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

Innovations in Climate Resilience Conference (ICR23)

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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

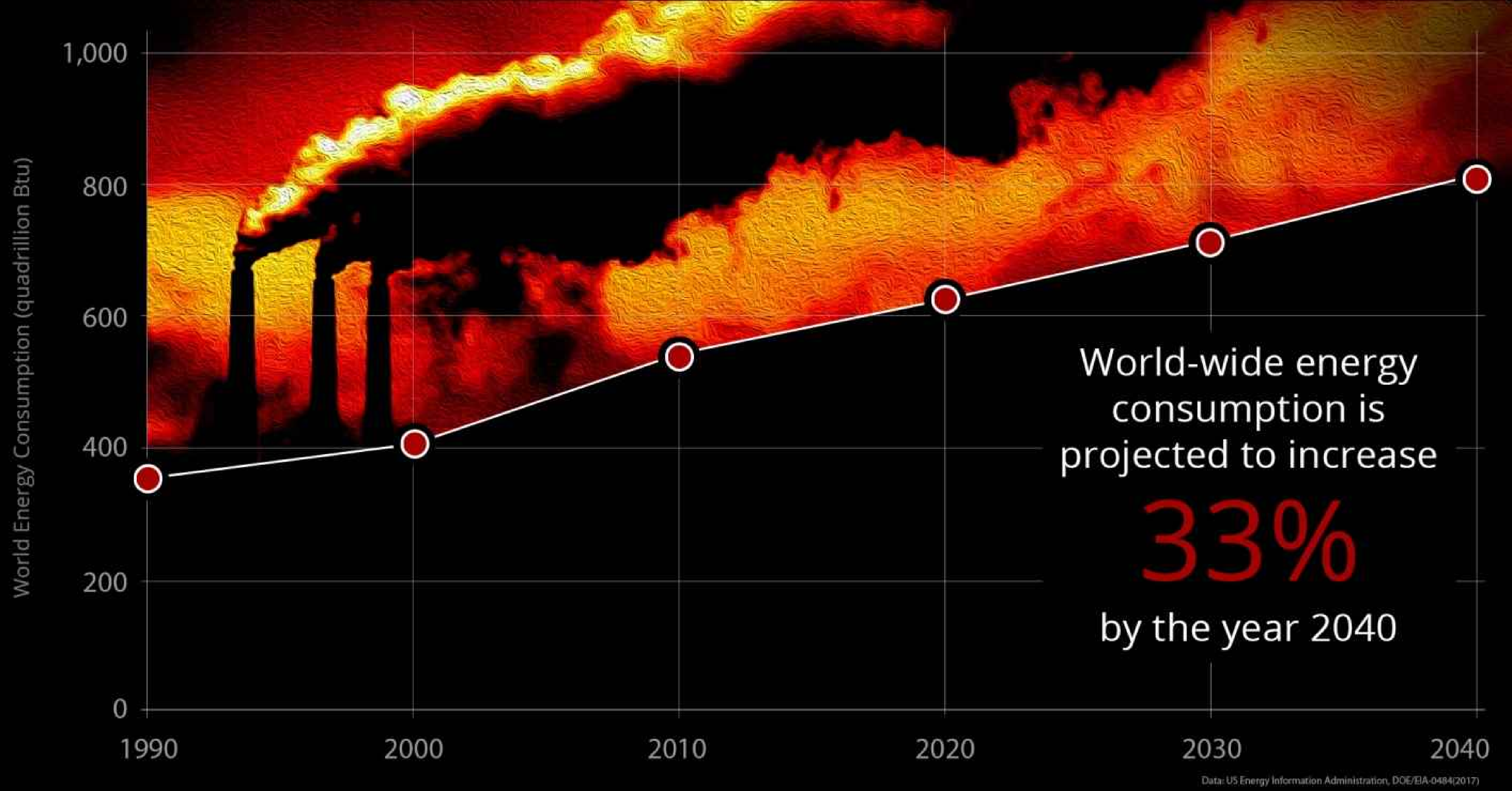
AWE

MIT PSFC Plasma Science and Fusion Center

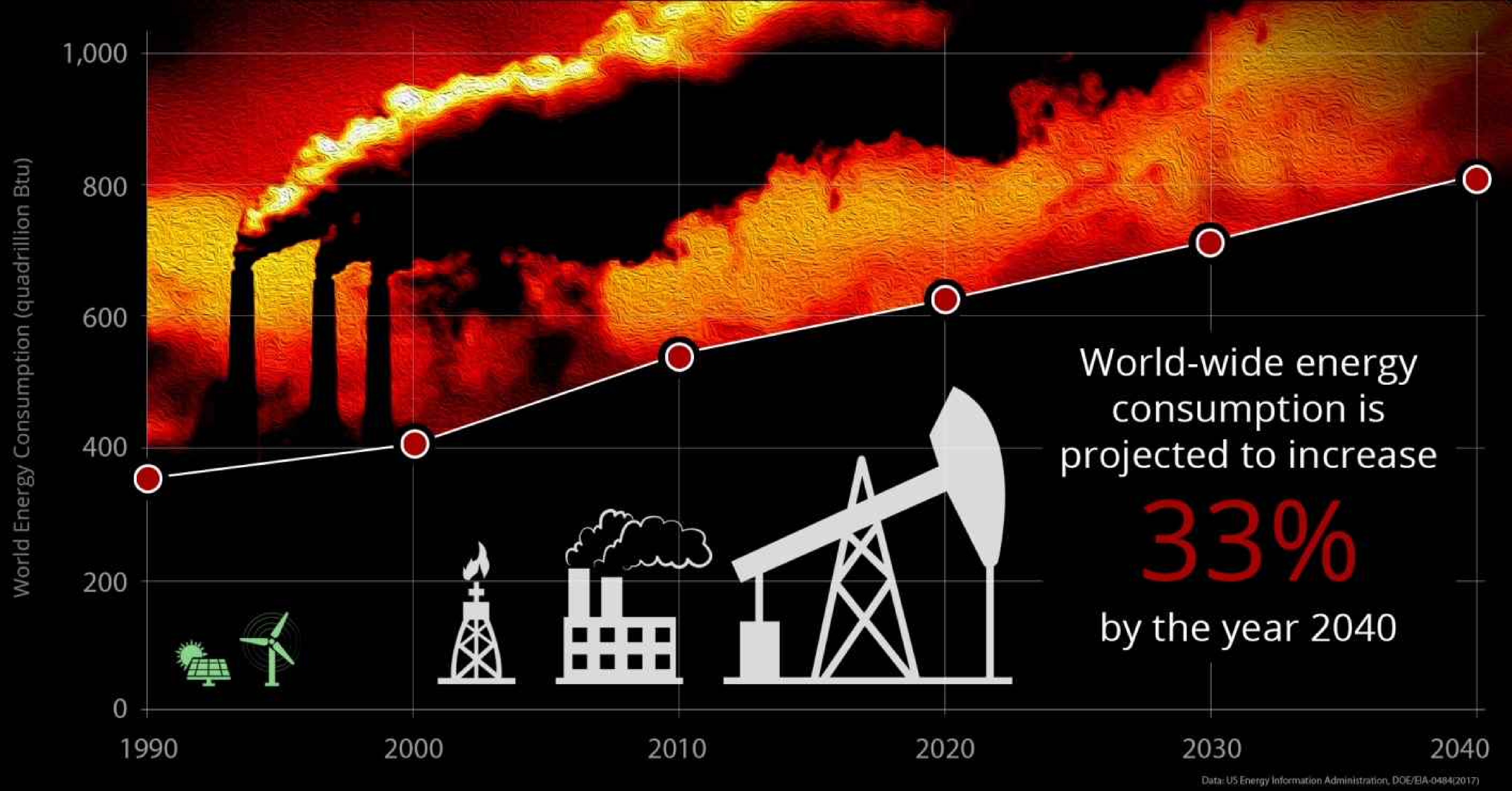
General Atomics

NNSA National Nuclear Security Administration

…and many more



World Energy Consumption (quadrillion Btu)
1,000
800
600
400
200
0
1990
2000
2010
2020
2030
2040
World-wide energy consumption is projected to increase
33%
by the year 2040
Data: US Energy Information Administration, DOE/EIA-0484(2017)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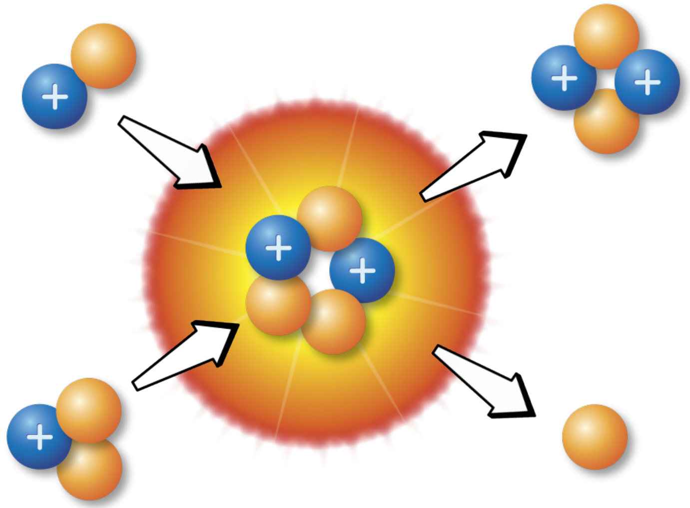
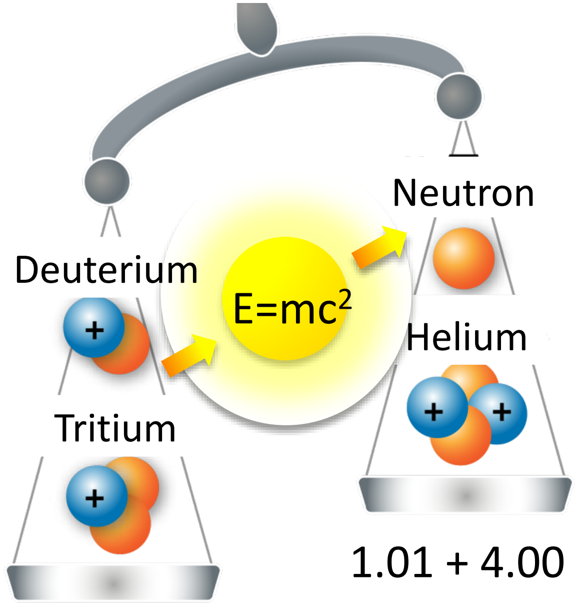
Could we build a miniature sun on earth?
…to provide significant carbon-free energy for humankind

The sun and the stars are powered by fusion





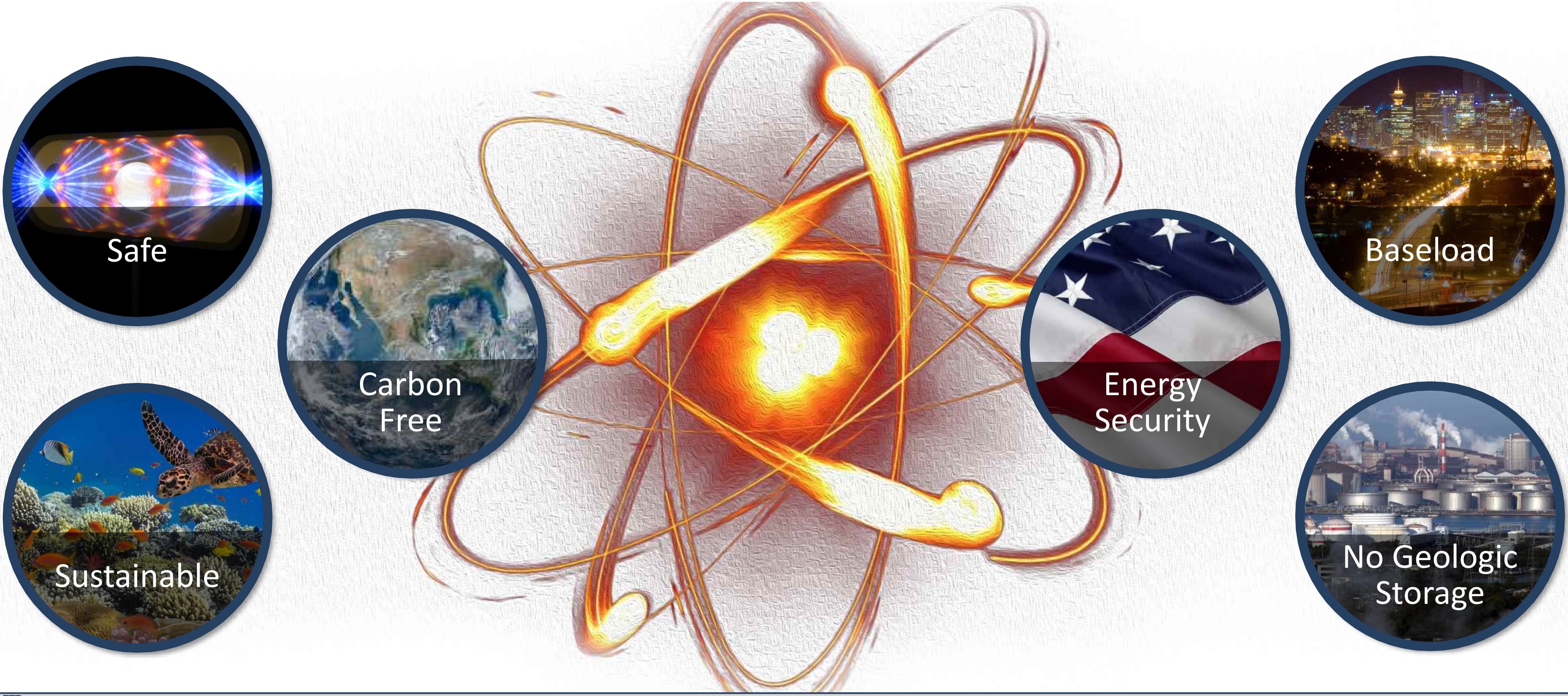
2.01 + 3.02 =
5.03 AMU

1.01 + 4.00 =
5.01 AMU
+ 17.6 MeV

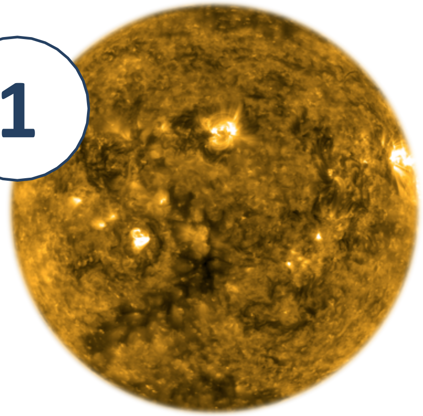
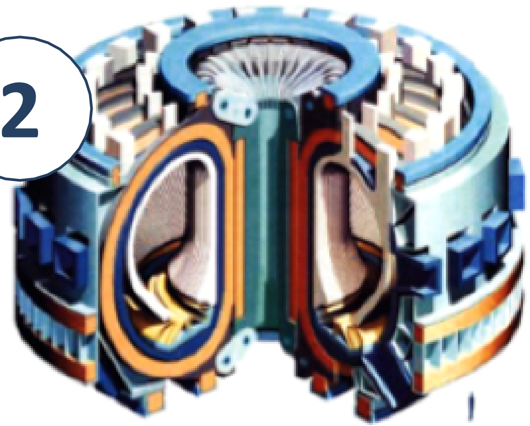
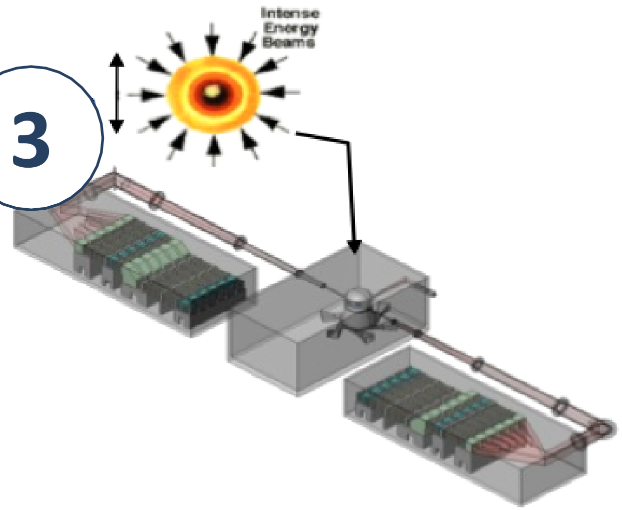
$$D + T \rightarrow \alpha(3.5\text{MeV}) + n(14.1\text{MeV})$$

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

Fusion energy is attractive for many reasons

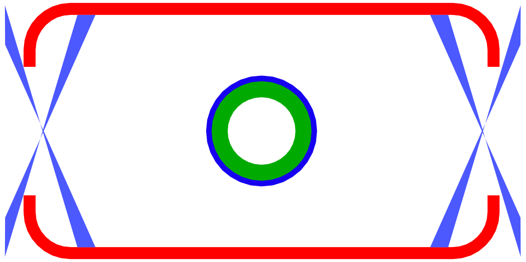


There are at least three ways to achieve nuclear fusion

	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**

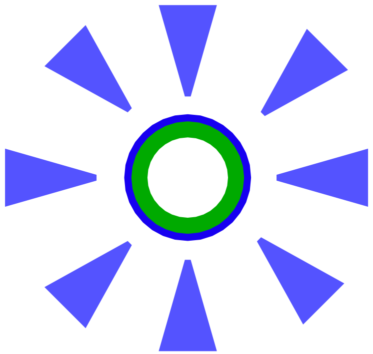
Inertial Confinement Fusion (ICF) can be achieved by using high power lasers to drive a spherical implosion

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

Thermonuclear burn spreads, yielding many times the input energy

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

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

Six decades of innovation

John Nuckolls

First concept of inertial confinement fusion

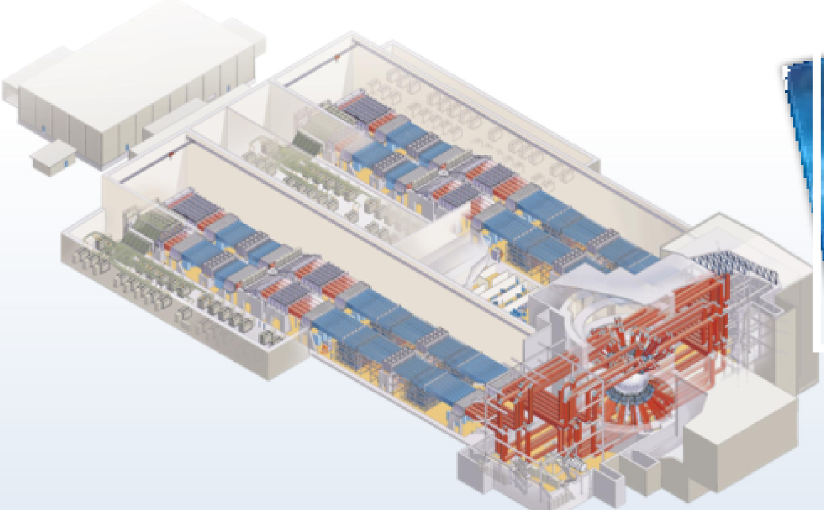
Invention of the laser

Janus laser (0.2 kilojoules)

Argus

Shiva

Nova (30 kilojoules)



National Ignition Facility key decision

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

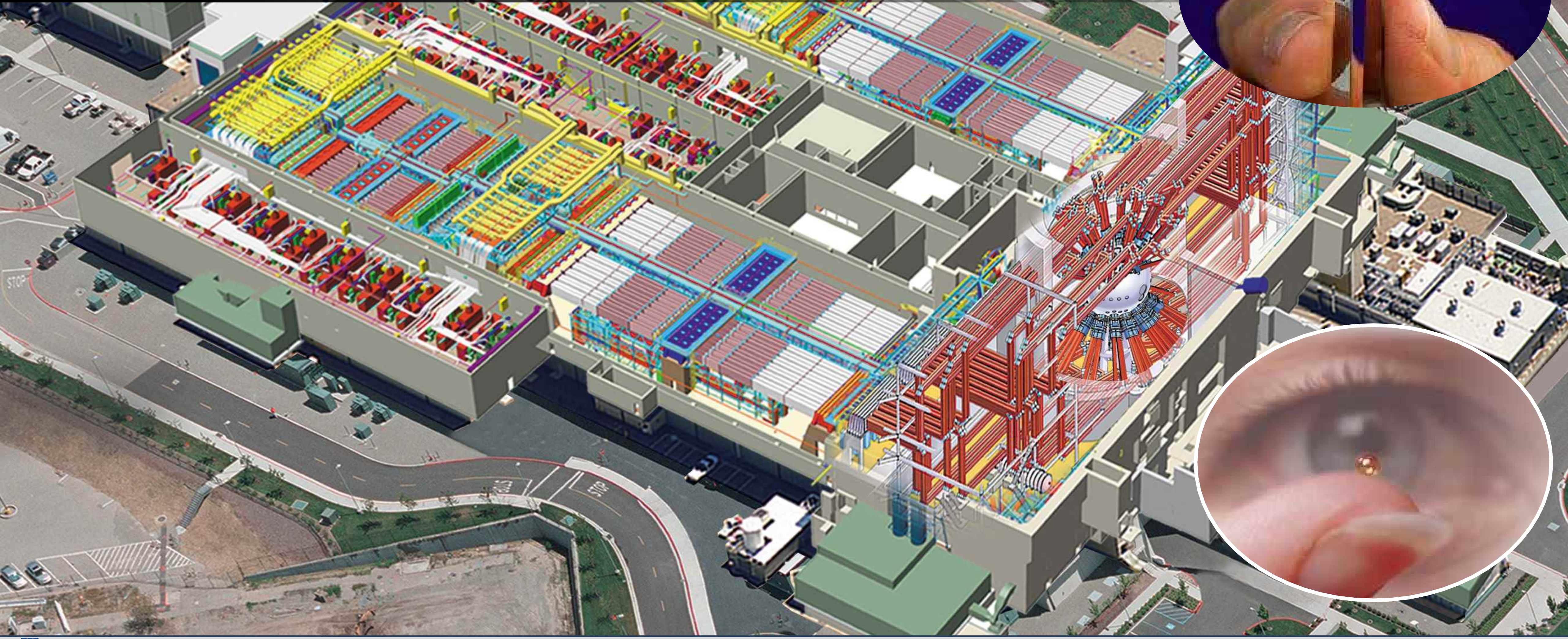
Reaching ignition is the culmination of decades of passion, hard work, and learning

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

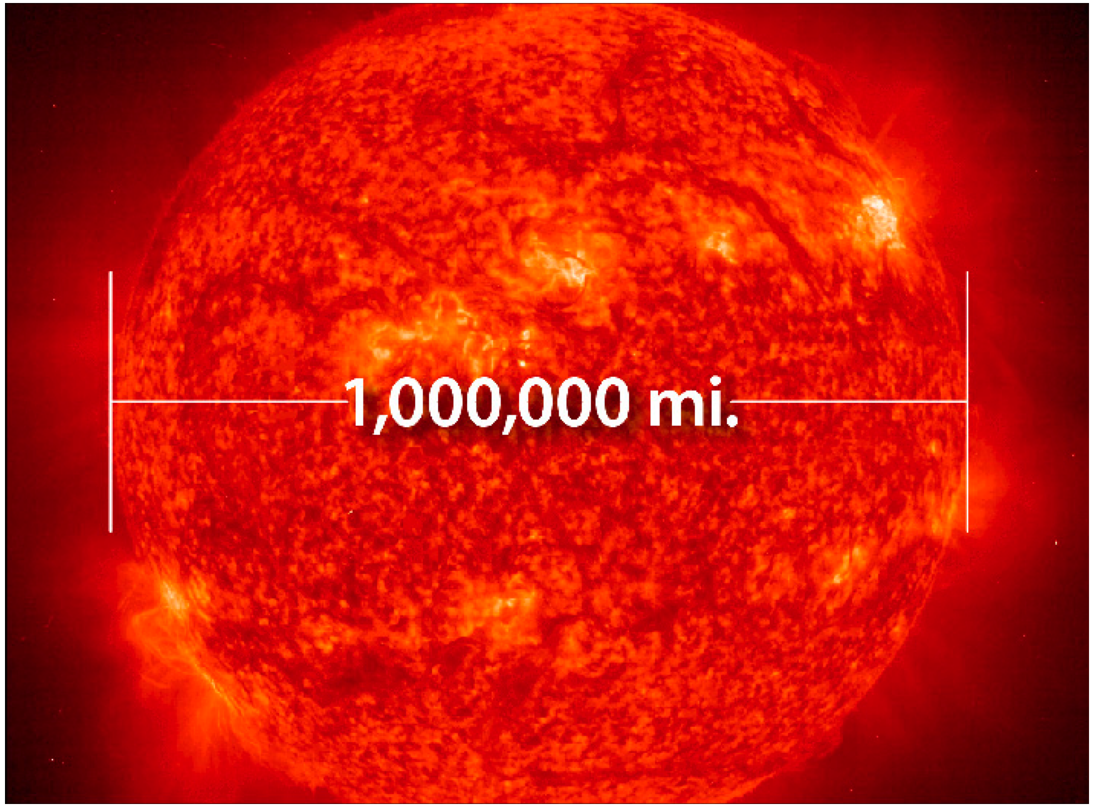
NIF is the world's largest and most energetic laser enabling the study of extreme conditions for high energy density science

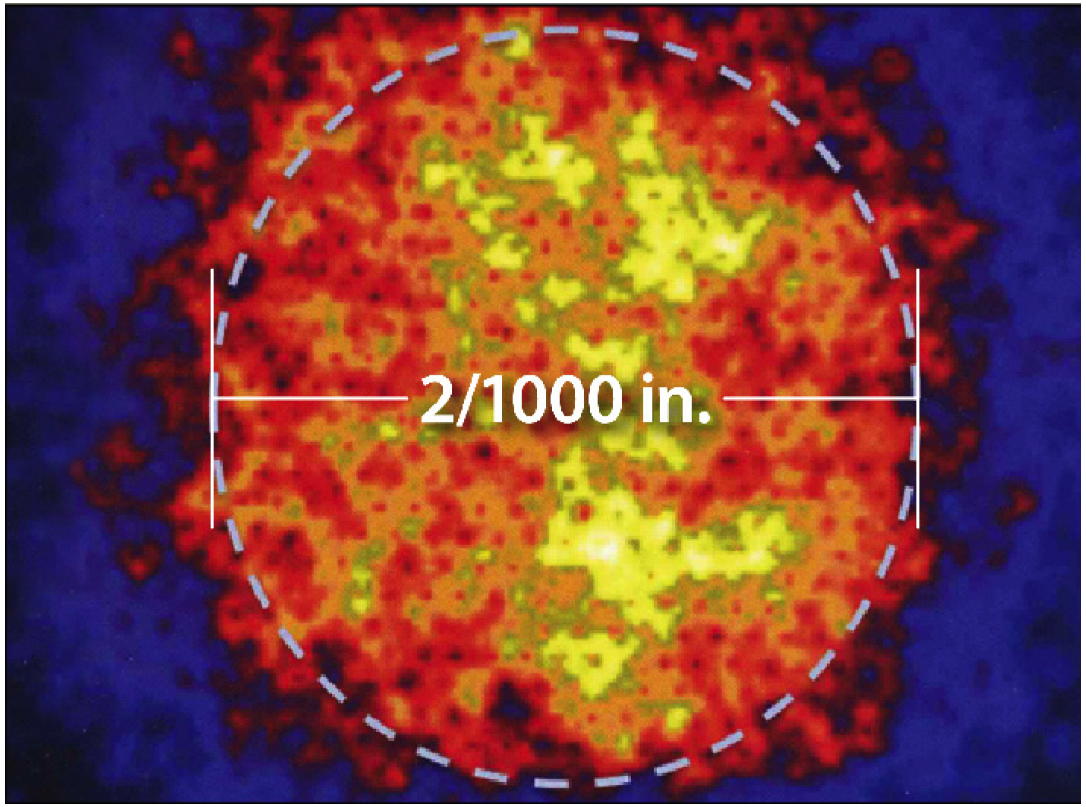
- 192 Beams
- Energy: 1.9 MJ
- Power: 500 TW
  (1,000x power of US electrical grid)
- Frequency tripled Nd glass
- Wavelength: 351 nm
- Pulse length: ~25 ns

192 laser beams are concentrated into a mm^3 target



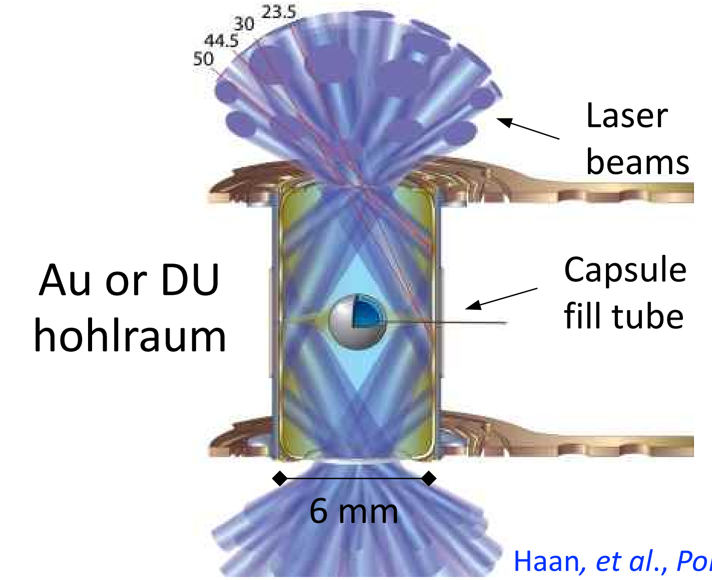
We use Inertial Confinement Fusion (ICF) to bring star power to earth





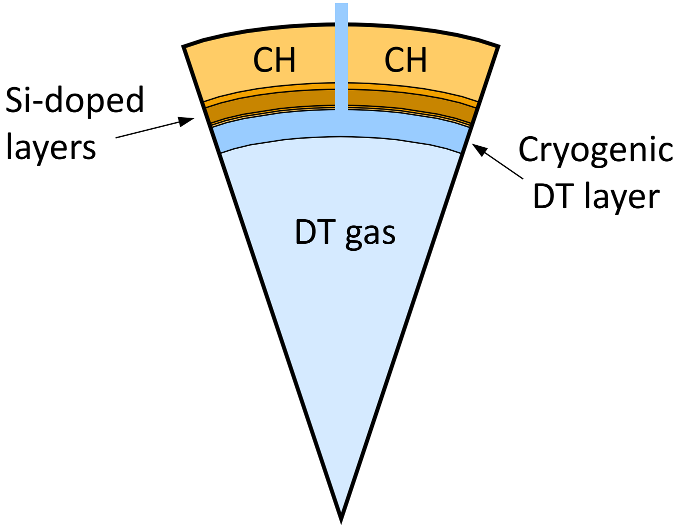
The NIF uses a laser driven hohlraum to compress a fuel pellet of deuterium and tritium to achieve the conditions for ignition

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

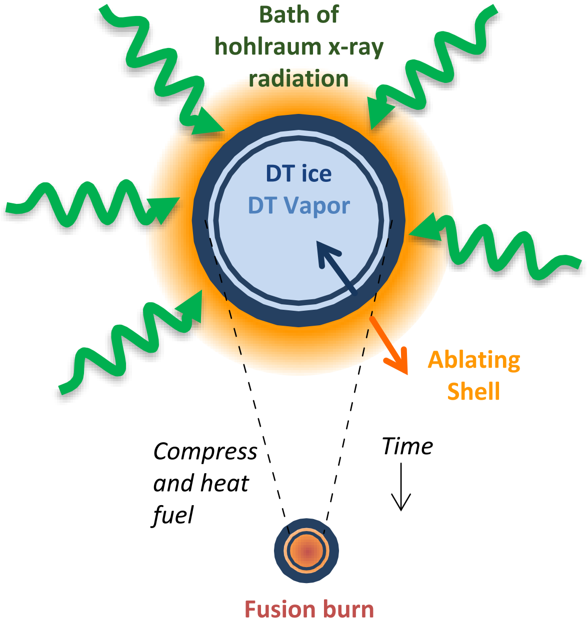


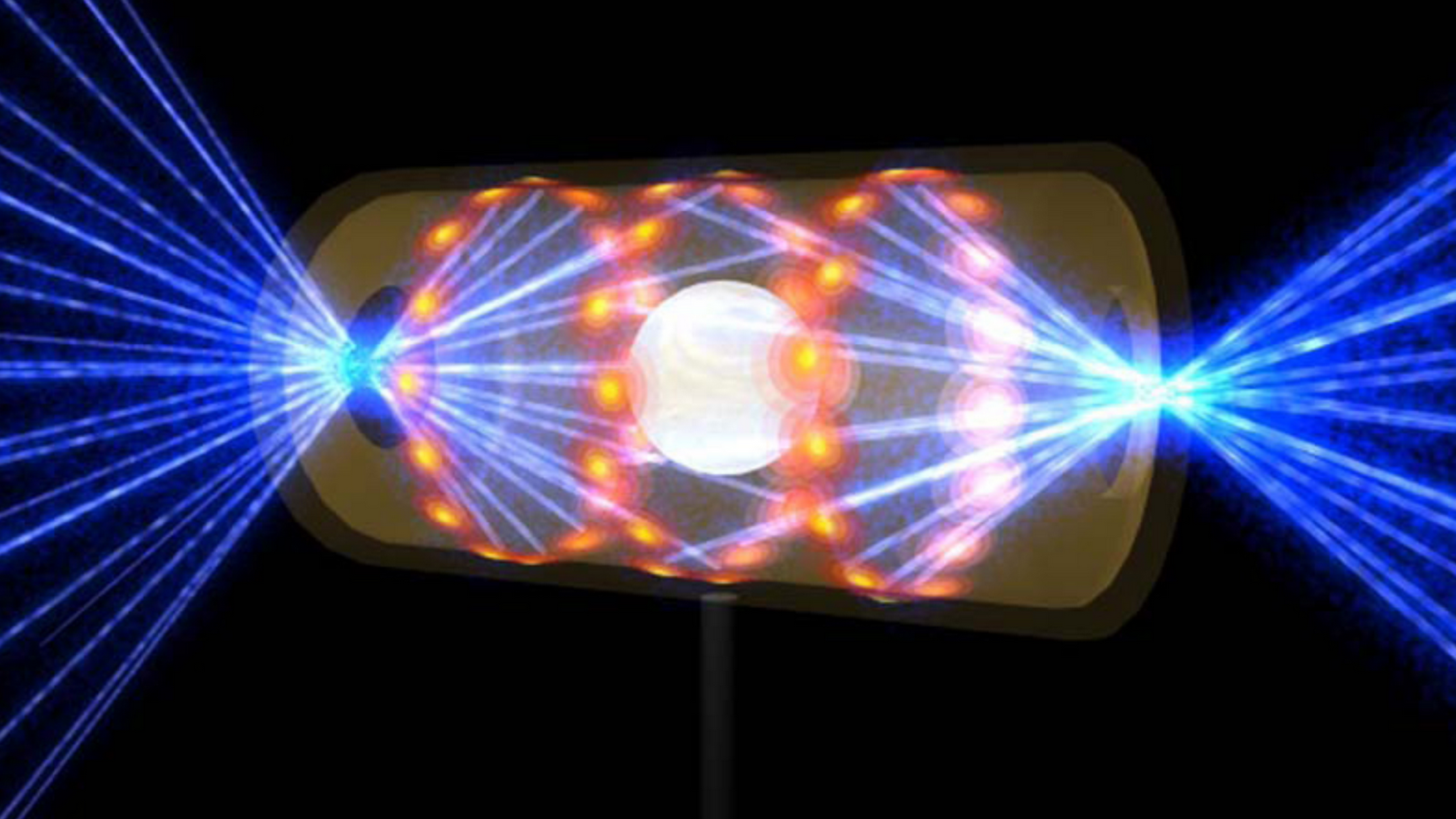
Haan, *et al.*, *PoP*, 2011

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



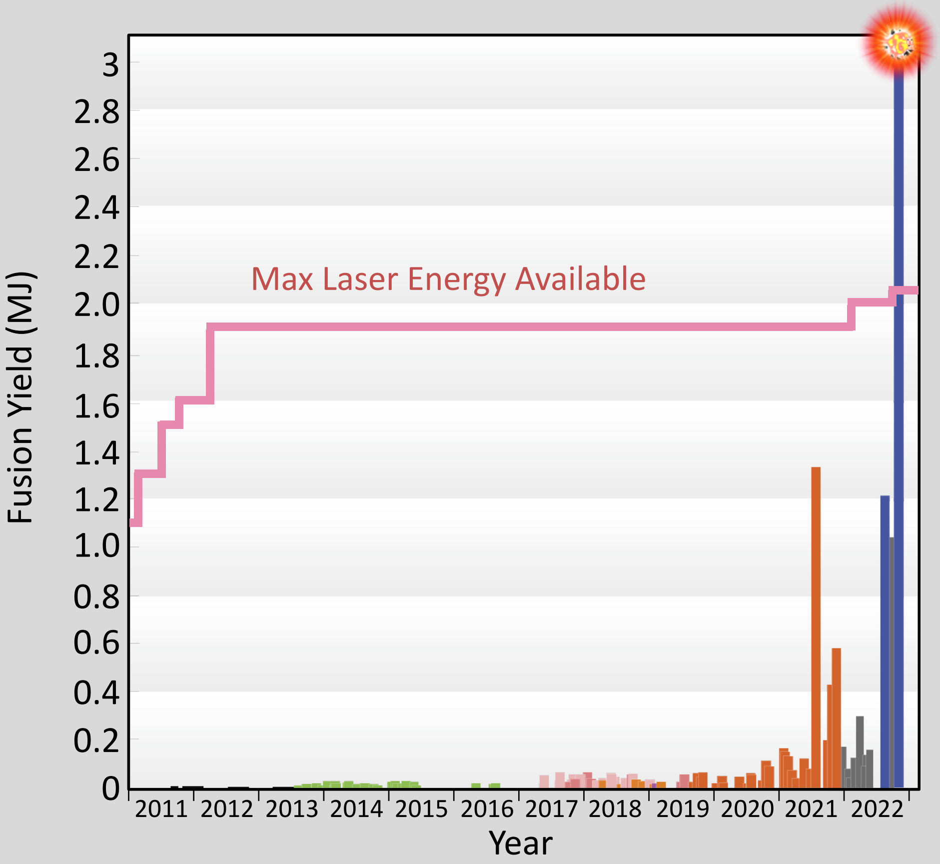
The trick of ICF is to turn 100 million atmospheres of pressure into 300 billion





On Dec 5, 2022 ignition was achieved on the NIF with 3.15 MJ of fusion energy out for 2.05 MJ laser energy in!

NIF Fusion Yield

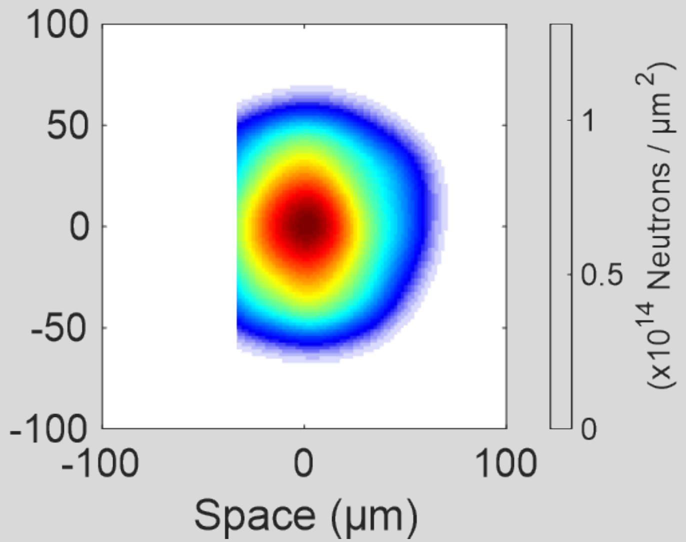


Output from 12/5/2022 Experiment

>30,000 trillion watts (30 PW),

~3.15 MJ with G_{target} ~ 1.5

10^{18} neutrons over ~100 ps



Fusion plasma ~100 μm

Temperature ~130,000,000 K

*National Academy of Sciences 1997 definition for ignition, target gain >1

[1]H. Abu-Shawareb et al., PRL, 129, 075001 (2022)
[2]A. L. Kritcher et al., PRE, 106, 025201 (2022)
[3]A. B. Zylstra et al., PRE, 106, 025202 (2022)

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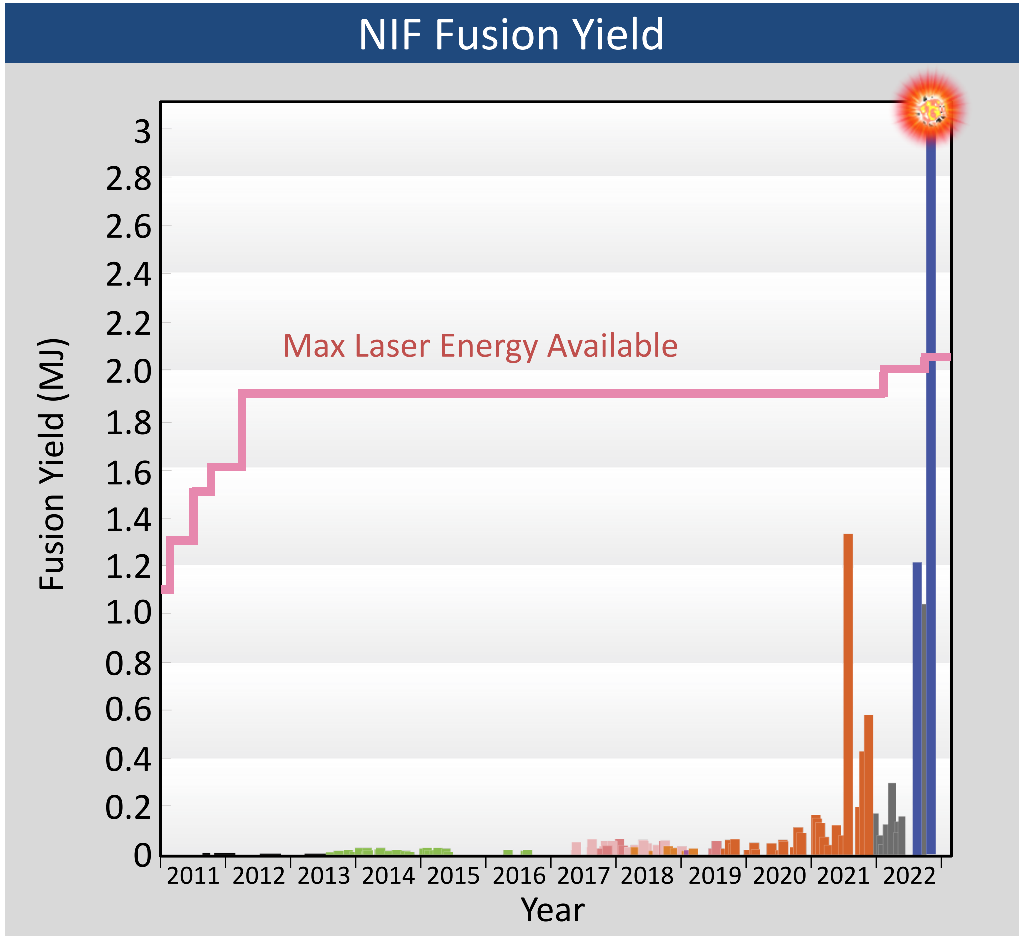

Ignition enables a new era of applications for Stockpile Stewardship and the foundation for Inertial Fusion Energy

*National Academy of Sciences 1997 definition for ignition, target gain >1

[1] *H. Abu-Shawareb et al., PRL, 129, 075001 (2022)*
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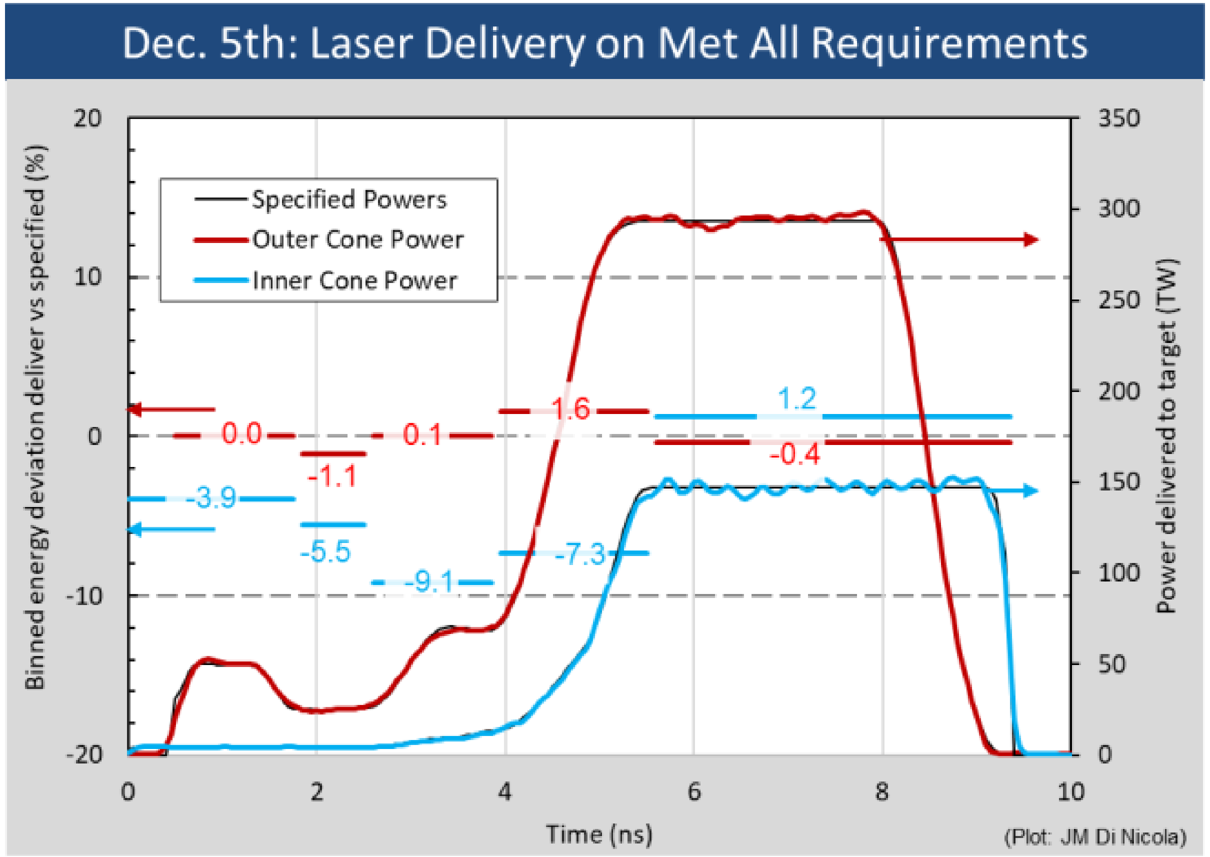
The achievement was announced at a DOE press conference

"Last week at the Lawrence Livermore National Laboratory in California, scientists at the National Ignition Facility achieved fusion ignition. And that is creating more energy from fusion reactions than the energy used to start the process. It's the first time it has ever been done in a laboratory anywhere in the world. Simply put, this is one of the most impressive scientific feats of the 21st century."

U.S. Secretary of Energy Jennifer Granholm
DOE Press Conference Announcing Major Nuclear Fusion Breakthrough
December 13, 2022

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

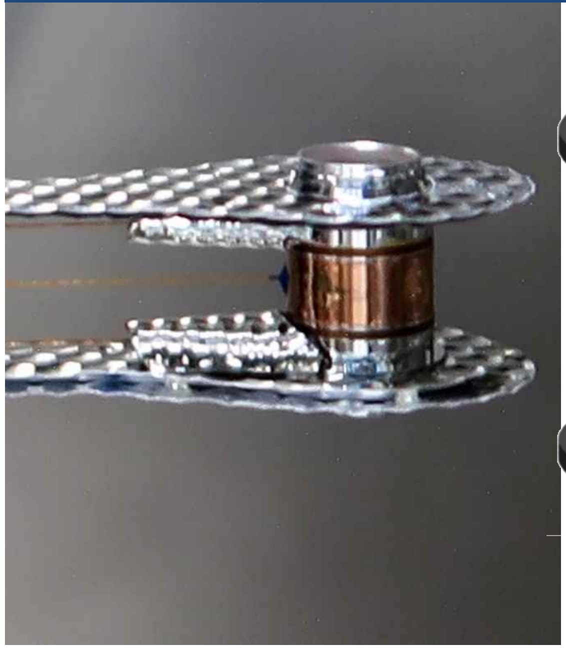


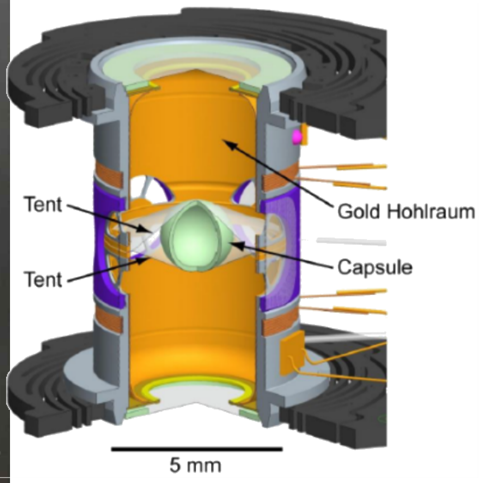
The NIF laser delivers requested energy within a 50 µm pointing, 30 ps timing, and a few % of power accuracy to provide the required conditions for ignition

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

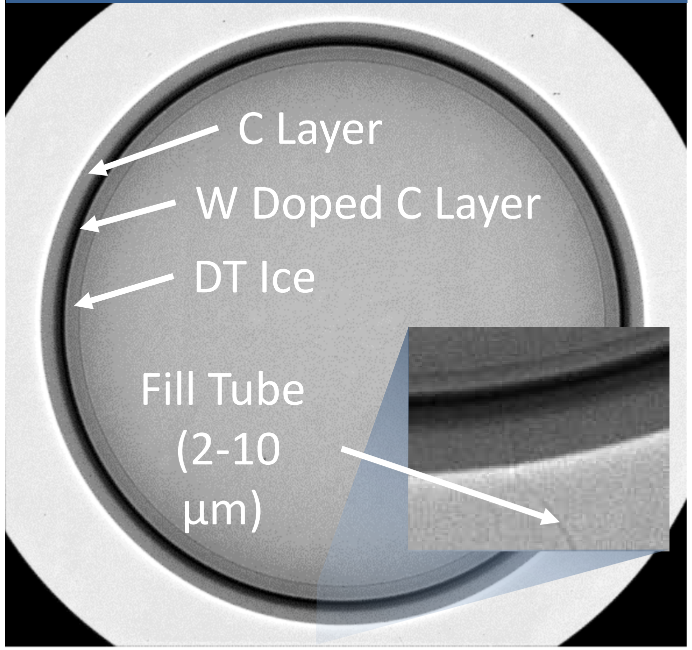




Diamond Nanocrystalline Capsule (High Density Carbon – HDC)

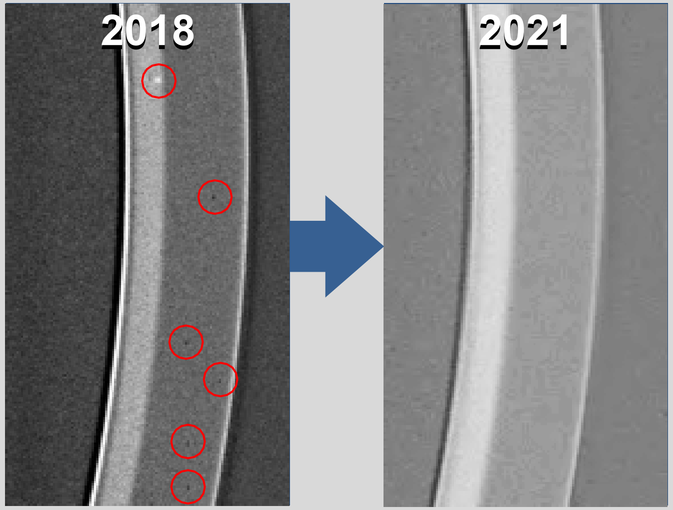
≈ 2 mm diameter, smooth to 10 nm

Capsule with DT Layer @ 19 K



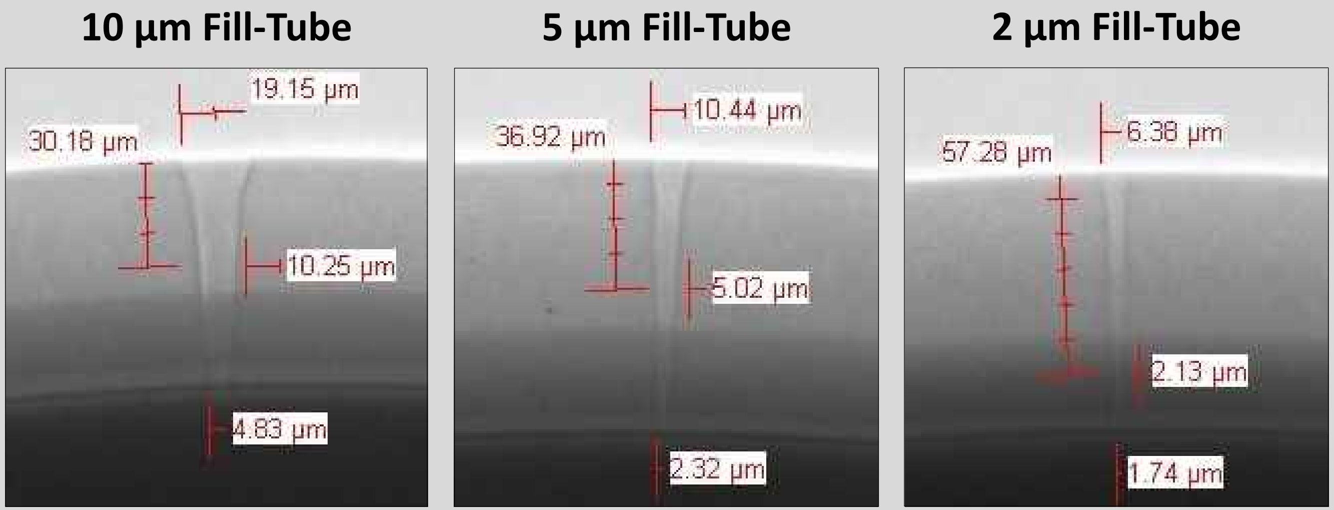
Target improvements have focused on reducing material and engineering defects

Capsule Quality



We have reduced pits and voids by two orders of magnitude

Fill-Tube Hole Diameter

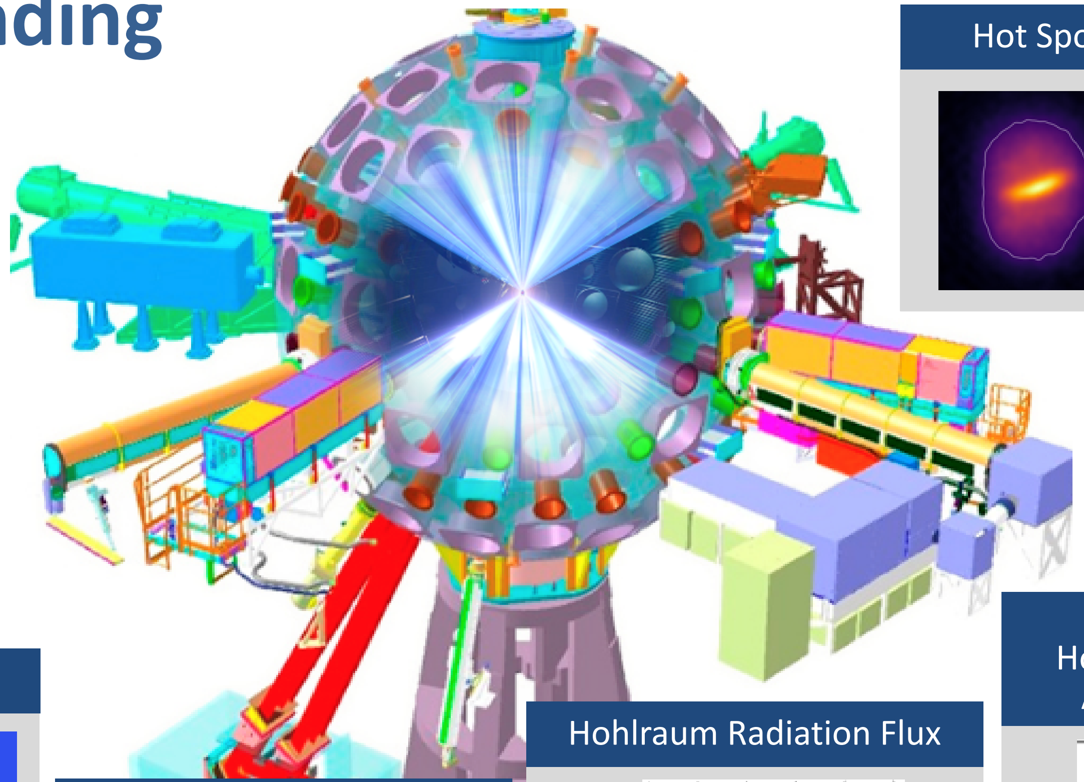


10x reduction in the surface area perturbation

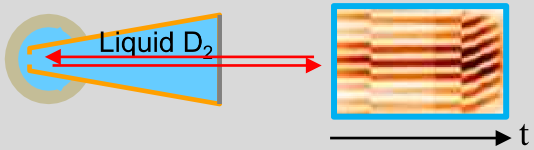
The advances in both target quality and our ability to characterize them have been pivotal in achieving our current implosion performance

Braun, et al, Nuc. Fusion (2022)

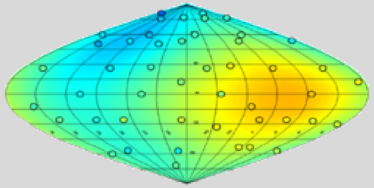
Dozens of diagnostics are applied to each experiment to improve understanding



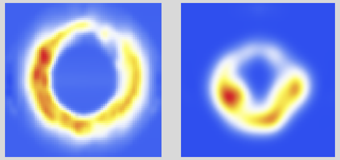
Shock Speeds, Timing



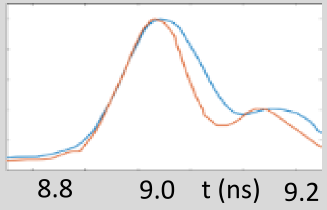
Yield / Fuel Uniformity



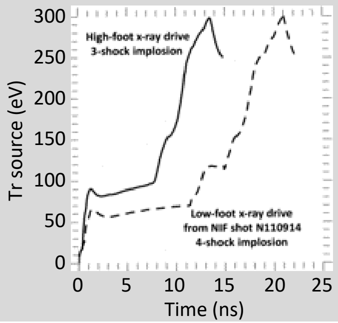
DT Fuel Uniformity



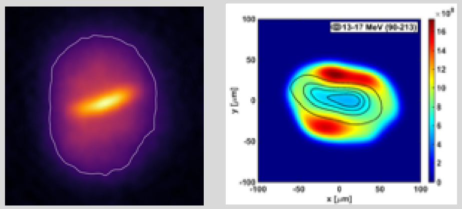
Burn Width, Bang Time



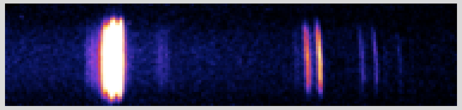
Hohlraum Radiation Flux



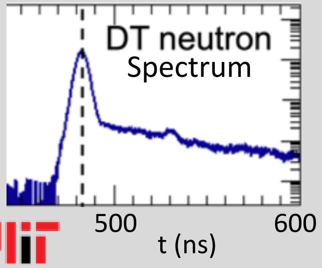
Hot Spot and Fuel Shape



Hot Spot Electron Temperature and Impurities

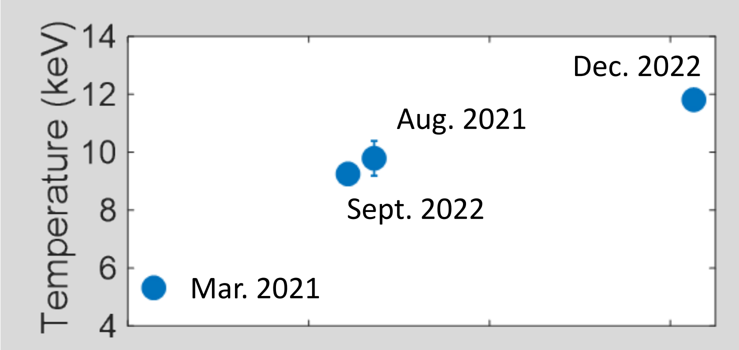


Ion Temperature, Hot Spot Velocity, Fuel Areal Density, Yield

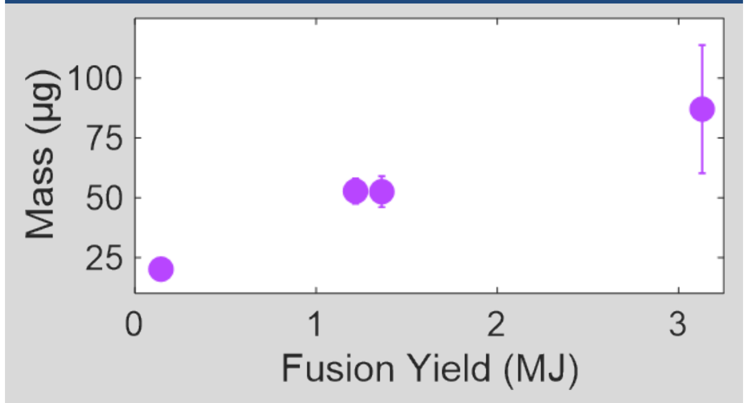


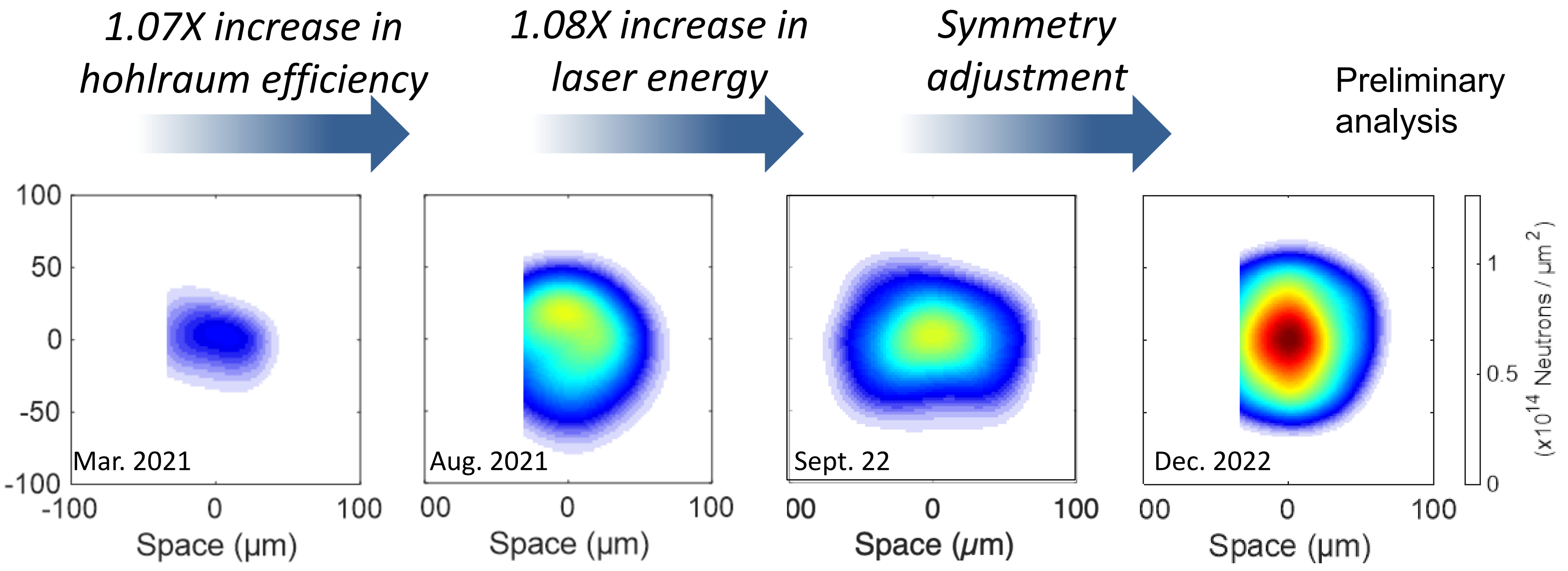
Over last two years, we increased hotspot reactivity and mass to achieve ~20x yield via improved targets and designs, laser energy, and tuning

Temp. increases 2.2X



Mass increases 4.3X

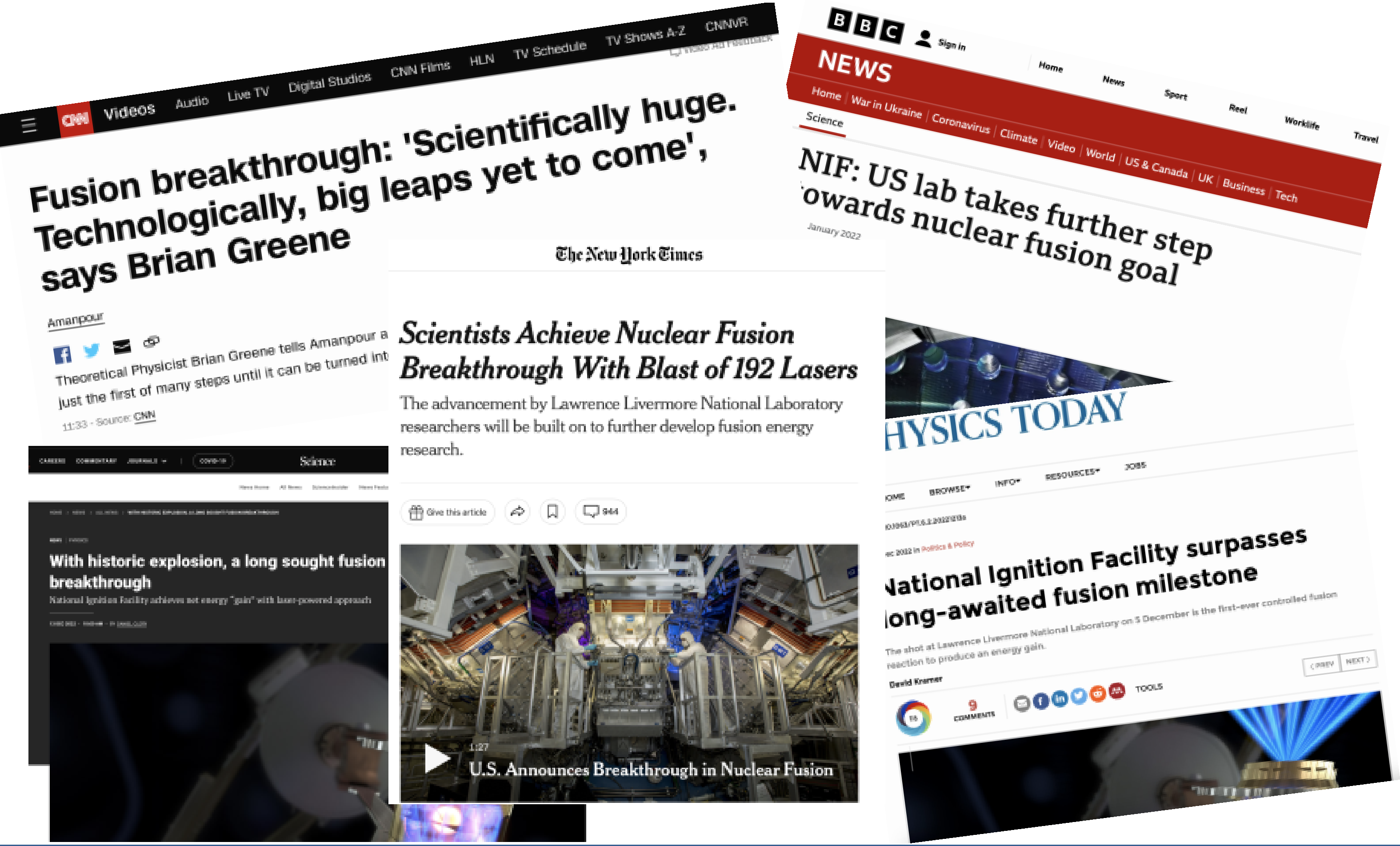


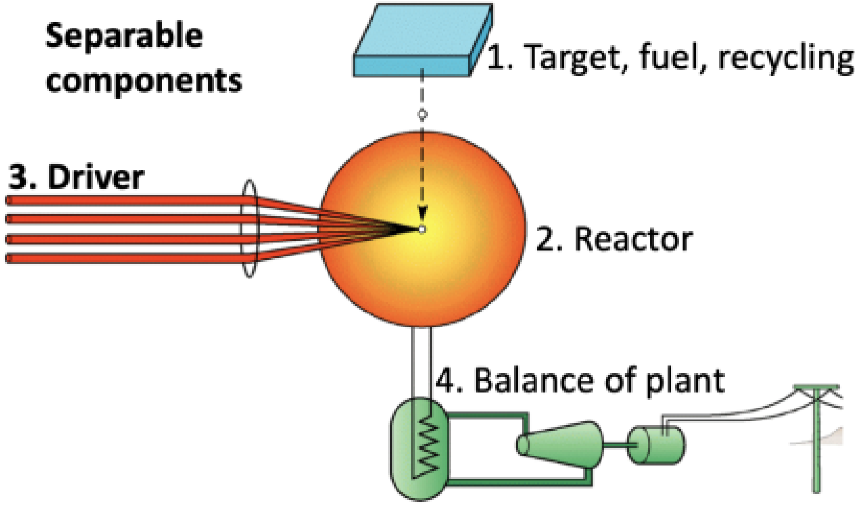


(Plots: A. Pak)

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

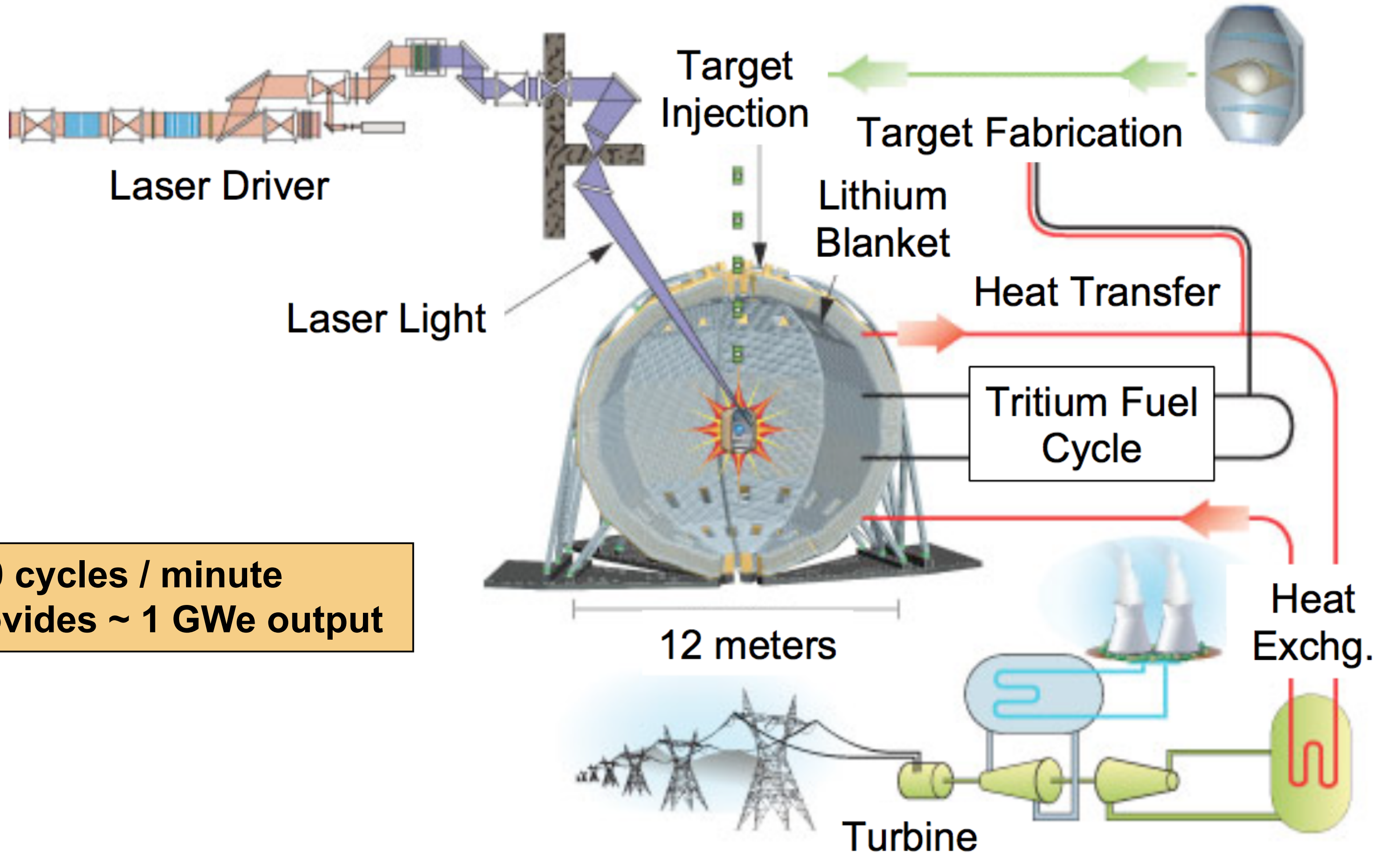
Ignition on the NIF establishes the basic scientific feasibility of laser-driven Inertial Fusion Energy (IFE)





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

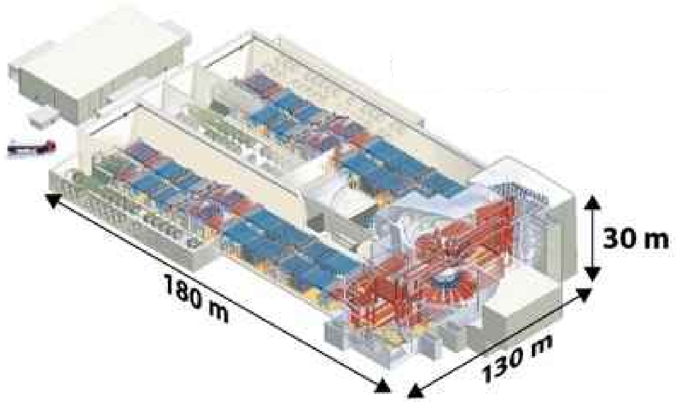
The concept for an IFE power plant includes a driver, target chamber, target factory, and a steam turbine to generate electricity



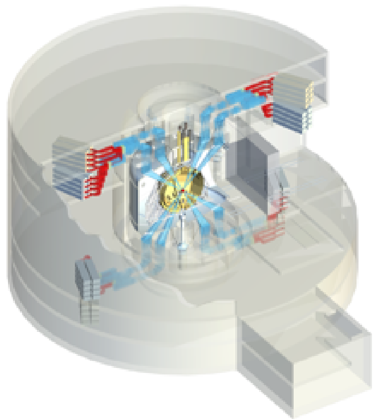
900 cycles / minute provides ~ 1 GWe output

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

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.

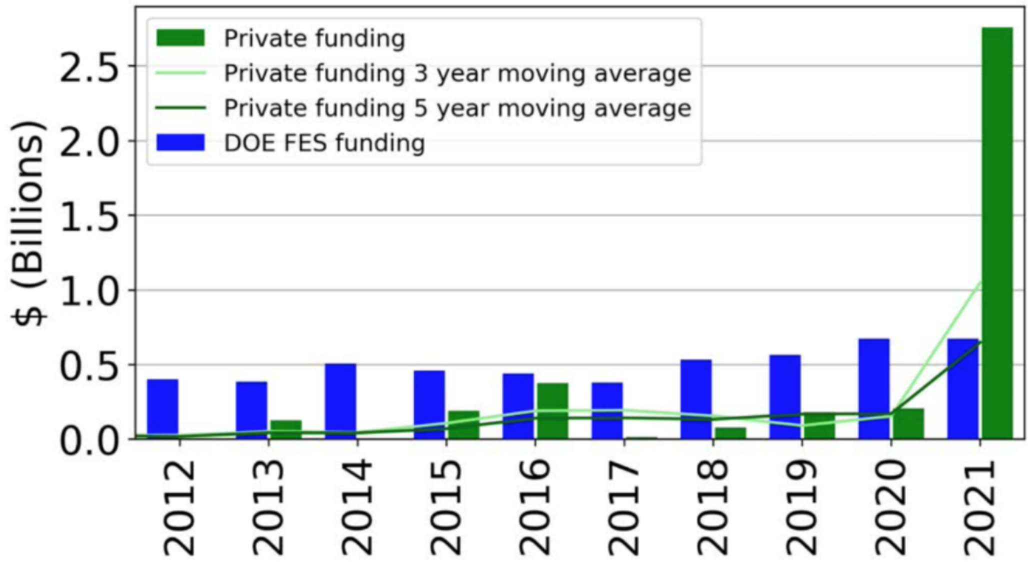
The US DOE recently held a Basic Research Needs in IFE to define a new national IFE program

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.

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



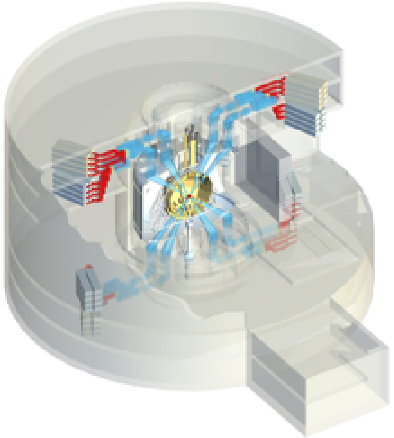
Plot credit: Sam Wurzel, Technology-to-Market Advisor, ARPA-E

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

From FIA 2022, ~$4.7B into private fusion industry, with ~$180M of that into IFE companies

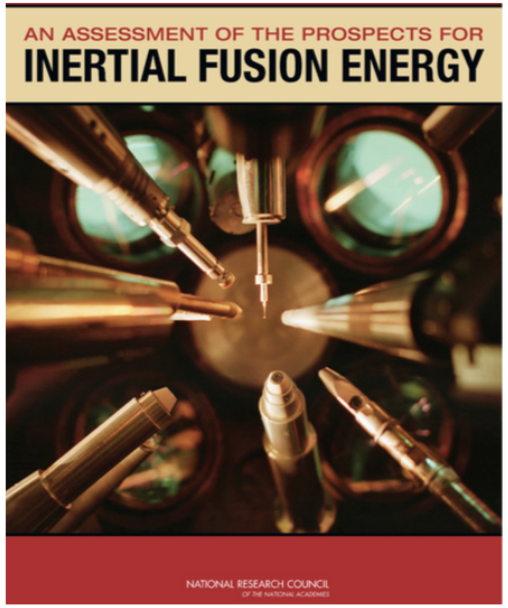
Public-Private Partnerships will accelerate progress

Why IFE? Why now?



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

- Separable components & highly modular
- Multiple target concepts with same driver
- Lower tritium inventory
- Attractive development path: Technology and science spin-offs
- Multiple sponsors for key technologies (e.g., laser diodes, high neutron yield sources)



"The appropriate time for the establishment of a national, coordinated, broad-based inertial fusion energy program within DOE would be when ignition is achieved."

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)

In partnership with the community, we seek to enable an ecosystem to accelerate IFE in support of DOE's decadal vision for accelerating commercialization of fusion energy. We must ramp up a large public sector program and we need to move now!

Fusion Energy may be the ultimate clean and limitless energy source

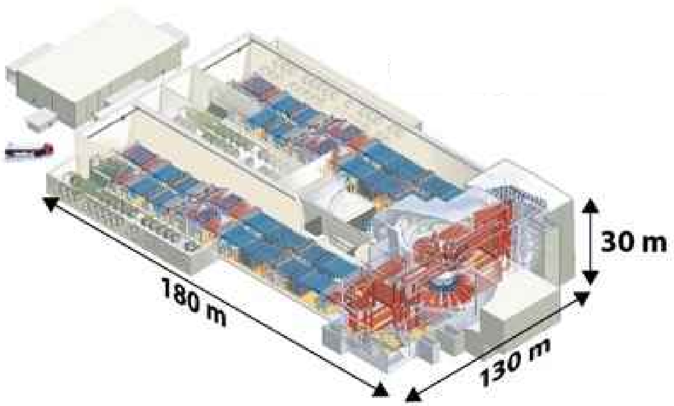
- Ignition has been demonstrated!
- Inertial Fusion Energy is a game-changing technology
  - Can provide abundant energy while helping to meet CO_2 goals
  - Bolsters science and technology leadership, security, and energy independence
- The time is now!
  - Scientific energy gain achieved on NIF
  - Unprecedented fusion energy momentum in the public and private spheres
- IFE is a multi-decadal 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!

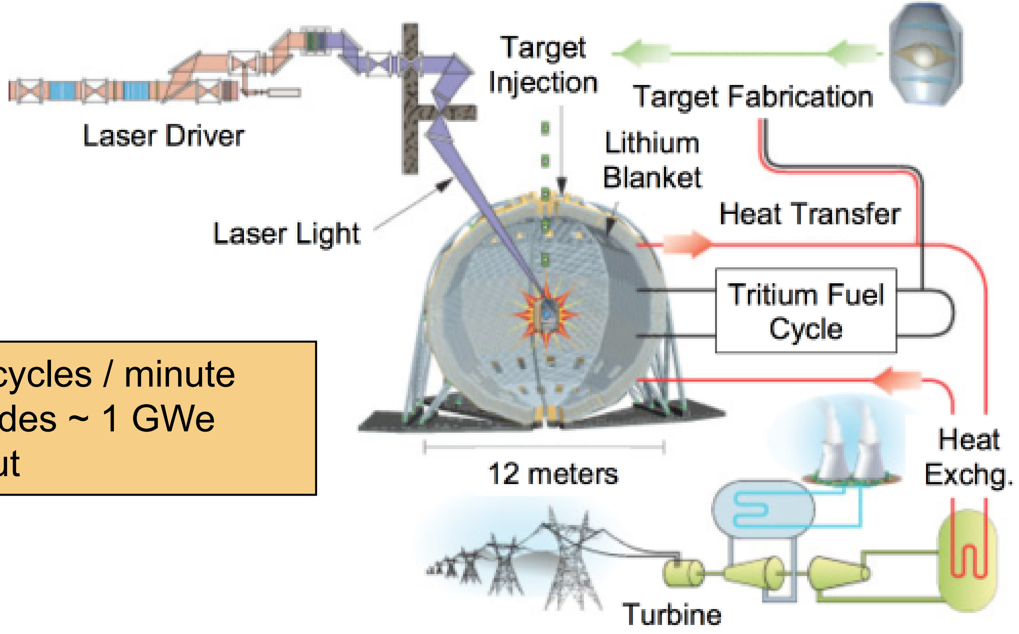
Fusion energy offers a long-term vision for enduring global climate and energy security.

Lawrence Livermore
National Laboratory

The leap from NIF to an IFE power plant requires an increase in repetition rate and complexity, the development of robust, repeatable, burning plasma platforms, and technological advances in many subsystems

NIF: Single Shot	IFE plant: >10 Hz

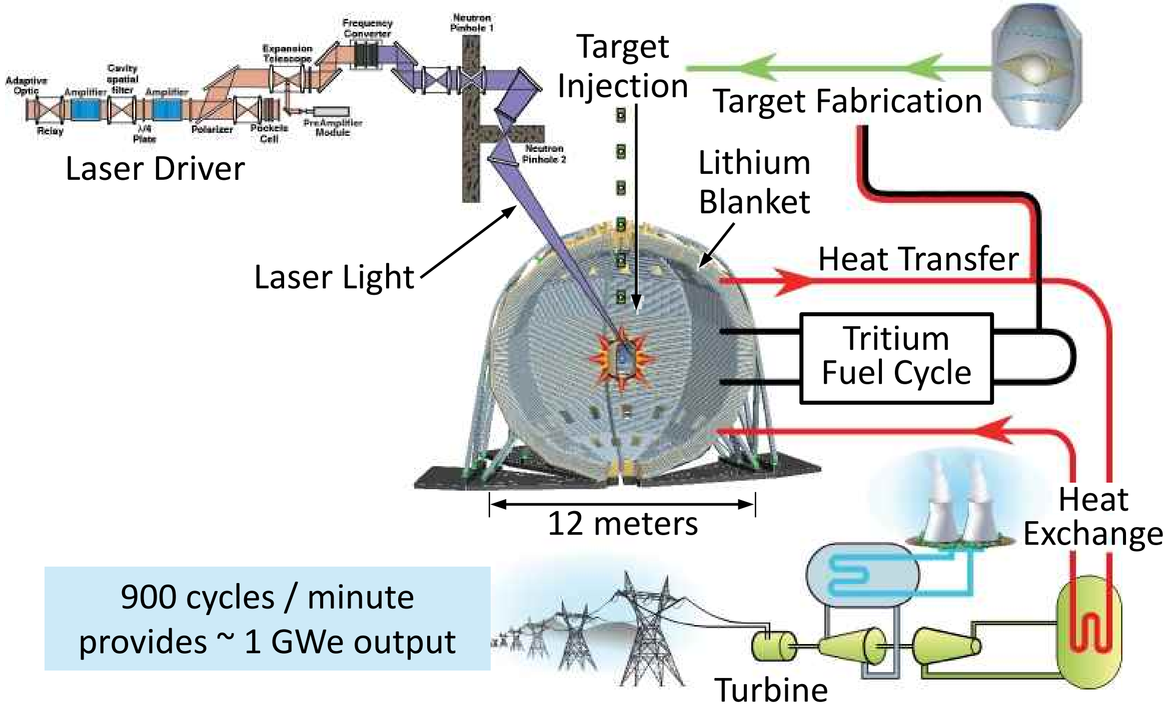




900 cycles / minute provides ~ 1 GWe output

The path forward for IFE research will require different, but synergistic, technologies from the stockpile stewardship mission.
Key question: can we achieve Gain ~100?
How can IFE leverage and spur emerging technologies?

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



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 public investment needed will be comparable or more to the investment required to obtain ignition

With community partnerships and in synergy with our stewardship mission, LLNL aims to enable an ecosystem to accelerate IFE in support of DOE's decadal vision for accelerating commercialization of fusion energy. How do we ramp up a large public sector program? We need to move now.