Status of NNSA ICF Research on the NIF

Presented to Fusion Power Associates

Washington, DC

John Edwards

Director ICF Program

December 14th, 2016

LLNL-PRES-715690

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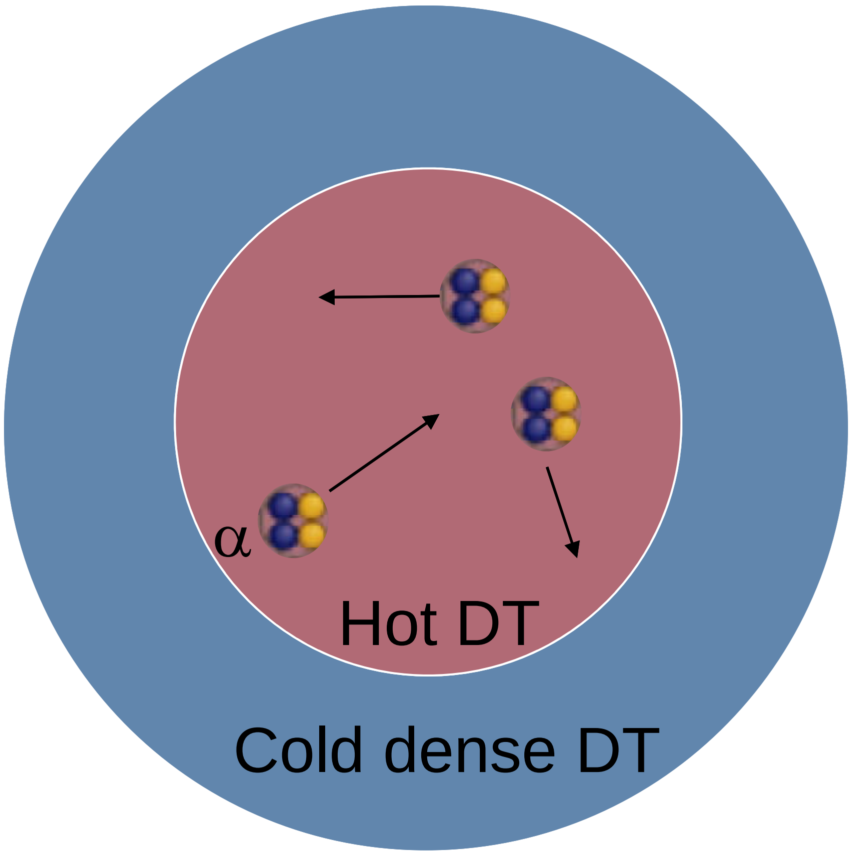
This talk will focus on progress in learning how to control drive symmetry

This was identified as a major factor limiting performance

Why is laboratory ignition hard?
Requires high convergence – amplifies "errors"



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

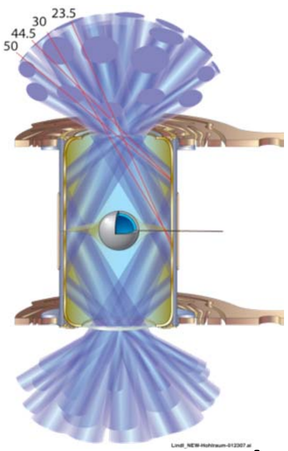
$$P_{stag}^2 \sim CR^6$$

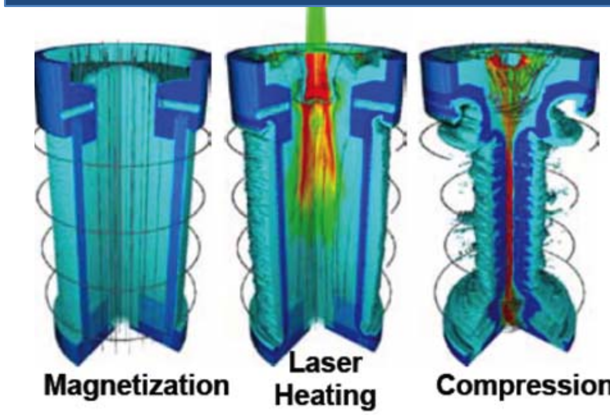
X-ray drive on NIF requires CR ~ 30

*ρR = Areal density

US ICF program evaluating 3 approaches – different convergence ratios, pros and cons

X-ray drive LLNL NIF	Laser Direct Drive Univ. Rochester (Omega, NIF)	Magnetic drive Sandia Nat'l Lab Z-machine





X-ray drive	Laser Direct Drive	Magnetic drive
$E_{Fuel\text{-}NIF}$~15 kJ	$E_{Fuel\text{-}NIF}$~100 kJ	$E_{Fuel\text{-}Z}$~100 kJ
CR ~ 30	CR ~ 20	CR_{2D} ~ 20
P_{ign} ~ 350 Gbar	P_{ign} ~ 150 Gbar	P_{ign} ~ 5 Gbar

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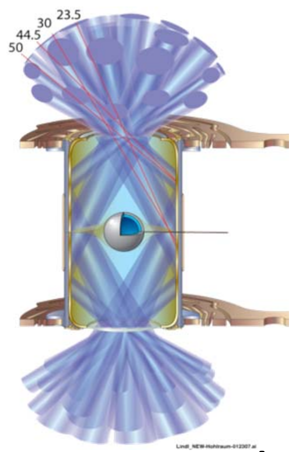		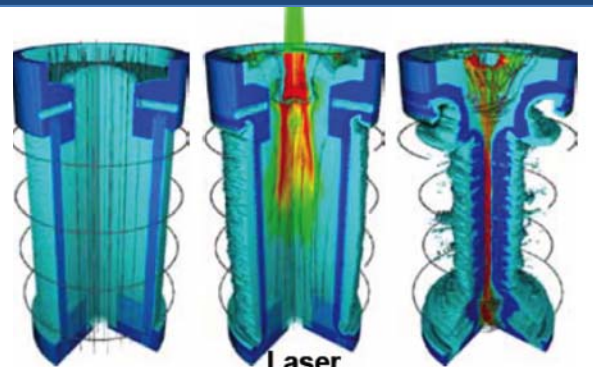
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Principal challenges (as understood today)

- Drive symmetry
- Engineering features
- Energy coupling
- Implosion uniformity
- Fuel preheating
- Radiation loss

2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020

NIC

“Path Forward”

ICF Framework

New diagnostics + model improvements

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NIC

"Path Forward"

ICF Framework

Execute NIC

NIC Pt design

◆ Fell far short of ignition

Asymmetry and mix suspected but details not understood

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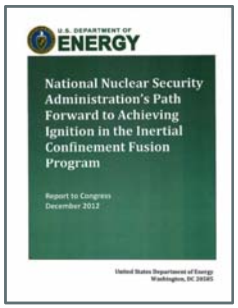
"Path Forward"


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

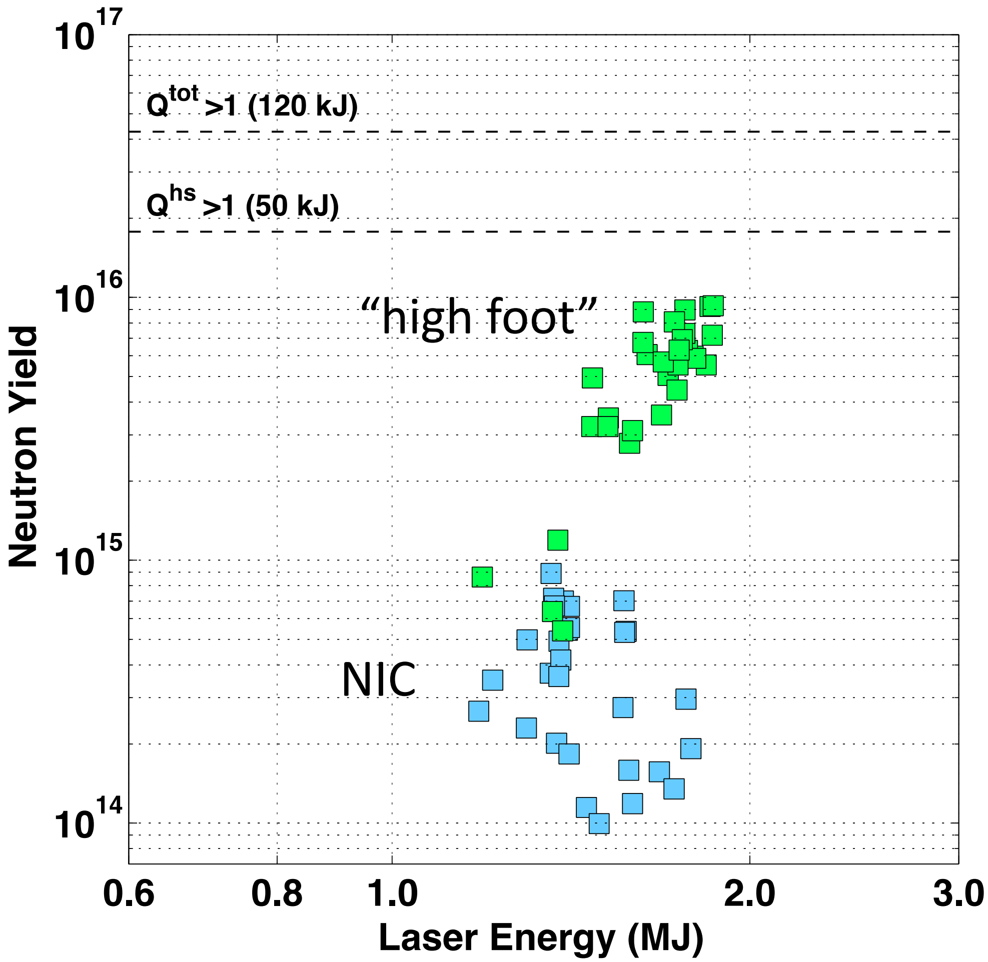
United States Department of Energy
Washington, DC 20585

Emphasis on understanding what's wrong

Lower convergence, more stable design

New diagnostics + model improvements

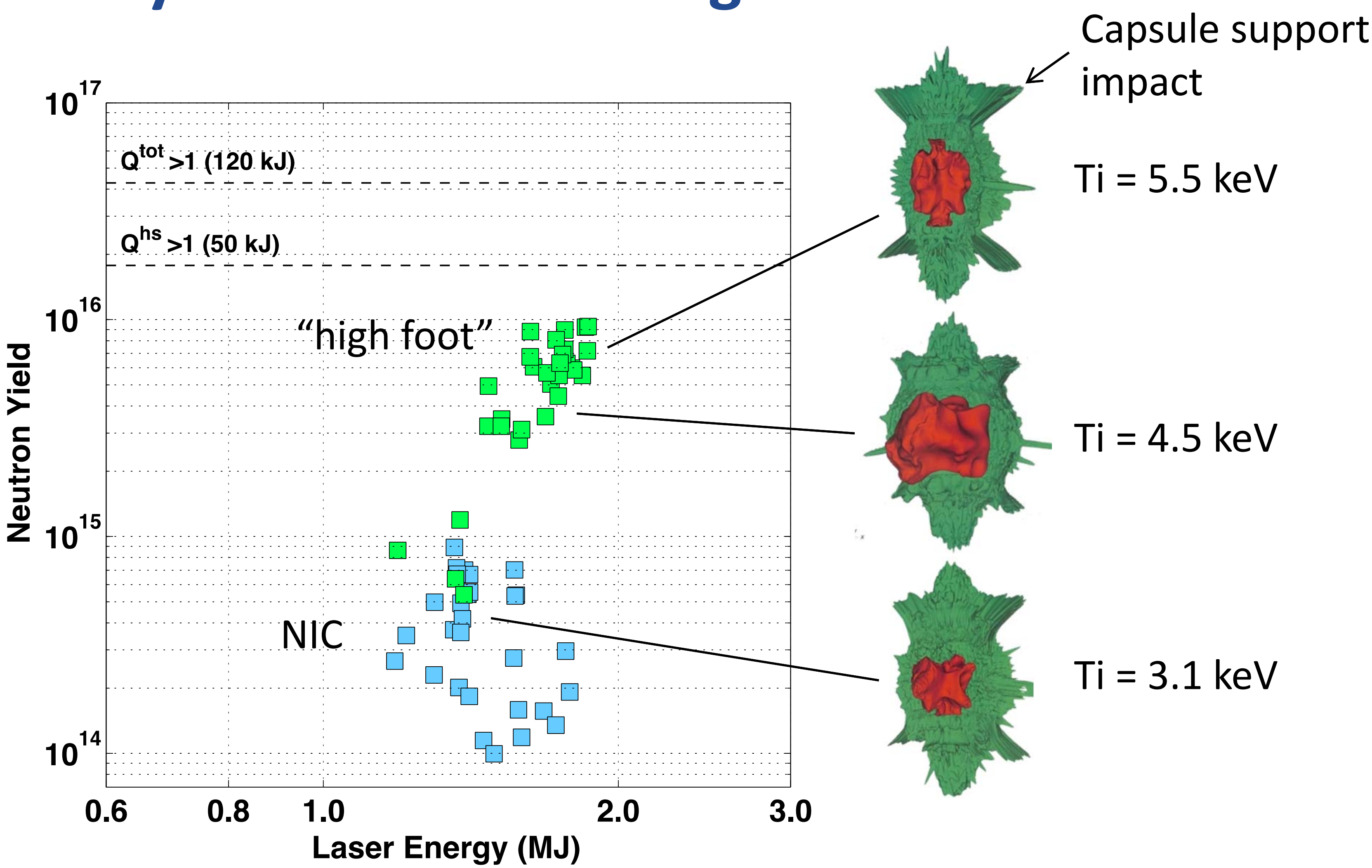
Post NIC, "high foot" implosions performed better, > 2X alpha heating – no mix observed



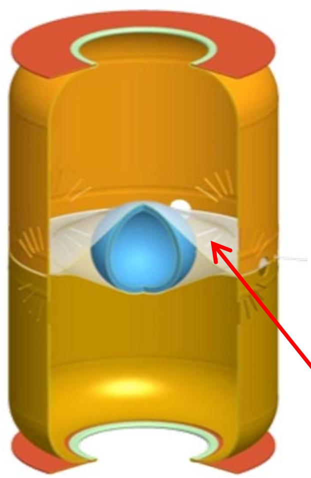
High foot was more stable and lower convergence

Accomplished by laser pulse shape change

Better stability and lower convergence of high foot delayed onset of limiting factors



2014 summer study concluded: appears **two major factors** preventing ignition – others may be found

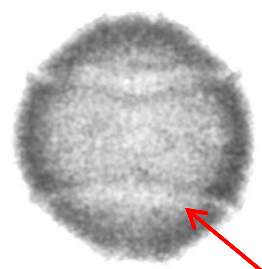


LPI dominated
Asymmetric x-ray drive

+

Capsule support
"Tent"

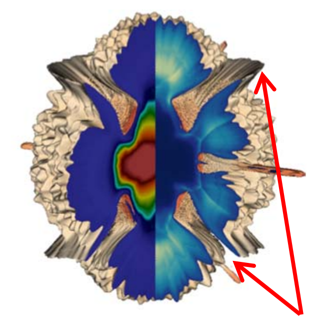
Distorted implosion



"Tent"

[1]Processed in-flight radiograph

Inefficient fuel assembly



"Tent"

[2]Simulated DT fuel at stagnation

[1]J.E. Field et al, Rev. Sci. Instrum. **85**, 11E503, (2014)
[1]R. Tommasini et al, Phys. Plasmas. **22**, 056315, (2015)
[2]2D. S. Clark et al, Phys. Plasmas, **22**, 022703, (2014)

Are these fundamental limiters or can they be addressed?
This directed follow on research

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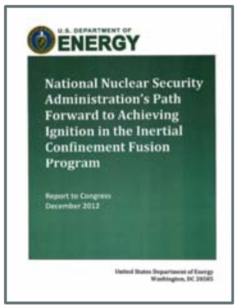
NIC | "Path Forward" | ICF Framework

Execute NIC

NIC Pt design

◆ Fell far short of ignition
Asymmetry and mix suspected but details not understood

"Path Forward"



Emphasis on understanding what's wrong

Lower convergence, more stable design

◆ 26kJ yield, no mix (high foot)
2X yield amplification due to alpha heating

◆ Appears LPI dominated asymmetry too large, capsule support -> mix in NIC, limits high foot

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New diagnostics + model improvements

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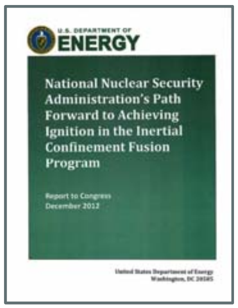

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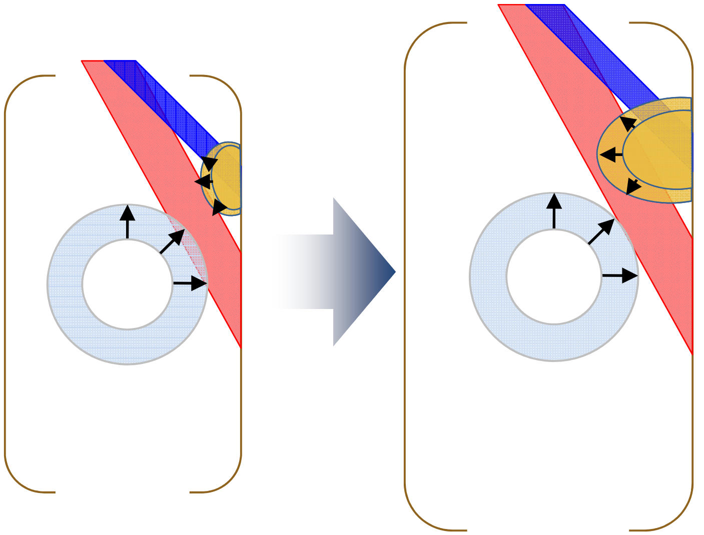
ICF Framework

Can LPI, asymmetry and engineering features be mitigated?

Low LPI (low fill) hohlraum designs

New diagnostics + model improvements

At the start of 2015 the program redirected to "eliminate" LPI and improve symmetry – did it work?



High fill
LPI dominated

Low fill
Low LPI
(more efficient)

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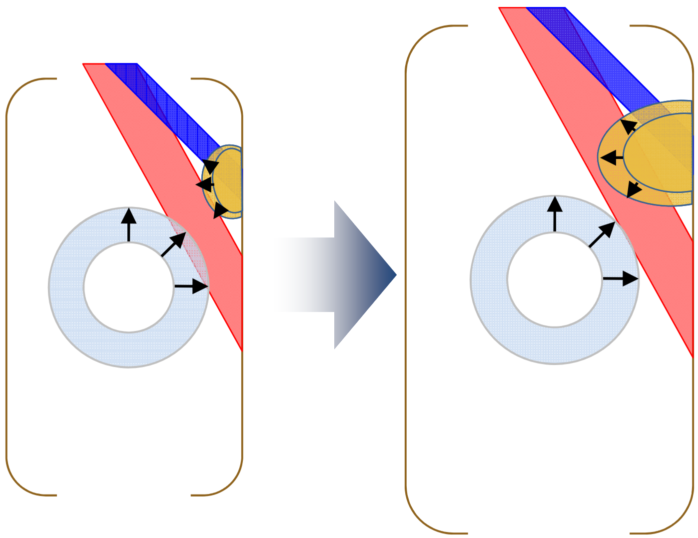

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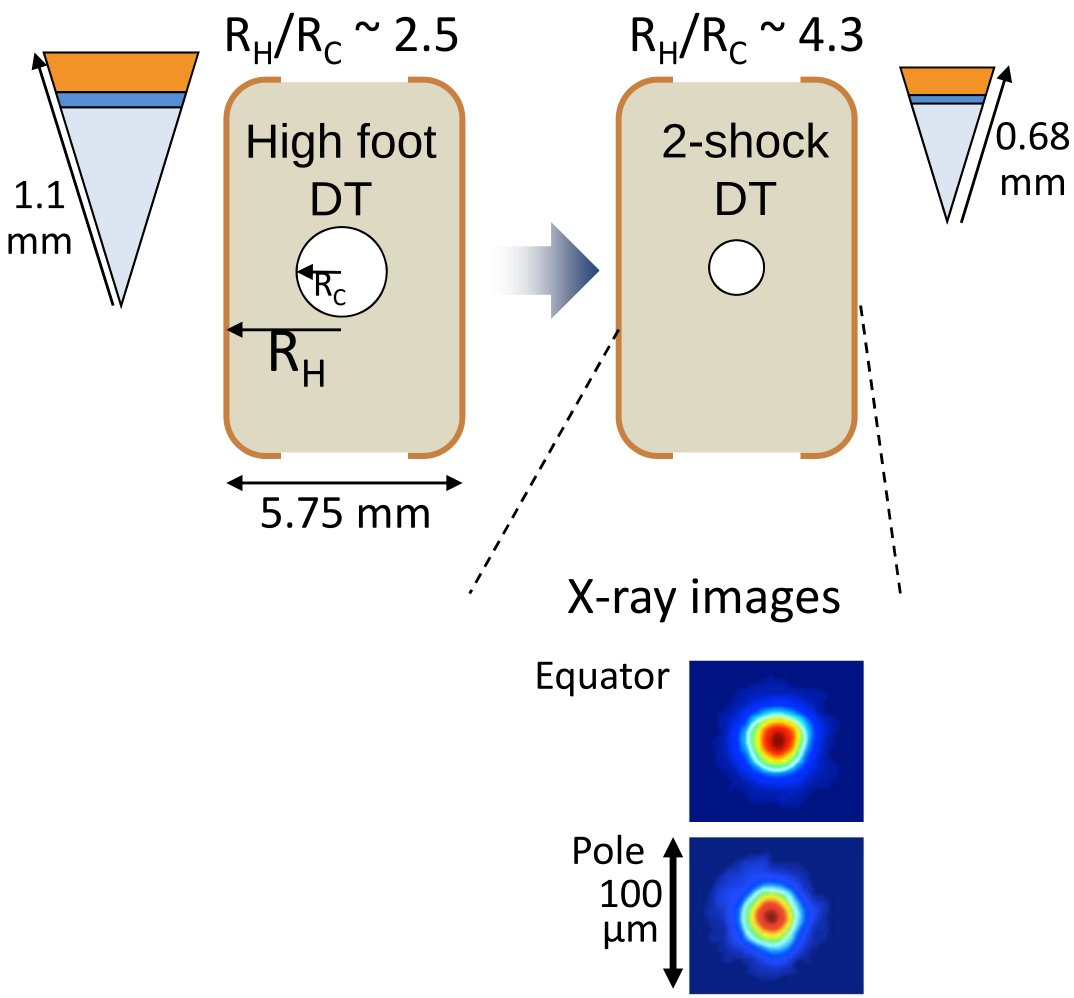
Key results

Learned could achieve: ✓

- Low LPI
- Low hot electrons
- Symmetric implosion

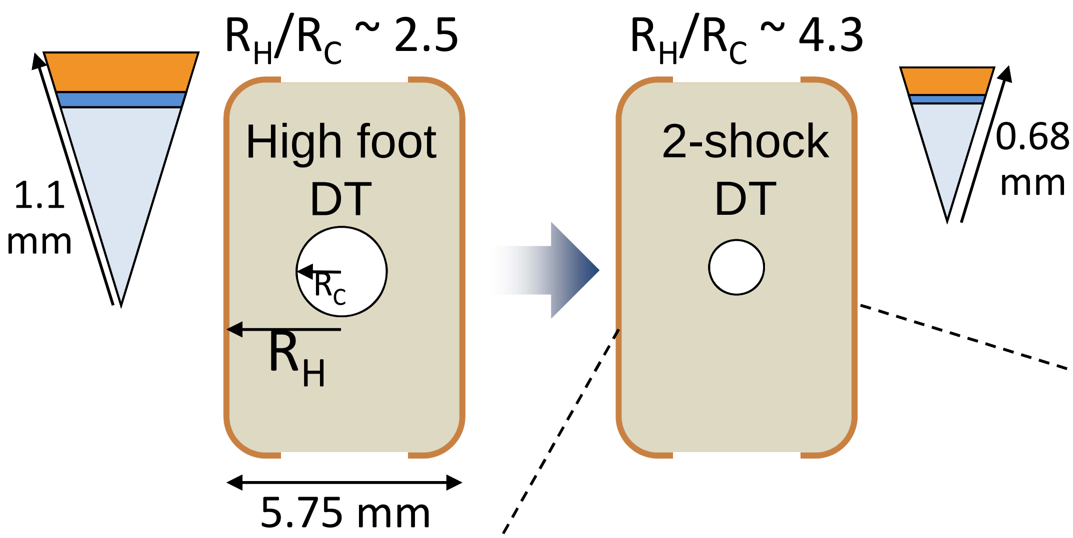
Implosions can be spherical if hohlraum is large enough



But, this capsule is not large enough to ignite

MacLaren et al

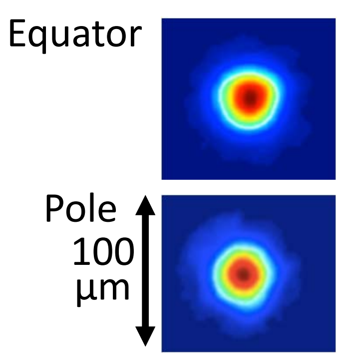
Implosions can be spherical if hohlraum is large enough



Spherical *and* stable DT implosions perform close to 1D *even at CR~32*

Preliminary analysis (also note Tion high as usual)

X-ray images

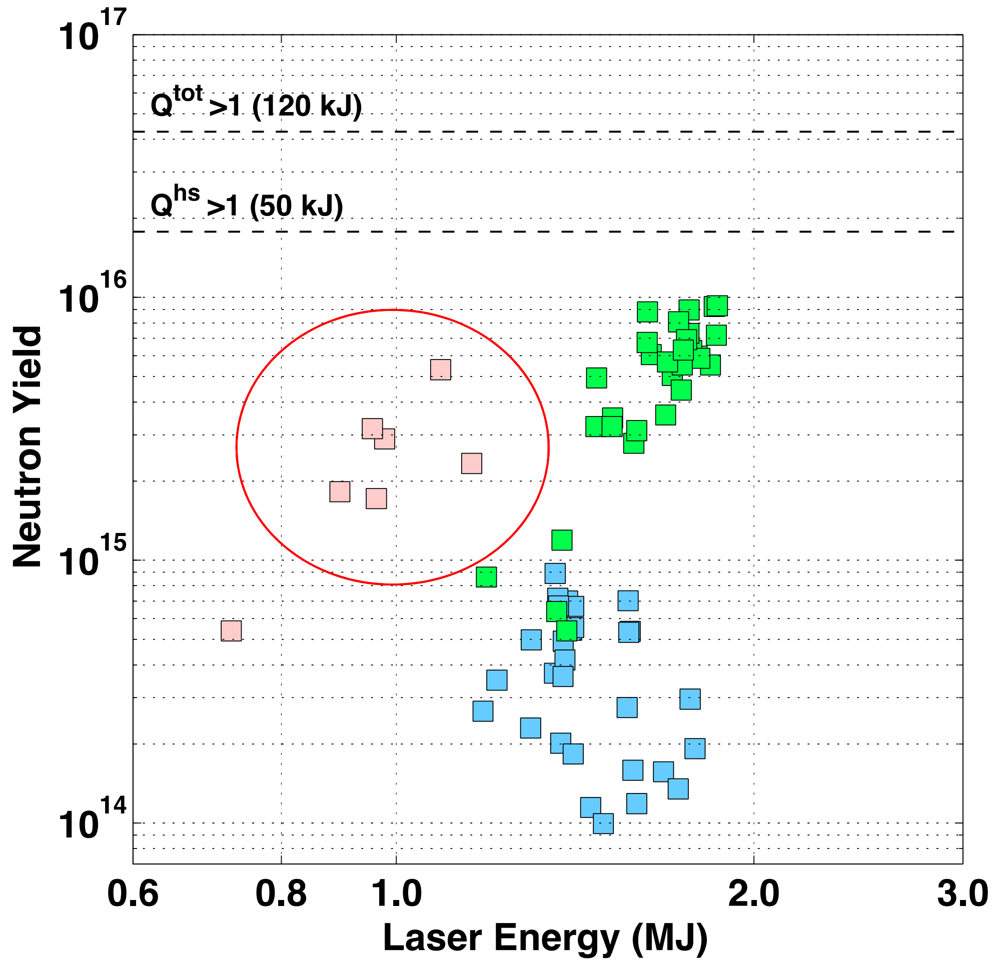


~ 88% YOC

	N161004	Preshot 1D simulation
Y_{DT} (10^{14})	1.67±0.3	1.9
T_{ion} (keV)	2.84±0.15	2.3
dsr	2.3±0.3	2

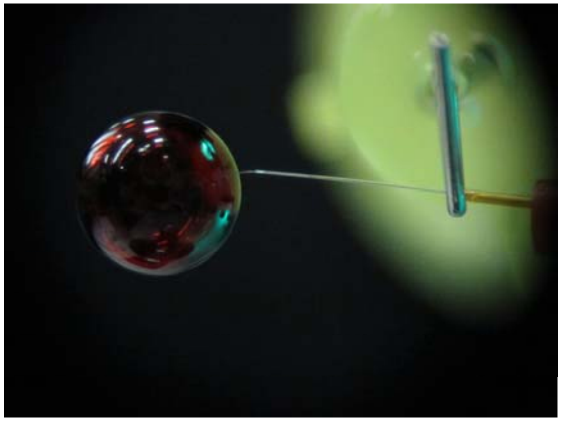
MacLaren et al

Beginning to apply these lessons to more ignition relevant designs –> improved efficiency



But not yet clear whether this approach can scale to ignition

Also new findings:
Fill tube may be larger impact than originally expected



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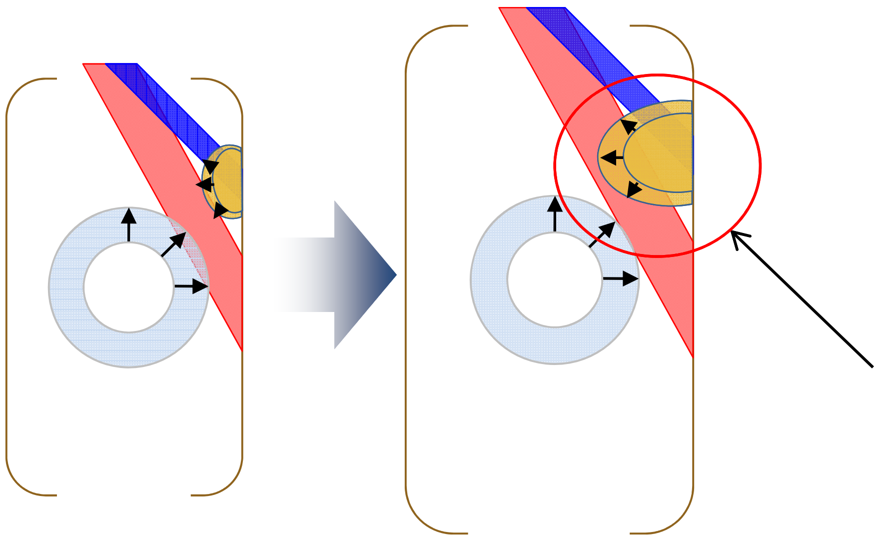

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- Low hot electrons
- Symmetric implosion

Also learned:

- Gold "bubble" limits time window for symmetric implosion – **sets limit on capsule size**

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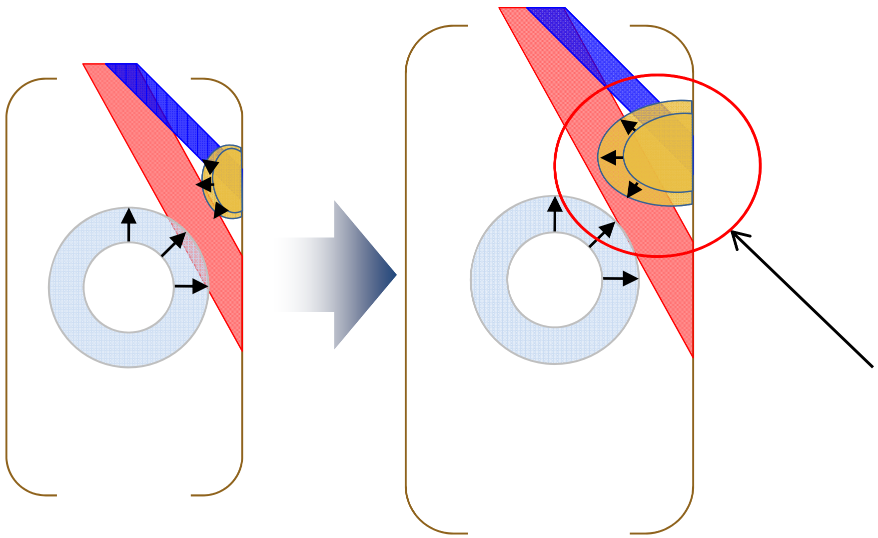

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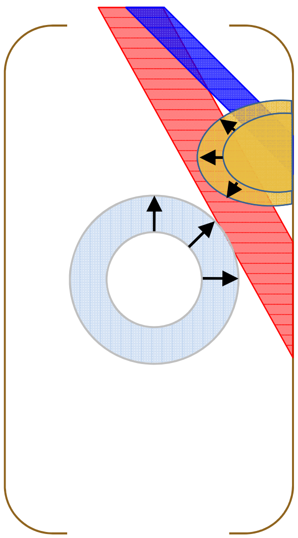
Also learned:
- Gold "bubble" limits time window for symmetric implosion – **sets limit on capsule size**

- Key question to answer going forward:
  In the largest hohlraum afforded by NIF's power and energy, can we control symmetry with a capsule that is large enough to ignite? If not, can we do anything about it?

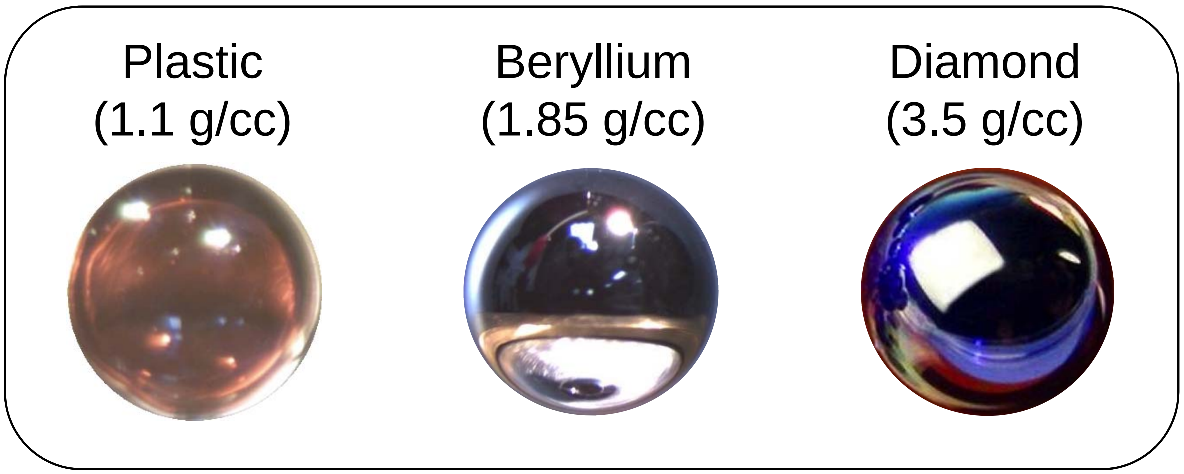
Going forward, goal is to determine how large a capsule can be imploded spherically on NIF

Low LPI, symmetric hohlraum driver



+

Will evaluate three capsule materials
– stress hohlraum and hydro stability differently

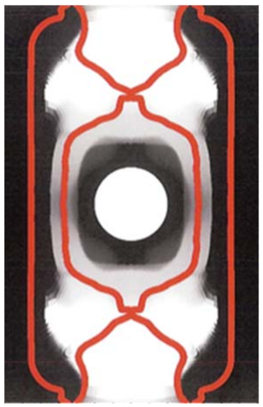


Longest pulse | Most stable | Shortest pulse

How will they perform, what are the remaining issues, can they be overcome ?

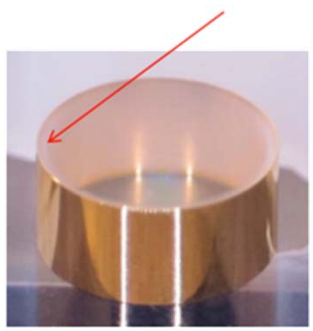
Can we lengthen the “safe” operating window for symmetric drive – eg reduce wall motion?

Example: foam liner concept



Regular hohlraum

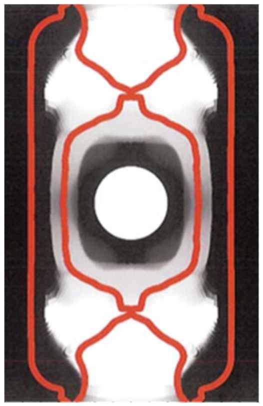
Foam lined hohlraum



Thomas et al

Beginning to explore new ideas to lengthen the "safe" operating window

Example: foam liner concept



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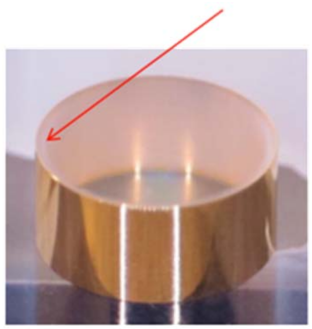
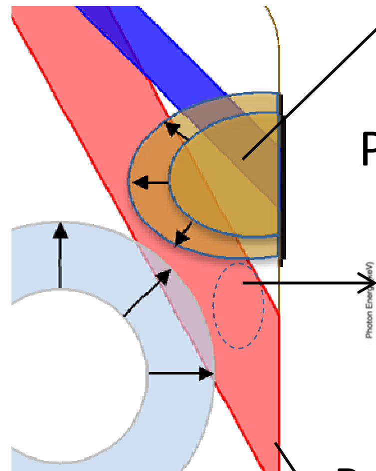
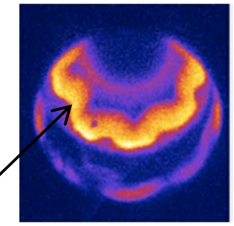
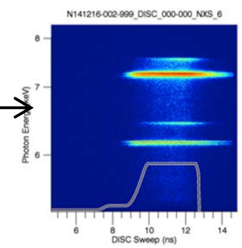




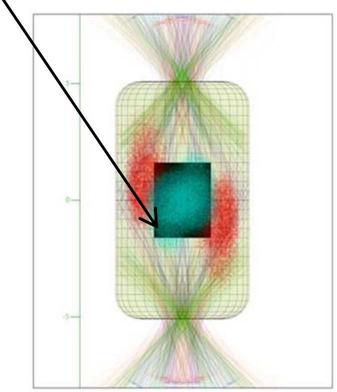
"Bubble" motion



Plasma ne,Te



Beam propagation



Thomas et al

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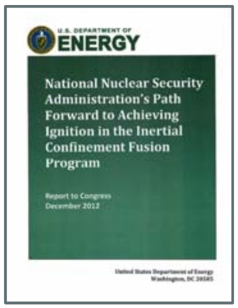

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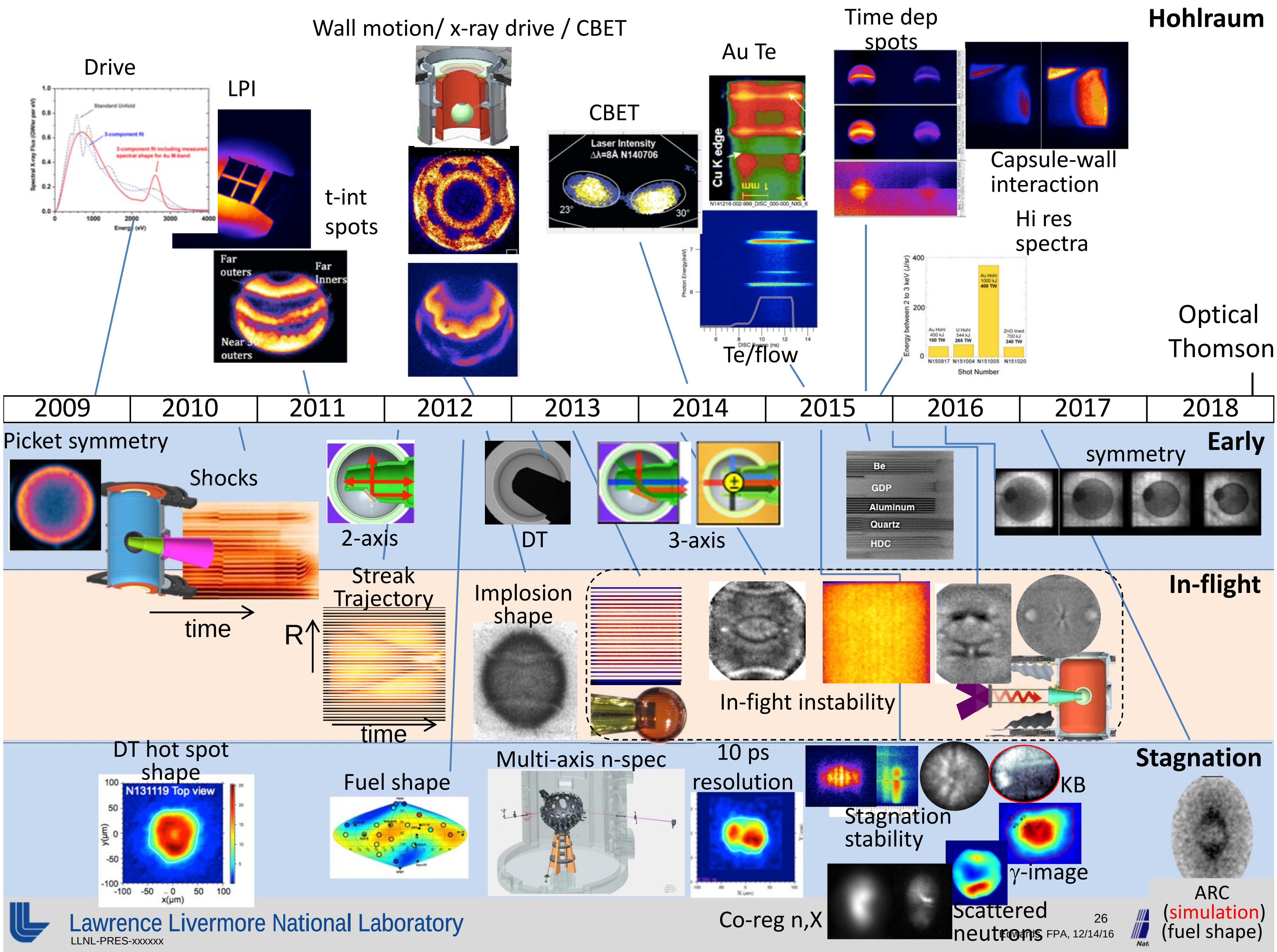
ICF Framework

Can LPI, asymmetry and engineering features be mitigated?

Low LPI (low fill) hohlraum designs

◆ Low LPI, symmetry demonstrated
Not yet clear if scales to ignition
Have plan to answer/improve

New diagnostics + model improvements


Hohlraum
Drive
LPI
t-int
spots
Far outers
Far Inners
Near 30° outers
Wall motion/ x-ray drive / CBET
CBET
Laser Intensity
Δλ=8Å N140706
23°
30°
Au Te
Cu K edge
Te/flow
Time dep
spots
Capsule-wall
interaction
Hi res
spectra
Shot Number
Optical
Thomson
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Early
Picket symmetry
Shocks
time
2-axis
DT
3-axis
Be
GDP
Aluminum
Quartz
HDC
symmetry
In-flight
Streak
Trajectory
R
time
Implosion
shape
In-fight instability
Stagnation
DT hot spot
shape
N131119 Top view
y(μm)
x(μm)
Fuel shape
Multi-axis n-spec
10 ps
resolution
Co-reg n,X
Stagnation
stability
KB
γ-image
Scattered
neutrons
ARC
(simulation)
(fuel shape)

Summary of X-ray drive ignition on the NIF

- Progress in learning how to control drive symmetry
  - Identified as major factor limiting performance
- Beginning to apply lessons to understand how far this can scale towards ignition – need time to evaluate
- Beginning to explore concepts to improve prospects of scaling
- Ongoing engineering effort to address the capsule support and fill tube (not discussed today)

These new directions need a methodical, scientific approach, new diagnostics, improved models and time to evaluate

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