Achieving Fusion Ignition on the National Ignition Facility

National Academy of Sciences

Board of Physics and Astronomy 2023 Spring Meeting

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Sandia National Laboratories · Los Alamos National Laboratory · UR LLE · General Atomics · Diamond Materials Advanced Diamond Technologies · NNSA National Nuclear Security Administration

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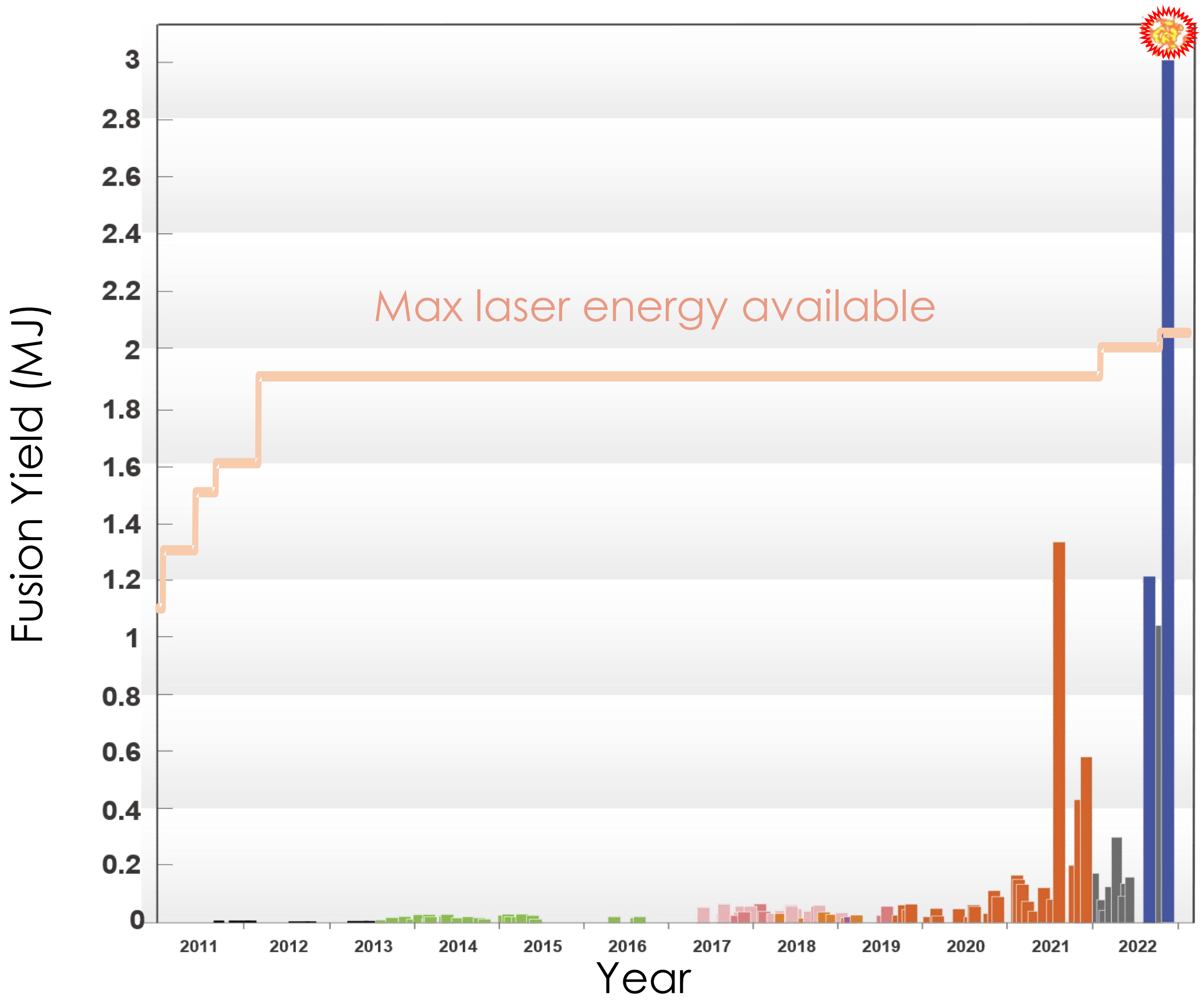
Lawrence Livermore National Laboratory

In an experiment on 12/5/2022, **NIF exceeded the threshold* for fusion ignition**

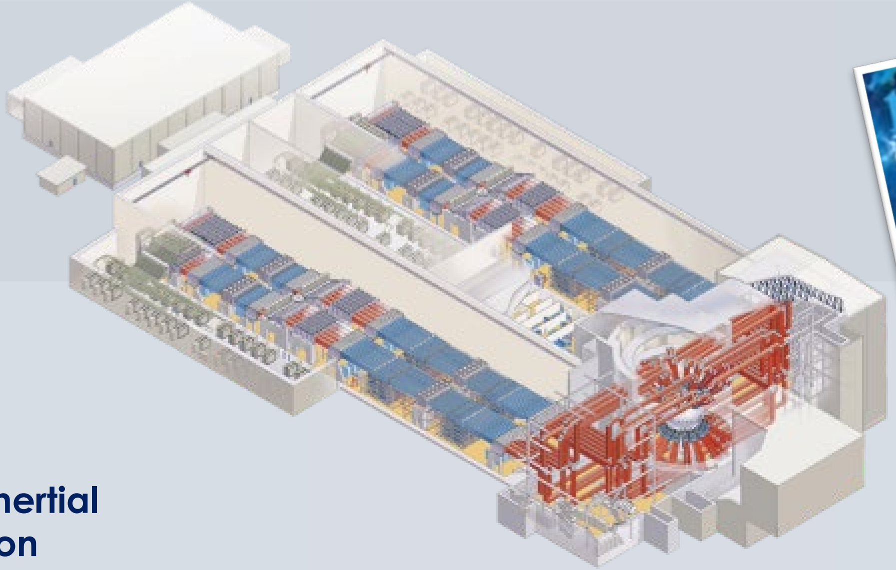
… reaching a goal that had been laid out at the beginning of the stockpile stewardship program, enabling access to a new experimental regime to help sustain our nuclear deterrent, and reenergizing the effort to explore inertial fusion as a path to carbon free energy



*National Academy of Sciences 1997 definition for ignition

Six decades of innovation

John Nuckolls



First concept of inertial confinement fusion

Invention of the laser

Janus laser (0.2 kilojoules)

Argus

Shiva

Nova (30 kilojoules)

National Ignition Facility receives funding as part of SBSSP

National Ignition Facility operations (1,900 kilojoules)

1.3 MJ 08/08/21

3.15 MJ **12/05/22**

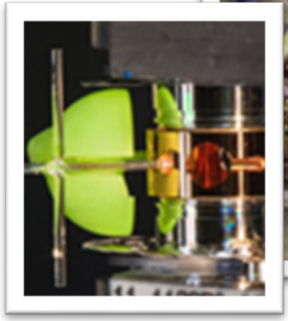
1960 1970 1980 1990 2000 2010 2020

End of underground nuclear tests

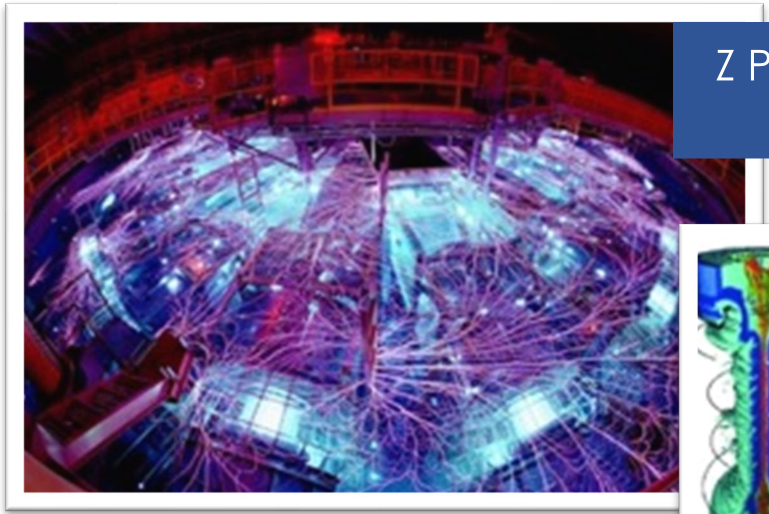
Science-based Stockpile Stewardship

NNSA's Inertial Confinement Fusion Program is a national effort to study HED matter in support of the Stockpile Stewardship Program

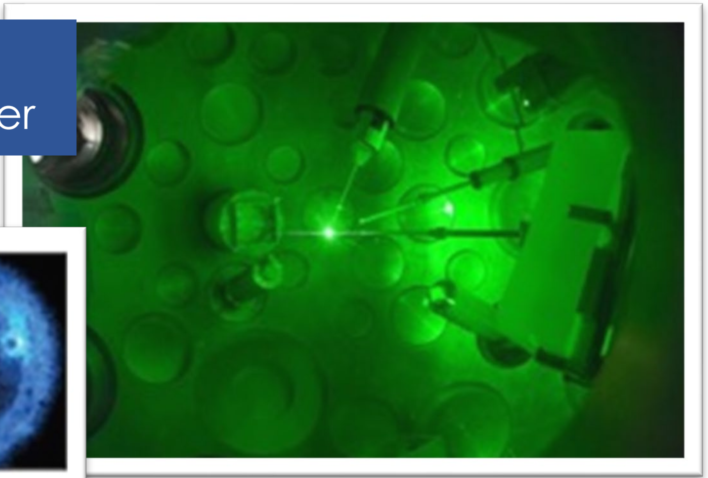
National Ignition Facility at LLNL

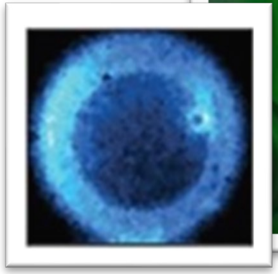


Z Pulsed Power Facility at SNL



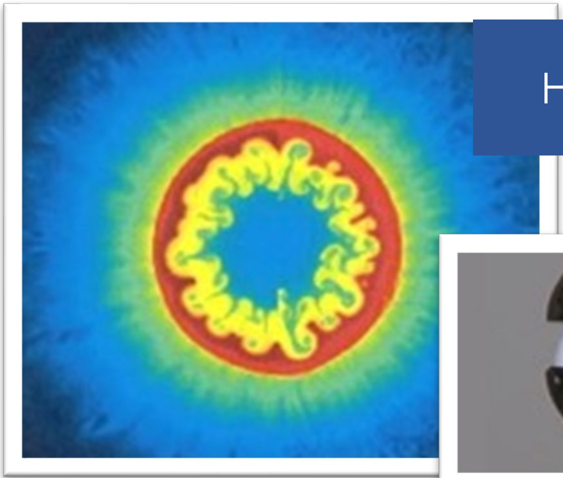
Omega Laser at University of Rochester



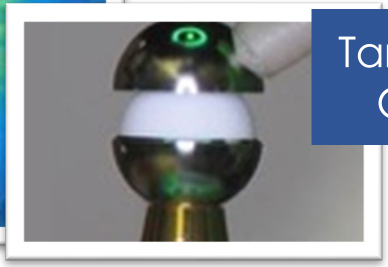


These facilities came online in 2007-2009

HED Physics at LANL



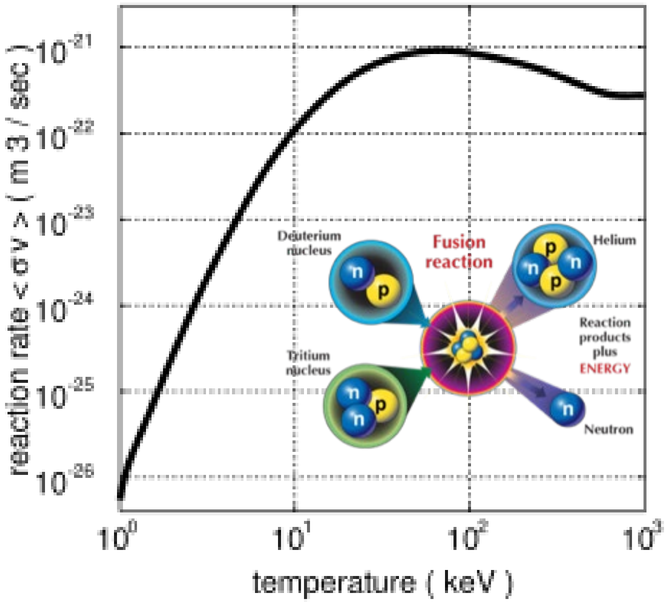
Target fabrication at General Atomics

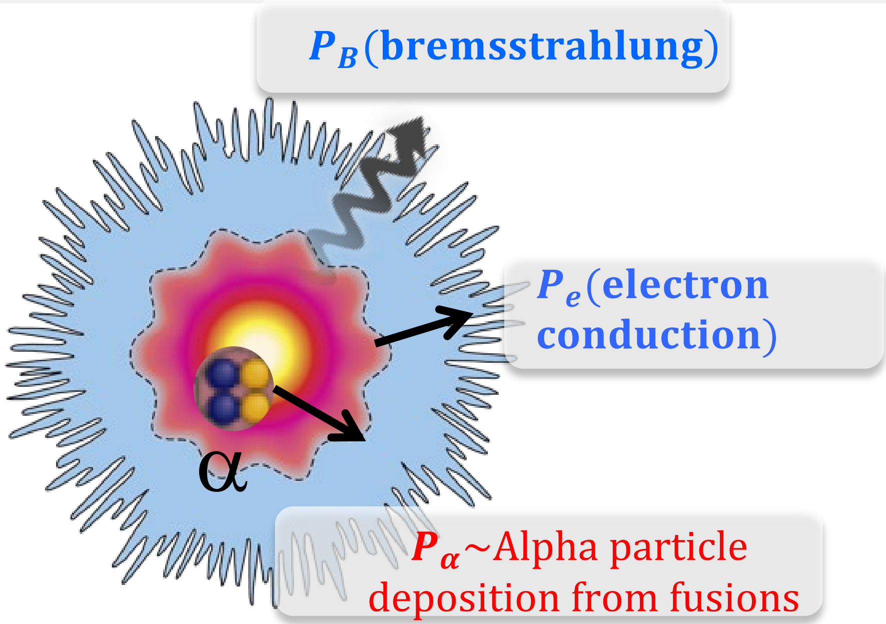


NIF, the world's most energetic laser, concentrates 192 laser beams into ½" scale targets to recreate the conditions in nuclear weapons

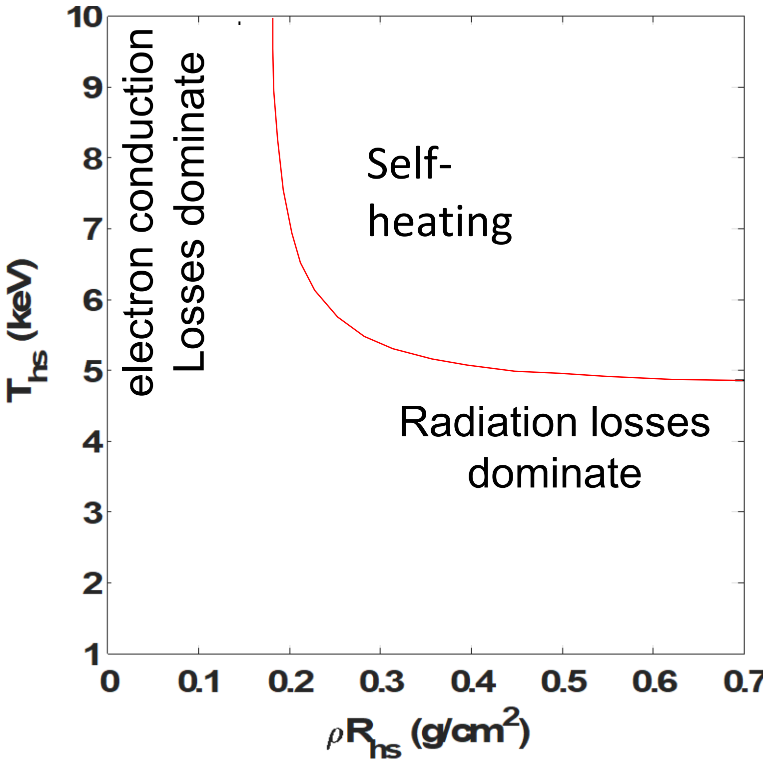
One of NIF's goals is to study fusion ignition of deuterium and tritium fuel, a key process in our thermonuclear weapons. The conditions required are extreme!

DT Fusion rate increases rapidly with temperature





$$c_{DT}\frac{dT}{dt} = f_\alpha P_\alpha - f_B P_B - P_e - \frac{1}{m} p \frac{dV}{dt}$$



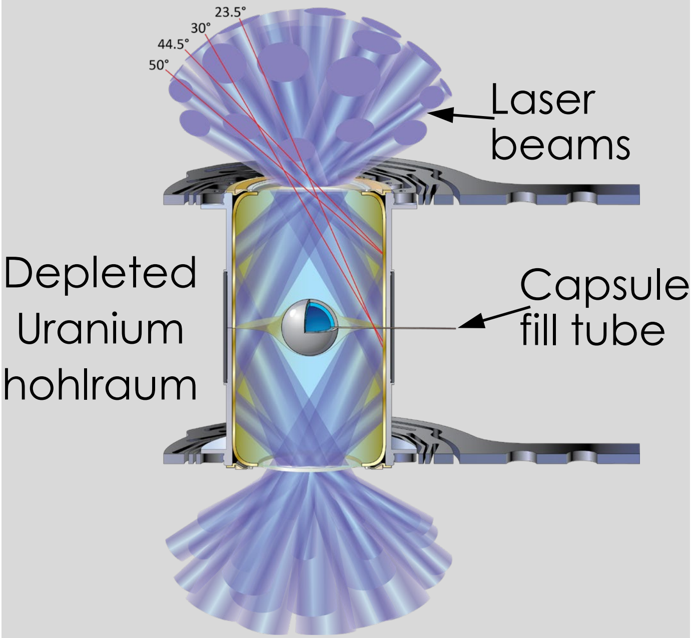
For self heating $\rho R \gtrsim$ 0.3 gm/cm^2, T $\gtrsim$ 5 keV

$$E_{HS} P_{HS}^2 \propto (\varrho_{HS} R_{HS})^3 T_{HS}^3$$

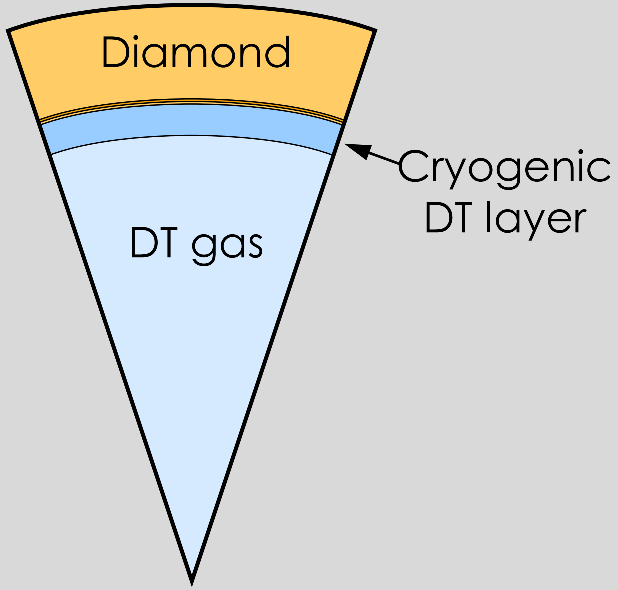
E_{HS}~25 kJ
P_{HS}~ 300 Gigabars!!

The ignition experiments were done using laser indirect drive

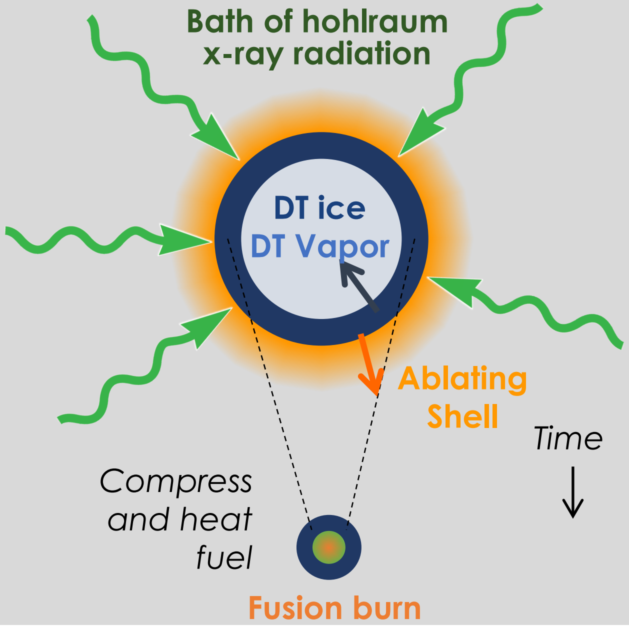
The Hohlraum is a Cylindrical Cavity that Serves as an X-ray Oven



The Fuel Capsule Consists of an Ablator Surrounding DT Ice and Gas

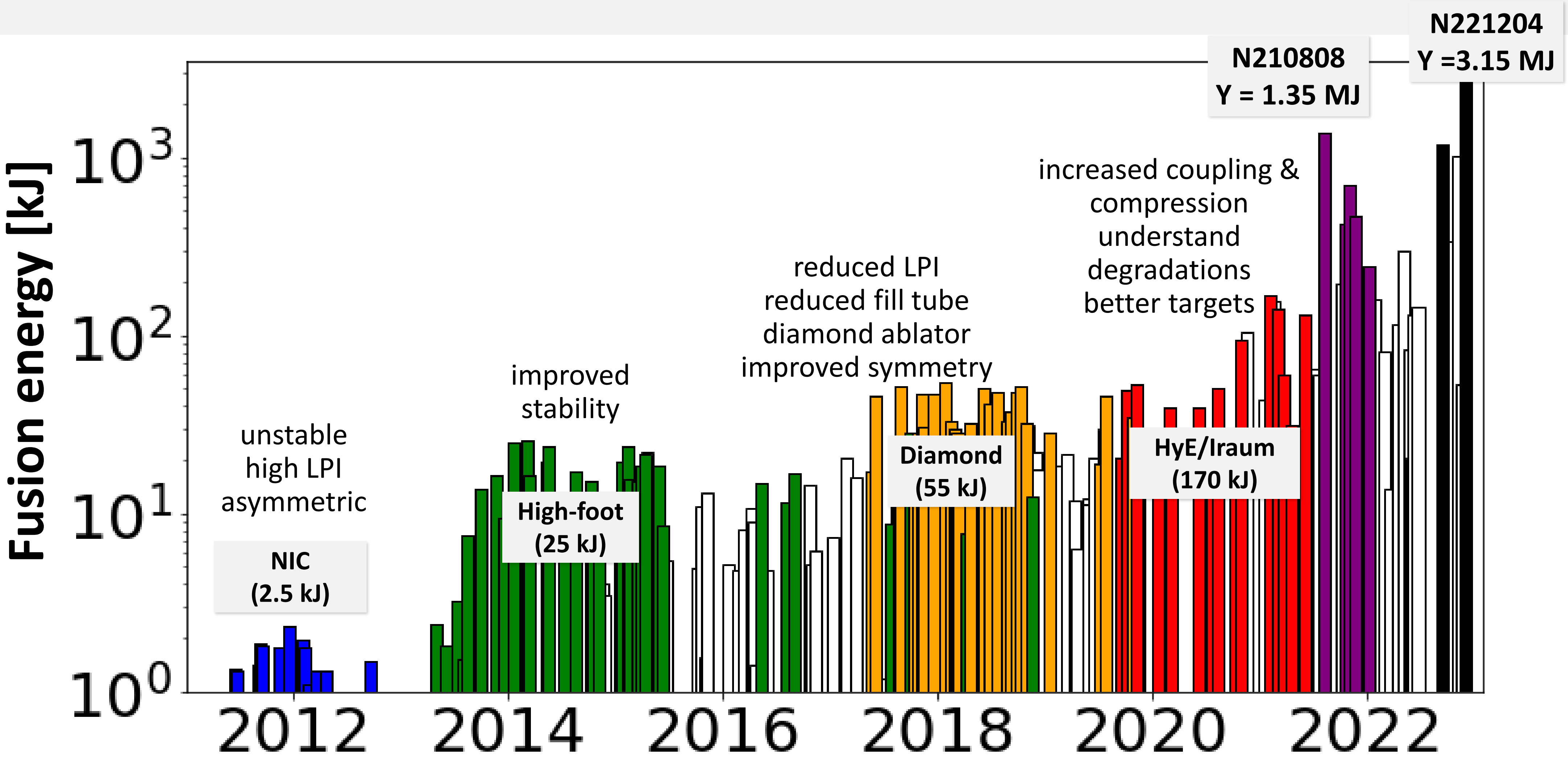


Turn 100 Million Atmospheres of Pressure into 300 Billion

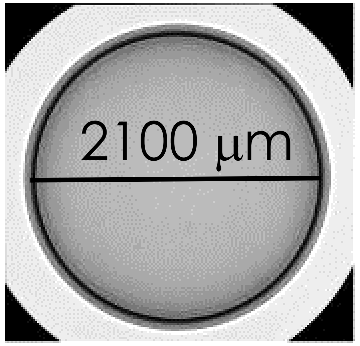


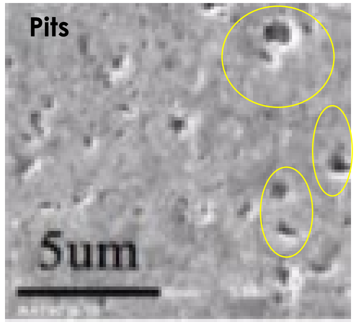
Achieving the conditions for ignition demands precise control of laser and target parameters for a high convergence implosion with low ablator fuel mix

These tools enabled steady advances in physics understanding and understanding, culminating in ignition (target gain >1) on Dec. 5th, 2022

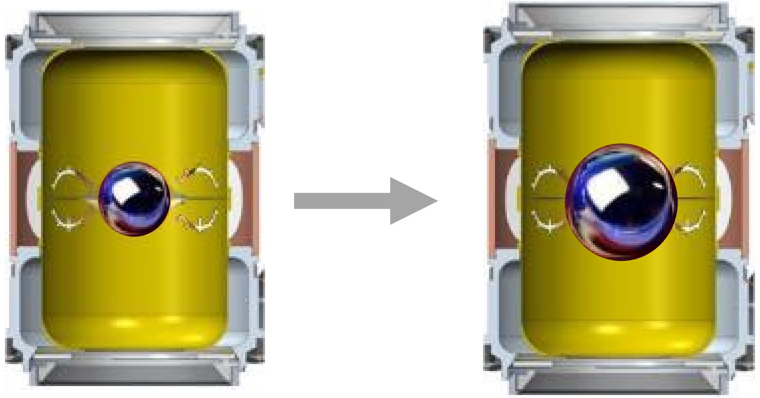


Spurred on by advances in diagnostics, targets, the NIF laser, and target designs progress accelerated in 2021





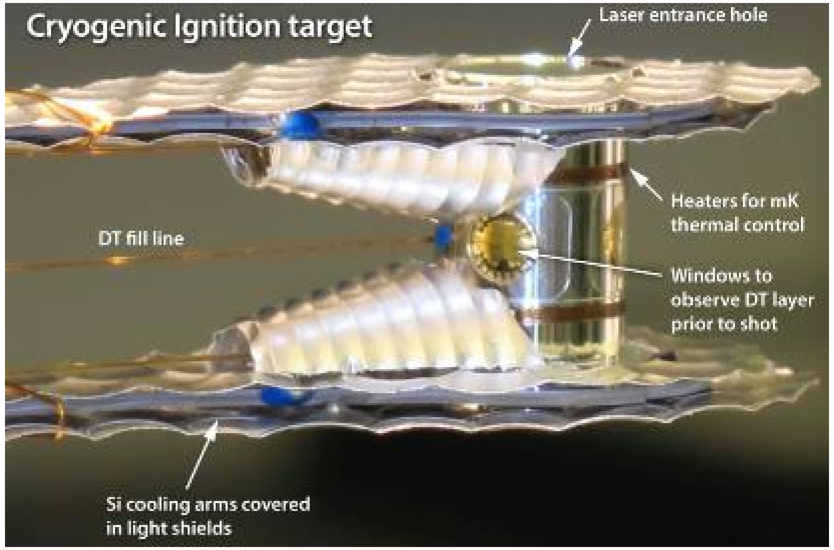
HDC & Bigfoot **HYBRID-E**



- Target Fabrication
- Laser
- Diagnostics
- Improved Simulations
- Design Changes

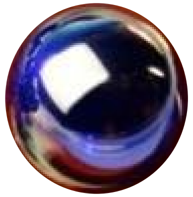
Targets require state-of-the-art microfabrication precision

Gold-lined uranium hohlraum



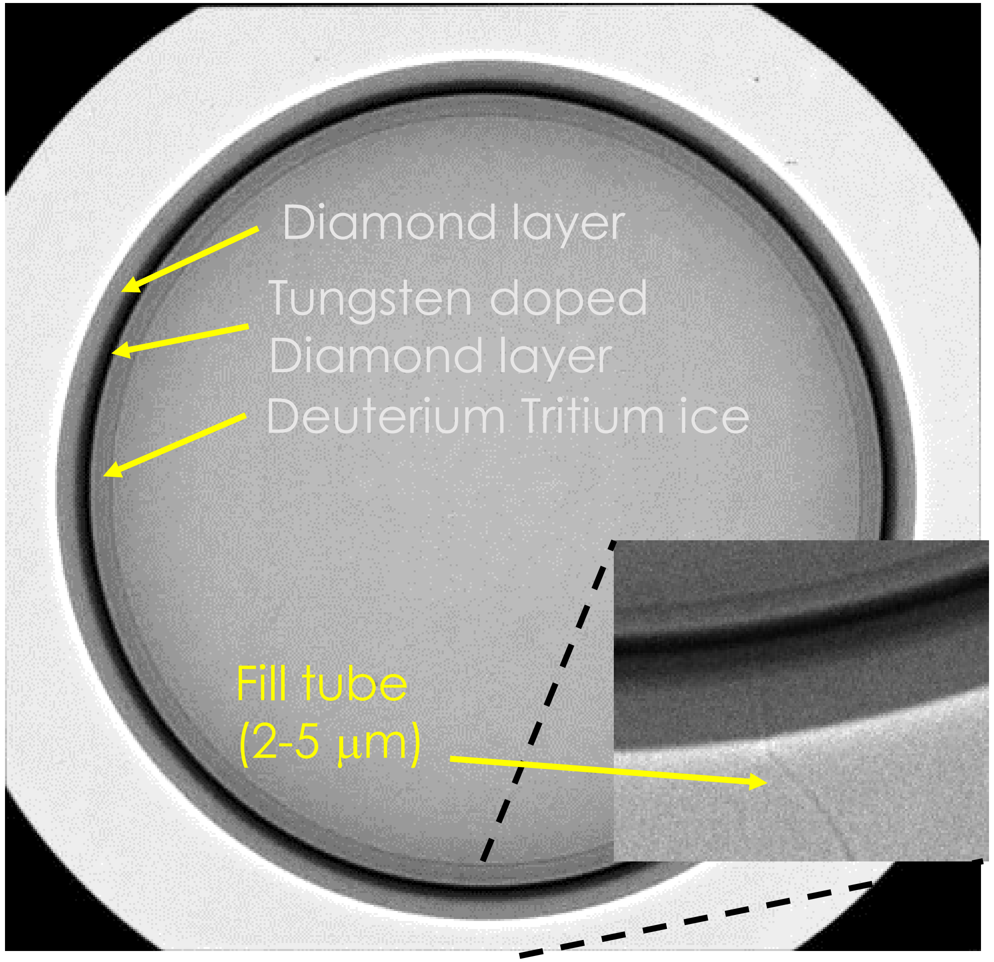
~ 1 cm long
Cryogenically cooled
w/ dozens of components

Diamond Nanocrystalline Capsule
(High Density Carbon – HDC)

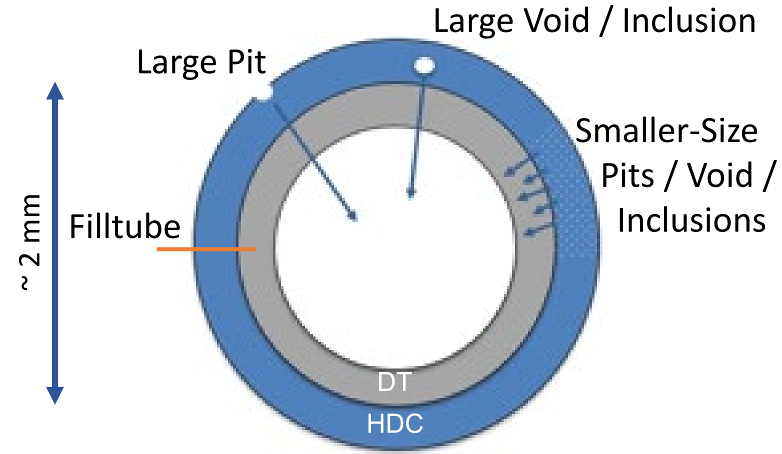


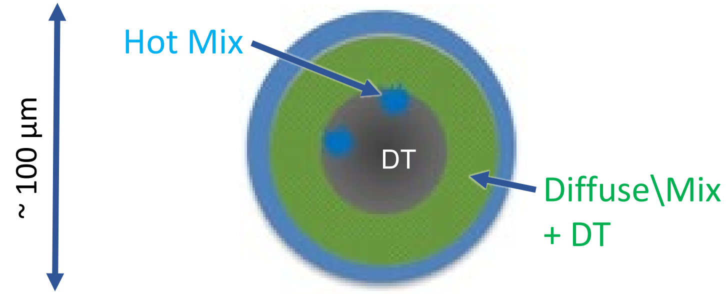
≈ 2 mm diameter,
smooth to 10 nm

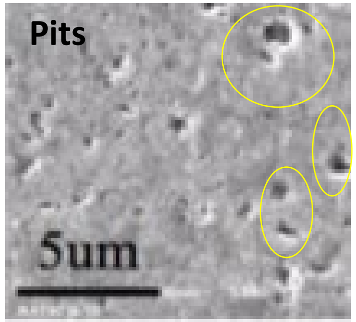
Capsule with DT layer @ 19 K

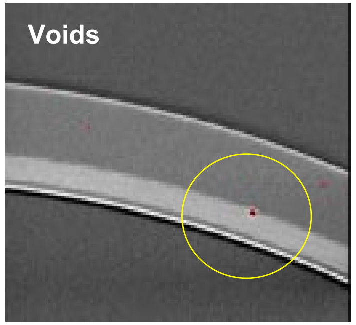


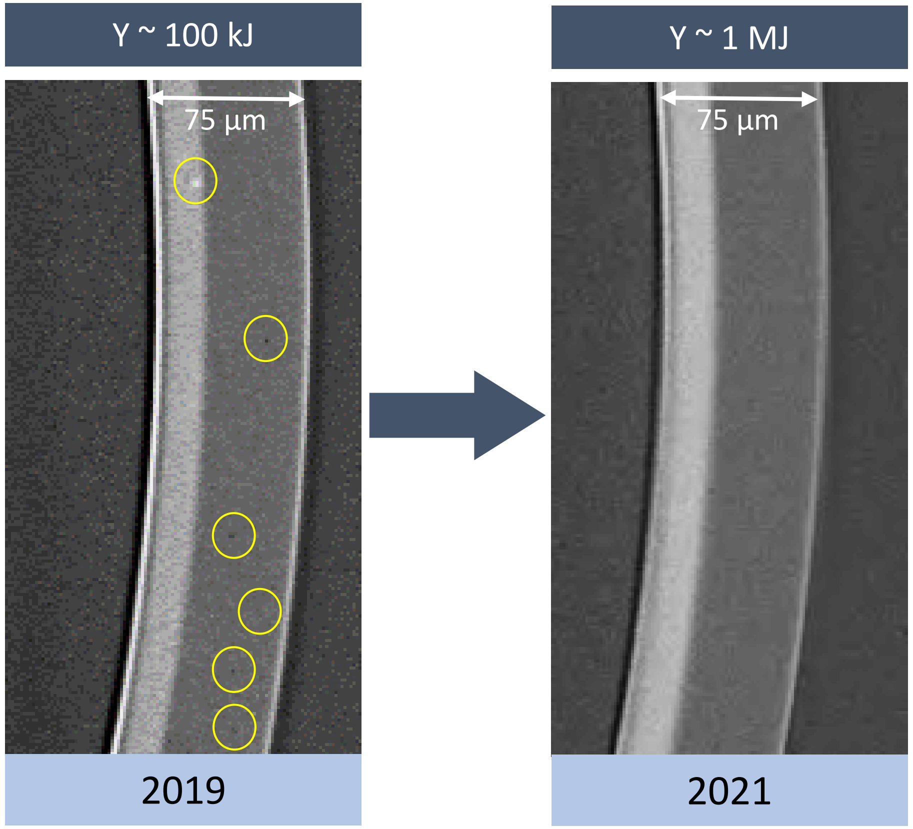
Substantial improvements in target quality and metrology in the past three years are a key component of recent advances





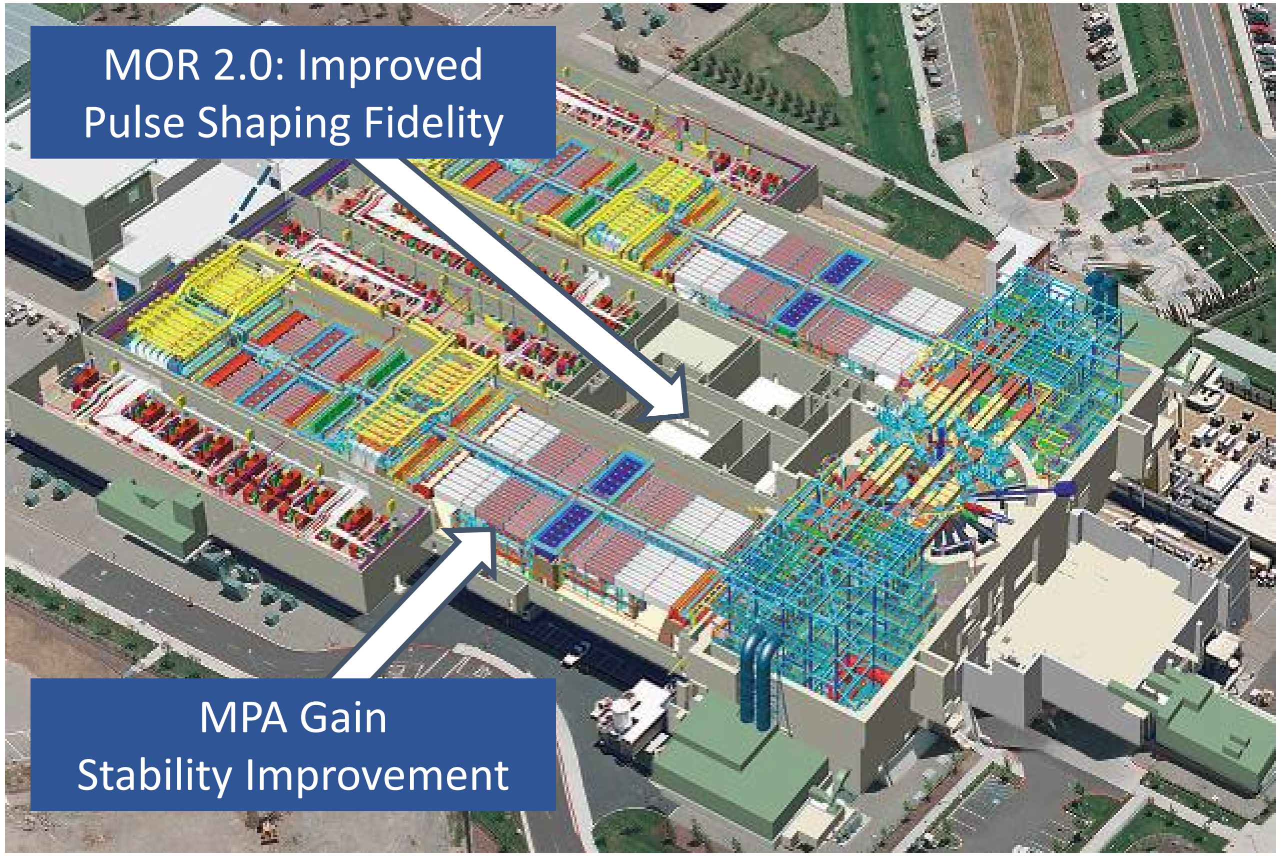


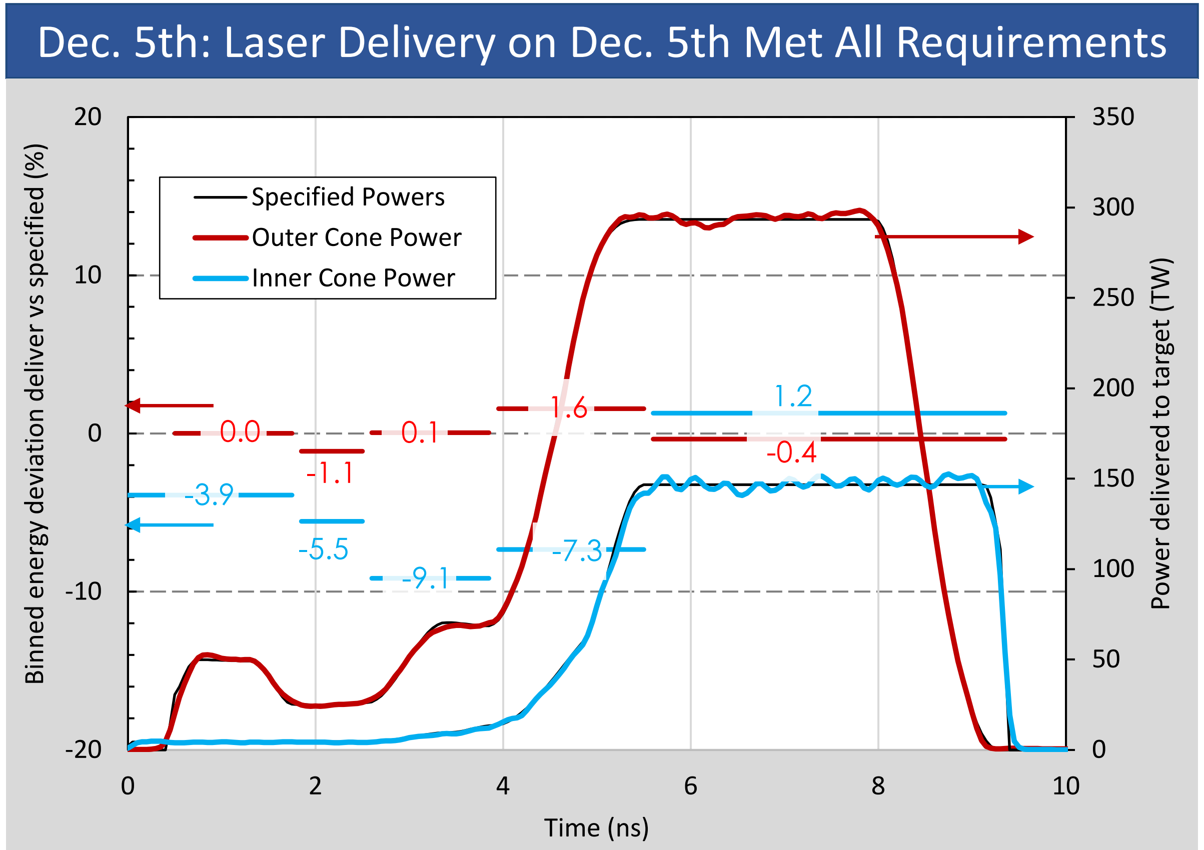




Current capsule quality has 100x reduction in pits and voids compared with pre- 8/2021 but the processes are not robust

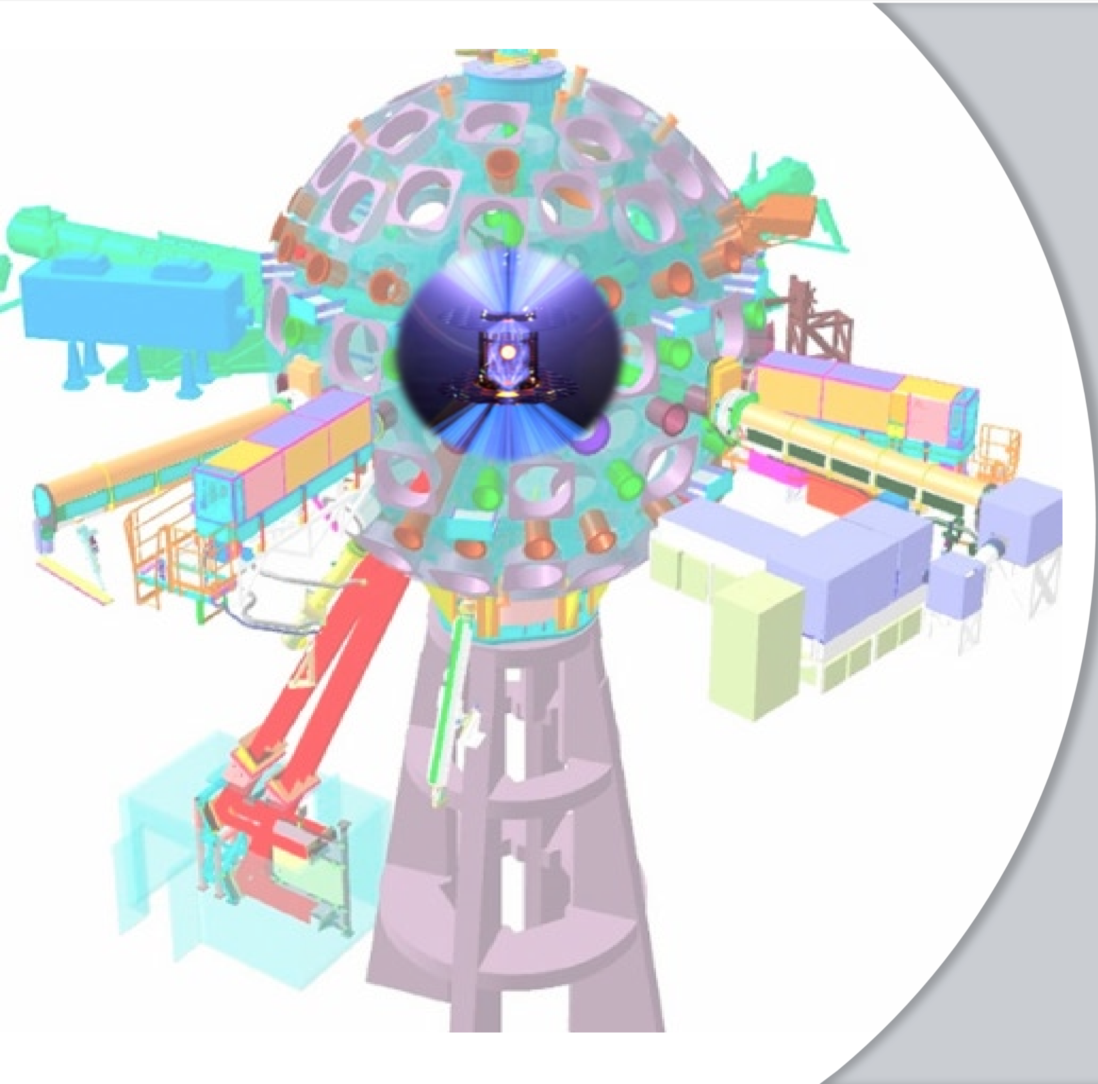
Significant improvements were made to the NIF laser to improve precision pulse shaping, power balance, and the total laser energy



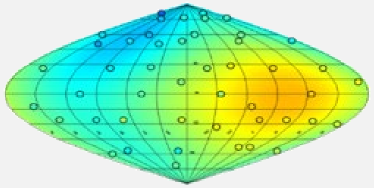


The NIF laser delivers requested energy within a 50 µm pointing, 30 ps timing, and a few % of power accuracy to provide the required conditions for ignition

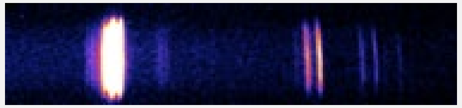
Diagnostics provided key insights into fusion degradation mechanisms



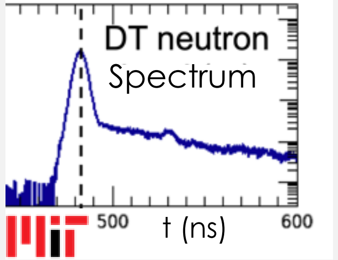
Yield / Fuel Uniformity



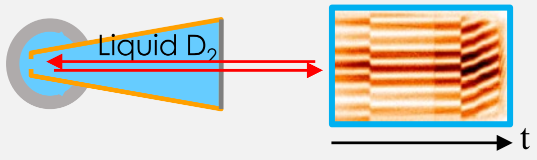
Hot Spot Electron Temperature and Impurities



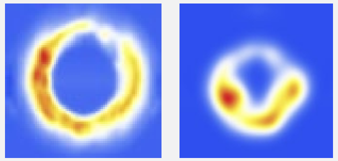
Ion Temperature, Hot Spot Velocity, Fuel Areal Density, Yield



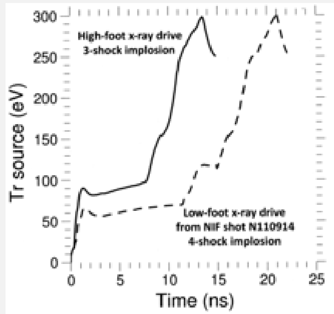
Shock Speeds, Timing



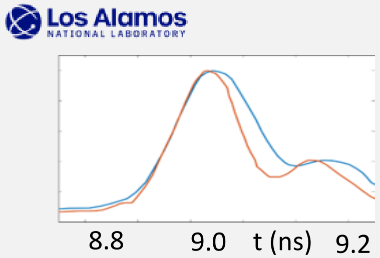
DT* Fuel Uniformity



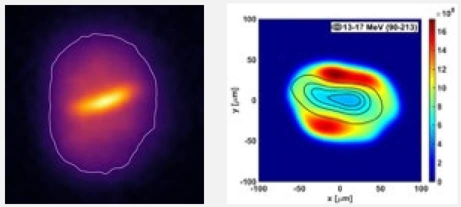
Hohlraum Radiation Flux



Burn Width, Bang Time

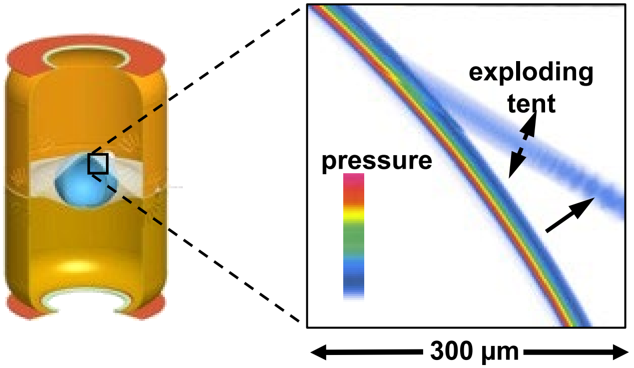


Hot Spot and Fuel Shape

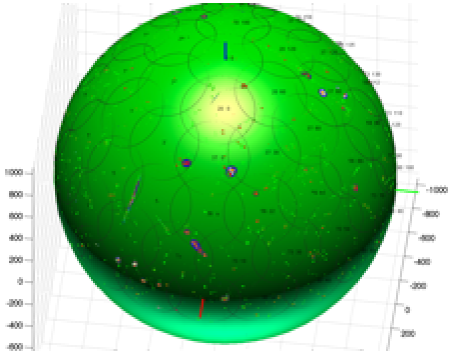


High fidelity simulations are an essential tool for navigating the vast parameter space and understanding potential degradations

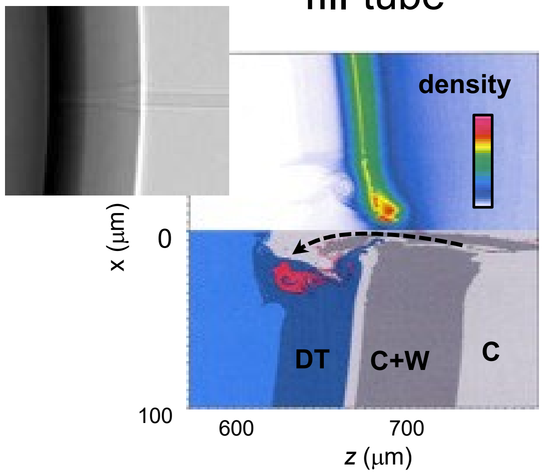
support tent



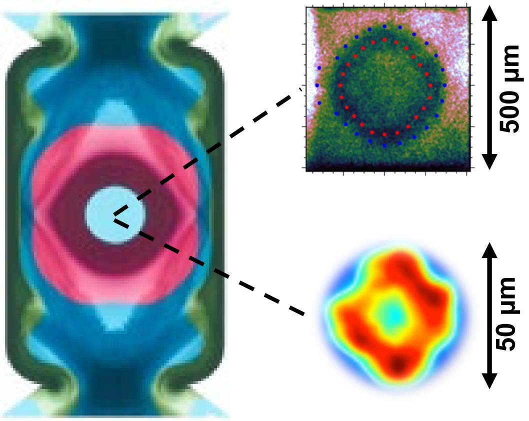
3-D surface metrology



fill tube

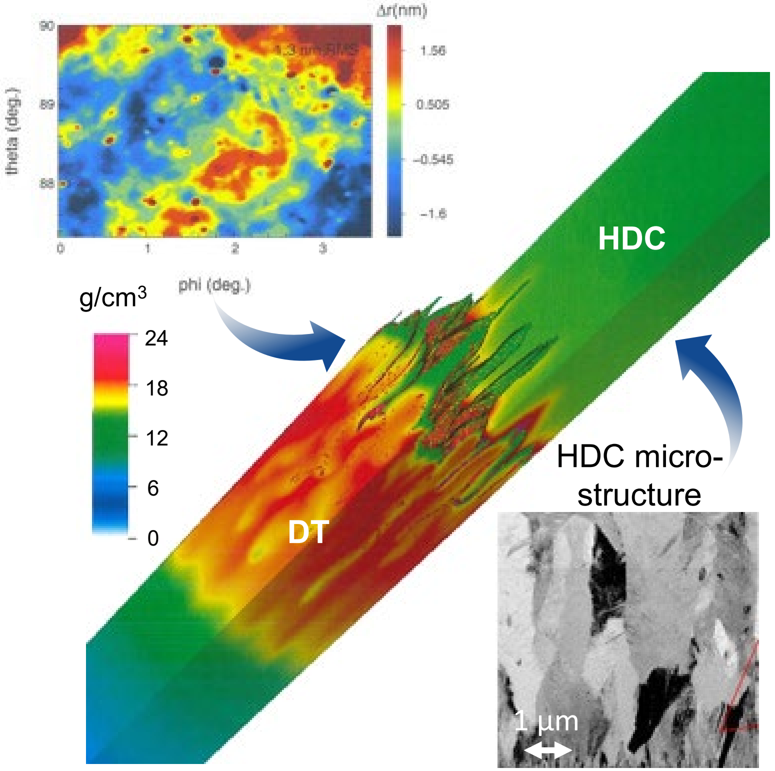


x-ray flux asymmetries



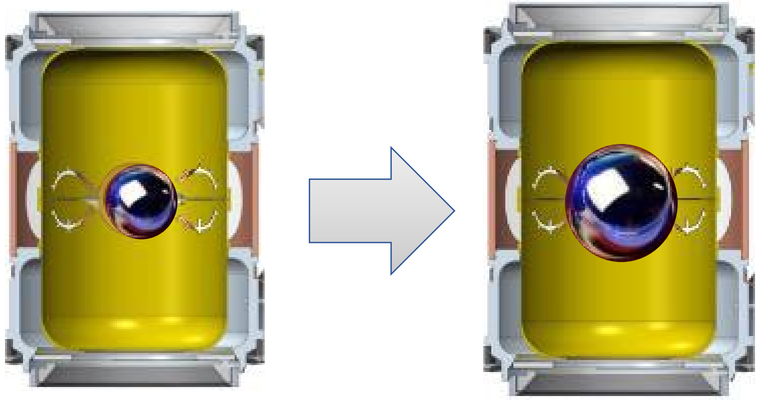
high-mode interface mix

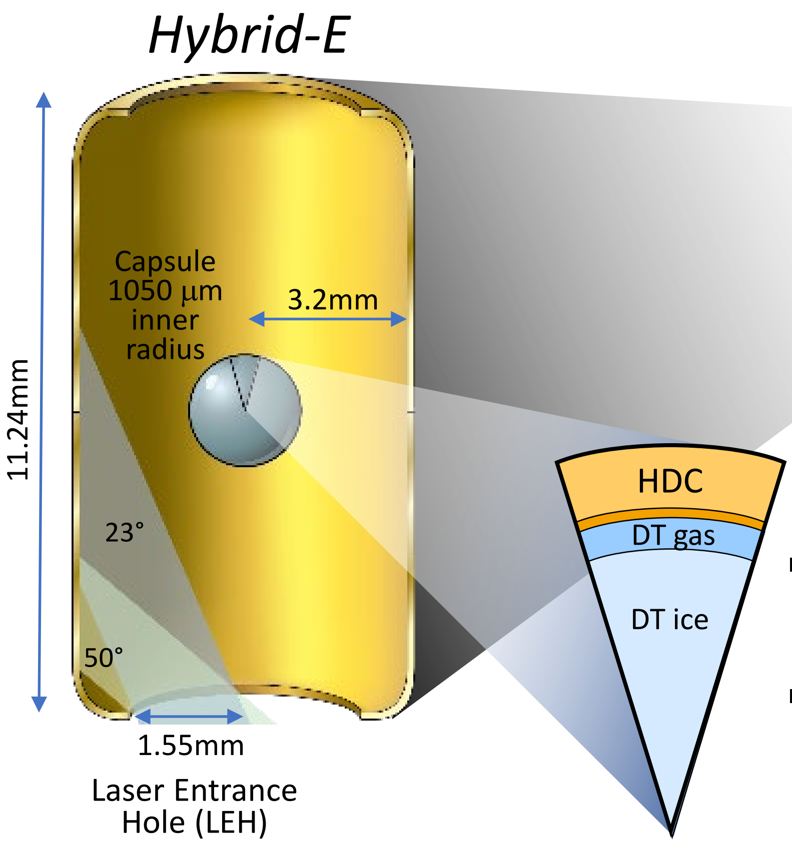
HDC inner surface



Design changes were made for improved coupling and robustness

HDC & Bigfoot → ***HYBRID-E***



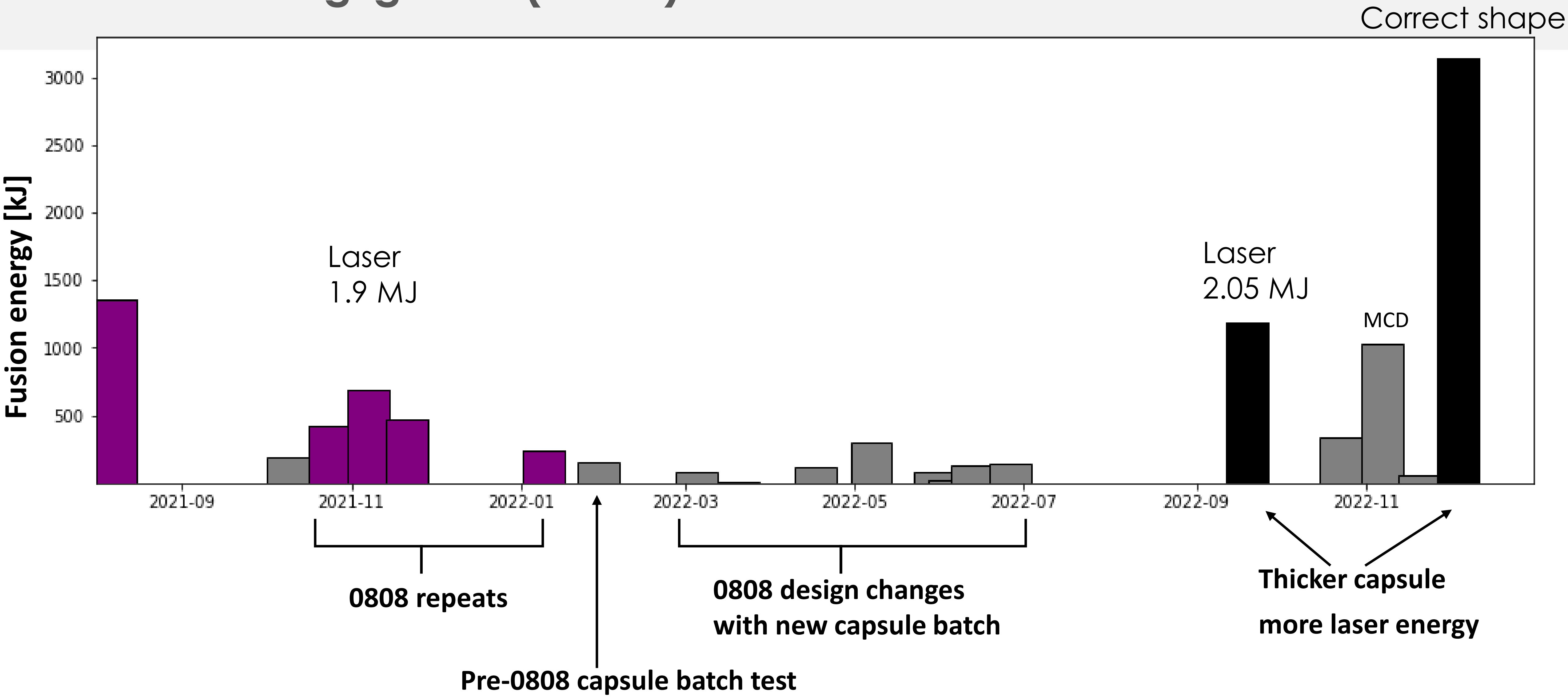


+6 um vs N210808

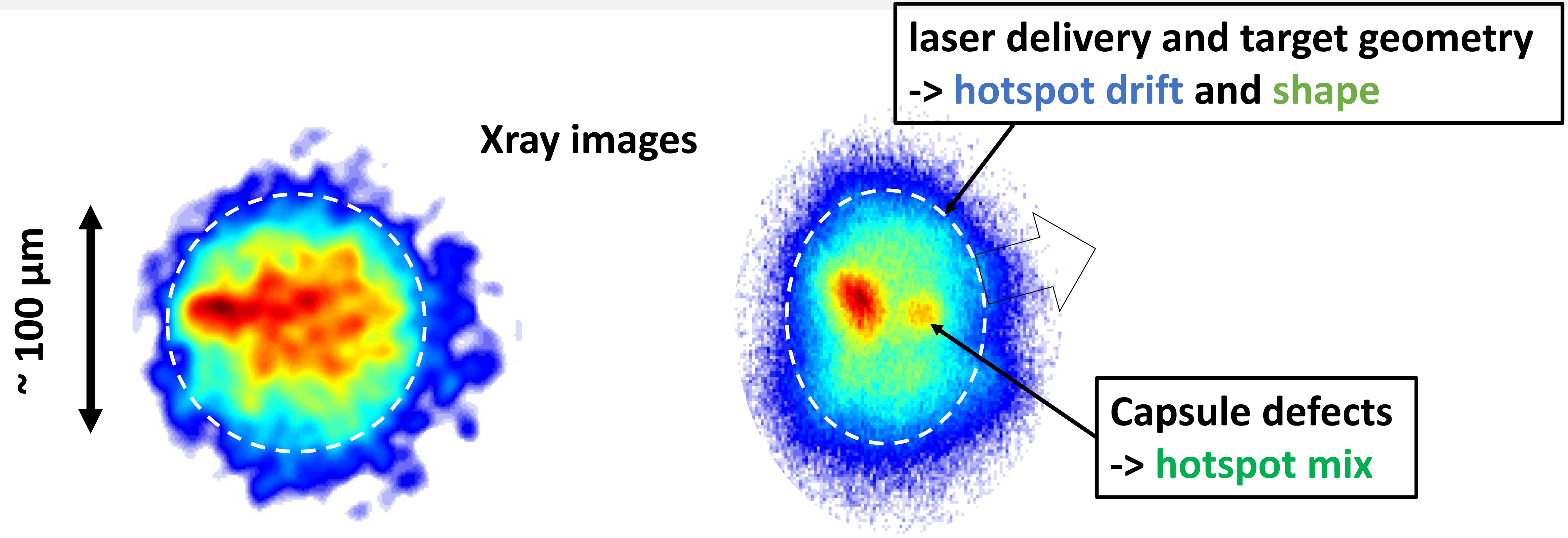
- Implosion symmetry optimization played a key role
- Only difference between first attempt (1.2 MJ) and N221204 was adjusting the design symmetry

210808 repeat attempts identified mix from target imperfections as main yield degradation mechanism; design refinements used new 2.05MJ laser capability to drive thicker, more stable capsule for ignition on 221204

The last 18 months: from trying to repeat N210808 (G=0.7) to achieving ignition (G=1.5)



The N210808 repeat series identified 3 main sources of variability

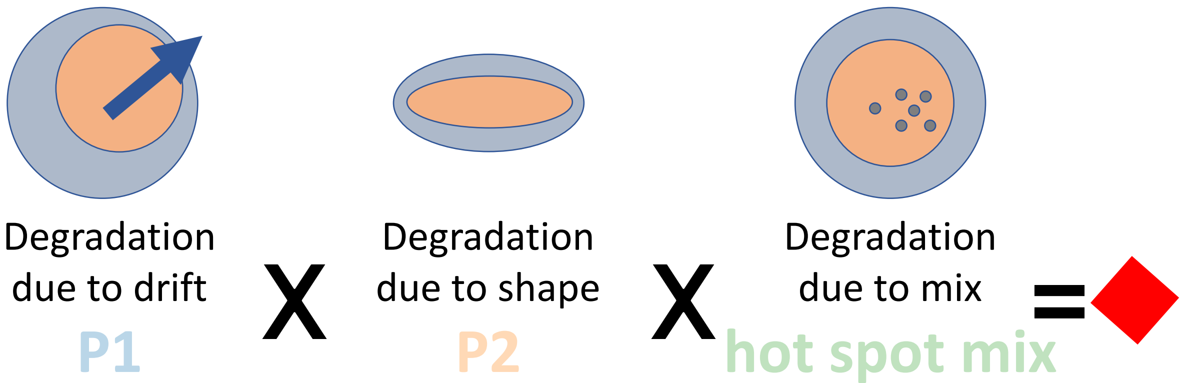


N210808 = 1.35 MJ

N211024 = 0.4 MJ

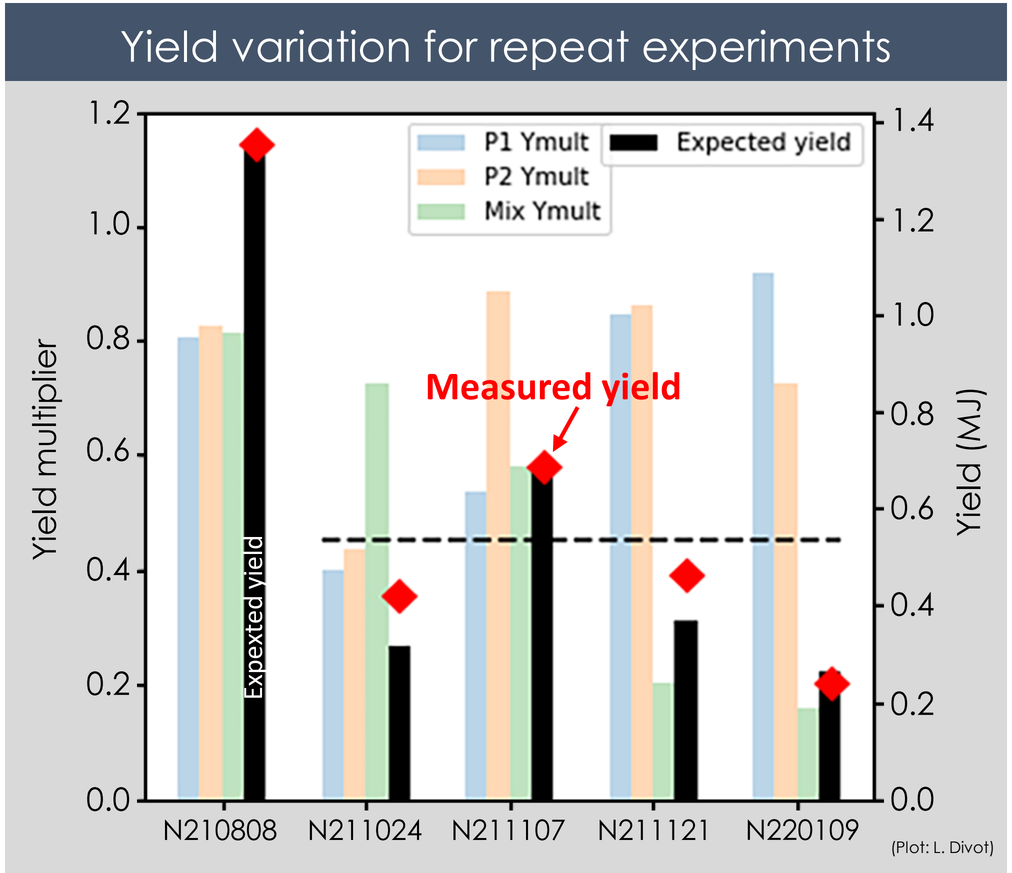
The key impact of the perturbations is to lower the internal energy of the hotspot at stagnation (minimum volume), impairing hotspot ignition and subsequent burn (either by radiative loss or reduced conversion of the pusher kinetic energy into hotpot internal energy)

Three main sources of degradations that affect the fusion yield were quantified



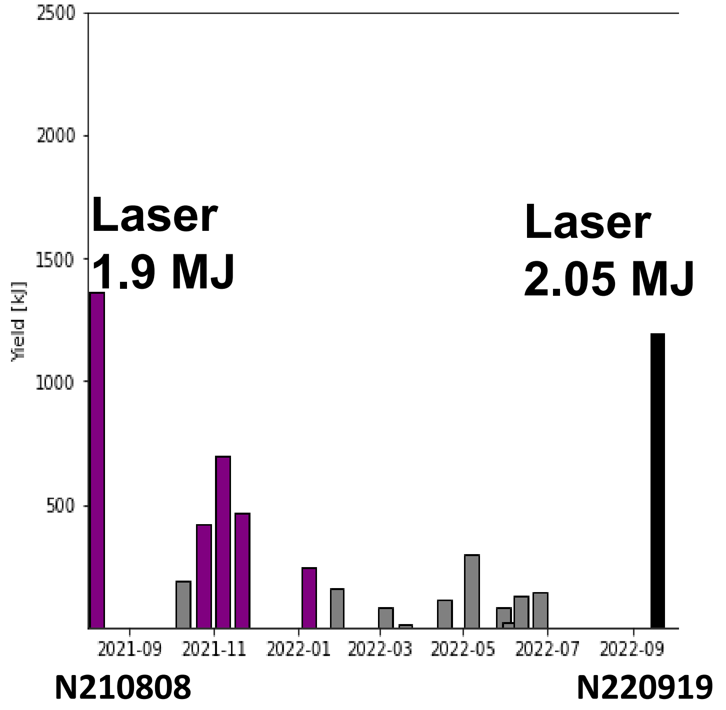
With N210808 capsule quality: <1.1MJ> ± 0.3

With current capsule quality: <0.5 MJ> ± 0.2

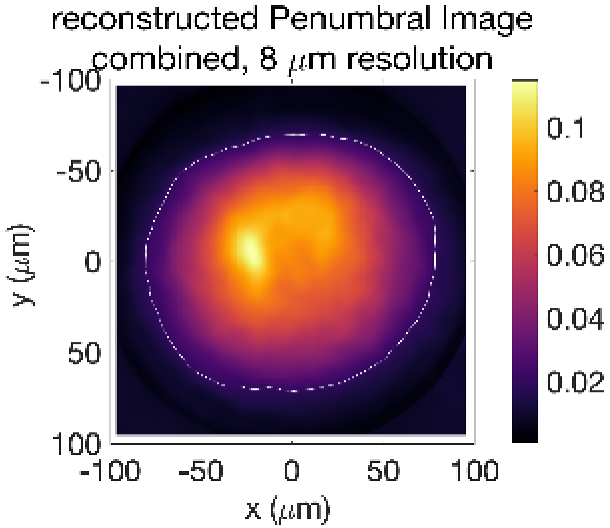


Mix was the dominant nuclear yield degradation mechanisms in the 1.35MJ repeats

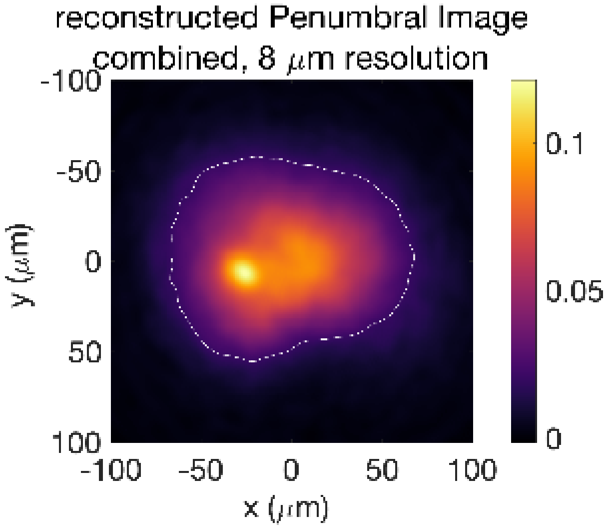
N220919 was the first NIF shot using 2.05 MJ of laser energy to drive a thicker diamond capsule (i.e. a bigger rocket)



N210808 : Y=1.35 MJ



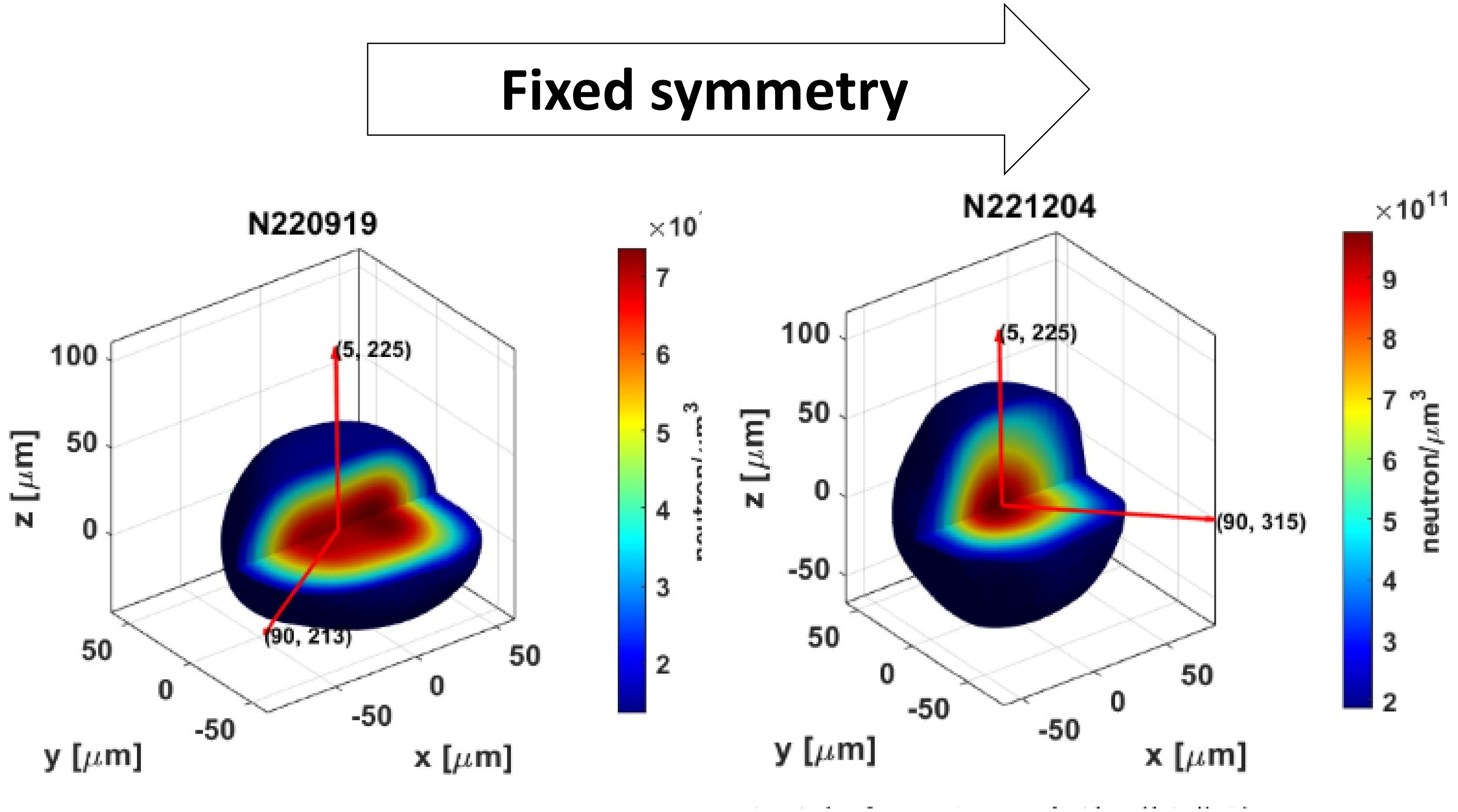
N220919 : Y=1.2 MJ



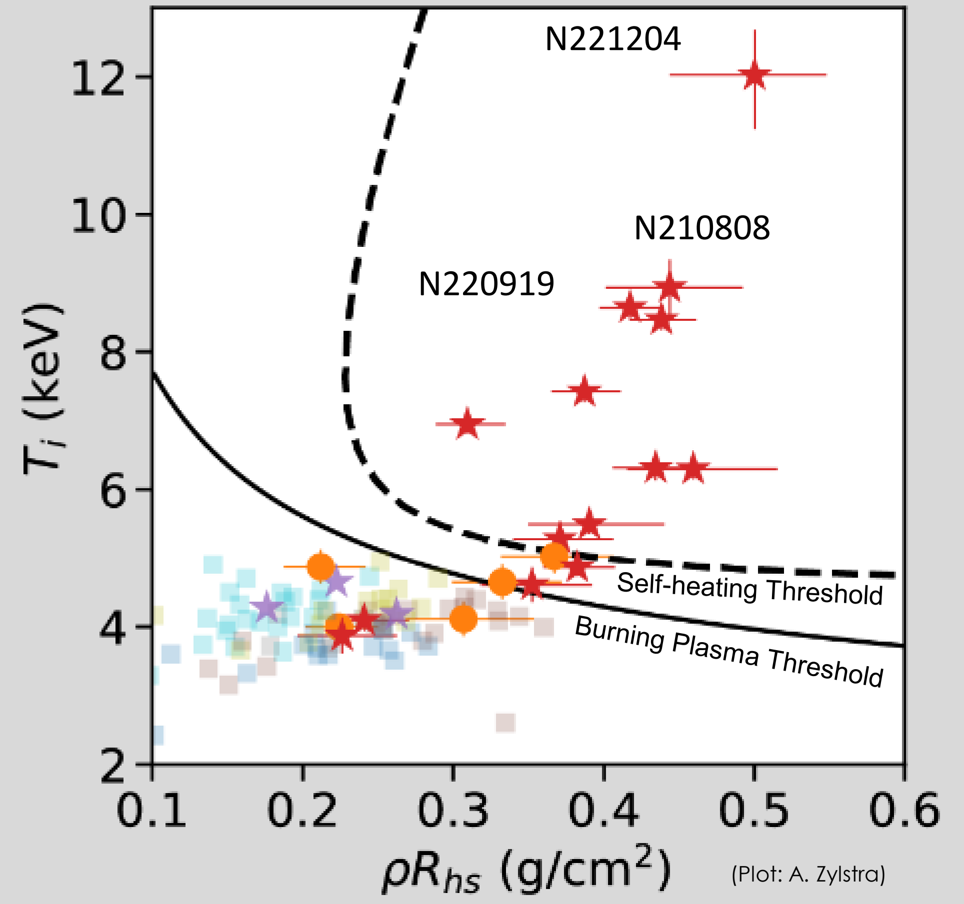
	N210808	N220919
Hotspot drift [km/s] :	68	51
P2 [μm]:	2.2 μm (-4%)	-11 μm (-20%)
Mix mass [ng] :	60 +/- 20	60 +/- 40

First shot with higher laser energy, looked promising but was not symmetric

Improving the symmetry from N220919 more than doubled the yield on N221204: Y=3.15 MJ (G=1.5)

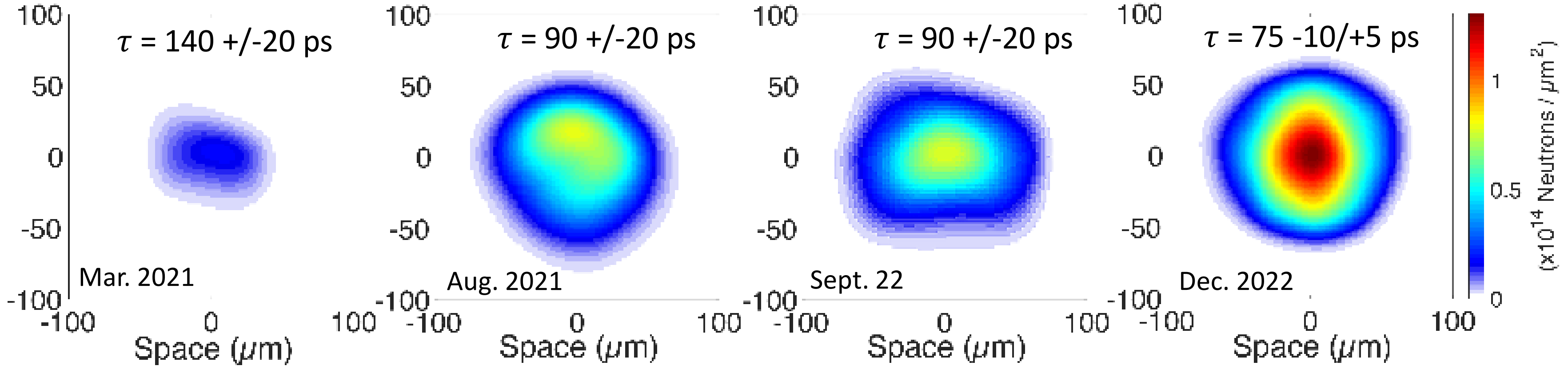


Preliminary Analysis



Over last two years, we increased hotspot reactivity and mass to achieve ~20x yield via improved targets and designs, laser energy, and systematic tuning

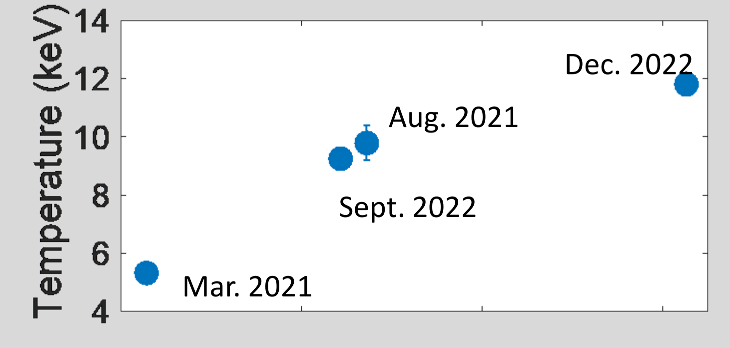
1.07X increase in hohlraum efficiency + improved target quality → *1.08X increase in laser energy* → *Symmetry adjustment* →



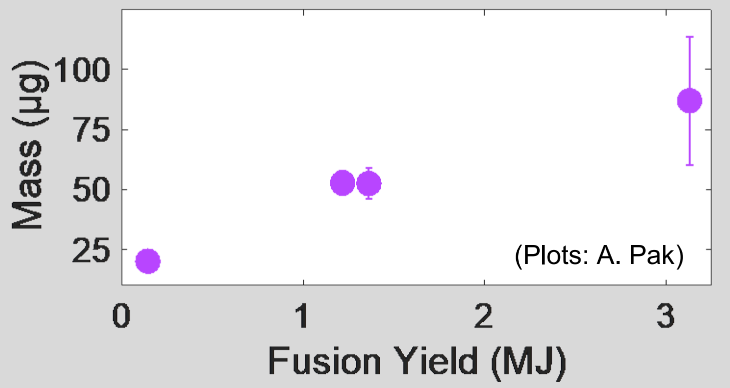
Y = 150 kJ **Y ~ 1.3 MJ** **Y = 3.15 MJ**

Preliminary analysis (A. Pak)

Temp. increases 2.2X

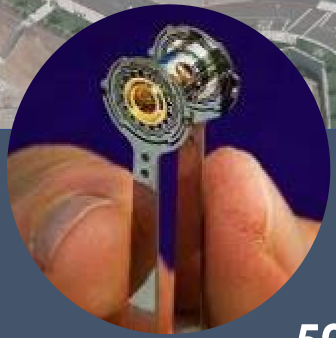


Mass increases 4.3X



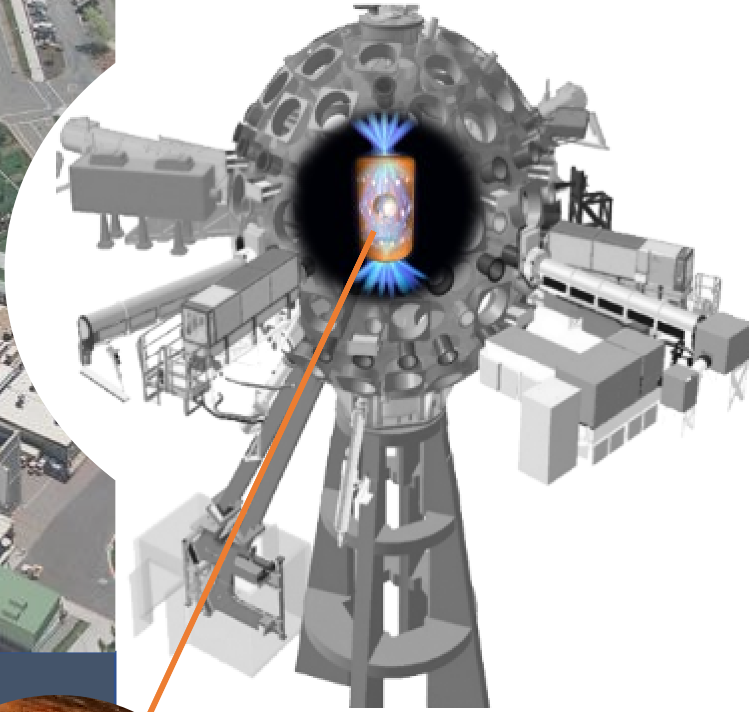
Upcoming shots in 2023 will continue efforts to make best use of higher quality targets and increasing laser energy

A burning inertial confinement fusion capsule releases fusion energy at very high power from a very tiny volume



NIF lasers

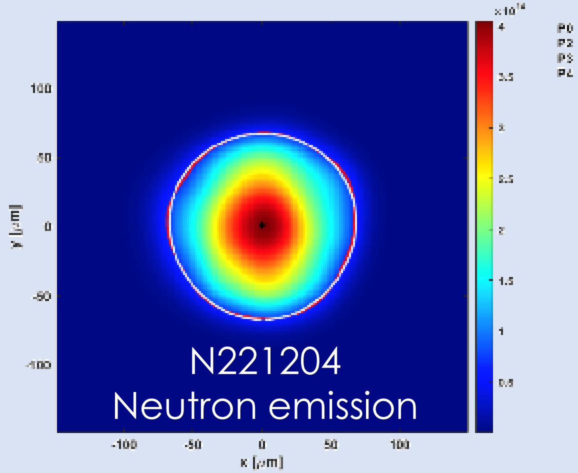
500 trillion watts for
> 4 nanoseconds (ns)
> 1.9 million joules (MJ)



Target
~ 1 cm
Temperature
~3,000,000 K

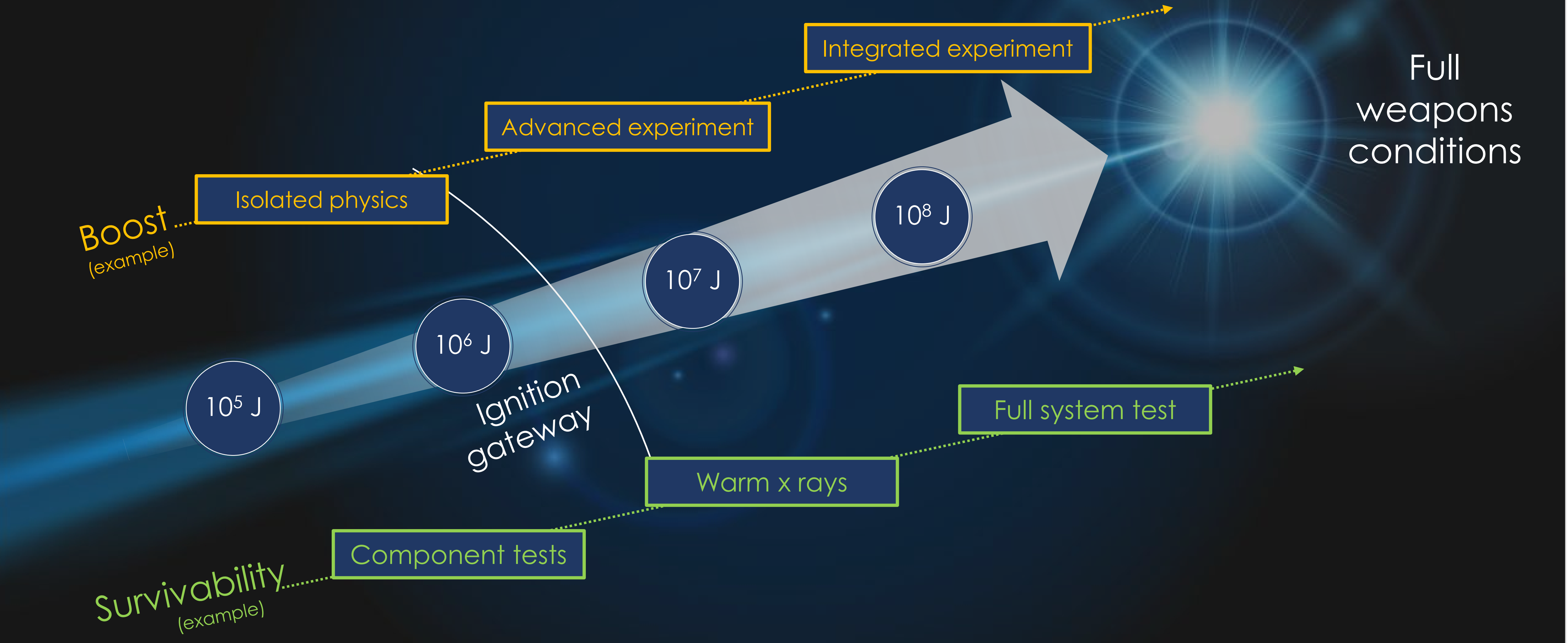
Energy output
from 12/5/2022 experiment

>40,000 trillion watts
~3.15 MJ
for ~0.075 ns

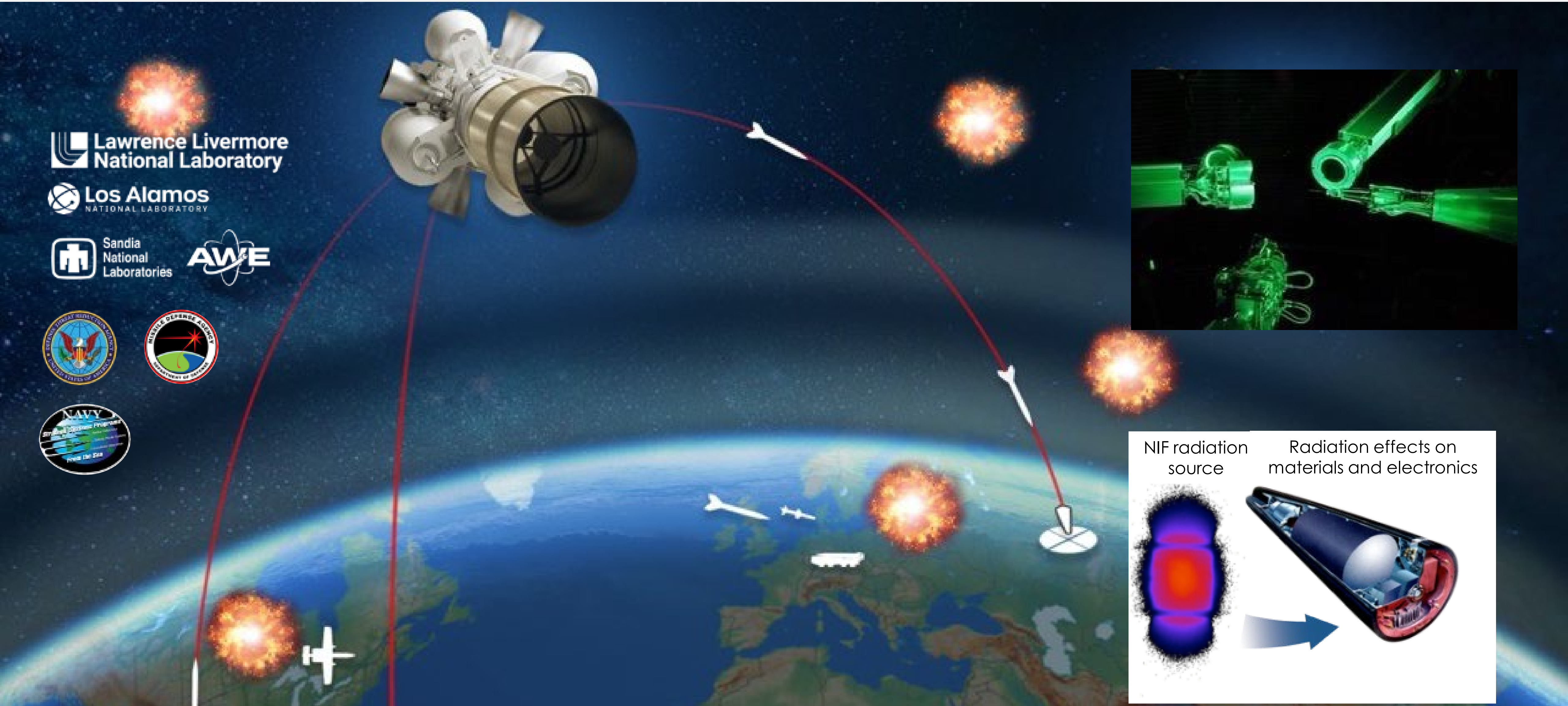


Fusion plasma
~0.01 cm
Temperature
~130,000,000 K

The output of an igniting capsule is the most powerful and energetic source we can envision in the lab, opening new capabilities for stewardship



In fact, on the December 5th experiment we fielded a new platform to ensure our strategic systems can survive hostile encounters



NEXT STEP: achieve ignition routinely and exploit it for stewardship while speeding up path to 10s of MJ yields and high gain

NIF has not yet reached its full potential

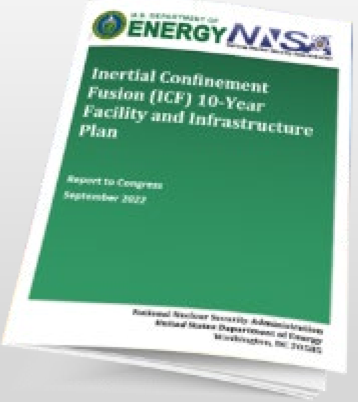
Few MJ → 10s of MJ → 100+ MJ??

2023

Routine MJ-yield operations and ignition

2023–2033

Long-term sustainment

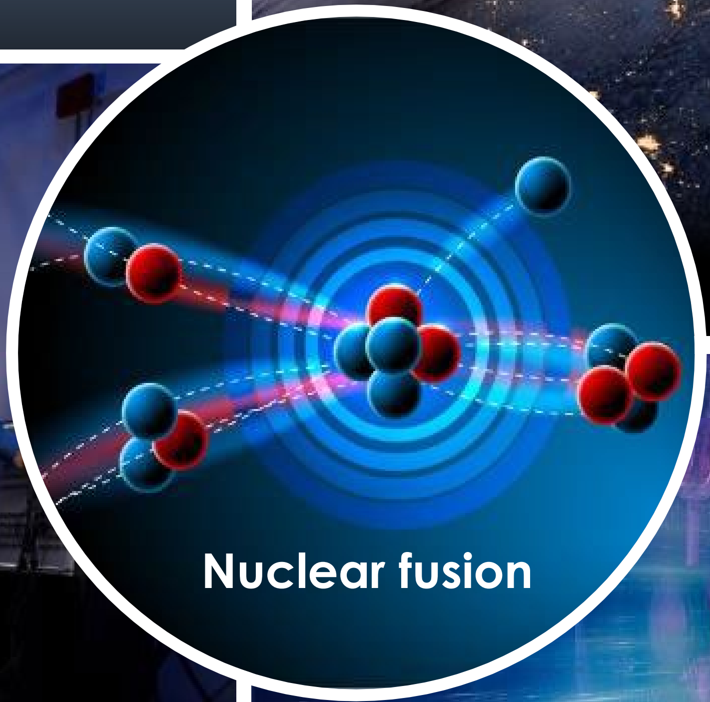


Increase energy and power

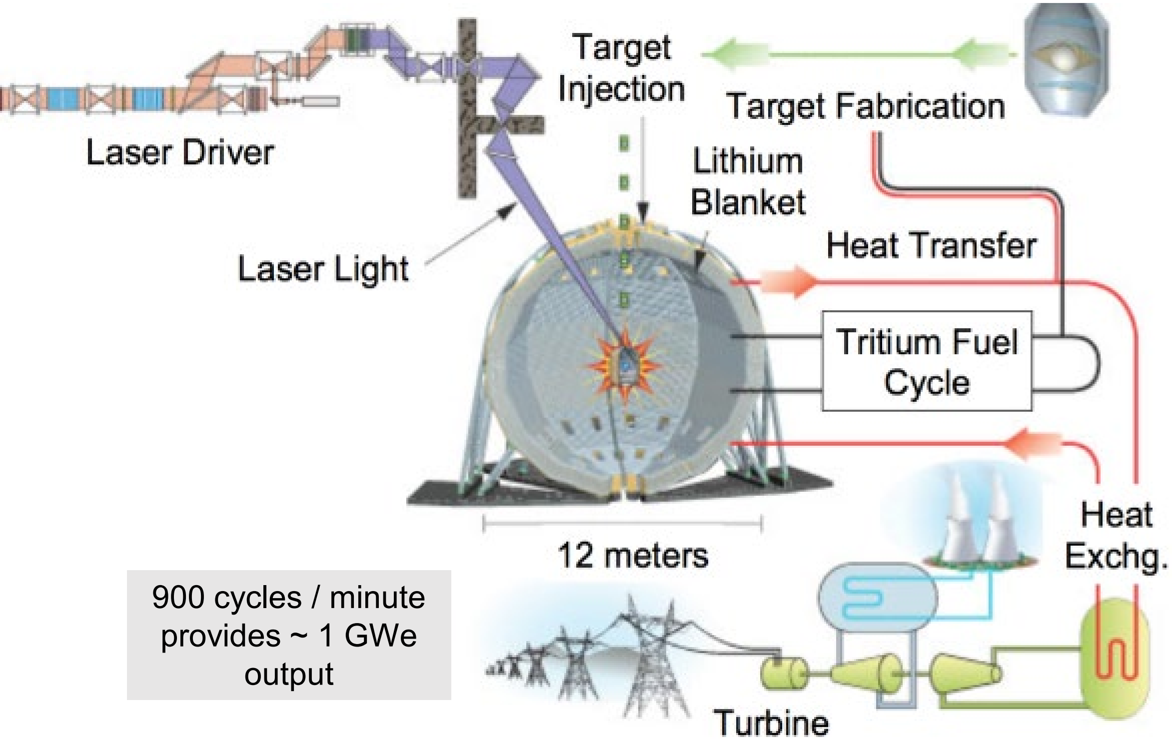
2033–

Explore high-yield, high-gain regime

Advancing science and technology to support our national security



Ignition on the NIF has spurred interest in the feasibility of laser-driven Inertial Fusion Energy (IFE)



900 cycles / minute provides ~ 1 GWe output

The path forward for inertial fusion energy will require technologies different from the Stockpile Stewardship Program

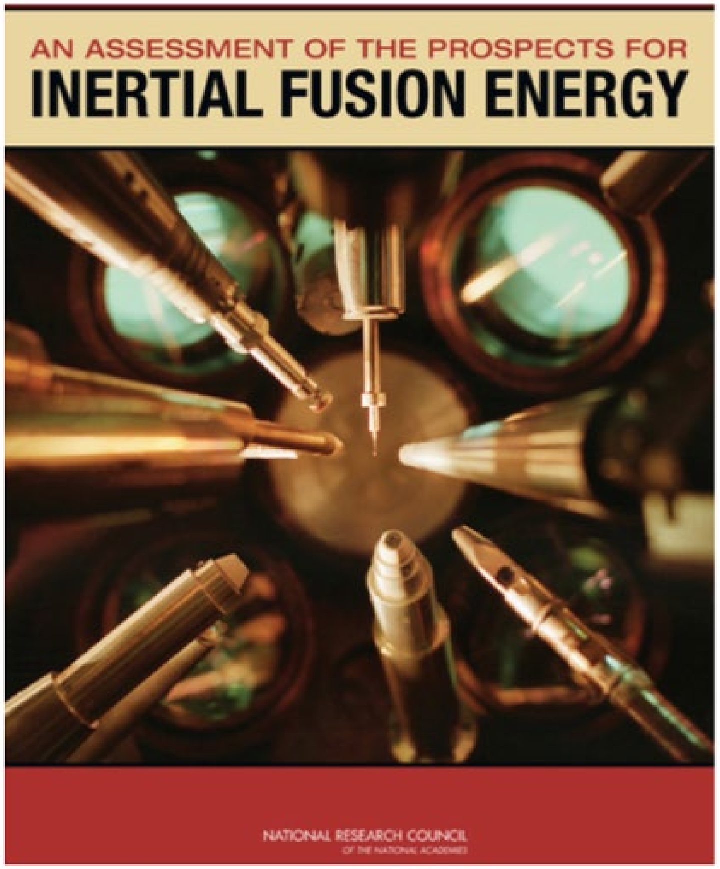
The challenges are many:	**But the benefits may outweigh the challenges:**
• Ignition and then high gain • High efficiency, high rep-rate laser • Target production and cost • Lifetime of the fusion chamber and optics • Safety and licensing • Plant operations	• Diversified risk from magnetic fusion (tokomaks) • Separation between driver and fusion source • Attractive economic development path (spin-out technologies) Energy security & US scientific competitiveness

The scale of investment needed will be at least comparable to the investment required to obtain ignition

The 2013 NAS Assessment on Inertial Fusion Energy provides a starting point for the next steps

NAS 2013 Study "An Assessment of the Prospects for Inertial Fusion Energy"* had a number of conclusions and recommendations including:

- "The appropriate time for the establishment of a national, coordinated, broad-based inertial fusion energy program within DOE would be when ignition is achieved."
- "The potential benefits of energy from inertial confinement fusion … also provide a compelling rationale for including inertial fusion energy R&D as part of the long-term R&D portfolio for U.S. energy."



An Assessment of the Prospects for Inertial Fusion Energy, Committee on the Prospects for Inertial Confinement Fusion Energy Systems, NRC (National Academies Press, Washington, D.C., 2013)

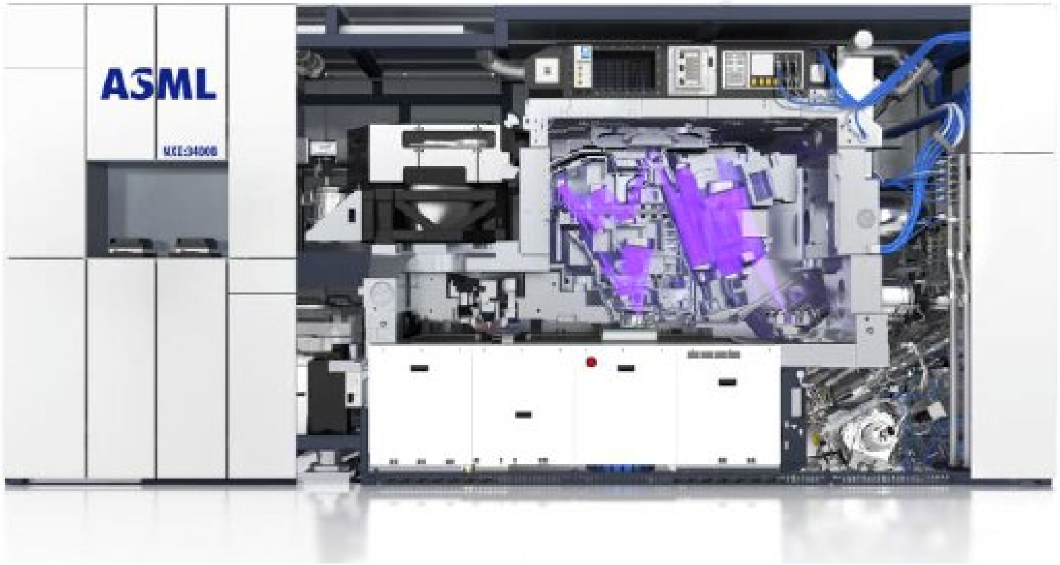
The U.S. DOE recently held a Basic Research Needs in IFE to define a new national IFE program

U.S. DEPARTMENT OF ENERGY | Office of Science

https://events.bizzabo.com/IFEBRN2022/home

Report provides a set of priority research opportunities to inform future research efforts in IFE and build a community of next-generation researchers in this area.

EUV lithography commercial systems demonstrate many of the elements of an eventual inertial fusion energy (IFE) powerplant, although decadal challenges remain



EUVL research was an outgrowth of a multi-lab CRADA in the 1990's (including ICF technologies)

25 years and $6B+ of investment

Advances in:
Laser, targets, x-ray optics, debris mitigation, precision alignment, …….

	EUVL	IFE
High Average Power laser	40 kW 10.6 μm	10,000-30,000 kW 200-500 nm
High Rep Rate Targets	30 μm tin droplet 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+

EUV = extreme ultraviolet

Lawrence Livermore National Laboratory

WCI WEAPONS AND COMPLEX INTEGRATION

NIF&PS

GENERAL ATOMICS

Sandia National Laboratories

cea
DE LA RECHERCHE À L'INDUSTRIE

Los Alamos NATIONAL LABORATORY

Diamond Materials
Advanced Diamond Technologies

UR LLE

AWE

MIT | PSFC Plasma Science and Fusion Center

NNSA National Nuclear Security Administration

...and many more