The National Ignition Facility: Laser Performance and First Experiments

16th ANS Topical Meeting
on the
Technology of Fusion Energy

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Lawrence Livermore National Laboratory

September 15, 2004


National Ignition Facility
NIF-1002-05559r2(lay)L1
22EIM/tr


NIF-1201-04097_1_r1
17JA/mcm
P5490
1/16/03/EIM/cld

The National Ignition Facility concentrates all the energy in a football stadium-sized facility into a mm^3

The National Ignition Facility

NIF-0404-08347 _L1
01ABC/def

P6842

The National Ignition Facility concentrates all the energy in a football stadium-sized facility into a mm^3

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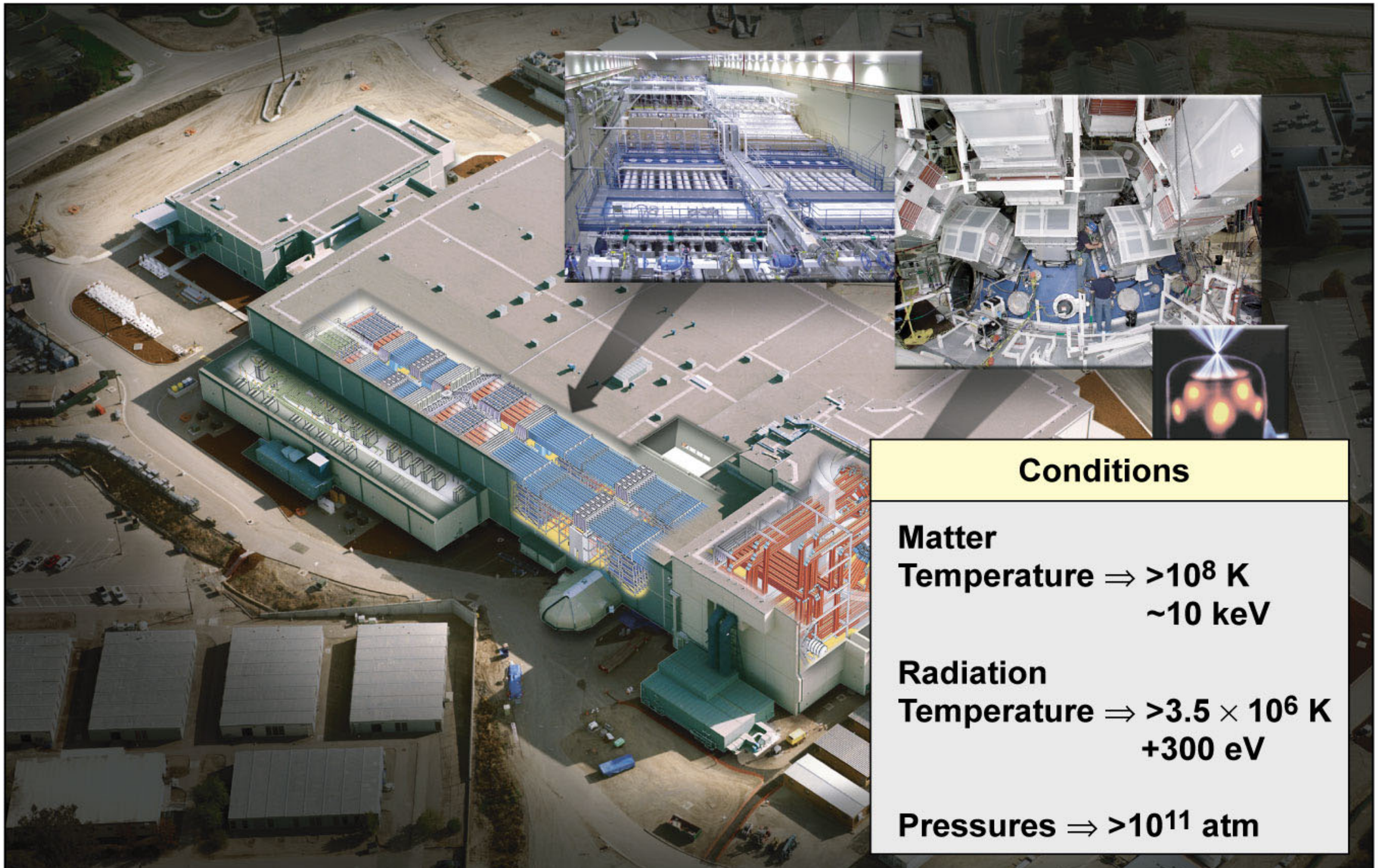

Conditions

Matter Temperature $\Rightarrow$ **>10^8 K**
~10 keV

Radiation Temperature $\Rightarrow$ **>3.5 $\times$ 10^6 K**
+300 eV

Pressures $\Rightarrow$ **>10^{11} atm**

192 beam, 1.8 MJ, laser organized into "bays," "clusters", "bundles", and "quads"

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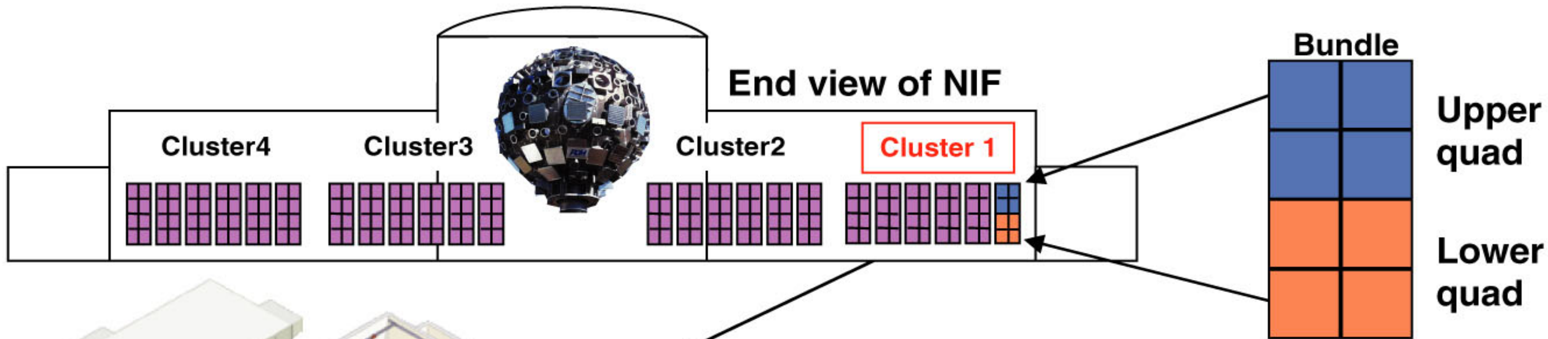

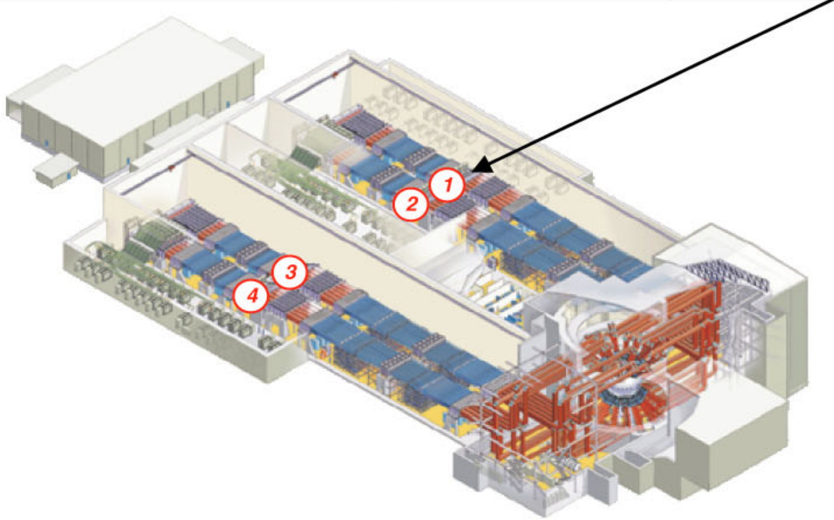

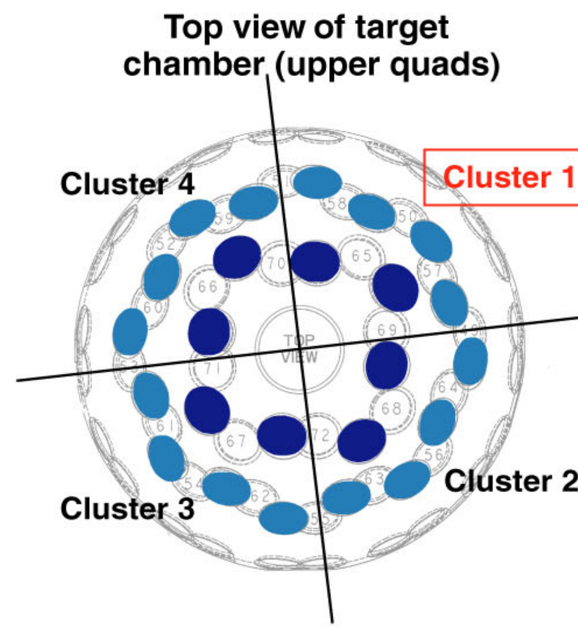

"Quads" are the basic building blocks of a NIF experiment, 4 beams with the same pulse shape and time delay

Specifications for NIF

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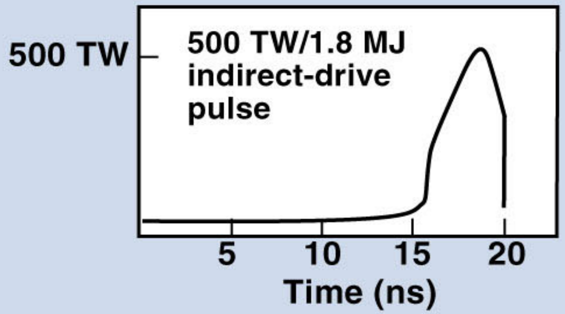
Performance parameter	Value
Energy	1.8 Megajoules
Power	500 Terawatts
Wavelength	351 nm
Pulse length	1 to 21 nsec
Pulse shape	Flexible, 
Power balance	8% over any 2-nsec interval in 48 beams spots
80% focal spot diameter	250 to 350 microns


Conventional
Facility
(100%)
NIF-1101-03958_7Ac-EIM


Beampath infrastructure (100%)
NIF-0804-09201

NIF-1103-07419c
2EIM/sb


Optics
(68%)
KDP
DANDY
THIS TANK CONTAINS:

The NIF uses modular cassettes that plug into a fixed mechanical structure

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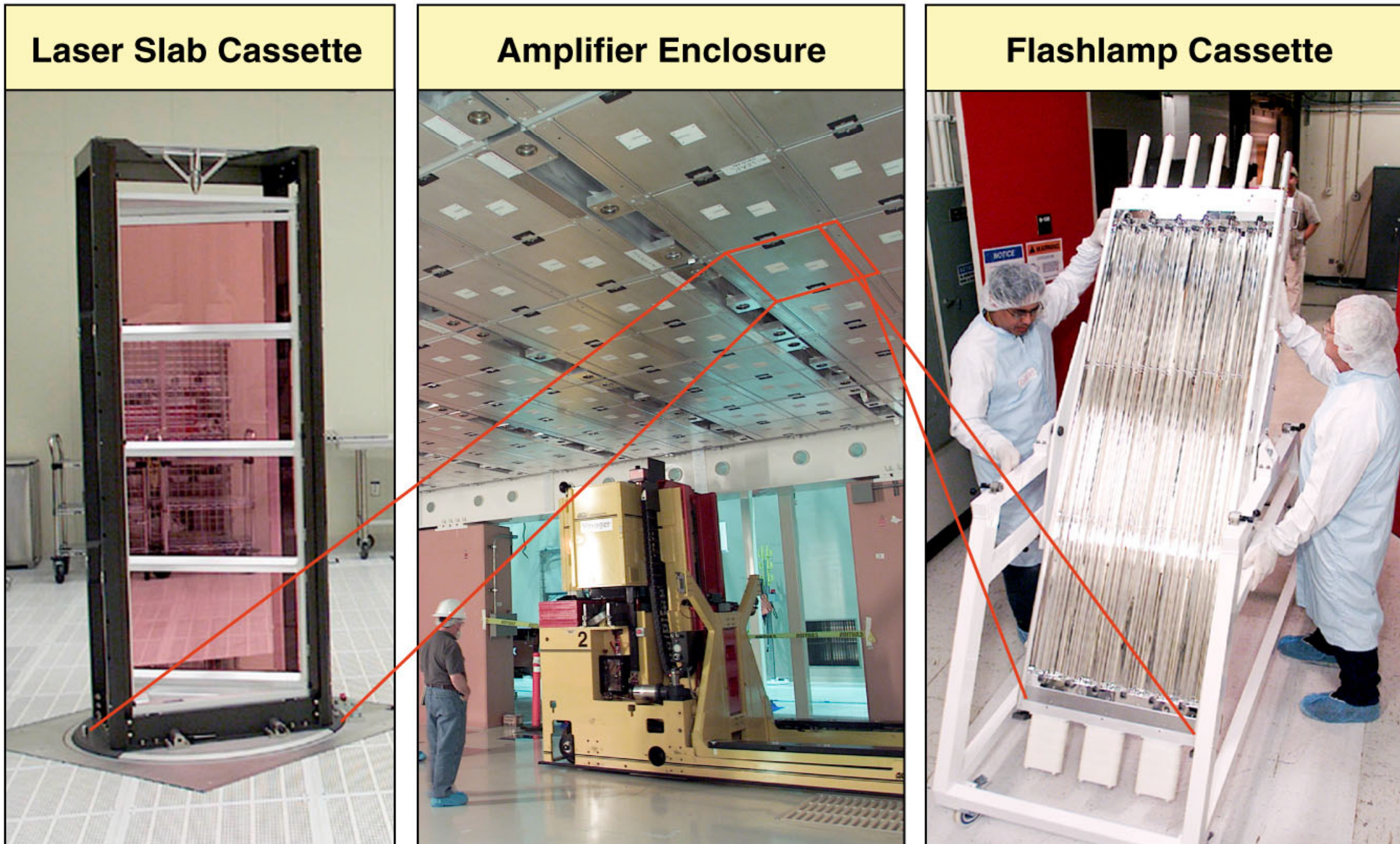

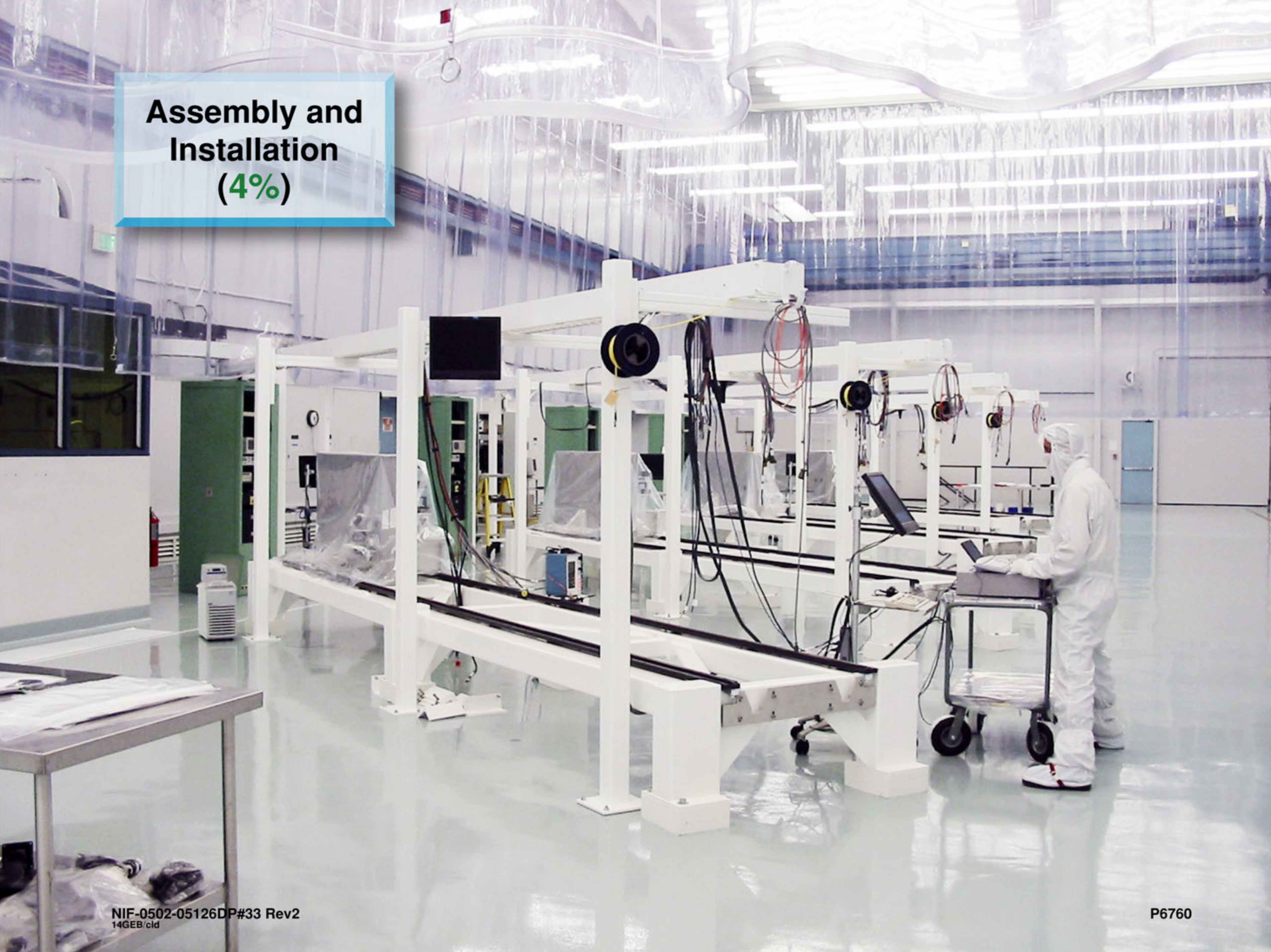
Assembly and
Installation
(4%)

LASER DIAGNOSTICS
ICCS DUTY ENGINEER
POWER CONDITIONING
NIF-0903-07262 L1
8EIM/cld
P6323

The first four NIF beamlines have been commissioned to the center of the target chamber

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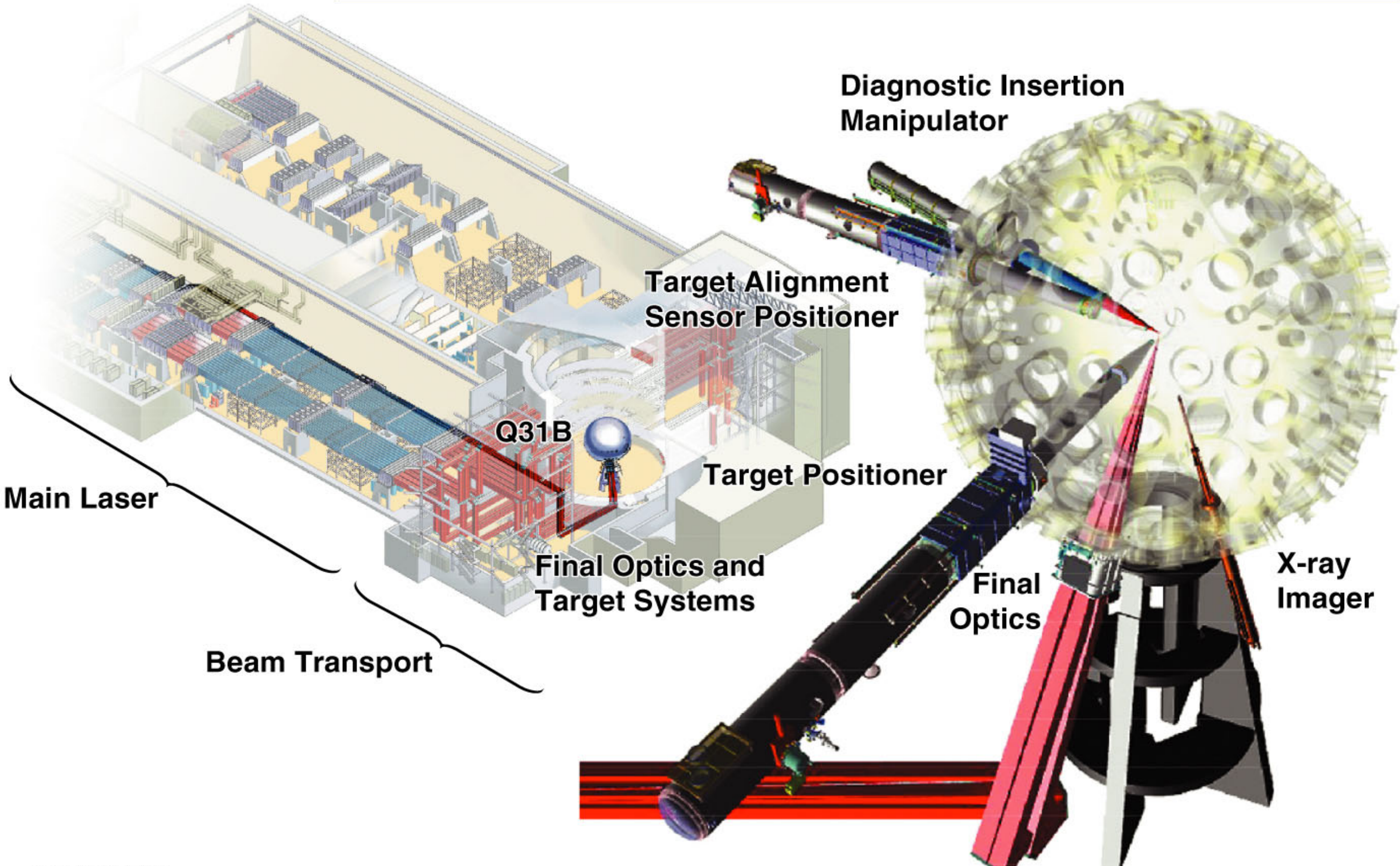
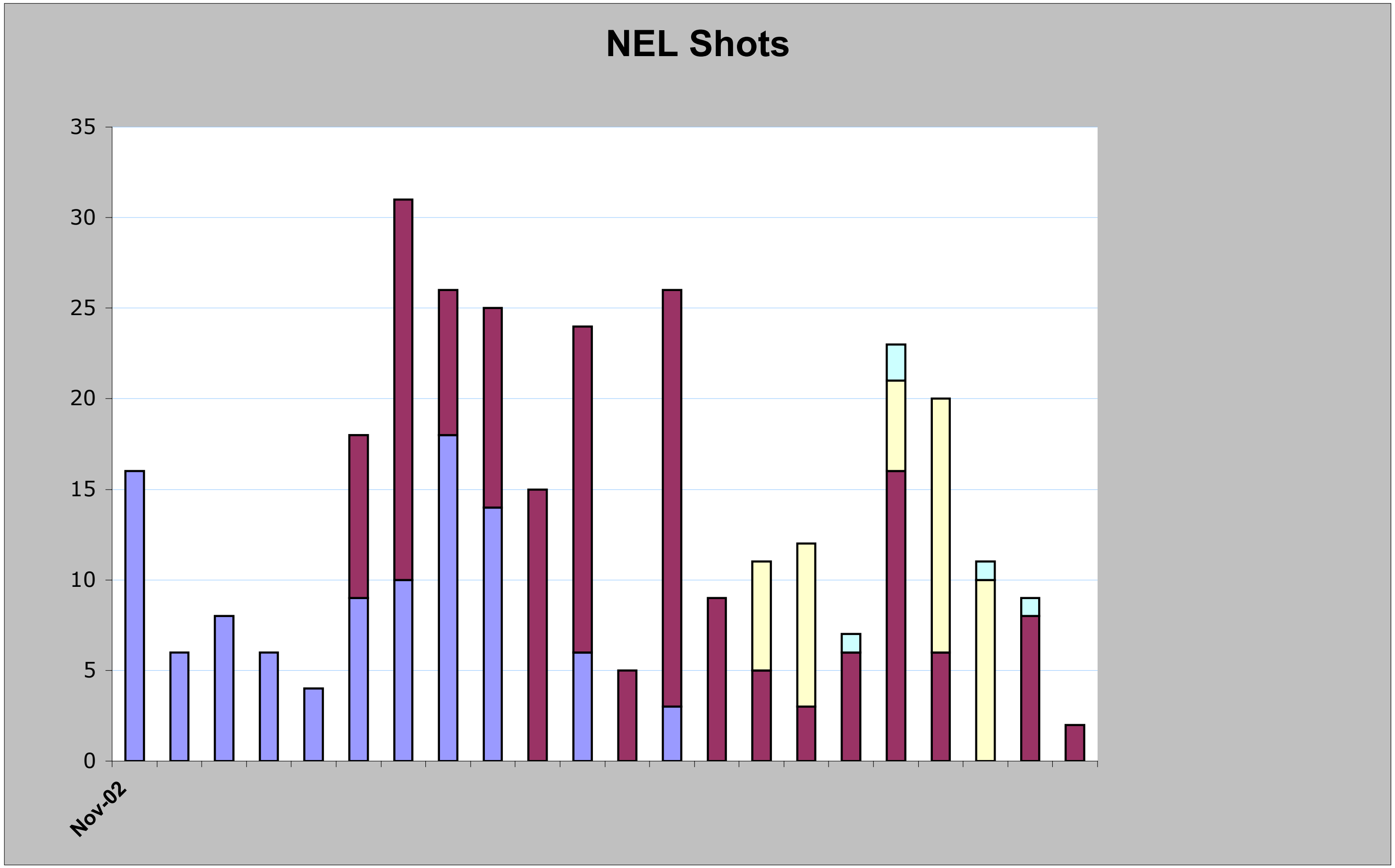
End-to-end functionality of all major subsystems demonstrated



NEL has fired over 300 full systems shots so far



Design goals for 1ω energy and power exceeded with high overall beam quality

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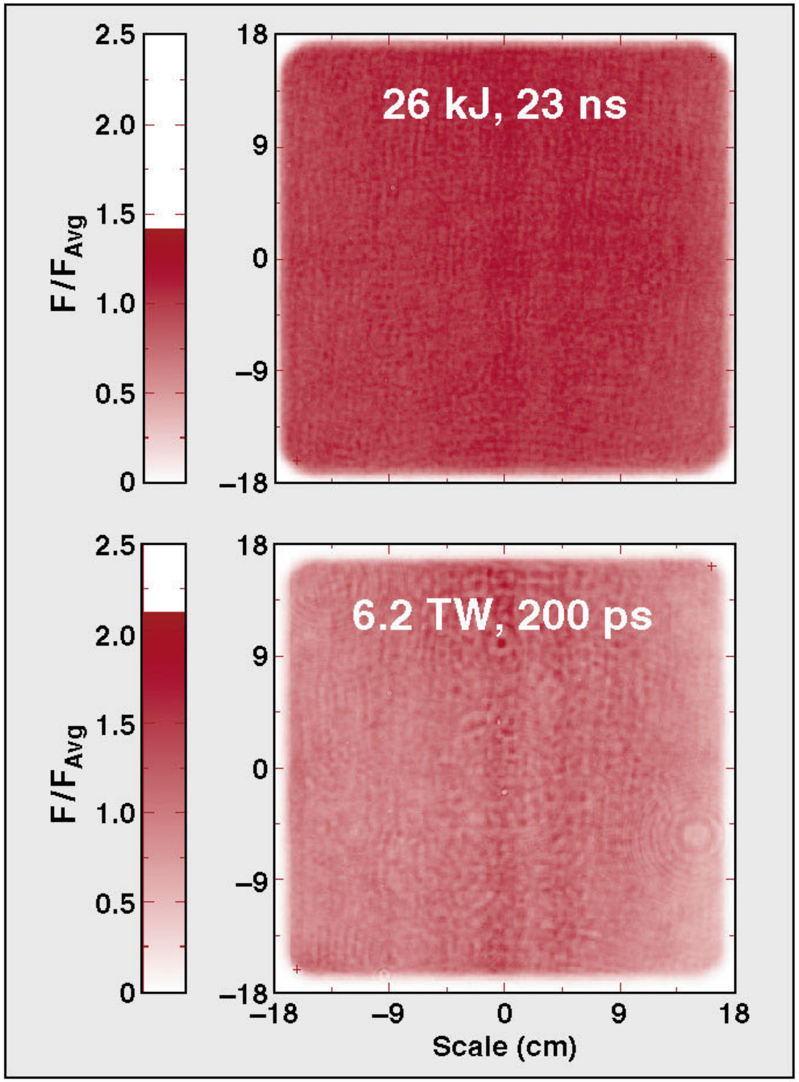
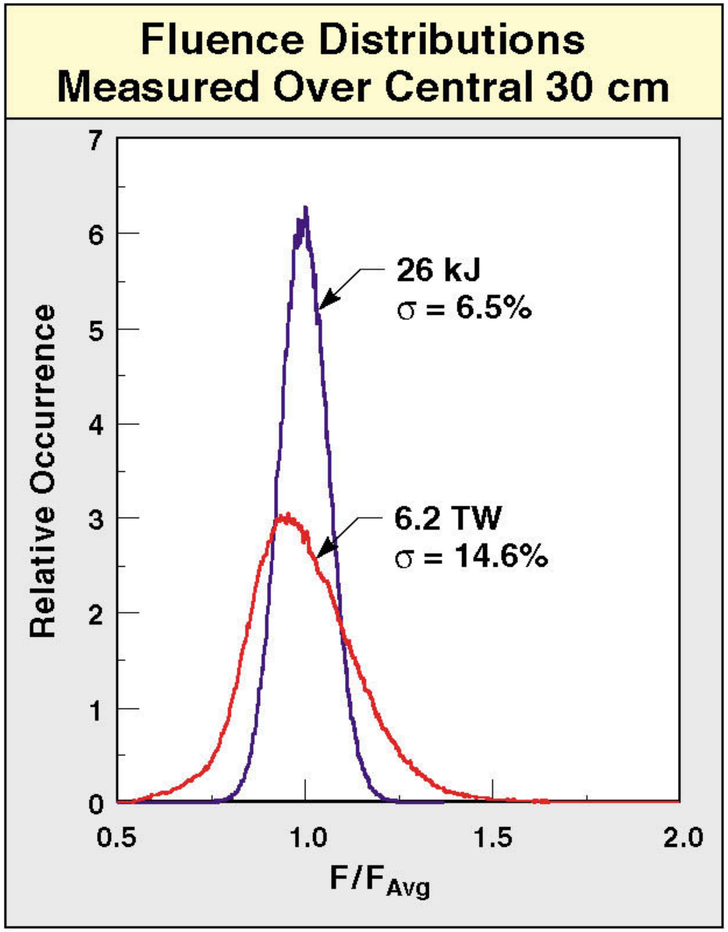
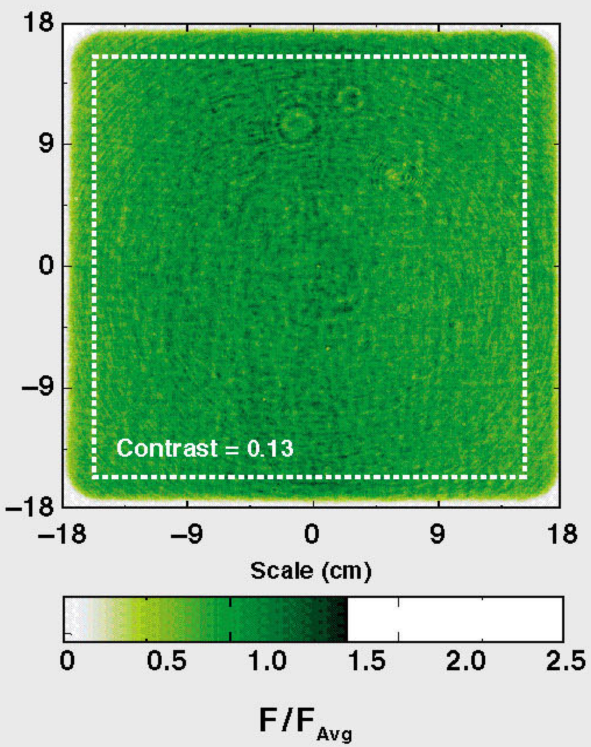


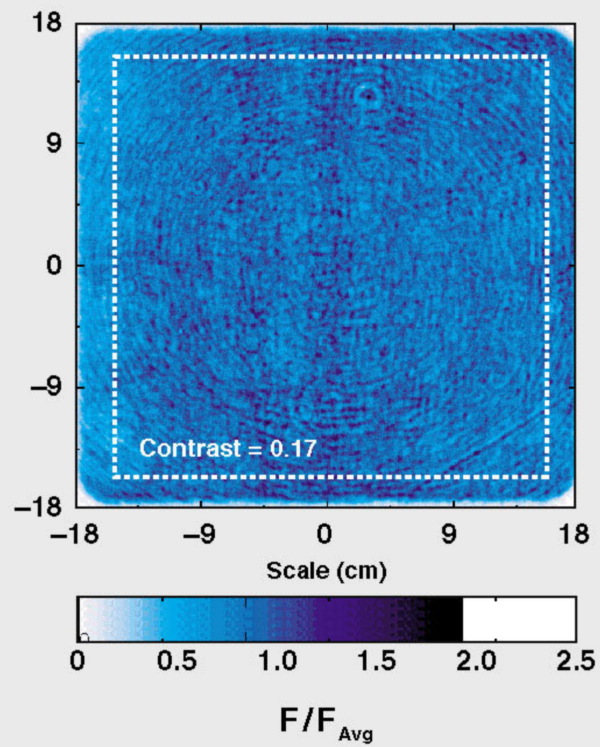


2ω and 3ω beamline energies are highest ever achieved: Near-field 2ω and 3ω intensity profiles are excellent

11.4 kJ 2ω, 5 ns



10.4 kJ 3ω, 3.5 ns



NIF 1ω laser exceeds power and energy requirements for entire operational parameter space

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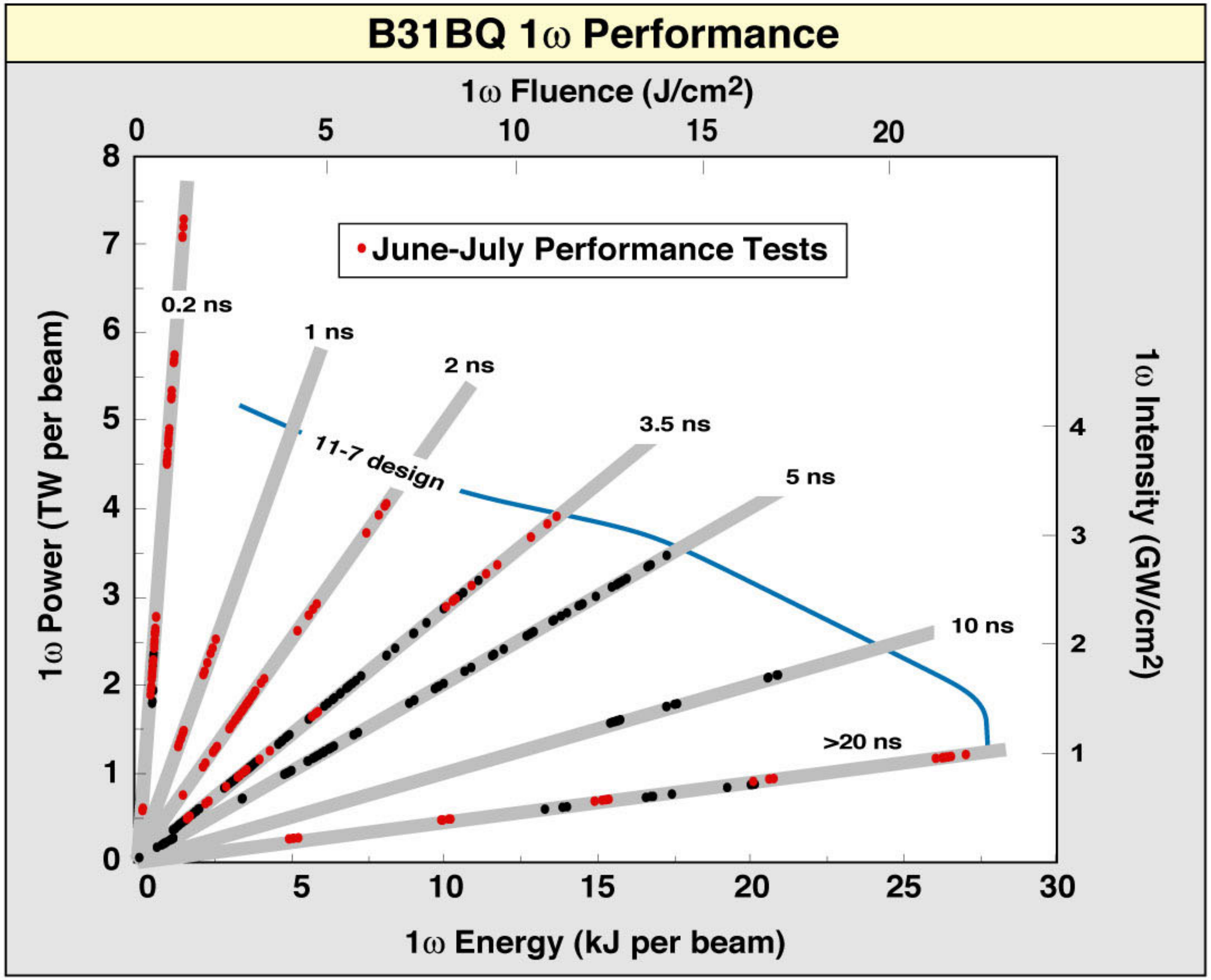

Summary

- Quad 31B beam path fully commissioned
- 500 kJ 3ω Full NIF Equivalent demonstrated on target
- 2.0 MJ 3ω Full NIF Equivalent demonstrated on PDS
- 2.2 MJ 2ω Full NIF Equivalent demonstrated on PDS
- 5 MJ 1ω Full NIF Equivalent demonstrated on Quad 31B latest-class final optics

- NIF has demonstrated all aspects of beamline and quad performance
- NIF has fired 240 full system shots

NIF Project completion criteria: Laser Performance

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Specification	96 Beam Performance	Single Bundle Performance	Status
Pulse Energy	500kJ (1000kJ)	75kJ (83kJ)	✓
Peak Power	200TW (400TW	21TW (32TW)	✓
Wavelength	.35 μm (.35 & .53 μm)	.35 μm (.35 & .53 μm)	✓
Positioning Accuracy	100μm rms at target plane (59 μm)	100 μm (59 μm)	✓
Pulse Duration	20ns (0.2 – 23ns)	20ns (0.2 – 23ns)	✓
Pulse Dynamic Range	>25:1 (22:1)	50:1 (22:1)	✓
Pulse Spot Size	600 μm (140 μm – 600 μm)	600 μm (140 – 600 μm)	✓
Pre-pulse power	$<10^8$ W/cm² ($<<10^8$ W/cm²)	$<4 \times 10^6$ W/cm² ($<<4 \times 10^6$)	✓
Cycle Time	8 hours max between full system shots (<4h)	8 hours max between full system shots (<4h)	✓

NIF Project milestone schedule

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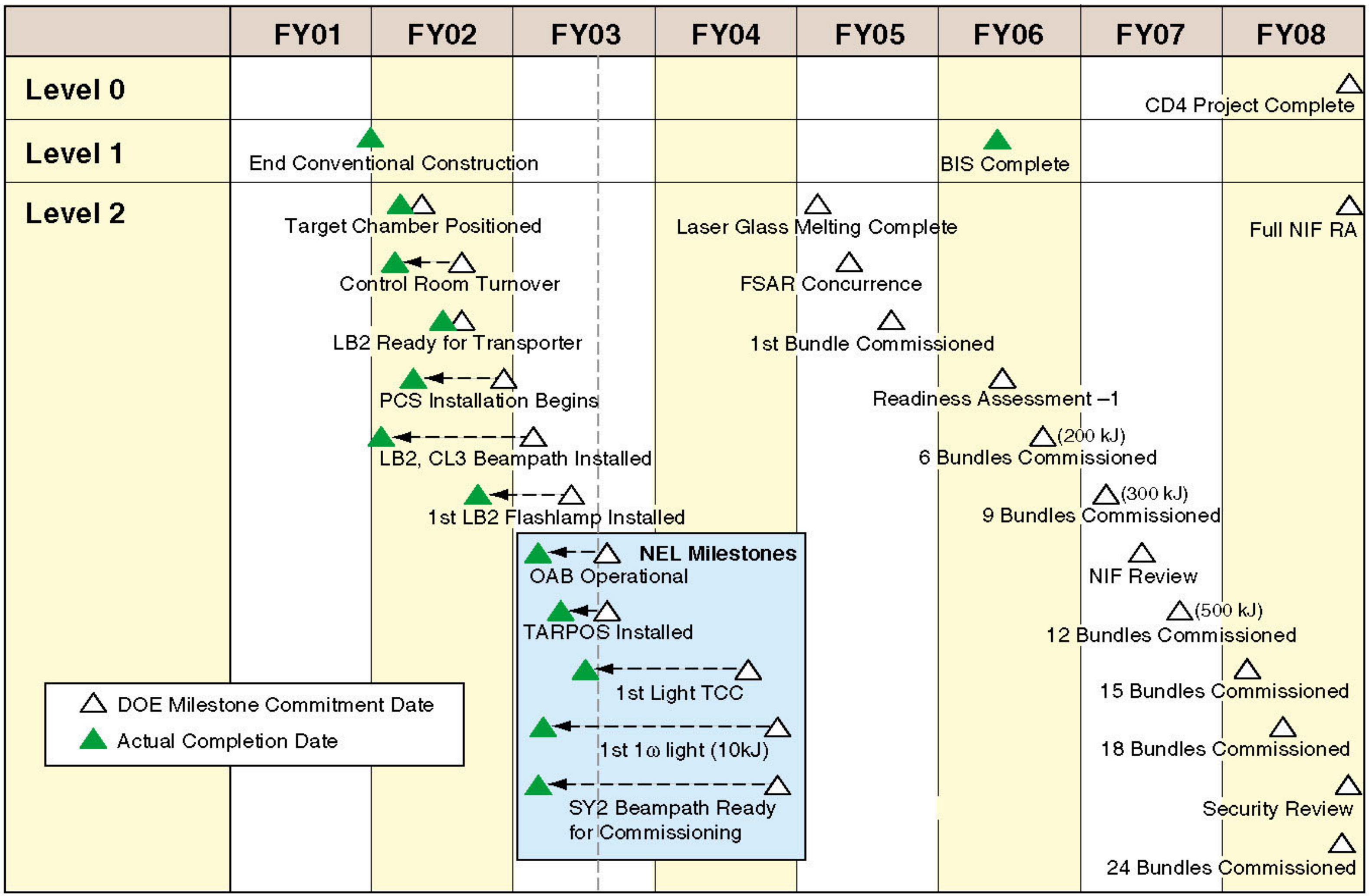

We are developing NIF into the premier facility for understanding matter at extreme conditions

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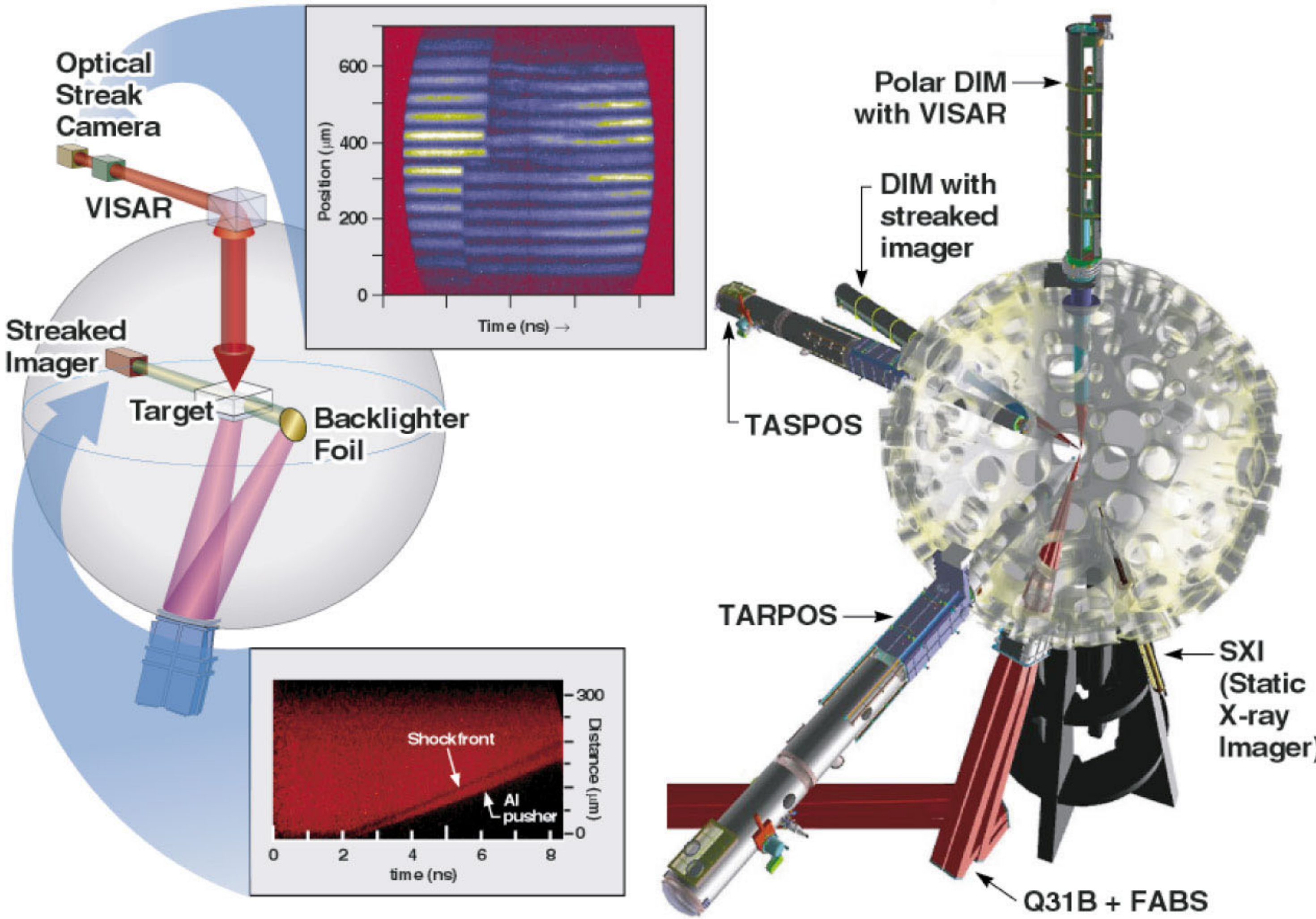
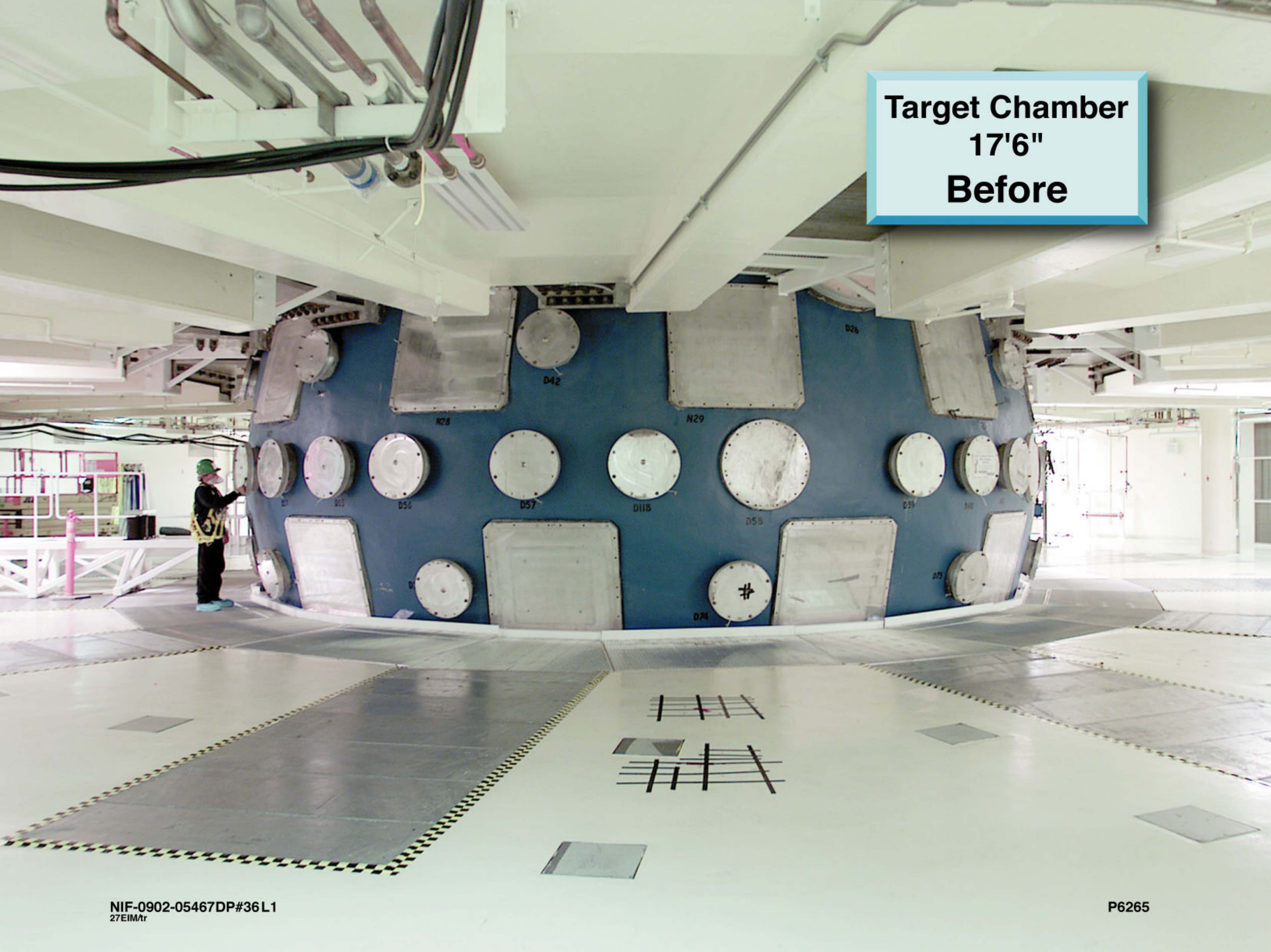
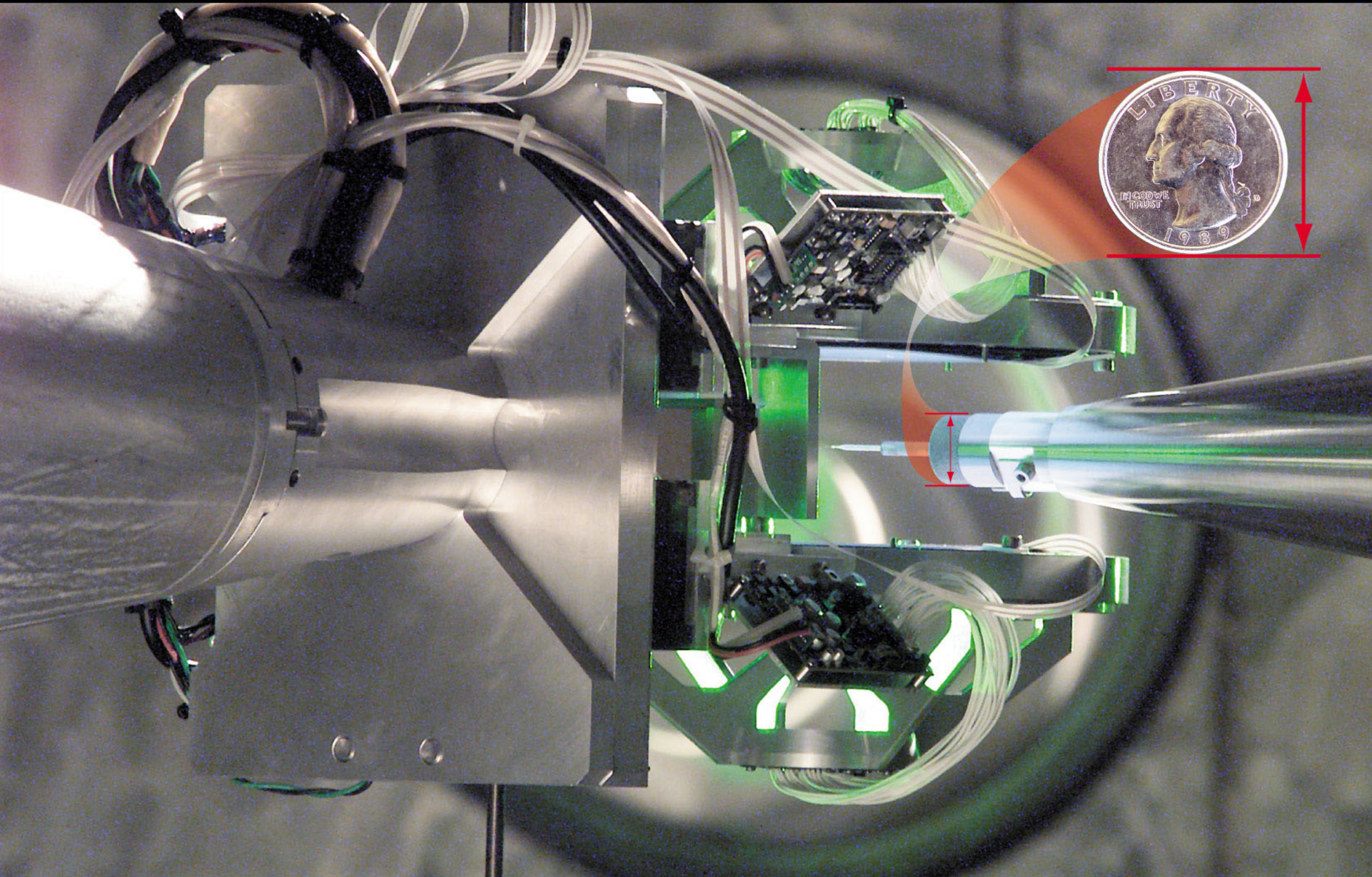



Target Chamber
17'6"
Before


Target Chamber
17'6"
After
NIF-0903-07263DP#86L1
01EIM/ld
P6266

Systems Engineer
Positioner
Target Alignment Sensor
NIF-0703-07087
P5924



NIF-0103-05749#1-r1
16GT/tr

P6072
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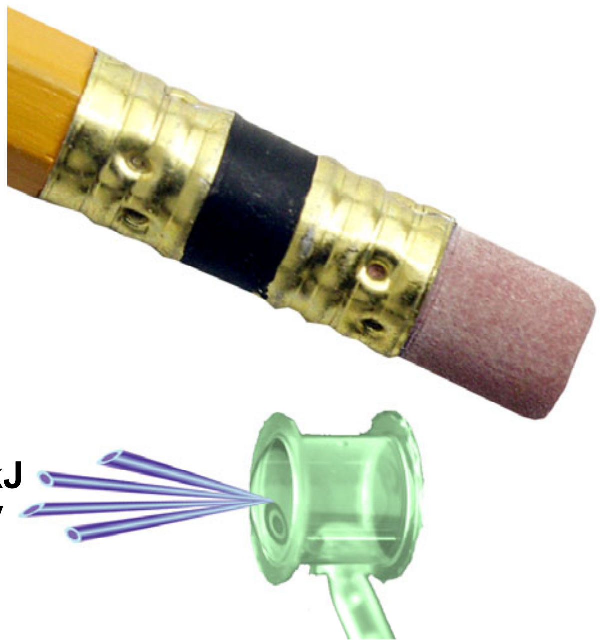
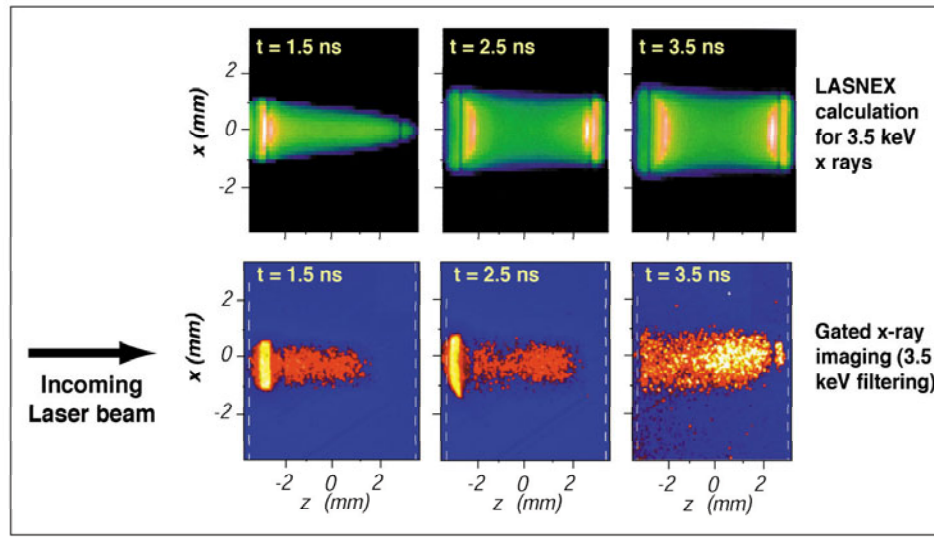
The first physics experiments on NIF measured laser-plasma interactions

16 kJ
UV





- **Understanding LPI is important for indirect drive ignition and laser performance**
- **These measurements could not be performed on any other laser system**

The experiment configuration uses a thin-walled shock tube containing an aluminum disk with an embedded defect

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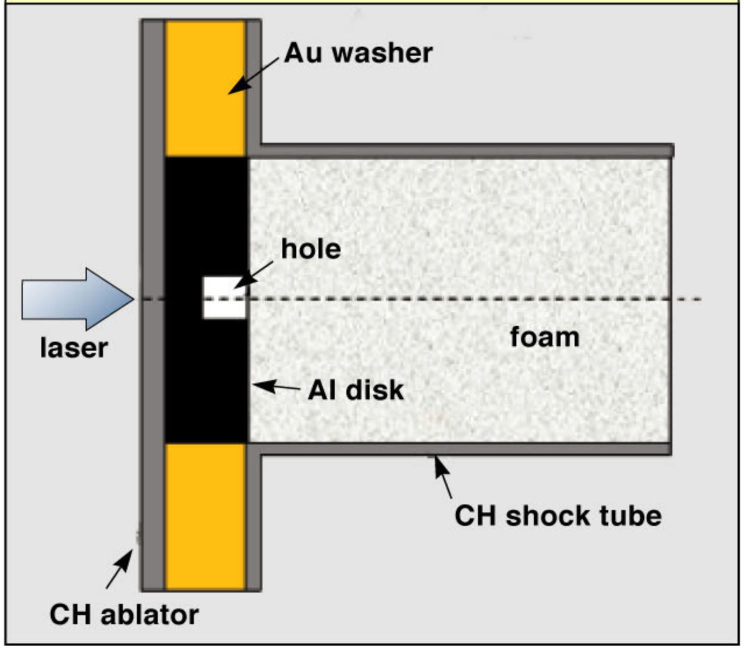
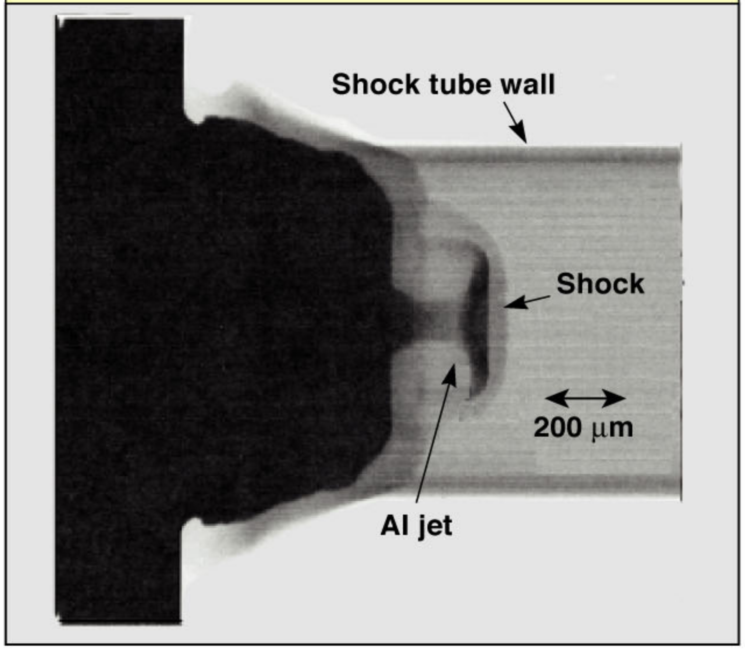
Shock-Tube Target Package



Simulated X-ray Radiograph



The same target package is used to study both 2D and 3D perturbations, and is used to accommodate experiment designs by both LLNL and LANL

Numerical simulation of these 2D jets has revealed information about the EOS behavior of the target materials

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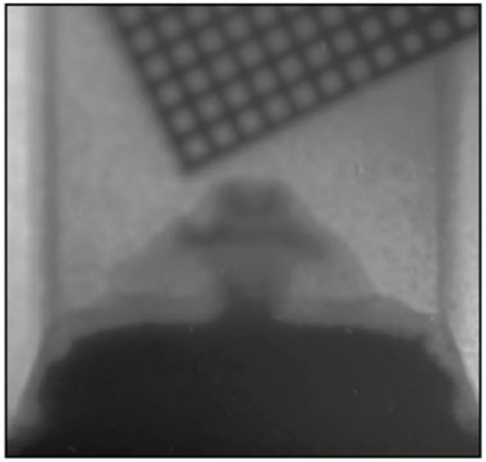
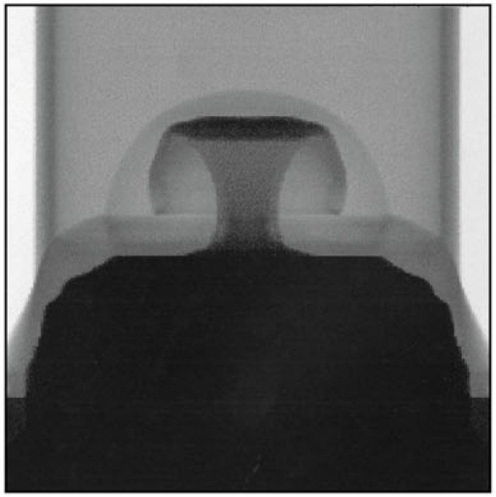
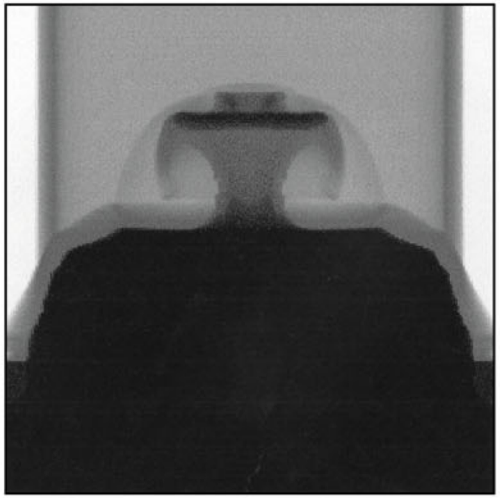
NIF data





Initial calculation



New foam EOS with increased compressibility gives better agreement with observed jet structure

The NAS recently recognized the exciting possibilities of High Energy Density experimental facilities

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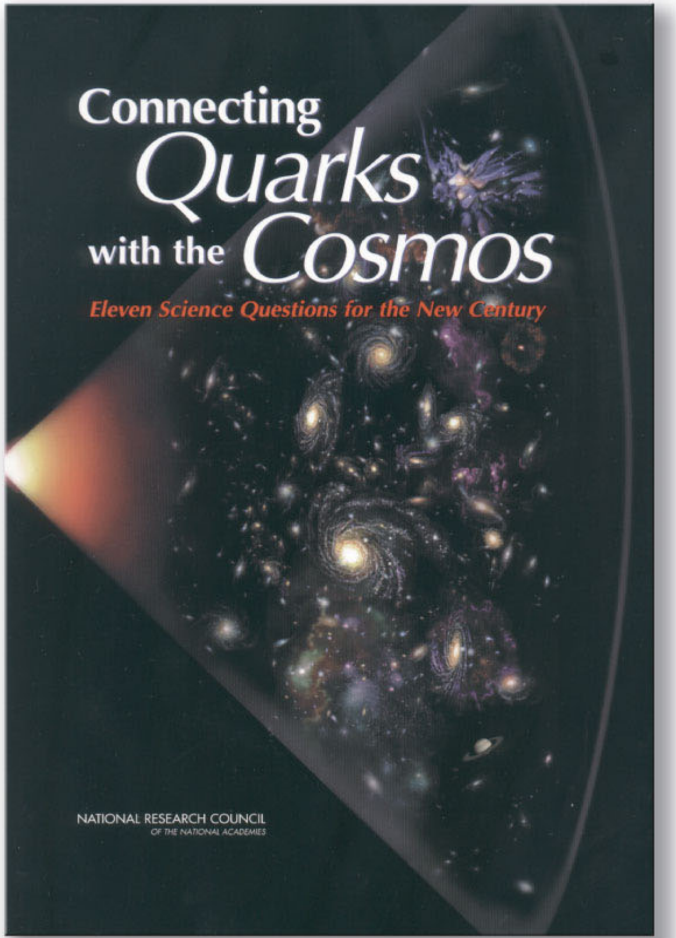

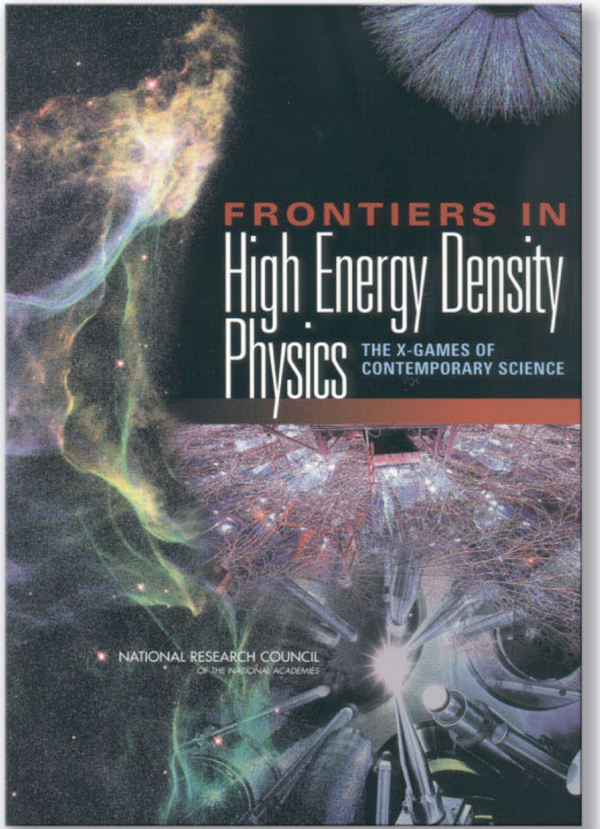

Why HED Physics?

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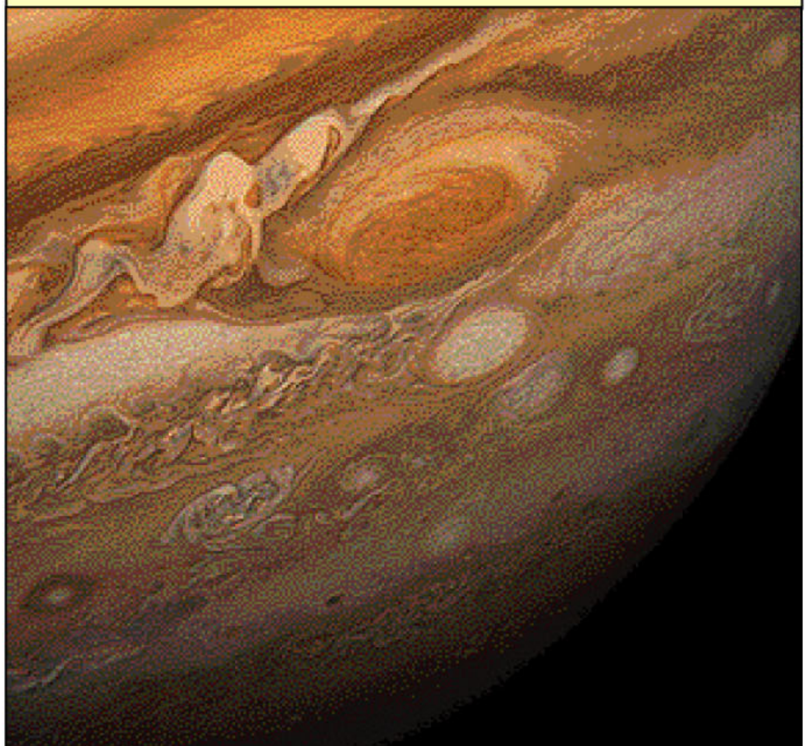
Non-ignition physics	Ignition physics
	
Equation of state, material dynamics, hydrodynamics, radiation transport	Thermonuclear burn, nuclear physics

High Energy Density in astrophysics

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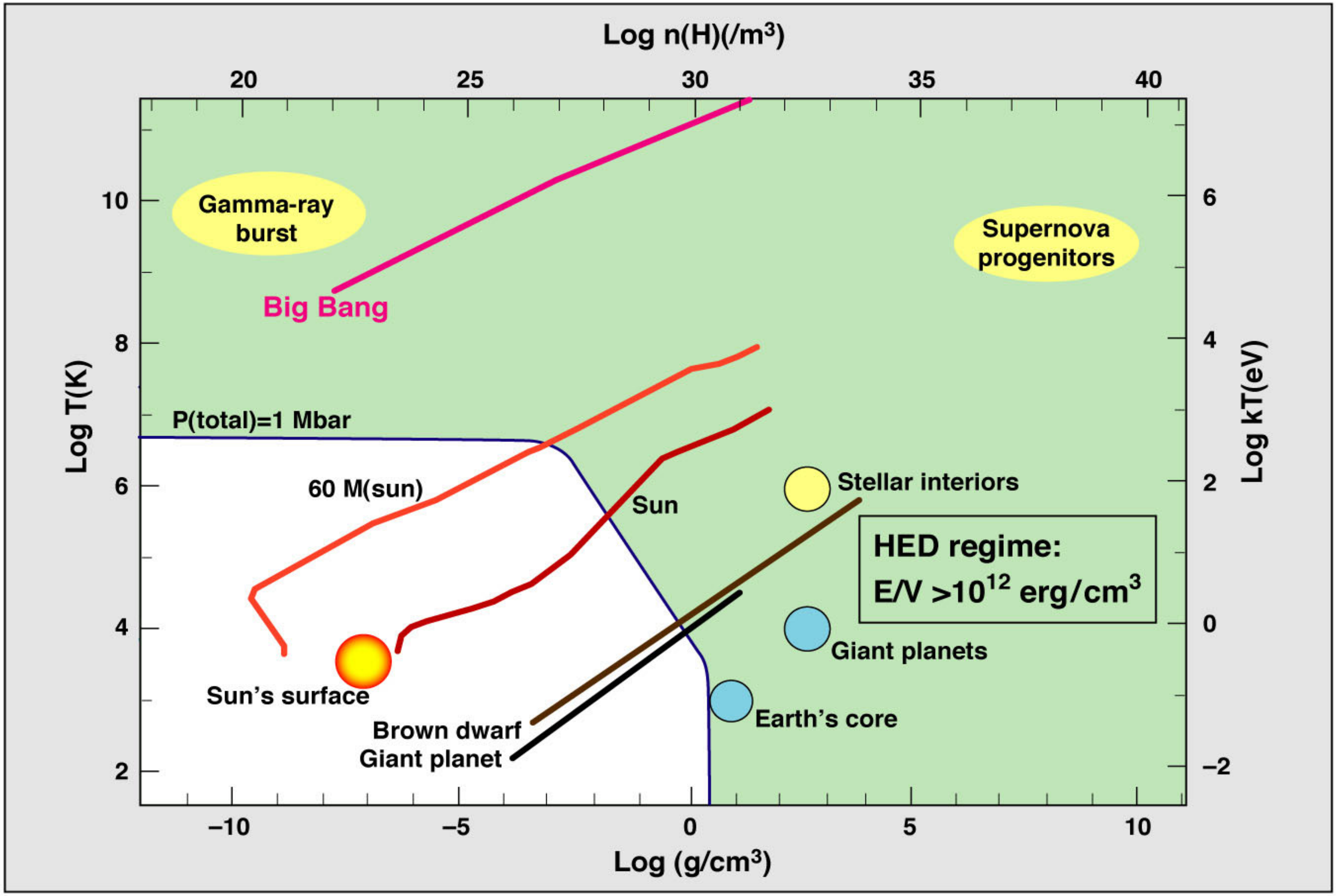

High Energy Density in astrophysics

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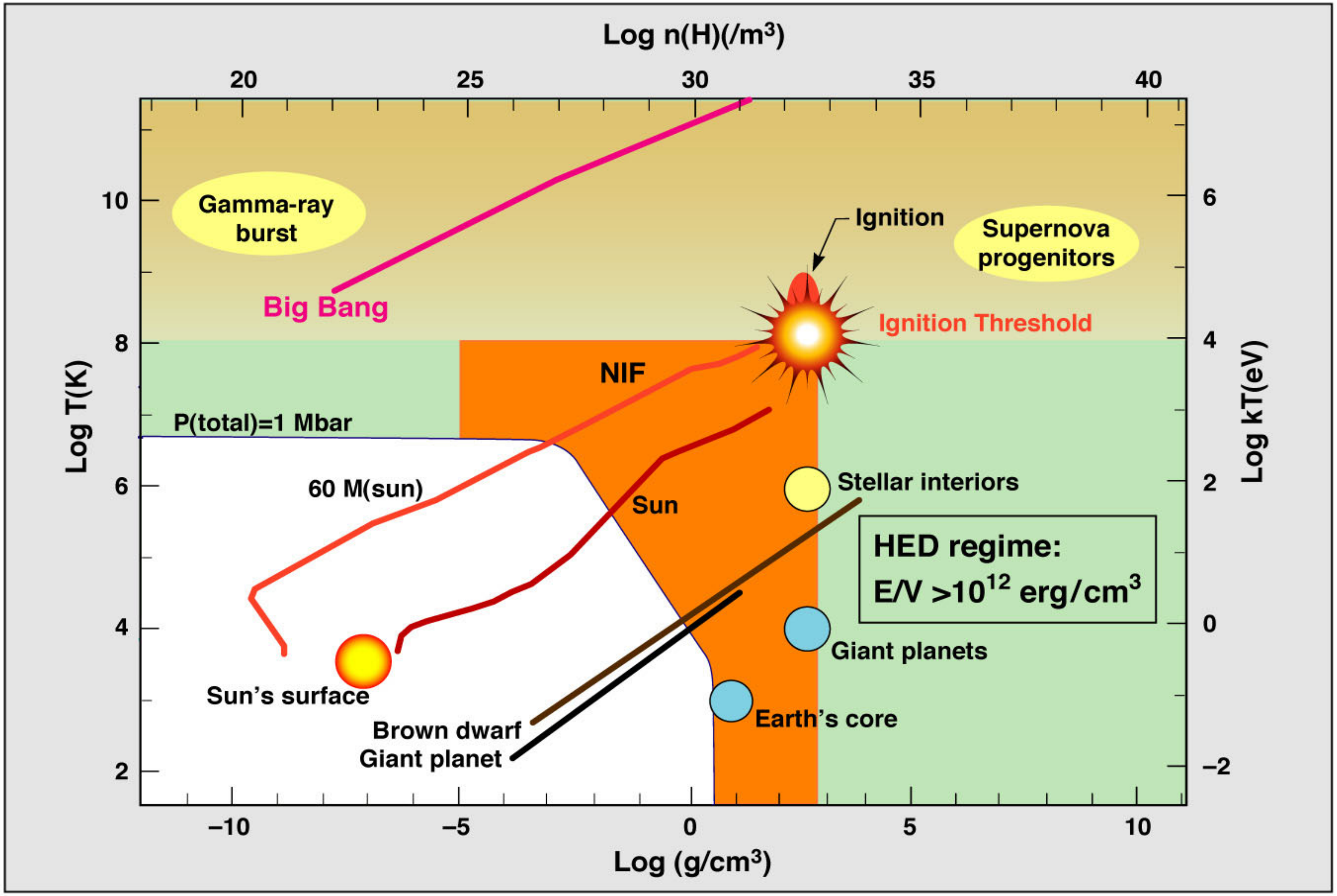

High Energy Density in astrophysics

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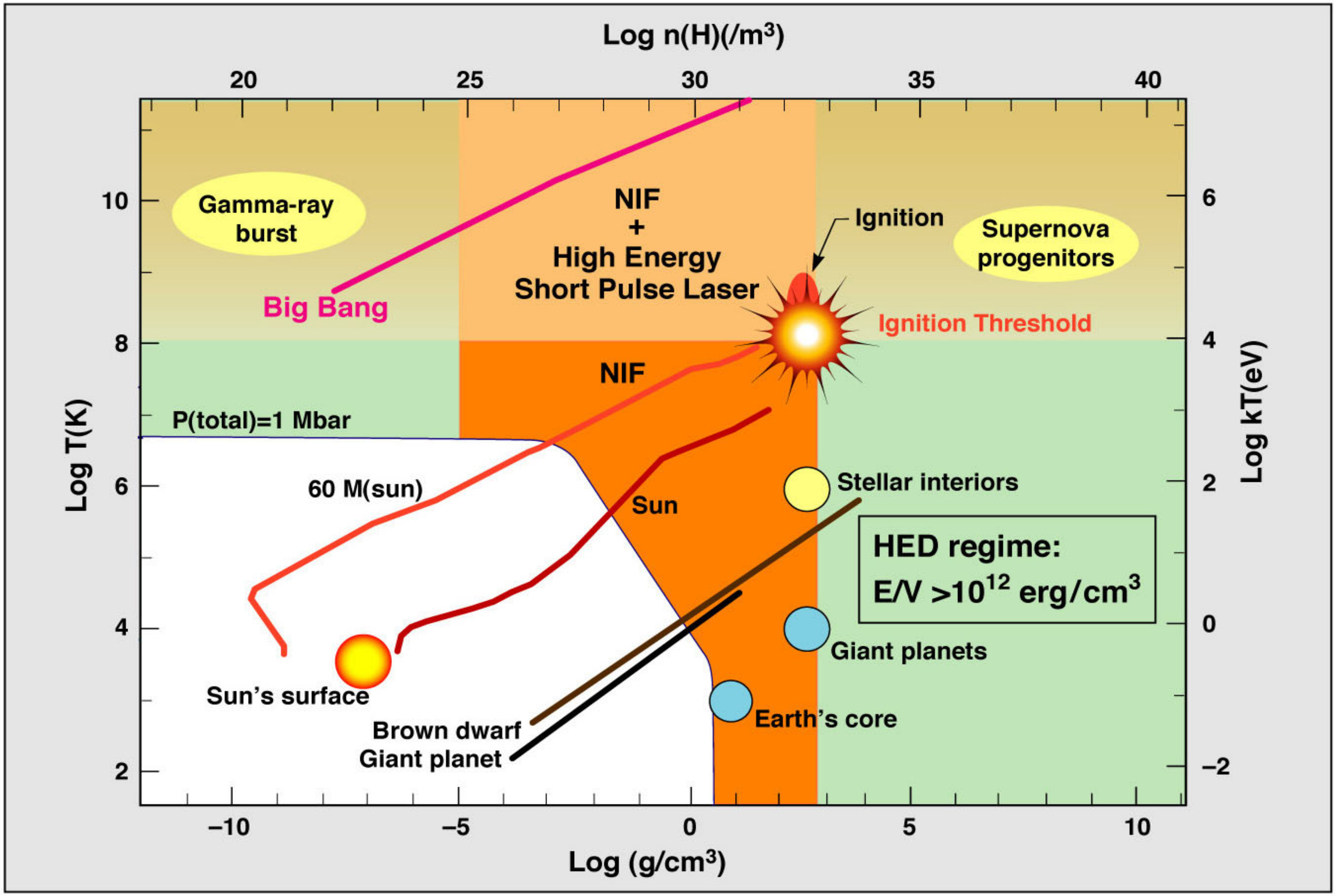

Single shock (Hugoniot) measurements is one of the first uses of NIF

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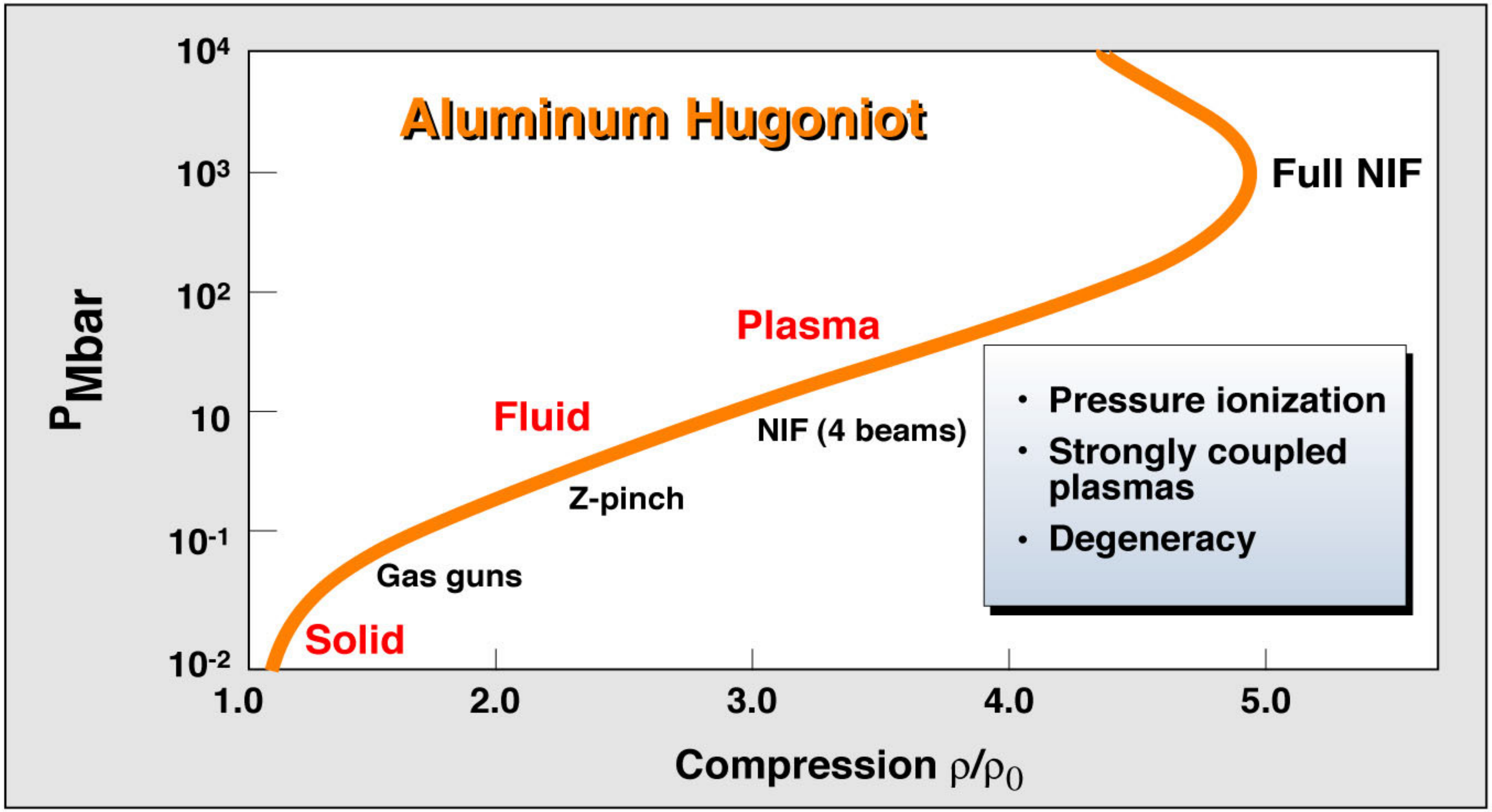

- Theoretical models for hot compressed matter differ widely
- All states of matter (solid, fluid, plasma) can be accessed in NIF experiments

Why HED Physics?

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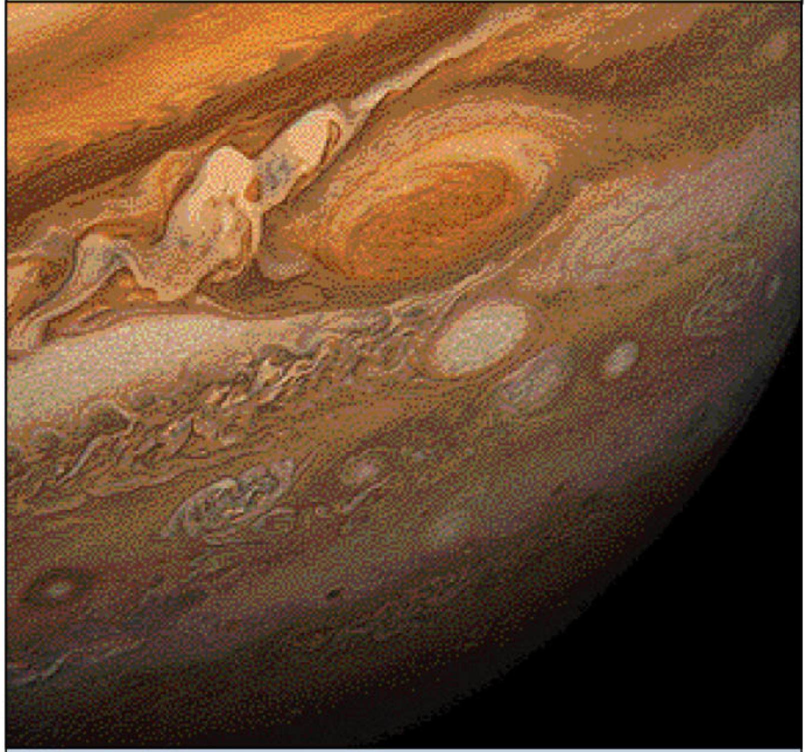
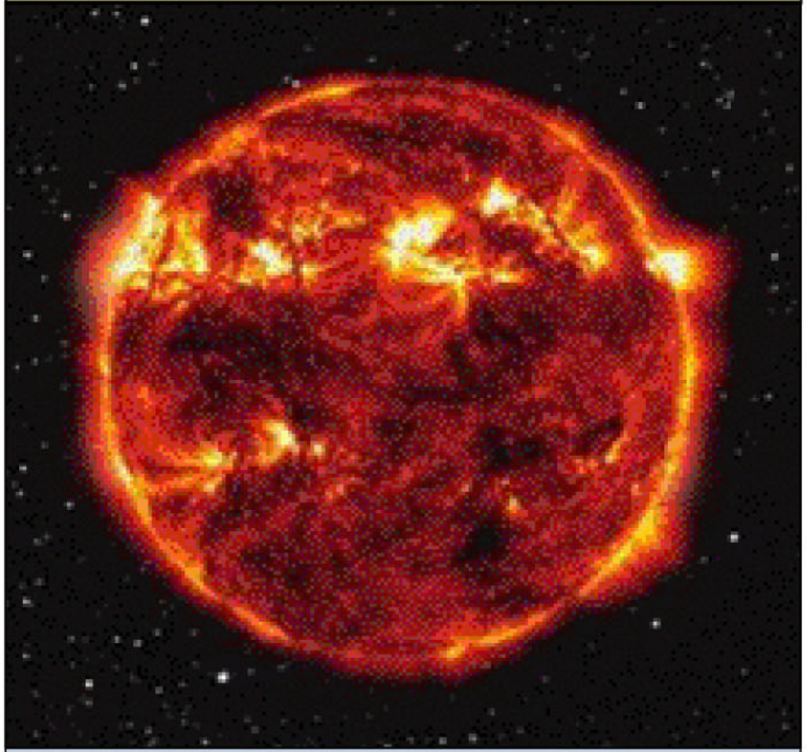
Non-ignition physics	Ignition physics
	
Equation of state, material dynamics, hydrodynamics, radiation transport	Thermonuclear burn, nuclear physics

NIF Indirect Drive target schematic

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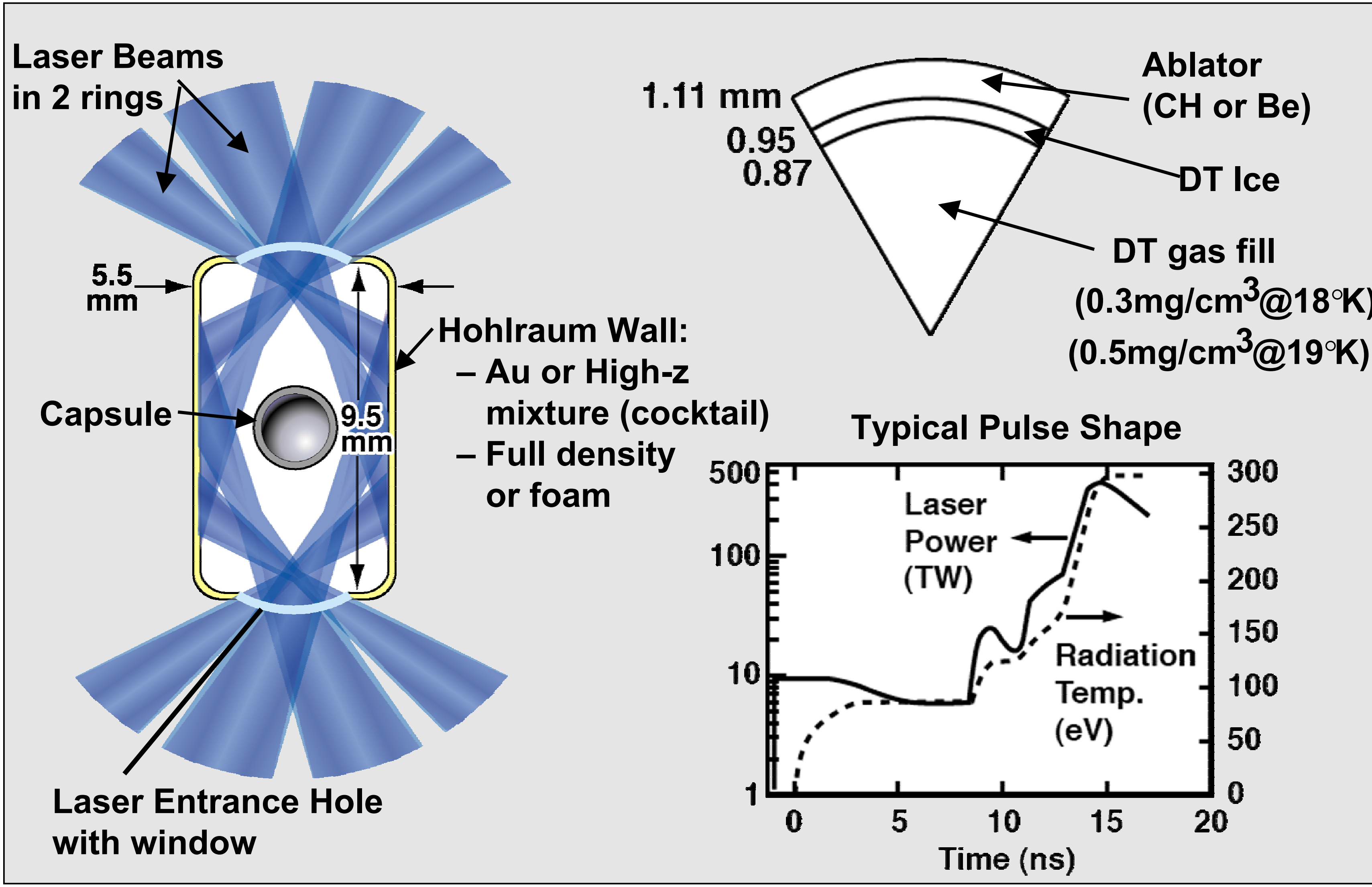

Ignition requires optimization of the energetics, symmetry, implosion dynamics, target design and fabrication

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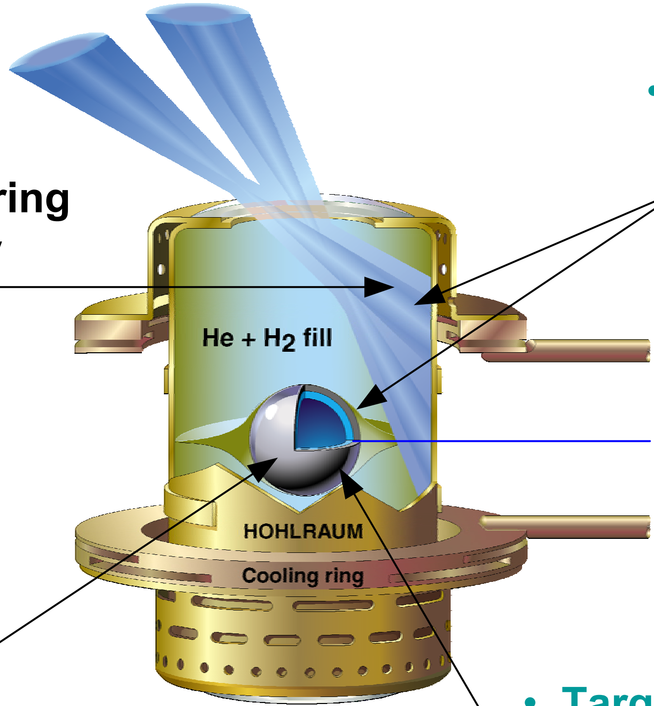
- Hohlraum Energetics
  - — Laser absorption
    - — Stimulated scattering
  - — Conversion efficiency to x-rays
  - — Albedo/X-ray wall loss

- Drive Symmetry
  - — Measurement
  - — Control (uniformity to 1% or 1 degree pointing)



- Implosion Dynamics
  - — Accurate measurement techniques for shock timing
  - — Material studies (EOS, ablation rate, etc. (Shock timing to 100 ps)

- Target Design and Fabrication
  - — Ablator choice (Be, CH)
  - — Capsules (smooth to 10's - 100's of nanometers)
  - — Cryogenic fuel layer (smooth to ~ 1 - 5 μm)

Research over the last 7 years has substantially increased confidence in ignition

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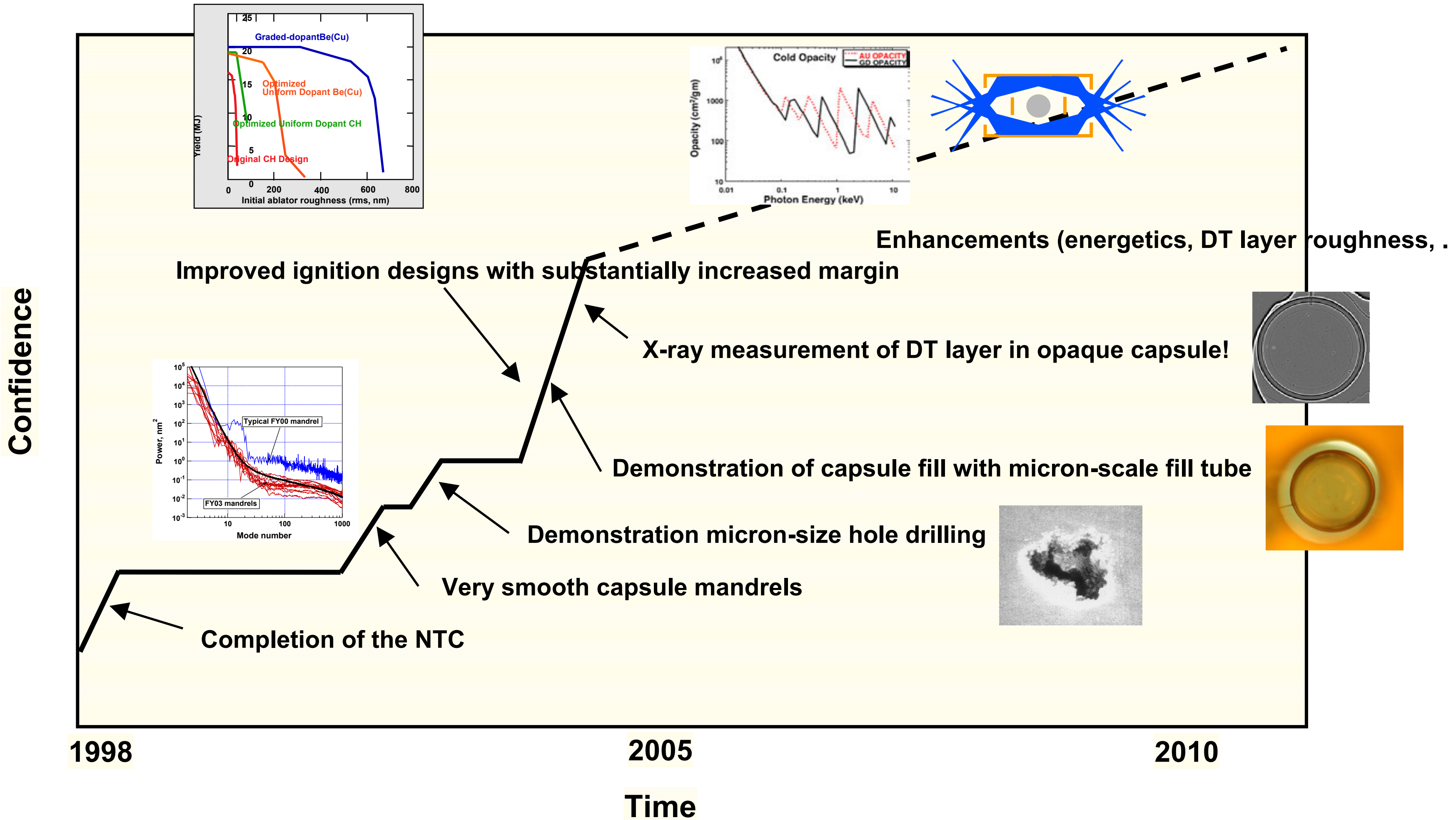

Detailed design calculations are being performed on LLNL's ASC systems

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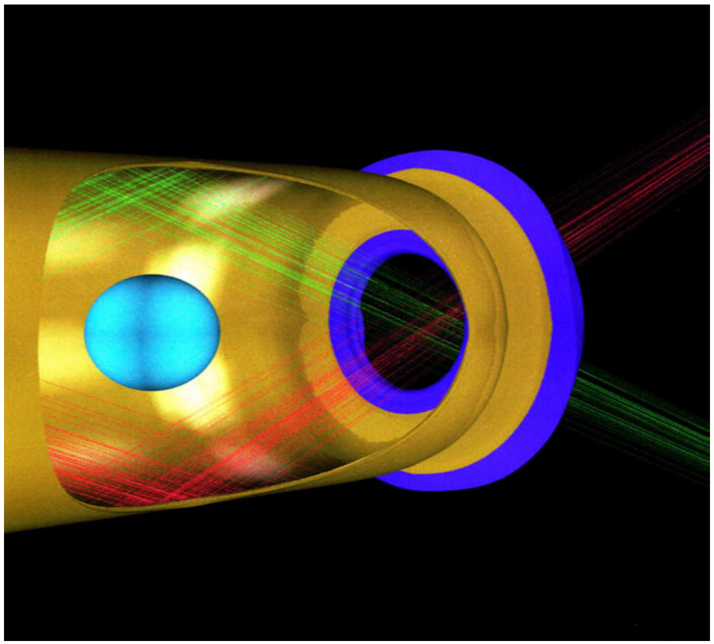
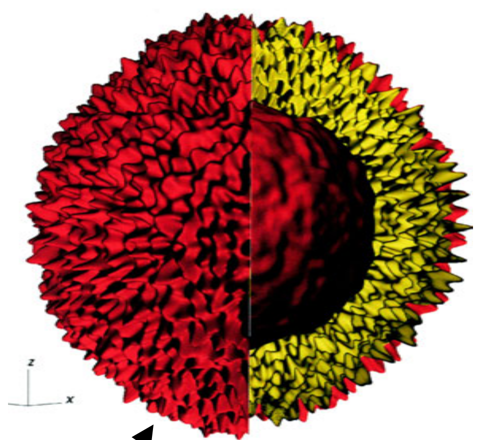
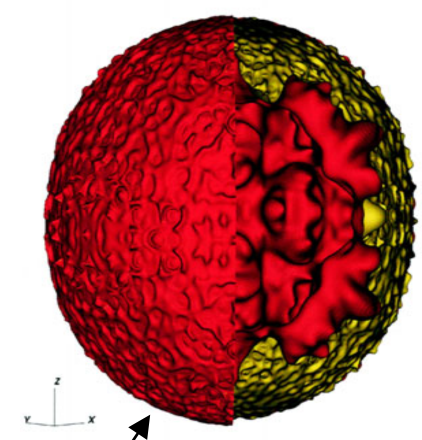


Gave 21 MJ (90% of 1D calculation)

140 ps before ignition time	Ignition time
 Plastic/DT interface; Hohlraum axis	 Stagnation shock
60 g/cc density isosurface	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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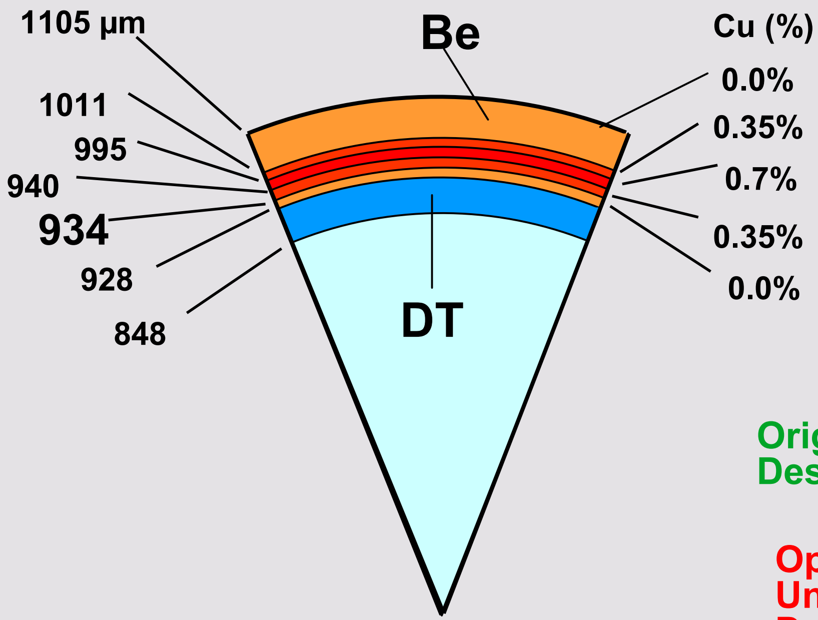
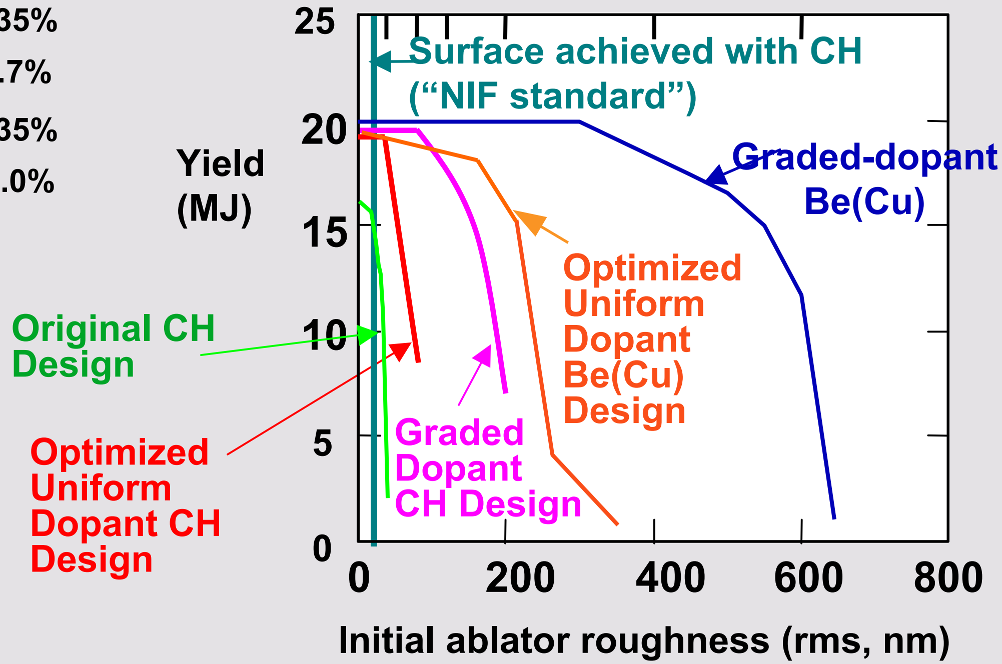
300 eV design:



The graded doped Be capsule can tolerate <u>60x the NIF standard</u>



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

Using NIF's green light (2ω) performance we may be able to couple ~1.5 MJ to a capsule at 250 eV drive temperatures

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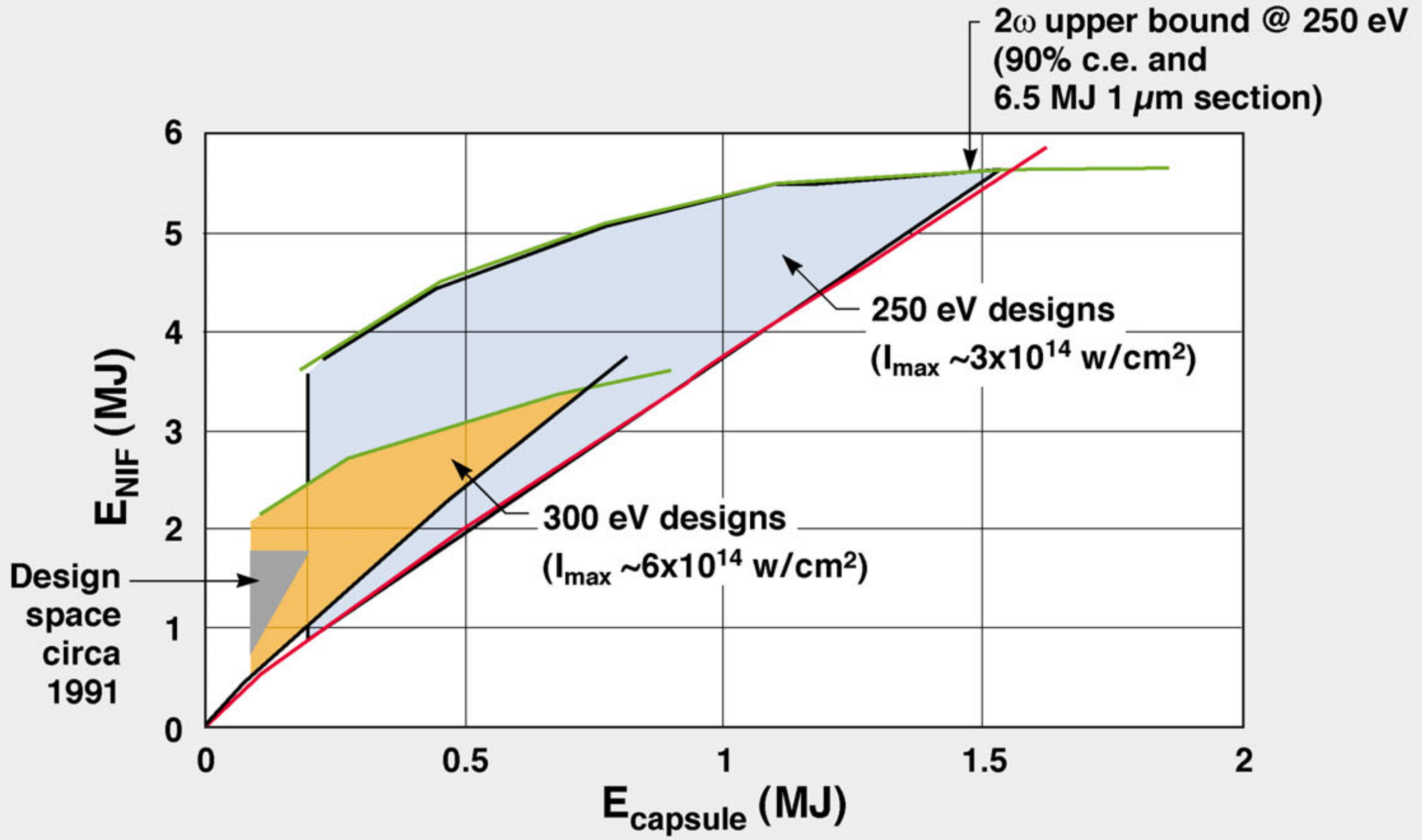
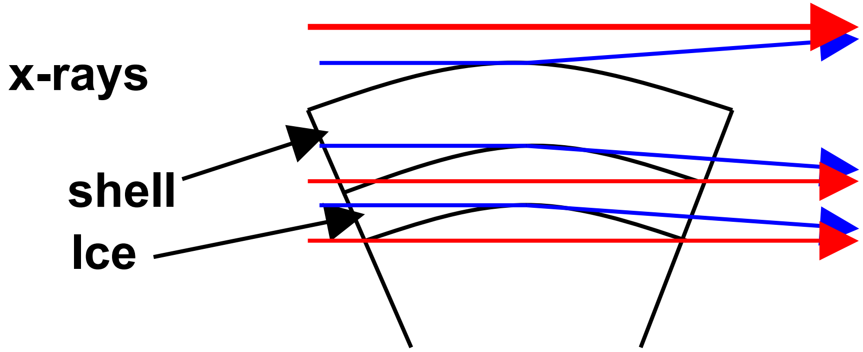
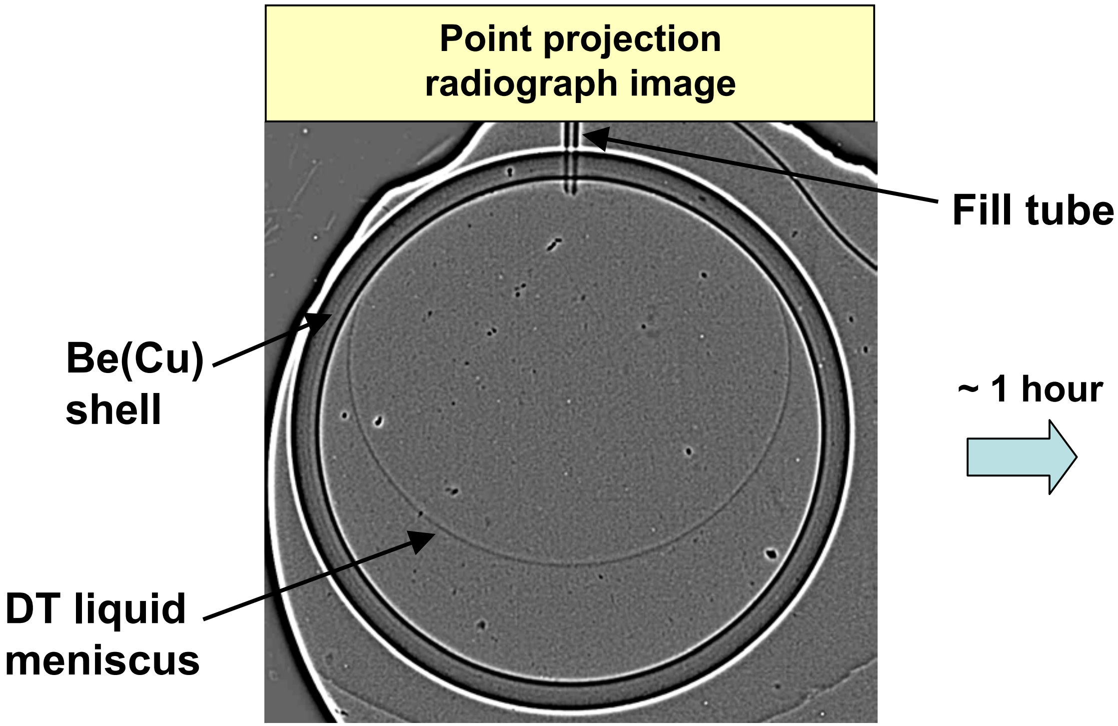


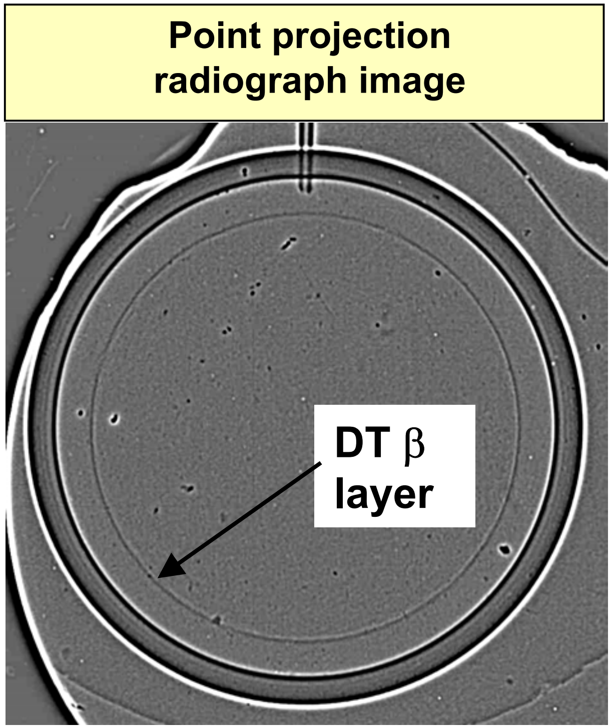
The DT fuel layer in optically opaque beryllium has been recently characterized with x-ray refraction



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



~ 1 hour



Our new approach fills the target through a micro fill-tube using a self-contained fuel reservoir

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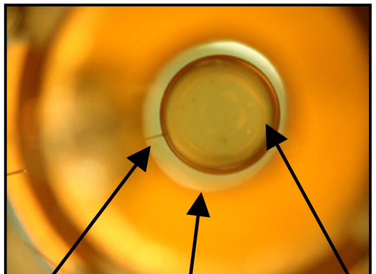
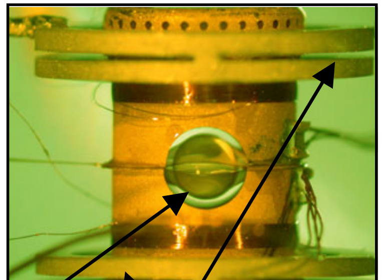
View of 2mm shell through laser entrance hole



View of 2mm shell through side hole



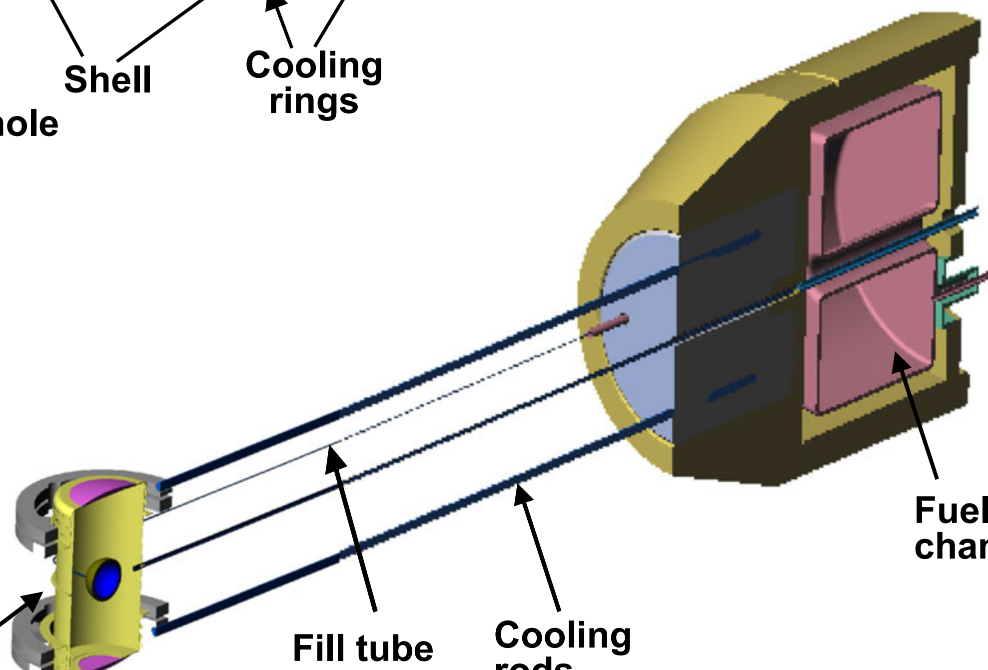
Fill tube
8 µm ID

Laser entrance hole

Shell

Cooling rings

- **Fuel pressure 2-3 atm**
  - **~ 4 - 5 Ci DT**
- **Capsule filled *in target positioner* by temperature control on fuel reservoir and hohlraum**



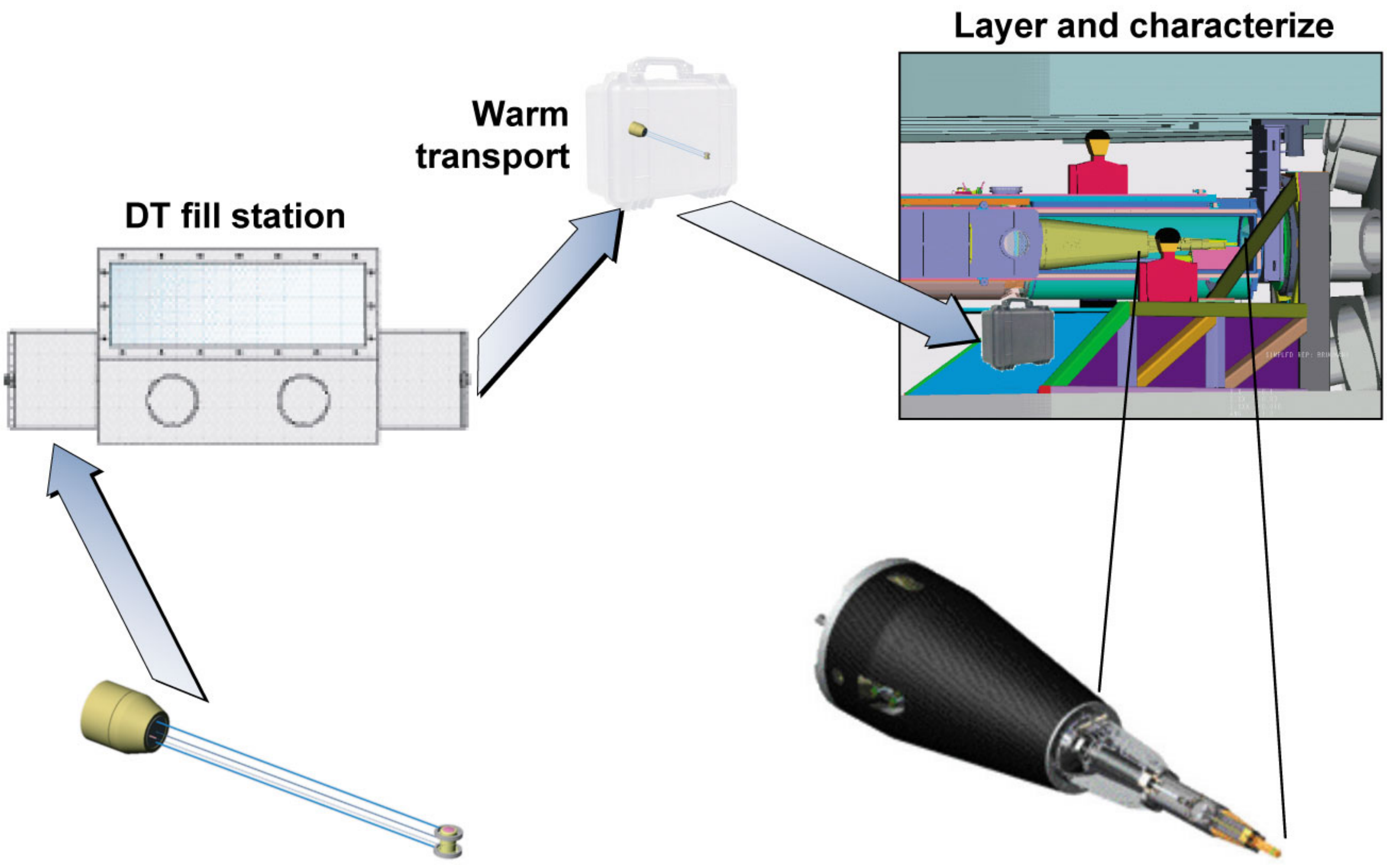
Fuel chamber

Hohlraum

Fill tube

Cooling rods

Decoupling the tritium fill system from the cryogenic positioner allows simple target handling



Our goal is the start of the cryo ignition campaign in FY10 and yearly HED data

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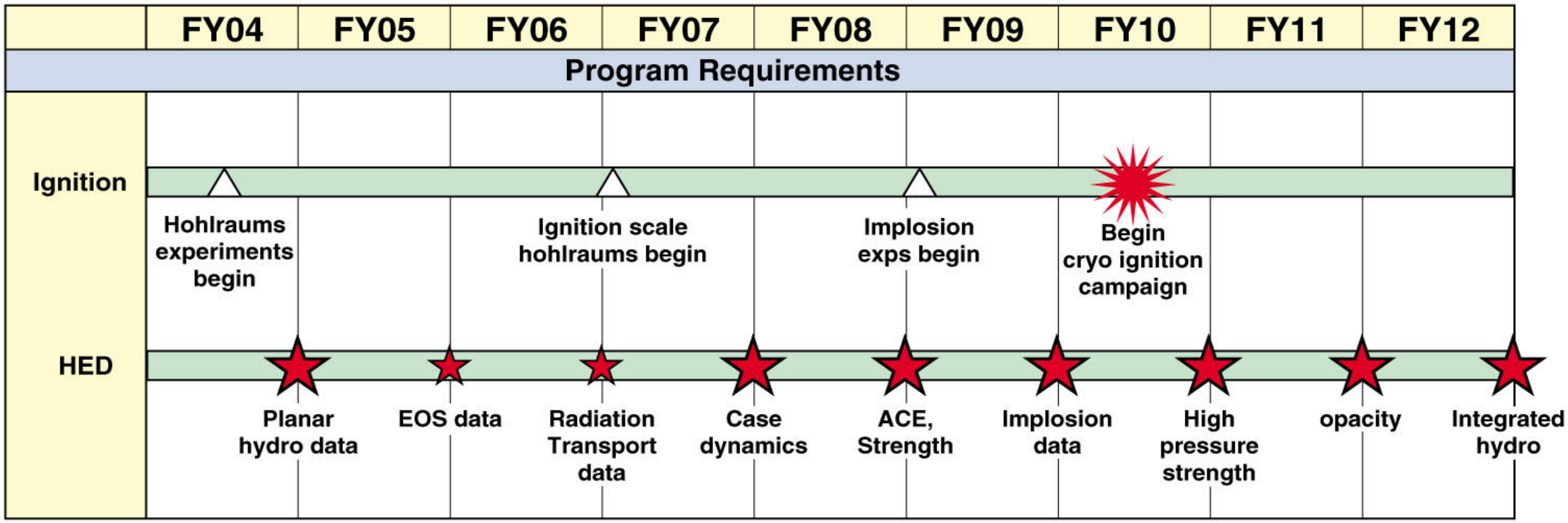

High energy, high irradiance lasers generate new physical phenomena

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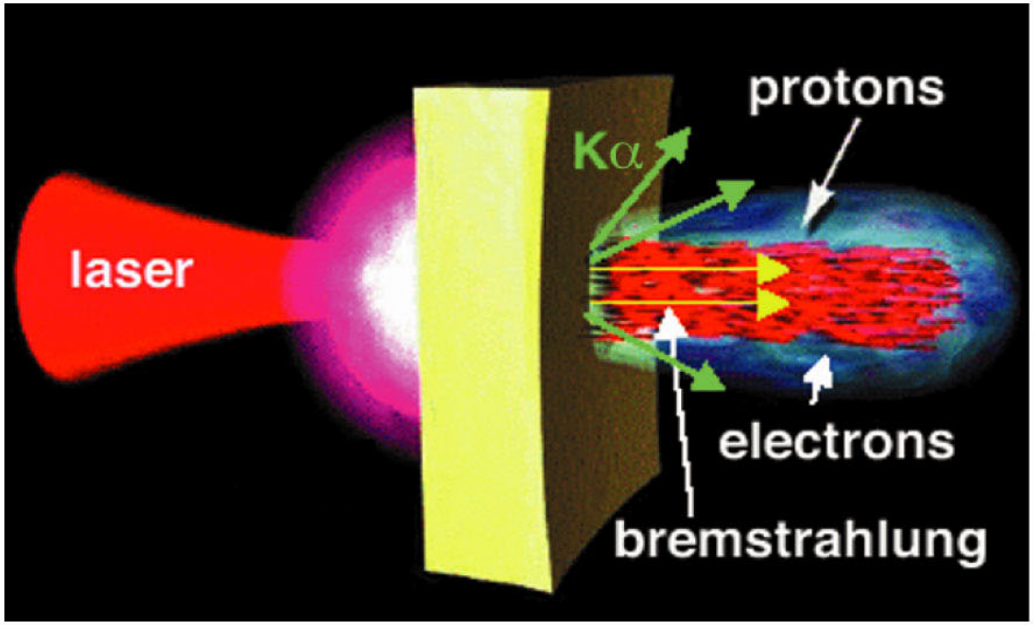

Novel intense source of hard X-rays, electrons and protons can be used for radiography and heating of matter

High laser irradiance on a target generates energetic electrons

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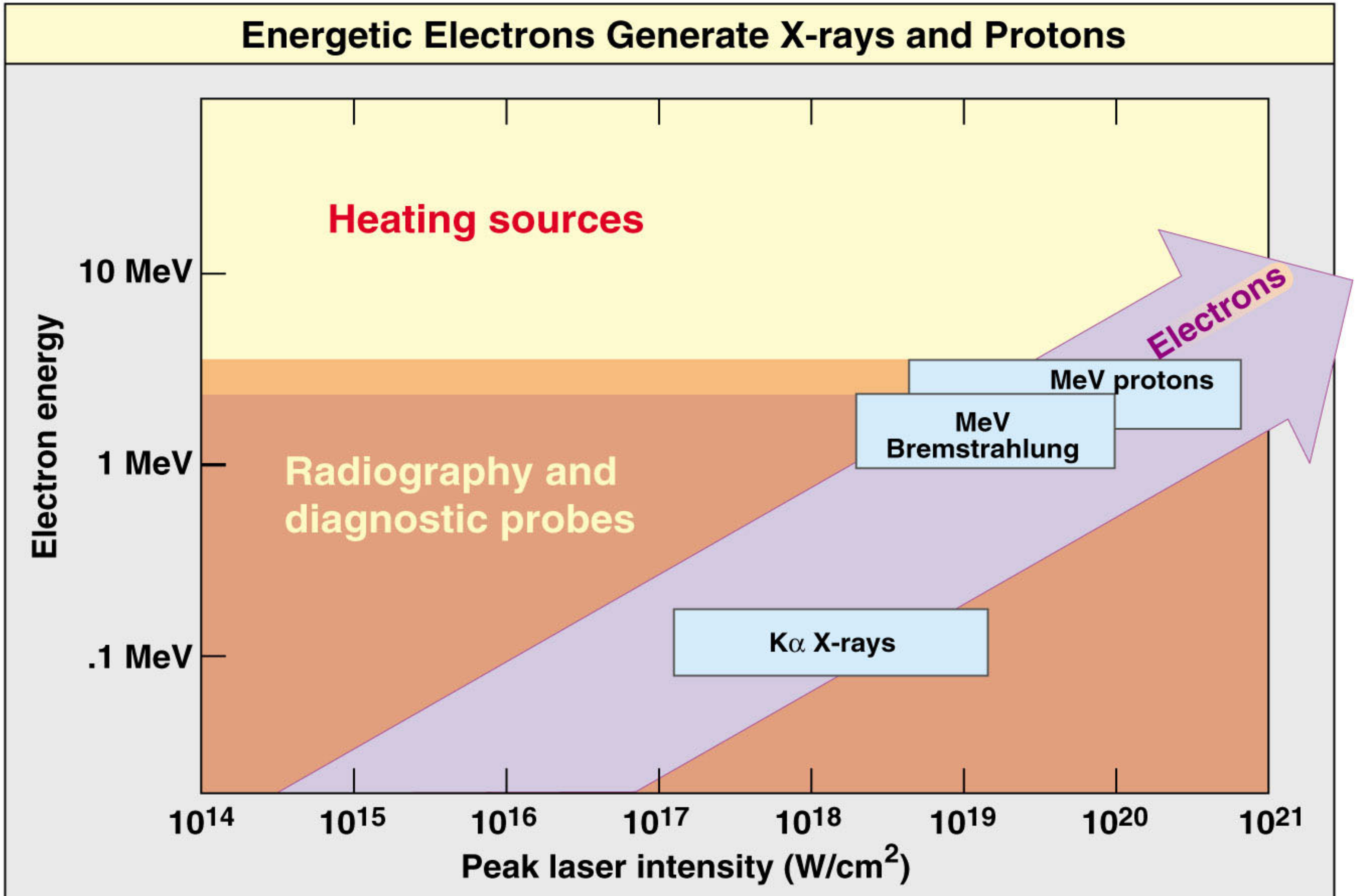

Hard X-ray sources enable compelling new capabilities

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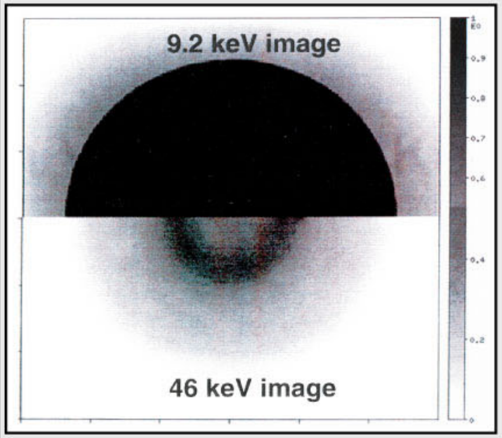
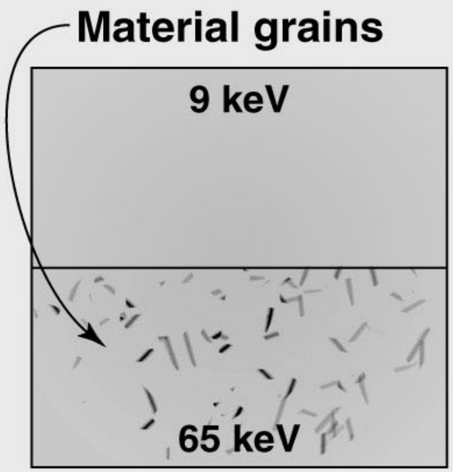
X-ray Radiography Allows Imaging of Dense, High Z Targets



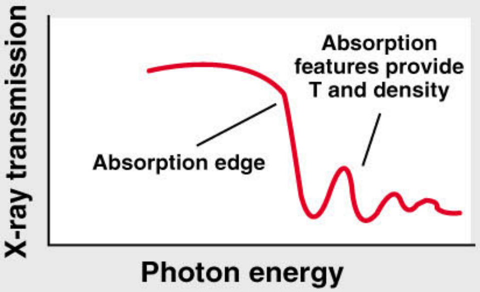
- Hydrodynamics
- Equation-of-state
- Material Dynamics

X-ray Diffraction Allows Study of Grain Effects



- Material Dynamics
- Phase change kinetics

X-ray Absorption Spectroscopy is Greatly Simplified



- Opacity
- Material dynamics

The ability to independently compress and heat expands the regimes for EOS and opacity

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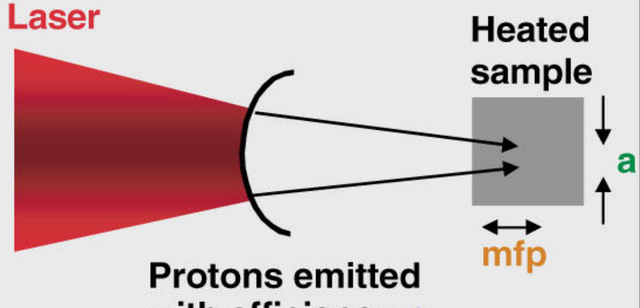
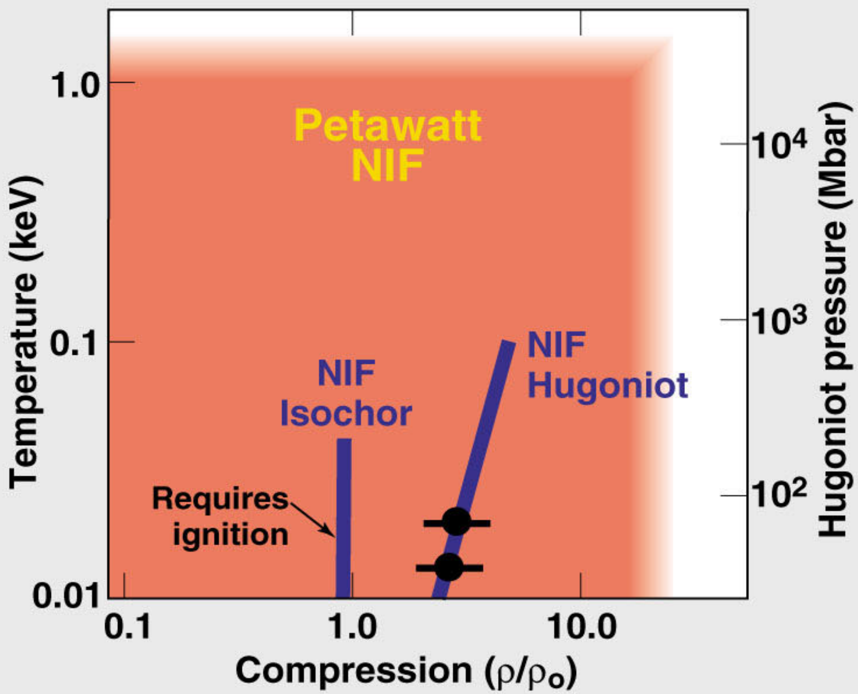
MeV Protons Deposit Energy Over a Short Scale Length



$$T_e \sim \frac{E_L\, \eta_p}{a^2\, \mathrm{mfp}}$$

A high energy 1-10 kJ laser is required to get high temperature

A Much Wider ρ,T Space Could be Available if Heating and Compression Were Independent



Energetic electrons and protons enable compelling new capabilities

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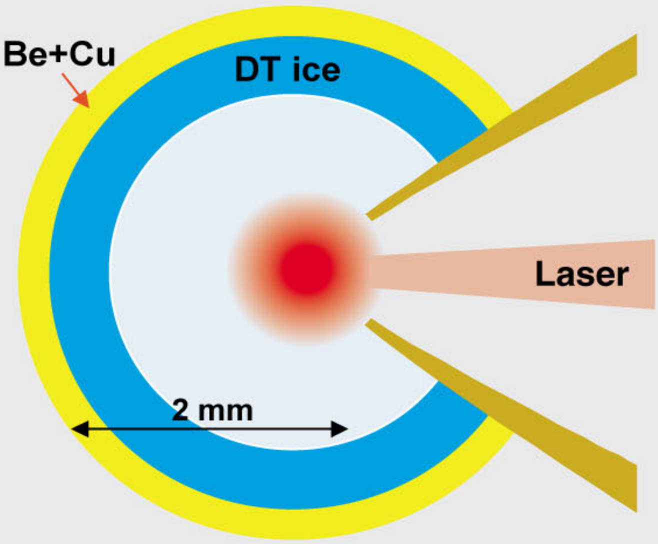
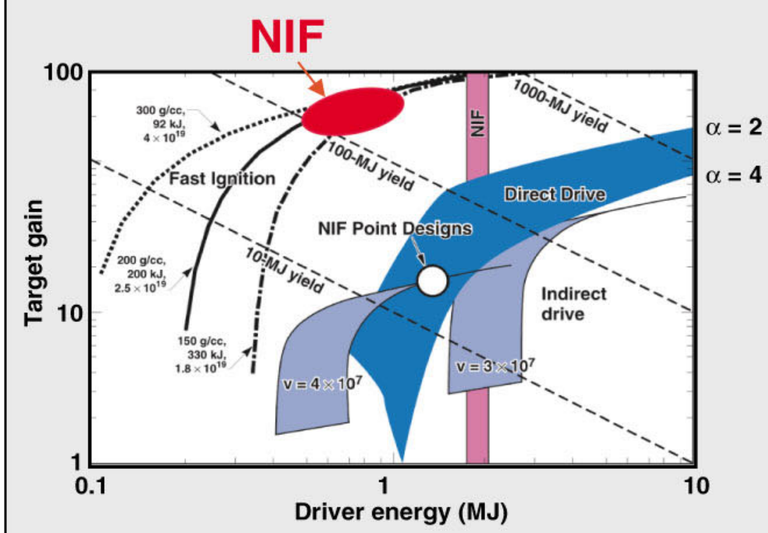
Energetic electrons heat DT rapidly to ignition – "fast ignition"



Robust high gain ignition
- **Energy**
- **Stewardship program**



NIF will be minimally affected by HEPW modifications

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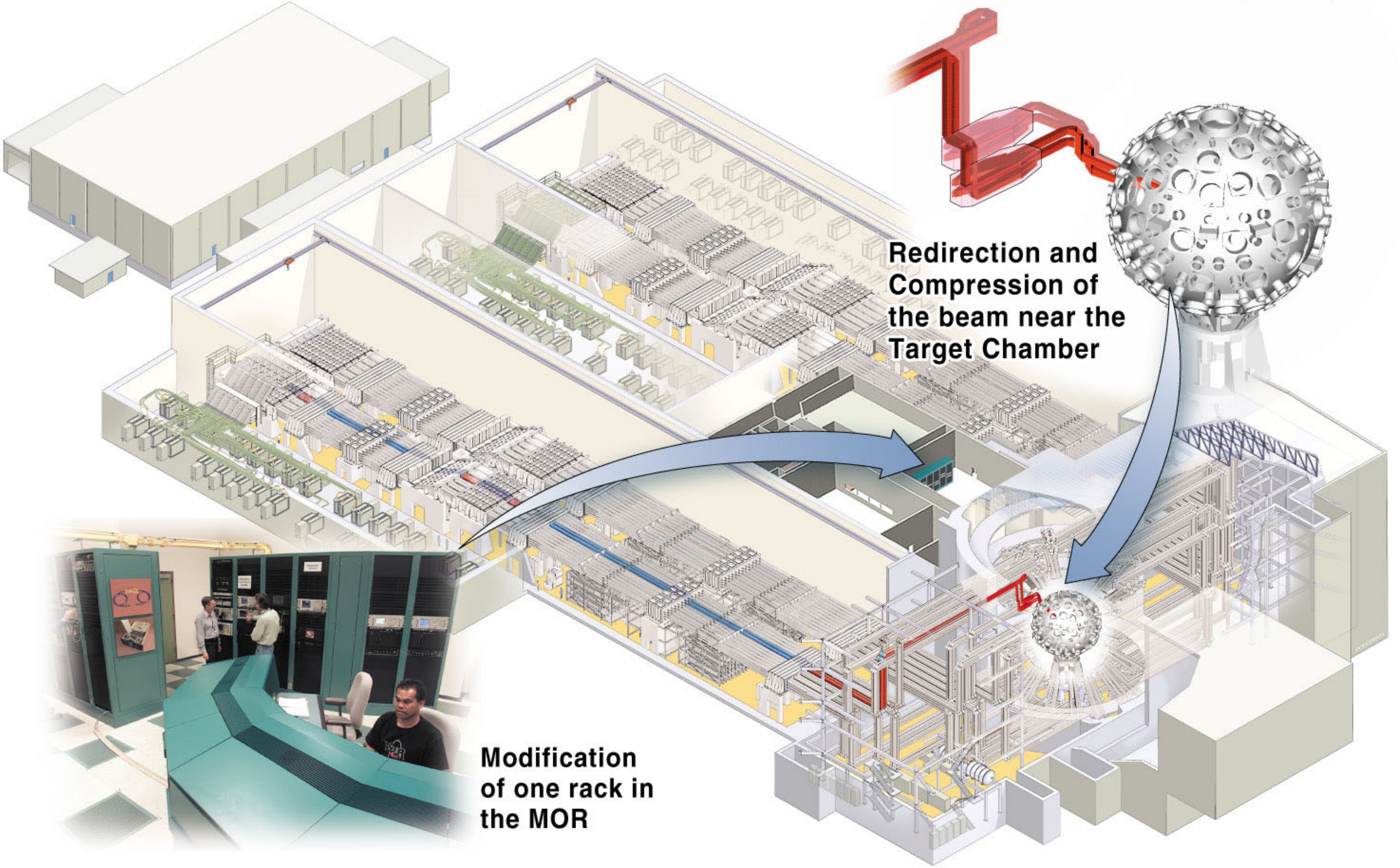

NIF is ready to deliver the next generation of High Energy Density Physics Experimental Capability

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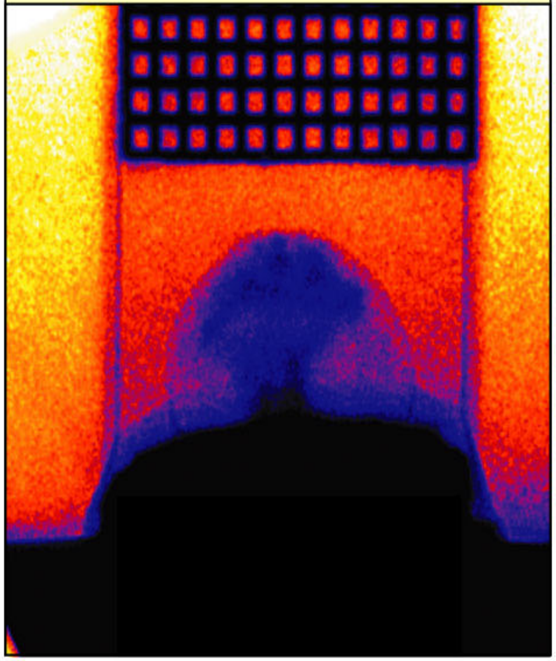
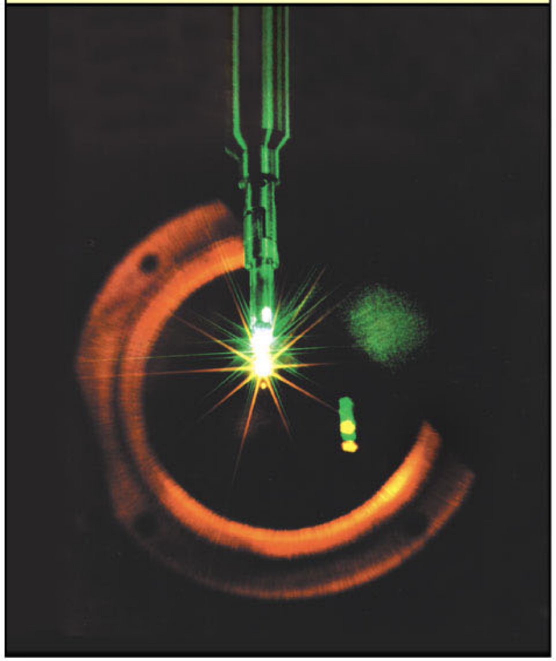
High Energy Density Physics

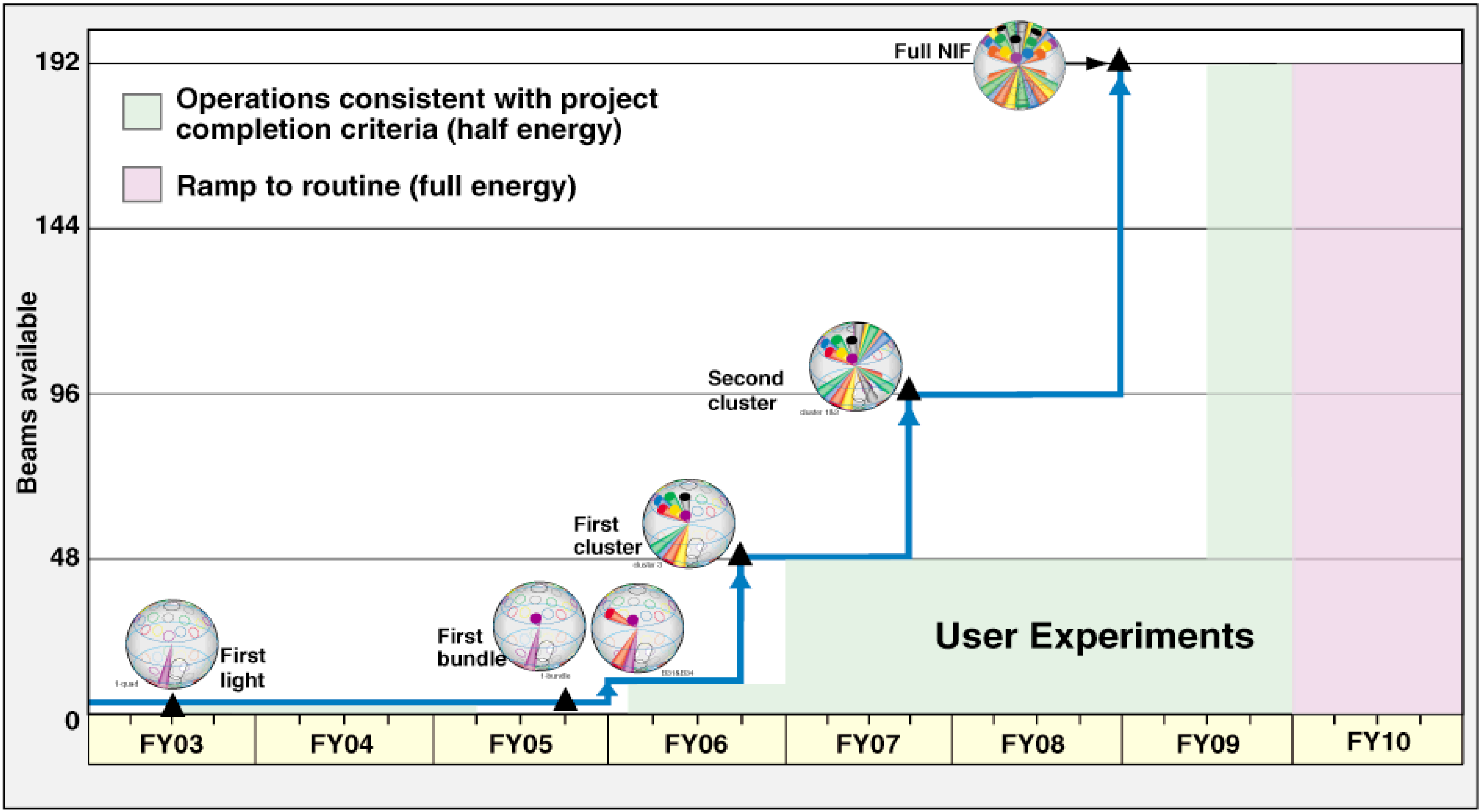


Fusion Ignition



Basic Science

NIF Energy Availability



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