Creating a Star on Earth, Ignition, and a Fusion Energy Future

DOE CSGF Annual Program Review

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Lawrence Livermore National Laboratory

This work builds on decades of research by an incredible team across LLNL and the wider community!

Lawrence Livermore National Laboratory

WCI WEAPONS AND COMPLEX INTEGRATION

NIF&PS

Sandia National Laboratories

DE LA RECHERCHE À L'INDUSTRIE cea

Los Alamos NATIONAL LABORATORY

Diamond Materials — Advanced Diamond Technologies

UR LLE

AWE

MIT PSFC Plasma Science and Fusion Center

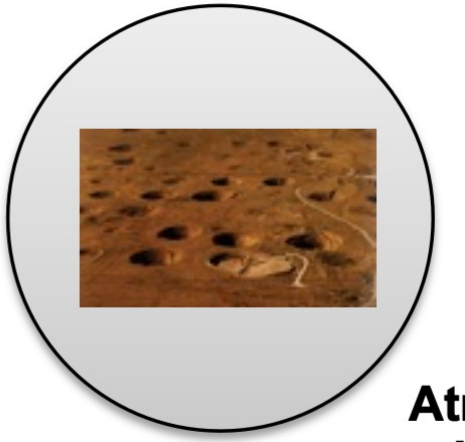
GENERAL ATOMICS

NNSA National Nuclear Security Administration

...and many more

Our earth faces an array of threats to its environmental and social balance

Nuclear Warfare



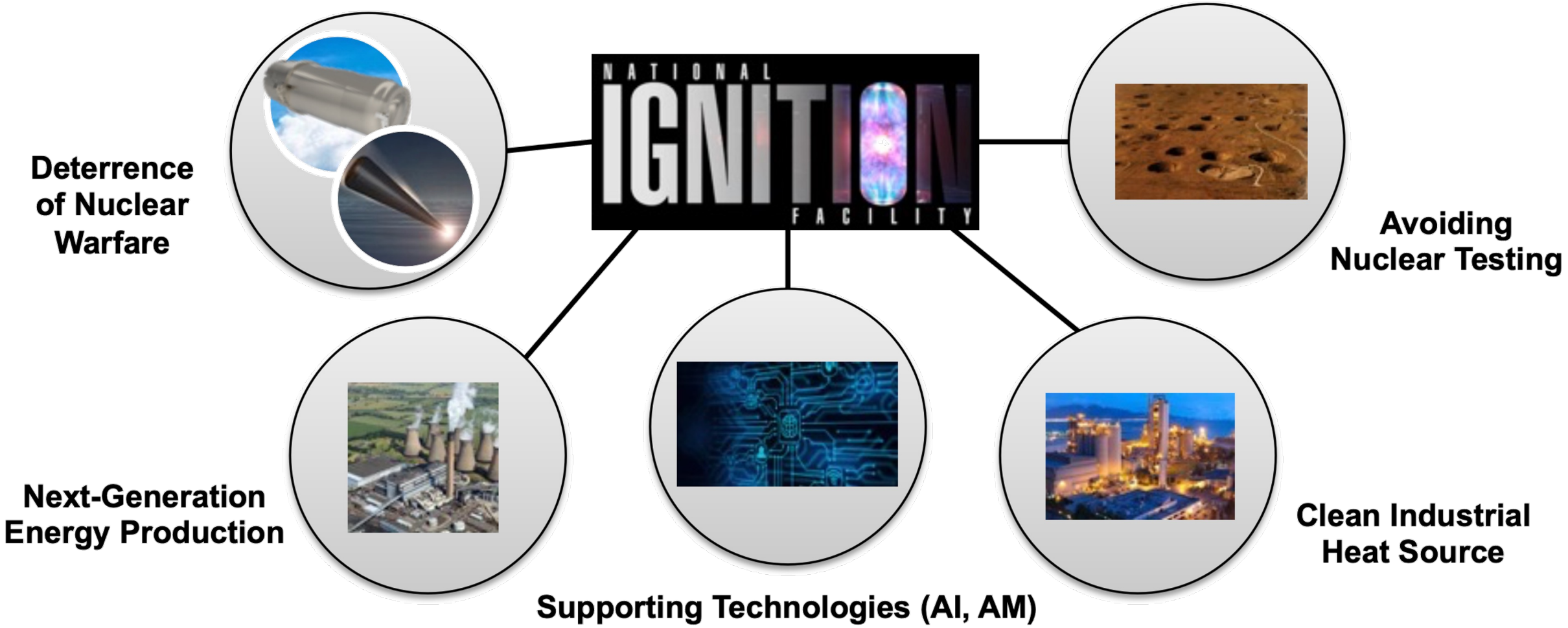
Atmospheric and Underground Nuclear Testing

Energy-Related Greenhouse Gas Production

Technology Disruption

Industrial Processing Greenhouse Gas Production

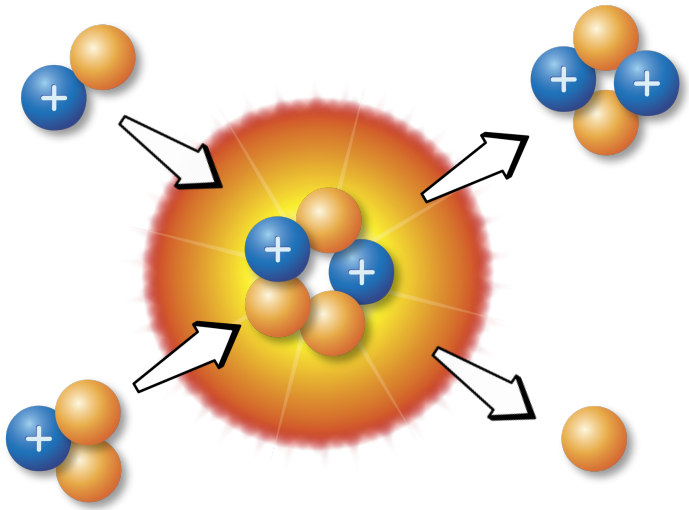
Fusion energy, and specifically fusion ignition on the NIF, has an impact on each of these areas



Fusion: the reaction that powers the sun and the stars

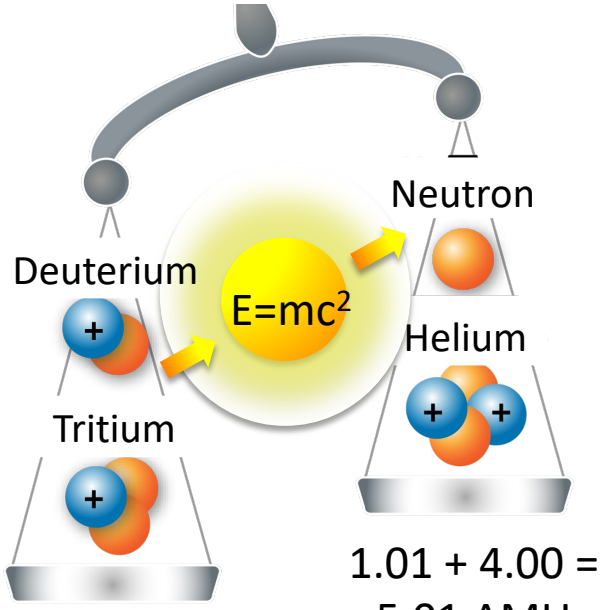
^{2}H - Deuterium

^{4}He – Helium



^{3}H - Tritium

neutron



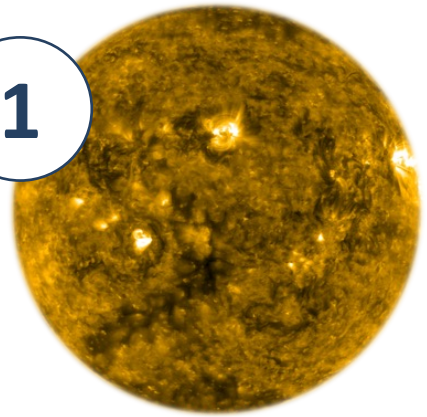
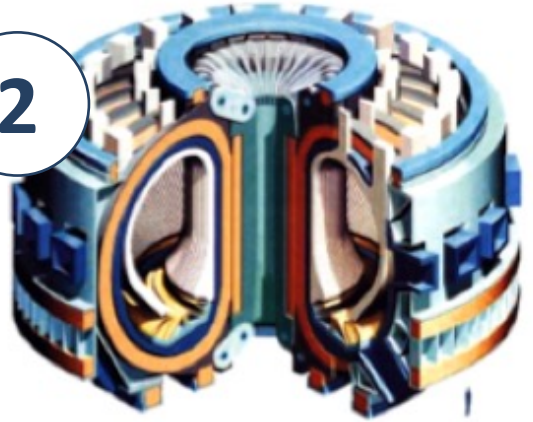
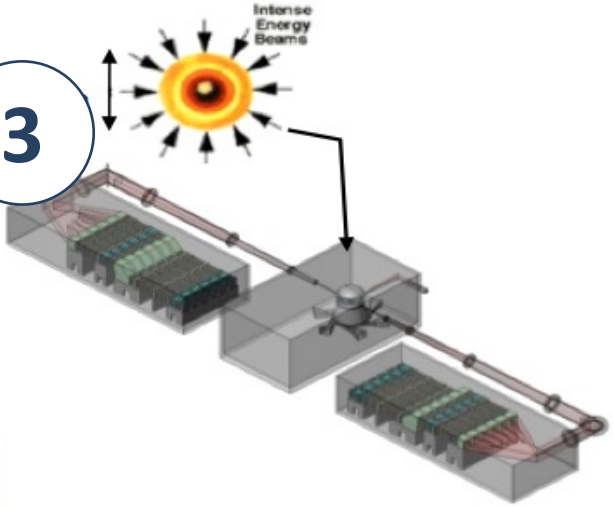
2.01 + 3.02 =
5.03 AMU

1.01 + 4.00 =
5.01 AMU
+ 17.6 MeV

$$D + T \rightarrow \alpha(3.5\text{MeV}) + n(14.1\text{MeV})$$

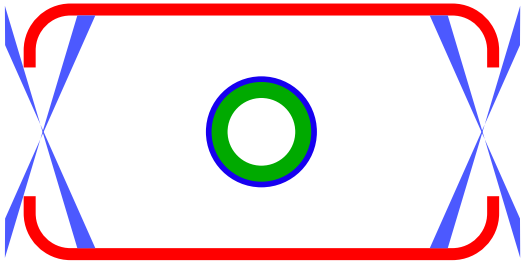
$$Q_{fusion} = 3.3 \times 10^{11}\ \text{J/g}$$

There are at least three ways to achieve nuclear fusion

	Gravitational Confinement	Magnetic Confinement	Inertial Confinement
	1 	2 	3 
Density	**10^4 x solid**	**solid / 10^8**	**10^3 x solid**
Temperature	**1 keV**	**10 keV**	**10 keV**
Confinement time	**10^5 years**	**seconds**	**10's ps**

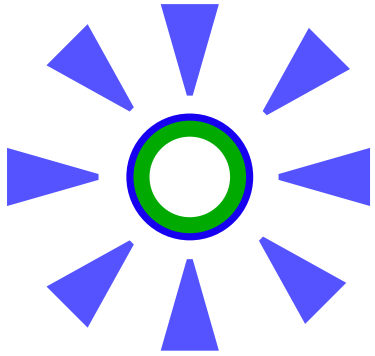
Inertial Confinement Fusion (ICF) can be achieved by using high power lasers to drive a spherical implosion

Indirect Drive



- Relaxed beam uniformity
- Reduced hydrodynamic instability

Direct Drive



- Higher coupling efficiency
- Reduced laser-plasma interaction effects

Fuel is compressed by blowoff in rocket-like reaction

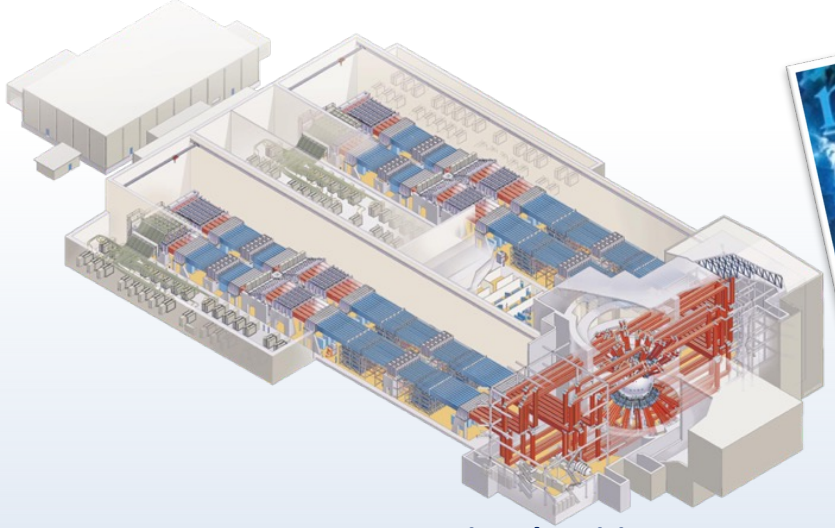
Fuel core reaches 20x density of lead, ignites at 100,000,000˚C

Thermonuclear burn spreads, yielding many times the input energy

Image taken from "Matter at High-Energy Densities," Univ of Rochester, Laboratory for Laser Energetics

Six decades of innovation

John Nuckolls



1.3 MJ
08/08/21

3.15 MJ
12/05/22

First concept of inertial confinement fusion

Invention of the laser

Janus laser
(0.2 kilojoules)

Argus

Shiva

Nova
(30 kilojoules)

National Ignition Facility key decision

National Ignition Facility operations
(1,900 kilojoules)

1960 1970 1980 1990 2000 2010 2020

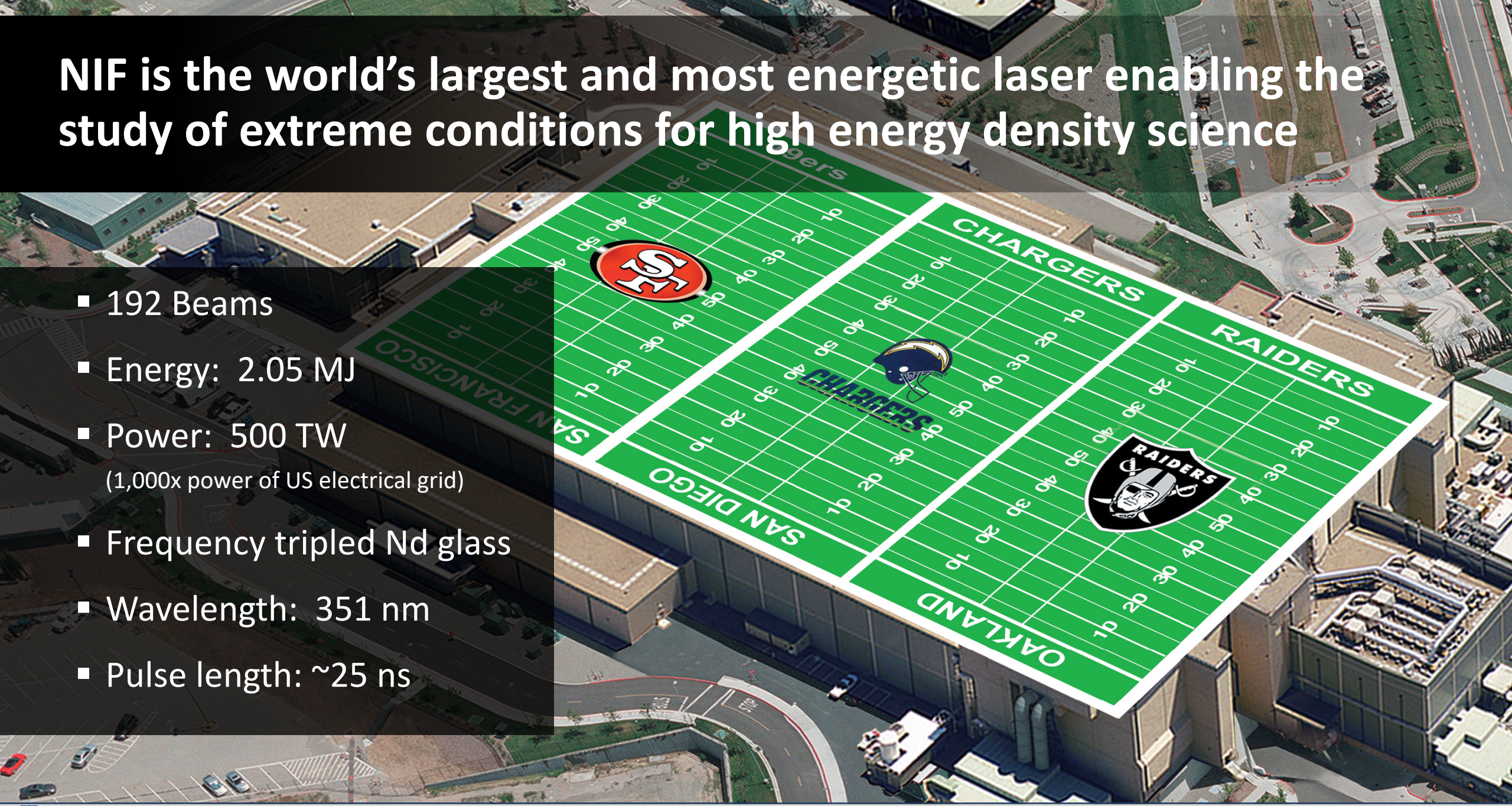
End of underground nuclear tests

Science-based Stockpile Stewardship

Reaching ignition is the culmination of decades of passion, hard work, and learning

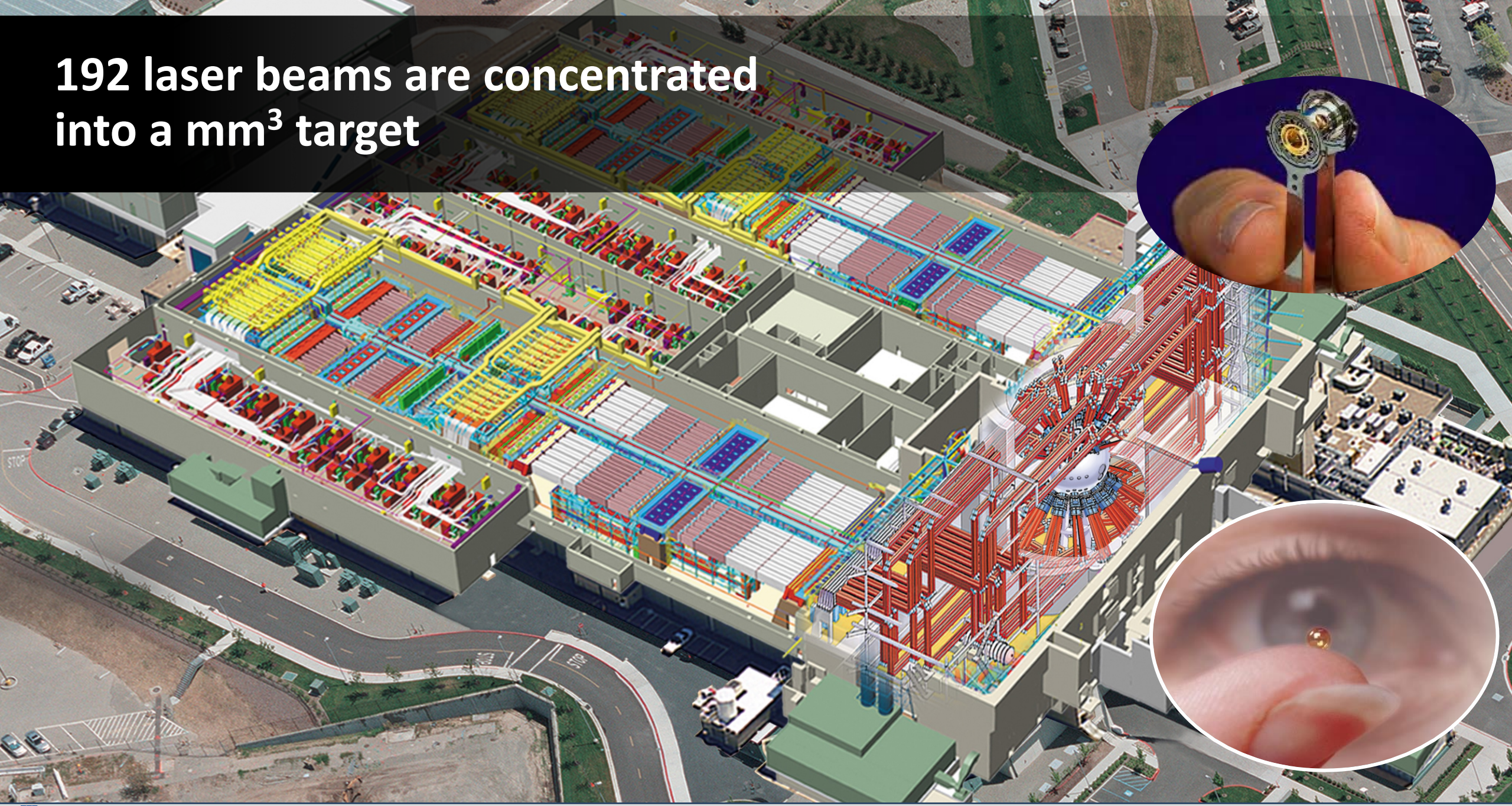
At the National Ignition Facility (NIF) we are building our own miniature sun

NIF is the world's largest and most energetic laser enabling the study of extreme conditions for high energy density science



- 192 Beams
- Energy: 2.05 MJ
- Power: 500 TW
  (1,000x power of US electrical grid)
- Frequency tripled Nd glass
- Wavelength: 351 nm
- Pulse length: ~25 ns

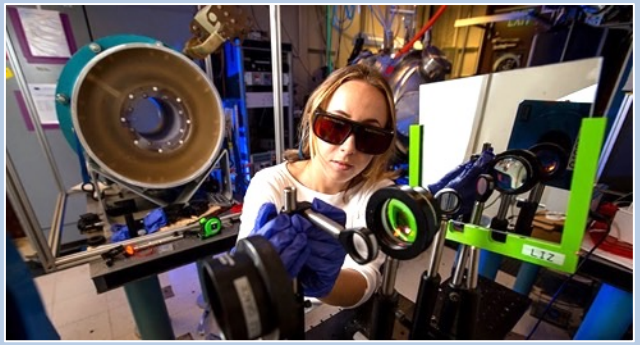
192 laser beams are concentrated into a mm^3 target



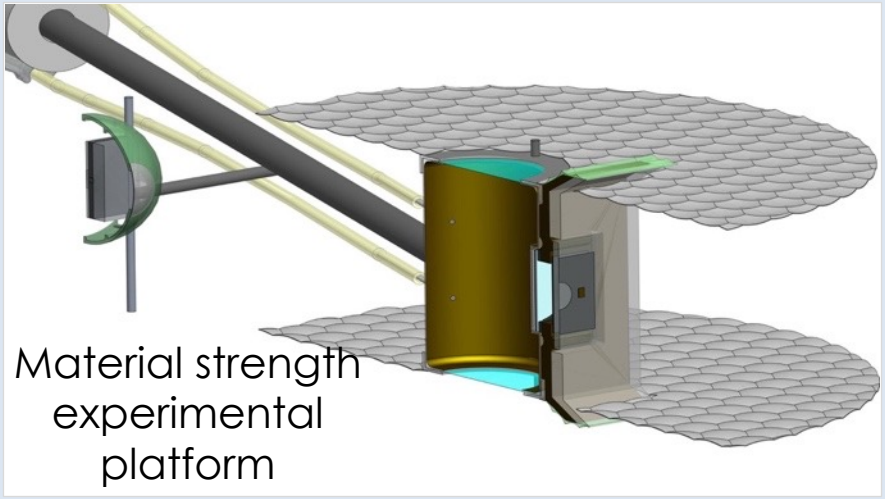
We utilize NIF in four main ways to ensure confidence in the current and future stockpile

Supporting stockpile decisions for current and future stockpile

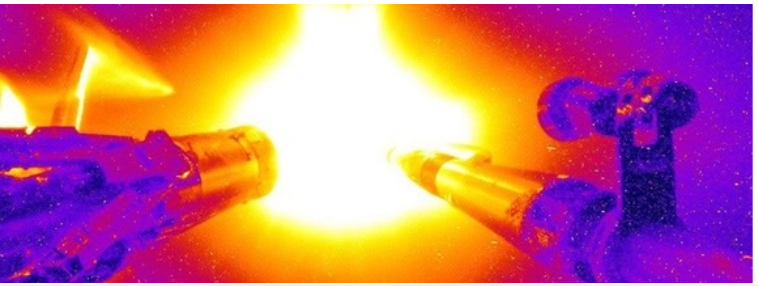
Training the next generation of nuclear weapons scientists and engineers



Advancing our understanding of weapons science

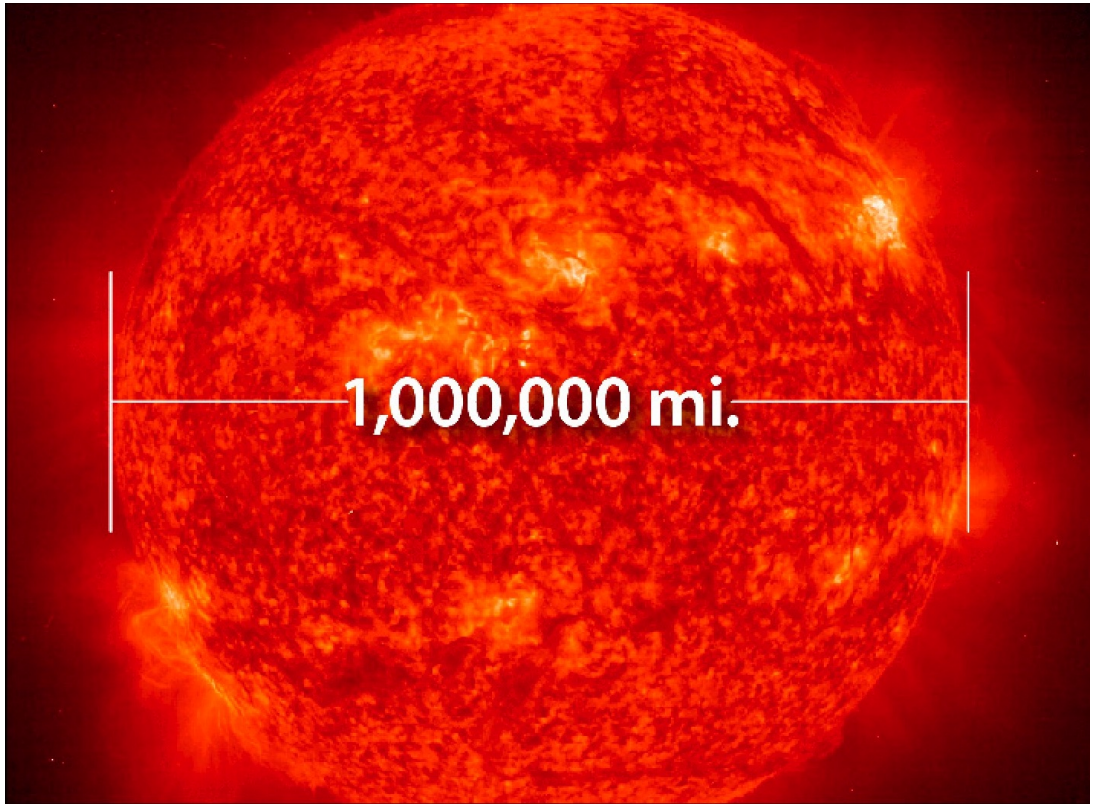


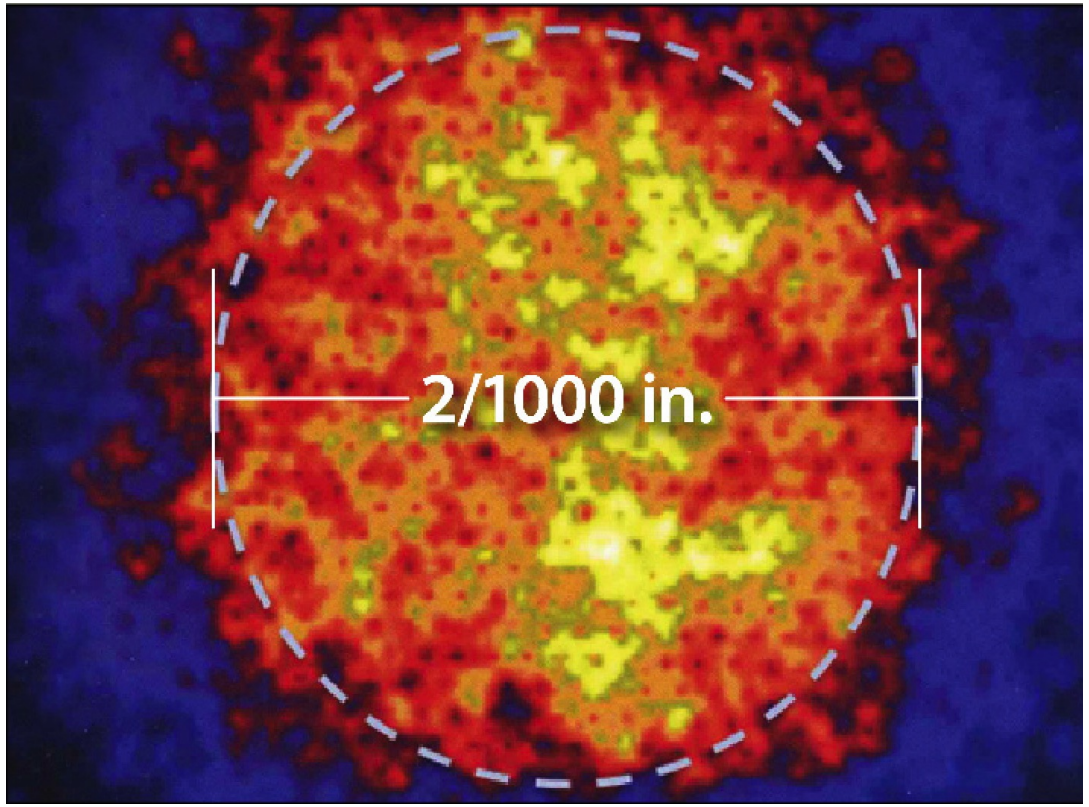
Material strength experimental platform



Expanding our capabilities to reach more extreme conditions (e.g. ignition)

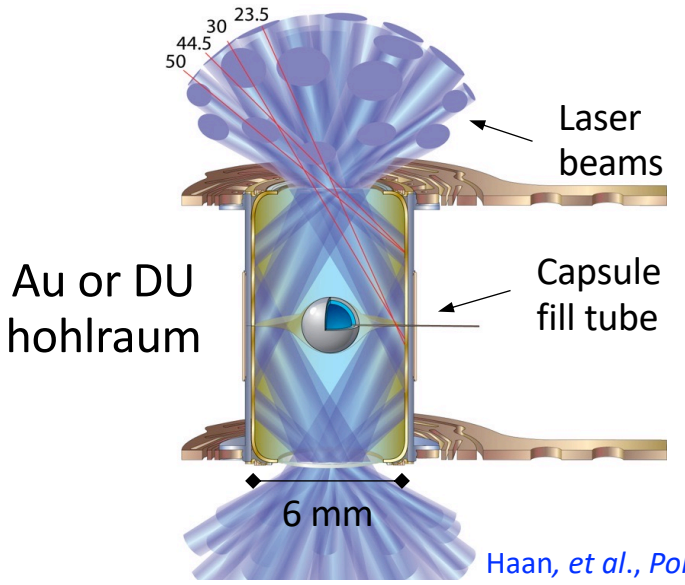
We use Inertial Confinement Fusion (ICF) to bring star power to earth





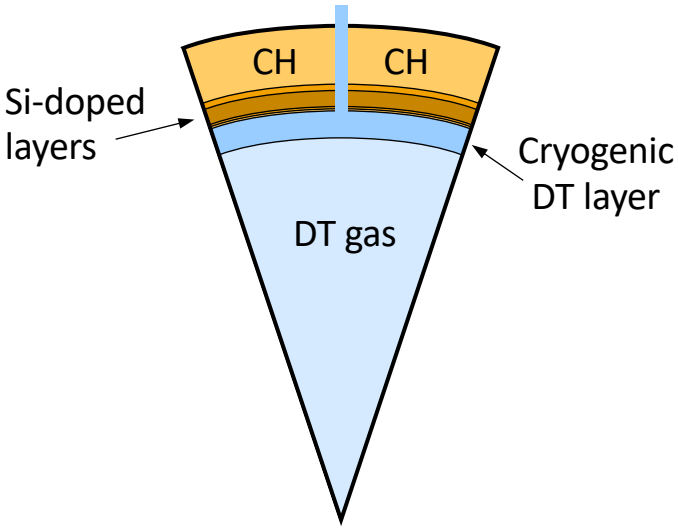
The NIF uses a laser driven hohlraum to compress a fuel pellet of deuterium and tritium to achieve the conditions for ignition

The hohlraum is a cylindrical cavity that serves as an x-ray "oven"

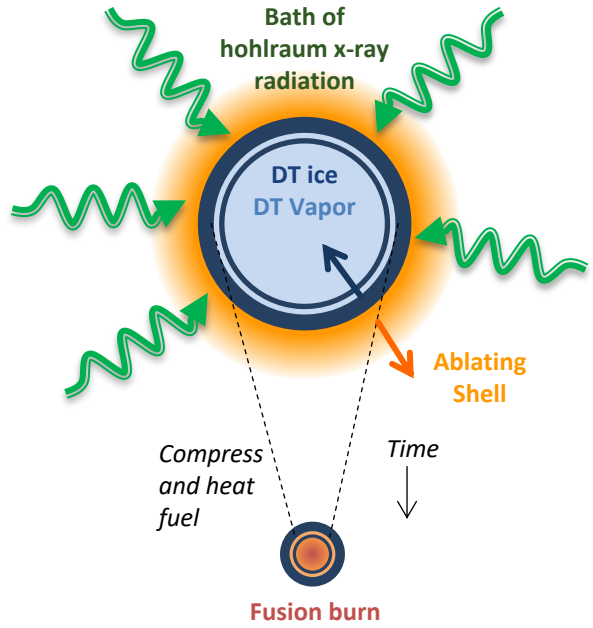


Haan, *et al.*, *PoP*, 2011

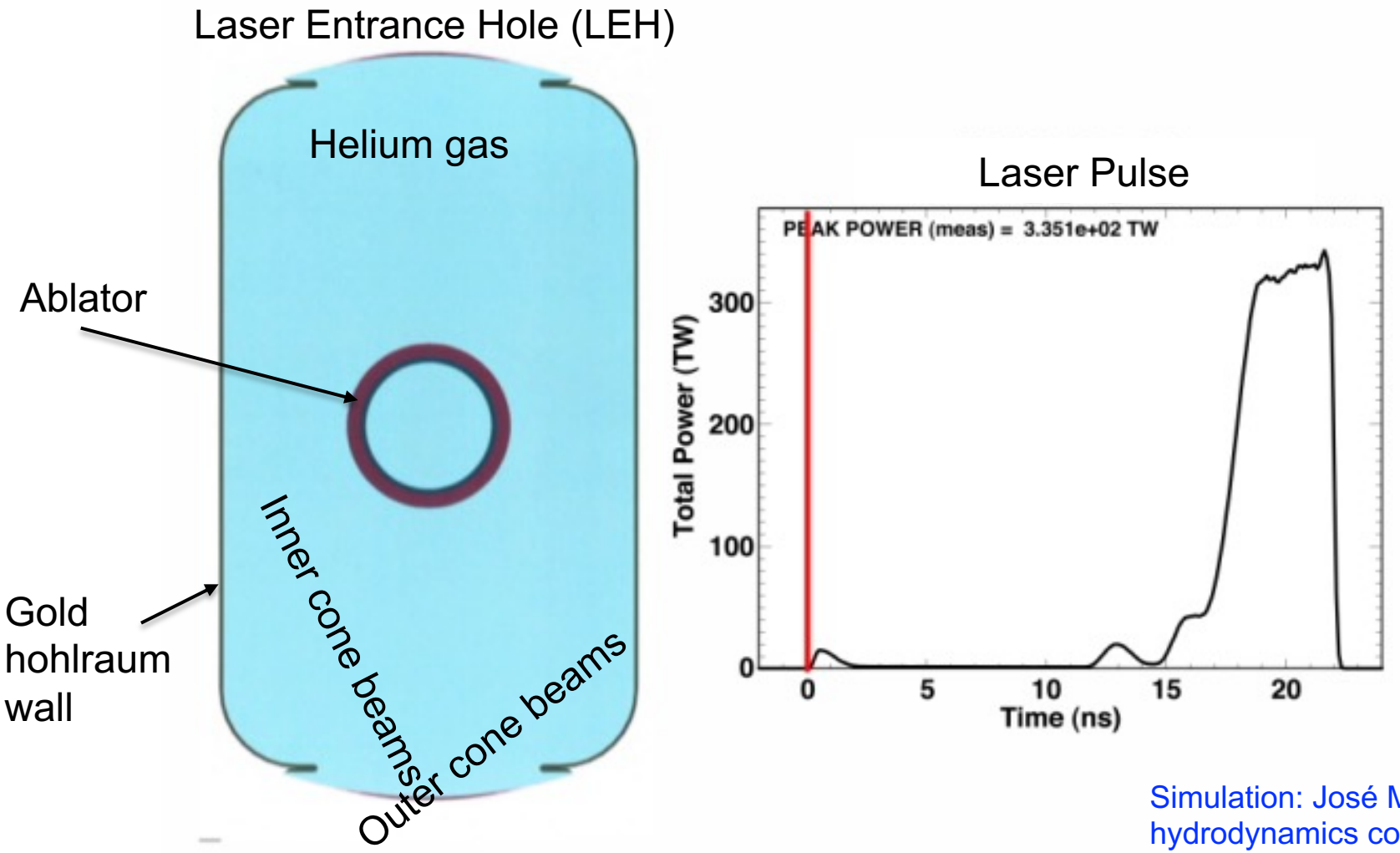
The fuel capsule consists of a plastic or HDC ablator surrounding DT ice and gas



The trick of ICF is to turn 100 million atmospheres of pressure into 300 billion



We must rely on numerical simulation to capture the multi-fidelity, multi-physics of ICF



Simulation: José Milovich with radiation-hydrodynamics code HYDRA

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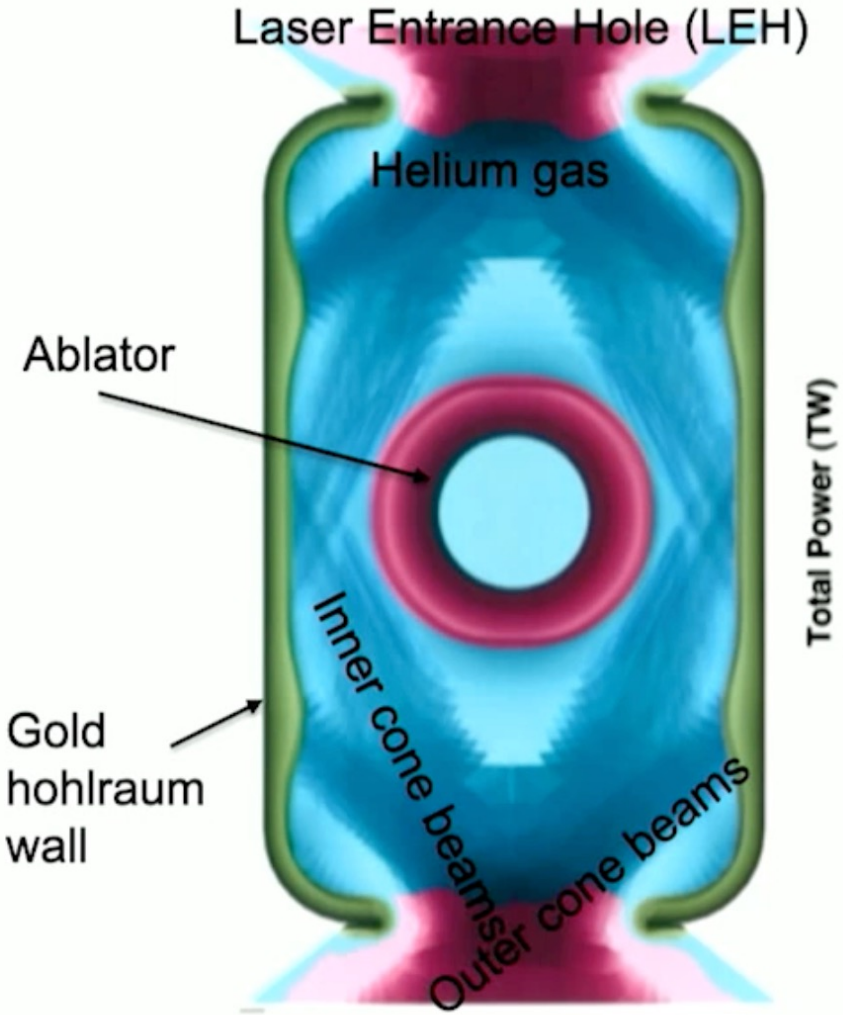

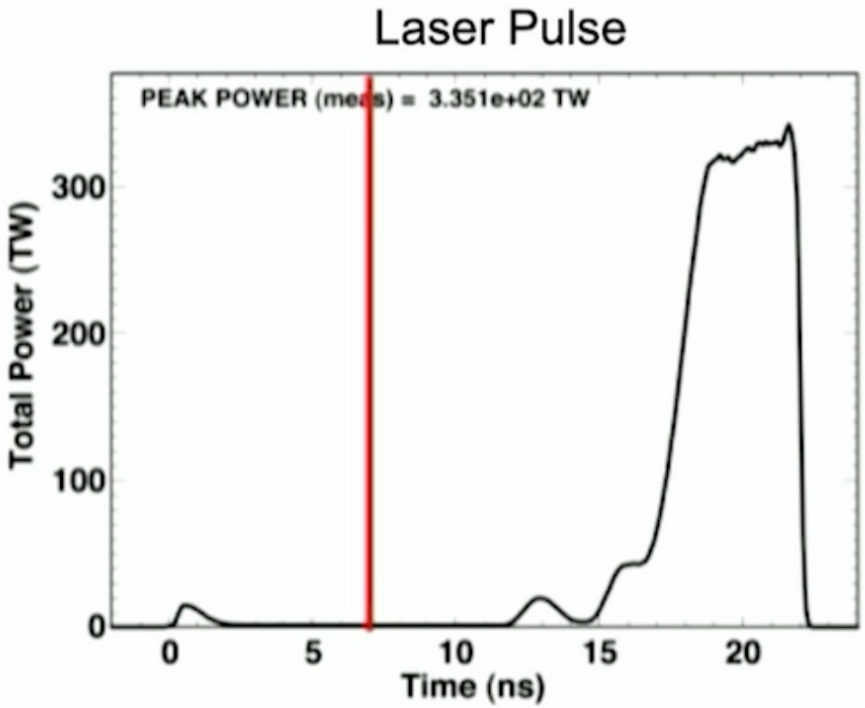

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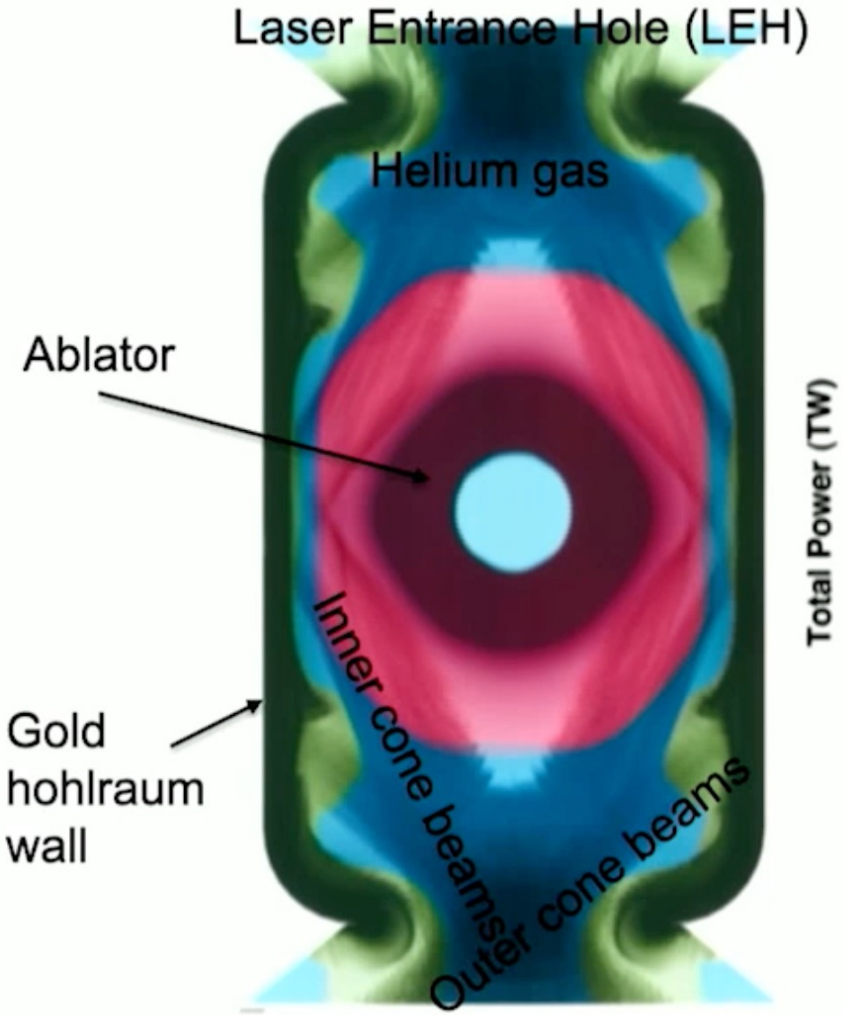

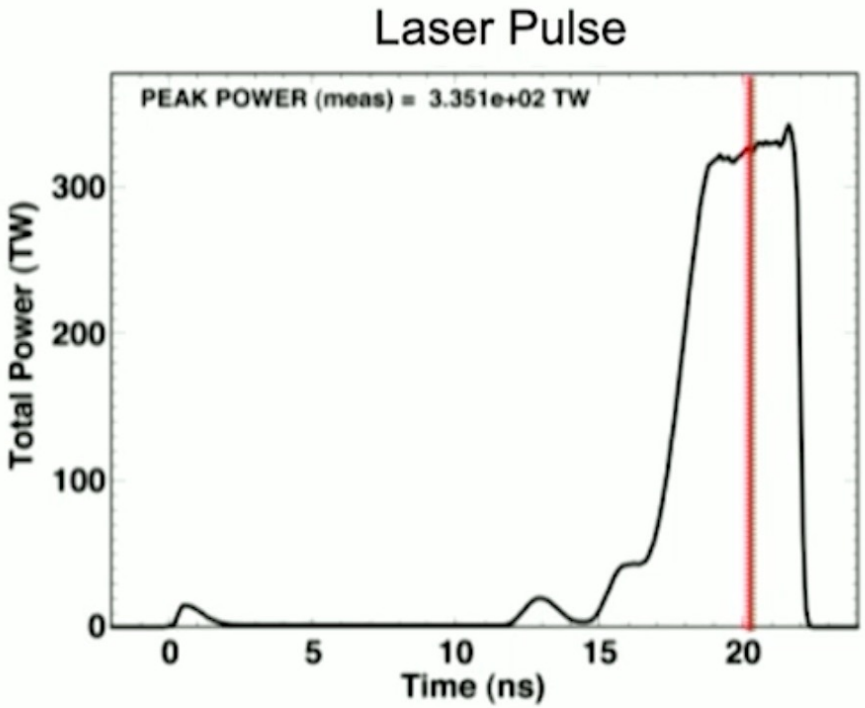

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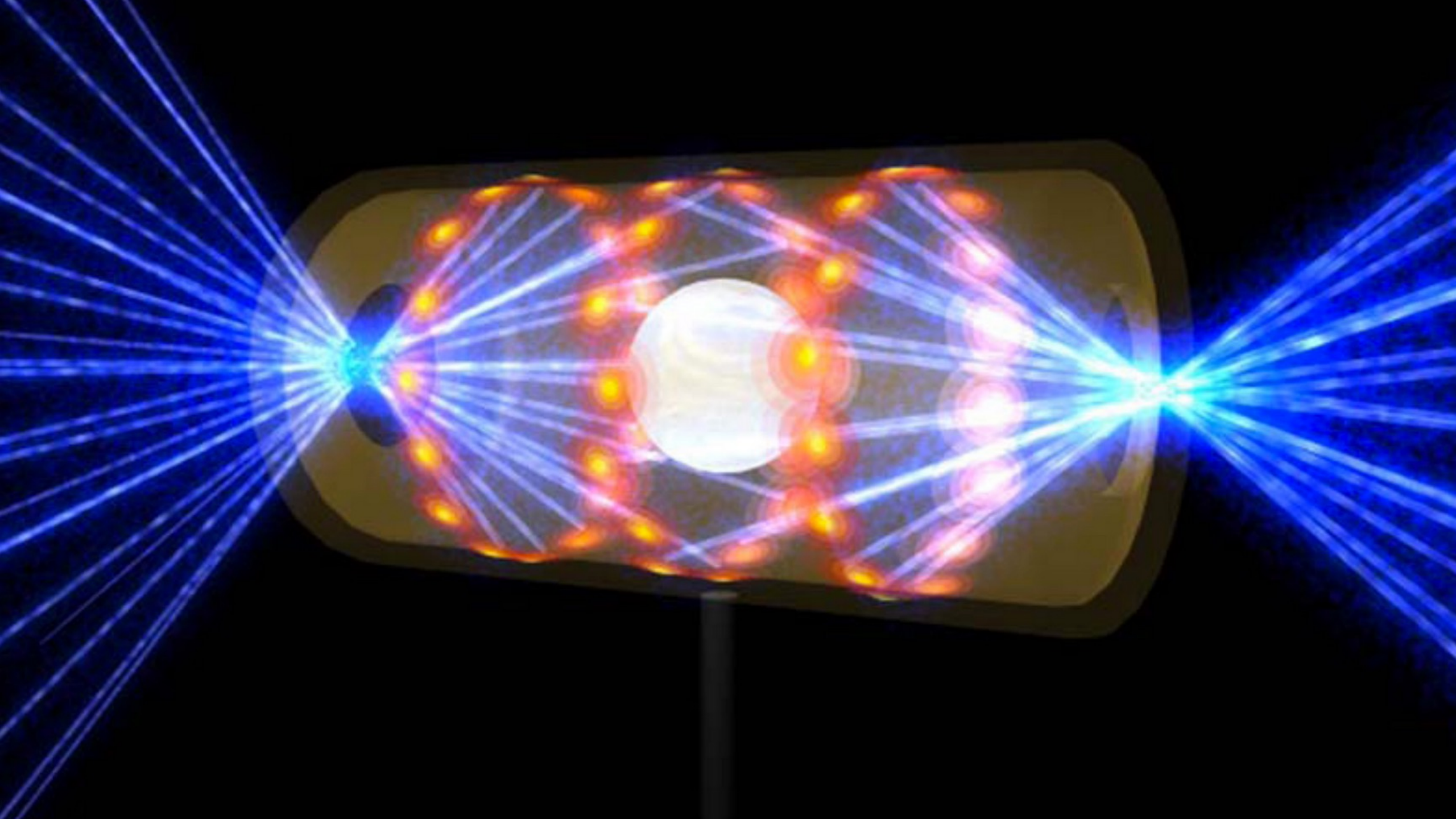
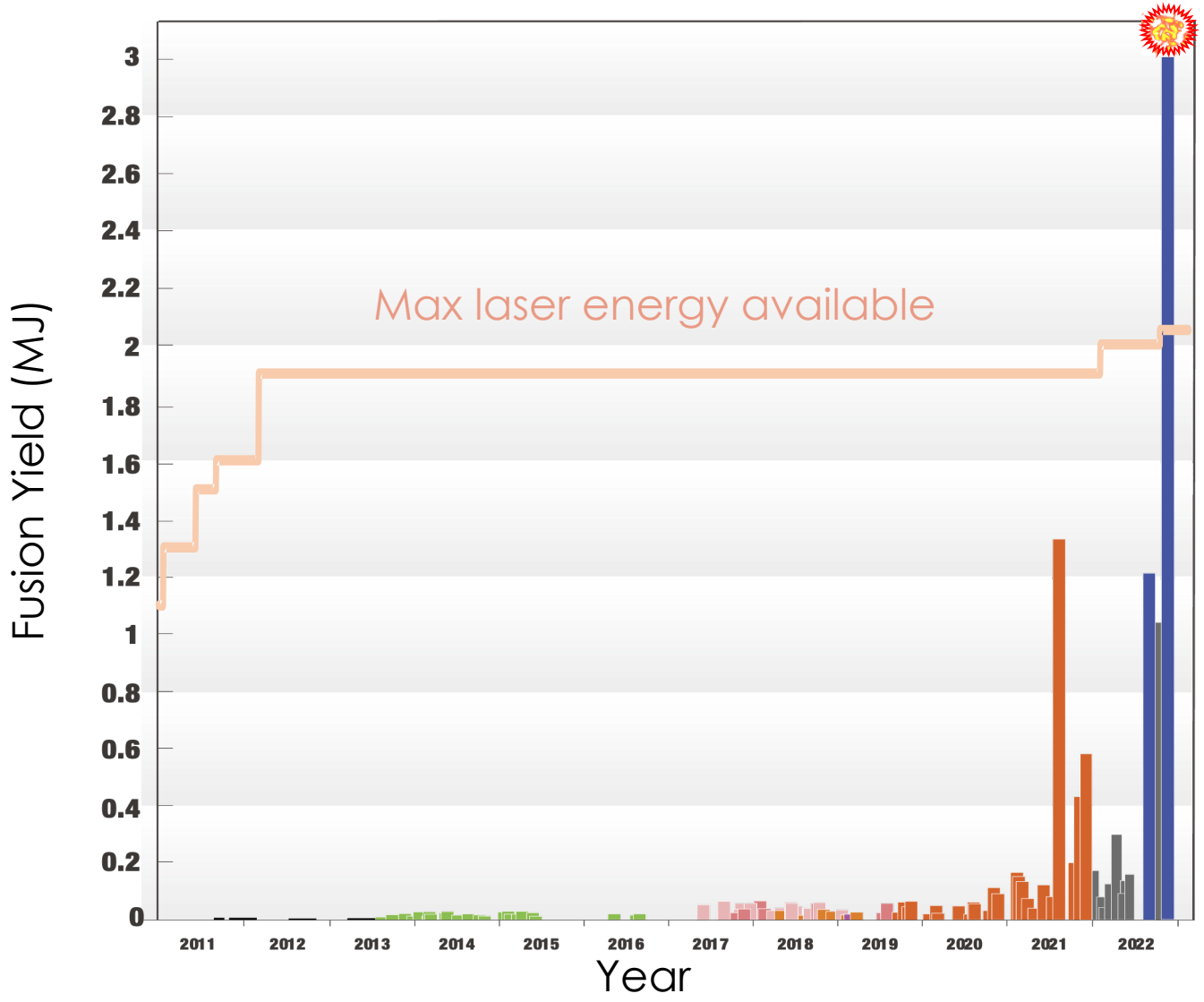


Dec. 5, 2022, *fusion ignition* was finally realized at the National Ignition Facility

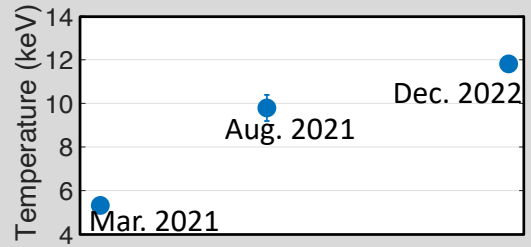
In an experiment on 12/5/2022, **NIF generated more energy out of the target than was put in**

… reaching a goal that had been laid out at the beginning of the stockpile stewardship program and opening new capabilities to sustain our nuclear deterrent

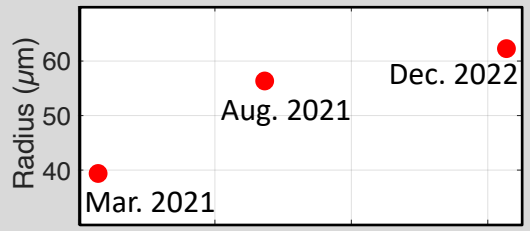


Ignition triggers rapid increases in the temperature, size, and mass of the fusion plasma which all contribute to increased fusion yields

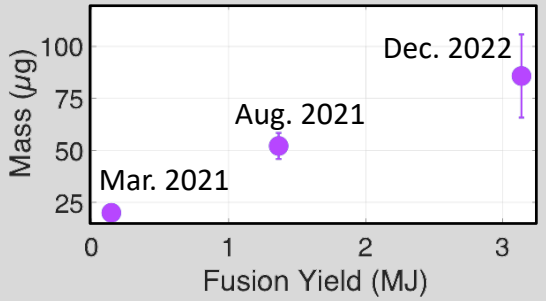
Temp. Increases 2.2×



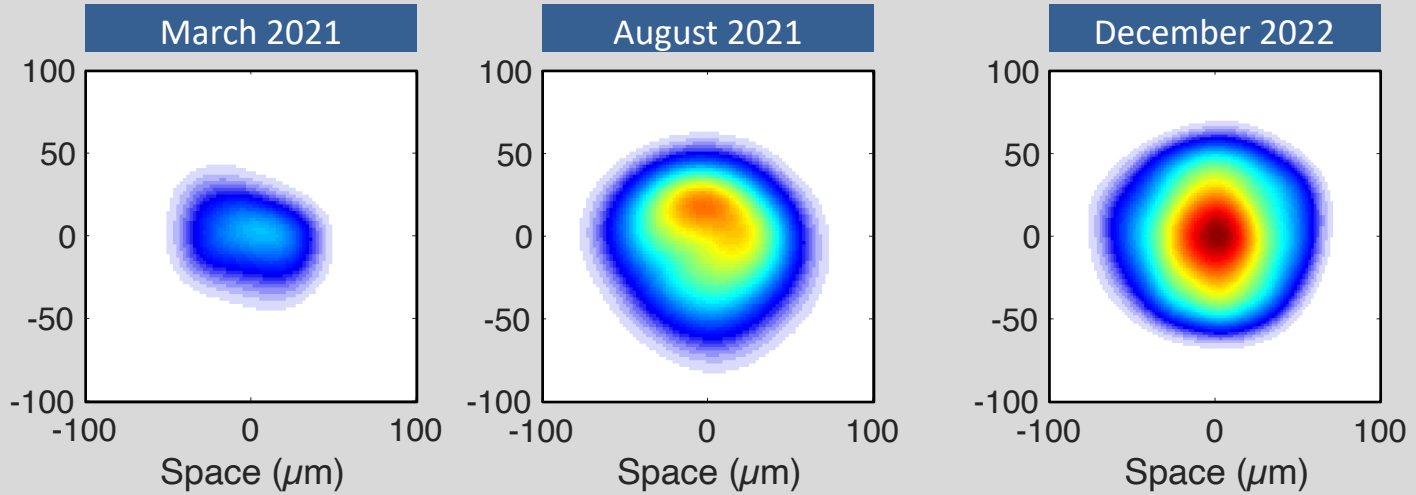
Radius Increases 1.6×

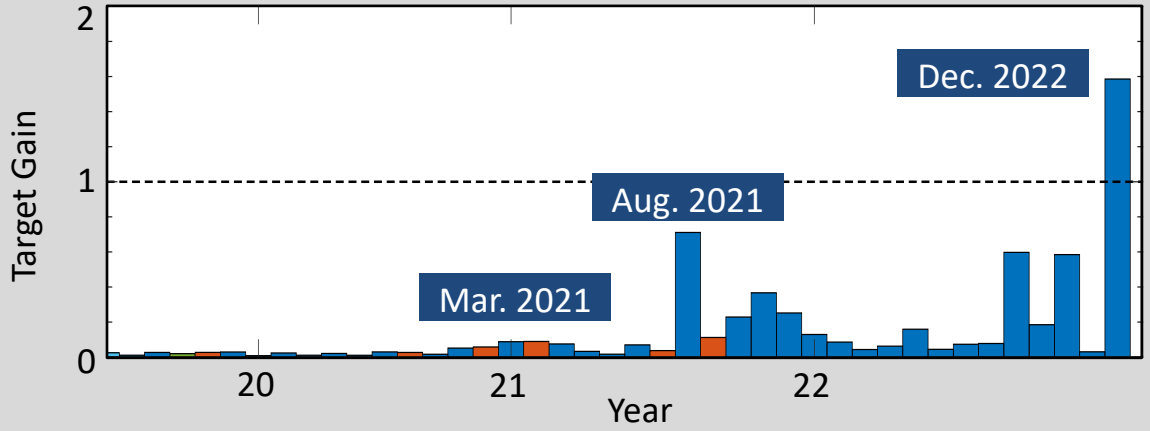


Mass Increases 4.3×

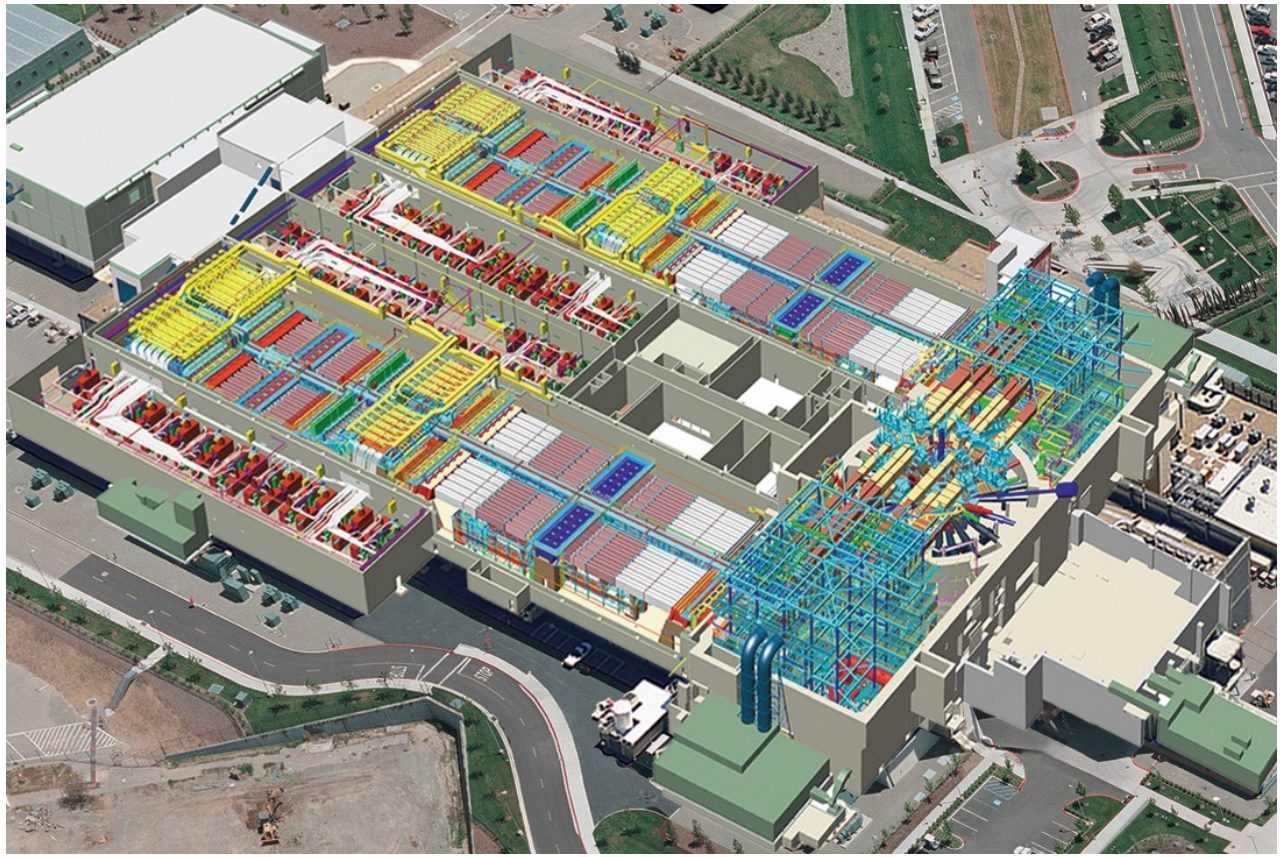


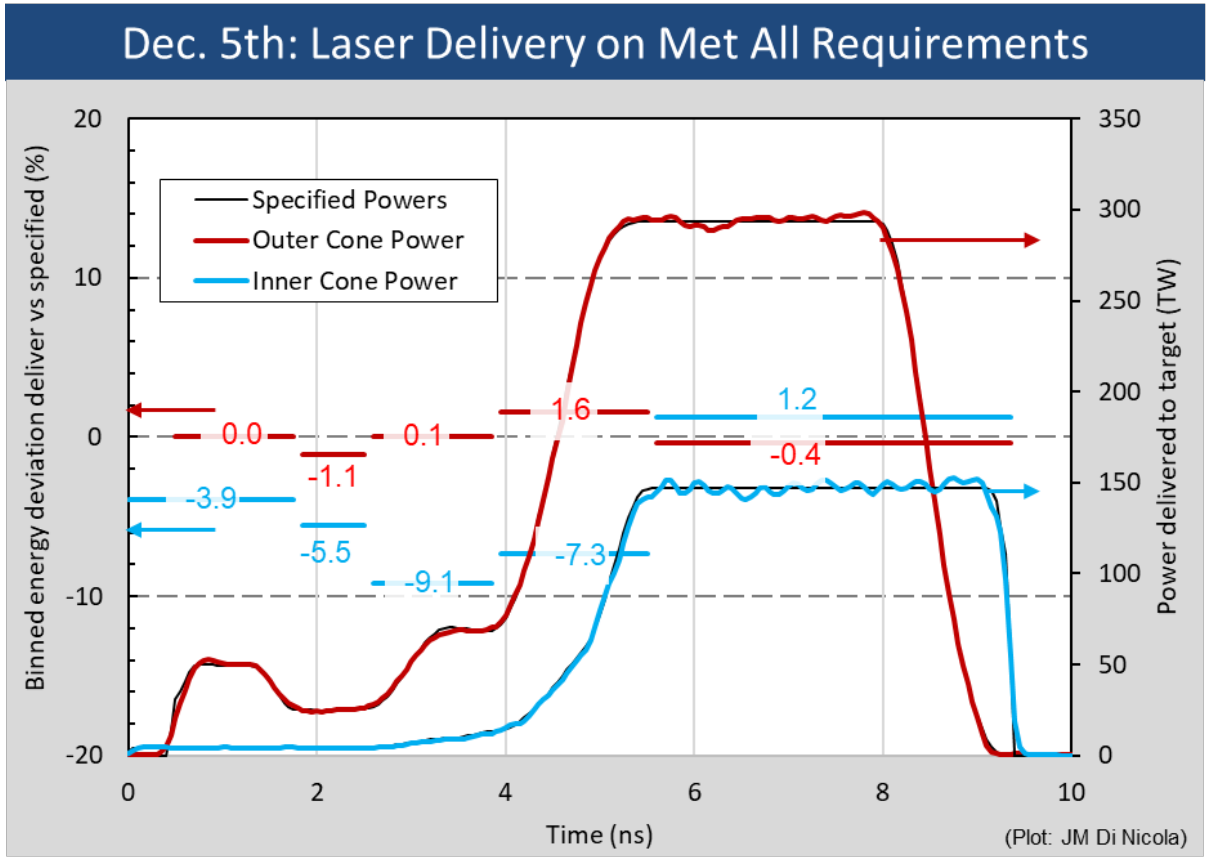
Neutron Emission Grows and Increases Brightness as Fusion Yield Increases





To ignite the target, the NIF laser delivered 2.05 MJ, 440 TW, an 8% energy increase compared to August 2021



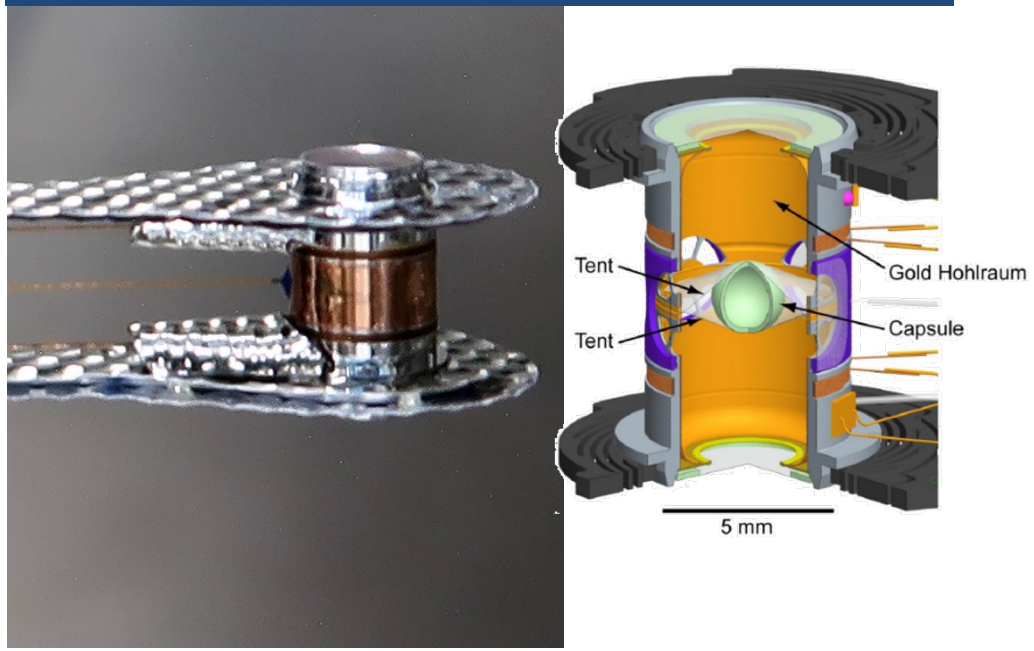


The NIF laser delivers requested energy within a 50 µm pointing, 30 ps timing, and a few % of power accuracy to provide the required conditions for ignition

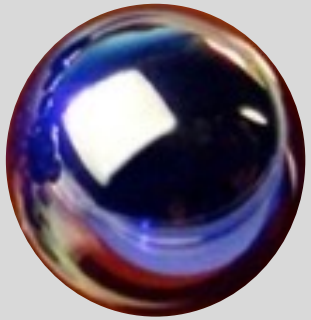
Di Nicola et al. *SPIE* **11666** (2021)

Ignition shots require some of the most precisely engineered targets made by our target fabrication team

N221204 Target

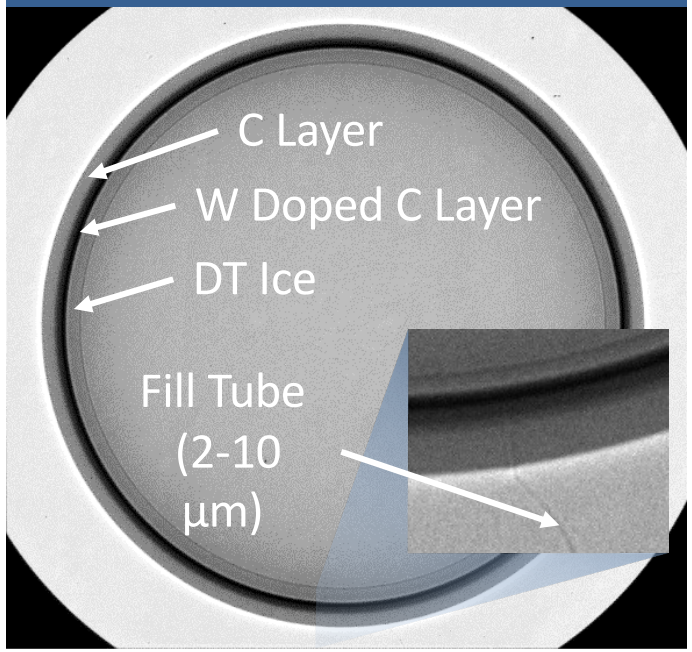


Diamond Nanocrystalline Capsule (High Density Carbon – HDC)



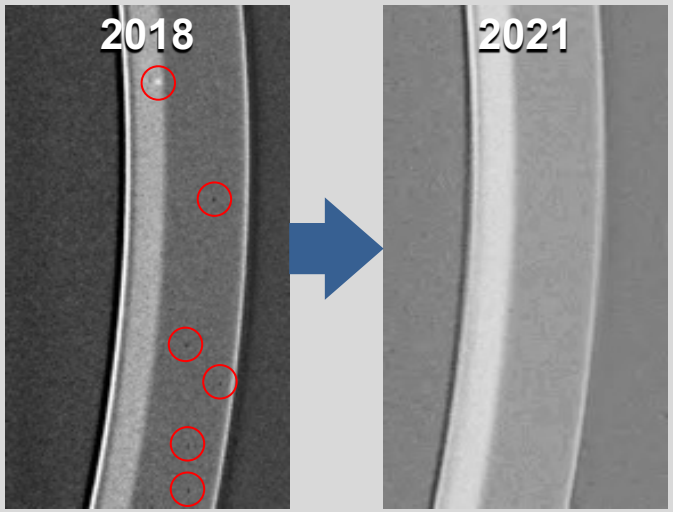
≈ 2 mm diameter, smooth to 10 nm

Capsule with DT Layer @ 19 K



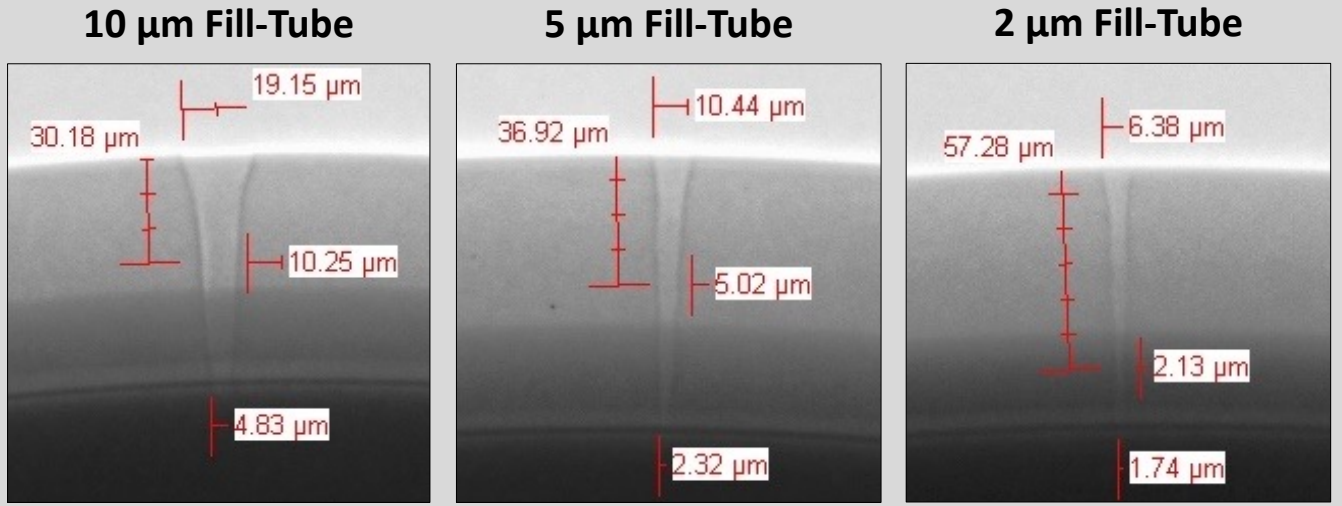
Target improvements have focused on reducing material and engineering defects

Capsule Quality



We have reduced pits and voids by two orders of magnitude

Fill-Tube Hole Diameter



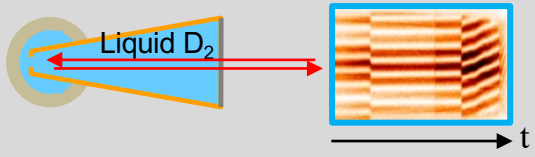
10x reduction in the surface area perturbation

The advances in both target quality and our ability to characterize them have been pivotal in achieving our current implosion performance

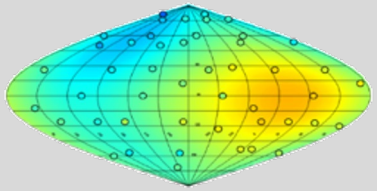
Braun, et al, Nuc. Fusion (2022)

Dozens of diagnostics are applied to each experiment to improve understanding

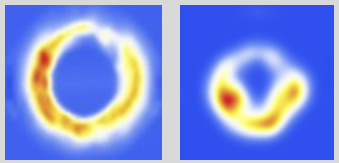
Shock Speeds, Timing

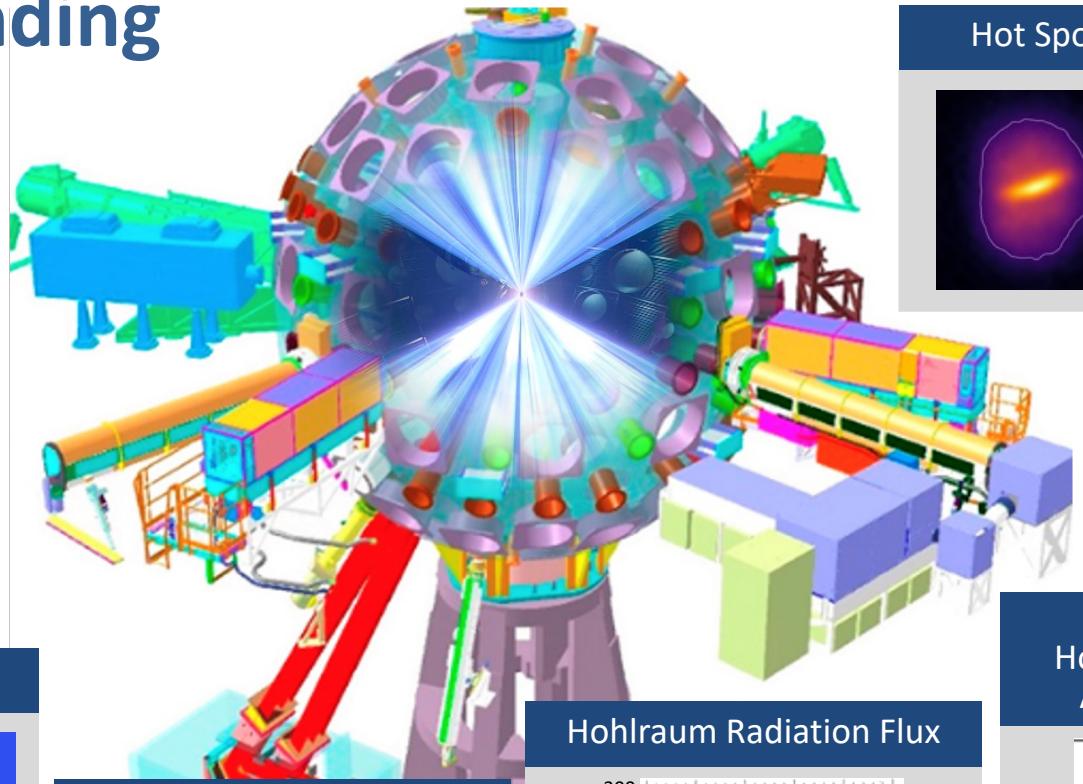


Yield / Fuel Uniformity

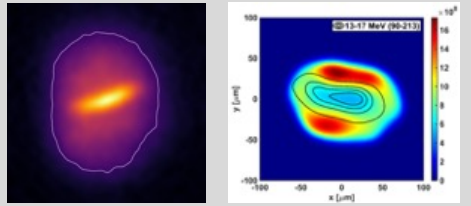


DT Fuel Uniformity



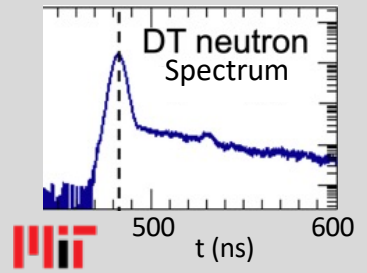


Hot Spot and Fuel Shape

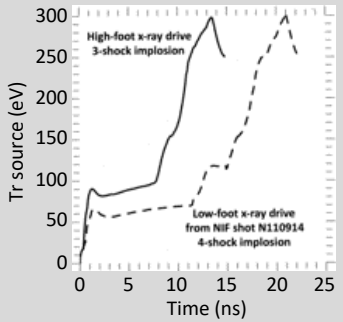


Hot Spot Electron Temperature and Impurities

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

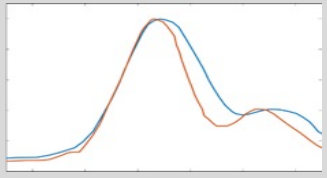


Hohlraum Radiation Flux

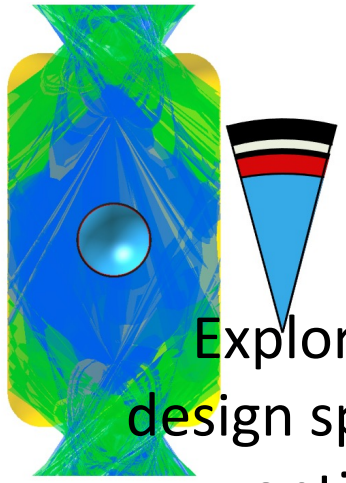


Burn Width, Bang Time

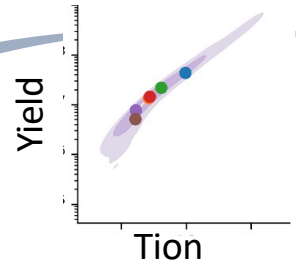
Los Alamos NATIONAL LABORATORY



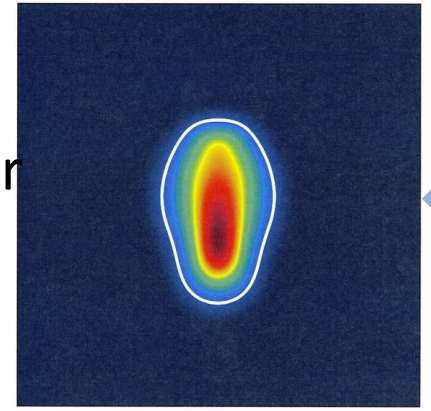
AI/ML combines simulations and data to improve our understanding of previous experiments, and aid in optimizing future designs



Explore vast design spaces for optimal performance



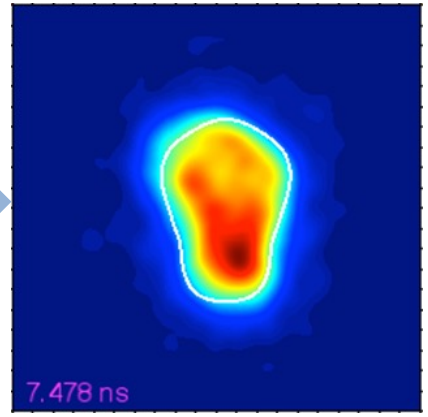
Predict



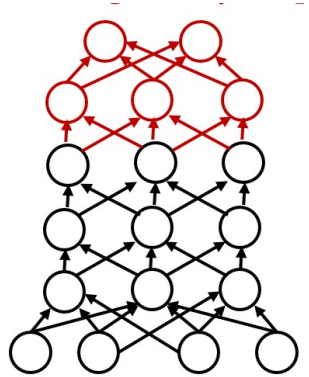
Quantify discrepancy

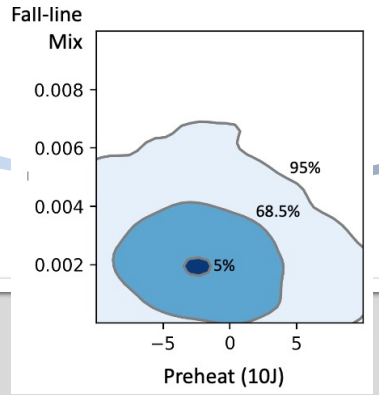
Find multiple explanations for the data

Learn



Update models for next design iteration





NEXT STEP: exploit ignition 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

2023–2028

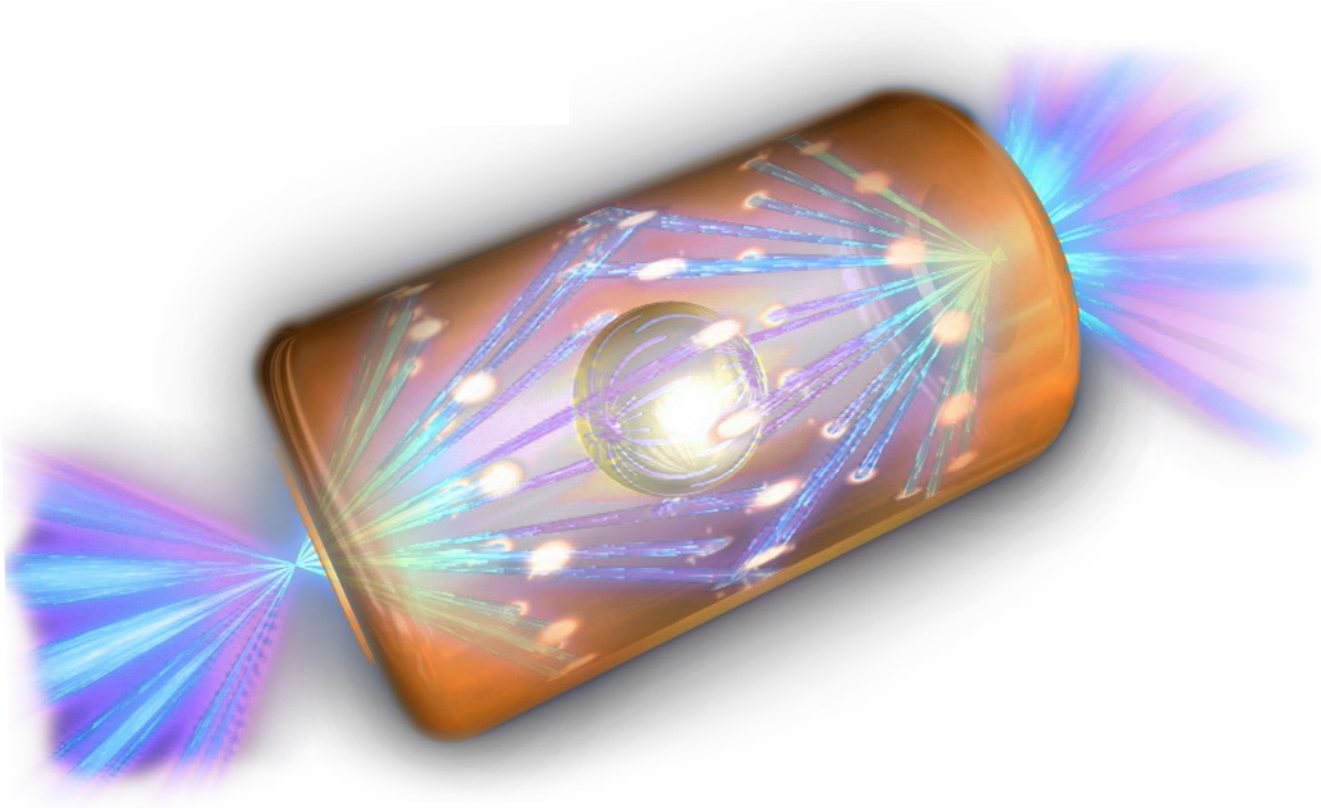
Long-term sustainment

Increase energy and power

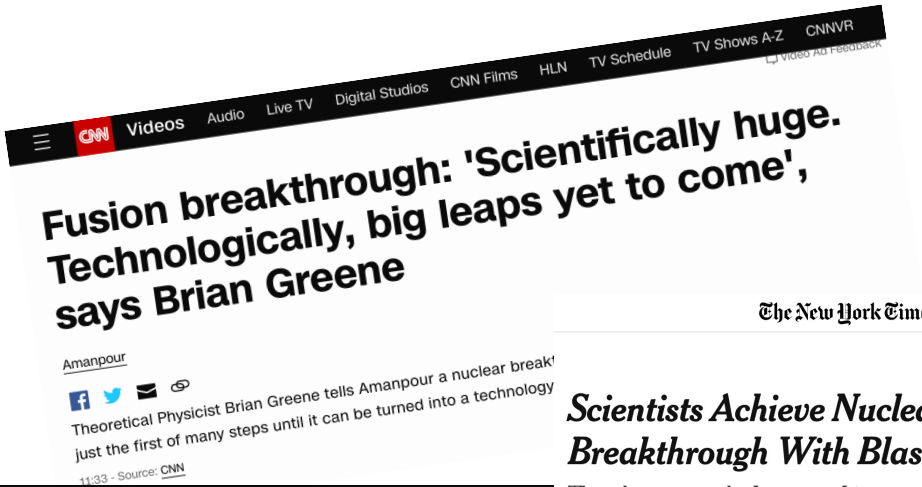
2030–2040

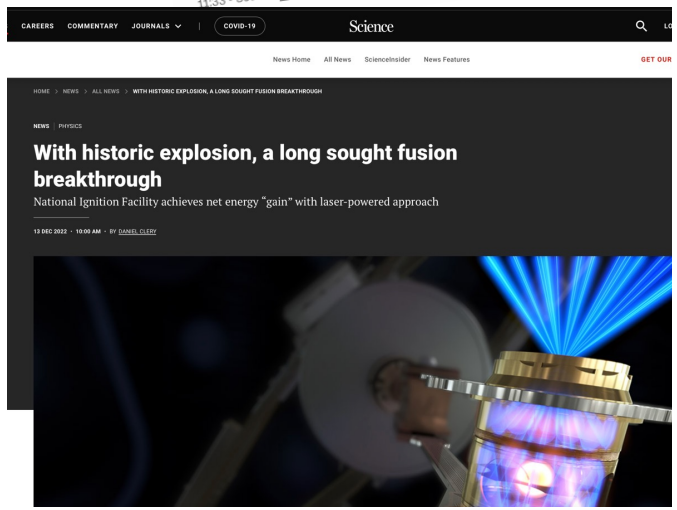
Explore high-yield, high-gain regime

The same fusion plasmas we create for national security applications can also be exploited to be the basis of a clean power source via Inertial Fusion Energy (IFE)



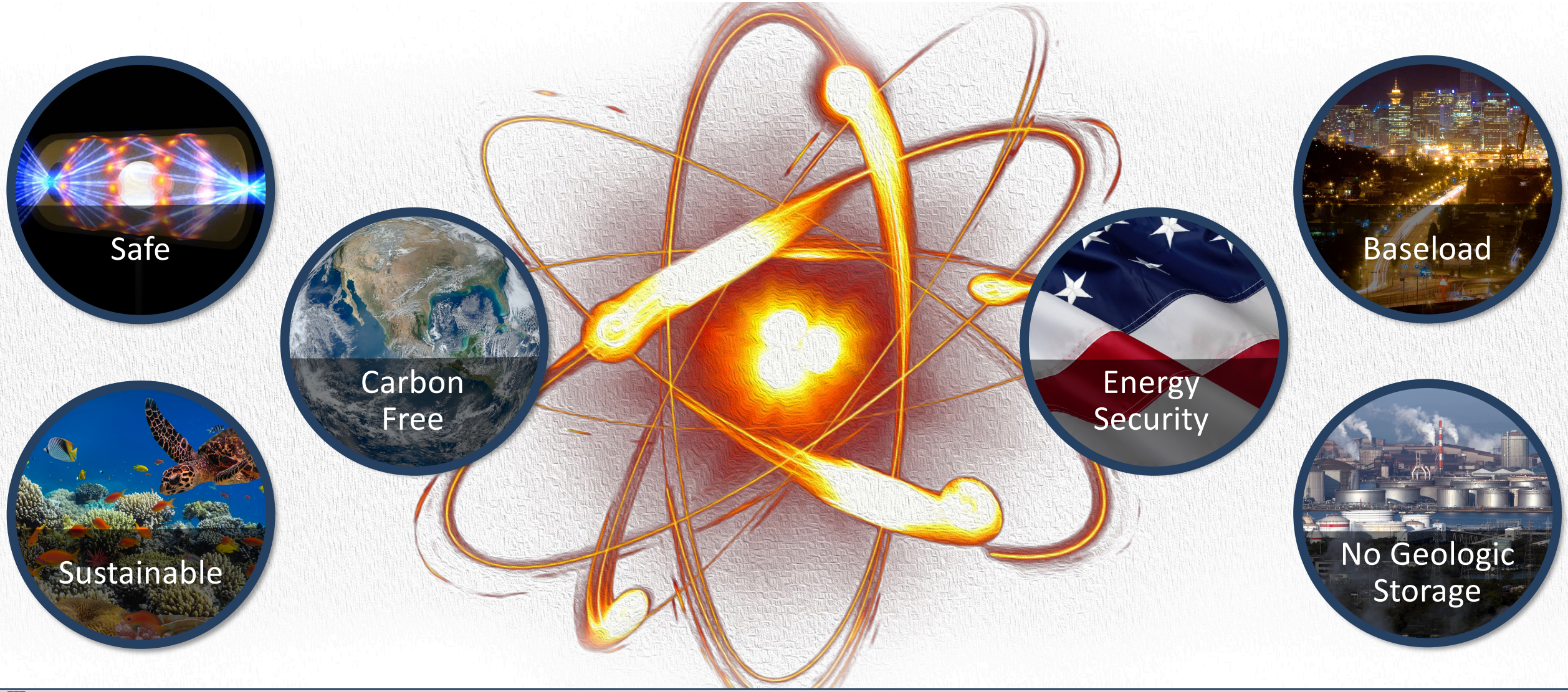
Ignition on the NIF establishes the basic scientific feasibility of laser-driven Inertial Fusion Energy (IFE)



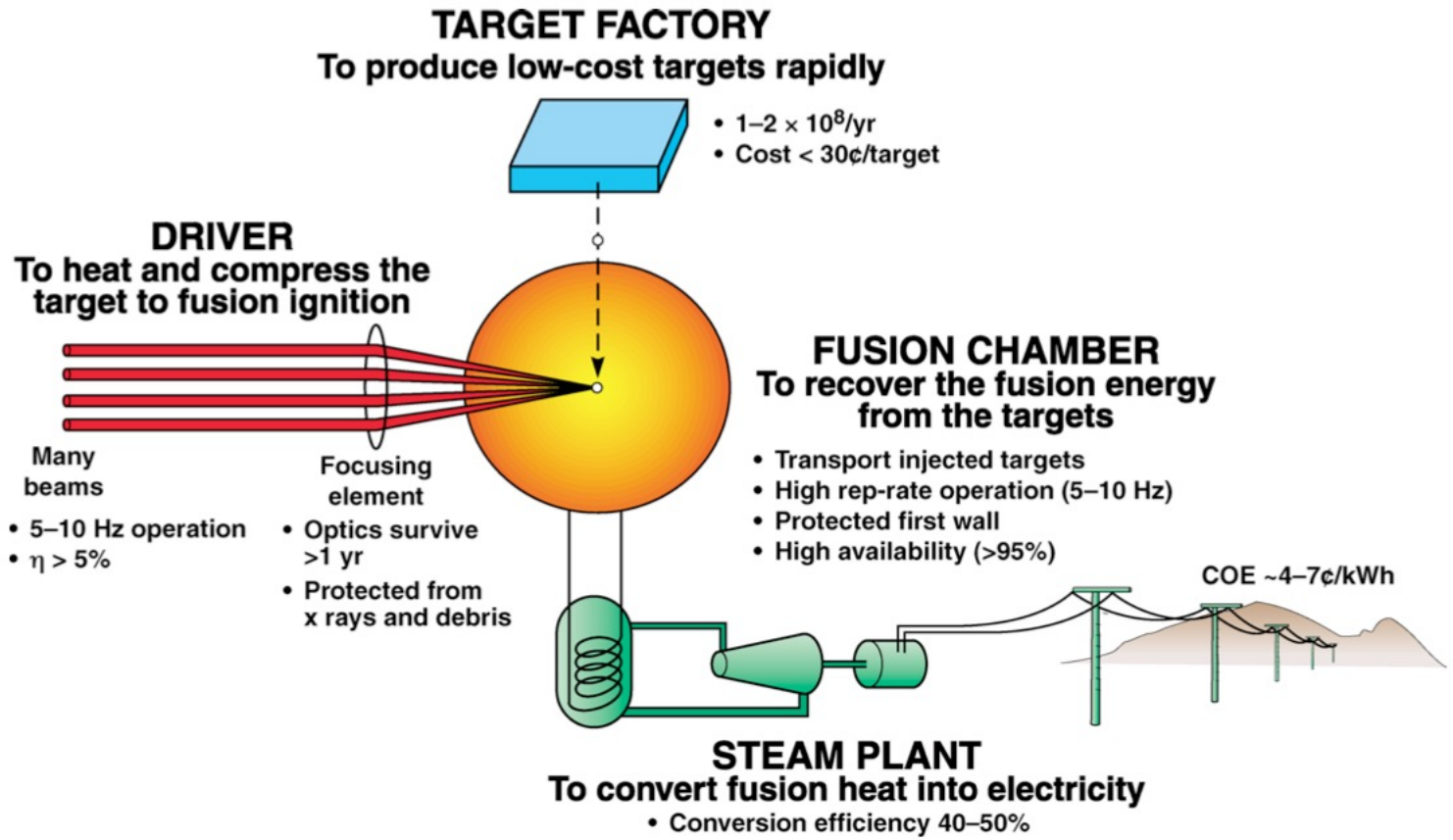


Developing an economically attractive approach to fusion energy is a grand scientific and engineering challenge

Fusion energy is attractive for many reasons



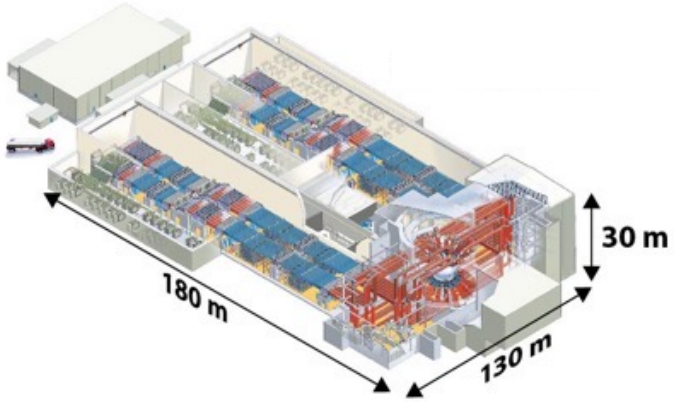
IFE power plants will consist of four main parts



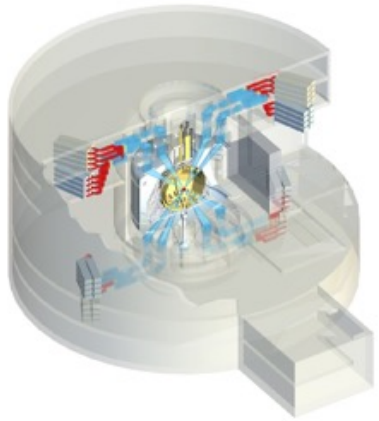
*E. M. Campbell, and W. J. Hogan, Plasma Phys. Control. Fusion **41** B39 (1999)*

The NIF is a scientific exploration facility, and very different from what would be needed for an IFE power plant

NIF: Single Shot



IFE plant: >10 Hz



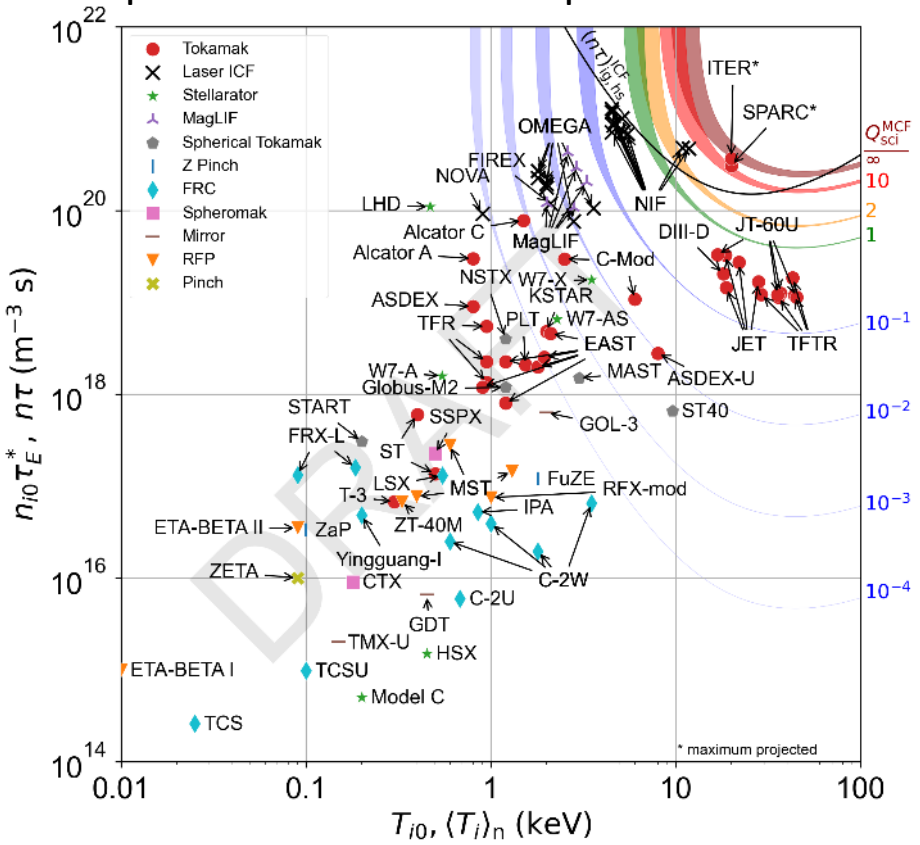
An electricity-producing IFE power plant would require:

- A more robust, high-margin ignition scheme
- A high-efficiency, high rep-rate driver
- High rep-rate target injection and tracking
- Energy conversion system
- Robust first walls and blankets for wall protection
- Tritium processing and recovery
- Remote maintenance systems
- Viable economics

A number of promising technologies key to eventual Inertial Fusion Energy systems are already making steady progress

It is time to broaden the nation's fusion energy portfolio to include both MFE and IFE

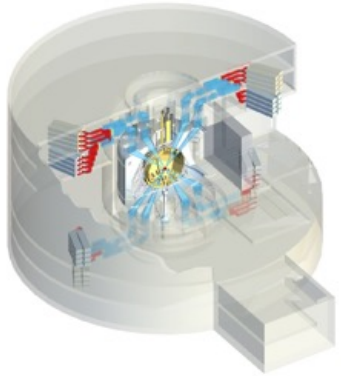
Comparison of all fusion experiments to date



Adapted from *Wurzel and Hsu, Phys. Plasmas* ***29****, 062103 (2022)*

ITER* & SPARC* are projections

NIF is the only experiment that operates in burning and ignited plasma regimes—the regime required for all fusion reactors



Advantages of the <u>inertial</u> fusion energy (IFE) path:

- Only concept with existing ignition platform
- Separable components & highly modular – allow for parallel tech development and upgrades of pilot
- Multiple sponsors for key technologies & spin-offs (e.g. lasers)
- 10x lower tritium inventory than MFE

A balanced and diverse fusion portfolio maximizes our potential pathways to success, and allows us to build on the U.S.'s significant and singular lead in IFE

OSTP/White House Summit injected new momentum and an audacious goal: a Decadal Vision for Commercial Fusion Energy

OFFICE OF SCIENCE AND TECHNOLOGY POLICY

EVENTS & WEBINARS

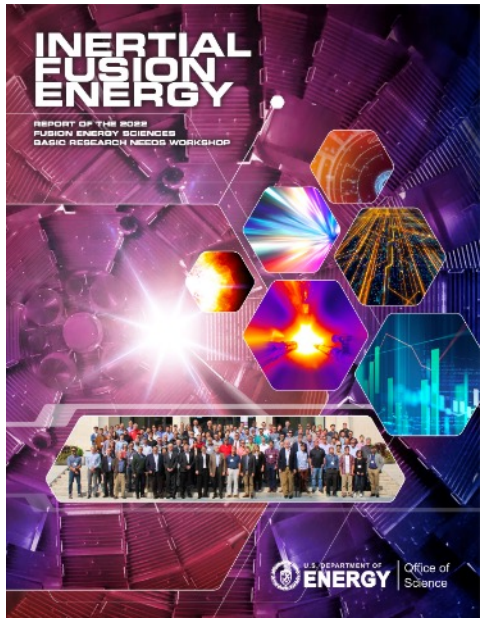
Upcoming Events

White House Summit: Developing a Bold Decadal Vision for Commercial Fusion Energy

Thursday, March 17, 2022 at 10:00 AM to 1:00 PM ET

Watch live as the White House Office of Science and Technology Policy (OSTP) and the U.S. Department of Energy (DOE) host a summit on Developing a Bold Decadal Vision for Commercial Fusion Energy. This summit will convene fusion energy leaders from government, industry, academia, and other stakeholder groups to showcase progress made and have inclusive conversations about an updated fusion strategy.

IFE is a national need that requires a national plan, program, and team, and sustained commitment



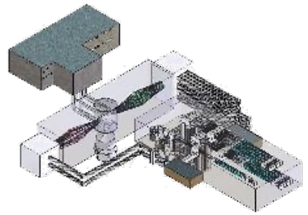
https://events.bizzabo.com/IFEBRN2022/home

A 2022 DOE Basic Research Needs (BRN) report provides priority research opportunities for a new IFE program

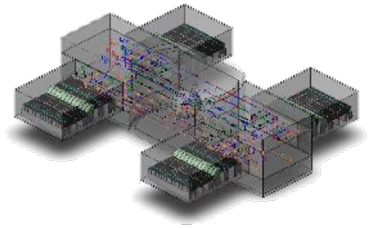
Technology maturation (start now)

- Public-led hubs for component R&D
- Leverage existing facilities for target R&D (NIF, Laboratory for Laser Energetics, University of Rochester)
- Private-led PPPs: pilot plant designs
- Dedicated IFE facilities

Demo Facilities and First Pilot Plants (2030-40)

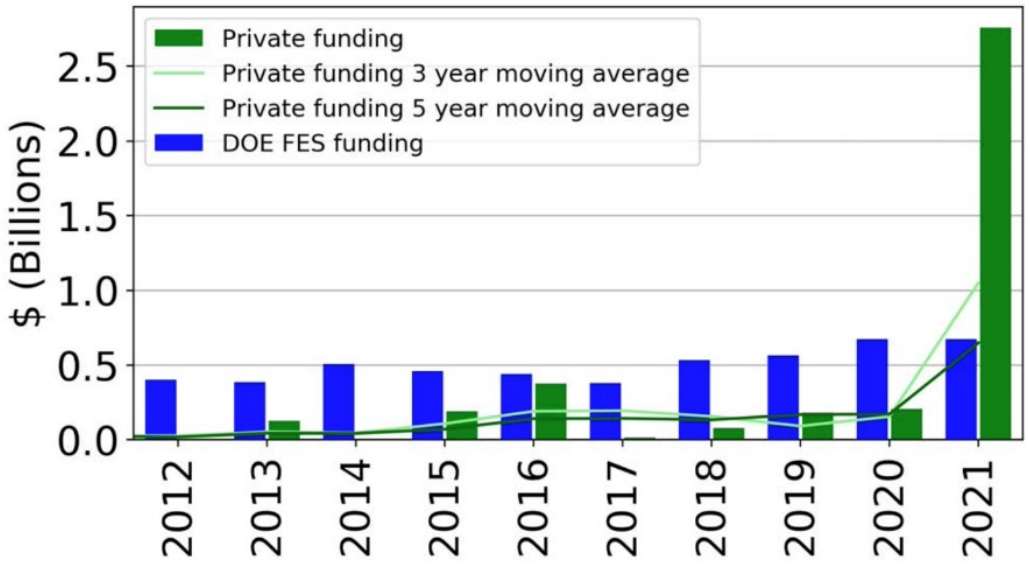


Economically Viable Commercial Power Plant



Community is ready for an accelerated IFE program that would jumpstart progress for an IFE pilot plant to advance U.S. leadership in this critical energy technology

Significant private investment into fusion startups have commenced in the past few years



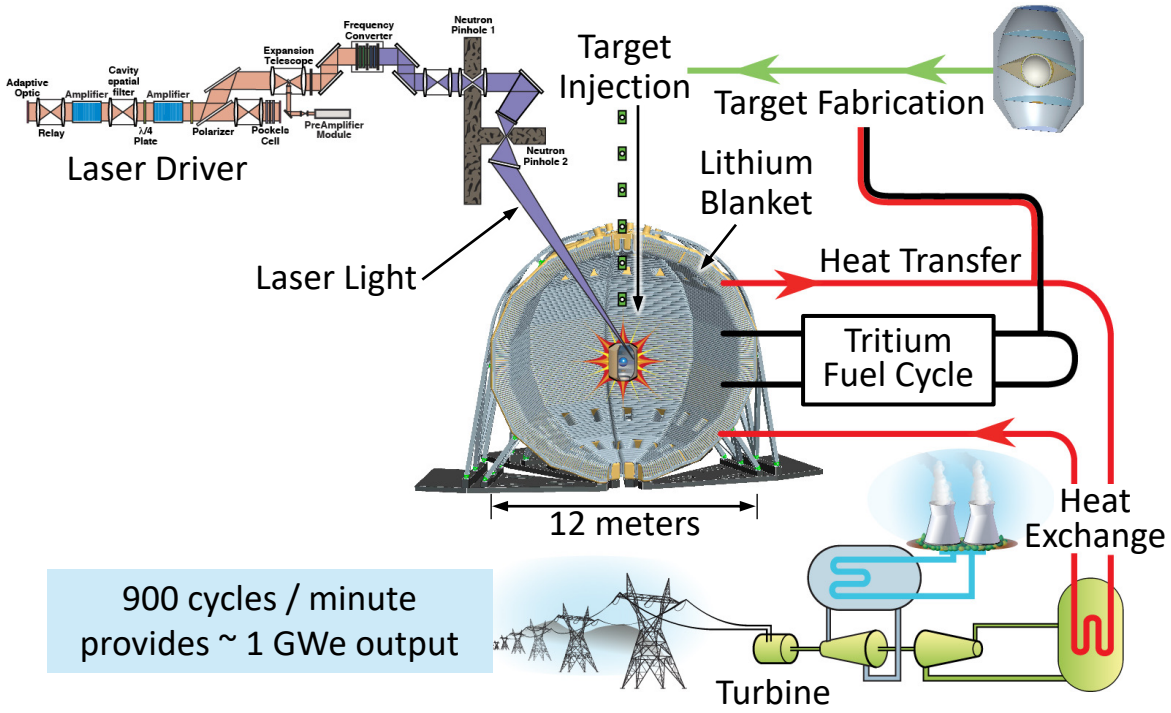
Plot credit: Sam Wurzel, Technology-to-Market Advisor, ARPA-E

From FIA, ~$5.5B into private fusion industry, with ~$180M of that into IFE companies

Fusion Industry Association, *The global fusion industry in 2022*

Public-Private Partnerships will accelerate progress

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



The Challenges are Many…

- 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

…But the Benefits Outweigh the Challenges

- Energy and climate security & US scientific competitiveness
- Attractive economic development path (spin-out technologies)
- Diversified risk from magnetic fusion

An IFE program that leverages the NIF as the world's only ignition platform for target R&D and accelerates in parallel the development of other required technologies could produce the quickest path to a fusion pilot plant

Partnership with Stockpile Stewardship/NNSA will be essential and mutually beneficial

Fusion ignition enhances our deterrence and offers a long-term vision for global climate and energy security

- Ignition has been demonstrated!
- Ignition on NIF opens access to a new range of physical conditions for weapons studies and paths to fusion energy
- Inertial Fusion Energy is a game-changing technology
  - Can provide abundant energy while helping to meet CO_2 goals
  - Bolsters science and technology leadership, security, and energy independence
  - IFE is a multi-decadal grand-challenge endeavor, and will require innovation to enable economical energy source

The US is the leader in ICF, and we must capitalize on it to realize fusion energy for the world!