Toward an Inertial Fusion Energy Future: Challenges and Opportunities in Science & Technology

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LLNL-PRES-
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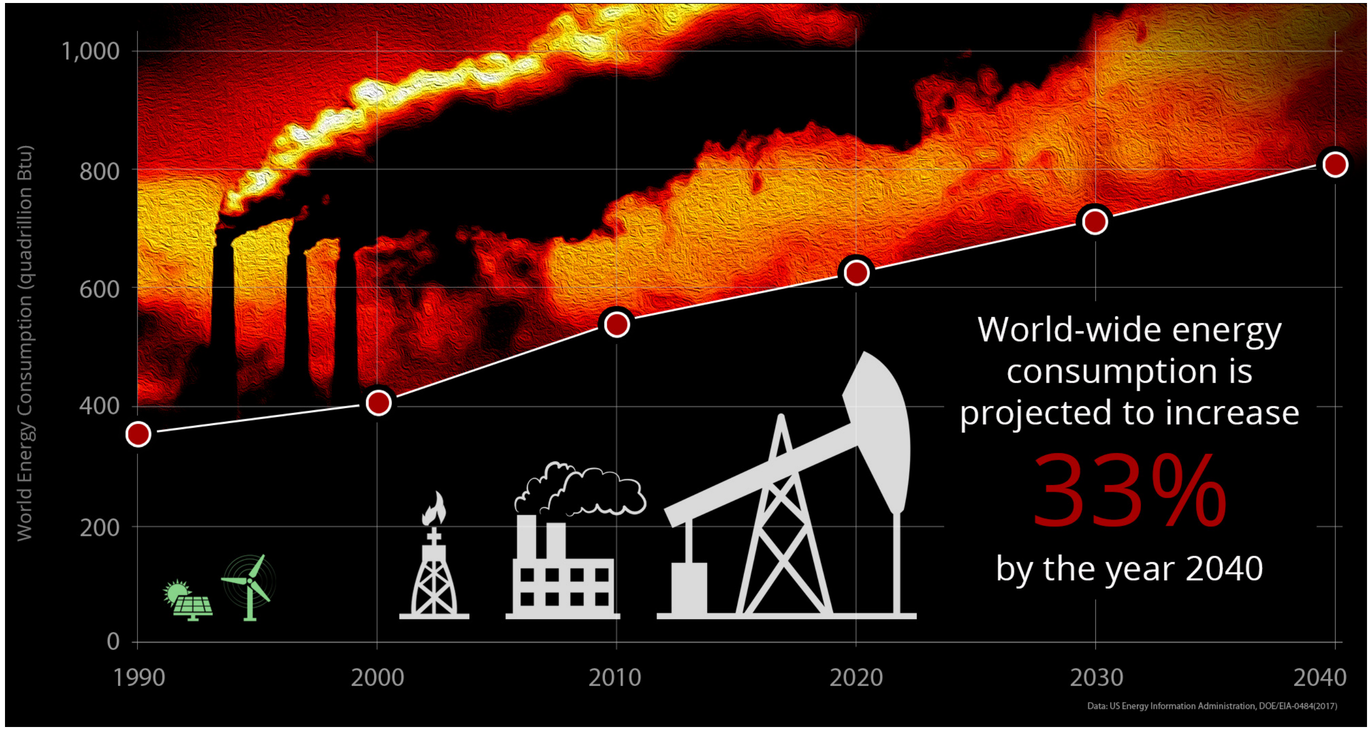
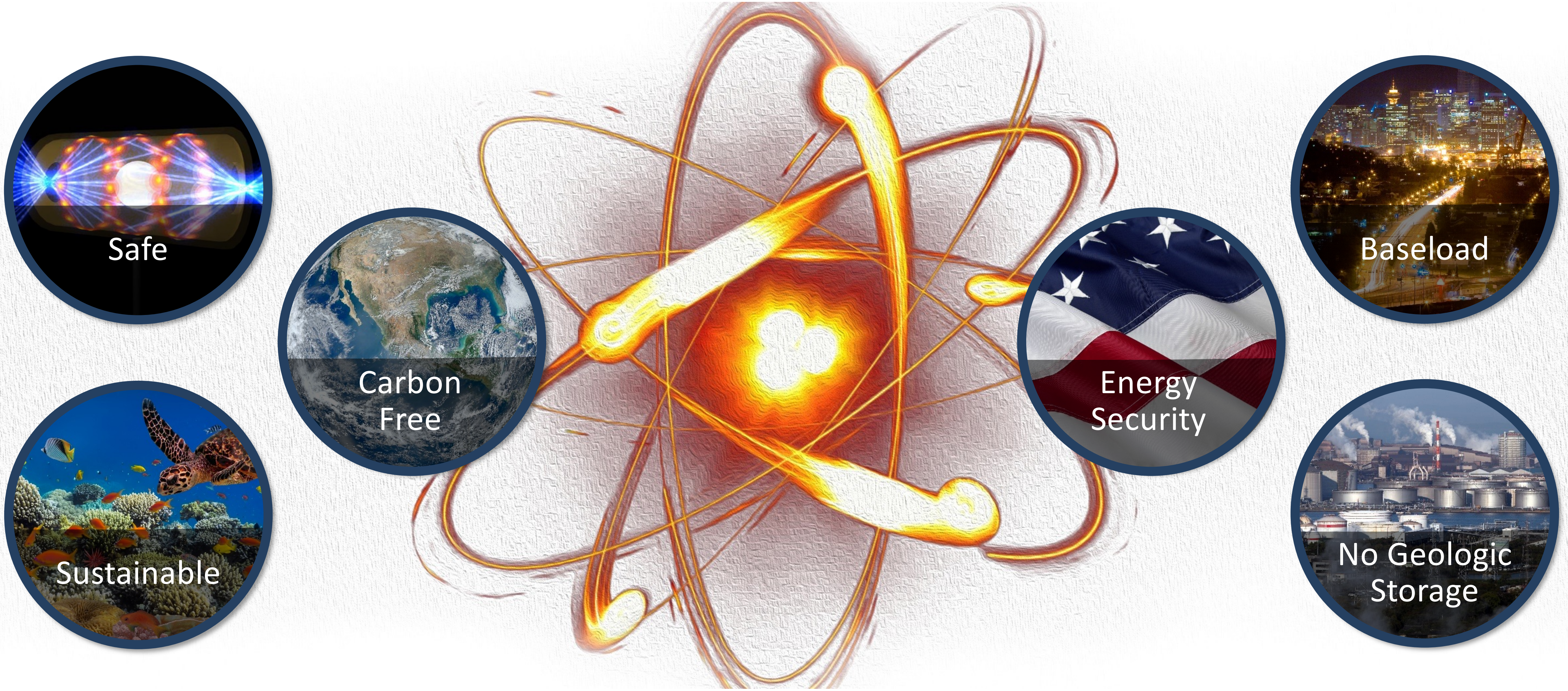
Energy is at the heart of modern economies, and with increasing consumption, new energy sources are required to meet demand



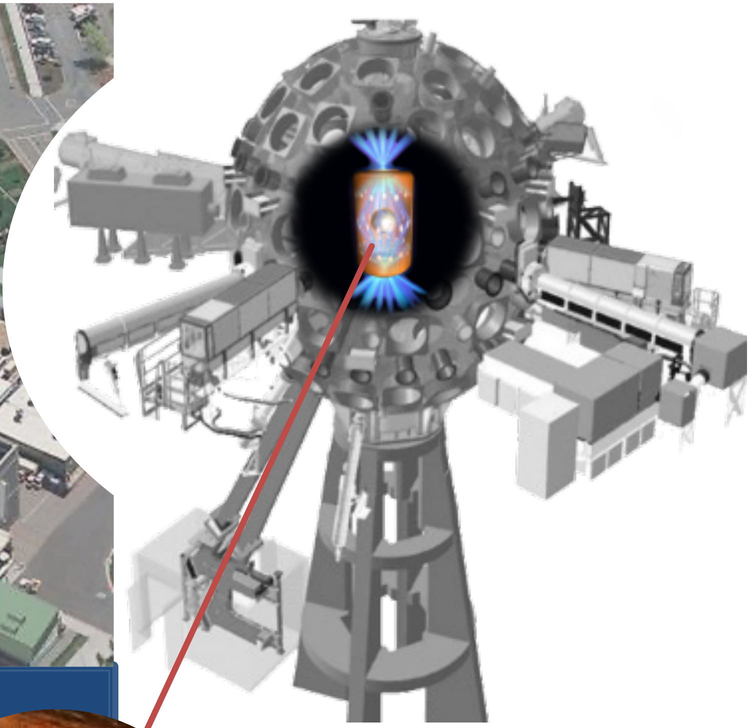
Desirable features for future energy sources

- Carbon-free
- Abundant and geographically diverse fuel
- Environmentally sustainable
- Passively safe
- Ability to meet baseload, while "load following" to meet variable demand
- Distributed energy sources with "smart grid" capability
- Can be generated near population centers
- Flexible energy products (electricity, process heat, H_2 and biofuels, H_2O production)
- Minimal proliferation concerns
- Energy security, sovereignty, and diversification

Fusion energy is attractive for many reasons



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

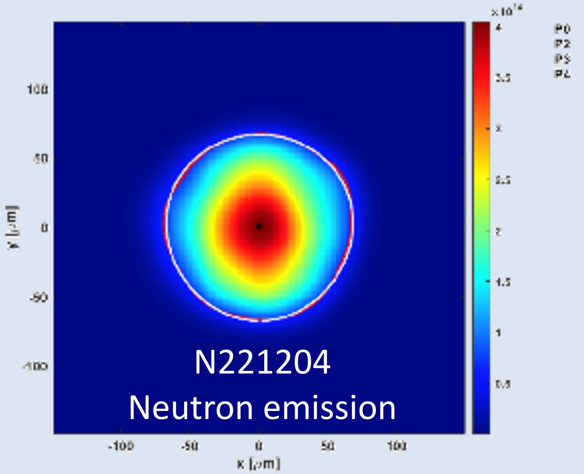
500 trillion watts for
> 4 nanoseconds (ns)
> 2.05 million joules (MJ)

Target
~ 1 cm
Temperature
~3,000,000 K

Energy output

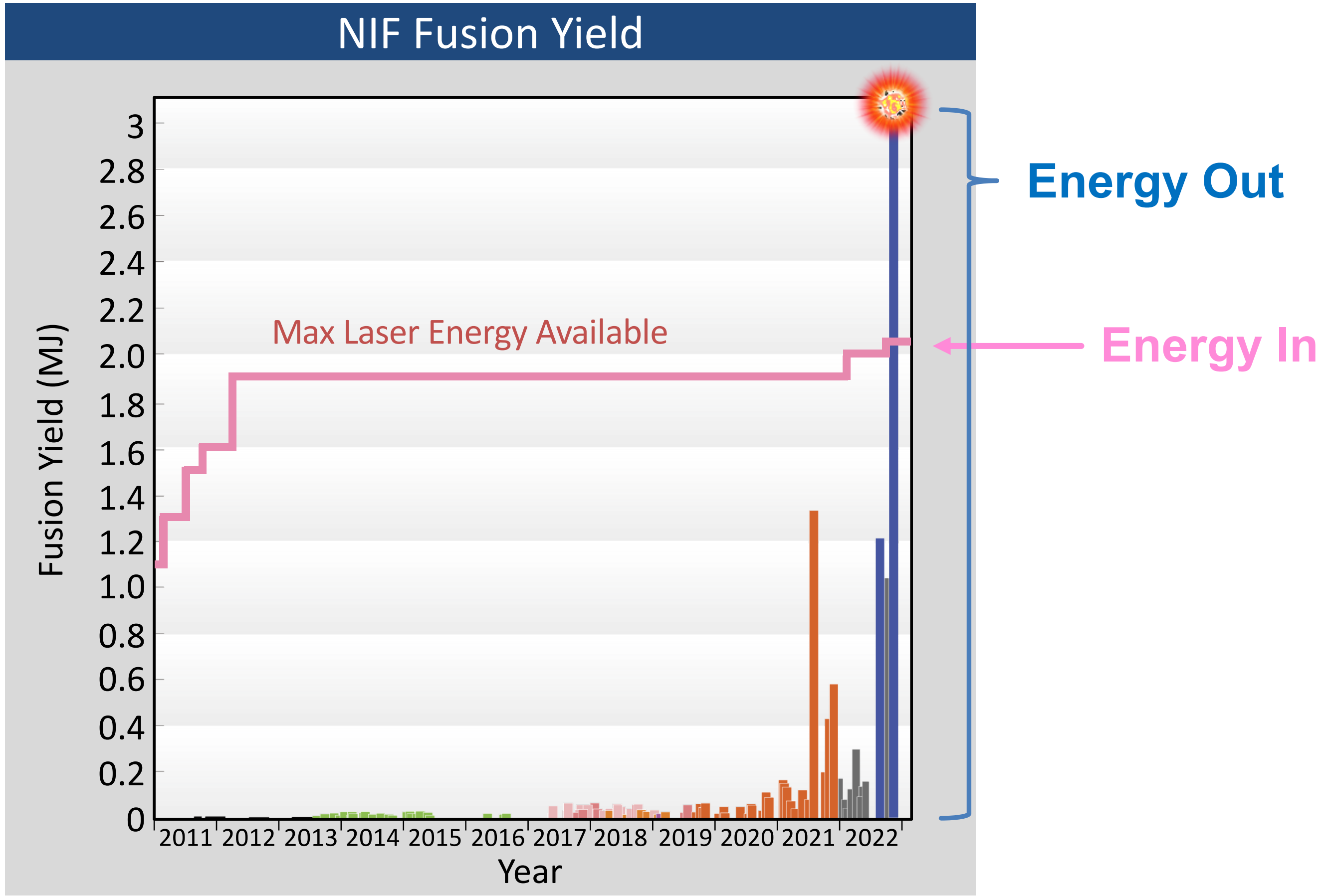
from 12/5/2022 experiment

>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

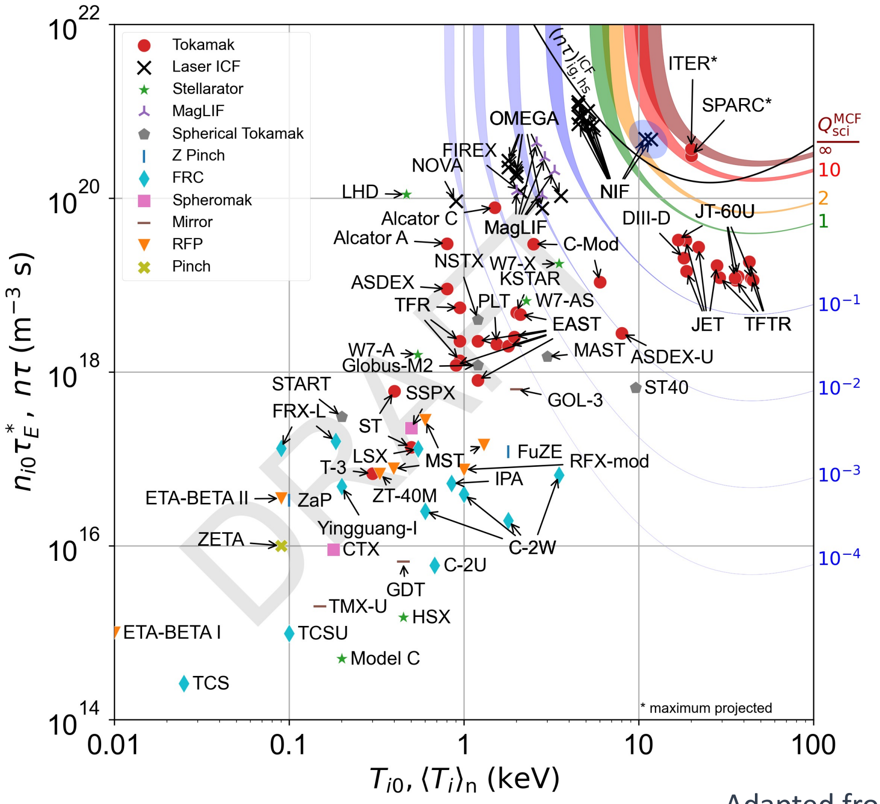


In Dec 2022, gain of 1.5 was achieved on the NIF with 3.05 MJ generated.
In July 2023, ignition was repeated with a yield of 3.88 MJ = gain of 1.9

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.

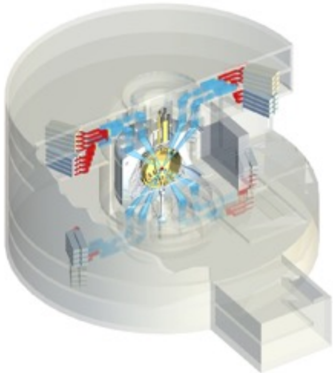
Inertial Fusion Energy (IFE) is an innovative approach to fusion energy with significantly different technological risks to magnetic fusion

Comparison of all fusion experiments to date



ITER* & SPARC* are projections

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

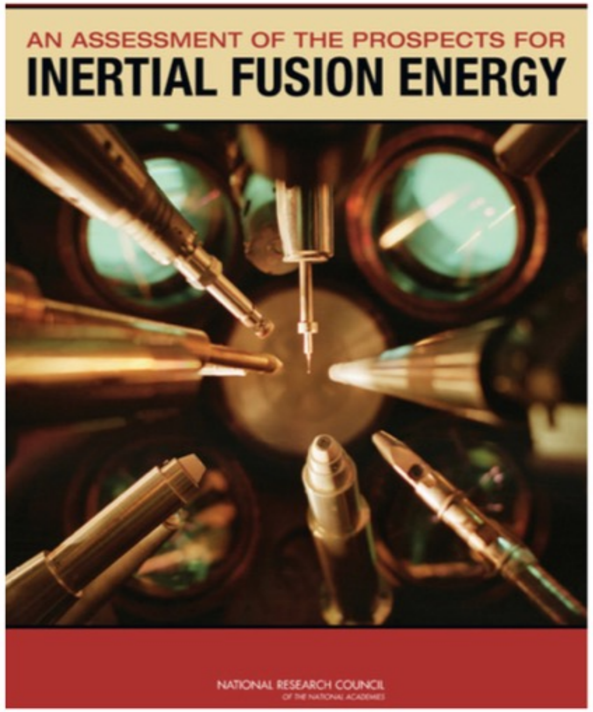


Advantages of the <u>inertial</u> fusion energy (IFE) path:

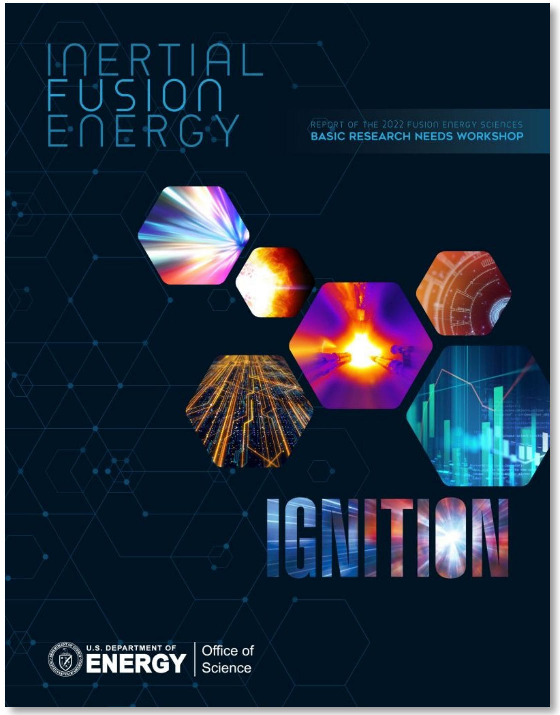
- Only concept with existing ignition platform
- Separable components & highly modular – allow for parallel tech development and upgrades of pilot
- Attractive development path: many technology and science spin-offs
- 10x lower tritium inventory than MFE

A balanced and diverse R&D portfolio maximizes our potential pathways to success

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



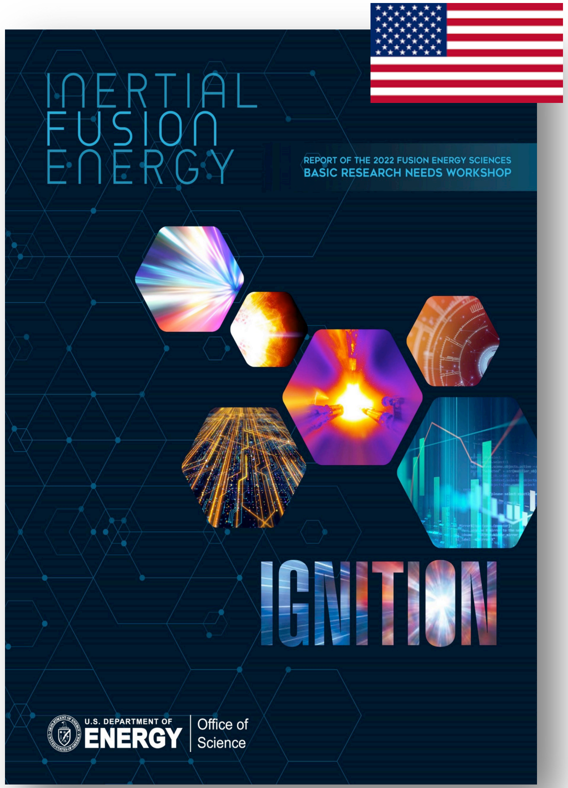
2013 → 2023



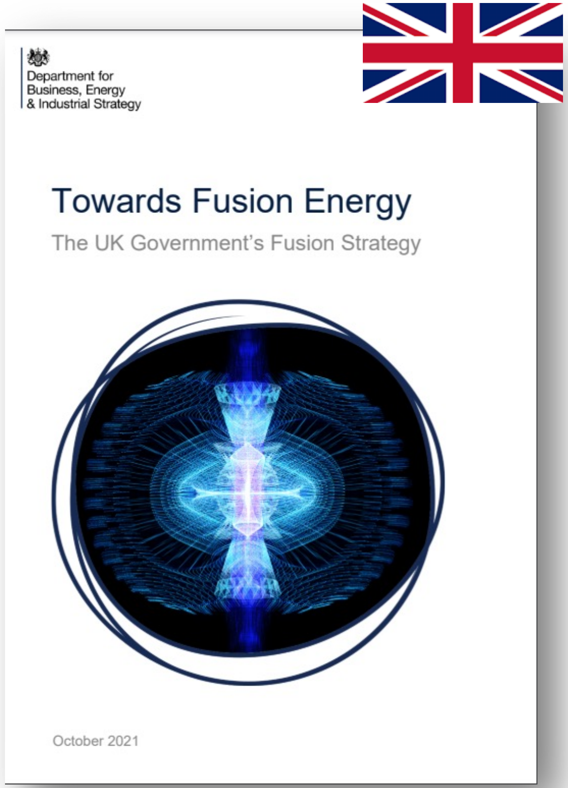
"The appropriate time for the establishment of a national, coordinated, broad-based inertial fusion energy program within DOE would be when ignition is achieved."
- NASEM 2013

"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



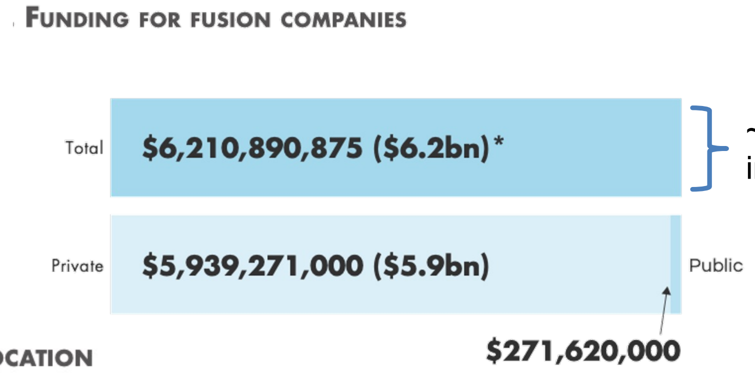
May 2023:
- ICF and MFE >$1B/yr
- IFE ~$21M/yr + private funding



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

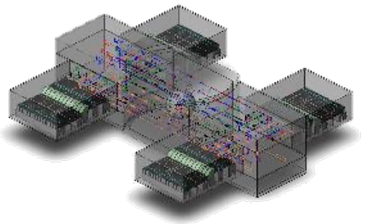
Considerable private investment into fusion startups in the past few years – can help accelerate to pilot plant



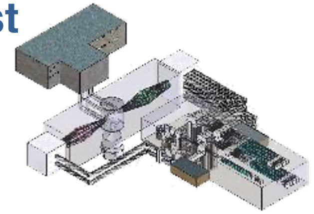
~$300M into IFE

Fusion Industry Associates
The Global Fusion Industry in 2023

Economically Viable Commercial Power Plant



Demo Facilities and First Pilot Plants (2030-40)



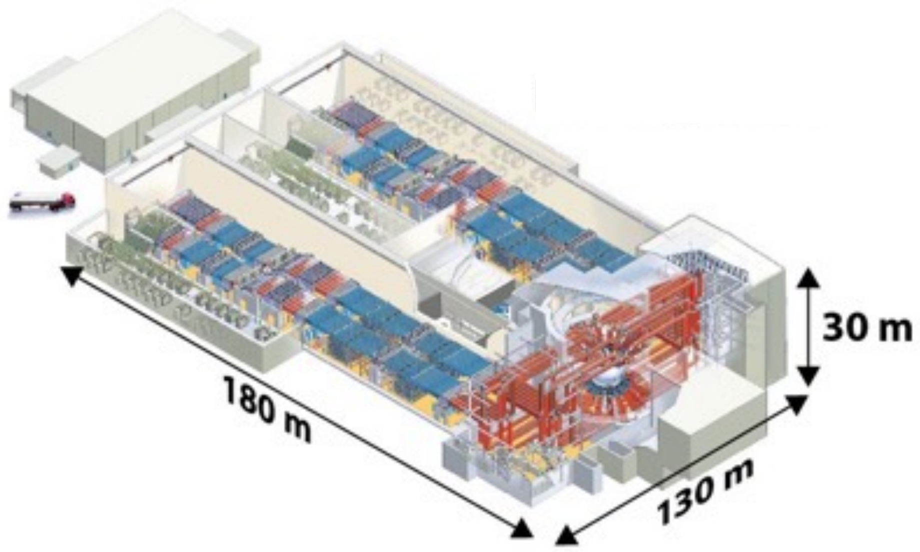
Technology maturation and workforce development (start now)

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

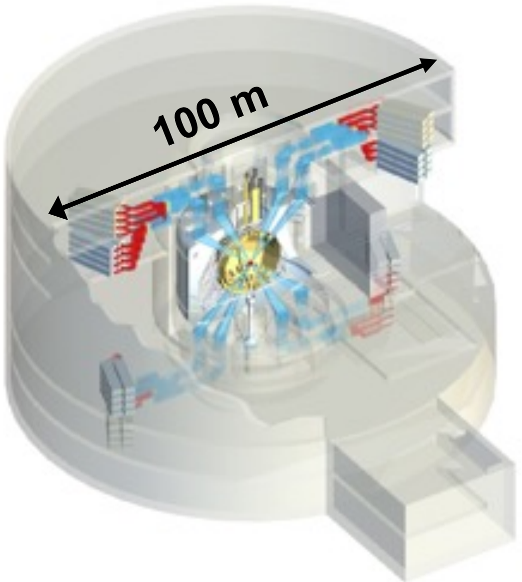
Each step of the plan will require significant public-sector investment and private sector partnerships as well as significant resolve

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



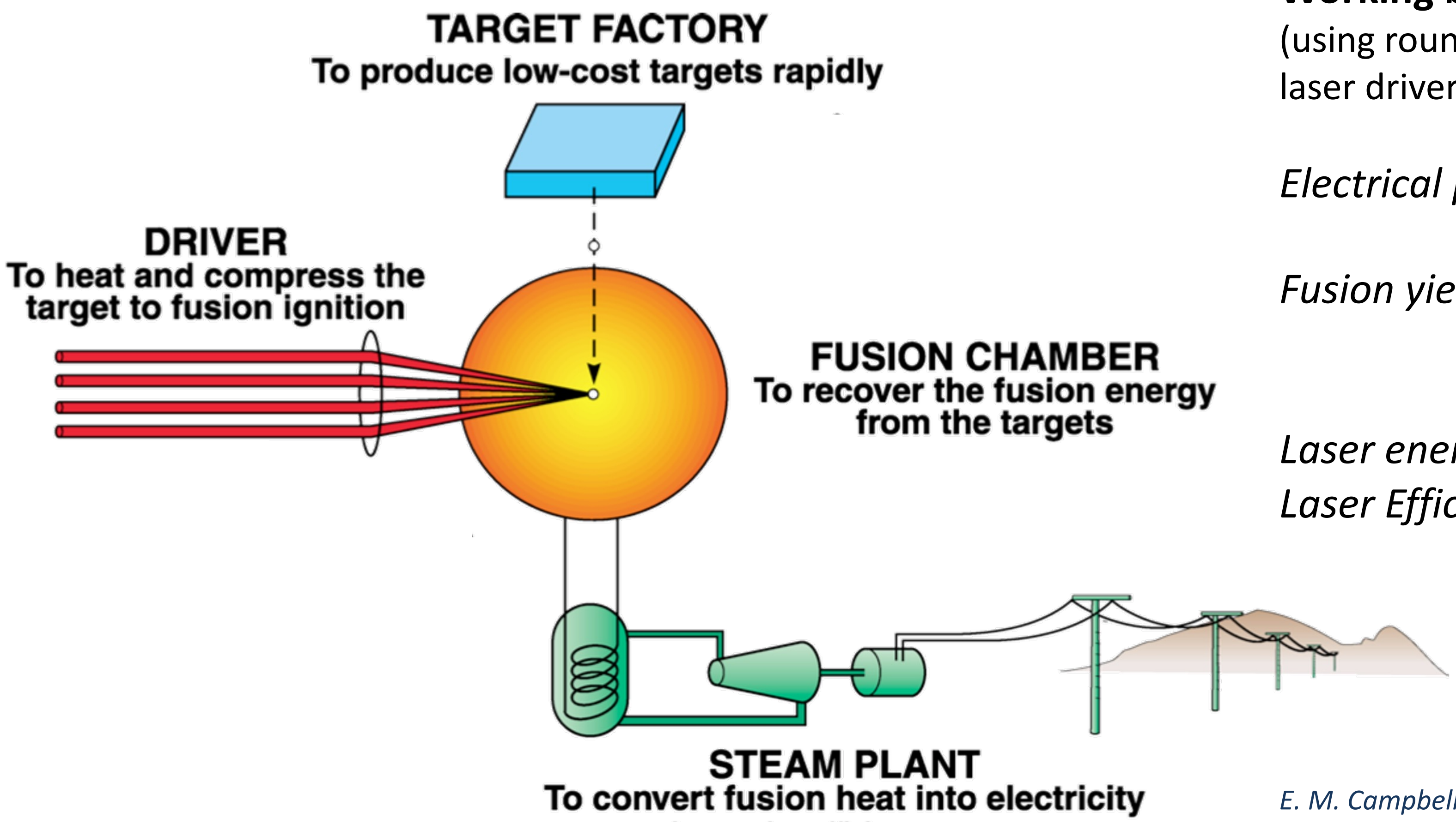
Gain of 1.9 has been achieved on the NIF

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%

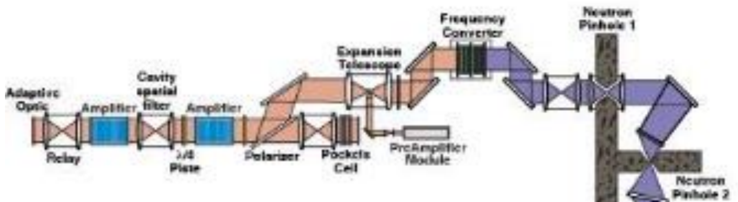
E. M. Campbell, and W. J. Hogan, Plasma Phys. Control. Fusion ***41*** *B39 (1999)*

The technology challenges of IFE are considerable

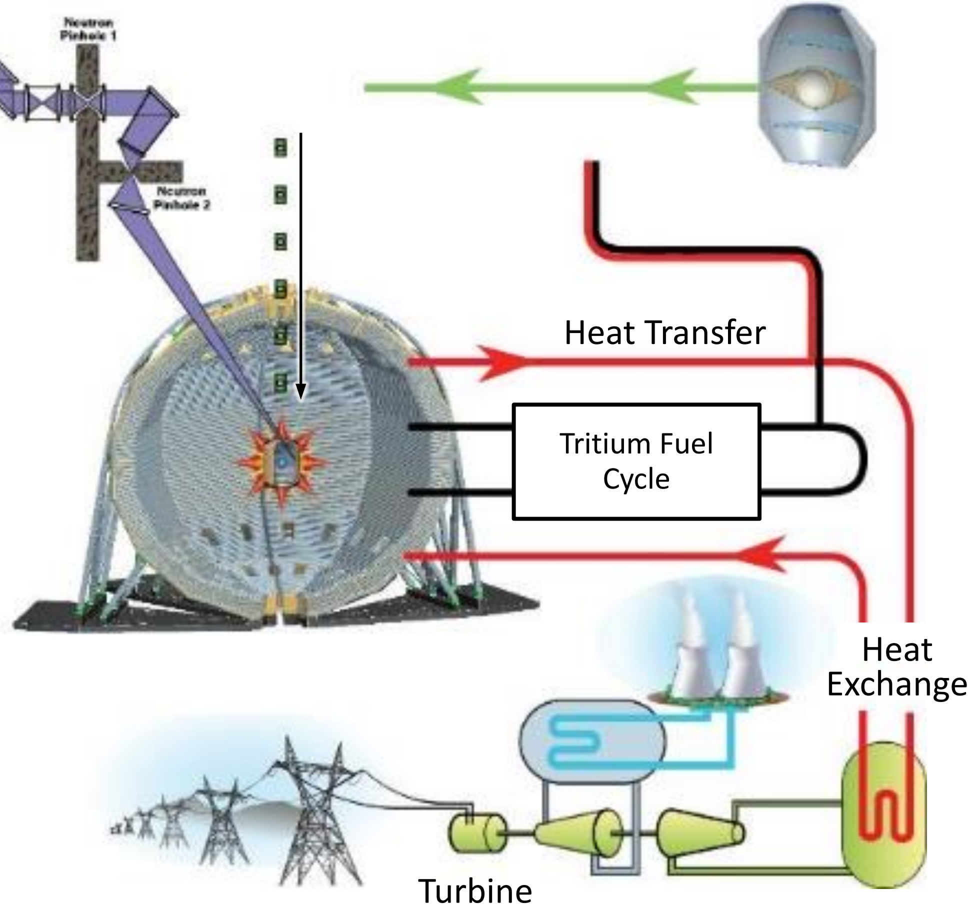
Laser Driver
- 10-20% efficient lasers
- Economical diode scale-up

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

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



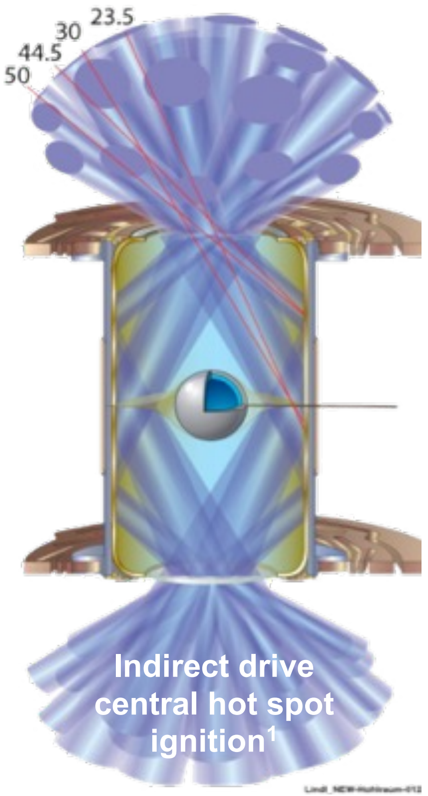
Tritium fuel cycle
- Extremely efficient at scale (~>kg level)
- Materials constraints

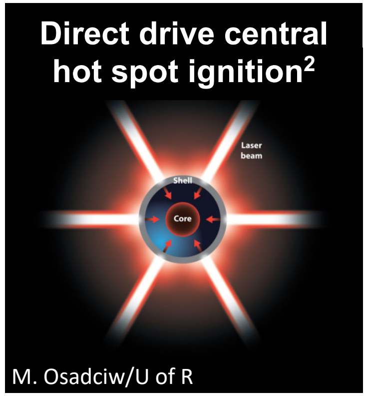
Blanket and Chamber System
- Buffer gas/protection system
- Long lifetime radiation resistance materials
- Full scale tritium breeding and heat transfer blankets

System Engineering and Plant Operations
- System design and tradeoffs
- Modularity and RAMI

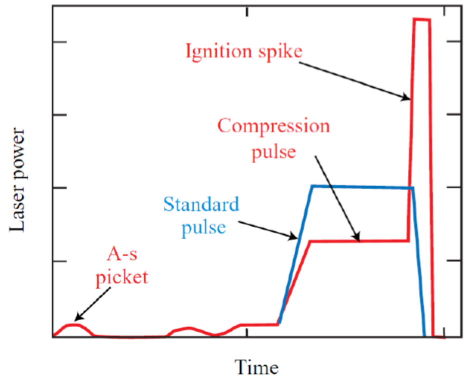
There are several target concepts for ICF that could be explored in an IFE program

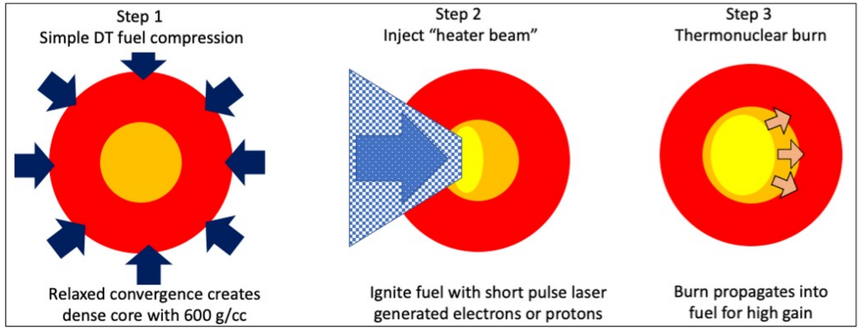
Laser Indirect Drive, Direct Drive, Shock Ignition, Fast Ignition





Direct drive shock ignition[3]

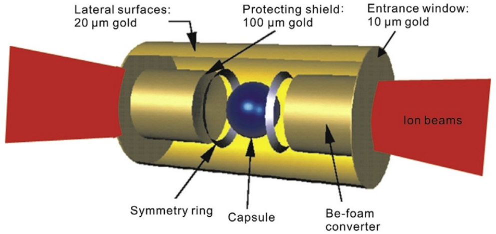




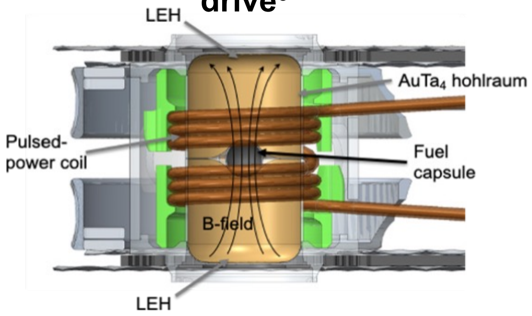
Direct drive + fast ignition[4]

Alternate Designs (Heavy Ion, Magneto-Inertial)

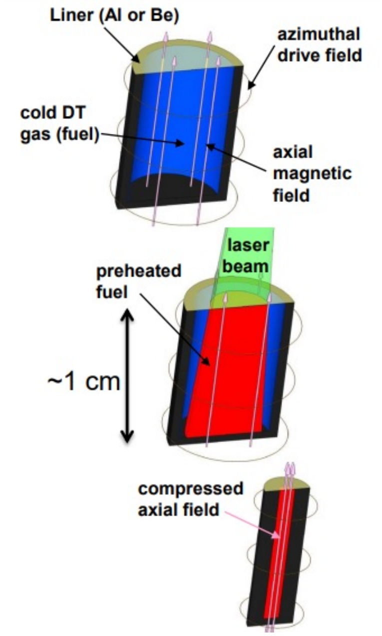
Heavy Ion[5]



Magnetized indirect drive[6]



Linear Magnetic[7]



Choice of target concept makes large impact on driver, chamber design and requirements

2022 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

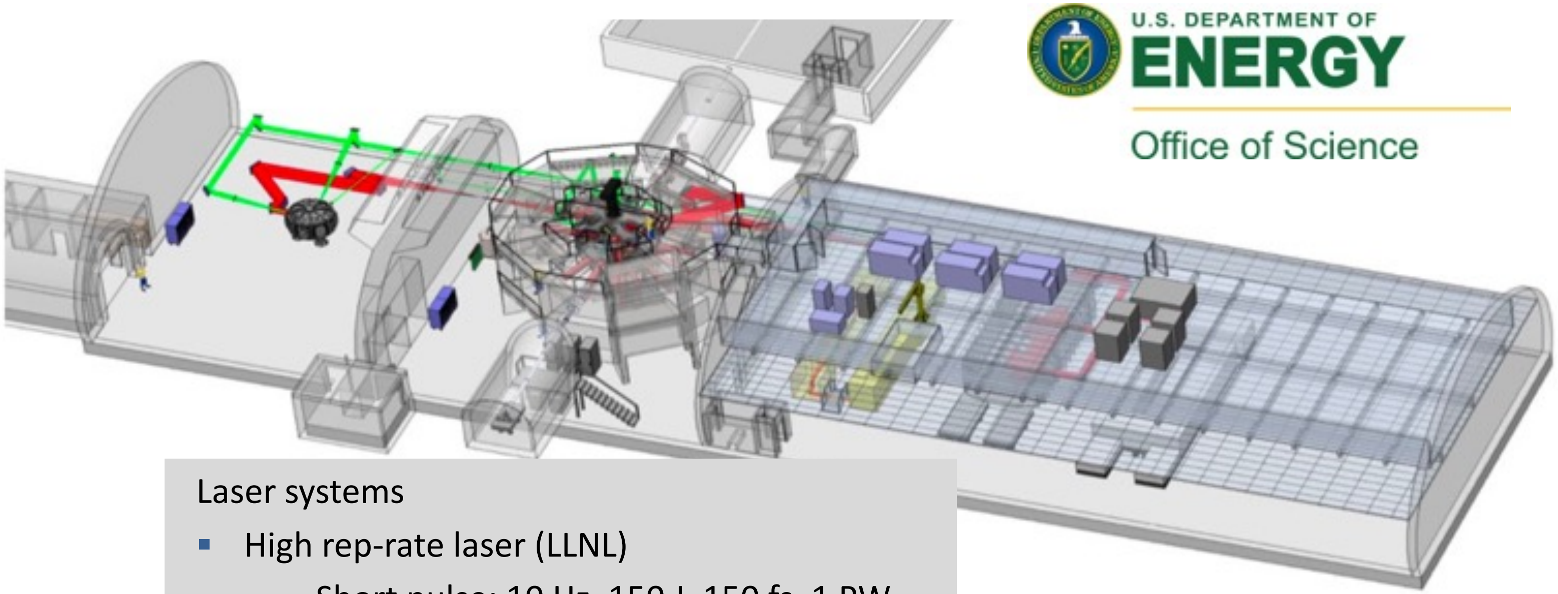
TRL 2 = Technology concept formulated

TRL 3 = Proof of concept

TRL 4 = Component validation in lab environment

TRL 9 = Demonstration plant

The SLAC MEC Petawatt Upgrade project is an example of key investments to advance some of those technologies



U.S. DEPARTMENT OF ENERGY
Office of Science

Laser systems

- High rep-rate laser (LLNL)
  - Short pulse: 10 Hz, 150 J, 150 fs, 1 PW
  - Long pulse: 10 Hz, 200 J @ 2w @ 10 ns
- High energy long pulse laser (LLE)
  - ~2 shots/hr, 1 kJ @ 2w @ 10ns
- LCLS XFEL (5 to 45 keV)

Key Technical Opportunities

- Advanced high average power laser architectures
- 10 Hz operations
- High-throughput targetry
- Rep-rate and hardened diagnostics
- Compute on time scales commensurate with experiment
- Optimization strategies to seek out desired performance
- Focused HED studies of IFE processes or regimes

MEC-U will bring together cutting-edge laser and high-rep-rate technology to be a unique R&D testbed for IFE technologies and materials problems

The national U.S. IFE program will form around hubs that bring together expertise and capabilities across the U.S.

IFE-STAR will provide a framework that leverages expertise and capabilities to advance foundational S&T using integrated and self-consistent solutions

LLNL submitted hub:

THE NATIONAL IFE "STARFIRE" HUB: SCIENCE & TECHNOLOGY ACCELERATED RESEARCH FOR FUSION INNOVATION & REACTOR ENGINEERING

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We will be opening up to additional partnerships if Hub awarded! This is the seed of the public U.S. IFE program.
Good start but needs to be significantly increased if we are to enable FPP in 2030's

A multi-lab IFE Collaboratory was formed to facilitate public-private partnerships

INERTIAL FUSION ENERGY COLLABORATORY

Lawrence Livermore National Laboratory
SLAC National Accelerator Laboratory
Los Alamos National Laboratory
Sandia National Laboratories
Berkeley Lab
UR LLE
General Atomics
Savannah River National Laboratory
Oak Ridge National Laboratory
U.S. Naval Research Laboratory
PPPL Princeton Plasma Physics Laboratory

In-person Industry Day held Nov. 10, 2022 @ LLNL's UCLCC

- The Collaboratory promotes fairness of opportunity for partnerships, and ensures strategic alignment with core missions
- Living website: *https://events.bizzabo.com/RFI-IFE/home*
- Two Industry Days held
  - 14 IFE companies + 9 Collaboratory institutions
- Capabilities and partnering opportunities listed on website

The Collaboratory continues to facilitate new partnerships – more industry days planned for the future

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

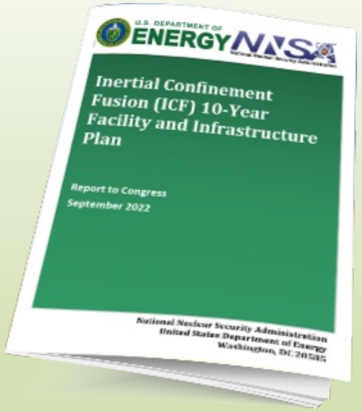
Few MJ → 10s of MJ → 100+ MJ??

2023

Routine MJ-yield operations and ignition

2023–2028

Long-term sustainment

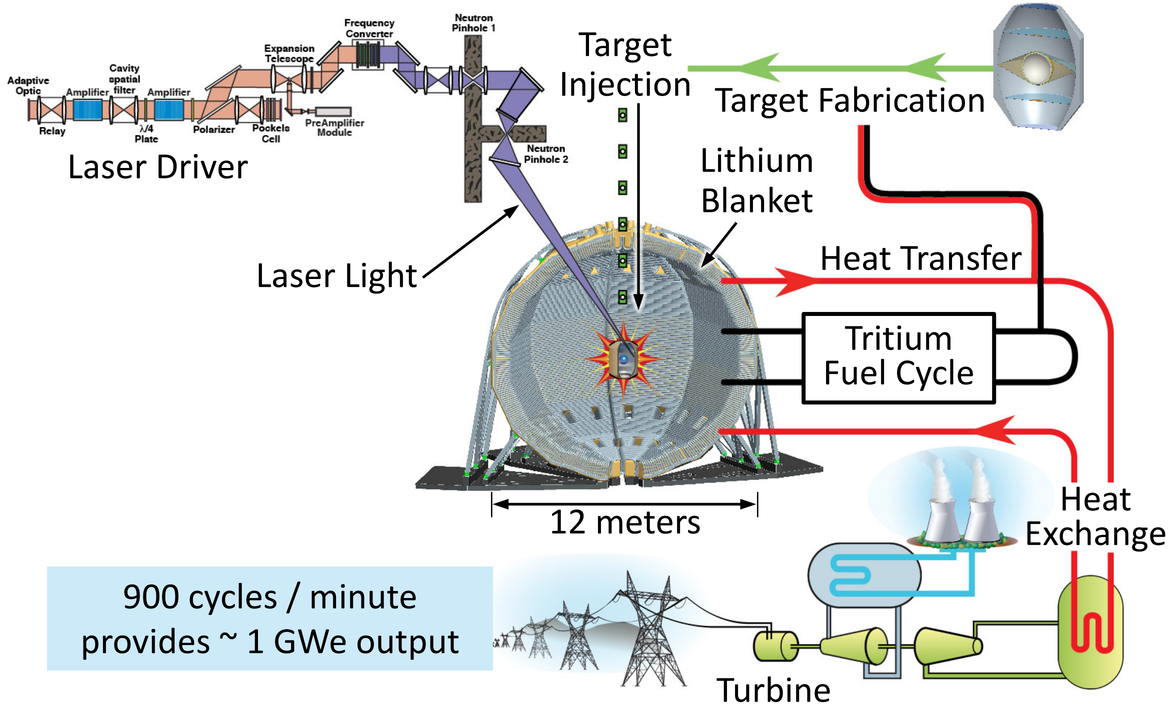


Increase energy and power

2030–2040

Explore high-yield, high-gain regime

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.

EUV lithography commercial systems demonstrate many of the elements of an eventual inertial fusion energy (IFE) powerplant, and required similar scaling and technology maturation

EUVL research was an outgrowth of the ICF program in the 1990s

25 years and $6B+ of investment

Advances in:
Laser, targets, x-ray optics, debris mitigation, precision alignment, …….

	EUVL	IFE
High Average Power laser	40 kW 10.6 mm	10,000-30,000 kW 200-500 nm
High Rep Rate Targets	30 mm tin droplet 50 kHz	Ignition target 10 Hz
Harsh Environment (X-rays and Debris)	250W x-ray, 5 mg/sec, vacuum/gas	200 MW x-ray, 800 MW neutron, 10 g/sec
Long Lifetime Optics	Gigashot	Gigashot+

EUV = extreme ultraviolet

Fusion Energy may be the ultimate clean and limitless energy source

- Inertial Fusion Energy is a game-changing technology
  - Can provide abundant energy while helping to meet long term CO_2 goals
  - IFE has very different risks/rewards compared with MFE
  - Bolsters science and technology leadership, offers a long-term vision for enduring global climate and energy security
- The time is now!
  - Ignition has been demonstrated on NIF!
  - Unprecedented fusion energy momentum in the public and private spheres – governments investing around the world
- IFE, like MFE, is a multi-decadal endeavor, and will require innovation to enable economical energy source
- Public-private partnerships are key

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

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