INERTIAL FUSION ENERGY

REPORT OF THE 2022 FUSION ENERGY SCIENCES
BASIC RESEARCH NEEDS WORKSHOP

IGNITION

U.S. DEPARTMENT OF ENERGY | Office of Science

DEVELOPING FUSION ENERGY

Fusion is the process that powers the Sun. The ability to harness this power would provide a source of reliable, abundant, safe, and clean energy to move us away from a reliance on hydrocarbon-based energy sources. Inertial fusion energy (IFE) is a particularly promising approach to achieving this grand scientific and technical challenge.

The DOE-sponsored Basic Research Needs (BRN) workshop, held in June 2022, produced a list of Priority Research Opportunities (PROs) to inform future research efforts in the areas constituting the building blocks of an IFE program:

- Target physics
  - Energy coupling
  - Compression and burn
  - Alternate fusion concepts
- Target design
- Driver technologies
- Power systems
- Cross-cutting fields
  - Theory and simulations
  - Machine learning and artificial intelligence
  - Measurement innovation
  - Workforce development
  - Research infrastructure

EXECUTIVE SUMMARY

Fusion has the potential to provide a reliable, limitless, safe, and clean energy source. Developing fusion energy is a grand scientific and technical challenge that will require diverse approaches and paths to maximize the likelihood of success. Inertial Fusion Energy (IFE) is one such highly promising approach. While the main approach previously pursued by the U.S. Fusion Energy Sciences (FES) program has been Magnetic Fusion Energy (MFE), a 2013 National Academies of Sciences, Engineering, and Medicine (NASEM) report concluded that

"The appropriate time for the establishment of a national, coordinated, broad-based inertial fusion energy program within DOE would be when ignition is achieved [1]."

In December 2022, after the conclusion of the Basic Research Needs (BRN) Workshop, the National Ignition facility (NIF) demonstrated greater energy out of the target (3.15 MJ) via fusion reactions than the lasers delivered to the target (2.05 MJ), well above the ignition threshold and with a target energy gain of 1.5. This latest achievement, along with increasing private investment, ideally positions IFE as a highly promising approach for harnessing fusion for our energy needs here on Earth.

Why Inertial Fusion Energy (IFE)?

In the pursuit of fusion as a clean energy source, IFE has numerous advantages over other fusion approaches:

- IFE would utilize separable components and is highly modular, allowing for flexibility now as subsystems are developed and later in a commercial reactor
- IFE has multiple target concepts that can be tested with the same driver, hedging risk and allowing for varied tests with the same facility
- IFE has an expected higher burn-up fraction of the deuterium-tritium (DT) fuel
- IFE presents an attractive development path that enables methodical progress on systematically more complex facilities
- IFE pursuits will result in myriad technology and science spin-outs that will undoubtedly strengthen the U.S. economy and competitiveness

One of the key milestones on the path to fusion energy is the demonstration of a self-sustaining burning plasma of DT in the laboratory. Scientists achieved this milestone for the first time for any type of fusion anywhere in the world in August 2021 at NIF. In this experiment, the NIF laser compressed and heated a tiny, mm-size capsule filled with DT to achieve the extreme conditions required for ignition. A thermal runaway driven by the fusion reaction products occurred and ignited the plasma, producing approximately 1.37 MJ of fusion energy, an amount about 50x larger than the mechanical work used to compress the plasma. This achievement carried profound implications as it demonstrated that laboratory ignition is possible. However, because of inefficiencies of the implosion process, only about 25 kJ of energy (out of 1.9 MJ of laser energy) reached the imploded DT plasma.

"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 Report entitled
"An Assessment of the Prospects for Inertial Fusion Energy" (2013)

In December 2022, scientists achieved the next step in the development of IFE by demonstrating a net target gain with the fusion energy output exceeding the laser energy on the target (scientific breakeven or Q>1). Net target gain is a critical step along the path of developing the science and technology to achieve the positive "engineering gain" (QE >1 where total energy out is greater than total energy in) required to establish the viability of IFE for energy production. The laboratory demonstration of ignition and net target gain has long been considered a critical milestone for initiating a coordinated program aimed at developing IFE, as stated in the 2013 NASEM report on IFE: "In the event that ignition is achieved on the National Ignition Facility or another facility, and assuming that there is a federal commitment to establish a national inertial fusion energy research and development (R&D) program, the Department of Energy should develop plans to administer such a national program (including both science and technology research) through a single program office [1]."

The private sector is showing rapidly growing interest in developing fusion energy, further augmenting the urgency to establish a federal IFE program. Private funding for fusion has skyrocketed in the last decade and surpassed $4.7B, with $180M going into IFE in the last two years [2].

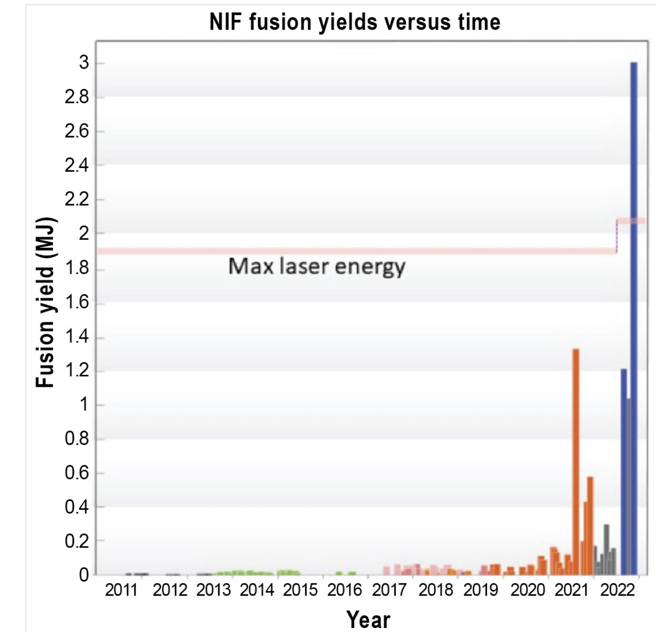

Figure ES.1: In December 2022, a shot on the NIF produced more than 3.15 MJ of fusion yield, achieving ignition, *a long-sought-after landmark in inertial confinement fusion (ICF) research.*

Establishing and growing a national IFE program while partnering with private industry could fast-track the development path for fusion energy.

Basic Research Needs (BRN) Effort

DOE FES invited a total of **120 subject matter experts** from across **the U.S. and internationally** to serve as workshop panelists for the BRN. The panelists, divided into twelve subpanels, worked over the months of March – November 2022 to address the charge elements and to identify focused PROs in each of the specific IFE research and development areas. An **online workshop, held June 21-23, 2022, gathered the community together** for targeted discussions. Engineers from U.S. and international academic institutions, national laboratories, private companies, and government officials attended. A series of closed working sessions attended only by the panel members followed the day-long open session.

In pursuit of such an outcome, in March 2022 the White House Office of Science and Technology Policy hosted a summit of fusion technology leaders from the public and private sectors to develop a decadal vision for commercial fusion energy [3]. Further, a renewed interest in IFE was already manifest in the two-year-long community planning process to provide input for the DOE Long Range Strategic Plan for Fusion Energy, first through the American Physical Society's Division of Plasma Physics (APS-DPP) Community Planning Process (CPP) and followed by the Fusion Energy Sciences Advisory Committee's (FESAC) subcommittee report, "Powering the Future: Fusion & Plasmas" [4, 5]. After the demonstration of ignition threshold in 2021, experts in inertial fusion and high energy density physics convened online in February 2022 for a community-led IFE planning workshop, to which attendees submitted more than 90 white papers. They released their community-driven report in May 2022 calling for near and long-term assessments for research opportunities in IFE [6].

Basic Research Needs (BRN) Inertial Fusion Energy (IFE) Effort

The 2022 BRN effort, organized under the auspices of the U.S. DOE Office of Science FES program, sought to identify the main priority research opportunities (PROs) that should be supported by a newly established IFE program within FES. In addition, the DOE charge for the BRN (see Appendix A) called for a technology readiness assessment of the different IFE concepts, an evaluation of the MFE efforts that could be leveraged to advance IFE, and an assessment of the private sector role in a national IFE Program.

An integrated IFE program will necessarily include many different science areas, technology development efforts, infrastructure needs, private industry involvement, and workforce recruitment. In June 2022, the DOE Office of Science–sponsored BRN laid out the foundations for an IFE program within the DOE FES Program. Following the workshop, BRN panel members worked to provide comprehensive guidance through PROs, developed at a high level (Overarching PROs), as well as at each area-specific level (Focused PROs). They provided additional guidance in the form of Structural Concepts that could benefit the development of a new IFE program at its inception.

Below we provide a summary of these BRN Findings, Structural Conceptsfor developing a new IFE program, and Overarching PROs that should be the main priority for this new program; the body of this report further details and supports these points, describing IFE-specific science and technology areas, as well as cross-cutting areas, and outlining their current statuses, challenges, and specific PROs.

Developing a New IFE Program from Inception: Structural Concepts

Structural Concepts are suggestions from the BRN panel on developing the framework for a new IFE program within DOE Office of Science.

BRN FINDINGS:

IFE is a promising approach to fusion energy with different technical risks and benefits with respect to MFE and must be an important part of the FES R&D portfolio.

The recent demonstration of thermonuclear ignition on the National Ignition Facility constitutes a **pivotal point in the development of inertial fusion energy.**

Major advances in IFE-relevant physics and technology, including demonstration of ignition, occurred over the last several decades funded mostly under the national security mission. **The United States is the recognized leader in IFE science and technology** because of this investment.

Private industry is driving the commercialization of fusion energy in the United States, and public-private partnerships could greatly accelerate the development of all fusion energy concepts.

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) for testing concepts to a wide range of component and sub-system development facilities (that can also test technologies in a modular way).

The ICF modeling codes that primarily reside at the NNSA national laboratories are built on decades of investment and expertise and constitute a valuable resource for advancing IFE science and technology.

The climate and culture of the broader field of fusion/plasma research **requires improvements to enhance diversity, equity, and inclusion.**

(The BRN Findings are observations or general conclusions reached as a result of the BRN panel's deliberations.)

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 PPP 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.

Overarching Priority Research Opportunities (PROs) for New IFE Program:

Overarching Priority Research Opportunities are PROs that are common across multiple IFE areas and of high importance to the FES mission space and a new IFE program.

- Take advantage of and spur emerging technologies (exascale computing, artificial intelligence (AI) and machine learning (ML), advanced manufacturing, high-repetition-rate laser systems, etc.) to accelerate progress toward the goal of a fusion pilot plant (FPP).
- Employ system-level integrated studies to guide IFE R&D in a coordinated fashion with the objective of advancing the different areas of IFE science and technology toward the goal of building and operating an FPP.
- 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 down-selection and to inform directions of technological development.
- Accelerate the pace of IFE and reduce risk through the pursuit of parallel development paths.
- Leverage existing facilities (including LaserNetUS), expertise, and international collaboration to advance IFE science and technology. Explore ways to expand shot time on existing U.S. facilities and develop upgrades to meet IFE-specific needs.

- 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 laboratories. Carry out the assessment with NNSA input.

Technology Readiness Assessment

In response to the charge letter, the BRN effort carried out a preliminary readiness assessment of different fusion approaches (or concepts) to determine their potential and maturity as candidates for an FPP. Using DOE technology readiness level (TRL) guidelines [7], we identified five fusion concepts as possible candidates based on current work and carried out our technology readiness assessment for seven aspects critical for any IFE development path:

Relative to the other concepts, we ranked laser indirect- and direct-drive at a higher readiness level. This ranking is in large part a consequence of the extensive development of laser fusion within the NNSA-funded Stockpile Stewardship Program and is not necessarily an intrinsic advantage of laser fusion toward IFE. Also note that no technology or component has yet been demonstrated at TRL 5 or greater. Thus, although some components have been validated in laboratory environments, they are still "low fidelity" (TRL 4) compared to the eventual system and have yet to be validated as prototypes at reasonable scale in IFE-relevant environments (at or near full shot-rate and/or lifetime or in simulated extreme environments) (TRL 5).

We emphasize that our assessment was only a preliminary step and is by no means exhaustive or conclusive. It should be viewed as a starting point for a more comprehensive

TRL levels for five IFE concepts for the seven aspects critical for any IFE development path

IFE Concepts → / *Critical aspects for IFE development ↓*	Laser Indirect-Drive (LID)	Laser Direct-Drive (LDD), including Shock Ignition (SI)	Fast Ignition (FI)	Heavy Ion Fusion (HIF)	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

assessment from a scoping study sponsored by FES as stated above as an overarching PRO.

Focused Priority Research Opportunities (PROs)

A major objective of the BRN workshop was to provide DOE-FES with the main PROs to inform future research efforts and funding opportunities in the specific areas constituting the building blocks of an IFE program. Twelve subpanels identified PROs in IFE-specific science and technology areas, as well as in six cross-cutting areas:

- 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 Learning
  - Measurement Innovations
  - Research Infrastructure
  - Public-Private Partnerships
  - Workforce

A summary of the main PROs within each of the nine areas is listed below.

Target Physics and Ignition

- Coupling: Develop techniques for laser-plasma instability (LPI) mitigation and control and improve understanding of mid- to high-intensity LPIs for all laser fusion concepts (LID, LDD, SI, and FI) and laser preheat for magnetized liner inertial fusion (MagLIF) and pulsed-power coupling.
- Compression and Burn: Identify the underlying physics limiting the convergence/areal density required for high gains (all concepts).
- Alternate Fusion Concepts: Demonstrate fuel assembly at high areal densities and localized heating of compressed fuel to thermonuclear temperatures (FI and SI). Develop alternative approaches to support future performance (e.g., HIF, magnetized fusion).

Driver and Target Technologies

- Drivers: IFE drivers must lead in technology to fully leverage their capabilities to deliver a successful IFE platform. Mitigating future risks to realizing IFE concepts requires a multi-pronged R&D approach: developing comprehensive driver concepts for an IFE demonstrator to derive modular development plans and pursuing key long-term R&D goals for improved IFE driver and gigashot (109 shot) capabilities, particularly in developing technical solutions in partnership with the private sector to reduce their cost.
- Targets: Develop innovative techniques for target mass production and begin studies of target injections, engagement, and survivability.

Fusion Power Plant Integrated Systems

- Power Systems, Science, Engineering, and Technologies
  - *Fusion Materials:* Establish an IFE-unique pulsed irradiation program, with combined experiment and modeling using mid-scale facilities.
  - *Chamber and Fuel Cycle:* Actively co-design across the target-physics community, fuel-cycle teams, and chamber-design teams.
  - *System Integration and Design:* Begin iterative integrated design activities to inform viability of concepts.

Cross-Cutting Areas

- Theory and Simulation: Take advantage of exa-scale computing, AI, and ML for improved speed and accuracy for 3D production runs, as well as for new physics modules. Extend simulation capabilities to include physics currently missing in ICF rad-hydro codes.
- Artificial Intelligence (AI) and Machine Learning (ML): Take advantage of AI/ML for data analysis of next generation of high-repetition-rated facilities for improving current predictive capabilities to bridge the gap between experiments and simulations and for developing surrogate physics models.
- Measurement Innovations: Diagnose quantities limiting or leading to high gain, enhance combined measurement resolutions (spatial and temporal), and develop diagnostics for high repetition rates and radiation-hardened environments.
- Research Infrastructure: Establish an Innovation Hub to perform integrated system studies for all the concepts. Form teams from the labs, universities, and private sector. Use these studies to begin initial upgrades of existing facilities.
- Public-Private Partnership (PPP): Facilitate partnerships between private IFE companies and government labs and universities to leverage substantial public sector capabilities toward joint development and acceleration of IFE commercialization and to aid private companies in capturing greater private investment monies.
- Workforce: Support education, collaboration opportunities, and research programs to attract and train a robust IFE workforce that minimizes obstacles to participation through considerations of diversity, equity, and inclusion. Actively engage more university departments and the emerging private sector.

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