

Target gain >1 from inertial confinement fusion experiments at the National Ignition Facility

Arthur Pak on behalf of the indirect drive inertial confinement fusion collaboration
IAEA Fusion Energy Conference, Oct 16th, 2023

LLNL-PRES-[1084645](#)

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NIF&PS


**STRATEGIC
DETERRENCE**



**Sandia
National
Laboratories**



Los Alamos
NATIONAL LABORATORY

**Diamond
Materials**

Advanced Diamond Technologies



MIT | PSFC

Plasma Science and Fusion Center



GENERAL ATOMICS



National Nuclear Security Administration

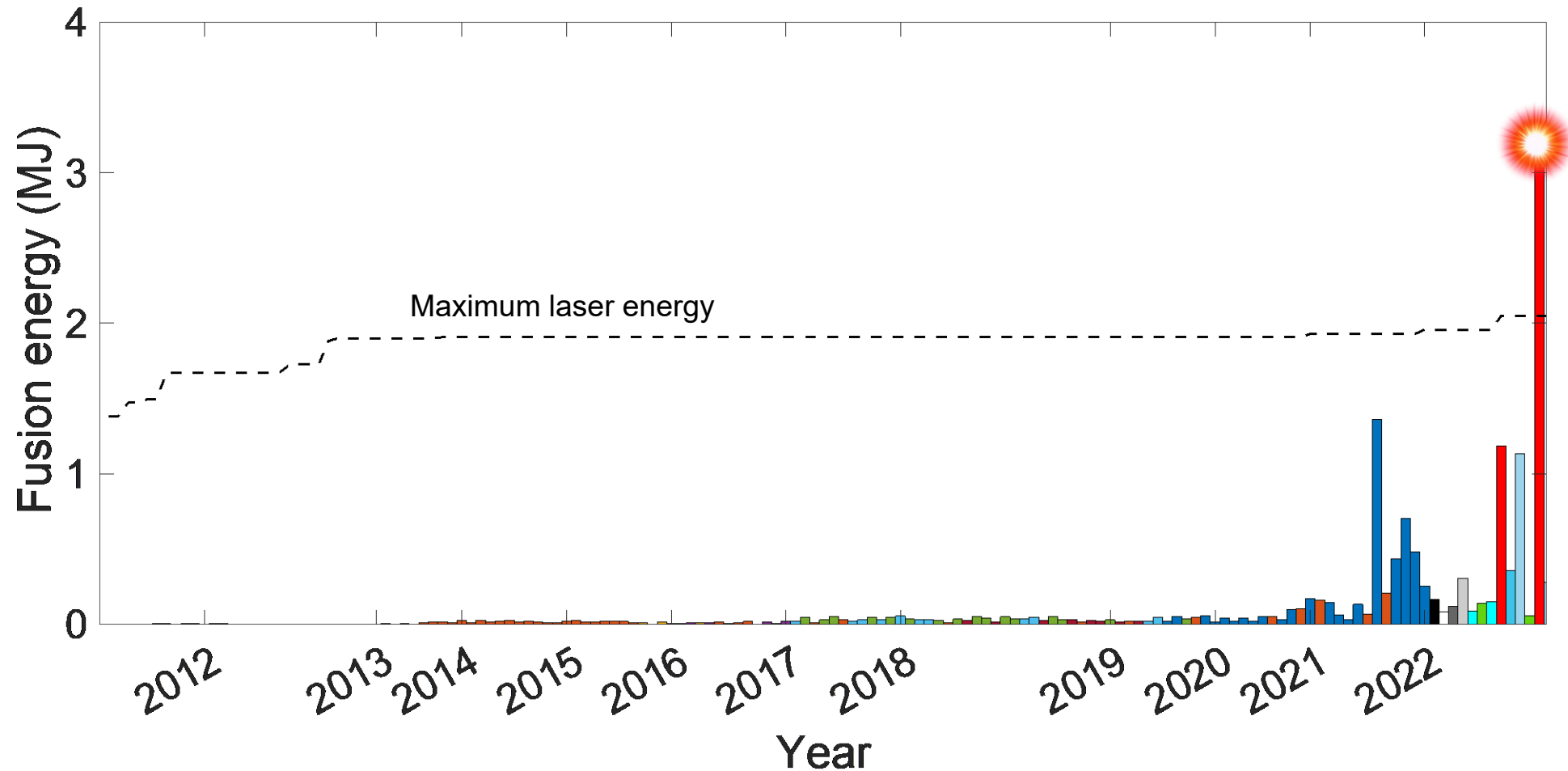
...and many more



Lawrence Livermore National Laboratory

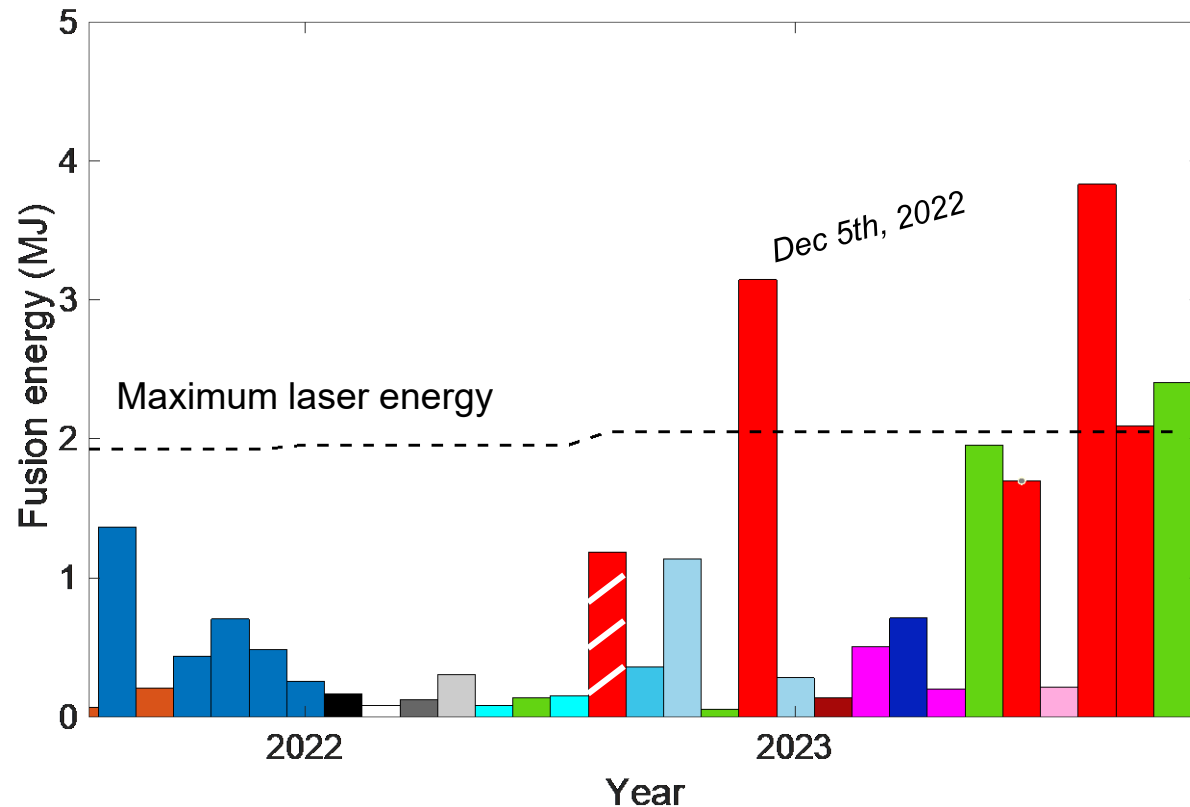


The first experiment to exceed the threshold for fusion ignition* was conducted on Dec. 5th 2022, achieving a target gain of 1.5



3.14 MJ of fusion energy produced from 2.05 MJ of laser energy

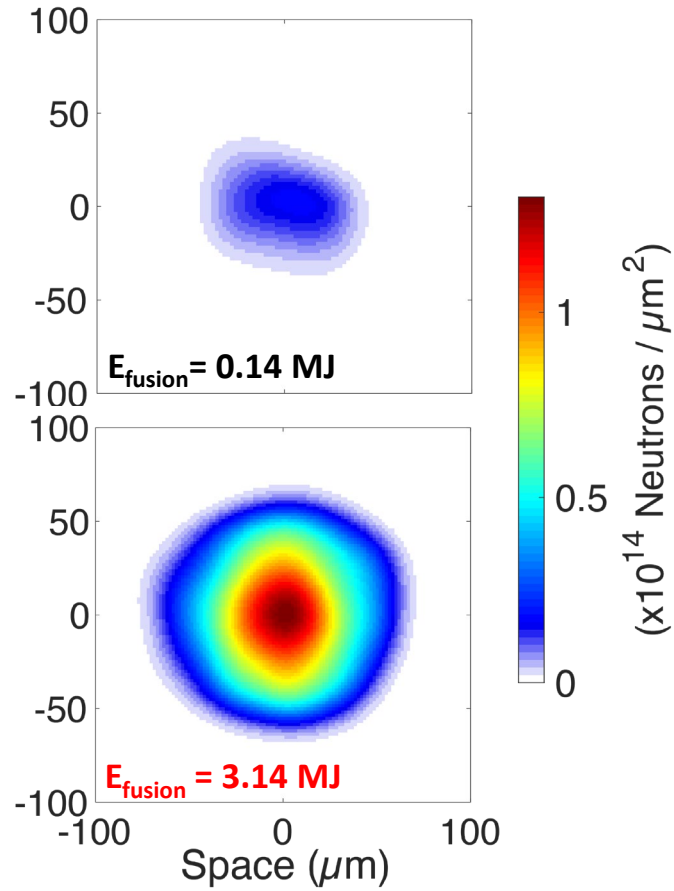
Our program is focused on developing paths to higher target gains and understanding the origin of variability in fusion output



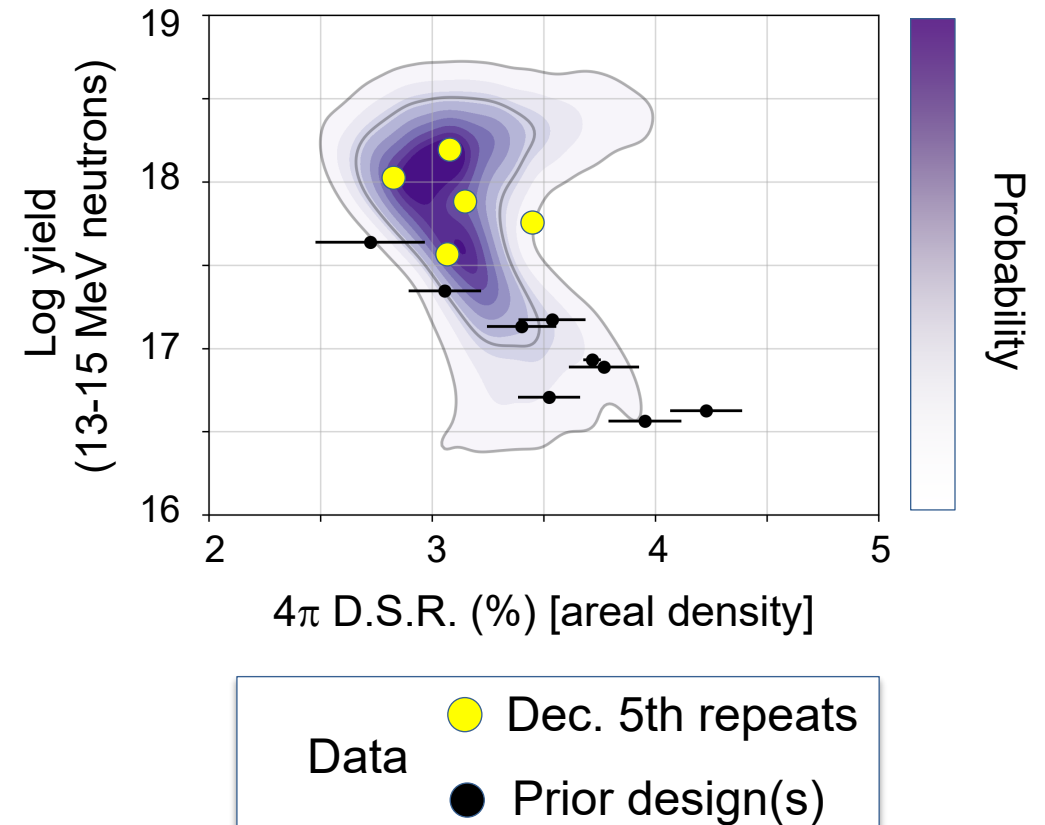
- Conducted 3 near repeat experiments of Dec. 5th experiment
- Fusion yields of up to 3.88 MJ and target gains of 1.9X have been achieved.
- Target gain ≥ 1 achieved 3 out of 4 times.
- A second approach has now also achieved target gain > 1 .

Measurements¹ and simulations² are informing our understanding of variability and how to make further improvements

Neutron emission evolution

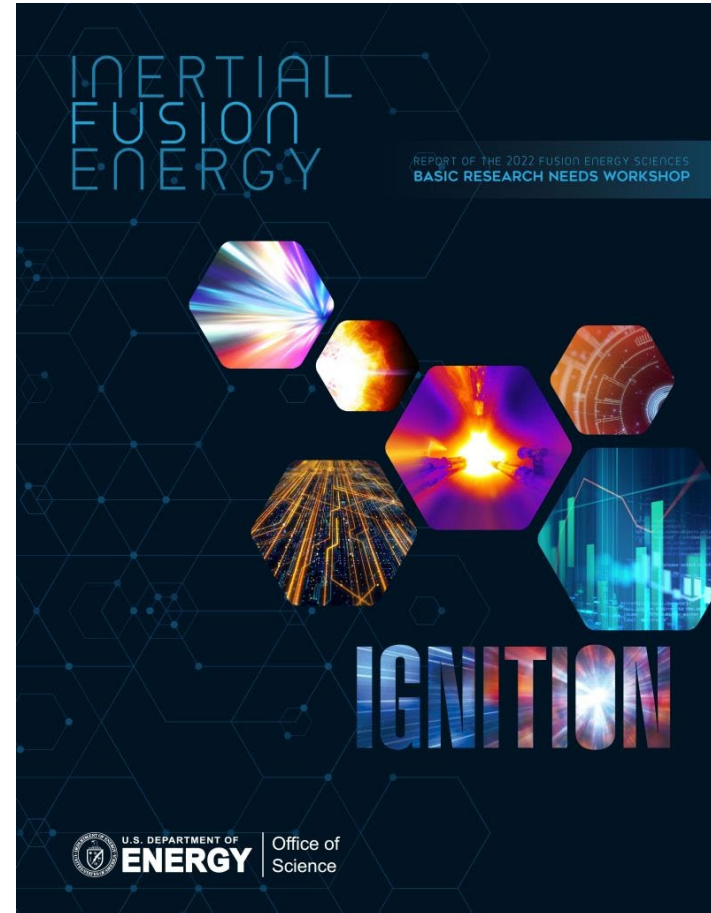


Dec. 5th Pre-shot predictions and data



Burning plasmas are revealing exciting new observations

The Inertial Fusion Energy (IFE) community has drafted a Basic Research needs document*

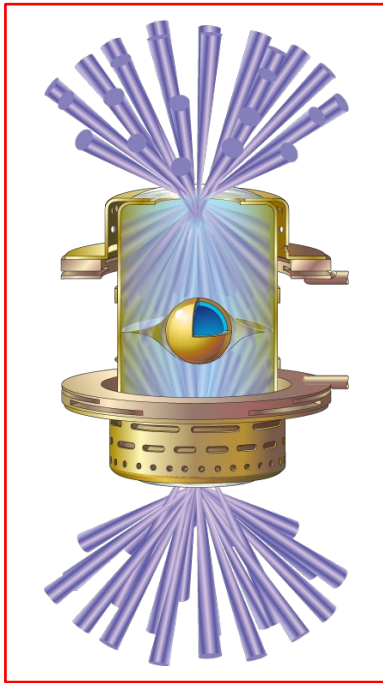


Public and private investment in IFE underway to begin to address the many challenges.



There are several complementary approaches to ignition in inertial confinement research

Laser Indirect Drive



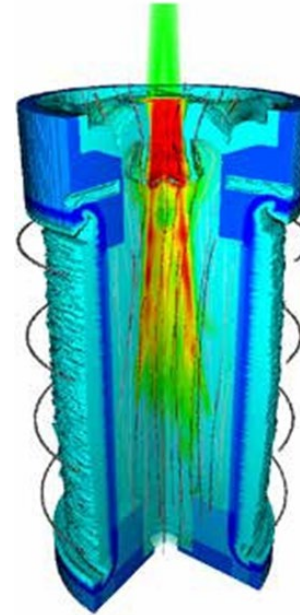
Lindl,
Phys Plasmas 1995, 2014

Laser Direct Drive



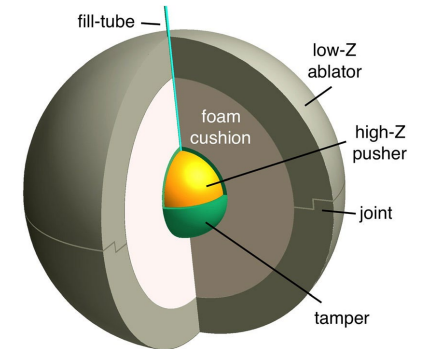
Craxton,
Phys Plasmas 2015

Magnetic Drive



Slutz,
Phys Plasmas 2010

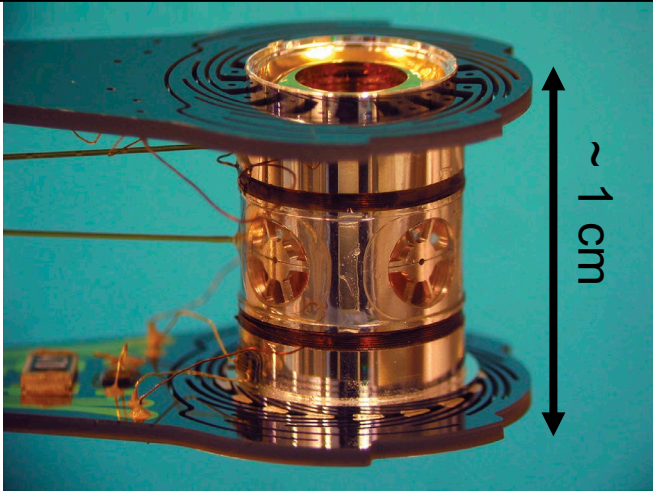
Double Shells



Montgomery,
Phys Plasmas 2018

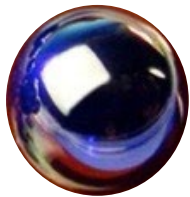
Targets require state-of-the-art microfabrication precision

Gold lined uranium hohlraum



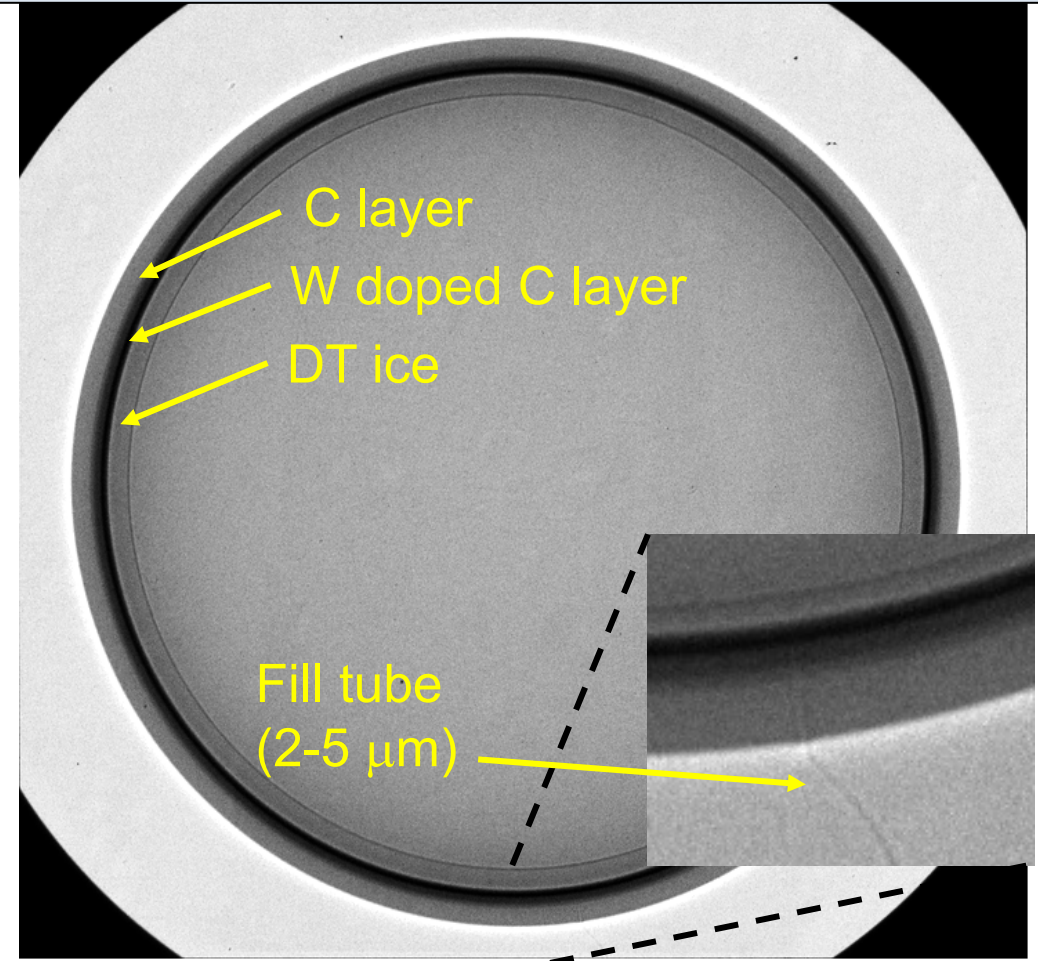
Cryogenic (19 K)
0.3 mg/cc He fill

Diamond Nanocrystalline Capsule (High Density Carbon – HDC)



≈ 2 mm diameter,
smooth to 10 nm

In-situ radiograph of capsule with DT layer



We perform ~15 experiments with cryogenic DT fuel a year at full laser energy.
It takes ~1-2 days to grow the DT ice layer and 1 day to execute the experiment

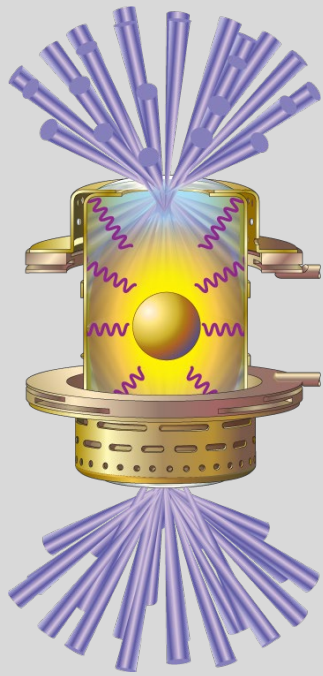
The National Ignition Facility (NIF) is the world's most energetic laser enabling the study of extreme conditions



- 192 Beams,
- 2.05 MJ Energy, 500 TW Power (300 MJ electric)
- Matter temperature $>10^8$ K
- Radiation temperature $>3.5 \times 10^6$ K
- Densities $>10^2$ g/cm³
- Pressures $>10^{11}$ atm
- Number of Diagnostics >120

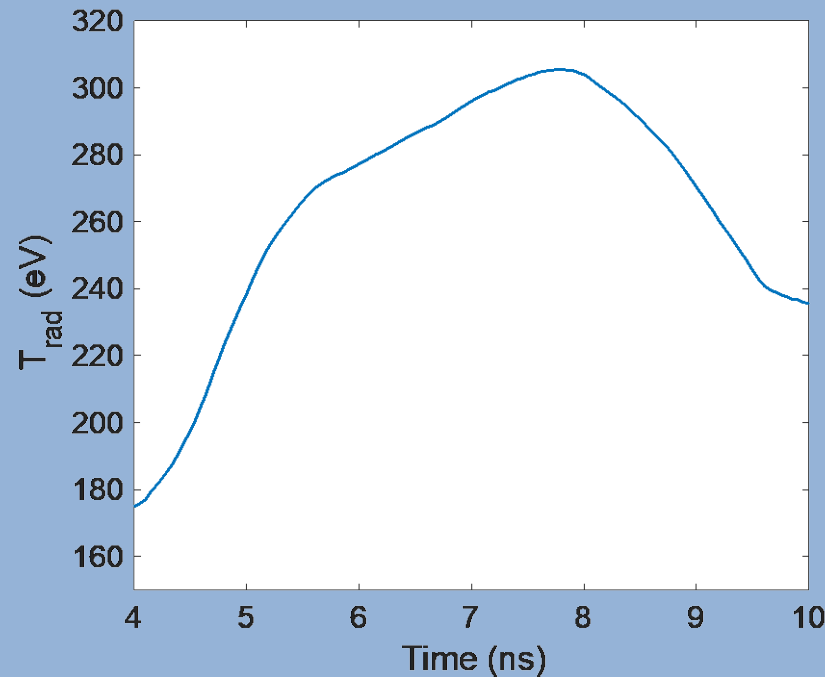
The NIF uses a laser driven high Z enclosure “hohlraum” to compress a fuel pellet filled with DT fuel to achieve the conditions for ignition

Laser beams rapidly heat the inside surface of the hohlraum creating x-rays



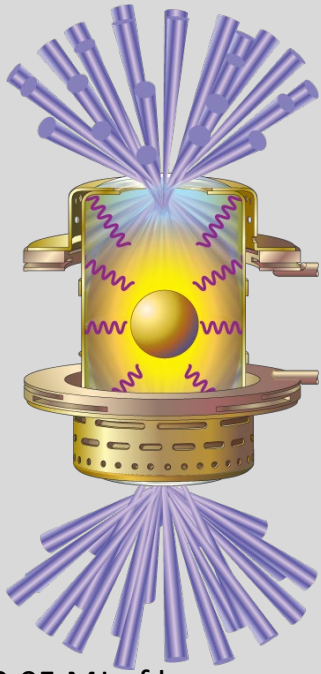
2.05 MJ of laser energy

X-ray radiation temperature vs. time



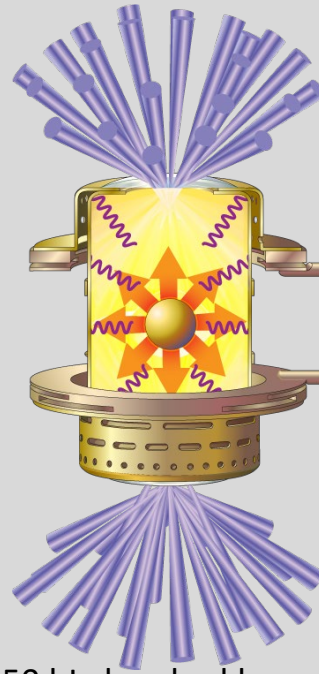
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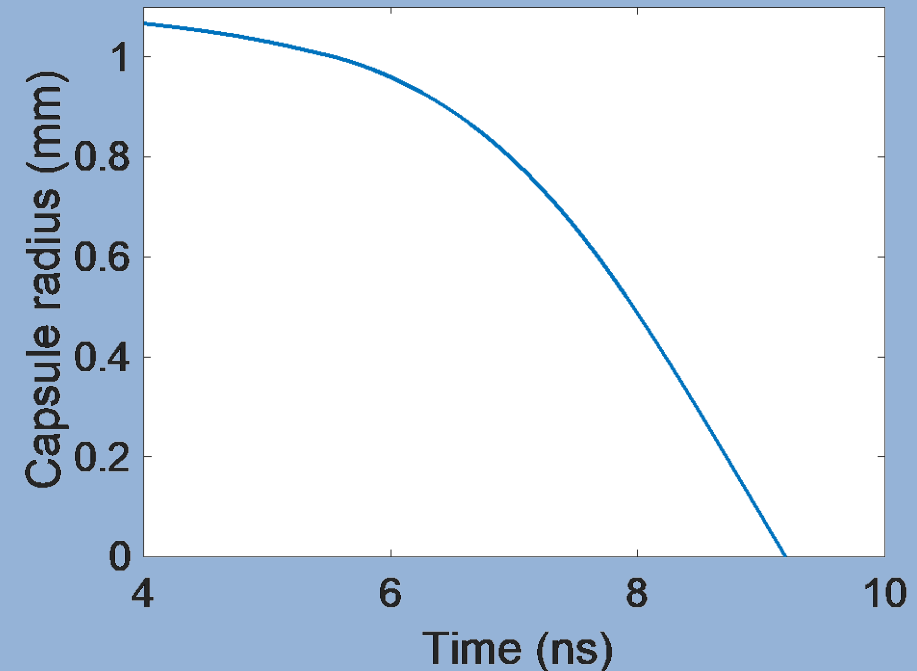
2.05 MJ of laser energy

The x-rays blow off the fuel capsule wall, accelerating the fuel inward to 1 million MPH



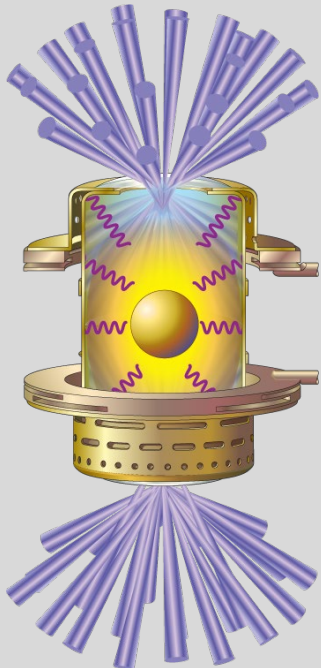
~250 kJ absorbed by capsule

Capsule trajectory vs time



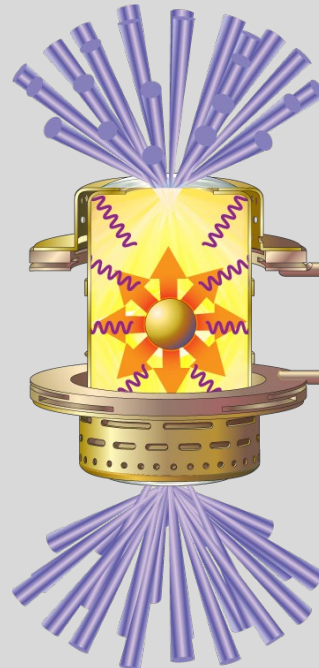
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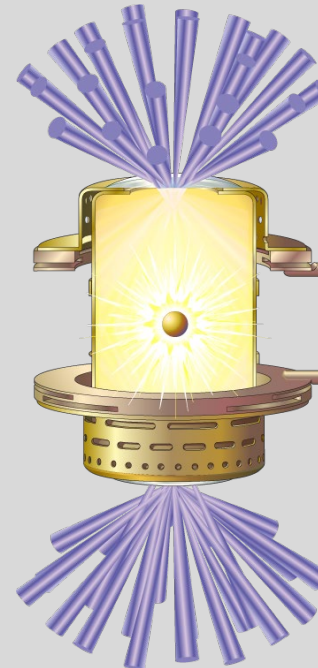
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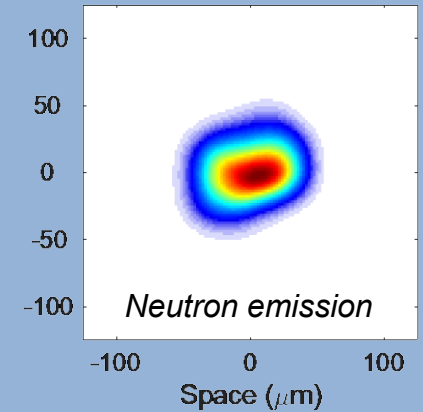
~250 kJ absorbed by capsule

The fuel is compressed to 100x the density of lead, its center heating and igniting at 100,000,000° C

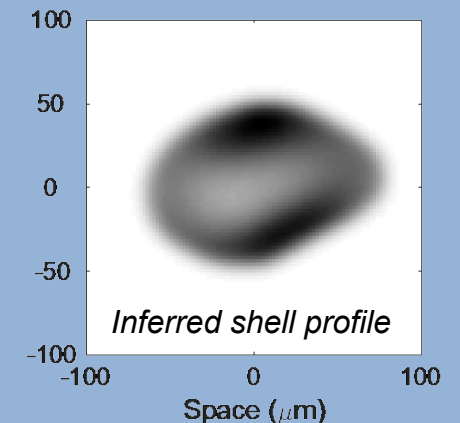


~20 kJ given to the DT fuel

Central ‘hot-spot’ and dense confining DT shell



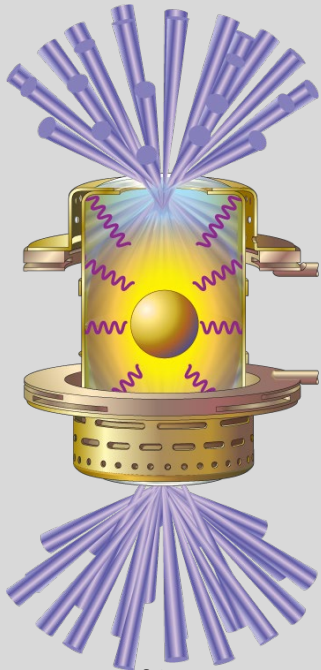
Neutron emission



Inferred shell profile

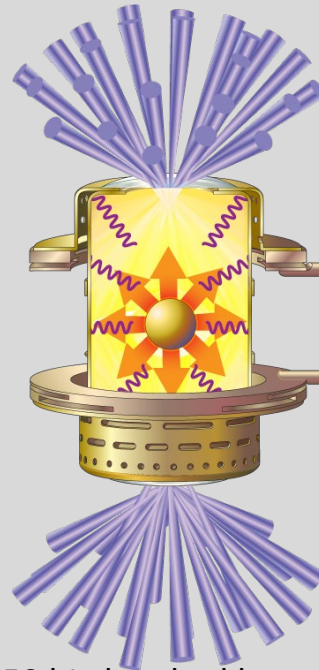
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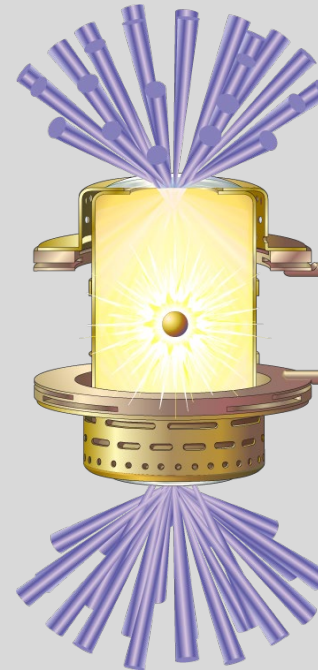
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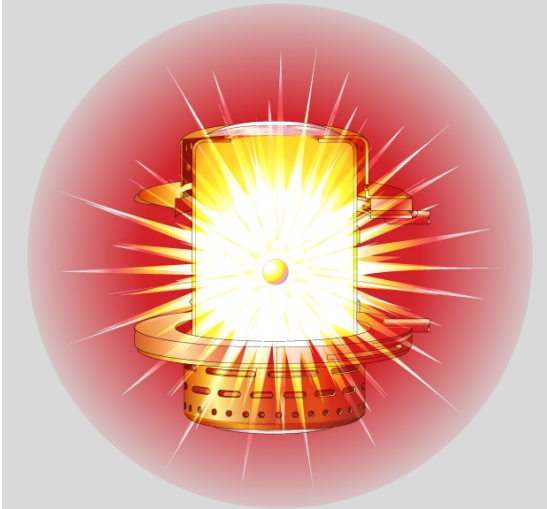
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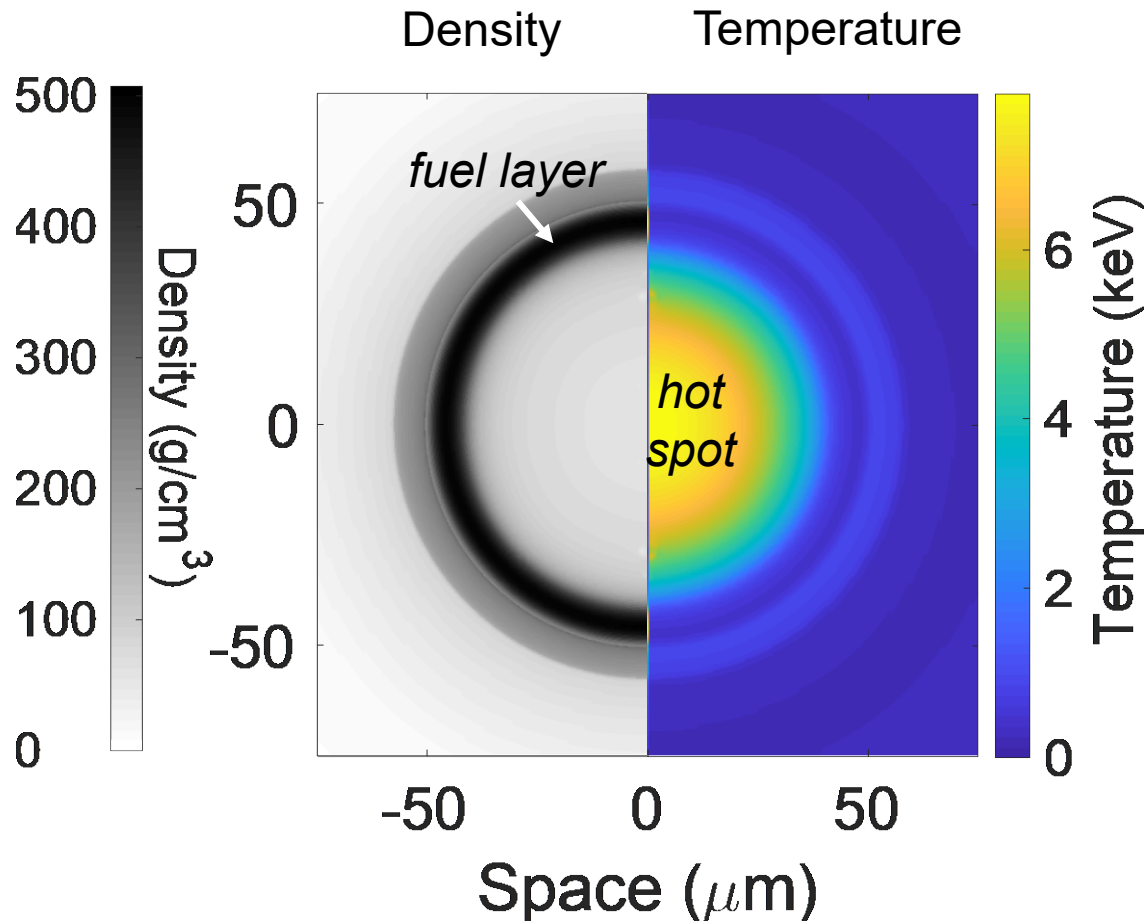
~20 kJ given to the DT fuel

Fusion burn spreads rapidly through the compressed fuel, yielding many times the input energy

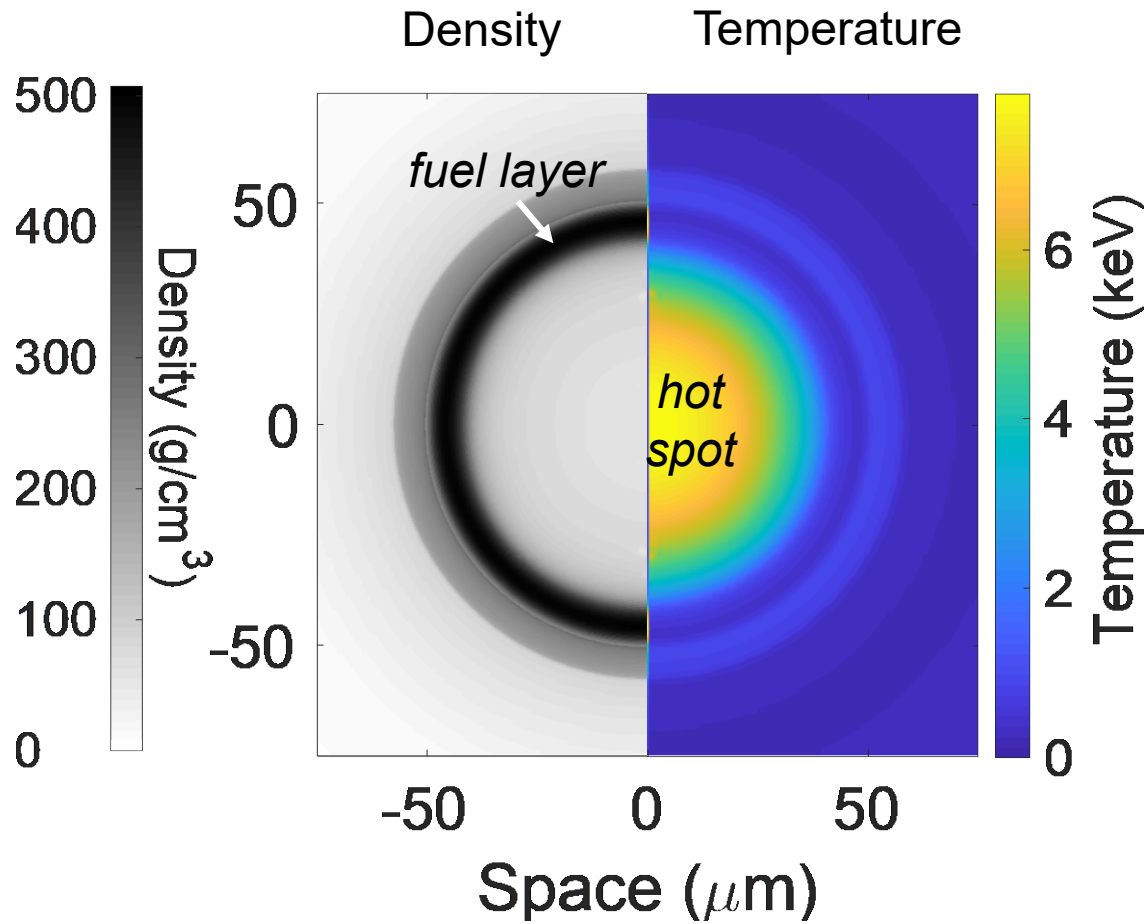


3.14 MJ fusion energy output on Dec. 5th, 2022

In ICF, a dense DT fuel layer first compresses and heats a central hot spot of DT plasma to the conditions for fusion to occur



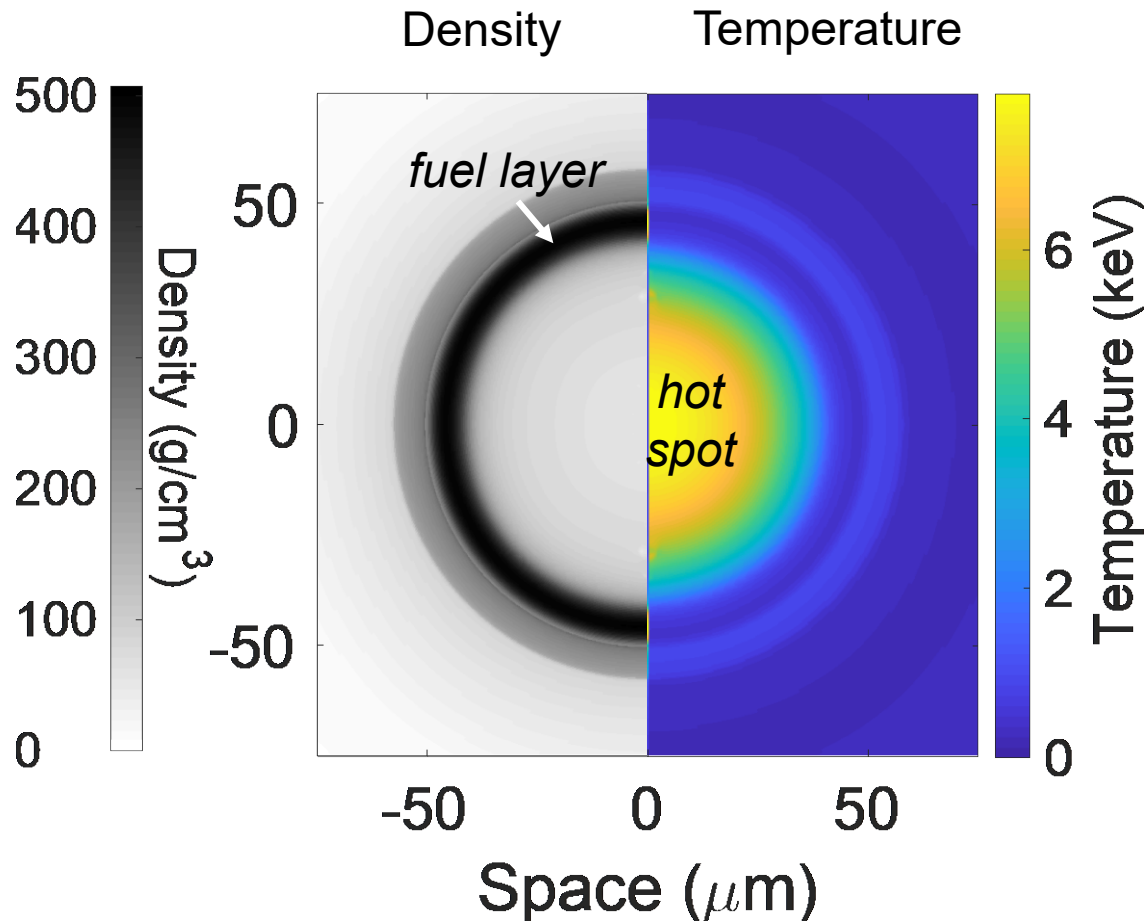
DT reactivity and α -heating rate are a strong function of temperature



*Number of DT reactions in hot spot**

$$\gamma \propto n_D n_T T_{DT}^4 \tau V$$

The hot spot temperature and yield depends on the competition between heating and loss rates



*Number of DT reactions in hot spot**

$$\gamma \propto n_D n_T T_{DT}^4 \tau V$$

DT temperature dependence / energy balance

$$C_{DT} \frac{dT}{dt} = Q_{\alpha} - Q_{rad.} - Q_{cond.} - Q_{PdV}$$

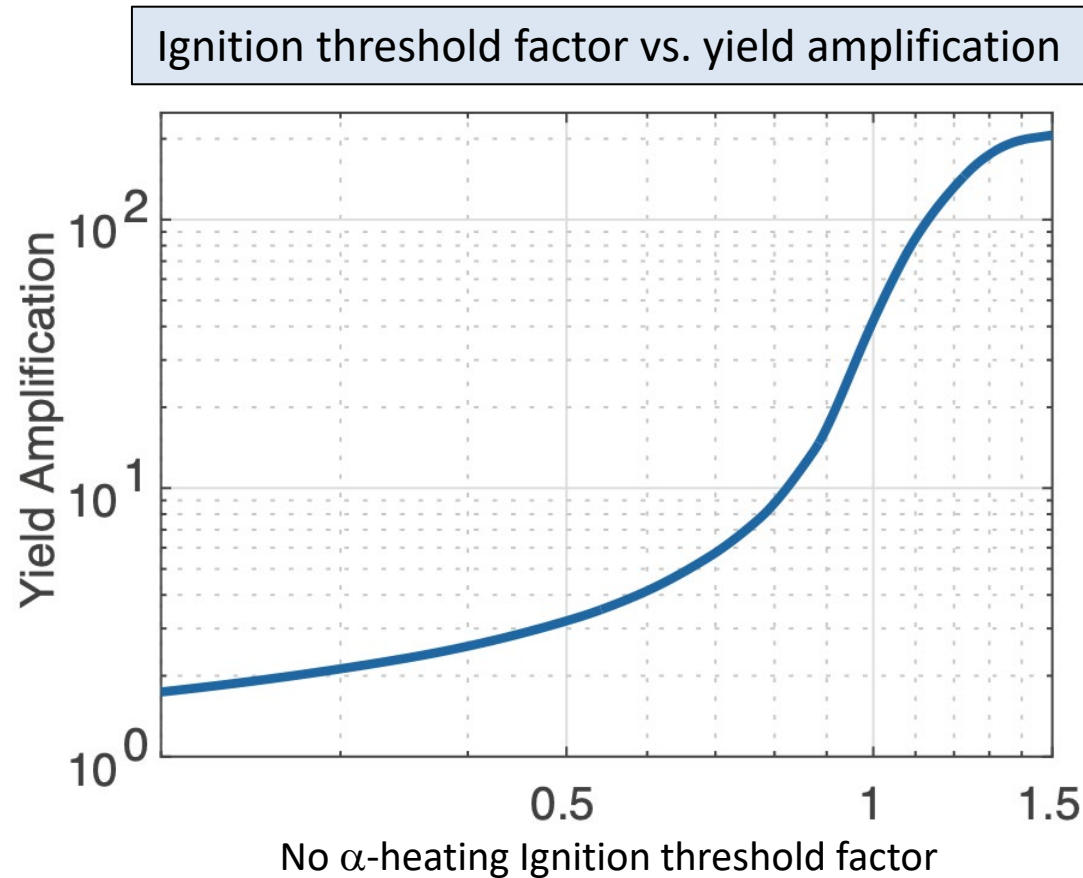
α -particle heating

Radiation losses
Conduction losses

Compressive work
/ Expansion losses

When $Q_{\alpha} >$ all losses and $dT^2/dt^2 > 0$ a sustained chain reaction occurs leading to ignition

Ignition is a threshold process where small changes in input conditions can lead to dramatic changes in performance



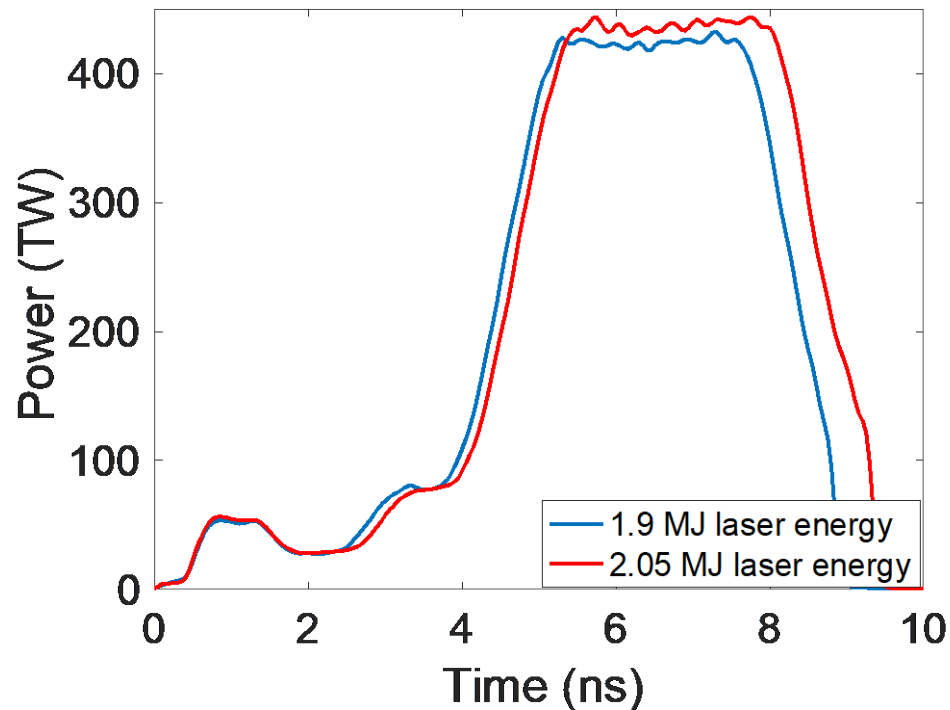
$$ITFX_{no\ \alpha} \propto Yield_{no\ \alpha} (\rho R_{no\ \alpha})^{2.1}$$

~2X changes in yield for 10% changes in $Y_{no\ \alpha}$ or $\rho R_{no\ \alpha}$ at onset of ignition

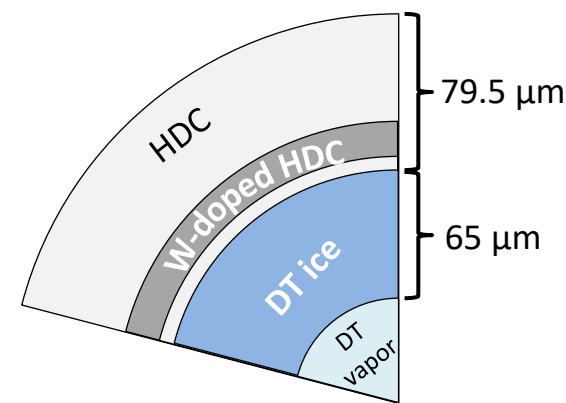
The ignition result was enabled by using a 1.08X increase in available laser energy to drive a ~1.07X thicker capsule

Design goal was to increase yield amplification by increasing ρR , while maintaining coupled energy

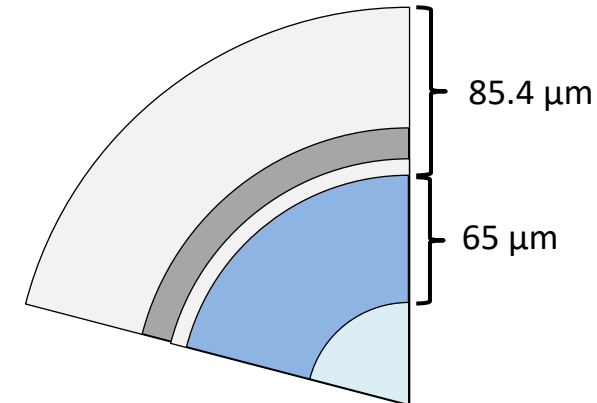
Laser power vs. time



Capsule target diagrams*



N210808
(1.9 MJ of laser energy)



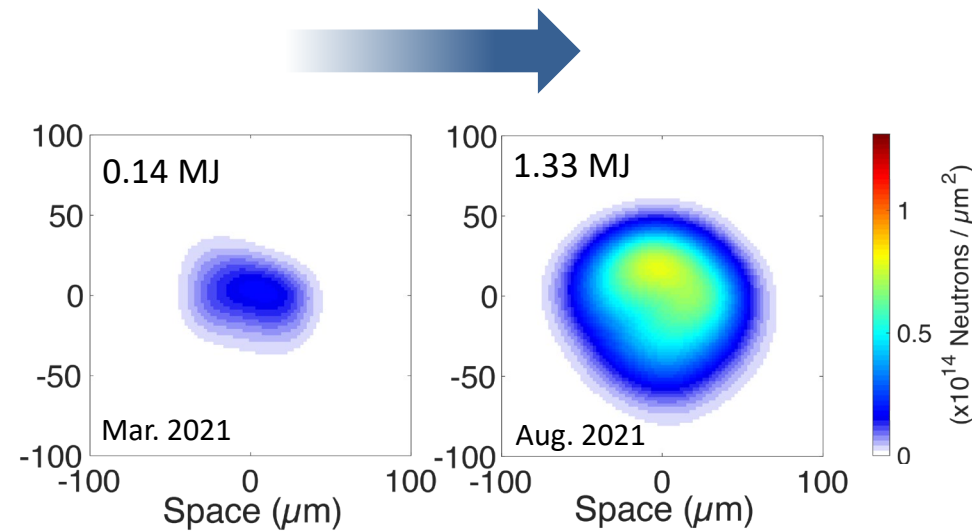
N221204
(2.05 MJ of laser energy)

Challenge is to achieve this increase in compression, while maintaining implosion symmetry (coupling)

Increases in x-ray drive and target quality enabled moving from a 'burning plasma' to one in which a Lawson criteria for ICF was satisfied

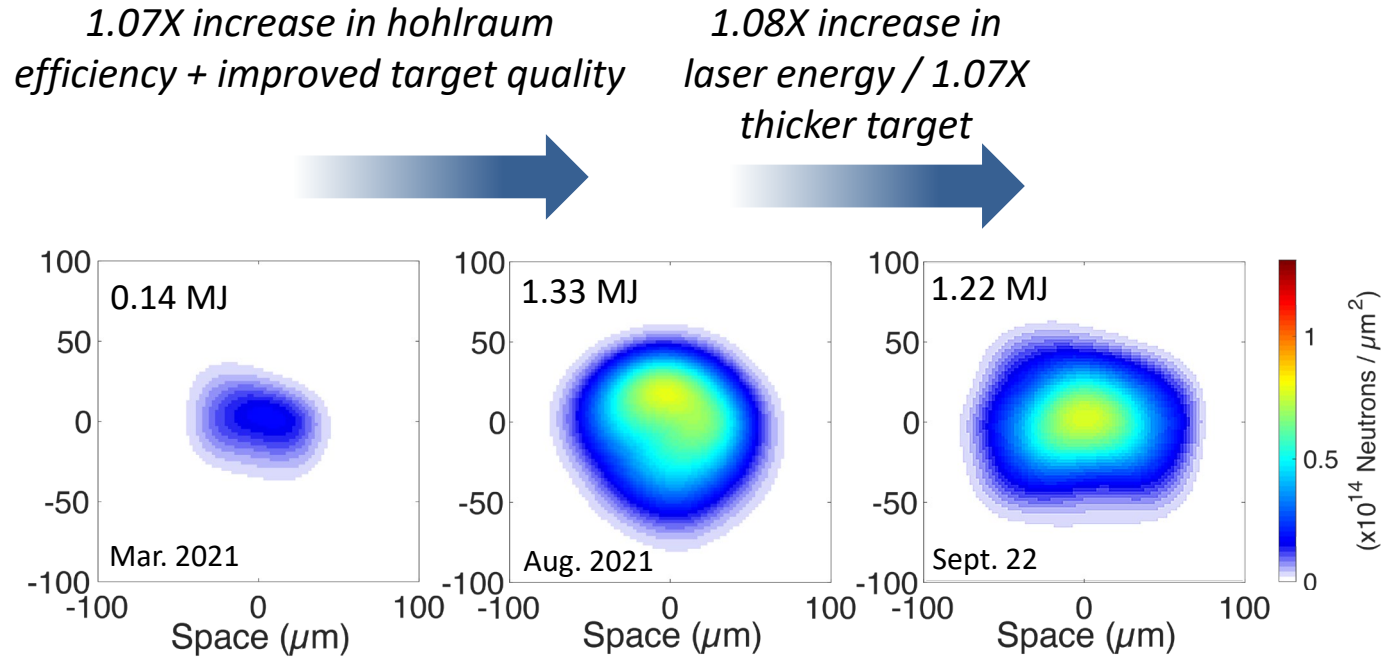
Burning plasma is one in which α -particle deposition is largest heating source ($Q_\alpha > P \frac{dV}{dt}$).

*1.07X increase in hohlraum
efficiency + improved target quality*



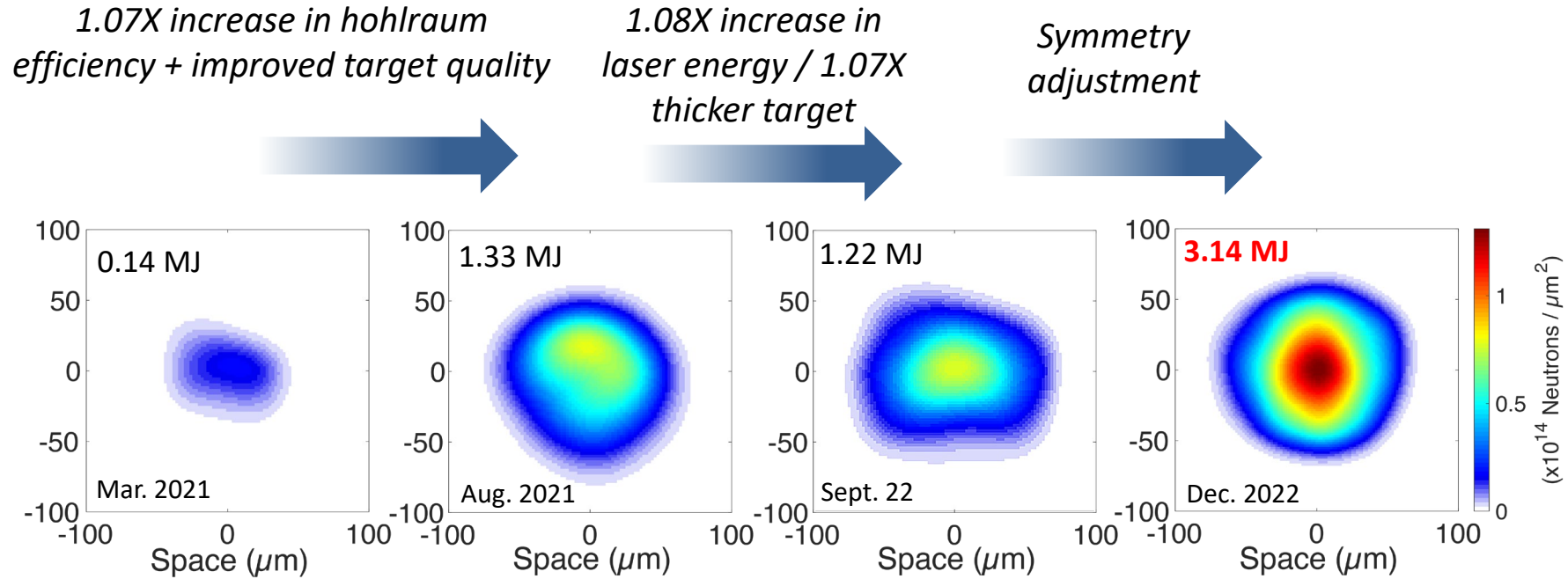
Lawson like criteria for ICF satisfied when α -heating larger than all power losses & $\frac{dT}{dt} > 0$, $\frac{dT^2}{dt^2} > 0$

Initial experiment with increased laser energy and thicker target gave significant fusion yield despite having an asymmetric shape



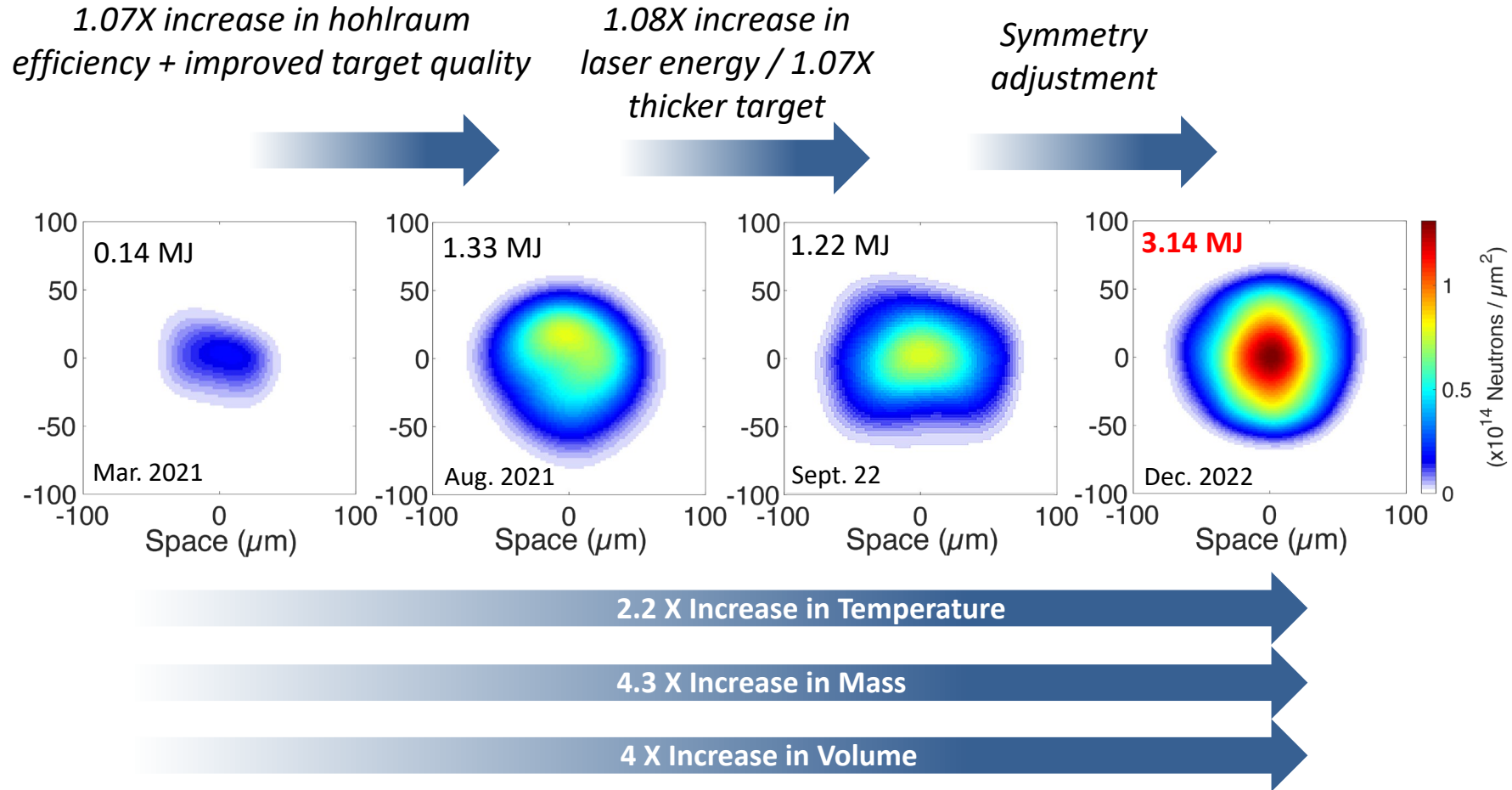
Asymmetries reduce rate and amount of $P \frac{dV}{dt}$ work lowering ignition threshold factor and achievable yields

Symmetry adjustment increased rate and amount of work done on reacting DT hot spot leading to Ignition



A 1.08X increase in laser energy increased the fusion yield by 1.5X-3X

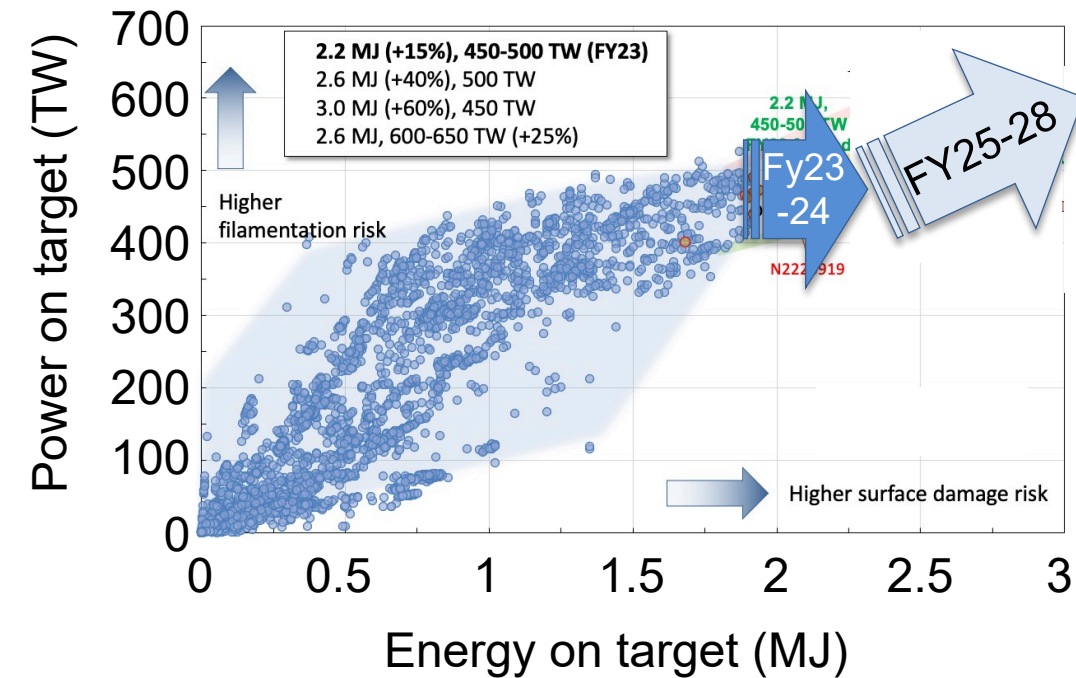
Over last two years, we increased hotspot temperature, mass and volume to achieve ~20x yield via improved targets and designs, laser energy



New burning dynamics = increases in temperature, mass, and size of hot spot all driven by increases in the alpha heating rate

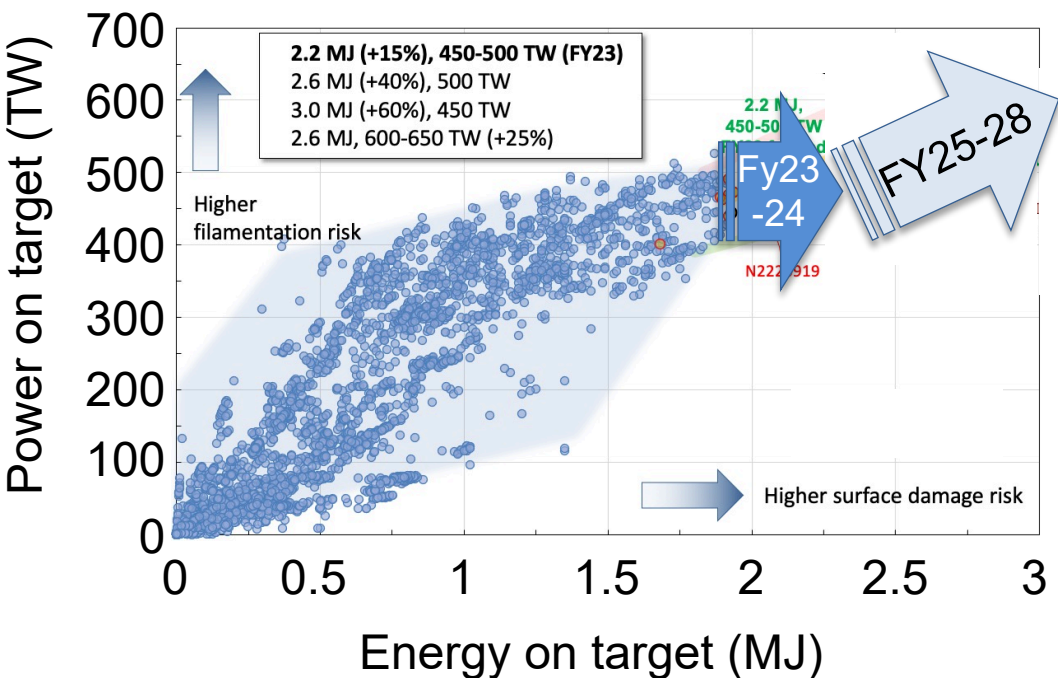
Increase fusion yields will be pursued multiple approaches with the near term (1-2 year) goal of 10 MJ

Increased laser energies and powers

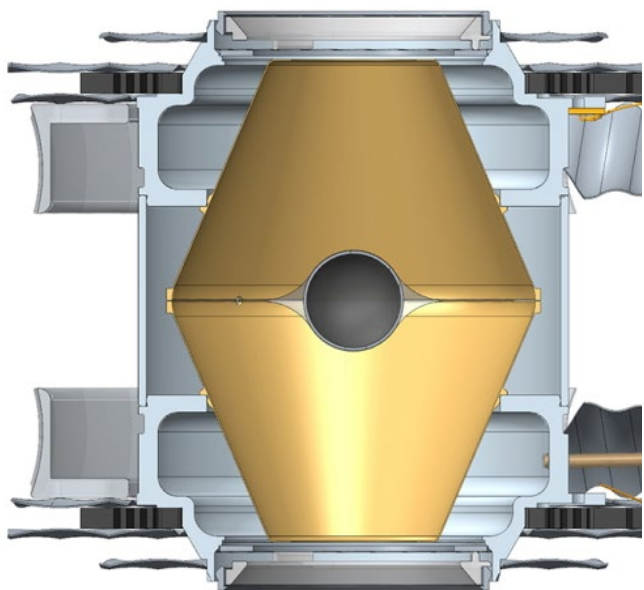


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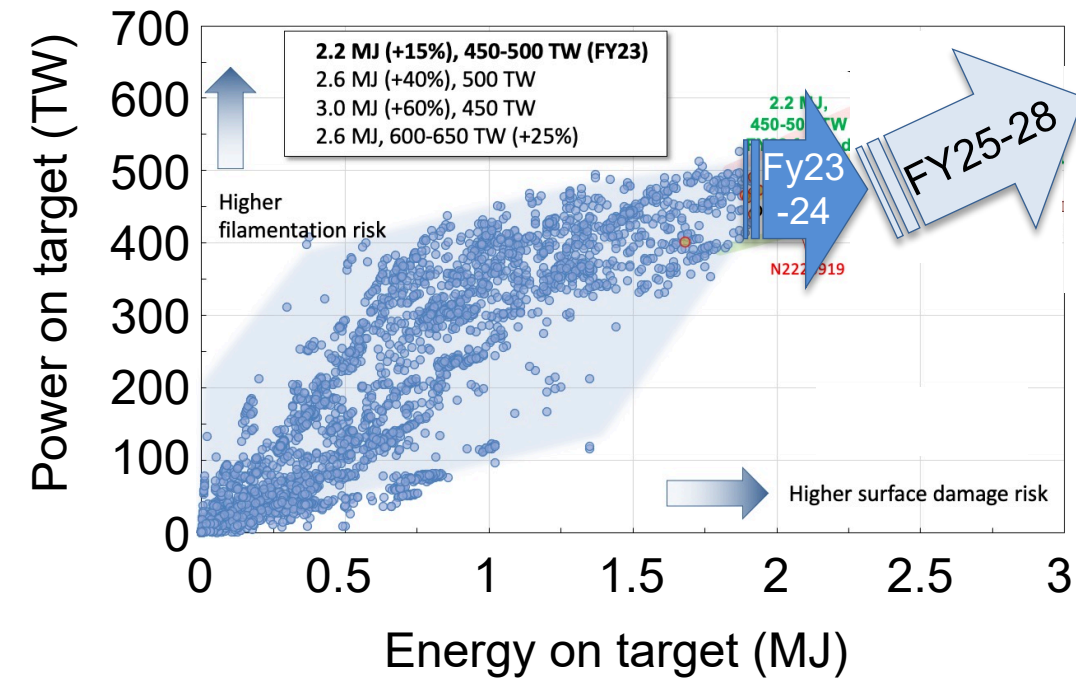


Higher efficiency radiation cavities

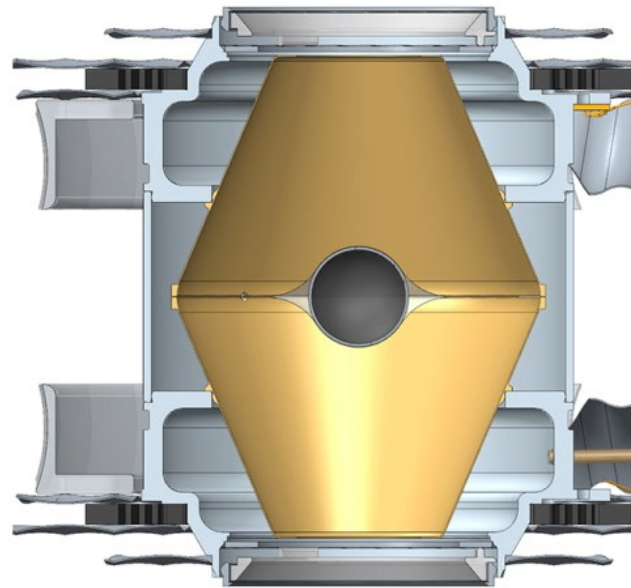


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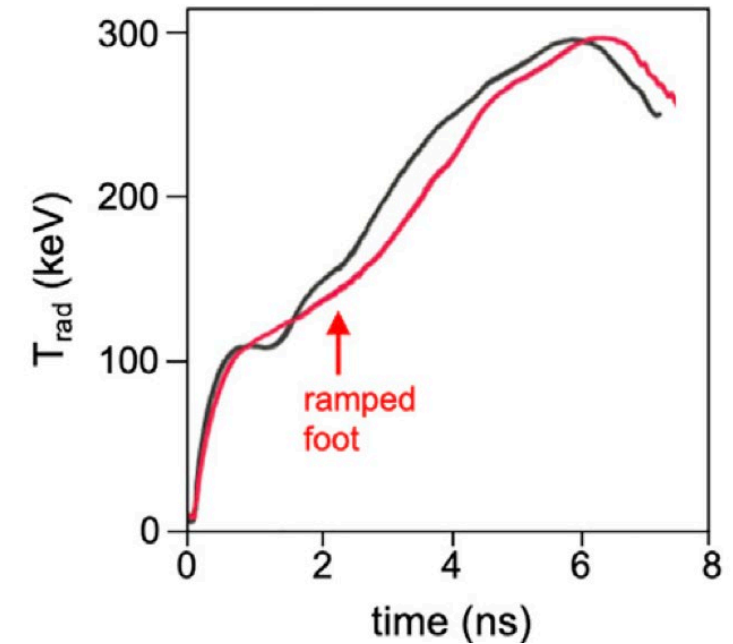
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Higher efficiency radiation cavities

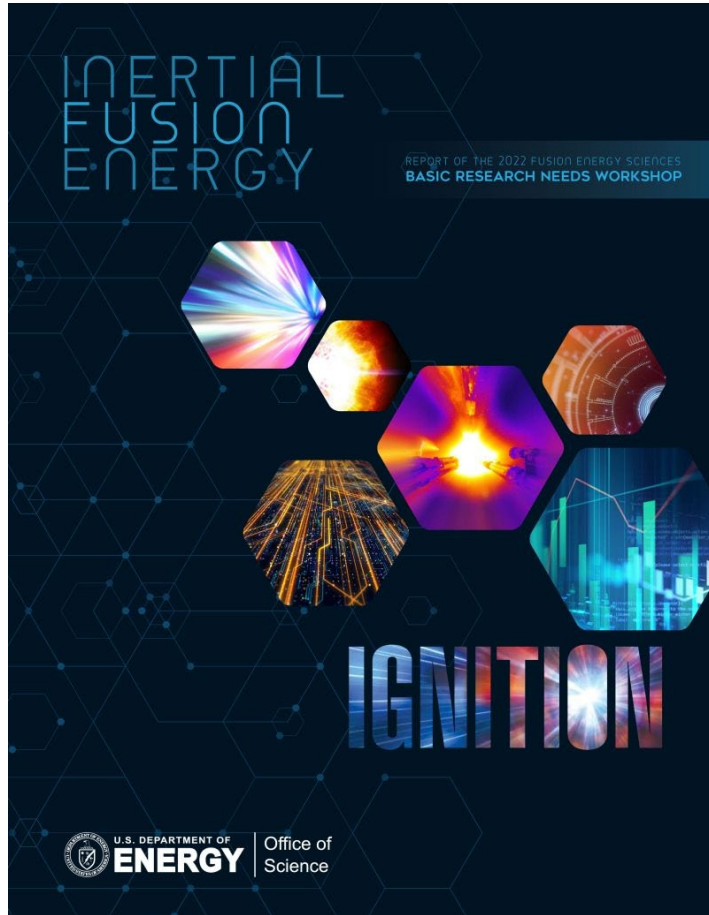


Higher compression / more stable implosions



Ignition provides fresh impetus and the scientific foundation for inertial fusion energy

Fusion Energy Sciences Basic Research Needs 2022 identifies priority research opportunities for IFE



Goals for 4 key research areas identified

1) Target Physics and Ignition

- Target gain ~ 50

2) Driver and Target Technologies

- Rep. rate ~ 10 Hz, high efficiency, low cost

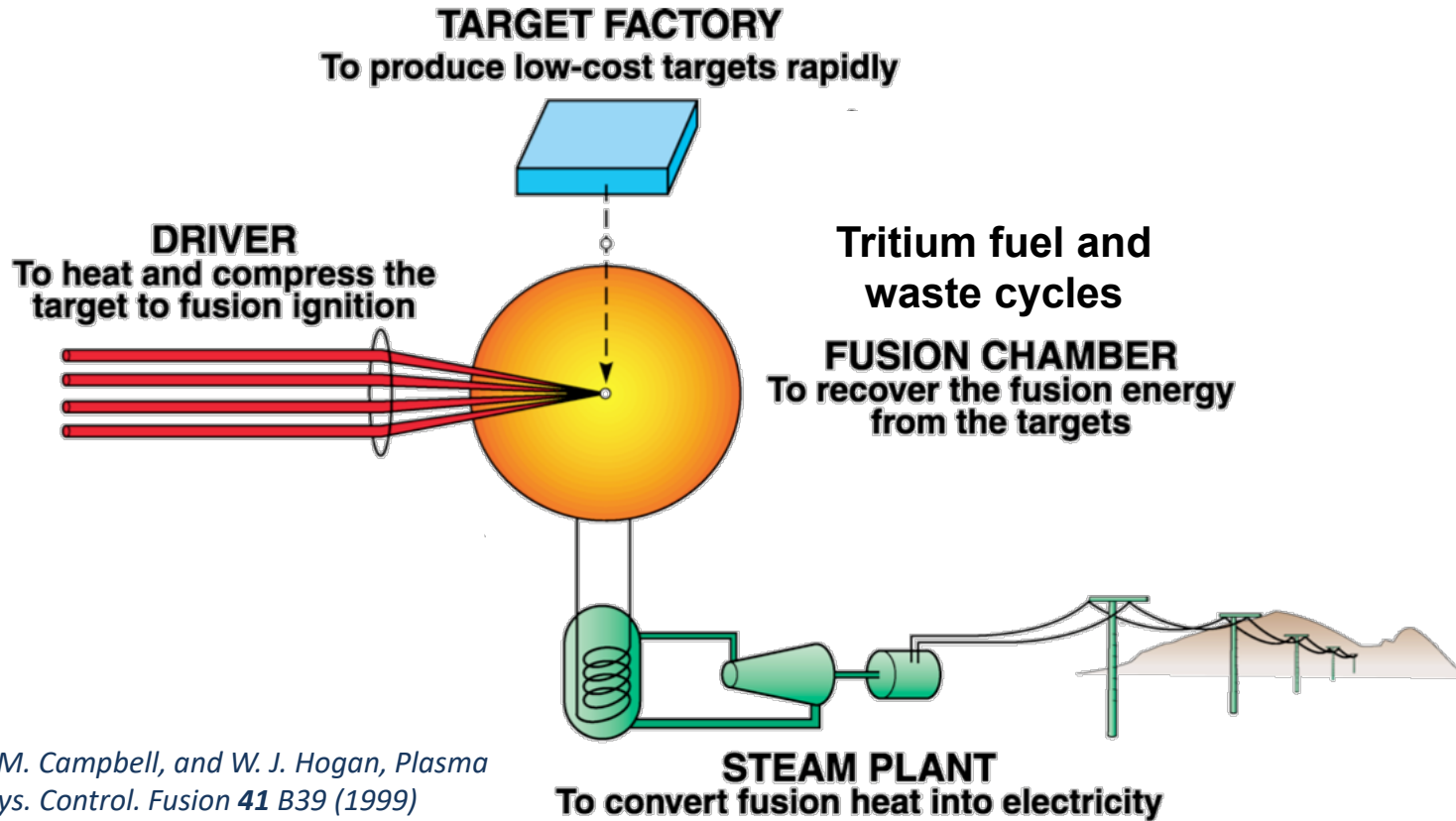
3) Fusion Power Plant Integrated Systems

- Tritium breeding / 1st wall

4) Cross Cutting:

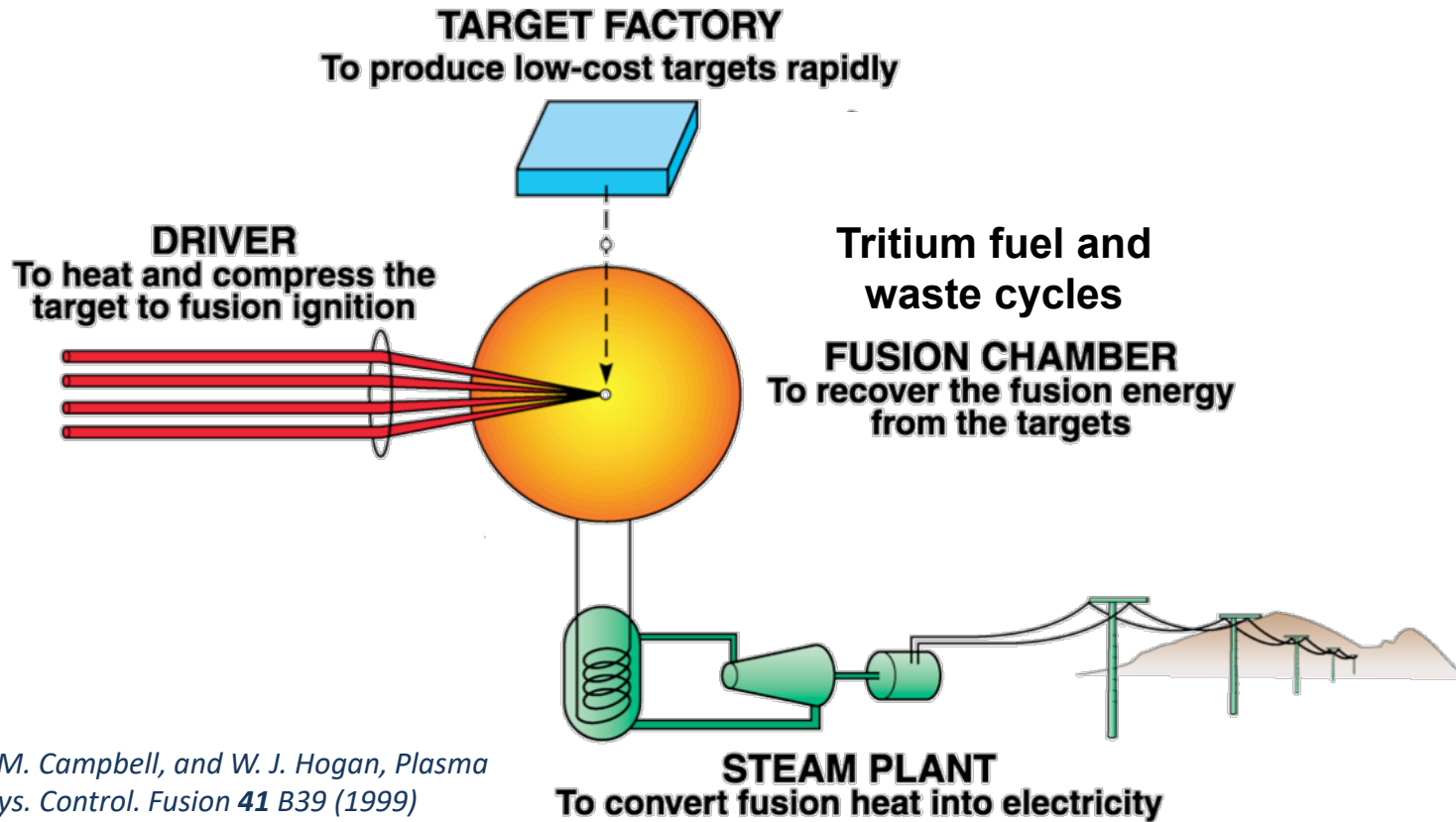
- Theory and Simulation
- Artificial Intelligence and Machine Learn
- Workforce

The concept for an IFE power plant includes a target, driver, chamber, target / fuel production, and a turbine to generate electricity



E. M. Campbell, and W. J. Hogan, Plasma Phys. Control. Fusion **41** B39 (1999)

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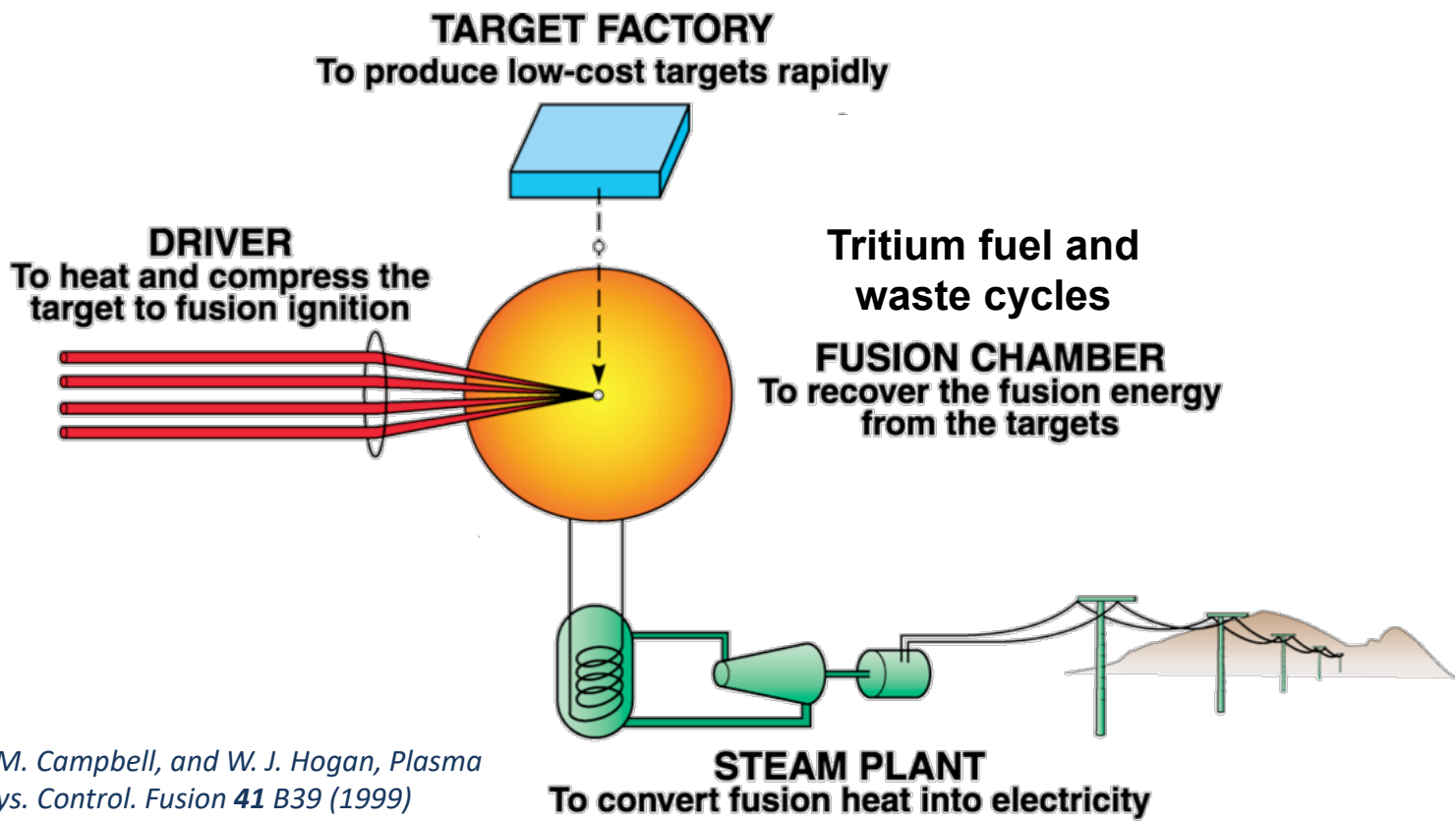


E. M. Campbell, and W. J. Hogan, *Plasma Phys. Control. Fusion* **41** B39 (1999)

Working backwards – example case:

Parameter	Value
Electrical Power (GWe)	1.25
Sub-system efficiency (%)*	50
Fusion Power (GWth)*	2.5
Fusion yield / shot (MJ)*	200
Repetition rate (Hz)*	12.5
Target gain*	65
Laser energy (MJ)*	3
Average Laser Power (GWe)*	0.25
Laser efficiency (%)*	15

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Laser energy (MJ)*	3
Average Laser Power (GWe)*	0.25
Laser efficiency (%)*	15

Near Term Goal: Develop target design with gain of ~15 to be able to test components at scale at integrated test facility



U.S. DOE has launched public-private partnership milestone program and an IFE Science & Technology Accelerated Research (IFE-STAR) program

Milestone Program: 46 M\$

“Within five to 10 years, the eight awardees will resolve scientific and technological challenges to create designs for a fusion pilot plant that will help bring fusion to both technical and commercial viability.”



IFE-STAR Program: 45 M\$

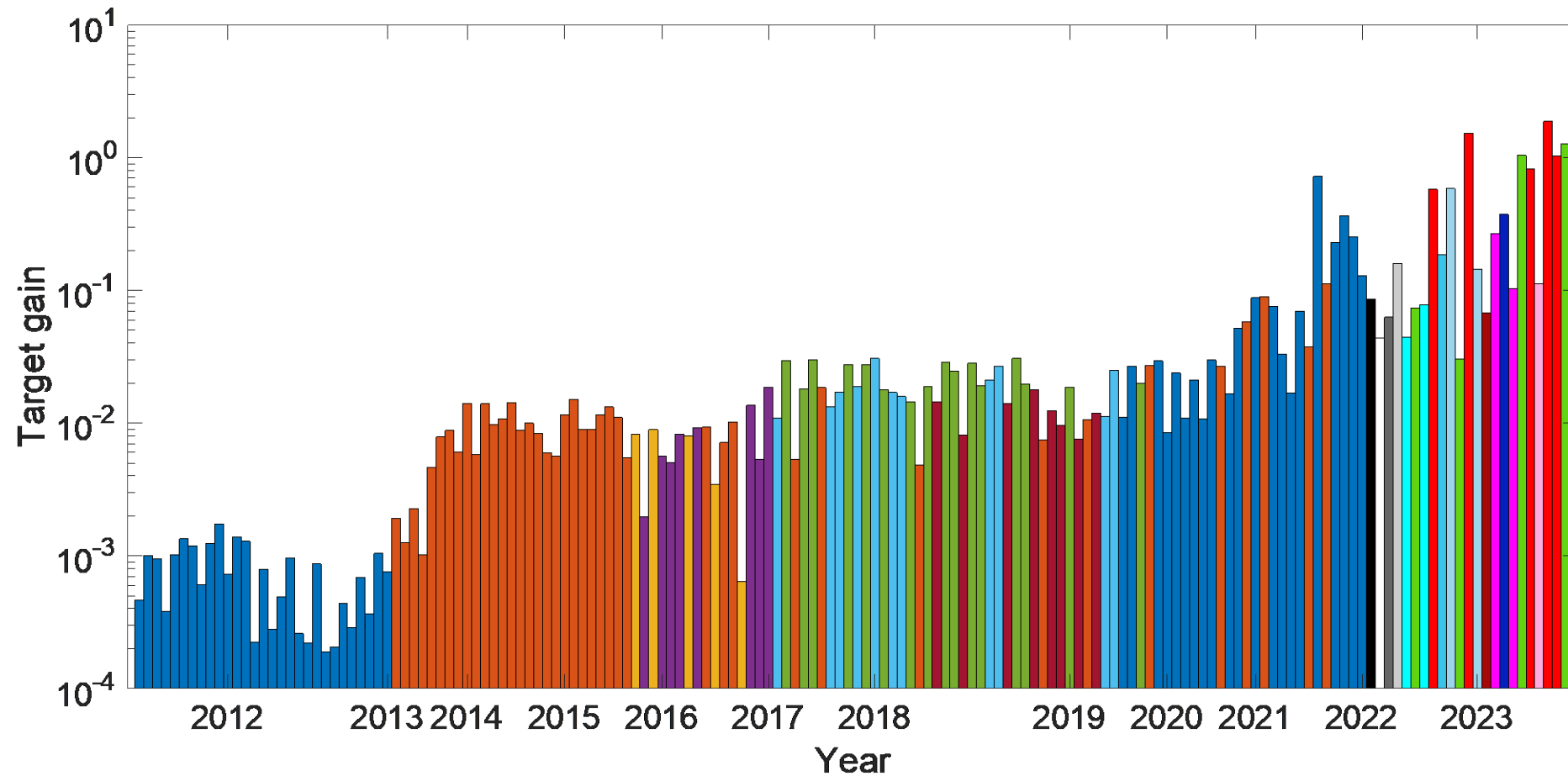
“The objective of IFE-STAR is to provide an IFE framework that leverages expertise and capabilities across national laboratories, academia, and industry to advance foundational IFE S&T using integrated and self-consistent solutions as outlined in the BRN report “



Awards will be announced in early FY24



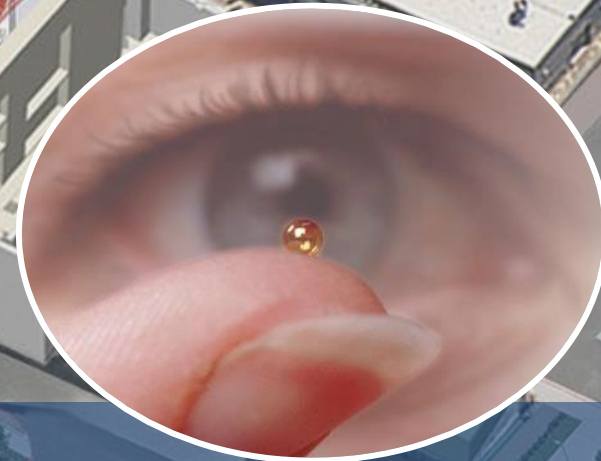
Many challenges remain, but there is proof that with sustained effort, we can accomplish challenging things together



Thanks!

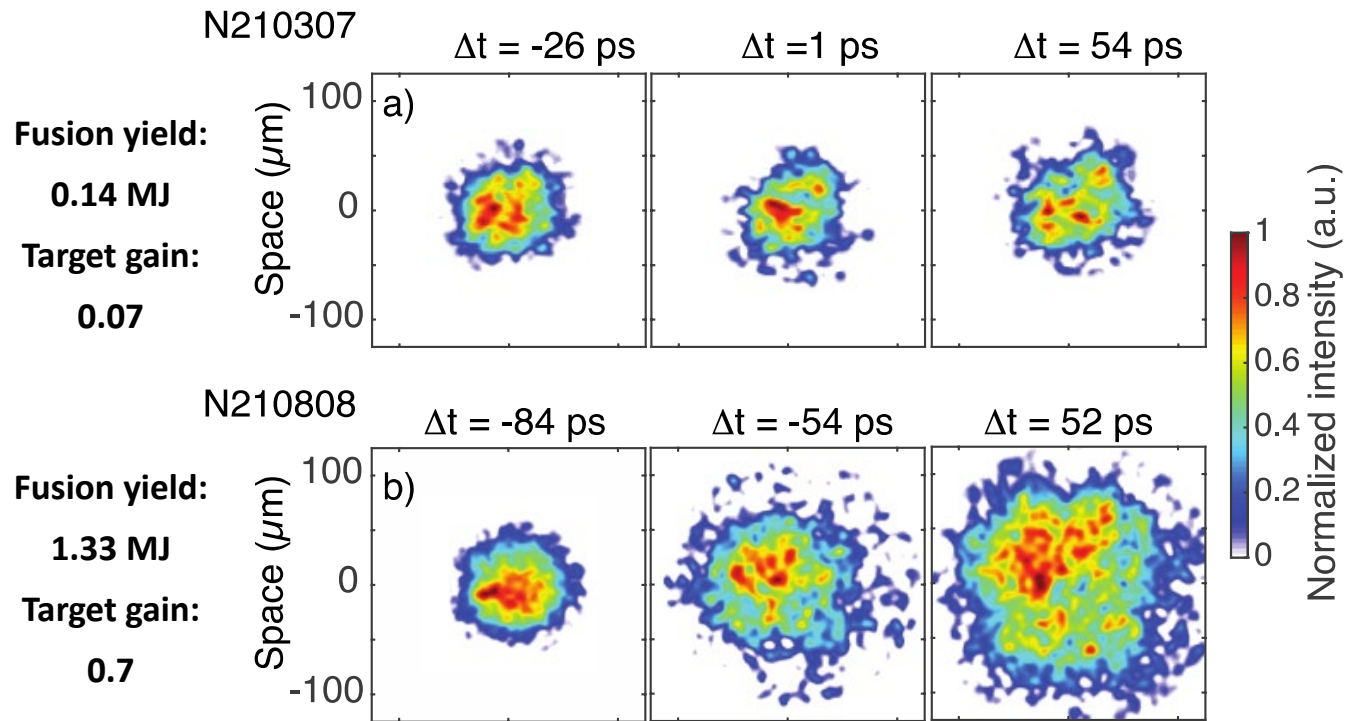


192 laser beams are concentrated into a $\sim\text{mm}^3$ target

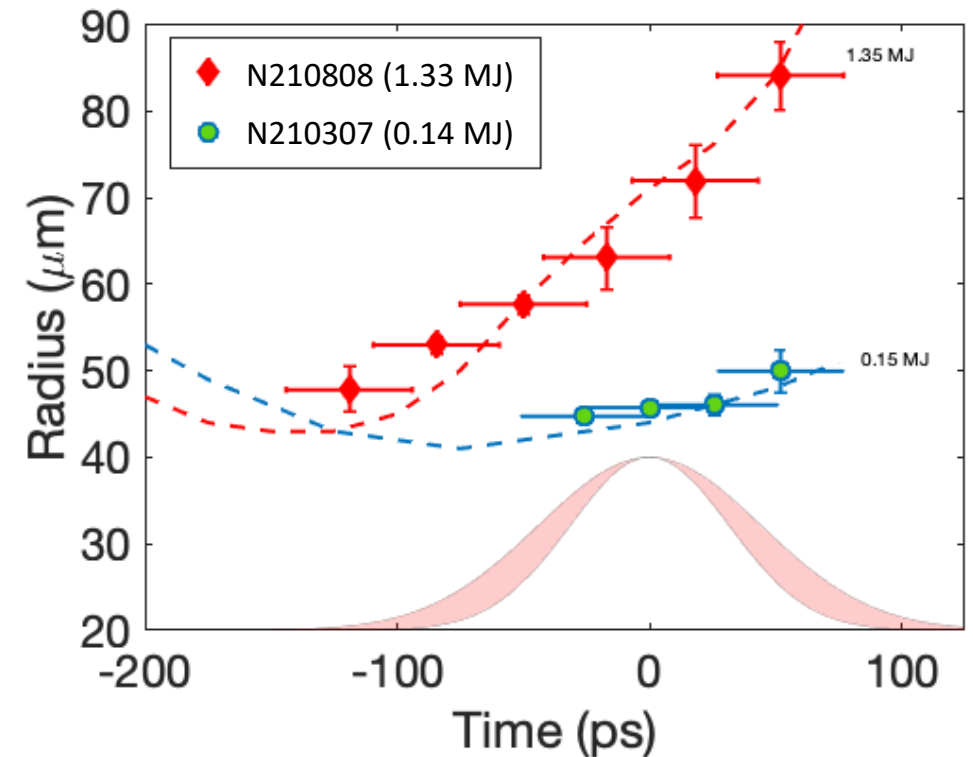
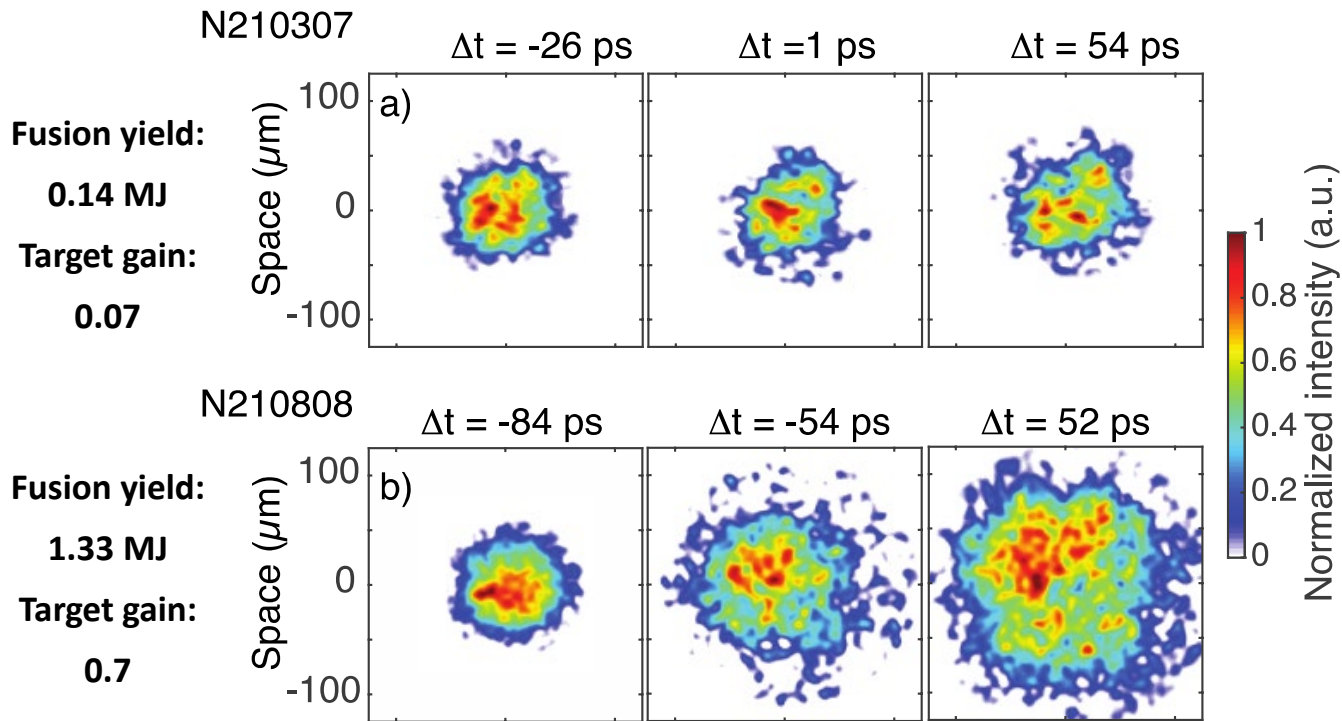


~ 300 MJ of stored electrical energy / shot

Time resolved x-ray emission shows a rapid change in DT plasma emission volume as fusion yield and target gain increase



Rapid expansion of the plasma, while neutron emissivity continues to rise direct evidence of alpha heating overcoming expansion losses



$$C_{DT} \frac{dT}{dt} = Q_{\alpha} - Q_{rad.} - Q_{cond.} - Q_{PdV}$$

Can use x-ray and nuclear emission data to examine the DT power balance

Near term goal (1-2 years) is to push towards 10 MJ of fusion yield, target gain of ~5



Longer term – Upgrades to laser + facility to enable 10's of MJ.