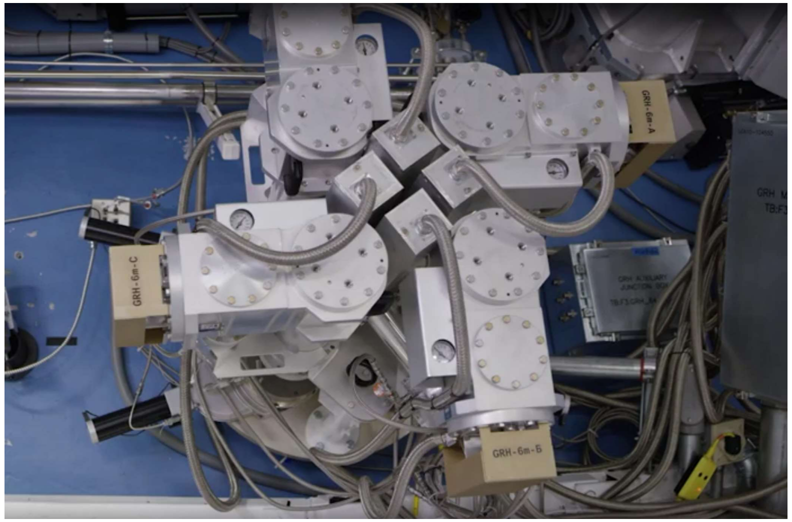
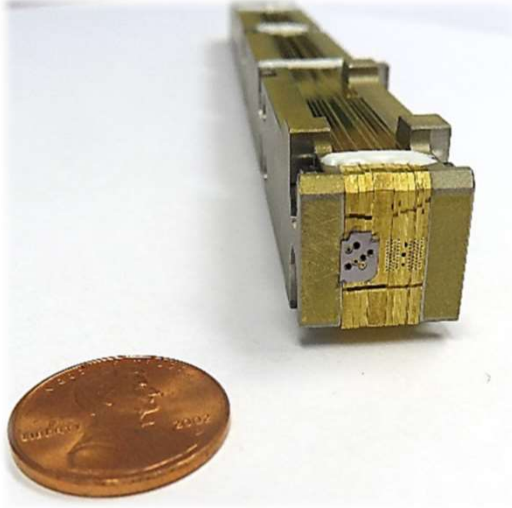




Los Alamos Nuclear Diagnostics at NIF: Reaction History and Neutron Imaging

Kevin Meaney, H. Geppert-Kleinrath, Y. Kim, J. Jorgenson, C. Fry and others (Los Alamos Thermonuclear burn team P-4)

V. Geppert-Kleinrath, M. Durocher, C. Danly, C. Wilde, G. Saavedra, V. Fatherley, M. Freeman and others (Los Alamos Neutron Imaging team P-1)

J. Carrera, E. Mariscal, D. Fittinghoff, P. Volegov, K. Prodanov, A. Moore, D. Schlossberg, M. Rubery, C. Waltz and others (Lawrence Livermore National Lab)

LA-UR-23-25830

Los Alamos NATIONAL LABORATORY

June 2023

LANL's nuclear diagnostic team leads a multi-institutional collaboration

Los Alamos National Laboratory

Y. H. Kim, K. D. Meaney, H. Geppert-Kleinrath, N. Hoffman, M. Schmitt, J. Langenbrunner, J. Oertel, T. Murphy, S. Batha, J. Kline, B. Albright, C. Hamilton, H. W. Herrmann

V. Geppert-Kleinrath, M. Durocher, G. Saavedra, C. Danly, C. Wilde, V. Fatherley, M. Freeman

Lawrence Livermore National Laboratory

A. B. Zylstra, J. Carrera, H. Khater, A. Carpenter, R. Hibbard, J. Liebman, G. Grim J., E. Mariscal, D. Fittinghoff, P. Volegov, K. Prodanov, A. Moore, D. Schlossberg, M. Rubery, C. Waltz

AWE

C. J. Horsfield, S. Gales, A. Leatherland

SYDOR TECHNOLOGIES — COMPLEX MEASUREMENTS—CRITICAL RESULTS

C. McFee

PHOTEK — ENVISAGE THE FUTURE

J. Milnes

GENERAL ATOMICS

T. Hilsabeck, J. D. Kilkenny

National Security Technologies LLC — Vision • Service • Partnership

R. Malone, E.K. Miller, M. Kaufman

Kentech Instruments Ltd.

J.D. Hares, A. Dymoke-Bradshaw

UR LLE

V. Glebov, W. Shmayda, D. Jacobs-Perkins, G. Pien

and more!

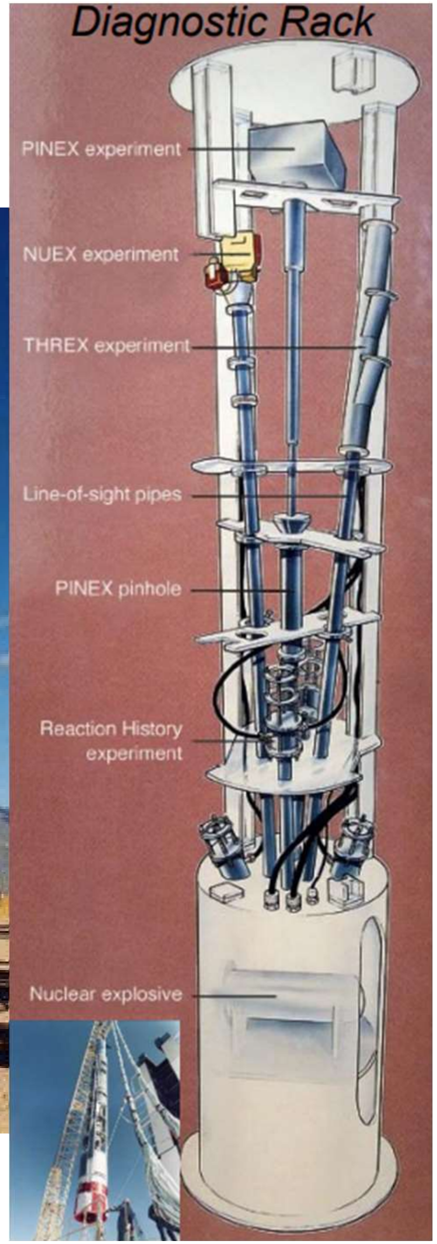
- **Nuclear diagnostics have played a critical role in understanding and improving NIF performance**

- **The US has invested a decade+ into nuclear diagnostics for ICF facilities**

- **Los Alamos National Lab has focused on gamma reaction history and neutron imaging system**

- **In part due to data from nuclear diagnostics, NIF has achieved and confirmed ignition and net gain (1.5x)**

LANL nuclear diagnostics continues the legacy of underground test diagnostics



Los Alamos NATIONAL LABORATORY

R. Webster 'Stockpile Stewardship at Los Alamos' (2012)

Nuclear diagnostics determine the conditions of the fusion hot spot

$$Y_{DT} = \int \langle \sigma v(T) \rangle * n_D n_T * dV * dt$$

Calibrated detectors
Activation diagnostics

FNADs (LLNL)

Neutron time of flight

nTOF (LLNL)

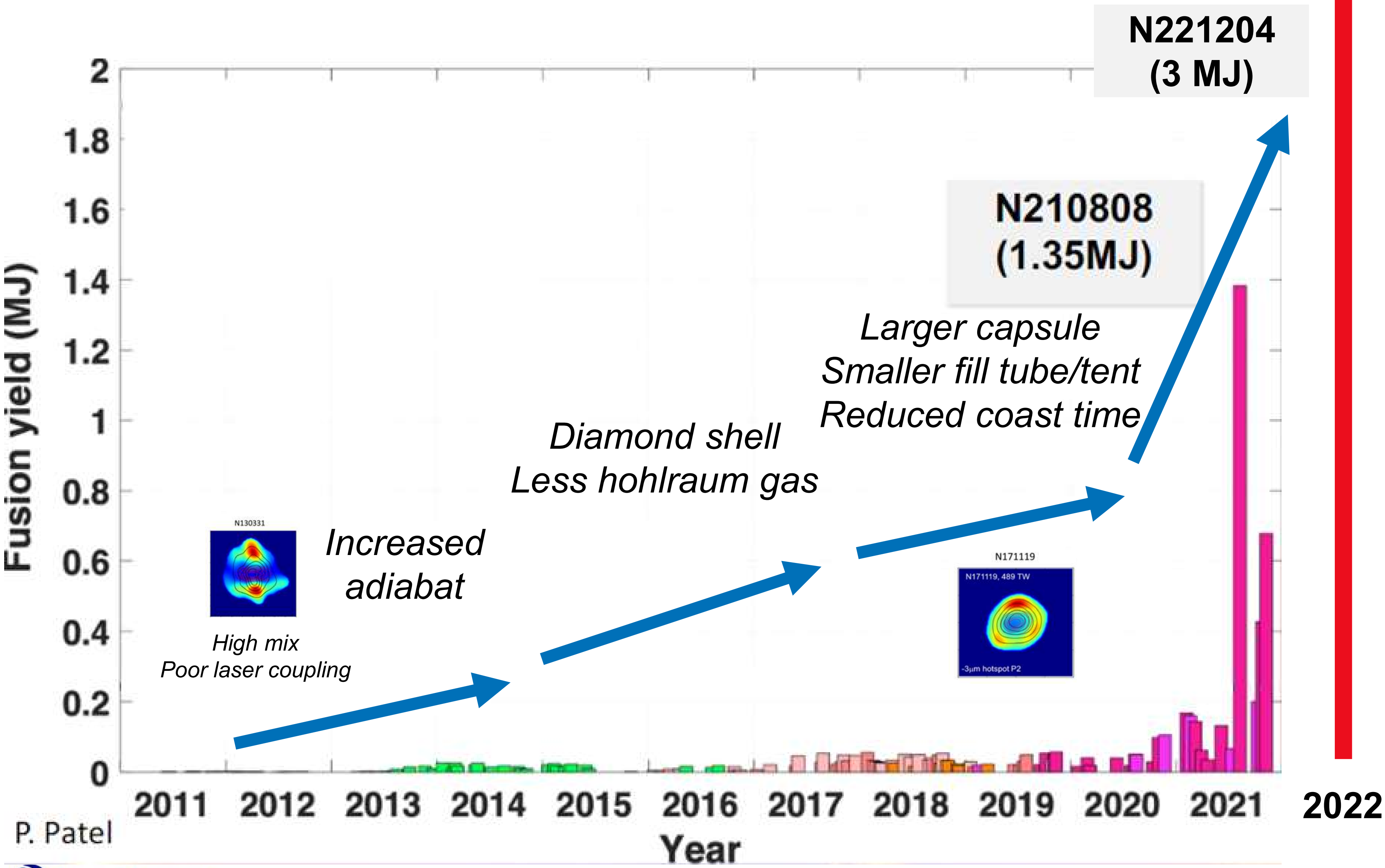
Neutron imaging
Neutron time of flight

NIS (LANL)

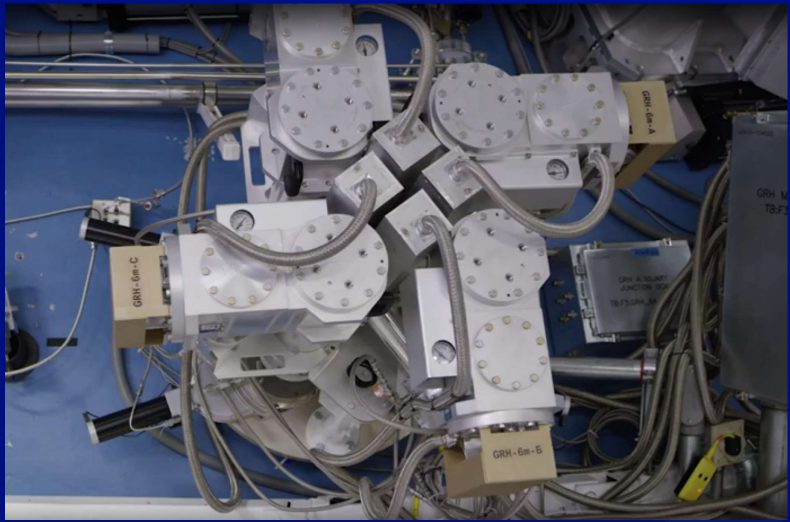
Gamma Reaction History

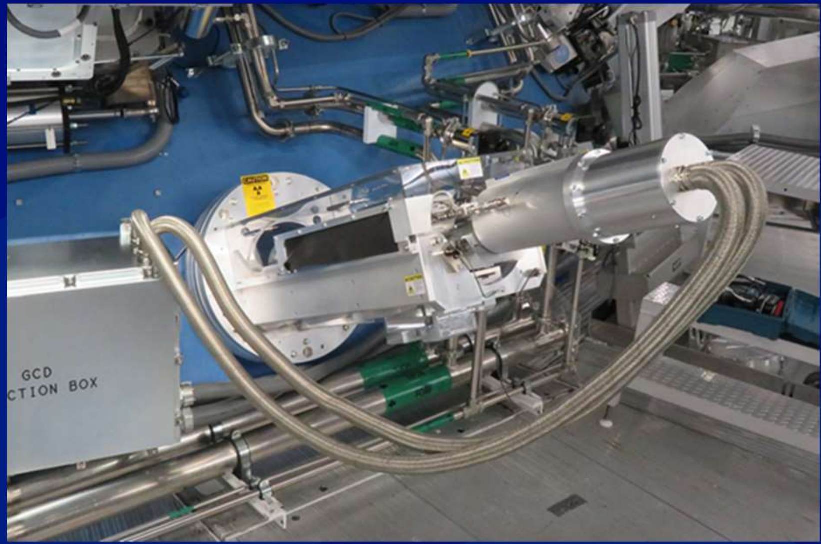
GRH (LANL)

After a decade NIF has achieved ignition (thanks in part to nuclear diagnostics)



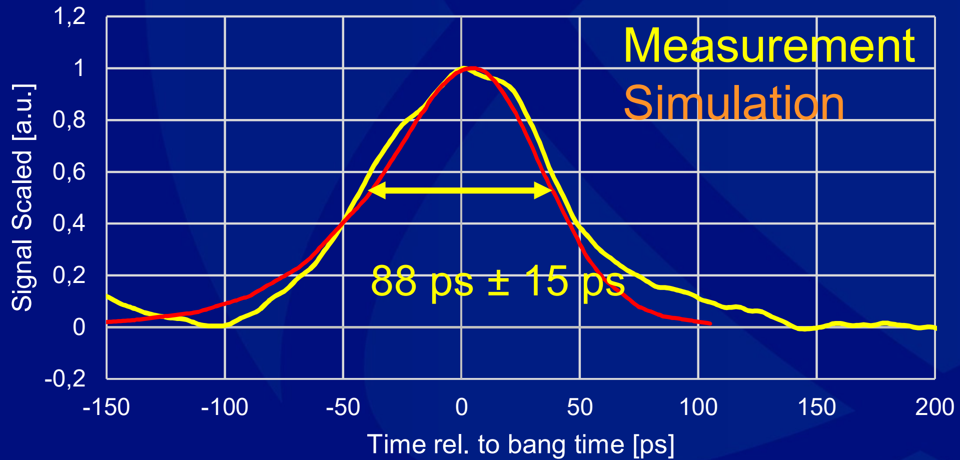
P. Patel





Gamma Reaction History Diagnostic

National Ignition Facility Shot (N210808)



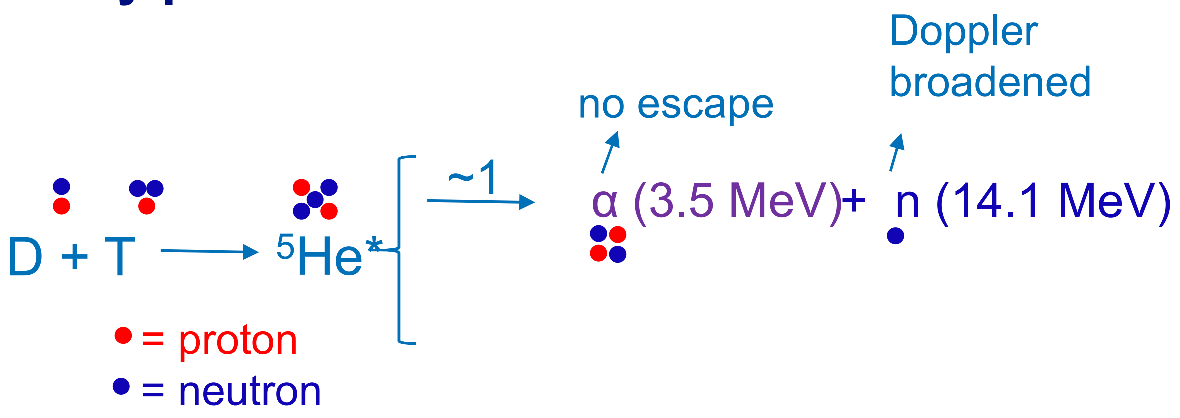
~ 60 ps

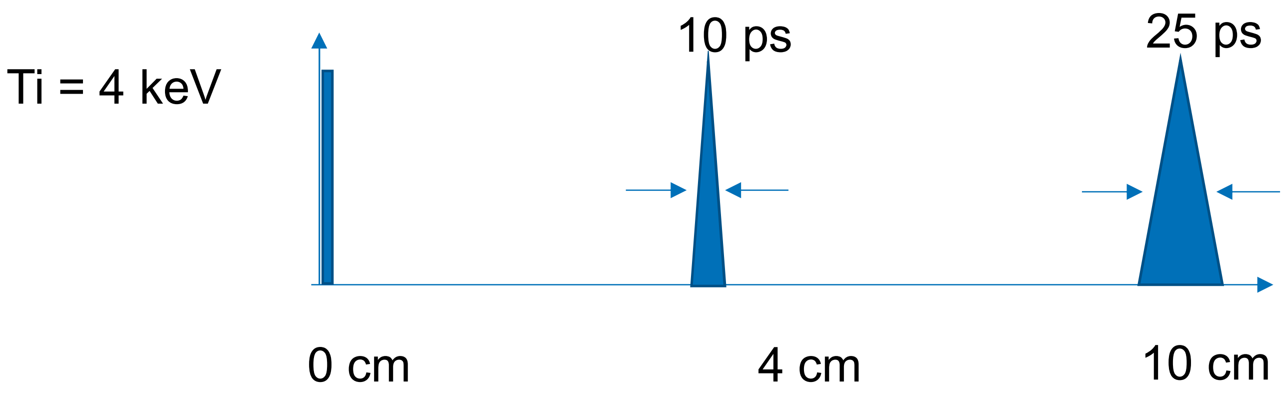
In 60 ps, light only travels across a penny

So, we need a fast detector!

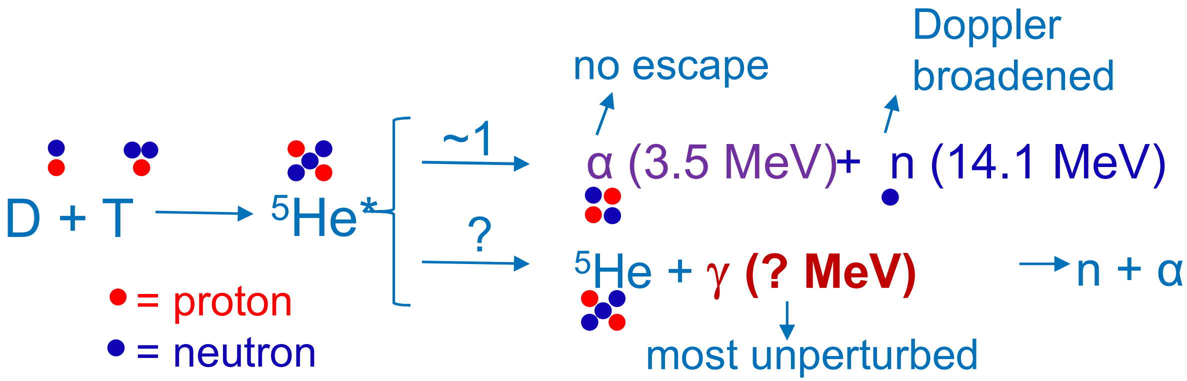
How can we do that?

The most accurate way to diagnose this is through measurement of the gamma ray produced in a rare branch of the D + T reaction.

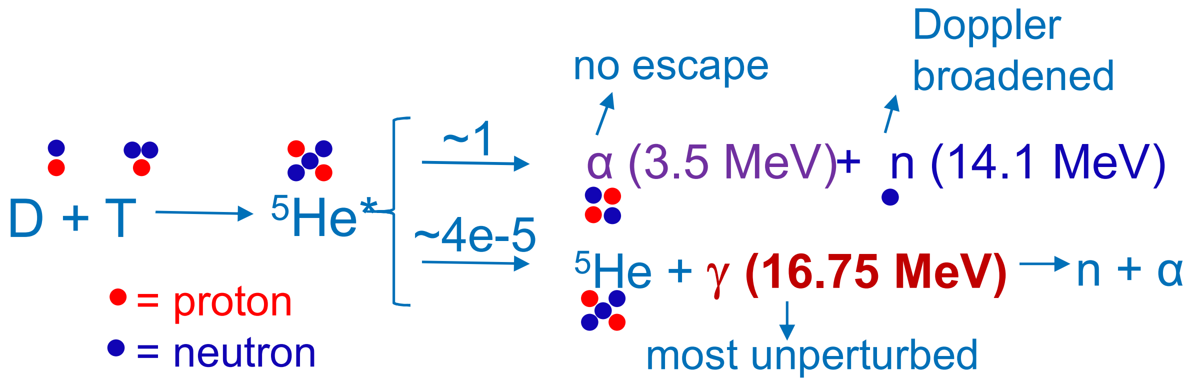


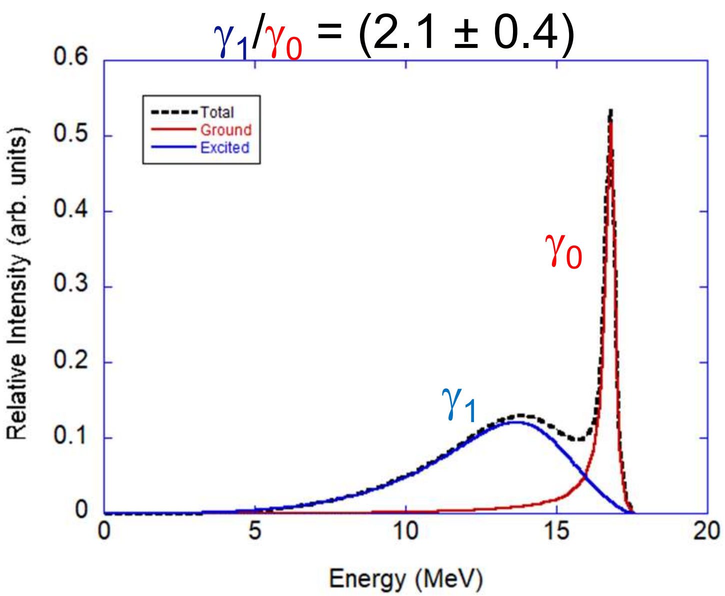


The most accurate way to diagnose this is through measurement of the gamma ray produced in a rare branch of the D + T reaction.

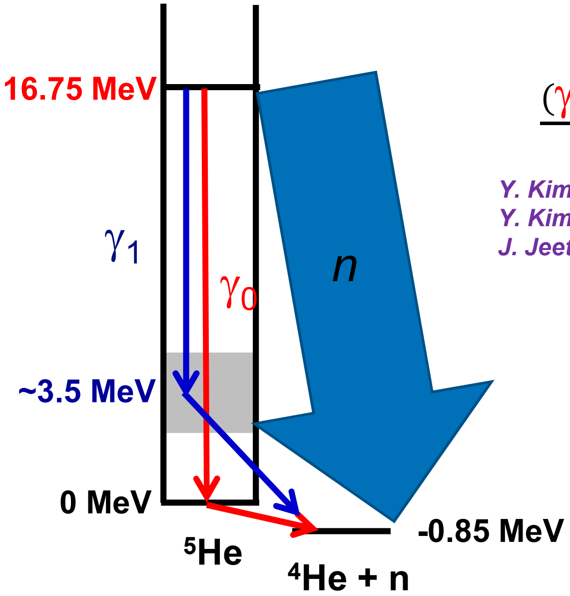


The most accurate way to diagnose this is through measurement of the gamma ray produced in a rare branch of the D + T reaction.





C. Horsfield, et al., PRC 104, 024610 (2021)



$$\frac{(\gamma_0+\gamma_1)}{n} = (4.2 \pm 2.0) \times 10^{-5}$$

Y. Kim, et al., Physical Review C 85, 061601 (2012)
Y. Kim, et al., Phys. Plasmas 19, 056313 (2012)
J. Jeet, et al., Physical Review C 104, 054611 (2021)

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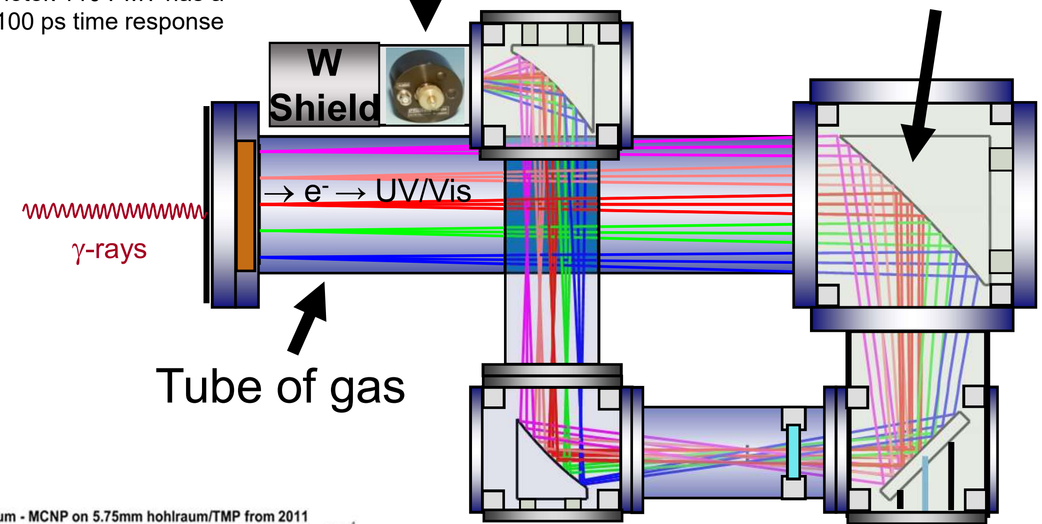
Cherenkov detector gives fast (~100 ps), energy selection to measure DT gamma rays

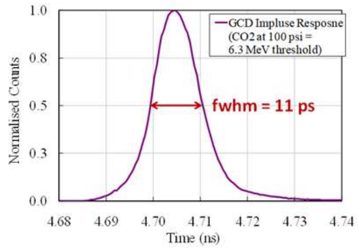
Photomultiplier tube

Off-axis parabolic mirrors

Photek 110 PMT has a ~100 ps time response

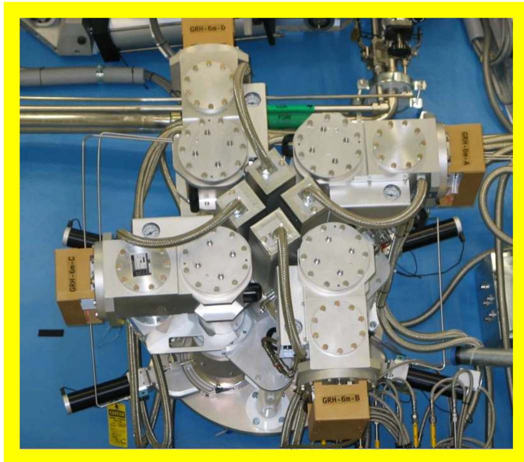


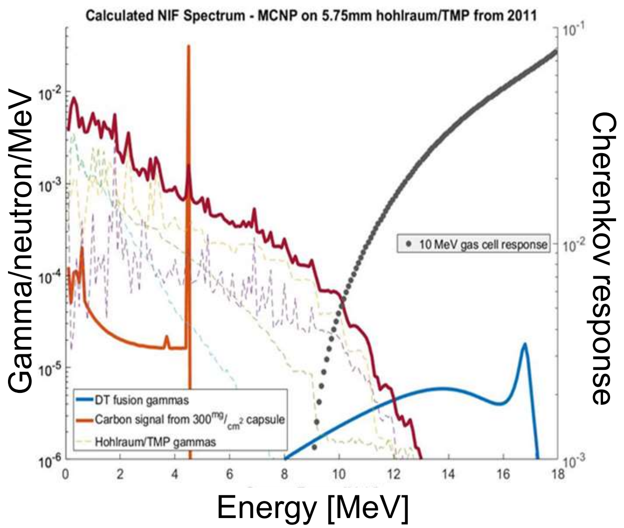
Tube of gas



Cherenkov process is fast, gas response is 10 ps

4 cells @ NIF 6 m from implosion

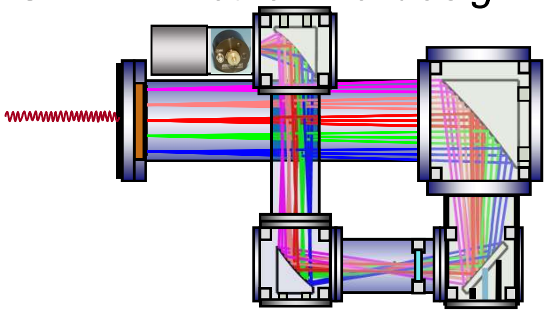




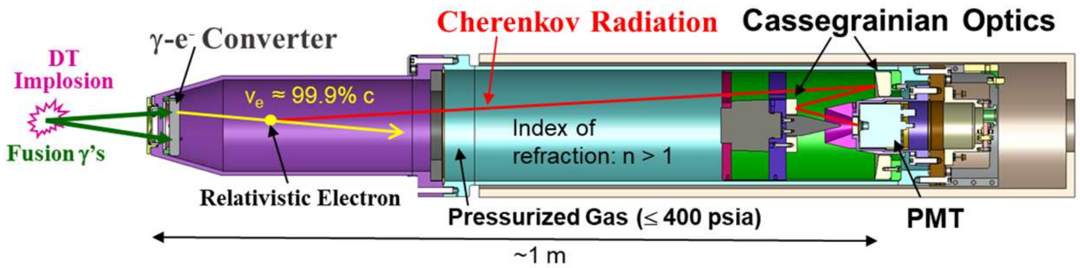
Gas pressure → index of refraction → γ's above a selected energy

US complex utilizes Gas Cherenkov detectors across sensitivities

GRH – 'Pretzel like' design

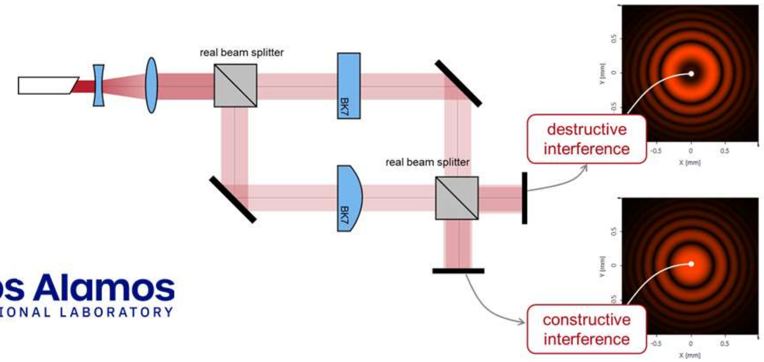


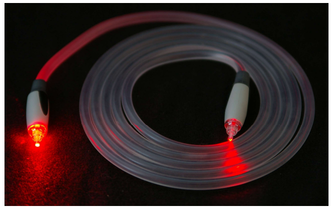
Gas Cherenkov Detector (GCD) – tube like insertable design

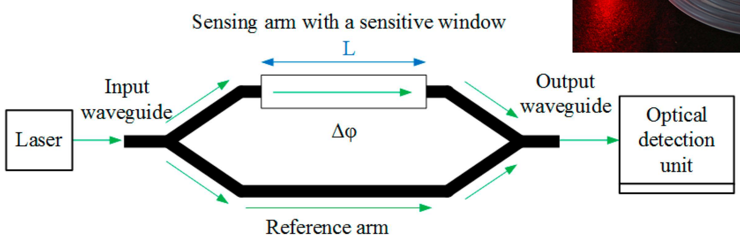


Name of Detector	Location	Distance to implosion	Min DT yield for statistics + time resolution
GCD1 GCD2 GCD3	OMEGA laser facility	20 cm	1e11 – 100 ps
GRH x4 GCD3	NIF	6 meters 4 meters	1e14 for 100 ps 1e16 for 10ps
GRH x1	Pulsed power Z-Machine	2.5 meters	1e13 – 100 ps 1e14 vs background

- Use an optical data link system to maintain the time resolution – Mach-Zehnder interferometer







Reaction history holds energy balance - expect later peak, narrow burn as performance increases

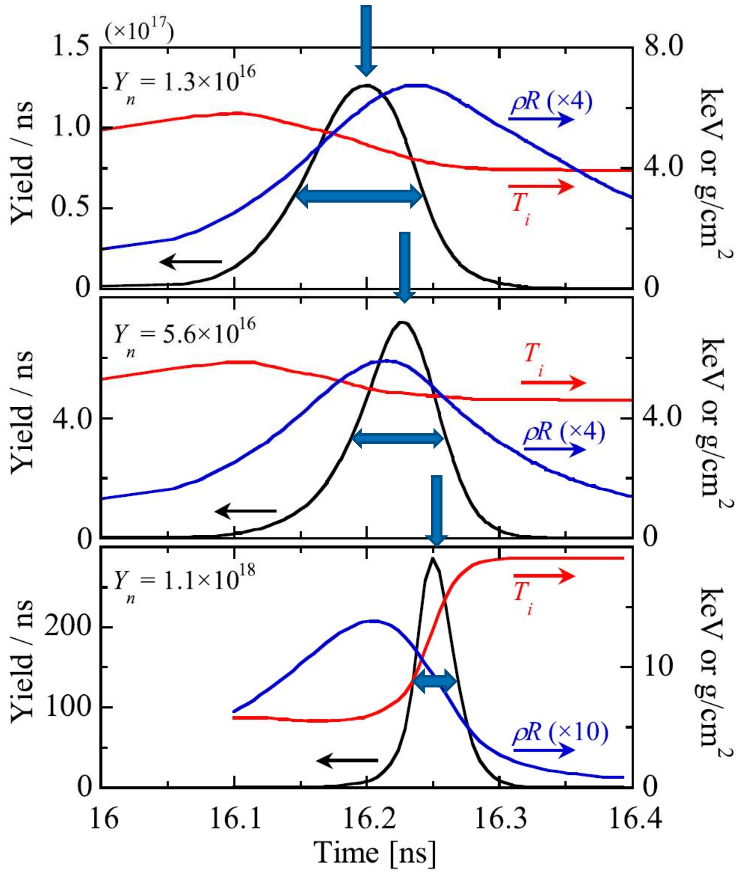
Energy in fuel — *DT fusion* — *Radiation* — *Conduction* — *Compression + Expansion*

$$c_{\mathrm{DT}}\frac{dT_{\mathrm{th}}}{dt} = f_\alpha Q_\alpha - f_B Q_{\mathrm{B,DT}} - Q_{\mathrm{e}} - \frac{1}{m} p \frac{dV}{dt},$$

No alpha heating

Artificial x4 alpha heating

Artificial x83 alpha heating



As alpha-heating increases,

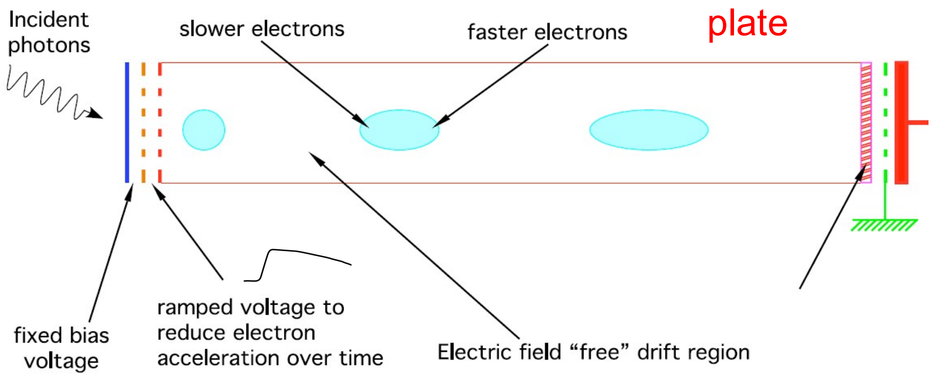
Peak reaction occurs after peak compression

Burn width gets narrow (< 100 ps)

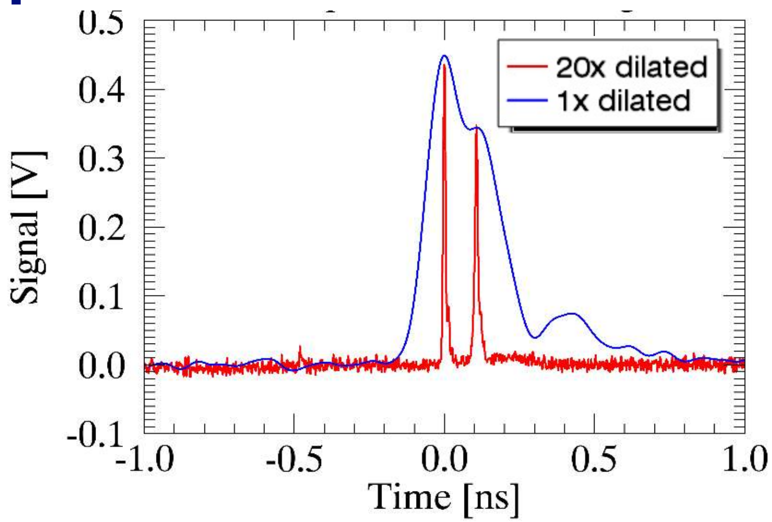
Johan A. Frenje (MIT) & Charlie Cerjan (LLNL) RSI 87, 11D806 (2016)

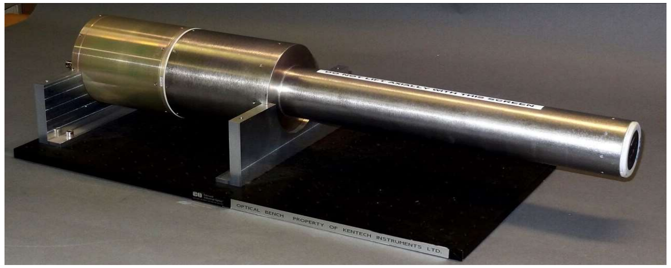
Los Alamos NATIONAL LABORATORY

Developed PD-PMT technology allows for ~10 ps time resolution

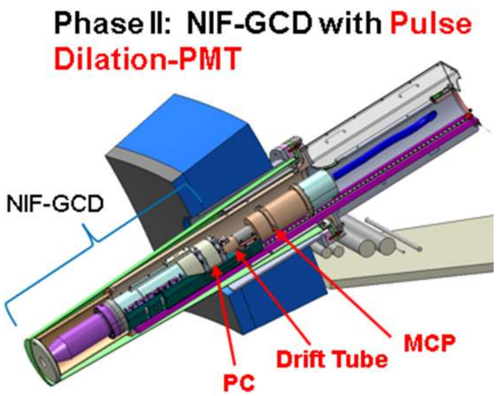


Hermann Geppert-Kleinrath High Energy Density Physics, 37, 100862 (2020)





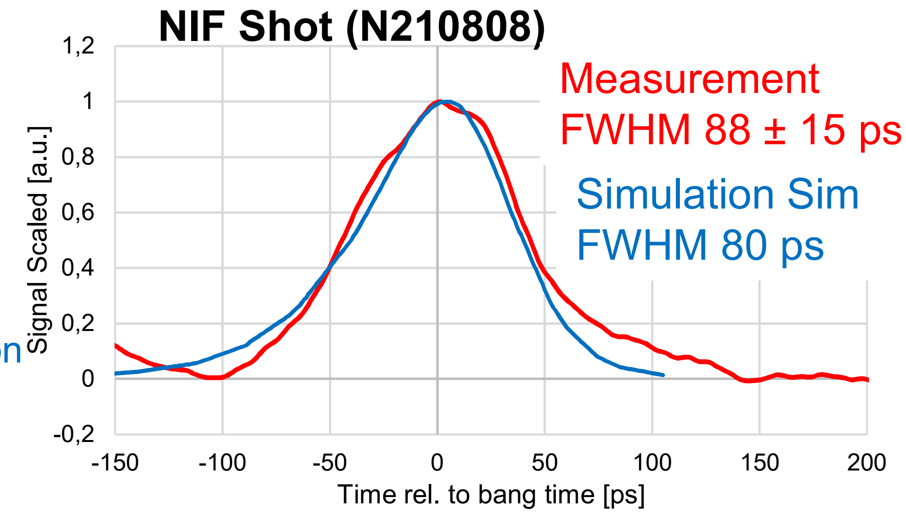
PD-PMT (~1 meter)



Unprecedented time resolution

Data from Hermann Geppert-Kleinrath (LANL)

Simulation by Annie Kritcher (LLNL)



GRH's nuclear bangtime is used to fix shell trajectory

- Based on radiography of SymCap surrogate experiments the bangtime can be related to the ablator remaining and max shell velocity
  - ~1% peak velocity per 30 ps in BT

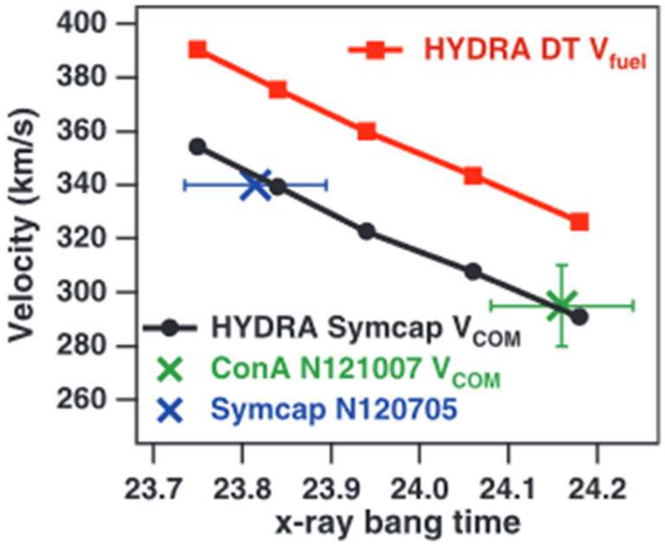


FIG. 8. Velocity vs. x-ray bang-time for symmetry capsule shot N120705 and convergent ablator shot N121007, compared with a 1D HYDRA flux-scaling. The convergent ablator data for center-of-mass velocity (V_{CoM}) and x-ray bang-time "pin" the scaling, allowing a velocity estimate for the higher-power N120705 shot based only on its bang-time.

Meezan PoP 2013

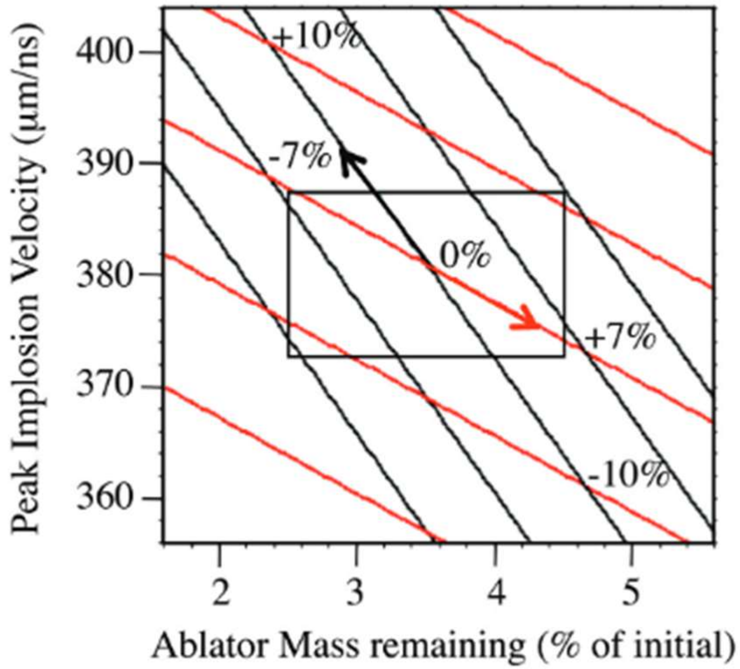


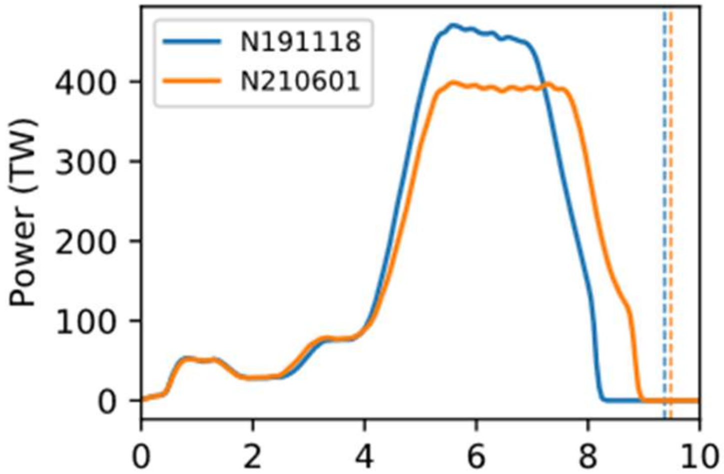
FIG. 20. (Color) Calculated peak implosion velocity and remaining ablator mass sensitivity to variations in peak laser power (along black contours spaced every 7% in thickness) and initial ablator mass (along red contours spaced every 10% in peak flux). The black and red arrows signify increasing flux and thickness, respectively.

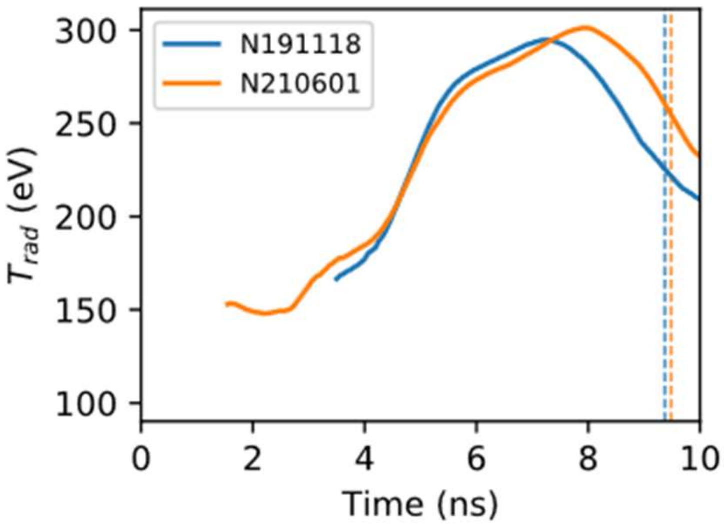
Landen PoP 2011

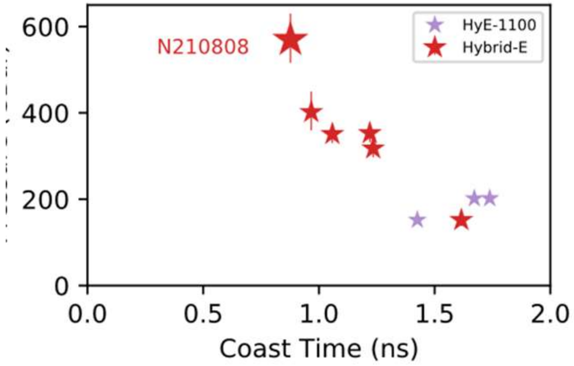
Nuclear bangtime determines the coast time, one of the vital design parameters

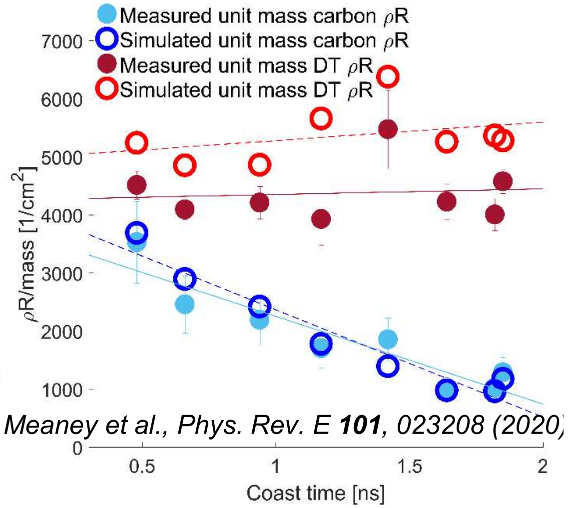
- Coast time defined as time between main laser shut off and bangtime

A. Zylstra Phys. Rev. E 2022

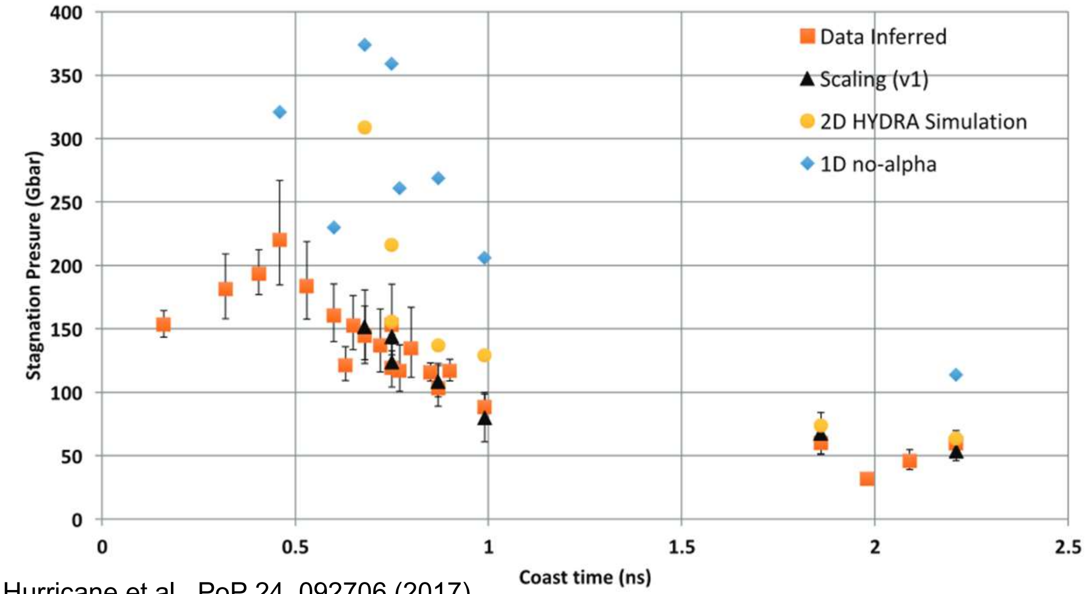






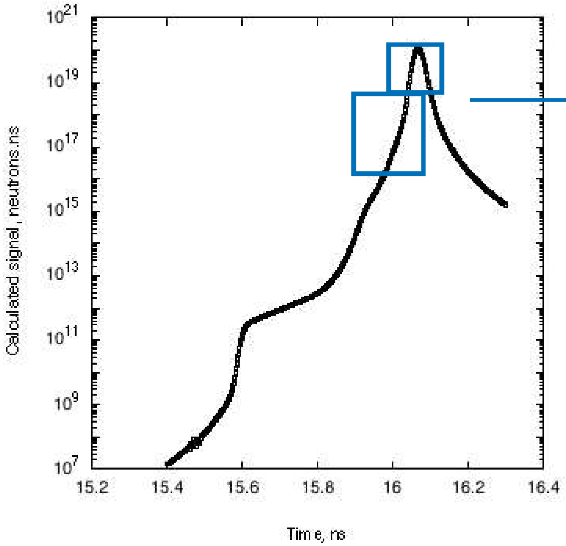


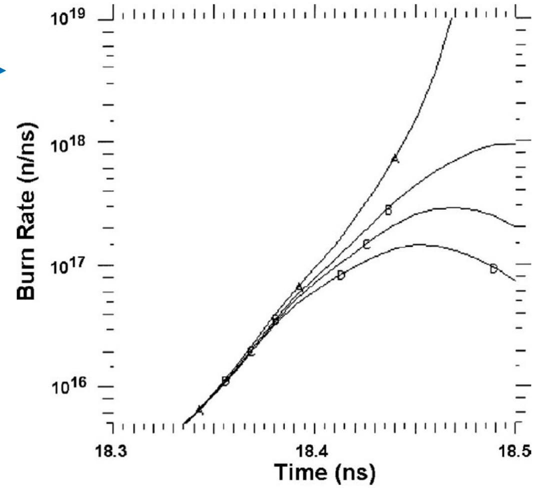
Meaney et al., Phys. Rev. E ***101****, 023208 (2020)*



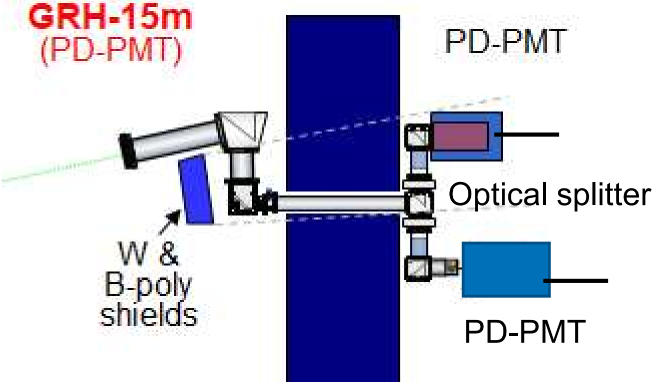
O. A. Hurricane et al., PoP 24, 092706 (2017)

Looking ahead, we want high dynamic range to generate alpha curves of ICF implosions to probe the ignition take-off

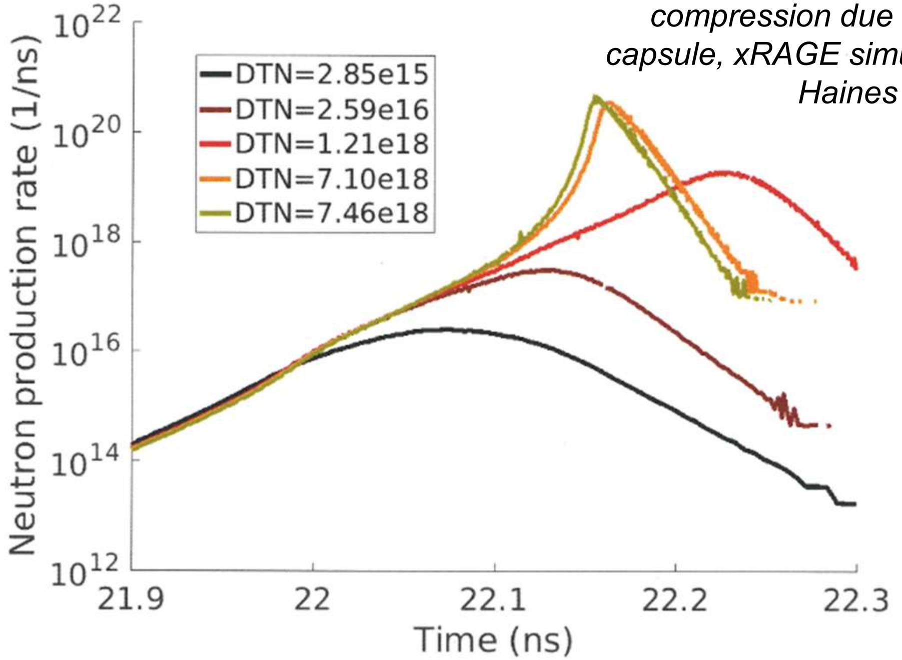




Doug Wilson (LANL) Rev. Sci. Instrum. 79, 10E525 (2008)



ICF implosion scaled by compression due to voids in capsule, xRAGE simulations by B. Haines



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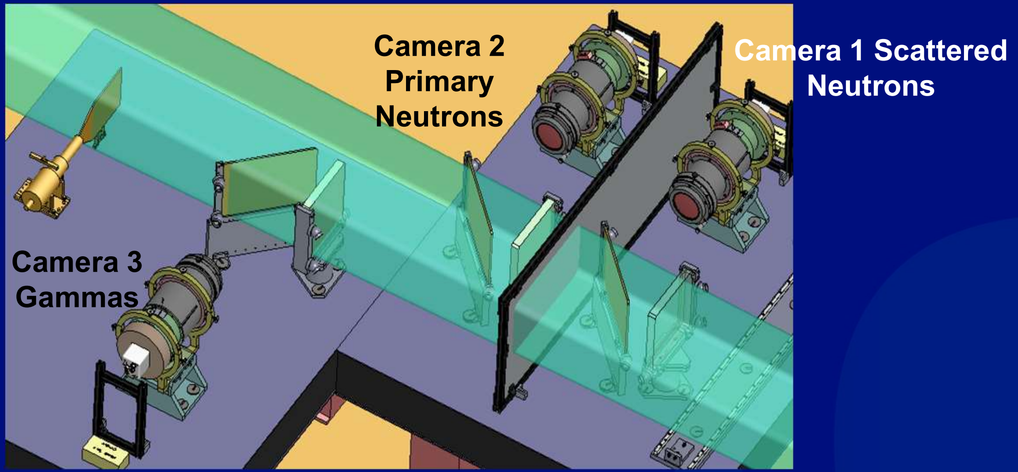
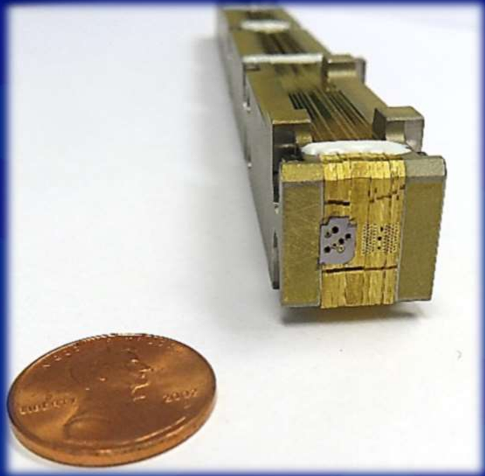
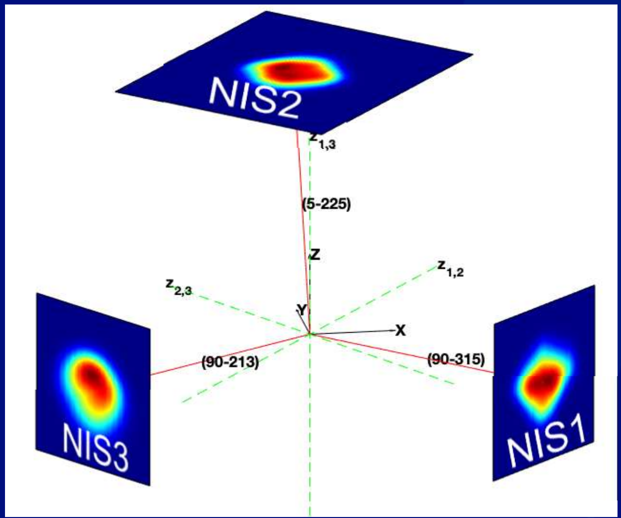
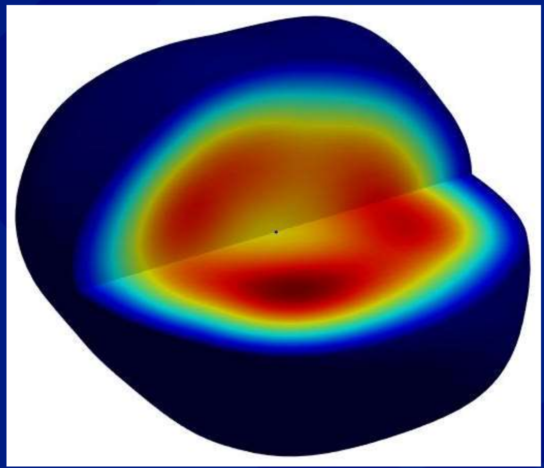




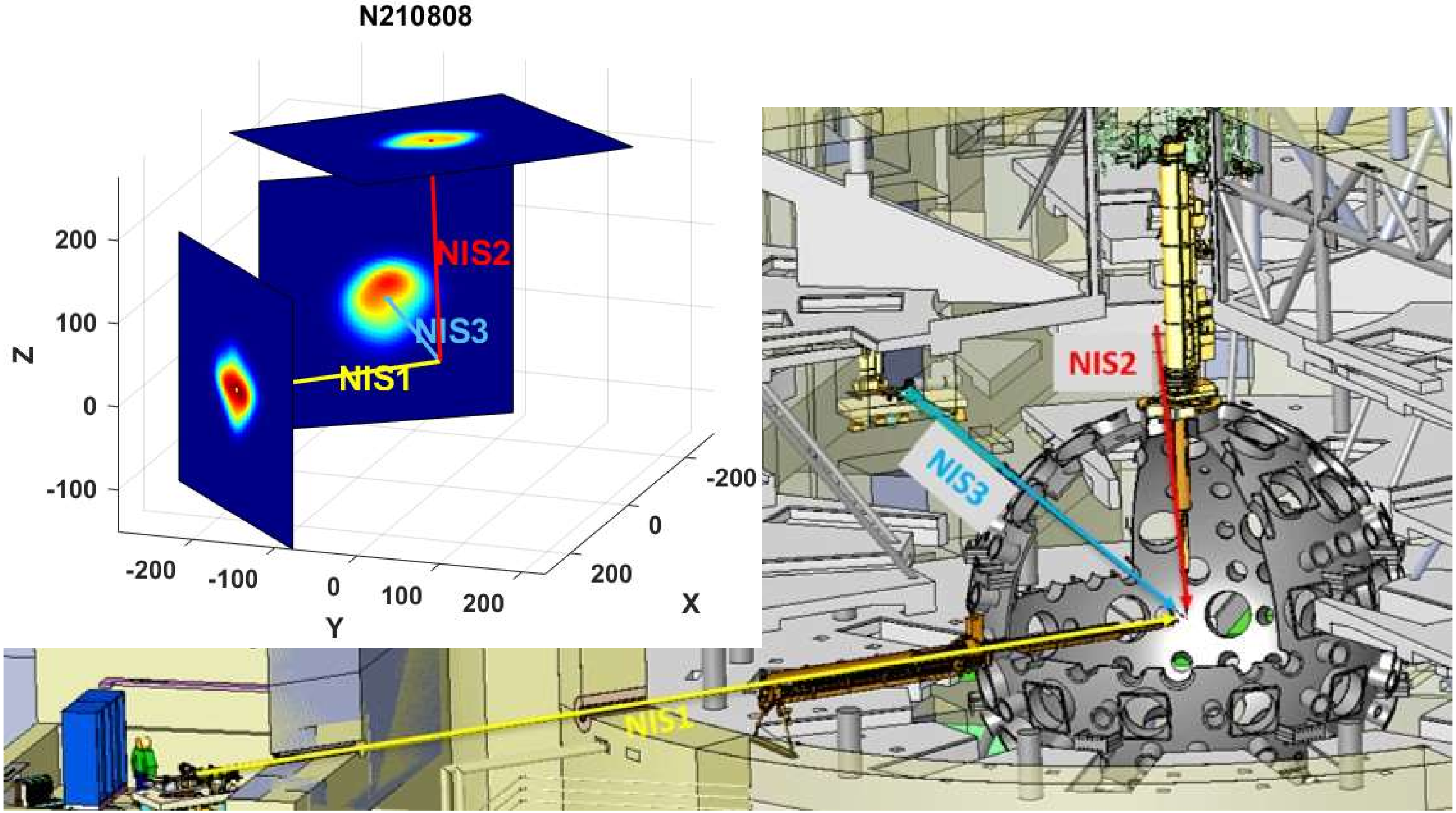
Neutron imaging system



N210808 3D emission reconstruction



Neutron imaging system has three lines of sight, allowing 3D reconstruction from 2D projections

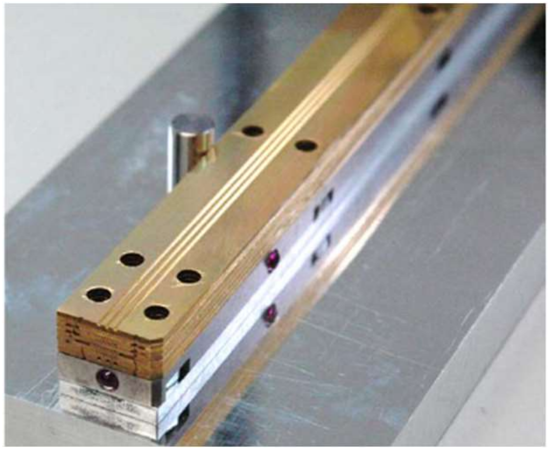


Slide from Mora Durocher + Verena Geppert-Kleinrath

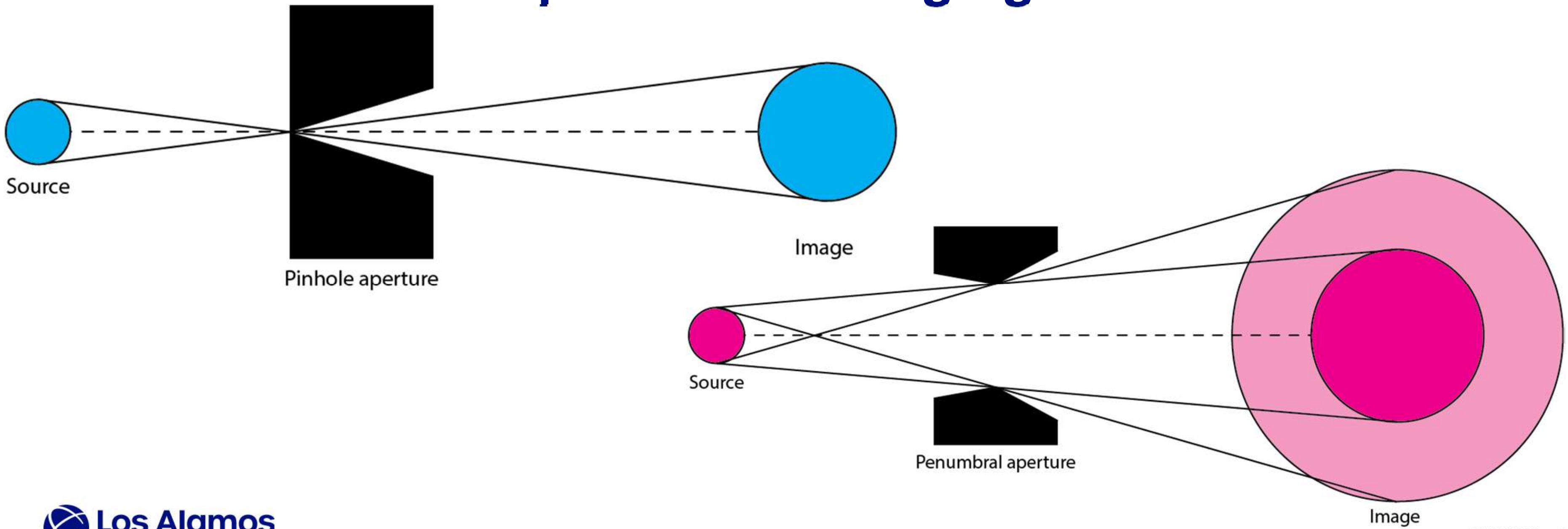
Volegov, P. et al., Journal of Applied Physics, 2015. 118(20): p.205903.
Volegov P. et. al., Journal of Applied Physics, 2017. 122(17): p.175901
Volegov P. et. al., Review of Scientific Instruments, 2021. 92(3): p.033508

How do you image something so small? Large magnification

- ICF hot spots are ~50 μm
- Pinhole @ at 25.5 cm, recording system @ 2802 cm
- **Magnification of ~76, resolution of 10-12 μm**



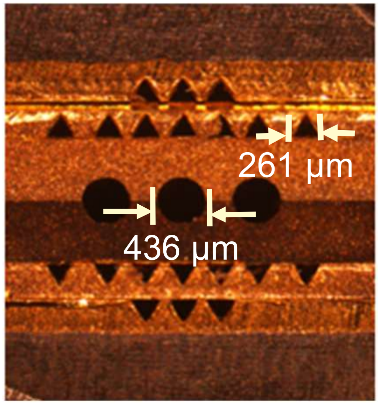
The neutron imaging system combines both pinhole and penumbral imaging



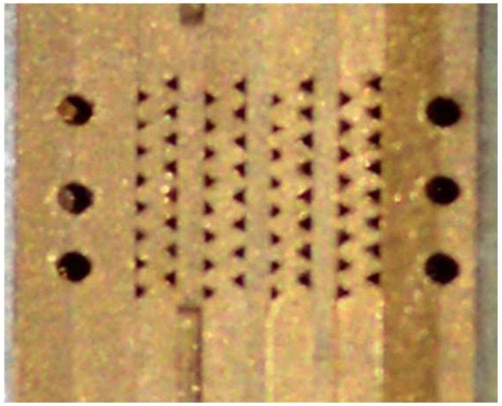
Images from Mora Durocher + Verena Geppert-Kleinrath

Apertures have iterated over time, improved manufacturing and characterization

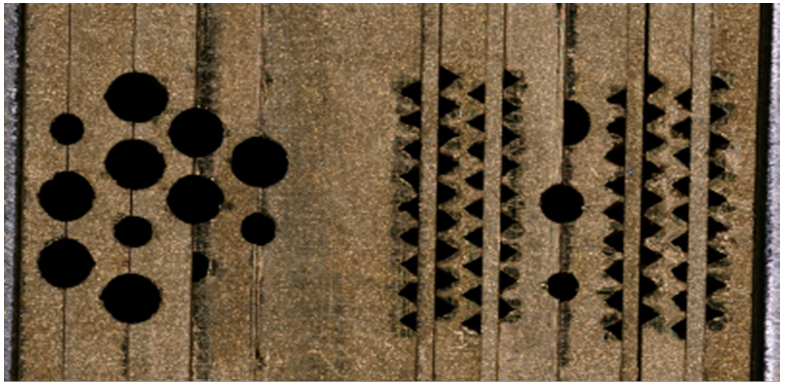
2010: NIS1



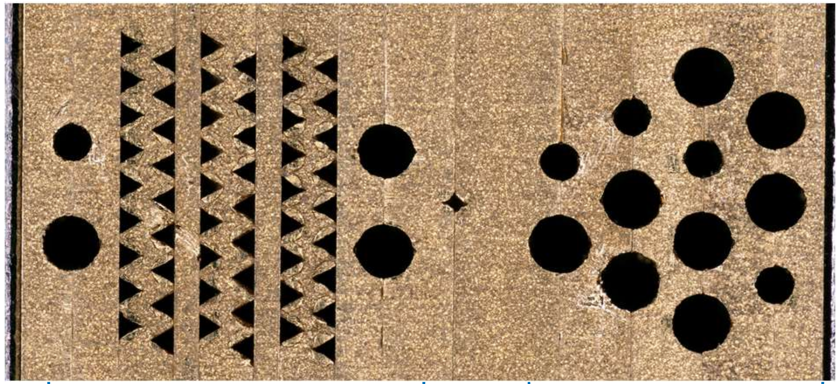
2016: NIS2



2019: NIS3



2022: NIS1U



Neutron aperture

γ aperture
(low yield/large source)

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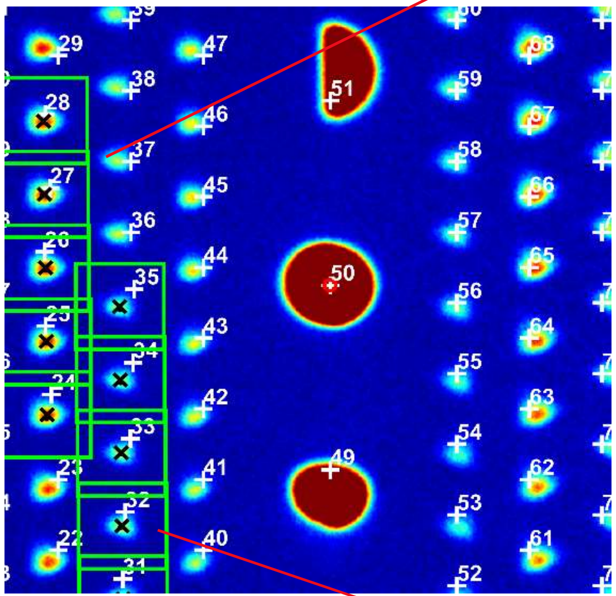
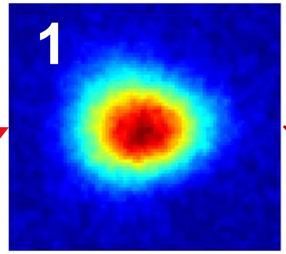
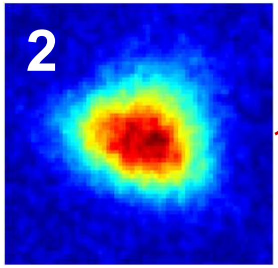
Slide from Mora Durocher + Verena Geppert-Kleinrath

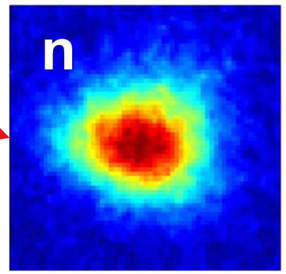
Each shot combines all the best images from each type of pinhole through Bayesian inference

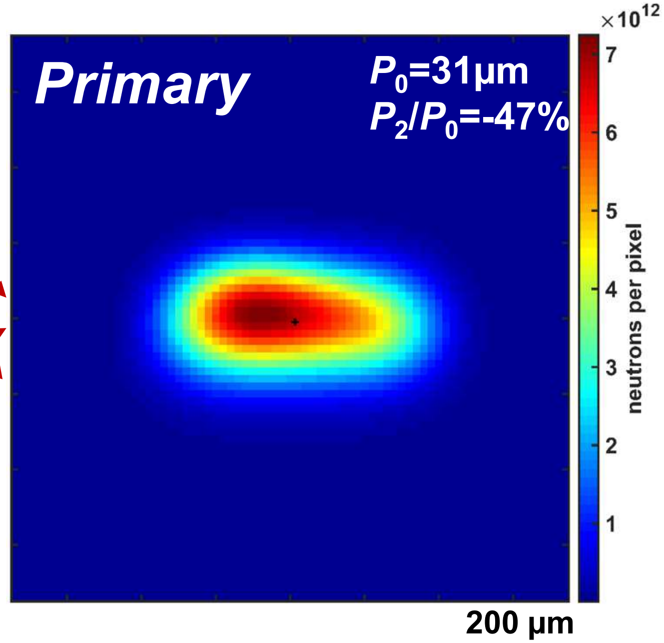
NIS3 raw image











Iterative Bayesian inference providing optimal source distribution and background fit

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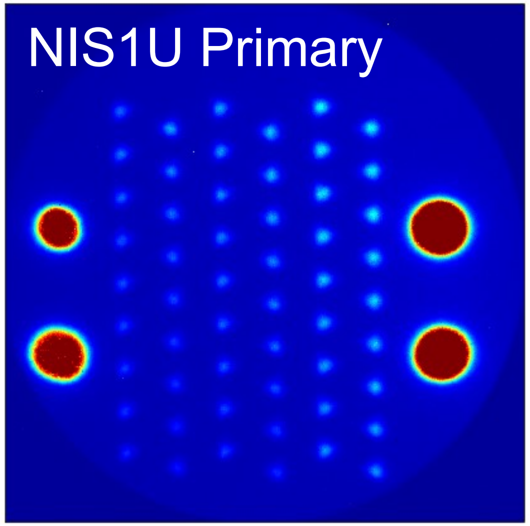
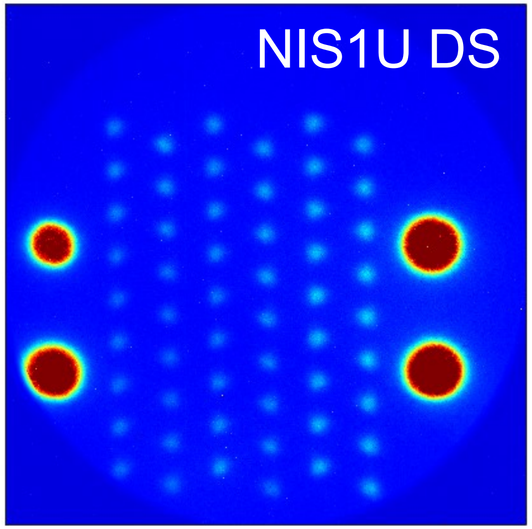
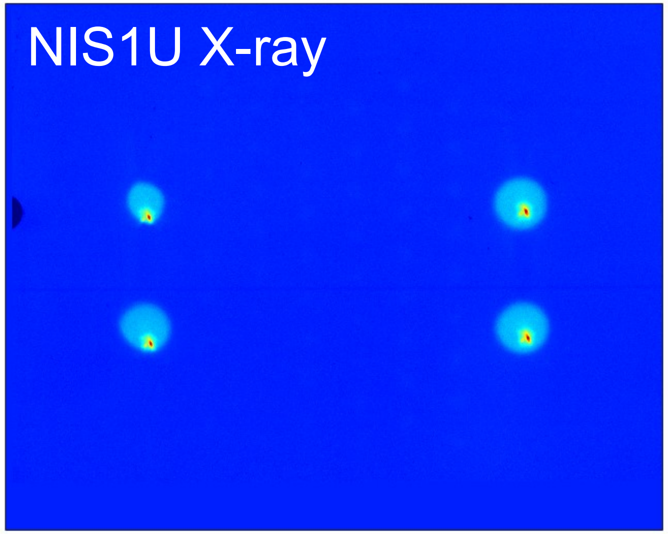
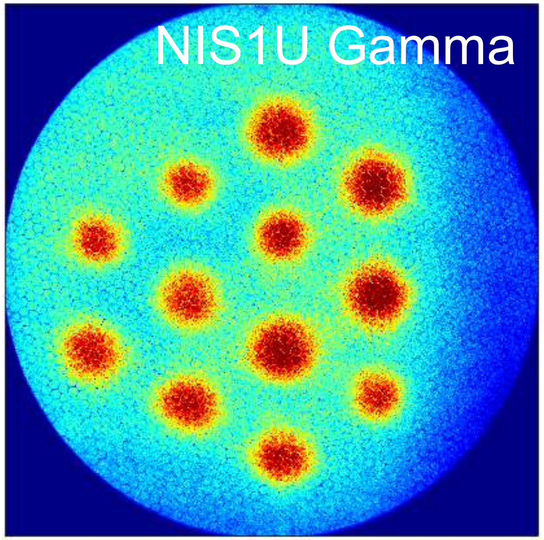




N220626 also available for NIS3





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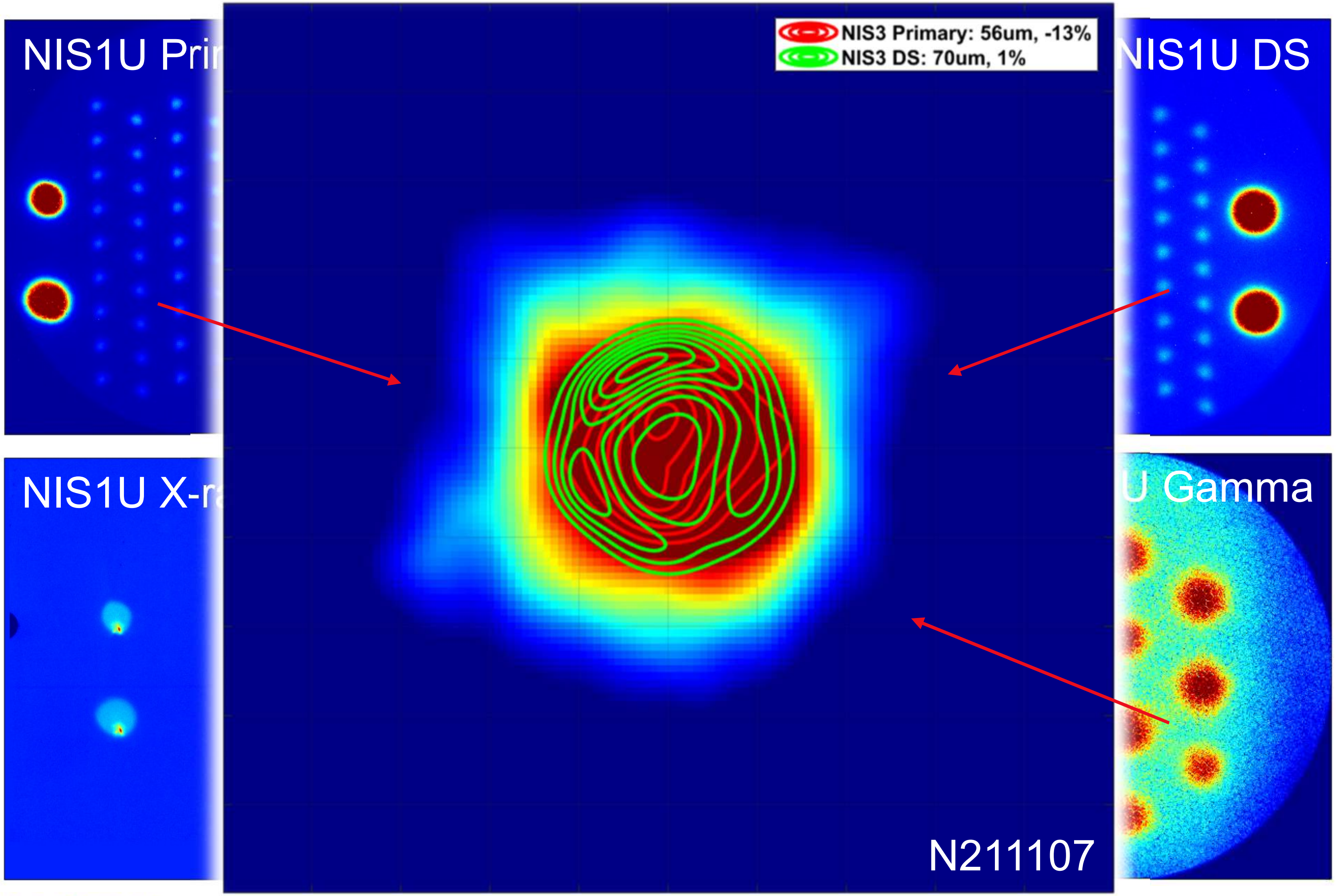

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Neutron imaging vital to quantifying asymmetry and effect of engineering features

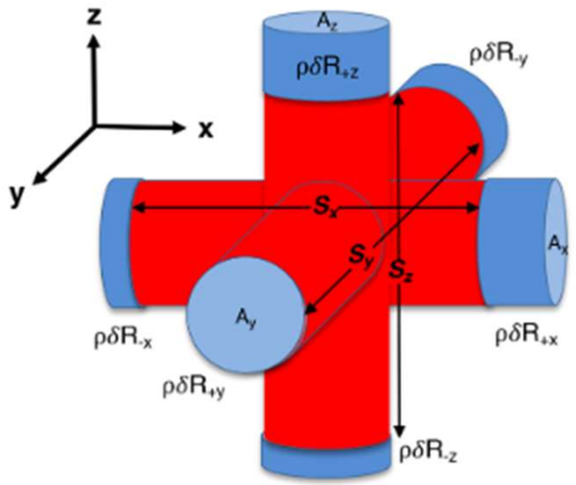


FIG. 2. Shown is an abstraction of 3D implosion that is made up of 6 pistons doing work on a common hot-spot. The configuration is that of three cylinders at right angles to each other. This geometry of the intersection volume is known as a "Steinmetz solid" and the calculation of the volume is non-trivial. The pairs of pistons that lay along a particular coordinate have a time-dependent separations, S_x, S_y, and S_z. Each piston has its own areal density and cross-sectional area.

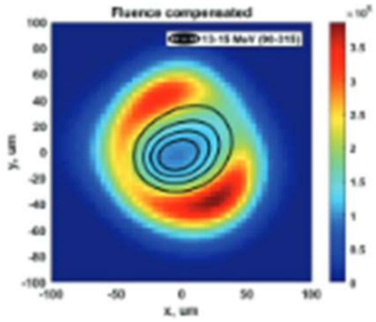
Modify hot spot parameters due to asymmetry

Property	General asymmetry	Pure mode-1
P_{stag}	$\left(\frac{\rho\delta R_{WHM}}{\rho\delta R_{ave}}\right)^{5/2}$	$(1-f^2)^{5/2}$
DSR, E_{hs}, $P\tau$, $T_{thermal}$	$\frac{\rho\delta R_{WHM}}{\rho\delta R_{ave}}$	$(1-f^2)$
Yield, $Y_{low-burn}$	$\left(\frac{\rho\delta R_{WHM}}{\rho\delta R_{ave}}\right)^{a}$	$(1-f^2)^a$
Y_{amp}	$\exp\left[-1.2(a-1)\chi_{1D}^{1.2}\left(1-\frac{\rho\delta R_{WHM}}{\rho\delta R_{ave}}\right)\right]$	$\exp[-1.2(a-1)\chi_{1D}^{1.2}f^2]$

O. Hurricane et al., Phys. Plasmas 29, 012703 (2022)

Neutron imaging

N181104
KC461-03



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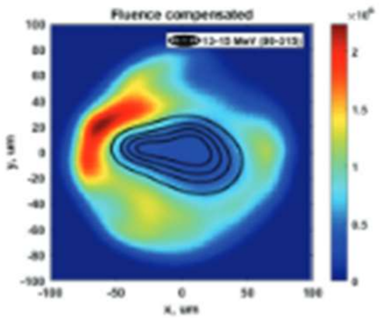
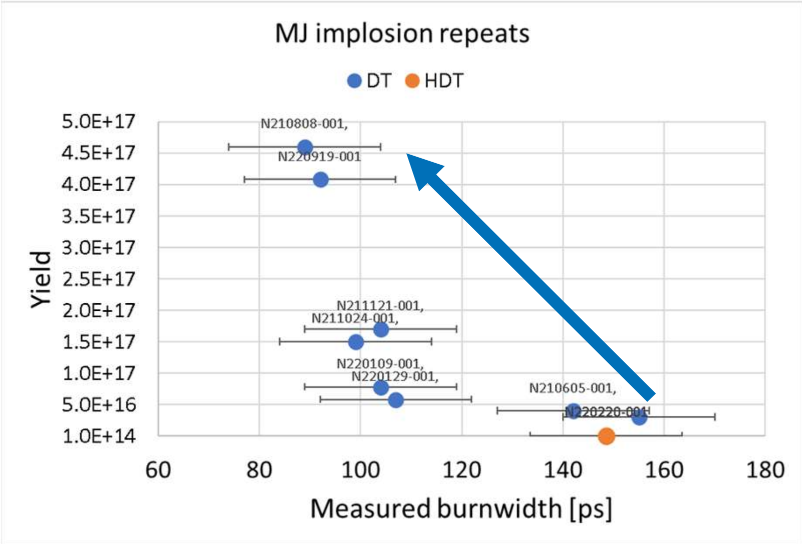
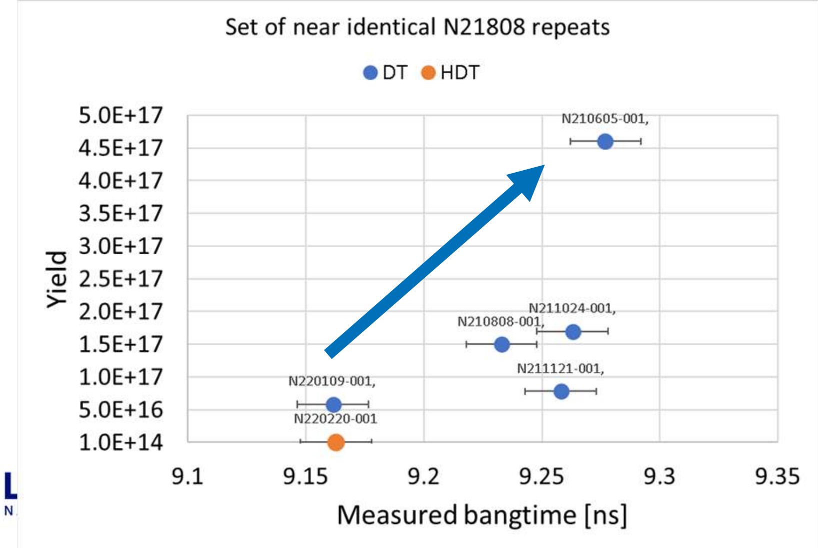


A. Zylstra et al., Phys. Plasmas 27, 092709 (2020);

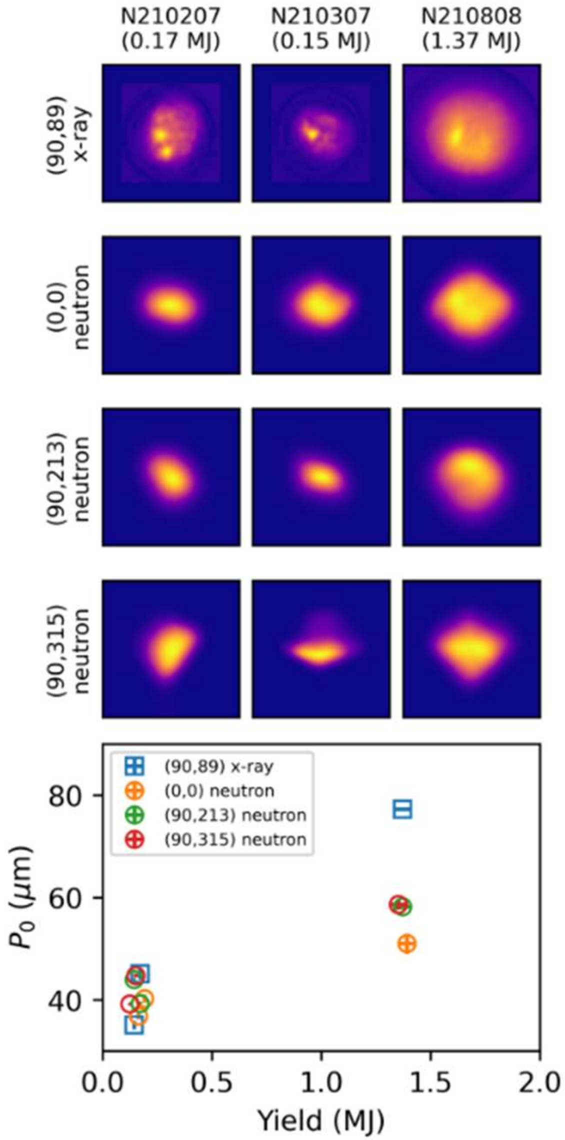
LANL nuclear diagnostics vital to confirm transition to a burning plasma

Gamma Reaction history shows the burnwidth narrow and bangtime pushed later





Neutron images show hot spot burning into the surrounding ice layer



Popular press on the achievement reference the nuclear measurements

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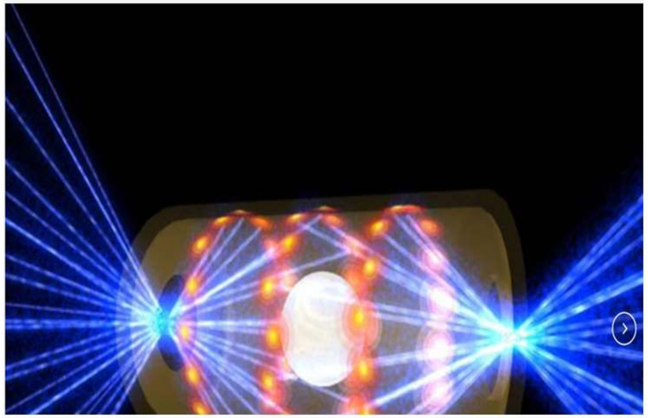
Hot stuff: Lab hits milestone on long road to fusion power

By SETH BORENSTEIN January 26, 2022



That capsule fits in a tiny gold metal can that researchers aim 192 lasers at. They heat it to about 100 million degrees, creating about 50% more pressure inside the capsule than what's inside the center of the sun. These experiments created burning plasmas that lasted just a trillionth of a second, but that was enough to be considered a success, Zylstra said.

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Disrupted

Researchers achieve milestone on path toward nuclear fusion energy

By Will Dunham

In these experiments, fusion produced about 10 times as much energy as went into heating the fuel, but less than 10% of the total amount of laser energy because the process remains inefficient, Zylstra said. The laser was used for only about 10 billionths of a second in each experiment, with fusion production lasting 100 trillionths of a second, Kritcher added.

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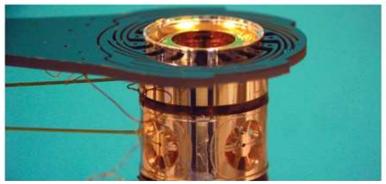
In a world first, the National Ignition Facility has generated a "burning plasma," a fusion reaction on the cusp of being self-sustaining

By Philip Ball on February 2, 2022



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- **Nuclear diagnostics have played a critical role in understanding and improving NIF performance**

- **The US has invested a decade+ into nuclear diagnostics for ICF facilities**

- **Los Alamos National Lab has focused on gamma reaction history and neutron imaging system**

- **In part due to data from nuclear diagnostics, NIF has achieved and confirmed ignition and net gain (1.5x)**

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Thank you!
Questions? Thoughts?

Further questions? Contact me: meaney@lanl.gov