# Toward an Inertial Fusion Energy Future

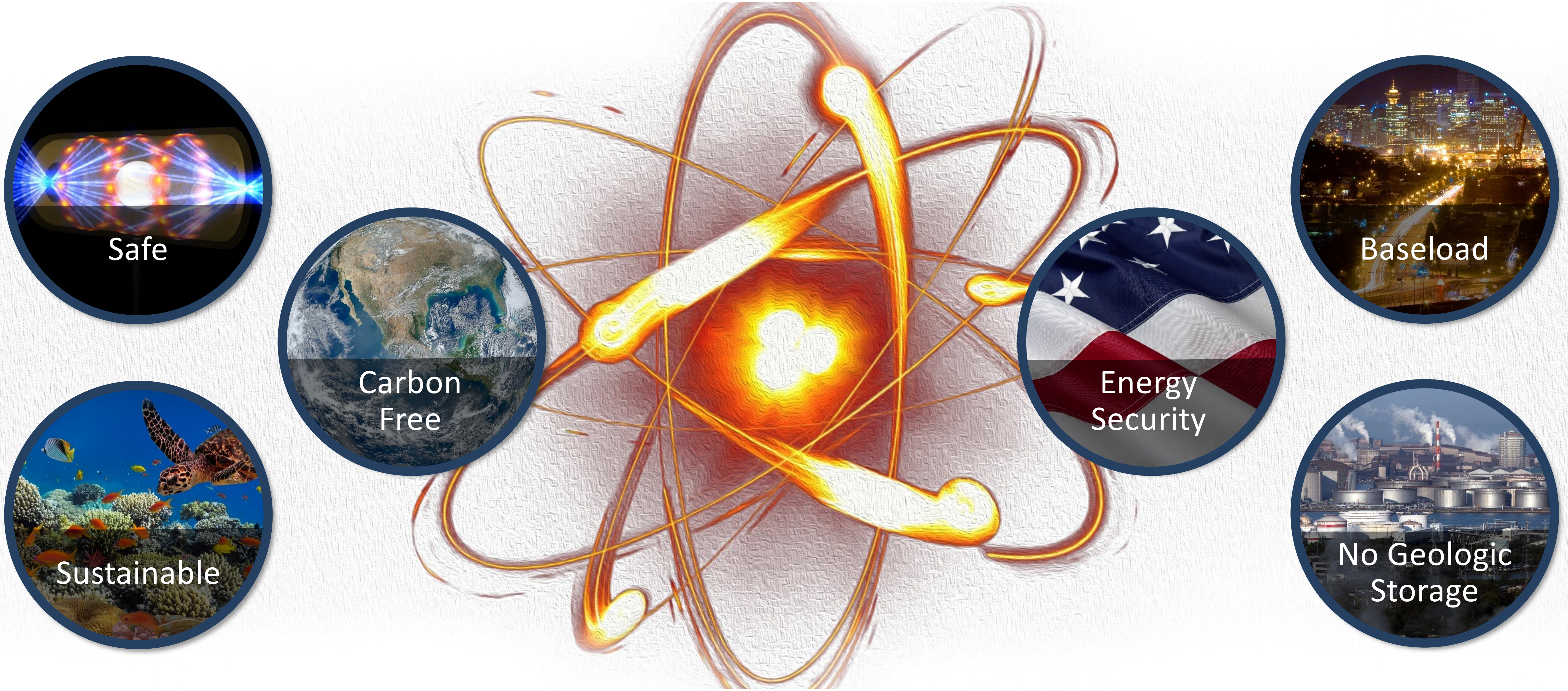
Oct. 2, 2023
MIT Center for Energy and Environmental Policy Research (CEEPR)
Fall 2023 Research Workshop

Dr. Tammy Ma
Lead, Inertial Fusion Energy Institutional Initiative
Lawrence Livermore National Laboratory

LLNL-PRES-
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

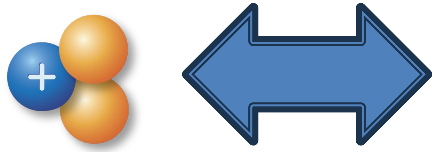
Lawrence Livermore National Laboratory

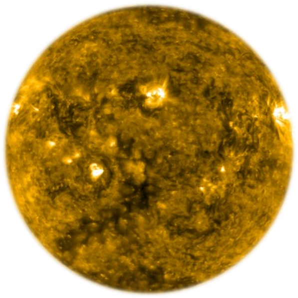
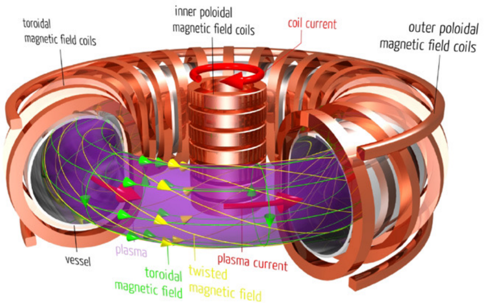
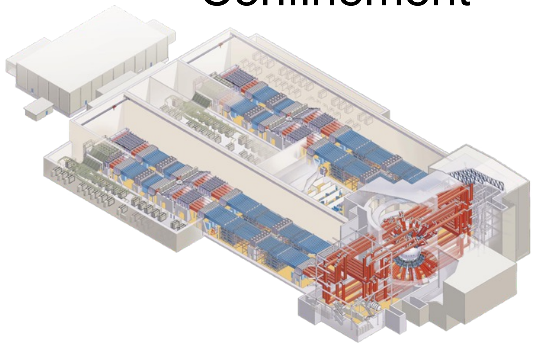
# Fusion energy is attractive for many reasons



# Fusion ignition requires incredibly high temperatures and densities to overcome Coulomb repulsion

$^{3}H$ - Tritium $^{2}H$ - Deuterium

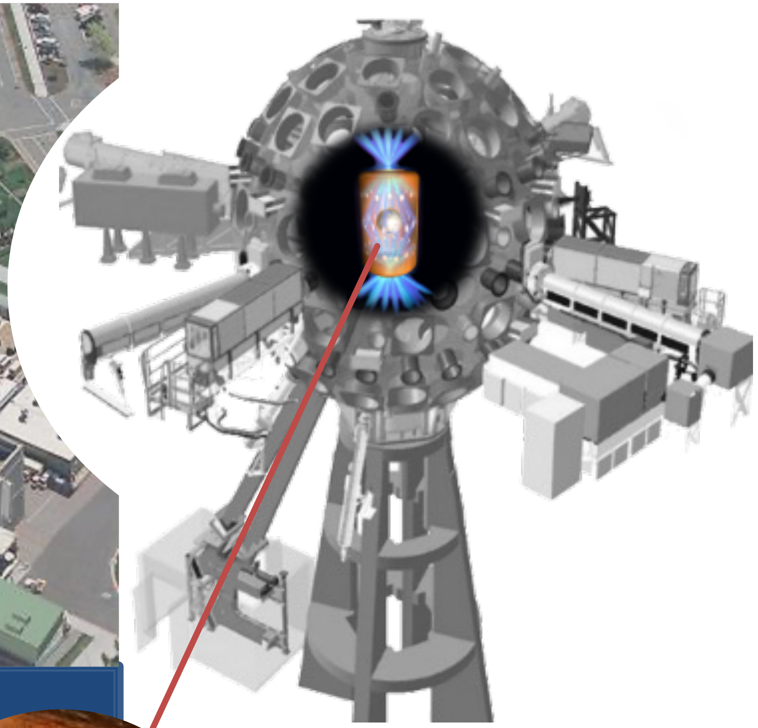


| | Gravitational Confinement | Magnetic Confinement | Inertial Confinement |
|---|---|---|---|
| |  |  |  |
| Density | 10,000 x solid | solid / 100,000,000 | 1,000 x solid |
| Temperature | ~15,000,000 C | ~150,000,000 C | ~150,000,000 C |
| Confinement time | 100,000 years | seconds | 10's picoseconds |

# Inertial Confinement Fusion creates a burning plasma within a capsule to release fusion energy at very high power from a very tiny volume

**National Ignition Facility (NIF) lasers**

**500 trillion watts for**
> 4 nanoseconds (ns)
> 2.05 million joules (MJ)



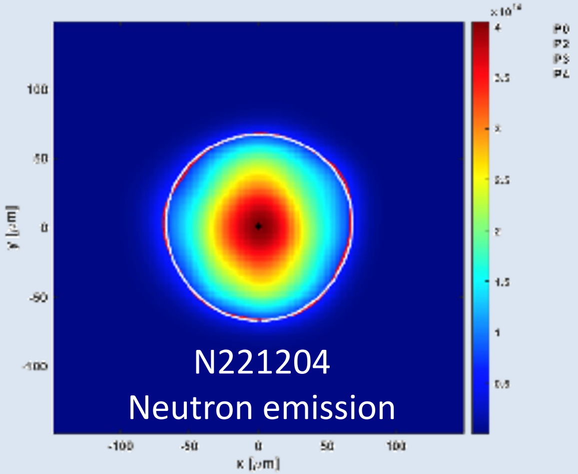
Target
~ 1 cm

Temperature
~3,000,000 K

## Energy output

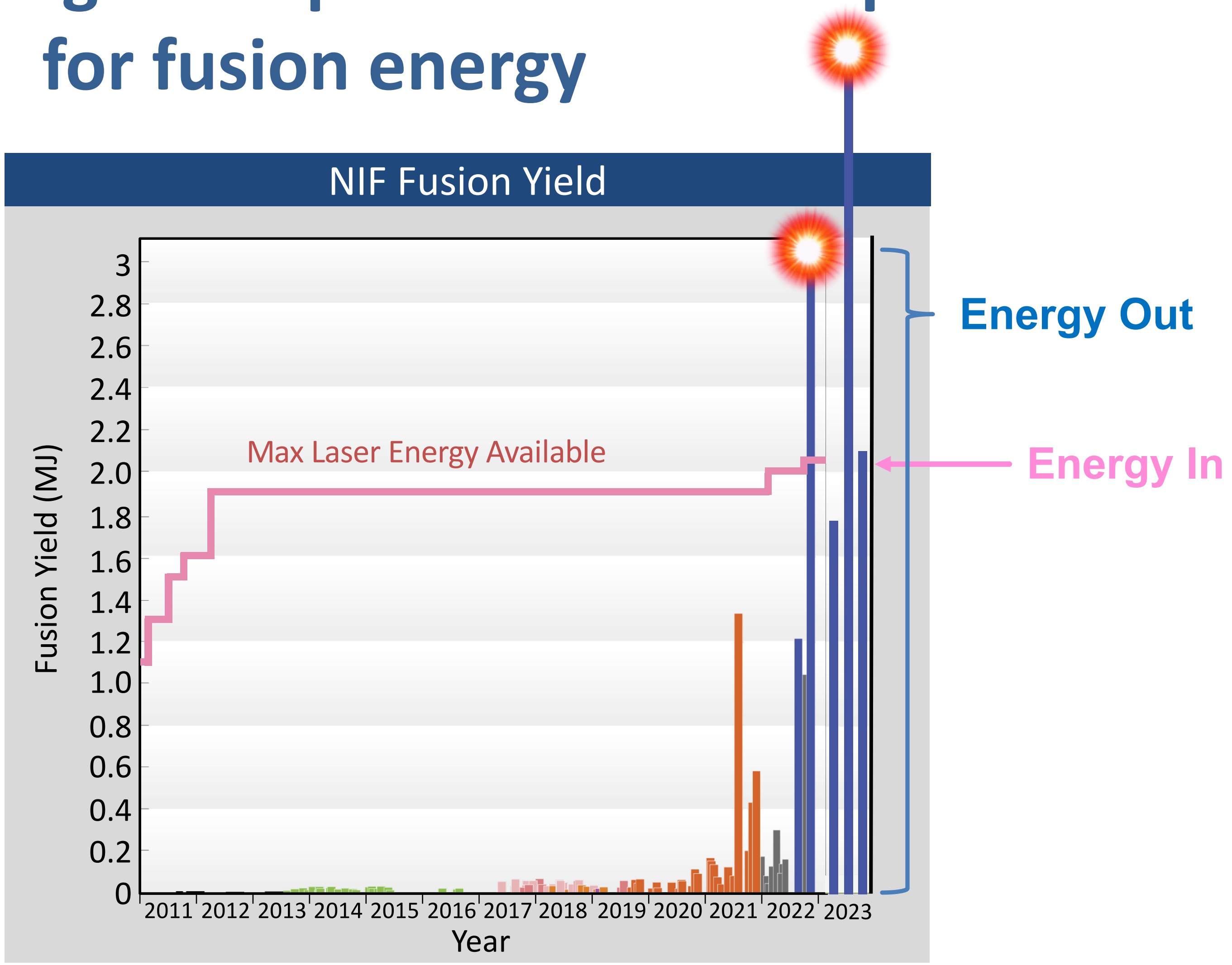
from 12/5/2022 experiment

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




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

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

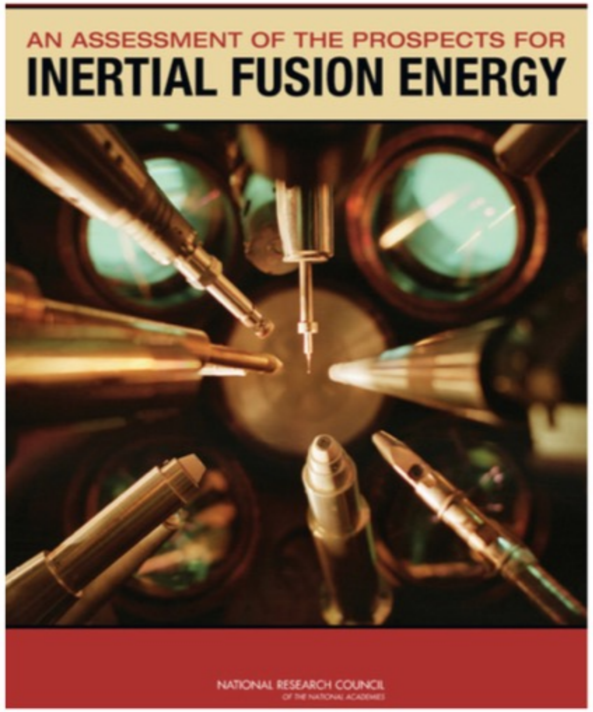




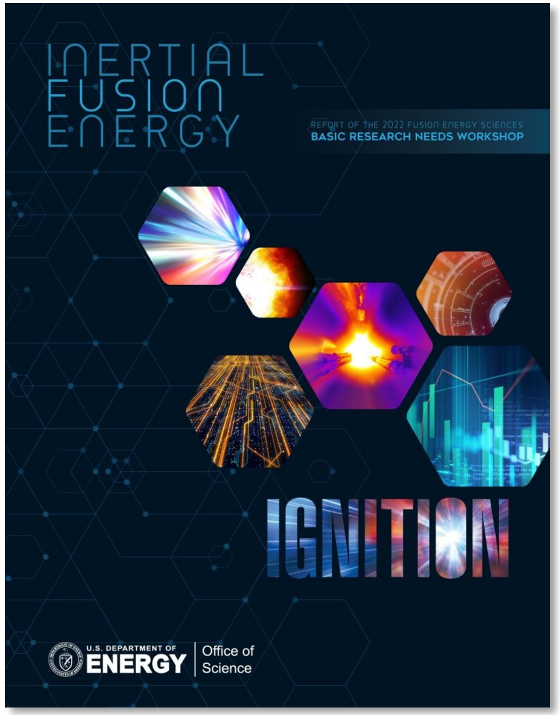
In Dec 2022, gain of 1.5 was achieved on the NIF with 3.05 MJ generated.
In July 2023, ignition was repeated with a yield of 3.88 MJ = gain of 1.9

**The fundamental physics of energy-producing fusion on earth has been demonstrated through ICF on NIF. The leap to a power plant now requires science and technology maturation for a range of subsystems.**

# We are at a pivotal moment in fusion research, with a well organized community poised take advantage of recent successes! It is the ideal time to focus on IFE



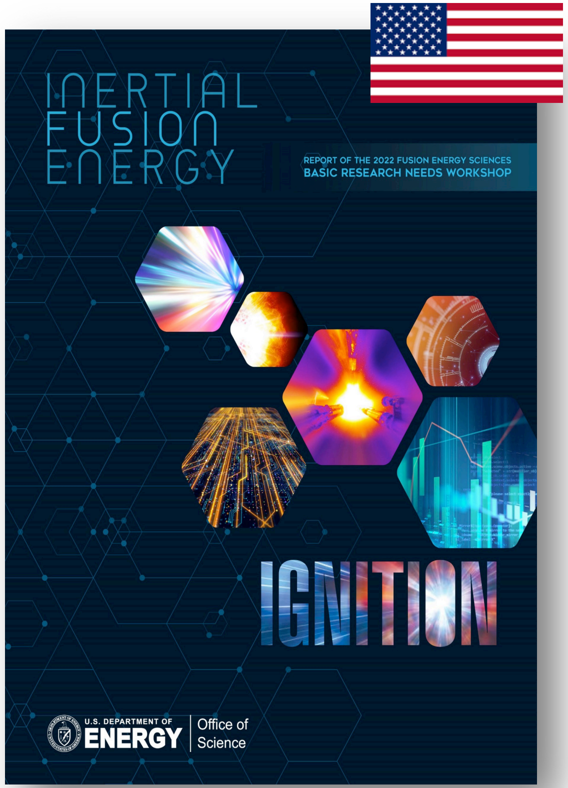

**2013 → 2023**



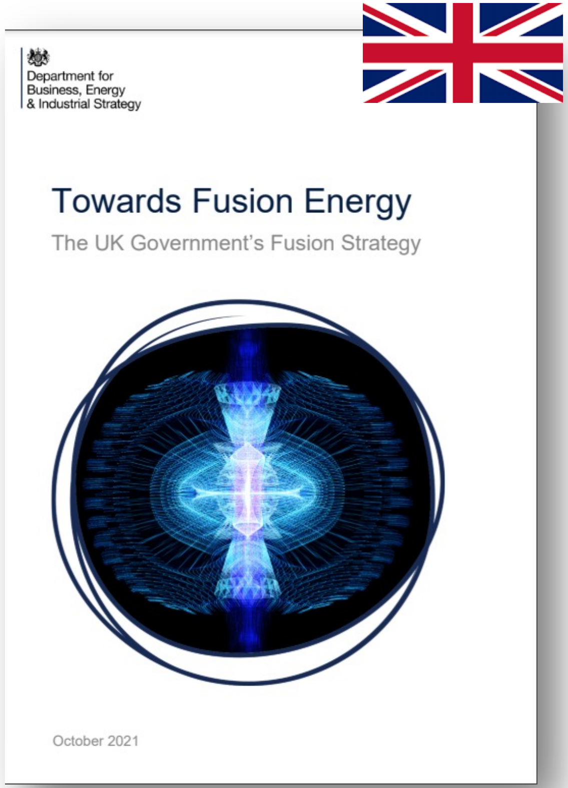

*"The appropriate time for the establishment of a national, coordinated, broad-based inertial fusion energy program within DOE would be when ignition is achieved."*
*- NASEM 2013*

*"Private industry is driving the commercialization of fusion energy in the United States"*
*"Accelerating IFE will require a suite of dedicated, new, and upgraded facilities"*
- IFE BRN 2023

# 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

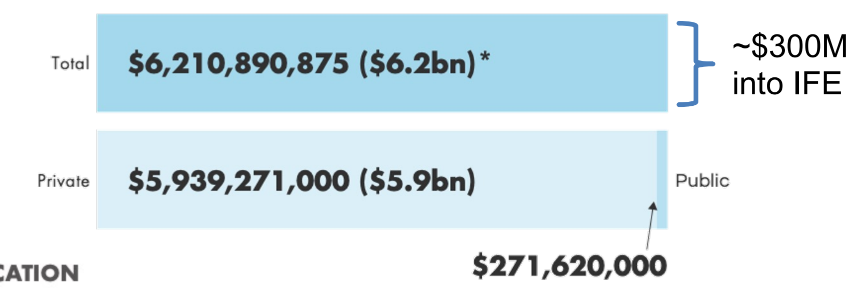



September 2023:
- £650M until 2027 (+ £126M announced in Nov. 2022 for U.K. fusion R&D programs)


September 2023:
- Additional funding €370M for IFE/MFE until 2028
- Incl institutional >$1B till 2028

# Considerable private investment into fusion startups in the past few years – can help accelerate to pilot plant

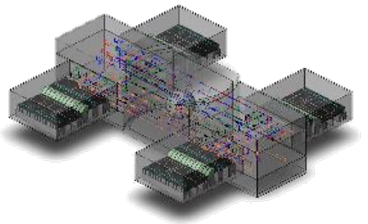
**Funding for fusion companies**



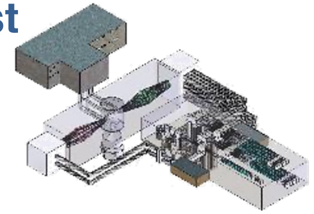

**Location**
By primary HQ


Fusion Industry Associates
*The Global Fusion Industry in 2023*

**Economically Viable Commercial Power Plant**



**Demo Facilities and First Pilot Plants (2030-40)**



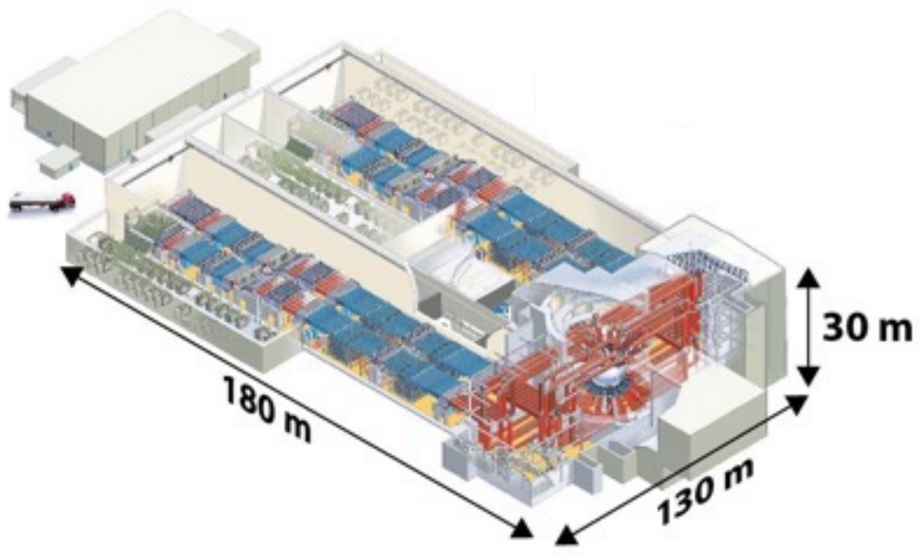
**Technology maturation and workforce development (start now)**

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

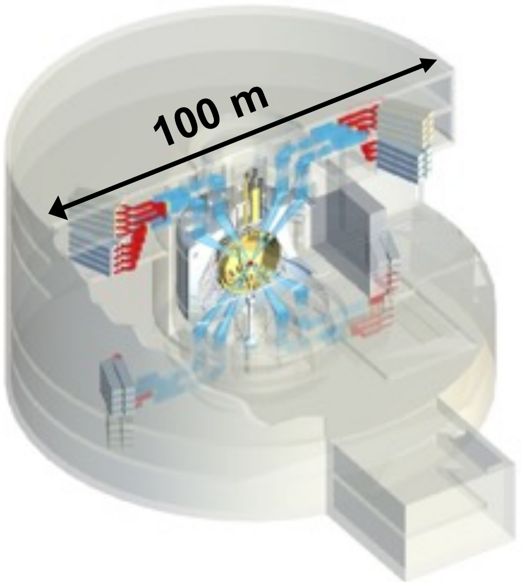
Each step of the plan will require significant public-sector investment and private sector partnerships as well as significant resolve

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

NIF: Single Shot




IFE plant: >10 Hz



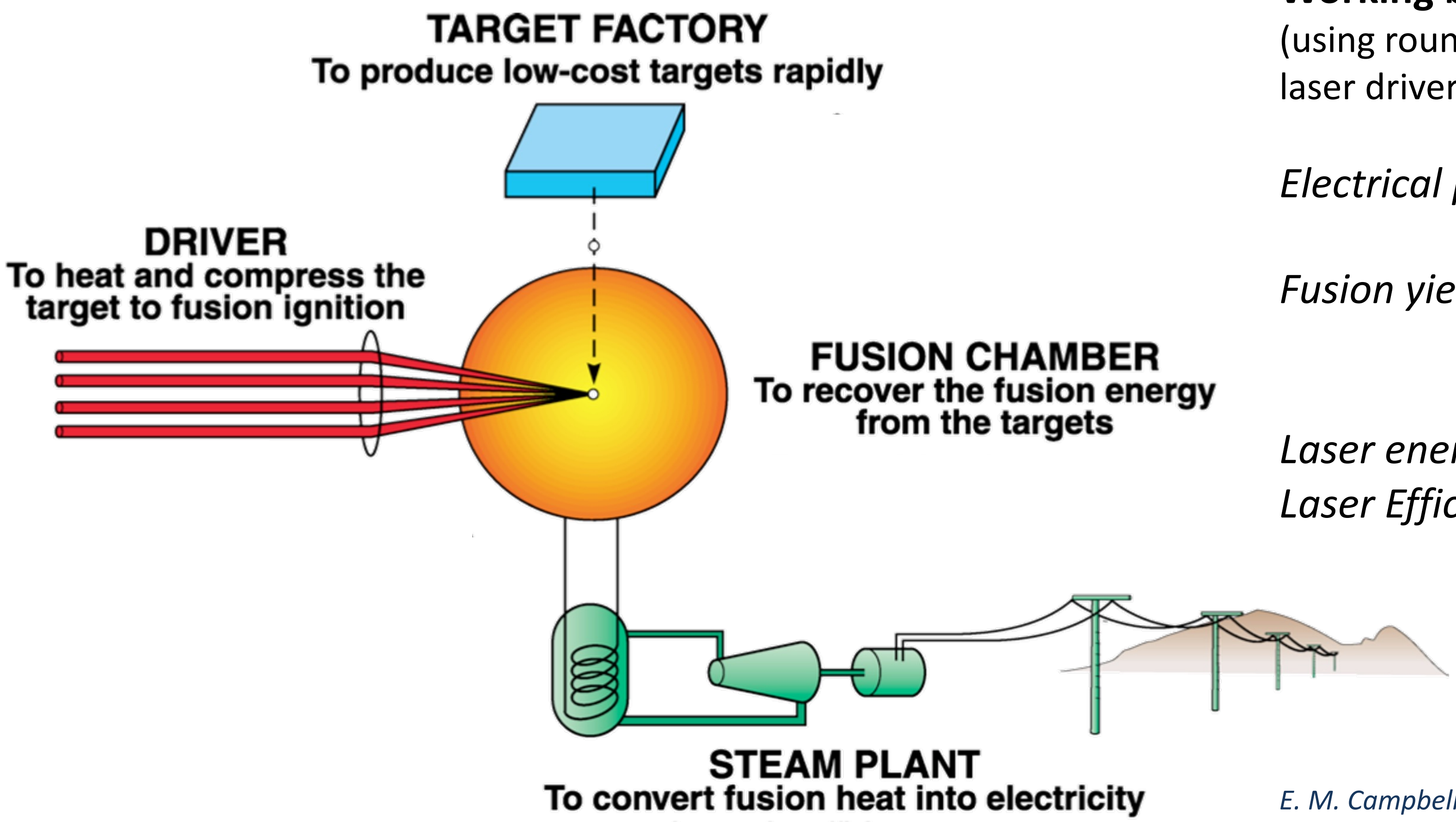

Gain of 1.9 has been achieved on the NIF

A gain of 15-16 is approximately what is needed for a self-sustaining plant

Over the past decade, we have improved our gains on NIF by factor 1000x

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




**Working backwards – example case:**
(using round numbers, ignoring some sub-systems, assuming laser driver)

*Electrical power*: ~1.25 GWe total (1 GWe to grid, 250 Mw back to driver)
*Fusion yield and power*: 200 MJ/shot at 12.5 Hz = 2.5 GWth to blanket (~50% net efficiency including blanket gain)
*Laser energy*: 3 MJ (Gain = ~65)
*Laser Efficiency*: ~15%

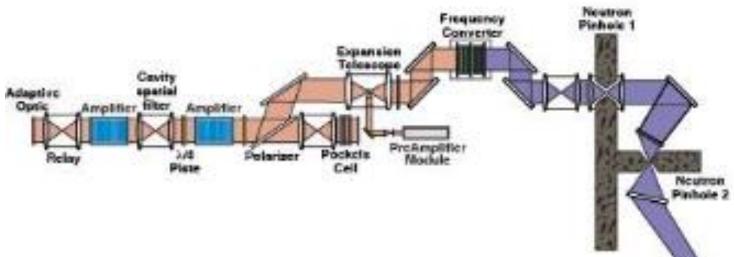
*E. M. Campbell, and W. J. Hogan, Plasma Phys. Control. Fusion **41** B39 (1999)*

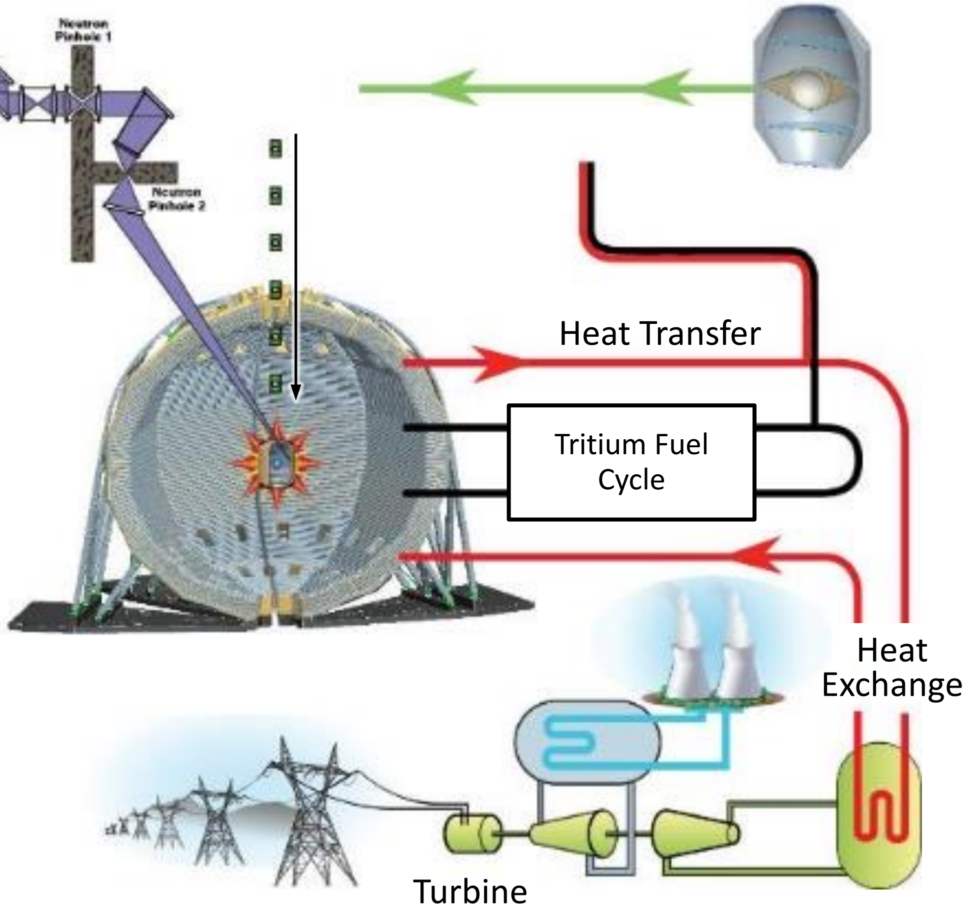
# The technology challenges of IFE are considerable

<u>Laser Driver</u>
- 10-20% efficient lasers
- Economical diode scale-up

<u>Target Injection</u>
- 10 Hz at 50-200 m/s
- Tracking to lasers at <25 um

<u>Target Design and Fabrication</u>
- High yield, high gain, survivable designs
- Scale up to ~1M targets/day
- Production at ~$0.25-0.50 each




<u>Final optics</u>
- Survivability, laser damage thresholds
- High average power 3ω conversion

<u>Tritium fuel cycle</u>
- Extremely efficient at scale (~>kg level)
- Materials constraints

<u>Blanket and Chamber System</u>
- Buffer gas/protection system
- Long lifetime radiation resistance materials
- Full scale tritium breeding and heat transfer blankets

<u>System Engineering and Plant Operations</u>
- System design and tradeoffs
- Modularity and RAMI

# 2023 IFE Basic Research Needs defined TRL levels for five IFE concepts for the seven aspects critical for any development path

| *IFE Concepts →* / *Critical aspects for IFE development ↓* | Laser Indirect Drive | Laser Direct Drive (including Shock Ignition) | Fast Ignition | Heavy Ion Fusion | Magnetically Driven Fusion |
|---|---|---|---|---|---|
| Demonstration of ignition and reactor-level gain | 4 | 3 | 2 | 1 | 3 |
| Manufacturing and mass production of reactor-compatible targets | 2 | 2 | 2 | 2 | 1 |
| Driver technology at reactor-compatible energy, efficiency, and repetition rate | 4 | 4 | 3 | 2 | 3 |
| Target injection, tracking, and engagement at reactor-compatible specifications | 2 | 2 | 2 | 2 | 1 |
| Chamber design and first wall materials | 1 | 1 | 1 | 1 | 1 |
| Maturity of Theory and Simulations | 3 | 3 | 2 | 2 | 2 |
| Availability of diagnostic capabilities for critical measurements | 3 | 3 | 2 | 2 | 2 |

TRL 1 = Basic principles observed

TRL 2 = Technology concept formulated

TRL 3 = Proof of concept

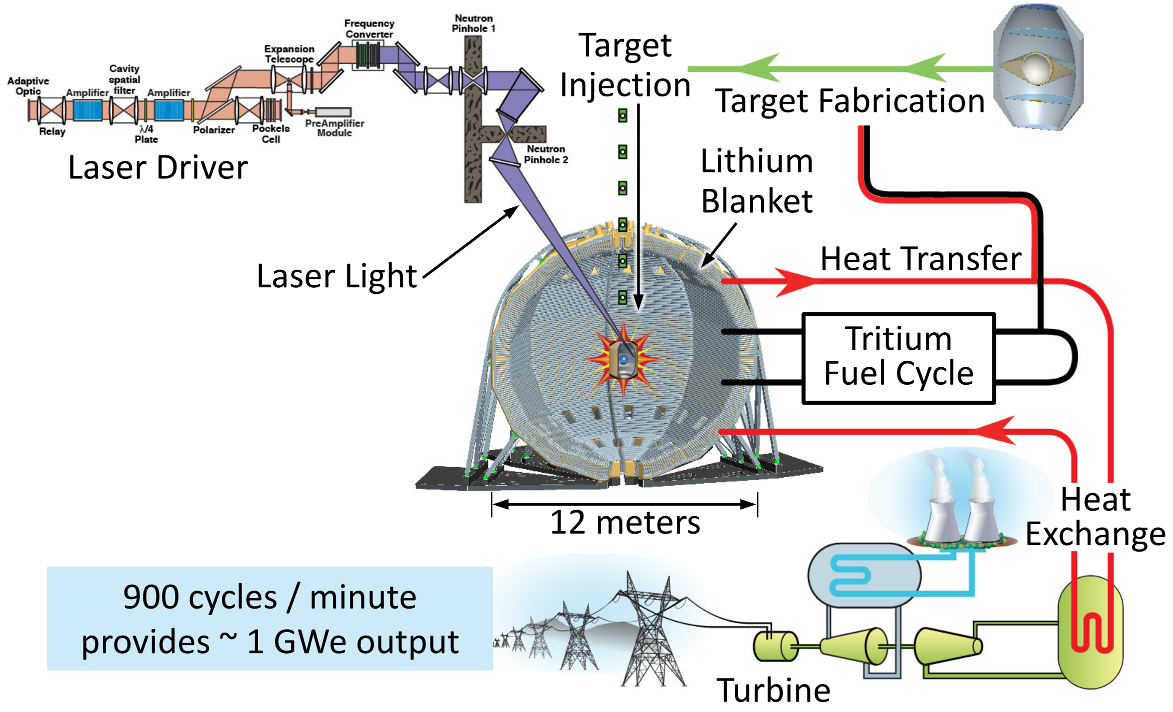
TRL 4 = Component validation in lab environment

TRL 9 = Demonstration plant



Table adapted from Report of the 2023 Inertial Fusion Energy Basic Research Needs Workshop.

# 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

- Diversified risk from magnetic fusion (tokomaks)
- Separation between driver and fusion source
- Attractive economic development path (spin-out technologies)
- Energy security & US scientific competitiveness

With ignition, we can accelerate progress toward the long-sought dream of fusion energy. This is consistent with the U.S. President’s “bold decadal vision” for fusion energy.

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

**Clear and Compelling National Need**

- Fusion energy strengthens our energy and climate security
- U.S. must maintain its competitive advantage and capitalize on its leadership in ICF to realize IFE

**The time is now!**

- Ignition has been demonstrated on NIF!
- Fusion is a multi-decadal endeavor, and will require innovation to enable economical energy source

**Public-Private partnerships are key to realizing the Bold Decadal Vision**

- Public sector long-standing expertise and large-scale facilities
- Private sector has an opportunity to leverage to push toward Fusion Pilot Plants

**"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

Lawrence Livermore
National Laboratory