Priority Research Opportunities from the 2022 DOE Basic Research Needs for Inertial Fusion Energy (IFE)

ELI Laser Fusion Workshop 2023

Dr. Tammy Ma
Chair, 2022 IFE BRN

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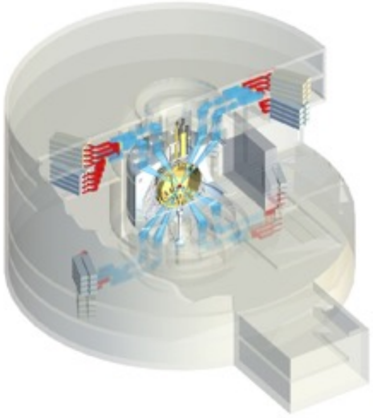
Lawrence Livermore National Laboratory

Fusion energy may be the ultimate clean and limitless energy source

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

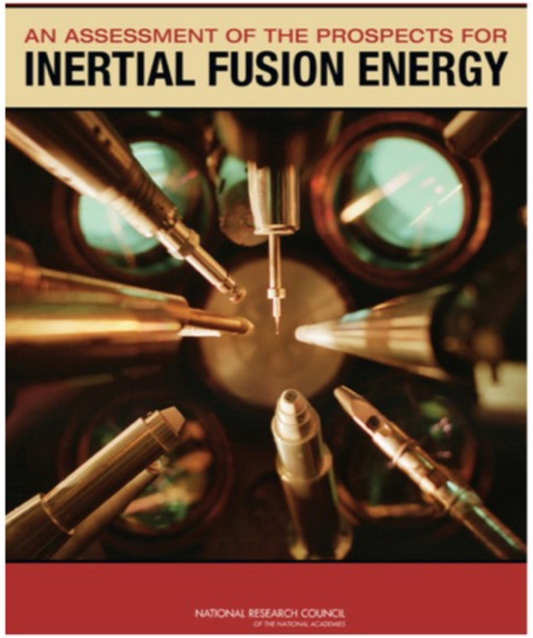
Fusion has the potential to meet all of these!



Advantages of the inertial fusion energy (IFE) concept:

- Scientific energy gain has been demonstrated
- Significantly different technological risks than MFE
- Separable components / Highly modular
- Multiple target concepts with same driver
- Reduced tritium inventory
- Pulsed which allows for plasma fuelling and ash removal (i.e., easier to shut down plant)
- Attractive development path: technology and science spin-offs
- Multiple sponsors for key technologies (e.g., laser diodes, high neutron yield sources)

We are at a pivotal moment in fusion research, and it is the ideal time to focus on Inertial Fusion Energy



"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, *An Assessment of the Prospects for Inertial Fusion Energy*

Progress across multiple laser drive and magnetic drive approaches

Private sector interest and investment

Sustained advocacy

New legislation

Together this sets up a supportive environment for a revitalized U.S. IFE program

Over 2022, the US Department of Energy (DOE) held a Basic Research Needs in IFE to define a new national IFE program

>120 experts from across the community

Process:

- Prior to BRN, a community strategic planning workshop in IFE was held (Feb. 2022)
  - >90 white papers
  - *https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/*
- DOE issues charge
- Structure of panel and report laid out
- Expert panelists invited by DOE
  - 120 participants from US & international institutions
- Panelists were split into 12 topical working groups; start group meetings to address aspects of charge
- 3-Day (virtual) workshop June 21-23, 2022
  - Plenary session June 21 open to all
  - Followed by 2.5 days of closed session discussions
- Each panel continued to meet and work together to assemble report

Basic Research Needs (BRN) Charge

1. **Assess current status of IFE**
2. **Define Priority Research Opportunities (PROs) that address the R&D challenges in IFE. Identify areas where IFE different from ICF**
3. **Assess the various concepts and component technologies for their TRL levels**
4. **Identify areas where MFE R&D can be leveraged; areas that require IFE-specific development**
5. **Role of public-private partnerships**

Department of Energy
Office of Science
Washington, DC 20585

5/27/2022

Dear Colleagues:

Thank you for agreeing to participate in the Fusion Energy Sciences (FES) Basic Research Needs (BRN) Workshop on Inertial Fusion Energy. The workshop will be held June 21-23, 2022, virtually using Zoom. Dr. Tammy Ma, Lawrence Livermore National Laboratory, and Prof. Riccardo Betti, University of Rochester, will together chair the workshop.

Charge:

1. Assess and summarize the status of science and technology for Inertial Fusion Energy (IFE) in the U.S. and abroad.
2. Assess enabling science and technologies common to Inertial Confinement Fusion and IFE and define a set of priority research opportunities that address the research and development (R&D) challenges unique to IFE, along with evaluation criteria to assess ongoing progress in an IFE technology development program.
3. Assess the maturity and potential of the various IFE concepts toward a path to a viable IFE fusion pilot plant. Use Technology Readiness Level (TRL) methodology to guide the R&D demonstration of ignition and reactor-level gain for each concept:

The workshop is expected to provide FES with a set of priority research opportunities that can inform future research efforts in IFE and build a community of next-generation researchers in this area. The findings of this workshop should be summarized in a report to be submitted to FES within three months after the meeting.

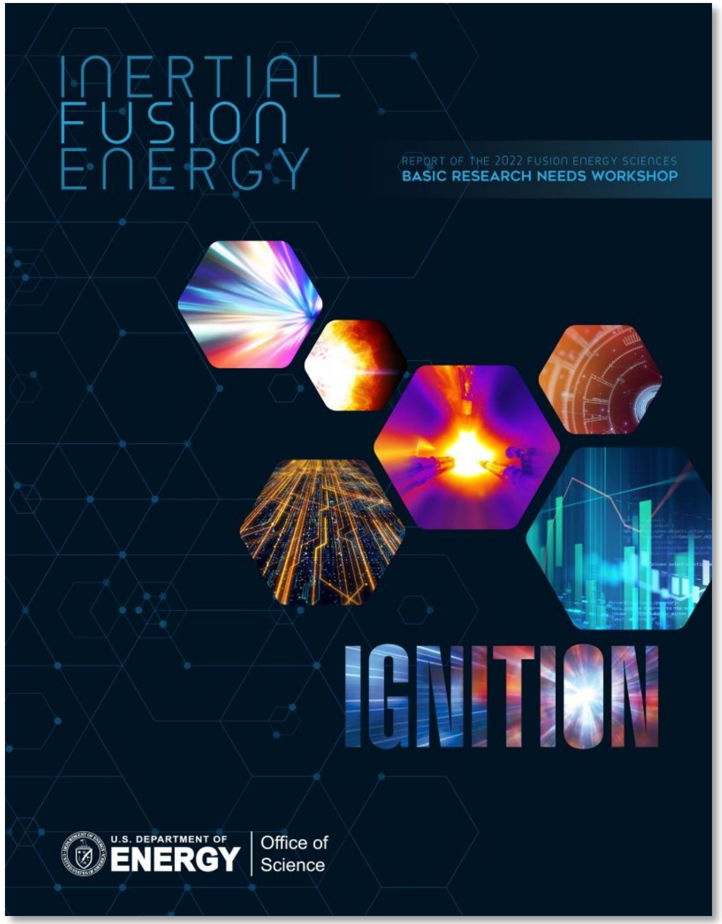
A website for the workshop is planned to keep the community informed on the progress and matters relating to the workshop.

Sincerely,

James W. Van Dam

James Van Dam
Associate Director, Office of Science
Fusion Energy Sciences

Report provides FES with a set of priority research opportunities (PROs) that can inform future research efforts in IFE and build a community of next-generation researchers in this area



Target Physics and Ignition:

- Coupling
- Compression and Burn
- Alternate Fusion Concepts

Driver and Target Technologies:

- Drivers
- Targets

Fusion Power Plant Integrated Systems:

- Power Systems, Science, Engineering and technology

Cross Cutting:

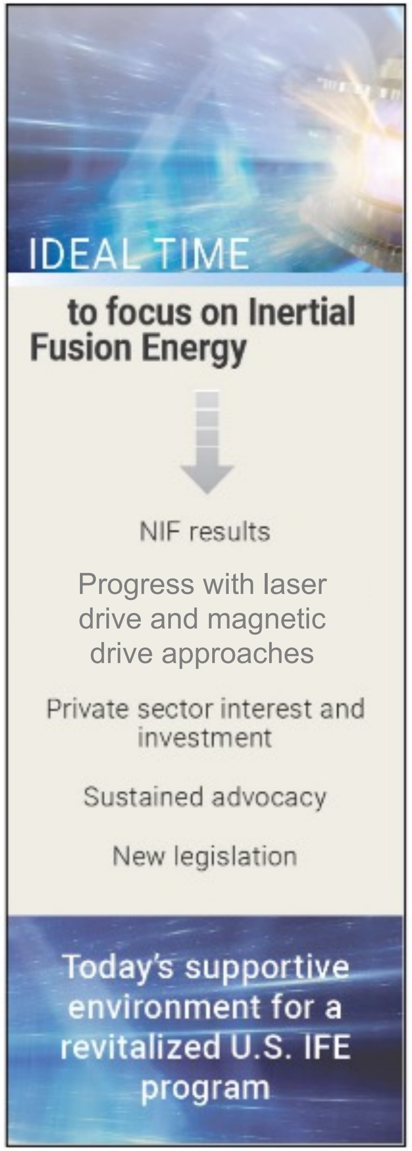
- Theory and Simulation
- Artificial Intelligence and Machine Learn
- Measurement Innovations
- Research Infrastructure
- Public-Private Partnership
- Workforce

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

Report provides DOE Office of Science Fusion Energy Sciences (FES) with a set of priority research opportunities (PROs) that can inform future research efforts in IFE and build a community of next-generation researchers in this area

Overarching **Findings**

1. **IFE is a promising approach to fusion energy with different technical risks and benefits with respect to MFE.** It should be an important part of the FES R&D portfolio.
2. The recent demonstration of the threshold of thermonuclear ignition on the NIF constitutes a **pivotal point** in the development of inertial fusion energy.
3. Major advances in IFE-relevant physics and technology, including demonstration of the threshold of ignition, occurred over the last several decades funded mostly under the national security mission. **The U.S. is the recognized leader in IFE science and technology because of this investment.**
4. **Private industry is driving the commercialization of fusion energy in the U.S., and public-private partnerships** could greatly accelerate the development of all fusion energy concepts.
5. Accelerating IFE will require a **suite of dedicated, new, and upgraded facilities** to increase the rate of learning and test new technologies. Facilities would range from “at scale” physics facility(ies) to test concepts, to a wide range of component and sub-system development facilities (that can also test technologies in a modular way).
6. The **ICF modeling codes that primarily reside at the NNSA** national labs are built on decades of investment and expertise, and constitute a **very valuable resource** for advancing IFE science and technology.
7. The climate and culture of the broader field of fusion/plasma research requires improvements to **enhance diversity, equity, and inclusion.**

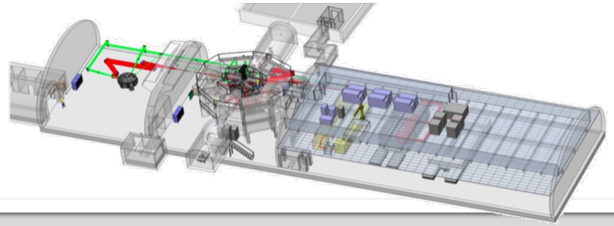


Overarching Priority Research Opportunities

1. Take advantage of and spur **emerging technologies** (exascale computing, artificial intelligence (AI) and machine learning (ML), advanced manufacturing, high-rep-rate laser systems, etc.) to accelerate progress toward the goal of a fusion pilot plant (FPP).
2. **Employ system-level integrated studies** to guide the IFE R&D in a coordinated fashion with the objective to advance the different areas of IFE science and technology towards the goal of building and operating an FPP.
3. **Develop scoping studies to evaluate the various IFE concepts**. With input from the energy industry and fusion science and technology experts, identify the most promising concepts to guide downselection and to inform directions of technological development.
4. **Accelerate the pace of IFE and reduce risk through the pursuit of parallel development paths.**
5. Leverage **existing facilities** (including LaserNetUS), expertise, and **international collaboration** to advance IFE S&T. Explore ways to expand shot time on existing U.S. facilities and develop upgrades to meet IFE-specific needs.
6. Assess how to **optimally and securely access and use ICF codes for IFE development**, and how to leverage the deep code expertise that resides at the NNSA-funded labs. Carry out the assessment with NNSA input.

LaserNetUS

MEC Petawatt Upgrade



Overarching Structural Concepts

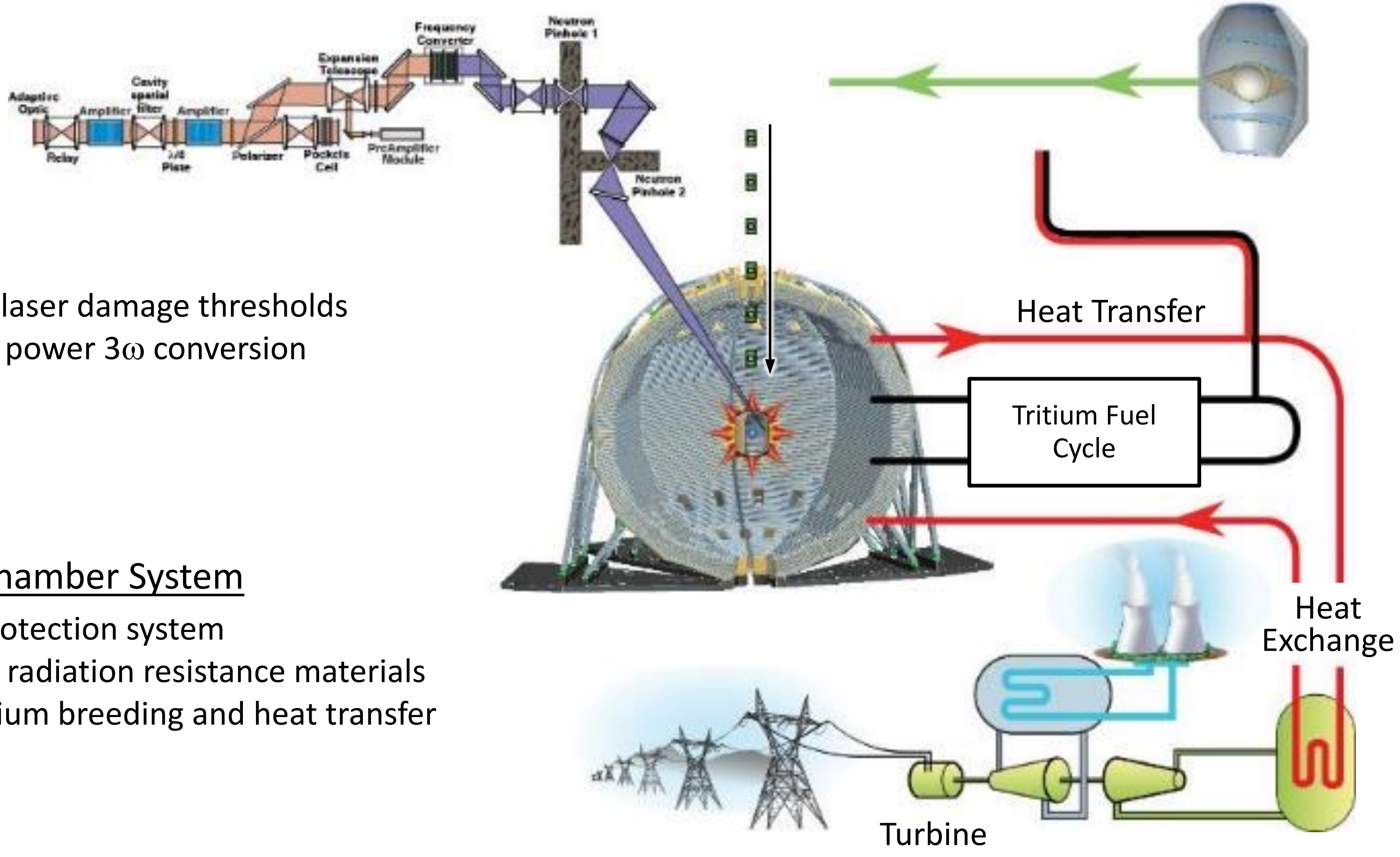
1. Grow a healthy IFE program and partnerships by leveraging MFE and other relevant technology development programs where appropriate. **Develop collaborations with MFE** to address common issues and IFE specific issues.
2. **Develop public-private partnership** as part of DOE's milestone program and other funding opportunities. Organize workshops, knowledge seminars, industry days, and technical exchange meetings. **Streamline partnering mechanisms.**
3. Foster engagement with community partners, universities, and the private sector to **promote partnership to recruit and develop the next IFE workforce.**
4. **Periodically re-evaluate IFE research opportunities to take advantage of the rapid developments within the larger NNSA-funded ICF program and private sector.**

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

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

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

BRN Opportunity: Develop scoping studies to evaluate the various IFE concepts

- **Use input from the energy industry and fusion science and technology experts to identify the most promising concepts to guide down-selection and to inform directions of technological development.**

- IFE concepts are currently being pursued at varying levels of effort

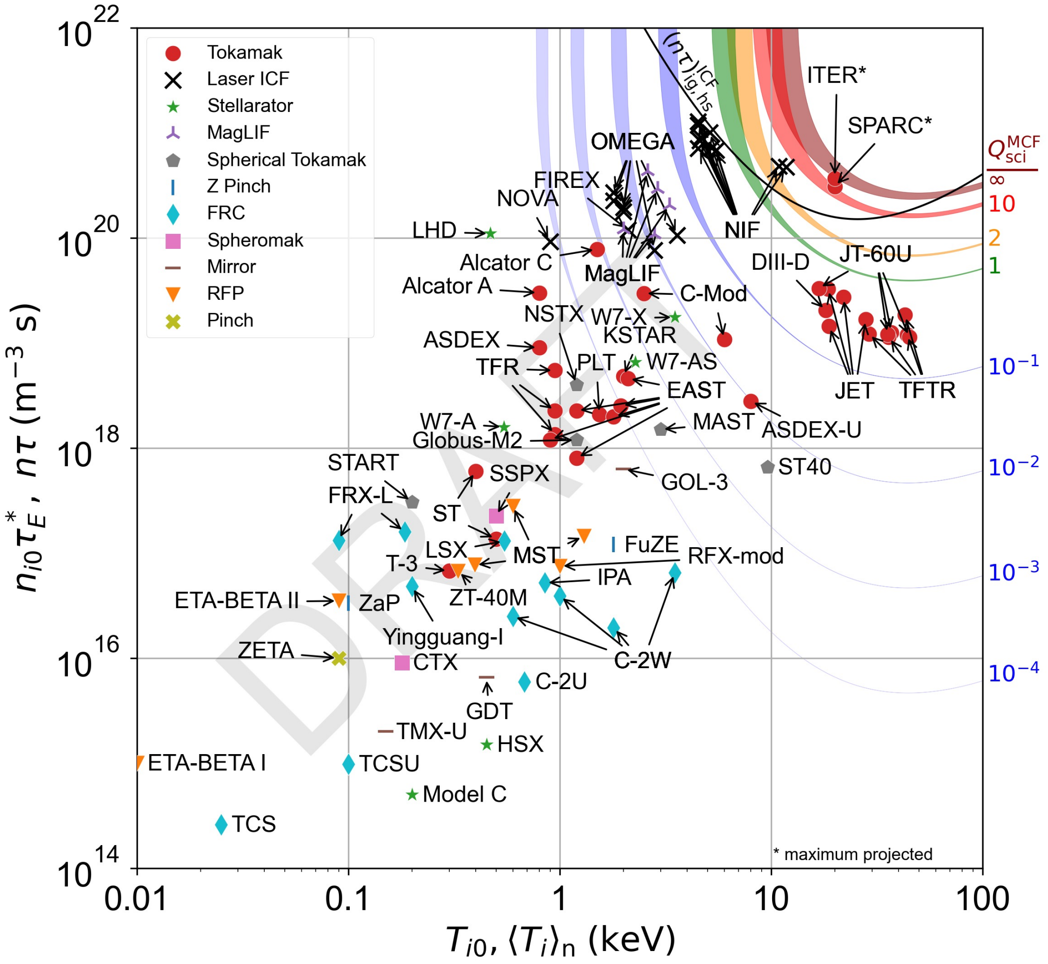
- Not enough resources to advance all concepts in realistic funding scenario and assuming IFE has to play a role in the energy portfolio in the not-too-distant future

- Community can be more effective if IFE concepts are assessed by the viability of each and down-select to a few to develop for demo and pilot plants

IFE Concept	Current Level of Research Effort
Indirect-Drive	High
Laser Direct-Drive, including Shock Ignition	Moderate
Fast Ignition	Low-Moderate
Heavy Ion Fusion	Low
Magnetically-Driven Fusion	Moderate

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

Comparison of all fusion experiments to date



ITER* & SPARC* are projections

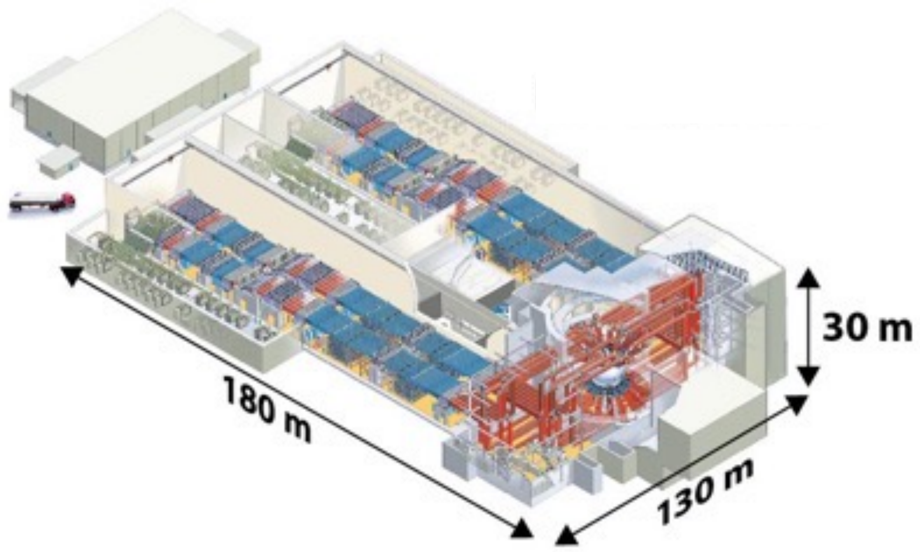
Adapted from *Wurzel and Hsu, Phys. Plasmas* ***29****, 062103 (2022)*

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

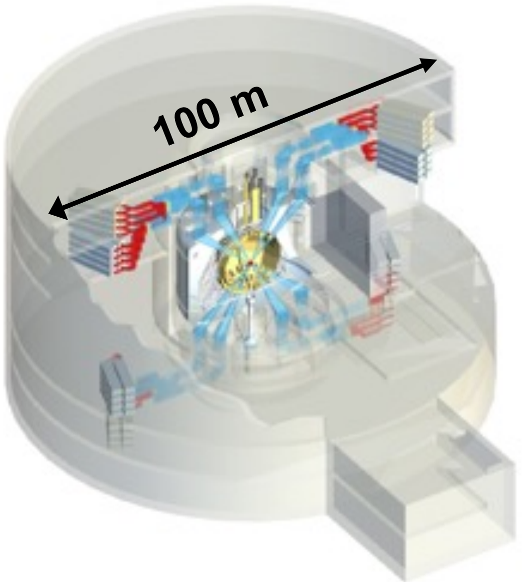
A balanced and diverse fusion portfolio maximizes our potential pathways to success,
and allows us to build on the U.S.'s significant and singular lead in IFE

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

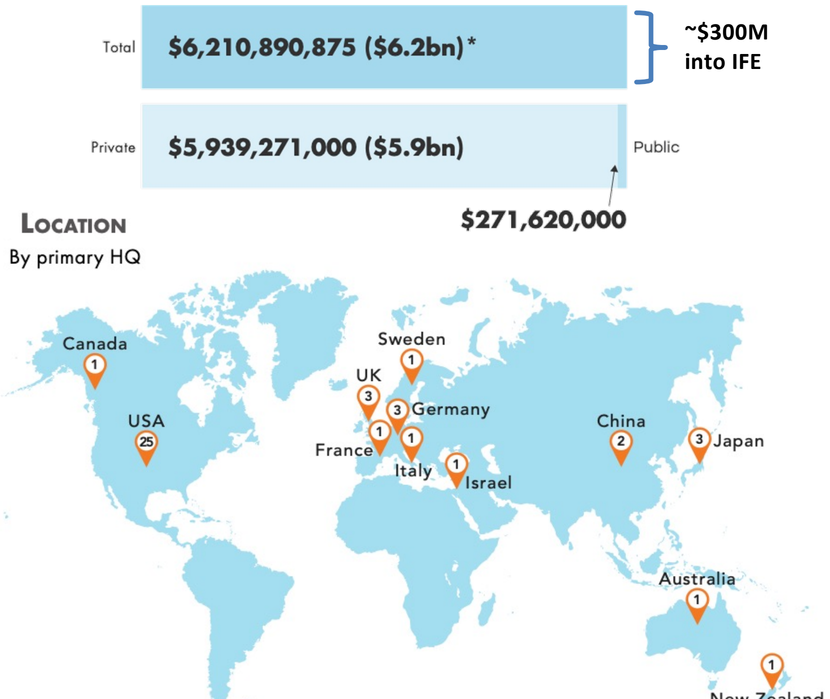
A gain of 15-16 is approximately what is needed for a self-sustaining plant

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

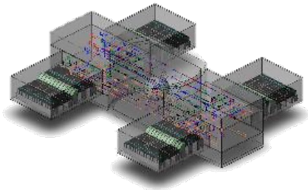
IFE is a national need that requires a national plan, program, and team, and sustained commitment

Funding for private fusion companies

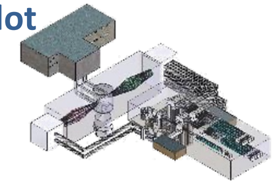


Fusion Industry Associates
The Global Fusion Industry in 2023

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

FY24 will mark the rebirth of the U.S. national public IFE program; numerous funding calls are supporting IFE

U.S. DEPARTMENT OF ENERGY | Office of Science

IFE-STAR establishes multi-institutional ”hubs”

IFE-STAR will award **$45M** over 4 years and provide a framework that leverages expertise and capabilities to advance foundational S&T using integrated and self-consistent solutions

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

Several calls center around foundational S&T

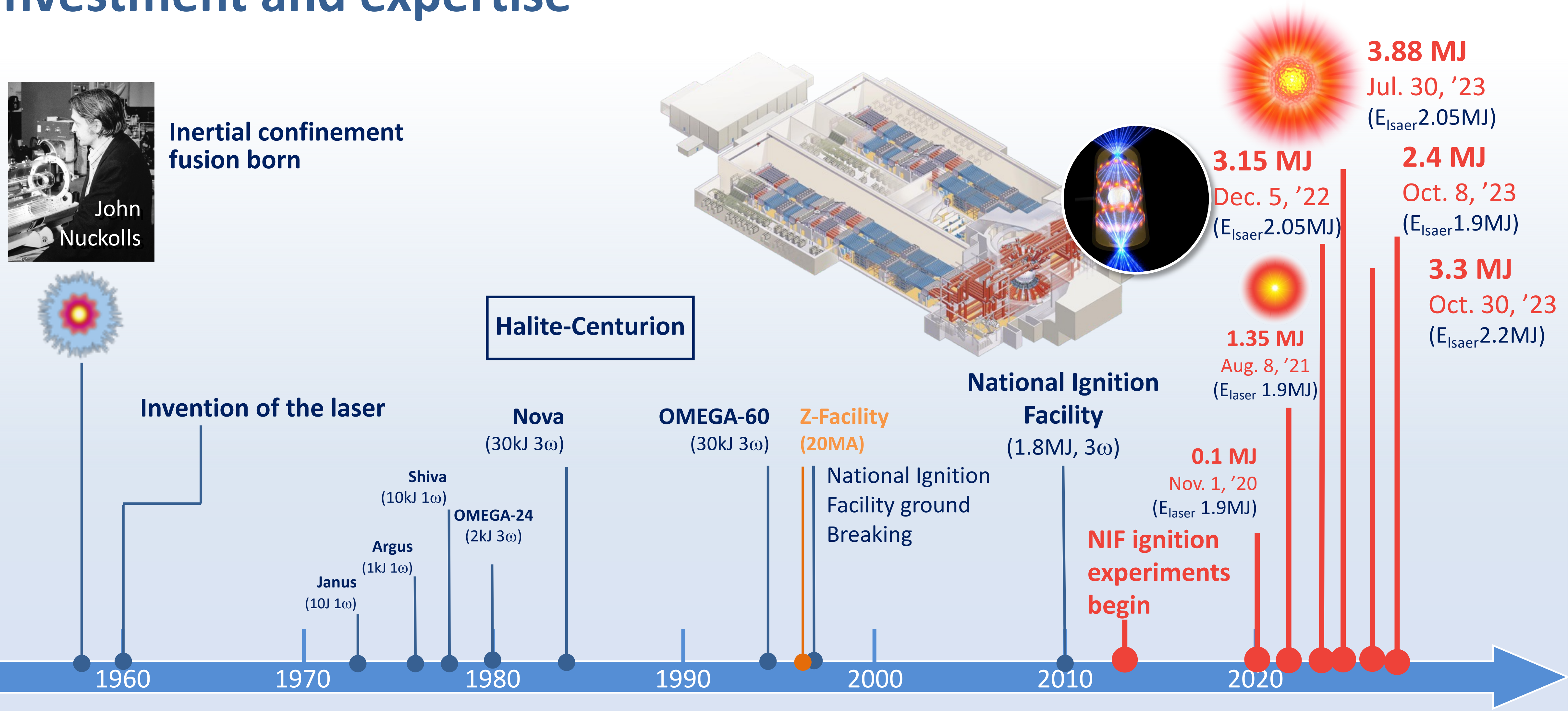
INFUSE (Innovation Network for Fusion Energy) to provide industry access to capabilities at DOE-funded institutions

INFUSE Innovation Network for Fusion Energy

ARPA-E fusion programs

arpa·e

We have now achieved ignition four times – built on decades of investment and expertise



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. International collaboration is necessary for the scale and complexity of the challenge.

Lawrence Livermore National Laboratory