In Pursuit of Ignition on the National Ignition Facility

Princeton Plasma Physics Laboratory
Princeton

March 26, 2014

Lawrence Livermore National Laboratory

LLNL-PRES-XXXXXX
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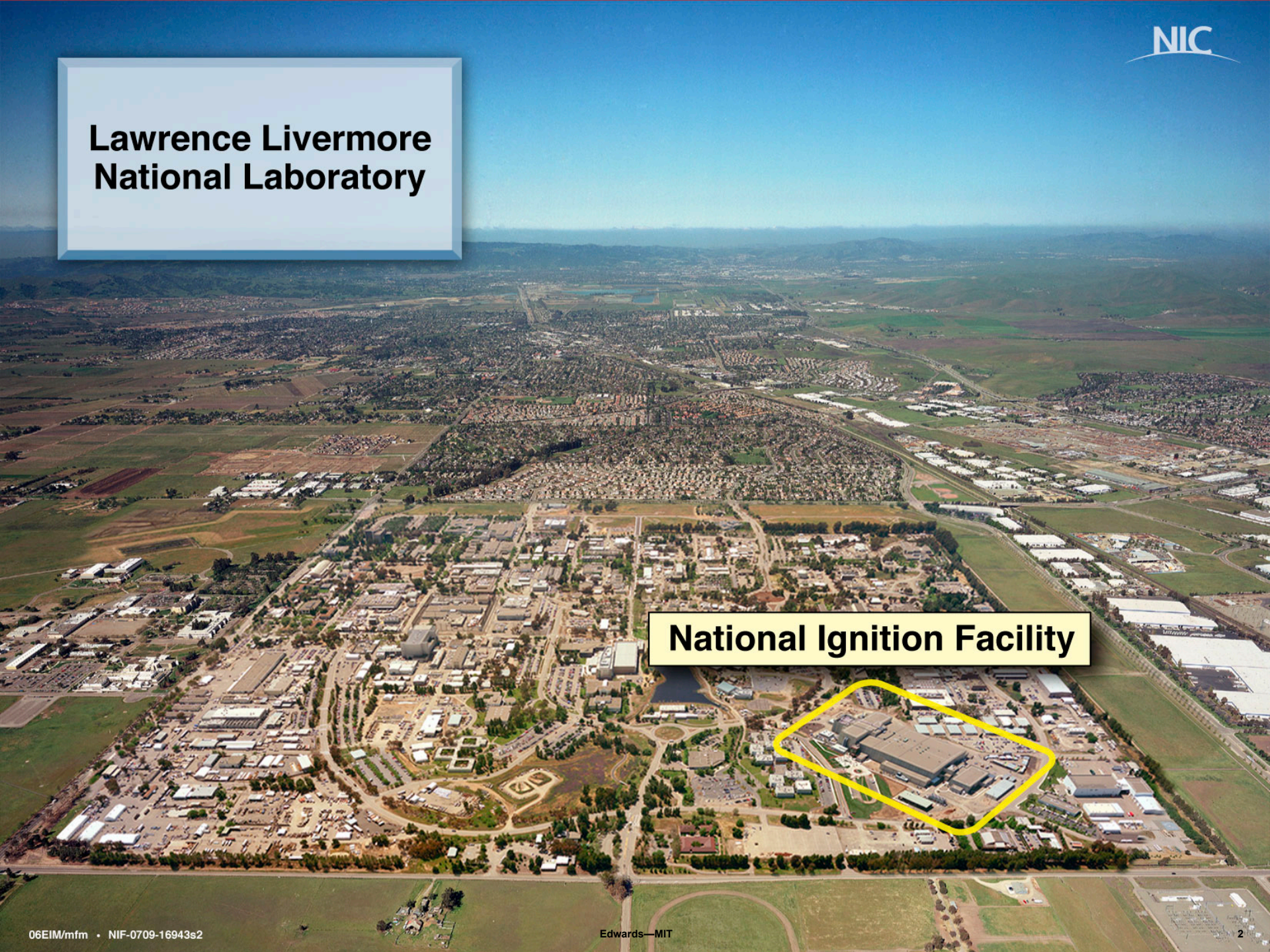
John Edwards for the ICF team
Associate NIF Director for ICF

Lawrence Livermore National Laboratory



NIF missions

Enabling stockpile stewardship & national security

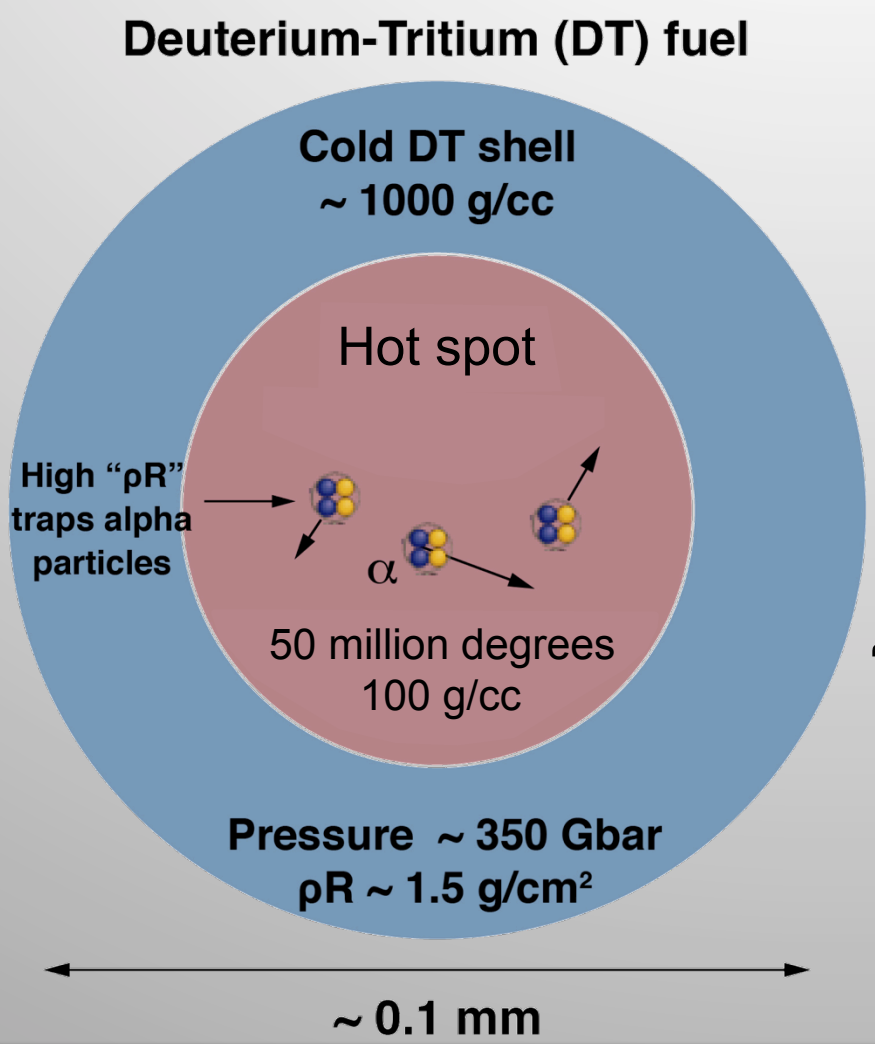
Advancing frontier science

Enabling clean energy

Building future generations of HED scientists

Ignition on NIF requires compression to extreme conditions

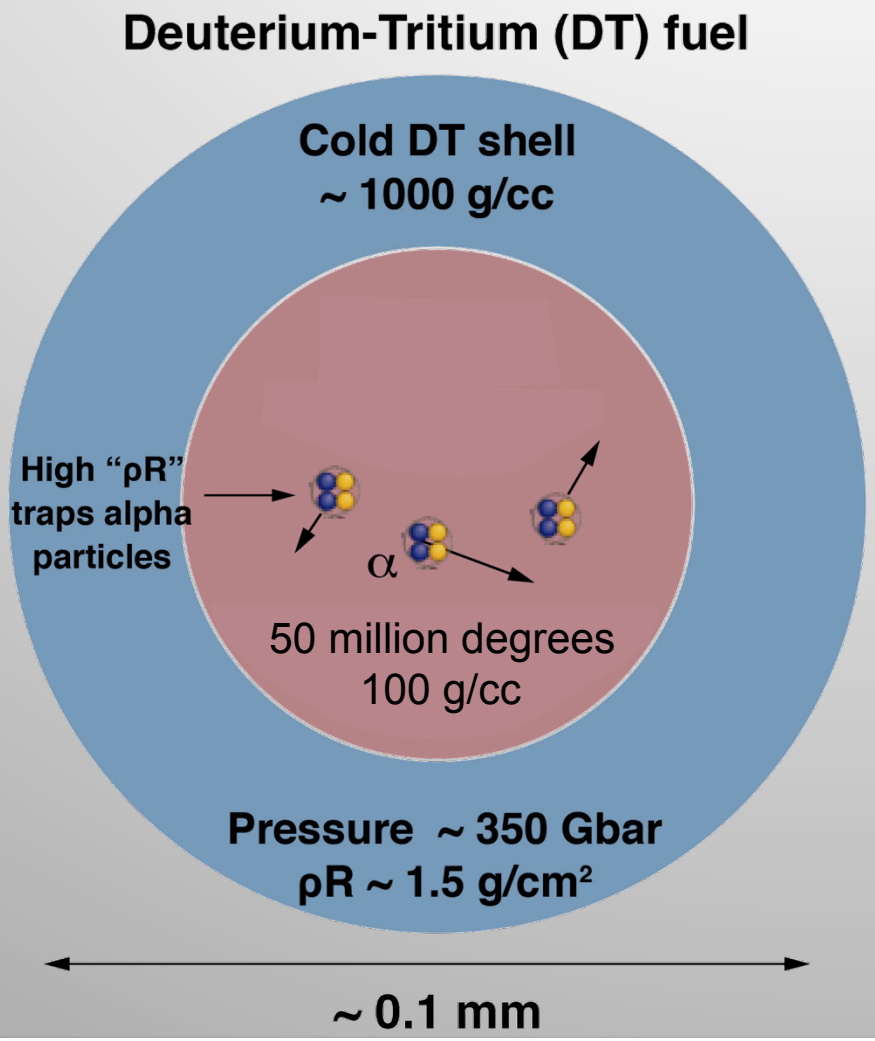
$$E_{ignition} \sim \rho R^3 T \sim \frac{(\rho R)^3 T^3}{P_{stag}^2}$$



"Cold" fuel

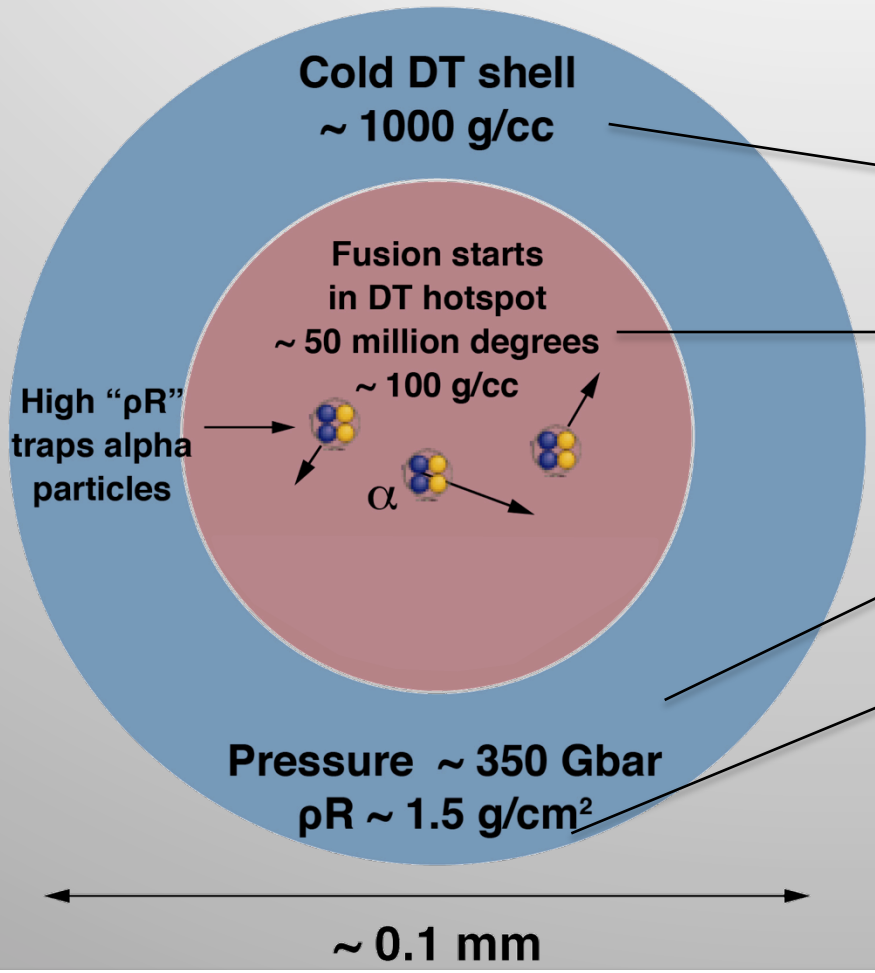
*ρR = Areal density

If the fuel ignites well on the NIF….



Energy release
~ 20 MJ
~ 1 Kg of coal

Conditions are currently ~ factor 2 from ignition



Best performance on single shot

~ 27kJ

~ 500 g/cc

~ 40 g/cc

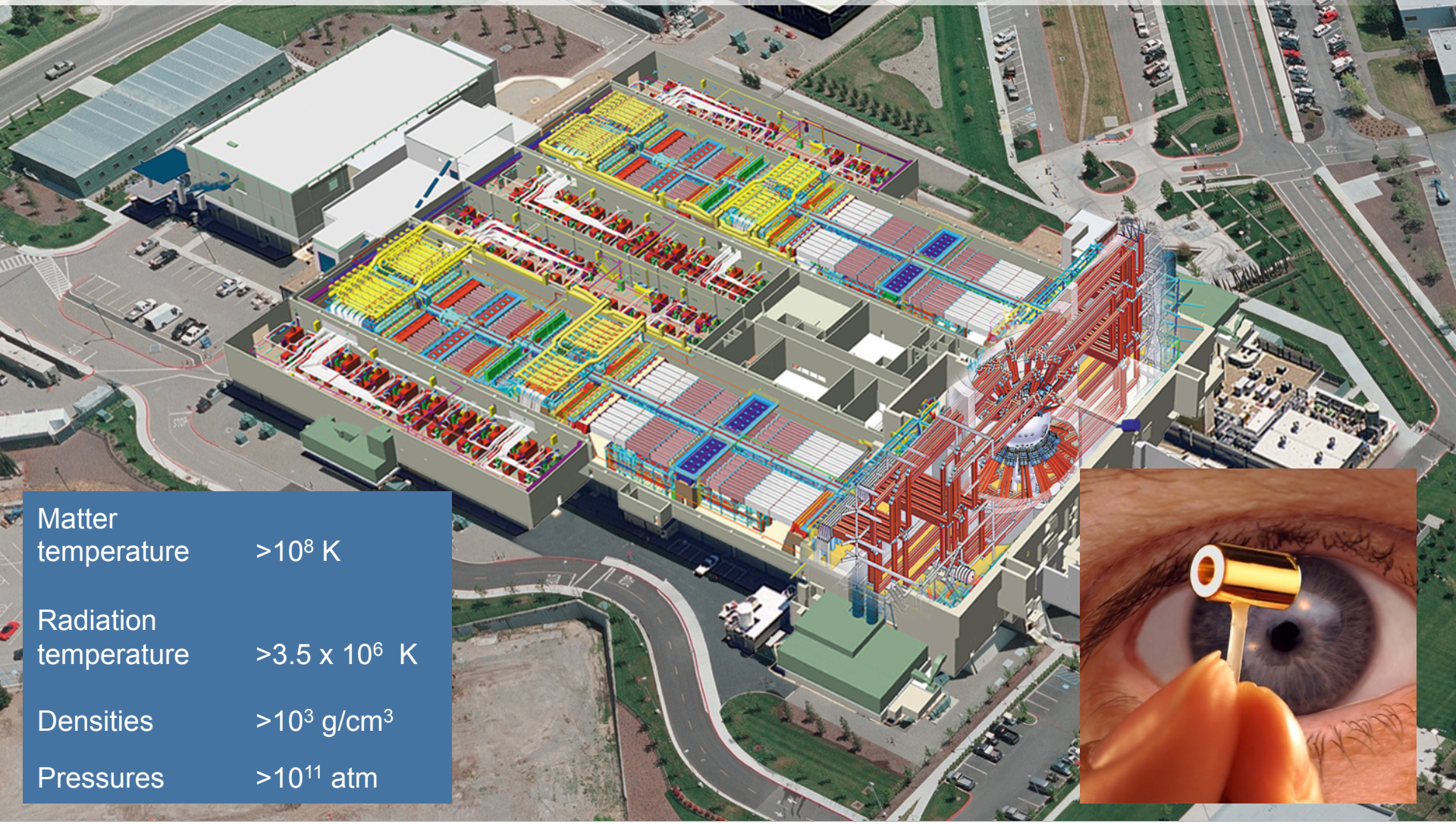
~ 180 Gbar

~ 0.75 g/cm ^{2}

*ρR = Areal density

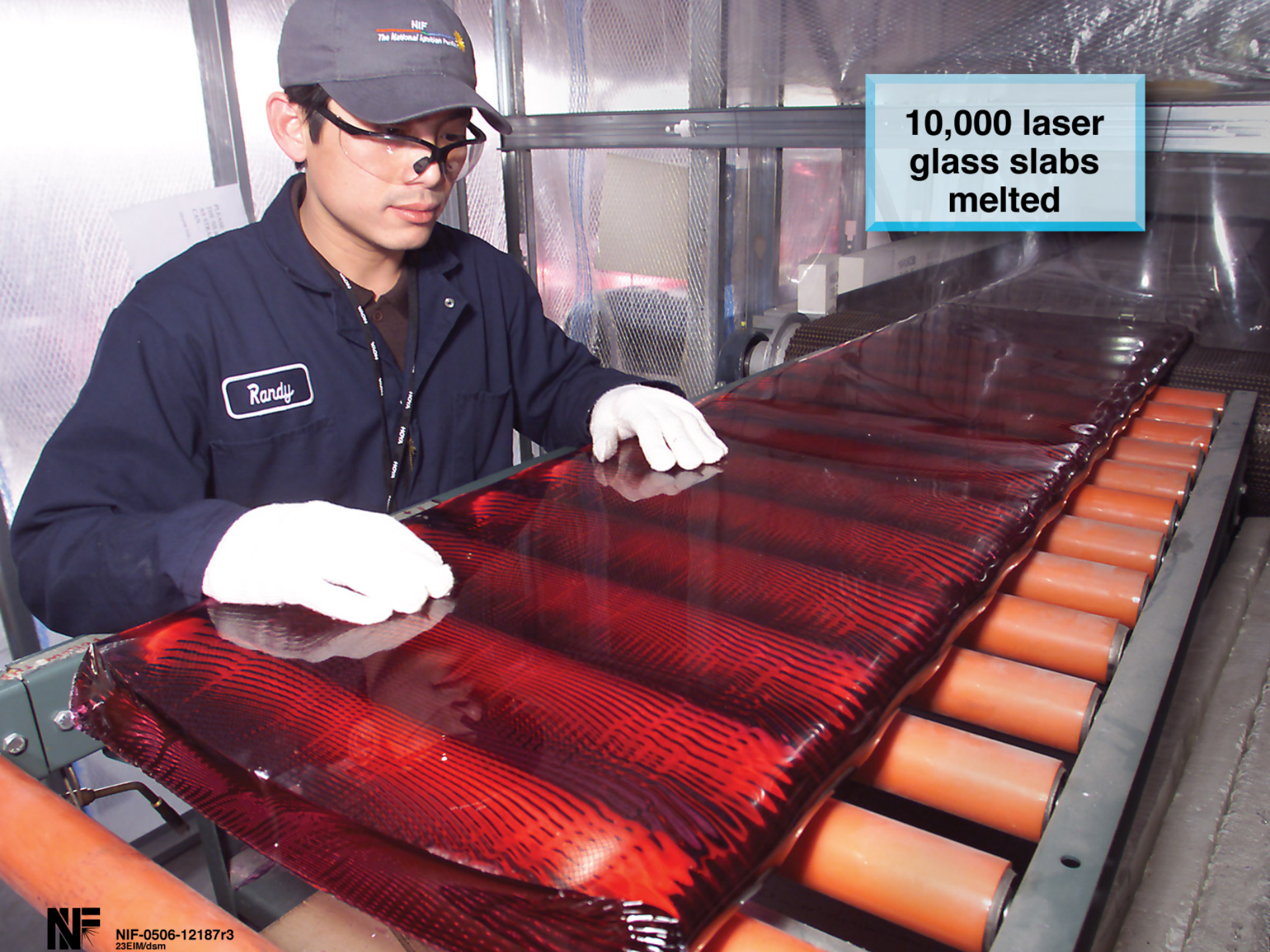
The National Ignition Facility

NIF concentrates all 192 laser beam energy in a football stadium-sized facility into a mm3



Matter temperature	$>10^8$ K
Radiation temperature	$>3.5 \times 10^6$ K
Densities	$>10^3$ g/cm^3
Pressures	$>10^{11}$ atm

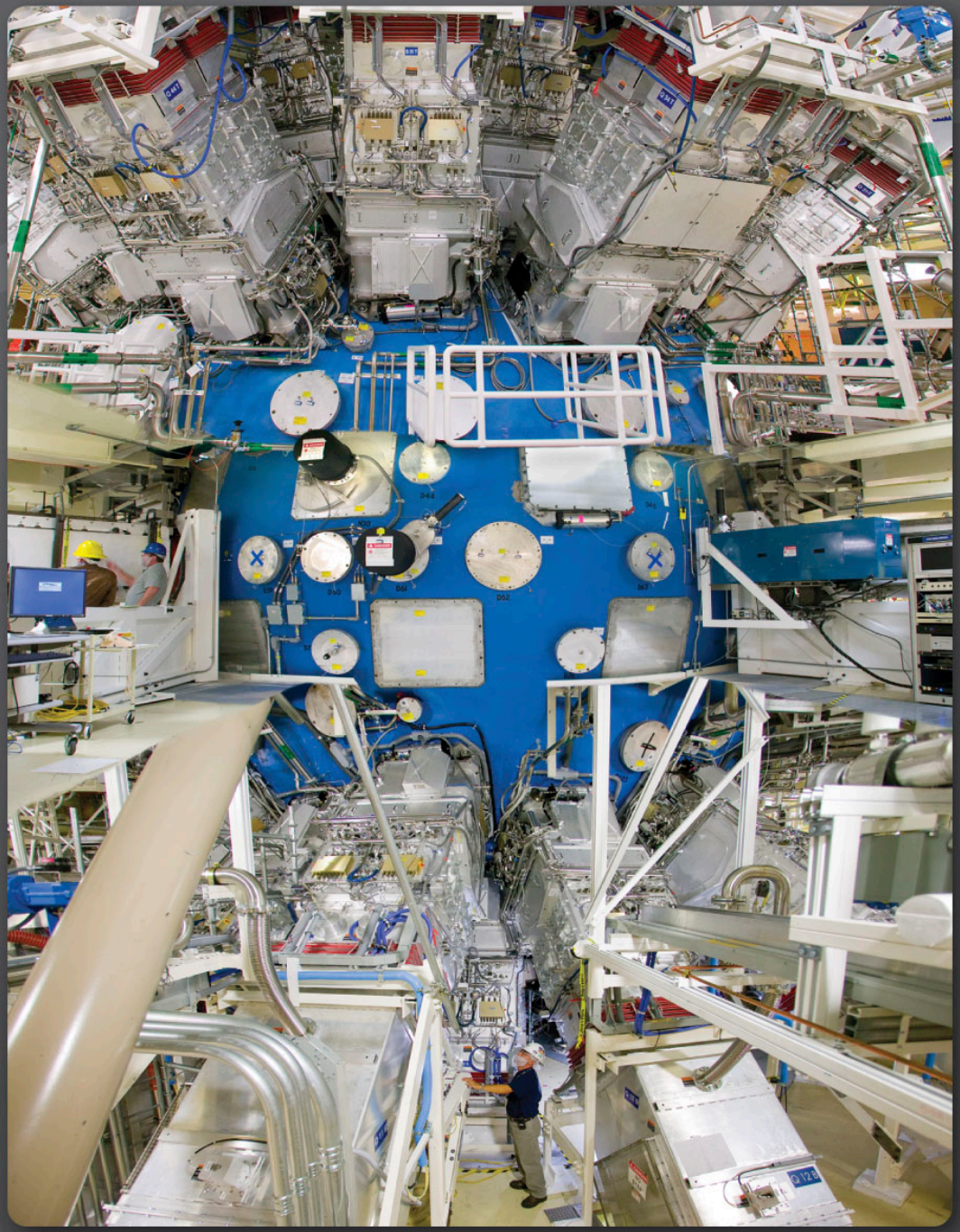
LER-BIM AY 1-18
LER-BIM AY 2-18


10,000 laser glass slabs melted
Randy
NIF-0506-12187r3
23EIM/dsm

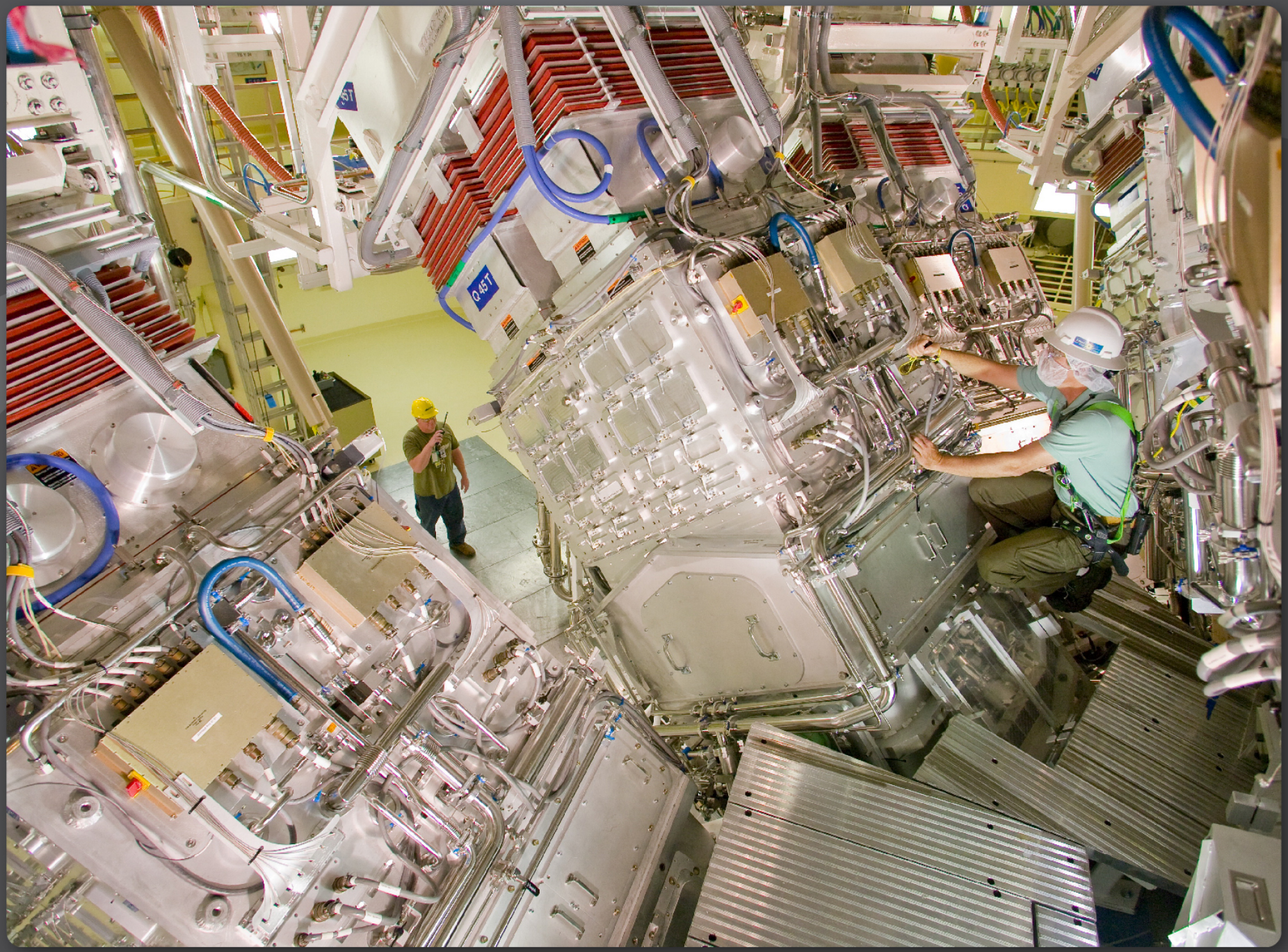
Laser Glass
Warehouse
3072 slabs required
NIF-0101-00025_1-r1
P6405

Target Chamber June 1999

05EIM/mfm • NIF-0609-16535s2



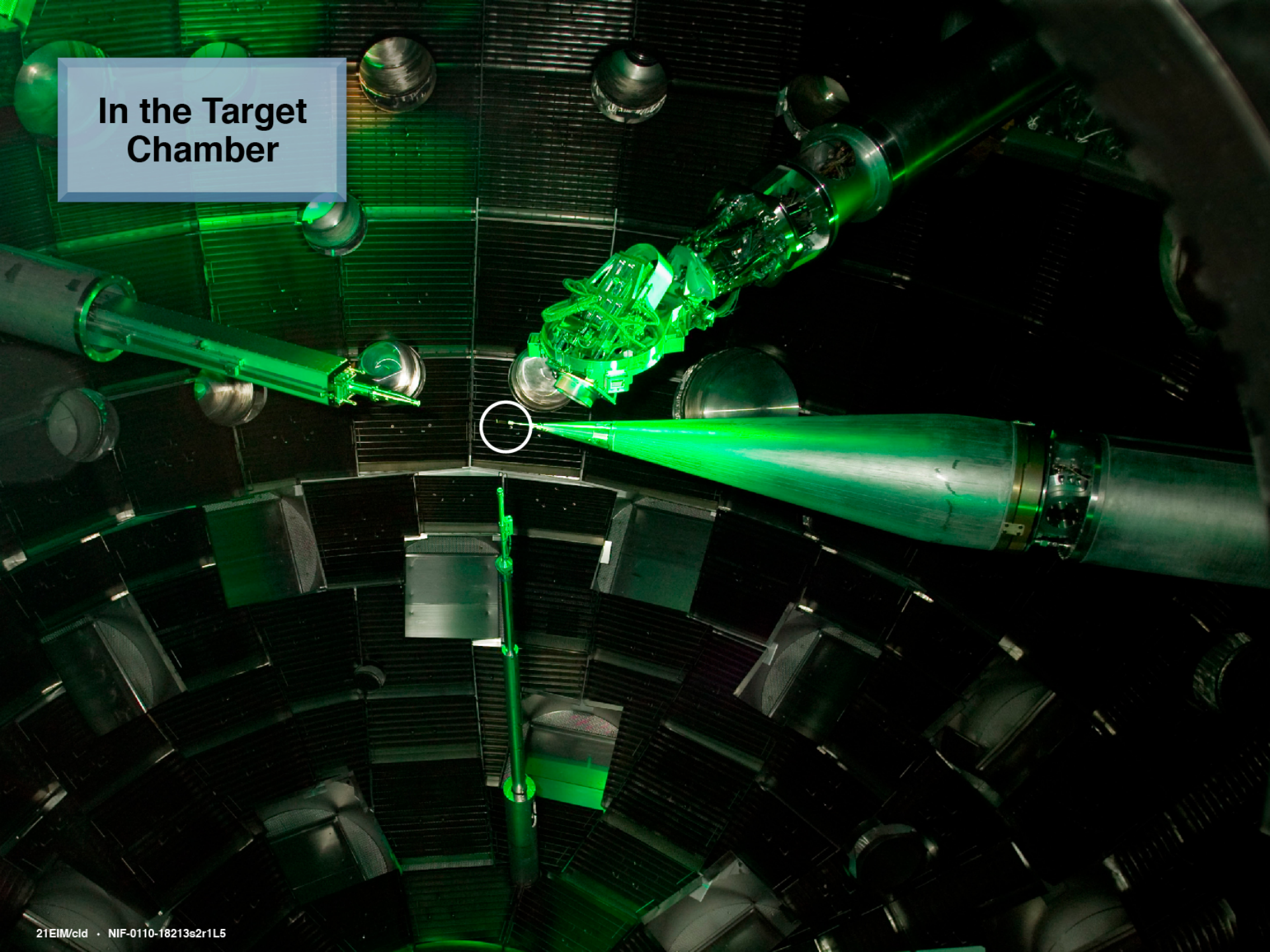
15EIM/dj • NIF-0609-16541s1


Q-45T

Laser bay

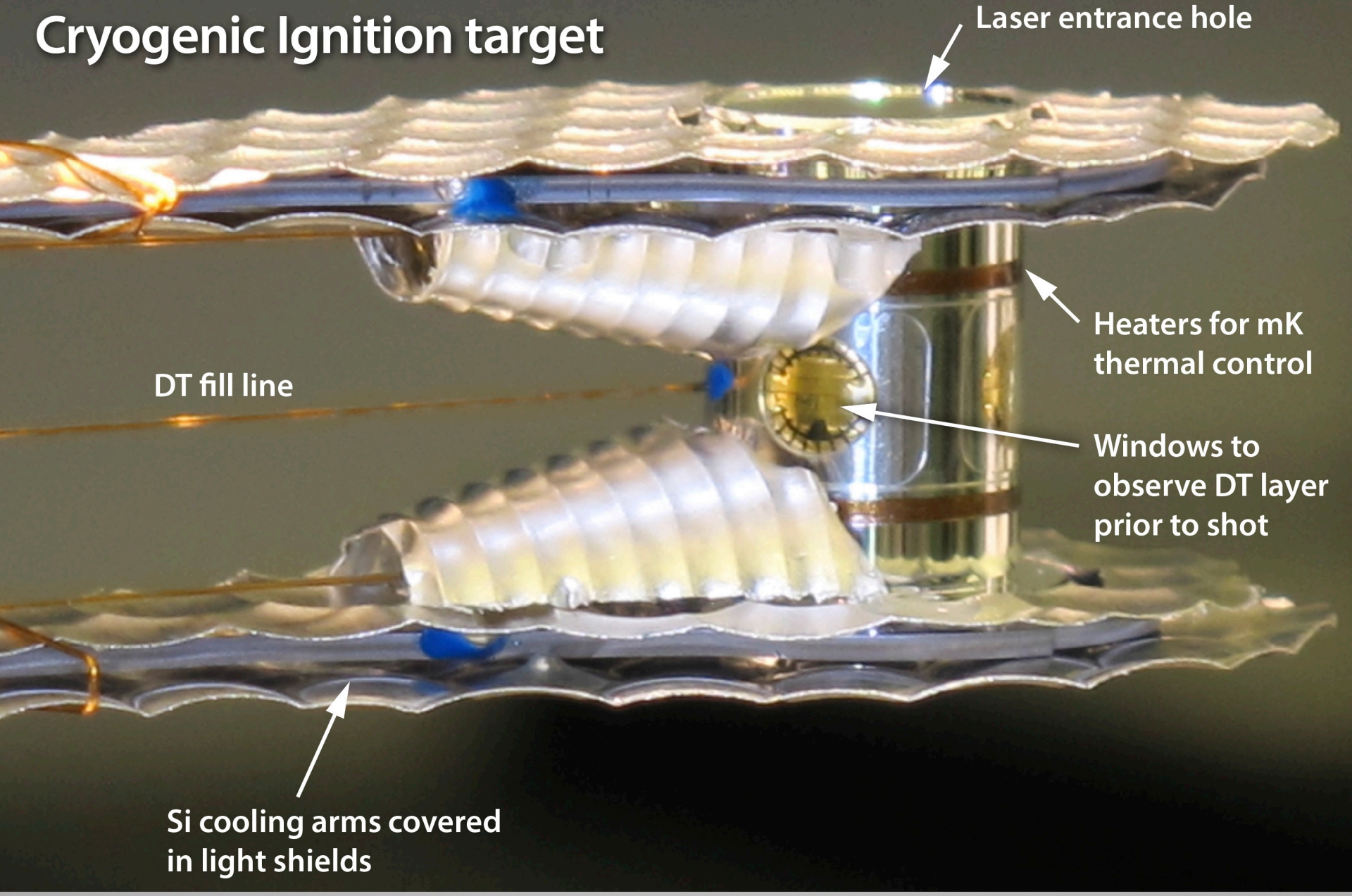
Target bay

In the Target Chamber



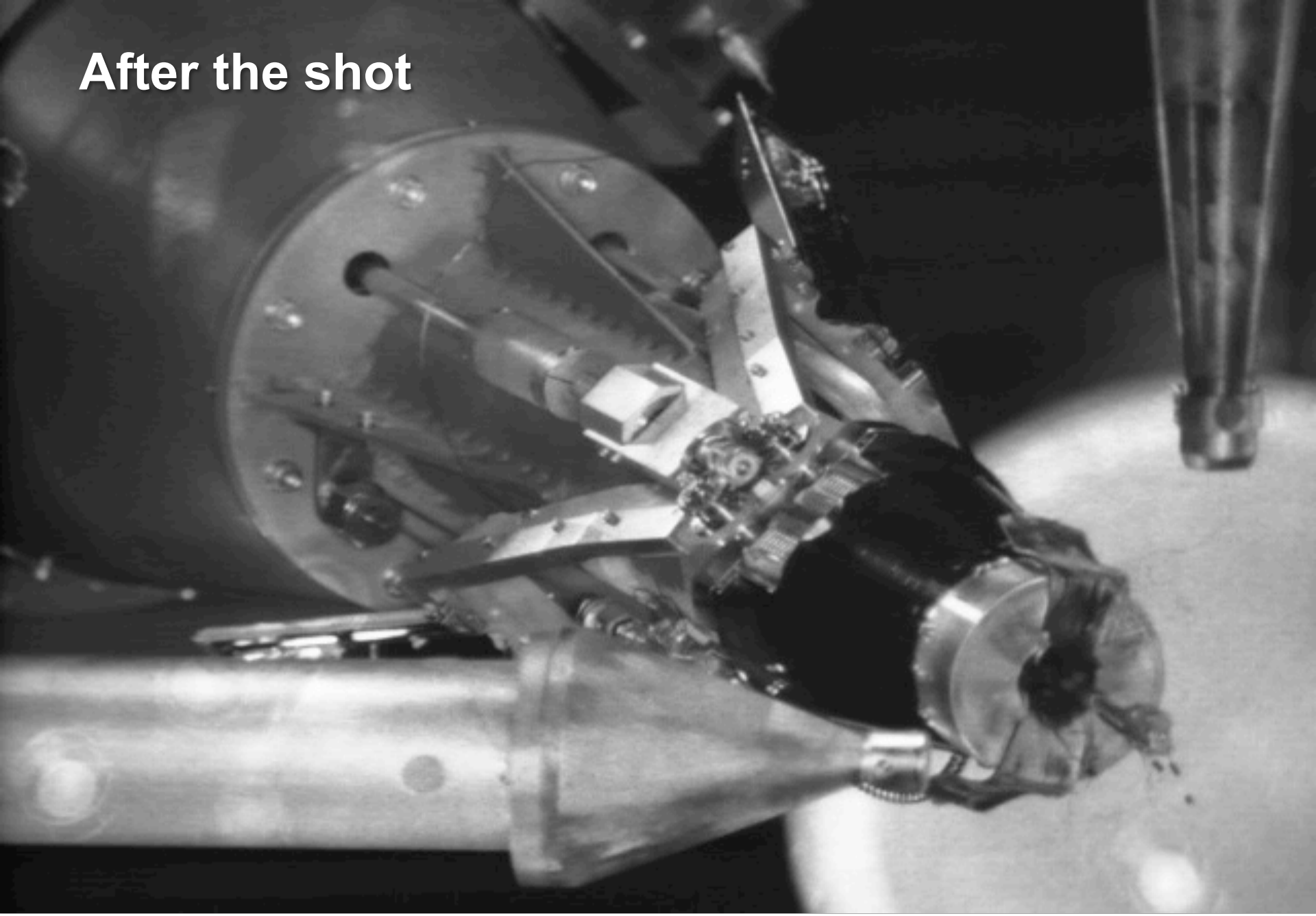
21EIM/cld • NIF-0110-18213s2r1L5

Cryogenic Ignition target



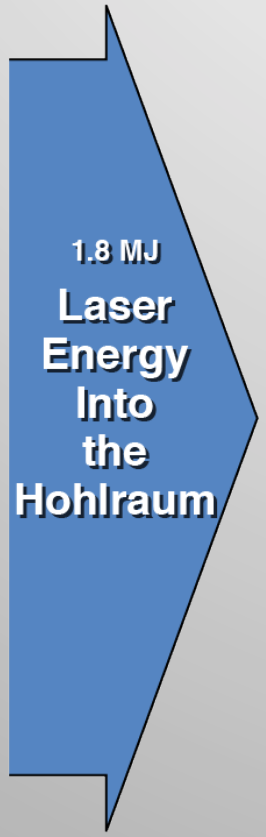
Special shrouds keep the target at – 290 degrees

After the shot

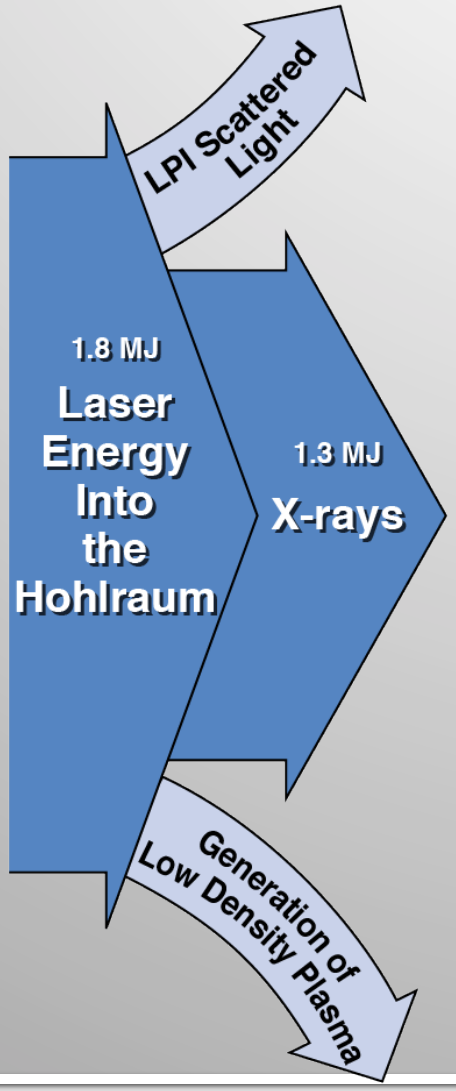


SHOT
DIRECTOR

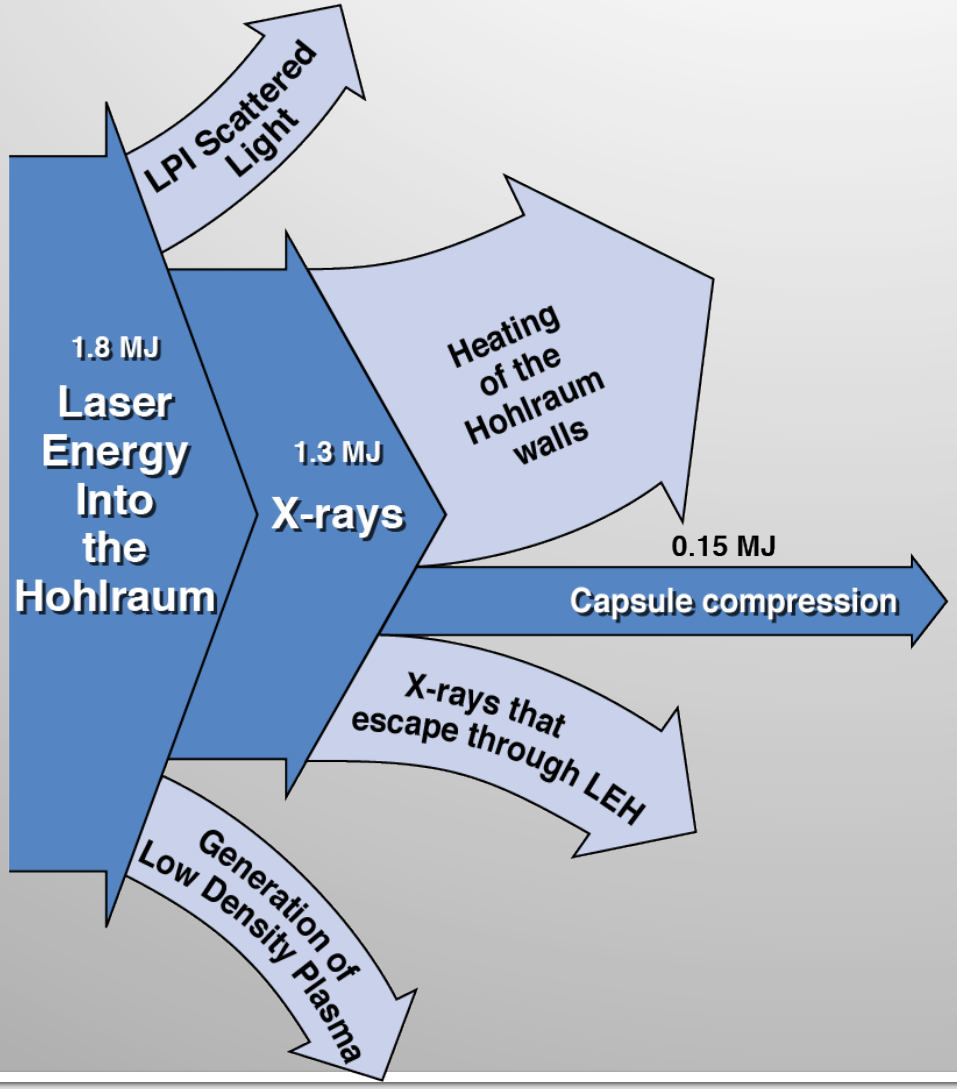
The laser delivers 1.8MJ of energy to target



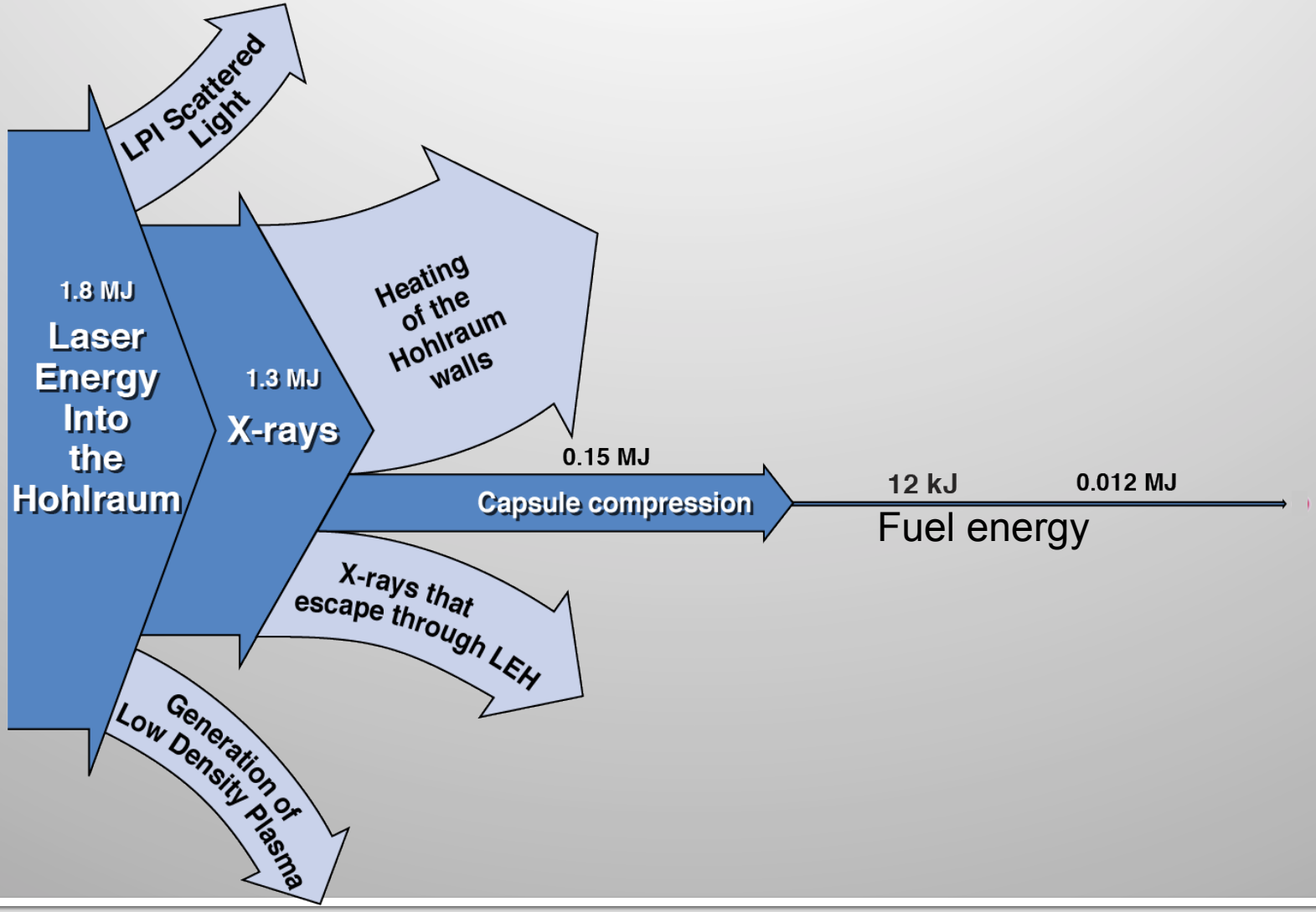
About 70% of the energy is converted to X-rays



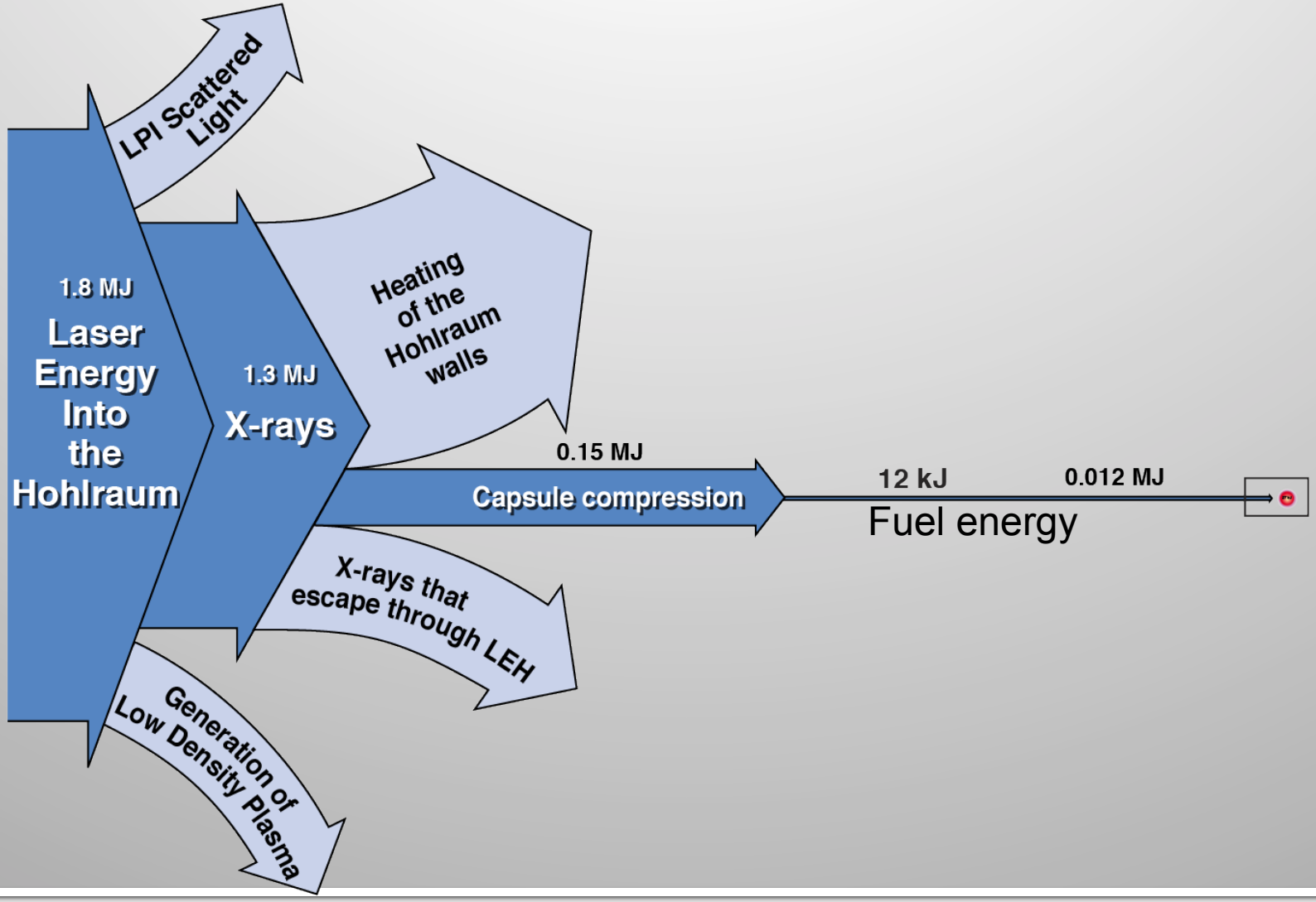
A little under 10% is absorbed by the capsule



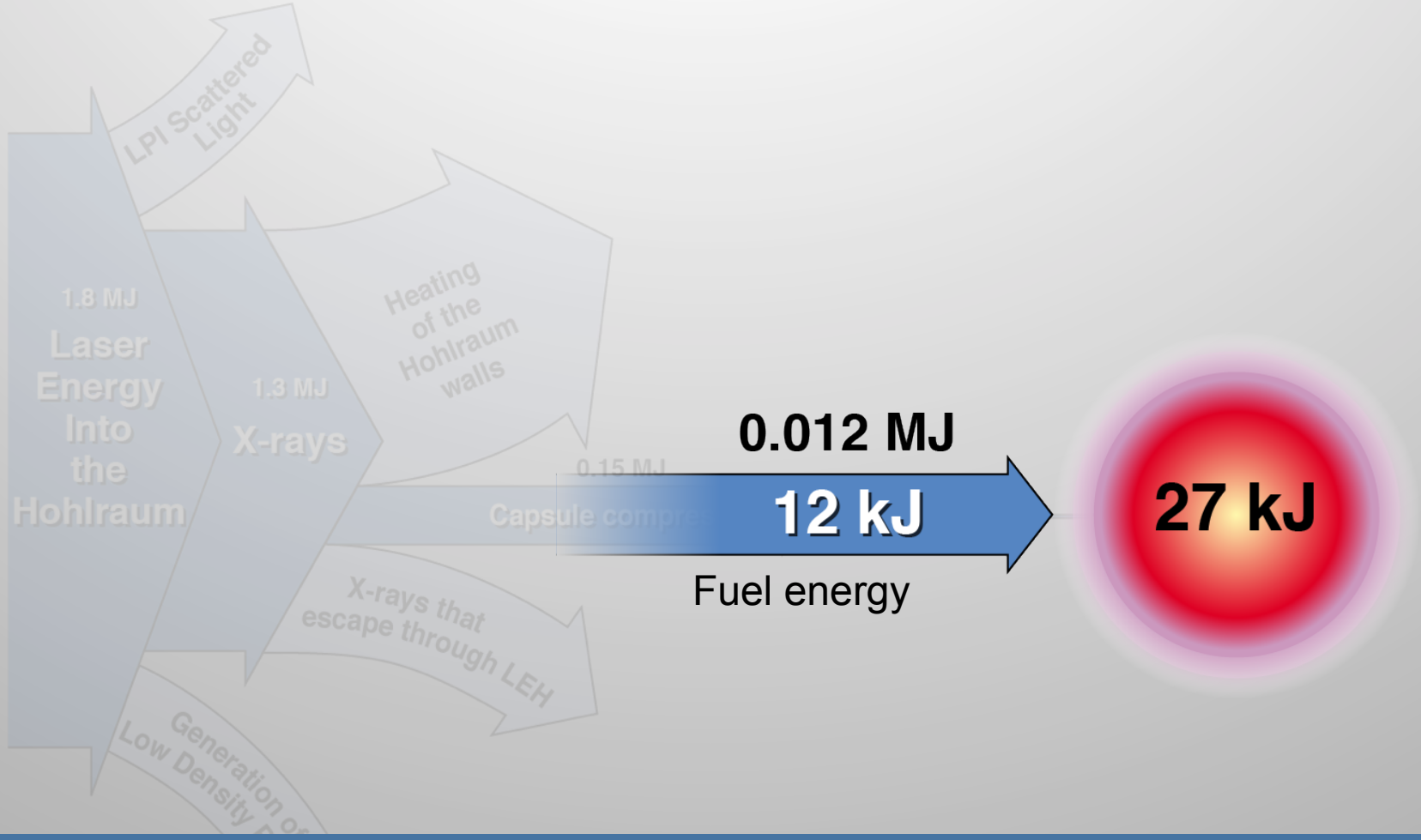
Less than 1% of the energy gets into the fuel



And the really exciting thing…

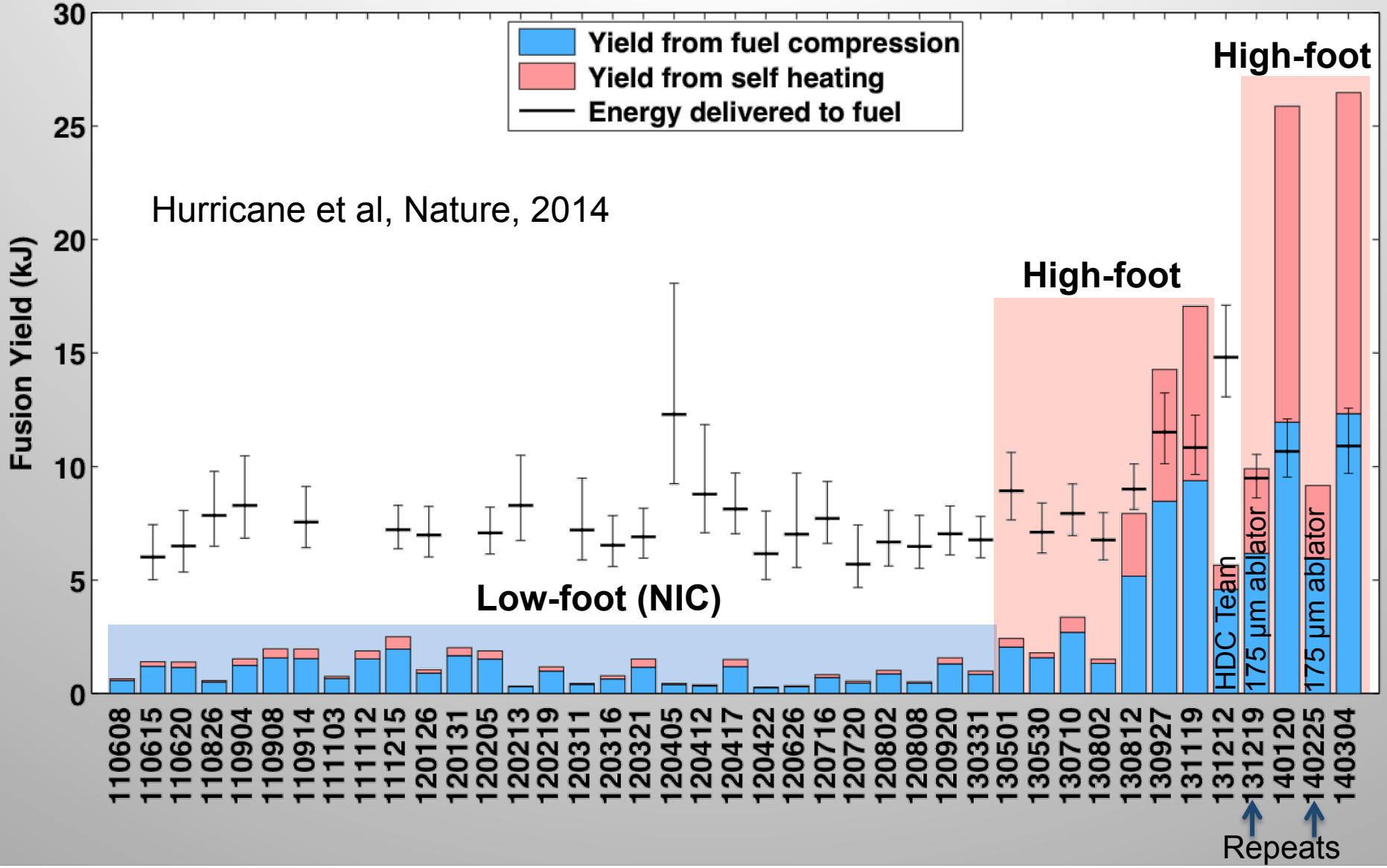


Self heating from alphas starting to become significant



Self heating results in ~2X yield enhancement

Recent experiments are entering a different regime



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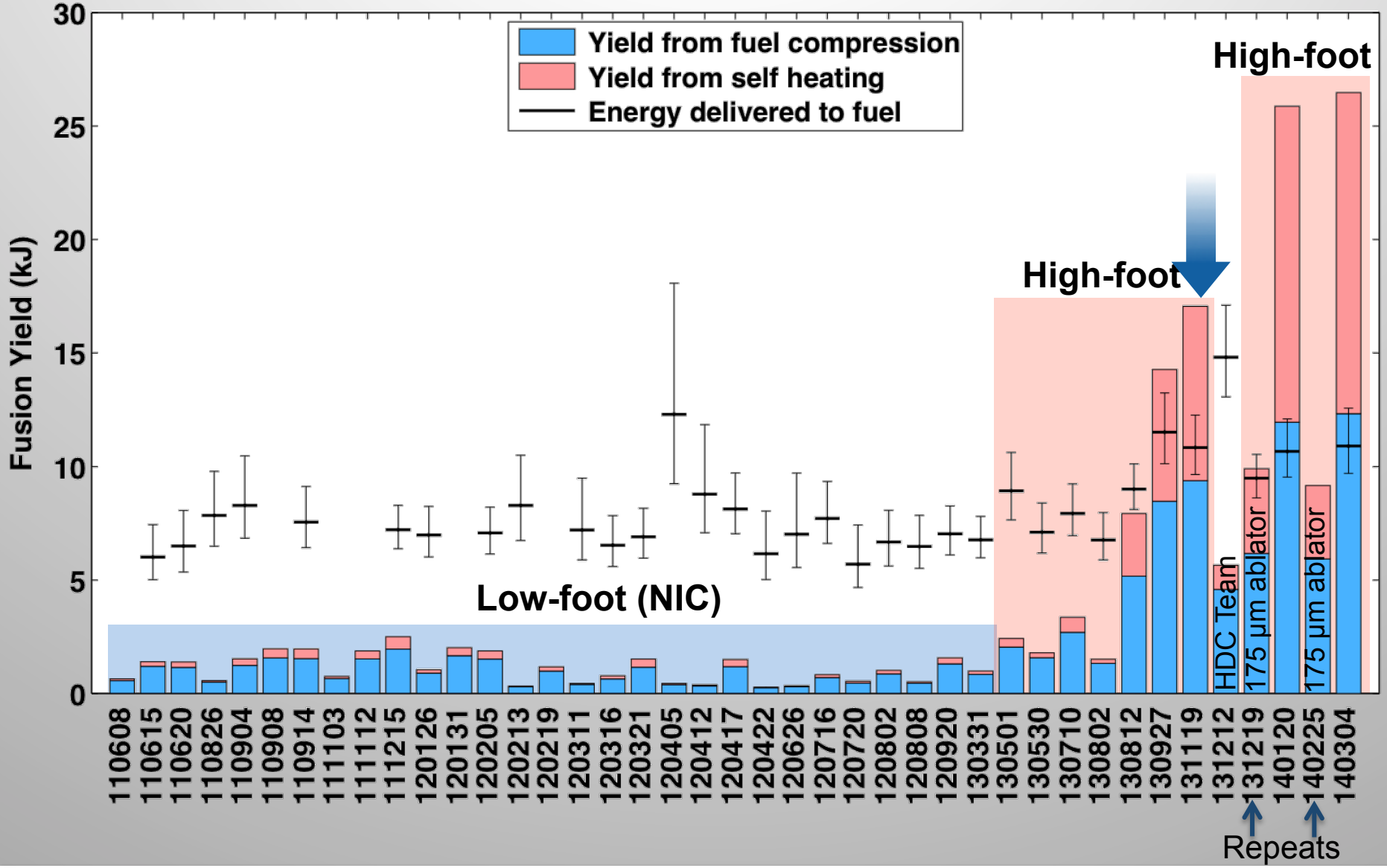
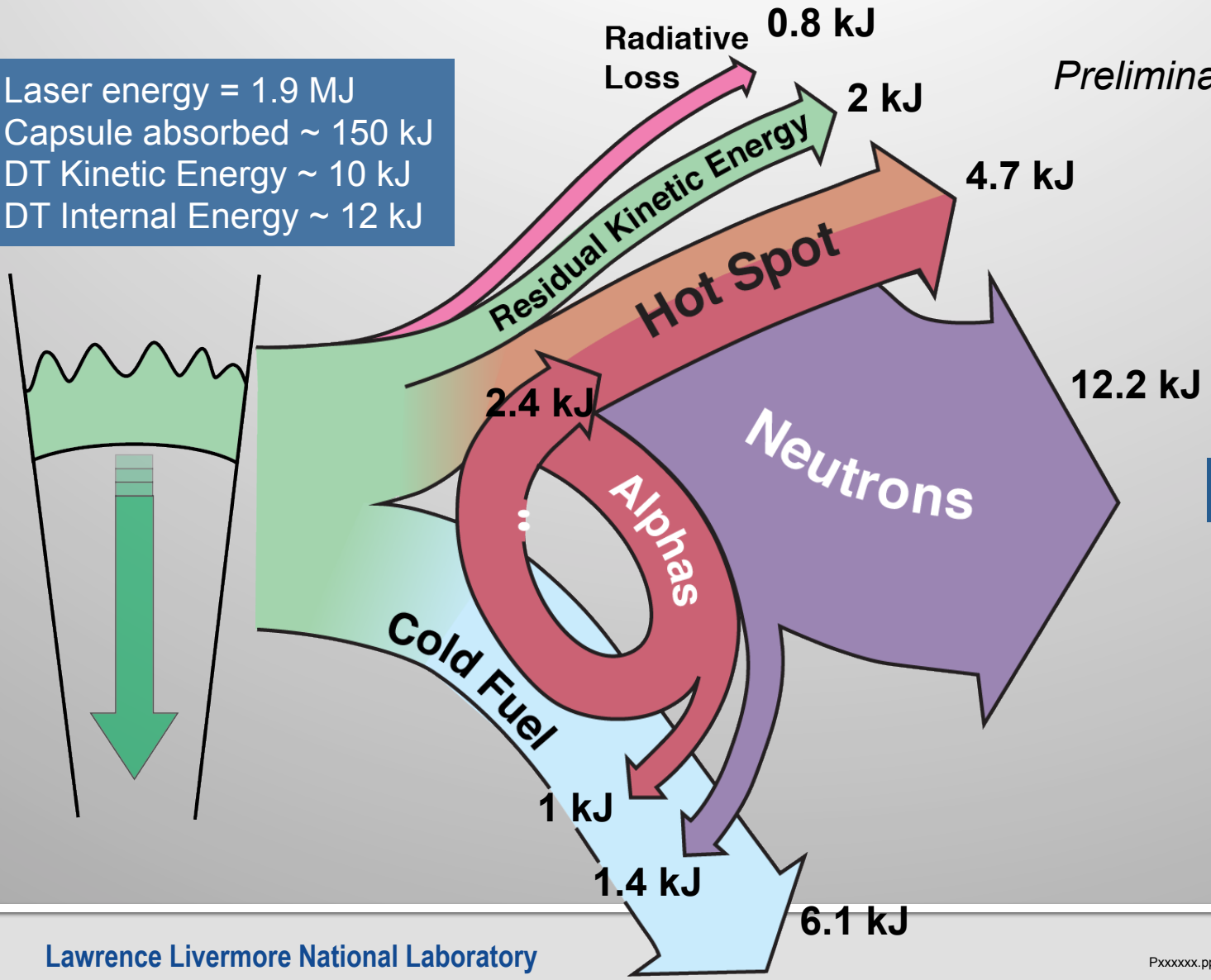


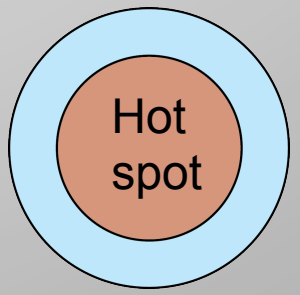
Alpha energy contributed ~ 50% of the hot spot energy at stagnation for DT shot N131119

Laser energy = 1.9 MJ
Capsule absorbed ~ 150 kJ
DT Kinetic Energy ~ 10 kJ
DT Internal Energy ~ 12 kJ

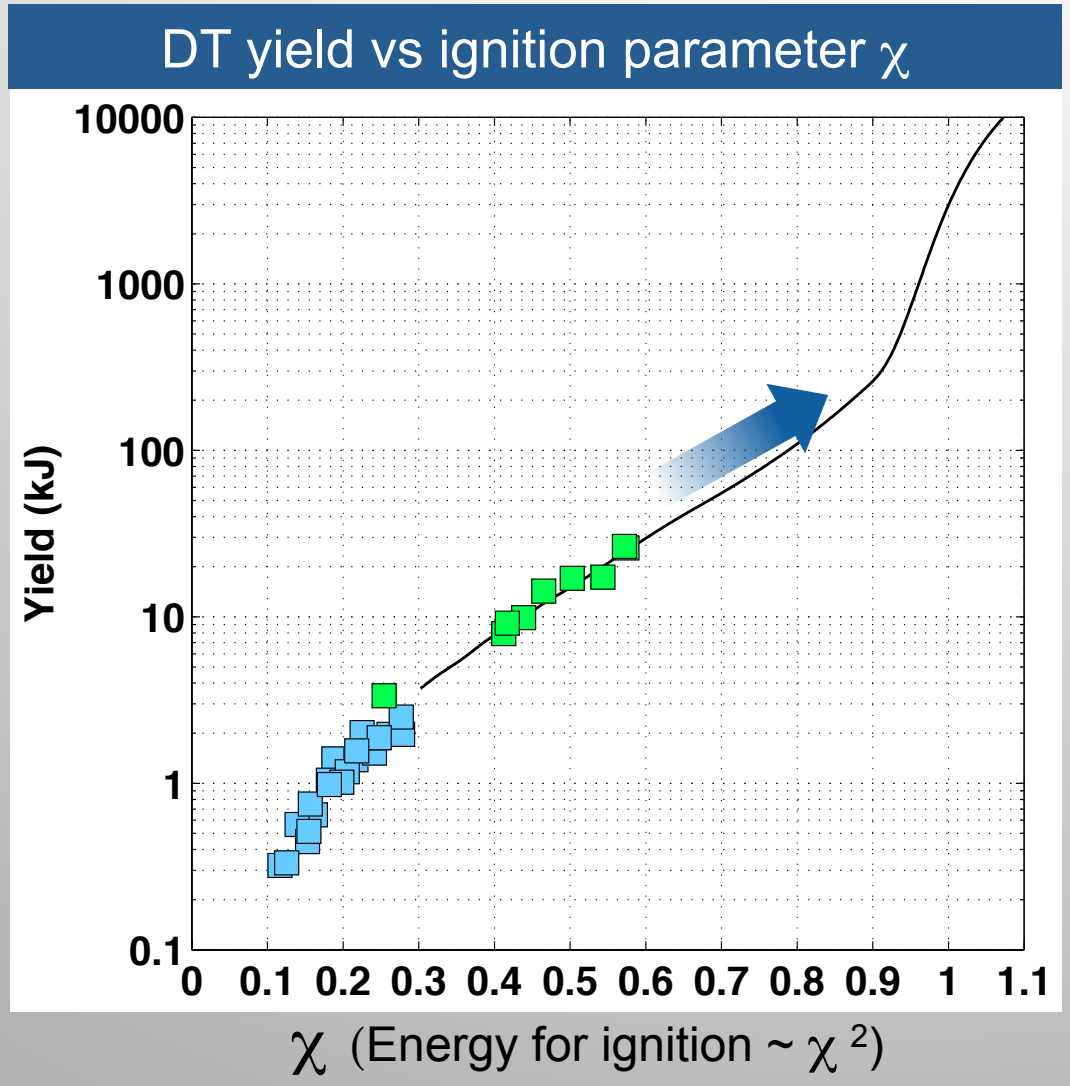
Preliminary analysis



Total yield ~ 17kJ



What about ignition?



Ignition requires higher velocity, convergence

Principal Challenges

Capsule stability

- Hydro instabilities increase as implosion velocity and convergence increase

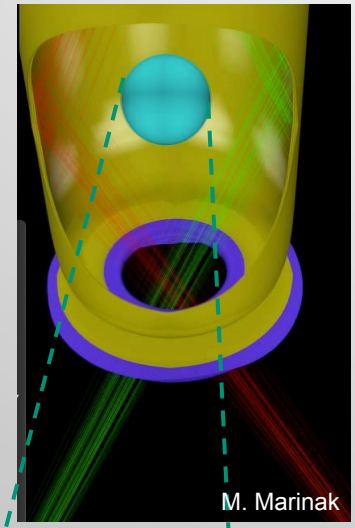
Hohlraum drive symmetry

- Symmetric drive is harder to achieve as laser power increased

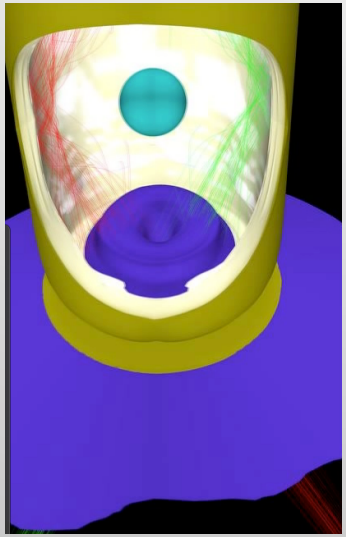
Hot electron preheat?

- Recent analysis suggests

The trick of ICF is to turn 100 million atmospheres of pressure into 300 *billion* atmospheres of pressure

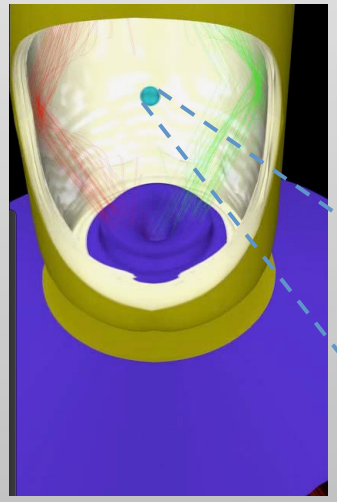


E_{laser} ~ 1.8 MJ
$E_{x\text{-}ray}$ ~ 1.3 MJ

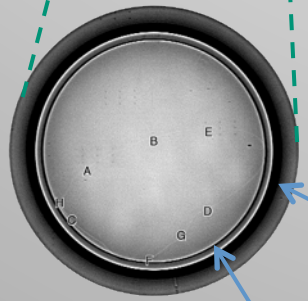


Surface explodes
$E_{absorbed}$ ~ 150 kJ
$P_{ablator}$ ~ 100 Mbar

The implosion's main purpose is to compress and act as a "pressure amplifier"



Fuel and remaining ablator accelerate inwards
KE_{fuel} ~ 14 kJ
Speed ~ 370 km/s

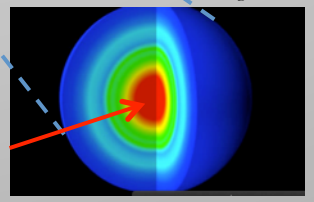


"Ablator"
(~195 microns thick)

DT ice (fuel) layer (~69 microns thick)

$P_{stagnation}$ ~ need 300+ Gbar

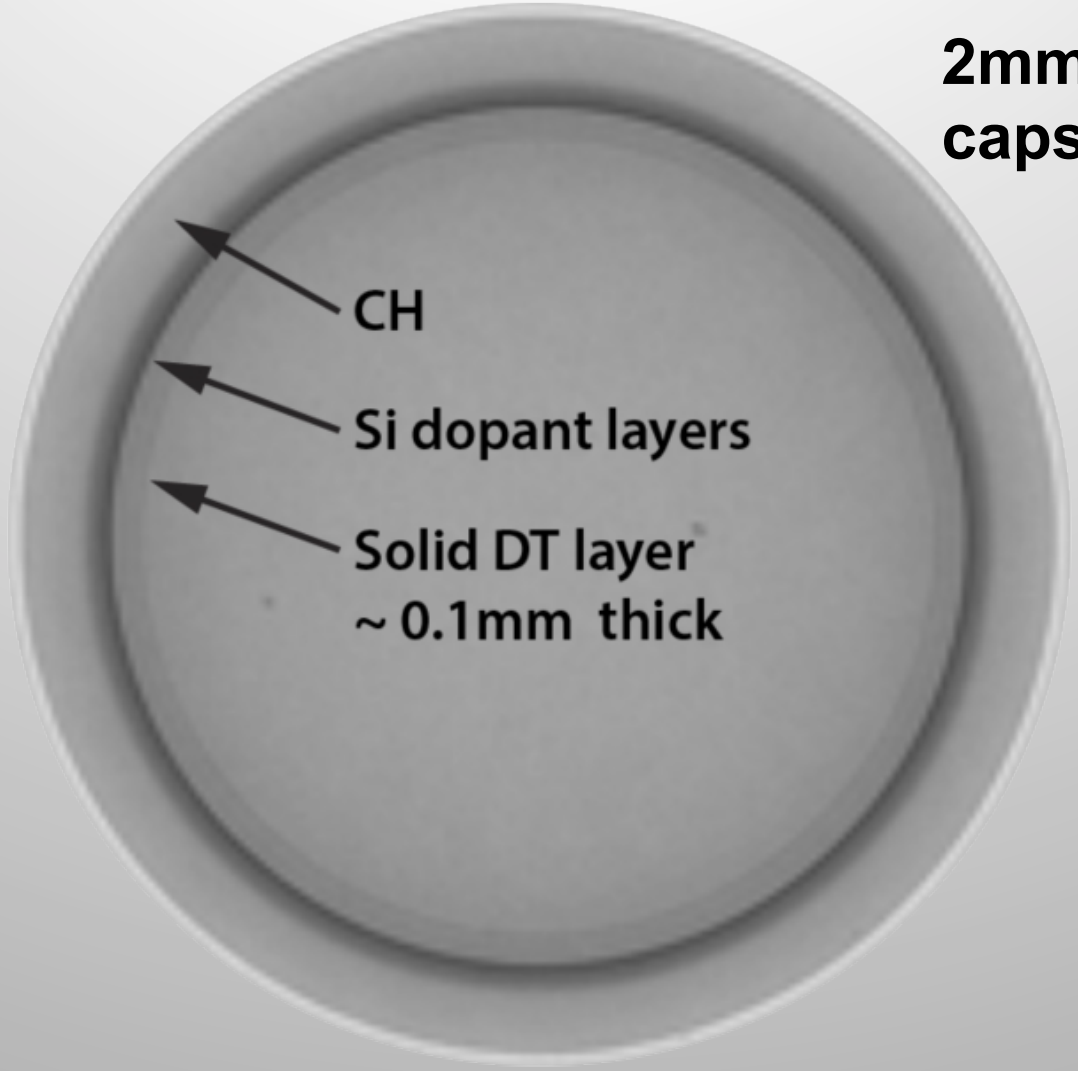
$$E_{ignition} \sim \frac{(\rho RT)^3}{P_{stag}^2} \sim \frac{const.}{P_{stag}^2}$$



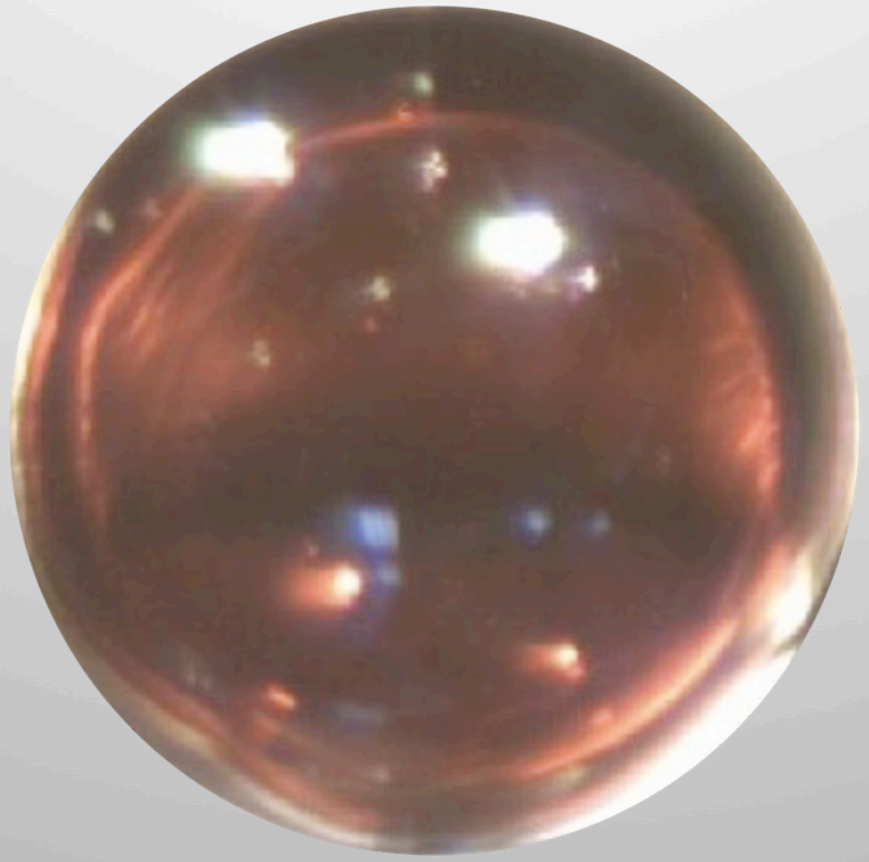
"hot-spot"

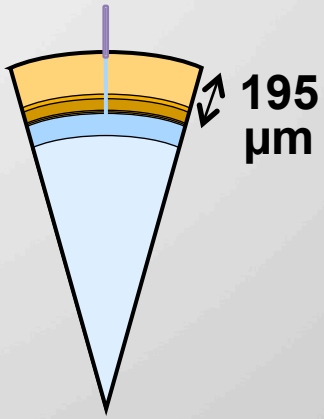
X-ray picture of capsule taken down axis of the hohlraum just before a shot

2mm diameter capsule



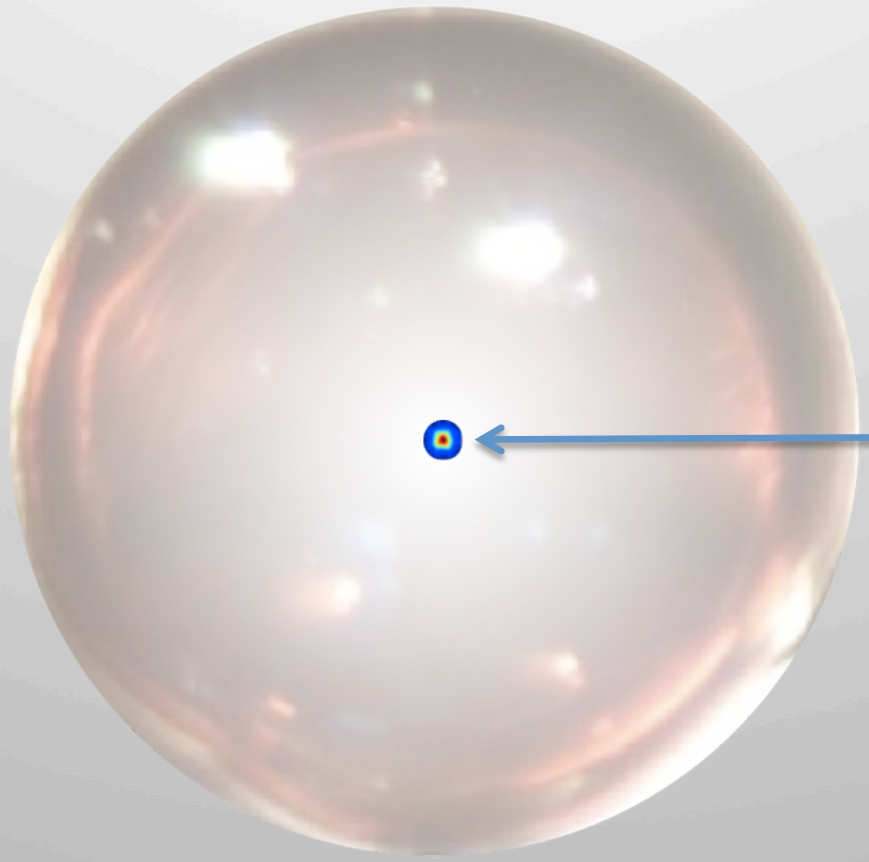
Plastic Ignition Capsule

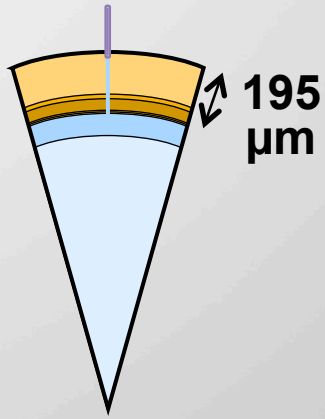




~2 mm diameter

Control is the challenge — near spherical implosion by ~35X

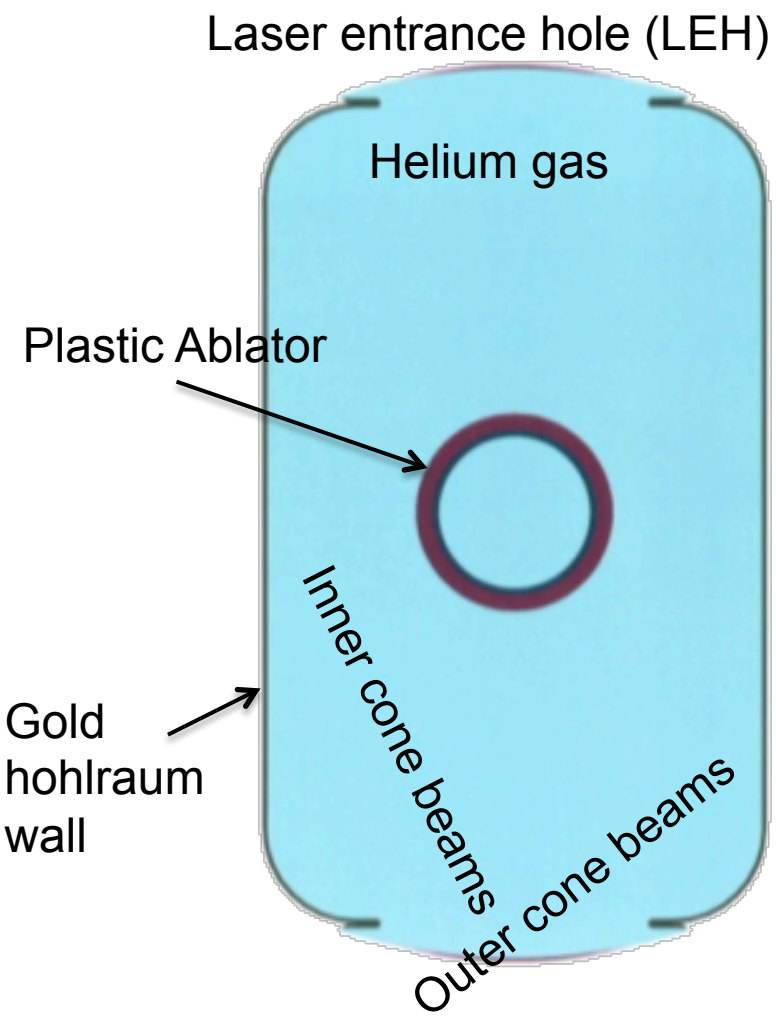


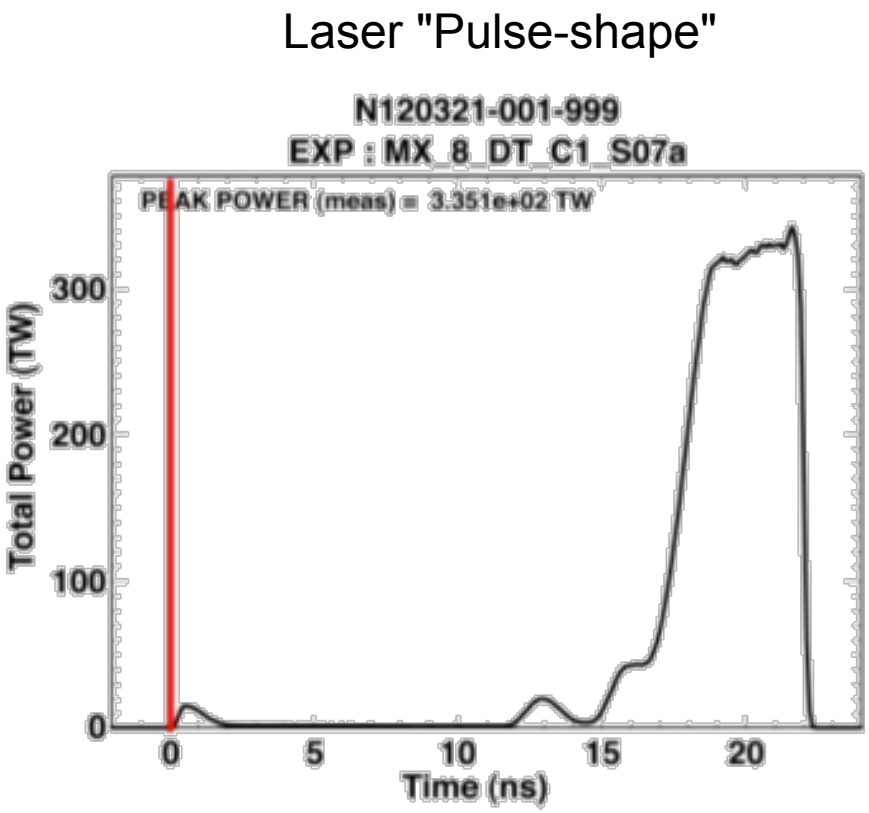


DT shot N120716
Bang Time
(less than diameter
of human hair)

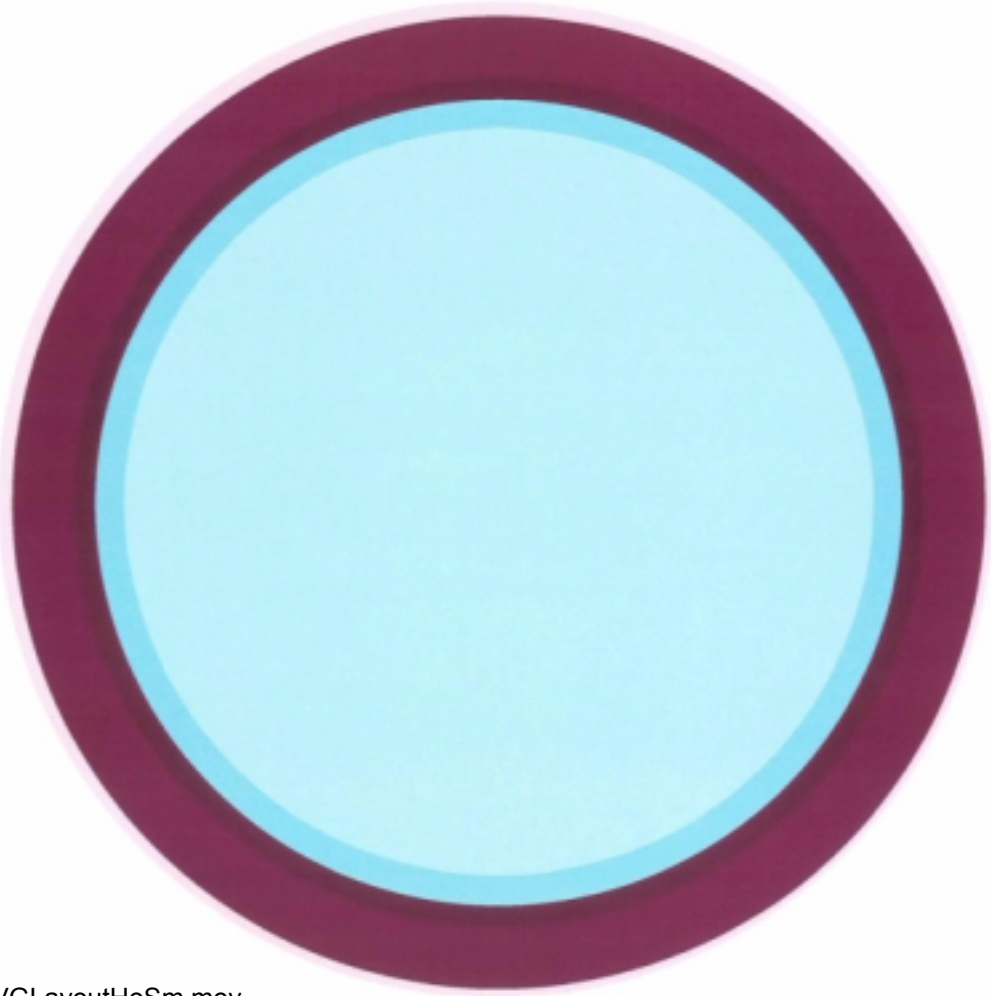
~2 mm diameter

The hohlraum must provide a symmetric implosion at the required velocity

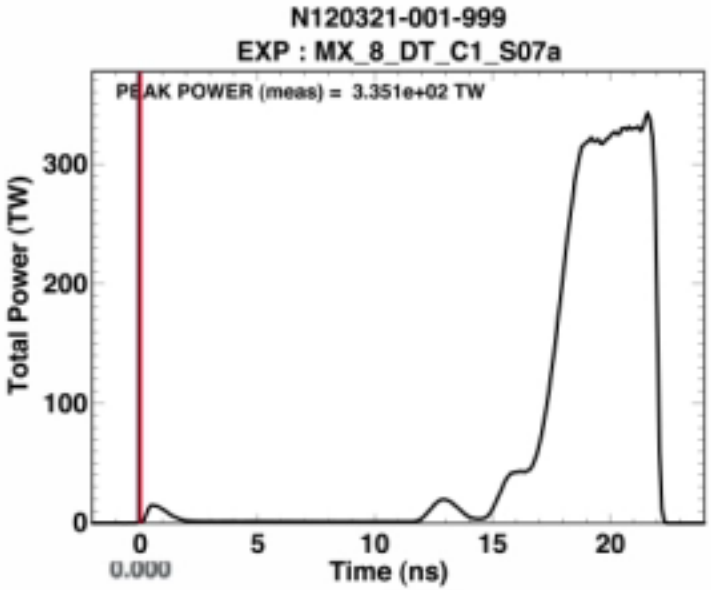




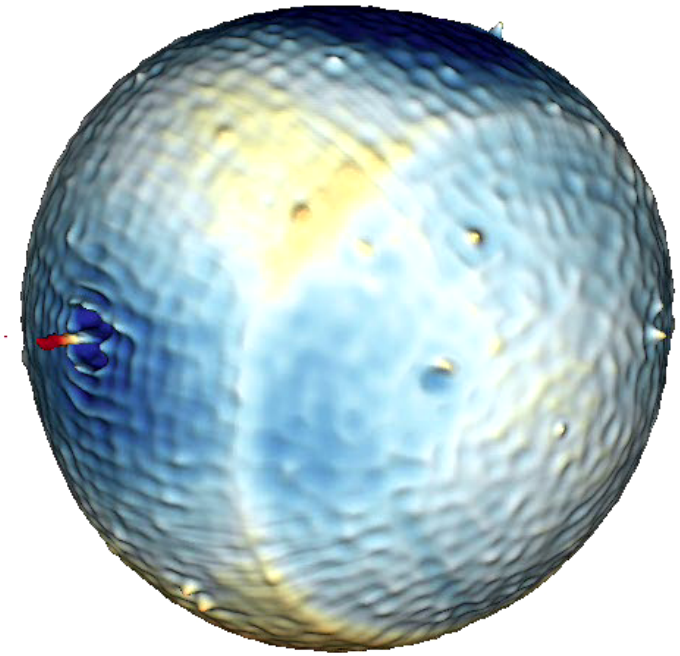
The capsule must be designed to withstand hydrodynamic instabilities



VGLayoutHoSm.mov



The real world is 3D…..



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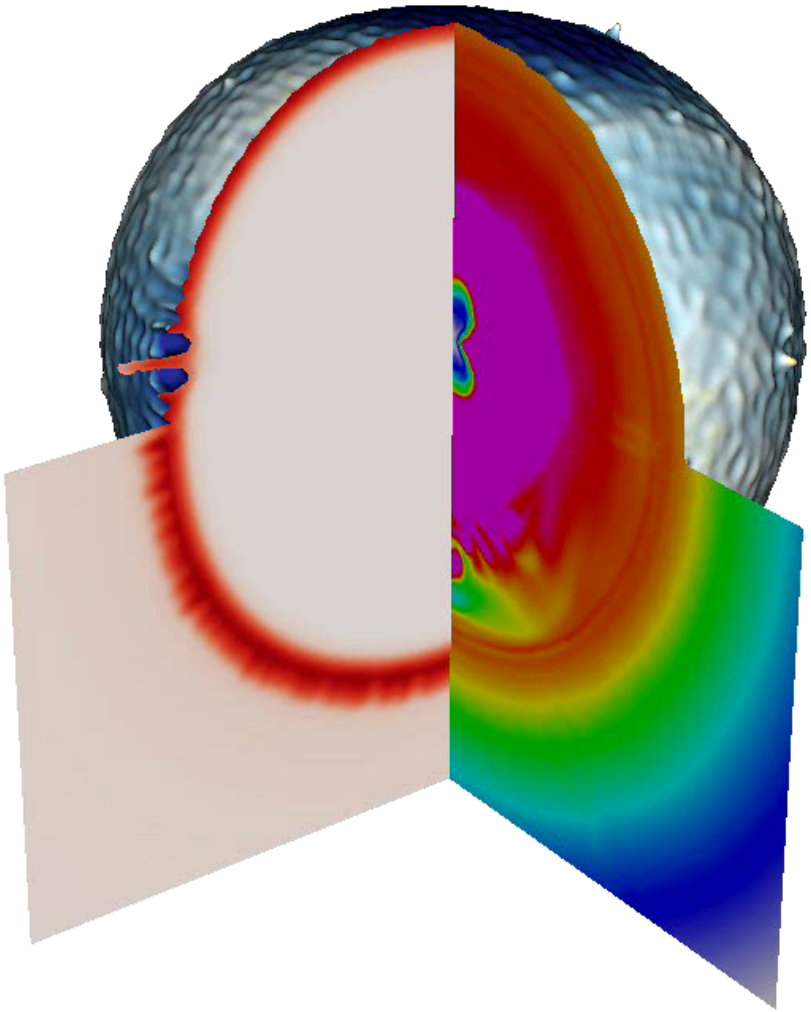
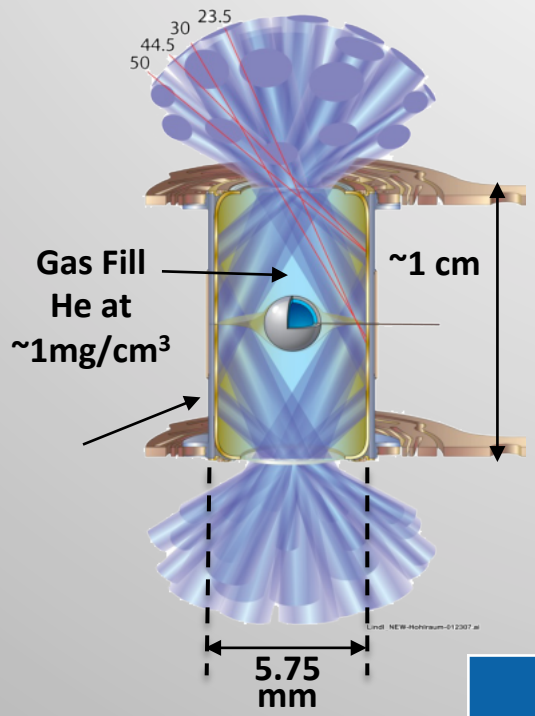
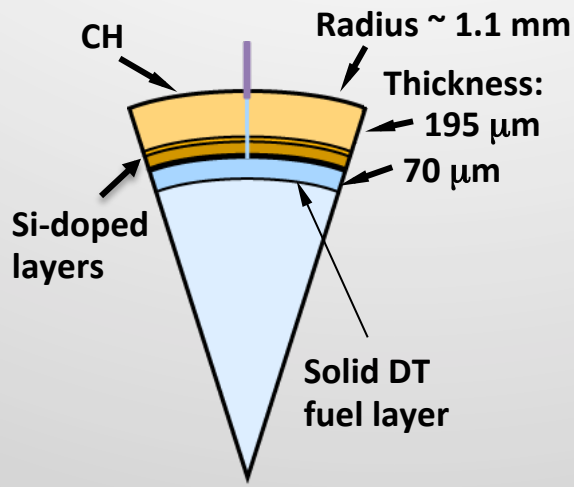
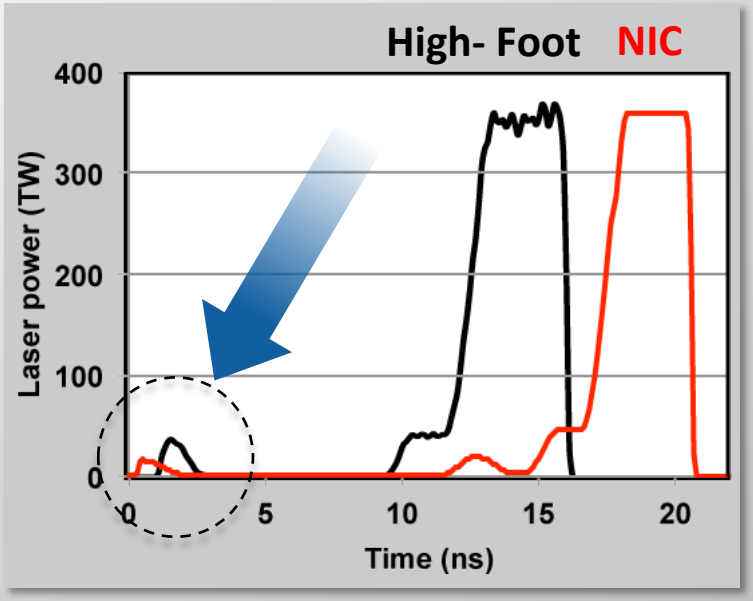


The new "High-foot" is a pulse-shape modification designed to reduce hydrodynamic instability





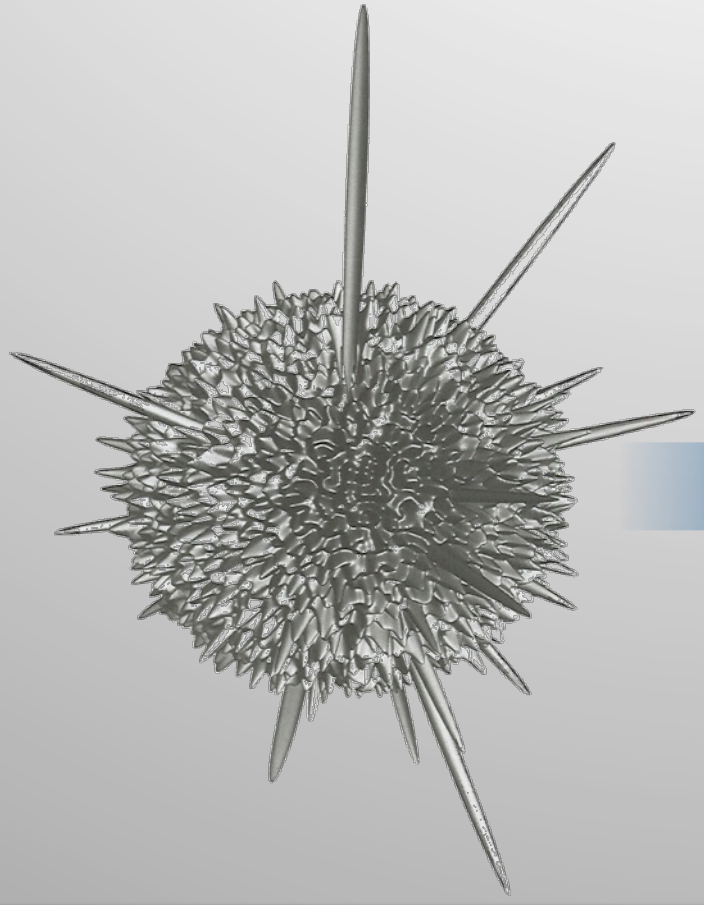


	NIC Low-foot		High-foot
Adiabat (a measure of entropy)	~1.5	**Increased to:**	~2.5
In-flight aspect ratio, (IFAR)	~20	**Reduced to:**	~10
Convergence	~45	**Reduced to:**	~30

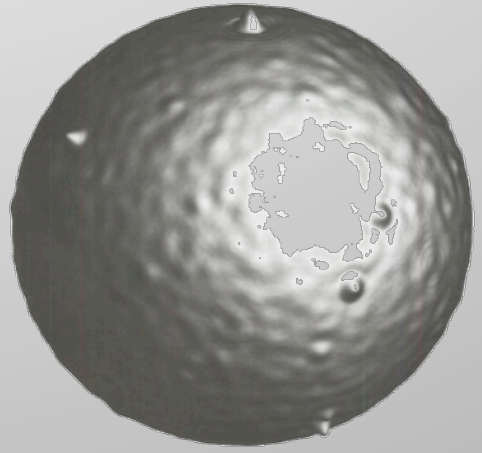
GOAL: Performance that is understood and well matched to calculations

Prediction – capsule surface at peak velocity

Low-foot

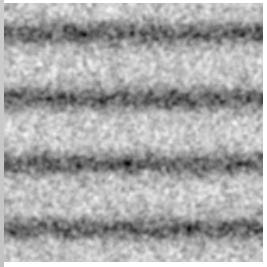


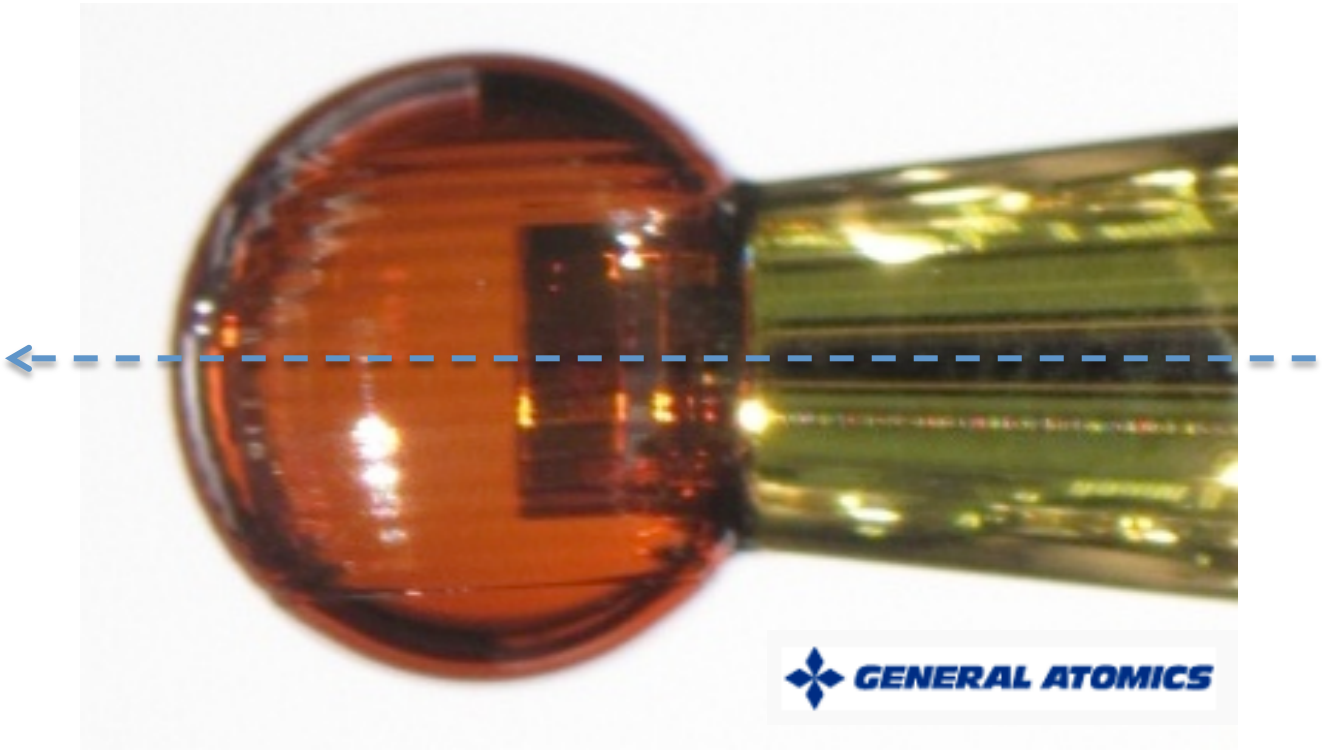
High-foot



Detailed experiments on ablation RT instability verified our assertions about stability and modeling

Image plane

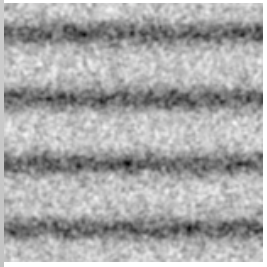


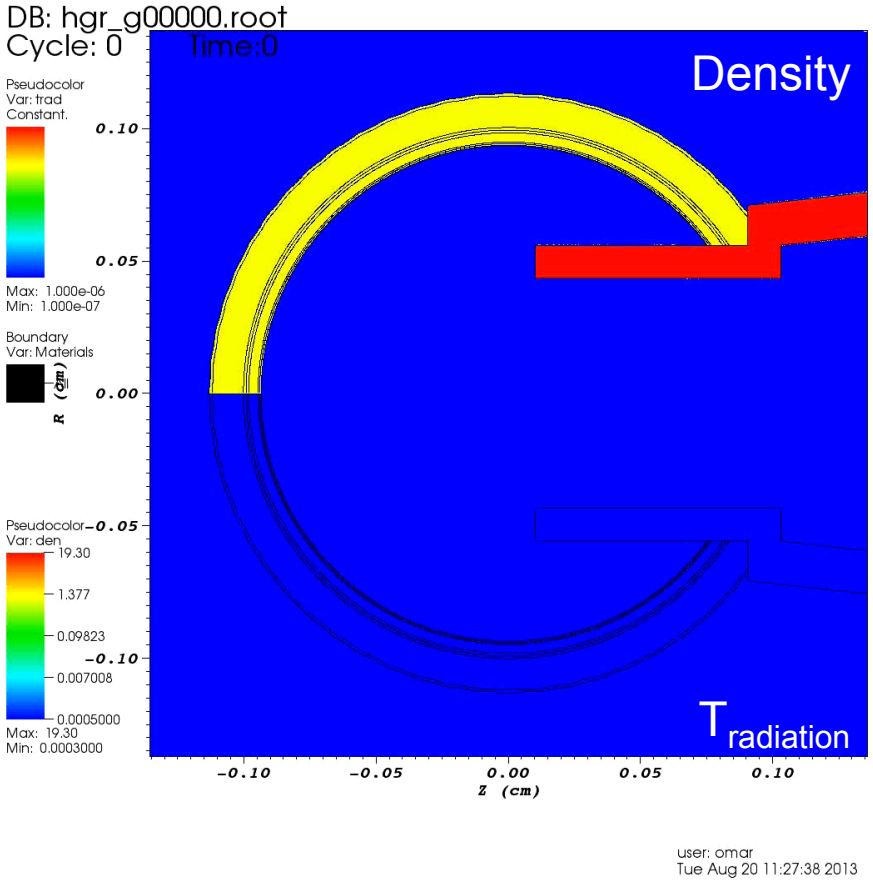


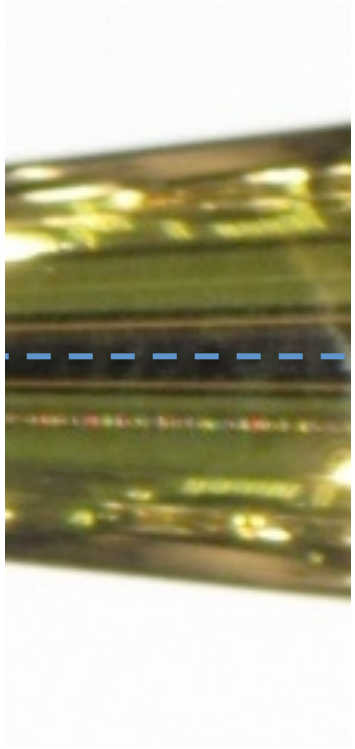
Backlighter x-rays

Detailed experiments on ablation RT instability verified our assertions about stability and modeling

Image plane

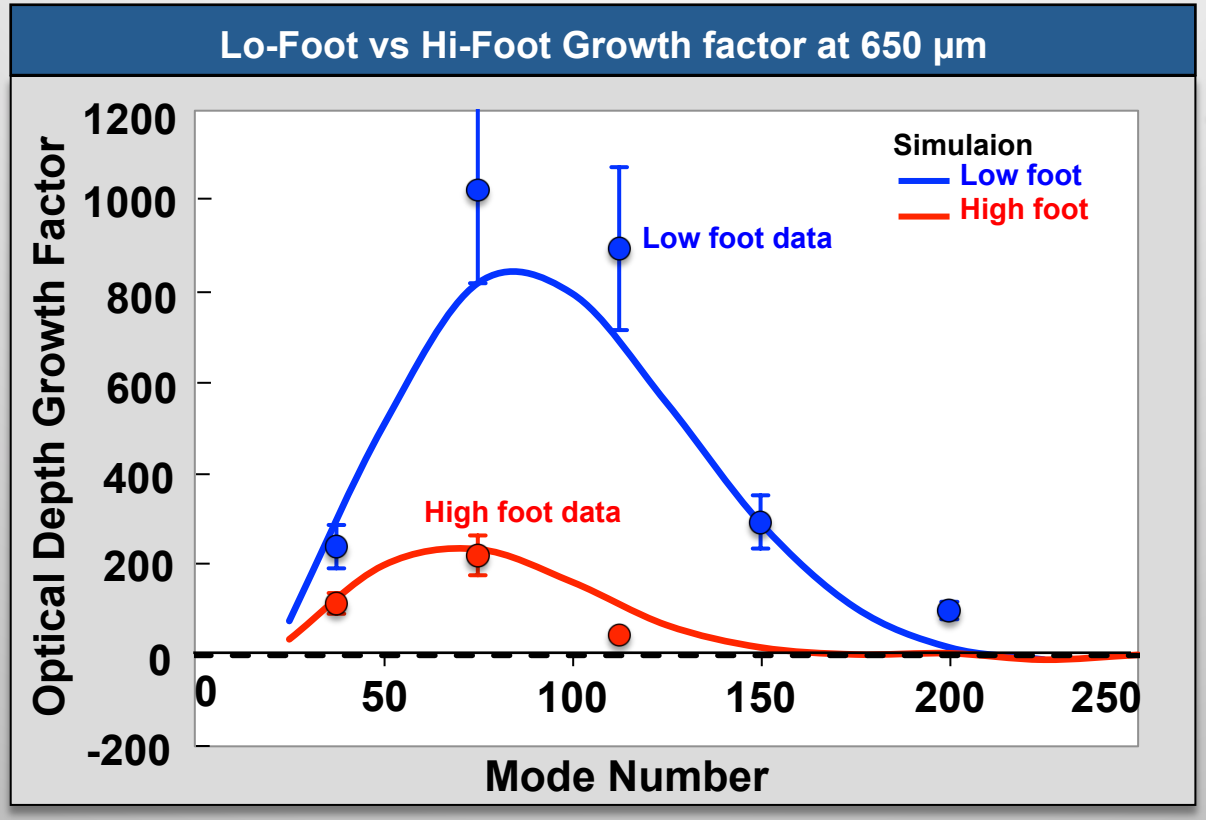


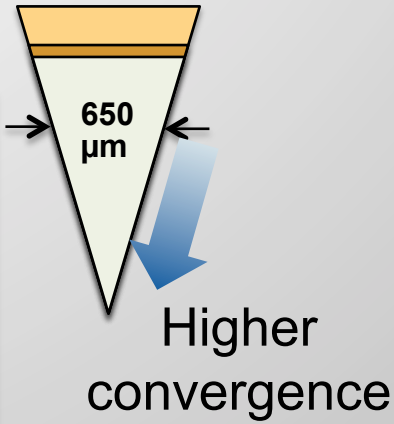




Backlighter x-rays

Predictive capability for implosions depends on our ability to simulate growth of perturbations



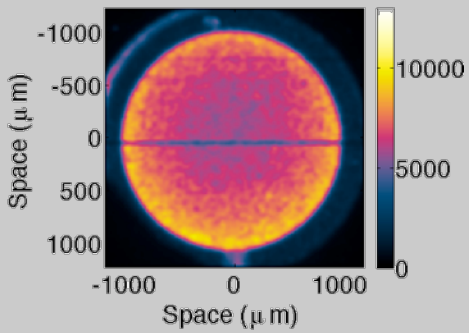


Future developments:

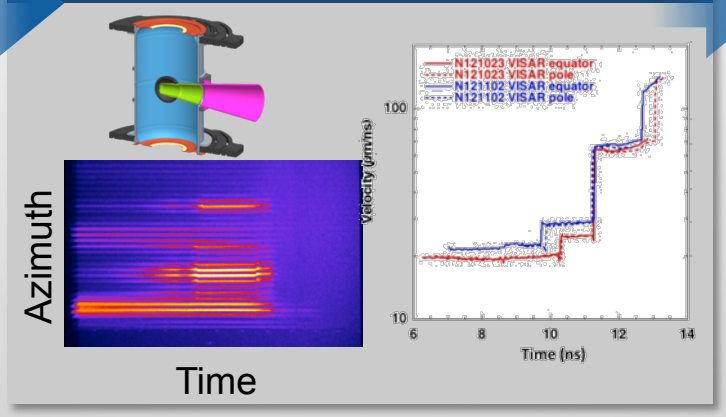
- Native surfaces
- Mitigation schemes – e.g. adiabat shaping, drive spectrum control

A number of prepatory experiments need to be performed before firing a yield producing DT shot

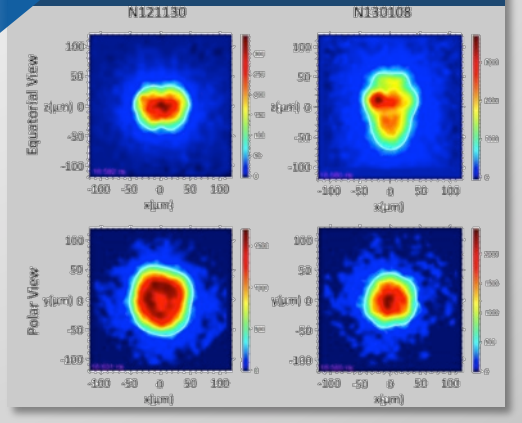
X-Ray drive symmetry ("Re-emit")



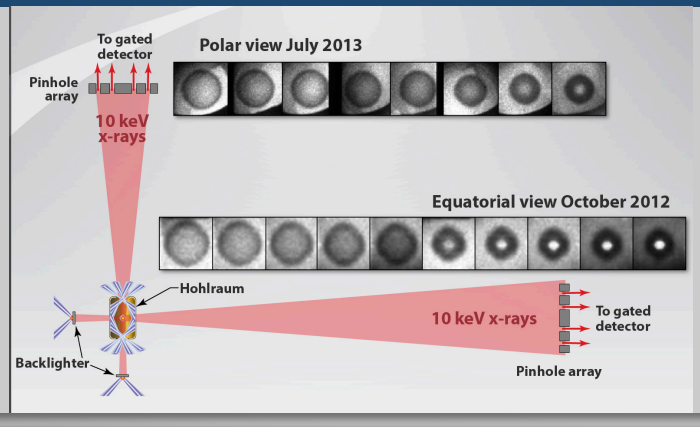
Shock-timing ("Keyholes")



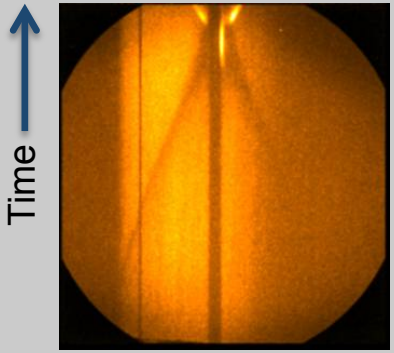
Hot-spot shape ("Symcaps")



Implosion shape ("2DConA's")



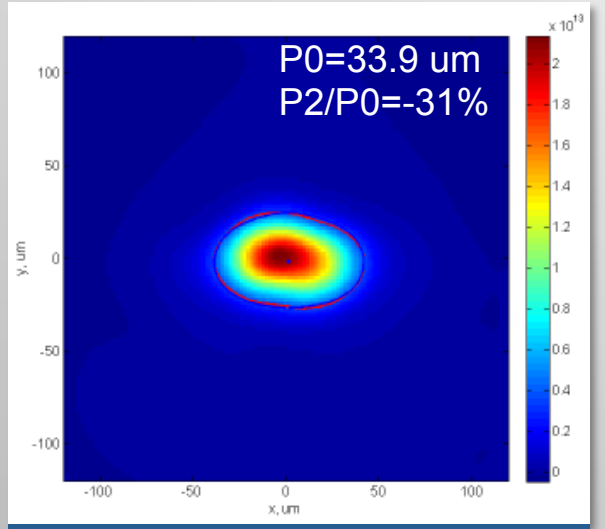
Ablator trajectory and speed ("1DConA's")



... DT shot!

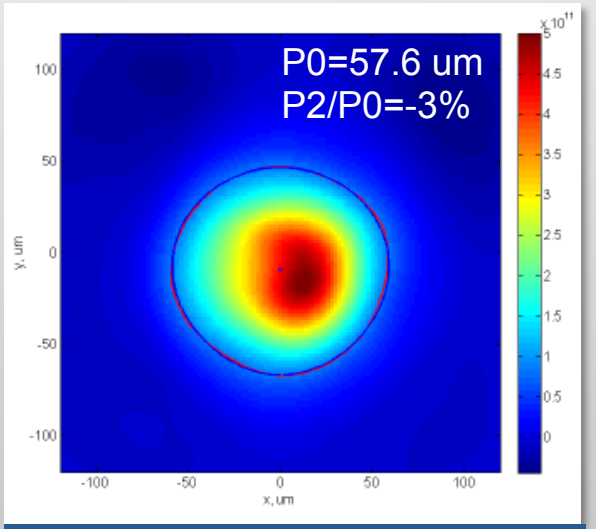
Neutron imager measures location of hot spot and cold fuel (N140304)

Unscattered
13-17 MeV



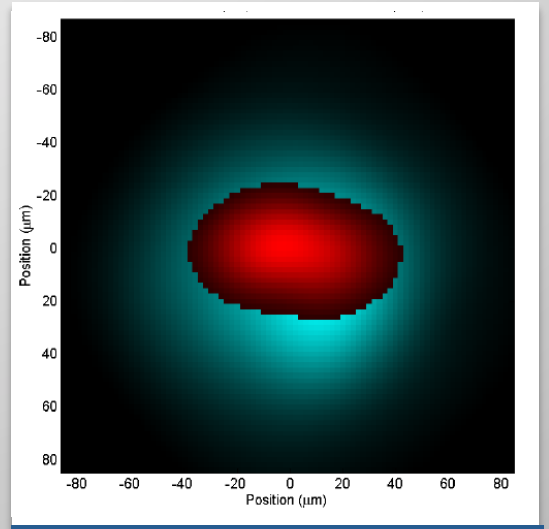
Hot spot

Downscattered
6-12 MeV

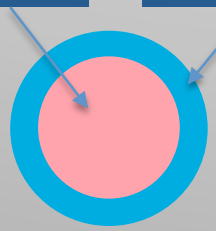


"Cold" fuel

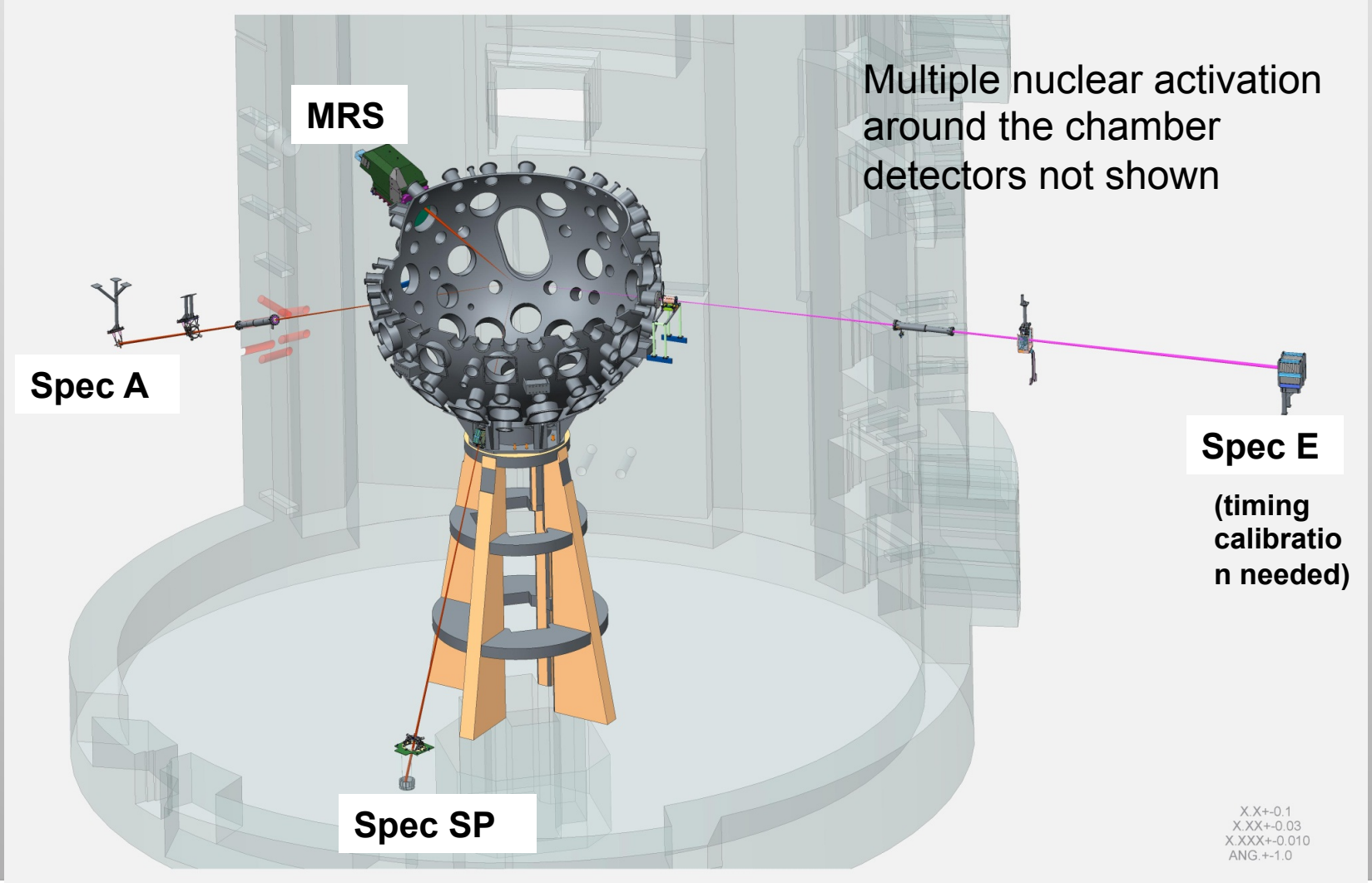
Over-layed images



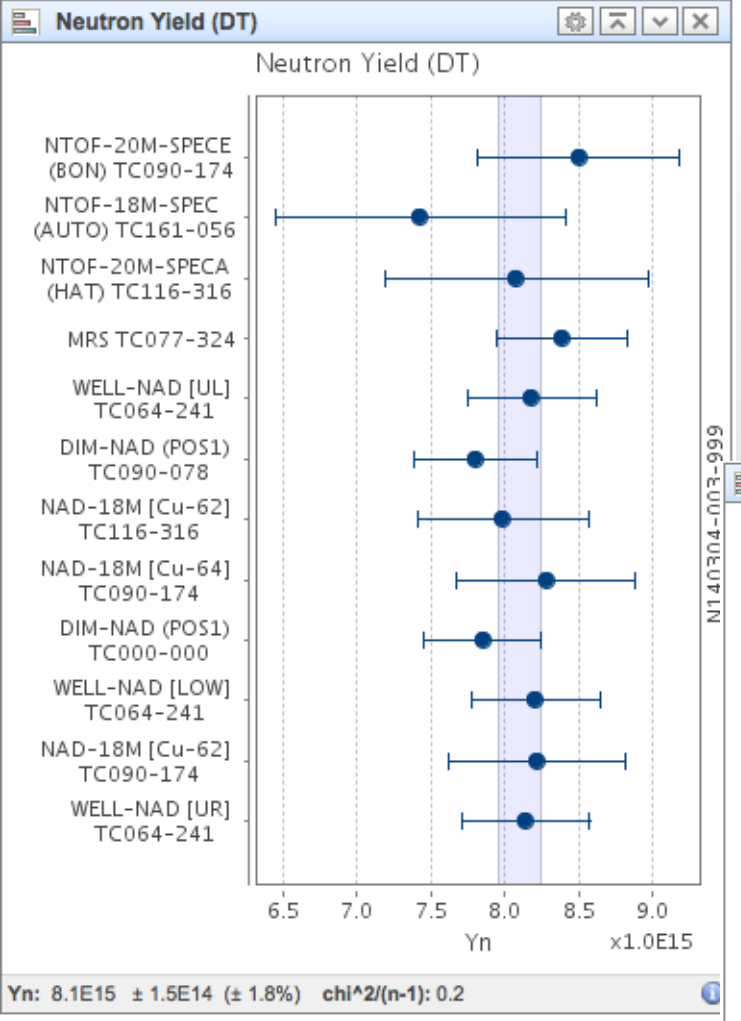
Registered



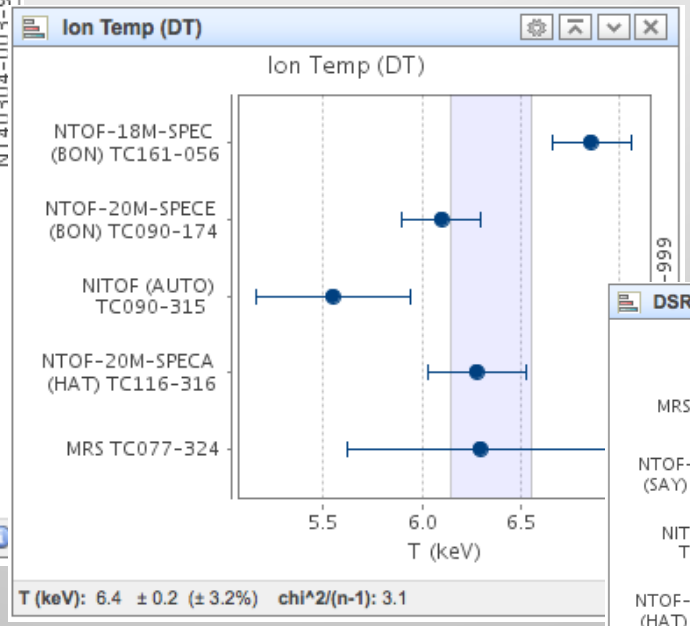
Neutron spectrometers to measure stagnated fuel



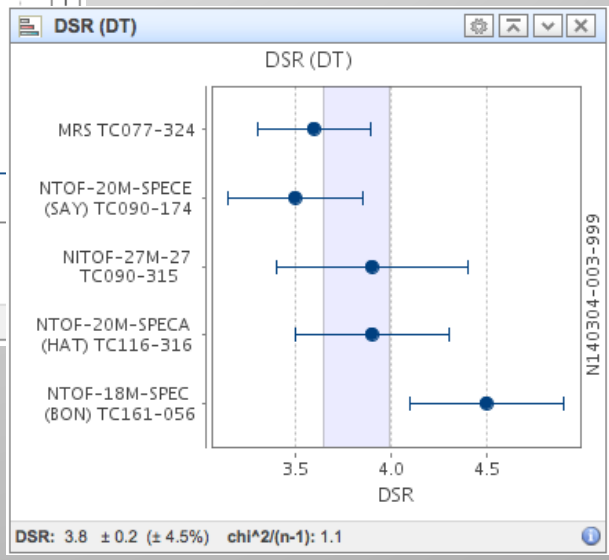
Nuclear data from typical shot (note asymmetries)



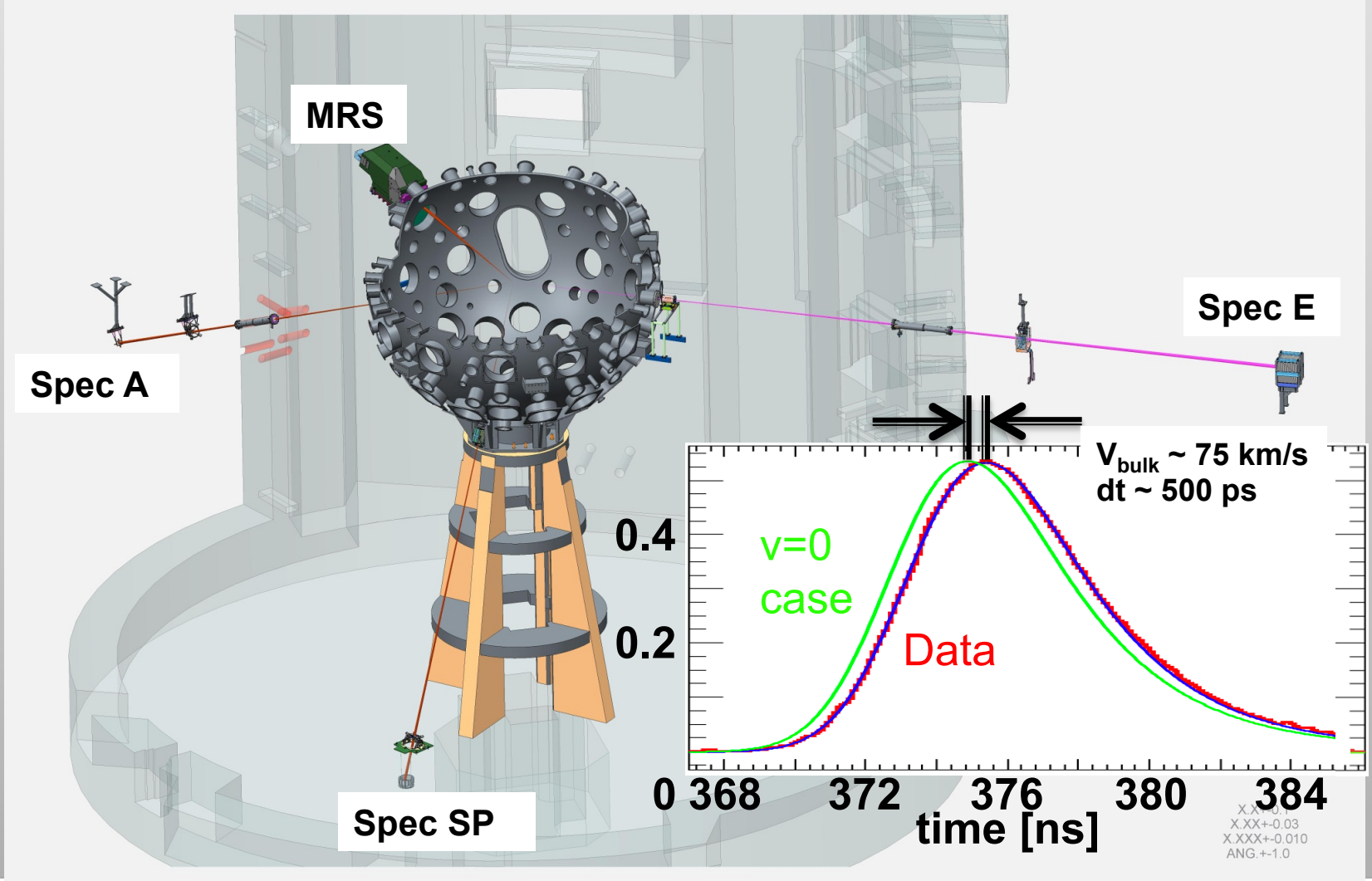
Tion



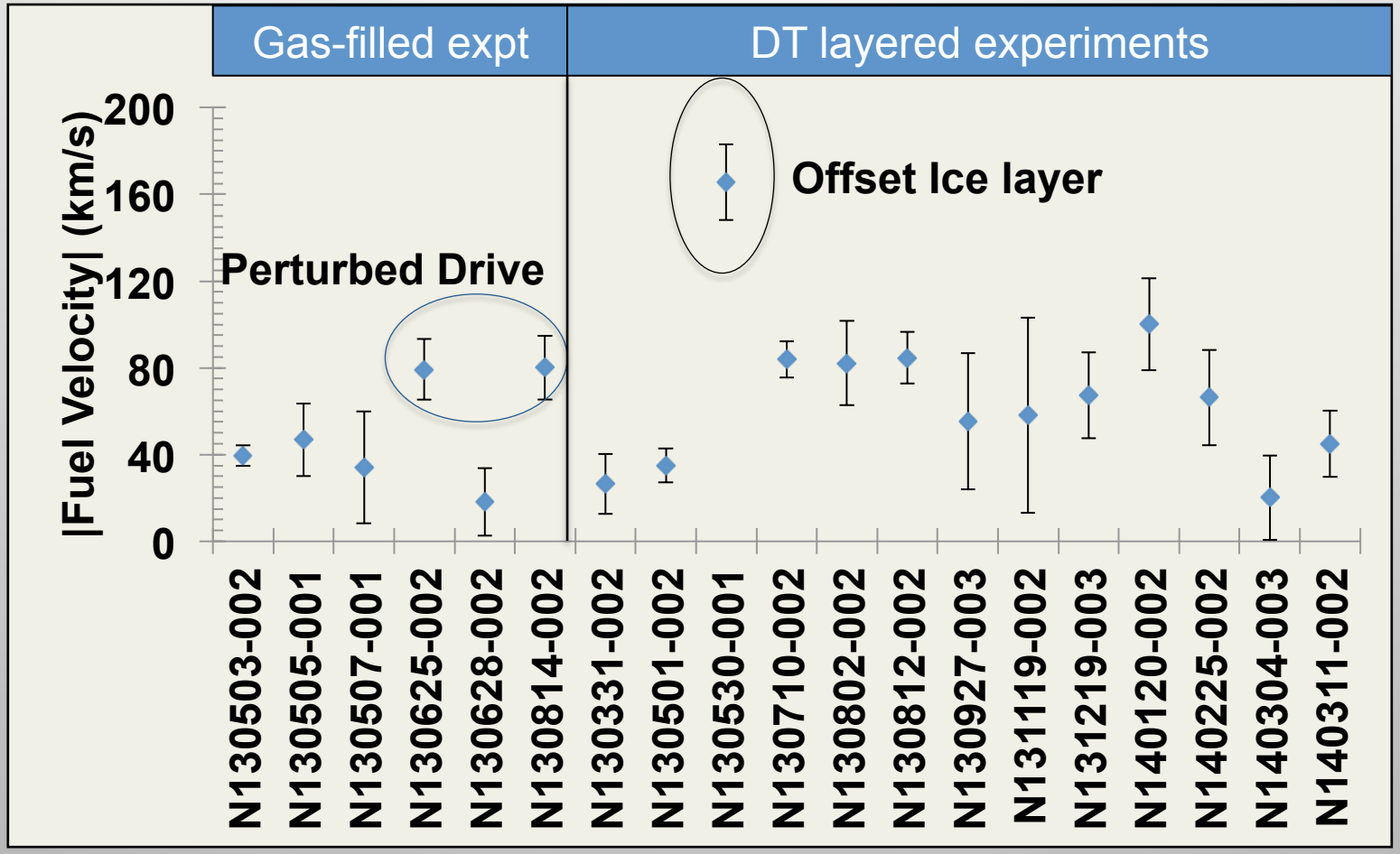
"dsr" ~ ρR/21 g/cm^2



Three nearly orthogonal nToF's and MRS -> high quality average fuel velocity

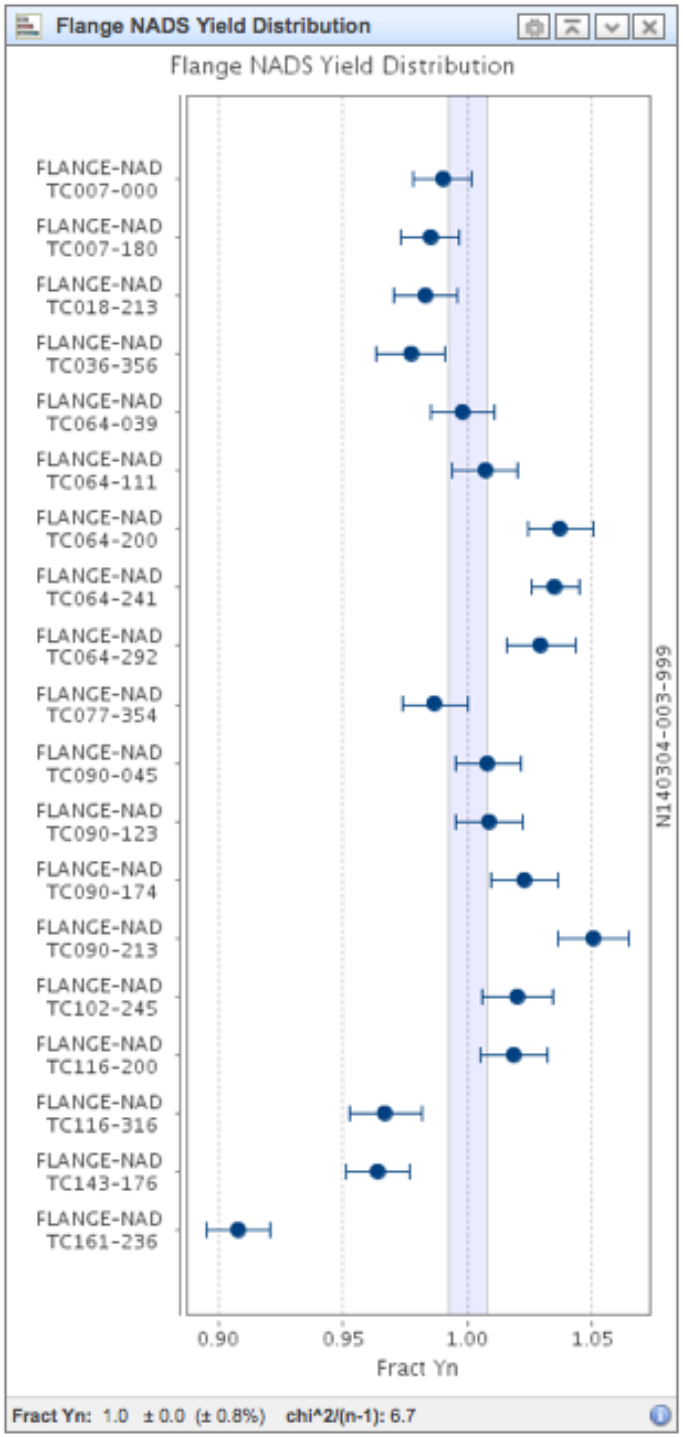


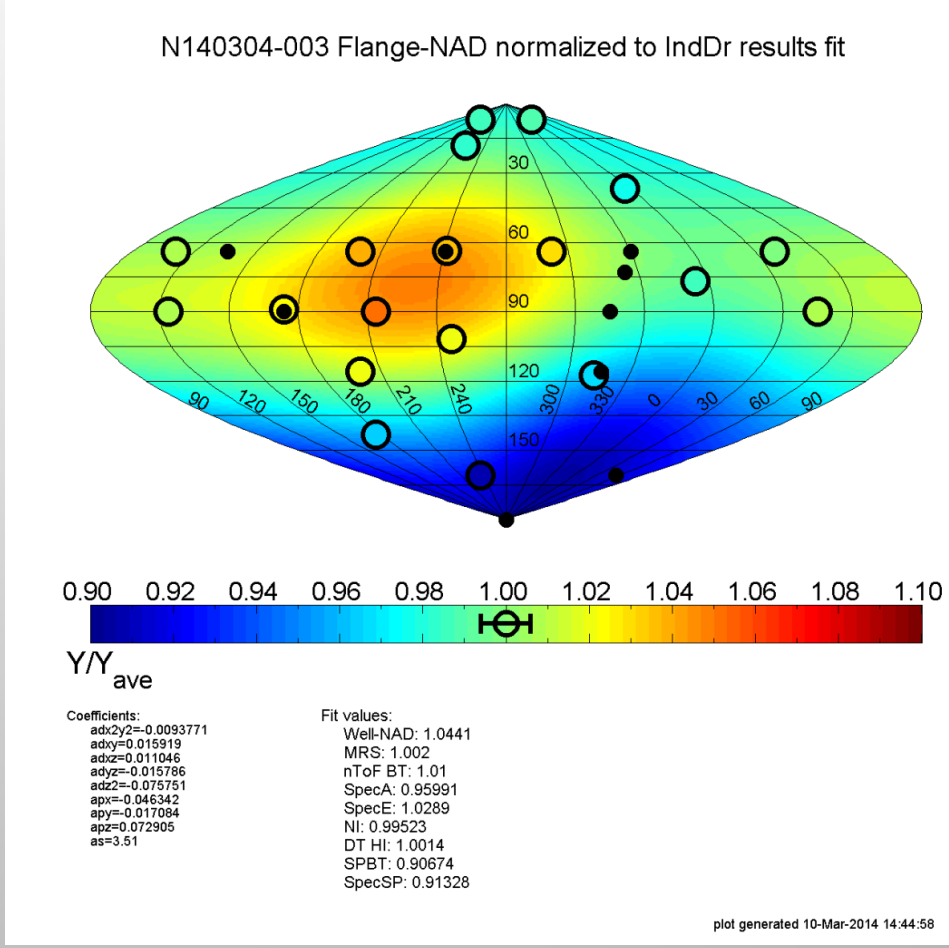
Preliminary analysis from new nToFs show sizable fuel velocities at "stagnation"



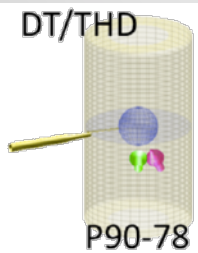
Some velocities are large enough to be significant
Currently subject of ongoing scrutiny

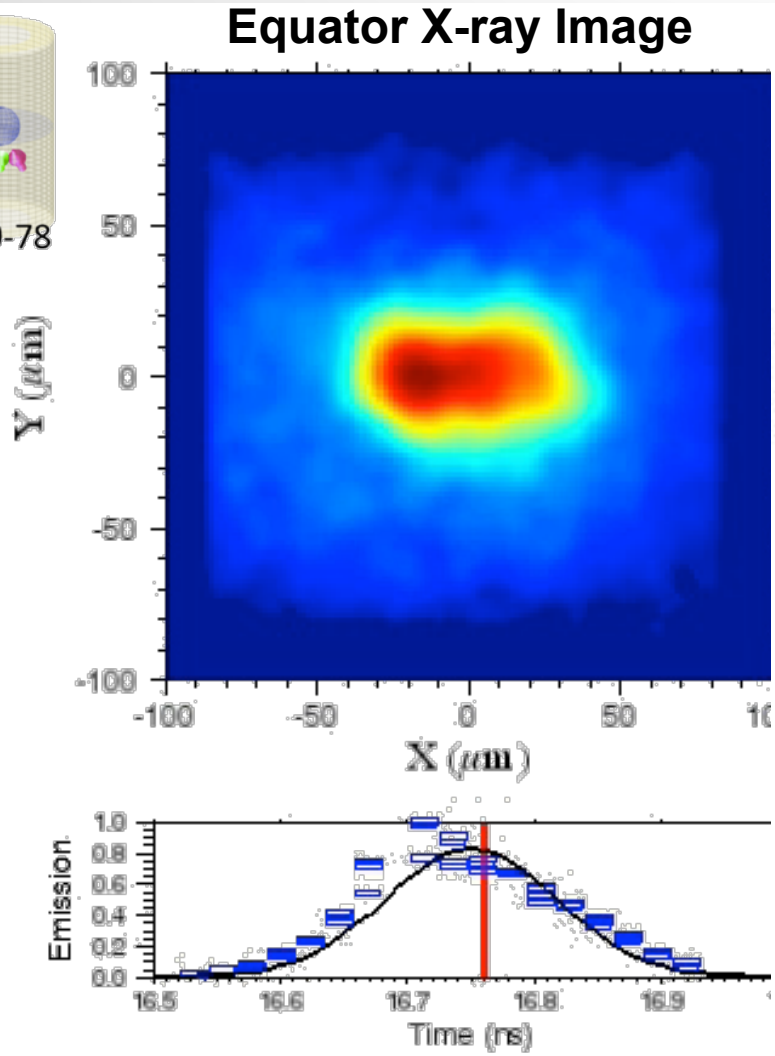
Nuclear activation data from N140304 (fuel ρR variations)

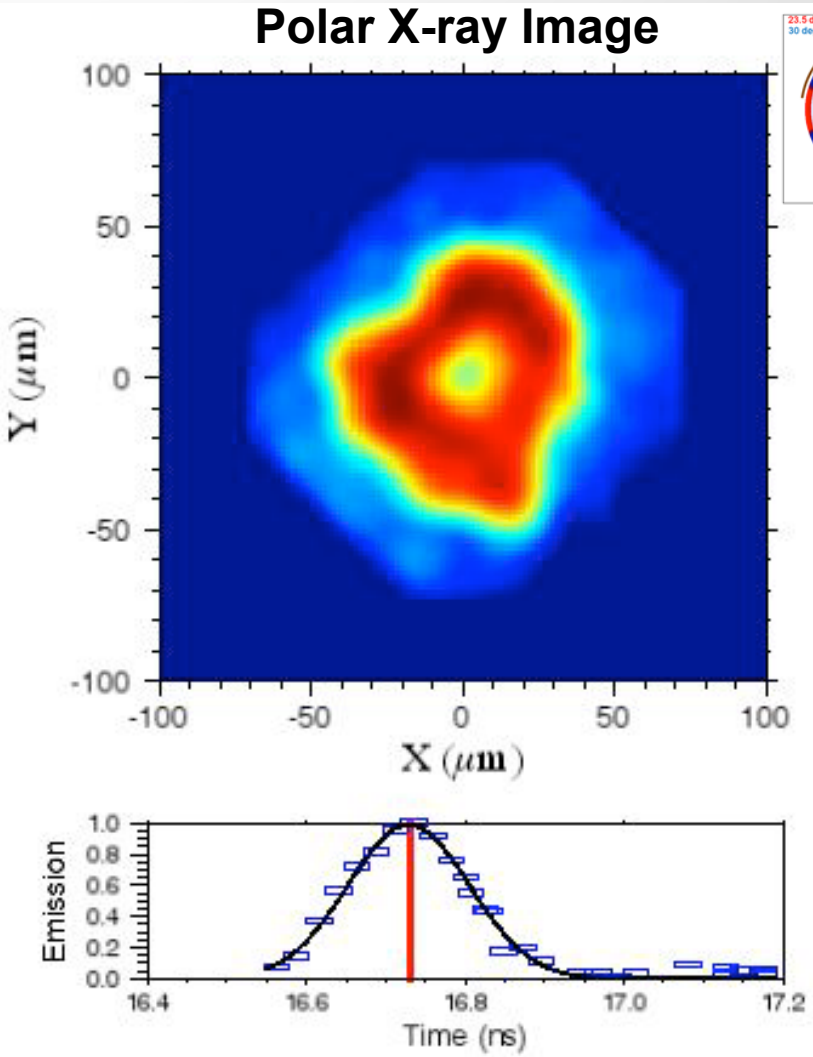


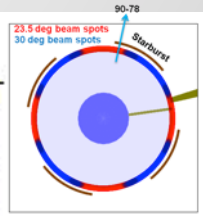


Many high-foot implosions had a toroidal shape









High-foot DT N130812

We can estimate the DT fuel energy balance from measured quantities

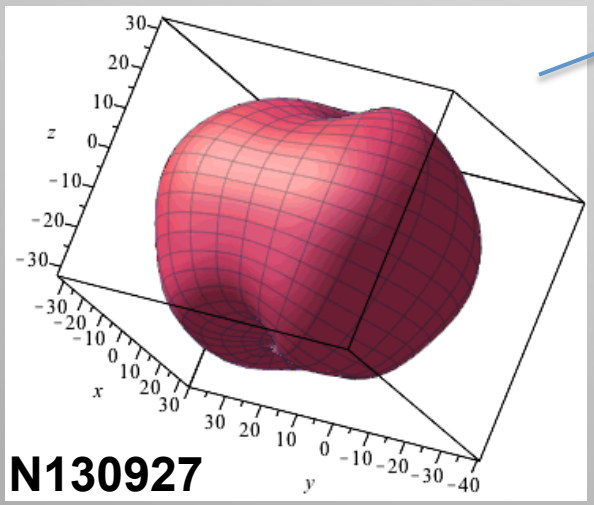
DT reaction-rate

$$T_{ion} \rightarrow \langle \sigma v \rangle$$

Fusion power density

$$E_{fusion} = 7.04 \times 10^{-13} n^2 \langle \sigma v \rangle V_{hs} \tau \quad \begin{cases} m_{hs} \\ P_{hs} \\ \rho r_{hs} \rightarrow f_\alpha \rightarrow E_\alpha \\ \frac{3}{2} P_{hs} V_{hs} \end{cases}$$

Reconstructed hot-spot shape to obtain volume



Mass conservation and *DSR* measurement (Check consistency with neutron images)

$$r_{fuel} - r_{hs} = \sqrt{\frac{m_{fuel}}{2\pi(\rho r)_{fuel}} - r_{hs}^2} - r_{hs}$$

Isobaric assumption

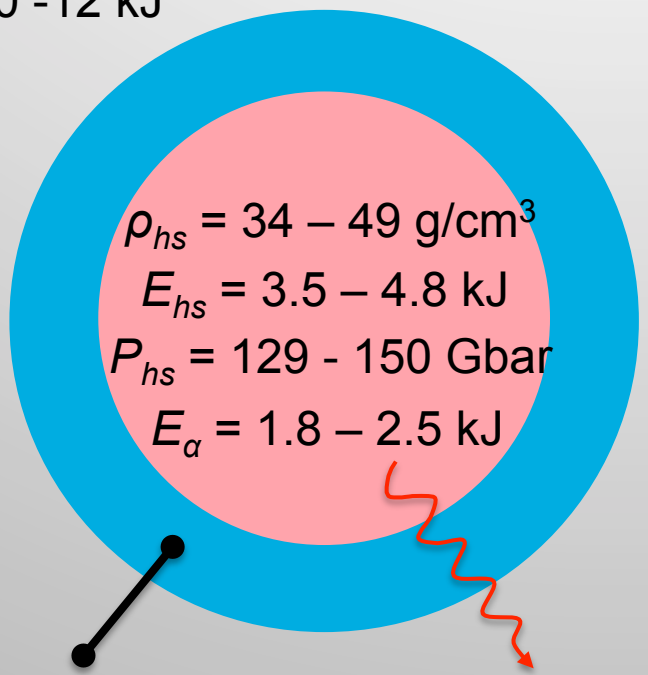
$$\frac{3}{2} P_{fuel} V_{fuel} \qquad \alpha = \frac{P_{fuel}}{P_{Fermi}}$$

Energy budget for N130927
$G_{fuel} = Y_{total}/E_{DT} > 1.2$

Y_{total} = 14.4 kJ

$$E_{DT} = E_{hs} + E_{fuel} + \tfrac{1}{2} e^{-\tau_{fuel}} E_{Brems} - \tfrac{1}{2} E_{\alpha}$$

= 10 -12 kJ



ρ_{fuel} = 385 – 402 g/cm^3 E_{Brems} = 2.3 – 4.5 kJ

E_{fuel} = 6.9 – 7.8 kJ τ_{fuel} = 0.32 – 0.66

α = 2.9 – 3.3

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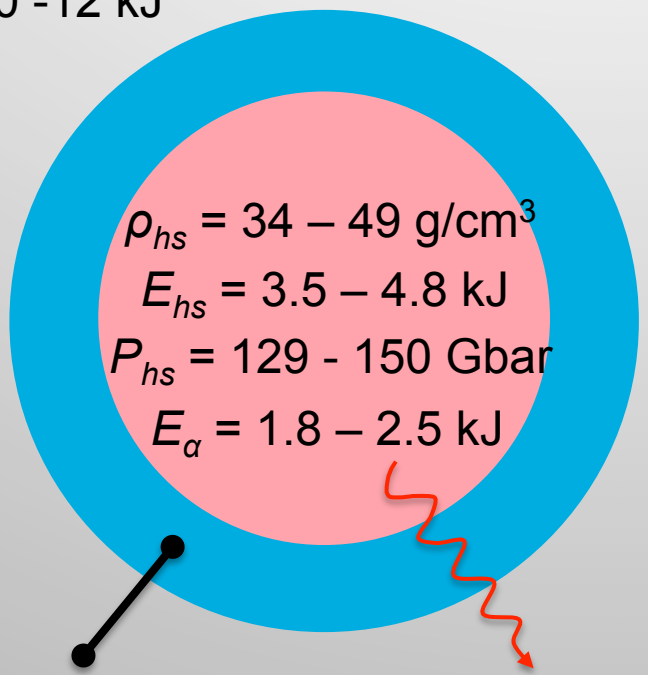

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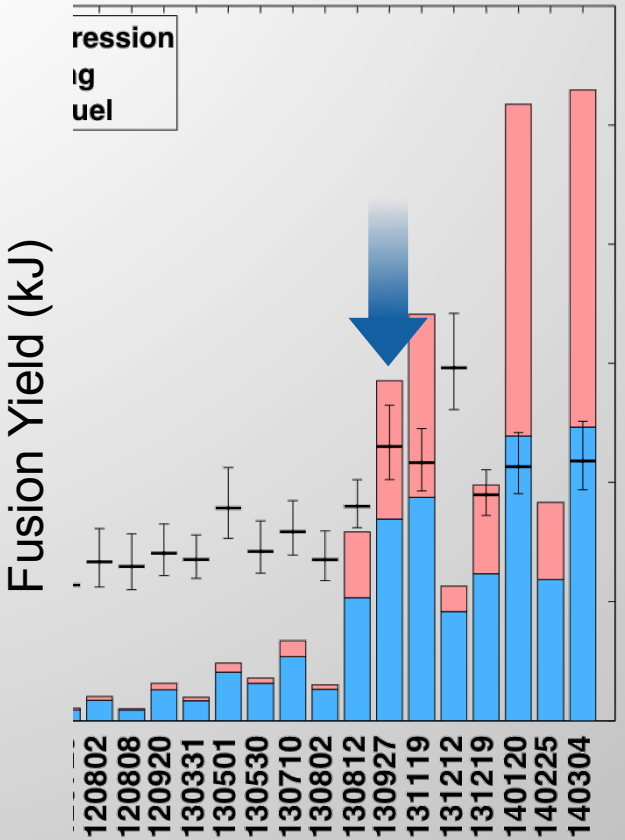
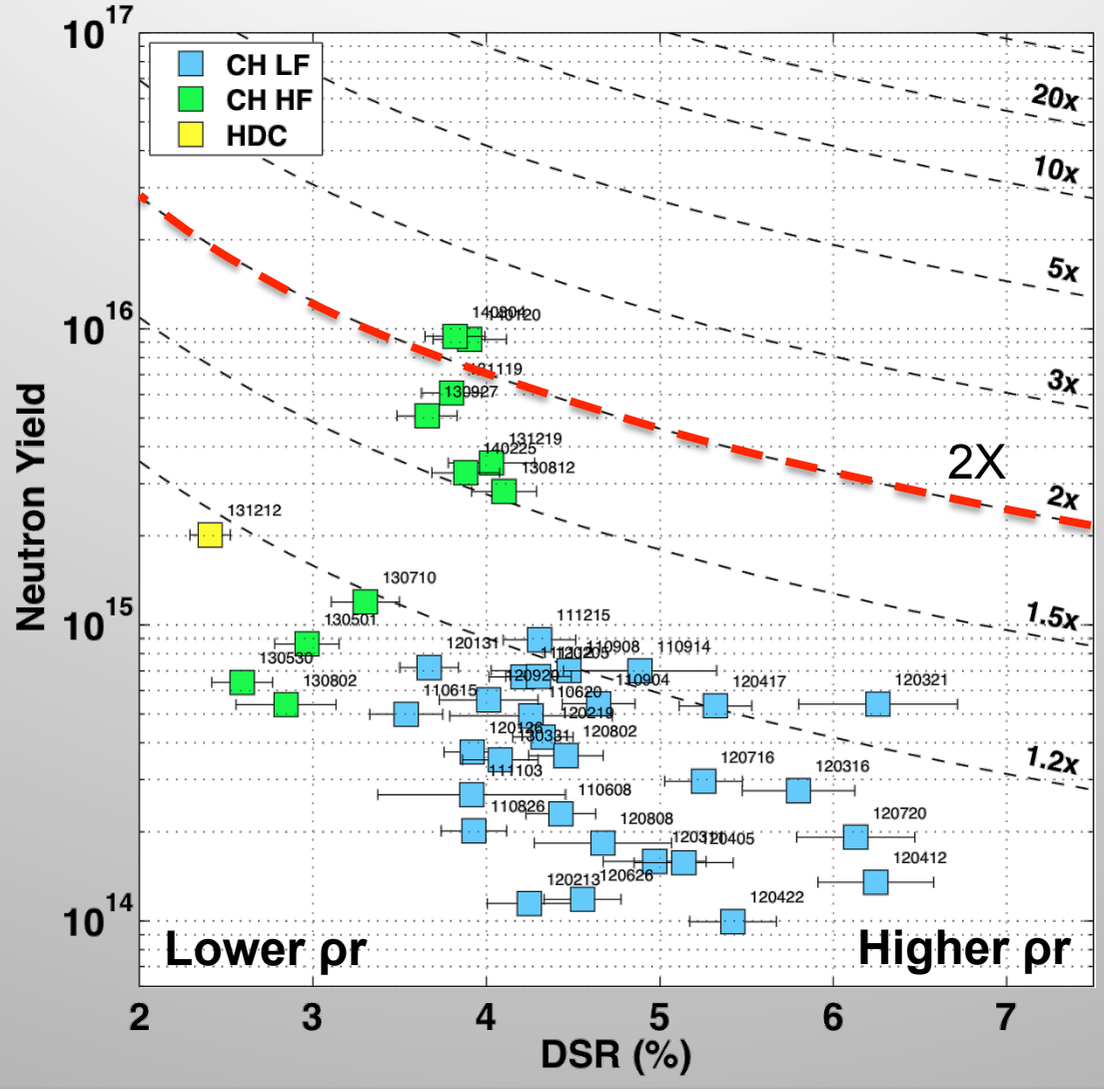


Experiments are entering a new regime "α-heating" becoming significant

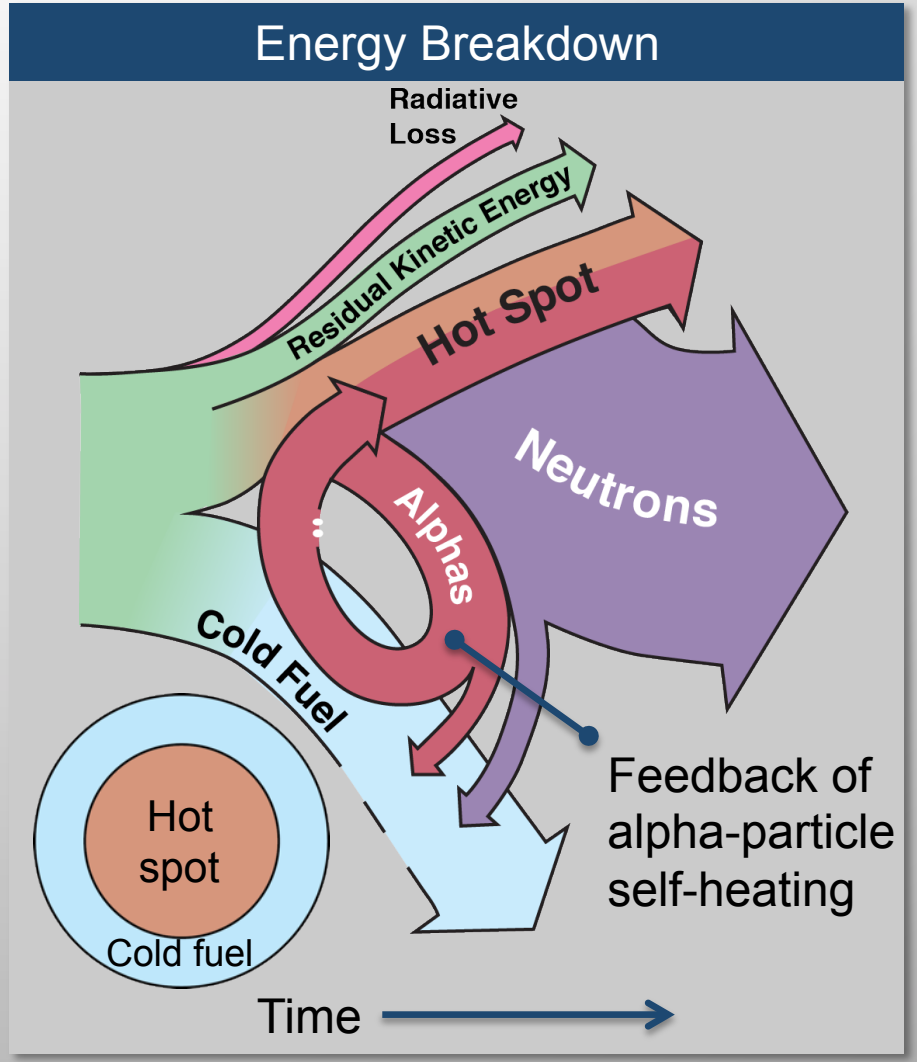


Yield multiplication (from alpha-heating) contours

$$\rho r_{fuel} \approx 20.3 \cdot f \cdot DSR$$

Key issues have been identified and self-heating is becoming significant

- Capsule instability and "mix" was a major factor limiting performance
- We must now get the implosion speeds up and try to compress the DT more while maintaining control of shape and mix
- We will likely encounter other phenomena that will have to be overcome eg recent work on impacts of hot electrons
- This will be challenging, but of course there are many ideas!
  - Adiabat shaping
  - Drive spectrum control
  - Hohrlaum dopants
  - Shaped hohlraums
  - Diamond/beryllium ablators
  -



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