Progress and challenges in x-ray drive ICF on the NIF

Fusion Power Associates, 2014

Washington DC

December 16th, 2014

Lawrence Livermore National Laboratory

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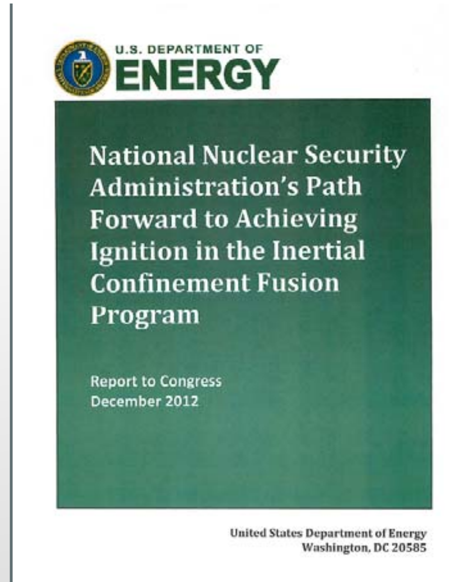
John Edwards for the ICF team
ICF Program Director, LLNL

NNSA's 2012 Path Forward report to Congress defines the current US ICF Program

- Increased emphasis on focused physics experiments to improve understanding and predictive capability
- Exploratory program with three approaches each with different potential benefits and risks

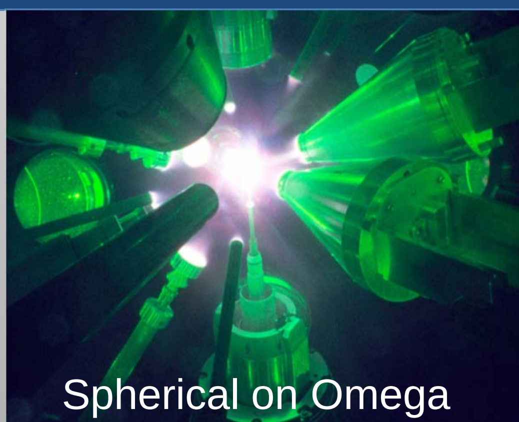

U.S. DEPARTMENT OF ENERGY

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

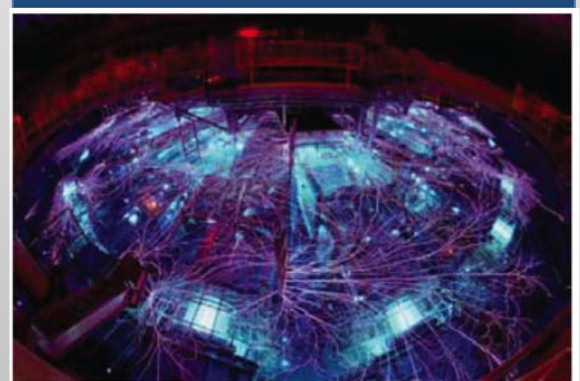
Report to Congress
December 2012

United States Department of Energy
Washington, DC 20585

Laser Direct Driven	Magnetic drive	X-ray drive
Univ. Rochester (Omega, NIF)	Sandia Nat'l Lab Z-machine	Internt'l team on NIF


Spherical on Omega

Sangster


Sinars


This talk

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

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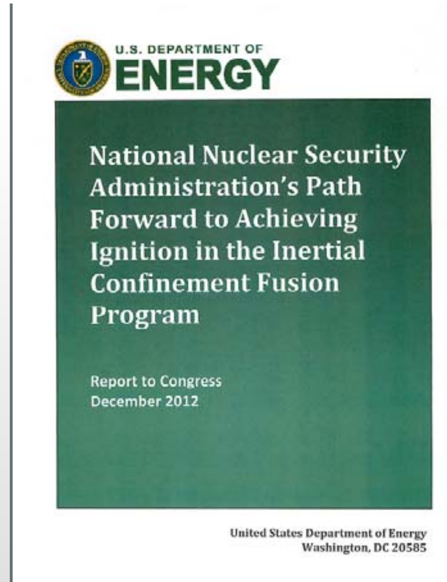
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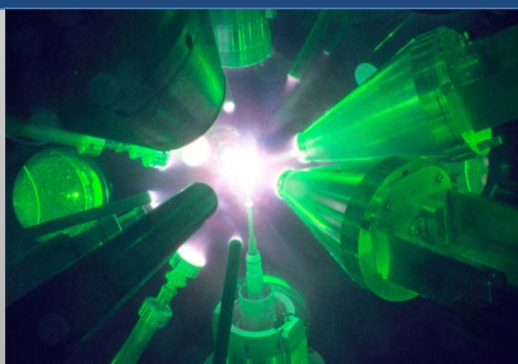
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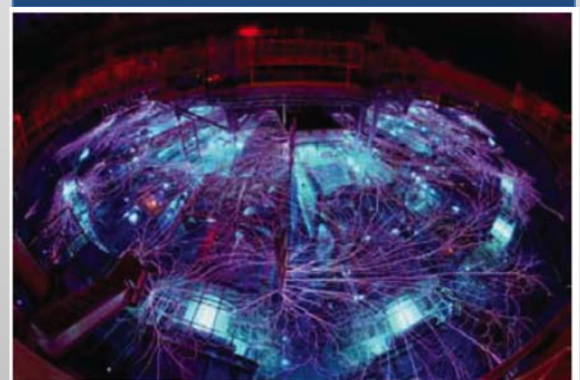
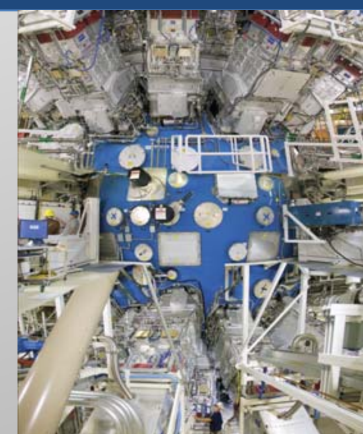
Magnetic drive
Sandia Nat'l Lab Z-machine

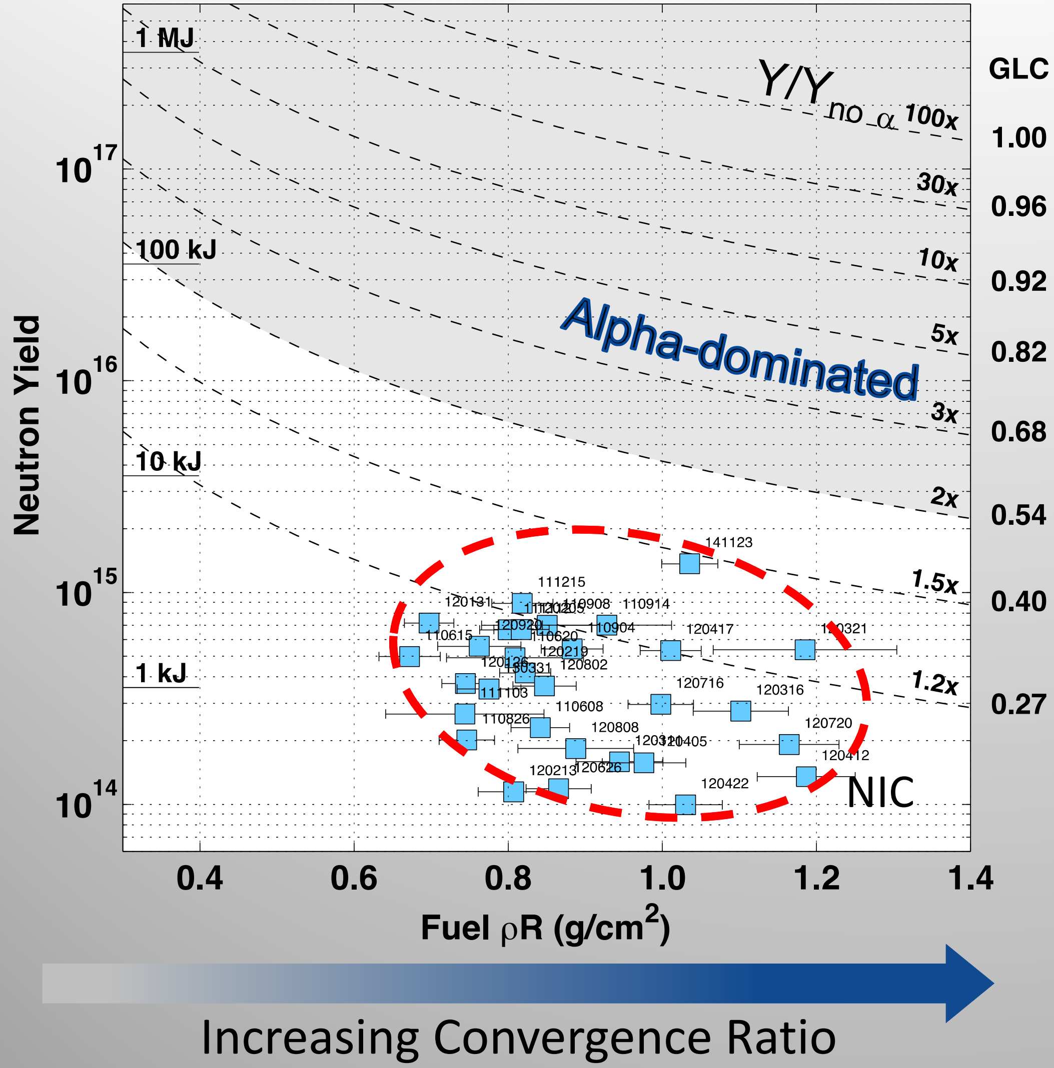

Sinars

X-ray drive
Internt'l team on NIF



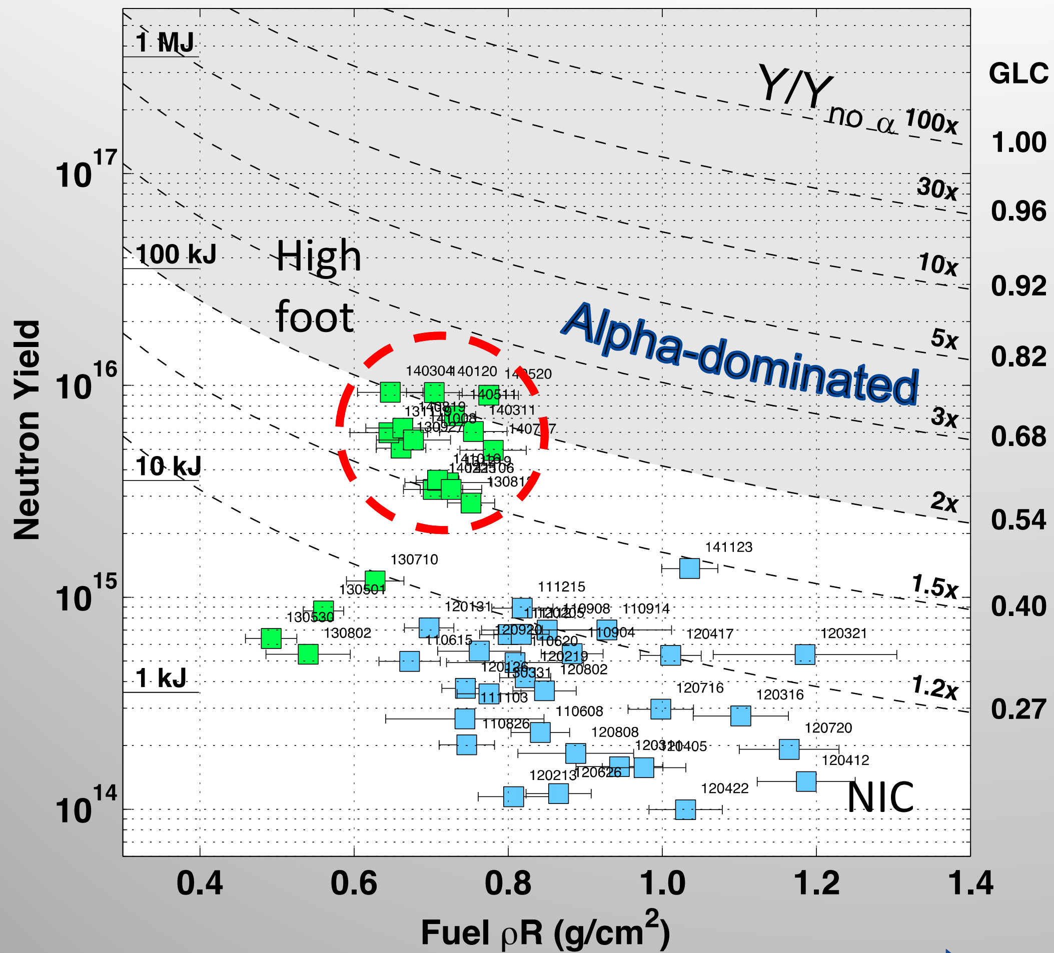
Significant progress in all areas over the last two years
Major challenges further clarified, potential solutions identified, tests beginning
Expect more of both!

From new focused experiments we now know multiple factors were degrading high convergence NIC implosions



- High convergence NIC implosions degraded by: asymmetry, hydro instability, mix

Lower convergence, more stable “high foot[1]” implosions performed better – but still asymmetric

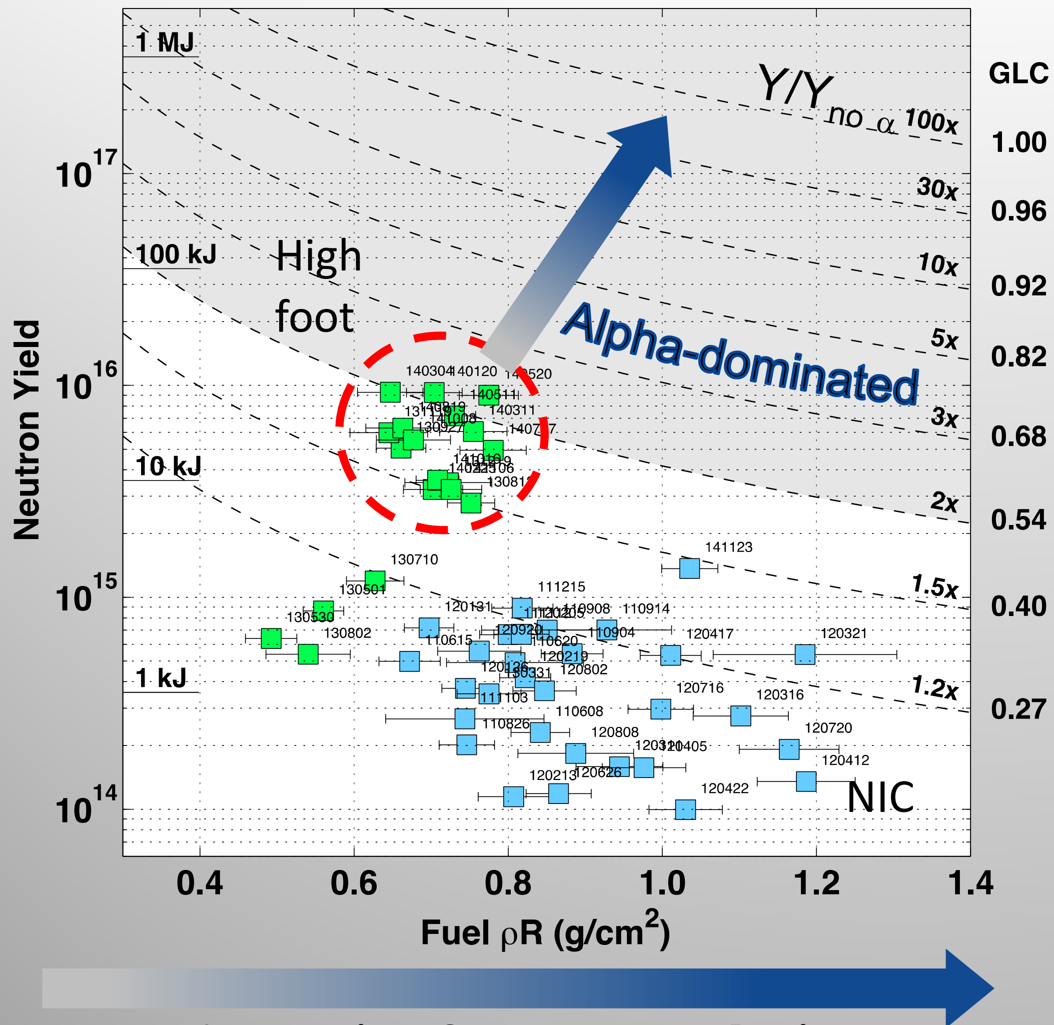


Increasing Convergence Ratio

- High convergence NIC implosions degraded by: asymmetry, hydro instability, mix
- Lower convergence, more stable implosions perform closer to simulations but still challenged by asymmetry

[1] O. Hurricane et al, Nature 506, 343–348 (20 February 2014)

Can the technical challenges be navigated as we push towards ignition?

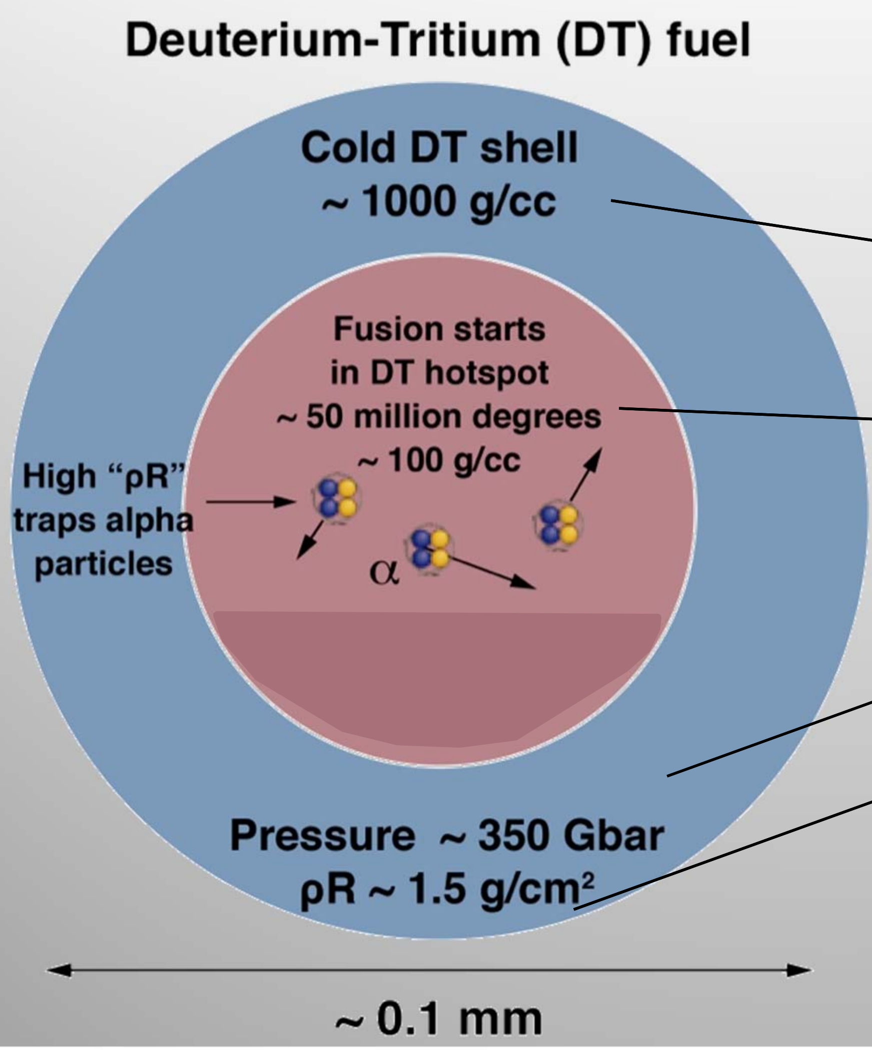


Increasing Convergence Ratio

- High convergence NIC implosions degraded by: asymmetry, hydro instability, mix
- Lower convergence, more stable implosions perform closer to simulations but still challenged by asymmetry
- Ignition requires higher convergence
- Need to improve:
  - Capsule stability
  - Hohlraum drive and symmetry

[1] O. Hurricane et al, Nature 506, 343–348 (20 February 2014)

Conditions are currently ~ factor 2 from ignition



Best simultaneous performance on single shot

~ 27kJ (2X from alpha heating)

~ 500 g/cc

~ 40 g/cc

~ 5 keV

~ 180 Gbar

~ 0.75 g/cm ^{2}

CR ~ 35

*ρR = Areal density

Outline

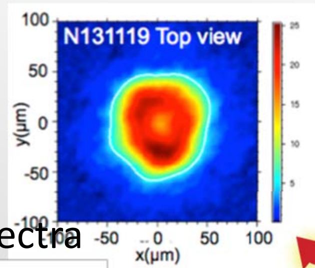
- Understanding the NIC implosions
- Status of high foot
- New approaches

~50 state of the art diagnostics on the NIF
– added to and refined since the NIC – some examples

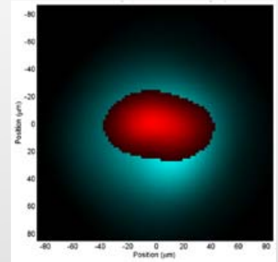
Hot spot

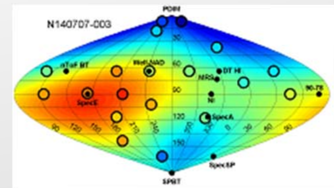
Cold fuel

X-ray imaging



Neutron imaging



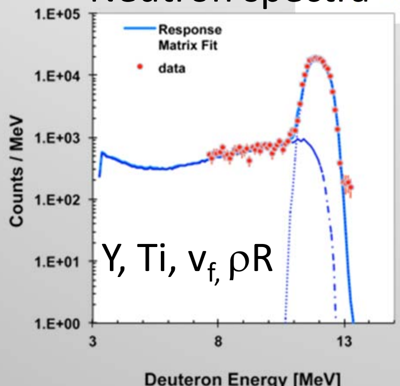


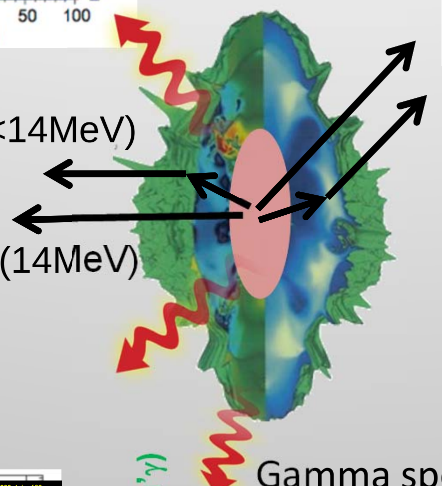
Nuclear activation

G. P. Grim, F. E. Merrill, LANL

J. Frenje,
M. Gatu Johnson, MIT

Neutron spectra

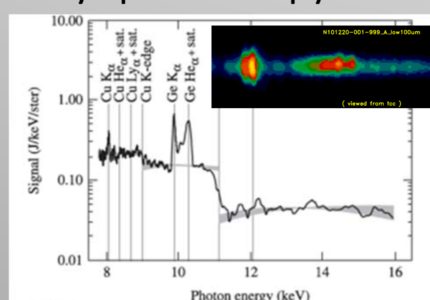




~ 50-100 keV radiography under development to view dense fuel

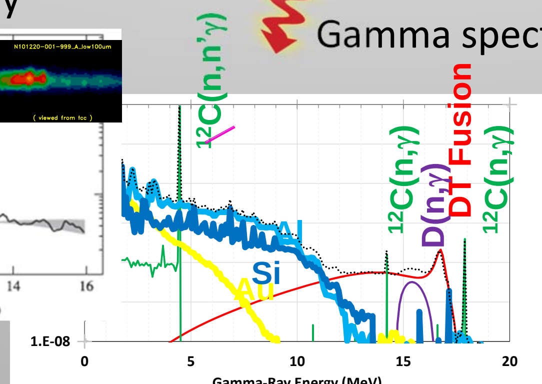
X-ray spectroscopy

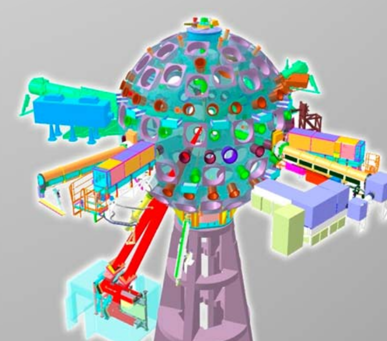
Mix



S. P. Regan, LLE

Gamma spectroscopy



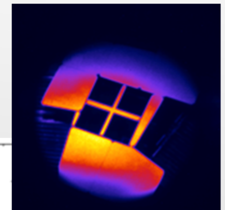


H. W. Herrmann, LANL

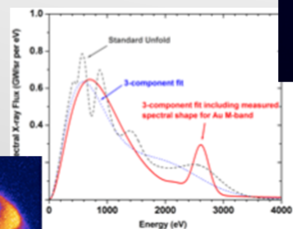
Multiple experimental platforms have been developed to study ignition target behavior (examples follow)

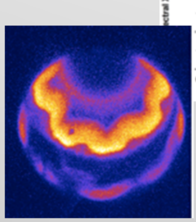
Hohlraum performance

Backscatter

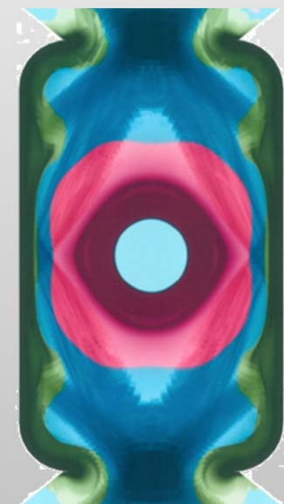


Spectrum

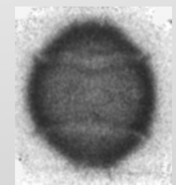




Wall motion

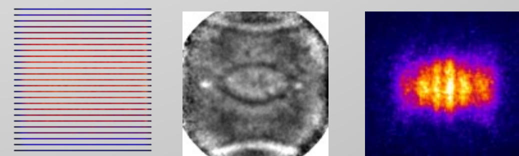


Capsule shape

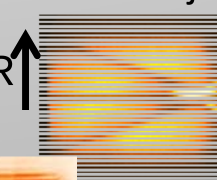


3D

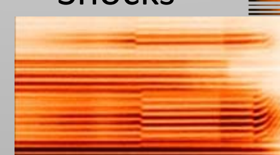
Instability



Streak Trajectory



Shocks



time

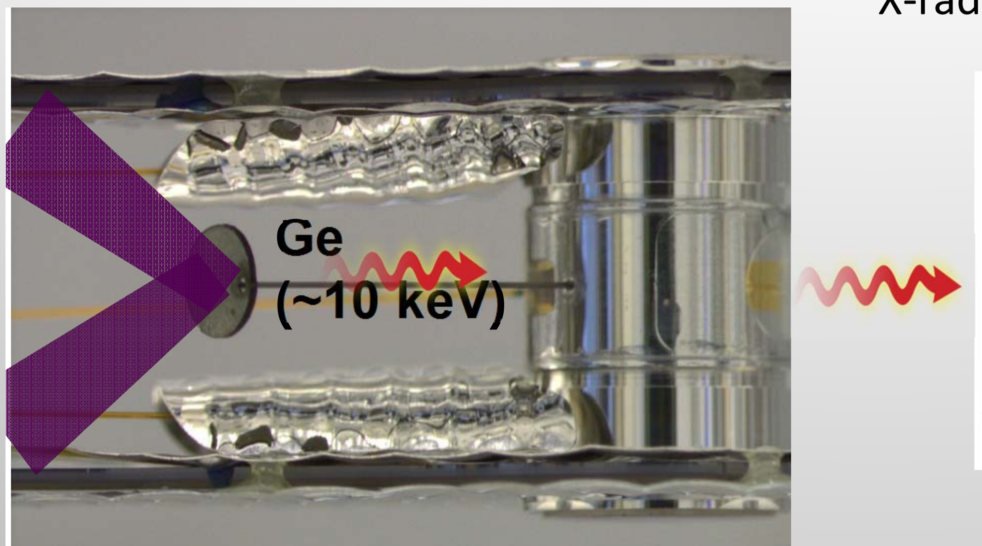
time

1D

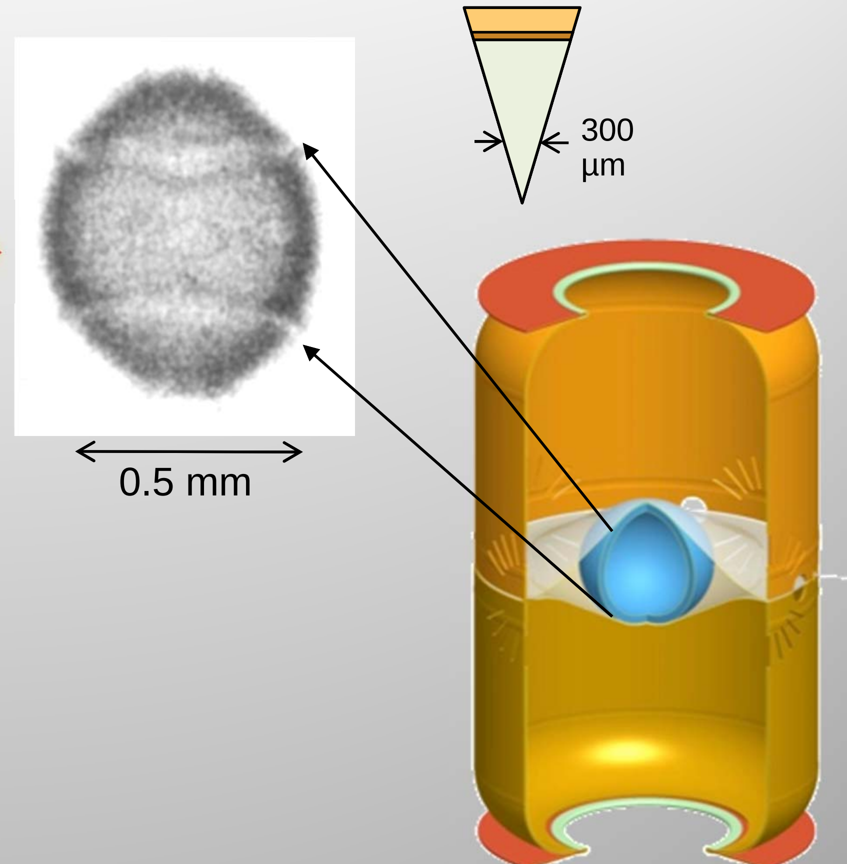
More are needed especially for hohlraum plasma conditions and capsule stagnation

Capsule implosion

X-ray backlighting revealed asymmetric implosion and a large “feature” due to the capsule support membrane – “tent”



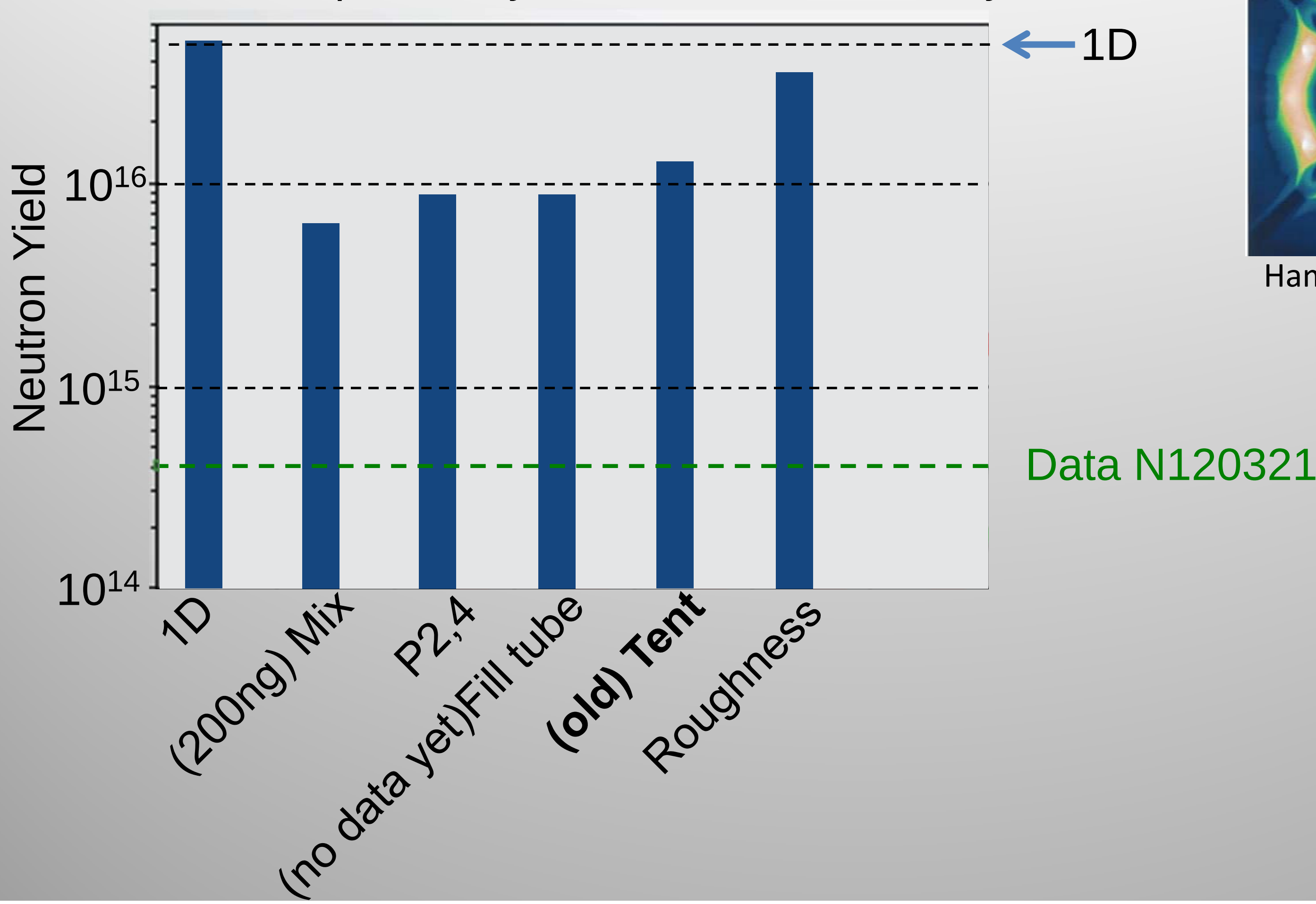
X-radiograph of NIC implosion



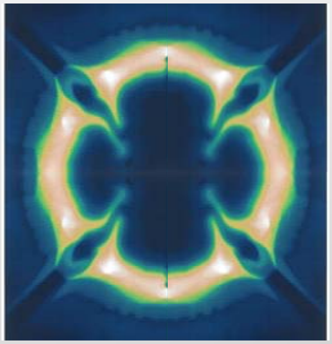
Both features degraded NIC implosions substantially

We now know NIC implosions were degraded by multiple ~ “5X” effects

Predicted impact of hydro features individually in 2D



2D tent simulation

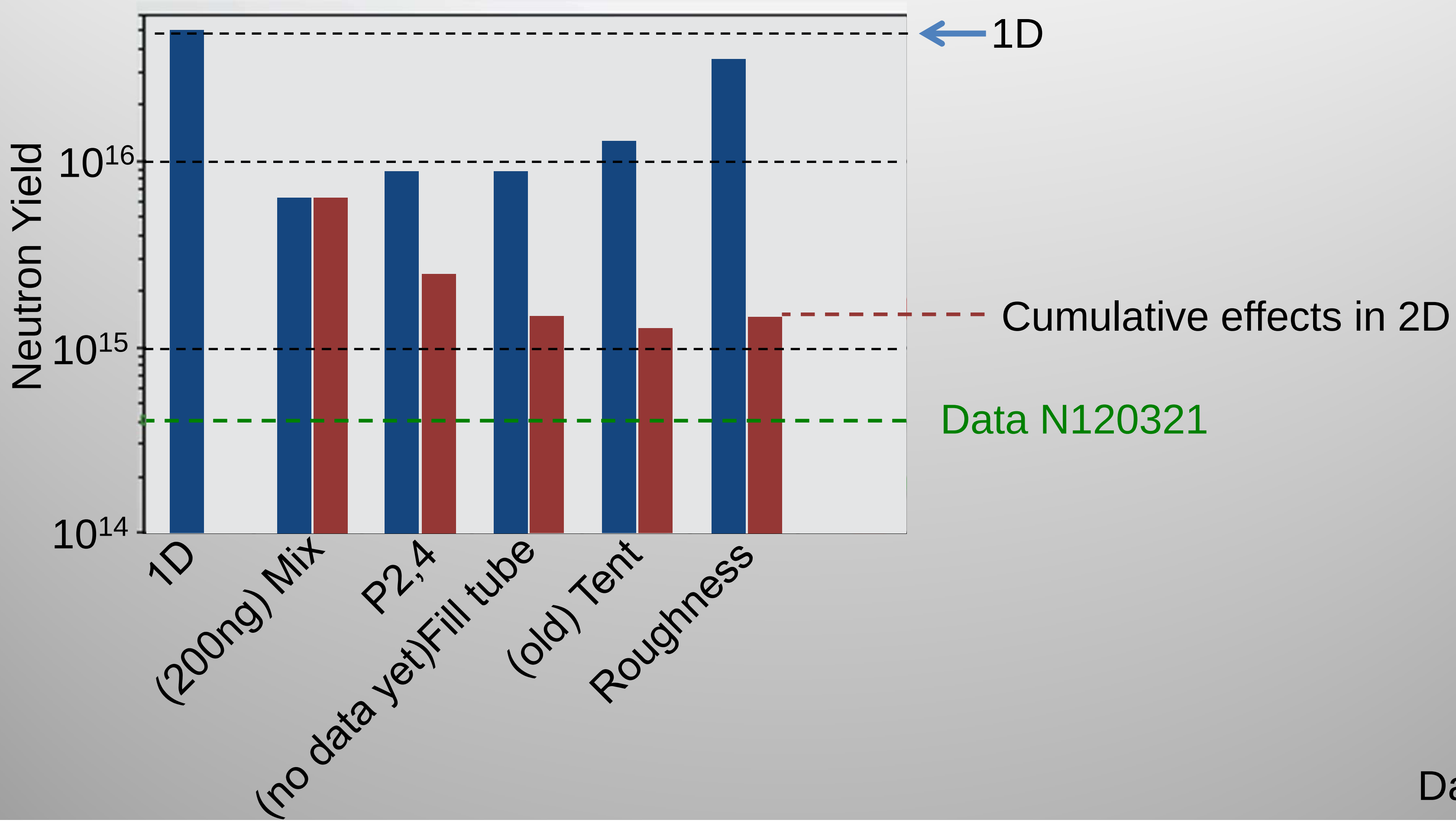


Hammel

Dan Clark

Simulations fall slightly short of explaining NIC data in 2D

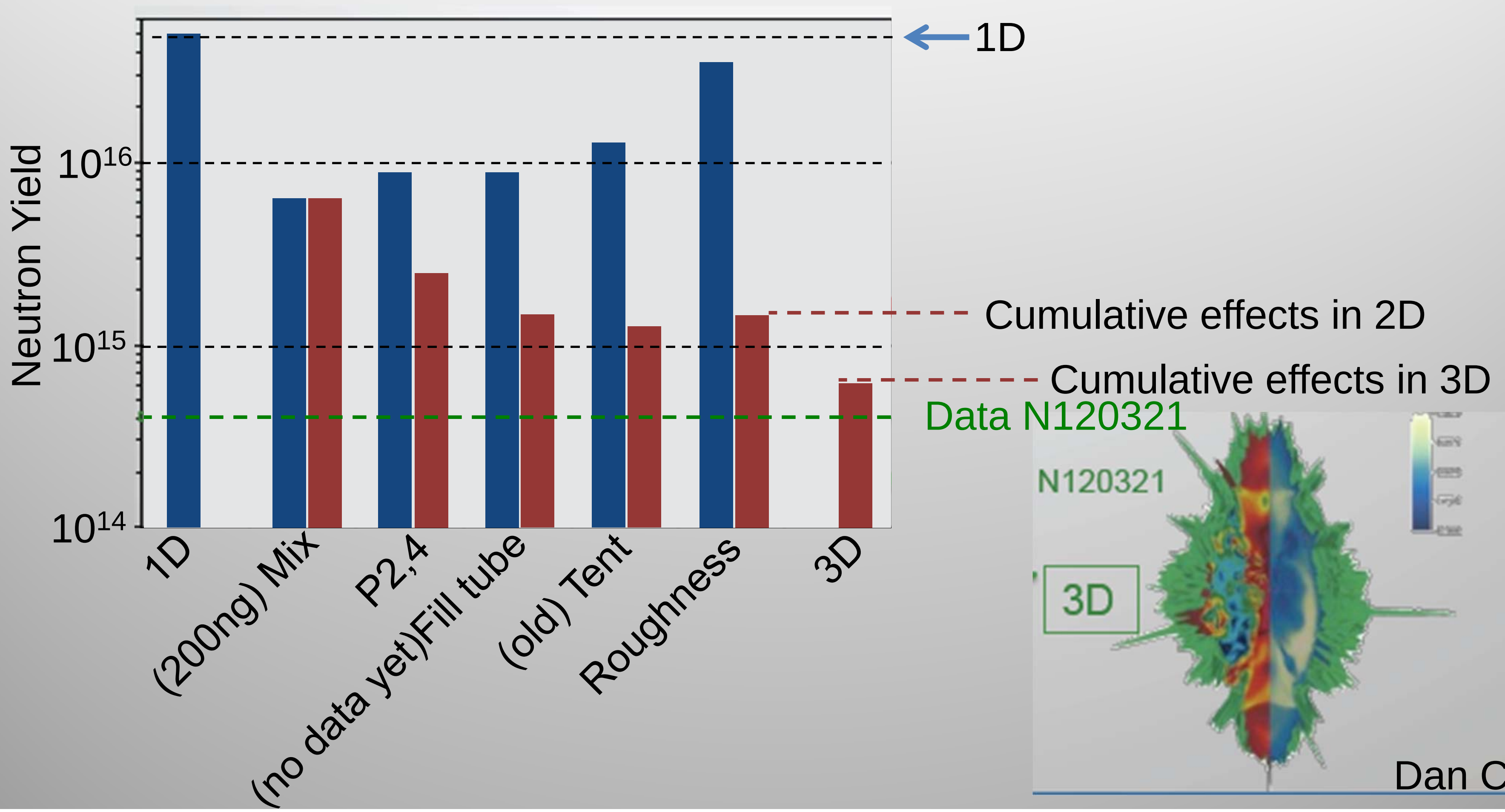
Predicted impact of hydro features individually and in combination in 2D



Dan Clark

Simulations including the known effects in 3D reasonably reproduce NIC capsule performance

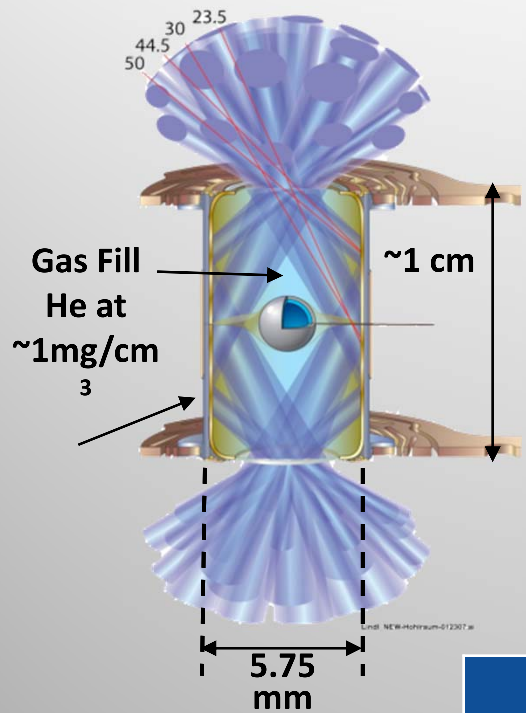
Predicted impact of hydro features individually and in combination in 2D

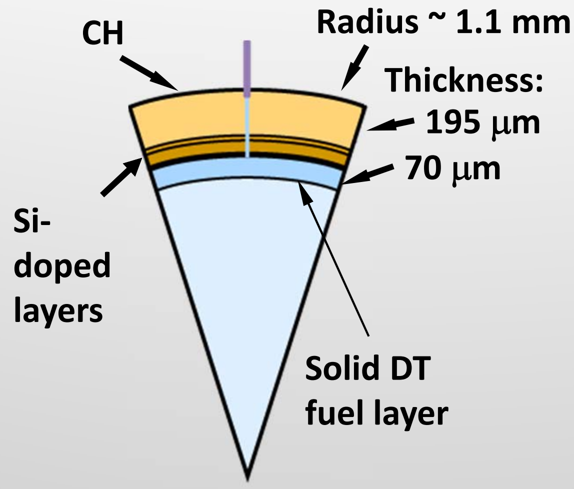


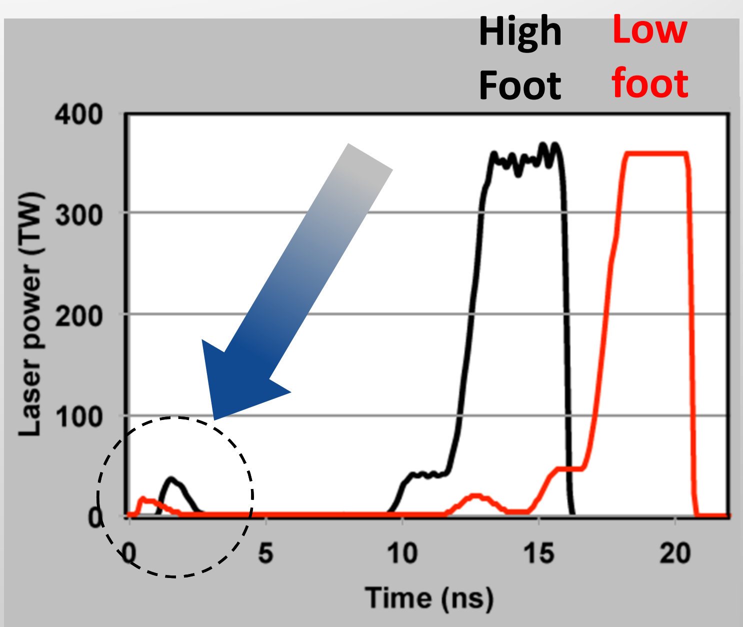
Outline

- Understanding the NIC implosions
- Status of high foot
- New approaches

The high foot pulse was designed specifically to improve capsule stability at the expense of convergence



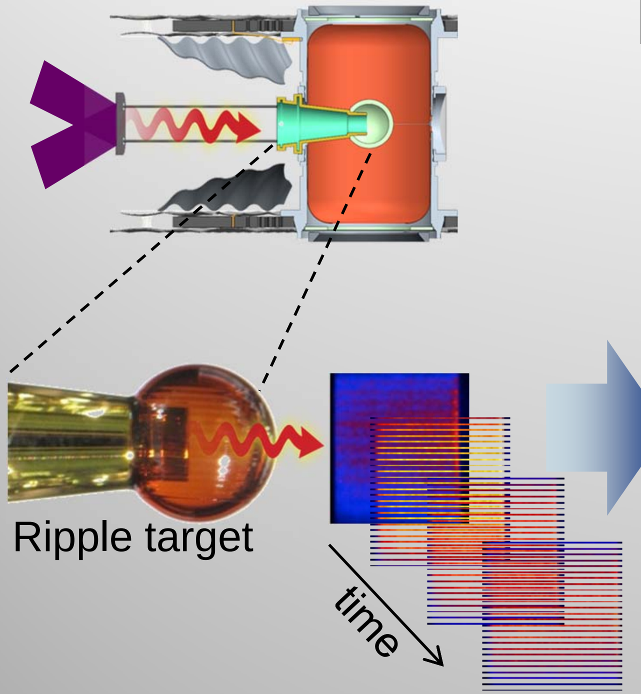




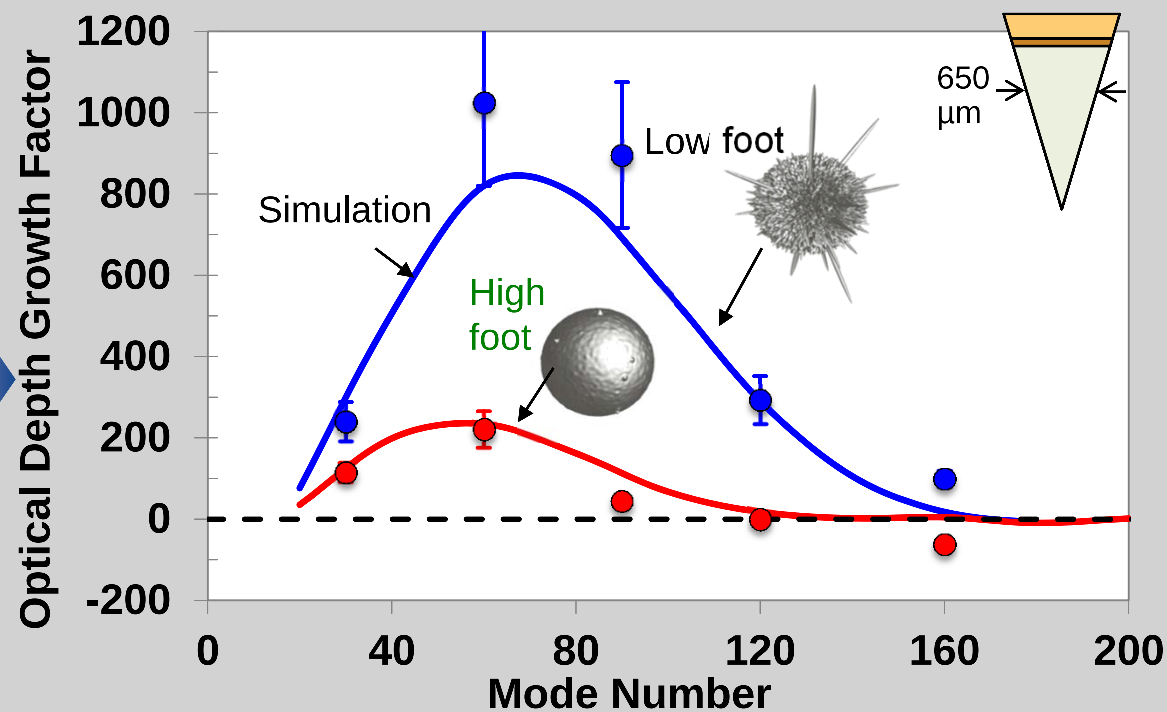
	NIC Low-foot	High-foot
Adiabat (a measure of entropy)	~1.5	**Increased to:** ~2.5
In-flight aspect ratio, (IFAR)	~20	**Reduced to:** ~17
Convergence	~45	**Reduced to:** ~35

Goal: implosion that was understood and performed close to simulations

Predictions of hydro growth were verified in focused experiments

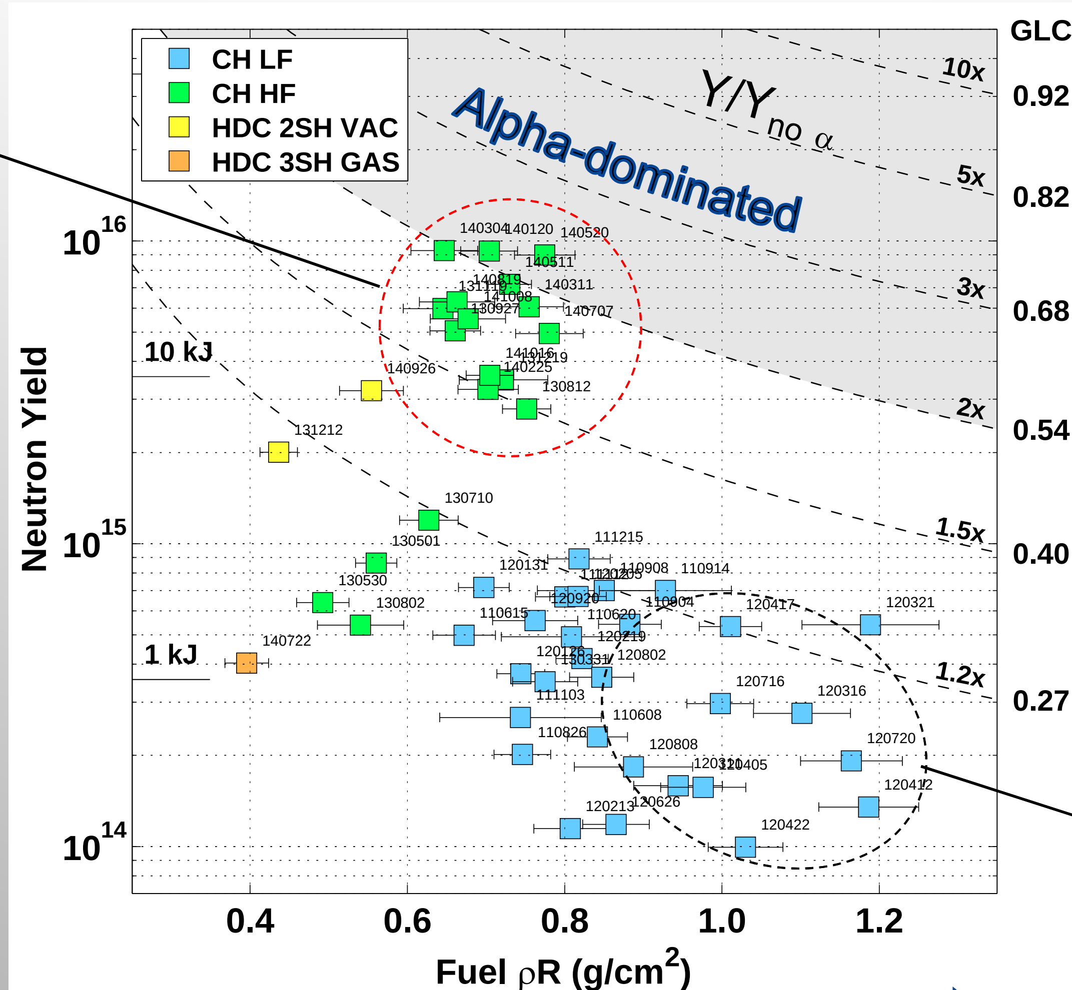


Lo-Foot vs Hi-Foot Growth factor at 650 µm



Lower convergence, more stable implosions behaved better than higher convergence, less stable implosions

High foot
CR ~ 35

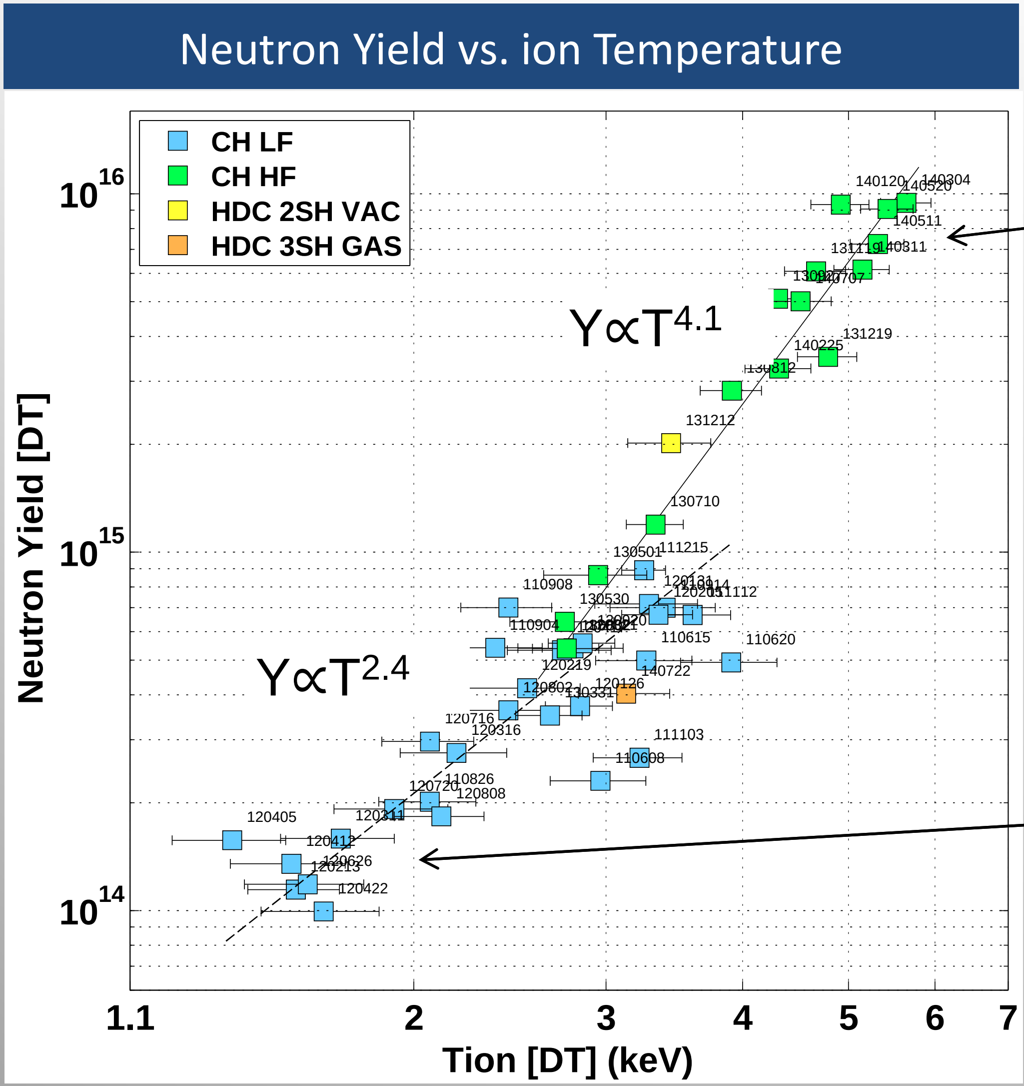


Low foot (NIC)
CR ~ 45

Increasing Convergence Ratio

[1] O. Hurricane et al, Nature 506, 343–348 (20 February 2014)

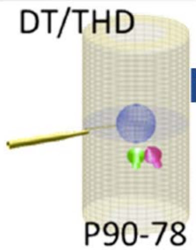
The high foot implosions scale as expected for *near 1D, clean* system – low foot did not

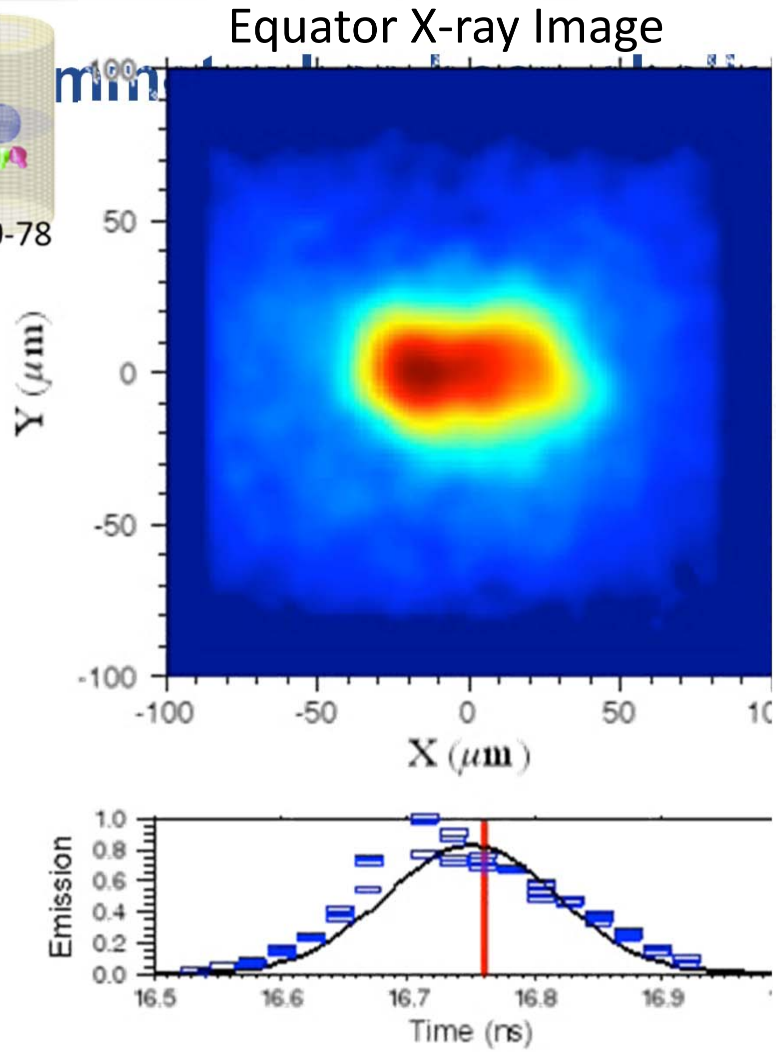


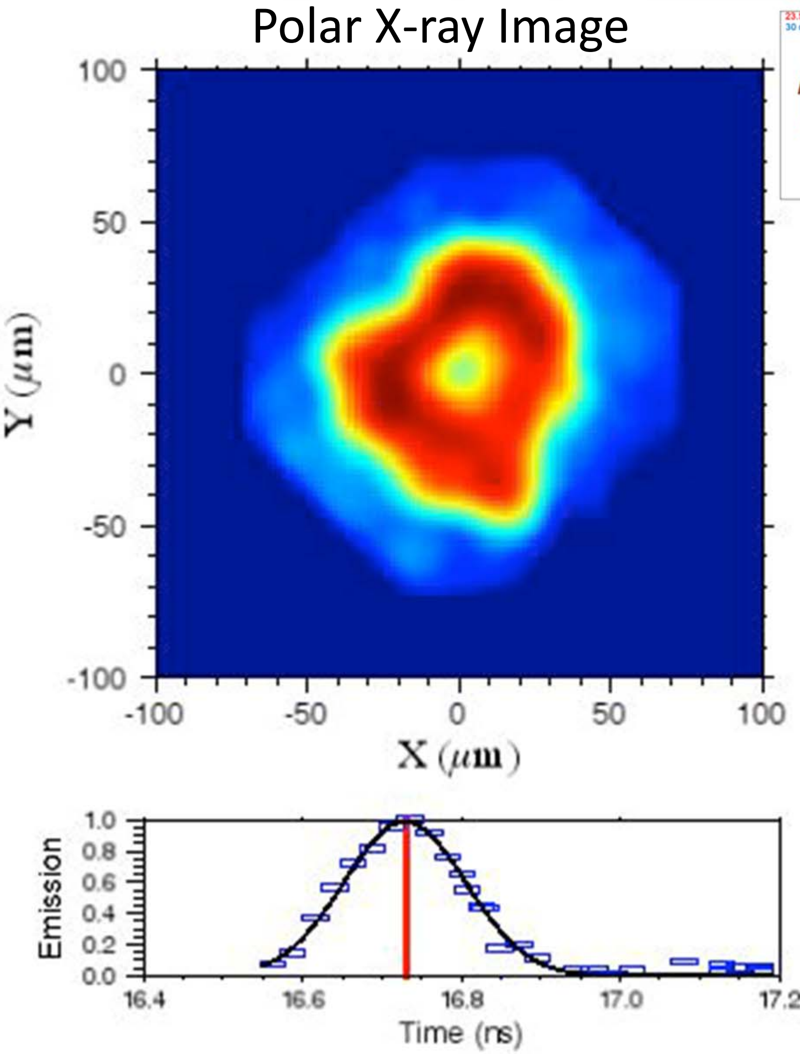
High foot:
Scaling consistent with theory

Low foot (NIC):
Scaling consistent with implosions that mixed

Symmetry has been challenging

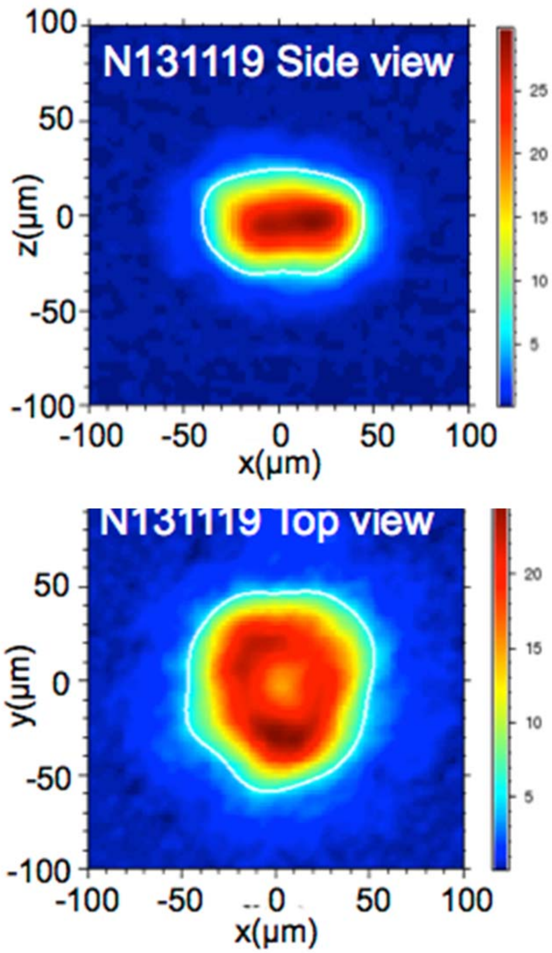
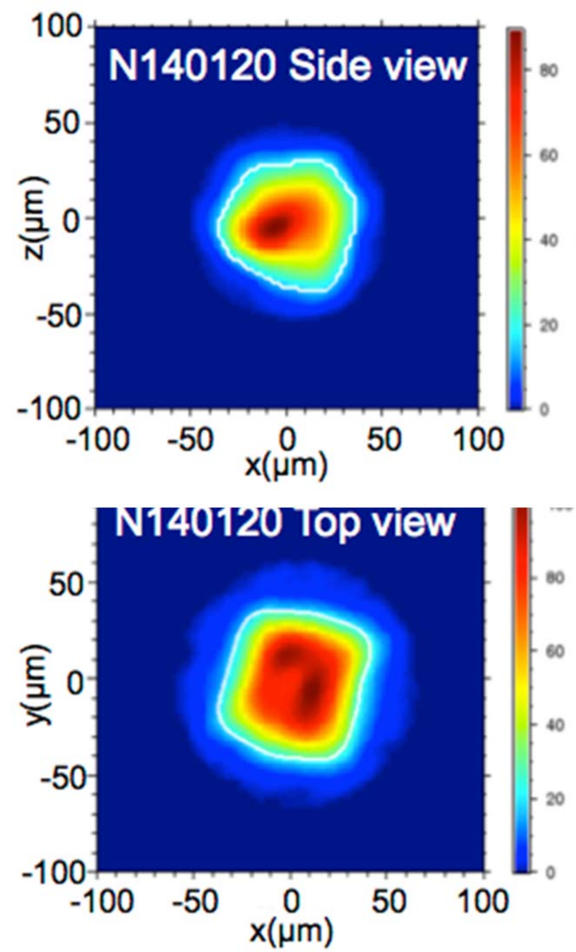






High-foot DT N130812

Symmetry has improved, but not yet good enough

$Y_{13\text{-}15}$ = 5.1e15 Au Hohlraum	$Y_{13\text{-}15}$ = 7.9e15 DU Hohlraum
	

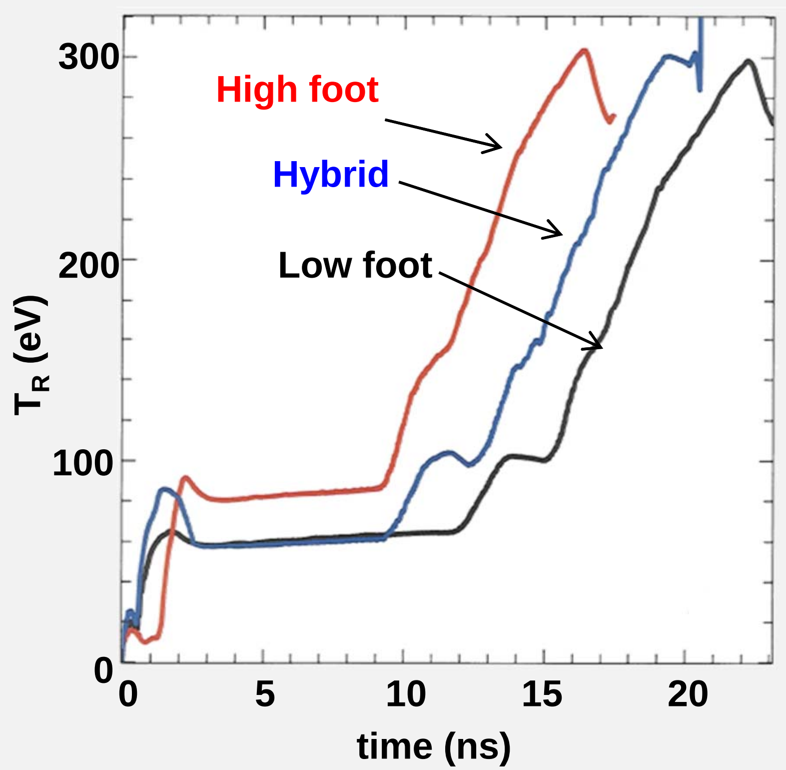
Identical implosion speed and bang-time

Outline

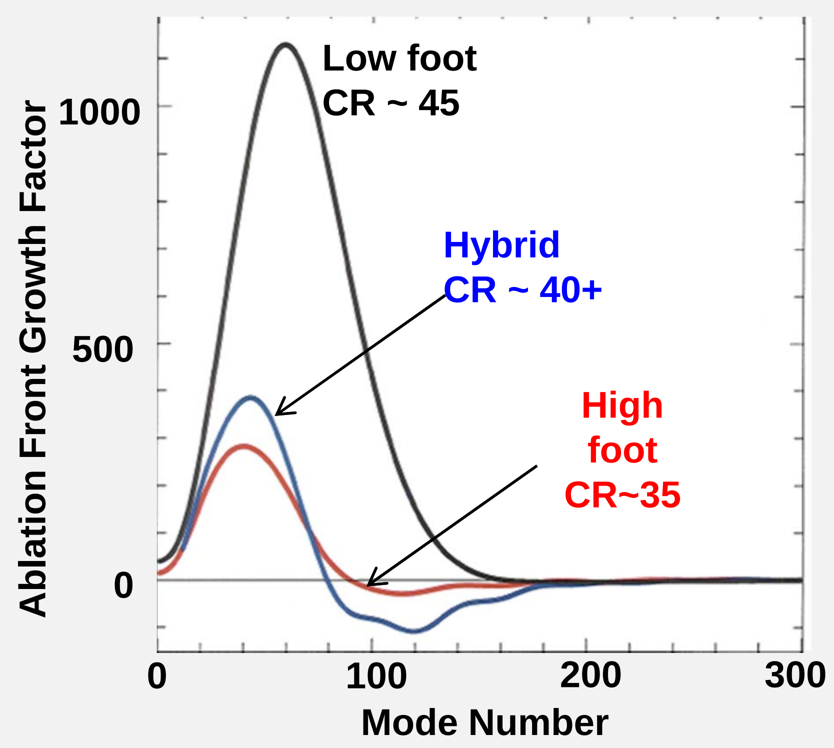
- Understanding the NIC implosions
- Status of high foot
- New approaches
  - Can we control mix at higher CR?
  - Can we improve symmetry?

Pulse shape controls hydro stability and convergence

Model radiation drive pulse



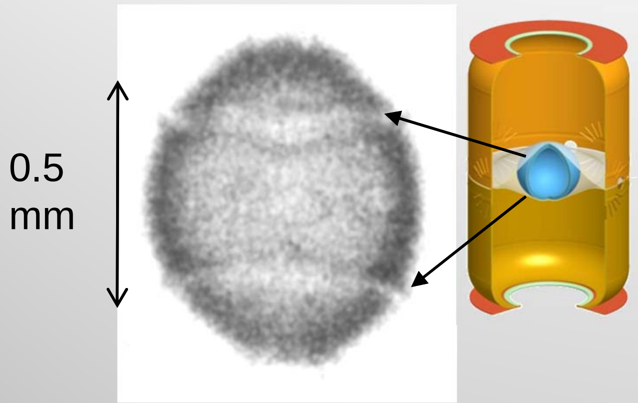
Predicted ablation front growth factors

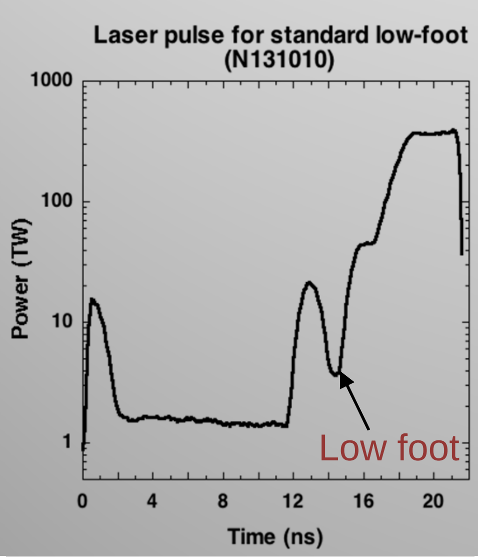


This was demonstrated in focused experiments

We now know the capsule "tent" was one of several factors degrading performance for the low foot

Low foot
$\alpha \sim 1.5$

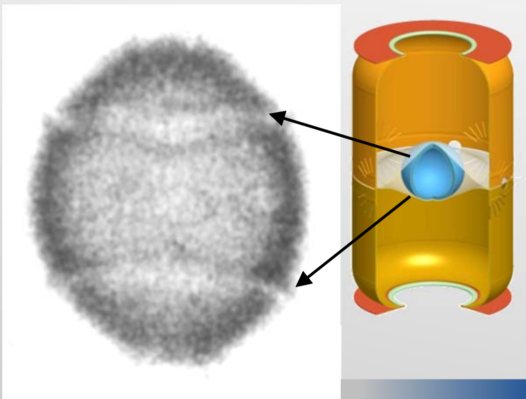


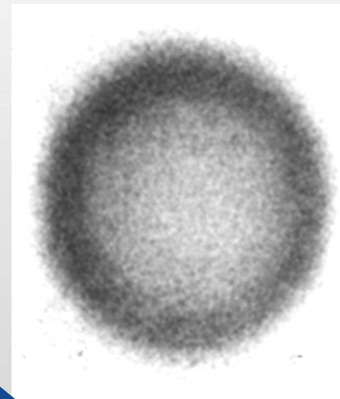


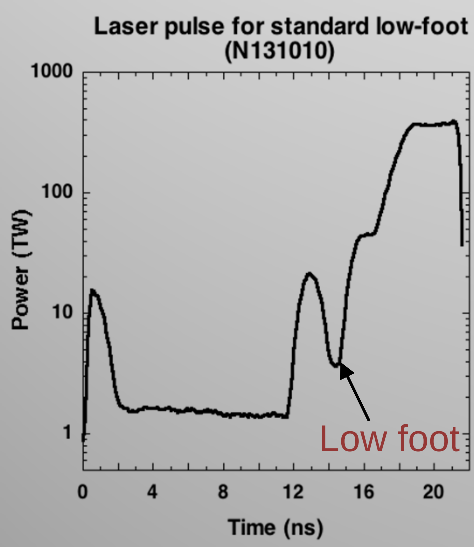
The "tent" largely disappeared for the more stable high foot – but need higher convergence for ignition

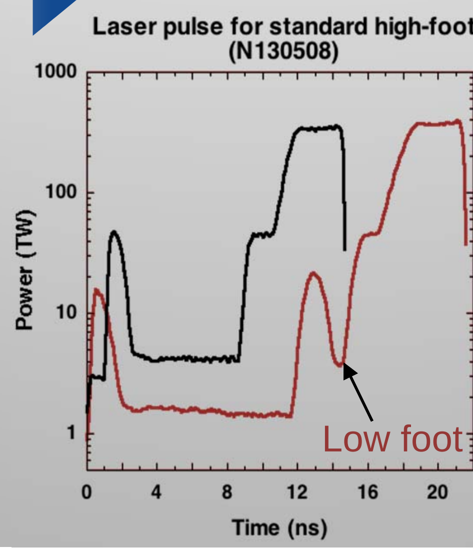
Low foot
α ~ 1.5

High foot
α ~ 2.5



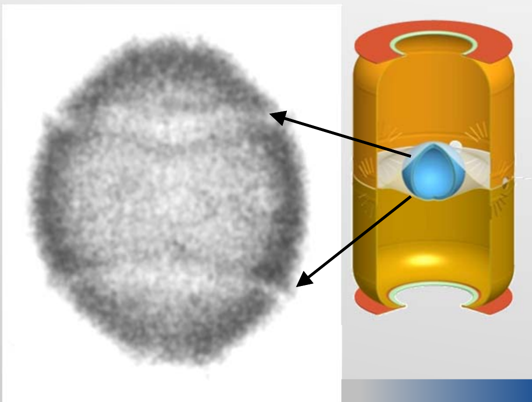




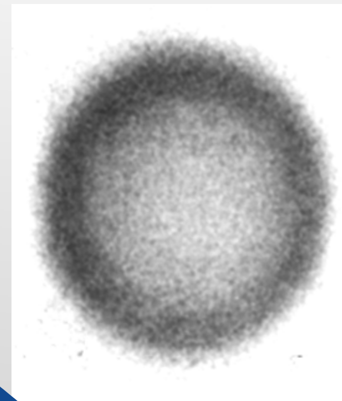


Pulse shaping is a way to have high convergence and good stability – more tests needed

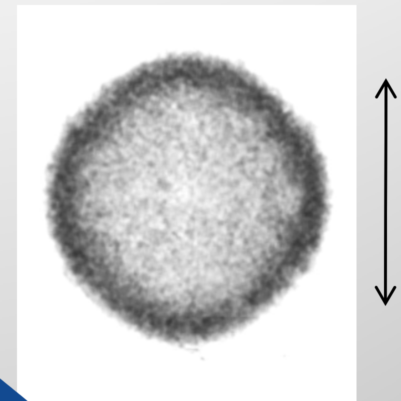
Low foot
$\alpha \sim 1.5$

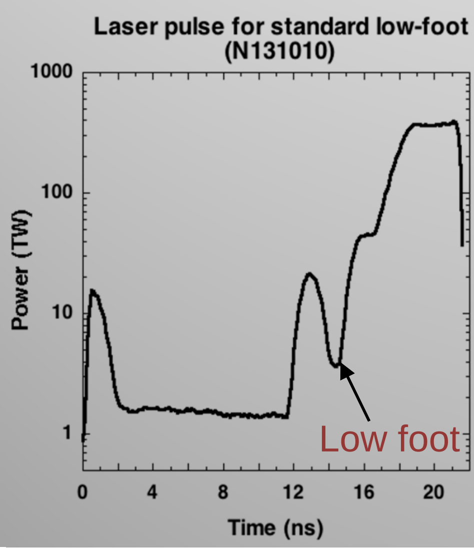


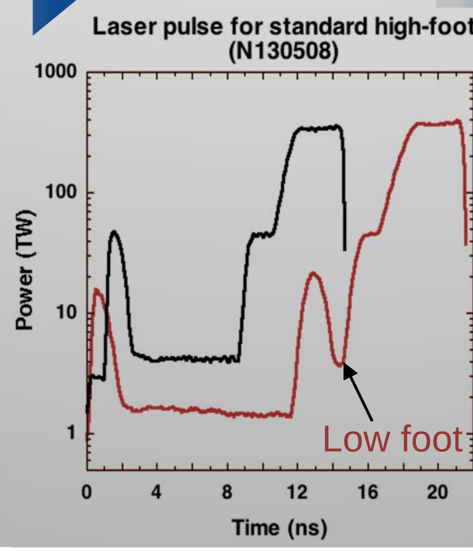
High foot
$\alpha \sim 2.5$

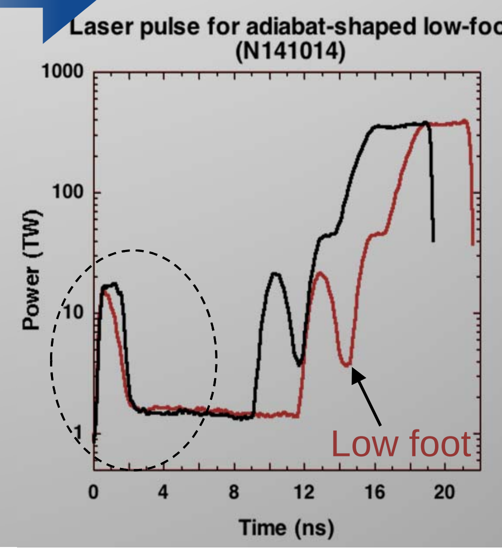


Right foot ?
$\alpha \sim 1.6$

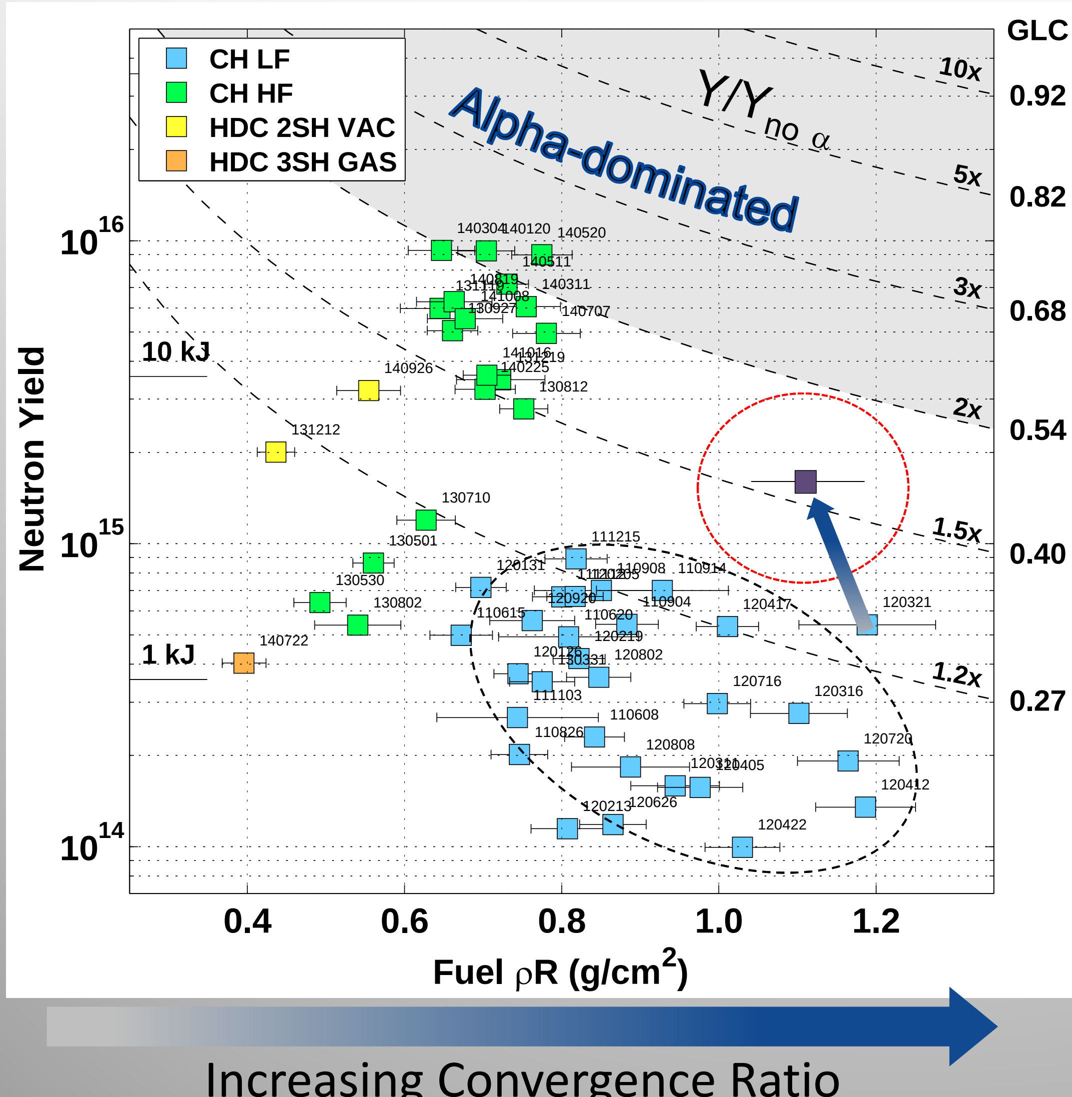






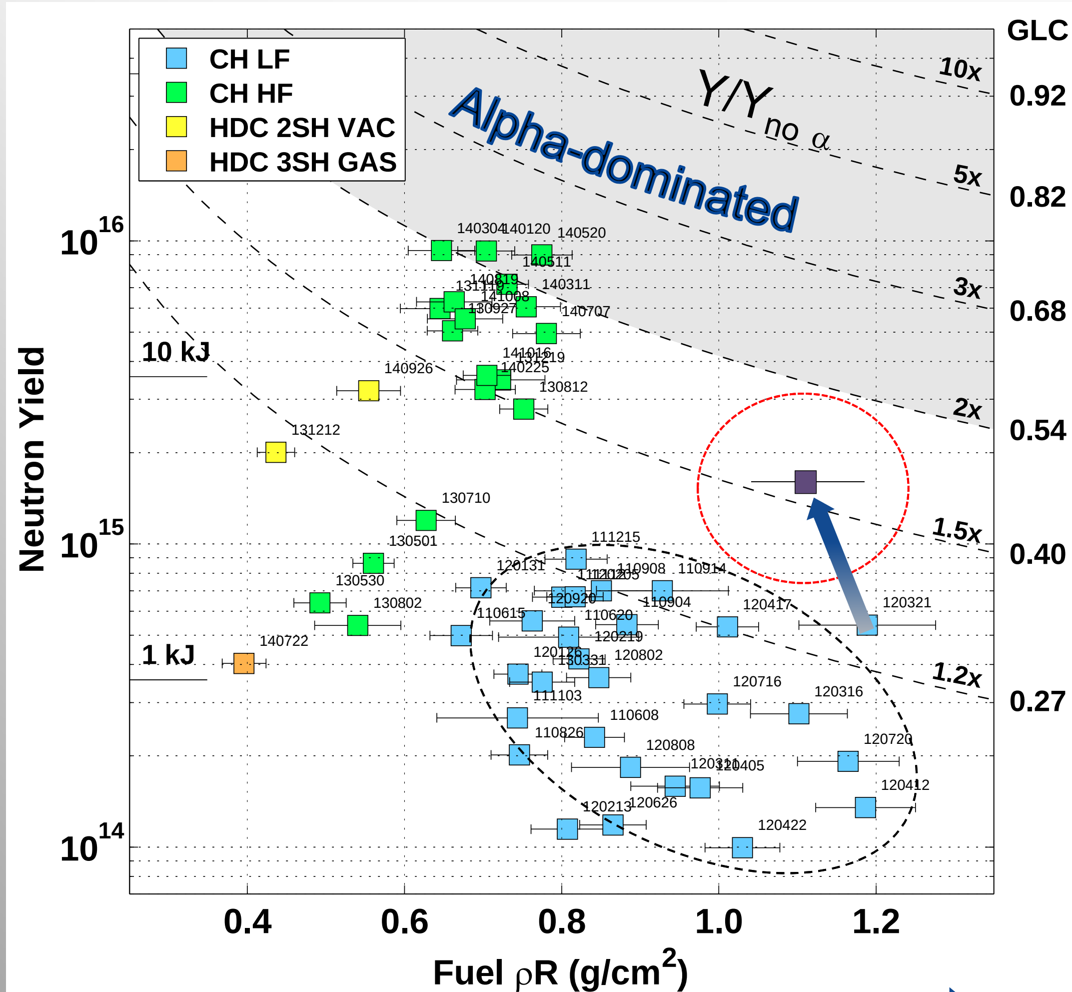


Initial test with new pulse shape is promising – will it be good enough to control mix?



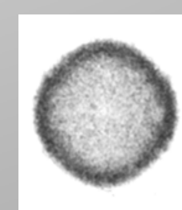
- Unlike during NIC, implosion shows no sign of mix – good
- Other pulse shape and capsule refinements are possible to improve stability (eg doping, material such as Be(LANL)) – experimental platforms exist to test

Initial test with new pulse shape is promising – will it be good enough to control mix?



Increasing Convergence Ratio

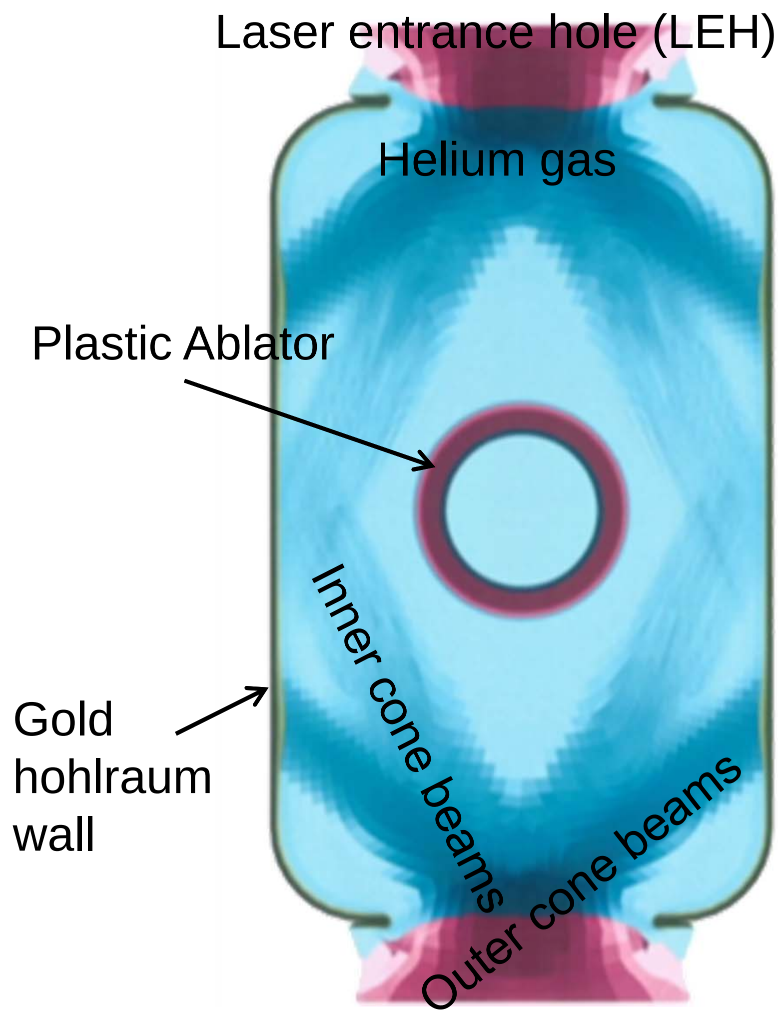
- Unlike during NIC, implosion shows no sign of mix – good
- Other pulse shape and capsule refinements are possible to improve stability (eg doping, material such as Be(LANL)) – experimental platforms exist to test
- BUT yield still much less than 1D simulation – suspect asymmetry amplified at higher convergence (other?)



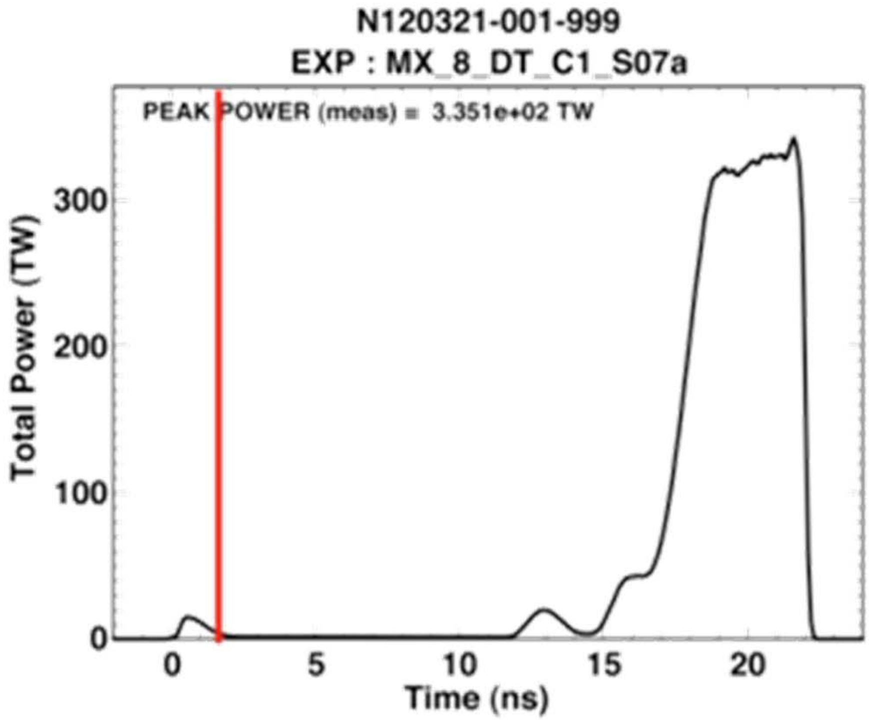
Outline

- Understanding the NIC implosions
- Status of high foot
- New approaches
  - Can we control mix at higher CR?
  - Can we improve symmetry?

Propagating the inner beam is a major challenge in conventional gas-filled hohlraums



Laser "Pulse-shape"



We do not yet know whether the "standard" hohlraum is adequate for ignition

"Standard gas-filled
hohlraum"

- Large SRS loss ~ 15%
- Hot electrons
- CBET: Symmetry strong f(t)
- Any pulse

We would like "better" more predictable hohlraums
– less LPI, lower hot electrons, better symmetry control
– many possibilities exist (fill, wall material, geometry… - examples follow)

Initial experiments with "Rugby" shaped hohlraums look promising, but early days

"Standard gas-filled hohlraum"

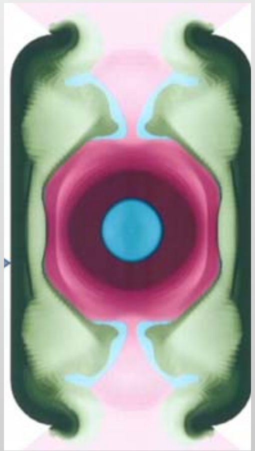
- Large SRS loss ~ 15%
- Hot electrons
- CBET: Symmetry strong f(t)
- Any pulse

Gas-filled "Rugby" hohlraums

- Large SRS loss ~ 10%
- **Low hot electrons**
- **Low CBET: better symmetry?**
- Any pulse

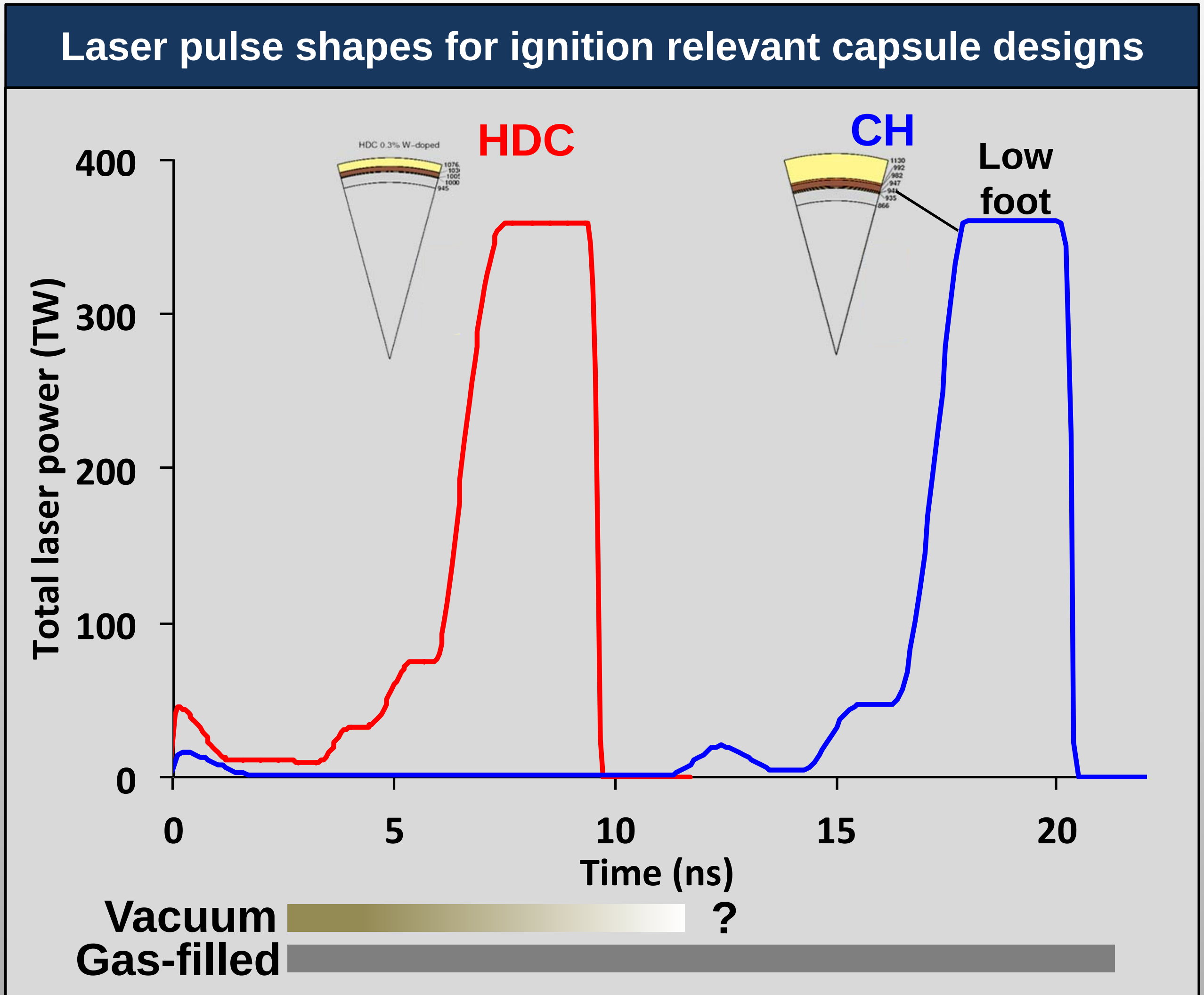
Experiments with layered DT targets are scheduled for later in FY15

Near vacuum holraums have significant advantages but quickly fill with plasma

"Standard gas-filled hohlraum"	Gas-filled "Rugby" hohlraums	Near vacuum / low gas-fill hohlraums
		
Large SRS loss ~ 15%	Large SRS loss ~ 10%	**~ 50% more efficient**
Hot electrons	**Low hot electrons**	**Low LPI, hot e's**
CBET symmetry, strong f(t)	**Low CBET: better symmetry?**	**Low CBET, but wall motion**
Any pulse	Any pulse	Short pulses

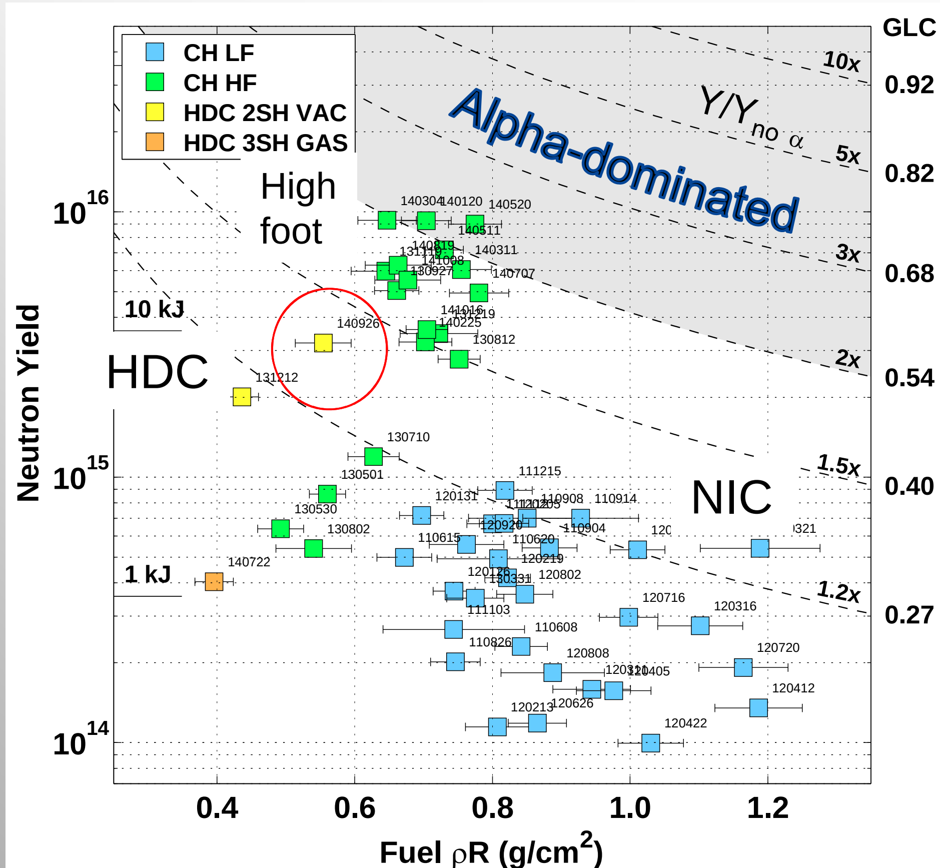
Can we implode a capsule symmetrically before the hohlraum fills with plasma?

The high density of diamond (HDC) ablators may enable near vacuum hohlraums? (on paper, yes! – are the codes right?)



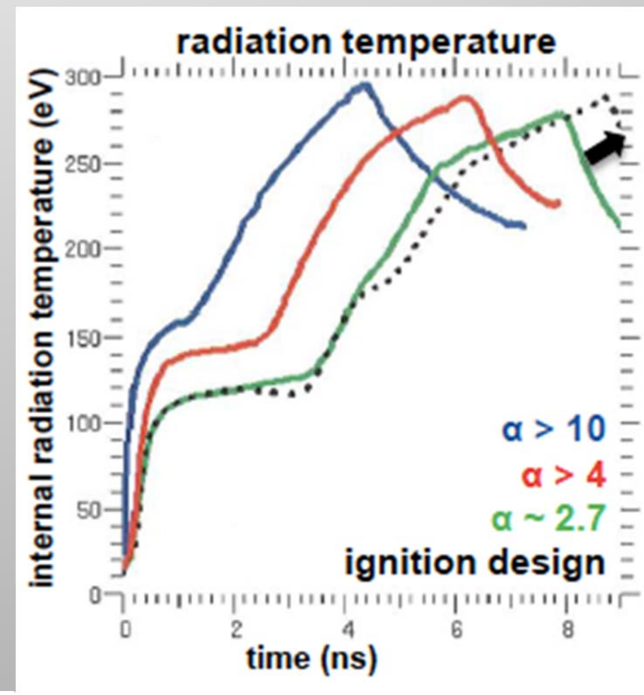
Be (LANL) is another viable capsule material with an intermediate pulse length

Initial capsule tests promising
– no sign of mix at ~ 360 km/s, CR ~ 30X



Increasing Convergence Ratio

- N140926 test 6.72 mm diameter hohlraum (vs. 5.75 mm)
- ~ 360 km/s, no sign of mix, prolate



Significant progress being made in understanding the physics of x-ray drive ignition targets

- Focused experiments have shed light on why NIC implosions were degraded and why high foot experiments perform closer to simulations

- Major obstacles to ignition have been identified
  – is the hohlraum the major challenge
  – will there be more?

- Promising solutions being developed
  – time will tell

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- Promising solutions being developed
  – time will tell

We fully anticipate a challenging road ahead, perhaps with new surprises!

Lawrence Livermore National Laboratory