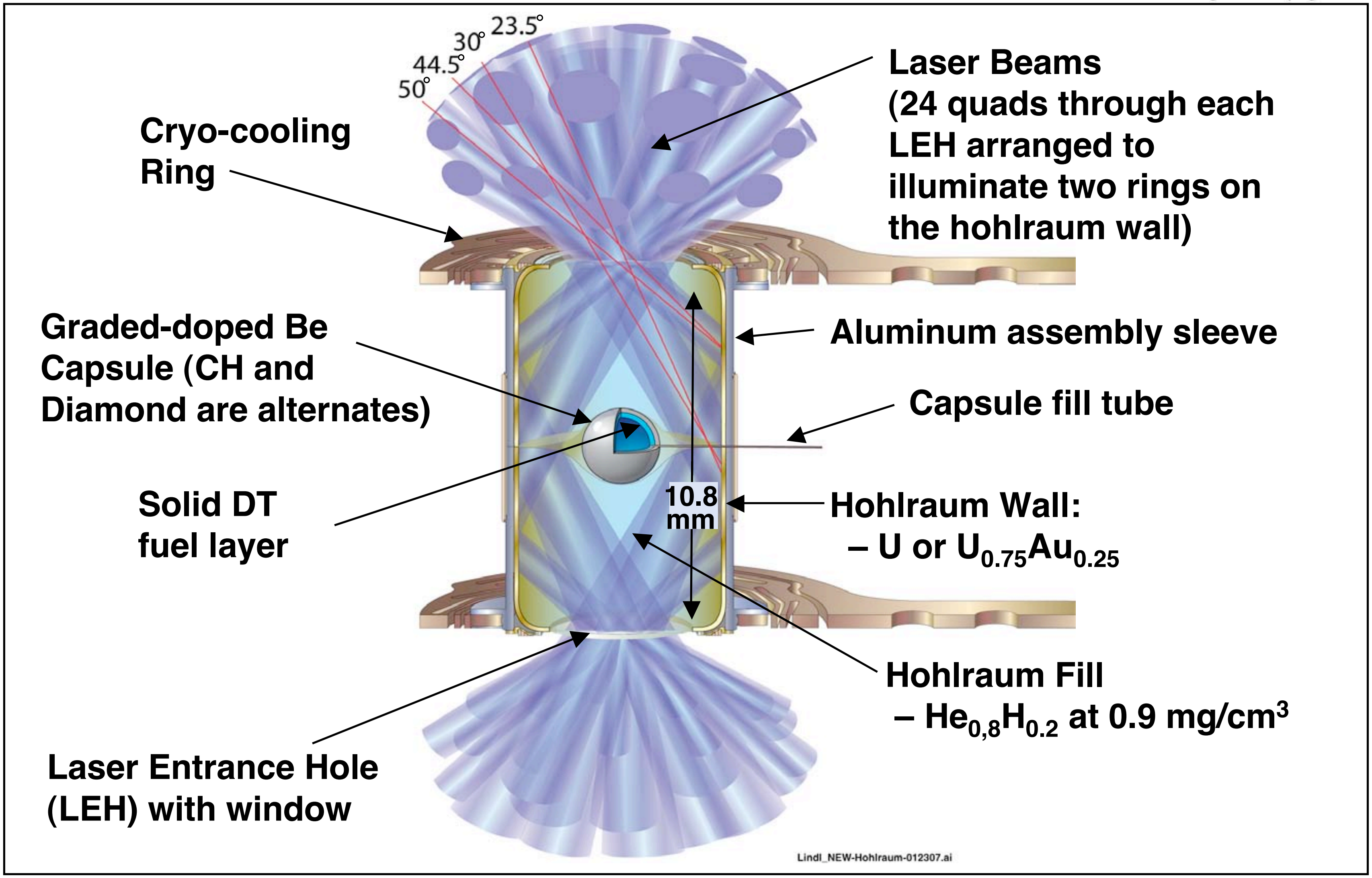
3ω SSD Bandwidth (100GHz)



NIF-0506-11982
15EIM/sf


A series of mirrors direct the beams to the target chamber
Mirrors break-up the "2-D" beam geometry into "3-D"

The NIF point design has a graded-doped, beryllium capsule in a hohlraum driven at 285 eV



Precision target fabrication and assembly techniques being developed for the NIF meet the ignition target requirements

NIC
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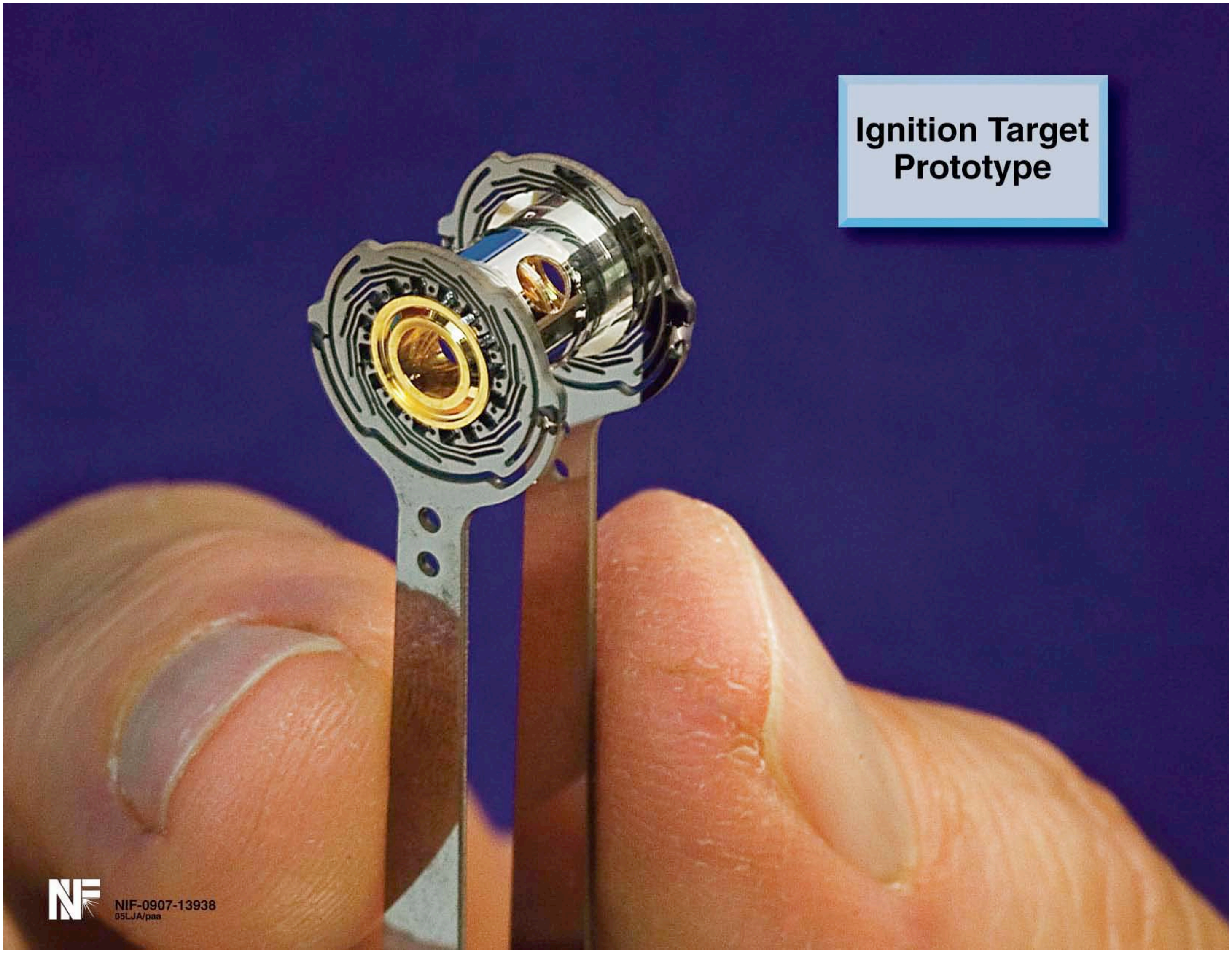
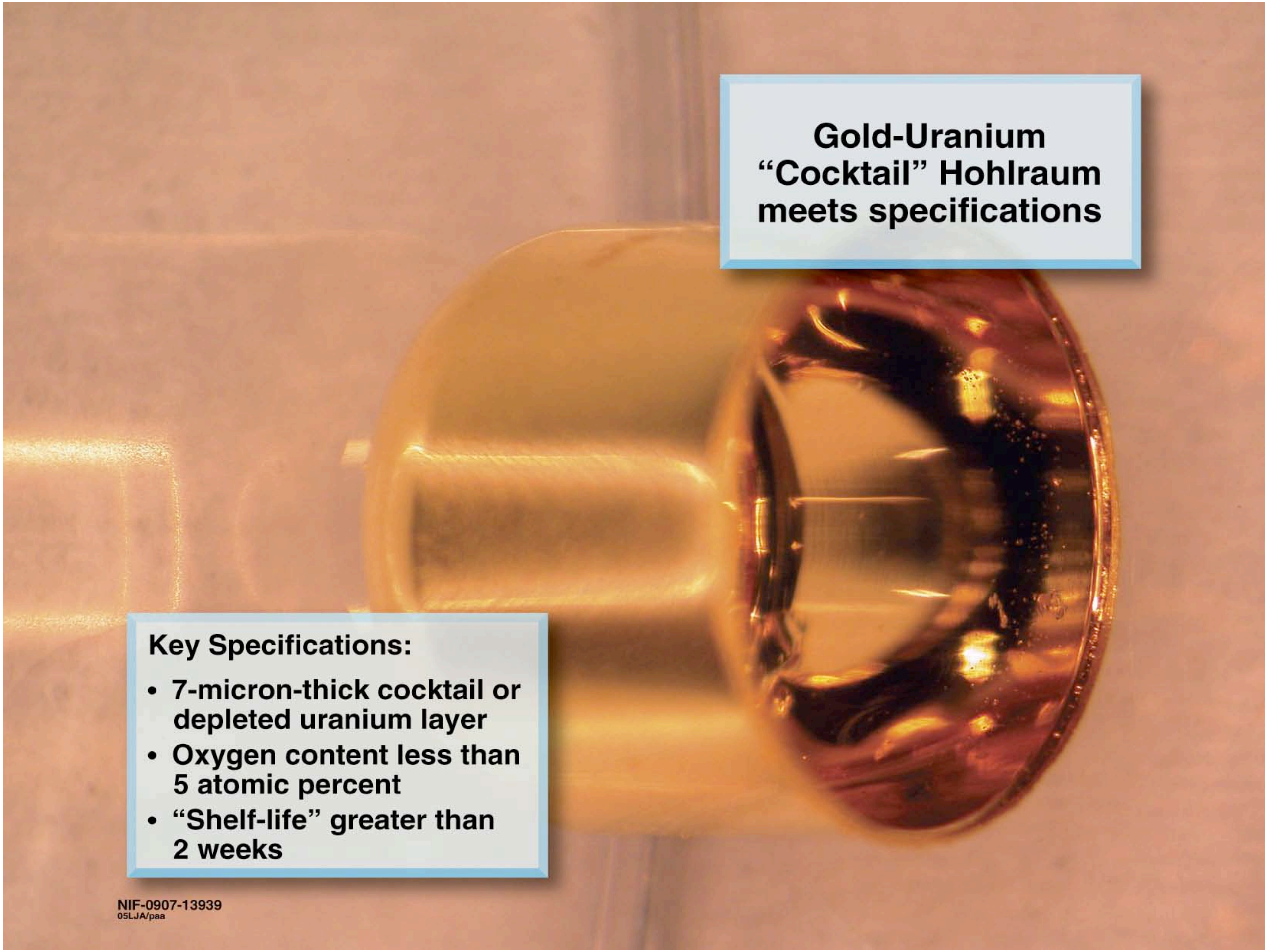


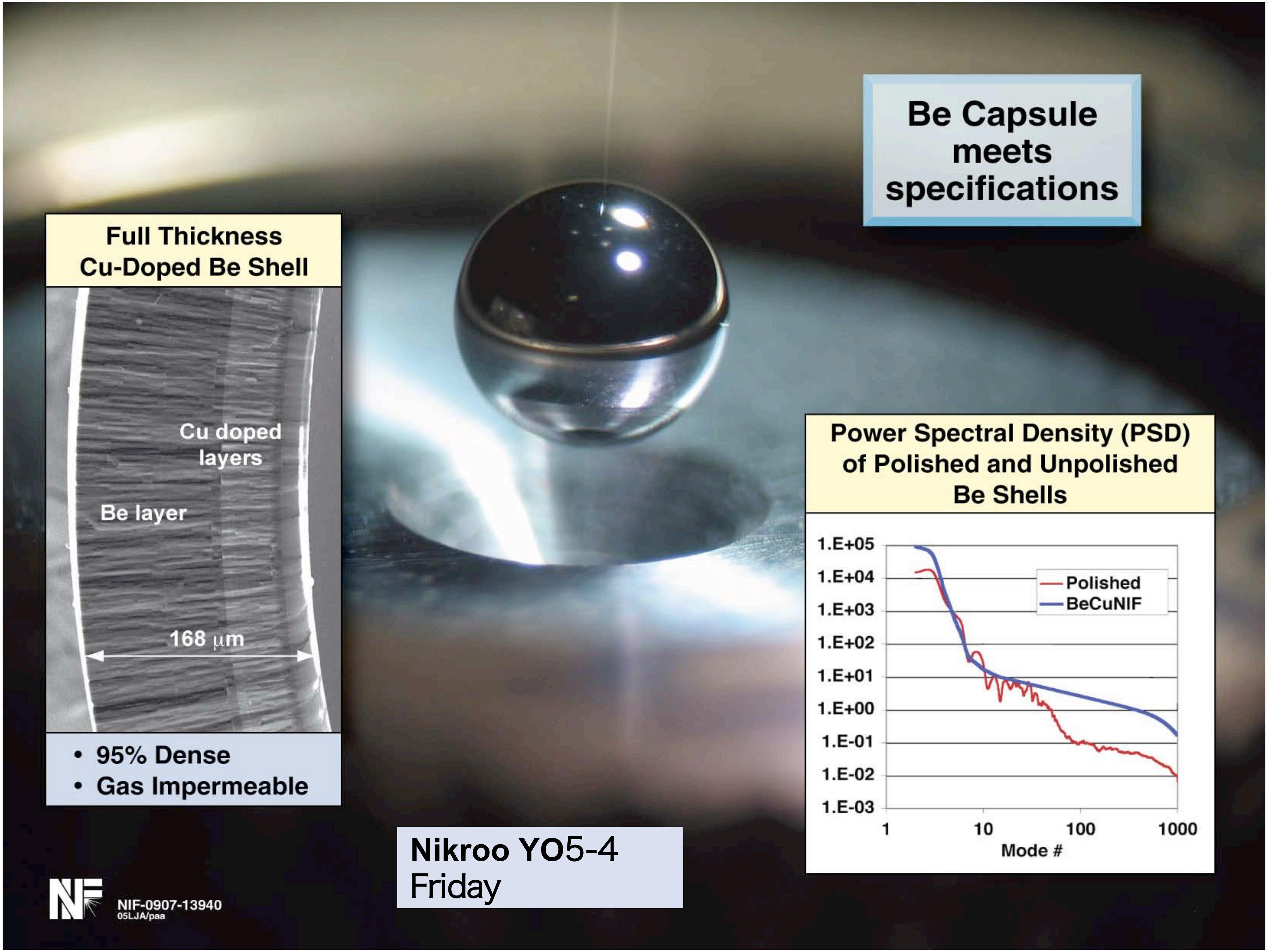
Gold-Uranium “Cocktail” Hohlraum meets specifications

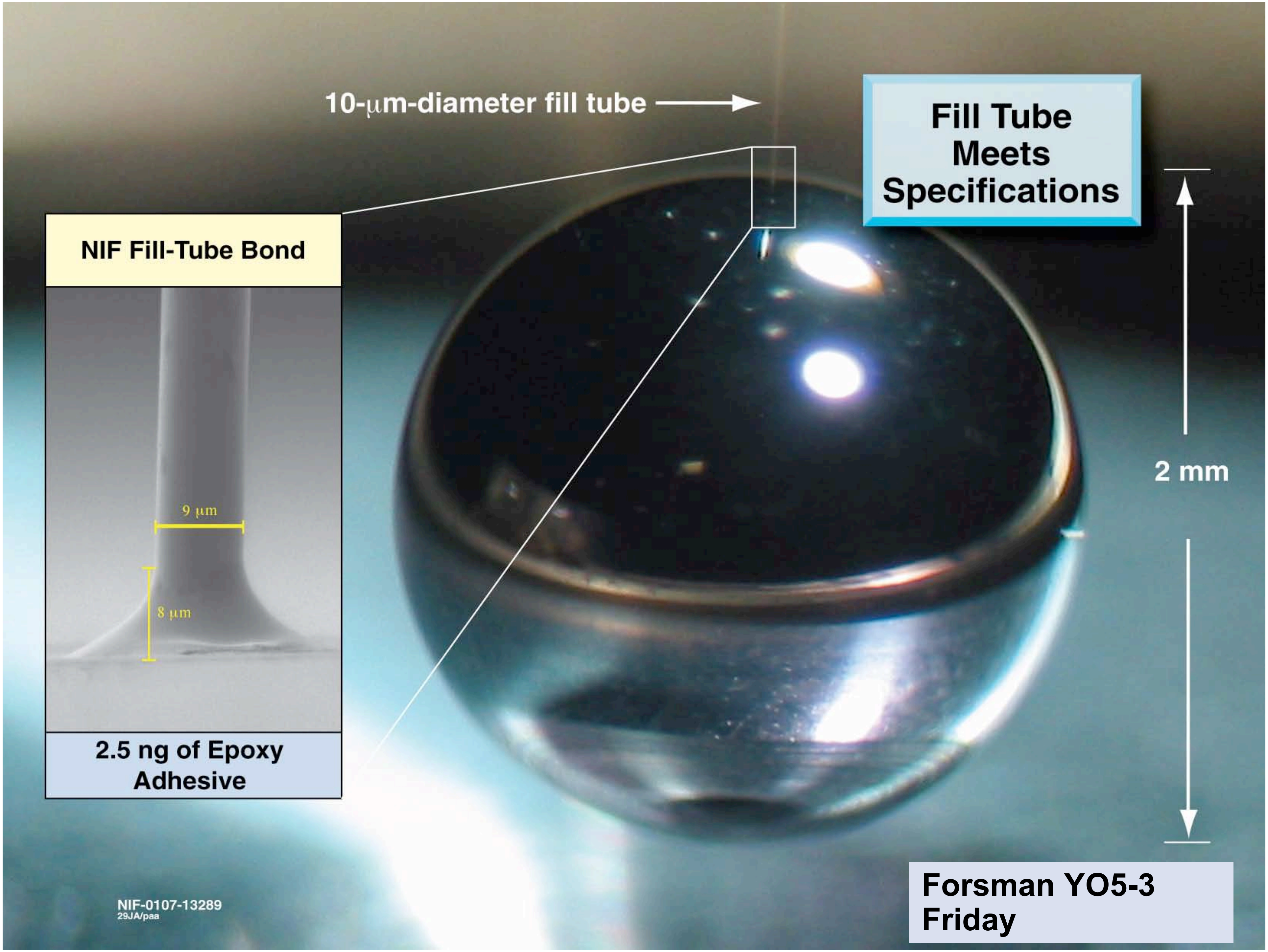


Key Specifications:

- 7-micron-thick cocktail or depleted uranium layer
- Oxygen content less than 5 atomic percent
- “Shelf-life” greater than 2 weeks

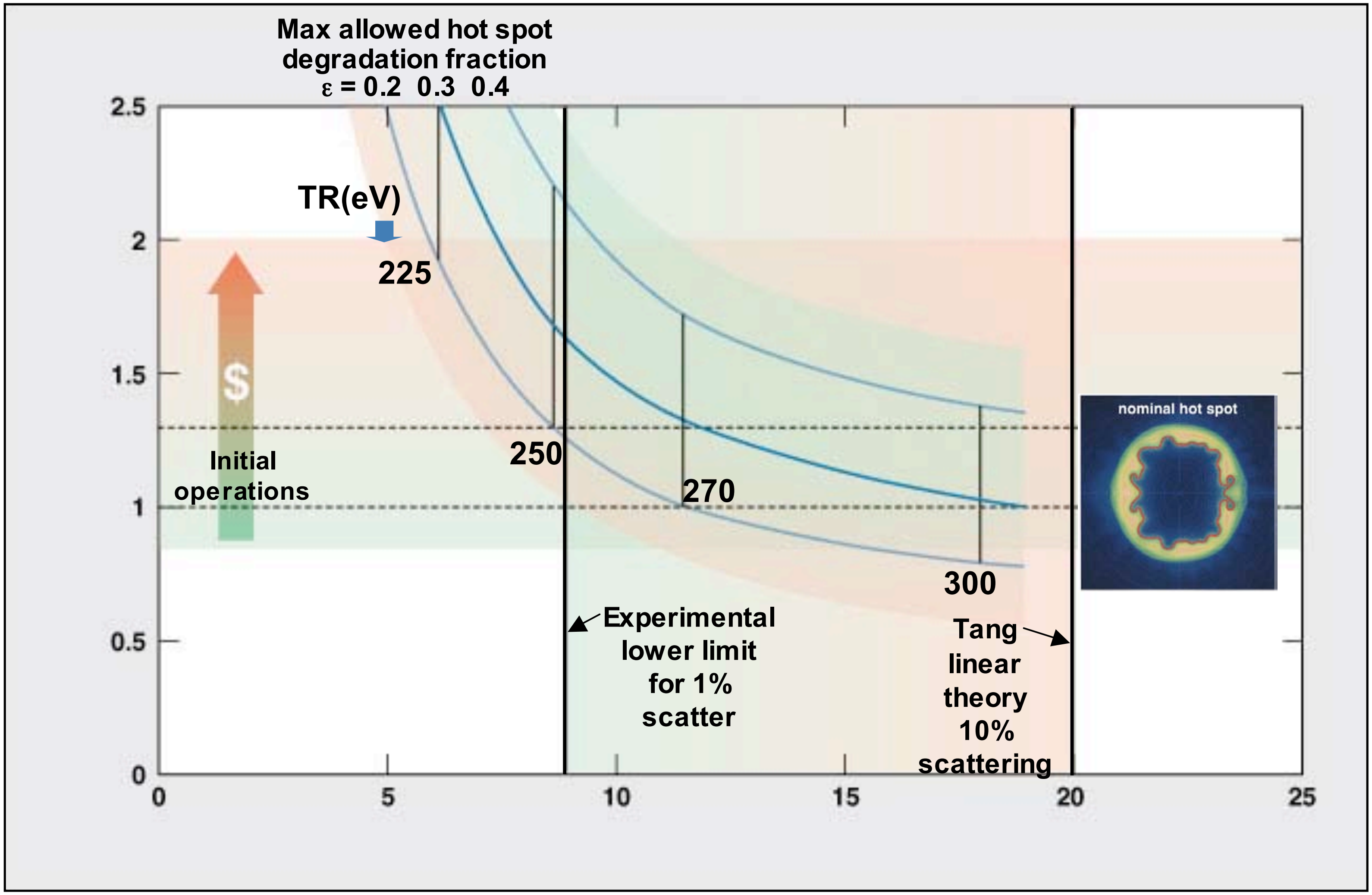
NIF-0907-13939
05LJA/paa


Be Capsule meets specifications
Full Thickness Cu-Doped Be Shell
Cu doped layers
Be layer
168 μm
• 95% Dense
• Gas Impermeable
Power Spectral Density (PSD) of Polished and Unpolished Be Shells
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1.E-03
1
10
100
1000
Mode #
Polished
BeCuNIF
Nikroo YO5-4
Friday
NIF-0907-13940
05LJA/paa

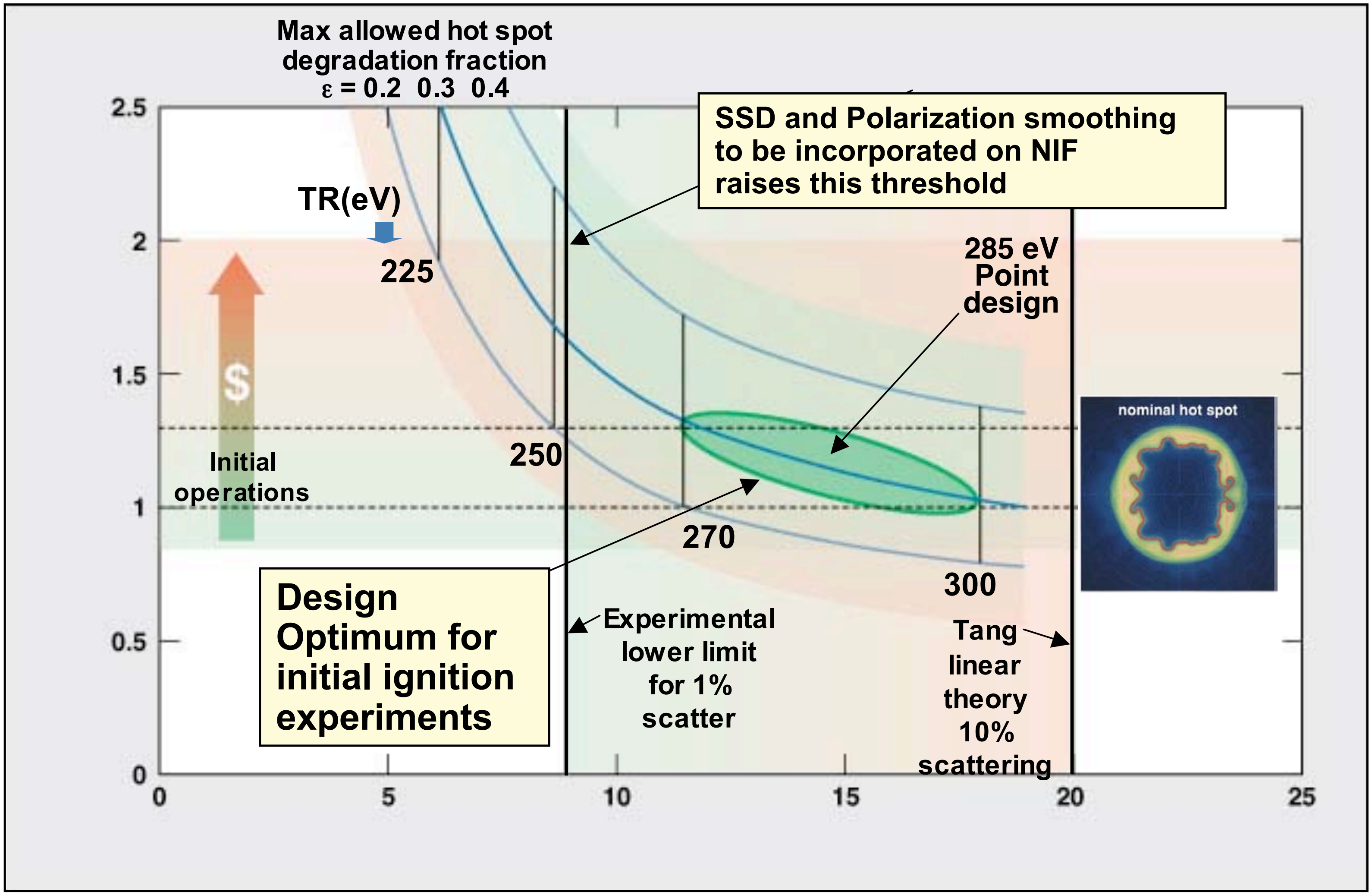

10-µm-diameter fill tube
Fill Tube Meets Specifications
NIF Fill-Tube Bond
9 µm
8 µm
2.5 ng of Epoxy Adhesive
2 mm
NIF-0107-13289
29JA/paa
Forsman YO5-3
Friday

Ignition point design optimization must balance LPI effects, laser performance impacts, and capsule robustness

NIC
The National Ignition Campaign

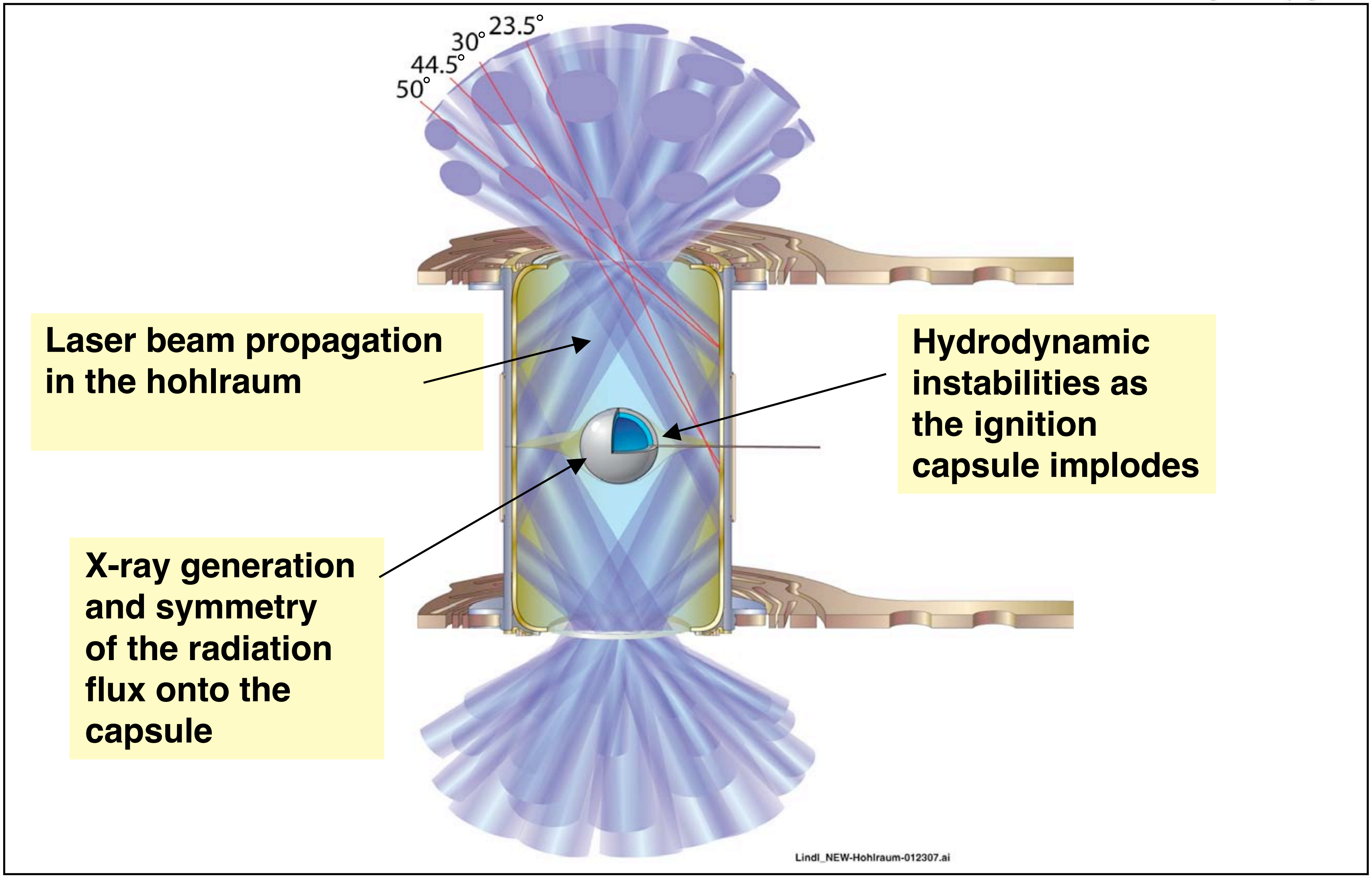


Ignition point design optimization must balance LPI effects, laser performance impacts, and capsule robustness



Detailed calculations of NIF ignition targets present a number of computational grand challenge problems

NIC
The National Ignition Campaign



The Advanced Simulation Capability (ASC) computers are essential for a wide variety of 3D effects which impact NIF ignition targets

NIC
The National Ignition Campaign

- Integrated hohlraum and capsule calculations - low spatial frequency perturbations (l=8 or less)
  - Hohlraum radiation flux asymmetry
  - Pointing errors
  - Power Imbalance
  - Capsule misplacement in the hohlraum
  - Hohlraum misalignment in the chamber
  - Missing beams or other off normal operation
  - Holes in the hohlraum or other inherently 3D structure
- Capsule only calculations - intermediate to high spatial frequency perturbations (l=10 to 1000)
  - DT ice roughness
  - Ablator roughness
  - Ablator microstructure
- Single Beam - Very high spatial frequency perturbations
  - laser wavelength and laser frequency scale features in the incident beam and in laser plasma interaction in the hohlraum

Resolving laser wavelength scale phenomena in the propagation of a laser beam in an ignition scale plasma is a grand challenge problem.

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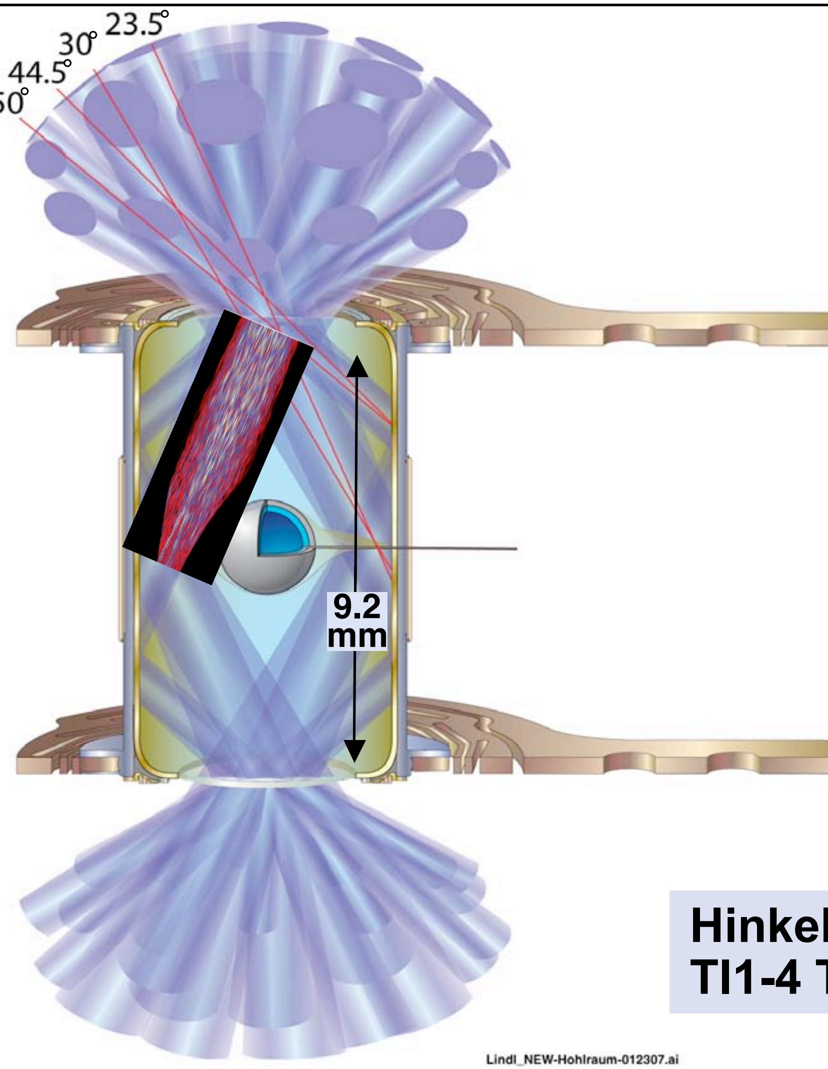
▪letterbox" simulations capture the essential physics for "near 2D" situations, like a NIF hohlraum, "

▪ A letterbox run for 10's of picoseconds using the code pF3D requires 8 Terabytes of memory and ~ 2.5M cpu-hours on the 8000 processor Atlas machine or ~ 15M cpu-hours on 32,000 processors of the 128,000 processor BG/L machine



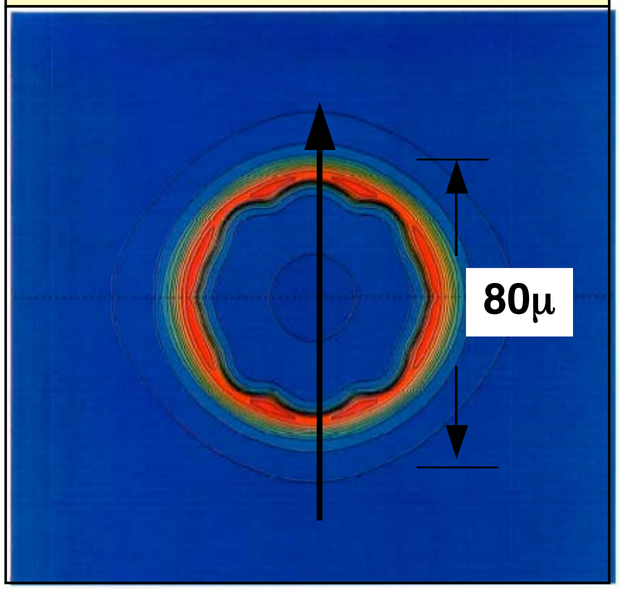
Lindl_NEW-Hohlraum-012307.ai

Hinkel
TI1-4 Thursday

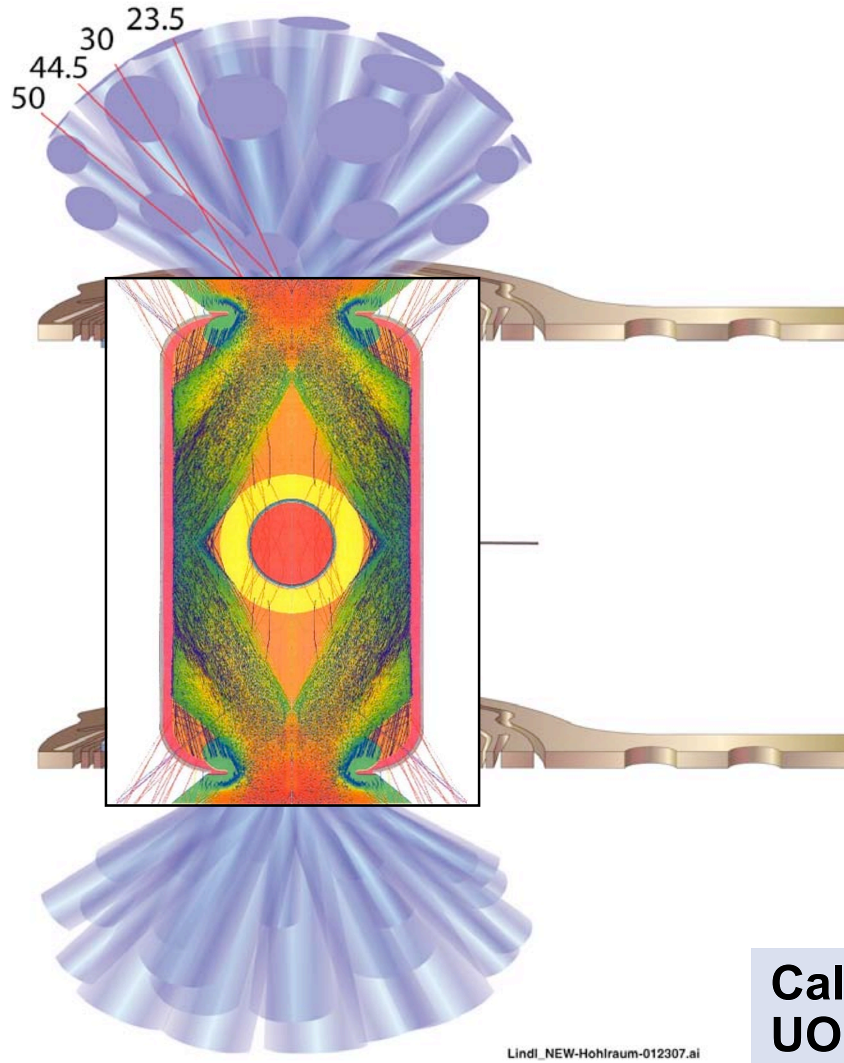
Optimized 2D symmetry calculations meet the point design requirements

The National Ignition Campaign

Be capsule fuel region at ignition



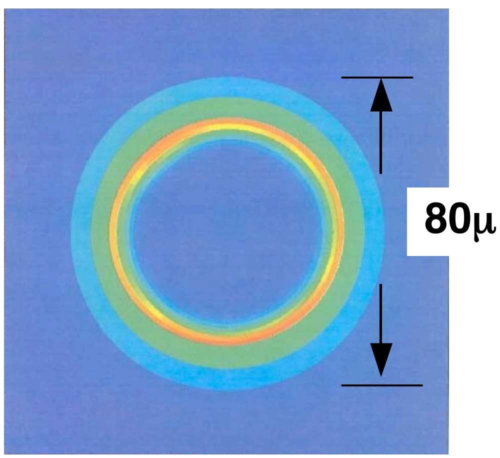
- **The imploded fuel core shows very little residual angular variation from the NIF multi-cone geometry**

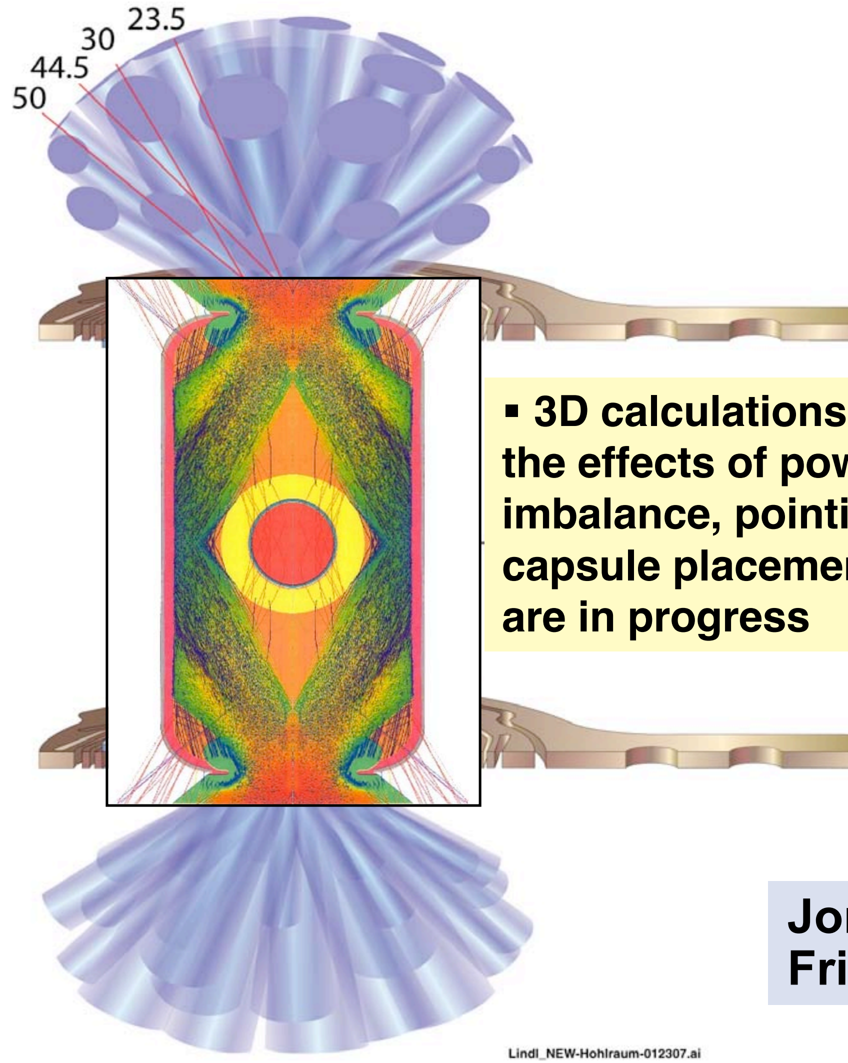


Callahan UO3-1 Friday

Calculations with Hydra of the 300 eV point design show very little intrinsic 3D azimuthal asymmetry

Cross section perpendicular to the hohlraum axis at ignition





- 3D calculations to assess the effects of power imbalance, pointing errors, capsule placement errors, etc are in progress

- A 3D hohlraum calculation capable of resolving l=8 radiation asymmetry requires about 0.2M CPU hours

Jones YO6-8
Friday

The ignition point design capsule is subject to hydrodynamic instability over a wide range of spatial scales

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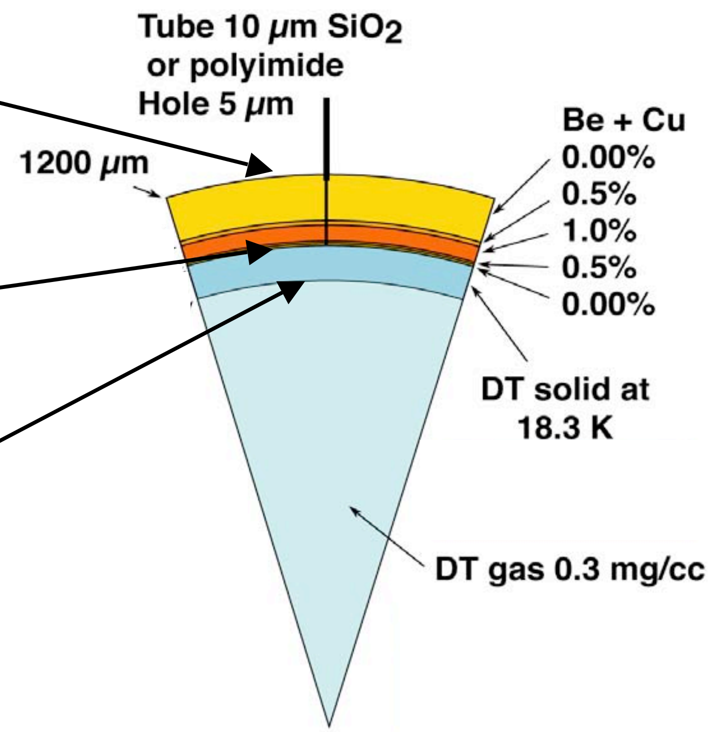
ignition point design capsule

- Outer surface of the Be ablator - up to about mode 120 during the acceleration process
- Interface between Be and DT - up to about mode 1000 during acceleration
- Inner surface of the DT fuel - up to about mode 30 during deceleration to ignition conditions



Detailed 3D effects of capsule surface roughness are evaluated using HYDRA calculations

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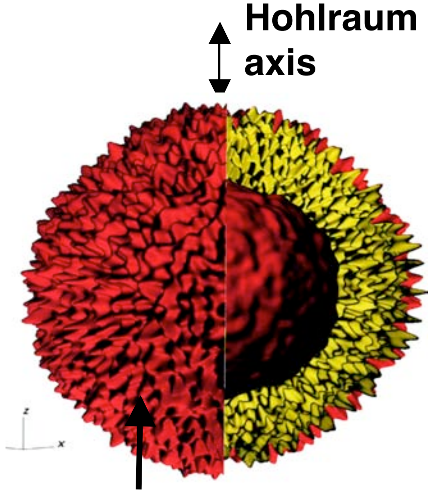
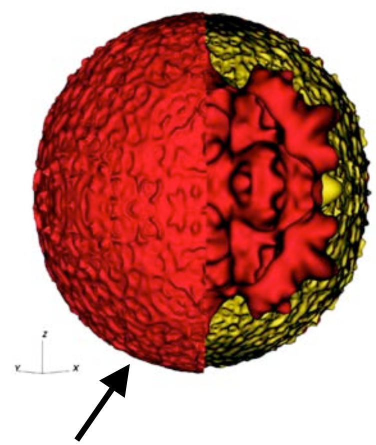
140 ps Before Ignition Time	Ignition Time
Hohlraum axis  Ablator/DT interface	 Stagnation shock
60 g/cc density isosurface	400 g/cc density isosurface (different scale)

- 3D radiation asymmetry is obtained from integrated hohlraum simulations
- Nominal “at spec” capsule fabrication perturbations are applied on the DT ice and the ablator

- A full sphere covering modes 1-30 or an octant covering modes 4-120 requires about 170 million zones and ~ 4 million cpu hours on 4000 processors of the 10,000 processor 100 TFLOP purple machine

Hydrodynamic instabilities at the capsule ablator-fuel interface are a particularly challenging problem

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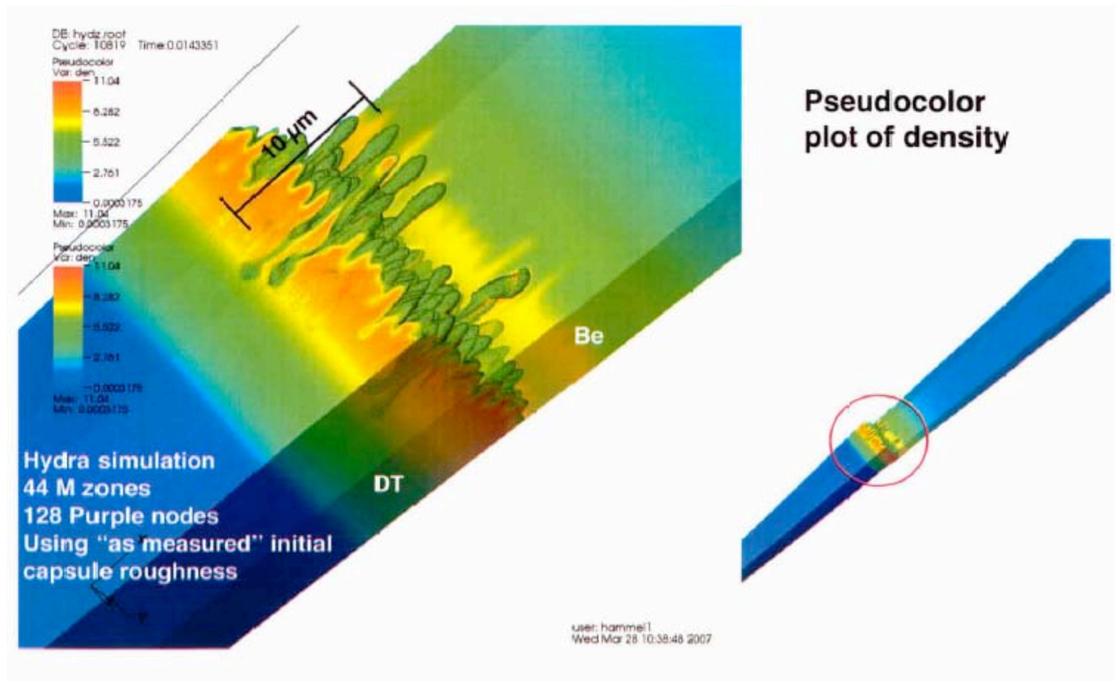
- Calculations resolve instability growth in 3D, up to mode 1000, at the Be/DT interface

- Benchmark calculations for a 4.5-9 degree wedge using the HYDRA Code require 44-176 million zones and 1-4 million CPU hours on 1000-4000 processors on the 10,000 processor, 100 TFLOP purple Machine



Hammel PO6-3
Wednesday

The point design capsule of copper doped Be driven at 285 eV has been specified in detail

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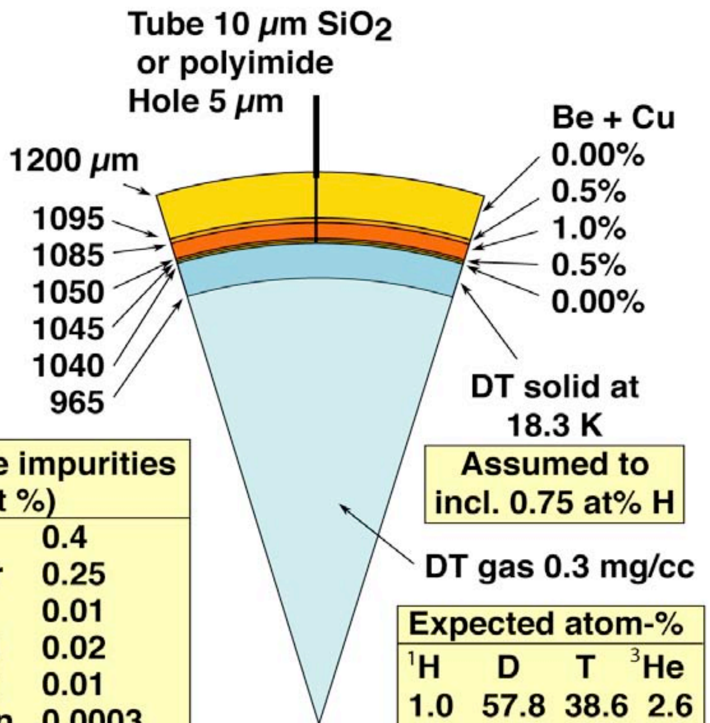
(Cu doped Be shell for 285eV, 1.3 MJ)



Assumed to incl. 0.75 at% H

Be impurities (at %)	
O	0.4
Ar	0.25
C	0.01
Al	0.02
Si	0.01
Mn	0.0003
Fe	0.01
Ni	0.002

Expected atom-%

^{1}H	D	T	^{3}He
1.0	57.8	38.6	2.6

Inner 0.75 μm of Be contains two layers of 12-at% Be(B)

Details in boxes are point-design specifics, not requirements

Parameter	Be(285) "current best calc"
Absorbed energy (kJ)	203
Laser energy (kJ) (includes ~8% backscatter)	1300
Coupling efficiency	0.156
Yield (MJ)	19.9
Fuel velocity (10^7 cm/sec)	3.68
Peak rhoR (g/cm^2)	1.85
Adiabat (P/P_{FD} at 1000g/cc)	1.46
Fuel mass (mg)	0.238
Ablator mass (mg)	4.54
Ablator mass remaining (mg)	0.212
Fuel kinetic energy (kJ)	16.1

A CH capsule at 300eV and 1.3 MJ is the principal alternate to Be at 285 eV

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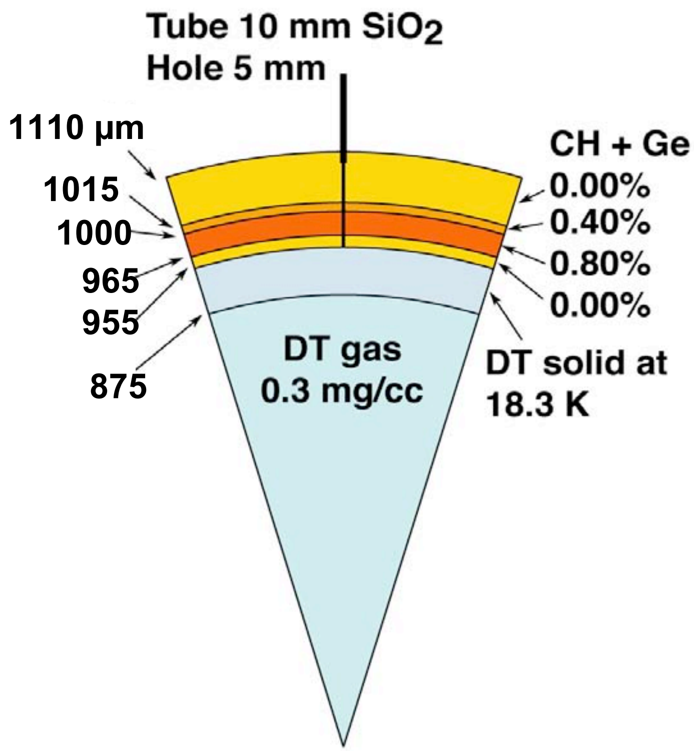

	CH(300)
Yield	17.6 MJ
Eabs	150 kJ
Implosion velocity	3.85×10^7
Fuel mass	cm/s 0.21 mg
Ablator mass	2.3 mg

- •Post-processed hohlraum simulations at 300 eV indicate LPI equivalent to or better than Be at 285eV
- •Amorphous material with no crystal structure issues
- •Large data base from Nova and Omega
- •Less efficient ablator but at 1.3 MJ (&300eV), this target looks attractively robust. More work in progress.
- •Transparency makes cryo layer easier to characterize but low thermal conductivity makes layer formation in the hohlraum more challenging

We are also evaluating a nanocrystalline diamond ablator option at 270 eV and 1.3 MJ

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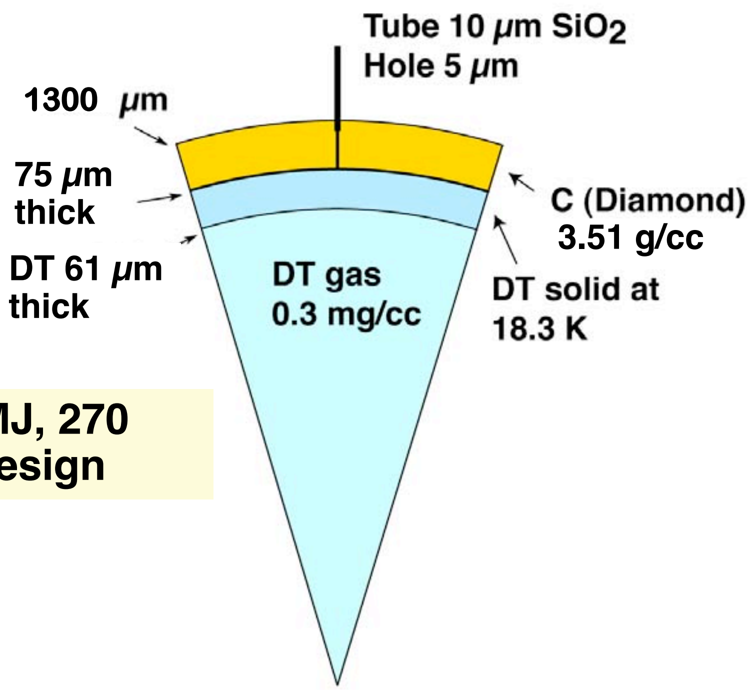

1.3 MJ, 270 eV design

	Diamond(270)
Yield	24.7 MJ
Eabs	260 kJ
Implosion velocity	3.58×10^7 cm/s
Fuel mass	0.27 mg
Ablator mass	5.26 mg

- Higher density: diamond absorbs energy at larger radius. Equivalent to 10 - 20% more laser energy.
- Ablator surface is very smooth. Can tolerate 20x the measured surface roughness.
- LPI analysis indicates 270 eV diamond hohlraum has less risk than Be hohlraum at 285eV
- Complex material properties during pulse shaping: Stays solid after 1st shock, melts with 2nd shock (Be melts with 1st)

Ho TI1-3 Thursday

Assessment of ignition targets utilizes computer calculations, coupled to planned precision target physics campaigns

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- We are designing experimental campaigns for hohlraum energetics, shock strengths and times, implosion velocity and ablated mass, and symmetry, which will take 100-200 shots leading up to the first ignition attempts
- Most physics uncertainties will be normalized out with these "optimization" experiments (Residual physics uncertainties for these items are set by how accurately we can do the experiments - the point design specs include estimates for the achievable accuracy)
- Specifications on target fabrication and laser performance are set to achieve the required precision and reproducibility.
- Uncertainty in some physics issues such as DT thermal conduction and alpha particle deposition in Fermi degenerate DT will remain after these experiments

Our key question is *not* "How well can the codes predict the ignition target a-priori?", but instead "Will the uncertainties and variability that remain after our tuning programs be acceptable?" This is a key focus of our preparations for ignition experiments

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

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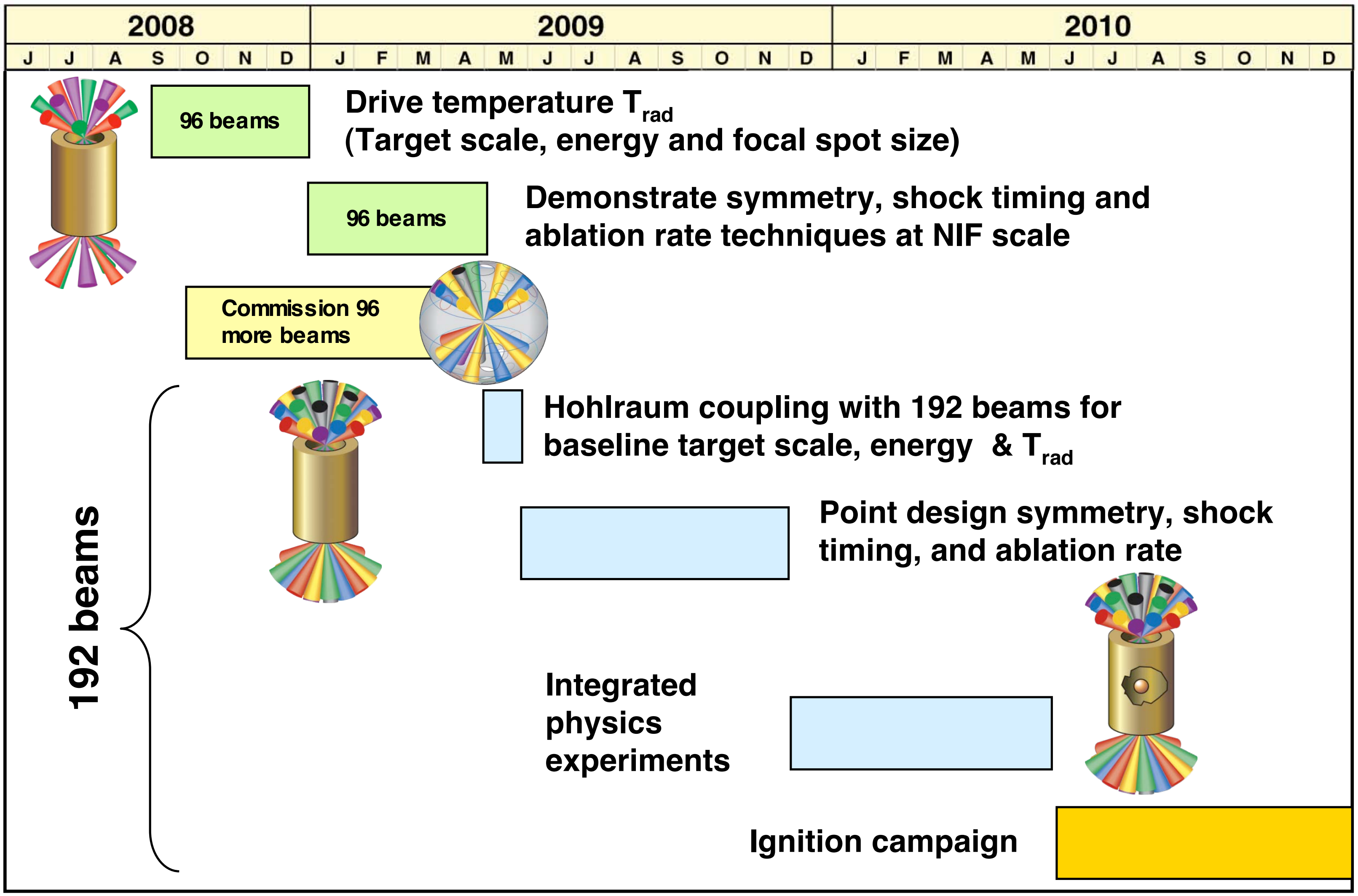

The 96 beam campaign will utilize the 30º and 50º beams to emulate the ignition target

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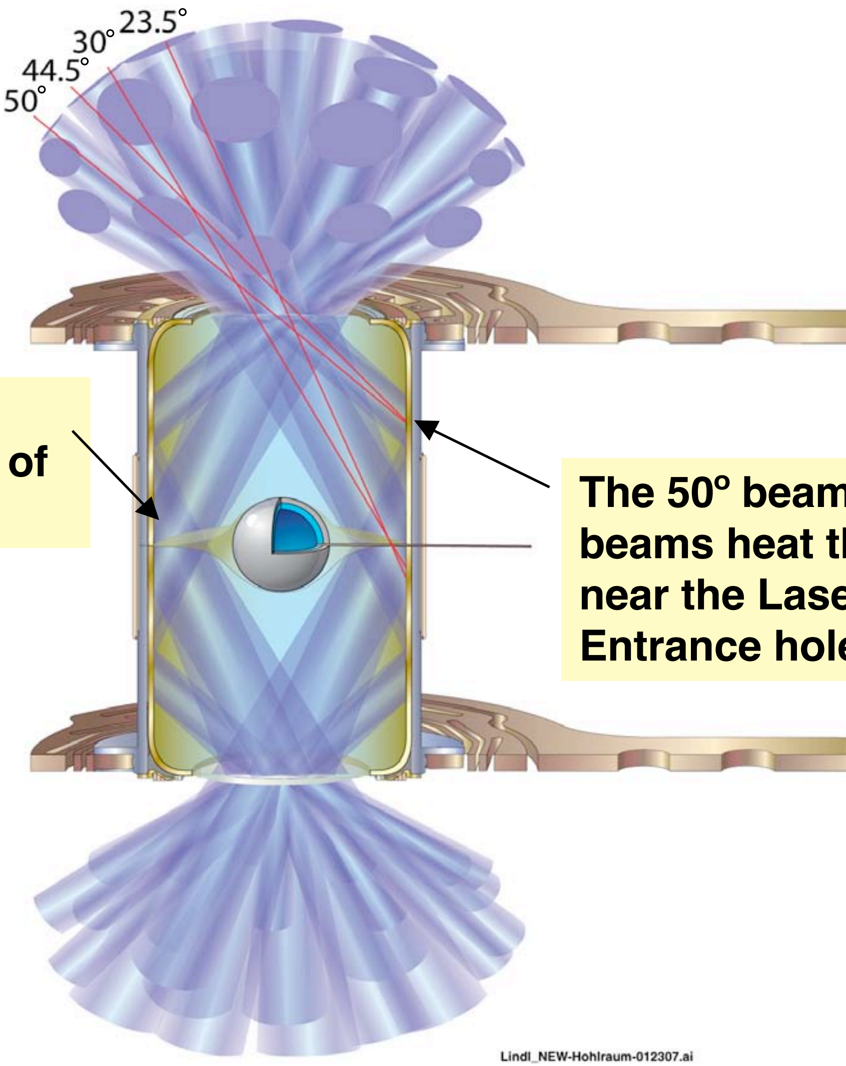
The 23.5º and 30º beams heat the waist of the hohlraum



The 50º beams and 44º beams heat the hohlraum near the Laser Entrance hole

Lindl_NEW-Hohlraum-012307.ai

The 96 beam emulators are scaled to preserve hohlraum energy density and per beam intensity

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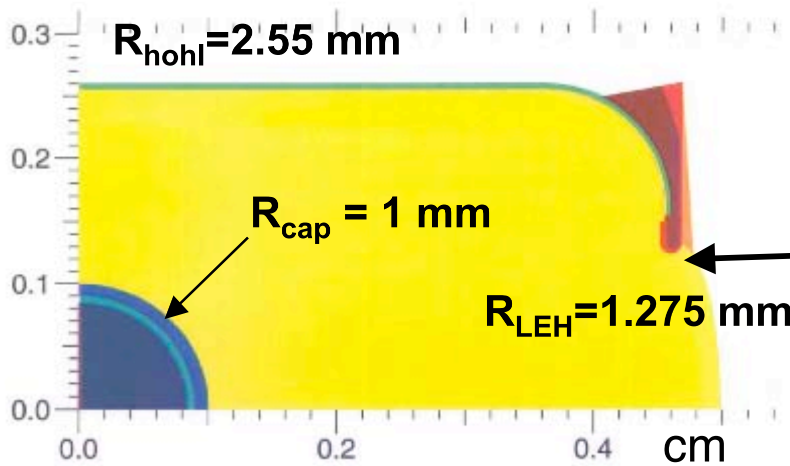
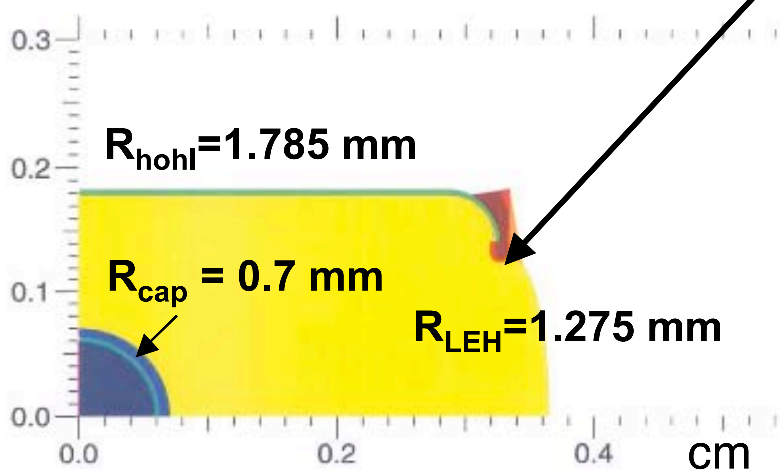
300 eV
1 MJ,
192
beams)



We use full-size phase plates, so the LEH is not scaled.

96-beam Emulator at 70% scale



We test various T_{RAD} ignition designs by changing only the laser pulse-shape.

Meezan YP8-38
Friday

The 96-beam scaled experiments closely match the ignition plasma conditions.

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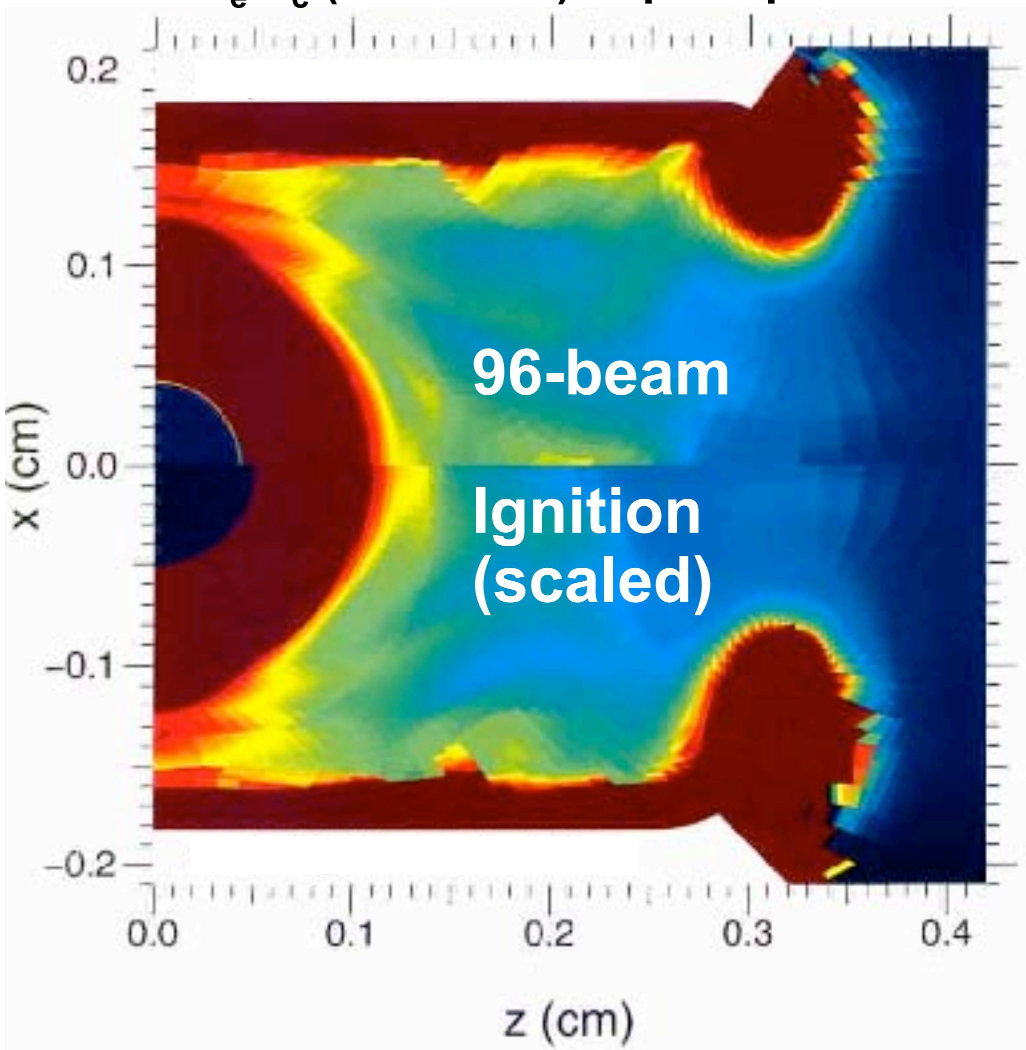
n_e/n_c (max = 0.3) at peak power



“Keyhole” targets to meet the shock timing requirements are one of the optimization targets which precede ignition experiments

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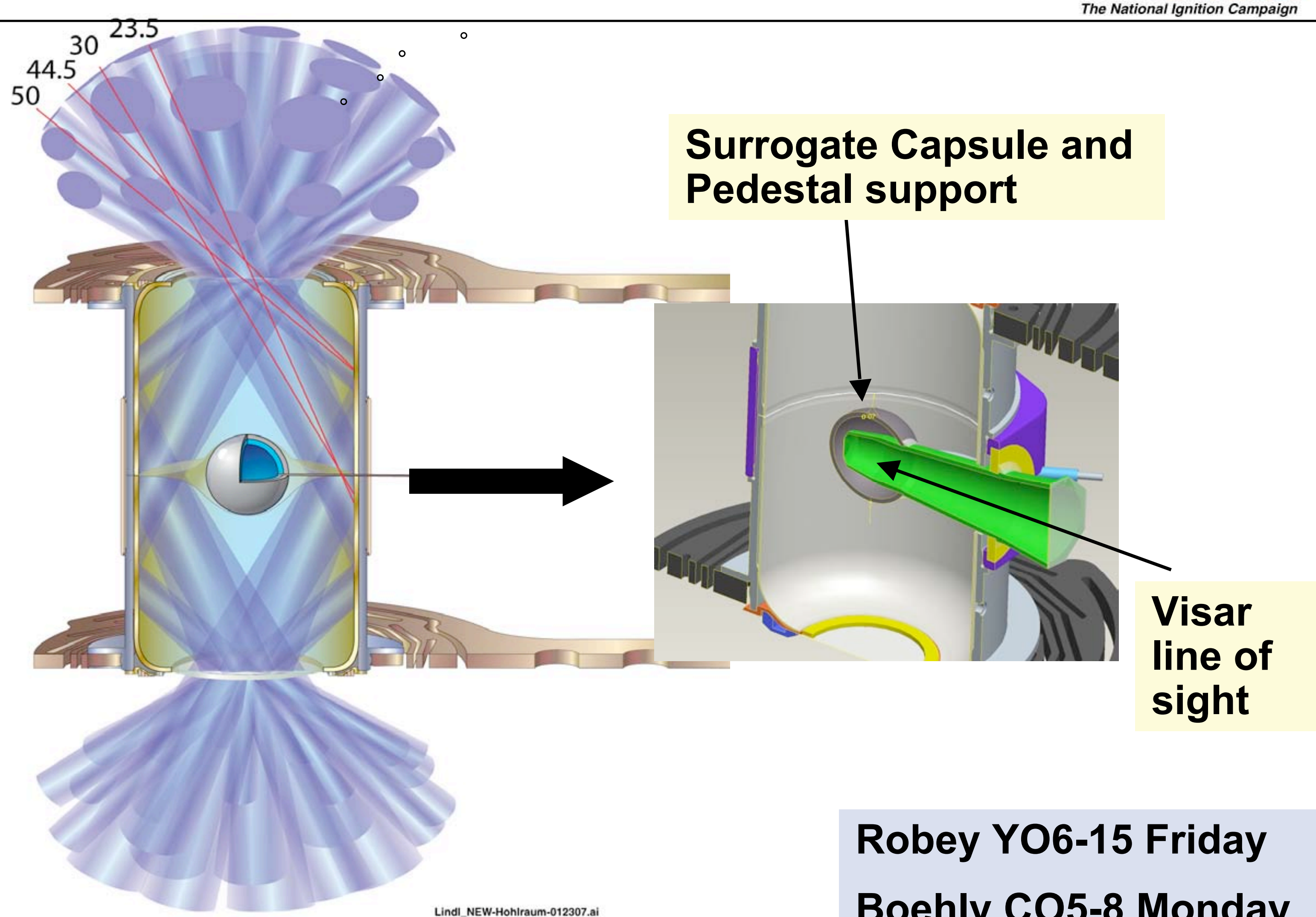
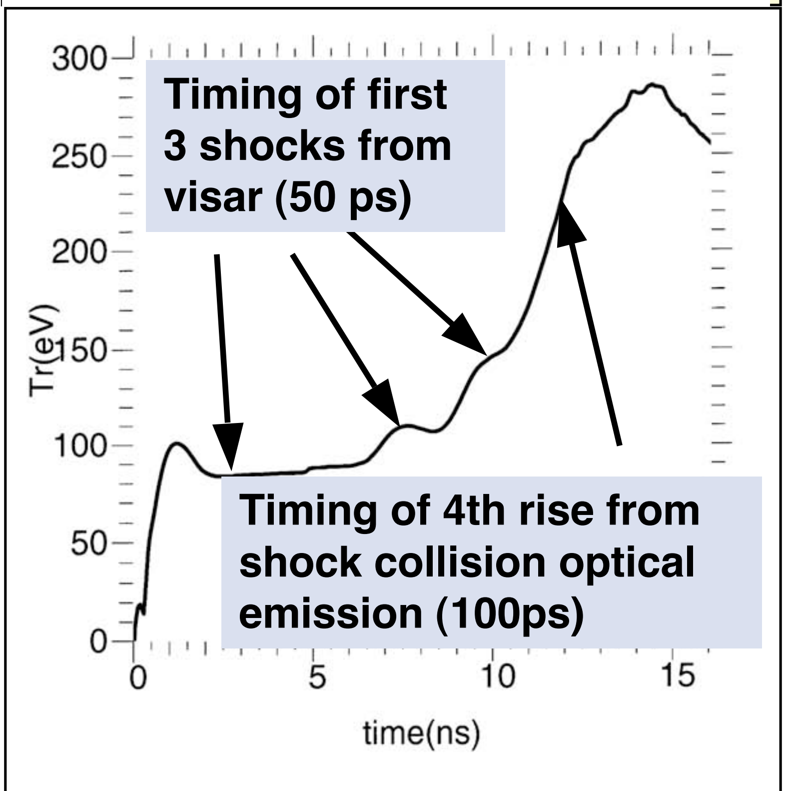


Robey YO6-15 Friday

Boehly CO5-8 Monday

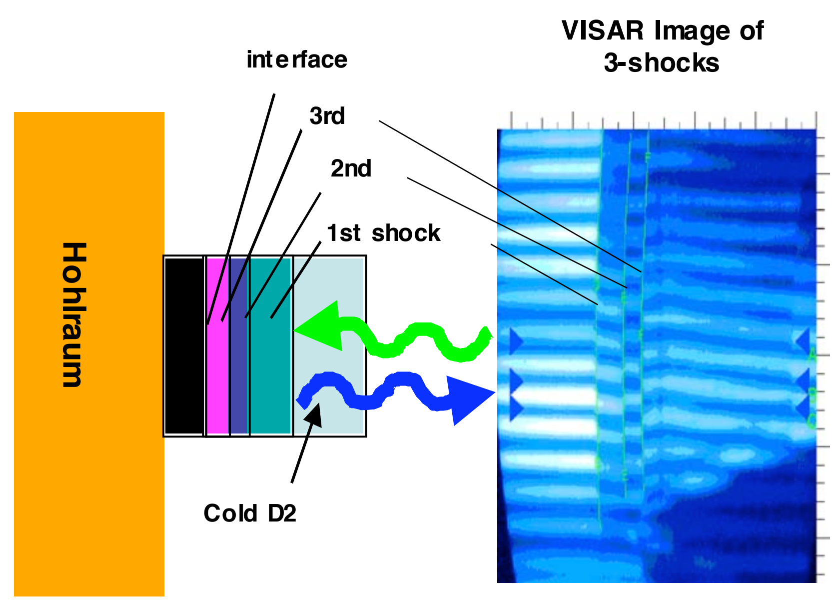
Accurate pulse shaping is a key to "1D" capsule performance

Pulse shape for Be at 1.3 MJ and 285 eV



NIF's pulse shaping system was designed specifically to meet these requirements

VISAR measures shock Front doppler shift



- **Jump in fringe shift gives shock arrival**
- **Fringe position gives shock velocity**

We are doing multivariable sensitivity studies to assess the margin and robustness of ignition target designs

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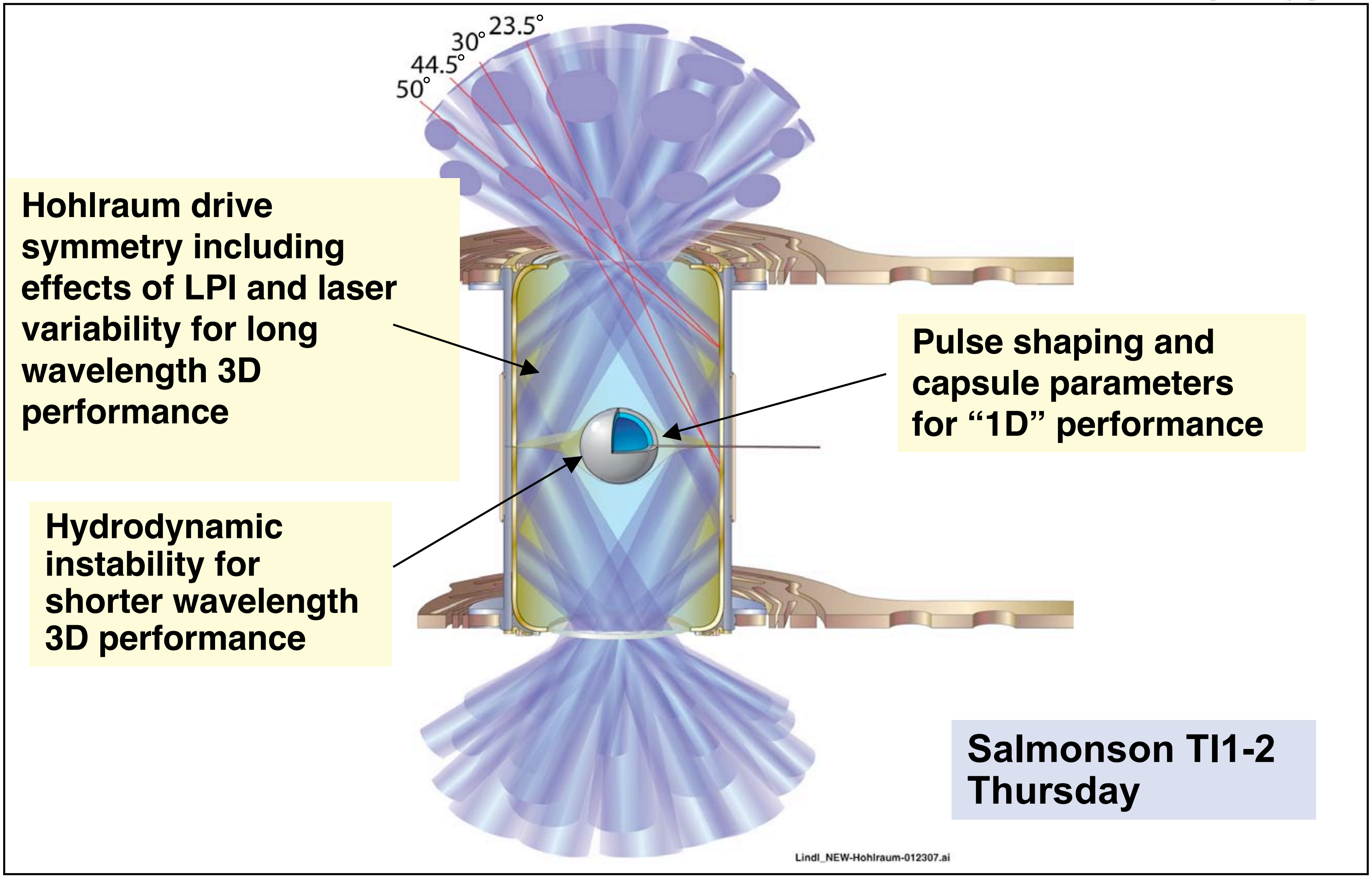
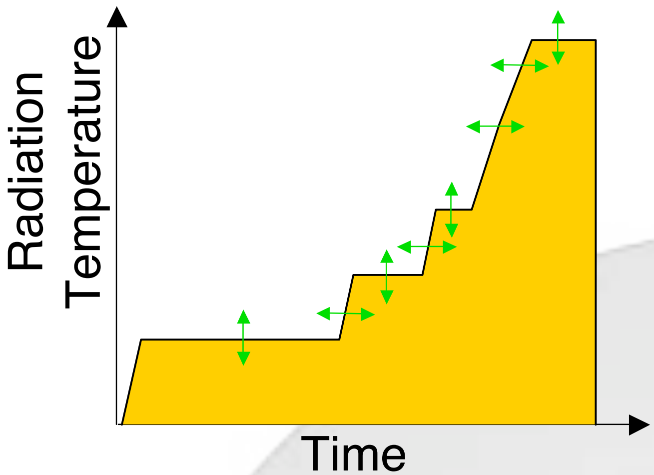
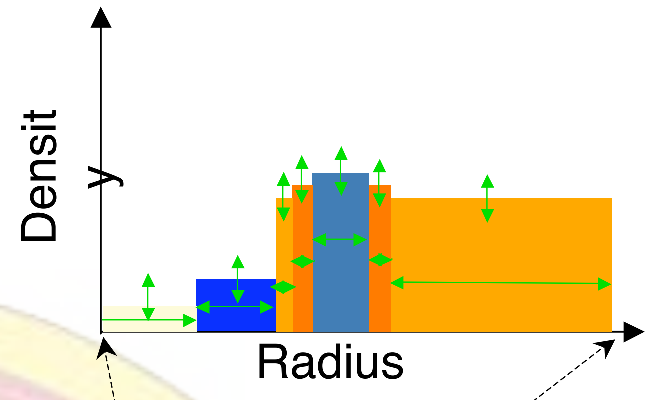
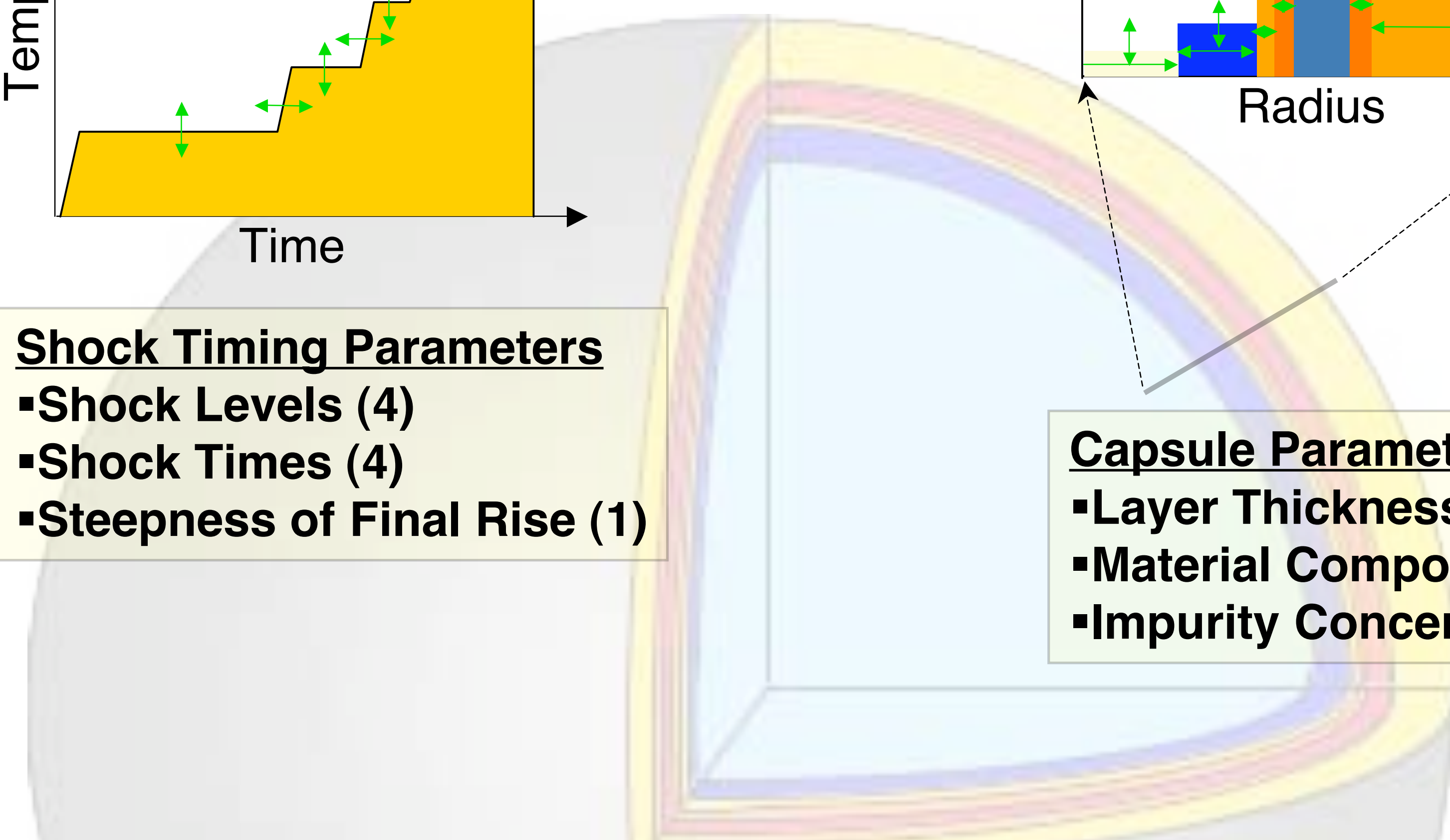


Salmonson TI1-2 Thursday

We have identified 34 pulse shaping and capsule parameters that impact 1Dcapsule performance







<u>Shock Timing Parameters</u>
- **Shock Levels (4)**
- **Shock Times (4)**
- **Steepness of Final Rise (1)**

<u>Capsule Parameters</u>
- **Layer Thickness (7)**
- **Material Composition (8)**
- **Impurity Concentration (10)**

In order to vary all parameters simultaneously, we incorporate a distribution for each

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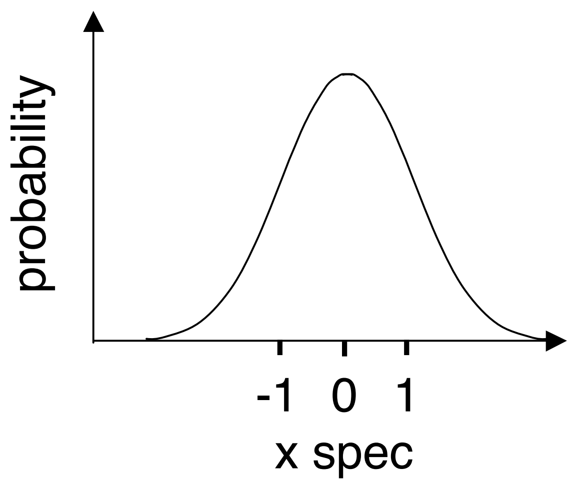
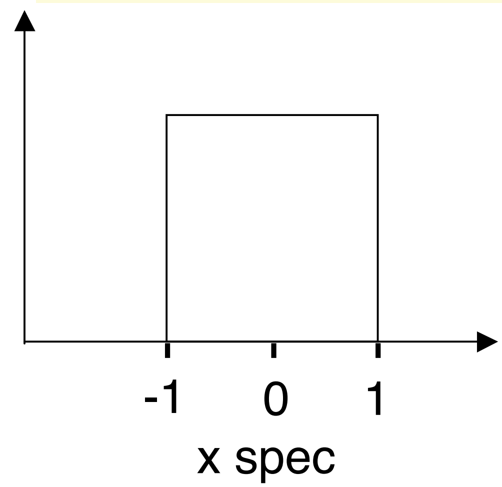
Normal distribution



Top-Hat distribution



For complex physical processes such as shock timing and levels that will likely vary normally.

For fabrication specs such as capsule dimensions that can be measured and rejected.

We use ensembles of simulations to estimate the probability of ignition

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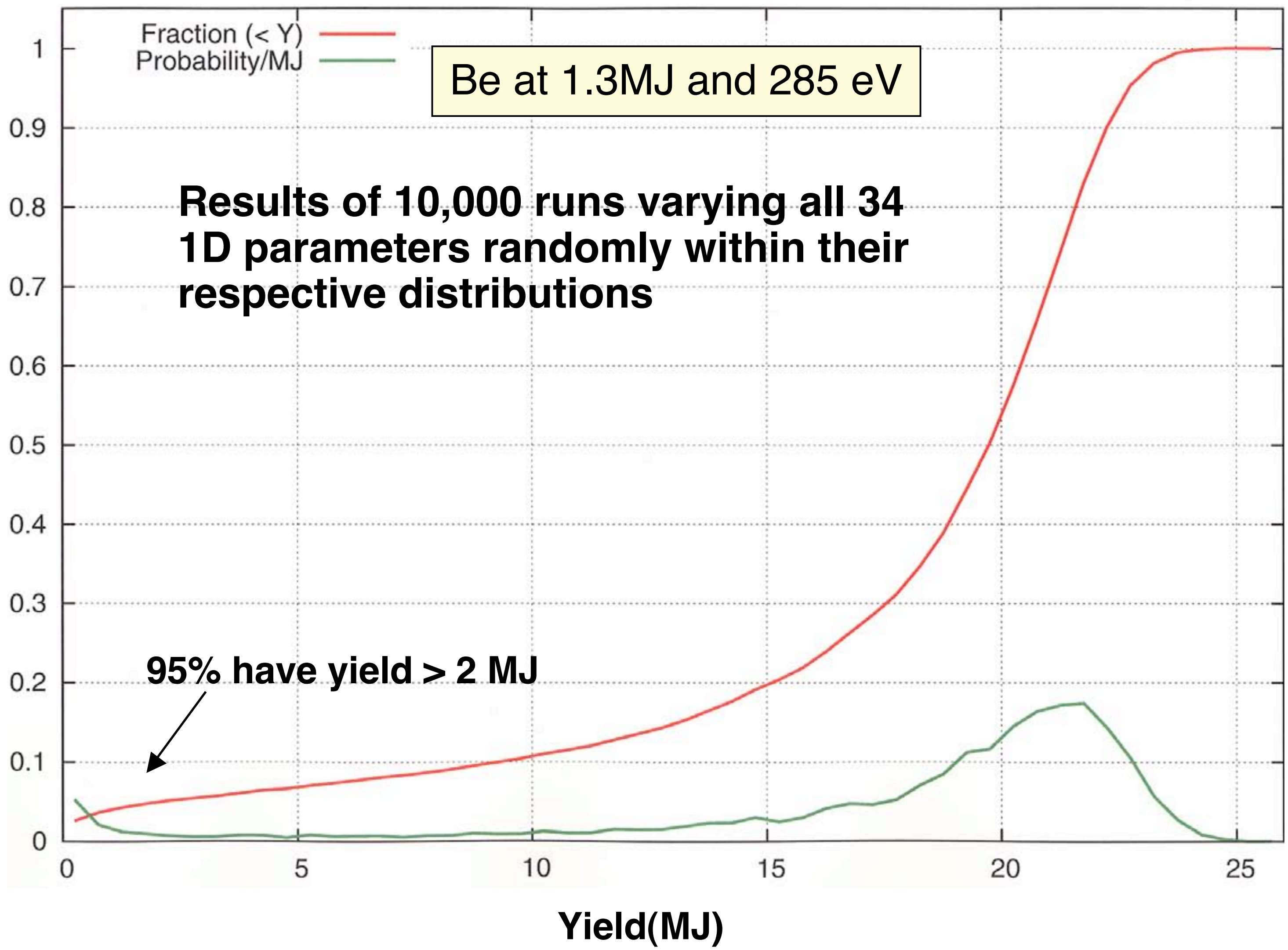

Statistical ensembles of 2D simulations include perturbations on all capsule surfaces

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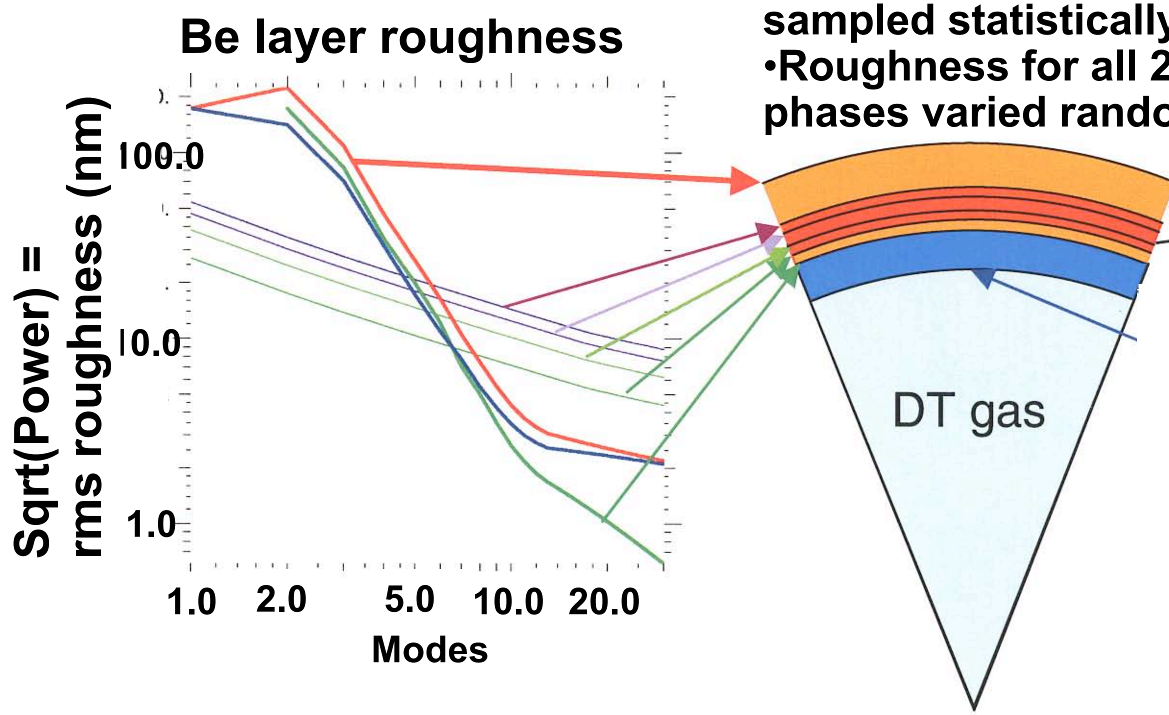
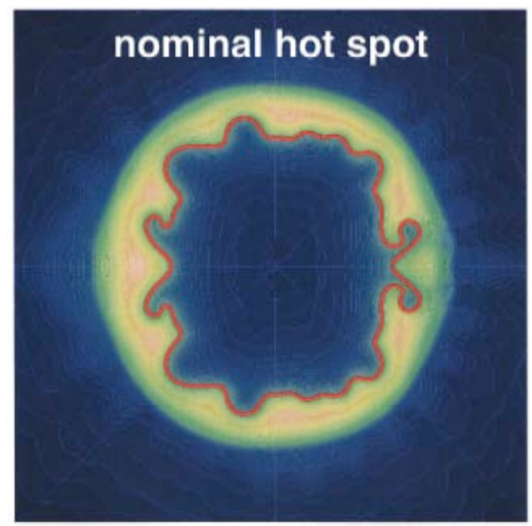


- All 1D parameters (dimensions, compositions, densities, drive parameters) sampled statistically
- Roughness for all 2D surfaces set "at spec," phases varied randomly



2D calculations provide an assessment of the impact of non-spherical effects

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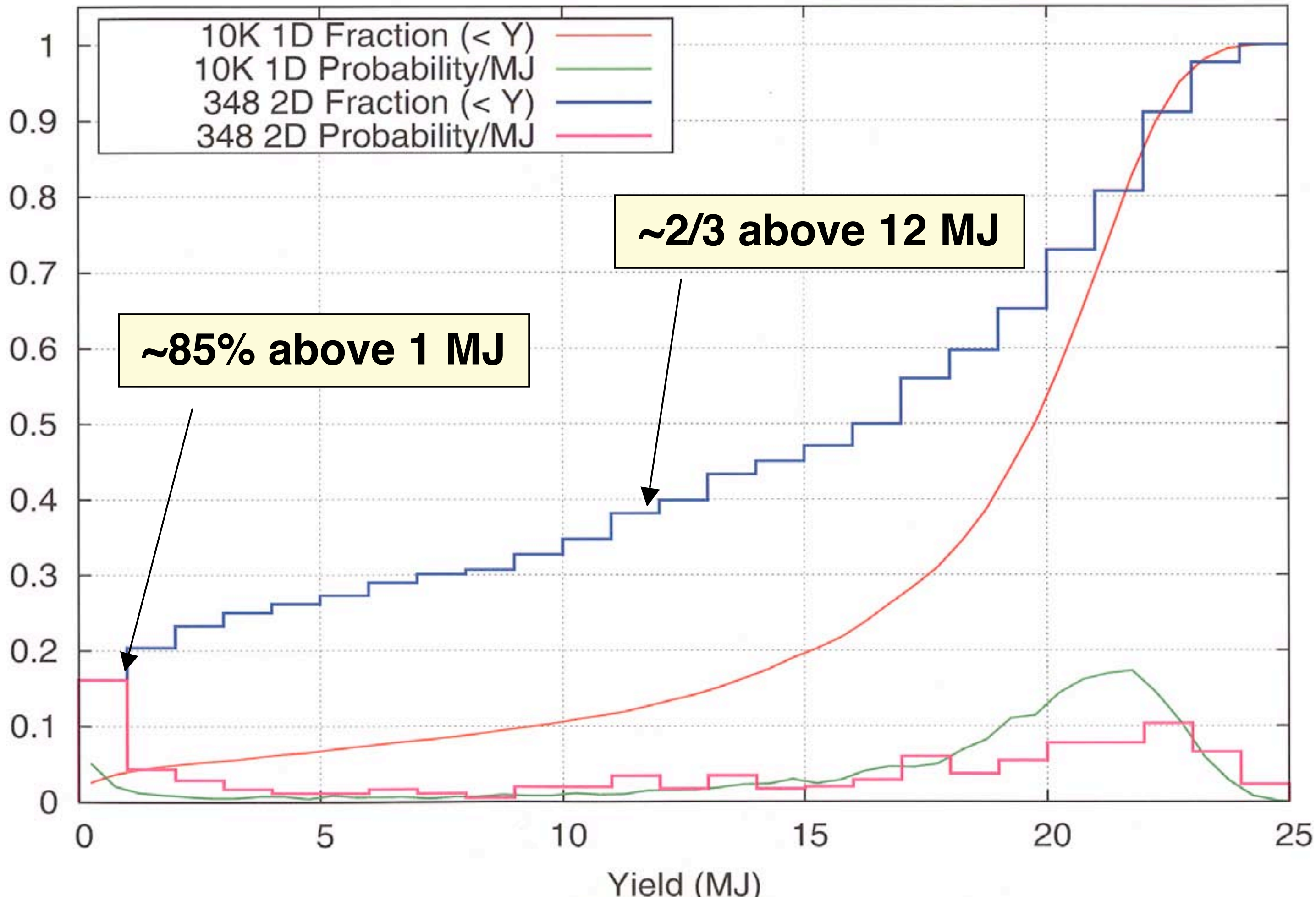
Results of 360 2D simulations (A statistical sample of 60 1D capsules with 6 random number seeds in 2D for each 1D point)



The 285 eV point design has a credible chance for ignition in early NIF operations….

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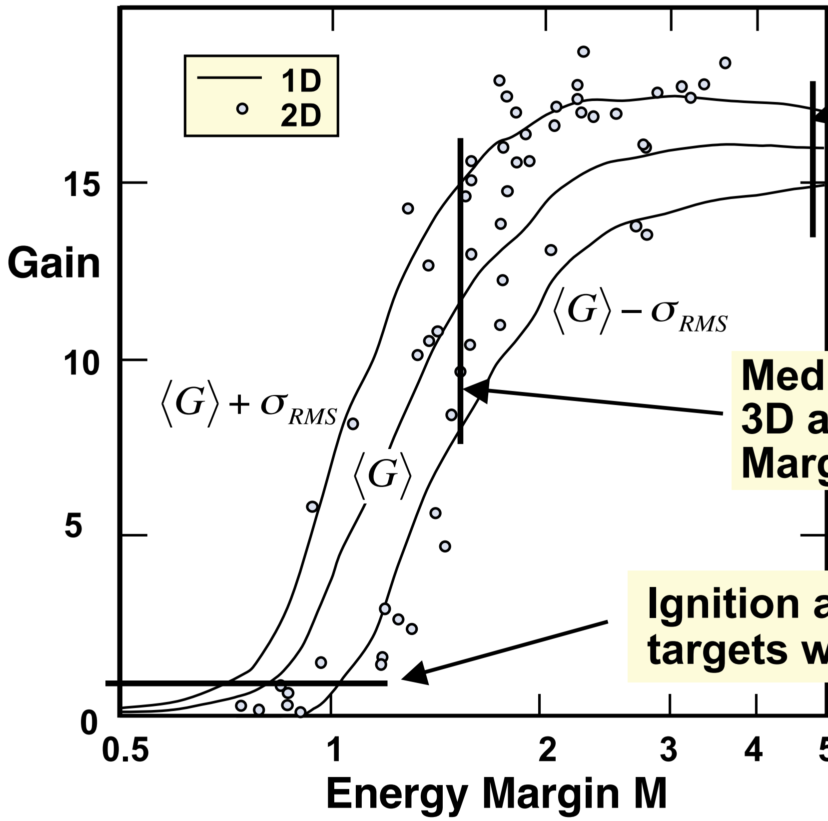
Energy Margin = Target Energy divided by the minimum energy required for ignition



Point design capsule has a margin of 4.8 with all 1D parameters nominal and no 3D effects

Median V,entropy
3D at spec
Margin 1.5

Ignition achieved for targets with Margin >1

Haan BP8-34 Monday

Clark TI1-1 Thursday

Ultimately, yields well in excess of 100 MJ may be possible on NIF

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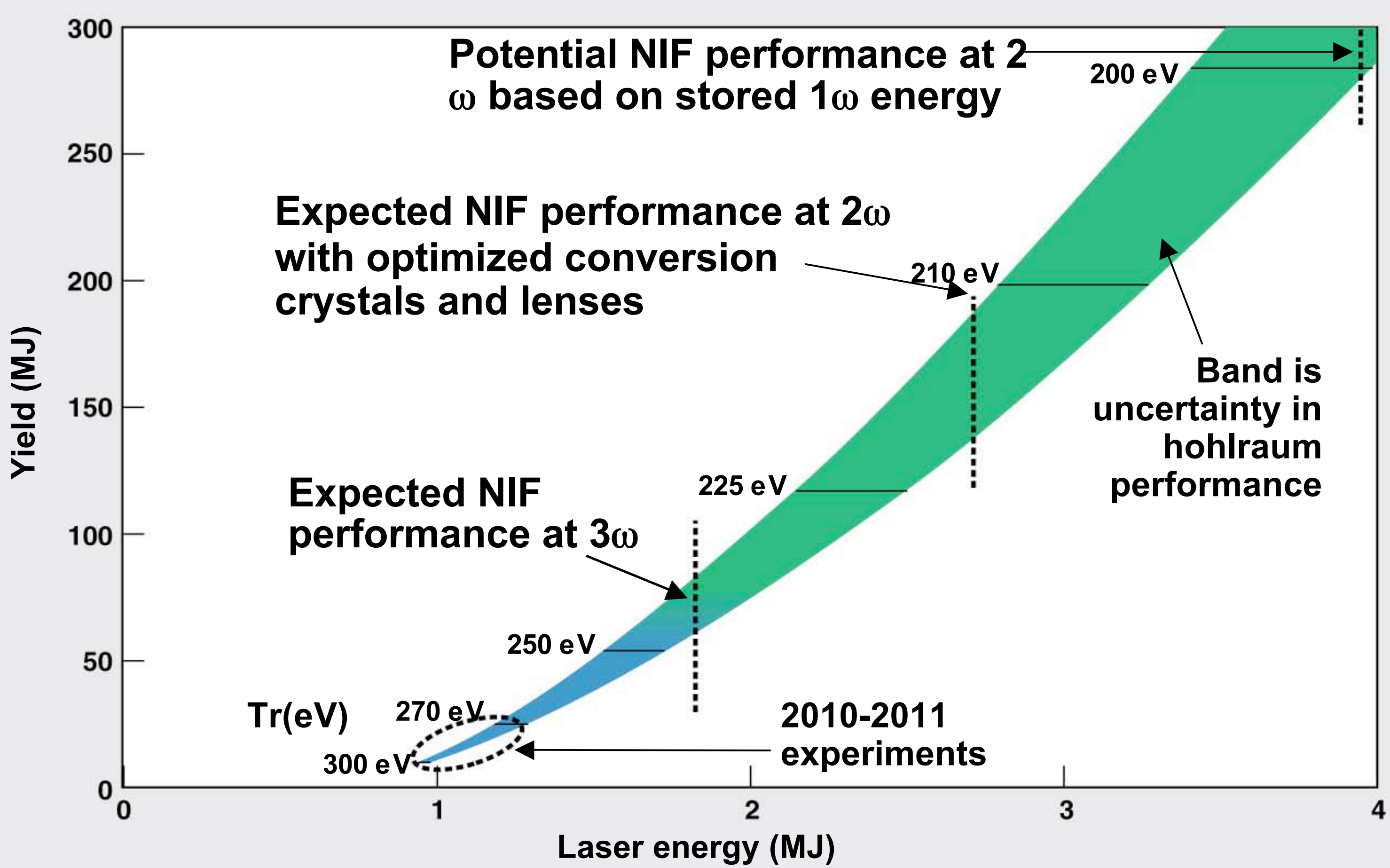
Yields versus laser energy for NIF geometry hohlraums



NIF-0107-13186
26JL/cld

Double shell indirect drive targets are a possible alternate for ignition

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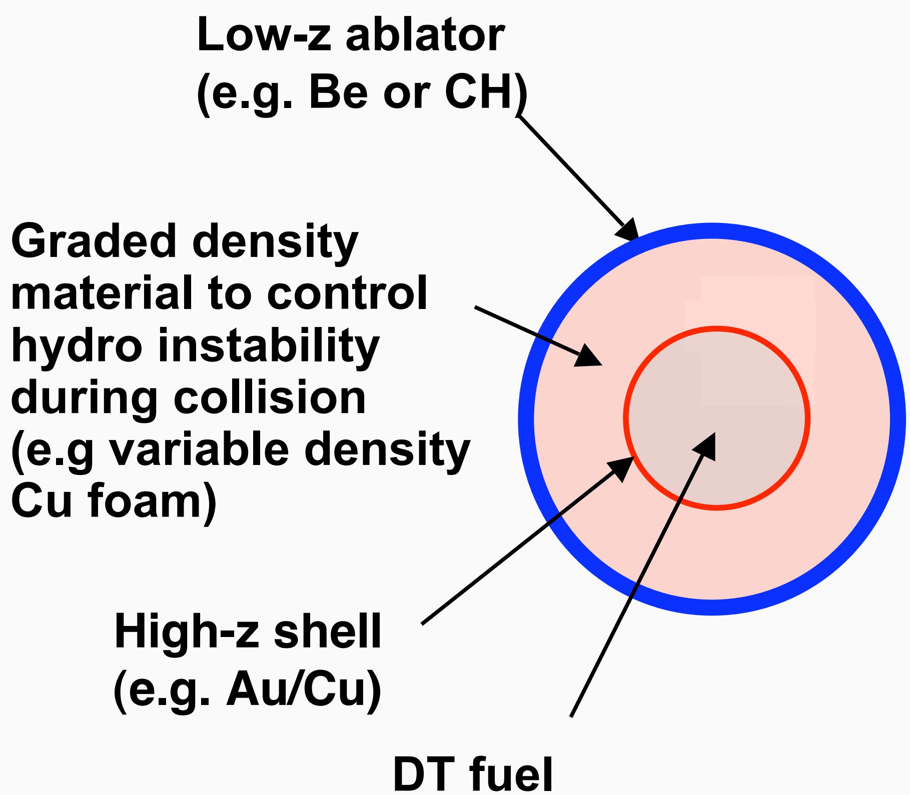

- Non-cryogenic
- Low radiation temperature relaxes LPI effects
- Fabrication to control mix is a major challenge
- Inherently limited to relatively low gain because most of the compressed mass is inert

NIF can explore direct drive or fast ignition as alternate approaches to ignition

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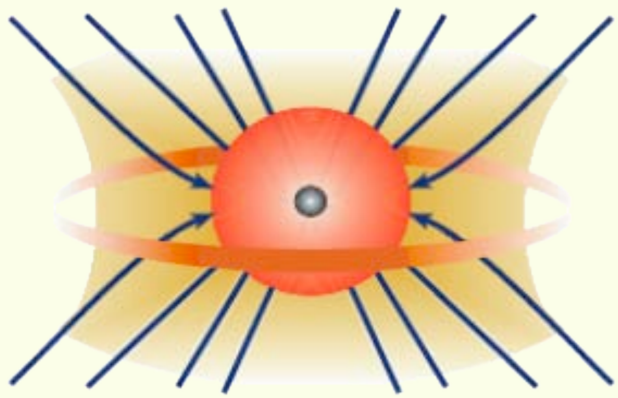
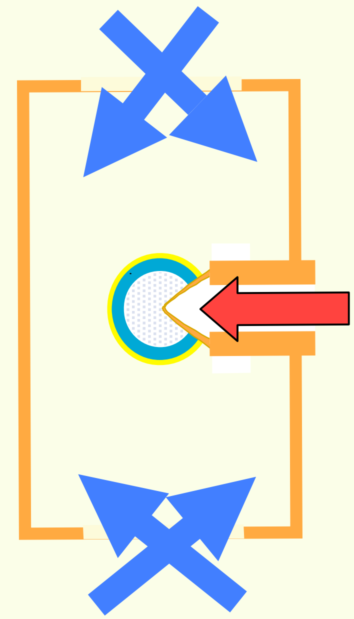
Polar Direct Drive



- Direct Drive in the Indirect Drive Geometry
- Higher coupling efficiency than indirect drive
- Beam smoothing and implosion symmetry are major challenges

Fast Ignition



- Separate compression and ignition
- Potentially highest gain
- Short pulse physics is major issue

05-00-0696-1321

The NIF ignition experiments will be the culmination of five decades of development which started with the invention of the laser in 1960

The National Ignition Campaign

- Dramatic advances in computations, lasers, diagnostics, and target fabrication over the past 3 decades have laid the groundwork for NIF and the National Ignition Campaign (NIC)
- Experiments for hohlraum energetics, shock strengths and times, implosion velocity and ablated mass, and symmetry, will normalize out most remaining physics uncertainties
- Targets near 1 MJ of laser energy have a credible chance for ignition in early NIF operations …..when the required precision of target experiments, laser performance, and target fabrication is achieved

Ignition is a grand challenge undertaking. It is likely to take a few years to achieve the required level of precision and understanding of the physics and technology needed for success.

- The initial ignition experiments only scratch the surface of NIF's potential

NIC

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