Progress on inertial confinement fusion research on the National Ignition Facility

Fusion Power Associates Annual Meeting
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Weapons Physics and Design Program

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It is an exciting time for High Energy Density (HED) Science and Inertial Confinement Fusion (ICF) Research at LLNL!

- Major reviews of HED/ICF are nearly complete.
  - Highlighted importance of HED/ICF for Stockpile Stewardship Program today
  - Revalidated goal of high yield on a future capability
  - Identified opportunities for increasing the program impact
  - Importance of pursuing all 3 approaches (Laser Indirect, Laser Direct, Magnetic Direct)

- Advances in measurements are leading to much greater understanding of Inertial Confinement Fusion implosions

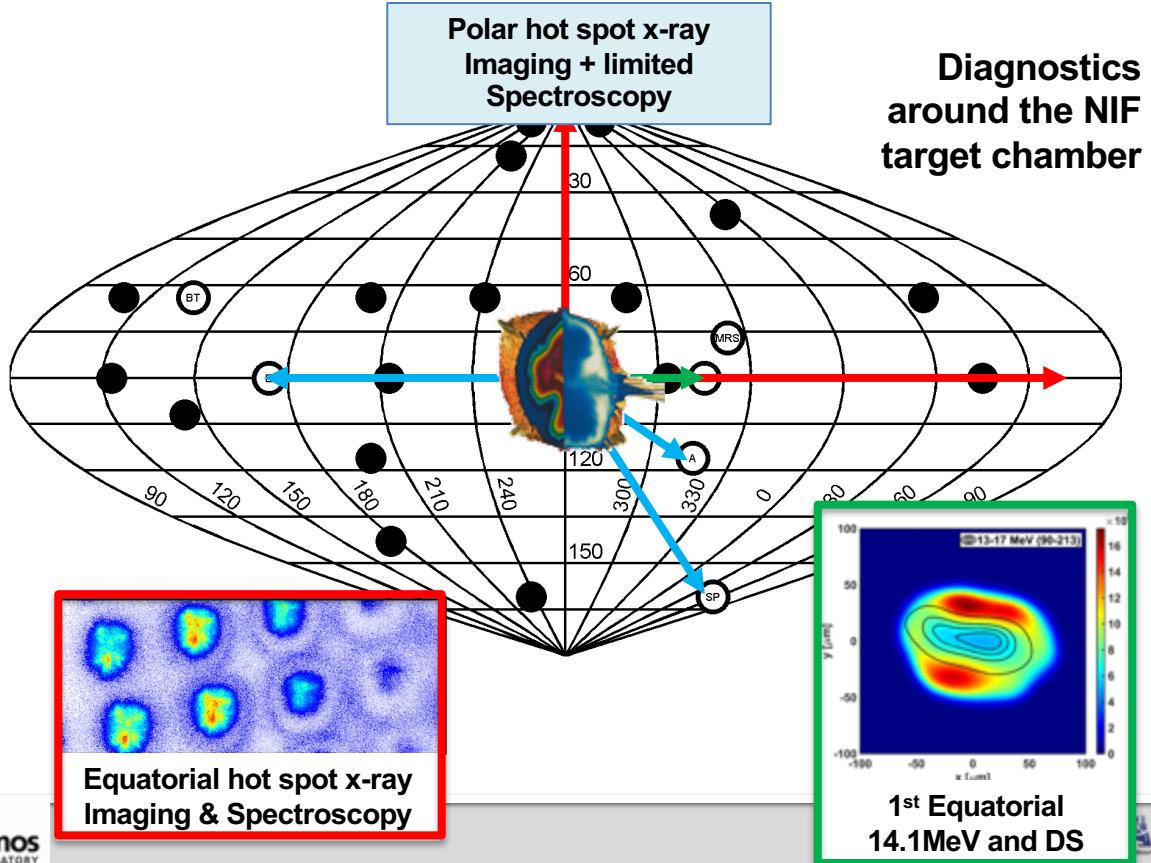
- LLNL assesses that we were about 2.5-3x in hot spot energy * hot spot pressure squared away from ignition at the time of the JASON review.

- Very recent (11/20) results have reach record performance

The 2020 process has strengthened the community partnership in ICF

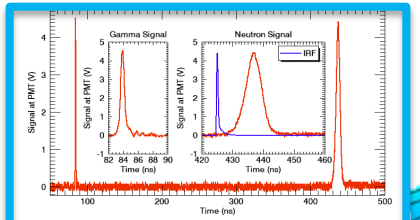
In early 2016 the diagnostics on NIF had a limited ability to diagnose 3D aspects of implosions

- Three scintillator based neutron time of flight (nToF) detectors (100ps precision)
- 17 FNAD's (Legendre mode ≤ 2) processed by hand
- 1 NIS 14.1MeV Lines of sight
- 1 NIS Down-scatter line of sight
- 2 lines of sight X-ray hot-spot shape + 1 spectroscopy LoS

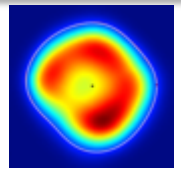


Key ICF diagnostics have been significantly advanced to greatly improve 3D diagnosis of implosions

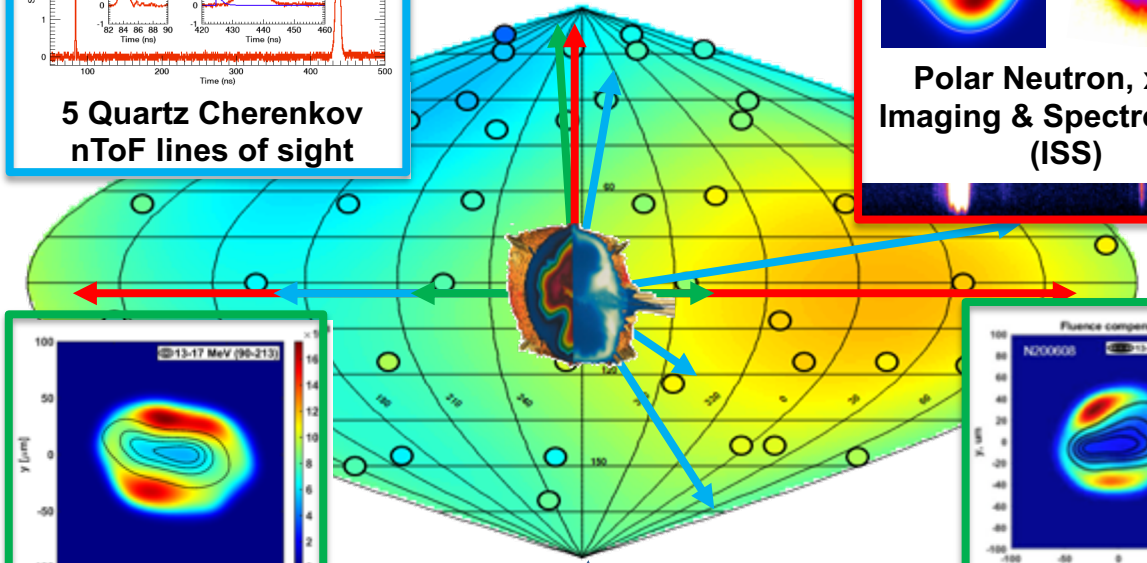
- Five scintillator and Cherenkov nToF's (20ps precision)
- 48 Real-time NAD's (Legendre mode ≤ 4) read out in real-time 24/7
- 3 NIS Lines of sight 3D reconstruction of neutron hot-spot
- 2 NIS down-scatter lines of sight
- 3 x-ray imaging lines of sight
- Tungsten x-ray spectroscopy to characterize T_e of mixed material
- 1 LoS Compton Radiography
- Crystal Backlit Imaging to measure mix at peak velocity

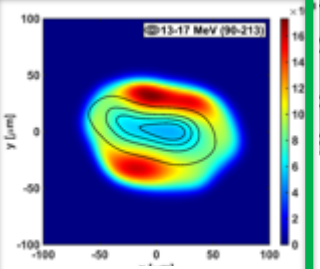


5 Quartz Cherenkov nToF lines of sight



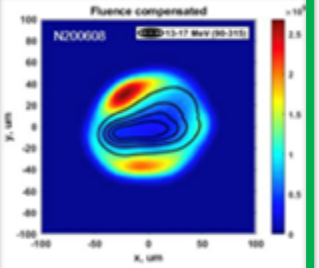
Polar Neutron, x-ray Imaging & Spectroscopy (ISS)





1st Equatorial Neutron Imager

RTNADS yield uniformity map

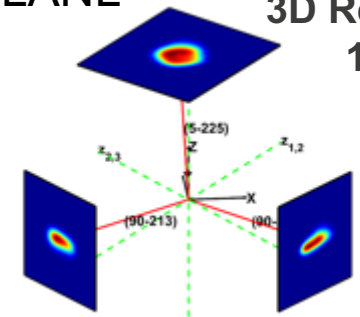


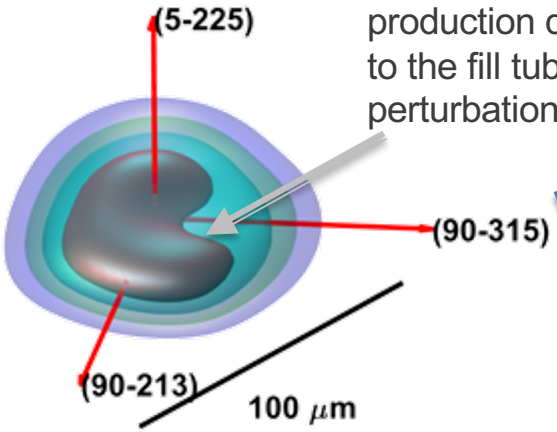
2nd Equatorial Neutron Imager

Routine 3D neutron and x-ray images reveal key features of the fusion hot spot

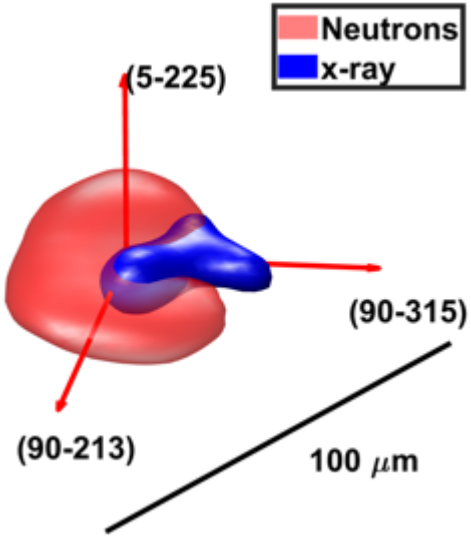
LANL

3D Reconstruction of 14.1MeV Neutron Hot-spot



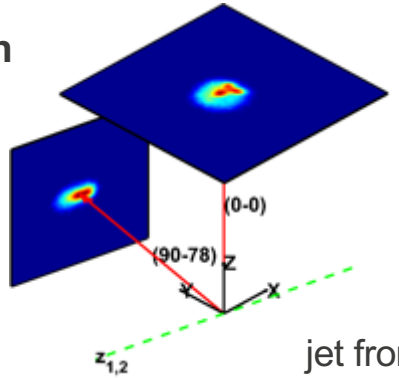


reduced neutron production due to the fill tube perturbations

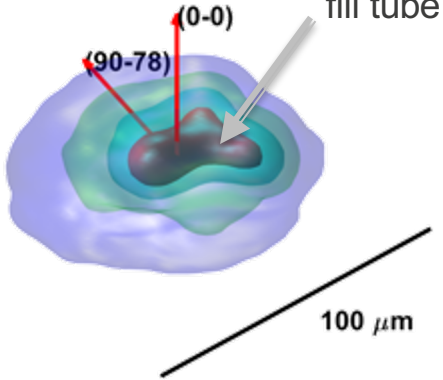


3D Reconstruction X-ray Hot-spot

LLNL

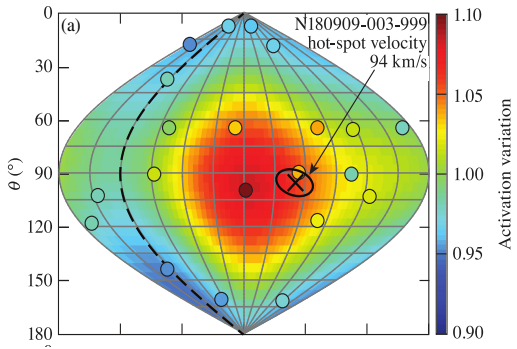


jet from the fill tube



New measurement capabilities enable improved understanding of fusion obstacles on NIF

Diagnosing shell asymmetry

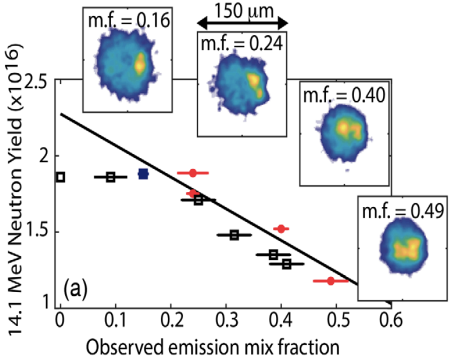



PHYSICAL REVIEW LETTERS **124,** 145002 (2020)

Azimuthal Drive Asymmetry in Inertial Confinement Fusion Implosions on the National Ignition Facility

Hans G. Rinderknecht*
Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA
D. T. Casey, R. Hatarik, R. M. Bionta, B. J. MacGowan, P. Patel, O. L. Landen,

X-ray images of hotspot mix

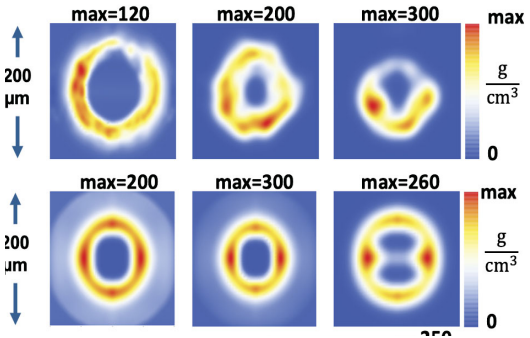


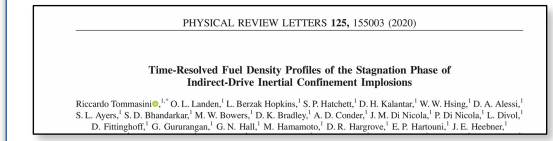

PHYSICAL REVIEW LETTERS **124,** 145001 (2020)

Impact of Localized Radiative Loss on Inertial Confinement Fusion Implosions

A. Pak,[1] L. Divol,[1] C. R. Weber,[1] L. F. Berzak Hopkins,[1] D. S. Clark,[1] E. L. Dewald,[1] D. N. Fittinghoff,[1] V. Geppert-Kleinrath,[2] M. Hohenberger,[1] S. Le Pape,[1] T. Ma,[1] A. G. MacPhee,[1] D. A. Mariscal,[1] E. Marley,[1] A. S. Moore,[1] L. A. Pickworth,[1] P. L. Volegov,[2] C. Wilde,[2] O. A. Hurricane,[1] and P. K. Patel[1]
[1]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*

Diagnosing fuel at stagnation




PHYSICAL REVIEW LETTERS **125,** 155003 (2020)

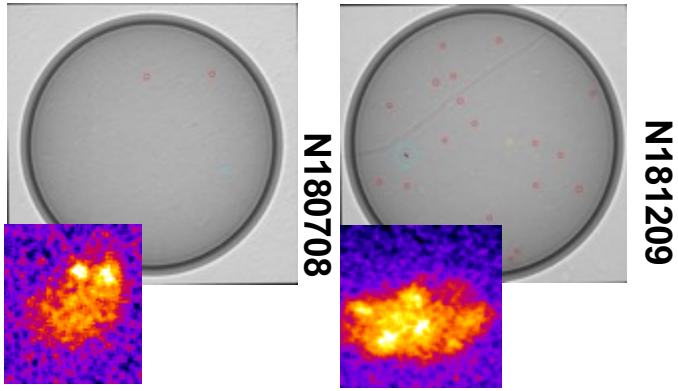
Time-Resolved Fuel Density Profiles of the Stagnation Phase of Indirect-Drive Inertial Confinement Implosions

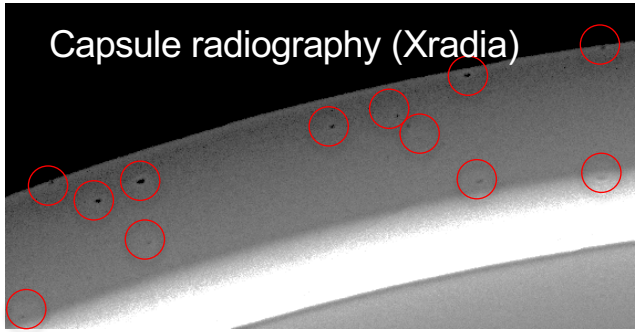
Riccardo Tommasini,[1,*] O. L. Landen,[1] L. Berzak Hopkins,[1] S. P. Hatchett,[1] D. H. Kalantar,[1] W. W. Hsing,[1] D. A. Alessi,[1] S. L. Ayers,[1] S. D. Bhandarkar,[1] M. W. Bowers,[1] D. K. Bradley,[1] A. D. Conder,[1] J. M. Di Nicola,[1] P. Di Nicola,[1] L. Divol,[1] D. Fittinghoff,[1] G. Gururangan,[1] G. N. Hall,[1] M. Hamamoto,[1] D. R. Hargrove,[1] E. P. Hartouni,[1] J. E. Heebner,[1]

Advances in understanding have led to improved target metrology, improved capsule selection, and improvements to the laser, enabling better implosion performance

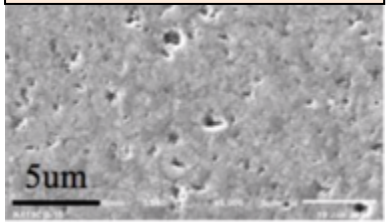
At the same time tremendous progress has been made in metrologizing and mitigating defects in diamond capsules

Capsule radiograph during layering

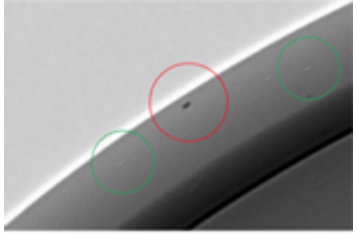




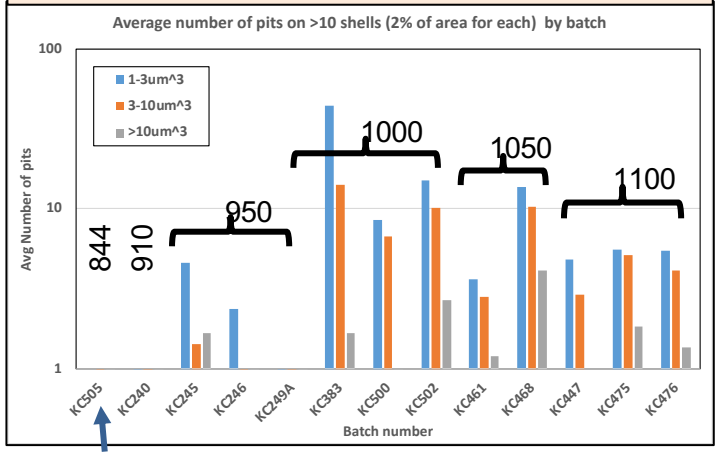
HDC pits on outer surface



HiZ and void in wall



Average number of pits on >10 shells



New batch!

- **Both pits and voids are of concern from a physics perspective**

Tremendous progress in metrologizing and mitigating these defects has been made over the last 2 years, experiments with improved capsules will take place in CY21

As part of the 2020 review, we have applied many different tools to infer our proximity to ignition, but all rely on extrapolation

- Simple hot spot models (ρr, T)
- 3D post shot simulations scaled to ignition
- Generalized Lawson Criterion, $P\tau/P\tau_{ign}$/ simulation based scaling laws
- Experimentally tuned Machine Learning models

R. Betti, Phys. Plasmas 17, 058102 (2010)
B. K. Spears, Phys. Plasmas 19, 056316 (2012)
J. D. Lindl, Phys. Plasmas 25, 122704 (2018)
P. K. Patel, Phys. Plasmas 27, 050901 (2020)
P. T. Springer, Nucl. Fusion 59, 032009 (2019)
O. A. Hurricane, Phys. Plasmas 26, 052704 (2019)
D. S. Clark, Phys. Plasmas 26, 050601 (2019)
J. A. Gaffney, Phys. Plasmas 26, 082704 (2019)


Laser Indirect Drive input to NNSA 2020 Report

Our net assessment based on several metrics was that we must increase the energy in the hot spot and the pressure of the hot spot squared by ~2.5-3x

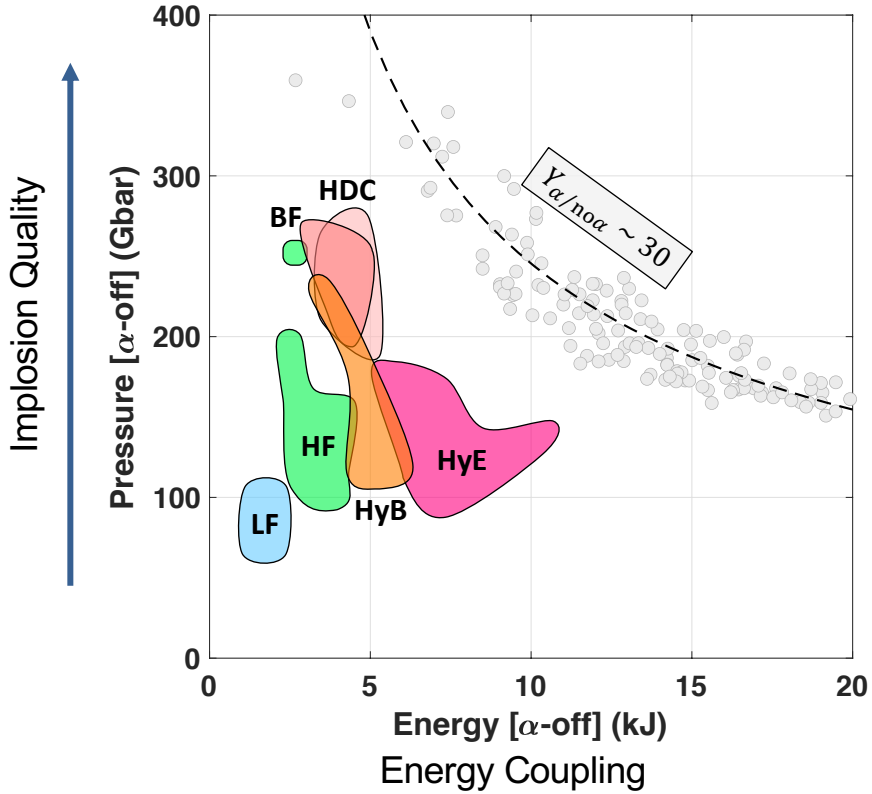


Figure of Merit ~ $E_{HS}P_{HS}^2 \sim (\rho R)^3 T^3$

LLNL's assessment is that we were a factor of 2.5-3x below the ignition threshold in this metric at the time of the review

We've increased $E_{HS}P_{HS}^2$ by ~30 since NIF experiments started and had a factor of 2.5-3X to go.

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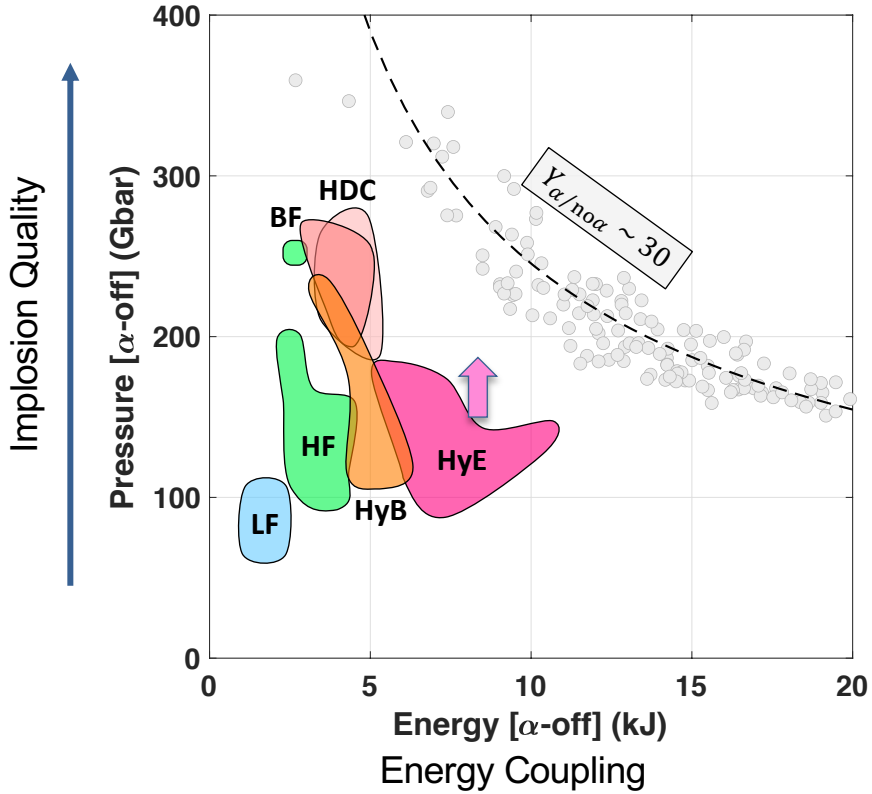

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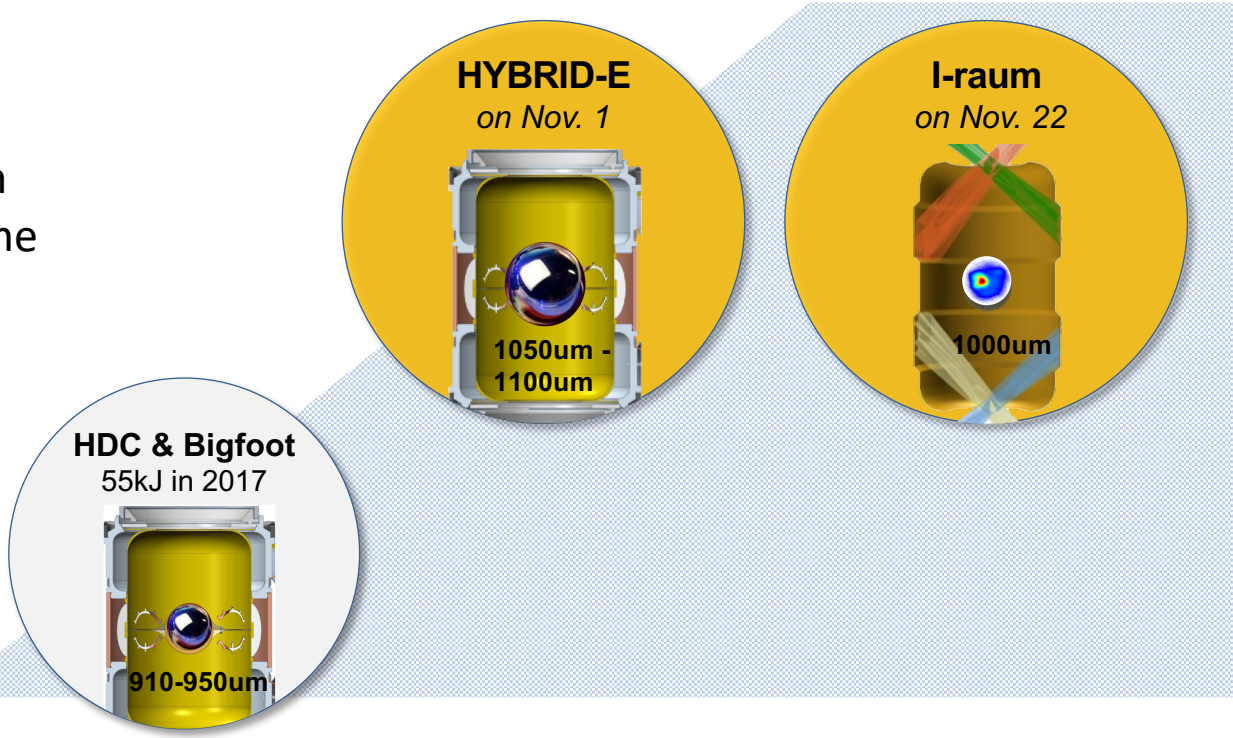
Recent (11/20) experiments have closed the gap, but analysis is ongoing

By building on this improved understanding and improved targets we've recently obtained record NIF yields

- HYBRID-E & I-raum implosions achieve record performance putting them closer to the ignition regime
- Both benefited from improved understanding, target fabrication and metrology of diamond capsules
- Both have significant features that degraded performance



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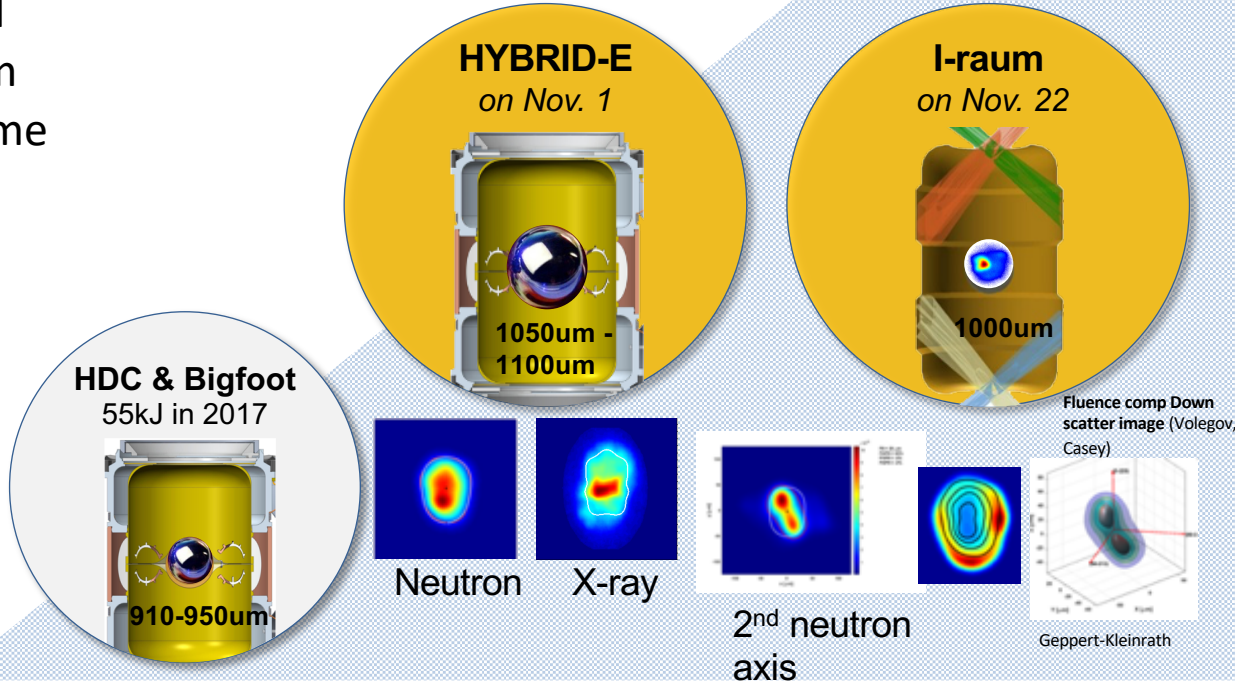
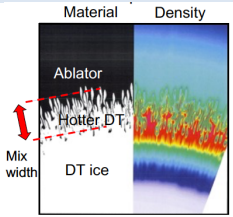
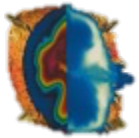


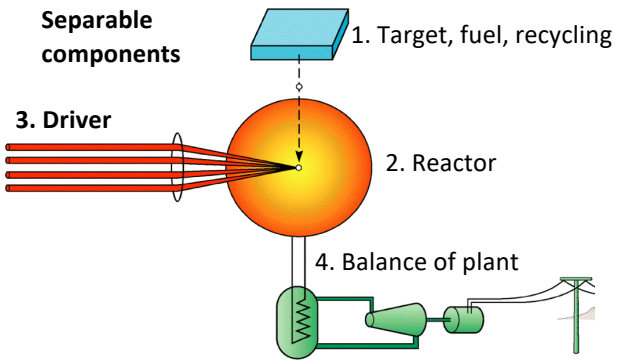
We will have additional opportunities to test these platforms in the spring

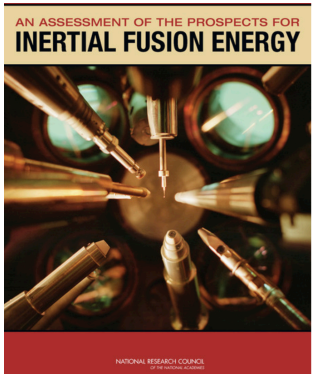
We've organized our program around these 3 goals while awaiting feedback from the NNSA 2020 review and the JASON review

Reduce the gap to ignition while advancing our predictive capability		
Goal	Enables	
Understand the limits of **compression**		Increasing pressure of stagnated fuel
Understand the limits of **coupling**		Increasing energy of stagnated fuel
Advance **simulation** tools	Hohlraum Model   Capsule Model	Improving predictive capability

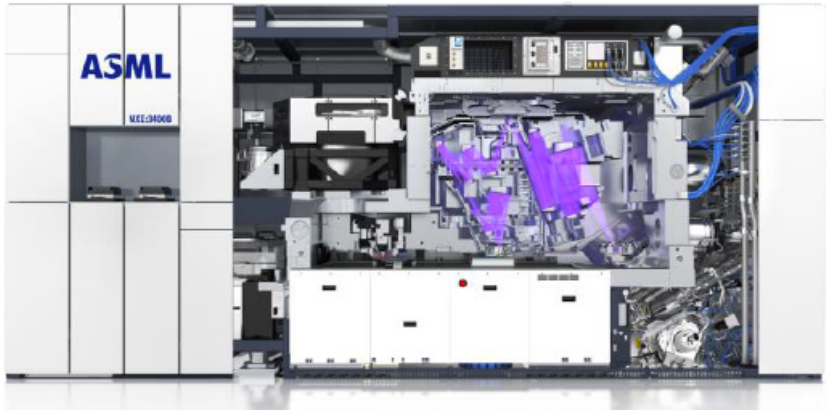
We are delighted to see inertial fusion energy recognized as an important goal in the recent planning process

- U.S. has made major investments in world leading capabilities, significant investments now in other countries
- Pursuit of Inertial Fusion Energy has played a key role in the history of this program
- IFE has very different risks/rewards compared with MFE
- IFE, like MFE, is a multi-decadal endeavor, requires innovation to enable economical energy source. Program would greatly add to our
  - Scientific capabilities
  - Innovation
  - HED research foundations
  - Workforce development
- Having no effort means we are unprepared for breakthroughs either in the US or elsewhere
- Strong support from stakeholders
- Rep-rated drivers are a key enabling technology with many potential spin off benefits (e.g. HAPLS Rep-rated PW laser)





EUV Lithography commercial systems demonstrate many of the elements of an eventual IFE powerplant



Dozens now operating ($120M per)
5M+wafers made
25+year development timeline
Advances in:
Laser, targets, x-ray optics,debris, precision alignment, …….

	EUVL	IFE
High Average Power laser	40 kW 10.6 μm	10-30 MW 200-500 nm
High Rep Rate Targets	30 μm tin 50 kHz	Ignition target 10 Hz
Harsh Environment (X-rays and Debris)	250W x-ray, 5 mg/sec, vacuum/gas	200 MW x-ray, 800 MW neutron, 10 g/sec
Long Lifetime Optics	Gigashot	Gigashot+

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  - Identified opportunities for increasing the program impact
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