Progress Towards Ignition on the National Ignition Facility (NIF)

Presented to ICTP-IAEA College on Advanced Plasma Physics

20th August, 2014

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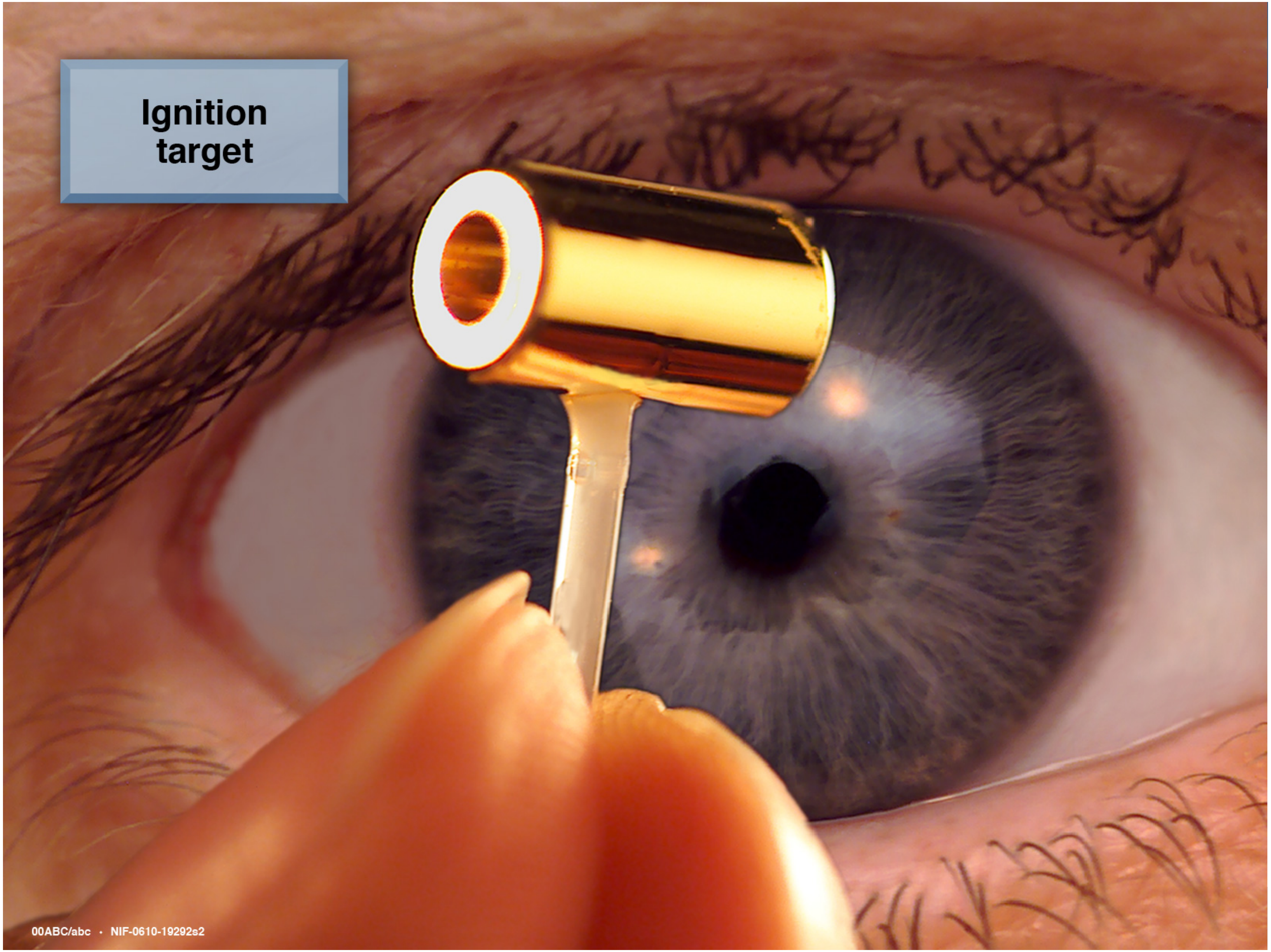
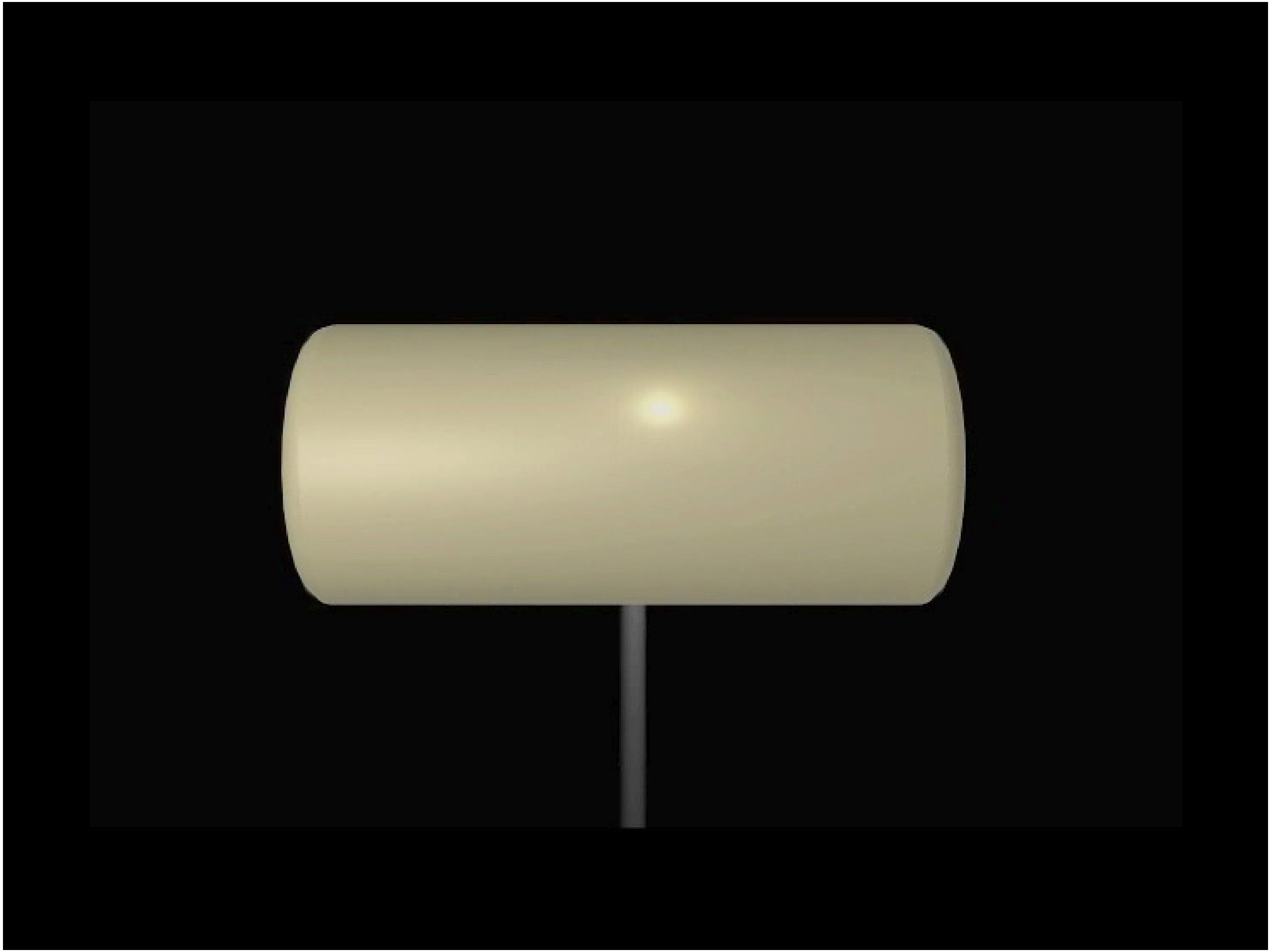
Lawrence Livermore National Laboratory

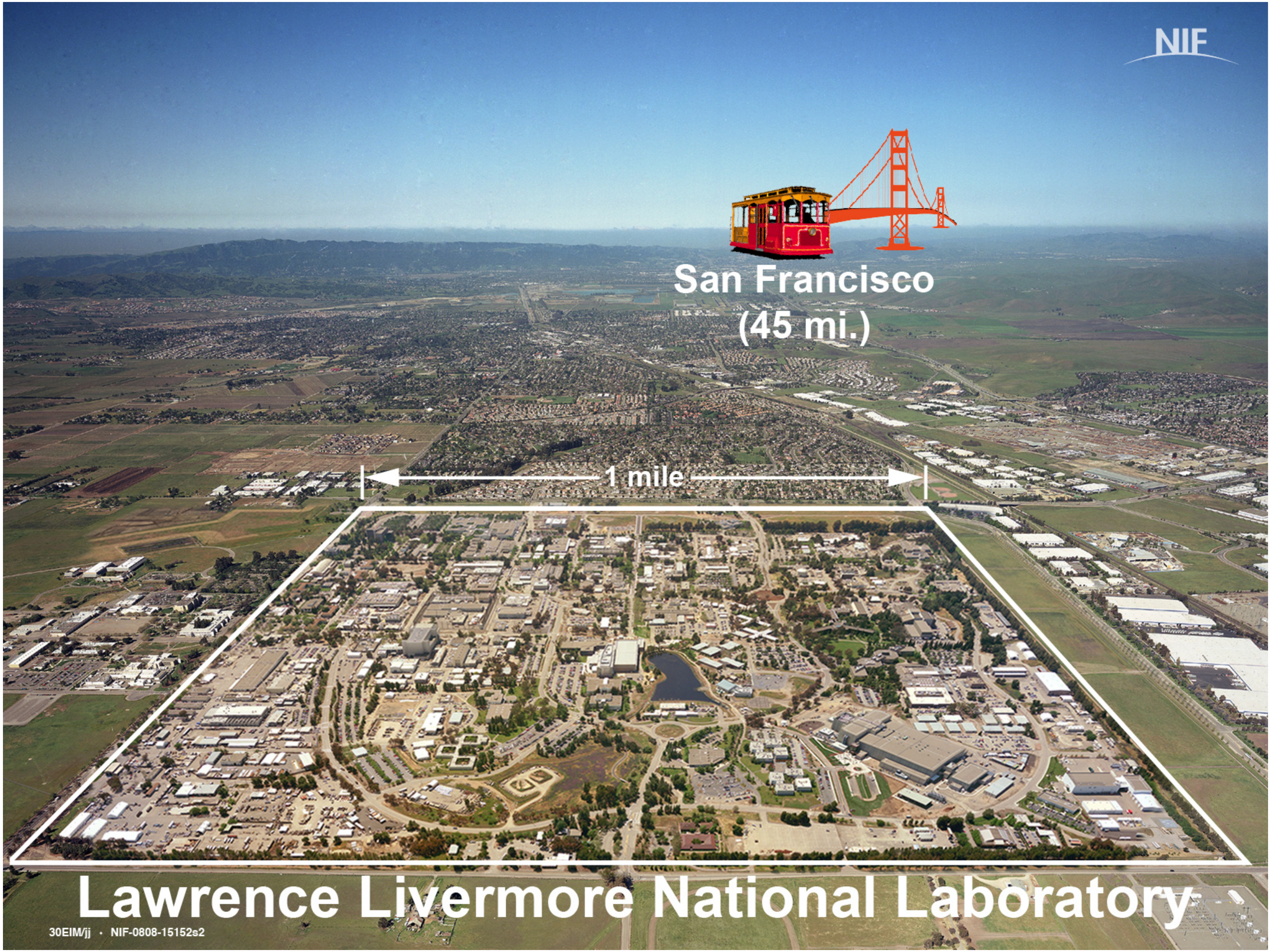
NIF

LLNL-PRES-XXXXXX

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC


Ignition target
00ABC/abc • NIF-0610-19292s2





NIF
San Francisco
(45 mi.)
1 mile
Lawrence Livermore National Laboratory
30EIM/jj • NIF-0808-15152s2

NIF is the first laser capable of producing ignition and energy gain

NIF is the culmination of over 40 years investment in this field

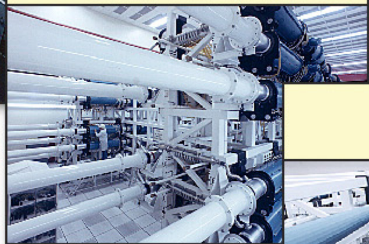
Janus, 1974

100J IR

Argus, 1976

1kJ IR

Shiva, 1977



10kJ IR

Nova, 1984

30kJ UV

NIF, 2009

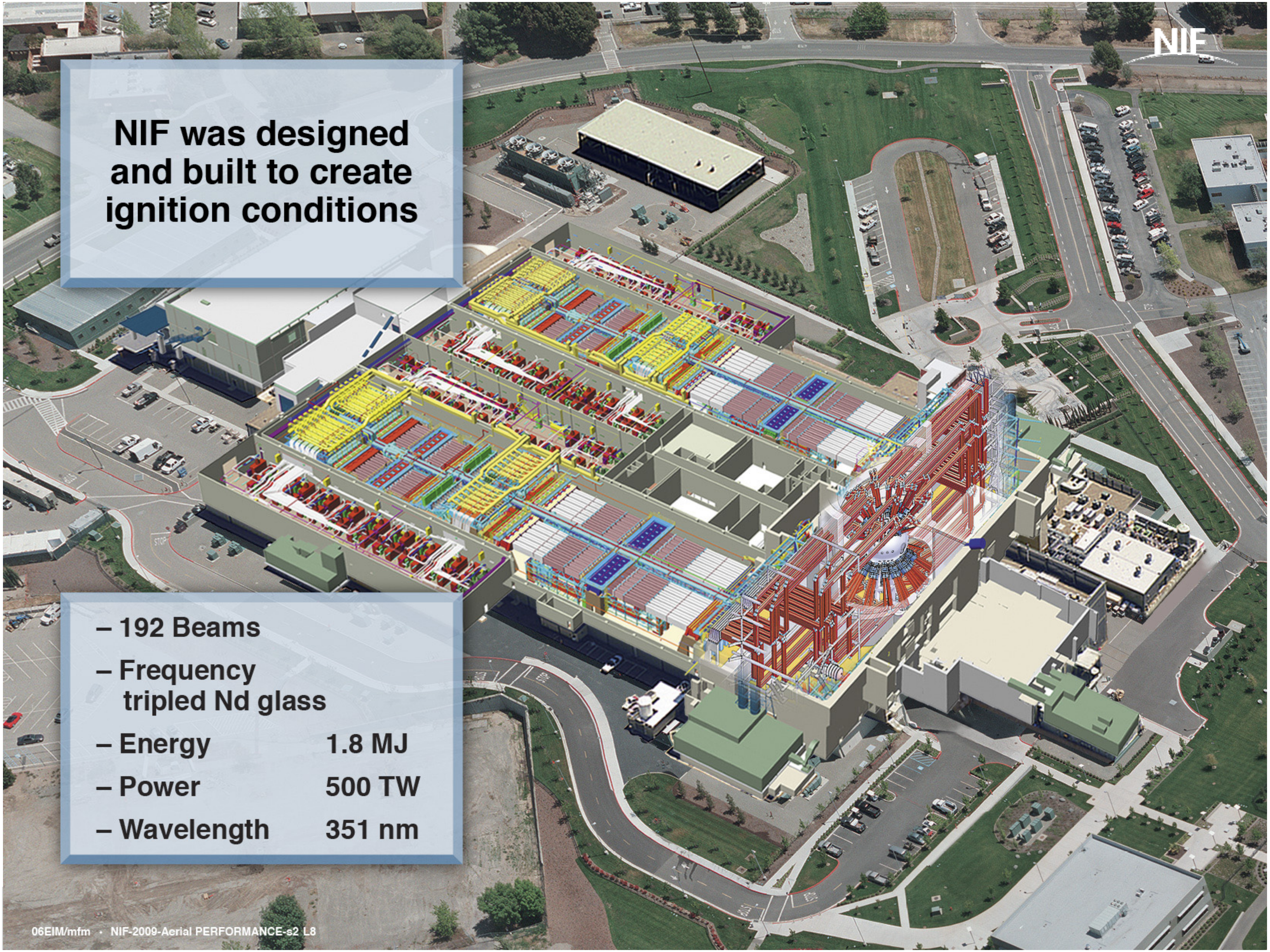
1.8 MJ UV


NIF
NIF is now operational and ignition campaigns are underway
NIF is the first laser capable of achieving fusion gain
07EIM/tr • NIF-2009-Aerial STATUS-s2 L4

NIF was designed and built to create ignition conditions

– 192 Beams
– Frequency tripled Nd glass

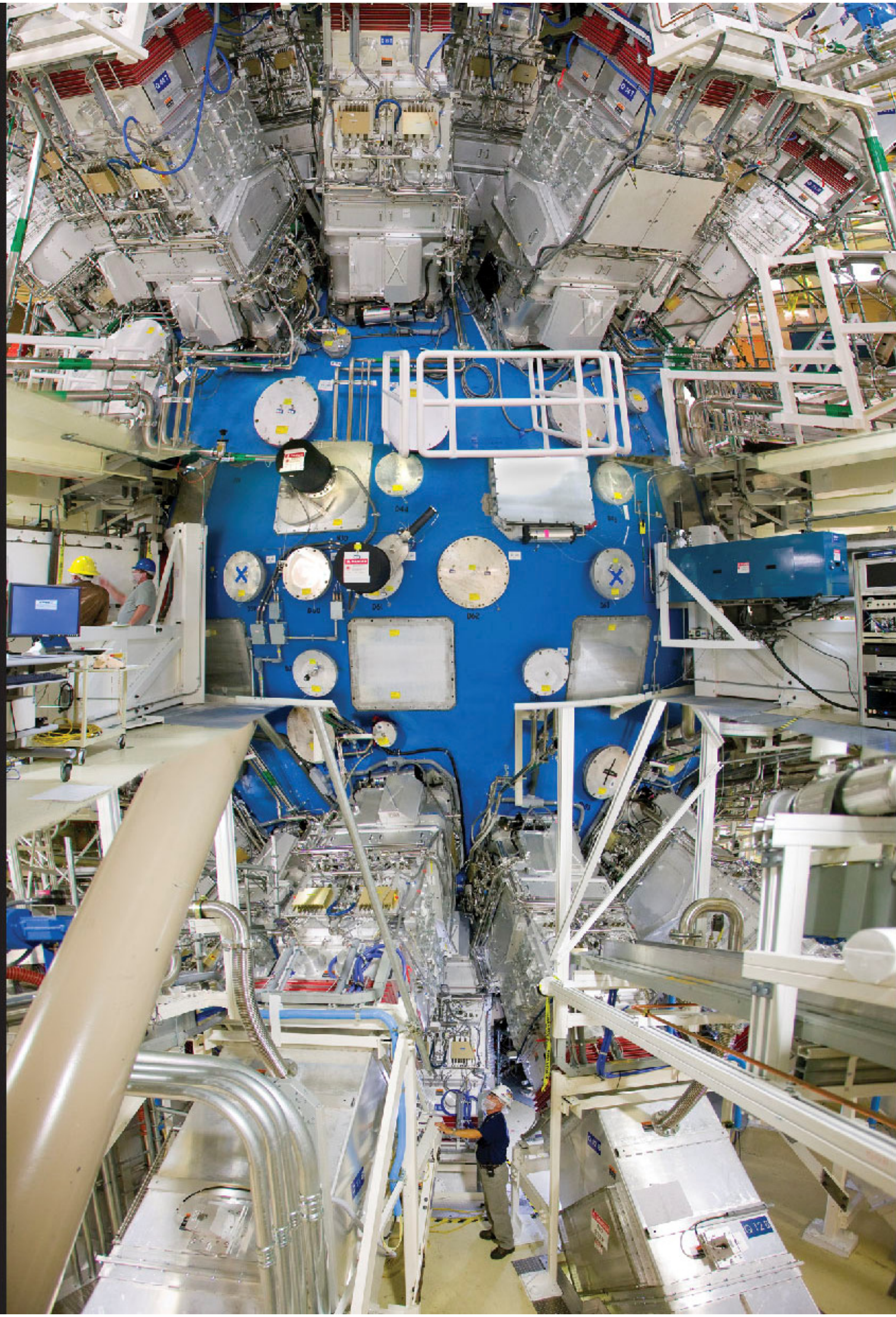
– Energy	1.8 MJ
– Power	500 TW
– Wavelength	351 nm



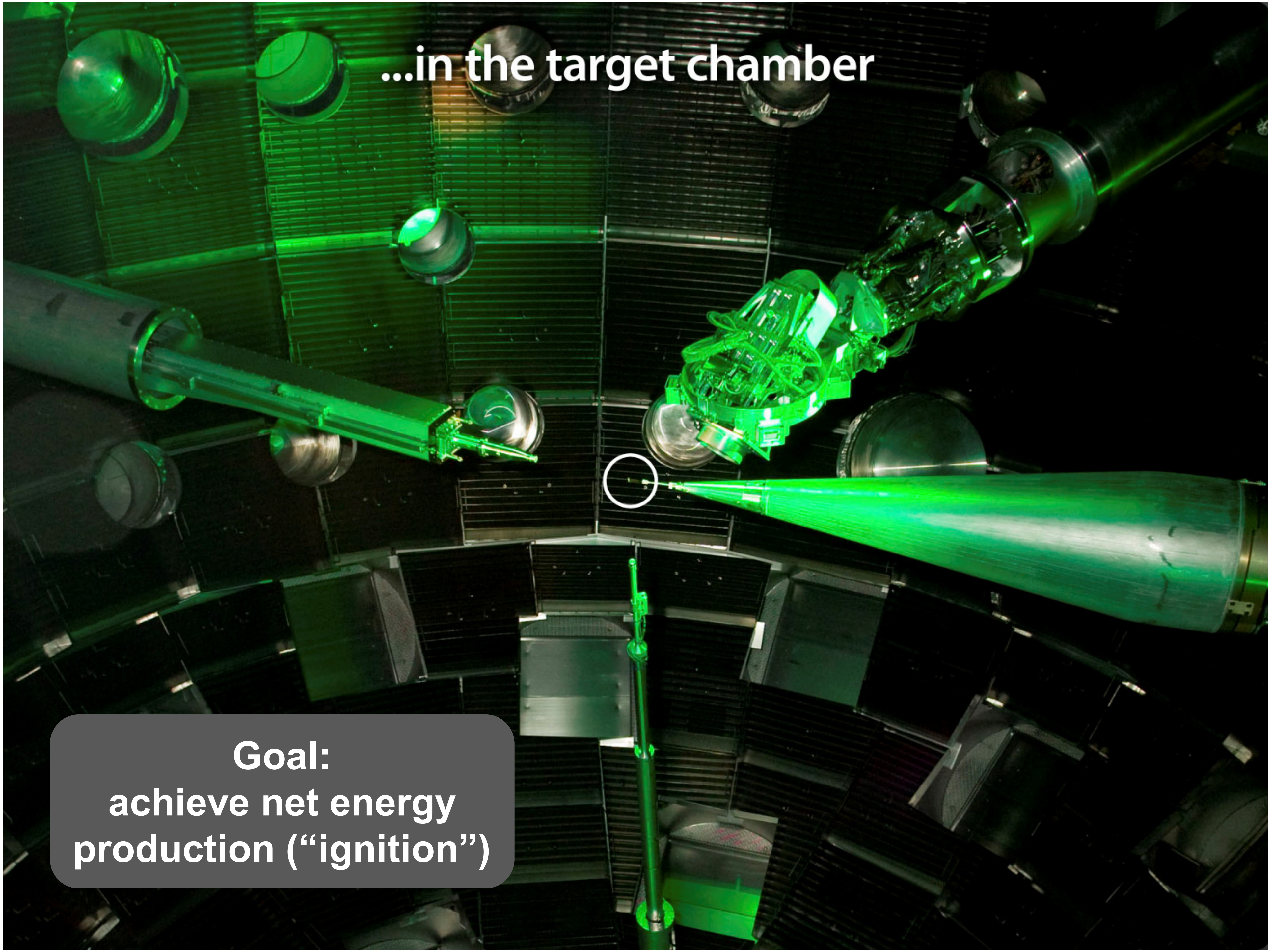

NIF
25/2T
KONECRANES
NIF-0409-16233
23EM/al


Target Chamber
Dedication
June 1999
NIF
05EIM/mfm • NIF-0609-16535s2r1

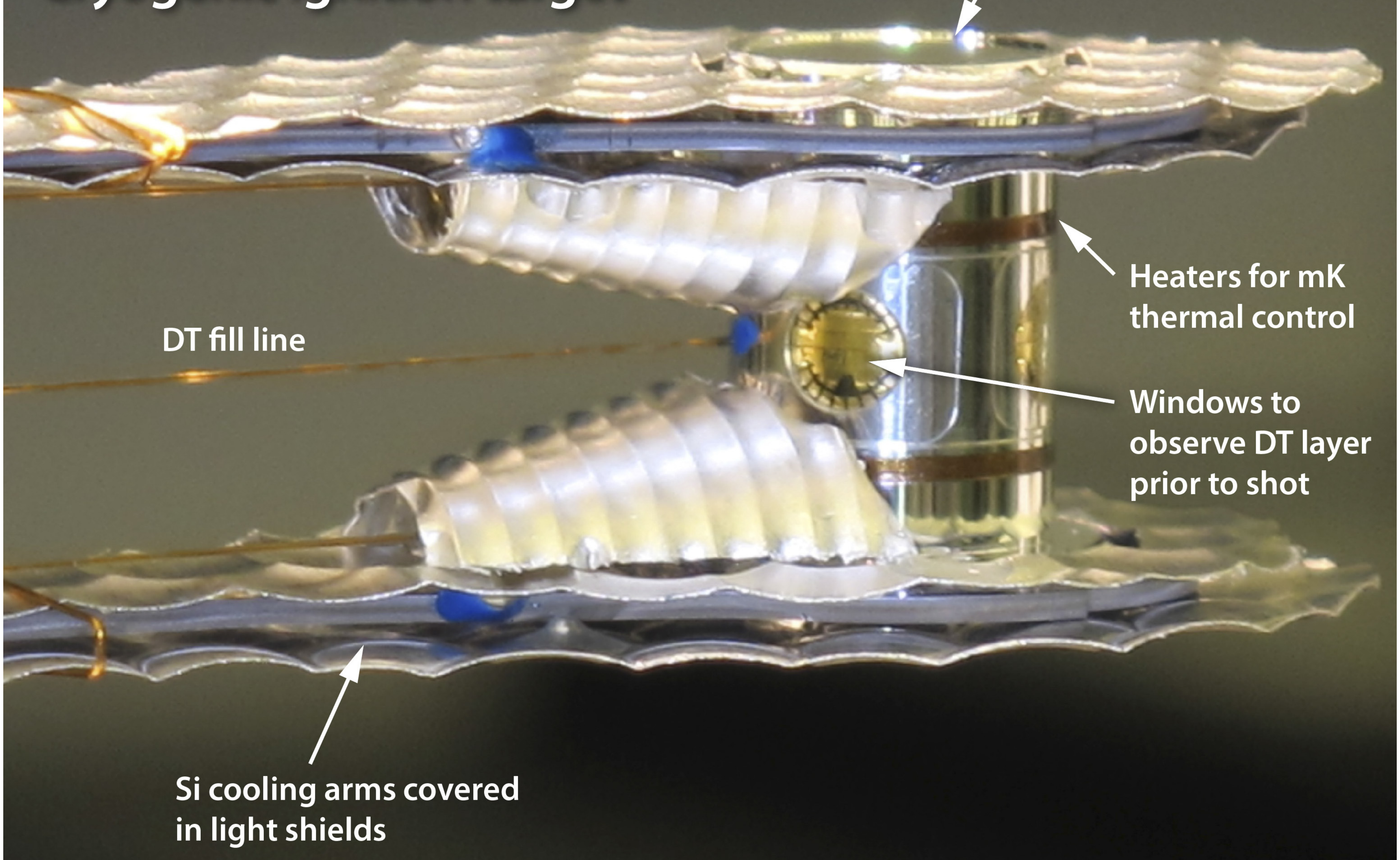
Fusion “target” chamber



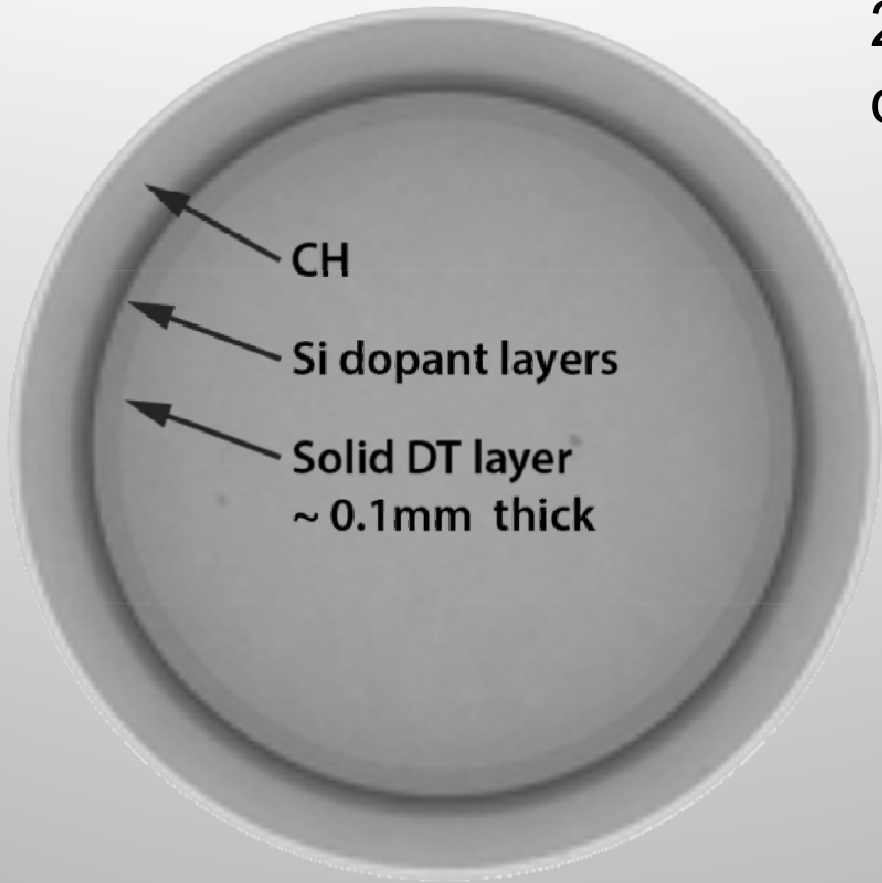

Inside the target chamber


...in the target chamber
Goal:
achieve net energy
production ("ignition")

Cryogenic Ignition target

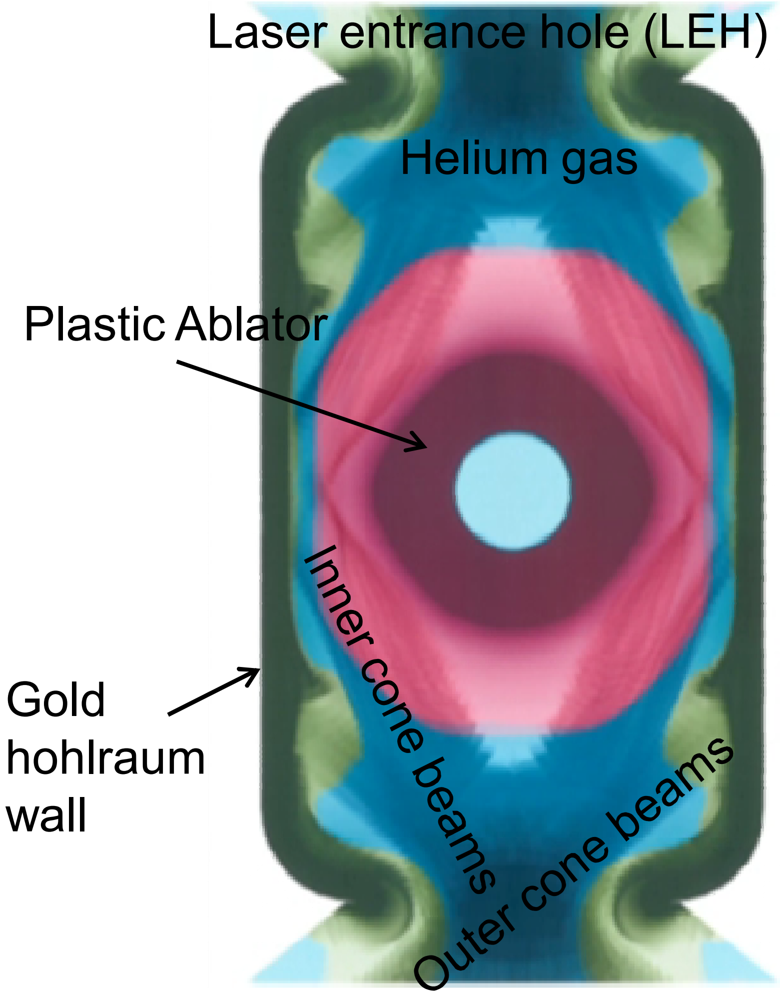


X-ray picture of capsule taken down axis of the hohlraum just before a shot

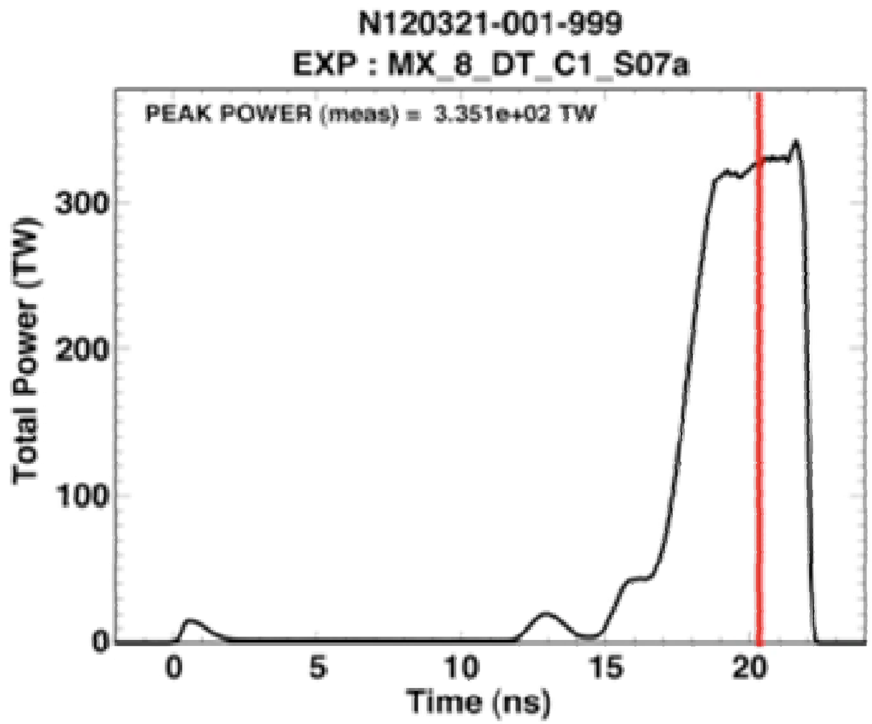


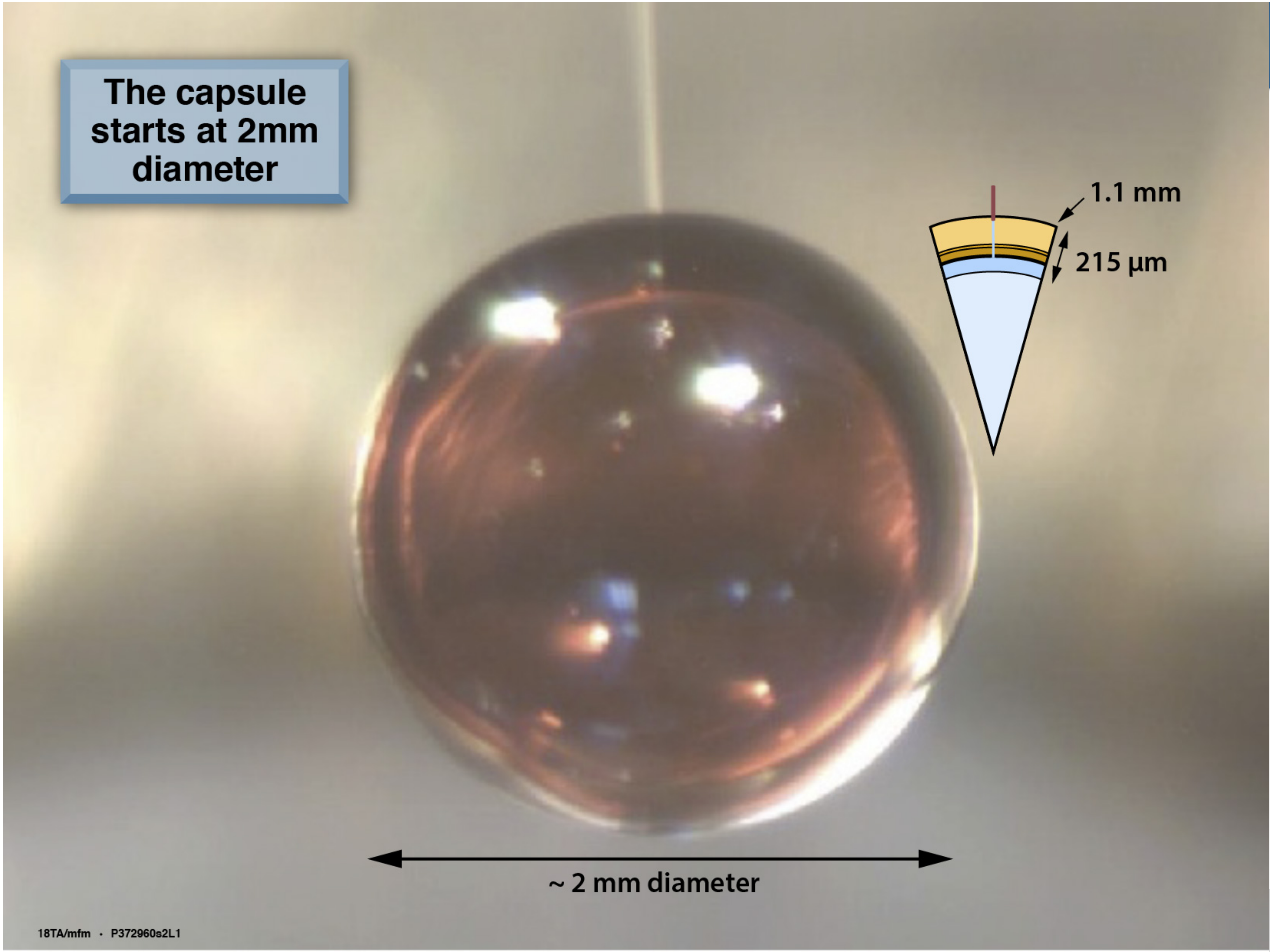
2mm diameter capsule

On the NIF we use a laser driven hohlraum to implode the capsule attempting to create conditions needed for ignition



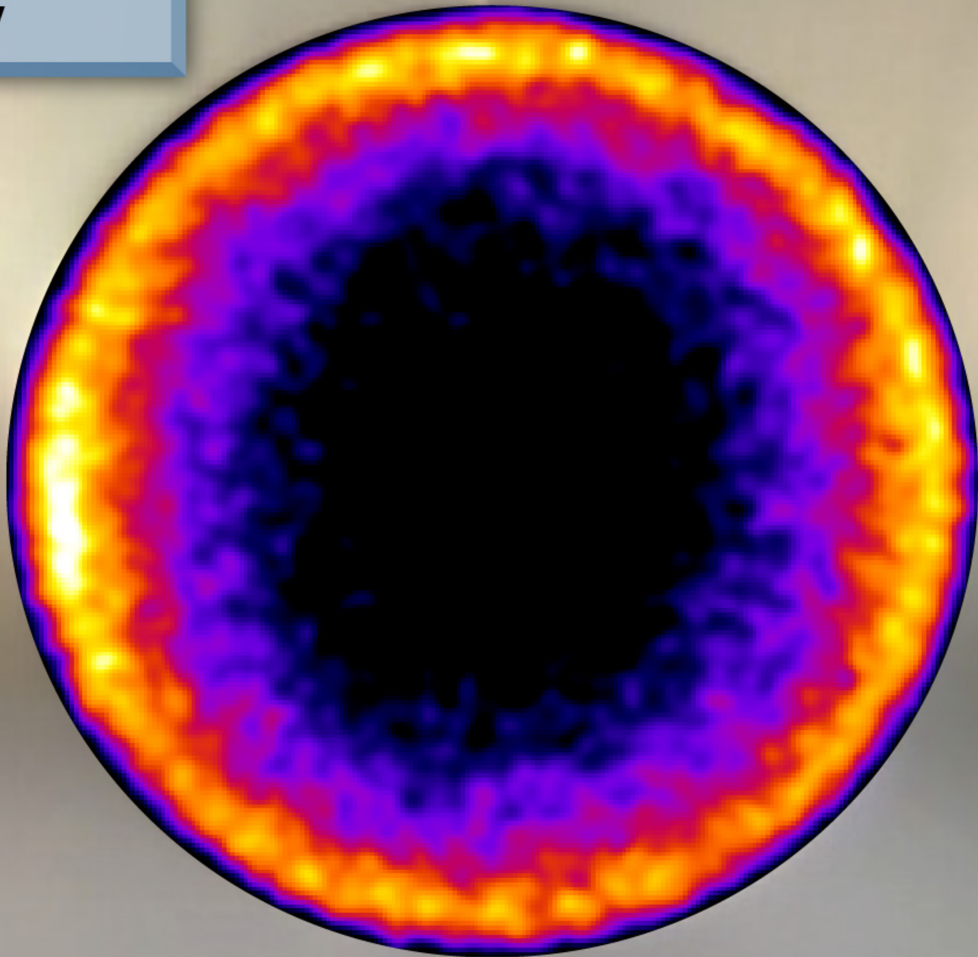
Laser "Pulse-shape"




The capsule starts at 2mm diameter
1.1 mm
215 µm
~ 2 mm diameter
18TA/mfm • P372960s2L1

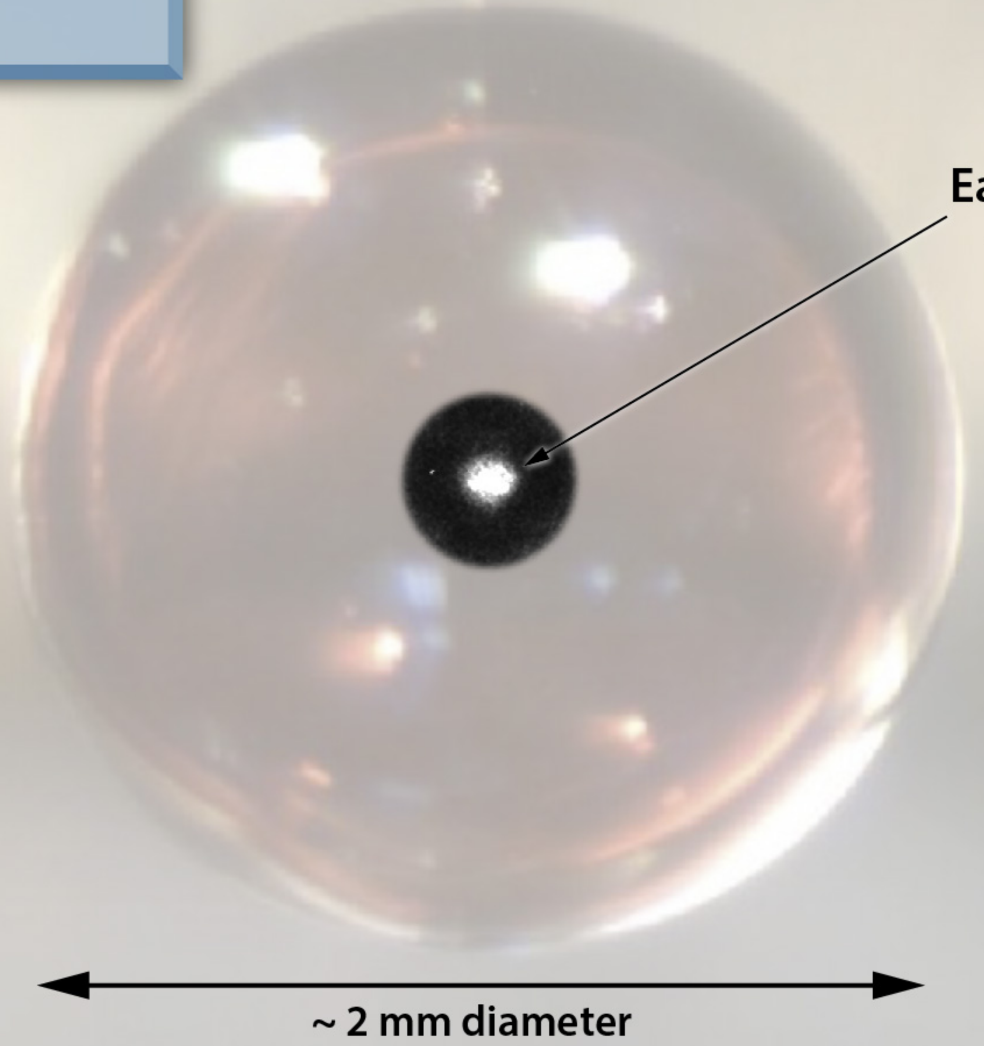
Re-emmission sphere measures early time x-drive symmetry

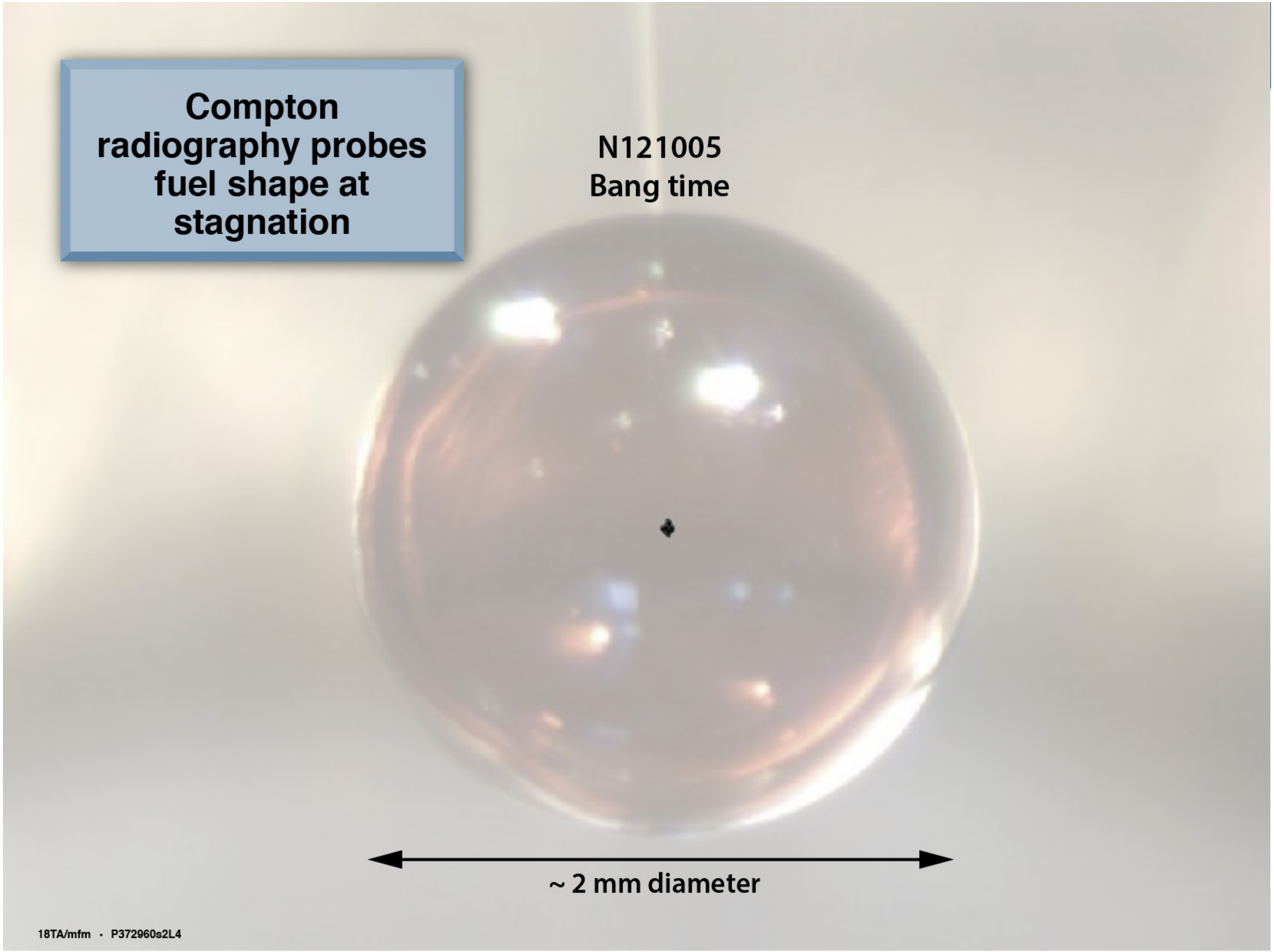
Bang time – 19 ns



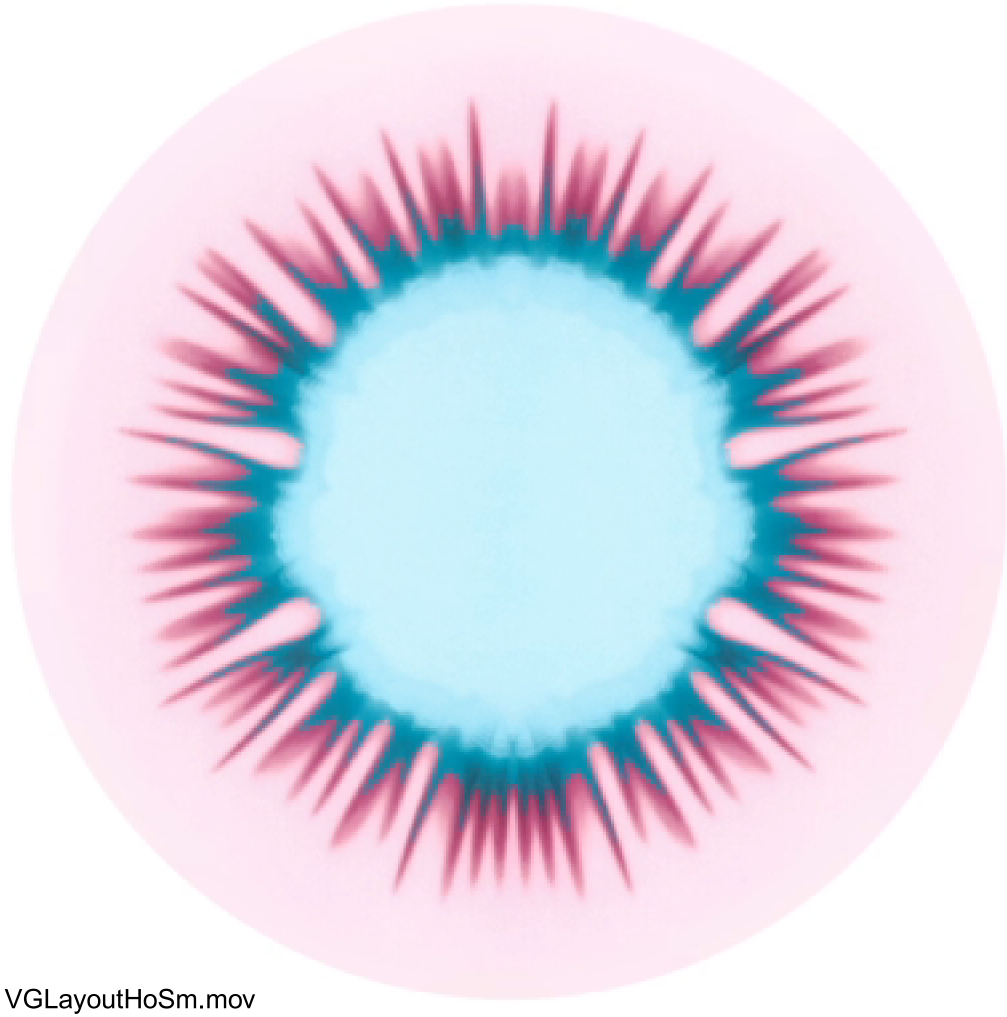
1 billionth of a second into the laser pulse

Radiography measures the shape of the capsule in-flight

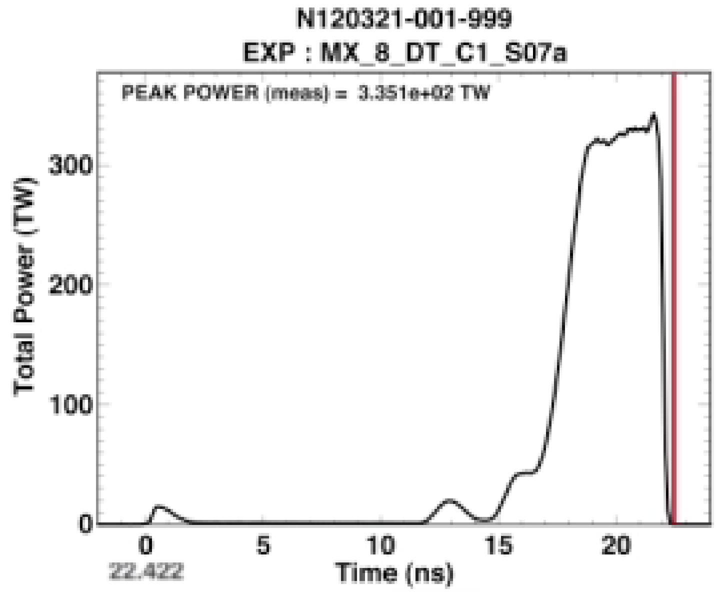


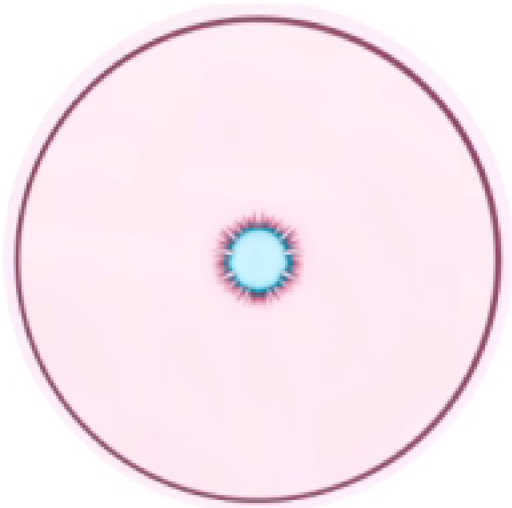

Compton radiography probes fuel shape at stagnation
N121005
Bang time
~ 2 mm diameter
18TA/mfm • P372960s2L4

The capsule must be designed to withstand hydrodynamic instabilities



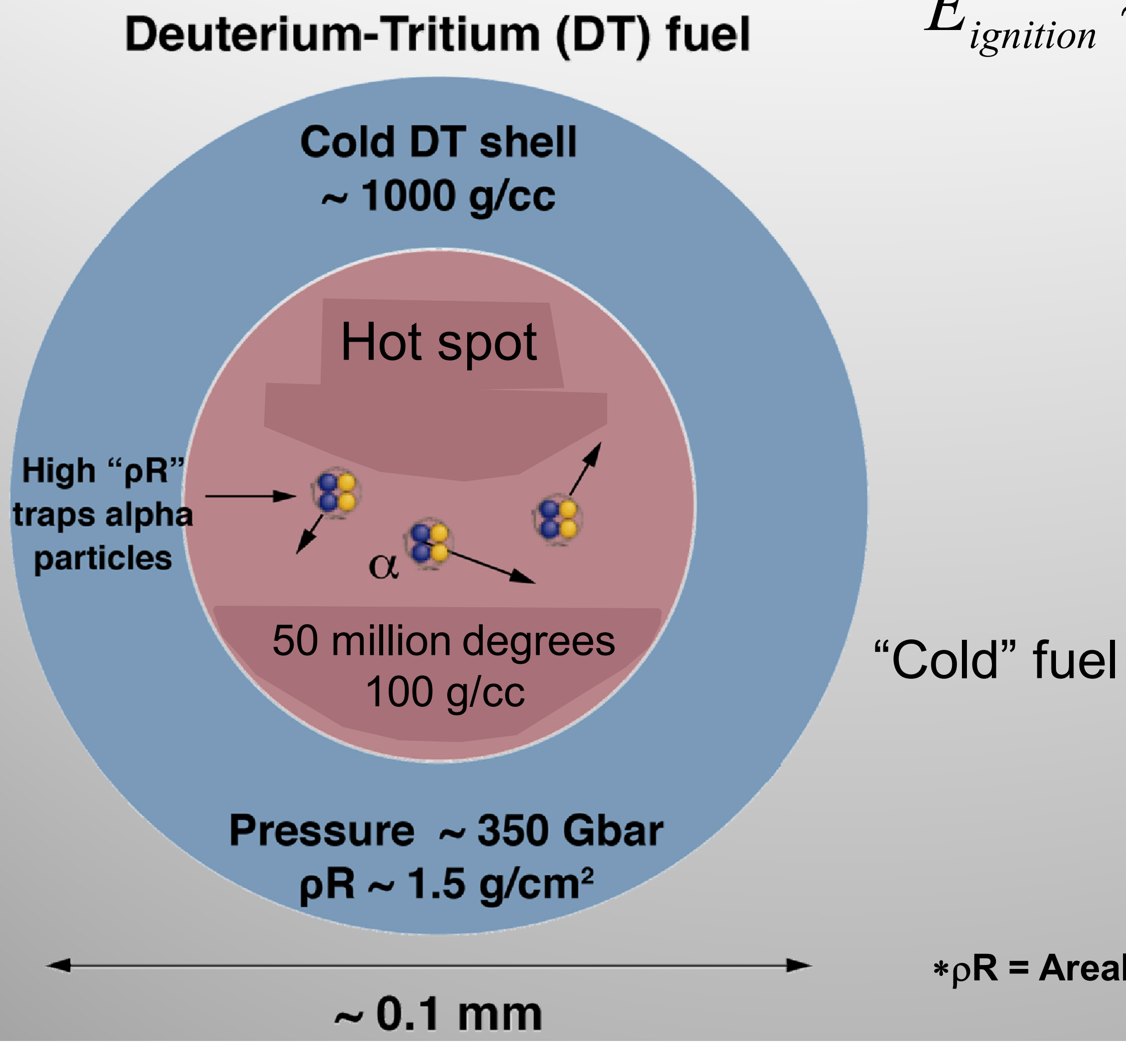
VGLayoutHoSm.mov





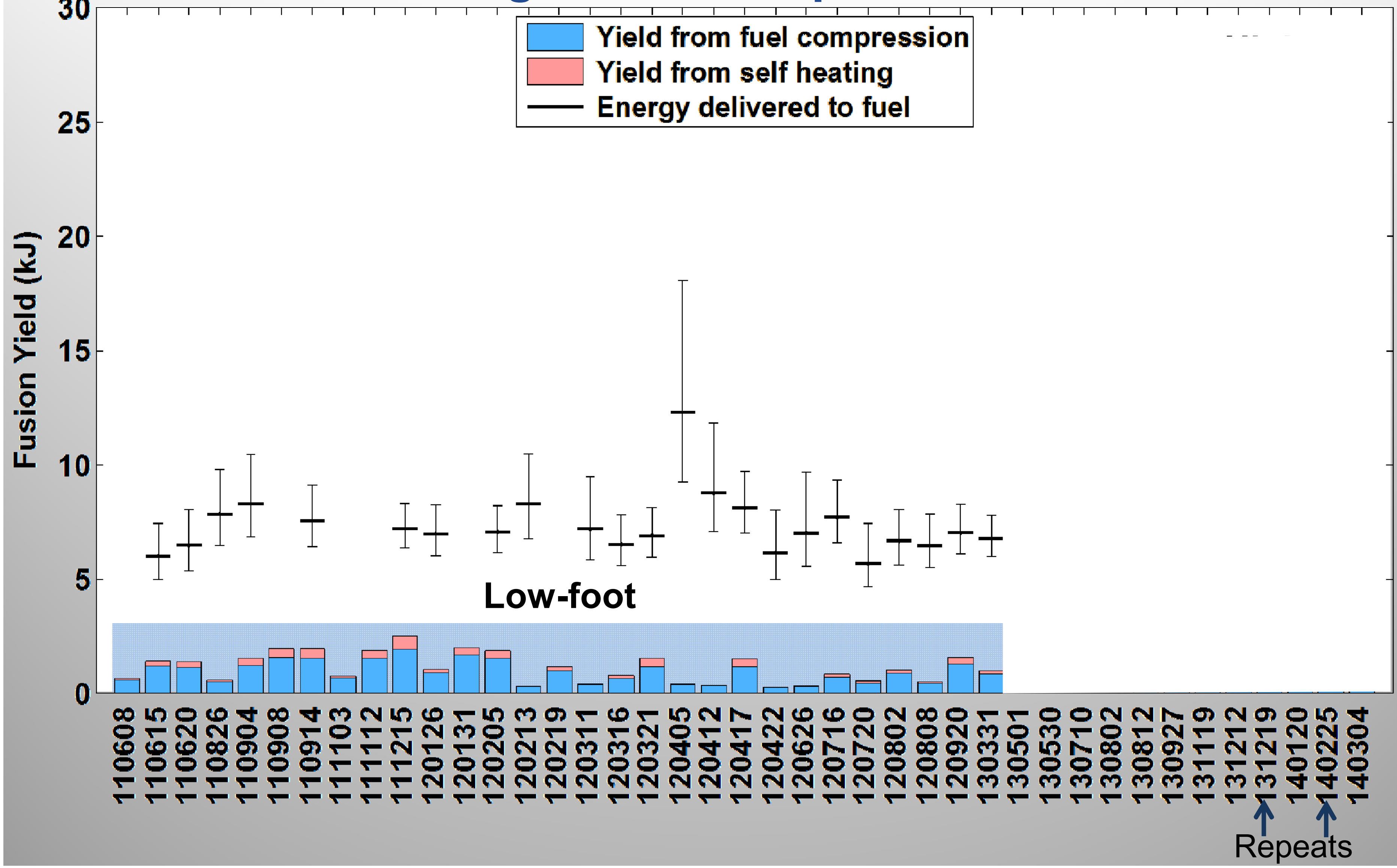
Ignition on NIF requires compression to extreme pressures and temperatures to self-heat

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



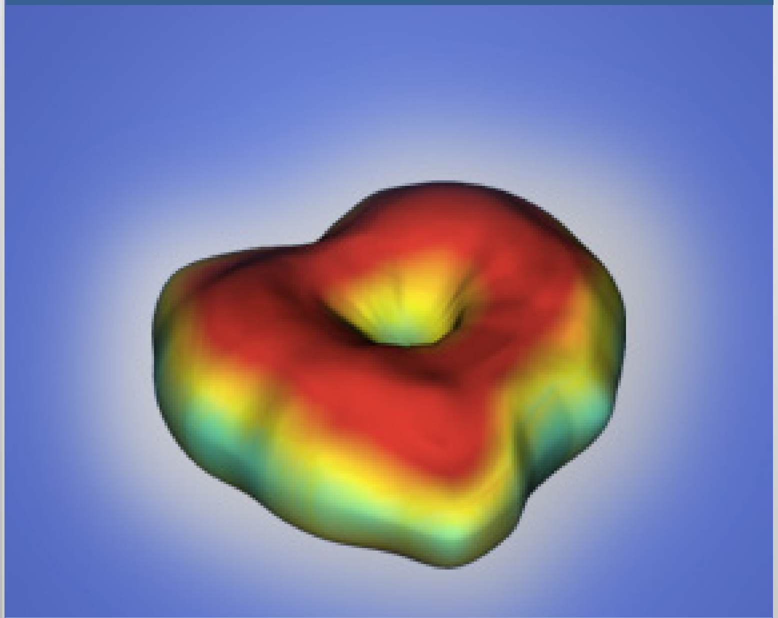
*ρR = Areal density

Self-heating yield during the NIC was low – simulations disagreed with experiments



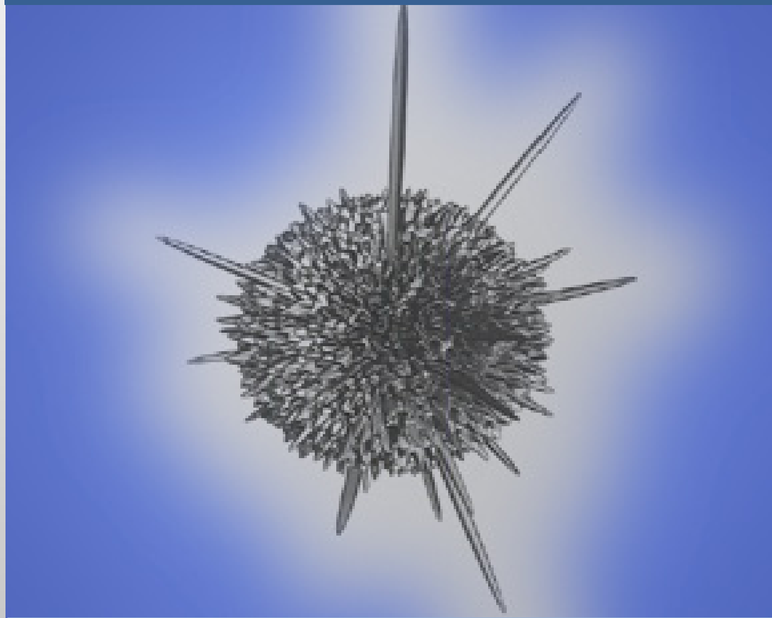
Two main potential problems were identified from results of the NIC campaign

Asymmetric hot spot



X-ray push on the capsule not symmetric enough

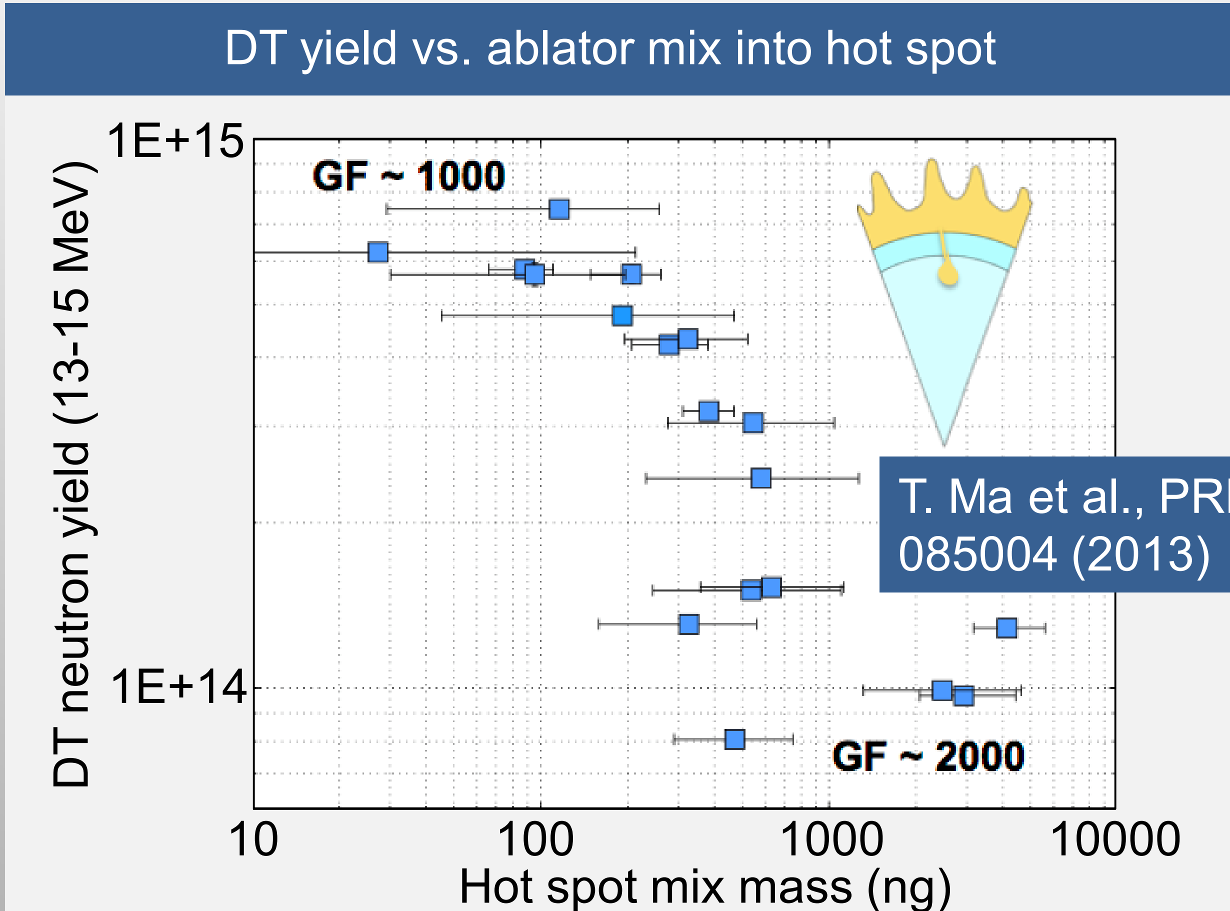
Capsule instability



Combination of growth X surface seeds too large

Performance ceiling likely due to combination of low mode X-ray drive asymmetry and higher than simulation hydrodynamic instability

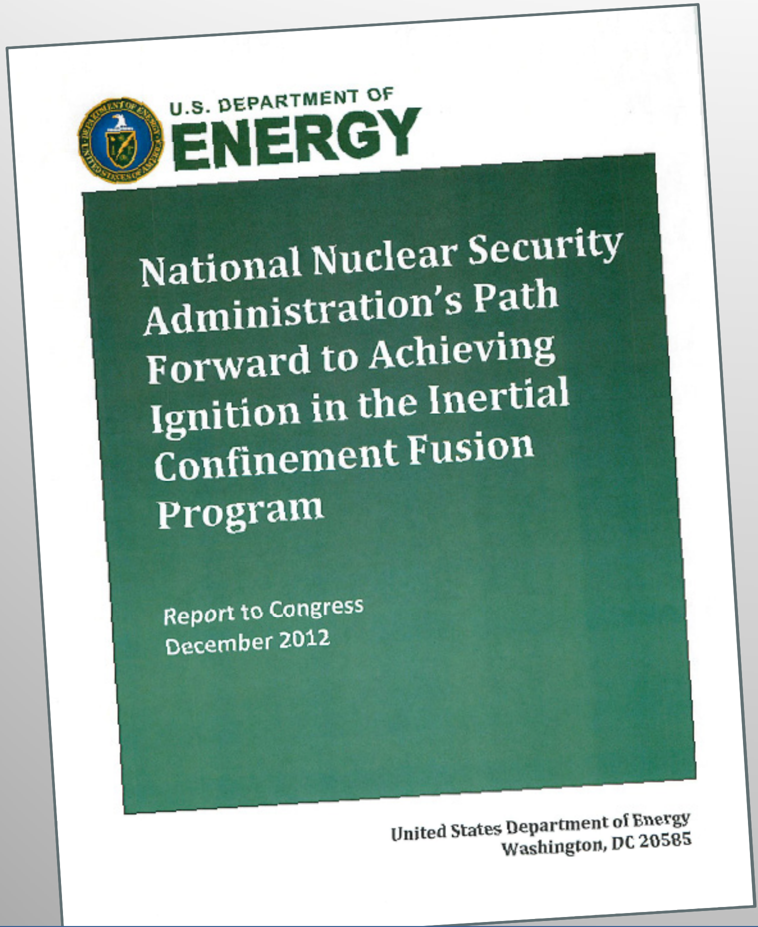
Neutron yield correlated strongly with hot spot mix, originating from Rayleigh-Taylor growth at the ablation front



T. Ma et al., PRL 111, 085004 (2013)

Motivated design of a more forgiving implosion

At the end of the National Ignition Campaign in 2012 Congress directed NNSA to provide a Path Forward for Ignition



The report outlined a 3-year go forward strategy that took a step back from ignition to identify major scientific obstacles

3 elements

- Less stressing integrated experiments
- Focused experiments to study individual physics eg
- Alternate x-ray driven concepts

The plan culminates in a Strategic Review at the end of FY15 addressing likelihood and schedule for ignition. Includes x-ray, direct and magnetic drive approaches

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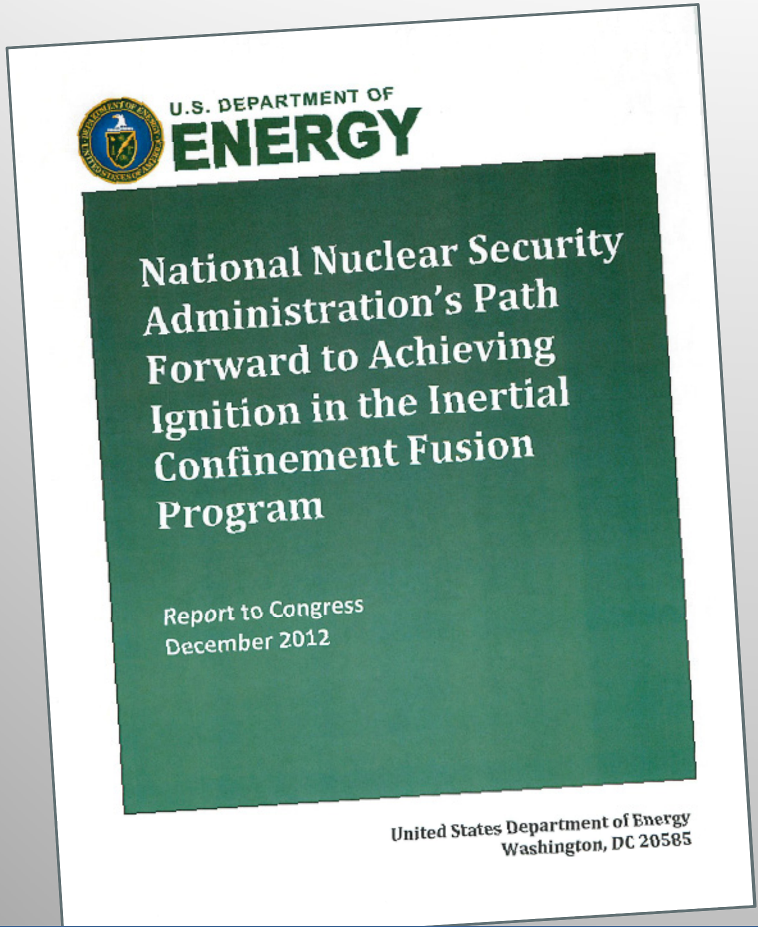

U.S. DEPARTMENT OF
ENERGY

National Nuclear Security Administration's Path Forward to Achieving Ignition in the Inertial Confinement Fusion Program

Report to Congress
December 2012

United States Department of Energy
Washington, DC 20585

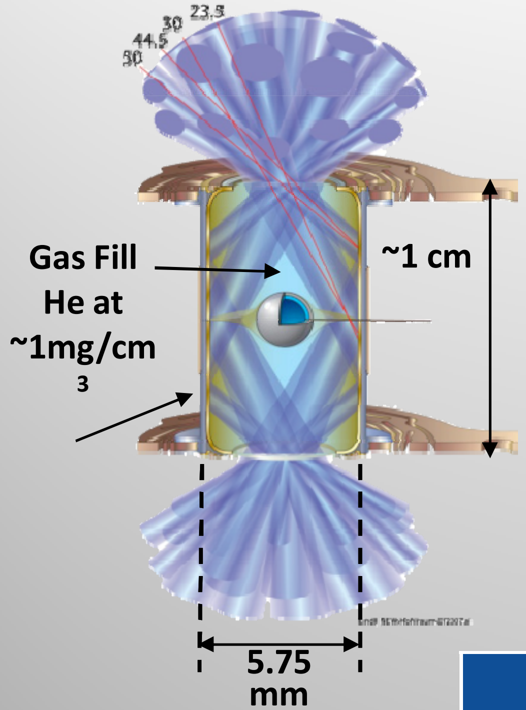
The report outlined a 3-year go forward strategy that took a step back from ignition to identify major scientific obstacles

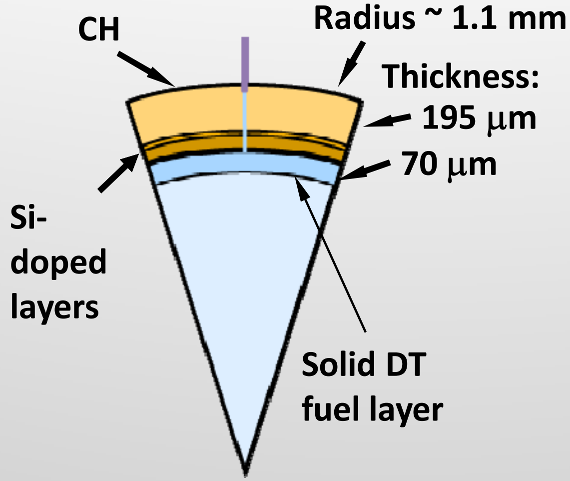
3 elements

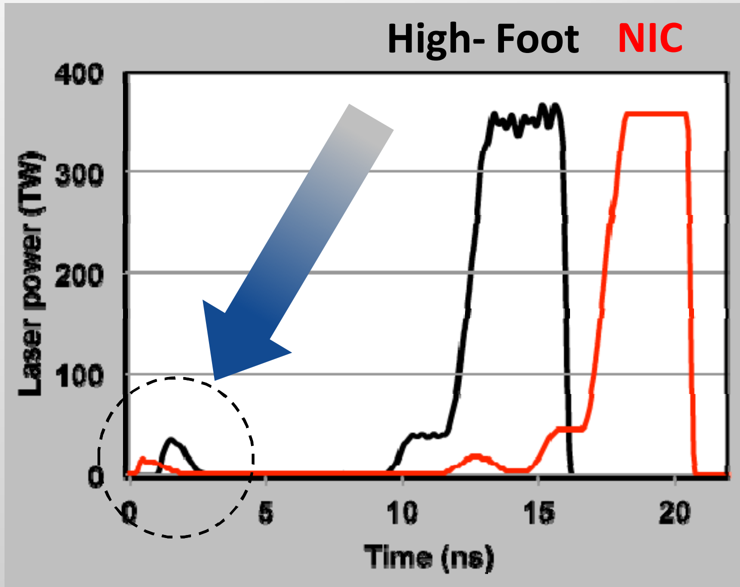
- Less stressing integrated experiments ✓
- Focused experiments to study individual physics eg ✓
- Alternate x-ray driven concepts

Good progress has been made on the elements of the Path Forward
Experiments indicate clear directions to make progress

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



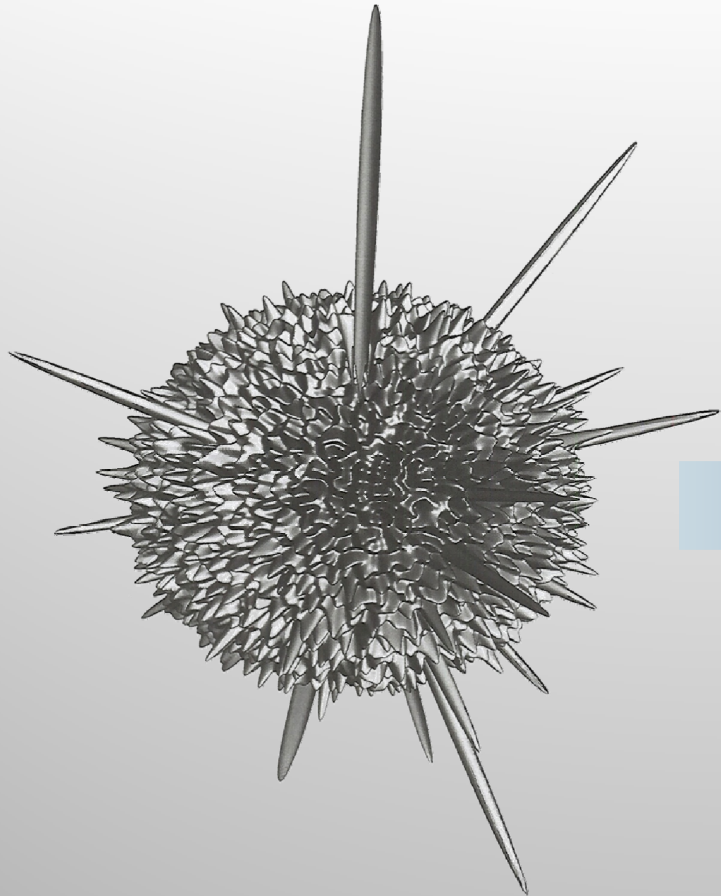




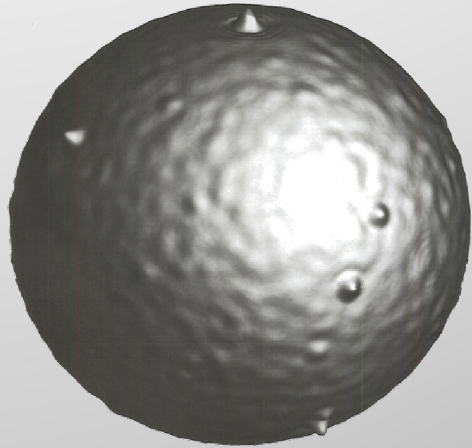
	NIC Low-foot	High-foot
Adiabat (a measure of entropy)	~1.5	**Increased to:** ~2.5
In-flight aspect ratio, (IFAR)	~20	**Reduced to:** ~10
Convergence	~45	**Reduced to:** ~30

GOAL: Performance that is understood and well matched to calculations

Prediction



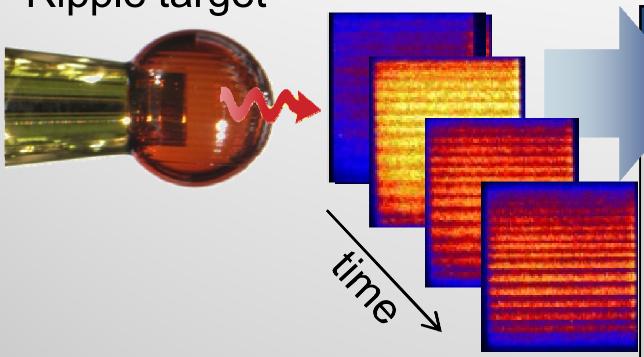
Low foot

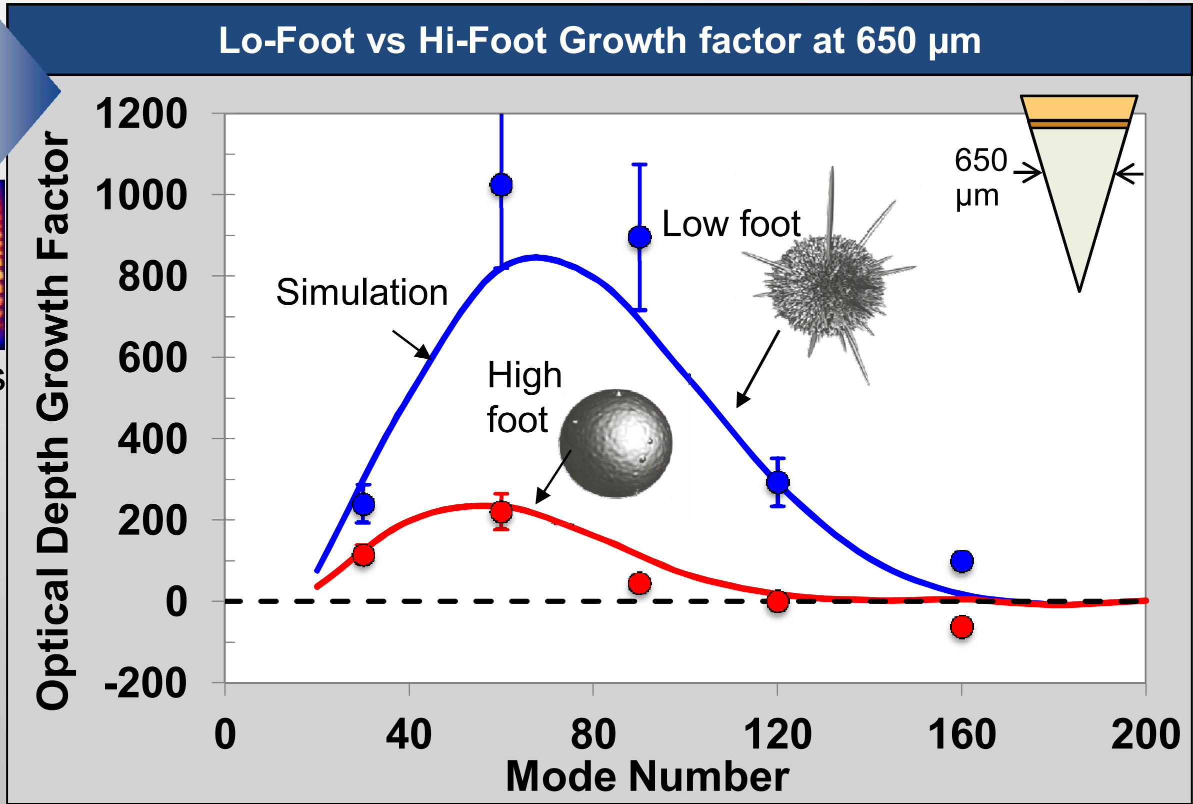


High foot

This improvement was verified in focused experiments

Predictions of hydro growth were verified in focused experiments



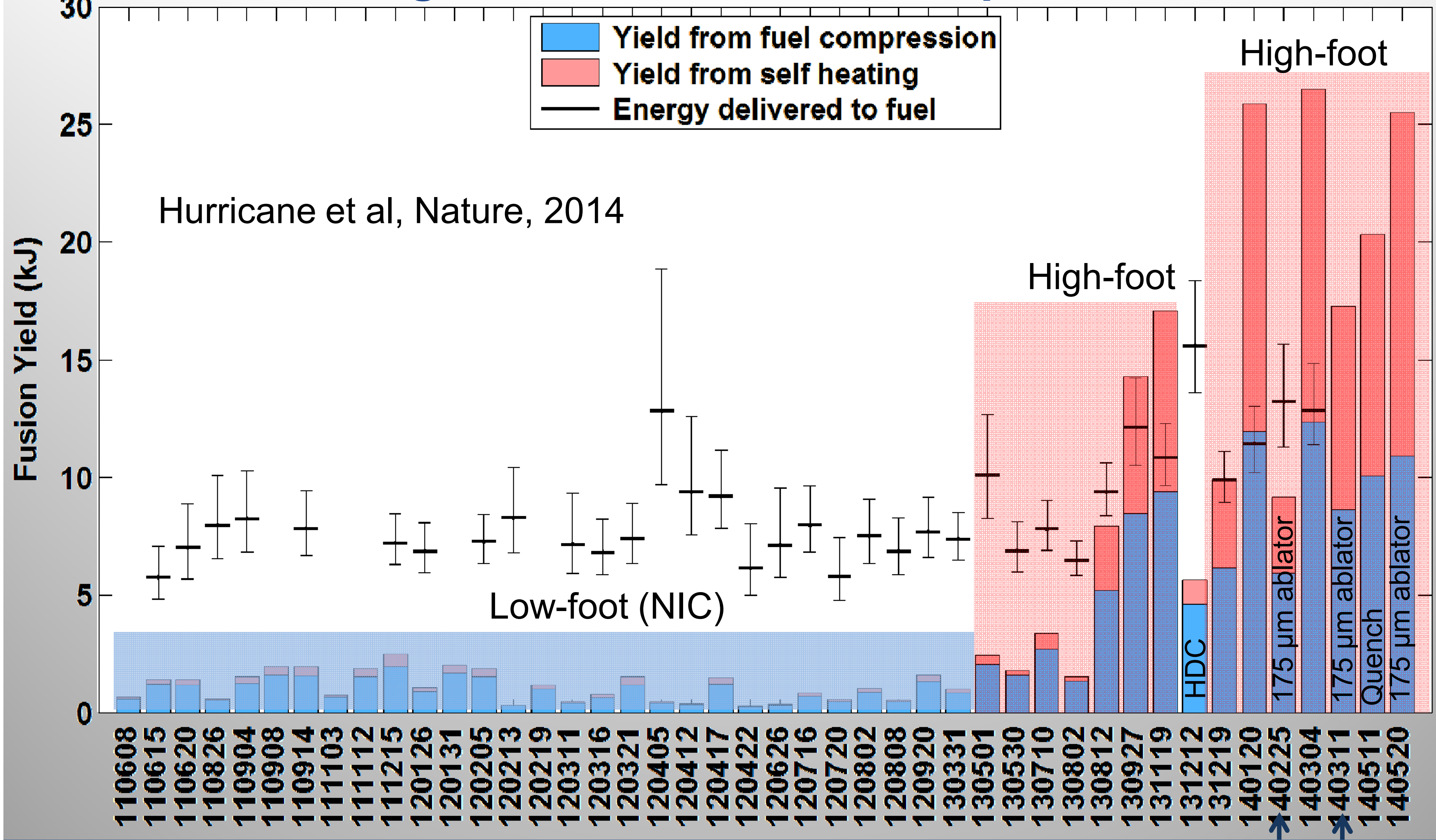


Raman, Peterson, Smalyuk

Future developments:

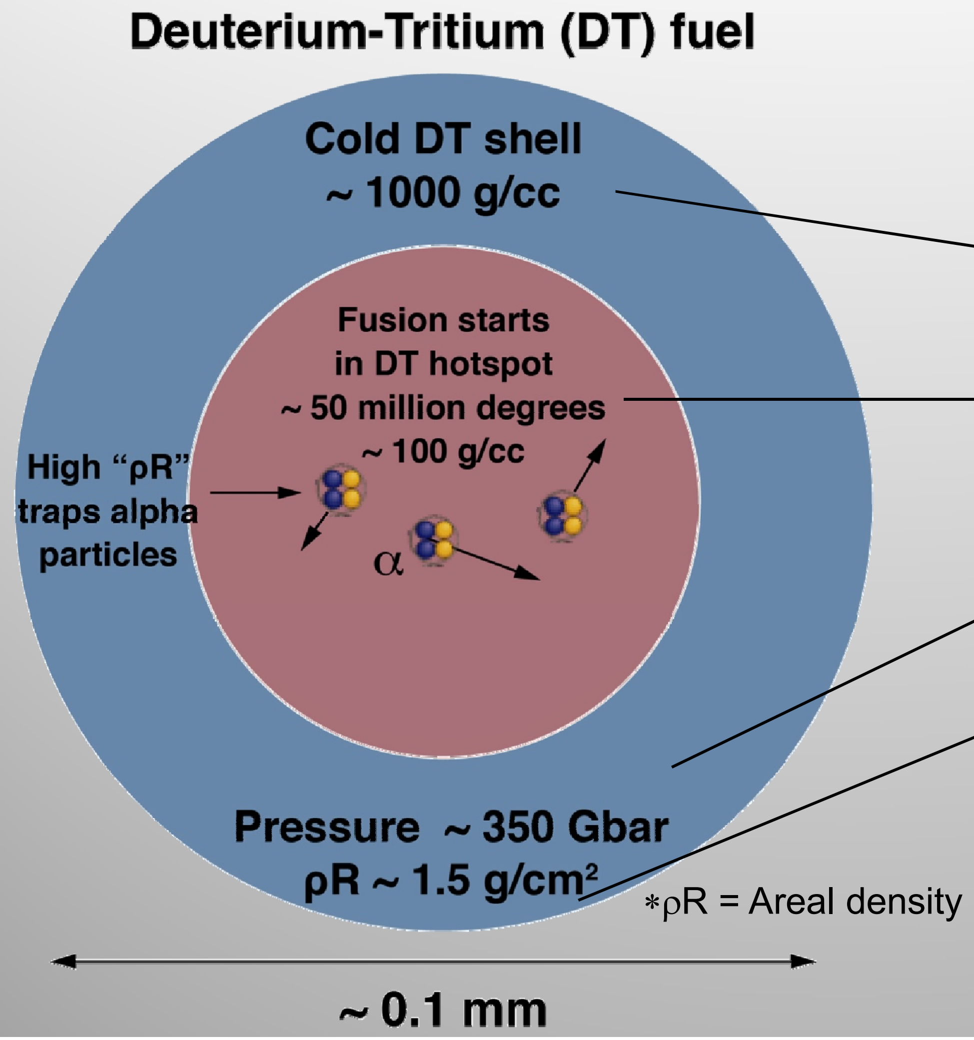
- Higher velocity and convergence, native surfaces
- Mitigation schemes – e.g. adiabat shaping, drive spectrum control

"High foot" experiments exhibit significant alpha heating – simulations agree much better with experiment



Experimental validation of alpha heating highly desirable

Conditions are currently ~ factor 2 from ignition



Best performance
on single shot

~ 27kJ

~ 500 g/cc

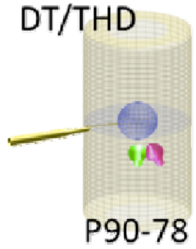
~ 40 g/cc

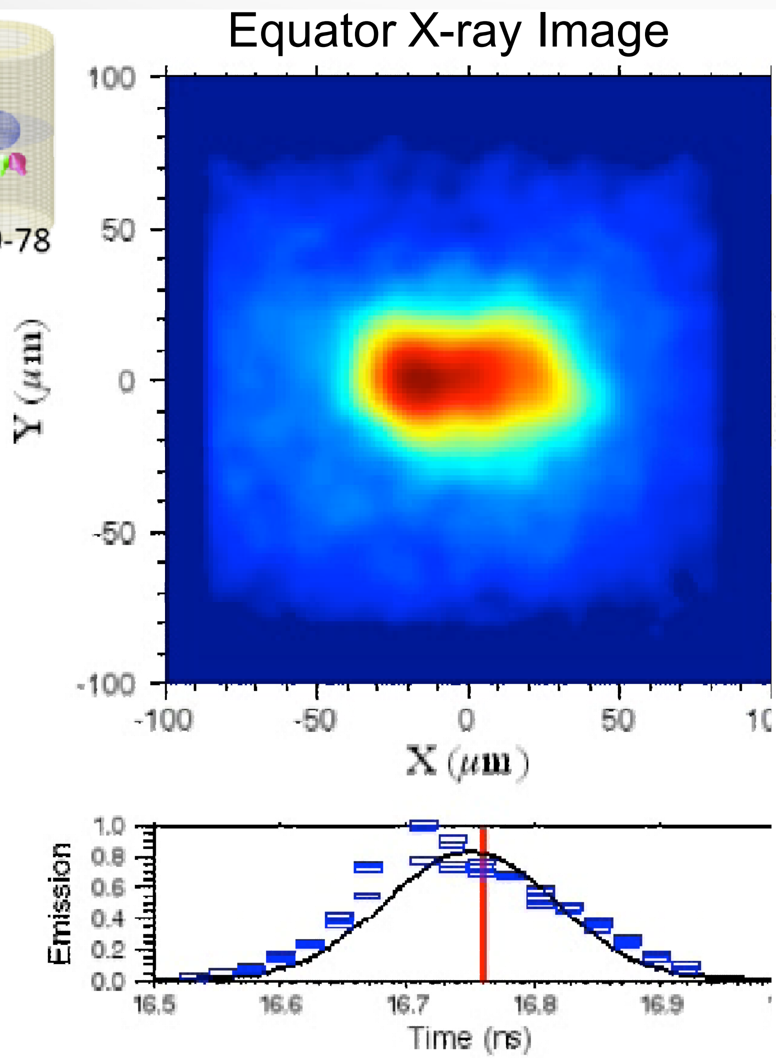
~ 180 Gbar

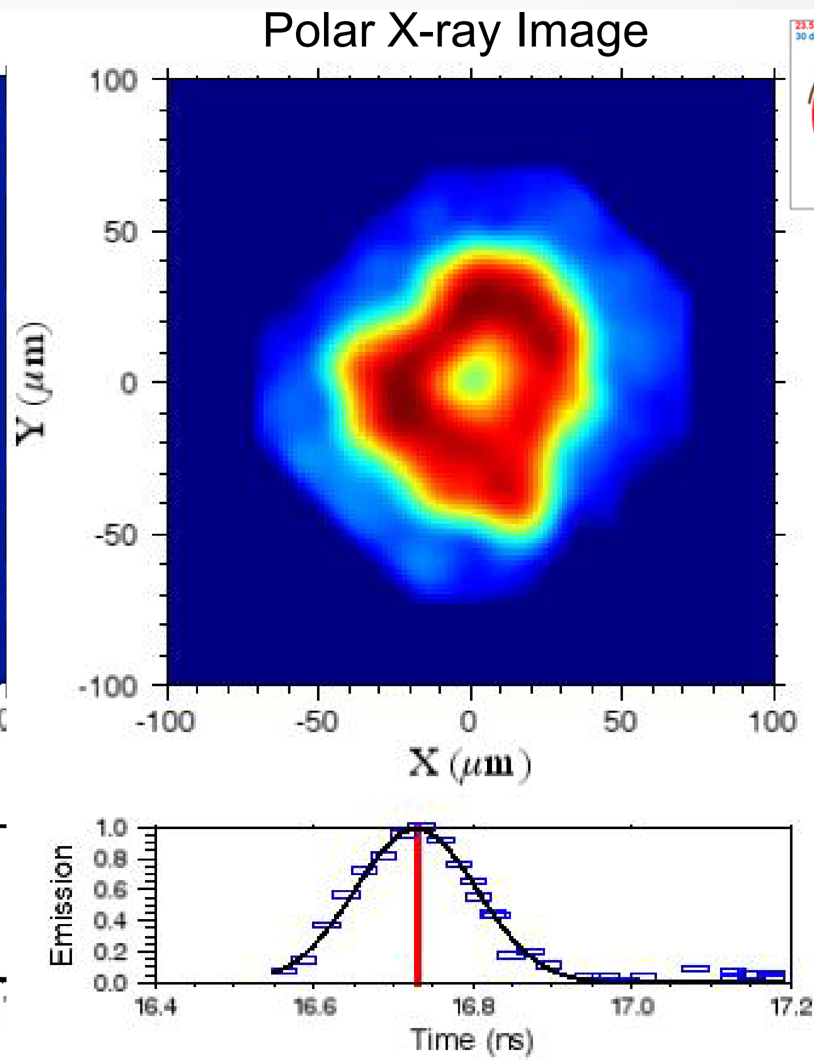
~ 0.75 g/cm ^{2}

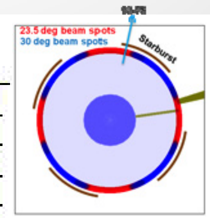
$$E_{ignition} \sim \rho R^3 T \sim \frac{(\rho R)^3 T^3}{P_{stag}^2}$$

Many high-foot implosions have a toroidal shape





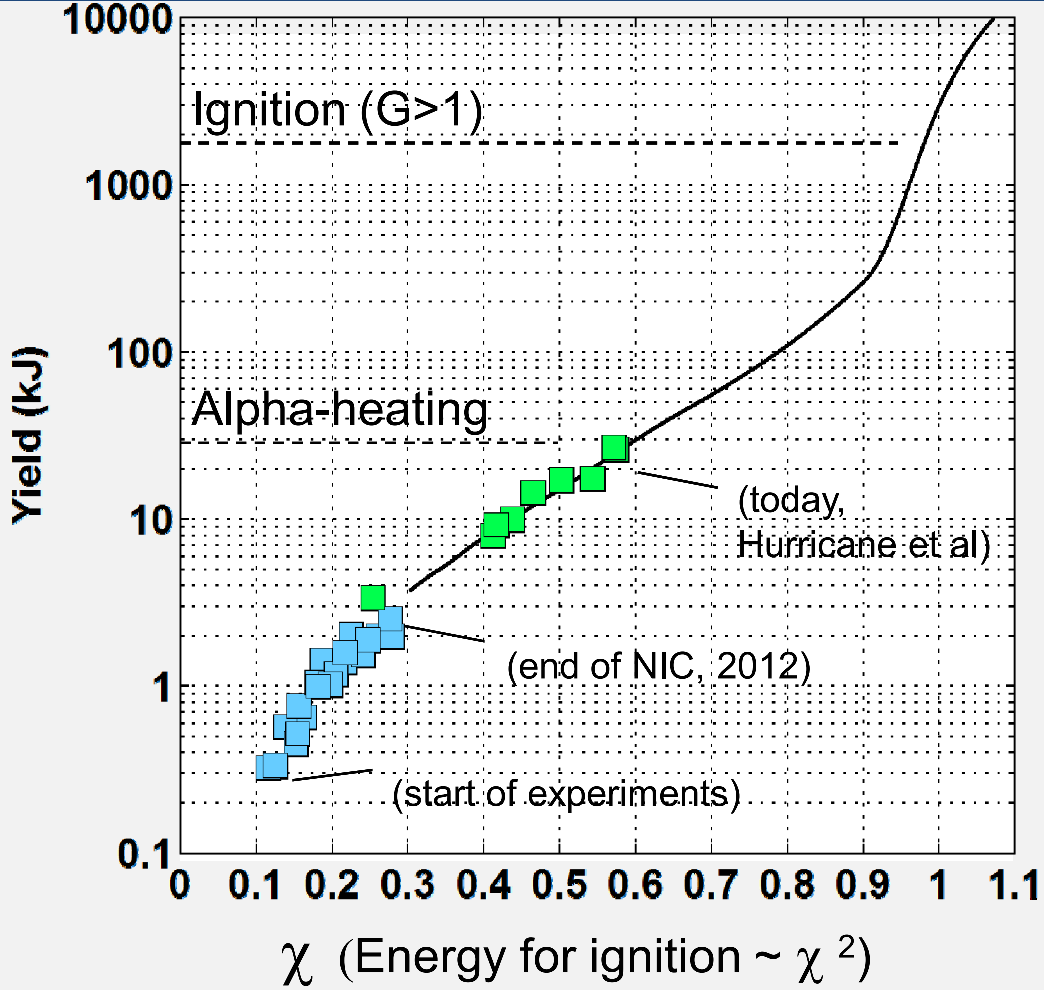




High-foot DT N130812

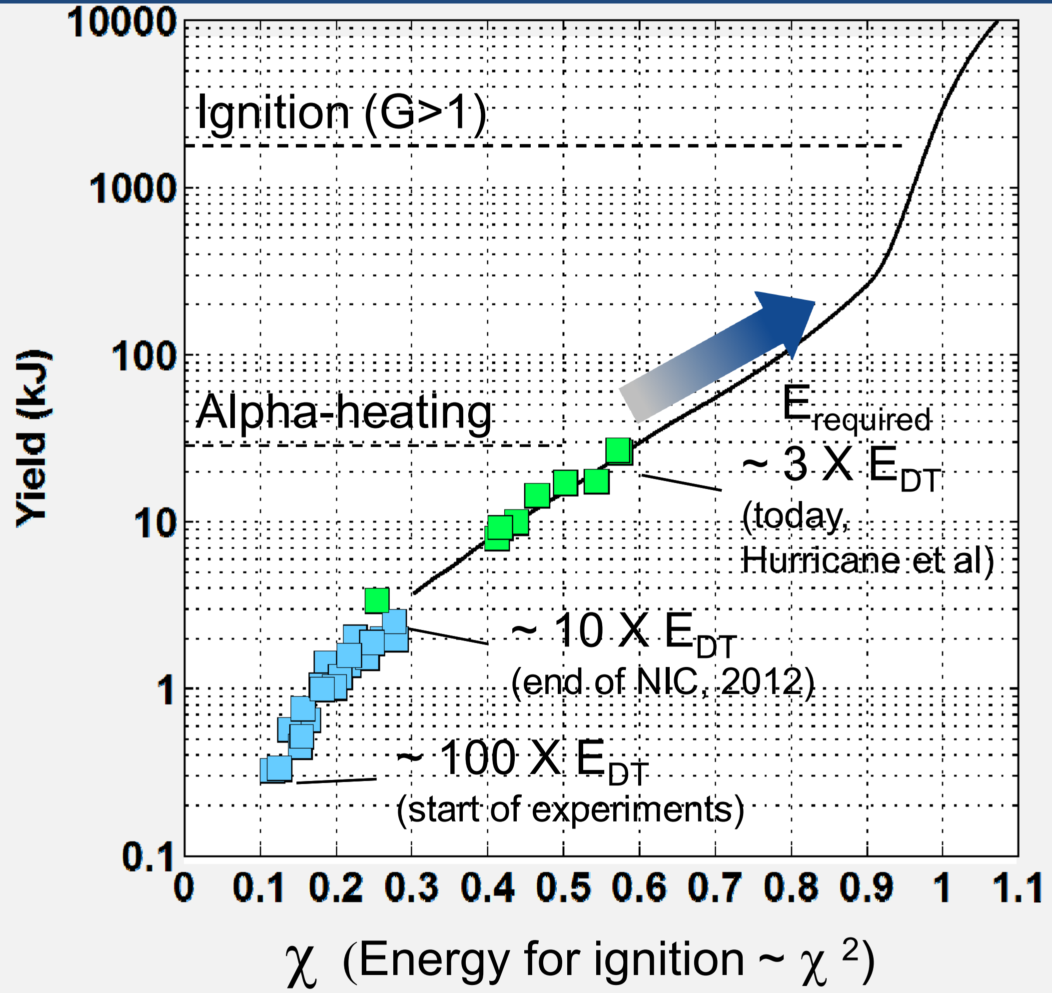
High foot experiments exhibit significant alpha heating, but what about ignition?

DT yield vs ignition parameter χ



Ignition requires closing the "energy gap"

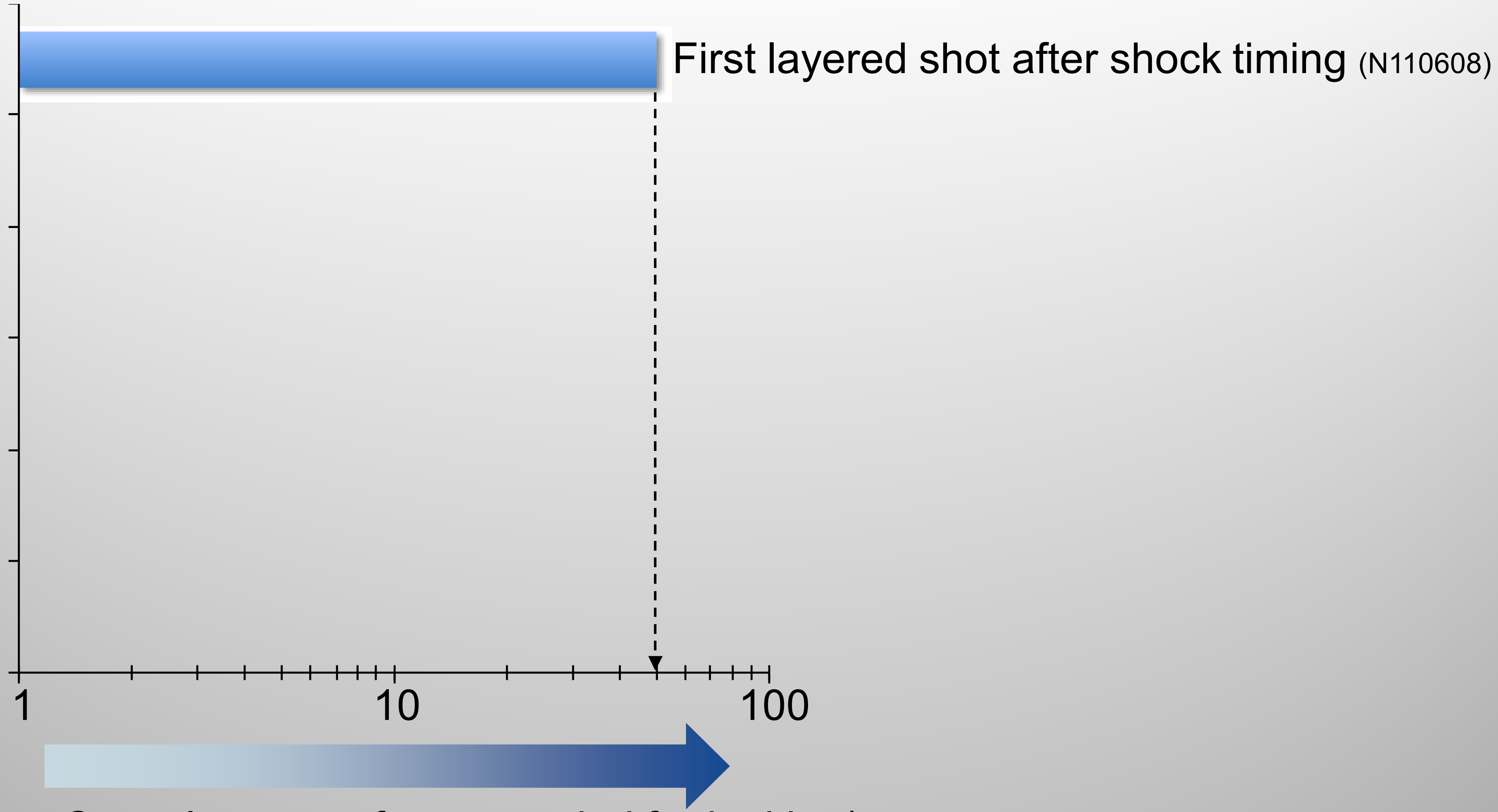
DT yield vs ignition parameter χ



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

- Increase driver energy and/or coupling efficiency
- Improve implosion "quality" – P^2_{stag}
  - Convergence ratio ~ CR^6
  - Implosion vel ~ v^6
  - Symmetry ~ S^{β}
- Challenges
  - Mix and symmetry get harder to control as velocity and convergence increase
  - Hot electron heating – adiabat / symmetry?

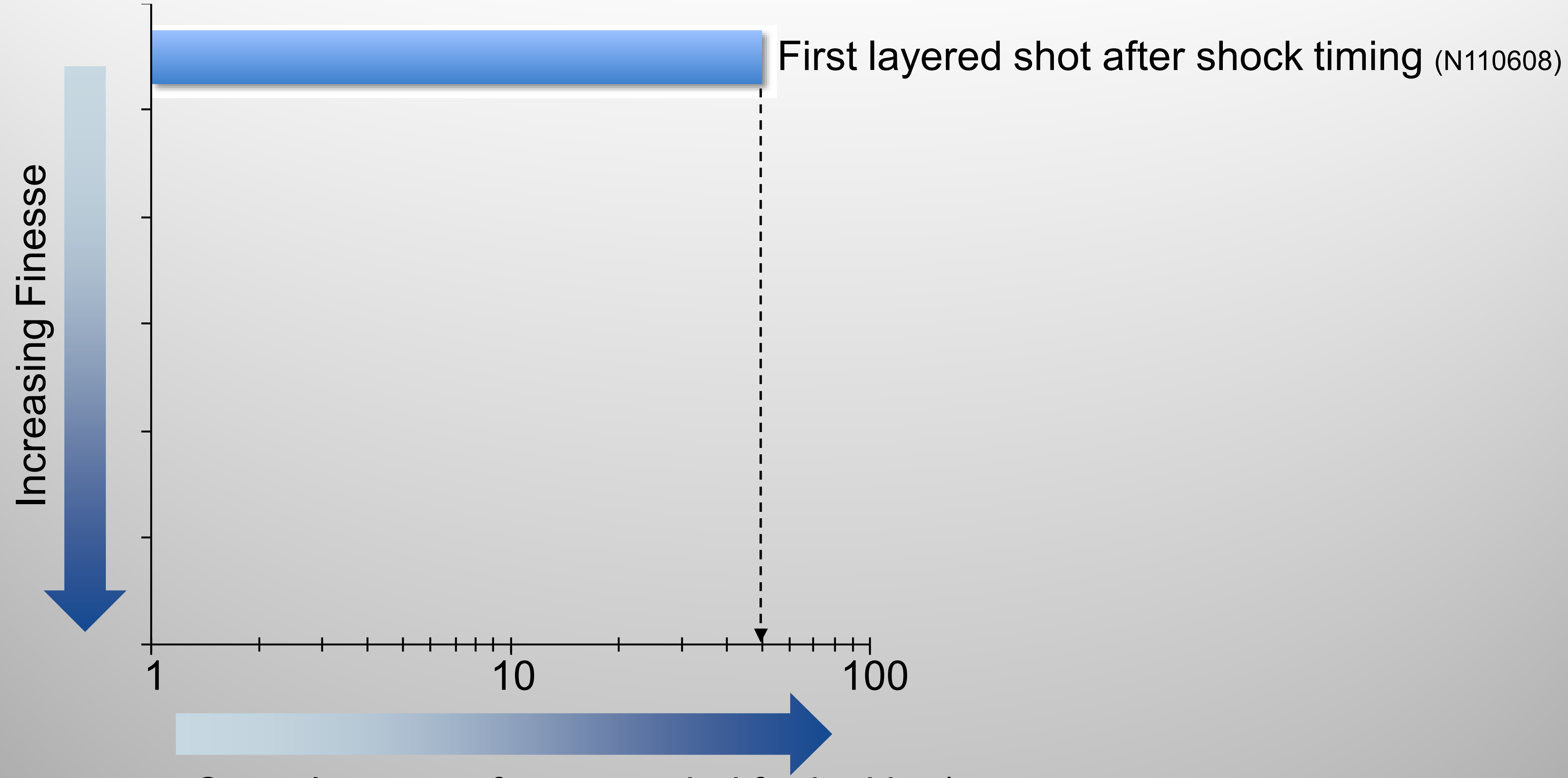
One metric of progress is how big a "sledge hammer" would be needed to ignite



Capsule energy factor needed for ignition*
("Sledge Hammer") . 1=current NIF energy

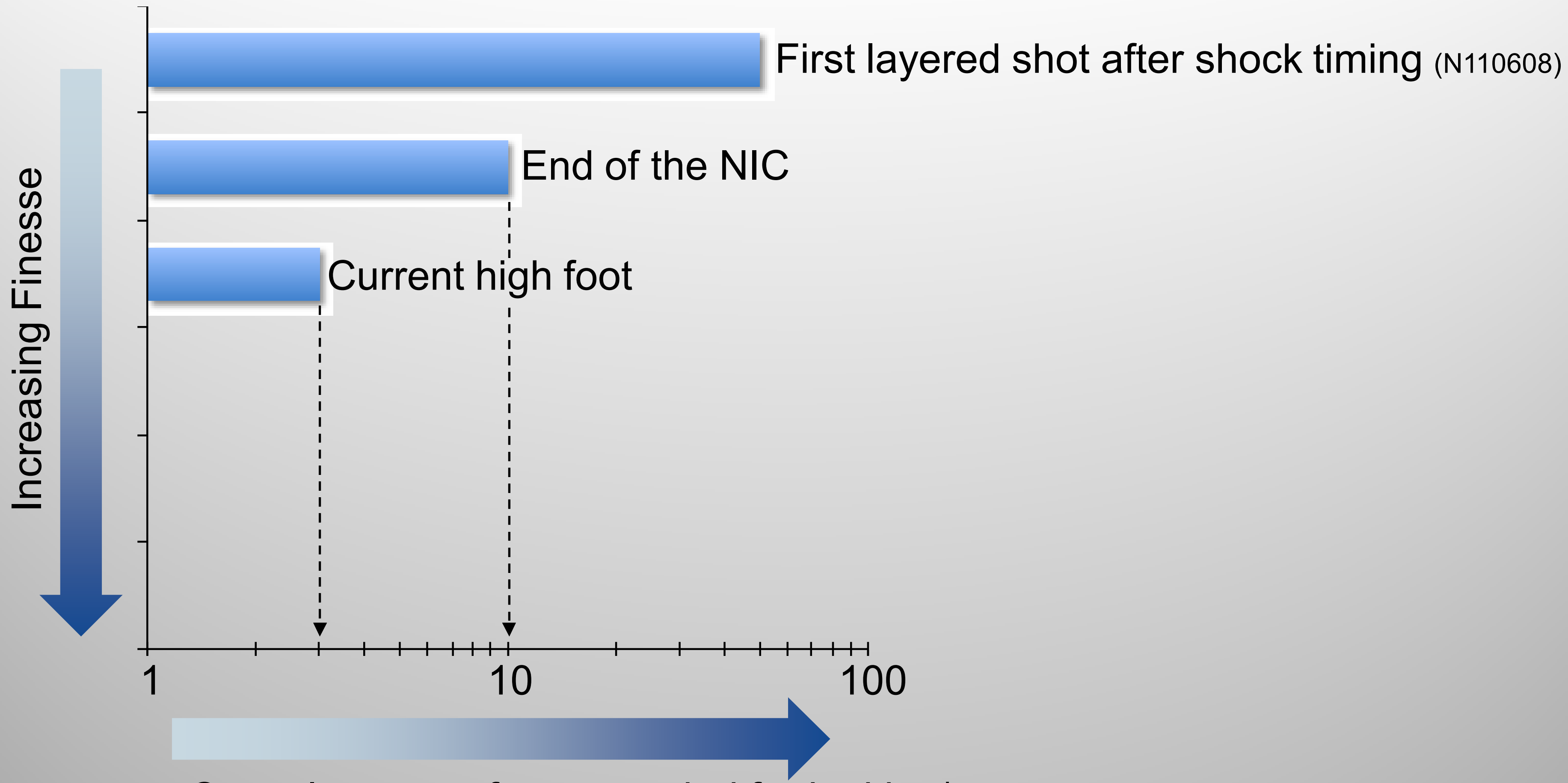
*assumes all else the same

To achieve ignition we have to close the energy gap by improving the finesse of the implosion



*assumes all else the same

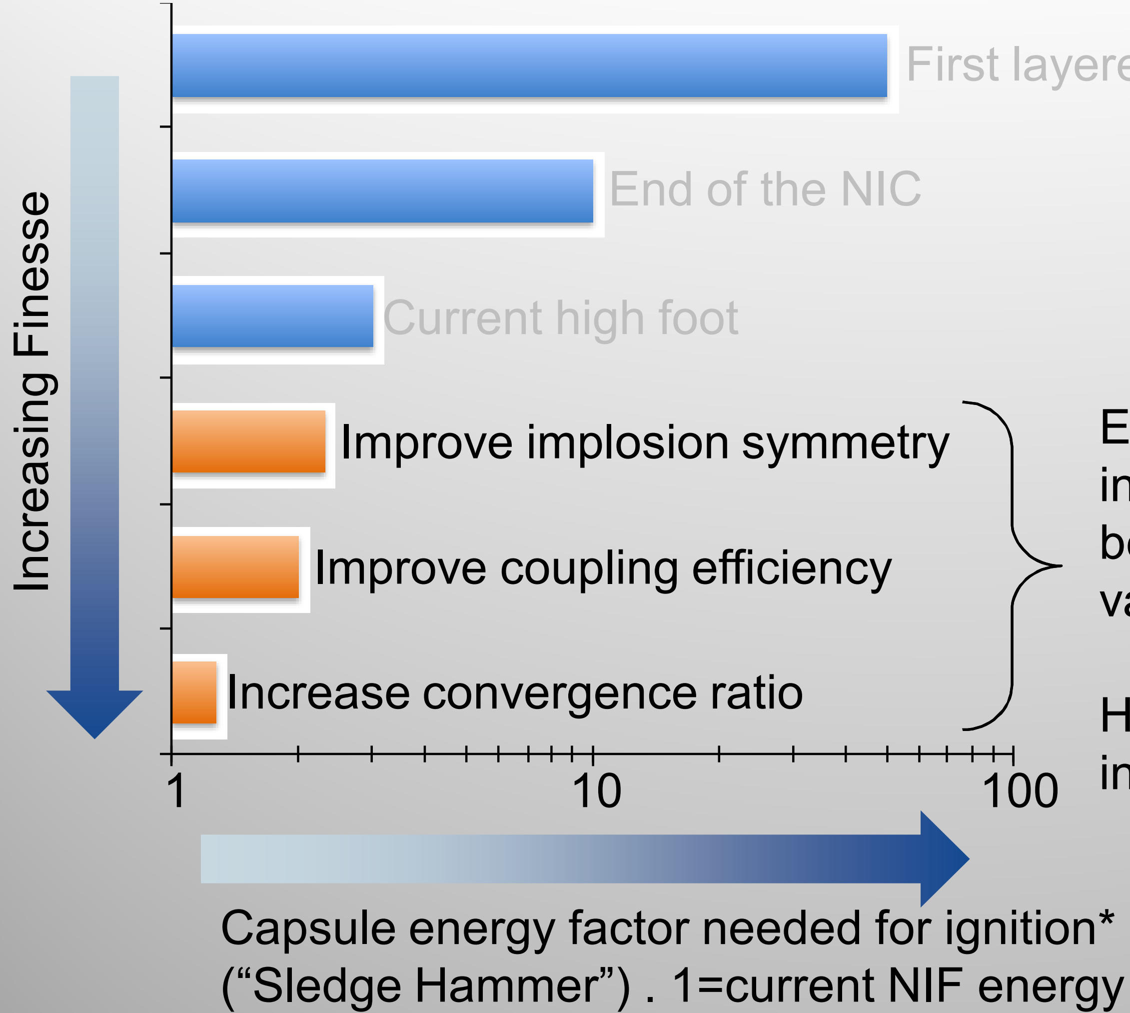
Current high foot implosions would ignite if they had ~ 3X more energy (~40-50% larger)



Capsule energy factor needed for ignition*
("Sledge Hammer") . 1=current NIF energy

*assumes all else the same

The experiment plan focuses on the major levers affecting implosion quality



Estimated potential effect of individual contributors if each can be realized independently – to be validated

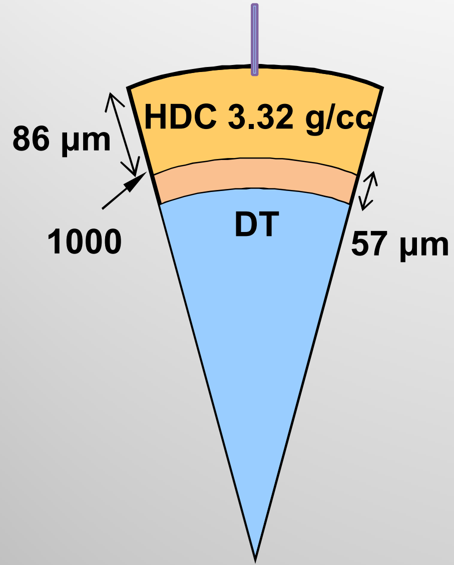
Higher convergence amplifies instability and asymmetry

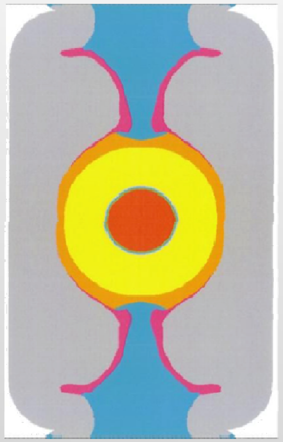
Several aspects of target performance will need to be improved to achieve ignition
Plan emphasizes understanding then mitigation

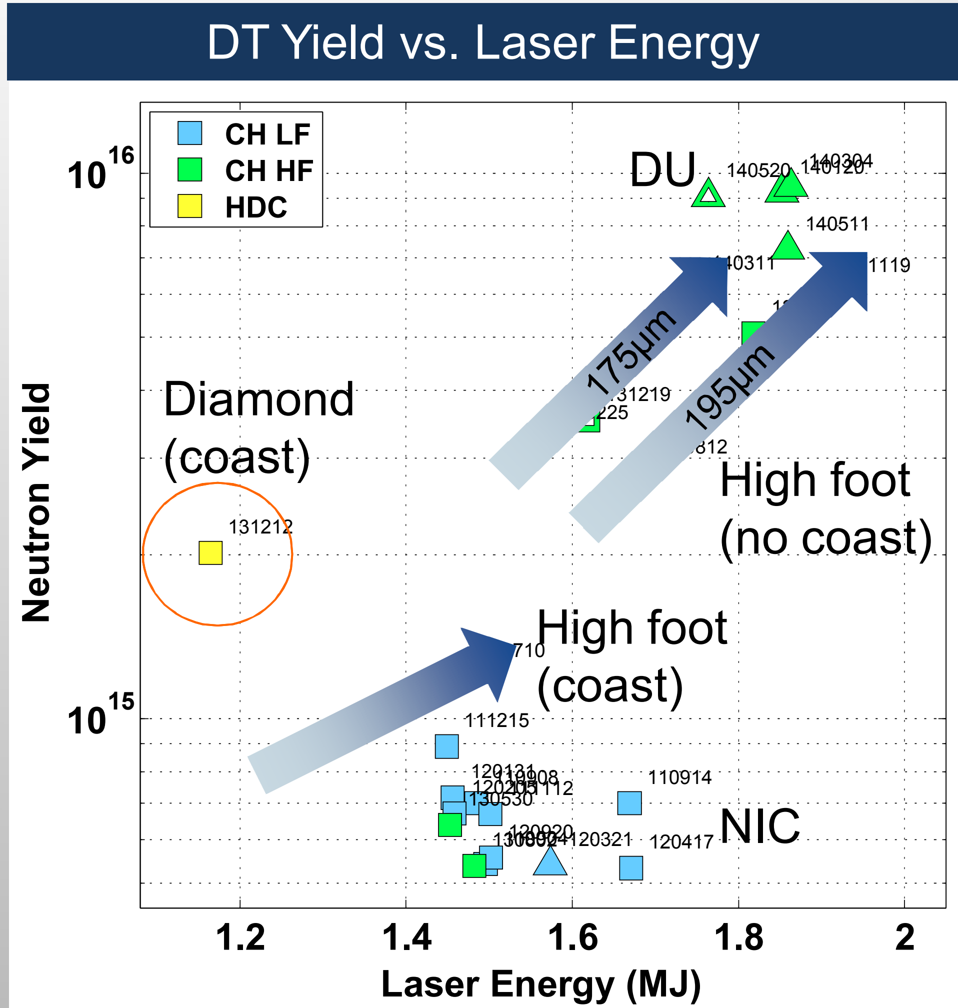
FY15 plan was developed with the (inter)national community

- Top level goals set by program leadership consistent with Path Forward
  - Emphasis on increasing data return by including sub-scale, warm targets for physics studies and testing new ideas
- Allocation of 80 days provided by NIF Director
- Detailed proposals developed (79), peer reviewed in national Campaign teams, ranked for importance, approach, feasibility by ~ 20 senior scientists across the program
- Campaign teams used this input to put their plans together; refined and integrated with program leadership; reviewed by ICF Council, PRP
- Resulting plan ~ 120 shots (vs. ~ 80 in FY14) :
  - Focused experiments / technique development for mix, hohlraum, symmetry physics
  - Integrated ignition cryo tests for CH, HDC, Be
  - 50:50 warm vs cryo, 2/3 sub-scale < 1MJ

Diamond capsule in near vacuum hohlraum much more efficient, performs well, but early days



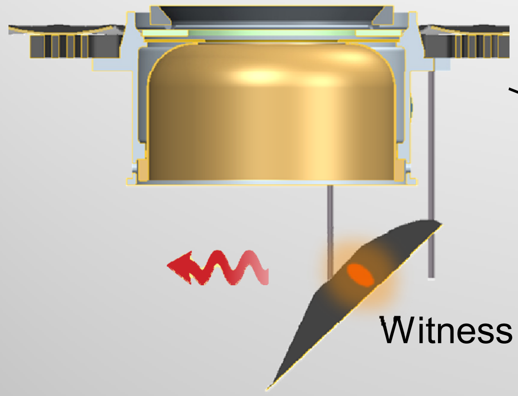




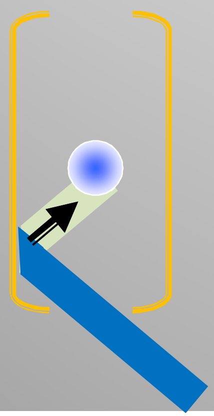
- ~ 6 ns 2-shock pulse (need ~ 9ns)
- High x-ray efficiency with minimal LPI, CBET, hot e's
- 30 % more energy incident on the capsule than CH at higher energy
- Challenge will be symmetry control

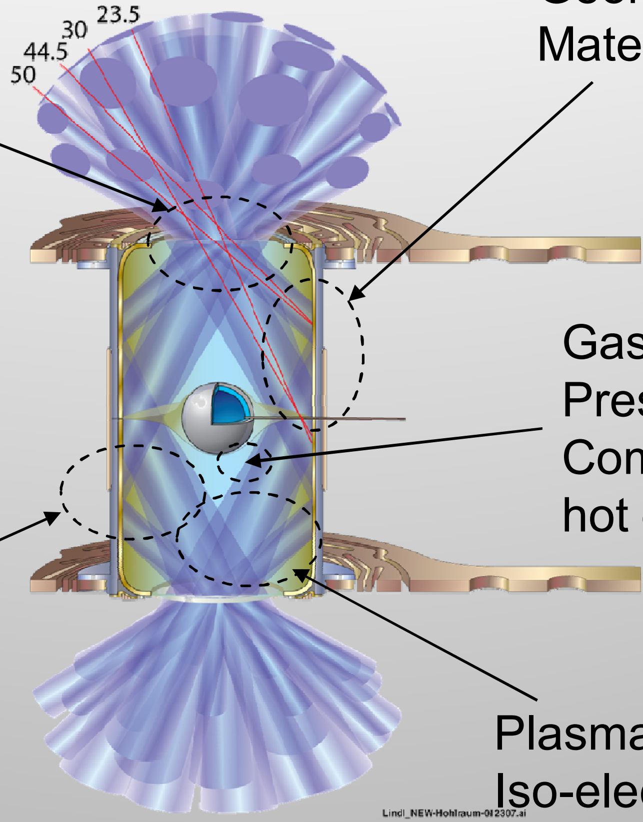
Experimental plans towards understanding hohlraum physics in FY15

Cross beam energy transfer
“Quartraum”



Glint: Outer-beam 3w
may strike capsule



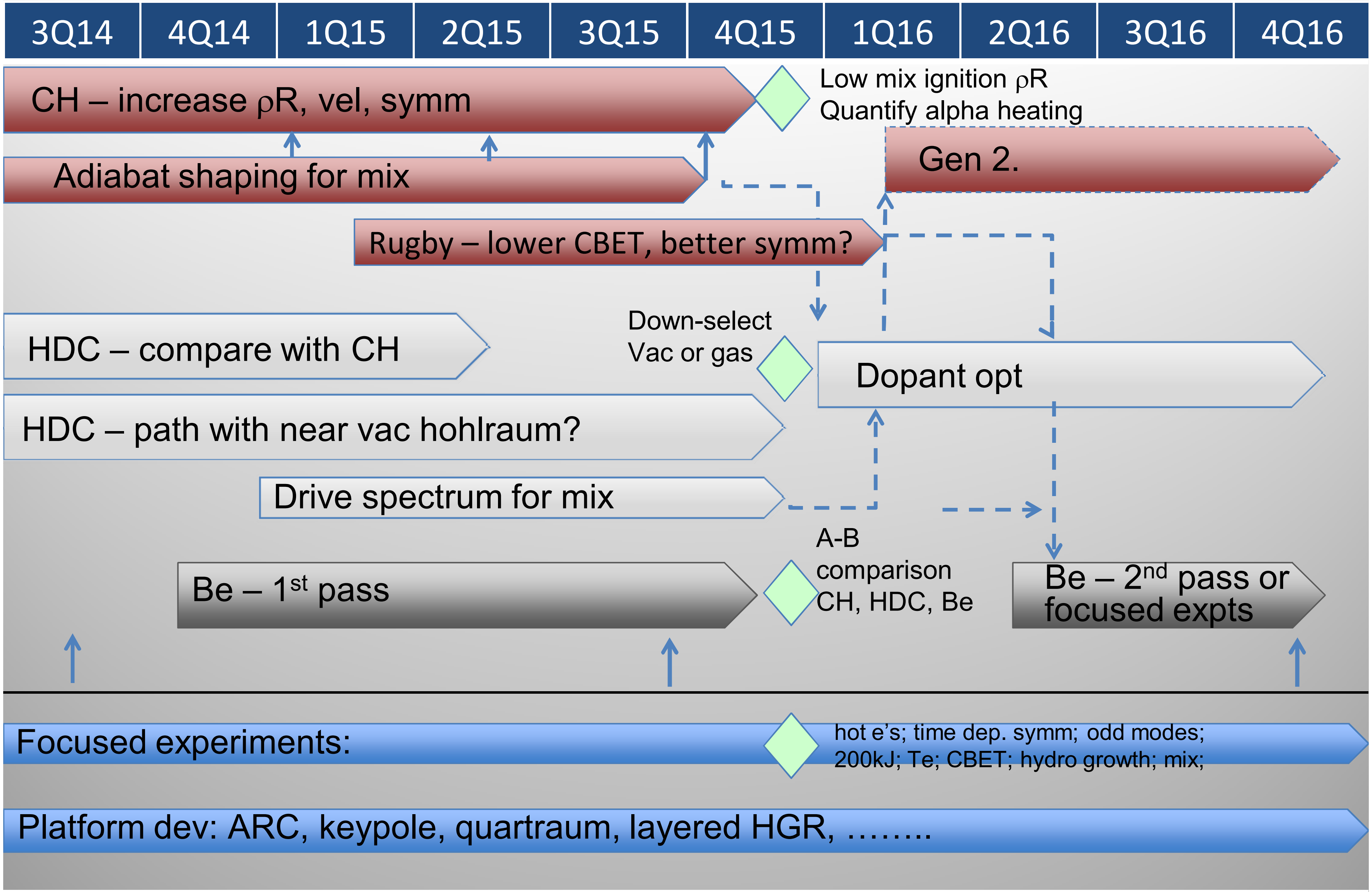


Hohlraum wall:
Geometry (eg rugby, thickness)
Material (DU, Cu-lined..)

Gas-fill:
Pressure scan – “200kJ”
Composition (eg Ne for hot e’s)

Plasma characterization:
Iso-electronic ratios with dots
Au-L-shell
Thomson scattering (begin)

IDI Key Elements



Summary – good progress, issues identified, plans to address them with goals for FY15

- Good progress has been made on the Path Forward
  - Onset of alpha heating, ~2X yield amplification
  - Major issues identified
- Developed a community based plan to improve understanding and predictive capability to address those issues
  - Understanding how capsules fail due to mix and asymmetry
  - Developing mitigations
  - Test new ideas and designs
- Key technical goals for FY15 identified

Goal is to narrow down the issues and improve understanding so we can articulate quantitatively what we need to improve to get ignition and how we might get there

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