Ignition and the Path Toward an Inertial Fusion Energy Future

Homeland Defense & Security Information Analysis Center

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February 13, 2025

Background image source: Brian Chavez/LLNL

LLNL-PRES-833900

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

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

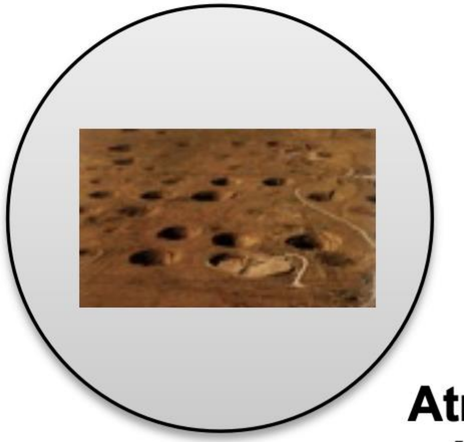
…and many more

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

Nuclear Warfare


USAF Graphic

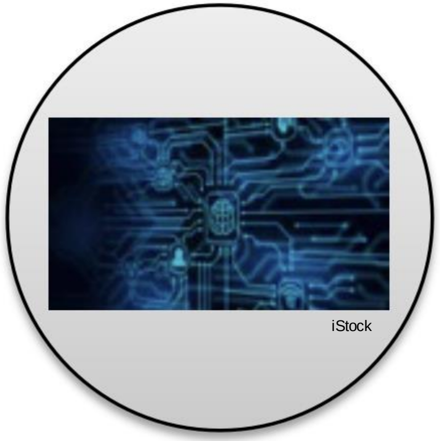

NASA



Atmospheric and Underground Nuclear Testing

Energy-Related Greenhouse Gas Production


Alamy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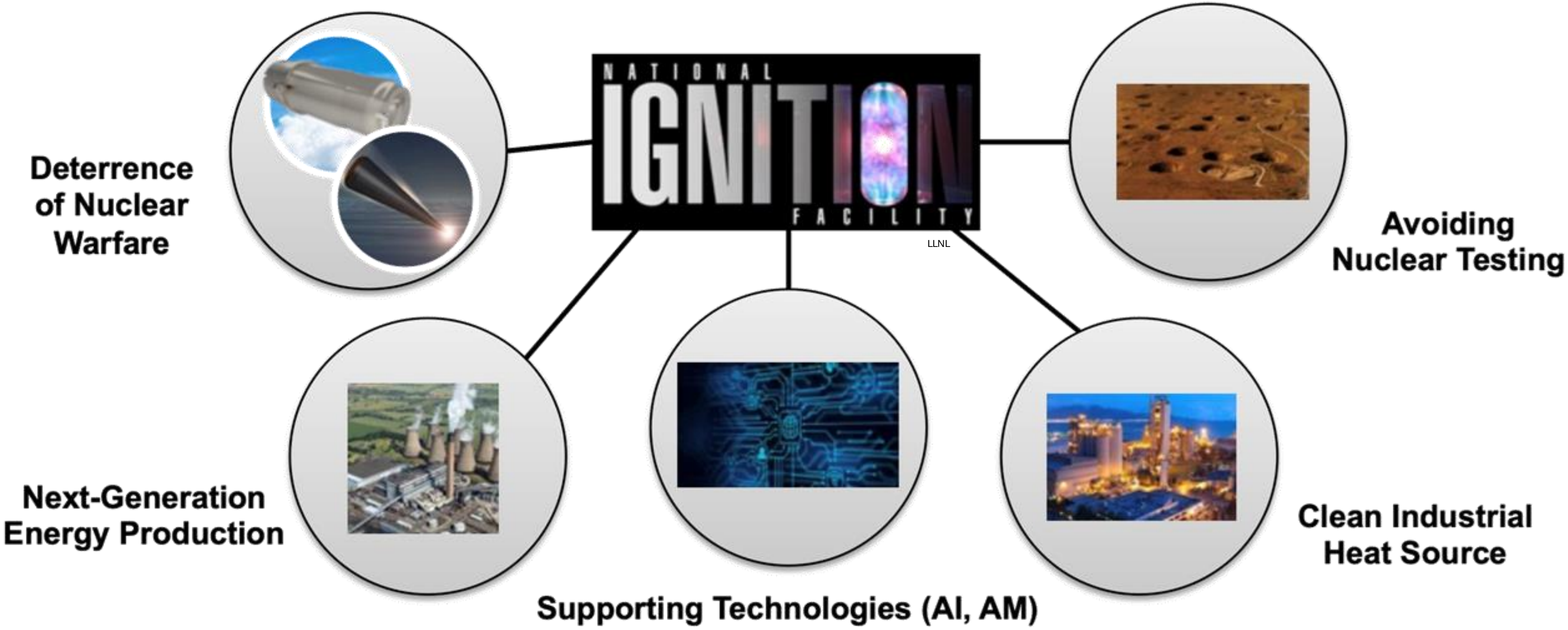
Technology Disruption

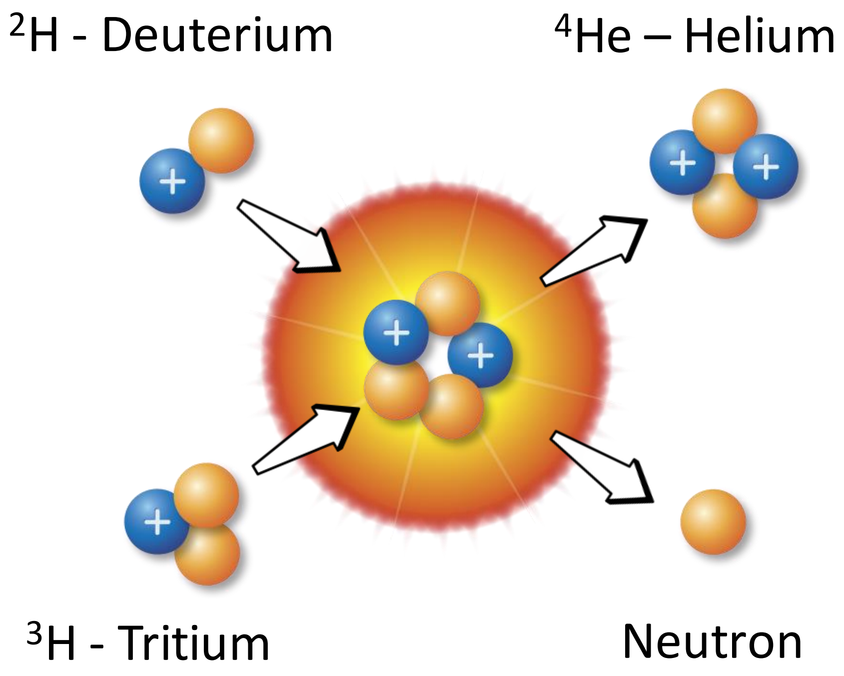

Shutterstock photo by Cozyta

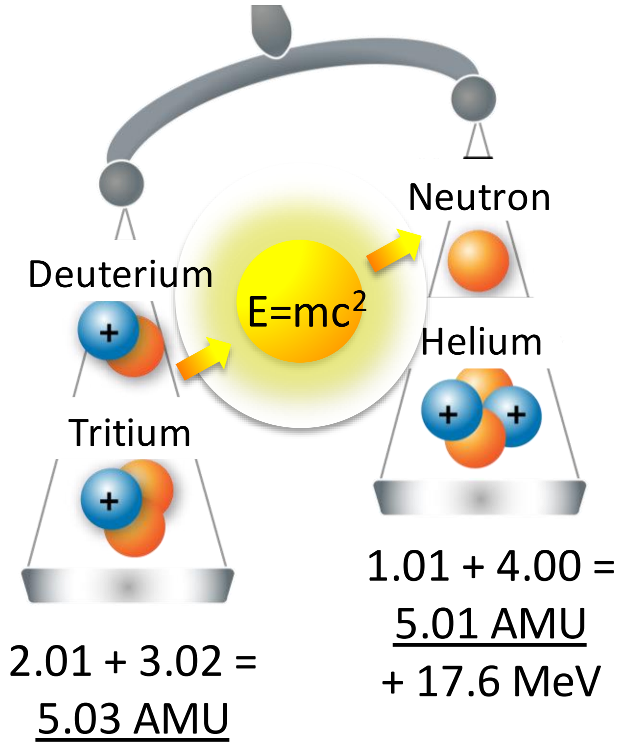
Industrial Processing Greenhouse Gas Production

Fusion energy, specifically fusion ignition on the National Ignition Facility (NIF), has an impact on each of these areas.



The sun, stars, and nuclear weapons are powered by fusion.



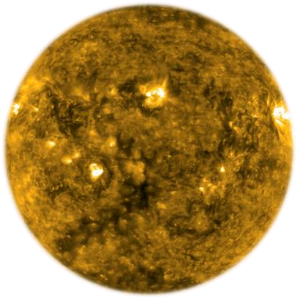
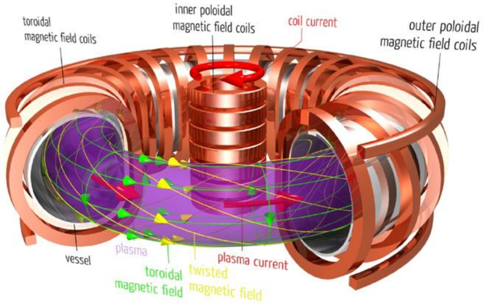
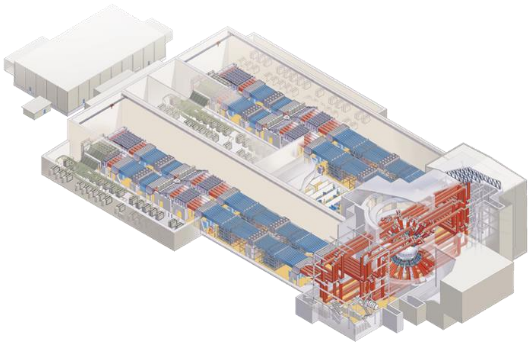


$$D + T \rightarrow a(3.5\text{MeV}) + n(14.1\text{MeV})$$

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

Graphics Source: Ma, T

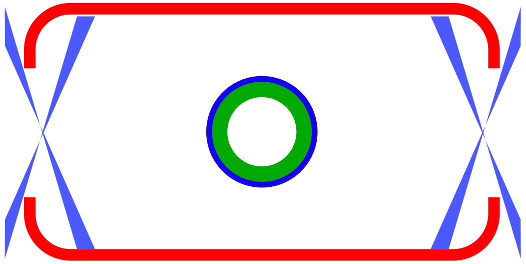
There are at least three ways to achieve nuclear fusion.

	Gravitational Confinement	Magnetic Confinement	Inertial Confinement
			
Density	10,000 x solid	solid / 100,000,000	1,000 x solid
Temperature	~15,000,000 °C	~150,000,000 °C	~150,000,000 °C
Confinement Time	100,000 years	seconds	10’s picoseconds

Graphics Source: LLNL

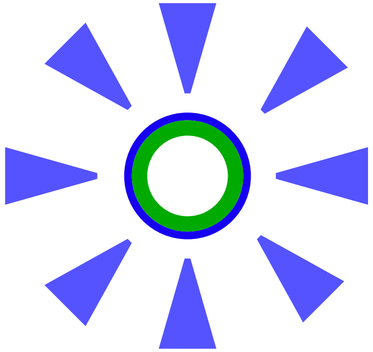
Inertial confinement fusion (ICF) can be achieved by using high-power lasers to drive a spherical implosion.

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 100x density of lead, ignites at 100,000,000 ˚C.

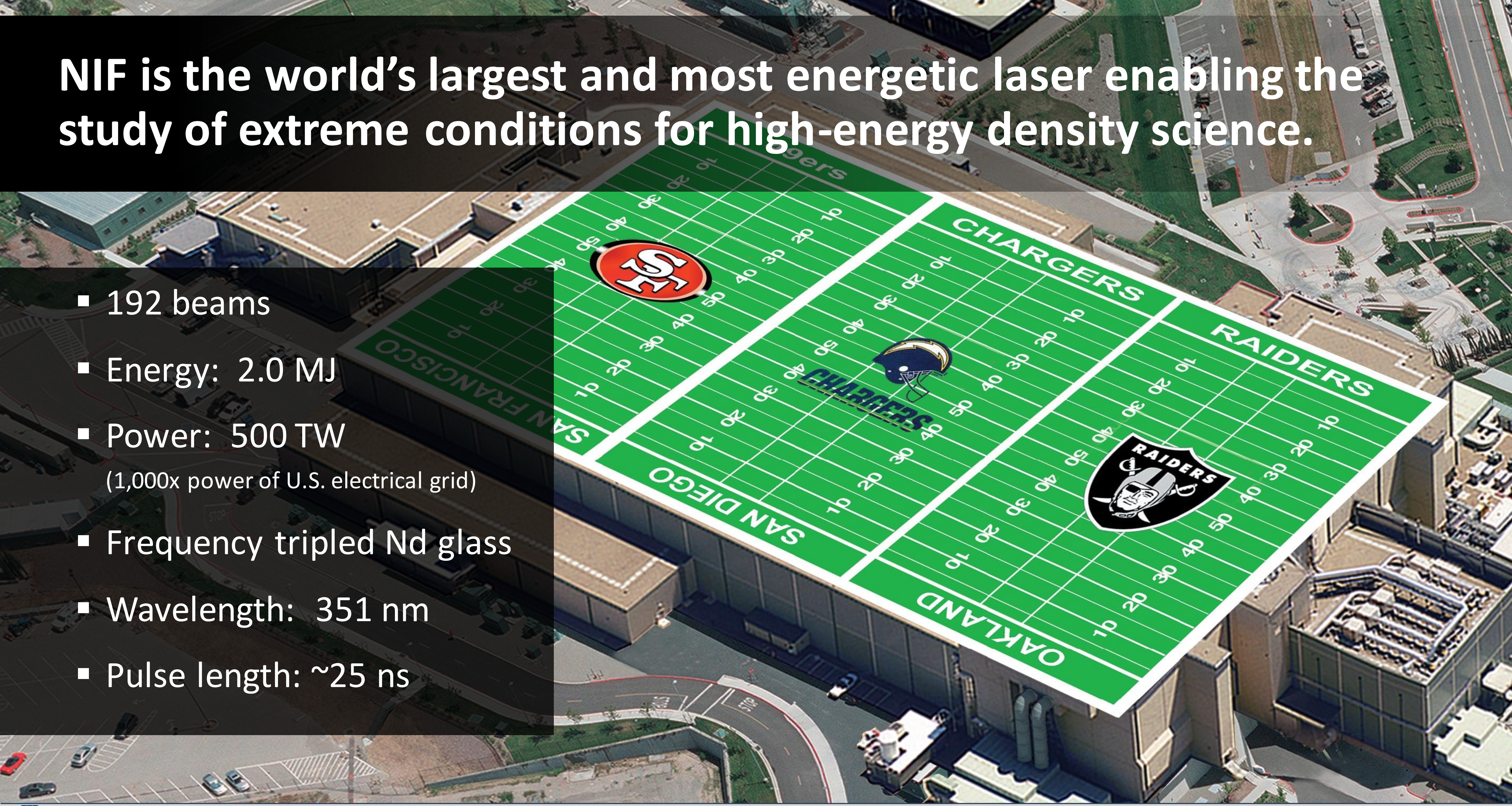
Image taken from "Matter at High-Energy Densities," Univ. of Rochester, Laboratory for Laser Energetics

At the NIF, we are building our own miniature sun.

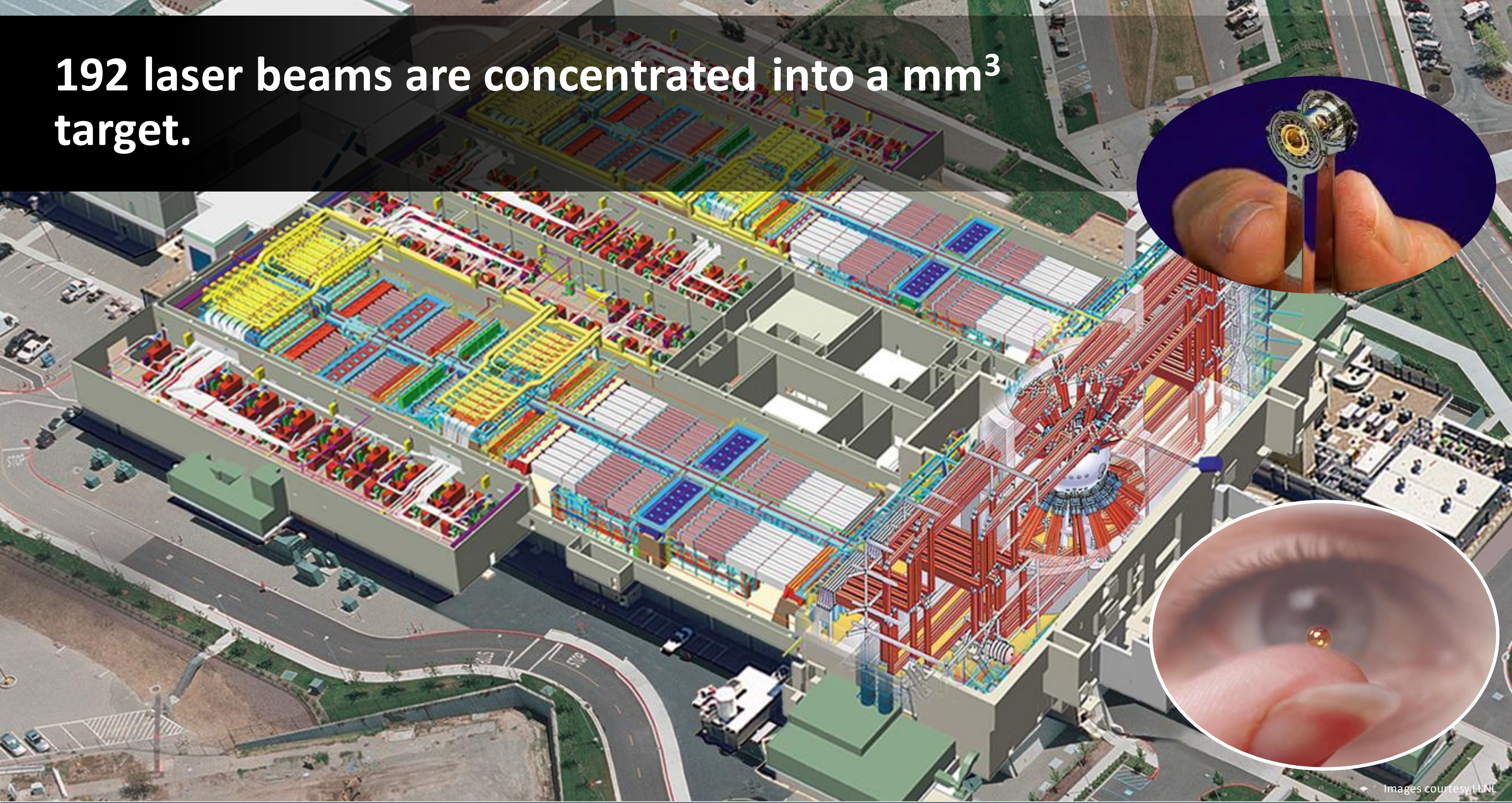
Image courtesy LLNL

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

- 192 beams
- Energy: 2.0 MJ
- Power: 500 TW
  (1,000x power of U.S. electrical grid)
- Frequency tripled Nd glass
- Wavelength: 351 nm
- Pulse length: ~25 ns



192 laser beams are concentrated into a mm^3 target.

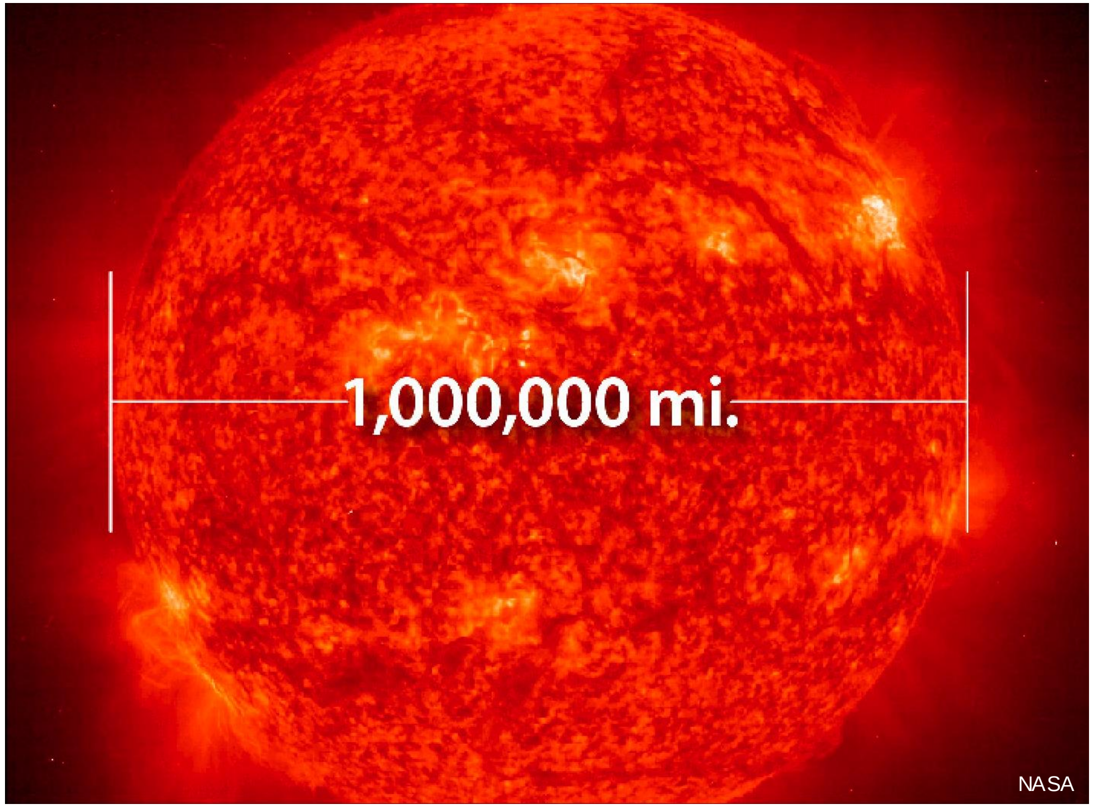


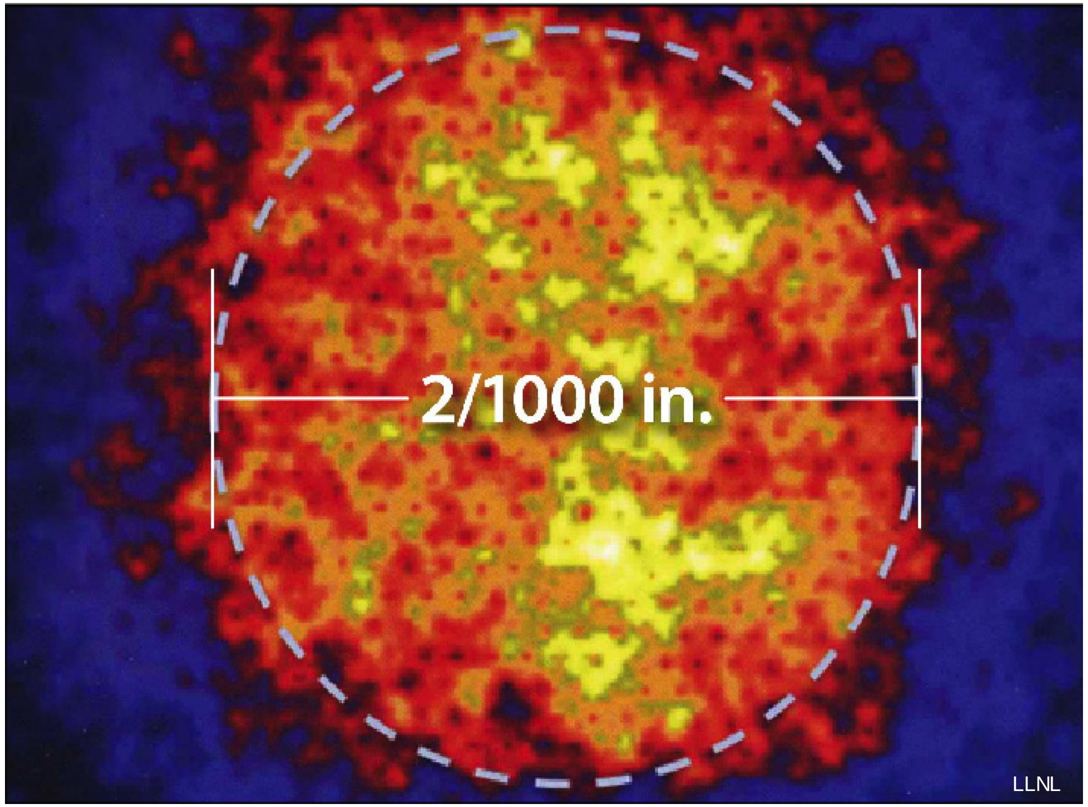
Images courtesy LLNL

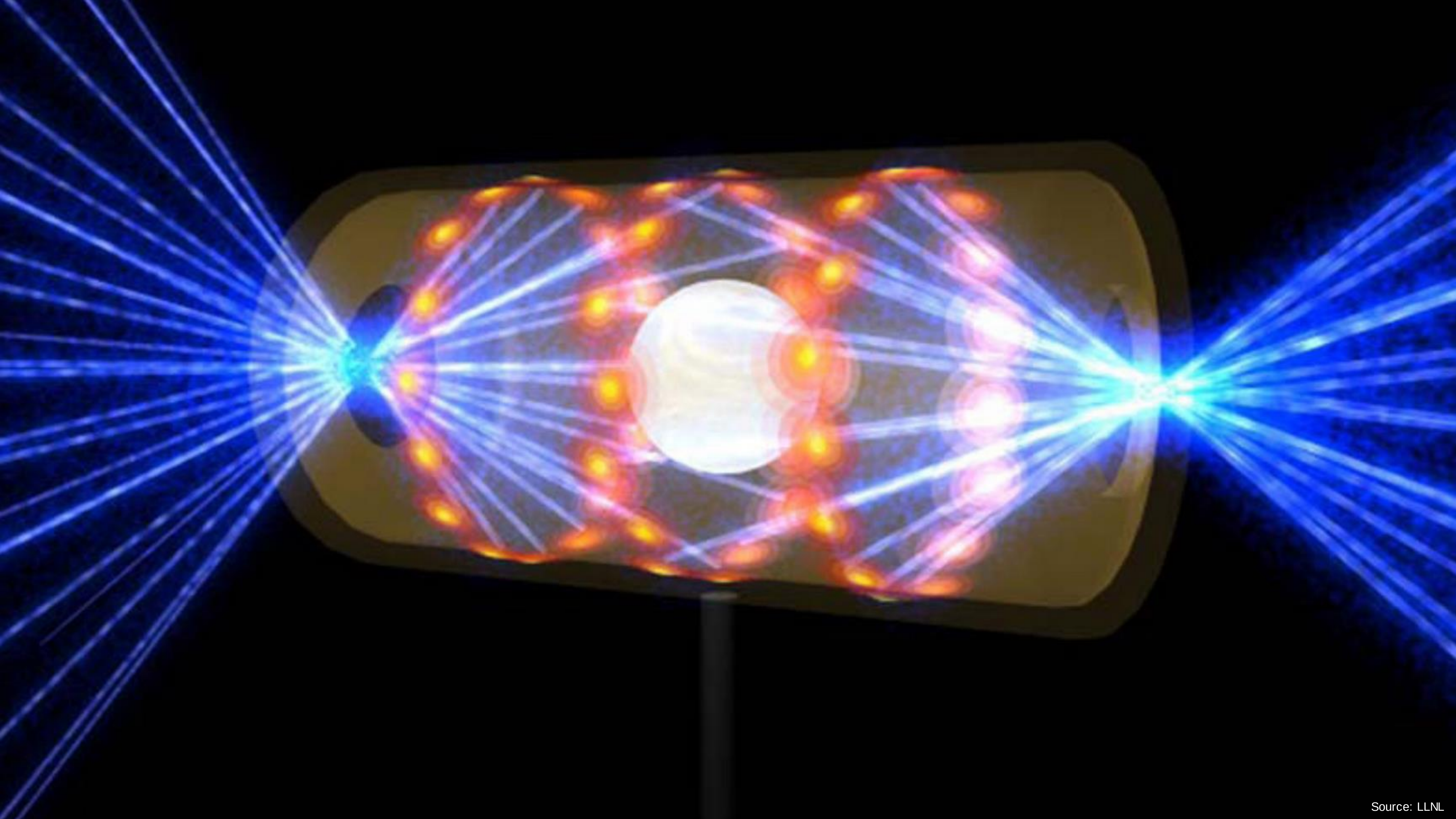
NIF ensures a safe and reliable nuclear deterrent without underground testing.

Image Credit: Nevada National Security Site and National Ignition Facility

We use ICF to bring star power to earth.







Source: LLNL

On December 5, 2022, *fusion ignition* was finally realized at NIF.

Image credits: DOE

In that experiment, **NIF generated more energy out of the target than was put in.**

… reaching a goal that had been over 60 years in the making and requiring a team of thousands.

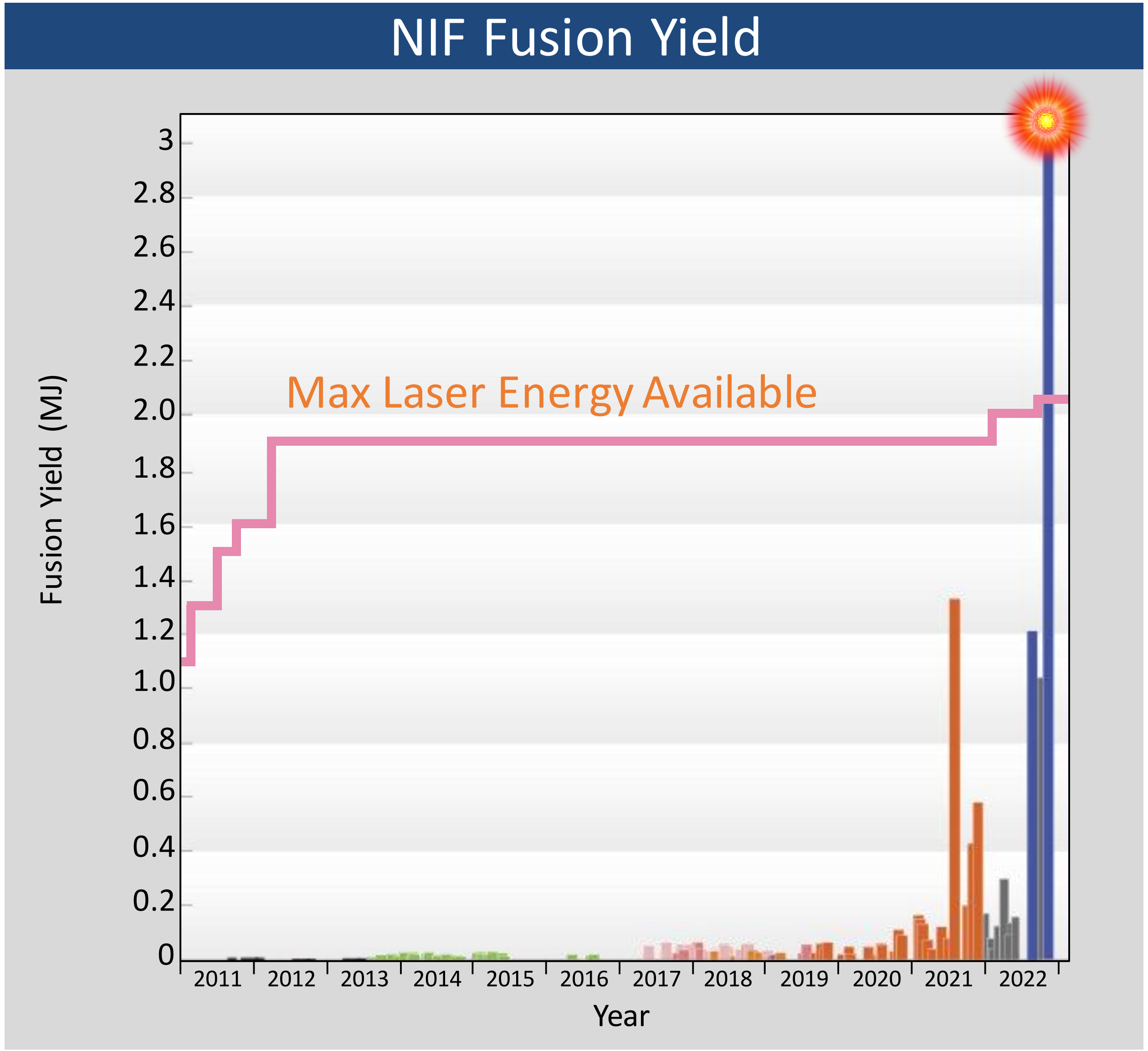
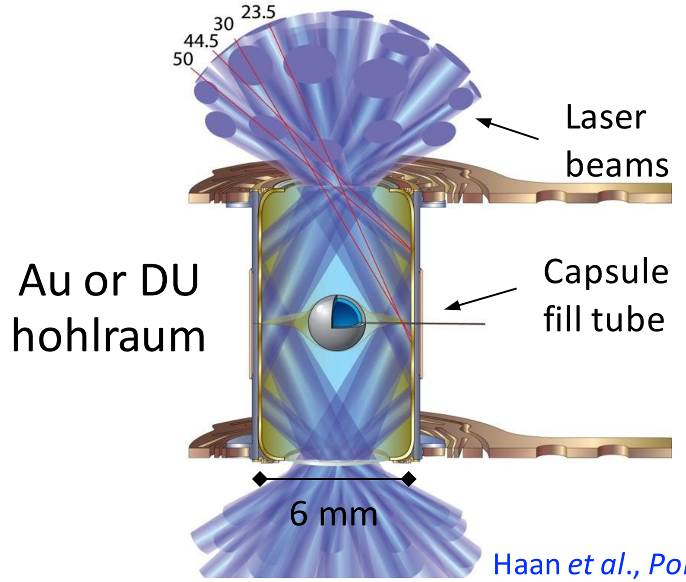


Figure credit: LLNL

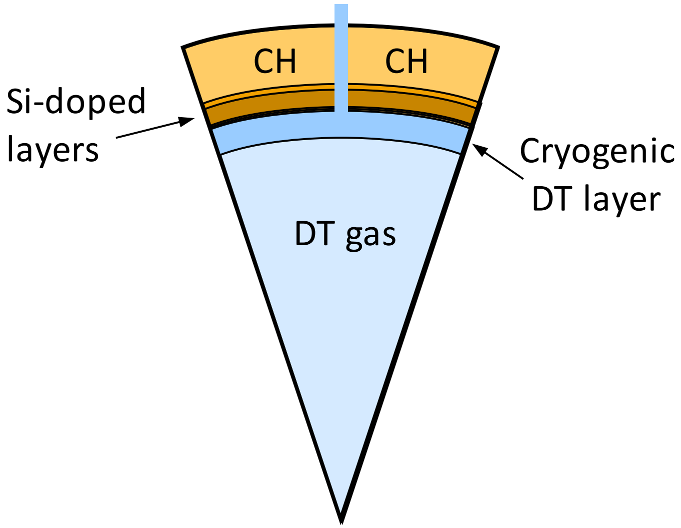
The NIF uses a laser-driven hohlraum to compress a fuel pellet of deuterium and tritium to achieve the conditions for ignition.

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.

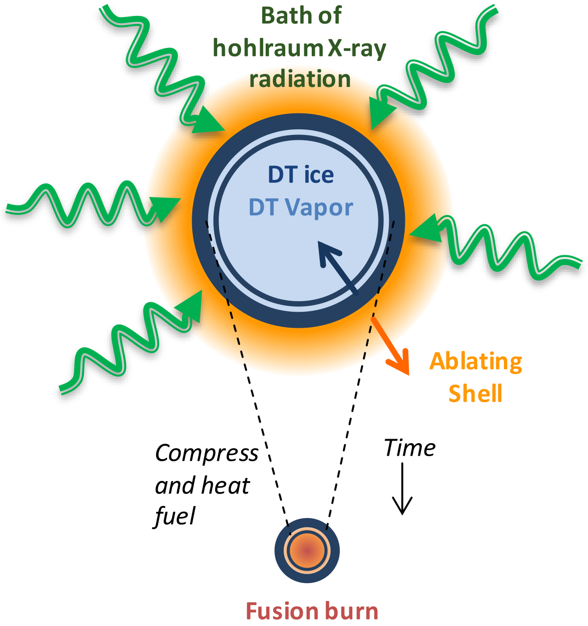
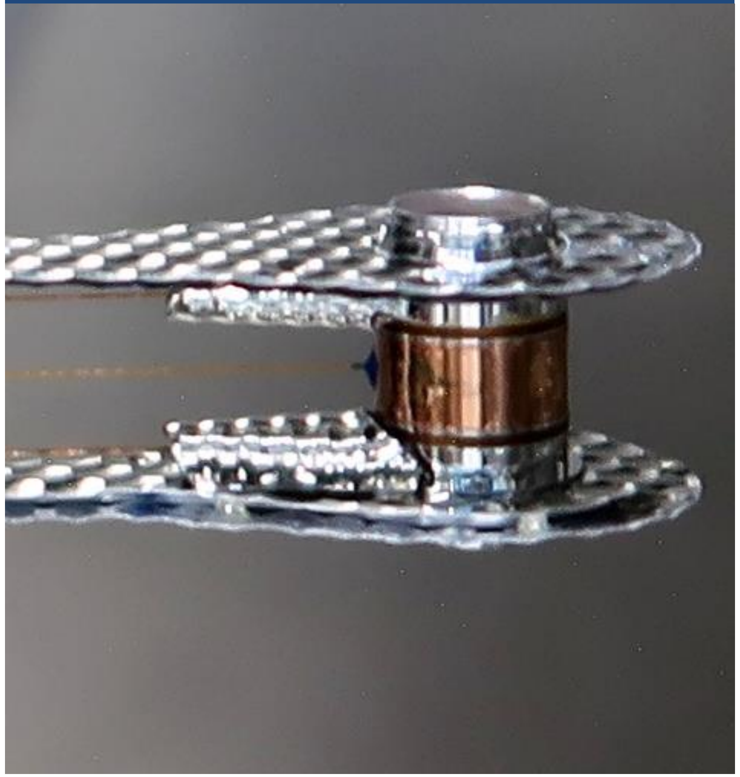


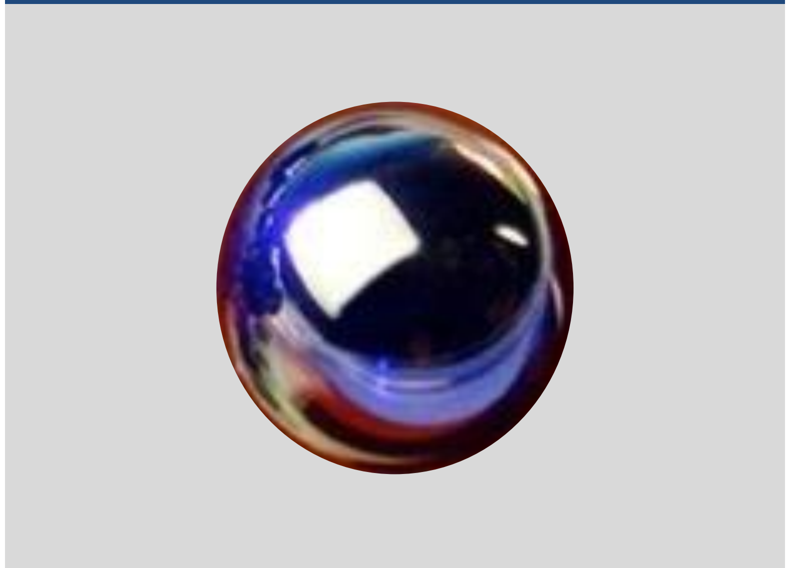
Image credits: LLNL

Ignition shots depend on precisely engineered fusion targets.

December 5, 2022, Ignition Target



Diamond Nanocrystalline Capsule (High-Density Carbon – HDC)



≈2-mm diameter, smooth to 10 nm

Capsule with DT Layer @ 19 K

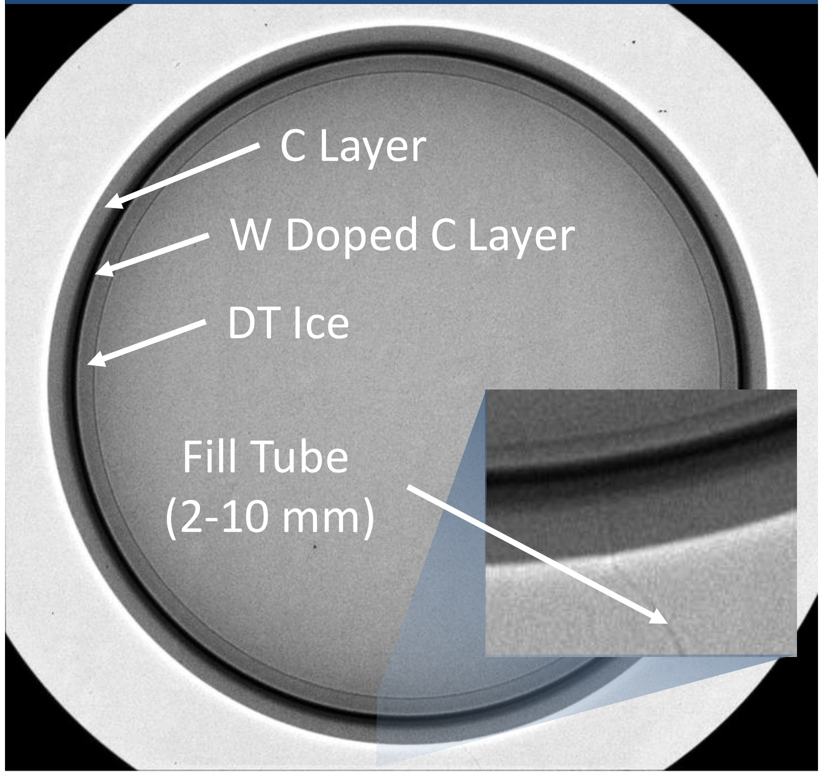
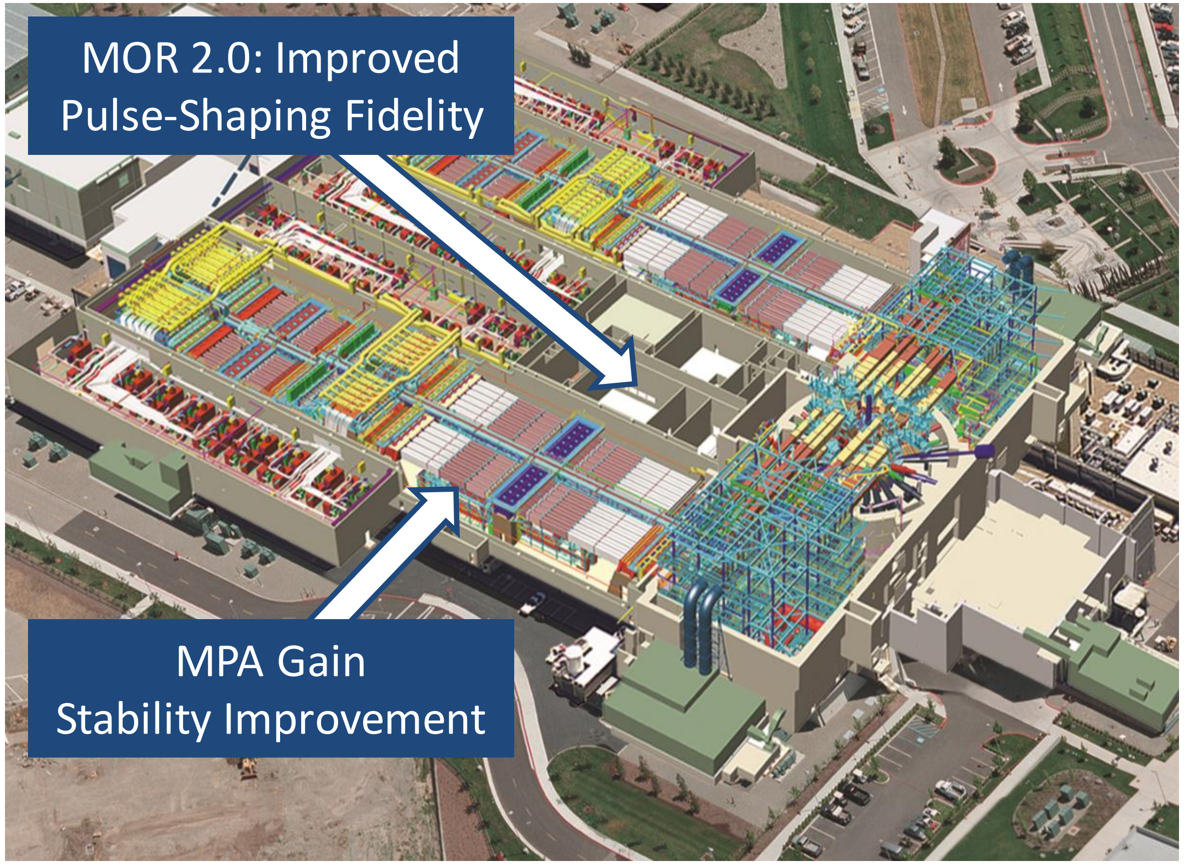


Image credits: LLNL

Ignition could not have been achieved without developing better targets and improving our ability to characterize them.

We have ignition: NIF delivered 2.05 MJ, 440 TW to the target with exceptional accuracy and precision.



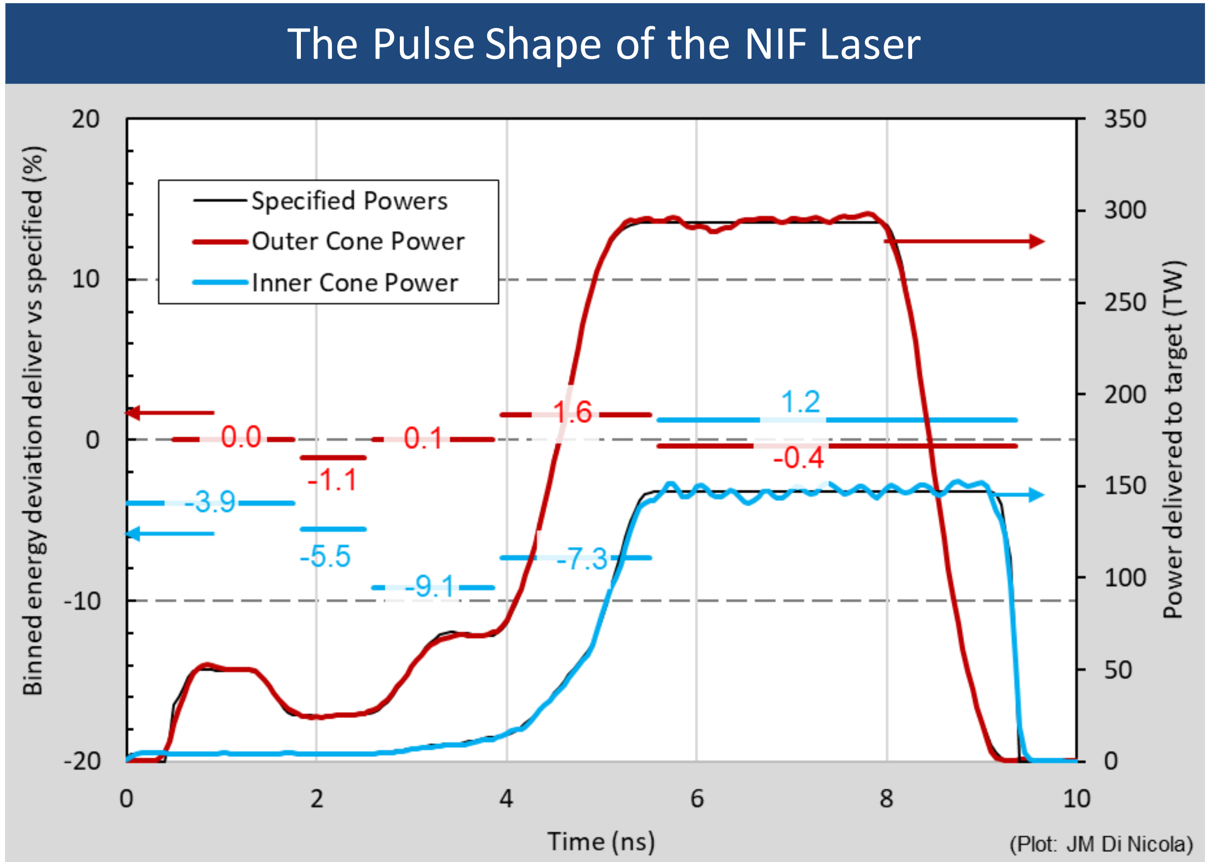


Image credits: LLNL

Scale with precision: NIF delivers its energy within a 50-µm pointing, 30-ps timing, and a few % of power accuracy to provide the required conditions for ignition.

Ignition was enabled by insights from developing world-leading diagnostics.

Shock Speeds, Timing

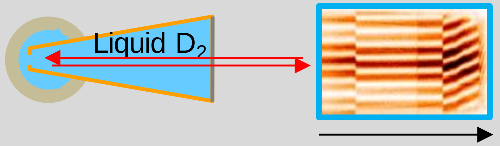


Image credit: LLNL

Yield / Fuel Uniformity

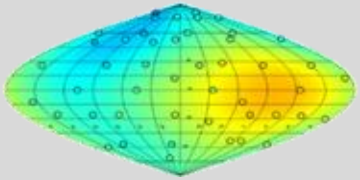


Image credit: LLNL

DT Fuel Uniformity

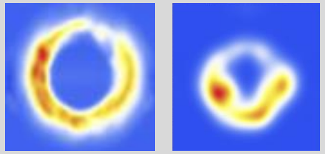
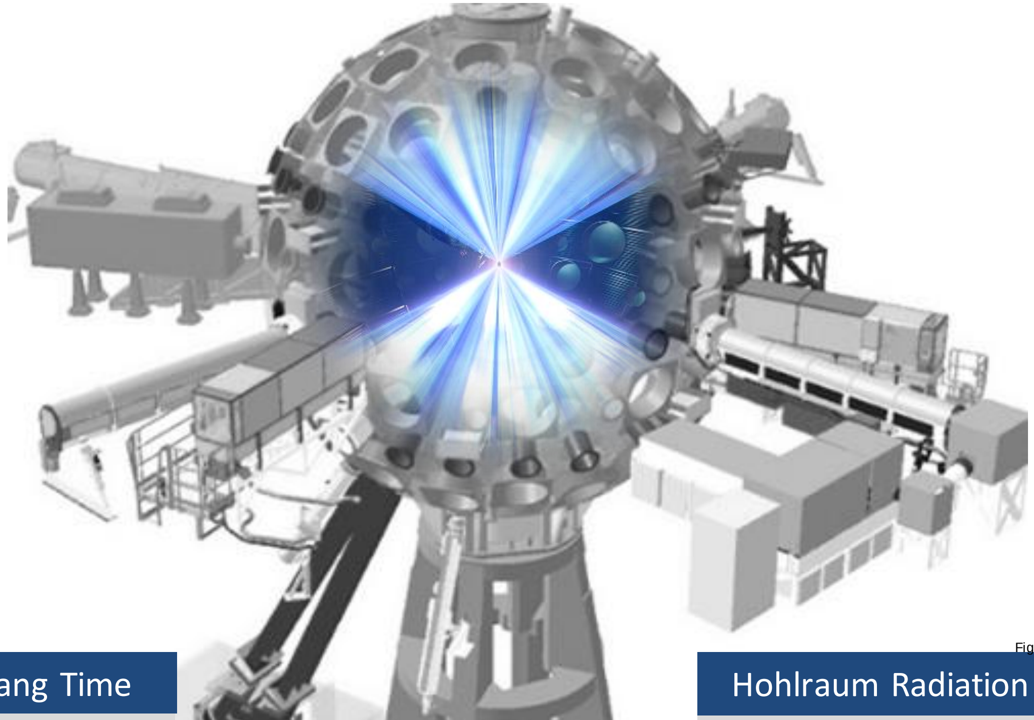


Image credit: LLNL



Burn Width, Bang Time

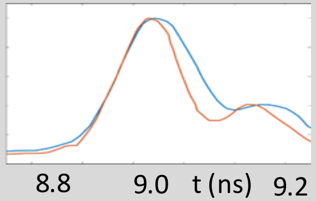
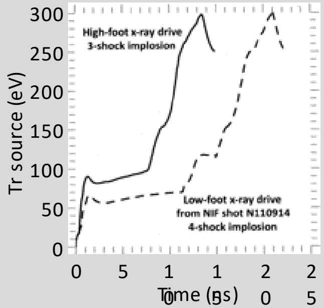


Figure credit: LANL

Figure credit: LLNL

Hohlraum Radiation Flux



Hot Spot and Fuel Shape

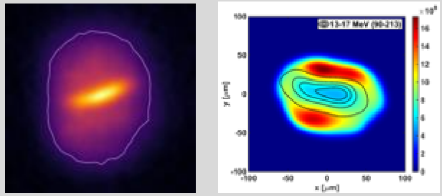


Image credit: LLNL

Hot Spot Electron Temperature and Impurities

Image credit: LLNL

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

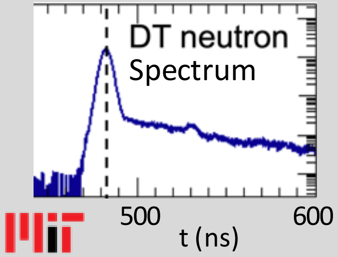
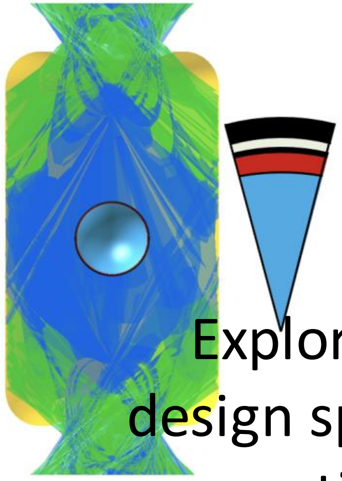


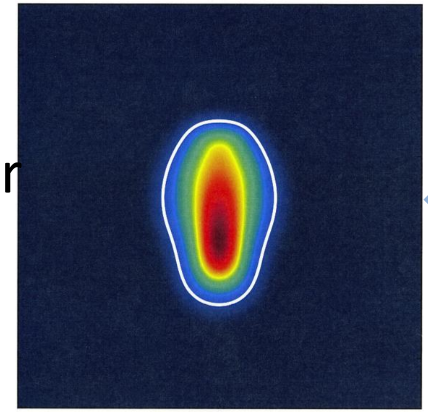
Figure credit: LLNL

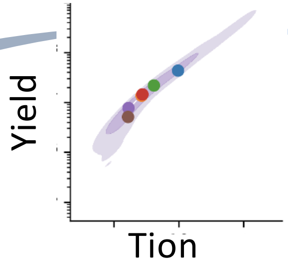
Artificial intelligence/machine learning (AI/ML) combines simulations and data to improve our understanding of previous experiments and aid in optimizing future designs.



Explore vast design spaces for optimal performance

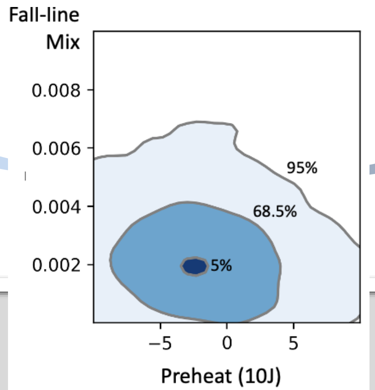
Predict



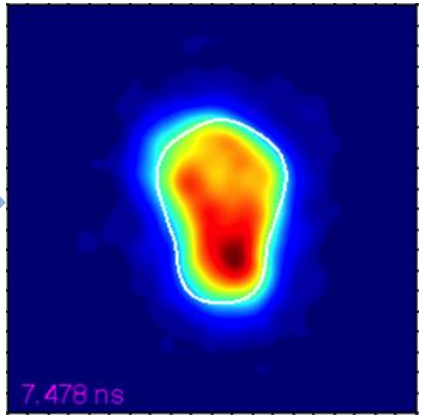


Quantify discrepancy

Find multiple explanations for the data



Learn



Update models for next design iteration

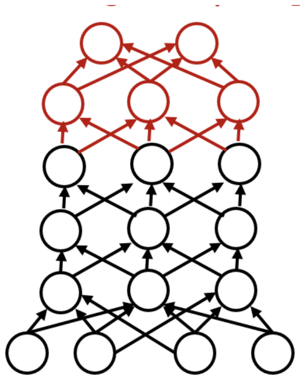
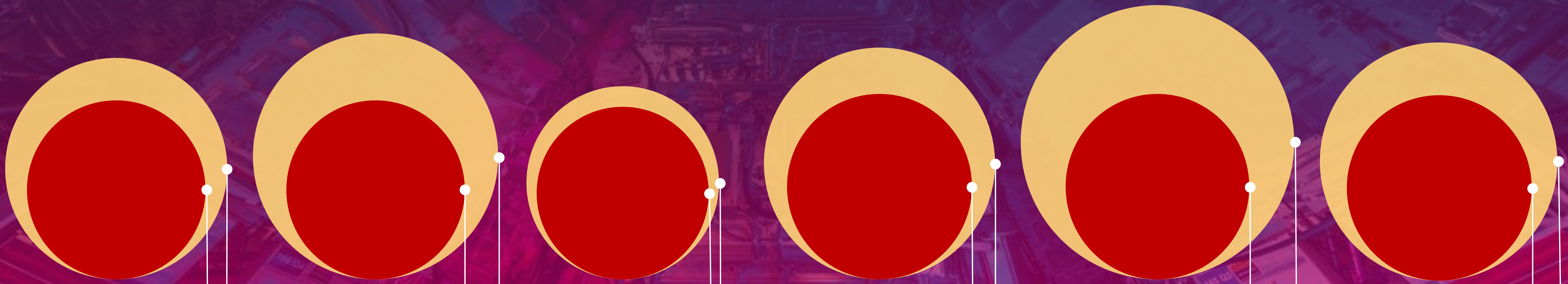


Image and figure credits: LLNL

Ignition has now been demonstrated 6x on the NIF.



First Ignition
December 5, 2022
2.05 MJ DELIVERED
3.15 MJ PRODUCED

Second Ignition
July 30, 2023
2.05 MJ DELIVERED
3.88 MJ PRODUCED

Third Ignition
October 8, 2023
1.9 MJ DELIVERED
2.4 MJ PRODUCED

Fourth Ignition
October 30, 2023
2.2 MJ DELIVERED
3.4 MJ PRODUCED

Fifth Ignition
February 12, 2024
2.2 MJ DELIVERED
5.2 MJ PRODUCED

Sixth Ignition
November 18, 2024
2.2 MJ DELIVERED
>3.8 MJ PRODUCED

Background image credit: Jason Laurea, LLNL

Fusion ignition has been a 60-year journey.

Invention of the Laser
1960

First Concept of Inertial Confinement Fusion

Janus Laser
1974 — 0.2 kJ

Seminal Paper Published
1972

Argus and **Shiva Lasers**
1976 / 1978

Nova Laser
1984 — 30 kJ

National Ignition Facility
Key decision

National Ignition Facility Operations
1.9 MJ

0.1 MJ
Burning Plasma
Nov 01, 2020

1.3 MJ
Ignition by Lawson Criterion
Aug 08, 2021

3.15 MJ
Target Gain >1
Dec 05, 2022

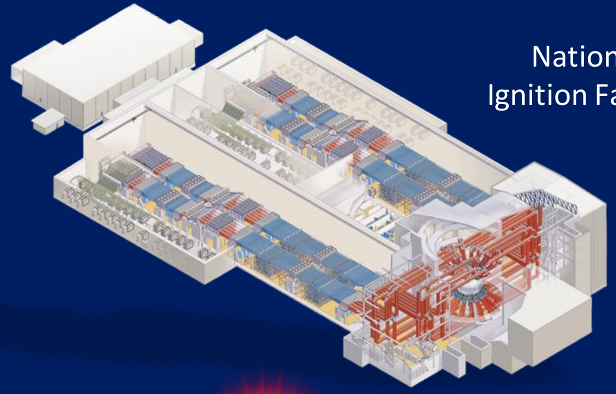
3.88 MJ
Target Gain ≈2
Jul 30, 2023

2.4 MJ
Target Gain ≈1.3
Oct 8, 2023

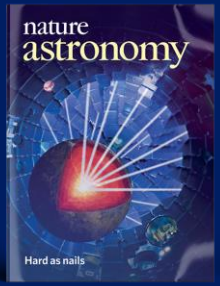
3.3 MJ
Target Gain ≈1.5
Oct 30, 2023

5.2 MJ
Target Gain ≈2.3
Feb 10, 2024

1960 | 1970 | 1980 | 1990 | 2000 | 2010 | 2020



National Ignition Facility

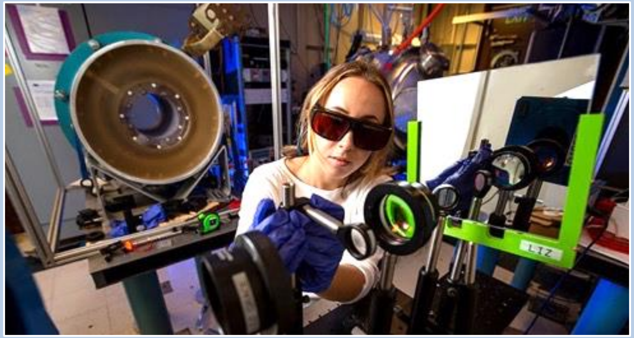


Timeline not to scale

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

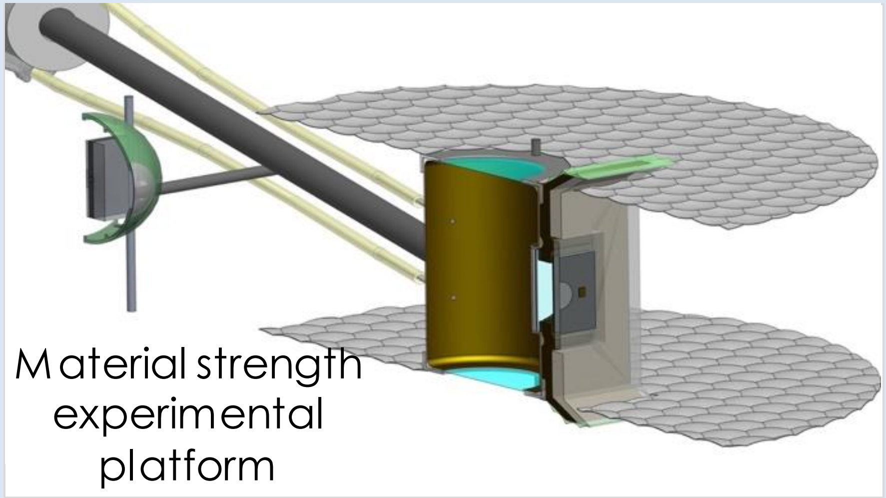
Supporting stockpile decisions for current and future stockpile

Training the next generation of nuclear weapons scientists and engineers



Credit: Photo by Jason Laurea/LLNL

Advancing our understanding of weapons science



Graphic: LLNL

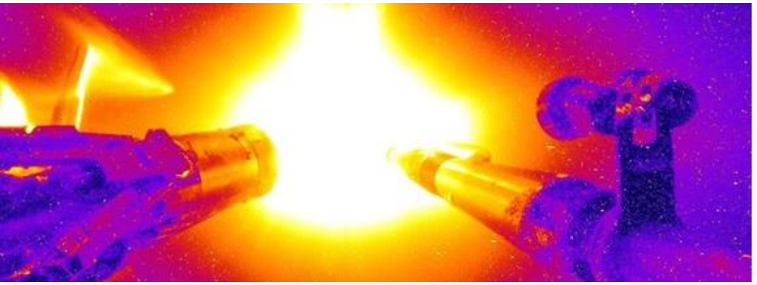


Image credit: Don Jedlovec/LLNL

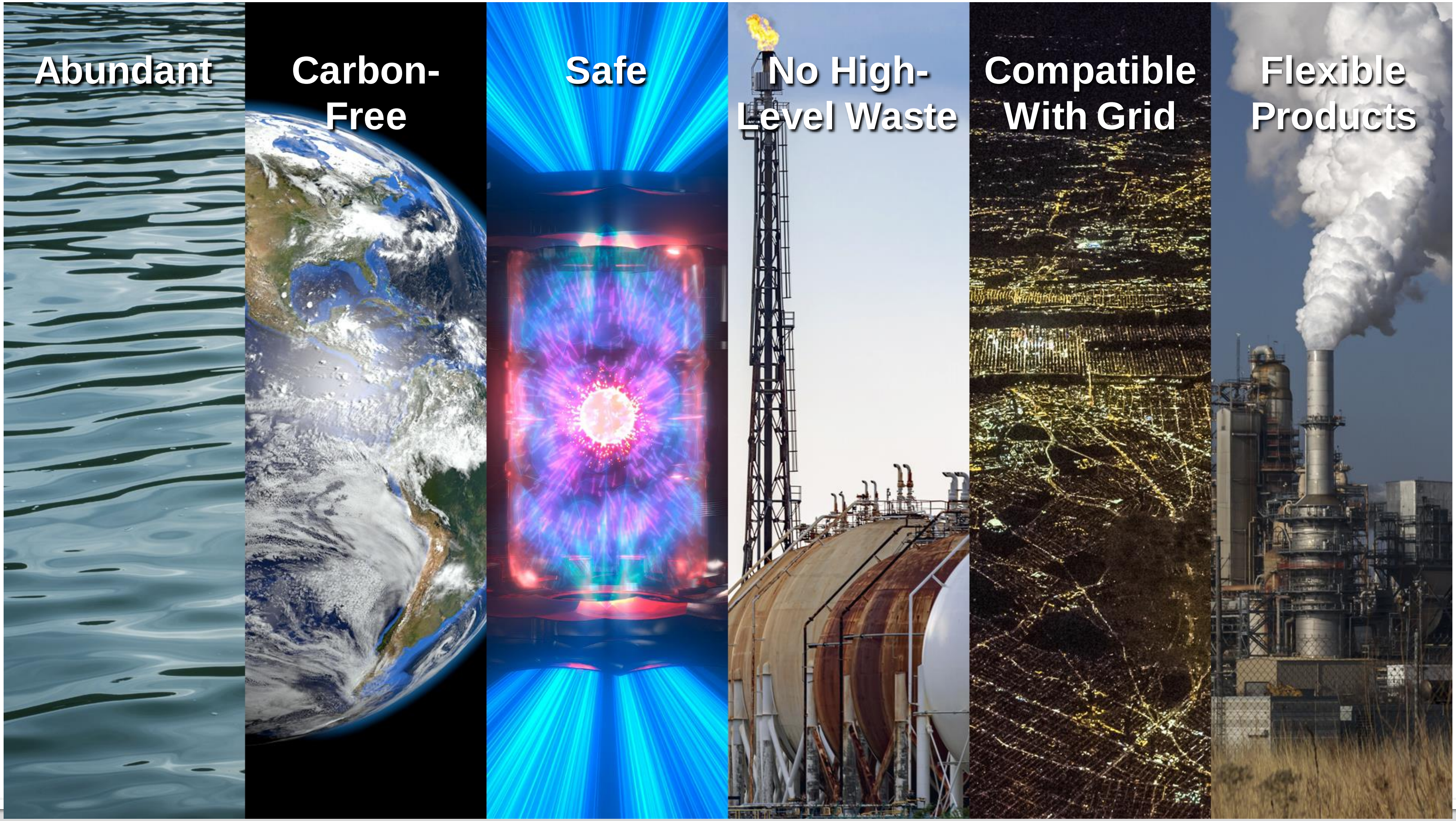
Expanding our capabilities to reach more extreme conditions (e.g., ignition)

Ignition on the NIF establishes the basic scientific feasibility of laser-driven inertial fusion energy (IFE).

LLNL

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

Fusion energy is attractive for many reasons.



The NIF is a scientific exploration facility, with a different purpose than an IFE power plant.

NIF: Single Shot	IFE plant: >10 Hz

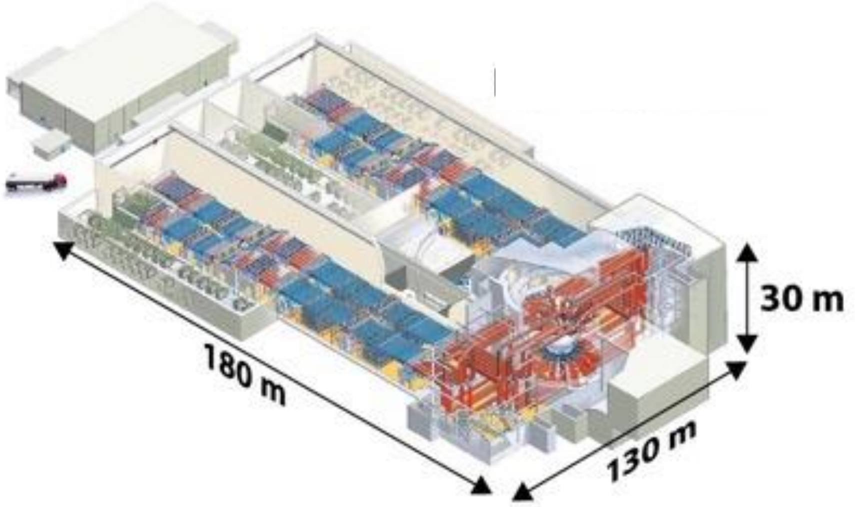
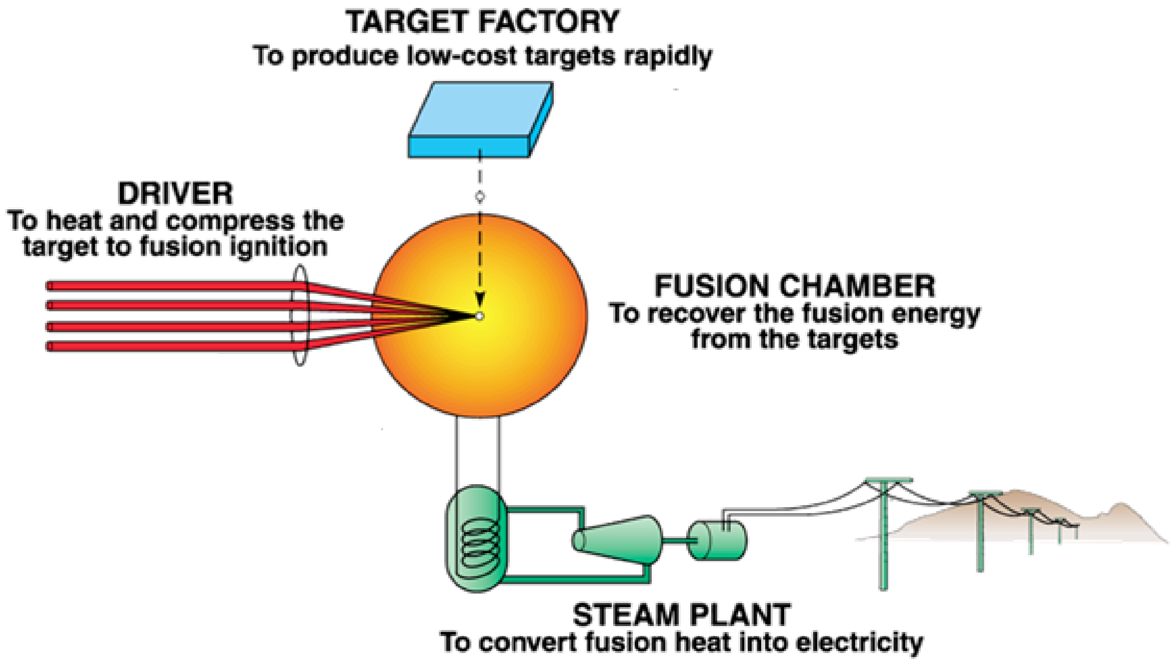


Image credit: LLNL



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

NIF provides a unique opportunity to experiment at “fusion scale” now, but there are yet many outstanding technical questions that must be solved to make IFE a reality.

The leap from NIF to an IFE facility requires technology advances in many subsystems.

Laser Driver

- kJ-level, rep-rated, 10-20% efficient lasers
- Economical diode scale-up

Target Injection

- ~1-10 Hz at 50-200 m/s
- Tracking to lasers at <25 µm

Target Design and Fabrication

- High yield, high gain, survivable designs
- Scale up to ~1M targets/day
- Production at ~$0.25-0.50 each

Final Optics

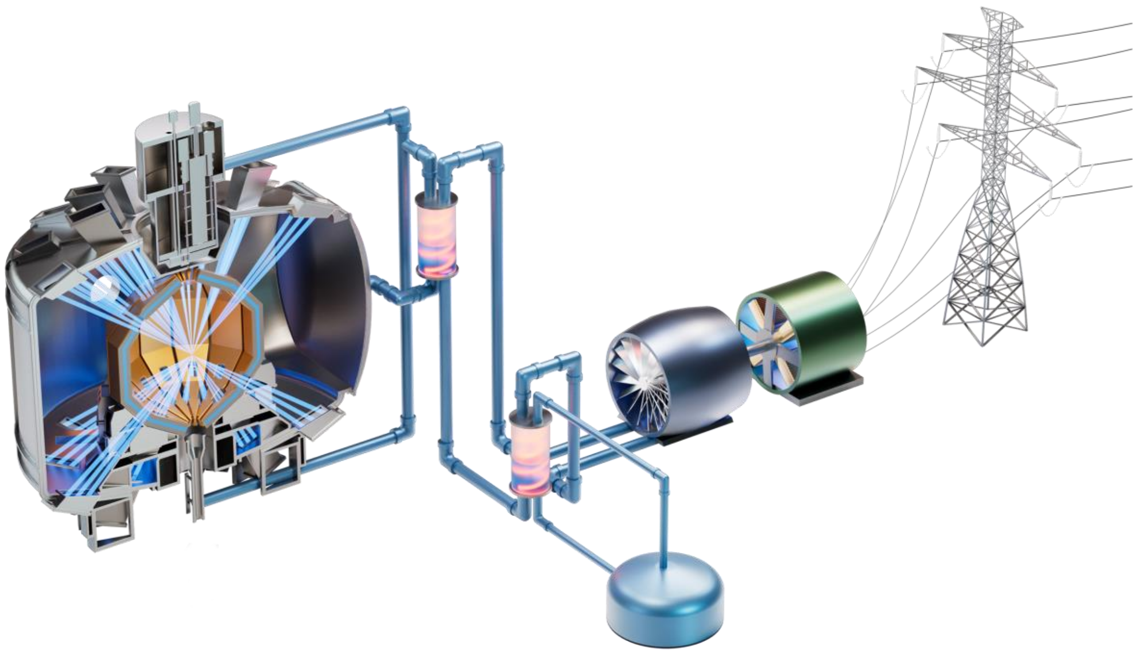
- Survivability, laser damage thresholds
- High average power 3ω conversion

Chamber System

- First wall protection (buffer gas, liquid wall,…)
- Long lifetime radiation-resistant materials

Recycling and Waste

- Target materials
- Isotopic separation



Tritium Fuel Cycle

- ~1 kg/day DT flowing through system
- Blanket and tritium breeding
- Tritium recycling
- Materials constraints

System Engineering and Plant Operations

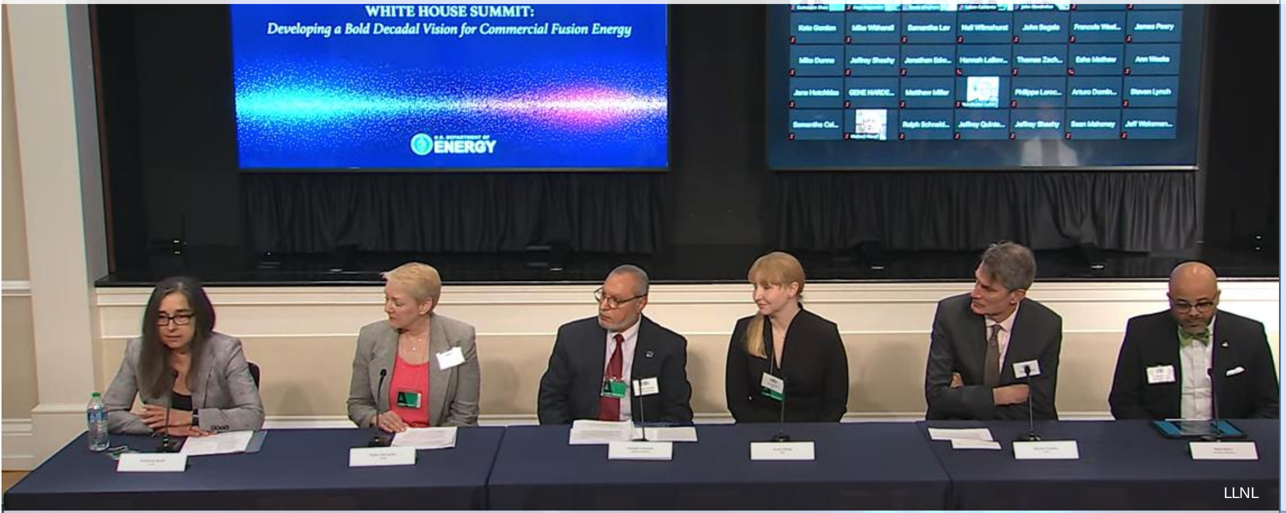
- System design and tradeoffs
- Modularity and RAMI (reliability, availability, maintainability, and inspectability)

Graphis source: LLNL

IFE research and development (R&D) provides many opportunities for spin-out and spin-in technologies.

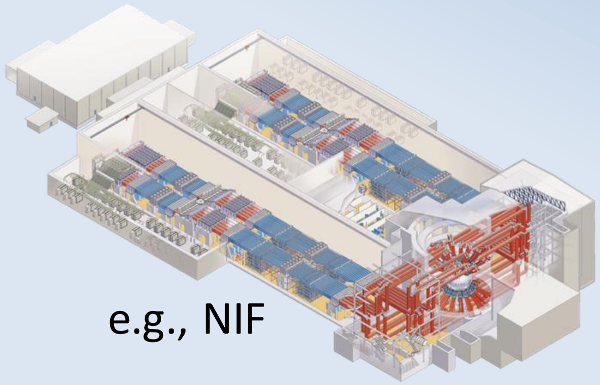
Fusion energy excitement in both policy and technology development

White House Bold Decadal Vision

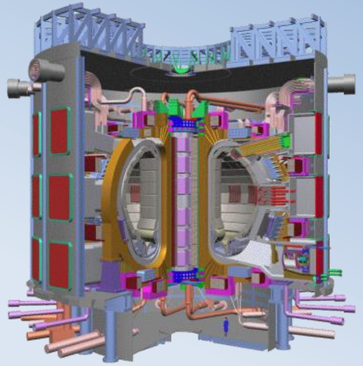


LLNL

70 years and >$40B*



e.g., NIF



e.g., ITER

*Public sector investment in U.S. fusion science (2020 $)

Fusion Ignition Demonstrated

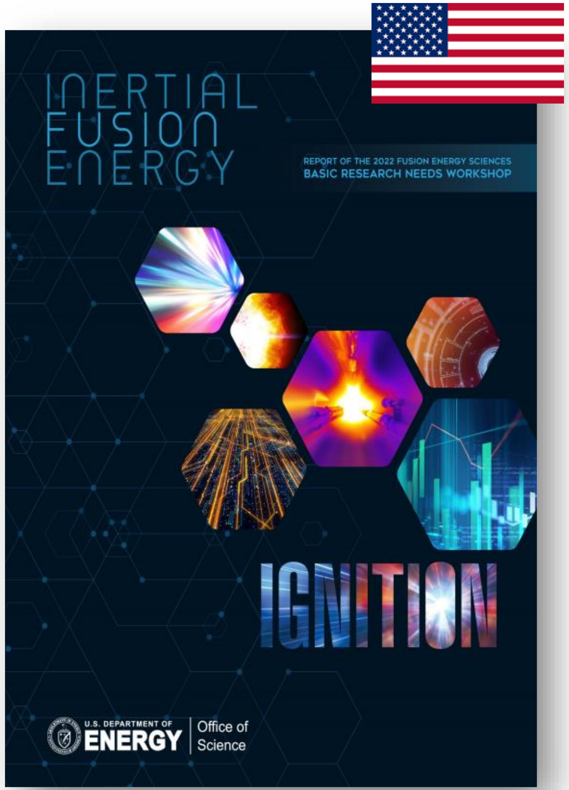
NIF

- December 4th, 2022
- 3.15 MJ fusion yield
- 2.05 MJ laser delivered
- Ignition repeated 5x now

Creativity and Concept Diversity

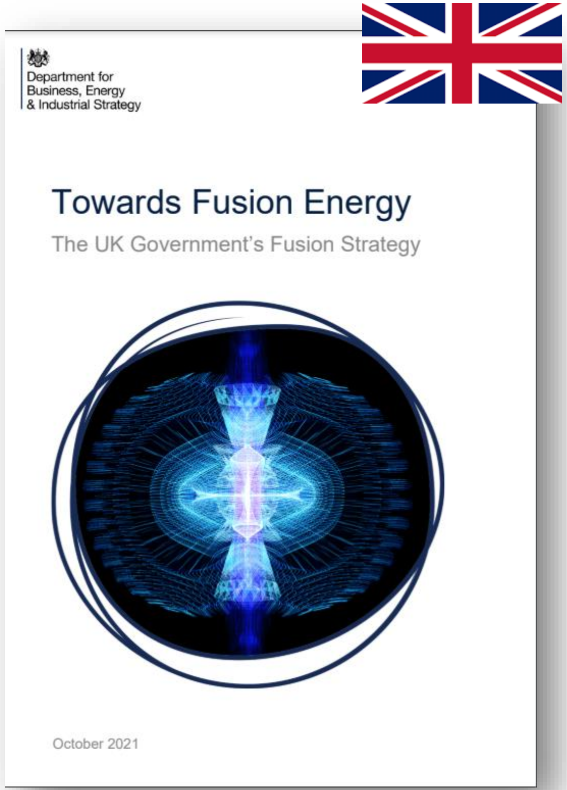
- >$8Bn in private investment
- >40 private fusion companies
- Product focused

Governments are paying attention! Fusion roadmaps and follow-on funding around the world.



May 2023:

- ICF and MFE >$1B/yr
- IFE ~$21M/yr + private funding



September 2023:

- £650M until 2027 (+ £126M announced in Nov. 2022 for U.K. fusion R&D programs)

September 2023:

- Additional funding €370M for IFE/MFE until 2028
- Incl. institutional >$1B till 2028

Significant competition exists, and the United States must build and leverage on its transformational leap in ICF.

THE WALL STREET JOURNAL.

EXCLUSIVE CHINA

China Outspends the U.S. on Fusion in the Race for Energy's Holy Grail

China wants to dominate commercial fusion, a long-dreamed-of clean energy source that is attracting new investment

By *Jennifer Hiller* Follow and *Sha Hua* Follow

Updated July 8, 2024 12:11 am ET

- At $1.5 billion annually (for MFE alone), China is outspending U.S. investments in fusion by about double.
- Germany and the UK are making large investments in fusion.
- The fusion start-up scene is globally distributed.

Image credit: SOPA Images

Gorshkov et al., CC BY

WIRED Russia Is Powering Up a Giant Laser to Test Its Nukes

The United States is at risk of ceding its global leadership in fusion science and technology for national and energy security.

Fusion energy is an international need that requires a coordinated plan, program, team, and sustained commitment.

Funding for private fusion companies

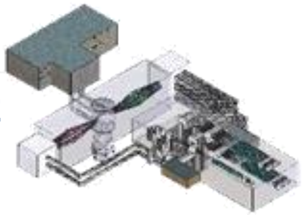
By primary HQ

Fusion Industry Associates
The Global Fusion Industry in 2024

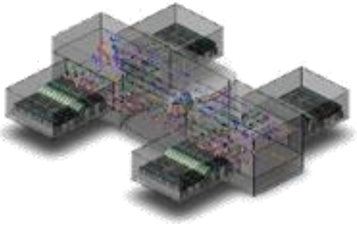
Technology maturation and workforce development (underway)

- Public-led hubs for component R&D
- Leverage existing facilities for target R&D
- Private-led PPPs: pilot plant designs
- Dedicated facilities

Demo Facilities and First Pilot Plants (2030s)



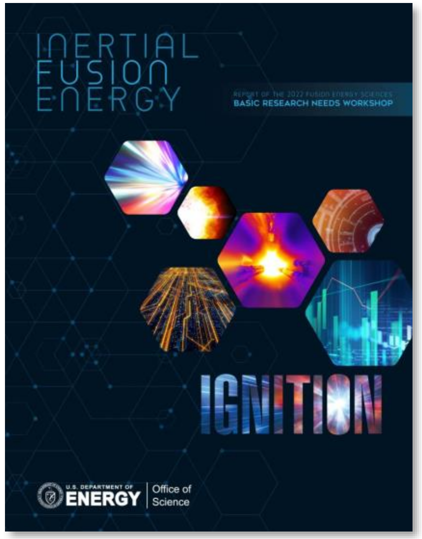
Economically Viable Commercial Power Plant



Graphics: LLNL

We have started: 2023 marked the rebirth of a modest U.S. national public IFE program.

U.S. DEPARTMENT OF ENERGY | Office of Science



Priority Research Opportunities as defined by 2022 IFE Basic Research Needs

IFE-STAR establishes multi-institutional "hubs"

LLNL

Milestone-Based Program encourages teaming to develop fusion pilot plants

Department of Energy Announces $50 Million for a Milestone-Based Fusion Development Program

This new public-private-partnership program is the first step toward realizing the Administration's bold decadal vision for commercial fusion energy

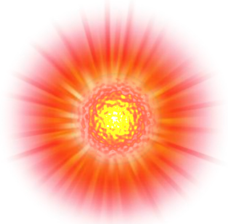
INFUSE: INFUSE (Innovation Network for Fusion Energy) to provide industry access to capabilities at DOE-funded institutions

arpa·e: ARPA-E fusion programs

The time is right for a serious drive toward fusion pilot plants.
We must build on these first steps to ensure the United States capitalizes on its ICF leadership to help make fusion energy a reality.

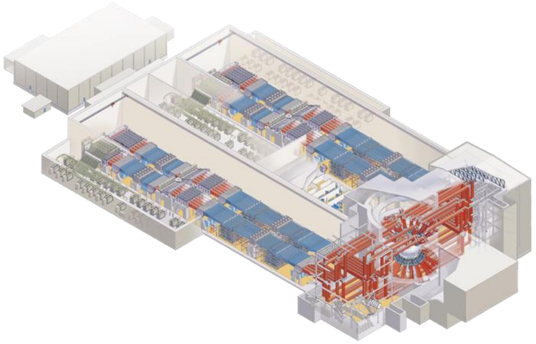
IFE has an emergent, highly coordinated national strategy to drive toward FPPs in the 2030s, founded on $B's investment in ICF.

Historical Foundation



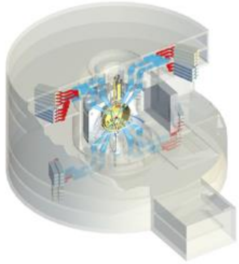
Robust, repeatable ignition

5x E_F > E_{laser}, only limited by target production and available shot opportunities



At-scale facility (NIF) to study burning plasma and demonstrate concepts

e.g. wetted foams, LPI



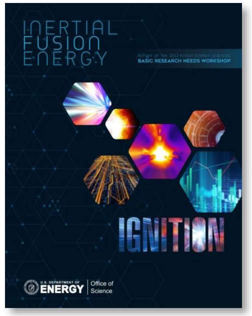
Multiple historical plant studies to build from

Self-consistent and with credible materials solutions

Graphics: LLNL

Going Forward

Priority Research Opportunities as defined by 2022 IFE BRN



HUBS coordinate national effort to support critical technology development

IFE STAR

Milestone program focused on FPP development

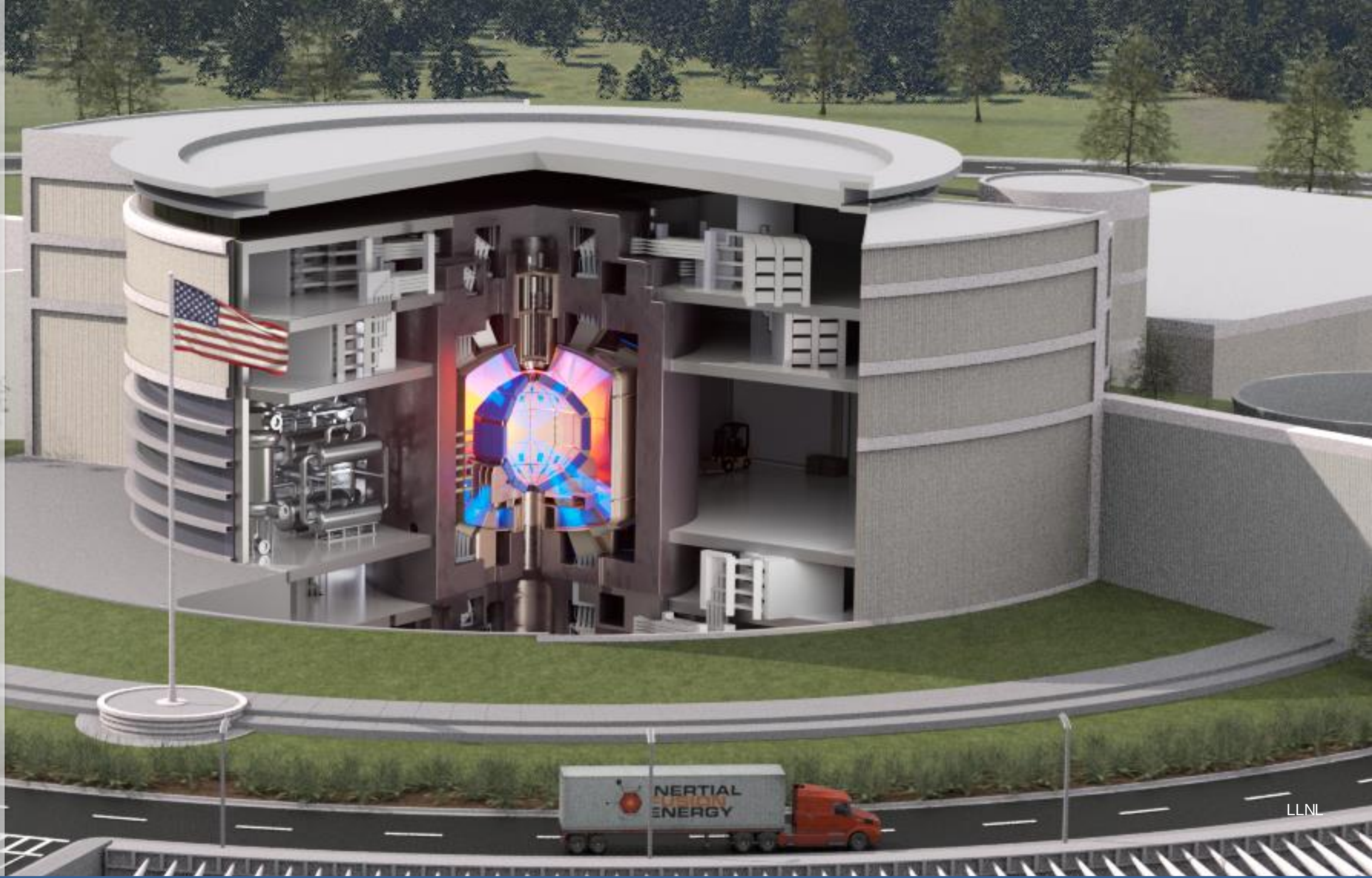
FOCUSED ENERGY

XCIMER ENERGY CORPORATION

Longview Fusion Energy Systems

The time is right for a serious drive to IFE FPP. The path to commercially viable fusion energy will require a level of investment and commitment on par with what it took to get to ignition.

- NIF has achieved a gain of 2.3.
- A gain of 50-100 is needed for an economically viable power plant.
- But a self-sustaining plant only needs a gain of ~15.
- Over the past decade, we have improved our gains on NIF by factor of 1000x.



We are making considerable progress toward realizing fusion energy.
The United States needs renewed and expanded investments at every stage of technological development to ensure we maintain and capitalize on our leadership.

With ignition, we can accelerate progress toward the long-sought dream of fusion energy!

"Fusion energy offers a step change that could amount to a zero-carbon way of producing energy that upends the long-standing energy geopolitics, reducing reliance on foreign energy markets, and advancing a wide array of other fields, including some that we cannot yet predict."[1]

[1]Special Competitive Studies Project, *"Mid-Decade Challenges to National Competitiveness,"* September 2022

Background image credit: iStock, Hayri Er

Lawrence Livermore National Laboratory

NIF's road ahead: ignition for stewardship while speeding up path to 10s of MJ yields and higher gains

	2023	2023–2030	2030–2040
Fusion Yield	**Few MJ**	**10s of MJ**	**200+ MJ**
NIF has not yet reached its full potential	**Routine MJ-yield operations and ignition**	**Long-term sustainment + Increased energy**	**Explore high-yield, high-gain regime**
Laser Energy	**2.2 MJ**	**2.6 MJ and potentially beyond**	