Progress of Indirect Drive Inertial Confinement Fusion in the US

John Kline

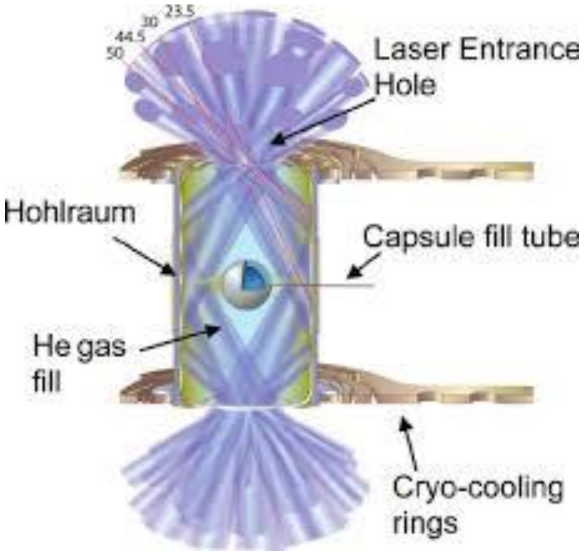
For Indirect Drive Working group

27th IAEA FES meeting

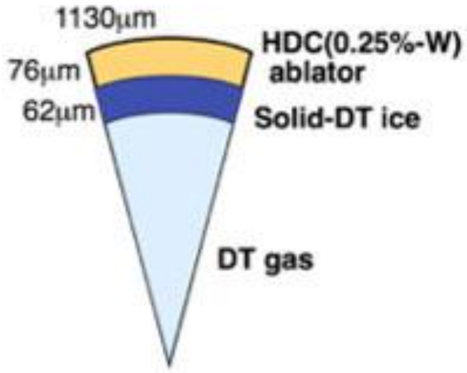
Gandhinagar, India

Oct. 22nd, 2018

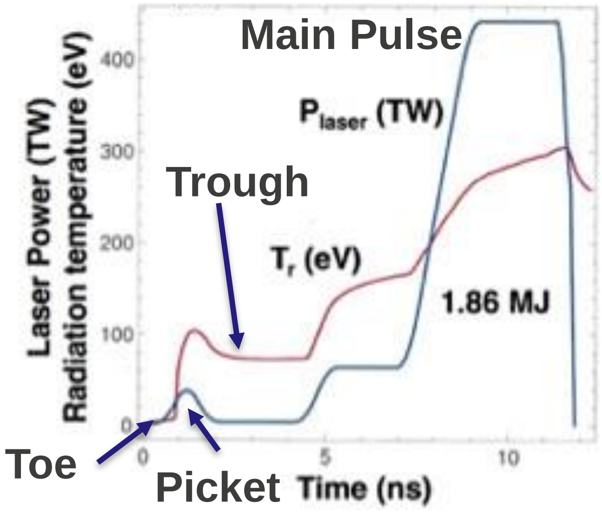
Hohlraum Target



Capsule



Laser Pulse



Adiabat:

α = DT ice internal energy/ Fermi energy @ 1000 g/cc

This work represents a large cross laboratory team effort!

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[5]*Massechusettes Institute of Technology, Boston, MA, USA*

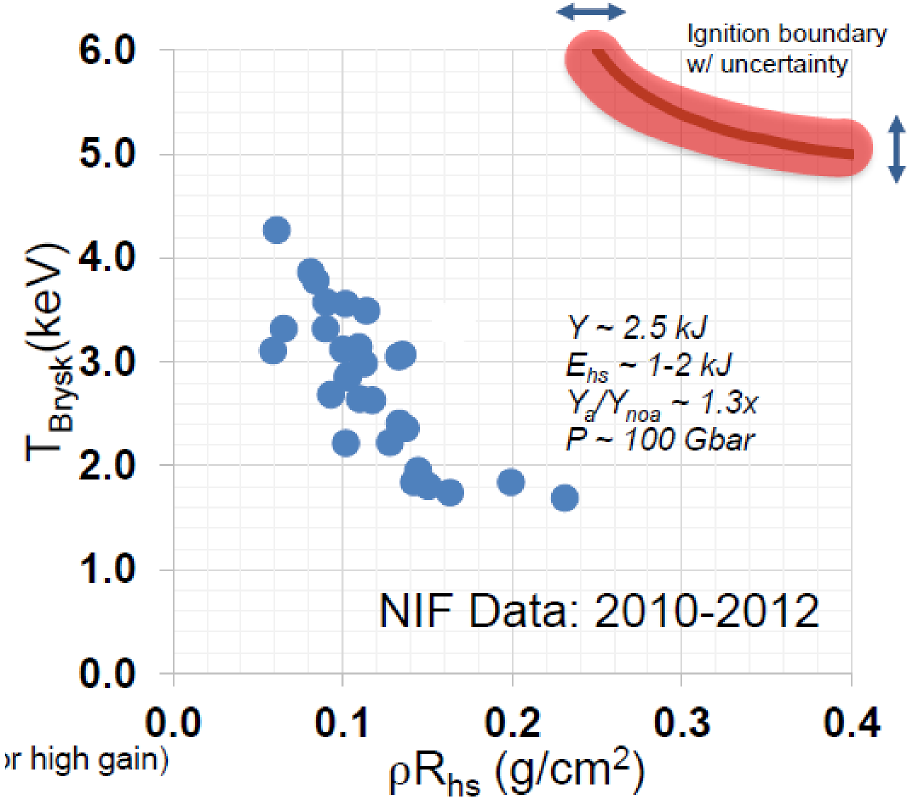
We've increased the energy delivery to the hot-spot by ~5x, stagnation pressures by ~3x, and fusion yields by ~21x since the National Ignition Campaign which ended in 2012

- **Low gas filled hohlraums with low LPI use x ray drive more effectively: improved symmetry & more energy coupled to the hot spot**

- **3D effects still significantly degrading performance: symmetry and hydro-instability**

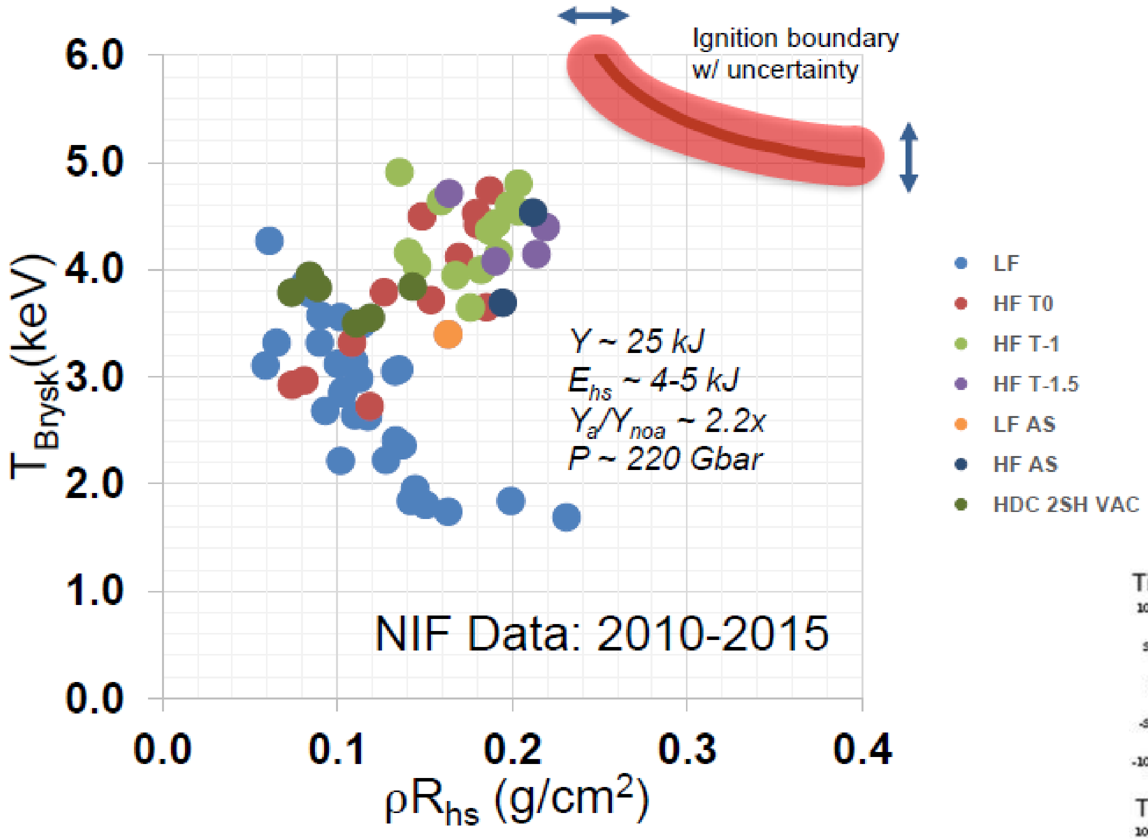
- **We plan to use our advances in understanding to optimize performance both in implosion quality and increased scale**

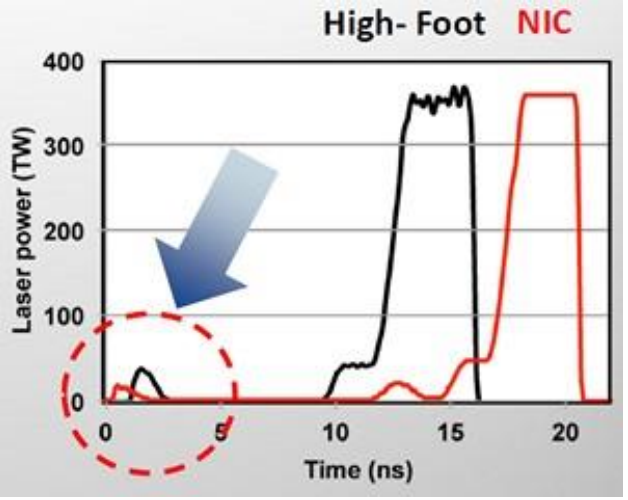
Low adiabat (α_{if} ~ 1.6) implosions in high gas-fill hohlraums resulted in implosions far from the ignition regime



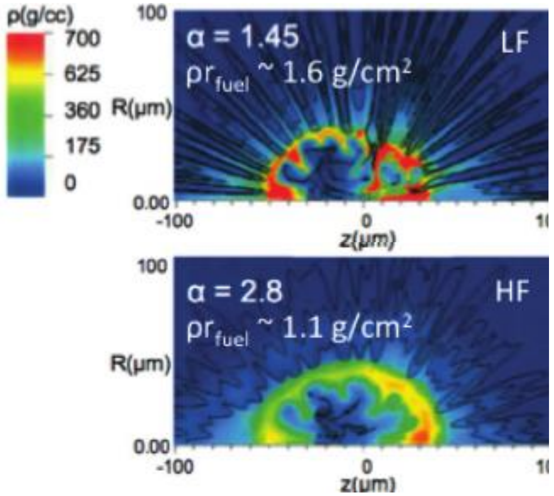
- Optimized high yield designs
- First attempts at ignition scale targets
- No validation data

Mid-adiabat (α_{if} ~ 1.8-2.8) implosions approached the ignition regime, but symmetry control limited with high (and no) gas-fills

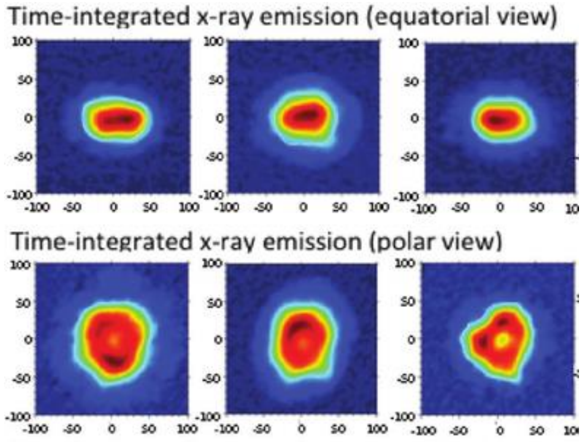


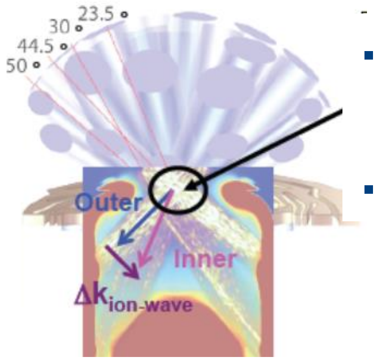


Simulations



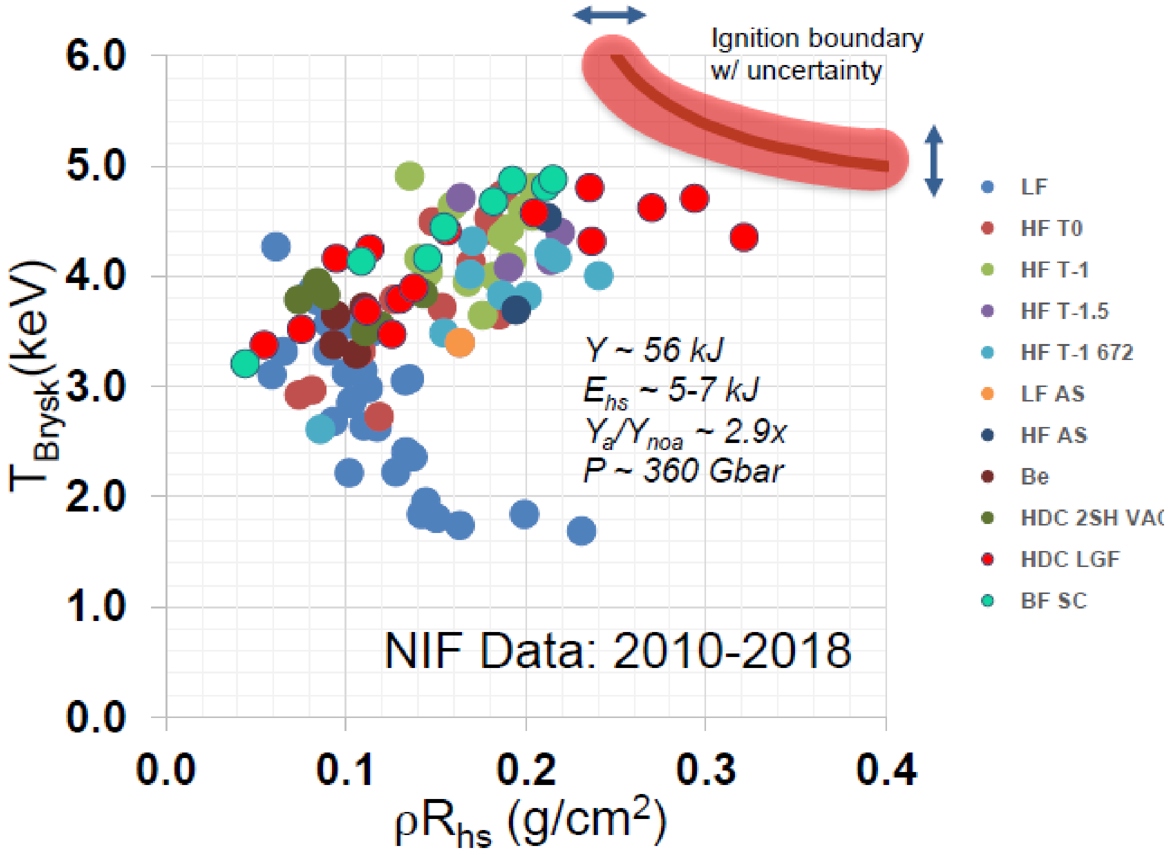
X ray self-emission



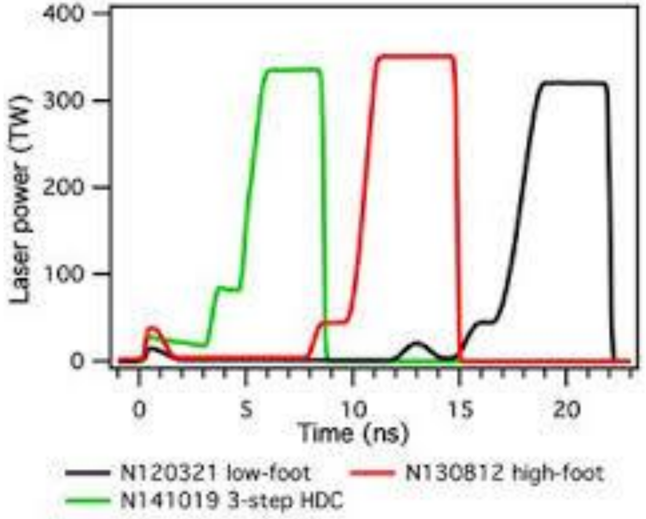


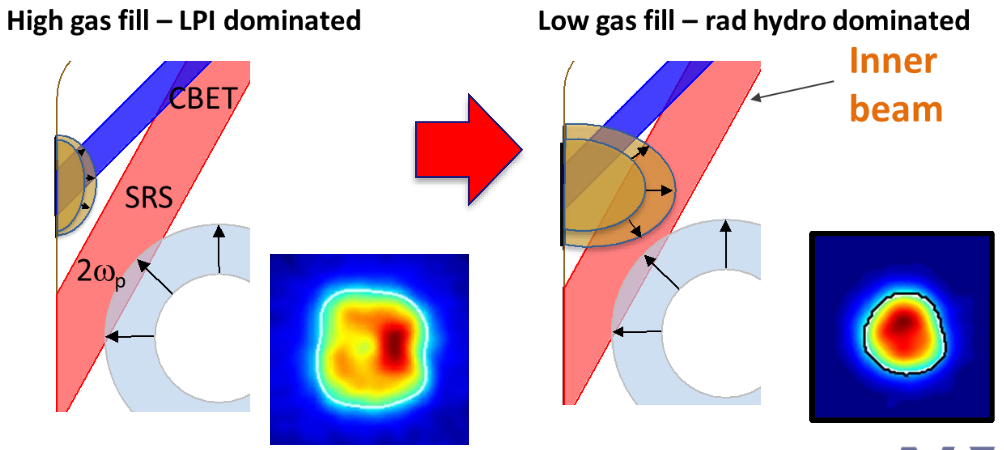
- X beam Transfer
- Backscatter

Low gas-fill hohlraum designs brought the ICF program closer to the ignition regime than any previous designs

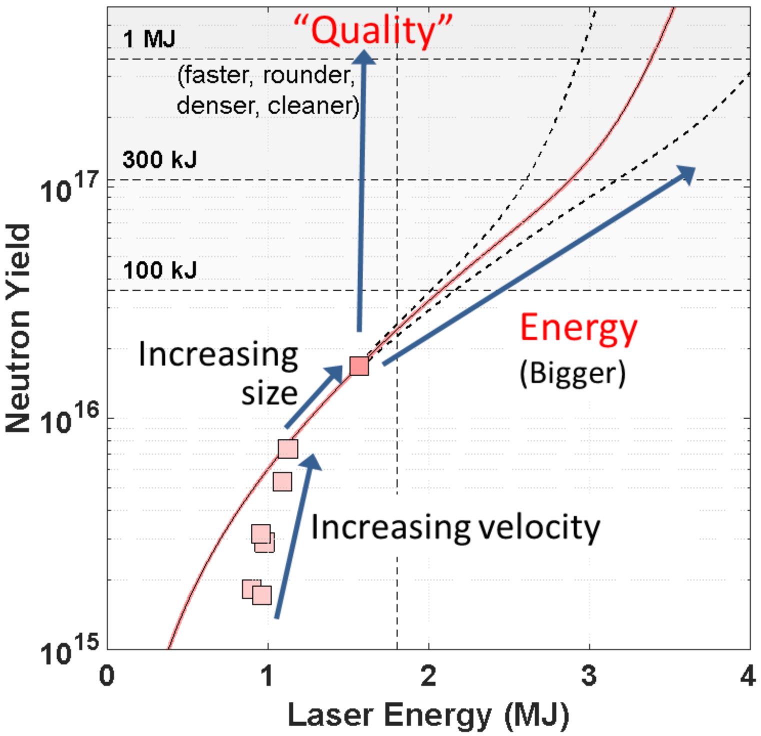


HDC enables short pulses

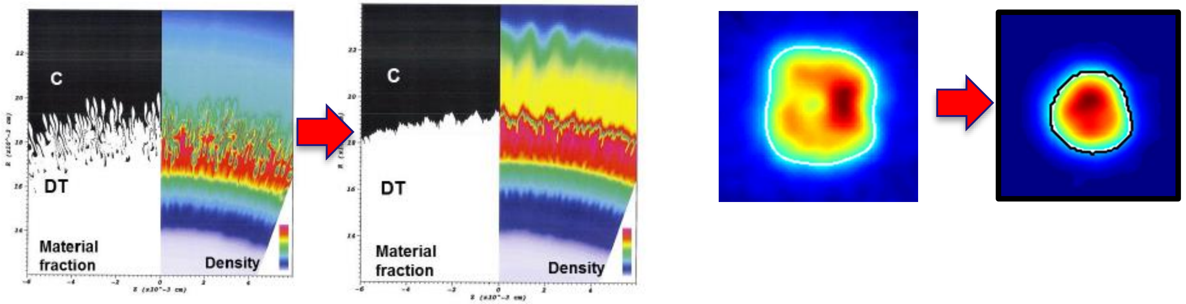




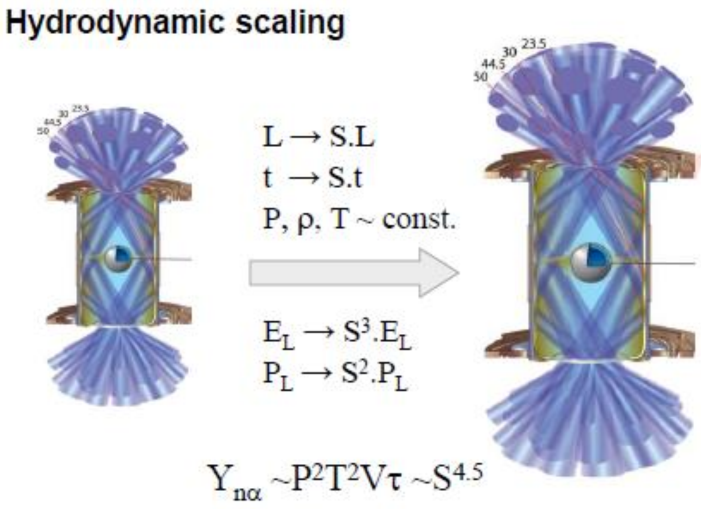
Moving forward both implosion quality and increasing capsule size will be used to improve performance



Quality axis represents progress towards 1D like implosions for fixed laser conditions



Hydro-scaling axis simply increases size of capsule without improvements in quality

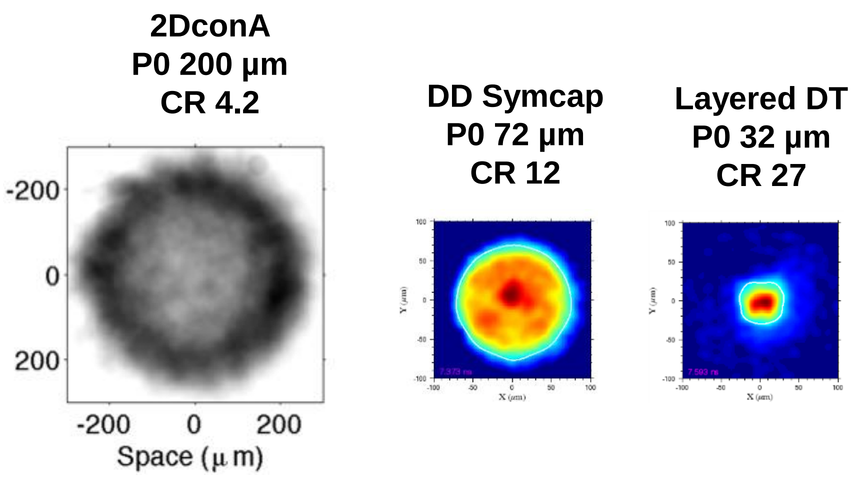


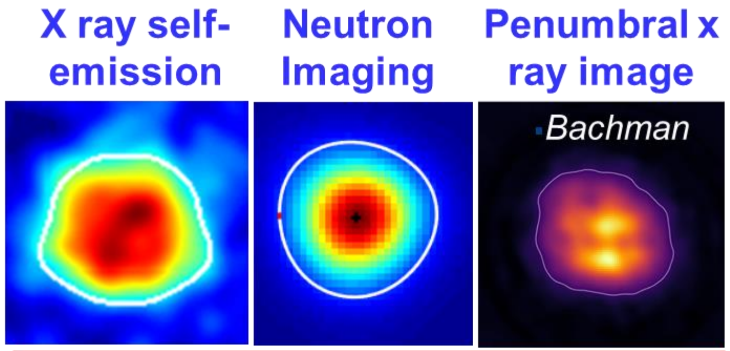
No alpha

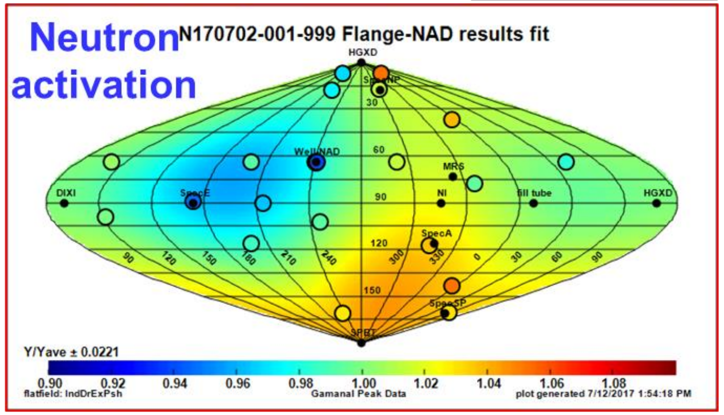
$$Yield \sim Scale^{4.5} \times \underbrace{P_{Ablation}^{4/5} \frac{Velocity^8}{Adiabat^2}}_{1D} \times \underbrace{[Mix < 1]\,[Shape < 1]}_{3D}$$

While symmetry control has much improved with low gas filled hohlraums, residual asymmetries still exists

Capsule shape measurements using different techniques under similar conditions

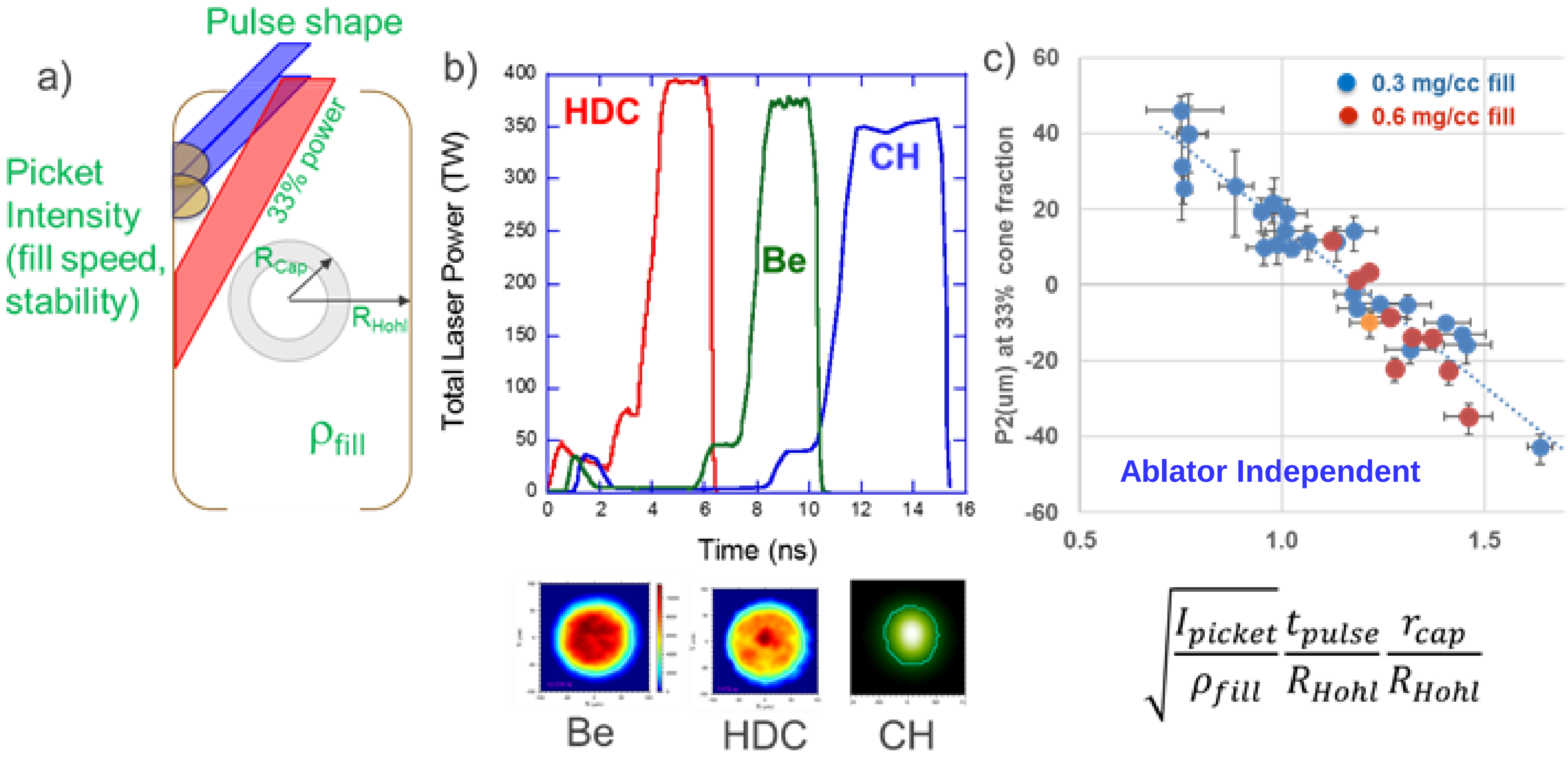






A comprehensive understanding of the shape of both the hot spot and cold fuel are needed

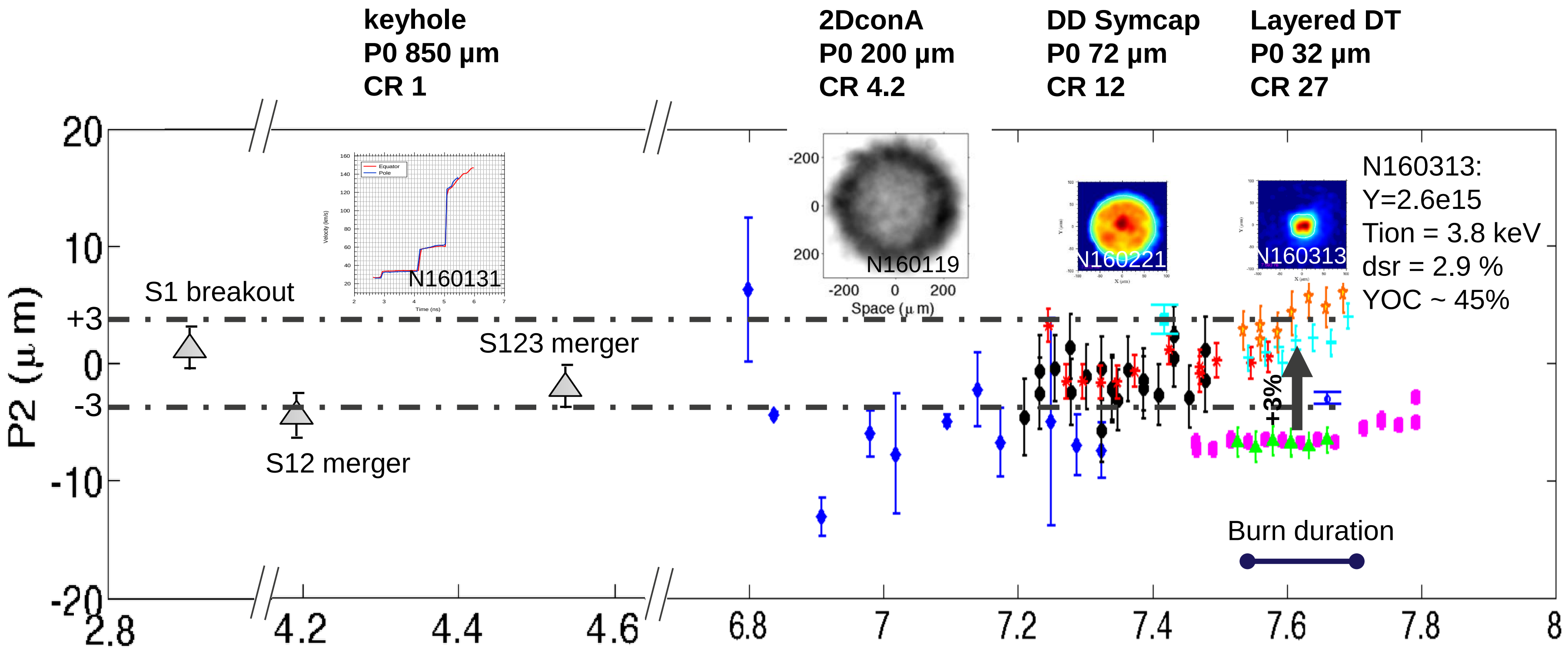
An empirical understanding consistent with simulations has been developed for low gas fill hohlraums[1]



$$\sqrt{\frac{I_{picket}}{\rho_{fill}}\frac{t_{pulse}}{R_{Hohl}}\frac{r_{cap}}{R_{Hohl}}}$$

[1]Callahan, D. A.; Hurricane, O. A.; Ralph, J. E.; et al. Exploring the limits of case-to-capsule ratio, pulse length, and picket energy for symmetric hohlraum drive on the National Ignition Facility Laser," Phys Plasmas 25, 056305 (2017)

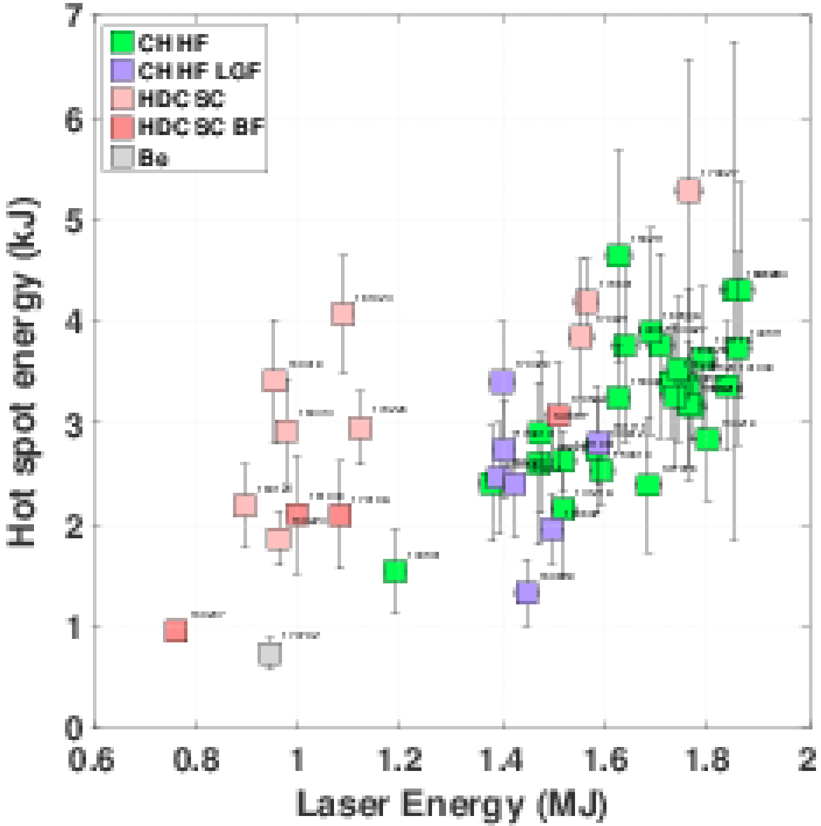
HDC capsule experiments demonstrated control of symmetry throughout the implosion



HDC team

L. Divol, A. Pak, L. F. Berzak Hopkins, S. Le Pape, N. B. Meezan, Symmetry control of an indirectly driven high-density-carbon implosion at high convergence and high velocity. *Physics of Plasmas* **24**, 056309 (2017).

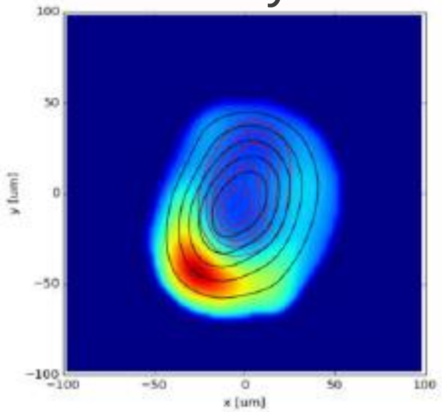
Examination of hot spot versus laser energy shows more efficient coupling for sub scale HDC capsules



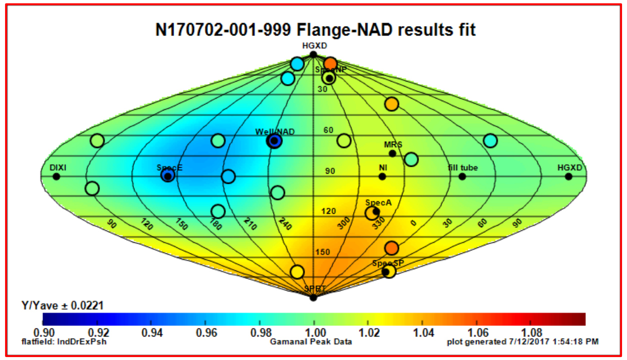
Efforts are underway to address remaining residual asymmetries

- Random P1 and semi-random m1 asymmetries persist
- Bulk hotspot flow (nToF), low fuel rr regions (FNADs and nToF) and fluence compensated downscattered neutron images all correlate in direction of mode 1
- Peak power laser imbalances
- SBS variations
- Bulk flow velocity sensitivity to drive mode 1 consistent with simulations, though much scatter
- Residual sensitivities to foot and Au bubble imbalances
- Maximum yield envelope follows expected bulk flow velocity sensitivity, and drops current yields up to 1.5x

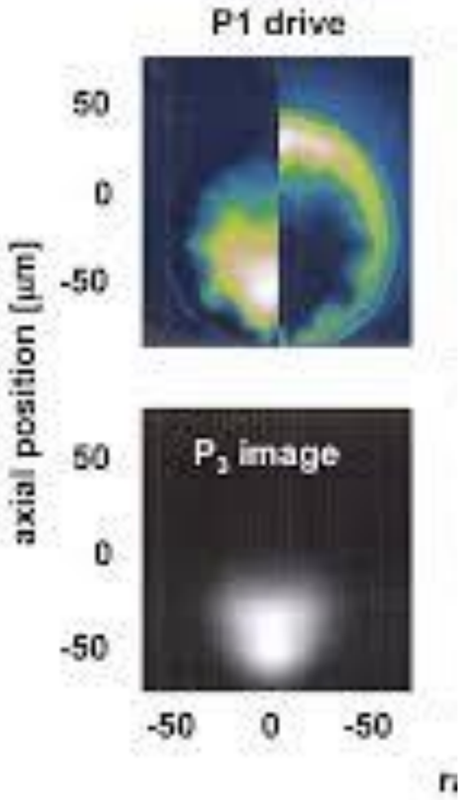
Reconstructed Ice layer



Neutron Activation

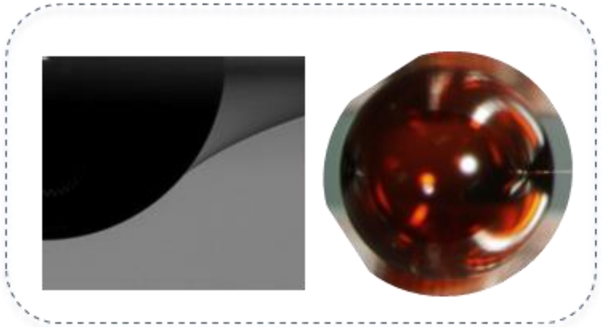


Simulated Asymmetry



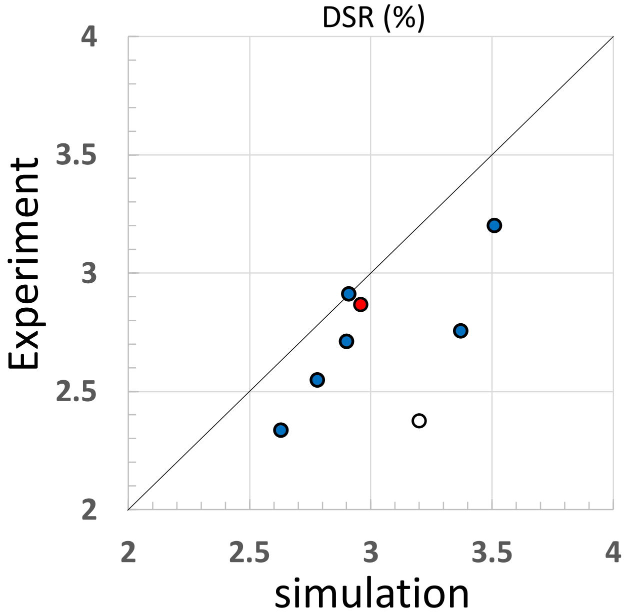
Address hydrodynamic instabilities near stagnation

Feature driven mix

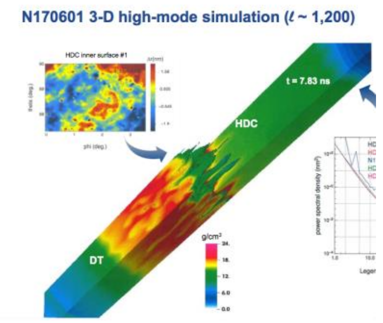


Feature driven Mix: Capsule support / fill tube, perforating shell, mix – needs to be better quantified

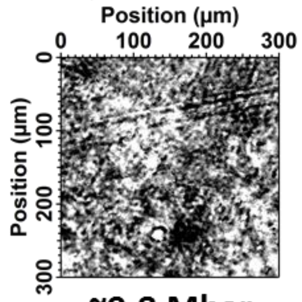
Ice compression less than expected



Native mix: Fuel appears less compressed than predicted by ~ 10-20% – not yet understood

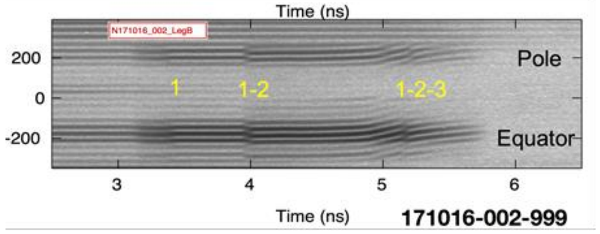


High modes



~9.8 Mbar
RMS = 85 m/s

Shock timing (FY18), EOS

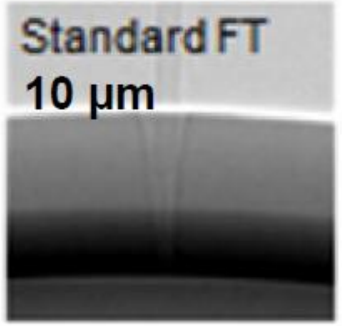


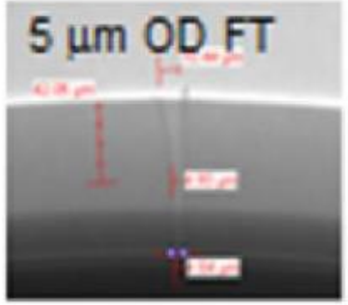
Unknown preheat

Understand magnitude and impact of hydrodynamic instabilities near stagnation

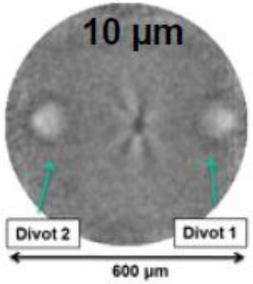
Measurements show smaller fill tubes reduced perturbations and produced an increase in implosion performance

Capsule radiographs

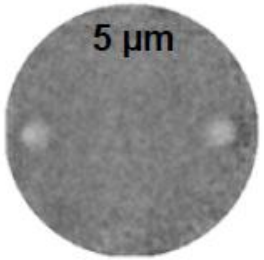




Reduced instability growth with smaller tube

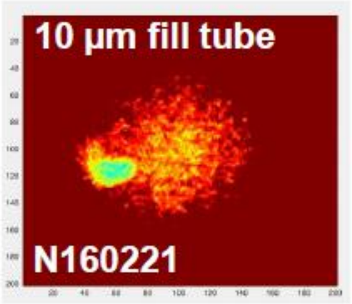


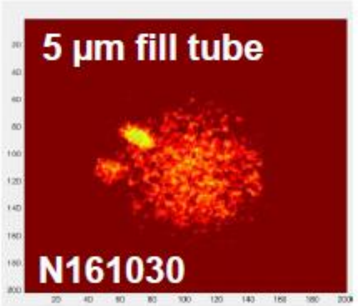
N160413



N170126

> 5 keV x-ray self emission (before stagnation)

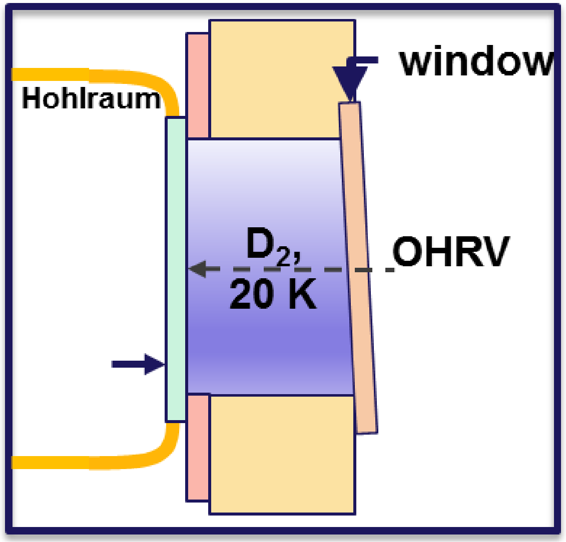


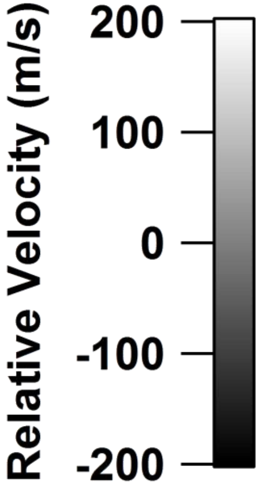


A performance increase was observed for 5 um fill tube leading to the development of a 2 um fill tube is underway and will be tested soon

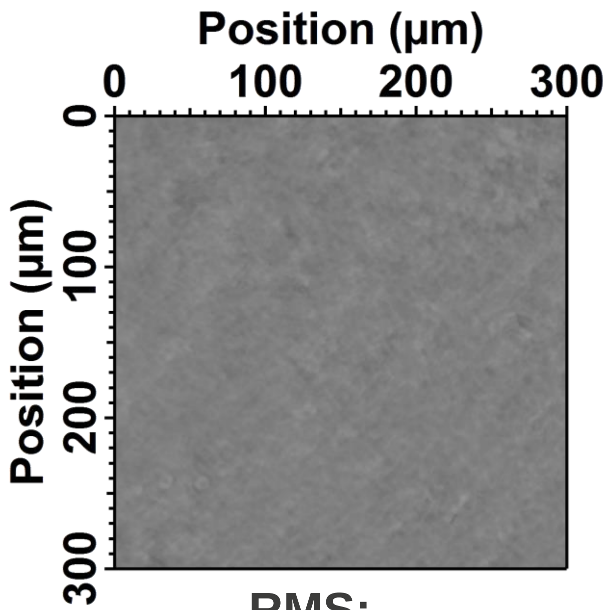
High Resolution Velocimetry (OHRV) measurements show velocity structure of the shock front released

Experiment



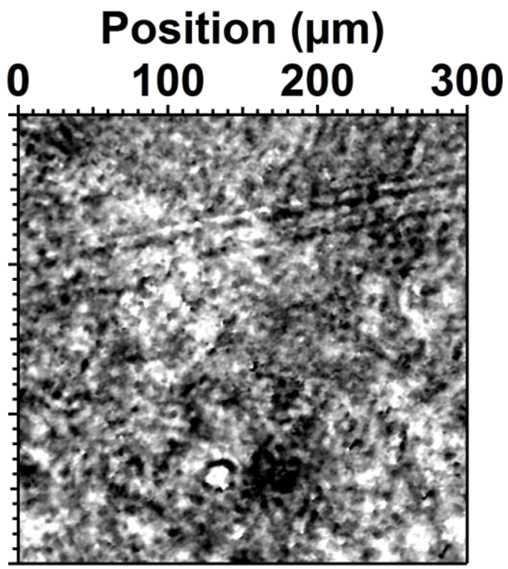


GDP 2.2 Mbar



RMS:
6 ± 4 m/s
~expected

HDC 10 Mbar*



RMS:
85 ± 11 m/s
~4x expected

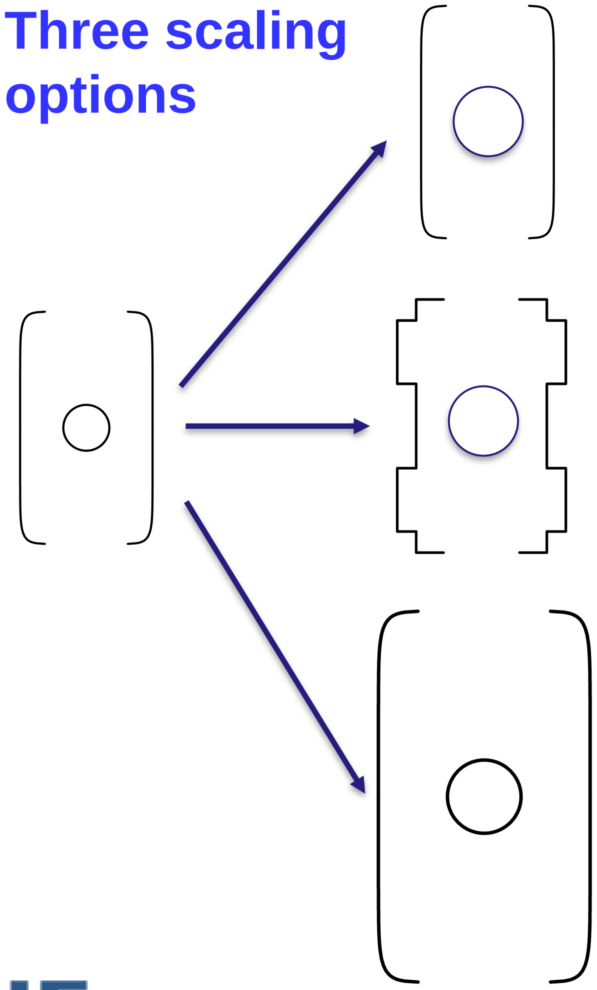
Nano-crystalline HDC capsules are under development

Ali et al, sub PRL 2017

*Design pressure 12+ Mbar

We want to maximize the energy available for heating and compressing the DT fuel

Three scaling options

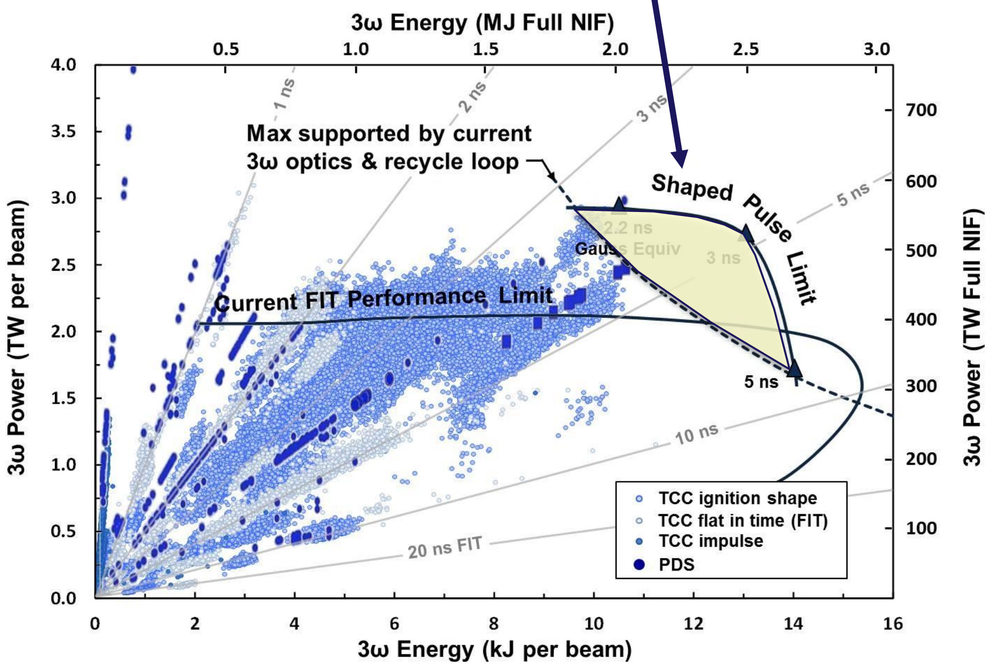


Bigger Capsule in current hohlraum

Bigger Capsule in new hohlraum

Bigger Capsule in bigger hohlraum

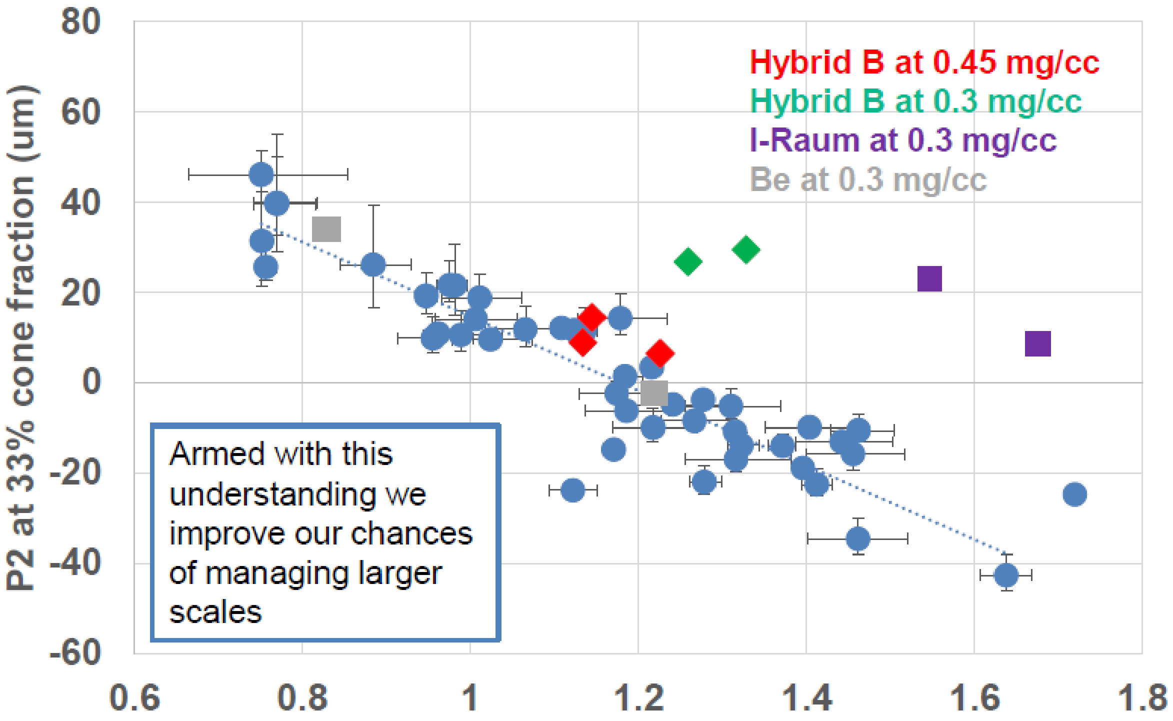
Increases in NIF power/energy



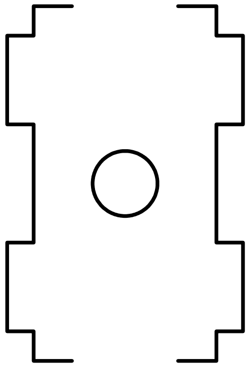
Advances in understanding optics damage and mitigation enable more energy/power

Demonstrated 2.15 MJ in July

Initial experiments with the I-raum[1] and variation of the gas fill pressure show promise



$$\sqrt{\frac{E_{picket\_outer}}{A_{outer}\,\rho_{fill}}}\;\frac{\tau}{R_{hohl}}\,\frac{r_{cap}}{R_{hohl}}$$

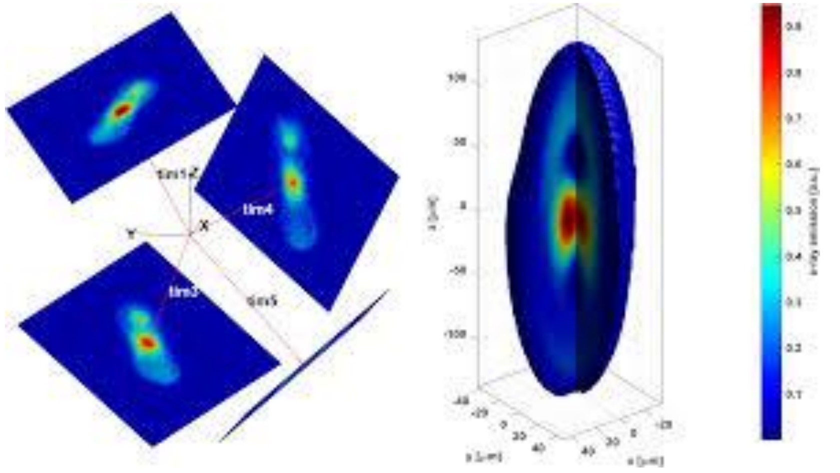


[1]H. F. Robey, L. Berzak Hopkins, J. L. Milovich, N. B. Meezan, "The I-Raum: A new shaped hohlraum for improved inner beam propagation in indirectly-driven ICF implosions on the National Ignition Facility," Phys. Plasmas 25, 012711 (2018)

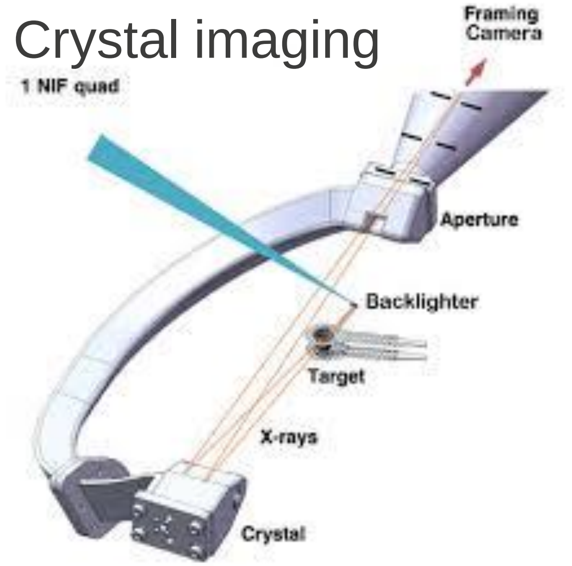
Improving our modeling and uncertainty quantification requires advances in diagnostics capabilities

Area	Knowledge Gap	Diagnostic
Hot spot shape	Shape changes / fill tube jet Time resolved Shape > 1e16n Improved x-ray imaging 3D, n emitting shape	DIXI equatorial Polar DIXI / Single line of sight Penumbral imaging / KBO NIS-3 primary image
Fuel	Is fuel Isotropic Fuel Shape vs time 3D fuel shape	More real time NADS Compton Imaging NIS-3 downscatter
Shell	Shape at Bangtime Shape near Bangtime	γ imaging of 4.4MeV carbon CBI + SLOS
Hot Spot Te	Te Te (t) Te (r,t) Burn quenching	Penumbral + Edge filter / Conspec SPIDER with edge filters Toroidal / Wolter Crystal / SLOS GCD + Dilation PMT
Hohlraum	Morphology of Au Bubble Better Modeling of Hohlraums	Gated LEH imager Optical Thomson Scattering

Multi-LOS neutron imaging

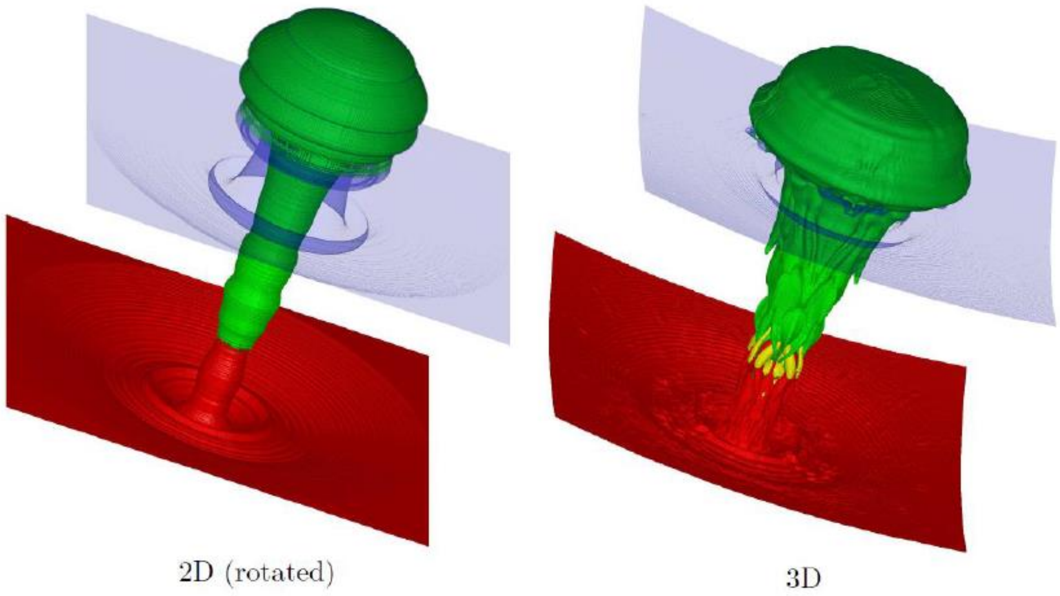


Spherical Crystal imaging

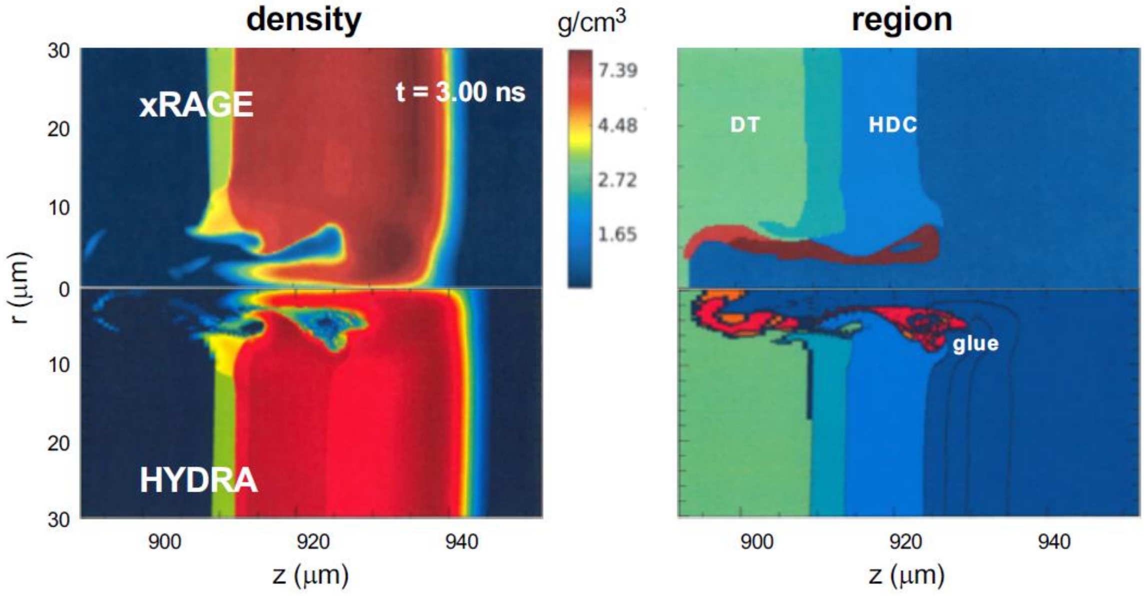


LANL has invested in improvements to the xRage Eularian AMR code expanding simulations capabilities

3D simulations of the fill tube



Code comparison for fill tubes



xRAGE shows more HDC on axis and at slightly larger radius than HYDRA.

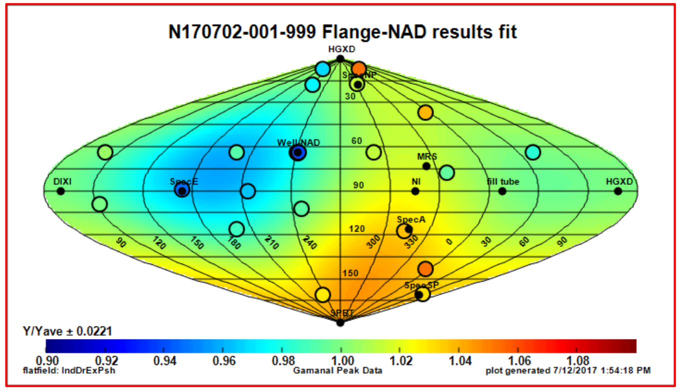
Multiple simulations tools provide insight using different computational algorithms helping to get to the underlying physics

Preview of IAEA FES 2020:

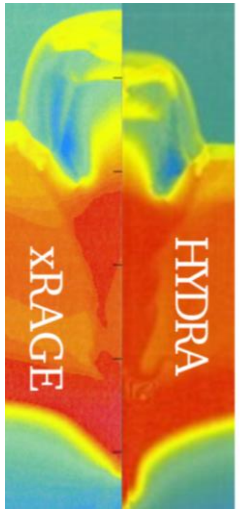
- Continued improvement in implosion performance

- Computational/empirical tools to quantify boundaries for low LPI
- Stagnation campaign to evaluate residual low/high mode asymmetries
- Next generation hohlraum designs to drive larger capsules
- Tools to assess hydro-instabilities at higher convergence
- Ranking of ablator performance
- Cross code comparisons with data to evaluate hydro stability

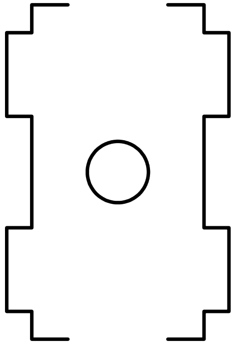
Stagnation



Codes



Hohlraums



We've increased the energy delivery to the hot-spot by ~5x, stagnation pressures by ~3x, and fusion yields by ~21x since the National Ignition Campaign which ended in 2012

- **Low gas filled hohlraums with low LPI use x ray drive more effectively: improved symmetry & more energy coupled to the hot spot**

- **3D effects still significantly degrading performance: symmetry and hydro-instability**

- **We plan to use our advances in understanding to optimize performance both in implosion quality and increased scale**

Efforts are also underway to find alternatives to the tent

Alt-tent (tetra-cage from LEH)