INERTIAL FUSION ENERGY

REPORT OF THE 2022 FUSION ENERGY SCIENCES BASIC RESEARCH NEEDS WORKSHOP

IGNITION

U.S. DEPARTMENT OF ENERGY | Office of Science

BASIC RESEARCH NEEDS WORKSHOP ON

Inertial Fusion Energy

REPORT OF THE FUSION ENERGY SCIENCES WORKSHOP ON INERTIAL FUSION ENERGY

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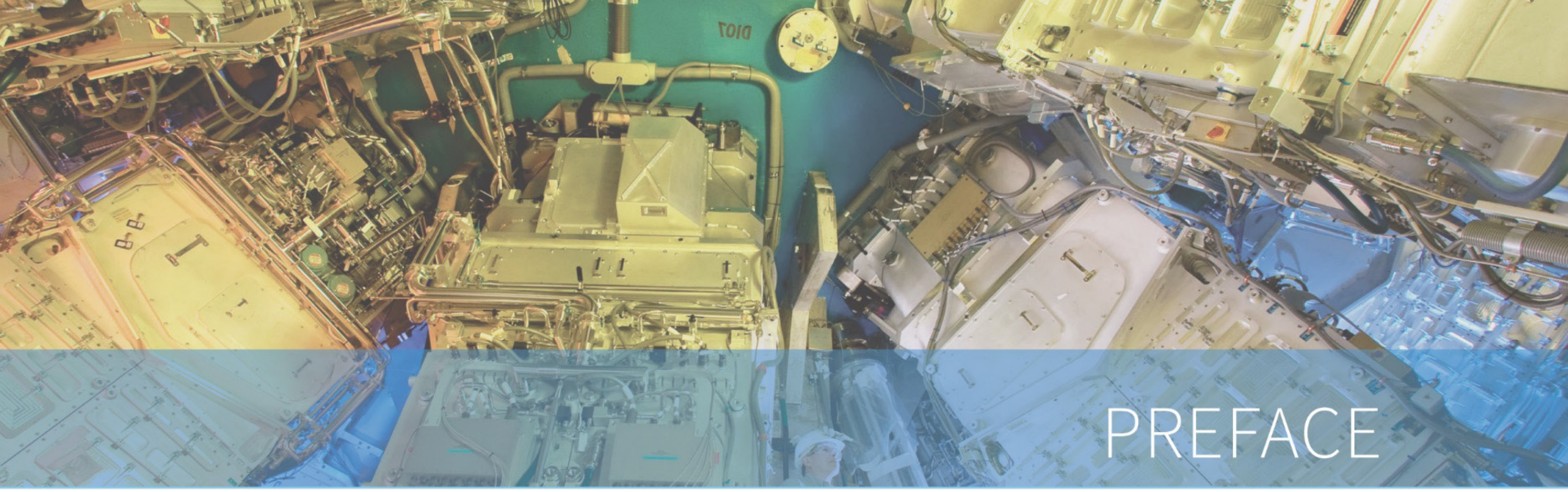
Inertial-Fusion-Energy-Report



PREFACE

"Last week at the Lawrence Livermore National Laboratory in California, scientists at the National Ignition Facility achieved fusion ignition. And that is creating more energy from fusion reactions than the energy used to start the process. It's the first time it has ever been done in a laboratory anywhere in the world. Simply put, this is one of the most impressive scientific feats of the 21st century."

U.S. Secretary of Energy Jennifer Granholm
DOE Press Conference Announcing Major Nuclear Fusion Breakthrough
December 13, 2022

"This achievement opens up new scientific realms for us to explore and advances our capabilities for our national security missions. It demonstrates the power of US leadership in science and technology and shows what we're capable of as a nation. And as the secretary mentioned, breakthroughs like this one have generated tremendous excitement in the fusion community and a great deal of private sector investment in fusion energy. But this is only possible due to the long-term commitment of public investment in fusion science. The science and technology challenges on the path to fusion energy are daunting, but making the seemingly impossible possible is when we're at our very best. Ignition is a first step, a truly monumental one that sets the stage for a transformational decade in high energy density science and fusion research, and I cannot wait to see where it takes us."

LLNL Director Dr. Kim Budil
DOE Press Conference Announcing Major Nuclear Fusion Breakthrough
December 13, 2022

"This astonishing scientific advance puts us on the precipice of a future no longer reliant on fossil fuels but instead powered by new clean fusion energy."

U.S. Senate Majority Leader Charles Schumer

"This monumental scientific breakthrough is a milestone for the future of clean energy."

U.S. Senator Alex Padilla (CA)

"We have had a theoretical understanding of fusion for over a century, but the journey from knowing to doing can be long and arduous. Today's milestone shows what we can do with perseverance."

Dr. Arati Prabhakar
the President's Chief Advisor for Science and Technology
and Director of the White House Office of Science and Technology Policy

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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

> "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)

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

- 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.

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” (Q_E >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]. Establishing and growing a national IFE

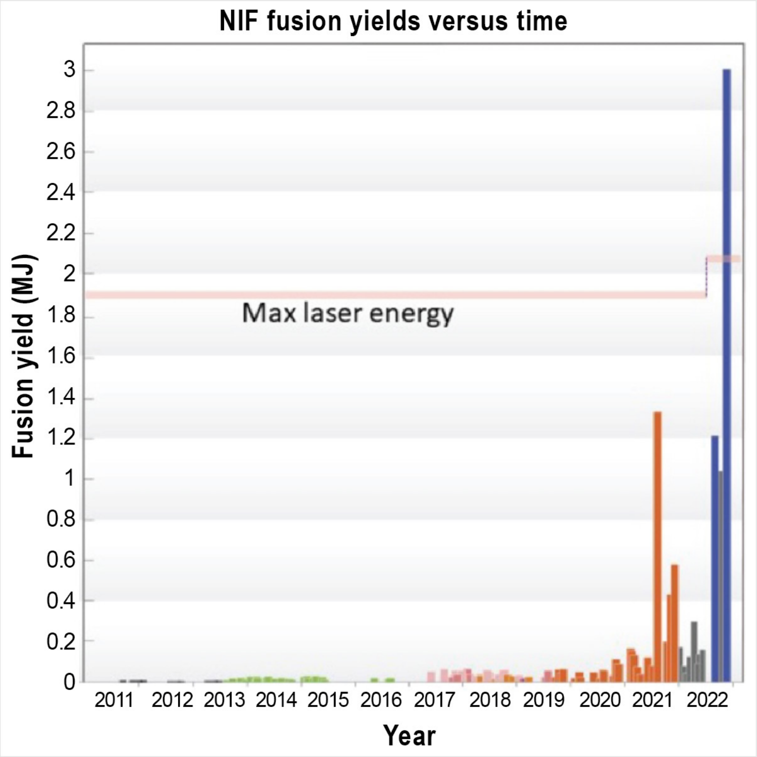


Figure ES.1. In December 2022, a shot on NIF produced more than 3.15 MJ of fusion yield, achieving ignition, a long-sought-after landmark in inertial confinement fusion (ICF) research.

program while partnering with private industry could fast-track the development path for fusion energy. 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.

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.

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 Concepts for 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.

BRN FINDINGS:

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

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 NIF constitutes a pivotal point in the development of IFE.

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 (PPPs) 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 National Nuclear Security Administration (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.

IDEAL TIME *to focus on* **Inertial Fusion Energy**

- NIF results
- Progress with laser direct drive and magnetic drive approaches
- Private sector interest and investment
- Sustained advocacy
- New legislation

Today's supportive environment for a revitalized U.S. IFE program

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.

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:

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

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 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
  - Target Physics and Ignition: 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 (10^9 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 exascale 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.

Bibliography

1. National Research Council of the National Academies of Science Engineering and Medicine, *An Assessment of the Prospects for Inertial Fusion Energy*. 2013, Washington, DC: The National Academies Press (doi: 10.17226/18289); https://nap.nationalacademies.org/catalog/18289/an-assessment-of-the-prospects-for-inertial-fusion-energy.

2. Fusion Industry Association. *The global fusion industry in 2022*. 2022; Available from: https://www.fusionindustryassociation.org/about-fusion-industry.

3. The White House. *Readout of the White House Summit on Developing a Bold Decadal Vision for Commercial Fusion Energy*. 2022; Available from: https://www.whitehouse.gov/ostp/news-updates/2022/04/19/readout-of-the-white-house-summit-on-developing-a-bold-decadal-vision-for-commercial-fusion-energy/.

4. Kate Kirby and David Newman, *Long Range Community Planning Process for Fusion Sciences and Plasma Physics (Final Technical Report) (doi: 10.2172/1741028)*. 2021, Office of Scientific and Technical Information (OSTI); https://www.osti.gov/biblio/1741028.

5. T. Carter, et al., *Powering the Future: Fusion & Plasmas*. 2020 (https://science.osti.gov/-/media/fes/fesac/pdf/2020/202012/FESAC_Report_2020_Powering_the_Future.pdf), Fusion Energy Sciences Advisory Committee.

6. A. Zylstra, et al., *IFE Science & Technology Community Strategic Planning Workshop Report*. 2022 (https://lasers.llnl.gov/content/assets/docs/nif-workshops/ife-workshop-2022/IFE-Workshop-Report.pdf).

7. U.S. Department of Energy, Technology Readiness Assessment Guide (G 413.3-4). 2009.

IFE

INTRODUCTION

INTRODUCTION

Energy is at the heart of modern economies and, as the world's energy demand grows, new clean and plentiful energy sources will be needed. Fusion energy holds exactly that promise—to become a virtually inexhaustible, safe, environmentally friendly, and universally available energy source, capable of meeting global energy needs.

Fusion energy powers the stars, shining light on the Earth and fueling life, but humankind has yet to recreate and harness it in a controlled manner. However, recent advancements have brought us closer than ever. First, in August 2021, scientists at the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) achieved a breakthrough record yield of 1.3 megajoules (MJ) from thermonuclear fusion reactions of an inertially confined deuterium-tritium (DT) plasma (See **Figure I.1**). This experiment demonstrated a robust burning plasma that achieved a fuel gain of 50x, a capsule gain of more than 5x, and a laser gain of 70% [1]. Fuel gain is the ratio of the fusion energy output (1.37 MJ) to the input energy acquired by the DT fuel (about 25 kJ) and is most indicative of the physics performance of the thermonuclear plasma. The large fuel gain of 50x is an indicator that ignition and burn propagation occurred in this shot. **Figure I.2**, taken from Wurzel and Hsu (2022) [2], compares the experimentally inferred Lawson parameters for magnetically confined and inertially confined fusion experiments, showing that these NIF results exceeded the Lawson parameters and ion temperature for hot-spot ignition.

The August 2021 experiment demonstrated the physics basis of ignition and burn for inertial confinement fusion (ICF) plasmas; the next landmark was to achieve energy gain with respect to the laser energy (scientific breakeven). In December 2022, NIF scientists reached this goal, demonstrating greater energy out of the target (3.15 MJ) than the laser put into the target (2.05 MJ), surpassing the ignition threshold with a gain of 1.5. *The achievement of this landmark milestone validated the basic scientific feasibility of laboratory-scale laser-driven inertial fusion energy (IFE) as a pathway to a fusion energy future.*

Moving Toward an Inertial Fusion Energy (IFE) Future

To date, the U.S. DOE Office of Science – Fusion Energy Sciences (FES) program has primarily pursued magnetic fusion energy (MFE) as its main fusion approach. However, the 2013 National Academies of Sciences,

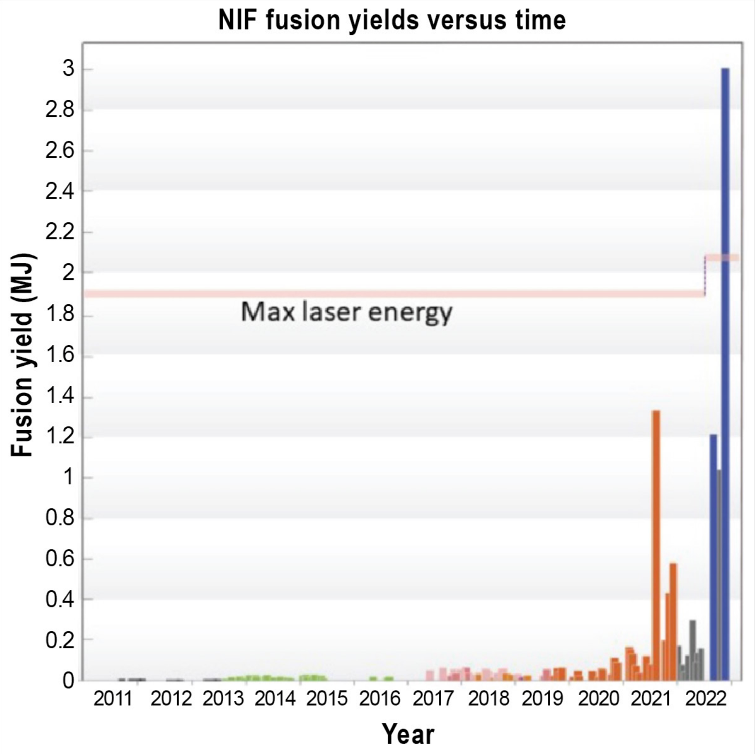


Figure I.1. In 2021, a shot on NIF produced more than 1.37 MJ of fusion yield, achieving a fuel gain of 50x and demonstrating the physics basis for ignition. In December 2022, a shot on NIF produced more than 3.15 MJ, achieving a target energy gain of approximately 1.5, a long-sought-after landmark in ICF research.

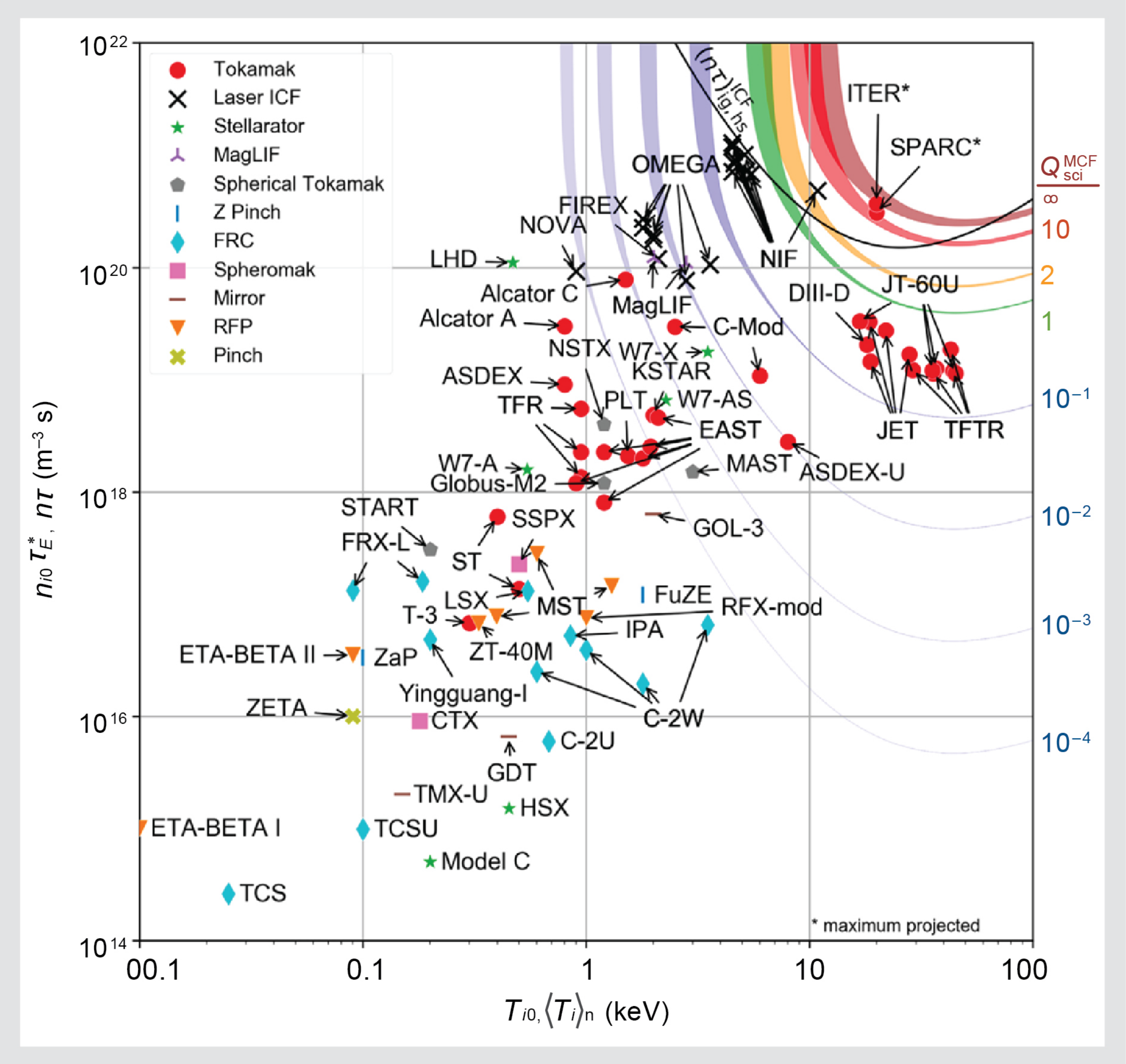


Figure I.2. Experimentally inferred Lawson parameter ($n_0\tau^*_E$ for magnetic confinement fusion (MCF) and $n\tau$ for ICF) of fusion experiments versus T_{i0} for MCF and $<T_i>n$ for ICF. Replicated from Figure 2 of Wurzel and Hsu (2022) [2]. Plot does not include Dec. 2022 NIF ignition point, which would sit just to the right of the designated NIF point.

Engineering, and Medicine (NASEM) report entitled “An Assessment of the Prospects for Inertial Fusion Energy” 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 [3].” This is now. The 2021 and 2022 NIF results coupled with the recent Fusion Energy Sciences Advisory Committee (FESAC) recommendation to establish an IFE program, along with strong Congressional support and large private equity interest in burgeoning new fusion companies, place us at a unique and exciting junction for IFE research and development (R&D).

IFE Technology Challenges and Strategies. The December 2022 breakthrough experiment on NIF, demonstrating laser-energy breakeven for the first time, now forms the basis of a possible path to fusion energy that has significantly different technological and engineering risk portfolios than the concepts being pursued for MFE. However, like all approaches to fusion energy, IFE has many scientific, technological, and engineering challenges yet to conquer. An IFE system would work by using a driver (such as a laser, pulsed power, or heavy-ion beams) to implode injected targets to achieve high energy gain conditions. Laser and heavy-ion drivers require high repetition rates up to 15 implosions per second, while pulsed-power drivers operate at lower repetition rates of a few per second. Net electrical energy gain should be possible when the product of the driver electrical efficiency (wall plug to energy on target) and the target gain is $\gtrsim 10$. To achieve this, we must overcome significant technological hurdles in several systems (see text box). Furthermore, we will have to engineer each of these systems with cost, operability, and maintainability in mind, which is required for economical energy production.

TECHNOLOGICAL HURDLES to Achieve Net Electrical Energy Gain

To achieve a product of the driver electrical efficiency and the target gain that is $\gtrsim 10$, we must first overcome several technological challenges:

- Develop ignition schemes with high yield and robust margin
- Devise drivers with high efficiency and high-repetition rates of several times per second
- Economically mass produce ignition-quality targets and inject them into the chamber, where they must survive, be efficiently driven, and stably implode at high rates
- Produce optics and hardware that can withstand continual exposure to both high optical irradiance and fusion radiation
- Design reactor chambers to contain the micro-explosion products and adequately protect the driver

Fusion energy research is a high-stakes endeavor, and as such, technological diversity is always good. IFE is one leading approach to fusion energy, and even within IFE there are numerous strategies to achieve high gain and develop an economical, workable pathway to a commercial reactor. These strategies include laser direct-drive (LDD), laser indirect-drive (LID), fast ignition (FI), shock ignition (SI), heavy-ion fusion (HIF), pulsed-power magnetically driven fusion (MDF), and other alternate schemes, which may also vary in fuel type. Each strategy has its own pros and cons, and the driver-target approaches, along with their accompanying component technologies, are at varying levels of maturity. At the current stage, each strategy is worthy of consideration before FES makes a down-selection, hopefully in the next few years, to focus the public U.S. IFE program on the path(s) of highest potential.

A number of promising technologies, key to eventual IFE systems, are also making steady progress. In particular, U.S. scientists have made exciting advances in high-repetition-rate, high-energy laser technology and repetition-rated pulsed-power technology over the last few years, which will potentially lower the cost of drivers for future IFE systems. Also, additive manufacturing and other automated manufacturing techniques are becoming more cost-effective and are enabling new materials for high-volume and high-quality fabrication methodologies. Finally, artificial intelligence

(AI) and machine learning (ML) are being deployed to improve predictive simulation models, quantify uncertainties, and train large-scale, high-performance, high-speed models.

Building a World-Leading U.S. IFE Program. Multiple government agencies have contributed to advancing fusion energy research in recent years, and we are in an excellent position to make rapid headway in IFE by leveraging these large investments and emerging technologies. Specifically, the National Nuclear Security Administration (NNSA) has invested significantly in ICF over the past several decades, including NIF and other ICF-relevant facilities (e.g., the Z Pulsed Power Facility at Sandia National Laboratories and the OMEGA Laser Facility at the University of Rochester), as well as forefront modeling and simulation capabilities. Advanced Research Projects Agency – Energy (ARPA-E) has developed several programs promoting high-risk, high-reward innovative research in alternate fusion energy concepts. DOD has put heavy investment into next-generation high-power lasers. NSF continues to fund foundational plasma science with relevance to the high-energy-density (HED) conditions necessary for IFE, and many other institutions, also already active in HED research, are well-positioned to contribute to this activity. The DOE FES program can and should leverage these relationships and resources across the agencies to help establish the IFE path forward.

> “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” (2021)

Now is the time to start a U.S. inertial fusion energy program

The United States is the current leader in HED and ICF research, which stems in large part from the historical pursuit of IFE. As such, we must continue to take a leading role in IFE to maintain preeminence in this arena. The United States has an opportunity now to grow the national program by nourishing and leveraging our leadership in ICF with unique and world-leading competencies in the science and technology that underpins IFE. Further, the electrifying vision of IFE also serves as an important recruitment and training tool for the next generation. The big science and challenging problem of fusion has drawn scores of plasma, HED, nuclear, laser, material, computational, and other scientists and engineers, ensuring the IFE field will remain strong as we move into the next phases of a fusion energy future.

This Basic Research Needs (BRN) workshop and report aims to highlight priority research opportunities (PROs) that will help the United States drive forward the science and technologies crucial to successfully realizing IFE on a relevant timescale.

Goal of Realizing a Fusion Pilot Plant (FPP) on an Accelerated Timescale

The White House Office of Science and Technology Policy (OSTP) and the U.S. DOE hosted a summit on Developing a Bold Decadal Vision for Commercial Fusion Energy in March of 2022. Amongst the initiatives announced was one to accelerate the viability of commercial fusion energy, including new funding to support the foundational science and technology research connected to high-priority issues for a future fusion pilot plant (FPP). This push represents something of a reorientation of the path that FES has been following, steering away from what has long been a foundational science and technology program to one more centered on the goal of an FPP.

Need-Gaps on the Path to a Fusion Pilot Plant (FPP). IFE and MFE have certain needs in common that must be mutually solved and for which both approaches can work together and leverage each other, including robust, radiation- and damage-resistant first walls; blanket technology, which includes the plasma-facing wall, neutron capture, heat conversion, and tritium breeding; unburned fuel recovery and processing; remote maintenance systems; plant safety technologies; and full-system engineering and viable economics.

Fusion energy also has some potential limitations that any commercial energy plan will need to address. While IFE offers the advantage of lower tritium inventory than MFE, IFE inventory will still need to be adequately monitored and maintained with careful extraction, handling, and fuel-cycle operations. Similarly, both IFE and MFE will create activated waste products and prompt radiation during operation, which imposes nontrivial requirements for shielding, confinement, and disposal, as well as the need for public consultation to help ensure acceptance of the residual risks versus the major benefits. Finally, as Section V: Analysis of Integrated Target-Drive Approaches shows, nearly all requisite IFE technologies still need significant development, which may necessitate a long development timeline, of course dependent on funding and resources. The economic viability of first-generation plants might also be a challenge.

To successfully develop and achieve widespread adoption of fusion energy will also require conquering non-technical challenges. Even though, compared to fission, fusion produces much less waste and has lower potential for

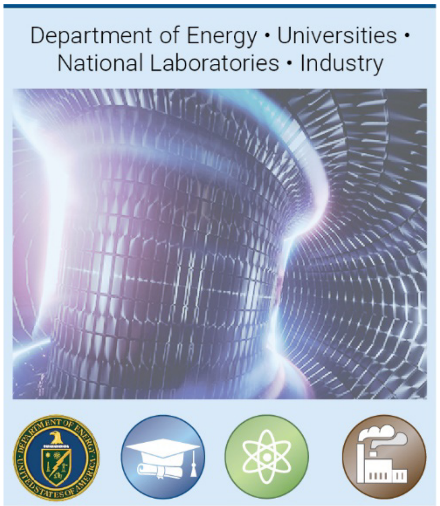
THE PROMISE OF FUSION POWER

Fusion energy is a game-changing technology that can help us achieve net-zero carbon emission by mid-century, protect national security, and enhance U.S. technology leadership. Fusion energy has the following qualities:

- Carbon-free
- Utilizes abundant and geographically diverse fuel
- Environmentally sustainable
- Passively safe
- Able to meet baseload, while "load following" to meet variable demand
- Distributable with "smart grid" capability
- Can be placed near population centers
- Nuclear energy with minimal proliferation concerns
- Profoundly lower radioactive inventories compared with nuclear fission, in terms of both accident potential and long-lived waste disposal
- Provides flexible energy products (not just electricity, but process heat, hydrogen, and biofuels)

Decades of public investment, rapid growth in private investment, and major recent scientific advances suggest that now is the time to quickly move toward demonstrating commercial fusion energy.

catastrophic accidents, public acceptance of fusion energy systems remains tenuous and siting large nuclear fusion reactors near population centers would currently most likely be unwelcome. Further, as an emerging energy technology, opportunities exist to facilitate the fusion industry's growth in a way that is diverse, equitable, inclusive, and just. Thus, regulatory bodies must be engaged early in developing and designing notional fusion plants, and we must ensure that the public is well-educated about the promise and benefits of fusion.



National Workforce and Facility Investments as a Path Toward a Fusion Pilot Plant (FPP). DOE FES now has a special opportunity to ensure a coordinated and collaborative national approach, leveraging expertise and capabilities across national laboratories, academia, and industry. An IFE program should provide an enduring vision to achieve full-scale prototypes and first-generation fusion plants on a relevant timescale, as well as sustained, robust, and sufficient funding in fusion to achieve this. This worthy and ambitious goal will require a long-term investment in the U.S. workforce, foresight and resolve in building the next generation of large-scale experimental facilities, commitment to leadership, and innovation and entrepreneurship in guiding spinouts, even as progress toward this goal moves in fits and starts.

More specifically, to realize an FPP on an accelerated timescale, IFE will require dedicated, large-scale experimental facilities capable of increased experimental rates, such that we can accelerate our rate of learning. While the existing network of mid-scale laser facilities (e.g., LaserNetUS) is incredibly valuable in targeted physics studies and training students, to make the fastest progress IFE will also require integrated studies at full ignition-scale and *in situ* testing of components. The OMEGA laser at the Laboratory for Laser Energetics (LLE) at the University of Rochester does allow for sub-scale implosion studies in a symmetric, direct-drive geometry, as well as experiments on a range of HED physics topics. However, presently NIF is the only ignition-scale ICF facility in the world. In its current configuration, NIF allows study of full-scale implosion physics but only at relatively modest energy gains (<20) and low repetition rates (i.e., 1 shot per day). Furthermore, NIF is oversubscribed, and experiments to fulfill the NNSA mission space take first priority.

As touched on in the Research Infrastructure chapter, we need to upgrade existing facilities at all scales and establish a series of high-repetition-rate, component test facilities before building a pilot plant(s). These steps are all necessary to develop the scientific understanding that will allow us to confidently project to the gain needed for a commercially viable power plant to be built and to advance the full set of IFE technologies to high maturity. This BRN only lays out suggestions for PROs; it should be a task for FES and the fusion community to develop a short-term plan that considers the directions private industry is pursuing and helps to lay out credible roadmaps and options for IFE to achieve an FPP.

Global Inertial Fusion Energy (IFE) Status

As of the writing of this report, no coordinated publicly (government) funded IFE programs exist anywhere in the world, although IFE development work is occurring in several world regions, including the United States, Asia, and Europe. The recent NIF results, in particular, have spurred considerable new interest.

High-Power Laser Energy Research (HiPER). Between 2006 and 2013, Europe developed the HiPER (High-Power Laser Energy Research) infrastructure project as part of the 2006 European Strategic Forum for Research Infrastructures (ESFRI) Roadmap. HiPER focused on exploring the science and technology of advanced laser-driven fusion schemes, particularly direct-drive FI and SI. The laser-fusion scientific community of Europe is now strongly advocating for establishing a new IFE program in Europe that builds off the original HiPER program and develops a roadmap toward an IFE power plant (called HiPER-Plus) [4, 5].

U.K. Inertial Fusion Consortium. U.K. scientists recently established a community-driven Inertial Fusion Consortium, comprising nearly 90 members from U.K. groups involved in inertial fusion research. The team developed a 15-year (2021–2035) Inertial Fusion Roadmap that includes near-term (to ~2025) goals of establishing a coordinated and collaborative IFE program, establishing a community-accessible simulation code, strengthening fundamental R&D, and enhancing collaboration both domestically and internationally [6]. Longer term goals include construction of dedicated and testbed IFE facilities.

Fast-Ignition Realization Experiment (FIREX). Japan continues its effort in R&D oriented toward the FI approach, using high-power lasers under the Fast Ignition Realization Experiment (FIREX). The majority of this research is centered at the Institute of Laser Engineering at Osaka University on their LFEX (Laser for Fast Ignition Experiment) and Gekko-XII lasers, while promoting the field of HED science through interdisciplinary collaborations, as well as industry-academia and international collaborations. In 2019, DOE and the Japanese Ministry of Education, Culture, Sports, Science, and Technology (MEXT) signed a Project Arrangement to jointly pursue HED and fusion research.

Laser Megajoule (LMJ). Several efforts in progress around the world aim to construct facilities similar to NIF. The Laser Megajoule (LMJ) currently under construction outside Bordeaux, France is a laser-based ICF research device expected to deliver over 1 MJ of laser energy using 176 beamlines. The first physics experiments using 80 operational beams took place in 2022, and the facility is expected to be fully operational by the end of 2025 [7]. LMJ is designed to be a cornerstone of the French Simulation Program, and one of its goals is to obtain ignition and burn of DT-filled capsules imploded through the indirect-drive scheme inside a rugby-shaped hohlraum (the high-Z cavity used to generate the x-rays necessary to drive the fuel capsule)] [8]. However, both NIF and LMJ have historically focused on nuclear weapons research.

UFL-2M. Russia is constructing the UFL-2M at their All-Russian Scientific Research Institute of Experimental Physics (RFNC-VNIIEF). While details are limited, the UFL-2M design is expected to feature 192 laser channels, with 2.8 MJ of laser energy (1.5x more impulse energy than NIF) at 2ω wavelength (527 nm), in a spherically symmetrical irradiation geometry. In early Dec 2020, VNIIEF launched the first module of the world’s most powerful laser unit. The goals of UFL-2M are two-fold: military applications and civilian energy production.

ShenGuang-III. China has a substantial effort in fusion nuclear technology, materials, and safety. In addition, the ShenGuang-III laser at their Laser Fusion Research Center in Shanghai consists of 48 beams with a maximum energy of 180 kJ within 3-ns duration and 351-nm wavelength; this laser is dedicated to ICF studies. Currently, the facility has more than 80 diagnostics for studying laser-target coupling, ablation and implosion physics, stagnation, hotspot dynamics, and the nuclear phase of the implosion [9].

Private Fusion Companies. As of October 2022, more than thirty private fusion companies around the world have been established, attracting nearly $5 billion in private capital. Of these, at least eight are pursuing IFE approaches, with approximately $180 million in funding to date [10].

Basic Research Needs (BRN) Main Findings & Opportunities

To make fusion energy production a reality, we still must overcome many scientific, technical, and organizational challenges. In addition to our high-level findings, the full BRN committee also developed Structural Concepts that could benefit the development of a new IFE program at its inception. BRN panel members also worked to provide comprehensive guidance through PROs, developed at a high level (Overarching PROs), which are listed here, followed by Focused PROs more specific to individual topical areas. We identified these PROs as critical areas that have the highest potential for impact. They represent opportunities that align with key scientific challenges, emerging research opportunities, and related technology priorities, both for the fundamental understanding of fusion science and for the expeditious development of commercial fusion energy.

BRN FINDINGS:

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

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 NIF constitutes a pivotal point in the development of IFE.

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 (PPPs) 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.

STRUCTURAL CONCEPTS: Developing a New IFE Program from Inception

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

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.

1. 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).
2. 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.
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 down-selection 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 science and technology. 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.

FOCUSED PRIORITY RESEARCH OPPORTUNITIES (PROS):

Target Physics and Ignition

Coupling:

- PRO 1-1: Demonstrate improved coupling with broad laser bandwidth
- PRO 1-2: Demonstrate energy coupling for fast ignition (FI)
- PRO 1-3: Advance theory and modeling of laser-plasma instabilities (LPIs) to increase understanding of experimental data, develop mitigation strategies, and increase predictive capability of LPI simulation

Compression and Burn:

- PRO 2-1: Investigate the physical mechanisms limiting fuel compression in low-adiabat implosions
- PRO 2-2: Explore failure mitigation and performance optimization strategies
- PRO 2-3: Evaluate and improve target robustness with respect to ignition and gain
- PRO 2-4: Experimentally evaluate implosion sensitivities
- PRO 2-5: Understand and quantify the impact of high repetition rates on target design and performance
- PRO 2-6: Develop metrics to assess progress in target design and implosion performance

Alternate Concepts:

- PRO 3-1: Develop the path for external short-pulse fast ignition (FI) of a compressed core to realize the theoretical gain advantage of separable compression and ignition
- PRO 3-2: Demonstrate isochoric fuel assembly at ignition scale for FI
- PRO 3-3: Demonstrate and improve laser energy coupling at scale in shock ignition (SI)
- PRO 3-4: Control/eliminate laser-plasma instabilities (LPIs)
- PRO 3-5: Explore alternate concepts and advanced fuels

Driver and Target Technologies

Drivers:

- PRO 4-1: Perform IFE driver system-level architecture conceptual design studies
- PRO 4-2: Reduce the cost of diode pumps in diode-pumped solid-state laser (DPSSL) technologies
- PRO 4-3: Increase the damage threshold of optics and crystals
- PRO 4-4: Build integrated laser-system demonstrators
- PRO 4-5: Improve reliability of high-power switching and capacitor energy storage
- PRO 4-6: Design systems for broadband bandwidth generation
- PRO 4-7: Design and implement final optic survivability at ultra-high intensity
- PRO 4-8: Develop low-cost, high-performance accelerator modules

Targets:

- **PRO 5-1:** Demonstrate high-volume techniques for spherical capsule or wetted foam capsule fabrication
- **PRO 5-2:** Demonstrate accurate engagement on-the-fly of IFE targets by a driver beam
- **PRO 5-3:** Develop an IFE target injector for cryogenic IFE targets capable of reaching reactor-relevant velocity without damaging the target or its fuel layer

Fusion Power Plant Integrated Systems

Power Systems, Science, Engineering, and Technology:

- **PRO 6-1:** Develop a modeling-informed, experimentally verified understanding of IFE structural materials at the macro- and microscopic levels when subjected to a pulsed, fusion-relevant spectrum (neutrons, ions, neutrals/debris, X-rays, thermal)
- **PRO 6-2:** Develop models and experimental data to inform damage thresholds in transmissive and reflective final optics and develop solutions to enable sufficient longevity in a fusion environment
- **PRO 6-3:** Develop synergistic target/fuel cycle co-design between the plasma physics community and the fuel-cycle teams and chamber-design teams to develop target designs and identify target materials and processing methods that have minimum impact on the fuel cycle and allow for inventory reduction
- **PRO 6-4:** Develop a test facility with a neutron source to evaluate blanket technologies and to test fuel-cycle components and systems at scale (including tritium extraction and transport) and the potential for direct internal recycle (DIR)
- **PRO 6-5:** Undertake a series of system-design studies to establish a suite of self-consistent, quantitative IFE plant models, and use these to guide each aspect of the research, development, and demonstration (RD&D) program

Cross-Cutting Areas

Theory and Simulation

- **PRO 7-1:** Develop an ecosystem of simulation and modeling tools to predict the gain in IFE-relevant target designs through integrated implosion physics and targeted physics codes
  - PRO 7-1a: Improve the theory and develop the simulation tools to accurately model and enable control of LPI in IFE-relevant regimes
  - PRO 7-1b: Develop the next generation of computational tools capable of simulating kinetic effects in thermal and magnetized plasmas
  - PRO 7-1c: Improve predictive calculations of static and transport material properties under IFE-relevant extreme conditions
  - PRO 7-1d: Improve modeling of magnetic fields to enable better predictions of current flow in the magnetized liner inertial fusion (MagLiF) approach; develop detailed numerical treatment of magnetic fields in integrated radiation hydrodynamic codes, including models

  for non-local heat and alpha transport with the goal of identifying IFE designs that can reduce driver energy and efficiencies for IFE-relevant gains

- PRO 7-2: Develop modern simulation tools that leverage heterogeneous hardware to accelerate the path toward reliable IFE designs

Artificial Intelligence (AI) and Machine Learning (ML)

- PRO 8-1: Develop and employ common interoperable metadata standards built upon modern data formats like HDF5 and following the FAIR (Findable, Accessible, Interoperable, Reusable) principles across all public, private, and academic participants in the IFE community
- PRO 8-2: Develop or upgrade experimental facilities to leverage advances in drivers, targets, diagnostics, and AI and ML to conduct IFE-relevant higher shot rate (HSR) experiments
- PRO 8-3: Develop AI and ML techniques to automate and improve data processing and analysis
- PRO 8-4: Develop and deploy autonomous, multi-scale, multi-physics simulations enabled by AI and ML
- PRO 8-5: Allocate workforce-development funding (e.g., fellowships and grants) to support the advancement of ML-enabled HED science and to help retain talent in the field

Measurement Innovations

- PRO 9-1: Leverage and develop diagnostics to assess factors limiting gain
  - PRO 9-1a: Diagnose which quantities are critical to propel implosions toward high gain
  - PRO 9-1b: Improve measurement resolution across energy, space, and time for key diagnostics
- PRO 9-2: Develop high-repetition-rate diagnostics transformative for IFE (and ICF) research
- PRO 9-3: Develop radiation-hardened diagnostics critical for IFE power plants; leverage MFE and high-yield NNSA efforts
- PRO 9-4: Adapt critical infrastructure diagnostics to IFE power-plant environment

Research Infrastructure

- PRO 10-1: Increase the number of experiments at existing large-scale facilities
- PRO 10-2: In the near-term, utilize and upgrade relevant, existing mid-scale facilities
- PRO 10-3: Form at least one national IFE team or partnership focused on best use of existing facilities, as well as continued research and design for developing future infrastructure to demonstrate inertial fusion

Public-Private Partnership (PPP)

- PRO 11-1: DOE should facilitate PPP structures and programs that enable appropriate leveraging of public sector capabilities for accelerating IFE R&D
- PRO 11-2: DOE should further identify and prioritize areas of foundational, pre-competitive R&D that serve the overall IFE community
- PRO 11-3: DOE should consider joint funding and partnerships for construction, modification, and/or operation of private sector or ally government–led facilities

- **PRO 11-4:** The public sector, either through DOE and/or its contractors, should continue to engage with the private sector to increase awareness and opportunities for mutually beneficial partnerships
- **PRO 11-5:** DOE and the public sector, in partnership with U.S. and international private industry, should consider workforce exchange and rotation programs

Workforce

- **PRO 12-1**: In anticipation of a possible growth of the IFE workforce, DOE FES should closely monitor the state of the field (including IFE development efforts in the private sector) to identify the right time for launching a workforce-development study
- **PRO 12-2:** Any future IFE workforce-development action plan should be coordinated with established DOE initiatives promoting diversity, equity, inclusion, and accessibility

Bibliography

1. H. Abu-Shawareb, et al., *Lawson Criterion for Ignition Exceeded in an Inertial Fusion Experiment.* Physical Review Letters, 2022. **129**(7): p. 19, https://doi.org/10.1103/PhysRevLett.129.075001.

2. S. E. Wurzel and S. C. Hsu, *Progress toward fusion energy breakeven and gain as measured against the Lawson criterion.* Physics of Plasmas, 2022. **29**(6): p. 33, 10.1063/5.0083990.

3. National Research Council of the National Academies of Science Engineering and Medicine, *An Assessment of the Prospects for Inertial Fusion Energy*. 2013, Washington, DC: The National Academies Press (doi: 10.17226/18289); https://nap.nationalacademies.org/catalog/18289/an-assessment-of-the-prospects-for-inertial-fusion-energy.

4. S. Atzeni, et al., An evaluation of sustainability and societal impact of high-power laser and fusion technologies: a case for a new European research infrastructure. High Power Laser Science and Engineering, 2021. **9**: p. 1-7, https://doi.org/10.1017/hpl.2021.41.

5. D. Batani, et al., *The continuation of HiPER- HiPER Plus: Proposal for a new "direct-drive" laser-fusion programme in the EU; https://www.cpht.polytechnique.fr/sites/default/files/The_continuation_of_%20HiPER-HiPER_Plus.pdf*.

6. THE UK Inertial Fusion Consortium. *The UK Inertial Fusion Roadmap*. Available from: https://www.inertial-fusion.co.uk/roadmap.

7. V. Denis, et al., *LMJ 2023 facility status*. SPIE LASE. Vol. 12401. 2023: SPIE; https://doi.org/10.1117/12.2647231.

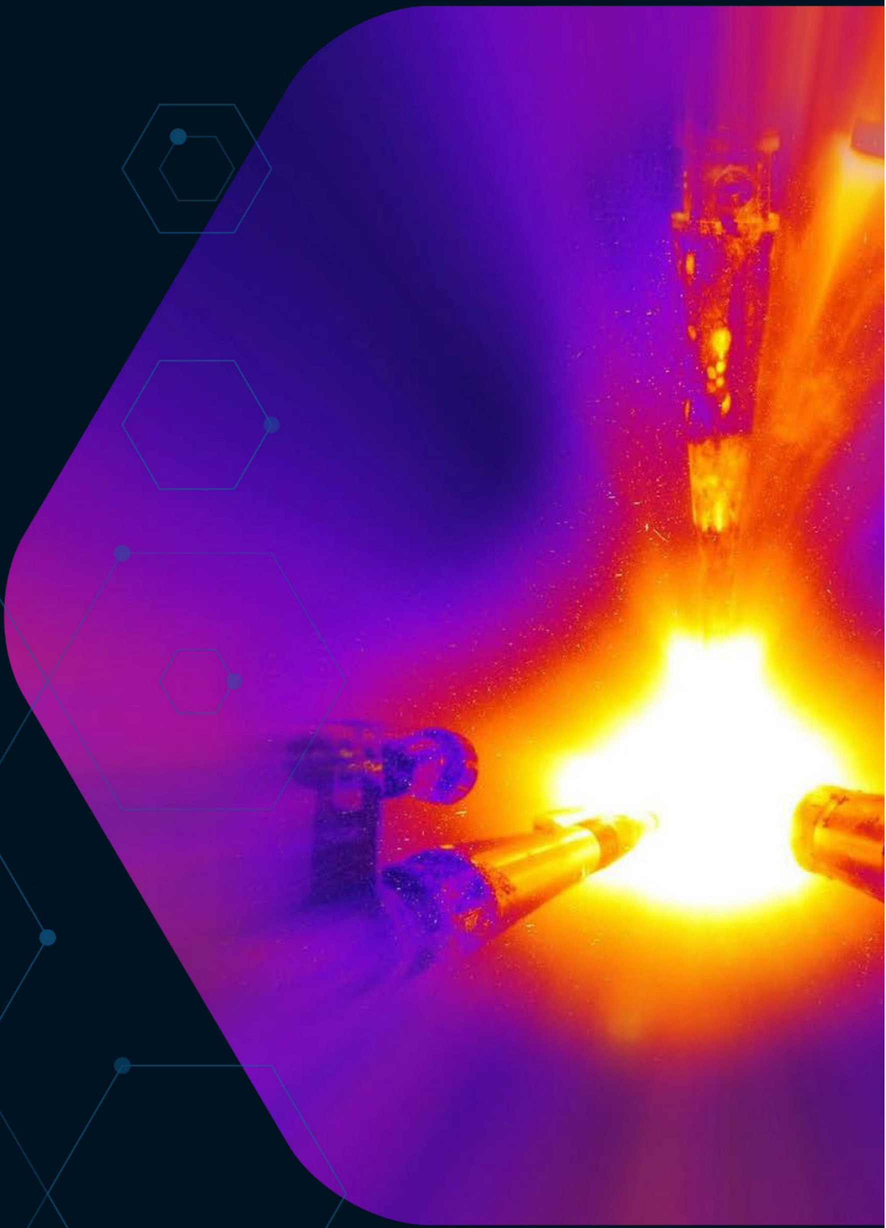
8. J. L. Miquel, C. Lion, and P. Vivini, *The Laser Mega-Joule : LMJ & PETAL status and Program Overview.* Journal of Physics: Conference Series, 2016. **688**(1): p. 012067, 10.1088/1742-6596/688/1/012067.

9. Shaoen Jiang, et al., *Experimental progress of inertial confinement fusion based at the ShenGuang-III laser facility in China.* Nuclear Fusion, 2019. **59**(3): p. 032006, https://doi.org/10.1088/1741-4326/aabdb6.

10. Fusion Industry Association. *The global fusion industry in 2022*. 2022; Available from: https://www.fusionindustryassociation.org/about-fusion-industry.

SECTION ONE

TARGET PHYSICS & IGNITION



Chapter 1: Coupling

1.1 Introduction

To achieve the fusion energy gain needed for a power plant, inertial fusion requires efficient and effective coupling of energy to the target to compress and heat the fuel to ignition. Fusion gain, G, is the ratio of fusion energy output to the driver energy input to the target. Practical considerations require a driver wall-plug efficiency (η) product $\eta G \geq 10$. The fusion energy gain inherently includes any loss of efficiency when coupling the driver energy to the fuel. The efficiency of this energy coupling is the subject of this section. G is also highly dependent on how effective the coupled power is at assembling and igniting the fuel. Besides energy loss, hot electron preheat is also a critical issue that can cripple an implosion even if optical losses are under control. Ultimately, more efficient and better controlled coupling can reduce the required driver energy and cost.

Coupling Efficiency and Instability Processes in Different Fusion Schemes. Inertial fusion by laser indirect-drive (LID) or laser direct-drive (LDD) irradiation requires effective laser beam propagation and deposition of laser energy into the fusion target. It produces a rocket-like acceleration of the fusion fuel inward in response to the ablation pressure created by radiation energy deposition, producing fuel densities up to 1000 g/cm^3 to enable fuel burn at reasonable driver scale. In central hotspot (CHS) ignition, this high-density shell of fuel surrounds a hotspot, which reaches temperatures in excess of 10 keV from a combination of PdV work (displacement work) and alpha deposition. Reaching these conditions launches a nuclear burn wave, igniting the surrounding dense fuel, sustained by alpha energy deposition and electron conduction without an external energy source. In experiments at the National Ignition Facility (NIF) in 2021, this approach demonstrated a burning fusion plasma and a 1.37-MJ fusion yield, exceeding the Lawson ignition threshold [1-3]. The yield is remarkable given that the fuel capsule absorbed only about an estimated 230 kJ of energy and only about 25 kJ of that transferred to the fuel in the form of inward kinetic energy. Advanced fusion schemes, such as fast ignition (FI) or shock ignition (SI), decouple the compression process from hotspot formation and require coupling of high-intensity laser beams to the fusion target. Magnetically driven inertial fusion—magnetized liner inertial fusion (MagLIF)—also requires efficient laser coupling. In this case, laser power is used to heat the fuel prior to current-driven magnetic compression.

KEY MESSAGES

Practical laser inertial fusion energy (IFE) schemes, including highly promising advanced fusion schemes, such as *fast ignition (FI)*, will require high fusion gain and thus efficient laser coupling. However, despite progress in achieving ignition, significant challenges remain in laser-target coupling. In particular, limiting deleterious effects of laser-plasma instabilities (LPI) is critical, as LPI are fundamental limiters of fusion performance for *all* laser-driven IFE approaches. Detailed simulations of LPI physics have indicated that certain laser hardware developments, such as *increased laser bandwidth*, show promise for improving laser coupling to fusion targets, while mitigating negative LPI effects. Building new facilities capable of testing such approaches at the required laser energies, powers, and intensities to test critical aspects of laser coupling for IFE will be high priority for facility investments. Further, to gain control of LPI and improve coupling, we must develop *theory and modeling capabilities*, repetition-rated laser facilities with precision diagnostics, strong efficient public-private collaborations, and our workforce.

Despite progress in achieving ignition, significant challenges and margin for (or strong motivation for) improvements remain in laser-target coupling. In particular, stimulated Brillouin (back-) scattering (SBS) will reduce the laser energy available to drive the target, and the amplitude-modulated SBS light poses a risk to the laser optics. Stimulated Raman scattering (SRS) and two-plasmon decay (TPD) instabilities can further reduce the available laser energy and preheat the fusion target with hot electrons that are accelerated in the driven electron plasma wave [4]. Further, in geometries where multiple laser beams cross inside the plasma, the lasers will produce standing density modulations that act as a plasma optical grating, scattering and redistributing the laser light. Some indirect-drive laser fusion experiments have used the latter process to manipulate the laser power distribution in the hohlraum target to tune the capsule implosion symmetry [5]. However, in direct-drive geometries, the same process—known as crossed beam energy transfer (CBET)—leads to a loss of about 30–40% of the incident laser light that is scattered into nearly opposing laser beam lines [6]. Figure 1.1 shows a schematic of relevant instability processes that potentially reduce laser coupling and result in fusion fuel preheat [7].

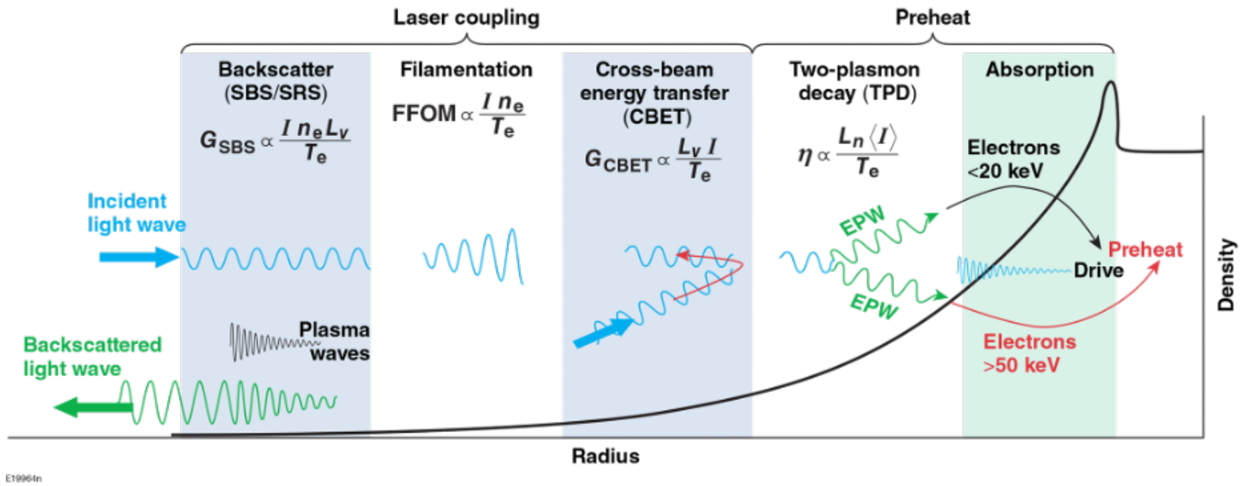


Figure 1.1. A schematic of laser-plasma instabilities (LPIs) as a function of plasma scale length and density is shown together with the figure of merit indicating the dependency of instability growth rates on the laser intensities and plasma parameters. (From D. H. Froula et al. (2012) [7]).

***Efforts in Understanding and Tackling Laser-Plasma Instabilities (LPIs):* Past and Present.** The study and mitigation of laser-plasma instabilities (LPIs) that can have deleterious effects on fusion target performance is a research component in the existing inertial confinement fusion (ICF) programs in the United States. Experiments since the 1980s have systematically advanced the coupling of high-energy laser beams by introducing short wavelength laser light (e.g., frequency conversion to the third harmonic) and laser beam smoothing techniques (e.g., induced spatial incoherence (ISI) [8], smoothing by spectral dispersion (SSD) [9], random phase plates [10], and polarization smoothing [11]).

The first large-scale-length laser-plasma and hohlraum experiments on NIF [12] demonstrated that these smoothing techniques were required for successful coupling experiments; thus, they were adopted for all 192 of NIF's beams. When subsequently operated with laser intensities in the range of 0.3×10^{15} to 1×10^{15} W/cm^2, these smoothed lasers achieved radiation temperatures of T_{RAD} = 300 eV at moderate laser scattering losses of 10% (i.e., coupling efficiencies of 90%) [13]. Since these early studies, shorter laser pulses have subsequently allowed for reduced hohlraum gas-fill densities that resulted in even smaller scattering losses and higher coupling efficiencies [14]. These advances in laser coupling, smoothing techniques, and crossed-beam laser power controls, are critically important for the pursuit of inertial fusion energy (IFE).

Nonetheless, when comparing present capsule implosion performance parameters with our best models, current estimates suggest that, in indirect-drive fusion experiments, about 20% of the laser energy is lost (i.e., simulations and experiments suggest that the capsule is driven by 80% of the absorbed laser energy). Both the 40% losses in direct-drive fusion experiments (described above) and these 20% losses in indirect-drive fusion experiments are subjects of active research within the National Nuclear Security Administration (NNSA)'s existing ICF program.

Further, moving to new indirect-drive fusion designs with lower adiabats (essentially, a compression trajectory with lower entropy in the system) to increase yield would require using longer laser pulses. This would in turn require increasing the gas-fill density inside the hohlraum to (1) slow down the expansion of the gold plasma from the hohlraum walls and (2) keep the hohlraum "open" for the duration of the laser pulse. Doing so is likely to re-introduce scattering losses by LPI.

Hardware Developments for Improving Energy Coupling. Several laser hardware developments have been proposed to improve laser coupling to fusion targets. In particular, detailed simulations of LPI physics have shown that (1) increased laser bandwidth, (2) laser pulses with spike trains of uneven duration and delay (STUD), and (3) increased driver laser frequency are promising options. Specifically, lasers with multi-THz bandwidth look promising for mitigating LPI for all high-gain laser fusion approaches. High bandwidth is also required to field STUD pulses to maximize coupling through advanced laser-pulse shaping. Finally, development of KrF or ArF lasers is currently the most promising approach for achieving high laser frequencies (short wavelengths). These lasers operate, respectively, at wavelengths of 248 nm and 193 nm and provide native laser bandwidths around 3 THz and 10 THz. These three developments are important for achieving high coupling for IFE schemes that pursue LDD geometries, including for FI and magnetic direct drive, in which higher density plasmas can be effectively heated using short-wavelength lasers.

The National ICF program—which is fielding the FLUX (Fourth Generation Laser for Ultrabroad Experiments) beamline at the OMEGA laser at the Laboratory for Laser Energetics (LLE) [15] and the SRRS-broadened (Stimulated Rotational Raman Scattering) beams on the Nike laser at the Naval Research Laboratory (NRL) [16]—is already pursuing some of these hardware developments; they will produce high bandwidth experimental capabilities to test the theoretical predictions for improved coupling but at moderate laser energies. In addition, there are institutions pursuing fast ignition approaches to IFE to investigate the target coupling of relativistic laser beams, albeit at moderate laser energies.

Keys to Improving Energy Coupling: Going Forward. Practical laser IFE schemes will require high fusion gain and thus efficient laser coupling, while limiting deleterious effects of LPI. Experiments on current facilities can continue to improve modeling, theory, and diagnostics of LPI. However, LPI mitigation approaches will ultimately require tests at the scale of high-gain target plasmas, which would require higher laser energies than are available at current facilities. Building new facilities capable of testing LPI mitigation approaches at the required laser energies, powers, and intensities to test critical aspects of laser coupling for IFE will be among the highest priority for facility investments. The FI approach should include capabilities to assess short-pulse laser drivers with energy around 100–200 kJ, as well as assessing efficiency of generating and coupling the electron or proton beams for igniting the fuel. Further, testing laser coupling physics with high bandwidth and deep ultraviolet

(UV) light at scale and with suitable laser intensities will be important and will require facilities with laser energies of 10–100 kJ and multiple beams, together with efforts in theory and modeling of laser coupling and simulated diagnostic observables.

In parallel, the national IFE program should take advantage of the developments currently supported and pursued within the ICF program and should develop the scientific capabilities unique to IFE. Important pillars include studying the physics unique to coupling lasers at high-repetition-rate operations, including high-repetition-rate laser and target diagnostics, at the frequencies and bandwidths selected by the future IFE scheme.

Managing Laser-Plasma Instabilities (LPIs) in Different Fusion Approaches. LPI are fundamental limiters of fusion performance for all laser-driven IFE approaches. Being able to predict, model, control, and mitigate LPI effects is thus crucial for the success of the IFE program. Controlling LPI requires the development of theory and modeling capabilities, laser technologies for mitigation, repetition-rated laser facilities with precision diagnostics, strong efficient public-private collaborations, and workforce development. LPI have broad applicability to advanced IFE concepts as well. FI drivers make use of nonlinear LPI, and LPI may affect the symmetry and efficiency of fuel assembly in FI concepts. Moreover, in SI, the high-intensity launch of the ignitor shock must also be robust to the effects of LPI.

The issues faced by the SI approach to laser inertial fusion are essentially the same as those of direct drive: CBET removes a substantial fraction of the incident drive energy; SRS and SBS reflect laser light, thereby reducing drive; and SRS and TPD generate hot electrons, which can pre-heat the fuel and thereby reduce compression. Where SI differs from direct drive, is the high peak intensity ($\sim 10^{16}$ W/cm^2) required in the power-spike used to drive the strong shock. This increased intensity means that, for SI, the saturated amplitude (the level at which non-linear saturation mechanisms balance the growth rates) of these instabilities will be higher during the power-spike (i.e., they will likely be worse). However, during the main part of the drive (used to accelerate the capsule), we expect the required intensity to be lower than that during conventional direct drive because simulations of SI predict ignition with lower implosion velocity. As a consequence, an accurate comparison of the LPIs in SI versus those in direct drive would require a temporal integral over a given implosion design. Like direct drive, we anticipate SI will benefit from broadband laser light, although the predicted bandwidth required to mitigate LPIs in SI is understood to be higher than required for direct drive due to the increased intensity during the ignitor shock launching. In addition, future work is needed to understand the role of SRS- and/or TPD-generated hot electrons on the generation of the strong shock.

The STUD pulse approach [17-21] for controlling LPI involves spike trains of uneven duration and delay (STUD pulses) as a means of combining both deterministic and random techniques at our disposal to scramble the speckle patterns that impinge upon the plasma in laser-based IFE schemes. The idea is to combat quasi-static irradiation patterns with a long duration compared to the typical growth rate of LPI, which then results in memory build up inside the plasma. This approach is equivalent to actively switching the laser on and off in time on the picosecond timescale, deterministically, with intervals optimized to remove plasma memory and scrambled randomly in space. For the laser front-end to generate arbitrary optical waveforms, such as are available in telecom (120-THz systems), requires state-of-the-art nonlinear optical technology. LLNL has implemented a system like this on an optical bench and is waiting to port it to the Jupiter Laser Facility as its refurbishments come to a close over the next two years.

The LPI mitigation techniques described above are promising and provide a rich research area that should be an important part of a future IFE program. Reaching effective and adaptive LPI control may open the door for the use of longer-wavelength lasers for IFE, such as the second harmonic (527 nm) green laser light option (as opposed to the third harmonic or blue laser light used on the NIF).

With heavy-ion fusion (HIF), ion beam target coupling relies on depositing the ion kinetic energy in the hohlraum in the case of indirectly driven targets and depositing it directly in the fuel in the case of directly driven targets. While some uncertainties remain in the range-energy relationships for heavy ions in hot, dense matter, simulations show that target performance is insensitive to plausible levels of uncertainty and that we can modify target design to match. Experiments at new accelerator facilities coming online soon [22] may be able to explore and decrease these uncertainties. In the case of indirect drive for lasers and ion beams, the driver beams heat the hohlraum and radiate a near-thermal distribution of photons. For this reason, ignition on NIF increases confidence in indirect-drive targets with hotspot ignition for HIF.

Studies have examined beam-plasma instabilities for both light ion fusion and HIF. These studies concluded that deleterious instabilities are unlikely in the target itself [23]. Nevertheless, the interaction of the beams with gas and/or plasma in the reactor chamber can be a concern. This concern is primarily related to chamber concepts that operate at pressures greater than about 1×10^{-4} Torr and to beam parameter regimes that require beam neutralization [24]. Also, when an ion beam strikes a target, it can produce energetic photons by exciting the inner shells of the beam and/or target particles. These effects did not appear to be a problem for early target designs, but more recent designs may be more sensitive to the details of the radiation spectrum. This topic requires additional research [25].

1.2 Priority Research Opportunities (PROs)

PRO 1-1: ***Demonstrate improved coupling with broad laser bandwidth***

Multi-THz laser bandwidth is desirable and could be required to mitigate LPI for all high-gain laser fusion approaches. For direct-drive implosions that make use of beam-smoothing schemes, broad bandwidth also reduces the laser imprinting during the early laser-target interaction before long-scale-length plasma has formed. This reduces the seeds for Rayleigh-Taylor instabilities. LPI simulations indicate that short coherence time is the most important parameter for mitigation of LPI; the shape of the spectral distribution and the spectral width are important.

CBET reduces the laser-target coupling efficiency in OMEGA laser direct-drive implosions by about 40%. Simulations indicate that we can substantially reduce CBET with 5-THz bandwidth and can essentially eliminate it with 8-THz bandwidth [26]. Predictions hold that still higher bandwidth will suppress other instabilities that produce hot electrons [27]. Mitigating LPI and laser imprint for LDD is a possible pathway to assembling more massive and energetic hotspot plasma for high-gain fusion targets.

Like conventional direct drive, we anticipate SI will benefit from broadband laser light, although the predicted bandwidth required to mitigate LPI in SI is understood to be higher than required for direct drive due to the increased laser intensity. Bandwidths of 3 THz and higher are also needed for the STUD-pulses approach to controlling LPI, coupled with arbitrary laser pulse-shape generation.

Current laser fusion facilities in the United States have limited capability to explore and verify the predicted mitigation of LPI by bandwidth. The OMEGA glass-laser facility presently operates at

0.3 THz, and we can push the Nike facility to 2.7 THz (0.35-ps coherence time). These bandwidths in concert with beam-smoothing are sufficient to mitigate filamentation but are not sufficient to mitigate other LPI, such as CBET.

The goal for the program should be to field experimental laser capabilities with high laser bandwidth on the order of 10 THz and to demonstrate efficient coupling and mitigation of LPI at scales relevant to IFE fusion targets. (Paths to provide ≥10 THz bandwidth light on target for both the 193-nm wavelength ArF lasers and the 351-nm wavelength DPSSL are described in the Drivers section.)

The most pressing need is to experimentally test the mitigation effects of broad bandwidth. Near-term opportunities with the LLE FLUX 150-J laser system will allow 10-THz-class broad-bandwidth LPI experiments on the OMEGA facility and SRRS-broadened beams on Nike at NRL. More definitive broad-bandwidth LPI experiments will require much higher energies (10s of kJ) and multiple beams. Plasma conditions are dependent on the laser wavelength (e.g., 193-nm light produces a lower temperature, shorter-scale-length plasma than 351 nm), so we should optimally conduct bandwidth experiments with both the 193-nm and the 351-nm candidate broad-bandwidth IFE drivers.

Ideally, these broad-bandwidth, laser-target interaction facilities would have high scientific repetition rate (many shots per hour). Further, we need such high-repetition-rated laser facilities to optimize a future STUD laser-pulse temporal profile on the picosecond timescale to potentially counter LPI and optimize coupling during the high-intensity part of a nanosecond-long compression laser pulse. **Combining laser and target diagnostics with machine learning (ML) capabilities will be important for optimizing broad-bandwidth laser coupling and to support STUD laser-pulse developments.**

Finally, the geometry of these facilities should allow for heating and compressing targets in planar-geometry experiments, which will maximize the accessible plasma scale-lengths. In addition, we need a provision to conduct CBET experiments at large laser-beam crossing angles. **The means to provide the bandwidth should be consistent with the efficiency, cost, and durability of an IFE laser driver.**

PRO 1-2: ***Demonstrate energy coupling for fast ignition (FI)***

FI presents unique driver and coupling challenges and opportunities for IFE, motivating its consideration as a PRO. In the FI concept, the compression and ignition phases are separated, with an external heating source (e.g., high-intensity laser-driven ion or electron beams) providing the energy needed to ignite a hotspot in a pre-compressed fuel. High gain for IFE is achieved by reducing the overall laser energy requirements for ignition while relaxing some of the symmetry requirements for assembling the fuel in the compression phase. This comes at the cost of requiring development of a more complicated system with separate fuel assembly and ignition subsystems.

One of the main challenges to FI is demonstrating robust, high areal density (ρR) fuel assembly using comparatively low driver energy (laser or pulsed power) in geometries with cone-in-shell targets, as is needed for the mainline FI concepts using laser-driven proton or electron beams. **We should explore and diagnose laser-driven FI fuel assembly at the sub-scale on laser systems such as OMEGA and at full scale on systems such as NIF with polar direct drive.** LPI in the compression phase is a potential concern, both at early times when it is crucial to minimize preheat and at late times in the fuel assembly that may require high laser intensity.

Another major challenge to FI is demonstrating efficient conversion of high-intensity short-pulse laser energy to fusion plasma heating beams (ions or electrons), as well as transport and coupling of these beams to a localized compressed fuel volume. Current short-pulse drivers are too small to evaluate the concept at IFE scales: they are 10s to 100s of J of short-pulse laser energy, whereas we need multi-kJ drivers at shot/min rates. A program for developing FI heater beams would require first demonstrating heater-beam efficiency and coupling to compressed cores at sub-scale, followed by demonstrating combined short-pulse ignition physics at or near ignition scale. Besides optimizing the ion/electron source, protecting this beam of particles in close proximity to the 100s-kJ implosion is a major challenge, so *integrated experiments are necessary*. Moreover, we need to invest in novel numerical simulation techniques (e.g., relativistic multi-species hybrid codes), as well as validate and verify these methods, to support the advancement of FI ignitor technology.

The program's working goal should be to demonstrate efficient fuel compression to ρR of 1–3 g/cm^2 in the cone-in-shell geometry using 100s of kJ of laser driver energy. The program should also aim to demonstrate production and transport of 10s of kJ of ignitor particle beam energy resulting from 100–200-kJ short-pulse lasers. The ultimate goal would be to integrate these technologies into a pilot repetition-rated power-plant.

PRO 1-3: ***Advance theory and modeling of laser-plasma instabilities (LPIs) to increase understanding of experimental data, develop mitigation strategies, and increase predictive capability of LPI simulations***

LPI in laser-driven IFE experiments involve complex coupling of multi-scale physics at a wide range of temporal and spatial scales and require linear theory, kinetic nonlinear micro-physics codes, and multi-physics design codes to model these processes properly. Key LPI challenges include controlling and mitigating CBET, SBS, SRS, and TPD for symmetry and laser-target coupling and keeping hot electron production at an acceptable level. Mitigating one type of LPI (e.g., CBET) may lead to an increase in laser intensities and growth of other LPI processes, such as SRS and TPD. To maximize the chances of success in a laser-driven IFE program, the community needs to extend theoretical and computational efforts to assess the full range of LPI risks and verify proposed mitigation schemes for all laser-driven IFE approaches. Supercomputers have increased the complexity of LPI problems we can realistically tackle today, and we now have much more detailed simulations of LPI than we did in the past. If LPI is not completely mitigated, then a major goal should be to develop accurate linear and nonlinear LPI models to couple LPI effects in design codes in a self-consistent manner. Improved coupling of LPI effects in IFE design codes would also enable efficient evaluation of various approaches to LPI control and mitigation.

1.3 Conclusions

We must consider several important questions as we evaluate LPI-mitigation approaches:

1. Can the approach mitigate CBET?
2. Can ablation pressure be increased? (If possible, this would open a pathway toward a more robust implosion with higher areal densities, burn fractions, and consequently higher fusion gain.)
3. Can hot electron preheat be reduced so implosions can be done at low adiabat? (If possible, this would open a path to high fusion gain.)
4. Is the approach compatible with a sufficient target gain–driver efficiency product for a power plant ($\eta G \geq 10$)?

As we build demonstration beamlines for new driver technologies (wide-bandwidth 2ω and 3ω solid-state lasers, deep UV excimer lasers), we should use them to validate LPI physics at ignition-relevant scale (1-mm spot; 2-ns drive, 2 × 10^{15} W/cm^2). These requirements to perform LPI experiments at scale translate into 10s of kJ laser facilities to successfully demonstrate laser coupling at IFE conditions.

Though not discussed in detail in this section, important requirements of target coupling are precise target engagement for injected targets and power balance. We should consider these requirements at the system-level and with specific driver design. Finally, better understanding of coupling requires understanding and modeling kinetic effects and heat transport (in particular, non-local heat transport, multi-species modeling) and magnetic field (self-generated and imposed) effects on coupling.

Bibliography

1. A. B. Zylstra, et al., *Burning plasma achieved in inertial fusion.* Nature, 2022. **601**(7894): p. 542-548, 10.1038/s41586-021-04281-w.

2. A. L. Kritcher, et al., *Design of inertial fusion implosions reaching the burning plasma regime.* Nature Physics, 2022. **18**(3): p. 251-258, 10.1038/s41567-021-01485-9.

3. H. Abu-Shawareb, et al., *Lawson Criterion for Ignition Exceeded in an Inertial Fusion Experiment.* Physical Review Letters, 2022. **129**(7): p. 19, https://doi.org/10.1103/PhysRevLett.129.075001.

4. W. L. Kruer, *Laser plasma interactions with intensities from 10(12)-10(21) W/cm(2).* Physics of Plasmas, 2003. **10**(5): p. 2087-2092, 10.1063/1.1559005.

5. P. Michel, et al., *Tuning the Implosion Symmetry of ICF Targets via Controlled Crossed-Beam Energy Transfer.* Physical Review Letters, 2009. **102**(2), 10.1103/PhysRevLett.102.025004.

6. I. V. Igumenshchev, et al., *Crossed-beam energy transfer in implosion experiments on OMEGA.* Physics of Plasmas, 2010. **17**(12), 10.1063/1.3532817.

7. D. H. Froula, et al., *Laser–plasma interactions in direct-drive ignition plasmas.* Plasma Physics and Controlled Fusion, 2012. **54**(12): p. 124016, 10.1088/0741-3335/54/12/124016.

8. R. H. Lehmberg and S. P. Obenschain, *Use of Induced Spatial Incoherence for Uniform Illumination of Laser Fusion-Targets.* Optics Communications, 1983. **46**(1): p. 27-31, Doi 10.1016/0030-4018(83)90024-X.

9. S. Skupsky, et al., *Improved Laser-Beam Uniformity Using the Angular-Dispersion of Frequency-Modulated Light.* Journal of Applied Physics, 1989. **66**(8): p. 3456-3462, Doi 10.1063/1.344101.

10. Y. Kato and K. Mima, Random Phase-Shifting of Laser-Beam for Absorption Profile Smoothing and Instability Suppression in Laser-Produced Plasmas. Applied Physics B-Photophysics and Laser Chemistry, 1982. **29**(3): p. 186-187,

11. K. Tsubakimoto, et al., *Suppression of Interference Speckles Produced by a Random Phase Plate, Using a Polarization Control Plate.* Optics Communications, 1992. **91**(1-2): p. 9-12, Doi 10.1016/0030-4018(92)90091-5.

12. S. H. Glenzer, et al., Experiments and multiscale simulations of laser propagation through ignition-scale plasmas. Nature Physics, 2007. **3**(10): p. 716-719, 10.1038/nphys709.

13. S. H. Glenzer, et al., Demonstration of Ignition Radiation Temperatures in Indirect-Drive Inertial Confinement Fusion Hohlraums. Physical Review Letters, 2011. **106**(8), 10.1103/PhysRevLett.106.085004.

14. S. Le Pape, et al., Fusion Energy Output Greater than the Kinetic Energy of an Imploding Shell at the National Ignition Facility. Physical Review Letters, 2018. **120**(24), 10.1103/physrevlett.120.245003.

15. C. Dorrer, E. M. Hill, and J. D. Zuegel, *High-energy parametric amplification of spectrally incoherent broadband pulses.* Optics Express, 2020. **28**(1): p. 451-471, https://doi.org/10.1364/OE.28.000451.

16. James Weaver, et al., Spectral and far-field broadening due to stimulated rotational Raman scattering driven by the Nike krypton fluoride laser. Applied Optics, 2017. **56**(31): p. 8618, 10.1364/ao.56.008618.

17. Bedros Afeyan. STUD pulses: spike train of uneven duration and delay for the control of laser-plasma instabilities in ICF, IFE and HEDLP. in APS Division of Plasma Physics Meeting Abstracts. 2009.

18. B Afeyan, J Garnier, and S Hueller. STUD Pulses for Shock Ignition and LPI Control. in International Workshop on ICF Shock Ignition. 2011. LLE, Rochester, NY.

19. B. Afeyan and S. Huller, *Optimal control of laser plasma instabilities using Spike Trains of Uneven Duration and Delay (STUD pulses) for ICF and IFE.* Ifsa 2011 - Seventh International Conference on Inertial Fusion Sciences and Applications, 2013. **59**, https://doi.org/10.1051/epjconf/20135905009.

20. B. J Albright, L. Yin, and B. Afeyan, Control of Stimulated Raman Scattering in the Strongly Nonlinear and Kinetic Regime Using Spike Trains of Uneven Duration and Delay. Physical Review Letters, 2014. **113**(4), https://doi.org/10.1103/physrevlett.113.045002.

21. Bedros Afeyan and Stefan Hüller Optimal Control of Laser-Plasma Instabilities Using Spike Trains of Uneven Duration and Delay: STUD Pulses. 2013. arXiv:1304.3960 DOI: 10.48550/arXiv.1304.3960.

22. Thomas Schenkel, et al. Ion beams and Inertial Fusion Energy "[White Paper]". in NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

23. D. W. Hewett, W. L. Kruer, and R. O. Bangerter, *Corona plasma instabilities in heavy ion fusion targets.* Nuclear fusion, 1991. **31**(3): p. 431, 10.1088/0029-5515/31/3/003.

24. J. L. Vay, et al., Propagation of Ion Beams in a Heavy-Ion Inertial Fusion System, in NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

25. R.O. Bangerter, Systems Studies, Accelerator Design, Target Design and Enabling Technologies for Heavy Ion Fusion "[White paper]", in NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

26. J. W. Bates, et al., Mitigation of cross-beam energy transfer in inertial-confinement-fusion plasmas with enhanced laser bandwidth. Physical Review E, 2018. **97**(6): p. 061202, 10.1103/PhysRevE.97.061202.

27. R. K. Follett, et al., *Thresholds of absolute instabilities driven by a broadband laser.* Physics of Plasmas, 2019. **26**(6): p. 10, 10.1063/1.5098479.

Chapter 2: Compression and Burn

2.1 Introduction

The field of inertial confinement fusion (ICF) made exceptional progress over the last few years on many fronts. Most notably, laser indirect-drive (LID) [1] experiments on the National Ignition Facility (NIF) produced fusion yields exceeding the energy absorbed by the capsule by >12x and exceeding the energy delivered to the target by the laser [2-4] using a strategy of increased hotspot energy delivery via increased capsule scale of a moderate adiabat implosion [5]. Laser direct-drive (LDD) [6] implosions on the OMEGA laser have also achieved core pressures approaching the ignition requirements for a driver energy of 2 MJ, and magnetically driven fusion (MDF) studies versus scale predict high levels of performance at and above 60-MA currents [7]. These results are exciting, build on years of research across the broader community, and motivate renewed investigation of implosion performance requirements for IFE—which are considerably more stringent than for ICF. At a minimum, IFE will require much higher gains, G (i.e., output energies relative to the input driver), at high efficiencies and repetition rates. IFE also necessitates management of cost, which is a strong function of target complexity and performance. This chapter discusses the challenges for compression and burn of IFE targets, including the research needed to advance traditional ICF target concepts into the IFE regime.

SUMMARY

For cost effective IFE, the required target gain is estimated to be 30–100, depending on implosion compression and driver efficiency. Further, 10–30% of the fuel must burn on each shot, which is primarily a function of the fuel's areal density; unfortunately, current driver and target designs do not achieve the areal densities needed for IFE. The paths to greater areal density are:

(1) increasing compression and

(2) raising fuel mass by increasing target scale.

However, many features that enable high gain also increase sensitivity to system imperfections. While degradation details may vary, different fusion concepts share commonalities, such as hydrodynamic instabilities, inadequate target quality, and inaccuracy of modeling tools. Determining the **primary sources of degradation and methods of mitigation** is central for getting all inertial fusion concepts to high gain. Further, we must evaluate required changes in assembly engineering to accommodate target injection to meet IFE's need for high repetition rates.

Achieving Sufficient Compression and Deuterium-Tritium (DT) Fuel Burn. Cost effective energy production for IFE requires that a substantial amount of the deuterium-tritium (DT) fuel must burn on each shot (10–30%). This approach can reduce inventory and the effort needed to recover and process tritium. The burnup fraction Φ is primarily a function of the areal density of the fuel (+pusher/liner), ρR; Fraley *et al.* [8] give a good approximation as

$$\Phi = \frac{\rho R}{\rho R + H_b}.$$

For conditions typical to IFE, we can take the temperature-dependent burn parameter H_b as ~6–7 g/cm^2 for a burn temperature of ~30 keV (the value is larger at lower burn temperatures). A high ρR is clearly desirable, but the range of values for existing concepts is rather small. Capsule implosions at NIF and the MagLIF have been designed to give ρRs of ~1–1.5 g/cm^2 and ~1 g/cm^2, respectively [7]. We can use a strong magnetic field to decrease plasma electron conduction cooling and increase alpha-particle stopping, allowing for burn at lower fuel areal densities. The most direct path to greater areal density is to increase the compression since ρR at a given mass scales with CR^2, where CR is the shell convergence ratio (the ratio of initial to final inner capsule radius). The other path is to raise the fuel mass by increasing target scale S. We can accomplish this feat by increasing the coupling between the driver and target, the size of the driver, or both.

For IFE, a typical expectation for the burn fraction is ~1/3, which corresponds to a ρR of ~3 g/cm^2. To achieve attractive economic performance, the estimated necessary target gain is G ~ 30–100 [9]; the exact value needed of course depends on the implosion compression levels, the energy efficiency of the driver, and the efficiency of converting fusion energy to useful work. All these figures greatly exceed any experimental demonstration to date, at scales yet to be applied to traditional ICF concepts or alternatives. At present, the ICF program has demonstrated a target gain value G of ~1.5 for indirect drive targets at a ρR of ~0.7 g/cm^2 (see **Figure 2.1**). This achievement took a decade of effort on NIF and is still far below original estimates (as alluded to above).

These findings are under study and may not indicate a limitation, but they effectively illustrate the distance-to-goal for IFE. To achieve an areal density that is higher by a factor of four, we would need to (1) further increase the compression ratio by a factor of two or (2) increase the implosion mass by a factor of 4^3 ~ 64. The latter would require a prohibitively large driver (in all likelihood), so the indirect drive program at LLNL has attempted to improve pulse-shaping [10] to lower the shell entropy and improve implosion convergence. This is the traditional path to increasing CRs when energy is limited. However, the general experience is that performance tends to *decrease* for a lower shell entropy, in stark contrast to expectations from 1D/2D theory and modeling. Indeed, detailed 3D modeling shows that low adiabat implosions have a tendency to fall apart and be ultra-sensitive to engineering features of the targets [9, 11]. LID experiments have achieved ignited hotspots and high

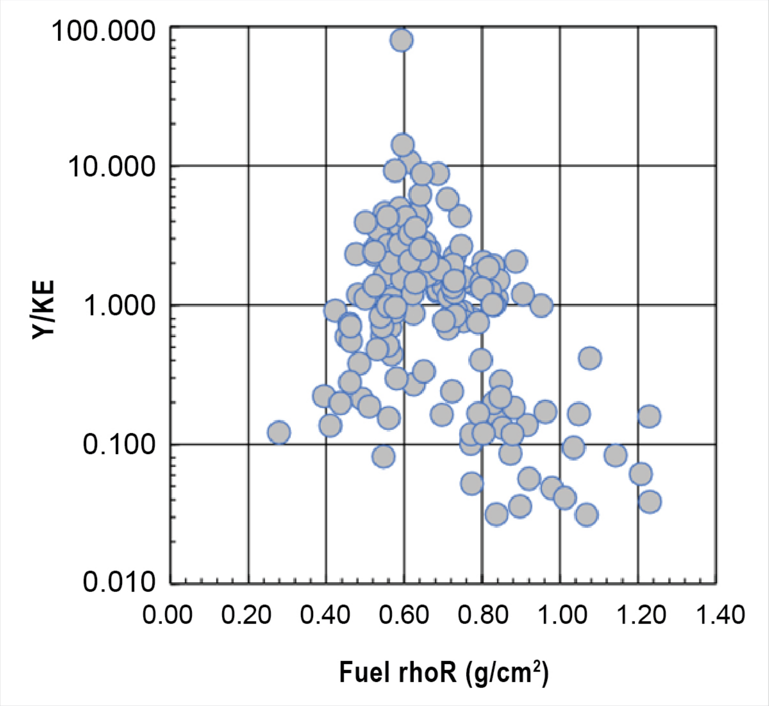


Figure 2.1. Measured total fusion yield normalized to inferred peak fuel kinetic energy (approximately "fuel gain," G_{fuel}) is plotted versus measured burn average areal density (via the neutron downscatter ratio of 10–13-MeV neutrons over 13–15-MeV neutrons) for the set of deuterium-tritium (DT) implosions tested on NIF between 2009 and 2022. As shown in the figure, fusion performance rapidly falls off at low areal density (as expected since 1D inertial confinement is reduced) and also at higher areal density (contrary to conventional wisdom), and an apparent optimum exists for fuel ρR ~ 0.6–0.7 g/cm^2. The leading, but not only, hypothesis for the performance degradation at high areal density is hydrodynamic instability, which is driven more strongly by the steeper gradients in density and higher levels of convergence associated with higher compression. Error bar ~7% in ρR and ~5% in Y/KE. Figure adapted from O. A. Hurricane, et al. [12]

areal densities but have not yet achieved both at the same time. LDD experiments have exhibited similar trends, although these experiments have only been conducted at significantly reduced scale.

Achieving Precision Control Over Targets and Drivers. Fundamentally, many of the features that enable high gain—a necessary requirement for IFE—make it more sensitive to imperfections in the laser and target system that limit performance (assuming laser drive). Based on the available data, this Basic Research Needs (BRN) panel asserts that we do not currently have the precision control over targets and driver (either laser or magnetic) necessary to ignite high-convergence, high-ρR implosions on existing facilities. We will need to achieve greater precision, better understanding, an improved or larger driver, or all the above.

LID and LDD stability control has so far required a significantly higher design adiabat than desired [12], where adiabat is the ratio of the internal energy in the ice layer to the Fermi degenerate energy and is a measure of the shell entropy and compressibility. Due to lower in-flight thickness and higher convergence, low adiabat implosions are more susceptible to growth of hydrodynamic instabilities. Such instabilities drive mixing of ablator and other target component material (tent and fill tube) with the cold fuel and hotspot plasma. While mitigation strategies have reduced its impact, mixing is still present and performance-limiting on almost every implosion, even some of the highest performing ones. Even when x-ray imaging implies a relatively clean hotspot, spectroscopy often implies cold mixing of ablator into the cold DT fuel. Some studies have used special laser pulses to shape the adiabat within the shell (e.g., [13-15]) to improve stability, thereby enabling higher convergence and areal densities, but have had mixed results. Low-adiabat, high-convergence implosions with high adiabat–like stability have so far performed like high-adiabat implosions despite having a higher total fuel areal density [16], implying a disconnect between expected (pre-shot) and actual fusion performance at high convergences. Retrospectively (post-shot), simulations can often reproduce the observed indirect-drive, adiabat-shaped implosion behavior when we include enough detail [17-19]. As expected, adiabat-shaping has a positive ablative-Rayleigh-Taylor (RT) stabilizing influence, enabling higher fuel compression than high-adiabat implosions and better hotspot performance than low-adiabat implosions; yet, experimentally, this higher fuel compression did not necessarily translate into higher fusion performance—this is an area of continued investigation.

Achieving Predicted Compression and Required Areal Density. There are cases in LID and LDD ICF in which high-convergence implosions do not reach the compression predicted by pre-shot simulations, which helps explain some of the difficulties at NIF [16, 19] and OMEGA [20, 21]. It is challenging to optimize and improve any system that does not respond to pulse-shaping as expected. Leading hypotheses include ultra-small-scale instabilities impacting the fuel-ablator interface region of the implosion, the statistical mechanics-derived equations of state (EOS) models getting shock compression/rarefactions wrong, and x-ray (or electron) preheat (levels and/or non-uniformity) being modeled incorrectly.

MDF faces similar problems with compression but for different reasons. MDF takes advantage of the increase in magnetic pressure for compression with decreasing radius along with enhancement in confinement times due to the magnetic field. These attributes offset the reduced work on the plasma during the implosion, along with a laser used to heat the plasma ahead of peak compression. While details of the degradation sources for MDF may differ from LID and LDD, all three fusion concepts share many commonalities, such as hydrodynamic instabilities, inadequate target quality, inaccuracy of modeling tools (or perhaps insufficient initial condition detail when using modeling tools), challenges with repetition rate, debris from previous shots, etc. Detailed 3D high-resolution measurements could help focus attention on the key underlying physics.

The bottom line is that current driver and target designs do not achieve the areal densities needed for IFE, even if they can, in principle, achieve ignition. LDD and MDF experiments have not been conducted at scale to explore proximity to ignition and levels of gain, though LDD experiments on the OMEGA facility do project to be in a similar fusion-yield regime as indirect implosions if scaled to NIF laser energy [22].

For IFE to be viable, we still must demonstrate high areal densities and gains. For conventional target designs, the goal is common to both ICF and IFE. The community has identified key research directions needed to solve issues related to high gain based on our current understanding with respect to each of the ICF approaches. The key question for capsule implosions is, "What prevents high compression ratio LID and LDD implosions from achieving the predicted high performance (i.e., why do low-adiabat implosions perform at or below the level of high-adiabat designs)?" Determining the primary sources of degradation and the methods of mitigation is central for answering this question and getting all inertial fusion concepts to high gain. Results published for the NIF low-adiabat, low-adiabat shaped, and higher-adiabat LID experiments (which include the highest CR implosions performed on NIF [11, 18]) showed that high-resolution 3D post-shot simulations are able to match performance metrics reasonably well. These results imply that the major physical effects responsible for limiting performance in these experiments are suitably accounted for in these simulations *a posteriori.* However, pre-shot predictions still tend to overestimate performance, likely in large part because our community standard simulation/theory practice does not yet include all the necessary details. We may need to improve the theory/calculation tools (or the way we use the tools, e.g., more detailed initial conditions) to determine if it is even possible to sufficiently mitigate hydrodynamic instabilities in high-gain targets for suitable IFE-sized drivers.

Additional Challenges for IFE. Beyond the common issues between ICF and IFE, IFE's need for high repetition rates and practical/low-cost targets leads to additional knowledge gaps. High repetition rate will require target injection, which will impose challenging new requirements on target design, such as the need for thermal shielding and mechanical robustness, as well as likely removal of layering as a fabrication option due to tritium inventory limitations. Debris affecting subsequent shots and/or shot rate may put additional requirements on target design, gain, and choice of target materials that could negatively affect the scale and viability of the fuel cycle systems (as discussed in Chapter 6). Target assembly robustness to acceleration during injection will put requirements on target complexity or add features for injection that could prohibit a functional high-gain design. Moreover, we do not know whether the acceleration process limits compression and burn in ways we have not yet identified. These considerations push target designs toward concepts that can balance ICF performance/gain needs with the engineering robustness needed to sustain high repetition rates. Trade-offs between the two may lead to additional requirements on other IFE components, such as driver efficiency, target engineering, etc. In summary, understanding the issues preventing designs from achieving high gain will be central to developing a path to IFE. To determine viable target designs for IFE, we will have to meet requirements pertaining to integration with the driver, the facility, the target engineering, and other physics components.

2.2 Priority Research Opportunities (PROs)

As discussed earlier, a solution to producing high-convergence, high-compression implosions must be found to achieve high energy gains. At present, the cause of the observed LID/LDD implosion performance threshold for low-adiabat, high-convergence implosions remains poorly understood, albeit for years the leading hypothesis has been limited to hydrodynamic instability control. Without determining the physics behind the performance cliff as target designs move to lower adiabats, there may be no credible path to IFE using conventional target designs, making this one of the most pressing issues for IFE. Once we develop fundamental understanding, the community can explore ways to mitigate the failure mechanisms or determine the required target and laser control necessary to produce high-gain implosions. This work should include assessments of design robustness, followed by studies aimed at increasing robustness. We summarize the research needs for compression and burn of capsules as follows:

PRO 2-1: ***Investigate the physical mechanisms limiting fuel compression in low-adiabat implosions***

High-convergence and high-compression implosion experiments perform well below designed expectations. Several known mechanisms may be limiting the ability to achieve the expected compression in ICF implosions, as well as potential unknown mechanisms. For ICF implosions, shocks and rarefactions are driven at the interfaces, which later seed hydrodynamic instability growth from isolated material defects that are amplified by convergence effects, such as the Bell-Plesset instability. We must address the lack of detailed measurements of initial conditions and errors in models to improve our understanding of the failure mechanisms occurring at high convergence. This requires experimentally validated material properties to test the accuracy of EOS models used in current hydrodynamic codes. Finally, we must accurately evaluate all preheat mechanisms (radiation and hot-electron preheat) to assess the true compressibility of the DT fuel.

PRO 2-2: ***Explore failure mitigation and performance optimization strategies***

As we understand more details on the failure mechanisms, we will need to devise mitigation strategies and implement a comprehensive target-design optimization process. We will need to carry out design optimization without sacrificing other design aspects (e.g., symmetry control). Even without a detailed understanding of failure mechanisms, several paths exist to optimize target designs. We need to explore target materials that increase opacity and density, which are believed to improve performance with higher ablation pressure. Exploring liquid-layered targets would prove valuable since there are outstanding questions both about their target performance and the potentially novel ways to fabricate targets with additive manufacturing methods.

PRO 2-3: ***Evaluate and improve target robustness with respect to ignition and gain***

IFE targets will require greater target robustness to ensure high compression at high repetition rates. Since this will require tracking and firing the laser, the use of mass-manufactured targets, and a high-repetition-rate laser, one can expect varying quality for each shot. Developing targets more robust to variation in these conditions will ensure consistent power output in a power plant. Research in understanding robustness will help evaluate IFE power-plant requirements for lasers and targets.

PRO 2-4: ***Experimentally evaluate implosion sensitivities***

In addition to evaluating and addressing implosion robustness, *we will need experiments to test ideas and quantify sensitivities to various target and laser parameters*. The coupled nature of the problem makes design simulations difficult, especially in regard to understanding the covariance between parameters—only integrated experiments can provide the necessary data.

PRO 2-5: ***Understand and quantify the impact of high repetition rates on target design and performance (see also PRO 5-3 and 6-3)***

Target design for current ICF experiments adopts manufacturing and assembly techniques of fragile targets. Elements such as fill tubes or tents to hold the target are not currently designed to withstand being accelerated and traveling through the target chamber where debris and background radiation from the previous shot may affect or damage the target. To ensure that targets can survive injection into the target chamber, we must evaluate the assembly engineering needed for an IFE environment. Because present ICF experiments do not require high repetition rates, targets and auxiliary features are not currently designed to maintain the structural integrity required for IFE. To develop a robust target design for IFE, it is important to understand these issues and incorporate them during the design and evaluation phase, without relying on sensitive design features used to increase yield in ICF.

PRO 2-6: ***Develop metrics to assess progress in target design and implosion performance***

As we make progress on the PROs, we need to develop metrics to assess progress in target design and implosion performance. Up to now, the Lawson Criterion has been the most common metric across all fusion concepts [23-25]. An issue with a Lawson metric for ICF is that we must make assumptions to infer quantities that are not directly measured. For non-igniting targets, the lack of spatial and temporal measurements of the compressed core properties, along with details near stagnation, such as the fuel adiabat, require *ad hoc* [26] corrections leading to uncertainties in estimating proximity to ignition across target designs. For ignited targets, the gain with respect to the driver energy provides a clean metric of progress and proximity to the conditions required for IFE. Since current and future facilities may not utilize the most efficient state-of-the-art drivers, there may be uncertainties in extrapolating target gains to what can be achieved in a viable IFE driver. Since LDD and MDD high-performance implosions are carried out on facilities far from ignition scale, we use hydrodynamic scaling to extrapolate implosion results to ignition scale. While hydrodynamic scaling is well established, other physics such as laser-plasma interactions, heat, radiation, and particle transport do not scale directly, creating uncertainties and perhaps unknowns that we must identify and investigate.

Cross-Cutting Needs to Advance Compression and Burn

As with any large-scale project, integration plays a critical role in finding solutions to the challenges. To address compression and burn issues, we must develop several key cross-cutting capabilities. The list here is not comprehensive but describes some of the key capabilities to advance target gains into the IFE regime.

Carry Out Feasibility Studies for a New Facility to Study Compression and Burn in IFE-Relevant Regimes. While current ICF facilities have the capability to address the lack of capsule compression, their ability to make additional time available to new studies is very limited. As such, close alignment between the IFE and ICF programs would provide high mutual benefit. In addition, to address either conventional or alternative approaches, a new facility at ignition scale would add substantial benefit to resolving outstanding issues and developing high-gain IFE target designs.

Enhance Computational Capabilities to Carry Out More Large-Scale Three-Dimensional Implosion Simulations. The ability to predict current ICF experiments rests with the capability to simulate implosions at the necessary fidelity, including the three-dimensional nature of implosions. Simulations in two dimensions, while useful, do not always capture the reality of target implosions. Thus, improving simulation codes and computing capabilities to enable three-dimensional simulations to run faster and/or at higher resolution will help further understanding of the physics relevant to high-convergence-ratio targets.

Develop High-Resolution Diagnostics for Probing Hydrodynamic Instability Growth. One of the major three-dimensional phenomena in ICF implosions is interfacial hydrodynamic instabilities, as well as seeds from volumetric defects in ablators, preventing high convergence. While higher fidelity three-dimensional simulation tools can help address this issue, we need to validate the physics models used in radiation hydrodynamic codes. This will require high-fidelity measurements of interface perturbation growth, as well as three-dimensional reconstructions of implosions.

Explore New Driver Technologies to Increase Laser Energy and/or Energy Coupling to the Target. Increasing the laser energy and/or the target-coupling efficiency increases the number of target design options available to achieve high gain. More energy coupled to the capsule can lead to high gains while relaxing the convergence needed for high ρR. Advances in driver technologies can increase the laser energy coupled and broaden target design space. For instance, shorter laser wavelengths lead to greater energy absorption, broader light bandwidth suppresses laser-plasma instabilities (LPIs), and improved laser efficiency relaxes target gain requirements. In addition, improving control over the laser pulse shape and energy balance would reduce three-dimensional effects that degrade target performance.

Improve Target Quality and Metrology. Target quality is believed to be a critical element for achieving high fuel compression and ignition. Instability seeds beyond the current fidelity of fully integrated target calculations appear to be important [27] and will only become more important at high compression ratios. Due to the required repetition rate, techniques to improve robustness will enable target design flexibility important for mitigating and solving current issues.

Develop New Transmission Lines for Magnetically Driven Fusion (MDF). For pulsed-power MDF designs, we must find solutions to improve coupling of the current to the target for a repetition-rated system. Protection of the water/vacuum interface of MDF systems may require long transmission lines designed with minimal inductance/length for efficient energy delivery to the target. We need to develop blast-mitigation techniques to reduce transmission line length. To keep these costs low, we must also develop low-cost recyclable transmission lines that can deliver 60–70 MA to the load.

2.3 Conclusions

At present, no credible target designs can achieve the high gains necessary for IFE with existing facilities (NIF, OMEGA, Z, etc.) at their existing capabilities. We need a solution for producing high-compression ICF targets, or we need to pursue alternate paths to more capable targets and driver concepts. The failure threshold for low-adiabat capsule designs is a common challenge for ICF and IFE. Overcoming these difficulties will require investments in facilities, diagnostics, and computation capabilities.

Bibliography

1. J. Lindl, Development of the Indirect-Drive Approach to Inertial Confinment Fusion on and the Target Physics Basis for Ignition and Gain. Physics of Plasmas, 1995. **2**(11): p. 3933-4024, 10.1063/1.871025.

2. A. B. Zylstra, et al., *Experimental achievement and signatures of ignition at the National Ignition Facility.* Physical Review E, 2022. **106**(2): p. 10, 10.1103/PhysRevE.106.025202.

3. A. L. Kritcher, et al., *Design of an inertial fusion experiment exceeding the Lawson criterion for ignition.* Physical Review E, 2022. **106**(2): p. 14, 10.1103/PhysRevE.106.025201.

4. H. Abu-Shawareb, et al., *Lawson Criterion for Ignition Exceeded in an Inertial Fusion Experiment.* Physical Review Letters, 2022. **129**(7): p. 19, https://doi.org/10.1103/PhysRevLett.129.075001.

5. O. A. Hurricane, et al., Beyond alpha-heating: driving inertially confined fusion implosions toward a burning-plasma state on the National Ignition Facility. Plasma Physics and Controlled Fusion, 2019. **61**(1): p. 10, 10.1088/1361-6587/aaed71.

6. R. S. Craxton, et al., *Direct-drive inertial confinement fusion: A review.* Physics of Plasmas, 2015. **22**(11): p. 153, 10.1063/1.4934714.

7. Stephen A. Slutz and Roger A. Vesey, *High-Gain Magnetized Inertial Fusion.* Physical Review Letters, 2012. **108**(2): p. 5, http://doi.org/10.1103/PhysRevLett.108.025003.

8. G. S. Fraley, et al., *Thermonuclear burn characteristics of compressed deuterium-tritium microspheres.* The Physics of Fluids, 1974. **17**(2): p. 474-489, 10.1063/1.1694739.

9. Stefano Atzeni and Jürgen Meyer-ter-Vehn, *The Physics of Inertial Fusion: BeamPlasma Interaction, Hydrodynamics, Hot Dense Matter*. 2004: Oxford University Press; doi: 10.1093/acprof:oso/9780198562641.001.0001.

10. D. S. Clark, et al., Exploring implosion designs for increased compression on the National Ignition Facility using high density carbon ablators. Physics of Plasmas, 2022. **29**(5): p. 052710, 10.1063/5.0087052.

11. D. S. Clark, et al., Three-dimensional simulations of low foot and high foot implosion experiments on the National Ignition Facility. Physics of Plasmas, 2016. **23**(5): p. 056302, 10.1063/1.4943527.

12. O. A. Hurricane, et al., *Physics principles of inertial confinement fusion and status in U.S.* Rev. Mod. Phys., 2023, (Accepted Paper).

13. T. R. Dittrich, et al., *Design of a High-Foot High-Adiabat ICF Capsule for the National Ignition Facility.* Physical Review Letters, 2014. **112**(5): p. 5, 10.1103/PhysRevLett.112.055002.

14. J. L. Peterson, et al., *Differential ablator-fuel adiabat tuning in indirect-drive implosions.* Physical Review E, 2015. **91**(3): p. 5, 10.1103/PhysRevE.91.031101.

15. D. S. Clark, et al., *A survey of pulse shape options for a revised plastic ablator ignition design.* Physics of Plasmas, 2014. **21**(11): p. 112705, 10.1063/1.4901572.

16. J. L. Milovich, et al., Design of indirectly driven, high-compression Inertial Confinement Fusion implosions with improved hydrodynamic stability using a 4-shock adiabat-shaped drive. Physics of Plasmas, 2015. **22**(12): p. 122702, 10.1063/1.4935922.

17. D. T Casey, et al., Improved Performance of High Areal Density Indirect Drive Implosions at the National Ignition Facility using a Four-Shock Adiabat Shaped Drive. Physical Review Letters, 2015. **115**(10), 10.1103/physrevlett.115.105001.

18. H. F. Robey, et al., Performance of indirectly driven capsule implosions on the National Ignition Facility using adiabat-shaping. Physics of Plasmas, 2016. **23**(5): p. 056303, 10.1063/1.4944821.

19. V. A. Smalyuk, et al., Experimental results of radiation-driven, layered deuterium-tritium implosions with adiabat-shaped drives at the National Ignition Facility. Physics of Plasmas, 2016. **23**(10): p. 102703, 10.1063/1.4964919.

20. C. A. Thomas, et al., *Deficiencies in compression and yield in x-ray-driven implosions.* Physics of Plasmas, 2020. **27**(11): p. 112705, 10.1063/5.0022187.

21. O. L. Landen, et al., *Fuel convergence sensitivity in indirect drive implosions.* Physics of Plasmas, 2021. **28**(4): p. 042705, 10.1063/5.0033256.

22. A. Lees, et al., *Experimentally Inferred Fusion Yield Dependencies of OMEGA Inertial Confinement Fusion Implosions.* Physical Review Letters, 2021. **127**(10): p. 7, 10.1103/PhysRevLett.127.105001.

23. V. N. Goncharov, et al., Improving the hot-spot pressure and demonstrating ignition hydrodynamic equivalence in cryogenic deuterium-tritium implosions on OMEGA. Physics of Plasmas, 2014. **21**(5): p. 28, 10.1063/1.4876618.

24. V. Gopalaswamy, et al., *Tripled yield in direct-drive laser fusion through statistical modelling.* Nature, 2019. **565**(7741): p. 581-+, 10.1038/s41586-019-0877-0.

25. J. D. Lawson, *Some Criteria for a Power Producing Thermonuclear Reactor.* Proceedings of the Physical Society of London Section B, 1957. **70**(1): p. 6-10, 10.1088/0370-1301/70/1/303.

26. R. Betti, et al., Thermonuclear ignition in inertial confinement fusion and comparison with magnetic confinement. Physics of Plasmas, 2010. **17**(5): p. 10, 10.1063/1.3380857.

27. S. E. Wurzel and S. C. Hsu, *Progress toward fusion energy breakeven and gain as measured against the Lawson criterion.* Physics of Plasmas, 2022. **29**(6): p. 33, 10.1063/5.0083990.

Chapter 3:
Alternate Concepts

3.1 Introduction

A key advantage of inertial fusion energy (IFE) and a corresponding research direction is its significant degree of modularity, which facilitates integration of advanced concepts that can potentially increase gain, robustness, and performance. Indirectly driven central hotspot (CHS) schemes, which place more modest demands on laser coupling and performance, should progress from recent ignition-scale demonstrations, while pursuing development of other concepts. Indirect-drive CHS and direct-drive CHS ignition (which offers more efficient laser-to-capsule coupling) are covered in other sections (coupling, compression and burn, etc.). This chapter describes alternate concepts beyond these, meant to further increase performance by shaping the drive (shock ignition, SI), separating compression and heating (fast ignition, FI), and utilizing potentially high-efficiency drivers (e.g., ion beams, applied fields, etc.). Alternative fuels and other ideas, such as cross section modification, may also offer increased performance and the possibility of aneutronic operation. Figure 3.1 illustrates the theoretical potential of a selection of approaches, for which different designs have very different levels of maturity and experimental validation.

SUMMARY

The modularity of IFE facilitates integration of advanced concepts with potential to increase gain, robustness, and performance. Such concepts range from those we can test at existing facilities, such as shaping the drive (shock ignition), to those that will require new facilities or extensions to allow separating compression and heating (fast ignition). However, both those concepts and others will ultimately **require new facilities** able to test their function with IFE-relevant processes and scales.

While laser-driven systems are at the highest technical readiness, we can also investigate other high-efficiency drivers (e.g., ion beams, applied fields) and alternative fuels to mitigate risk and determine any performance advantages. Further, other ideas (dual-hemisphere implosion concept, impact FI, wetted foam targets) may be able to mitigate hydrodynamic instability growth. Finally, we should explore new techniques that potentially offer greater LPI control, a long-standing issue particularly important to many alternate concepts.

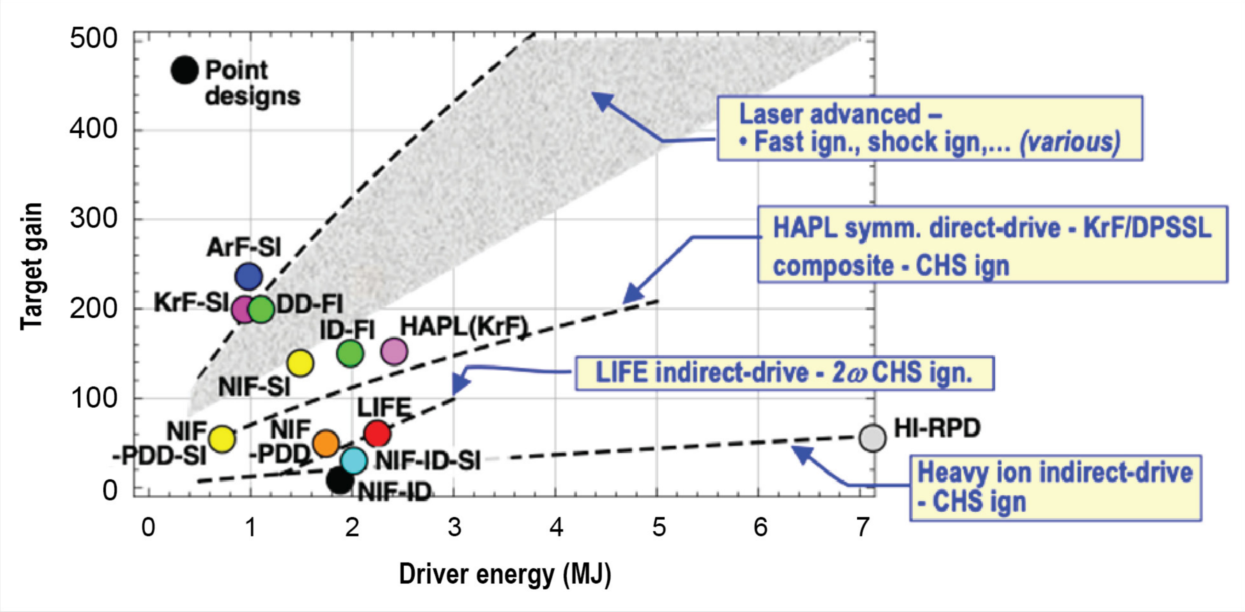


*Figure 3.1. Sample theoretical gain curves and point designs for various advanced inertial fusion energy (IFE) schemes compared to direct and indirect drive central hotspot (CHS) (Perkins, 2021 [2]). **NIF-ID**: National Ignition Facility (NIF) indirect drive, CHS (low adiabat); **NIF-PDD**: NIF polar direct drive, CHS; **NIF-PDD-SI**: NIF polar direct drive, shock ignition; **NIF-ID-SI:** NIF indirect drive, shock ignition; **HI-RPD**: heavy ion, robust point design, indirect drive, CHS; **LIFE:** laser inertial fusion energy, indirect drive, CHS; **NIF-SI**: NIF symmetric direct drive, shock ignition; **HAPL(KrF)**: high average power laser, direct drive, CHS (KrF driver); **ID-FI**: indirect drive, fast ignition; **DD-FI**: direct drive, fast ignition; **KrF-SI**: direct drive, shock ignition (KrF laser with zooming); **ArF-SI:** direct drive, shock ignition (ArF laser with zooming)*

Shock Ignition (SI)

SI is a two-stage hotspot variant of ICF that separates the assembly phase from the ignition phase in a high-areal-density implosion with the potential for high gain ($G \gtrsim 100$) [1, 2]. The fuel is assembled in a similar manner as with more conventional hotspot concepts and can be accomplished by direct drive or indirect drive, although most designs to date are directly driven. Typically, SI capsules are compressed at low velocity and low adiabat to enable higher-areal-density fuel assemblies with stability characteristics similar to or better than those of standard hotspot implosions. The assembled fuel is then ignited by launching a strong spherical shock inward into the capsule. This ignitor shock propagates through the fuel, collides with the return shock from the fuel assembly phase, and raises the hotspot pressure and temperature above the ignition threshold. The collision of return shock and ignitor shock establishes non-isobaric conditions in the hotspot, allowing for higher hotspot pressures than for conventional CHS designs of the same input laser energy. In most SI designs, a high-intensity (5×10^{15} to 10×10^{15} W/cm^2) laser spike pulse at the end of the main assembly pulse launches the ignitor shock (**Figure 3.2** [3]), using the same beams as the fuel assembly and/or a subset of dedicated ignitor beams. However, other spherically symmetric drivers (e.g., heavy-ion beams) could potentially drive the ignitor shock.

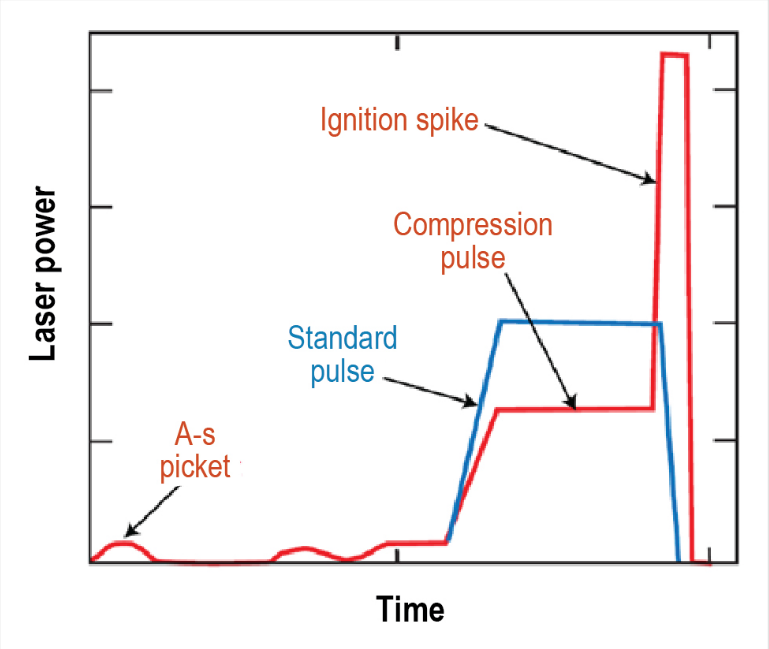


Figure 3.2. Shock ignition (SI) laser-pulse design (red) compared to a direct-drive central hotspot (DD-CHS) design (blue) (from Atzeni et al., 2014 [3]). A-s stands for adiabat-shaped.

Advantages of Shock Ignition (SI). SI has many advantages over typical CHS schemes. SI may enable substantial increases in gain (3–10x) at the same laser energy and reduce the laser energy for marginal ignition by half. This means that an IFE power plant operating with the SI scheme could potentially be a smaller, less expensive laser facility or could provide more electrical power in a facility designed at CHS-scale laser energies. Sub-scale spherical experiments at the OMEGA laser facility that added a lower-intensity (8×10^{14} W/cm^2) SI-like spike at the end of the laser drive resulted in a four-fold increase in yield compared to a no-spike design at the same laser energy, while areal densities also increased by 30 to 50% [4].

We can accomplish SI using the same or similar laser systems as standard hotspot schemes, without the complexity and expense of short-pulse, ultra-high-power lasers. The main difference between a laser system designed specifically for SI schemes and one designed for CHS schemes is that an SI laser system would be capable of stronger pulse shaping with a higher peak-power-to-energy ratio to allow for a more optimal ignitor pulse. We could test the feasibility of SI experimentally on the National Ignition Facility (NIF). Designs for NIF exist both in polar-direct-drive, requiring relatively minor system upgrades (e.g., direct-drive cryogenic handling, improved smoothing by spectral dispersion (SSD) beam smoothing), and in indirect-drive, using present-day hardware with no upgrades. While SI designs using indirect drive would experience the same reduced coupling efficiency as indirect drive–CHS designs (and therefore lower gains), such experiments would draw on the extensive experimental database of the present NIF indirect-drive ignition program and could provide near-term proof-of-concept of the SI scheme at ignition scale.

SI designs are typically imploded at a lower implosion velocity with higher shell/fuel mass than in CHS designs. Lower implosion velocity leads to more stable implosions, allowing the possibility of accessing lower-adiabat regimes without net-stability penalties. Lower-adiabat implosions can then enable higher areal densities, which in turn allow for higher burn-up fraction and gain. Since implosion velocities are lower, the main drive laser intensity in SI is also generally lower (3×10^{14} to 7×10^{14} W/cm^2) than in standard CHS schemes (8×10^{14} to 12×10^{14} W/cm^2). Lower laser intensity mitigates the risk of laser-plasma instabilities (LPIs) and fuel preheat by hot electrons during the fuel assembly phase. This can increase main drive efficiency, maintain low fuel adiabat for improved compression, and lead to higher areal density.

The SI concept is very flexible and can be applied to various hotspot designs, including direct drive, indirect drive, hybrid indirect-direct drive, double shells, and dynamic-shell implosions [5]. SI has a relatively large research community worldwide (see **Table 3.1**).

COUNTRY	INSTITUTION	FACILITY
United States	Laboratory for Laser Energetics (LLE) (University of Rochester)	OMEGA and OMEGA-EP (extended performance)
	Lawrence Livermore National Laboratory (LLNL)	NIF (National Ignition Facility)
	U.S. Naval Research Laboratory (NRL)	
	University of California, San Diego (UCSD)	
United Kingdom	Science and Technology Facilities Council (STFC) Rutherford Appleton Laboratory (RAL)	Vulcan
	York Plasma Institute (University of York, School of Physics, Engineering and Technology)	
	Center for Fusion, Space and Astrophysics (CFSA) (University of Warwick, Department of Physics)	
France	Alternative Energies and Atomic Energy Commission (CEA; French: Commissariat à l'énergie atomique et aux énergies alternatives)	
	Centre Lasers Intenses et Applications (CELIA) (University of Bordeaux, Centre national de la recherche scientifique (CNRS))	LMJ (Laser Megajoule) LULI (Laboratoire pour l'utilisation des lasers intenses)
Italy	Università di Roma "La Sapienza," Dipartimento di Scienze di Base e Applicate per l'Ingegneria (SBAI)	
	National Institute of Optics (CNR-INO; Italian: Consiglio Nazionale delle Ricerche – Istituto Nazionale di Ottica)	
Czech Republic	Prague Asterix Laser System (PALS)	PALS

Challenges with Shock Ignition (SI). Laser energy coupling and LPIs during the high-intensity SI spike-pulse remain uncharacterized experimentally at the relevant laser intensities and scale lengths. Many experiments have been conducted at ignition intensities in sub-scale plasmas and at ignition scale but with sub-ignition intensities. These experiments show encouraging results, with levels of LPI scattering and hot-electron generation that are tolerable or for which we may be able to compensate with existing techniques [6]. If we show the ignitor pulse–shock coupling efficiency at full scale and intensity to be lower than anticipated, increasing the implosion velocity of the fuel assembly may compensate and/or allow for higher ignition margin.

The spike pulse is likely to generate hot electrons due to stimulated Raman scattering (SRS) and two-plasmon decay (TPD) LPIs. Capsule ρR during the spike pulse should be sufficient to stop hot electrons less than ~50 keV in the outer layers of the fuel. However, hot electrons with higher energy could preheat the fuel, reduce compression, and preclude ignition. Angular spread of hot electrons may mitigate such preheat. Use of high-bandwidth and short-wavelength (e.g., ArF) lasers should further mitigate both types of deleterious LPIs, increase energy coupling, and reduce preheat.

More detailed information on SI can be found in relevant IFE Workshop whitepapers [7, 8].

Fast Ignition (FI) (electron, proton)

The FI concept is a laser-based method of achieving a controlled thermonuclear burn in a small (~20–50-µm radius), inertially confined, dense plasma [9]. Unlike CHS ignition, FI is a two-step process in which the compression and ignition phases are separate, requiring two markedly different laser systems. The first is the compression laser, which is similar in (temporal) length to that used in CHS ignition but contains considerably less energy (~ 500 kJ). The second “ignitor” laser produces a short (~10 ps), high-energy (~100 kJ) laser pulse that ignites the compressed fuel. Unlike CHS ignition, requirements on fuel assembly—such as symmetry and stability of the pusher-fuel interface—are significantly relaxed since FI only requires a small (r_hs ~ 20 µm), dense (~300–600 g/cm^3) central region of deuterium-tritium (DT) fuel with an areal density of ~1–3 g/cm^2. The requirements on the second (ignition) laser pulse are such that the particles (electrons, protons, or ions) it generates must be of sufficient energies to deposit their energy in the small volume of assembled fuel with sufficient total energy (~20–100 kJ, depending on the FI design) in a time less than the hydrodynamic expansion time of the assembled fuel (~10–20 ps). **Figure 3.3** illustrates the FI concept.

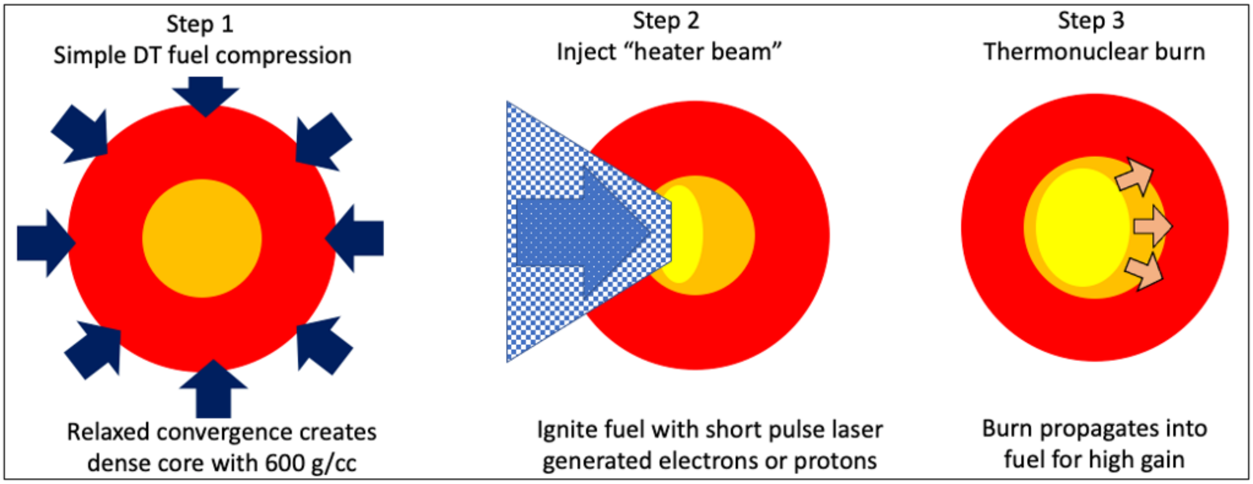


Figure 3.3. Schematic of fast ignition (FI) concept.

Advantages of Fast Ignition (FI). The main strength of this path to ignition is that, by separating the compression and ignition phases of laser fusion, we can greatly reduce the total laser energy, in addition to relaxing the symmetry and stability requirements relative to those for CHS ignition. Because we can greatly decrease the total required energy to achieve ignition with the FI concept while burning similar amounts of fuel as in CHS ignition, the energy gain could be much higher for FI [10]. Note that the partition between long- and short-pulse laser energy is such that the compression laser technology required for FI fuel assembly is already available, albeit not at the repetition rate (~10 Hz) required for IFE, but the short-pulse laser energies fall considerably short of what is required for the ignition phase of FI.

Between 1994 and 2004, a substantial effort in the United States investigated the electron FI idea with initial results from the NOVA PetaWatt laser at LLNL leading to interest worldwide [11]. Key experiments carried out at OMEGA-EP then showed the combination of ignition plus compression at small scale with encouraging results [12, 13]. These experiments used x-ray backlighting to measure compressed core assemblies in cone-in-shell geometry and found good agreement with 2D DRACO simulations [12]. The Osaka team in Japan also conducted integrated electron-based FI experiments [14]. In these experiments, according to their transport calculations, they improved the heating efficiency of the hot electrons from 0.4 to 4% by magnetizing the cone in the target and improving the contrast of the short-pulse laser. A team at LLNL did significant work on high-gain, reactor-scale designs of 2D cone-in-shell implosions using an indirect-drive implosion configuration with the HYDRA code [15].

Challenges with Fast Ignition (FI). A major challenge for electron FI is that the electron source during the ignition phase has a large angular divergence. Because the deposition region is so small and we can only generate the electrons at the critical surface tens of µm away from the compressed fuel, the estimated number of actual electrons delivered to the compressed fuel is low. One solution to this problem is to apply magnetic fields to the target, and preliminary experiments with magnetic-field guiding are encouraging [14, 16]. Another challenge is that for 1-µm light, the electron energies tend to be too high to deliver the required amount of energy to the compressed core. In principle, we can solve this problem with higher-frequency lasers.

Use of heavier particles, such as protons or light ions, can potentially overcome both these challenges [17, 18]. Experiments to date indicate that proton-beam generation through the target normal sheath acceleration (TNSA) mechanism is extremely robust [19, 20]. Because protons are almost 2000 times more massive than electrons, their trajectories are far less affected by the presence of self-generated electric and magnetic fields. We can ballistically focus protons to a small areal spot using hemispherical curved foils [21]. However, whether ballistic focusing will scale to the high-current proton beams required for FI in proximity to an implosion, or if space charge and magnetic field effects will cause the beams to diverge before achieving the required spot, is a critical question. While a portion of the proton energy spectra (10–50 MeV/nucleon) produced in TNSA have stopping powers in DT that are well matched to heating to the required hotspot areal density of ~1–3 g/cm^2, the spectra are exponentially falling with energy, so only a fraction of the proton beam energy will contribute to heating the hotspot [22].

A large amount of research has been performed on short-pulse facilities in the United States and throughout the world on the physics of ion acceleration, focusing, and heating [22-27]. The number of publications in this area, as well as the number of separate research groups involved, supports using short-pulse proton heating in the generation and study of HED plasmas. While some experiments have studied proton focusing in a cone-in-shell geometry, no experimental campaigns to date have studied the proton FI concept in an integrated system (spherical long-pulse compression with a short-pulse-produced proton beam) [28, 29]. In terms of proximity to ignition, studies using existing short-pulse lasers (100s of J) have shown that proton heating is effective at heating solid density matter to >100 eV, but no one has performed experiments of heating compressed matter [30].

Alternate Driver Concepts: Heavy Ions and Magnetic Drive

Accelerator-based heavy-ion and pulsed-power-magnetic drivers are alternatives to lasers and have the potential to efficiently deliver large energies to IFE targets, leading to favorable efficiency-gain product for power-plant operation. They also offer risk mitigation for optical damage. We can also potentially use applied magnetic fields to enhance laser-driven systems.

Heavy-Ion Drivers. Heavy-ion fusion (HIF) concepts use high-current particle accelerators to drive targets for IFE. Heavy-ion pulses (~100–200 amu, ~1–20 GeV, ~10 ns) would deliver a few MJ of energy into targets and have the potential to provide efficient energy coupling in direct or indirect drive, including a concept allowing single-sided illumination [31-37]. Heavy-ion accelerators have high wall-plug efficiency (20 to >30%), heavy-ion optics are robust, and high-power accelerators have operated reliably for years. Scaled experiments and simulations indicate that we can reach required focused-beam intensities on targets. Existing accelerators are comparable to projected HIF drivers in total beam energy, focusing, average beam power, repetition rate, reliability, and durability but are far from the high peak power of several 100 TW in ~100 beams and ~10-ns pulses at ~10 Hz, which we still need to develop. Further, we have yet to extend beam transport and focusing simulations to multiple beams. Since we may need to employ on the order of a hundred beams (in both the driver and the chamber), additional studies on the electromagnetic forces these beams exert on each other are warranted. Driver-design studies at a modest level could address whether new accelerator technologies offer cost-attractive and efficient paths, comparing findings to evolving laser and other driver studies to assess driver attractiveness. In the near-term, HIF research and development (R&D) should focus on conducting target-heating and beam-coupling physics studies, in particular at high currents, leveraging LaserNetUS facilities, as well as international facilities, such as the FAIR (Facility for Antiproton and Ion Research) ion accelerator at GSI (Helmholtz Centre for Heavy-Ion Research). Research should identify a cost-effective path to a HIF target-heating facility based on data from scaled experiments and benchmarked models.

Magnetic Drive. Pulsed-power Z-pinches have been proposed as a source of energy via thermonuclear fusion since Thomson and Blackman investigated linear discharges for fusion reactions [38]. Since then, both indirect-drive and direct-drive pulsed-power-based concepts have been developed and studied for magnetized inertial fusion energy. Importantly, magnetized inertial fusion uses a large-volume plasma, which promises significantly higher efficiency. One concept recently pursued at Sandia National Laboratories is called magnetized liner inertial fusion (MagLIF). In this concept, a beryllium cylinder containing the fusion fuel at high pressure is pre-magnetized with an axial field by external coils. As the magnetically driven implosion of the cylinder is initiated, a laser pre-ionizes and preheats the fuel to several 100 eVs.

The fuel is then compressed and heated to ignition temperatures by the imploding metal cylinder. **Figure 3.4** illustrates the various phases of heating and implosion. Scaling models and 2-D target designs estimate the required preheat energy and magnetization and the pulsed-power-driven current's time-history tradeoffs, with validation studies conducted within the range presently accessible on the Z facility. IFE requires several modifications to existing MagLIF targets including developing (1) "automag" pre-magnetization, (2) a pulsed-power-driven preheat system, and (3) a DT "ice" layer system for the liner's inner surface [39, 40]. The engineering challenges of repetitively delivering large energy and current in a closely coupled system, managing multi-GJ yields, recycling debris, and robotically installing new power flow and target assemblies are formidable, and we must address them [41-43]. Sandia's National Nuclear Security Administration (NNSA) ICF program will continue to provide single-shot data on Z, and the proposed Next-Generation Pulsed-Power (NGPP) for NNSA's high-yield ICF mission would develop integrated target designs that we could adapt for IFE. Smaller scale, few-MA university drivers can supplement the limited data available from the Z generator at Sandia. However, if we are to develop magnetic drive as an IFE concept, then the pulsed power community will need to design and propose a mid-scale facility (10 MA) to either NNSA or FES.

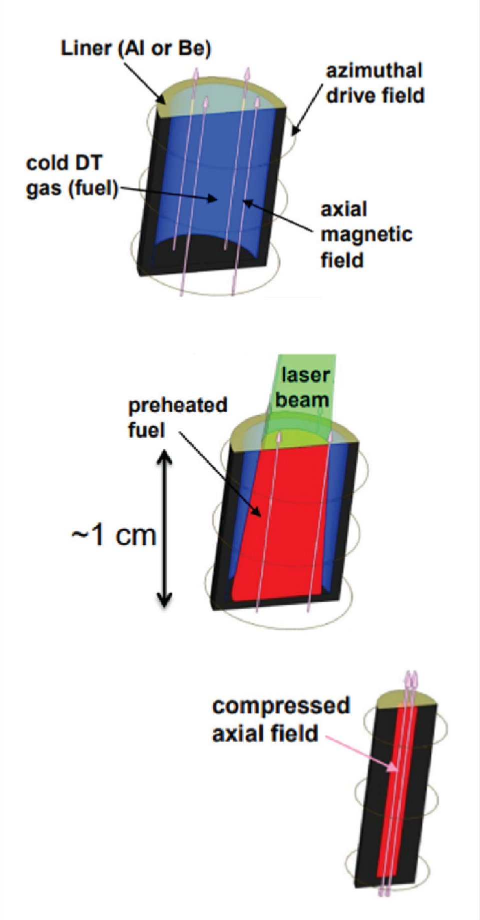


Figure 3.4. Schematic of the magnetized liner inertial fusion (MagLIF) concept showing (left) initial target components, (center) heating of the fuel by a laser, and (right) compression of the heated fuel by pulsed power.

The potential advantages of applied magnetic fields in laser-compressed ICF were recognized four decades ago [44, 45]. Imposed fields of tens of tesla that increase to greater than 10 kT (100 MGauss) under capsule compression could relax conditions for ignition and propagating burn in ICF targets through reduction of fusion alpha particle range, suppression of electron heat conduction, and stabilization of higher-mode Rayleigh-Taylor instabilities [46]. These relaxed conditions could result in improved ignition robustness and higher yield/gain performance. Researchers have recently observed that a 500 kG, externally applied B field increases the mode-two asymmetry in shock-heated, directly driven inertial fusion implosions on the OMEGA 60 laser facility [47]. Using a direct-drive implosion with polar illumination and imposed field, the magnetization produces a significant increase in the implosion oblateness. In contrast, in indirect drive, imposed fields may have only small perturbing effects on the hohlraum drive symmetry and on the final imploded fuel configuration, even at high convergence ratios of >30 [46, 48]. Recent experiments show that applying an initial external pulsed 26-T axial magnetic field to a room-temperature, D_2 gas-filled capsule, indirectly driven on NIF, increases ion temperature 40% and neutron yield by a factor of 3.2 in a hotspot with areal density and temperature approaching that required for fusion ignition (see **Figure 3.5**) [49]. The fundamental research need in the immediate term is to assess magnetohydrodynamic (MHD) ignition and burn

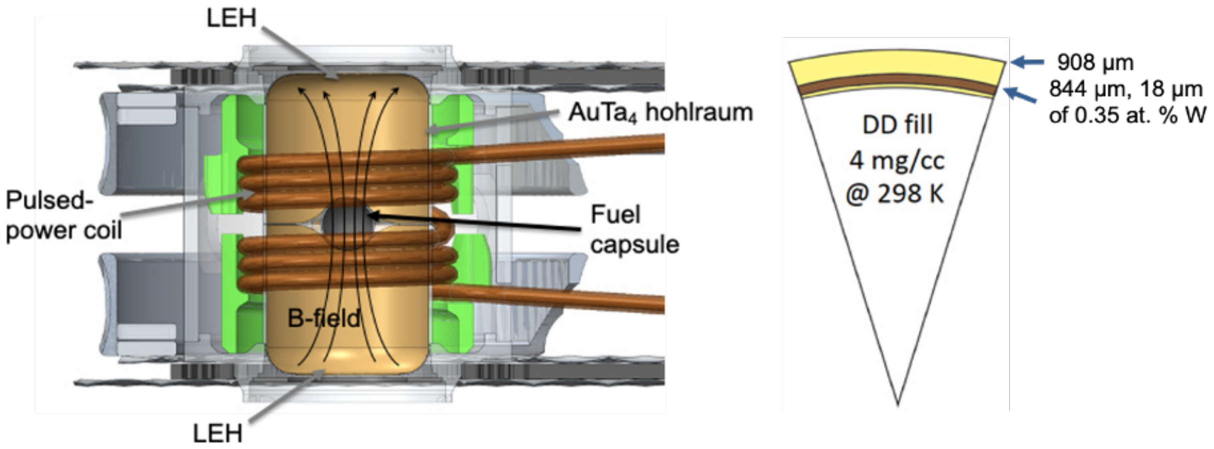


Figure 3.5. *National Ignition Facility (NIF) pulsed-power coil and hohlraum for experiments with room-temperature gas capsules.*

conditions in magnetized cryogenic fuel experiments, together with supporting theoretical and computational studies. A cryo-capable, pulsed-power supply/coil system is now under construction on NIF for DT ignition targets and is scheduled for completion in 2024; developing concepts for high-rate IFE operation will be important.

Alternate Fuels

Aneutronic fusion is a potentially attractive alternative to the DT fuel cycle [50]. The primary products are charged particles, enabling higher energy conversion and limiting neutron damage to reactor structures. However, the Lawson criterion for aneutronic fusion reactions is substantially higher than for DT because the cross sections are lower and peak at higher ion energies. Margarone *et al.* (2022) proposed interesting IFE-relevant concepts using p-B^{11} that combine fuel assembly with the interaction of protons accelerated by chirped pulse amplification lasers to produce high gain (despite lower cross-section), but this approach would require further development of target point designs and experiments [51]. This proposed concept does not require cryogenic handling—as the fuel is already in a solid state—and avoids the difficulties of tritium startup inventory and breeding [52]. We can also minimize tritium inventories via combined fuel cycles that use tritium-poor fuels to initiate the burn of alternate fuels, including deuterium, D-He^3, and p-B^{11} [53]. The tradeoff between target gain penalties and reductions in reactor engineering costs require further study. Fusion cross-section enhancement via strong electric fields produced by x-ray free-electron lasers (XFELs), by nuclear shape enhancement of deformed nuclei, and by using spin-polarized fuel have been proposed as paths toward alternate and more efficient fuel cycles [54, 55]. The direct illumination of fusion fuels with ultra-intense laser pulses or x-rays may also result in larger tunneling and increased fusion reaction rates [56].

These approaches are still largely in the conceptual stage and require considerable further development and experimental validation. The science and technology challenges and knowledge gaps include (1) designs and experimental data for alternate fuels, combined cycles, and cross-section enhancements that are only a small fraction of that for DT; (2) ignition criterion and point-target designs required for p-B^{11} IFE; (3) maturation of advanced energy conversion concepts; (4) tritium-poor designs studied in the context of reactor and system costs and tradeoffs; and (5) validation of cross section enhancements on smaller laser systems, XFELs, etc., as well as development of a credible pathway for applying these enhancements to IFE systems. Enabling technologies and areas of overlap with ICF include the following:

1. Alternate fuels and combined cycles will utilize similar driver technologies to DT IFE
2. Target-design methodologies and generalized Lawson criteria are shared with NNSA ICF
3. Existing ICF and LaserNetUS platforms can be used for initial validation experiments
4. p-B^{11} targets may utilize FI concepts

Other Ideas

The flexibility provided by separation of driver and target in inertial fusion continues to allow new ideas that may offer the potential for future high-performance fusion energy. These include the idea of fusion energy amplification using a dual-hemisphere implosion concept, impact FI, and wetted foam targets that may have the ability to mitigate hydrodynamic instability growth.

Dual-Hemisphere Implosion. In 2010, Nuckolls suggested a novel IFE design that would make use of a density gradient in the assembled fuel to amplify the fusion yield [57]. As an initial concept, he proposed a design consisting of two different hemispheres with a density step between them. The first hemisphere was based on a typical fast-ignited fuel assembly (density $\rho = 300\ \mathrm{g/cm^3}$, areal density $\rho R = 3\ \mathrm{g/cm^2}$, and temperature $kT = 10$ keV). The other hemisphere was much larger and consisted of cold fuel at $\rho = 30\ \mathrm{g/cm^3}$ and $\rho R = 1.4\ \mathrm{g/cm^2}$. The high-density hemisphere ignites, and the burn then propagates into the cold fuel reservoir provided by the second hemisphere, which has a much larger fuel mass. Simulations performed by Zimmerman and presented in Nuckolls' paper suggest that this reservoir of cold fuel amplifies the yield of the first hemisphere by ten times and offers an improvement in yield of 2.5 times compared to a full spherically symmetric capsule based on the first hemisphere only. We could realize this design in practice by placing a high-density carbon or higher-Z glide plane between two hemisphere capsules (the hemispheres are kept separate by the glide plane) [58]. By applying different pulse sequences to the two hemispheres, an assembled fuel forms at the time of peak compression, and the benefits in yield amplification are realized. Such a design could be considered an extreme form of cone-guided compression, where the "cone" (glide plane) has an angle of 180 degrees and the fast ions would be

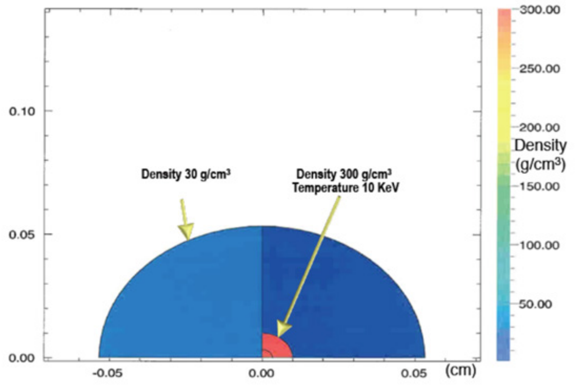
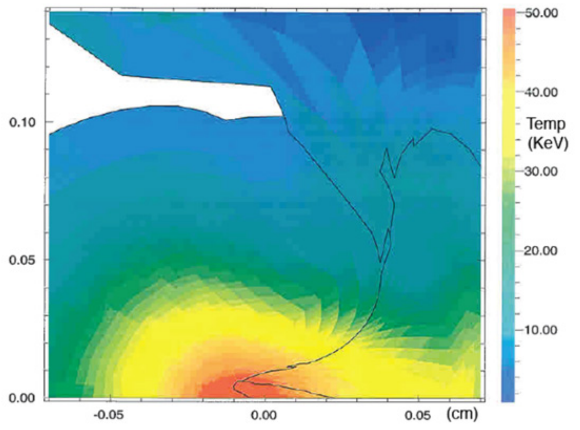


Fig. 1 Initial configuration for calculations of ignition across a 10X density step



Fusion driven explosion of the high-density fuel ignites the 10X lower density fuel (George Zimmerman – private communication)

Figure 3.6: *The schematic of the Nuckolls' dual-hemisphere approach (top), demonstrating the potential for significant fusion yield amplification (bottom). From Nuckolls (2010) [57].*

alpha particles, generated *in situ* by fusion reactions in the high-density hemisphere. As Nuckolls proposed that this hemisphere is itself ignited by electron-driven FI, this design would essentially mean using FI (or auxiliary heating) to ignite this hemisphere, which in turn acts as an ion source to fast-ignite the larger hemisphere [59]. Indeed, one notes that the existing NIF laser indirect-drive HYBRID-E target and laser driver design (3.15-MJ fusion yield) would be suitable for the ignition side of the dual hemisphere design, with the corresponding amplification in fusion yield [60].

Impact Fast Ignition (FI). Application of high-velocity projectiles on pre-compressed fusion fuels provides a potential route to FI and high gain. The kinetic energy of the projectile—one that also contains the fusion fuels—operates at high velocities (10^8 m/s) and provides the thermal energy to produce the hotspot spark at the collision point [61]. The NIKE laser facility has demonstrated the required high-fidelity acceleration of planar targets using KrF laser drivers [62].

Wetted Foam Targets. Replacing the cryogenic ice layer with a liquid-soaked DT foam layer may offer advantages in fill/layering time that could reduce DT inventory and are hence attractive. Wetted foams also allow much greater control of the initial vapor layer in the target's central gas region and thereby much greater control over the convergence ratio. Smaller convergence ratios (less than 17) give reduced hydrodynamic instability growth and mix at bang time (time of peak fusion energy production) [63]. In pioneering indirect-drive wetted-foam implosion experiments on NIF, Olson *et al.* demonstrated near 1D-like performance [64]. Following this success, Paddock *et al.* explored directly driven low-convergence-ratio wetted foam implosions numerically, in which both hydrodynamic and parametric instabilities are minimized [65, 66]. Gains of 0.75 ($Q = 0.75$) might be possible using third harmonic light of Nd:glass laser facilities (351 nm) at NIF-scale energies (1.7 MJ). Further work has shown that we can increase this gain by using deeper ultraviolet (UV) laser light (e.g., 193 nm from ArF excimer lasers or 5th harmonic from Nd:glass (210 nm)) and auxiliary heating schemes. Individually, studies have investigated the impact of both deep-UV laser pulses and auxiliary heating, reporting gains of around 15–17 for a total input of ~2 MJ of energy. These studies demonstrate that by augmenting the gain of robust, wetted-foam implosions, we might achieve consistent high-gain implosions. These implosions offer yields that, when accounting for the expected improvement from the dual-hemisphere design concept, would approach and surpass the gains of 50 we expect will be required for a commercially competitive IFE reactor at the MJ-drive energy level [57, 58]. We can use indirect-drive experiments on NIF, as well as polar direct-drive experiments, to test the hydrodynamic performance of these capsules. Indeed, Olson *et al*. have shown that polar direct-drive wetted-foam implosion designs (at 1.4-MJ drive-energy level) might also give impressive performance [67].

3.2 Priority Research Opportunities (PROs)

PRO 3-1: ***Develop the path for external short-pulse fast ignition (FI) of a compressed core to realize the theoretical gain-advantage of separable compression and ignition***

The ability to efficiently heat and ignite high-density DT fuel with an external particle source would be a game changer for IFE, dramatically expanding design space, significantly relaxing implosion requirements, and enabling access to high fusion gains by simply increasing the pre-assembled fuel mass, independently of the ignitor energy. The single biggest question for this scheme is whether or not it is possible to generate a particle beam with the required energy and efficiency and then focus it into the fuel within the volume and time necessary to initiate ignition. Two main approaches to FI, electron and proton, each have their own challenges and opportunities.

Electron FI has an advantage of high laser-to-electron conversion efficiency (>40%) [10]. In addition, transport distances are minimized since the electrons are generated quite close to the compressed fuel. However, the relativistic laser-solid interaction physics are complex, which has resulted in both energy distribution and angular distribution that do not efficiently couple to the core. A potential mitigation strategy for the energy distribution issue is to use shorter wavelength lasers (e.g., 2ω laser irradiation). One solution to the angular distribution problem is to collimate the electrons, such as through self-generated or externally applied magnetic fields. While applying external fields increases target complexity and reduces relevancy to IFE, experiments on LFEX have successfully demonstrated this approach. The main challenges for the electron FI scheme include the following:

1. Focusing the laser to a spot size similar to the required electron source size (<40-µm diameter) with high pointing accuracy
2. Sufficiently controlling the electron source distribution, which is dependent on the laser intensity and contrast

Proton FI was envisioned as an alternative approach soon after the discovery of laser-generated proton beams through target-normal-sheath-acceleration (TNSA). It reduces or eliminates many of the challenges in electron FI: (1) the TNSA mechanism is very robust and relatively insensitive to details of the incident laser conditions since the proton acceleration region is physically separated from the LPI region, (2) a large fraction of the proton energy spectrum is well-matched for stopping in the fuel, (3) protons may be ballistically focused to a small volume, and (4) the laser focusing requirements are far less demanding (~800-µm diameter focal spot versus ~40 µm for electron FI). The main challenges for proton FI include (1) achieving laser-to-proton conversion efficiencies of >10–15% in the relevant energy range and (2) maintaining the focusability of the protons in the presence of increasingly strong self-generated fields as the proton beam current approaches IFE-relevant values and nears an implosion.

The high-repetition-rate, short-pulse laser facilities in LaserNetUS, at 10s of J per pulse, provide an excellent opportunity to address many issues in both electron and proton FI, in particular studying and optimizing proton acceleration and focusing. We also need an intermediate-scale combined short-pulse and long-pulse facility at multi-kJ levels to demonstrate efficient electron generation and transport in the compressed fuel assembly, as well as proton acceleration and focusing, and sub-ignition heating physics. Finally, demonstrating short-pulse energy coupling at scale will require a full-scale, 150–200-kJ short-pulse in conjunction with an ignition-scale compression facility (perhaps 400–600 kJ long-pulse).

PRO 3-2: ***Demonstrate isochoric fuel assembly at ignition scale for fast ignition (FI)***

One of the main advantages of FI is that the compression and ignition phases are independent of each other. While the challenges associated with the ignition phase as outlined above are considerable, the compression phase is relatively simple in comparison. The fuel assembly is common to all FI schemes. Indirect- and direct-drive isochoric compression schemes with cone-in-shell geometry have both been proposed, and both achieve the requisite peak and areal density [15, 68]. In contrast to the ignition phase discussed above, in which the short-pulse laser energy required for FI (~50–200 kJ) is orders of magnitude higher than current lasers (~3 kJ for multi-beam lasers like NIF-ARC and OMEGA-EP), lasers already exist that are capable of demonstrating isochoric fuel assembly at, or near, ignition scale.

Several existing laser facilities have the capabilities needed to study various aspects of fuel assembly for FI. For example, kilojoule nanosecond laser facilities, like OMEGA and Gekko/LFEX, are already studying the fuel assembly required for FI, albeit to date these studies have been limited. Designs for half-scale implosions on NIF have already been proposed using ~0.5-MJ indirect drive, implying that FI-relevant experiments could be proposed in the very near future [15]. While the NIF laser is suitable for ignition-scale indirect-drive isochoric implosion studies at near-full-scale energies (~2 MJ), the absence of a symmetric-drive beam configuration is problematic for direct-drive studies, which promise more efficient implosions. For example, Atzeni *et al.* (2007) proposed designs with as little as 100–200 kJ of implosion laser energy that would provide the required compressed core to achieve gains of 200 using a 20–100-kJ short-pulse laser [68]. OMEGA is suitable for and has already performed integrated direct-drive cone-in-shell compression (including short-pulse heating) in sub-ignition-scale experiments [12]. However, for all these kilojoule, nanosecond facilities, limited access to shots and low shot rate pose a challenge for developing electron and proton FI or other IFE concepts.

To make significant progress on FI, we need the following new and higher repetition-rate facilities dedicated to IFE:

1. An intermediate kJ-class multi-beam facility with shot-on-demand repetition rate to study isochoric fuel assembly, including direct-drive compression and compression-phase LPI physics. The shot-on-demand laser capability (i.e., ~minutes/shot) would increase data return by 1–2 orders of magnitude over current ~hour/shot facilities, whilst avoiding the complexity of ~10-Hz operation.
2. An ignition-scale FI facility of ~400–600-kJ long-pulse that also includes a ~150–200-kJ short-pulse capable of demonstrating gain and propagating burn.

PRO 3-3: ***Demonstrate and improve laser energy coupling at scale in shock ignition (SI)***

For SI to succeed, we must experimentally investigate laser energy coupling and LPIs at SI spike-pulse intensities (5×10^{15} to 10×10^{15} W/cm^2) and ignition-scale lengths (~350–500 µm). This effort would provide a baseline for shock energy coupling and inform the level of LPI reduction needed to launch a robust ignitor shock. It would also provide a benchmark for validating radiation-hydrodynamics codes in this regime. One path forward is to extend the existing strong spherical shock (SSS) platform at NIF to higher laser intensities (up to 5×10^{15} W/cm^2) to provide data at scale and intensity [12]. These data would advise future experiments at next-generation high-bandwidth laser facilities. In parallel, we can investigate the feasibility of SI on NIF in indirect drive, including optimizing target designs relative to blue/green laser energies and powers, characterizing LPI, and planning for proof-of-principle experiments in the near-term. This effort should be reinforced by fundamental LPI control experiments (see PRO 3-4, below).

SI also requires that we demonstrate a low-adiabat, high-mass fuel assembly with high areal density (also necessary for FI and CHS IFE). A short-term experimental path toward accomplishing this demonstration in direct drive would require that we implement a direct-drive-specific cryogenic handling system and improved beam smoothing (SSD) on NIF. Prior experiments on NIF have already demonstrated such fuel assembly in indirect drive, albeit at somewhat higher adiabat than is ideal for SI. Regardless, the indirect-drive platform may prove useful in demonstrating such fuel assemblies, and we could directly apply it to indirect-drive SI.

PRO 3-4: ***Control/eliminate laser-plasma instabilities (LPIs)***

We should explore the use of new techniques that offer potential for greater control of LPI, a long-standing issue particularly important to numerous alternate concepts, many of which motivate increased laser intensity and/or finer control. Introducing significant bandwidth into the laser pulses required for direct-drive reduces the homogeneous growth rate and intensity thresholds of two important parametric instabilities: stimulated Raman scatter (SRS) and two-plasmon decay (TPD). This reduction will allow increased ablation pressure and implosion velocities, resulting in greatly reduced drive energy for ignition and high gain for direct drive [69, 70]. On the other hand, the thermal filamentation instability, which counteracts the increased thresholds for both SRS and TPD, is itself bandwidth-independent, so it may provide a new intensity threshold barrier for unacceptable parametric instability growth. We should also study additional approaches using STUD Pulses (Spike Train of Uneven Duration and Delay) for the control of LPI in ICF, IFE, and HEDLP. Unfortunately, no existing laser facilities where we could explore this competition have sufficient energy and bandwidth to suppress SRS or TPD for fully symmetric implosions. Most existing high-energy laser systems have relative bandwidths of ~0.1%. We should elucidate the growth rates, thresholds, and control of SRS, TPD, and thermal filamentation instability using these techniques with new laser capabilities. Optical parametric amplification of a broadband seed beam using a high-energy pump beam provides a potential path toward the high-energy broadband laser pulses needed. Stimulated rotational Raman scattering (SRRS) also provides a promising path toward increasing the bandwidth of high-energy laser pulses. Several facilities offer platforms for sub-scale tests supporting future larger scale studies, including the Zeus facility at the University of Michigan and the multi-terawatt laser (MTW) testbed for the OPAL laser facility and the broadband laser beamline (FLUX)(both currently being built at the University of Rochester), in addition to LaserNetUS facilities.

PRO 3-5: ***Explore alternate concepts and advanced fuels***

While laser-driven systems are at the highest technical readiness, we must also investigate alternative driver concepts, which is important for risk mitigation and potential performance advantages. Examples include HIF and magnetic drivers, advanced fuels, and other methods. Alternate concepts will likely have a longer timescale than evolution of existing concepts but could have disruptive impact. Modest investment could have significant impact in preserving and advancing such alternatives.

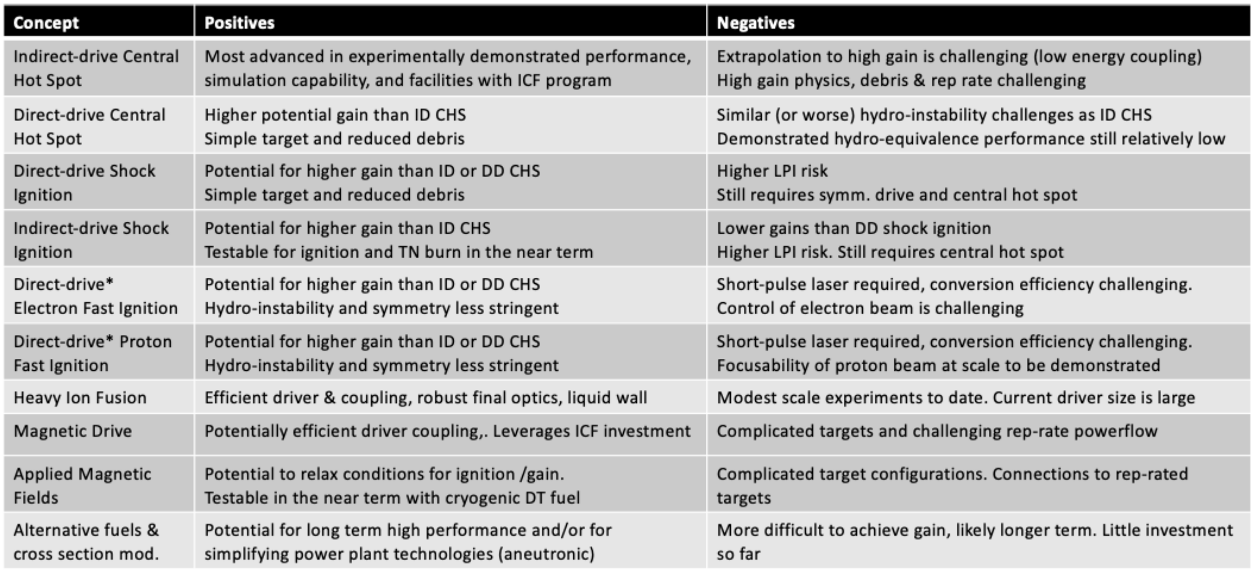
A near-term focus of HIF R&D should be to conduct target and coupling physics, leveraging newly available facilities (conventional and laser-driven), and to conduct studies to identify a cost-effective path to a HIF target-heating facility based on data from scaled experiments and benchmarked models. Experiments with kilojoule beams may be available in 2026 at the Facility for Antiproton and Ion Research (FAIR) at GSI in Darmstadt, Germany and, combined with LaserNetUS facility-generated ion beams, these facilities will have the potential to retire key residual risks at a modest cost. We should also extend beam transport and focusing simulations to multiple beams to understand and control electromagnetic forces between beams. In the longer term, this approach will enable us to propose new accelerators, taking advantage of significant advances in accelerator technology (in collaboration with DOE High-Energy Physics (HEP)).

For magnetic drive, the proposed Next Generation Pulsed Power (NGPP) for the NNSA high-yield ICF mission should develop integrated target designs that we could adapt for IFE. IFE target design requires several modifications to existing MagLIF targets including (1) developing an “automag” pre-magnetization system to replace the Helmholtz coils, (2) developing a pulsed power–driven preheat system to replace laser preheat optics, and (3) developing the ability to generate and maintain a DT "ice" layer on the inner liner wall. The greatest need for IFE pulsed power is the development of a repetitive transmission line or an alternative repetitive current delivery technique.

Alternative fuels and cross-section modification concepts should focus on developing these schemes (underpinned by robust physics models) toward potential system concepts and experiments to benchmark and validate. This will include maturing the evaluation of generalized Lawson criteria for alternate fuels and combined cycle, measuring proposed cross-section modifications, and developing ignition-point designs for alternate fuels (e.g., p-B^{11}).

3.3 Conclusions

While inertial fusion has entered the ignition regime based on well-established CHS ignition schemes, achieving the very high gains needed for IFE motivates development of advanced concepts to further increase performance. These range from techniques at high technical readiness that we can test in the near future at existing facilities, such as shaping the drive (shock ignition; SI), to those that will require new facilities or extensions to separate compression and heating (fast ignition; FI) and to driver risk-mitigation and/or efficiency methods, which require further exploration to provide future alternatives (e.g., ion beams, magnetic fields, etc.). Alternative fuels and other concepts, such as cross-section modification, auxiliary heating, and dual-hemisphere implosions, may also offer potential increased performance and the possibility of aneutronic operation. Table 3.2 gives an overview of the range of ideas presented in this chapter and notes key motivating positive traits for each. The table's "negatives" column notes important current limitations or constraints, alongside the main R&D needs for each concept. Exploring a range of these ideas, in many cases at a moderate level, will provide both risk mitigation and potential for high-performance systems. Because they are integrated concepts, developing advanced methods will require input from the other areas of this workshop.



Concept	Positives	Negatives
Indirect-drive Central Hot Spot	Most advanced in experimentally demonstrated performance, simulation capability, and facilities with ICF program	Extrapolation to high gain is challenging (low energy coupling) High gain physics, debris & rep rate challenging
Direct-drive Central Hot Spot	Higher potential gain than ID CHS Simple target and reduced debris	Similar (or worse) hydro-instability challenges as ID CHS Demonstrated hydro-equivalence performance still relatively low
Direct-drive Shock Ignition	Potential for higher gain than ID or DD CHS Simple target and reduced debris	Higher LPI risk Still requires symm. drive and central hot spot
Indirect-drive Shock Ignition	Potential for higher gain than ID CHS Testable for ignition and TN burn in the near term	Lower gains than DD shock ignition Higher LPI risk. Still requires central hot spot
Direct-drive* Electron Fast Ignition	Potential for higher gain than ID or DD CHS Hydro-instability and symmetry less stringent	Short-pulse laser required, conversion efficiency challenging. Control of electron beam is challenging
Direct-drive* Proton Fast Ignition	Potential for higher gain than ID or DD CHS Hydro-instability and symmetry less stringent	Short-pulse laser required, conversion efficiency challenging. Focusability of proton beam at scale to be demonstrated
Heavy Ion Fusion	Efficient driver & coupling, robust final optics, liquid wall	Modest scale experiments to date. Current driver size is large
Magnetic Drive	Potentially efficient driver coupling,. Leverages ICF investment	Complicated targets and challenging rep-rate powerflow
Applied Magnetic Fields	Potential to relax conditions for ignition /gain. Testable in the near term with cryogenic DT fuel	Complicated target configurations. Connections to rep-rated targets
Alternative fuels & cross section mod.	Potential for long term high performance and/or for simplifying power plant technologies (aneutronic)	More difficult to achieve gain, likely longer term. Little investment so far

Table 3.2: Key positive traits and issues, which should focus development for each scheme.

**Indirect drive versions also exist*

References

1. R. Betti, et al., *Shock ignition of thermonuclear fuel with high areal density.* Physical Review Letters, 2007. **98**(15): p. 4, 10.1103/PhysRevLett.98.155001.

2. L. J. Perkins, *And Now on to Higher Gains: Physics Platforms and Minimum Requirements for Inertial Fusion Energy*. 2021: IFE Strategic Planning Workshop, Lawrence Livermore National Laboratory.

3. S. Atzeni, et al., *Shock ignition of thermonuclear fuel: principles and modelling.* Nuclear Fusion, 2014. **54**(5): p. 21, 10.1088/0029-5515/54/5/054008.

4. W. Theobald, et al., *Initial experiments on the shock-ignition inertial confinement fusion concept.* Physics of Plasmas, 2008. **15**(5): p. 9, 10.1063/1.2885197.

5. V. N Goncharov, et al., Novel Hot-Spot Ignition Designs for Inertial Confinement Fusion with Liquid-Deuterium-Tritium Spheres. Physical Review Letters, 2020. **125**(6), 10.1103/physrevlett.125.065001.

6. D. Barlow, et al., Role of hot electrons in shock ignition constrained by experiment at the National Ignition Facility. Physics of Plasmas, 2022. **29**(8): p. 9, 10.1063/5.0097080.

7. K. S. Anderson, et al., Shock Ignition: High Gain Target Performance for Inertial Fusion Energy "[White paper]", in NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

8. L. J. et al. Perkins, *Shock Ignition in Indirect Drive "[White paper]"*, in *IFE BRN*. 2022 (see Accepted White Papers at https://events.bizzabo.com/IFEBRN2022/page/2133559/white-papers).

9. M. Tabak, et al., *IGNITION AND HIGH-GAIN WITH ULTRAPOWERFUL LASERS.* Physics of Plasmas, 1994. **1**(5): p. 1626-1634, 10.1063/1.870664.

10. M. H. Key, *Status of and prospects for the fast ignition inertial fusion concept.* Physics of Plasmas, 2007. **14**(5): p. 15, 10.1063/1.2719178.

11. S. P. Hatchett, et al., Electron, photon, and ion beams from the relativistic interaction of Petawatt laser pulses with solid targets. Physics of Plasmas, 2000. **7**(5): p. 2076-2082, 10.1063/1.874030.

12. W. Theobald, et al., *Spherical strong-shock generation for shock-ignition inertial fusiona).* Physics of Plasmas, 2015. **22**(5): p. 056310, 10.1063/1.4920956.

13. L. C. Jarrott, et al., Visualizing fast electron energy transport into laser-compressed high-density fast-ignition targets. Nature Physics, 2016. **12**(5): p. 499-+, 10.1038/nphys3614.

14. S. Fujioka, et al., Fast ignition realization experiment with high-contrast kilo-joule peta-watt LFEX laser and strong external magnetic field. Physics of Plasmas, 2016. **23**(5): p. 11, 10.1063/1.4948278.

15. H. D. Shay, et al., *Implosion and burn of fast ignition capsules-Calculations with HYDRA.* Physics of Plasmas, 2012. **19**(9): p. 8, 10.1063/1.4751839.

16. D. J. Strozzi, et al., Fast-ignition transport studies: Realistic electron source, integrated particle-in-cell and hydrodynamic modeling, imposed magnetic fields. Physics of Plasmas, 2012. **19**(7): p. 14, 10.1063/1.4739294.

17. A. P. Fews, et al., *Plamsa Ion Emission from High-Intensity Picosecond Laser-Pulse Interactions wIth Solid Targets.* Physical Review Letters, 1994. **73**(13): p. 1801-1804, 10.1103/PhysRevLett.73.1801.

18. M. Roth, et al., *Fast ignition by intense laser-accelerated proton beams.* Physical Review Letters, 2001. **86**(3): p. 436-439, 10.1103/PhysRevLett.86.436.

19. P. K. Patel, et al., *Isochoric heating of solid-density matter with an ultrafast proton beam.* Physical Review Letters, 2003. **91**(12): p. 4, 10.1103/PhysRevLett.91.125004.

20. S. C. Wilks, et al., *Energetic proton generation in ultra-intense laser-solid interactions.* Physics of Plasmas, 2001. **8**(2): p. 542-549, 10.1063/1.1333697.

21. Teresa Bartal, et al., *Focusing of short-pulse high-intensity laser-accelerated proton beams.* Nature Physics, 2012. **8**(2): p. 139-142, 10.1038/nphys2153.

22. S. Atzeni, M. Temporal, and J. J. Honrubia, *A first analysis of fast ignition of precompressed ICF fuel by laser-accelerated protons.* Nuclear Fusion, 2002. **42**(3): p. L1-L4, 10.1088/0029-5515/42/3/101.

23. M. Roth, et al., *Proton acceleration experiments and warm dense matter research using high power lasers.* Plasma Physics and Controlled Fusion, 2009. **51**(12): p. 7, 10.1088/0741-3335/51/12/124039.

24. J. C. Fernandez, et al., *Fast ignition with laser-driven proton and ion beams.* Nuclear Fusion, 2014. **54**(5): p. 36, 10.1088/0029-5515/54/5/054006.

25. J. J. Honrubia and M. Murakami, *Ion beam requirements for fast ignition of inertial fusion targets.* Physics of Plasmas, 2015. **22**(1): p. 10, 10.1063/1.4905904.

26. D. Mariscal, et al., First demonstration of ARC-accelerated proton beams at the National Ignition Facility. Physics of Plasmas, 2019. **26**(4): p. 7, 10.1063/1.5085787.

27. E. Boella, et al., Collisionless shock acceleration in the corona of an inertial confinement fusion pellet with possible application to ion fast ignition. Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences, 2021. **379**(2189): p. 11, 10.1098/rsta.2020.0039.

28. C. McGuffey, et al., Focussing Protons from a Kilojoule Laser for Intense Beam Heating using Proximal Target Structures. Scientific Reports, 2020. **10**(1): p. 10, 10.1038/s41598-020-65554-4.

29. K. Bhutwala, et al., Transport of an intense proton beam from a cone-structured target through plastic foam with unique proton source modeling. Physical Review E, 2022. **105**(5): p. 11, 10.1103/PhysRevE.105.055206.

30. P. K. Patel, et al., *Integrated laser-target interaction experiments on the RAL petawatt laser.* Plasma Physics and Controlled Fusion, 2005. **47**: p. B833-B840, 10.1088/0741-3335/47/12b/s65.

31. Thomas Schenkel, et al. Ion beams and Inertial Fusion Energy "[White Paper]". in NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

32. R.O. Bangerter, Systems Studies, Accelerator Design, Target Design and Enabling Technologies for Heavy Ion Fusion "[White paper]", in NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

33. Constantin Haefner, Inertial Fusion Energy Drive Technology "[White paper]", in NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

34. Igor D. Kaganovich, et al. Collective Effects and Intense Beam-Plasma Interactions in Ion-Beam-Driven High Energy Density Matter and Inertial Fusion Energy "[White paper]". 2022. arXiv:2201.13183 DOI: 10.48550/arXiv.2201.13183.

35. National Research Council of the National Academies of Science Engineering and Medicine, *An Assessment of the Prospects for Inertial Fusion Energy*. 2013, Washington, DC: The National Academies Press (doi: 10.17226/18289); https://nap.nationalacademies.org/catalog/18289/an-assessment-of-the-prospects-for-inertial-fusion-energy.

36. J. J. Barnard, et al., *Integrated experiments for heavy ion fusion.* Laser and Particle Beams, 2003. **21**(4): p. 553-560, 10.1017/s0263034603214130.

37. J. L. Vay, et al., Propagation of Ion Beams in a Heavy-Ion Inertial Fusion System, in NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

38. M. G. Haines, *A review of the dense Z-pinch.* Plasma Physics and Controlled Fusion, 2011. **53**(9): p. 168, 10.1088/0741-3335/53/9/093001.

39. S. A. Slutz, et al., *Auto-magnetizing liners for magnetized inertial fusion.* Physics of Plasmas, 2017. **24**(1): p. 8, 10.1063/1.4973551.

40. S. A. Slutz, et al., *Scaling magnetized liner inertial fusion on Z and future pulsed-power accelerators.* Physics of Plasmas, 2016. **23**(2): p. 11, https://doi.org/10.1063/1.4941100.

41. Simon Bott-Suzuki, et al., Inertial Fusion Energy Technology: Repetitive Driver-Target Coupling in Hostile Fusion Chamber Environments "[White paper]", in NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

42. C. Olson, et al., *Development path for Z-Pinch IFE.* Fusion Science and Technology, 2005. **47**(3): p. 633-640, 10.13182/fst05-a757.

43. A. Zylstra, et al., *IFE Science & Technology Community Strategic Planning Workshop Report*. 2022 (https://lasers.llnl.gov/content/assets/docs/nif-workshops/ife-workshop-2022/IFE-Workshop-Report.pdf).

44. J. N. Olsen, et al., *FUEL PRECONDITIONING STUDIES FOR E-BEAM FUSION-TARGETS.* Journal of Applied Physics, 1979. **50**(5): p. 3224-3230, 10.1063/1.326360.

45. I. R. Lindemuth and M. M. Widner, *Magnetohydrodynamic behavior of thermonuclear fuel in a preconditioned electron beam imploded target.* The Physics of Fluids, 1981. **24**(4): p. 746-753, 10.1063/1.863415.

46. L. J. Perkins, et al., The potential of imposed magnetic fields for enhancing ignition probability and fusion energy yield in indirect-drive inertial confinement fusion. Physics of Plasmas, 2017. **24**(6): p. 7, 10.1063/1.4985150.

47. A. Bose, et al., Effect of Strongly Magnetized Electrons and Ions on Heat Flow and Symmetry of Inertial Fusion Implosions. Physical Review Letters, 2022. **128**(19): p. 7, 10.1103/PhysRevLett.128.195002.

48. D. J. Strozzi, et al., *Imposed magnetic field and hot electron propagation in inertial fusion hohlraums.* Journal of Plasma Physics, 2015. **81**: p. 21, 10.1017/s0022377815001348.

49. J. D. Moody, *Boosting Inertial-Confinement-Fusion Yield with Magnetized Fuel.* American Physical Society, 2021. **14**(51), 10.1103/Physics.14.51.

50. T. Mehlhorn, p-B11 ignition via ps & ns lasers: burn physics, target design, & experimental validation "[White paper]", in NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

51. D. Margarone, et al., *In-Target Proton-Boron Nuclear Fusion Using a PW-Class Laser.* Applied Sciences-Basel, 2022. **12**(3): p. 7, 10.3390/app12031444.

52. D. Clery *Out of gas: A shortage of tritium fuel may leave fusion energy with an empty tank (doi: 10.1126/science.add5489)*. Science, 2022; https://www.science.org/content/article/fusion-power-may-run-fuel-even-gets-started.

53. M. Tabak, *What is the role of tritium-poor fuels in ICF?* Nuclear Fusion, 1996. **36**(2): p. 147-157, 10.1088/0029-5515/36/2/i03.

54. S.H. Glenzer, X-ray Free Electron Laser Driven Fast Ignition "[White paper]", in NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

55. Giuseppe Ciullo. Polarized Fusion: An Idea More Than Thirty Years Old! What Are We Waiting For? in Nuclear Fusion with Polarized Fuel. 2016. Cham: Springer International Publishing.

56. John Jasper Bekx, et al., *Applicability of semiclassical methods for modeling laser-enhanced fusion rates in a realistic setting.* Physical Review C, 2022. **105**(5): p. 054001, 10.1103/PhysRevC.105.054001.

57. J. H. Nuckolls, *Grand challenges of inertial fusion energy.* Journal of Physics: Conference Series, 2010. **244**(1): p. 012007, 10.1088/1742-6596/244/1/012007.

58. R.W. et al. Paddock, Potential High Gain Target Designs for IFE "[White paper]", in NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

59. P. A. Norreys, et al., *Preparations for a European R&D roadmap for an inertial fusion demo reactor.* Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences, 2021. **379**(2189): p. 12, 10.1098/rsta.2020.0005.

60. H. Abu-Shawareb, et al., *Lawson Criterion for Ignition Exceeded in an Inertial Fusion Experiment.* Physical Review Letters, 2022. **129**(7): p. 19, https://doi.org/10.1103/PhysRevLett.129.075001.

61. M. Murakami, et al., *Innovative ignition scheme for ICF - Impact fast ignition.* Nuclear Fusion, 2006. **46**(1): p. 99-103, 10.1088/0029-5515/46/1/011.

62. M. Karasik, et al., *Acceleration to high velocities and heating by impact using Nike KrF laser.* Physics of Plasmas, 2010. **17**(5): p. 7, 10.1063/1.3399786.

63. R. E. Olson and R. J. Leeper, Alternative hot spot formation techniques using liquid deuterium-tritium layer inertial confinement fusion capsules. Physics of Plasmas, 2013. **20**(9): p. 12, 10.1063/1.4822342.

64. R. E. Olson, et al., *First Liquid Layer Inertial Confinement Fusion Implosions at the National Ignition Facility.* Physical Review Letters, 2016. **117**(24): p. 5, 10.1103/PhysRevLett.117.245001.

65. R. W. Paddock, et al., *One-dimensional hydrodynamic simulations of low convergence ratio direct-drive inertial confinement fusion implosions.* Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences, 2021. **379**(2189): p. 22, 10.1098/rsta.2020.0224.

66. R. W. Paddock, et al., Pathways towards break even for low convergence ratio direct-drive inertial confinement fusion. Journal of Plasma Physics, 2022. **88**(3), 10.1017/S0022377822000265.

67. R. E. Olson, et al., A polar direct drive liquid deuterium-tritium wetted foam target concept for inertial confinement fusion. Physics of Plasmas, 2021. **28**(12), 10.1063/5.0062590.

68. S. Atzeni, A. Schiavi, and C. Bellei, *Targets for direct-drive fast ignition at total laser energy of 200-400 kJ.* Physics of Plasmas, 2007. **14**(5): p. 16, 10.1063/1.2716682.

69. E. M. Campbell, et al., *Direct-drive laser fusion: status, plans and future.* Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences, 2021. **379**(2189): p. 23, 10.1098/rsta.2020.0011.

70. S. P. Obenschain, et al., *Direct drive with the argon fluoride laser as a path to high fusion gain with sub-megajoule laser energy.* Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 2020. **378**(2184): p. 20200031, 10.1098/rsta.2020.0031.

SECTION TWO

DRIVER & TARGET TECHNOLOGIES

Chapter 4: Drivers

4.1 Introduction

Inertial fusion approaches depend on the physics platform and driver technology required for fuel ignition. Principal research efforts in the United States align with four general driver technologies:

- Solid-state lasers, such as the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL), which primarily operates in a laser-indirect-drive (LID) configuration, and OMEGA at the University of Rochester's Laboratory for Laser Energetics (LLE), which primarily operates in a laser-direct-drive (LDD) configuration. Similar facilities exist in France (Laser Megajoule, LMJ; LID), China (SG-III, LID), and Russia.
- KrF and ArF excimer lasers, such as Nike and Electra (LDD) at the Naval Research Laboratory (NRL), with smaller facilities in Russia and China.
- Pulsed-power systems, such as the Z Machine at Sandia National Laboratories, that drive high currents to achieve high magnetic fields with compression for magnetic direct-drive (MDD). Some universities have smaller facilities, as well.
- Heavy-ion particle beams for compression drivers and laser-driven particle beams for fast ignition (FI), being explored by a series of groups, including at Lawrence Berkeley National Laboratory (LBNL) for compression and a large number of national laboratory and university groups for FI. A large facility or notable technology demonstrator does not exist yet.

Adapting these technologies for inertial fusion energy (IFE) (i.e., electrical power plants based on inertial confinement fusion (ICF) physics) will require target-physics designs; driver and energy conversion systems that can operate at 0.1–20 Hz, with the repetition rate impacting the electric power of the plant (typically ~1000 MWe) and cost of electricity (COE); fusion target yield or gain (typically 30–100); thermal-to-electrical conversion efficiency and capacity factor (typically 45% and >80%, respectively); and recirculating power fraction that depends on the product of the driver's wall-plug efficiency (10–30%) and target gain [1]. Each driver technology represents different opportunities and risks, but all require major advances to achieve a high technical readiness level (TRL 6).

SUMMARY

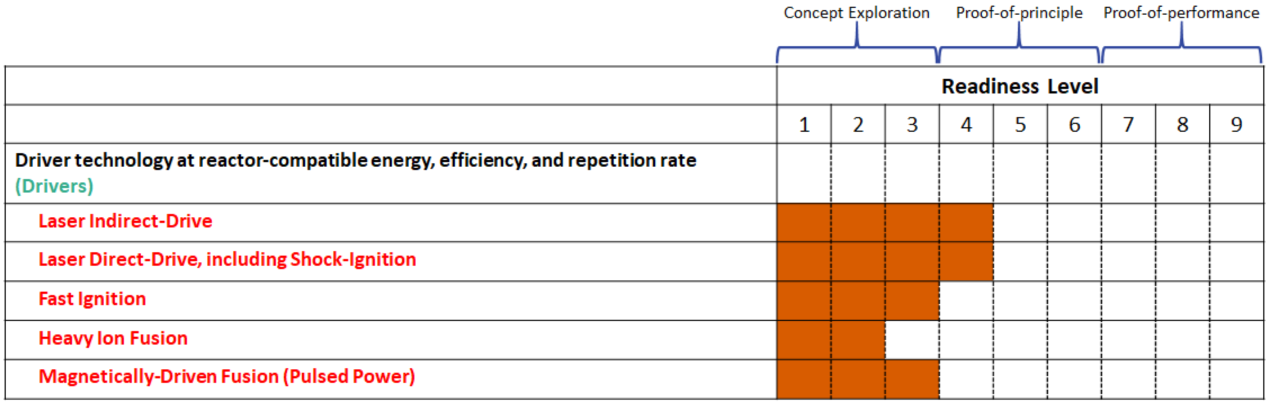
IFE driver concepts include lasers, pulsed-power systems, and heavy ion particle beams. IFE research and development should start with system-level studies that address both driver and target physics with sufficient detail to capture the challenges in generating and delivering energy to the target. **Developing conceptual designs** for IFE concepts at a similar level of detail for each driver would provide a basis for considering future implementation and reduce risk.

Further, laser drivers for an IFE power plant will require engineered beam transport and focusing optics systems able to operate at high repetition rates over extended periods of time. **Integrated laser system demonstrators are needed.** Mitigating debris, neutron bombardment, sensitivity to vibration and thermal cycling, and ease of maintenance are also challenges for optics. Developing solid-state switching, multi-THz bandwidth drivers to mitigate LPIs, and low-cost, high-performance accelerator modules for generating heavy-ion beams is also important for driver technology. Furthermore, IFE will require a massive expansion of capability, competency, and production in the laser and photonics industry, including a focus on **reducing the cost of diode pumps. A public-private partnership could leverage the deep expertise within the DOE complex along with the vision and investment available from private industry.**

Our Basic Research Needs (BRN) drivers working group evaluated these known driver technologies along with their projected requirements for a net 1-GWe demonstrator power plant, identified technology gaps, and derived primary research opportunities (PROs) to reduce technical risk for each driver platform, with particular emphasis given to research and development (R&D) that would enable us to demonstrate new capabilities for each physics platform.

Assessments of Technical Readiness Levels (TRLs) for Drive Technologies

TRLs are based on evaluating the maturity of critical elements of a product's technologies. Typically, TRL is regularly assessed in the system development process and is based on data generated during technology development. TRL does not measure the level of risk or assess the ability to complete the project at projected cost, schedule, or performance goals; rather, TRL provides a basic means of assessing the maturity of the technology and its readiness or ability to function as part of a larger system. Thus, TRLs help identify critical technology concerns and provide a measure of technical maturity for a fusion power plant (FPP) system. The BRN panel used its expert opinion to estimate TRLs for the driver technologies. **Figure 4.1** lists the driver-specific TRLs for the main options under consideration discussed further below.



	Concept Exploration			Proof-of-principle			Proof-of-performance		
	Readiness Level								
	1	2	3	4	5	6	7	8	9
Driver technology at reactor-compatible energy, efficiency, and repetition rate **(Drivers)**									
Laser Indirect-Drive	■	■	■	■					
Laser Direct-Drive, including Shock-Ignition	■	■	■	■					
Fast Ignition	■	■	■						
Heavy Ion Fusion	■	■							
Magnetically-Driven Fusion (Pulsed Power)	■	■	■						

Figure 4.1. Estimated technology readiness levels (TRLs) for the IFE-relevant driver technologies.

Diode-Pumped Solid-State Lasers (DPSSLs). DPSSLs for indirect and direct drive and FI leverage the basic physics and technology developed for NIF [2, 3]. The main changes necessary for IFE will likely include the following:

- Semiconductor laser diode arrays along with high-efficiency pulse-forming circuits [4], which will replace flashlamp pumping to reduce heat intake and increase wall-plug efficiency, which is tightly linked to the recirculating power [5]
- Active cooling of laser gain materials will replace convective cooling [6]
- Additional optical features, such as gain isolation, average power frequency conversion [7, 8], and high-average-power spatial filtering and beam image relaying [9]

These key architectural changes and technology developments were reduced to practice in the nsec-pulse high-energy pump laser of the High-Repetition-Rate Advanced Petawatt Laser System (HAPLS) [8, 10], which was fully constructed and delivered to the Extreme Light Infrastructure (ELI) Beamlines. Building on the basis of the TRL estimate of DPSSL technology, HAPLS would be at TRL 5. However, owing to cost issues associated with the diode arrays, we set the overall TRL at 4. Further, potential substitution of Nd:glass slabs with crystalline gain media (preferably with lower quantum defect) [1, 11] promises future development paths to high-energy IFE drive lasers that do not require the bandwidth of Nd:glass.

The cost of laser diode arrays is a key issue, although the large and growing market for diode arrays has led to tremendous improvements in performance since the early 1980s—from 10 watts per diode bar to 500 watts per diode bar, pulsed. A comprehensive IFE design study in 2013 found that the laser diodes are about 60% of the cost of an FPP laser driver [12], even with economies of scale in production and further technical developments. An update to this study, performed in 2022 [13], concluded that achieving high-power laser diode manufacturing costs of $0.05/W or less with the performance and reliability required for an IFE power plant is possible in a time frame of 5–10 years. However, the volume needed for a fusion demonstrator exceeds today's worldwide annual production volume of all laser diodes. Current prices are as low as $0.4/W_{Peak}$, and companies assert that $0.1/W_{Peak}$ is on the horizon (<10 years) with targeted developments in epi-growth/facet-coating, along with a growing market. We would need to further reduce the cost of diodes for pumping Nd:glass to $0.01/W for an economically competitive power plant, which is only achievable via new innovations and fully automated manufacturing. Currently this cost issue represents a major bottleneck, and overcoming it will require a comprehensive R&D program. Importantly, the development of gain media with longer storage times than Nd:glass would support a higher acceptable diode price and/or lower total capital cost (e.g., 3x storage time would lead to a 3x reduction in price). As a side note, reduction in diode cost would also benefit DOD and the LED industry.

The damage threshold of optics is an issue for all laser-based systems. For DPSSLs, the damage threshold is currently ~12 J/cm^2 for 100s of shots, with the damage manifesting in the silica lenses, frequency conversion crystals, and mirrors [14]. Increasing optics' lifetimes to 10^{10} shots requires improved bulk- and surface-damage thresholds, which is an ongoing subject of research and is steadily rising. Lastly, an IFE laser would need to be far more efficient than flashlamp-pumped lasers; IFE DPSSL lasers need to achieve ~15% to keep the cycling energy in an IFE power plant under 10%. We can meet this need mainly with use of laser diodes, but the laser architecture design also impacts this specification via the energy extraction, mode and aperture size, and the trade-off between pumping efficiency and diode cost.

DPSSL direct-drive requires bandwidth to mitigate or even suppress laser-plasma instabilities (LPIs) and to deliver required on-target irradiation uniformity. Ultraviolet (UV) bandwidth greater than 10 THz ($\Delta\omega/\omega$ = 1.5%) has been demonstrated at small scale using optical parametric amplification (OPA) and sum-frequency generation (SFG) [15, 16] in a scalable scheme (known as FLUX). Stimulated rotational Raman scattering (SRRS) offers a less-explored approach to broaden laser output bandwidth. Another concept is the StarDriver, which employs many different gain media operating at different wavelengths to deliver the required bandwidth on target [17]. We estimate direct drive with DPSSLs is at TRL 4 since it has not functioned at high energy (>kJ) but it employs well-known nonlinear processes that have been demonstrated.

Fast-ignition (FI), either proton-driven or electron-driven, will likely rely on very similar technology as the nano-second drive laser architectures and will likely employ DPSSL platforms for efficiency reasons, where Nd:glass could serve as the "workhorse" gain medium owing to its suitable bandwidth [18]. We assessed FI at a lower overall TRL because of its need for large diffraction gratings beyond the current state-of-the-art, grating tiling, and/or beam-aperture combining approaches to compress the laser pulses at high energies, as well as needing large off-axis parabolic mirrors to focus the pulses. Both of these large optics (diffraction gratings and off-axis parabolic mirrors) present challenges in fabrication, cost, and optical damage at the high energies (100 kJ and beyond) and corresponding fluences required.

Excimer Lasers. In principle, excimer lasers could be well-suited for direct drive, with very short wavelength and very large bandwidth: 10 THz at 193 nm for Argon Fluoride (ArF) and 3 THz at 248 nm at for Krypton Fluoride (KrF) [19, 20]. The commercial utility of excimers has been proven at low energy with high repetition rate for lithography. The estimated overall efficiency for excimers is 10% (ArF) and 7% (KrF) after accounting for efficiencies, such as the power supply, electron deposition, and fill-factor for multiplexed beams, as well as the intrinsic efficiency of the gain medium. Complexities in the angular multiplexing or pulse compression, beam down-collimation to higher fluence, pulse shaping, and optical damage require a detailed optical model for a full understanding. Alternatively, the ASPEN KrF concept [21] applies beam combining and pulse compression and promises to be much simpler than multiplexed beams but is at an early stage. Excimer lasers have been demonstrated at 4 kJ for NIKE with 56 beamlines [22], so the TRL is 4. The smaller 750-J Electra KrF facility demonstrated 5-Hz operation for thousands of shots and 100,000 shot operation at 2 Hz [22]. Elevation to TRL 5 would require a new facility that offers ~10 kJ to demonstrate the scaling capability, along with high wall-plug efficiency and IFE-relevant repetition rate. The lithography industry has greatly advanced the 193-nm optic, coating, and mirror technologies, but laser IFE involves higher flux (J/cm^2) and still requires further development of 193-nm optics and coating. An interesting possibility exists in compressing fuel with excimer lasers combined with an FI pulse. Because of their short wavelengths, KrF and ArF can achieve high density, which may ease the constraints on an FI short-pulse system.

Heavy-Ion Fusion (HIF) Accelerator Drivers. HIF drivers promise efficiencies as high as 30% [23-25], and deep technological expertise exists from accelerators implemented mainly for high-energy-physics (HEP) experiments. We assessed HIF drivers to be TRL 2 because they still require demonstration of key physics issues, such as delivering high (kJ) ion beam energy, low emittance, ion neutralization for focusing, pulse shaping, beam combining, and propagation. Moreover, ion beam–driven target heating has thus far been limited to creating “warm” (<100 eV) matter [26-28]. Results with relatively low-intensity ion pulses and extensive modeling suggest feasibility, but substantial effort remains to demonstrate these critical features. The FAIR facility currently under construction in Germany is actively pursuing the building of a kJ-class heavy-ion beam system [26].

Pulsed-Power Drivers. Pulsed-power drivers for magnetically driven fusion show promise as a nascent field based on extensive Z-pinch research and relevant technology development. In principle, the driver can efficiently deliver >10% of stored energy to the target and can function at extremely high energy (and therefore high fusion yield) as this concept has no intermediate steps, proceeding directly from stored electrical energy to current delivered to the target [29]. Creative target designs have been developed (e.g., magnetized liner inertial fusion (MagLIF)) to accommodate compression, control the plasma, and sustain symmetry, but these designs are at an early stage of development. Our TRL 3 assessment reflects the actual level of target demonstrations.

The pulsed-power driver technology itself is at a higher level of development, whether it be conventional Marx-based systems, newer systems that use fast-Marx technology, or linear transformer driver (LTD) technology, but repetition rates with robust gigajoule shot operation pose a challenge. The most demanding issue entails recycling the transmission lines (RTLs), where notional concepts have been discussed. We did not consider RTLs for our TRL estimate here in this section, as they are considered part of the fusion target. In a fusion power plant, the RTLs must be removed and installed in <10 seconds following a very high-yield fusion event.

Driver options

Inertial Fusion Energy (IFE) Laser Drivers. Over the last 60 years, lasers have emerged from being the famous "solution looking for a problem" to a ubiquitous part of our everyday lives. Many of the most momentous accomplishments, such as fiber-based communications, materials-processing, medical procedures, and even fusion research can trace their roots to visionary ideas that scientists began to develop in the 1960s and 1970s. Laser fusion has played a significant part in the history of lasers, pushing needed technology to extremely high energies with distinct challenges. Two options, DPSSLs and excimer lasers, look viable at the MJ-level and credibly offer a pathway to precise control of the pulse shape and coherence required by target physics. While laser architectures and technologies are fairly developed, all laser approaches require demonstration of efficiencies and scaling, showing we can mature architectures and technologies to FPP-ready devices while driving down production and future maintenance and operation costs, as well as securing and establishing supply chains. All laser options require target tracking and beam steering, the latter of which can be accomplished electro-optically by various means [30, 31]. In addition, we need a control system to manage machine safety and performance, which is a significant cost center today. However, a reliable system would only require measurements on the beamlines, such as energy/pulse shape and possibly beam profile, to discern off-normal behavior and determine if it is correctable or in need of repair.

DPSSL-Based Laser Indirect-Drive (LID)-Inertial Fusion Energy (IFE) Drivers. DPSSL designs suitable for LID would leverage aspects of existing ICF laser systems. Owing to past ICF laser development, similar laser system deployments, and the large commercial vendor base for many of the key components (with a few exceptions, such as the laser glass), DPSSL-based LID-IFE drivers offer a relatively high level of technical readiness for near-term construction of an FPP. ICF laser amplifiers rely on Nd:glass, the only laser gain material that has been demonstrated (1) to be producible at scale in large quantities, (2) to have sufficient optical quality, and (3) to be consistent with commercially available diode pumping, required average power capability, and energy storage capability for an FPP. Nd:glass, however, has some drawbacks, such as the short gain lifetime and average power-induced stress birefringence affecting beam quality.

IFE-suitable laser architectures have been demonstrated with the Mercury Laser [6], the HAPLS pump laser [8, 10] (**Figure 4.1**), and the DIPOLE [32] laser. For its laser gain material, HAPLS uses diode pumped Nd:glass, while DIPOLE uses diode pumped, cryo-cooled Yb:YAG. Mitigating LPI in the hohlraum requires broadening the frequency spectrum of the laser pulse. While both approaches are suitable for repetition rate (for comparison see Erlandson, *et al.* 2011 [11]), in addition to the aforementioned advantages, Nd:glass has a much larger gain-bandwidth (~20 nm or ~5.4 THz). If 100–200 GHz 3ω bandwidth is sufficient for controlling plasma instabilities with increasing laser drive power and energy, we may be able to replace Nd:glass with alternative optical storage gain media, such as Nd:SrF_2 (e.g., as transparent ceramics). Optical pump energy is stored in laser amplifiers of the laser gain medium, where ideally the energy stored (in J) is the product of optical pump power (in W) and the storage lifetime (in seconds). Therefore, increasing the storage lifetime of the gain medium allows for the use of lower diode-pump power, assuming the same stored and extractable

__Figure 4.1__: The High-Repetition-Rate Advanced Petawatt Laser System (HAPLS) architecture is based on eight major key laser technology leaps that enable high peak power pulses with 10Hz repetition rate.

energy. Because diode laser costs are typically tied to the peak power capability and packaging complexity, gain media with longer storage lifetime have the potential to significantly reduce the quantity of diode pumps and therefore the total diode cost, which is a dominant capital cost of an FPP. An assessment of diode costs for an FPP projected that ~$0.01/W would be cost-competitive, assuming Nd:glass. For example, the Nd:SrF_2 alternative would have ~3x the storage lifetime of Nd:glass and would require a more readily achievable diode cost of $0.03/W. Similarly, 2-µm gain media, such as Tm:$LiYF_4$ (Tm:YLF) and Ho:$LiYF_4$ (Ho:YLF), exhibit a further ~10x increase in storage times (requiring diode costs <$0.30/W assuming linear scaling, only a moderate ~3x decrease from current diode costs at large volume). However, a laser source using these types of 2-µm gain materials would require an additional frequency conversion step, which would reduce the achievable system wall-plug efficiency. We need to evaluate these possibilities in detail, but an “optimal” solution will be inextricably linked to and derived from target physics requirements.

Science and technology gaps: Several aspects of LID DPSSL technologies that are critical for an IFE FPP need additional development:

- Achieving >10% wall-plug-efficiency (from wall plug electrical power to photons delivered on target and including full system cooling) will require careful attention to design details. To date, we have not fully optimized gas-cooled Nd:glass architectures for wall-plug efficiency and, although aperture up-scaling favors improved extraction efficiency, meeting the >10% target remains an R&D process.

- Efficient average power frequency conversion from the fundamental to the third harmonic, particularly at relevant aperture sizes, is an unsolved challenge. We understand 3ω laser damage of optics well due to experience with NIF, but we do not have good understanding of the additional constraints of repetition rate and heat removal in large-aperture frequency-conversion crystal lasers.
- Active gain isolation, switching, and back reflection mitigation for 1ω short-pulse drivers (via the electro-optic/Pockels and/or the magneto-optic/Faraday effects) is important for DPSSL architectures, and the combination of average power and aperture we expect to need for LID DPSSLs makes this particularly challenging. There is currently no gain-isolation or polarization-switching device available that is consistent with aperture sizes >10 cm x 10 cm and operating with fluencies >10 J/cm² and at average power >100 W/cm².
- Passive polarization control through half and quarter waveplates is currently unresolved with transparent optics (if needed).
- Work on HAPLS addressed beam transport and robust spatial filtering at high average power; however, we still must demonstrate scaling to full aperture for high energy.
- We must develop high average power laser diagnostics and active control, such as target tracking and real-time beam steering.
- All system components must undergo cost optimization and the corresponding development of mass production technology.

Aside from these specific component technologies, scaling existing repetition-rated DPSSL architectures from the current energy level of about 100 J to the level of several kJ for an FPP beamline poses a technology integration risk that we can mitigate through detailed design and construction of a demonstrator with 3 to 10 kJ. This demonstrator would build on experience with large-aperture, single-shot, Nd:glass lasers (NIF) and smaller-aperture, repetition-rated, high-energy lasers (HAPLS) and would provide a platform for component integration, laser operation, and detailed understanding of longer-term risks, such as laser damage and electronics in the multi-billion-shot (>1 GShot) regime.

DPSSL-Based Laser Direct-Drive (LDD)-Inertial Fusion Energy (IFE) Drivers. LDD-IFE has the potential for high-gain performance for commercial power production that can leverage decades of LDD-ICF research and extend existing laser and target technologies. LDD-ICF with hotspot ignition or shock ignition (SI) promises to deliver five to six times higher laser energy coupling for imploding capsules than x-ray indirect-drive schemes [33, 34]. If the physics of the LDD-ICF platform and its self-consistent integration into a power plant proves suitable, the aforementioned advantages along with advanced LDD target designs suitable for mass production and commercial implementation [5, 35] could make LDD-IFE an attractive technology route. However, challenges and gaps exist for LDD-IFE approaches, including SI.

LPIs pose a challenge to realizing the higher coupling efficiency potential of LDD [36, 37]. Research indicates that broadband laser irradiation can mitigate and even suppress LPIs, as well as improve target irradiation uniformity. Simulations predict UV laser bandwidth $\Delta\omega/\omega \leq 1.5\%$ can eliminate cross-beam energy transfer (CBET) and increase the laser absorption resulting in higher drive pressures, mitigating hot-electron generation at ignition intensities, and eliminating imprint asymptotically within a few picoseconds [38-41]. Broadband UV lasers may provide a path to LPI-free and robust LDD-IFE, potentially including SI [42], in which high laser drive intensities exacerbate LPI.

Operating these lasers at the second instead of the third harmonic frequency may be possible in schemes that do not require high compression drive intensity, such as FI schemes.

Laser-glass gain and frequency-tripling limit the bandwidth available for LPI mitigation and beam smoothing on current ICF lasers, such as NIF [43] and OMEGA [44]. Several approaches exist to deliver the bandwidth required for LPI suppression and irradiation uniformity: each laser source in a multi-beam facility can produce the full required bandwidth, portions of the bandwidth, or discrete wavelengths spanning the required spectrum. Broadband incoherent systems raise laser damage concerns due to temporal modulation resulting from the excess bandwidth, and broadband frequency up-conversion to UV wavelengths proves challenging. Lasers operating at discrete wavelengths should prove simpler and advantageous, though they may require spectral beam combination [45] to deliver all laser irradiation to targets, given practical constraints on the solid angle available for IFE reactor vessels.

Laser-based systems or nonlinear processes, such as optical parametric amplification (OPA) can provide the required broadband amplification for LDD-IFE. Achieving the required bandwidth for LDD based on DPSSL technology requires new concepts (e.g., [46-49]):

- Technology employing OPA [15] and sum frequency generation (SFG)[16] to produce broadband incoherent UV laser pulses from a single aperture has been demonstrated. A fiber front-end seeds a broadband signal into a noncollinear OPA (NOPA) stage for subsequent collinear OPA (COPA) seeded by the NOPA signal output only. The COPA output signal and idler waves (1ω) both upconvert to the UV (3ω) using SFG.
- A laser system may also consist of many (10^3–10^5) relatively small beamlines [17] or fibers [45] to deliver broadband irradiation to direct-drive targets by combining on target the output of lasers operating at many discrete wavelengths spanning the required spectrum. Ideally, incoherent interference of these lasers exists only *after* the laser beamlines, which greatly simplifies both laser system design and operation. It may however complicate their integration into a power plant, where many other considerations apply, such as the need to constrain the optical solid angle to be consistent with blanket coverage for a high tritium breeding ratio (TBR); accessibility to final optics assemblies for regular replacement during operations; and radiological issues associated with multiple penetrations through the bioshield wall. The smaller apertures open a wider range of gain material options. The modular approach provides scalability across a range of IFE facilities to enable complex pulse shapes, many wavelengths, and focal-spot zooming to optimize the LDD drive. The large number of lasers using relatively small, off-the-shelf optical components would spur competitive commercial development, leading to economies of scale with high-volume manufacturing that would benefit industrial and other applications for nanosecond lasers of this scale.
- A new concept [47] combines the aforementioned technologies in novel configurations that optimize cost and performance in scalable architectures. This concept employs OPA and SFG using common pump lasers to produce a multiplicity of UV drive wavelengths in a single beamline using a novel time-multiplexing architecture. This method reduces the required number of distinct DPSSL wavelengths.
- “STUD” pulses (“spike train of uneven duration and delay”) are another LPI mitigation technique. This method is an extension of induced spatial incoherence (ISI) in which, not only is the speckle pattern scrambled, but the intensity is also cycled on and off to help inhibit plasma-

wave growth in localized hotspots [50]. Mittelberger *et al.* (2021 and 2022 [48, 49]) describe the experimental means of generating low-energy STUD pulses for injection, and studies will likely test its implementation on high-energy lasers in the next few years.

Science and technology gaps: These approaches all build on advanced DPSSL technologies to enable the repetition rates, wall-plug efficiency, and reliability required for both LDD-IFE and LID-IFE. Integrated system efficiencies at the FPP scale remain a challenge and require further development. Several areas of early laser R&D can advance LDD-IFE technology as part of a technology maturation plan [51] and prepare for IFE commercialization: (1) system design and optimization studies, (2) leveraging advanced DPSSL technology to build and test a prototype laser module, (3) commercial development of less common laser gain materials, and (4) clarification of the relative merit for methods that suppress LPI. This R&D will involve university and industrial partners to leverage their unique capabilities.

DPSSL Ultra-High Intensity (UHI) Lasers for Fast Ignition (FI). The laser drivers for FI schemes, either proton- or electron-driven, rely on similar laser architectures as the nanosecond DPSSL compression drivers described above. FI requires short-pulse operation of a subset of these lasers in chirped pulse amplification (CPA) mode, where the beamline will amplify broadband, chirped pulses and employ a grating pulse compressor [52] to achieve high ($>10^{19}$ W/cm^2) intensities. This places constraints on the type of gain material we can use since we must maintain broad bandwidth (a few nm). Nd:glass and Yb:CaF$_2$ are mature materials that provide gain bandwidth sufficient to support pulses ~500 fs or longer and that we can obtain with large apertures. Yb:YAG operated at room temperature also exhibits broad bandwidth, but the largest diameters are ~10 cm. Yb-doped materials provide longer storage times and are advantageous for diode pumping, but the generally lower gain cross-sections (i.e., higher saturation fluences) limit extraction efficiency and drive, as well as demanding higher coating damage thresholds for transmissive and reflective optical coatings. The second consequence of adapting DPSSL drivers for FI means that the pulse emerging from the amplifier chain demands the use of diffraction gratings to temporally compress the pulse, which imposes challenges related to optics manufacture, optics survival in the fusion environment, and integration into the blanket systems in a manner that allows for a closed fuel cycle and *in situ* maintenance. An advantage of FI is that the compression-drive lasers can operate at lower intensity than LDD-IFE because lower implosion velocities are needed for creating the hotspot. Therefore, LPI may present less of a problem. However, isolating the laser against 1ω back-reflections from a target is a challenge that requires mitigation studies.

Proton fast ignition (FI) represents a promising IFE concept requiring UHI lasers. Current estimates show that such a scheme will likely need >150 kJ of short-pulse laser energy, assuming we can maintain 10% conversion efficiency into MeV protons at these high energies with pulses of duration between 3 and 10 ps [53].

Nonthermal high-intensity drivers include some exotic fusion schemes currently under investigation that require even shorter laser pulses [54], perhaps as short as 15 fs. Such drivers will have to employ broadband amplification schemes based on laser-pumped-laser architectures (e.g., Ti:Sapphire, parameric amplifiers) in which the DPSSL serves as the pump laser. Here, the multiple steps required for ultrashort pulse generation greatly limit wall-plug efficiency. The largest technology gap in this area is in finding schemes to increase electrical efficiency of the laser output if it is to be the main fusion driver (as opposed to FI schemes in which long-pulse compression drivers provide most of the laser energy and have good wall-plug efficiency).

Science and technology gaps: The low damage threshold of dielectric diffraction gratings at ~1 J/cm^2 (or lower for pulses <1 ps) constrains the energy per beamline [55, 56]. Consequently, FI pulse drivers will operate at pulse energies significantly below that of the long-pulse (5–10 ns) beamlines used to compress targets. While multi-layer dielectric (MLD) gratings have higher damage thresholds at a few picoseconds duration when compared to sub-picosecond pulses, the operating conditions using current MLD gratings (e.g., 1740 lines/mm at 1-µm wavelength) are still limited to 2 J/cm^2 [56] on the grating surface and the single grating sizes are limited to ~1 meter. This indicates that proton FI single-beamline DPSSLs will be limited to ~2 kJ per beam. If higher damage threshold gratings or novel compression schemes (e.g., the combination of gratings and large aperture chirped mirrors) are further developed, significant gains in cost savings and system-complexity reduction could be achieved. Another technology gap for these systems is in developing compact front ends to package into short-pulse DPSSL modules. We could make progress on the use of Bragg gratings to eliminate the need for bulk stretchers. We also need to develop compact, simpler forms of temporal pulse cleaning to provide the high contrast required for generating proton beams.

Krypton Fluoride (KrF) and Argon Fluoride (ArF) Lasers for Inertial Fusion. There has been interest in the KrF and ArF excimer lasers for inertial fusion since their invention in the early 1970s. The short wavelength (248 nm and 193 nm, respectively) improves laser target coupling efficiency and helps mitigate LPI. In addition, these lasers can deliver broad bandwidth light to the target, with 3-THz bandwidth demonstrated on the NRL Nike KrF facility and 10-THz bandwidth projected for large ArF systems. The broad bandwidth reduces laser imprint on the target using beam smoothing schemes that rely on controlled spatial and temporal incoherence. Simulations indicate that broad bandwidth can further mitigate deleterious LPIs at high intensity [57]. The ISI beam-smoothing scheme enables implementation of temporal zooming of the focal diameter to follow an imploding direct-drive target [58]. KrF or ArF lasers are suitable for direct-drive implosions, and hydrocode simulations indicate that KrF/ArF drivers may enable high fusion gains with laser energy below 1 MJ [19].

The largest KrF amplifiers built were the Large Aperture Module (LAM) of the Aurora system at Los Alamos National Laboratory (LANL) in the 1980s and the presently operating Nike laser system at NRL. The 1-m aperture LAM module demonstrated 10-kJ energy in oscillator mode, which serves as a straightforward means of measuring the energy possible in the more complex amplifier configurations [22]. The Nike 60-cm aperture module demonstrated 5-kJ output as an amplifier in 56 beams. Both the LAM and Nike utilized electron-beam pumping of the large amplifiers. Both Aurora and Nike employed angular multiplexing, in which numerous nanosecond-pulse beams follow one after another to continuously extract energy from the amplifiers that are pumped for several hundred nanoseconds. The Nike system demonstrated the most uniform target illumination to date using 1–3-THz ISI beam smoothing (to <1%), as well as the capability to zoom the focus [20]. Future ArF laser systems could use a similar angularly multiplexed optical system. The ArF laser is projected to have higher intrinsic efficiency than KrF owing to the fundamental kinetics of the gain medium, enabling wall-plug efficiency near 10% versus about 7% for KrF. (The “intrinsic efficiency” is the stored energy divided by the energy deposited from the electron beams, while the wall-plug efficiency would take the power supply, electron deposit, and extraction into account.)

Science and technology gaps: The recent IFE work at NRL has focused on the ArF laser because of its superior wavelength for target interaction and projected higher efficiency than KrF. A conceptual design for a 30-kJ-class amplifier with a 90-cm aperture using multiplexed beam extraction and all-solid-state switched pulsed power has been formulated [19, 20]. A smaller scale prototype pulsed-power system has demonstrated 10-million-shot operation [59], which we would need to extend to at least a billion shots for an IFE system. Recent data from a 200-J ArF system have confirmed the accuracy of the earlier measurements of the intrinsic efficiency. The same billion-shot-class reliability requirement applies to all components of the amplifier and associated laser beam line. A billion shots corresponds to almost three years of operation at 10 Hz. In addition to advancing the longevity of the components, we need to conduct system studies of how to effectively make repairs, such as changing a pressure foil in an amplifier.

One concern for a 193-nm system is the damage threshold and longevity of optics. While we still need more research, studies have reported up to 5-J/cm^2 damage threshold for high-reflectivity mirrors and 2.5-J/cm^2 anti-reflection coatings for 193-nm laser light [60]. Additional research will determine maximum loading for the transport optics to target after the final ArF amplifier. The windows in the large amplifiers need to survive the laser flux, the dilute fluorine environment, and the x-radiation from the electron-beam pumping. Electra KrF (**Figure 4.2**) operations demonstrated that fused silica windows can survive 100,000 shots of continuous operation. Increasing to the gigashot level may require alternate window materials, such as calcium fluoride.

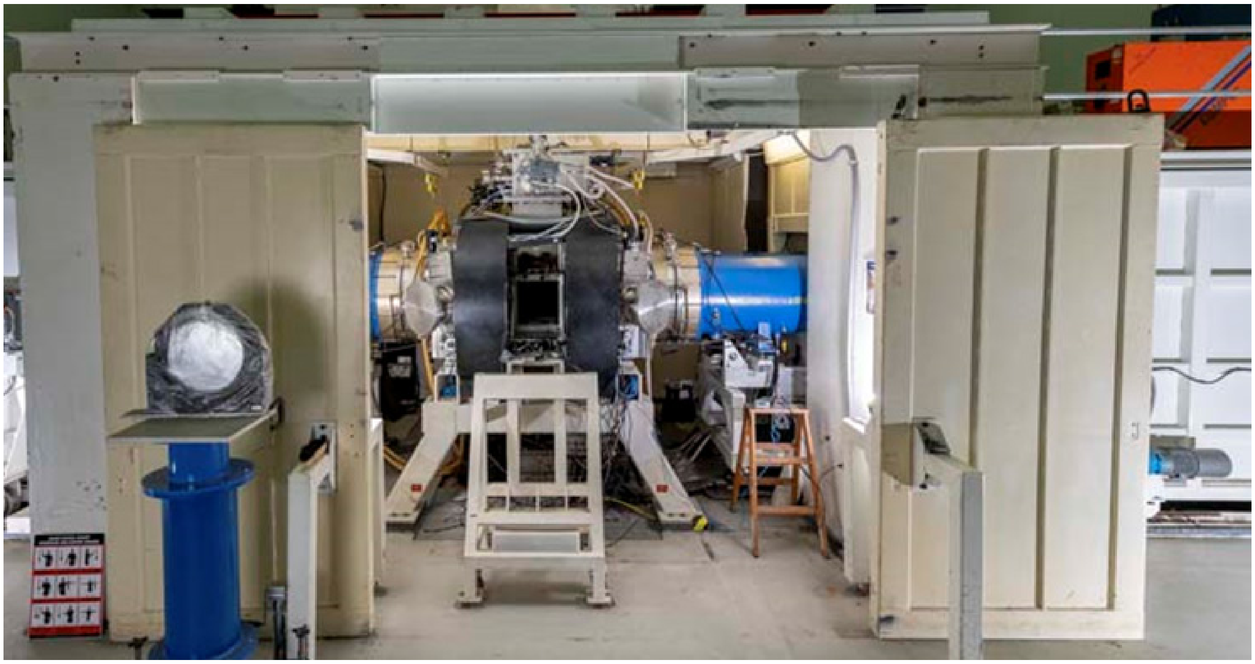


Figure 4.2. The ELECTRA Test facility at the Naval Research Laboratory (NRL).

The Nike laser uses Pockels cell shutters to provide pulse shaping, but high-gain, direct-drive implosions require more precise and complex pulse shaping. Pulse-shaping technology developed for Nd:glass lasers could be applicable to ArF by using a pulse-shaped 1-mm beam to modulate a 193-nm beam [61], although overlapping “foot” and “main” sections of the pulse shape will require development.

A privately funded effort (Xcimer Energy) is exploring the feasibility of combining the output from KrF or ArF amplifiers using stimulated Raman scattering (SRS) in a neutral gas followed by pulse shortening via stimulated Brillouin scattering (SBS) in a neutral gas. This system would replace the angularly multiplexed system. LLNL [62], as well as researchers in the United Kingdom [63] and elsewhere, have previously investigated pulse compression of excimers via stimulated scattering, but prior architectures suffered from challenges such as Stokes pulse breakup, second-Stokes super fluorescence, and other nonlinear optical thresholds that made it difficult to scale to high power and energy with sufficient efficiency. Xcimer Energy is pursuing an architecture that may solve these outstanding challenges, which would reduce the cost of the optics in the laser system and enable use of longer-pulse, higher-energy KrF/ArF amplifiers, providing a path to a 10-MJ-scale ICF/IFE driver.

Beam Transport and Optics for UV Compression Lasers and Ignition Drive Lasers with Large Optics. One of the most sensitive components limiting laser performance, lifetime, and operating cost are the multilayer coatings necessary for optical components, including crystals, transport and focusing optics, and diffraction gratings. These components need to have very long operational lifetimes with manageable service requirements. The typical failure mode of optics used in high-power laser systems arises from laser-induced damage and contamination, predominantly in the focusing optics. Additional constraints for the final optics assemblies (lenses, windows, gratings, etc.) include damage from neutron irradiation (e.g., color center formation), degradation in performance due to surface contamination and damage (e.g., for grazing incidence mirrors), and chemical reactivity associated with the complex products in the fusion environment (e.g., for optical coatings). Given that optical coatings fail at lower fluence and at greater rates than bulk materials, IFE-relevant optical coatings need to be robust at high laser fluence over extended periods of time, as well as being cost effective to fabricate.

Science and technology gaps: Different IFE-driver architectures will require different coated optical elements [61]. These include (1) optics for nanosecond pulses at 3ω (via 3rd harmonic generation of ω = 1-µm light) for solid-state lasers, (2) coatings for 193-nm vacuum UV light from excimer lasers, (3) gratings and transport/focusing optics for high-intensity picosecond duration pulses for FI and other new IFE schemes, and (4) spatial filters for beam contrast management and angular gain isolation:

1. MLD are mature and likely the most suitable technology for the mirrors. Optical metasurfaces (sub-wavelength patterned layers that interact strongly with light) are a topic of current research and might also offer solutions for some of the optics in the IFE drivers [64].
2. Nanosecond UV coatings consist mainly of stacks of amorphous oxides (i.e., SiO_2 and HfO_2). An approach used to ensure these coatings have high laser-induced damage threshold (LIDT) is to control the electric field distribution in the stack such that its maximum field amplitude occurs on the lower refractive index, higher LIDT SiO_2 layers. The LIDT depends on wavelength and pulse duration. For nanosecond pulses, a rule of thumb is that in high reflectors (HR) LIDT typically scales with that of 1ω (ω = 1064 nm) as LIDT(3ω) = LIDT(2ω)/2 = LIDT(1ω)/6. The LIDT(1ω) for HR coatings can be higher than 100 J/cm^2 [65-67]. For NIF, the 1ω coatings have an operational fluence specification of ~22 J/cm^2 at 3 ns and have only rarely suffered damaged. However, we must also manage contamination of the optics, which can lead to much lower damage thresholds. Finally, LLNL operates NIF final optics at the damage threshold of the optics. Thus, we do still need higher damage threshold coatings or architecture changes to reduce fluence on the final optics.

   The most challenging coatings to develop are for the 193-nm ArF excimer driver. These coatings are typically a combination of fluorides and SiO_2 or Al_2O. Mirrors with large angles of incidence (as are being considered) use a combination of metal and dielectric layers. The astronomy community has played a key role in advancing fluoride coatings, concentrating on achieving the highest UV reflectivity. Specifications from industry claim that fluoride coatings have a typical guaranteed LIDT of 0.5 J/cm^2, which can be accommodated in fusion of some laser designs with larger beams. The research literature has reported higher damage thresholds for anti-reflection (AR)/high-reflection (HR) coatings with 193-nm light (see section above on "Krypton Fluoride (KrF) and Argon Fluoride (ArF) Lasers for Inertial Fusion").

3. Grating damage represents the primary limitation on the drivers for picosecond pulses. Sustained operation for gigashots without damage in a variety of environments poses a major challenge to overcome in all cases. In UV fluoride coatings, opportunities may arise from adapting the deposition process to implement a reactive process.
4. The final optics would necessarily encounter the neutron yield of the target. Several studies on this topic have indicated a pathway that would have acceptable levels of neutron damage that would avoid disturbing optical transport for compression-drive lasers in some system designs [68, 69]. However, specifically for high-intensity ignition-drive lasers (picosecond duration pulses, for FI and other concepts), the required high-reflective beam-steering and focusing optics must be in the line of sight of the igniting target, resulting in a major technical and feasibility risk.

Pulsed-Power for Magnetic Direct Drive. Pulsed-power-driven fusion concepts apply an electrical current pulse directly to the fusion target. The state-of-the-art pulsed-power driver today is the 30-MA, 100-ns, 80-TW Z facility at Sandia [70], which fires about once per day. The benefit of using a pulsed-power driver to directly implode a fusion target is the large driver-target coupling efficiency we can obtain. For example, the Z facility at Sandia stores 11–22 MJ of electrical energy and can deliver 2–3 MJ of that energy to targets, for a coupling efficiency of >15% [71-73]. This large efficiency is obtained by cylindrical implosions. Specifically, the current pulse runs axially along the length of the cylindrical target, which generates an azimuthal magnetic field that smoothly encloses the cylindrical target. The J x B force density (i.e., the Lorentz force or, equivalently, the magnetic pressure gradient) then acts to implode the cylindrical target [74]. The cylindrical targets of the MagLIF program on the Z facility have generated a lot of interest over the past decade.".

Science and technology gaps: For future IFE applications, potential modifications to present-day MagLIF designs include the use of a cryogenic deuterium-tritium (DT) "ice" layer for achieving high-gain performance on a future 65-MA driver. With such high-gain targets, simulations predict a 7-GJ fusion yield and an overall facility gain of 70 (total fusion energy out divided by total electrical energy stored in the facility's capacitors) [75-77]. At the conceptual level, Stygar *et al.* (2015) have studied future generators that could provide ~65 MA in 100 ns (~800 TW) for single-shot operations [78]. Such systems place very challenging requirements on the underlying pulsed-power architecture, as they require delivery of many 100s of TW of electrical power to the target chamber (i.e., many megavolts and many mega-amperes, simultaneously). Such driver systems have not been studied thoroughly for use with high-gain, high-repetition-rate conditions, which leaves a critical science and technology gap. For example, for IFE, high-gain targets would have to be physically connected to transmission lines (electrodes) that are destroyed out to a radius of several feet on every shot. Thus, for every shot, we would have to fabricate, install, clear, and replace assemblies consisting of a pre-vacuum-pumped section of transmission line, complete with a preinstalled liner target. Additionally, we would have to recover and recycle the materials to avoid excessive waste and cost (thus, these transmission lines are often called "recyclable transmission lines" or RTLs). Therefore, to realize an IFE power plant operating at 0.1–1 GW, we would have to fabricate, install, clear, and recover these coupled high-gain target-RTL assemblies every 10 seconds (i.e., a system repetition rate of 0.1 Hz), which would require robotics. No one has yet demonstrated such an automated RTL system, which leaves a critical technology gap. The engineering challenges associated with IFE target production at high repetition rates are significant and should not be understated [79]. Nevertheless, Mazarakis *et al.* (2010) did demonstrate sub-scale driver modules (0.5 MA) at 0.1 Hz [80].

Heavy-Ion Compression Drivers. Pulses of heavy ions can theoretically compress fusion fuel capsules to the conditions required for IFE. Key beam parameters are the acceleration of heavy-ion beams (100–200 amu) with ~10^{16} ions/pulse (a few mC) to multi-GeV energies. In principle, we could combine and compress a series of lower intensity heavy-ion beams to ≈10-nsec pulses to deliver 1–10 MJ into a few-millimeter beam spots on fusion targets [27, 81]. Scientists have studied the HIF approach for radiofrequency and induction accelerators and in scaled experiments [27, 82]. HIF is compatible with combinations of compression modes (direct, indirect) and ignition modes (hotspot, FI), although most detailed driver designs are based on indirect drive with hotspot ignition [23, 27]. Specifically, ions are accelerated in radiofrequency fields or induction cells then deposit their energy into targets through Coulomb collisions. Heavy-ion drivers have several innate advantages [24, 25, 83, 84]:

- Heavy-ion drivers can have wall plug efficiencies of >30%
- Ion optics are non-contact and based on electromagnetic fields and hence do not suffer from the optical damage limitations of laser-based schemes
- High (>60 pulses per second) repetition rate is a standard feature of high-power accelerators

Studies have demonstrated these attributes separately and at sub-scale but not simultaneously in a facility with parameters suitable for IFE.

Science and technology gaps: No one has demonstrated multi-kilojoule beam physics and heavy-ion beam interactions with targets because no multi-kilojoule heavy-ion-beam facility exists. The FAIR heavy-ion facility, under construction in Germany, will offer the potential for studying heavy-ion beam control, focusing, and target interactions with multi-kilojoule pulses once the facility is complete [26]. Further, China is developing the multi-kilojoule heavy-ion facility HIAF [81]. The key technological risks to realizing a heavy-ion-based fusion driver are efficient beam transport and beam-target coupling, first at the multi-kilojoule scale and then at the full megajoule scale. Leveraging the development of lower-cost, higher-gradient (>1 MV/m) ion accelerator components than are available today presents an opportunity to significantly lower the driver cost, thereby lowering the barrier to developing megajoule-scale heavy-ion beam facilities toward pursuit of HIF.

4.2 Priority Research Opportunities (PROs)

IFE R&D should start with system-level studies that address both driver and target physics with sufficient detail to capture the challenges in generating and delivering energy to the target. One key recommendation is to invest in prototype technology demonstrators that would reduce risk on the needed high-energy (~3–10 kJ), high-wall-plug-electrically-efficient beamlines for IFE and multi-Hz repetition rates. One of our most critical recommendations is the necessary R&D to improve semiconductor diode-laser performance (brightness, lifetime, efficiency, heat removal) and cost. We recommend potential investment in both the diode-pump solid-state laser demonstrator that could address the needs of multiple laser-driven IFE approaches and a potential excimer laser demonstrator. A DPSSL facility could develop the laser technology platform for indirect drive, direct drive, and FI experiments. Such a facility would also establish an integrated testbed for advanced laser diodes, focusing on improving performance and production processes to lower costs and also serving as a lifetime at-scale test facility for optics.

Solid-state and excimer lasers present credible approaches for delivering the broad laser bandwidth required to overcome LPIs and for providing laser irradiation uniformity on target. Establishing an integrated, ignition-class implosion facility with high shot rates (shots per few minutes) will be important for providing ample opportunities to optimize LDD implosion performance. A 30-kJ excimer laser with ~10x the energy of the existing Nike Laser at NRL would be a significant step toward demonstrating LDD principles using this technology. Both MagLIF pulsed-power fusion and HIF are at an earlier stage of development with respect to IFE goals, despite the single-shot Z facility and the breadth of the accelerator community (mainly for particle physics studies), respectively. Therefore, it seems reasonable at this point to define component-level development, such as reliable pulsed power, advanced magnet technology, etc. Below, we offer further recommendations for investing in large aperture optics technology (i.e., mirrors and diffraction gratings) to make them more robust and damage resistant for IFE applications.

PRO 4-1: ***Perform IFE driver system-level architecture conceptual design studies***

IFE driver concepts run the gamut from multiple variations of laser drive to heavy ion and magnetic direct-drive. Each IFE driver approach promises its own advantages and challenges. All driver-technology-related PROs described below depend fundamentally on the specific IFE concept(s) for which the technology will be applied. Top-level, conceptual design studies represent the first step to identifying and fleshing out potential paths forward and determining the most promising IFE concept(s). The High-Average Power Laser (HAPL) program in the United States (ending in the mid-2000s) initiated important IFE technology R&D and design concepts that led to the current DPSSL and excimer laser systems [85]. The Laser Inertial Fusion Energy (LIFE) program went farther to outline an LID approach [6], and the HIF [23] and magnetic direct drive [73] approaches generated design studies as well. *These previous efforts all need updating and peer review given advances in target performance and driver technologies.*

We recommend developing conceptual designs for IFE concepts at a similar level of detail for each driver that would provide a basis for considering future implementation. Each effort needs to present at least one architecture with an integrated design that identifies risks, opportunities, technology gaps, supply chain developments and issues; an overall timeline and a cost estimate for realizing the first-of-a-kind; and an economy-of-scale estimate. A public-private partnership (PPP) could leverage the deep expertise existing within the DOE complex along with the vision and investment available from private industry. Starting PPPs at this fundamental stage will prove essential to long-term success. Design studies will enable further focusing of funding and resources globally on the most promising and pressing R&D topics. The stakeholders (national laboratories, universities, private industry) would jointly define the deliverables. The design studies would identify specific R&D topics requiring further coordinated support by federal agencies, private industry, and/or PPPs.

PRO 4-2: ***Reduce the cost of diode pumps in DPSSL technologies***

We have an urgent need for strategic development of diode lasers with the goal of providing robust, high-power sources at economically feasible price points for IFE. While the performance of laser diodes has improved over the last decade, the costs are currently more than an order of magnitude too high to be competitive for IFE [13]; assuming established ICF laser gain media, an FPP will need ~10 million diode bars operating at today's industrial standard of 500 W/bar. This is more than the current combined annual production capacity of all diode manufacturers in the world. IFE requirements are such that applications of industry alone will not drive the required IFE-specific technology transitions to lower the cost per watt. The long timeframes required to develop such technology to market maturity and to then establish production capabilities consistent with the requirements in supply for an IFE drive demonstrator will require a focused investment.

We need an IFE diode-development program, which would be ideally suited for PPPs. This program should have a high-level goal of demonstrating robust diode arrays relying on scalable >1-kW-class bars with >10-Gshot reliability for operating wavelengths of 8xx nm or 9xx nm (depending on laser gain media) at repetition rates of >10 Hz. Additional requirements include high electro-optical efficiency (>60%), high beam quality, long lifetime (>10 Gshots), and reduced cost <0.05 $/Wpeak for the83ackageed diode pump stack. A 2022 study on this topic [13] concluded that achieving high-power laser diode manufacturing costs of <$0.05/W is possible if we address the following development areas [10, 13, 86, 87]:

- Improving electro-optic efficiency at high brightness through novel chip and epitaxial design and through enhanced thermal management technology
- Advancing diode reliability and mean-time-to-failure (MTTF) assurance by improving crystal growth, advancing facet passivation technologies, optimizing package development, and establishing test facilities to validate the new designs
- Reducing the cost of diode production through development of advanced manufacturing processes and technologies that improve fabrication yields
- Developing a standardized supply ecosystem that includes multiple sources of standardized pump-diode components

Furthermore, builds of interim >10 kJ pulsed (~10 Hz) DPSSL facilities would provide impetus in the near-term for beginning to implement the processes outlined above.

PRO 4-3: ***Increase the damage threshold of optics and crystals***

The interaction of laser light and the optical materials used in precision laser optics limits the energy than can be delivered, the extraction efficiency (i.e., the fraction of the stored energy that can be effectively extracted from the gain medium), and the footprint of the laser and optics for all laser-driven IFE schemes, particularly for FI-type schemes that employ chirped pulse amplification (CPA). The high-reflection (HR) and anti-reflection (AR) coatings on IFE-class laser optics are typically operated at repetition rates and fluences (optical energy per unit area) below what we will need in an operating and cost-effective IFE power plant. Laser-initiated defects accumulate and grow during prolonged operation and ultimately lead to coating and optic failure. Large-scale systematic studies of coating and bulk optic survivability have not yet been performed at large apertures, very large pulse count (10^{10} shots = 10 gigashots = 1 decade of operation), and in the presence of the significant neutron flux, x-ray flux, and debris and contamination we expect to be present in an operating IFE power plant. Developing the laser drivers for an IFE power plant will require engineered beam transport and focusing optics systems capable of operating at high repetition rates over extended periods of time.

Developing superior optical fabrication techniques and materials (including optical figuring, polishing, and coating) will require a sustained effort with close interactions between design, fabrication, and testing experts. While the extreme ultraviolet (EUV) lithography industry has tackled and minimized some of these challenges in the case of short-wavelength 193-nm optics, and the multiple industrial and academic applications of solid-state lasers operating at >kHz rates have helped as well, IFE drivers have a sufficiently different operating regime that they will require additional effort for their optics. Areas of R&D under this PRO include (1) investigating new coating materials and architectures (including rugate and metasurface structures), (2) developing more sophisticated models that will predict the laser-induced damage threshold (LIDT) more realistically to guide experimental efforts, (3) identifying and parameterizing coating degradation in different environmental conditions and in the presence of neutron and x-ray flux and debris deposition (multilayer coatings used for highly reflective optics are susceptible to damage in high-neutron-flux environments), (4) effectively addressing damage due to contamination by developing a practical solution to eliminate damage growth, and (5) deploying high-repetition-rate testbeds to evaluate gigashot (>10^9 shot) survivability.

PRO 4-4: ***Build integrated laser-system demonstrators***

Because of the commonality of the likely drive lasers for LDD, LID, and FI, the DPSSL laser architecture of all three will greatly benefit from construction of a prototype testbed laser. The excimer approach should also develop a technology demonstrator. Below we describe two testbed prototypes that could be of interest to future IFE needs. Each of them is strongly coupled to how the target is engaged, which of course will become clearer as experiments and modeling continue to yield more information.

Prototype LID-IFE, LDD-IFE, and LDD-FI DPSSL Module. Demonstrating a 10-Hz, 3–10-kJ per pulse, 10–20-ns shaped pulses, with a >10% electrical wall-plug efficient beamline would retire most of the driver risks for all three potential approaches: indirect drive, direct drive, or direct drive coupled with FI. While the needs of all three approaches have some subtle differences, including the need to equip some modules with CPA front end and compressors, the similarity means that investments in a single demonstrator module would retire the risks of the laser driver for all three approaches. Concurrently, a program to demonstrate a prototype IFE laser module in an IFE laser testbed can leverage and extend advanced DPSSL technology driven by scientific, industrial, and defense applications [6, 88, 89]. This program would raise the TRL and prepare for commercial IFE deployment. The principal research need is to demonstrate in a laboratory a single, compact laser module producing >1 kJ/pulse from an amplifier at ~10 Hz with high wall-plug efficiency. This would allow us to demonstrate high efficiency with large aperture (~20 cm) amplifiers. This facility could serve multiple functions: refining the architecture for efficiency, providing a testbed for 3ω damage studies, and inspiring the next generation of higher performing diodes. Its architecture would be related to the gas-cooled diode-pumped HAPLS laser but scaled by a factor of 10–100x in energy (1–10 kJ) and a factor of several in fluence and would deploy established technologies for the front-end and frequency conversion. As discussed above, we would need to reassess the selection of the gain medium and would target certain high-leverage improvements in the diode performance and cost in support of the large diode order associated with the laser build (e.g., slow axis brightness, kW-level diode bars, etc.). Such a DPSSL facility would be at a high level of readiness owing to prior experience (current HAPLS and the prior generation in the repetition-rated Mercury Laser) and, moreover, to an extensive understanding of the basic laser physics deduced from the operation of NIF. The existing infrastructure in diodes and large aperture optics serves to reduce risk as well. Furthermore, such a driver could act as the pump for optical parametric amplification (OPA)-based broadband drivers for LDD-hotspot approaches. For FI manifestation, the compression driver may operate at either 2ω or 3ω of Nd:glass because LPI constraints are not as stringent as for LDD hotspot schemes. We could configure the testbed prototype to work at either wavelength. FI also requires some of these modules to be adaptable for CPA operation at the 500-fsec- to 5-psec-pulse duration regime, so we should design a prototype with this mode of operation in mind as well, with an alternate CPA front end.

*Prototype LDD-IFE KrF/ArF Module***.** As envisioned, the ArF conventional or SI approach would utilize about thirty 30-kJ amplifiers (with numerous angularly multiplexed beams for each) to obtain fusion gains above 100. The 30-kJ amplifiers should deliver the shaped pulses required for conventional implosions, as well as the high-power short pulses needed for SI. In addition, the system should provide broad bandwidth (6–10 THz), induced spatial incoherence (ISI) beam smoothing, and the capability to zoom the focus to follow the imploding target. We anticipate that first building a high-repetition-rate 30-kJ amplifier with many multiplexed beamlines (~1 shot/minute) would be advantageous, as we could field it more quickly and it would enable ArF laser-target interaction experiments.

A first-generation 30-kJ ArF system (utilizing about 80 angularly multiplexed beamlets) would retire the risk of scaling to high enough energy for a direct-drive implosion facility. It would also demonstrate other parameters, such as pulse-shaping and the focal distribution uniformity needed for a high-gain implosion facility. We could use these first-generation 30-kJ ArF amplifiers for an implosion physics facility operating at much higher repetition rate than is deployed currently.

A second-generation 30-kJ amplifier would retire the risk of durable operation at about 10 Hz and with the electrical efficiency (about 10%) required for a power plant. To reach this goal, we would need to test the candidate pulsed-power and diode components for efficiency and longevity prior to final design and construction. Similarly, we would need to test beamline components, such as optics, for longevity.

Alternative concepts envision using high-energy amplifiers at microsecond pulse length and then using one stimulated Raman scattering (SRS) amplifier and two stimulated Brillouin scattering (SBS) amplifiers in sequence to combine amplifier output into a small number of very high-fluence beams and temporally compress it over 1000:1 in time. The large, high-energy amplifiers (1–2 MJ or more) are enabled by the long pulse length and associated low pump rates, reducing amplified stimulated emission (ASE) and allowing higher-fluence operation without optical damage.

The final beams-to-target can use multiple sub-apertures for zooming and pulse time delay. Operating at the 10-MJ-scale and 1 Hz reduces requirements on component shot lifetime. However, the ability to use SBS to achieve 1000:1 overall temporal compression with sufficient efficiency and target illumination uniformity has not yet been demonstrated experimentally. The next step for this path will demonstrate this novel regime of SBS at sufficient scale to reduce risk. Xcimer Energy is in the process of designing such a demonstration facility, where they will operate a single phase-preserving, saturating SBS amplifier at a 248-nm wavelength with over 2 kJ output at 1 ns with over 1000x amplification factor. The scale (20-cm beam size, 38-m amplifier length, 15 dimensionless small signal gain) of the SBS amplifier will be sufficient to probe other non-linear processes that affect amplifier performance—such as B-integral and amplified spontaneous emission—to confirm predictions and understanding of these processes.

PRO 4-5: ***Improve reliability of high-power switching and capacitor energy storage***

ArF/KrF LDD-IFE, pulsed-power-driven IFE, and heavy-ion-driven IFE all require high-reliability switching and capacitor energy storage with low maintenance over long lifetimes. Many switches and capacitors in an IFE power plant will need to operate in parallel at high repetition rates (0.1–10 Hz) for long lifetimes (several years of operation) corresponding to 100s of millions to billions of shots. The IFE concepts mentioned above have overlap in their needs for component development related to high-speed switching. To address these overlapping needs, we should establish a program to develop solid-state switching with cost reductions to replace the present reliance on spark-gap switching. Additionally, small test-stand experiments that function over long lifetimes at high-switch rates with many switch-capacitor systems in parallel can establish reliable statistics. If we could demonstrate 100s of millions to billions of shots at full repetition rate reliably (which we could accomplish in 3–5 years if testing many units in parallel in an accelerated lifetime testbed), this would inform next-step decisions toward the design, construction, and demonstration of an integrated, repetition-rated IFE facility.

PRO 4-6: ***Design systems for broadband bandwidth generation***

As noted, LDD-IFE and, to a lesser degree, LID-IFE require multi-THz bandwidth drivers to mitigate LPIs. Plasma conditions depend on the laser wavelength (e.g., 193-nm light produces a cooler, shorter scale-length plasma than 351-nm), so bandwidth experiments would optimally evaluate the various candidate broad-bandwidth IFE drivers. We can perform many useful experiments and demonstrations of bandwidth on existing laser systems. For example, the 351-nm FLUX laser system [90] currently under construction at LLE will enable laser-target-interaction experiments using a single, broadband (>10-THz) 150-J pulse in plasmas created by other OMEGA laser beams. A prototype laser system could enable us to demonstrate other means of generating bandwidth, as described above.

Kinetics simulations and initial measurements indicate that ArF amplifiers can provide 10-THz full-width at half-maximum (FWHM) bandwidth. We need to extend this work to studies of the amplification of spectrally shaped ArF light that overcomes the gain narrowing. This would involve shaping the ArF spectrum from the ArF oscillator using etalons and adding amplifiers to provide the input energy into the amplifier to enable saturated gain measurements. These measurements would enable us to test and further develop kinetics codes used to design high-energy, broad-bandwidth, angularly multiplexed ArF systems with accommodation for pulse-shaping.

PRO 4-7: ***Design and implement final optic survivability at ultra-high intensity***

Several high-gain schemes relevant for an IFE energy-producing pilot plant involve FI, which requires high-energy, picosecond pulses. These schemes may require as much as 200 kJ in a bundle of igniting beams with pulse duration of 1–10 ps. These beams require large aperture gratings for final pulse compression and reflective focusing optics near the target chamber. The final optics for such high-intensity beams, such as these gratings and focusing parabolas, are subject to damage from high-intensity pulses over many shots.

Mitigation of debris, neutron bombardment, sensitivity to vibration and thermal cycling, and ease of maintenance are also important challenges for optics delivering picosecond pulses to an FI target.

Using transmissive optics is challenging because of nonlinear effects of short pulses in transmissive materials. For FI approaches, we need solutions to these challenges. One research opportunity exists in developing coatings and gratings that have higher damage threshold in the picosecond pulse-duration range.

In FI schemes, it is important to deliver picosecond pulses at 10 Hz in compact pulse compressors over billions of shots without damaging gratings. The main challenge here is making final broadband compression optics that have high damage threshold at >1 J/cm^2 that are durable over billions of shots. It is also important to focus these picosecond pulses at moderate f/# with all reflective optics. In this case, the challenge is to mitigate debris on these final optics from the exploding FI target. Thus, we may need constantly replaceable debris shields or other debris-mitigating designs.

For compression optics, we may be able to improve the damage threshold of dielectric gratings with new coatings or different line-density designs. Other approaches might also work, particularly if we only need pulses of ~10 ps. Advanced compression techniques, such as chirped mirrors for final compression to the shortest pulses after the gratings, could significantly increase durability. Furthermore, designs that incorporate thin transmissive optics could protect final optics assembly. National laboratories and private companies can collaborate (1) to advance grating designs to impact ignition facility design and compressor compactness/aperture and (2) in conceptual studies on debris mitigation that will impact ignition-scale target-chamber design.

PRO 4-8: ***Develop low-cost, high-performance accelerator modules***

Heavy-ion beams delivering megajoules of beam energy into millimeter-sized beam spots within a few nanoseconds at repetition rates of ~10 Hz and with a wall-plug efficiency of >30% are a driver technology for realizing fusion energy. However, such a megajoule driver may be prohibitively expensive using the accelerator components available to date. Recent advances in ion-accelerator science and technology—including high-power models and simulations, novel laser-driven ion sources, induction accelerator cells, high-power switches, superconducting high-field magnets, and multibeam radiofrequency linear accelerators—show promising avenues for ion acceleration and transport in lower-cost and more compact accelerators. In parallel, performance tests at a soon to be commissioned multi-kilojoule facility can provide important insights for these goals.

Roadmap elements with high-impact opportunities for heavy-ion compression drivers include the following:

- Modeling and simulations of high-power heavy-ion drivers can identify a new integrated driver design for megajoule heavy-ion beams that includes recent advances in accelerator modules and that is enabled by high-performance codes that have recently become available. This approach can lead to a new blueprint for a highly efficient (>30% wall plug) and robust HIF driver.
- Superconducting magnet R&D can advance higher-performance, lower-cost multi-beam magnetic-quadrupole-focusing elements and magnets for beam transport and focusing. This effort will lead to lower-cost magnet modules, also leveraging recent advances in high-temperature super-conducting magnet R&D. Heavy-ion source R&D can identify high-brightness heavy-ion sources, leveraging recent advances in laser-ion acceleration. This effort will lead to sources for efficient ion injection into heavy-ion driver modules and will also enable many near-term applications in materials science and industrial applications. Pulsed-power R&D can identify low-cost, high-performance pulsed-power switches for induction acceleration cells,

leveraging synergies with pulsed-power and ArF-development paths. Broad leverage of advanced pulsed-power technology across IFE paths also benefits many near-term applications in industry.

- Induction cell R&D can advance the acceleration gradient to >1 MV/m with more efficient induction cells (with wall-plug efficiency of >40%), leveraging recent National Nuclear Security Administration (NNSA) investments in electron-induction linacs. Advanced induction acceleration modules enable more compact, lower-cost heavy-ion drivers with many applications across DOE and industry. Experiments at multi-kilojoule heavy-ion beam facilities overseas can allow U.S. researchers to conduct critical demonstration experiments in beam transport, focusing, and beam-target interactions at facilities such as FAIR. These first-of-a-kind experiments will enable rapid iteration of experimental results with modeling and simulations to quickly converge on viable beam transport solutions and to retire residual uncertainties in beamfuel coupling with new physics data.

4.3 Conclusions

Advancing the technology of laser, heavy-ion, and pulsed-power drivers for IFE would benefit from partnership with private industry. We should advance some of the key technologies, such as laser diodes for pumping gain media, optics development, or crystal growth, in close partnership between industry and leading research groups. Furthermore, from a drivers perspective, making IFE happen translates into a massive expansion of capability and competency in the lasers and photonics industry, as well as in scale and production capability. For example, continuous laser-glass-melting factories, that produced material for over 10,000 slabs for NIF and LMJ by Schott Glass and Hoya, are an excellent example of industrial partnership to meet mission need—although these companies have now shut down and been dismantled. We would need to re-establish and expand similar-scale capabilities, as well as similar mass-production capability for tens-of-cm to meter-sized large aperture optics-coating facilities, diode production, crystals for frequency conversion and polarization control, or specialized materials, such as gratings for FI concepts, or standardized diagnostics. Overall, we would need to study and develop automated production lines for IFE lasers. In addition, securing access to raw materials used in optics represents a priority. DOE might consider targeted investments in key areas that are critical to advancing the laser R&D effort.

Private companies with an IFE mission need to play an integral role in shouldering the large development investment and need to maintain focus in an IFE program that aims at a commercial power plant. The modular nature of IFE provides opportunities for IFE start-ups to participate and accelerate pace in developing the technology. However, we should create and maintain an overarching program that is responsive to national needs. Funding jointly through the DOE PPP Fusion program and private sector investment is likely the best path to fielding a full energy beamline demonstrator in the coming five years (a project likely to require investment of >$100M). Thus, the IFE program should consider how best to utilize funds across relevant federal programs to aid in developing the key technology demonstrators described above.

References

1. C. D. Orth, S. A. Payne, and W. F. Krupke, *A diode pumped solid state laser driver for inertial fusion energy*. Nuclear Fusion, 1996. **36**(1): p. 75-116, 10.1088/0029-5515/36/1/I06.

2. Mary L. Spaeth, et al., *National Ignition Facility wavefront requirements and optical architecture.* Optical Engineering, 2004. **43**(12): p. 2854-2865, 10.1117/1.1815332.

3. Mary L. Spaeth, et al., *Description of the NIF laser.* Fusion Science and Technology, 2016. **69**(1): p. 25-145, 10.13182/FST15-144.

4. E. Stephen Fulkerson, et al. Pulsed power system for the HAPLS diode pumped laser system. in 2015 IEEE Pulsed Power Conference (PPC). 2015. IEEE; Doi: 10.1109/PPC.2015.7296854.

5. V. N. Goncharov, et al., Inertial Fusion Energy Target Designs with Advanced Laser Technologies, in NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

6. A. Bayramian, et al., *Compact, efficient laser systems required for laser inertial fusion energy.* Fusion science and Technology, 2011. **60**(1): p. 28-48, https://doi.org/10.13182/FST10-313.

7. A. J. Bayramian, et al. *High average power frequency conversion on the Mercury laser*. in *Advanced Solid-State Photonics*. 2006. Optical Society of America; https://doi.org/10.1364/ASSP.2006.MB1.

8. Constantin Haefner. *Application-enabling kiloWatt Average Power Petawatt Lasers*. in *Laser Applications Conference*. 2016. Optica Publishing Group; Doi: 10.1364/ASSL.2016.JM2A.1.

9. K. Chesnut, et al., *Entirely reflective slit spatial filter for high-energy laser systems.* Optics Express, 2019. **27**(19): p. 27017-27027, 10.1364/ASSP.2006.MB1.

10. C. L. Haefner, et al. High average power, diode pumped petawatt laser systems: a new generation of lasers enabling precision science and commercial applications. in Research Using Extreme Light: Entering New Frontiers with Petawatt-Class Lasers III. 2017. SPIE; https://doi.org/10.1117/12.2281050.

11. A. C. Erlandson, et al., Comparison of Nd: phosphate glass, Yb: YAG and Yb: S-FAP laser beamlines for laser inertial fusion energy (LIFE). Optical Materials Express, 2011. **1**(7): p. 1341-1352, 10.1364/OME.1.001341.

12. W. R. Meier, et al., *Fusion technology aspects of laser inertial fusion energy (LIFE).* Fusion Engineering and Design, 2014. **89**(9-10): p. 2489-2492, https://doi.org/10.1016/j.fusengdes.2013.12.021.

13. C. Haefner, Status and Perspectives of High-Power Pump Diodes for Inertial Fusion Energy Lasers "[White paper]", in NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

14. Raluca A. Negres, et al. *355-nm, nanosecond laser mirror thin film damage competition*. in *Laser-Induced Damage in Optical Materials 2017*. 2017. SPIE; https://doi.org/10.1117/12.2279981.

15. C. Dorrer, E. M. Hill, and J. D. Zuegel, *High-energy parametric amplification of spectrally incoherent broadband pulses.* Optics Express, 2020. **28**(1): p. 451-471, https://doi.org/10.1364/OE.28.000451.

16. C. Dorrer, et al., *Broadband sum-frequency generation of spectrally incoherent pulses.* Optics Express, 2021. **29**(11): p. 16135-16152, https://doi.org/10.1364/Oe.424167.

17. David Eimerl, et al., *StarDriver: a flexible laser driver for inertial confinement fusion and high energy density physics.* Journal of Fusion Energy, 2014. **33**(5): p. 476-488, 10.1007/s10894-014-9697-2.

18. M. D. Perry, et al., *Petawatt laser pulses.* Optics letters, 1999. **24**(3): p. 160-162, https://doi.org/10.1364/OL.24.000160.

19. S. P. Obenschain, et al., *Direct drive with the argon fluoride laser as a path to high fusion gain with sub-megajoule laser energy.* Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 2020. **378**(2184): p. 20200031, 10.1098/rsta.2020.0031.

20. Stephen Obenschain, et al., *High-energy krypton fluoride lasers for inertial fusion.* Applied optics, 2015. **54**(31): p. F103-F122, https://doi.org/10.1364/AO.54.00F103.

21. C. Galloway, et al., *ASPEN Laser and A New IFE Power Plant Concept*, in *NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop*. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

22. J. A. Sullivan, et al., *Design of a 100-kJ KrF Single-Pulse Inertial Confinement Fusion Driver.* Fusion Technology, 1991. **19**(3P2A): p. 652-663, https://doi.org/10.13182/FST91-A29419.

23. R. O. Bangerter, A. Faltens, and P. A. Seidl, *Accelerators for inertial fusion energy production*, in *Reviews of Accelerator Science and Technology*. 2014, World Scientific; https://doi.org/10.1142/9789814583251_0005. p. 85-116.

24. Arthur W. Molvik and Andris Faltens, *Induction core alloys for heavy-ion inertial fusion-energy accelerators.* Physical Review Special Topics-Accelerators and Beams, 2002. **5**(8): p. 080401, https://doi.org/10.1103/PhysRevSTAB.5.080401.

25. M. H. Tahar, F. Méot, and S. Peggs. Energy efficiency of high power accelerators for ADS applications. in IPAC 2016 - Proceedings of the 7th International Particle Accelerator Conference. 2016 (Doi: 10.18429/JACoW-IPAC2016-TUPOY044.

26. K. Schoenberg, et al., High-energy-density-science capabilities at the Facility for Antiproton and Ion Research. Physics of Plasmas, 2020. **27**(4): p. 12, 10.1063/1.5134846.

27. Ingo Hofmann, *Review of accelerator driven heavy ion nuclear fusion.* Matter and Radiation at Extremes, 2018. **3**(1): p. 1-11, https://doi.org/10.1016/j.mre.2017.12.001.

28. M. S. Derzon, et al., *Li-beam-heated Hohlraum experiments at particle beam fusion accelerator II.* Physical review letters, 1996. **76**(3): p. 435, https://doi.org/10.1103/PhysRevLett.76.435.

29. Lin Chen, et al., *Development of a fusion-oriented pulsed power module.* Physical Review Accelerators and Beams, 2019. **22**(3): p. 030401, 10.1103/PhysRevAccelBeams.22.030401.

30. Scott R. Davis, et al. *Liquid crystal waveguides: new devices enabled by> 1000 waves of optical phase control*. in *Emerging liquid crystal technologies V*. 2010. SPIE; https://doi.org/10.1117/12.851788.

31. Qi Wang Song, et al., *Electro-optic beam-steering device based on a lanthanum-modified lead zirconate titanate ceramic wafer.* Applied optics, 1996. **35**(17): p. 3155-3162, https://doi.org/10.1364/AO.35.003155.

32. Saumyabrata Banerjee, et al., *DiPOLE: a 10 J, 10 Hz cryogenic gas cooled multi-slab nanosecond Yb: YAG laser.* Optics Express, 2015. **23**(15): p. 19542-19551, https://doi.org/10.1364/OE.23.019542.

33. R. Betti and O. A. Hurricane, *Inertial-confinement fusion with lasers.* Nature Physics, 2016. **12**(5): p. 435-448, 10.1038/nphys3736.

34. E. M. Campbell, et al., *Direct-drive laser fusion: status, plans and future.* Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences, 2021. **379**(2189): p. 23, 10.1098/rsta.2020.0011.

35. K. S. Anderson, et al., Shock Ignition: High Gain Target Performance for Inertial Fusion Energy "[White paper]", in NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

36. I. V. Igumenshchev, et al., *Crossed-beam energy transfer in direct-drive implosions.* Physics of Plasmas, 2012. **19**(5): p. 056314, https://doi.org/10.1063/1.4718594.

37. D. H. Froula, et al., *Increasing hydrodynamic efficiency by reducing cross-beam energy transfer in direct-drive-implosion experiments.* Physical Review Letters, 2012. **108**(12): p. 125003, https://doi.org/10.1103/PhysRevLett.108.125003.

38. R. K. Follett, et al., *Thresholds of absolute two-plasmon-decay and stimulated Raman scattering instabilities driven by multiple broadband lasers.* Physics of Plasmas, 2021. **28**(3): p. 032103, https://doi.org/10.1063/5.0037869.

39. R. K. Follett, et al., *Thresholds of absolute instabilities driven by a broadband laser.* Physics of Plasmas, 2019. **26**(6): p. 10, 10.1063/1.5098479.

40. R. K. Follett, et al., Full-wave and ray-based modeling of cross-beam energy transfer between laser beams with distributed phase plates and polarization smoothing. Physics of Plasmas, 2017. **24**(10): p. 103128, https://doi.org/10.1063/1.4998713.

41. R. K. Follett, et al., *Suppressing two-plasmon decay with laser frequency detuning.* Physical Review Letters, 2018. **120**(13): p. 135005, https://doi.org/10.1103/PhysRevLett.120.135005.

42. R. Betti, et al., *Shock ignition of thermonuclear fuel with high areal density.* Physical Review Letters, 2007. **98**(15): p. 4, 10.1103/PhysRevLett.98.155001.

43. C. A. Haynam, et al., *National Ignition Facility laser performance status.* Applied optics, 2007. **46**(16): p. 3276-3303, https://doi.org/10.1364/AO.46.003276.

44. T. R. Boehly, et al., *Initial performance results of the OMEGA laser system.* Optics communications, 1997. **133**(1-6): p. 495-506, https://doi.org/10.1016/S0030-4018(96)00325-2.

45. Anping Liu, et al. *Spectral beam combining of high-power fiber lasers*. in *Fiber Lasers: Technology, Systems, and Applications*. 2004. SPIE; https://doi.org/10.1117/12.529598.

46. J. D. Zuegel, et al., Advanced Laser Concepts and Technologies for Laser Direct-Drive Inertial Fusion Energy (LDD-IFE), in NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

47. J. D. Zuegel and C. Dorrer, *PolyKrōm: Two New Broadband Laser Architectures for Laser Direct-Drive Inertial Fusion Energy (LDD-IFE) "[White paper]"*, in *IFE BRN*. 2022 (see Accepted White Papers at https://events.bizzabo.com/IFEBRN2022/page/2133559/white-papers).

48. D. E. Mittelberger, R. D. Muir, and J. E. Heebner, *Dynamic wavelength control of laser pulse profiles at picosecond to nanosecond timescales.* Optics Express, 2022. **30**(2): p. 1875-1884, https://doi.org/10.1364/OE.447494.

49. D. E. Mittelberger, et al., *Programmable, direct space-to-time picosecond resolution pulse shaper with nanosecond record.* Optics Letters, 2021. **46**(8): p. 1832-1835, 10.1364/ol.417080.

50. B. Afeyan and S. Huller, *Optimal control of laser plasma instabilities using Spike Trains of Uneven Duration and Delay (STUD pulses) for ICF and IFE.* Ifsa 2011 - Seventh International Conference on Inertial Fusion Sciences and Applications, 2013. **59**, https://doi.org/10.1051/epjconf/20135905009.

51. U.S. Department of Energy, Technology Readiness Assessment Guide (G 413.3-4). 2009.

52. Colin Danson, et al., *Petawatt class lasers worldwide.* High power laser science and engineering, 2015. **3**, https://doi.org/10.1017/hpl.2014.52.

53. J. C. Fernandez, et al., *Fast ignition with laser-driven proton and ion beams.* Nuclear Fusion, 2014. **54**(5): p. 36, 10.1088/0029-5515/54/5/054006.

54. John Jasper Bekx, et al., *Applicability of semiclassical methods for modeling laser-enhanced fusion rates in a realistic setting.* Physical Review C, 2022. **105**(5): p. 054001, 10.1103/PhysRevC.105.054001.

55. Dale H. Martz, et al., *Large area high efficiency broad bandwidth 800 nm dielectric gratings for high energy laser pulse compression.* Optics express, 2009. **17**(26): p. 23809-23816, https://doi.org/10.1364/OE.17.023809.

56. David A. Alessi, et al., *Picosecond laser damage performance assessment of multilayer dielectric gratings in vacuum.* Optics express, 2015. **23**(12): p. 15532-15544, https://doi.org/10.1364/OE.23.015532.

57. J. W. Bates, et al., Mitigation of cross-beam energy transfer in inertial-confinement-fusion plasmas with enhanced laser bandwidth. Physical Review E, 2018. **97**(6): p. 061202, 10.1103/PhysRevE.97.061202.

58. D. M. Kehne, et al., *Implementation of focal zooming on the Nike KrF laser.* Review of Scientific Instruments, 2013. **84**(1): p. 013509, https://doi.org/10.1063/1.4789313.

59. Frank Hegeler, et al. A durable, repetitively pulsed, 200 kV, 4.5 kA, 300 ns solid state pulsed power system. in 2010 IEEE International Power Modulator and High Voltage Conference. 2010. IEEE; https://doi.org/10.1109/IPMHVC.2010.5958284.

60. Holger Blaschke, et al. Laser resistivity and causes of damage in coating materials for 193 nm by photothermal methods. in Laser-Induced Damage in Optical Materials: 1998. 1999. SPIE; https://doi.org/10.1117/12.344383.

61. R. H. Lehmberg, J. L. Giuliani, and A. J. Schmitt, *Pulse shaping and energy storage capabilities of angularly multiplexed KrF laser fusion drivers.* Journal of Applied Physics, 2009. **106**(2): p. 023103, https://doi.org/10.1063/1.3174444.

62. J. Murray, et al., *Raman pulse compression of excimer lasers for application to laser fusion.* IEEE Journal of Quantum Electronics, 1979. **15**(5): p. 342-368, 10.1109/JQE.1979.1070009.

63. M. Damzen and Henry Hutchinson, *Laser pulse compression by stimulated Brillouin scattering in tapered waveguides.* IEEE Journal of Quantum Electronics, 1983. **19**(1): p. 7-14, 10.1109/JQE.1983.1071718.

64. Douglas S. Hobbs. Laser damage threshold measurements of anti-reflection microstructures operating in the near UV and mid-infrared. in Laser-Induced Damage in Optical Materials: 2010. 2010. SPIE; https://doi.org/10.1117/12.867411.

65. Raluca A. Negres, et al. 1064-nm, nanosecond laser mirror thin film damage competition. in Laser-Induced Damage in Optical Materials 2018: 50th Anniversary Conference. 2018. SPIE; https://doi.org/10.1117/12.2324022.

66. Raluca Negres, et al., *1064-nm, nanosecond laser mirror thin film damage competition*. SPIE Laser Damage. Vol. 11173. 2019: SPIE; https://doi.org/10.1117/12.2531861.

67. Christopher J. Stolz and Raluca A. Negres, *Ten-year summary of the Boulder Damage Symposium annual thin film laser damage competition.* Optical Engineering, 2018. **57**(12): p. 121910, https://doi.org/10.1117/1.OE.57.12.121910.

68. Christopher D. Marshall, Joel A. Speth, and Stephen A. Payne, *Induced optical absorption in gamma, neutron and ultraviolet irradiated fused quartz and silica.* Journal of non-crystalline solids, 1997. **212**(1): p. 59-73, https://doi.org/10.1016/S0022-3093(96)00606-0.

69. M. S. Tillack, et al., *Grazing-Incidence Metal Mirrors for Laser-IFE.* UCSD Center for Energy Research internal report, UCSD-CER-05-08, 2005, https://cer.ucsd.edu/_files/publications/UCSD-CER-05-08.pdf.

70. D. B. Sinars, et al., *Review of pulsed power-driven high energy density physics research on Z at Sandia.* Physics of Plasmas, 2020. **27**(7): p. 070501, https://doi.org/10.1063/5.0007476.

71. M. E. Cuneo, et al., *Characteristics and scaling of tungsten-wire-array z-pinch implosion dynamics at 20 MA.* Physical Review E, 2005. **71**(4): p. 046406, https://doi.org/10.1103/PhysRevE.71.046406.

72. R. B. Spielman, et al., *Tungsten wire-array Z-pinch experiments at 200 TW and 2 MJ.* Physics of Plasmas, 1998. **5**(5): p. 2105-2111, https://doi.org/10.1063/1.872881.

73. C. Deeney, et al., *Enhancement of X-ray power from a Z pinch using nested-wire arrays.* Physical Review Letters, 1998. **81**(22): p. 4883, https://doi.org/10.1103/PhysRevLett.81.4883.

74. R. D. McBride, et al., *A primer on pulsed power and linear transformer drivers for high energy density physics applications.* IEEE Transactions on Plasma Science, 2018. **46**(11): p. 3928-3967, 10.1109/TPS.2018.2870099.

75. S. A. Slutz, T. J. Awe, and J. A. Crabtree, *Dense hydrogen layers for high performance MagLIF.* Physics of Plasmas, 2022. **29**(2): p. 022701, https://doi.org/10.1063/5.0081177.

76. Stephen A. Slutz and Roger A. Vesey, *High-Gain Magnetized Inertial Fusion.* Physical Review Letters, 2012. **108**(2): p. 5, http://doi.org/10.1103/PhysRevLett.108.025003.

77. S. A. Slutz, et al., *Scaling magnetized liner inertial fusion on Z and future pulsed-power accelerators.* Physics of Plasmas, 2016. **23**(2): p. 11, https://doi.org/10.1063/1.4941100.

78. W. A. Stygar, et al., *Conceptual designs of two petawatt-class pulsed-power accelerators for high-energy-density-physics experiments.* Physical Review Special Topics-Accelerators and Beams, 2015. **18**(11): p. 110401, https://doi.org/10.1103/PhysRevSTAB.18.110401.

79. A. Zylstra, et al., *IFE Science & Technology Community Strategic Planning Workshop Report*. 2022 (https://lasers.llnl.gov/content/assets/docs/nif-workshops/ife-workshop-2022/IFE-Workshop-Report.pdf).

80. Michael G. Mazarakis, et al., *High-current linear transformer driver development at Sandia National Laboratories.* IEEE transactions on plasma science, 2010. **38**(4): p. 704-713, https://doi.org/10.1109/TPS.2009.2035318.

81. Peter A. Seidl, et al., *Research and development toward heavy ion driven inertial fusion energy.* Physical Review Special Topics-Accelerators and Beams, 2013. **16**(2): p. 024701, https://doi.org/10.1103/PhysRevSTAB.16.024701.

82. Peter A. Seidl, et al., *Short intense ion pulses for materials and warm dense matter research.* Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2015. **800**: p. 98-103, https://doi.org/10.1016/j.nima.2015.08.013.

83. A. W. Molvik and A. Faltens, *Induction accelerator efficiency at 5 Hz.* Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2001. **464**(1-3): p. 445-451, https://doi.org/10.1016/S0168-9002(01)00103-6.

84. Ken Takayama and Richard J Briggs, *Induction accelerators*. 2010: Springer Science & Business Media; https://doi.org/10.1007/978-3-642-13917-8.

85. Y. T. Zhao, et al., *High-energy-density physics based on HIAF.* Scientia Sinica-Physica Mechanica & Astronomica, 2020. **50**(11): p. 23, http://doi.org/10.1360/sspma-2020-0275.

86. A. Pietrzak, et al. Heading to 1 kW levels with laser bars of high-efficiency and emission wavelength around 880 nm and 940 nm. in High-Power Diode Laser Technology and Applications XIII. 2015. SPIE; https://doi.org/10.1117/12.2078642.

87. Martin Adams, et al. Modeling of influencing factors driving thermal runaway in 9xx-nm high-power laser diodes. in 2021 27th International Semiconductor Laser Conference (ISLC). 2021. IEEE; https://doi.org/10.1109/ISLC51662.2021.9615699.

88. General Atomics. *GA-EMS and Boeing Team to Develop 300kW-class HELWS Prototype for US Army*. 2021 23 May 2022]; Available from: https://www.ga.com/ga-ems-and-boeing-team-to-develop-300kw-class-helws-prototype-for-us-army.

89. Jonathan P. Phillips, et al., *High energy, high repetition rate, second harmonic generation in large aperture DKDP, YCOB, and LBO crystals.* Optics Express, 2016. **24**(17): p. 19682-19694, https://doi.org/10.1364/OE.24.019682

90. Dustin Froula, et al. Fourth-Generation Laser for Ultra-Broadband Experiments-Expanding Inertial Confinement Fusion Design Space Through Mitigation of Laser-Plasma Instabilities. in APS Division of Plasma Physics Meeting Abstracts. 2019; http://meetings.aps.org/link/BAPS.2019.DPP.GO6.2.

Chapter 5: Targets

5.1 Introduction

Realization of more effective targets is an essential part of any inertial fusion energy (IFE) solution. The private investment community and those pursuing integrated power plants consider target efficacy to be a big technical risk for all of IFE because National Nuclear Security Administration (NNSA) research and development (R&D) has never focused on target mass production. R&D toward low-cost, high-performing mass production of targets for repetition-rated drivers is a necessary part of any viable IFE program. Targets are currently fabricated to exquisite precision, though at markedly insignificant quantities for what even a single IFE power plant would require. The current focus for inertial confinement fusion (ICF) targets is to enable physics understanding and modeling and to demonstrate proof-of-principle concepts. Thus, present-day target fabrication facilities, capabilities, and staffing are structured to enable support of a wide variety of diverse designs and concepts to explore the realm of possible and to elucidate the physics basis of implosions. Present-day target fabrication facilities provide and support ICF experiments utilizing indirect drive, direct drive, fast ignition (FI), heavy ion, and pulsed power schemes. Note that relaxing the dimensional fabrication precision in IFE targets relative to current ICF targets will significantly increase the likelihood of successful mass-production of IFE targets at reactor-scale quantities. The manufacturing readiness level for mass production of targets to achieve ICF-stringent specifications is extremely low. We need significant manufacturing technology advancement and investment for IFE to be a credible and attractive energy source.

Today’s ICF target R&D is not nationally coordinated and is instead aimed at discrete, near-term objectives with low inter-ICF-site connectivity. R&D for repetition-rated target-fielding science and technology is a patchwork of narrowly focused efforts, generally championed by individual research groups attempting to achieve higher data output, and is not part of a broad capability-development effort. ICF target-quality yield is less than desired for present-day experiments demonstrating physics principles. Acceptable targets are currently selected from batches of fabricated targets. Today’s fabrication processes are lengthy and expensive owing to the wide variety of targets fielded and

SUMMARY

Current target types include those for laser direct-drive and indirect-drive, fast ignition, indirect-drive heavy-ion fusion, and pulsed-power. Compared to ICF, we must be able to manufacture all IFE targets at much lower cost and in much higher quantities. Further, an IFE power-plant system must accommodate target manufacturing variation while still achieving the average neutron output flux required for the reactor.

Thus, we must **demonstrate mass production of a single target design at high rate, low cost, and with high manufacturing yield.** To scale current manufacturing processes to economically mass produce targets for IFE, we will need to considerably **relax today’s target specifications and simplify target design.** We will need to develop **rapid target characterization methods for sorting and measuring** production-process witness targets for proofing and maintaining process parameters in target-fabrication production equipment. Further, **target injectors require development,** including target loaders that operate at reactor shot-frequency, are capable of cryogenic operation, and have proven long life. Finally, any future IFE integrated activity should include **developing and demonstrating target-tracking and beam-steering for full-power, full-size laser beams or full-current ion beams to accurately hit a target on the fly at full reactor velocity.**

the lack of standardized target designs and specifications, as well as the use of discrete batch processing to meet various discrete experimental campaign requests. Extensive characterization of the dimensions and characteristics of each target, as well as the fuel layer, add to ICF target cost. We can reduce IFE target cost by focusing on one design (per reactor) made by proofed out processes by which we characterize occasional witness targets to maintain production process parameters.

ICF shot rate is infrequent enough that it does not require target injection. In current ICF experiments, targets are inserted, held, and positioned in the target-chamber center attached to the stalk of a manipulator. ICF has no target injector or tracking of moving targets, as would be needed in IFE. Thus, target injection and tracking and accuracy in hitting a moving target with driver beams (target engagement) are R&D areas unique to IFE, although these areas have some commonalities in high-repetition-rate laser-target engagement in related fields, such as high energy density science (HEDS), extreme ultraviolet (EUV) lithography, x-ray free-electron laser (XFEL) science, and others.

The anticipated shot rate for pulsed-power IFE is low enough (≤0.1 Hz) that we do not envision target injection for reactors. Rather, the targets would be attached to replaceable transmissions lines and mechanically placed into the reactor chamber. However, the anticipated shot rate for direct drive, indirect drive, FI, and heavy-ion fusion (HIF) IFE is high enough (1–10 Hz) that these schemes will require target injection and the ability to hit the target on the fly. Thus, we will need to be able to track target position and velocity so we can steer the driver beams and accurately engage (hit) the target.

The Basic Research Needs (BRN) target panel examined the status and discussed issues concerning fabrication and delivery of targets at the quantities and rates required for IFE. A significant concern we expressed in our discussion is that we must assume more knowledge about target specifics than we could possibly know because a major BRN consideration for IFE target designs is maximizing yield for different driver concepts. Since the combination of the driver and the target is what enables IFE, divorcing these two topics is impossible; trade-offs between driver and target specifications are of paramount importance. Note that this panel did not consider (1) driver-beam steering/deflection technologies, (2) required reactor conditions to enable tracking, (3) tritium-related fueling concerns, or (4) a specific driver-target design/concept. Ultimately, an IFE program will need to address all these issues.

Status of IFE Target Fabrication

Around the world, researchers are pursuing various aspects of target fabrication to varying degrees.

- Presently no publicly funded program(s) in the United States are developing target fabrication for IFE concepts. The last such efforts were part of the High Average Power Laser (HAPL) and Laser Inertial Fusion Energy (LIFE) programs, which ended in 2008 and 2013 and were based on laser direct drive (LDD) and laser indirect-drive (LID) concepts, respectively.
- The European Union started an IFE program, called High Power Laser Energy Research (HiPER), based on FI or shock ignition (SI) targets that ended around 2012–2013. A small target fabrication effort was undertaken [1], including conceptualizing the cryogenic fielding of single-shot experiments on Laser Megajoule (LMJ) [2].
- The United Kingdom funded investigations at Cardiff University regarding the use of micro-fluidics based micro-encapsulation to mass produce targets [3]).

- Japanese researchers have envisioned an FI reactor, KOYO-F, and have carried out work at Osaka University and Hamamatsu concerning IFE capsule production by micro-encapsulation.
- Chinese research appears to be focused on developing ICF target capabilities, including micro-encapsulation of capsules and glow discharge polymerized deposition coating [4].
- For direct-drive concepts, Russian researchers at the Lebedev Physical Institute have developed methods for capsule production, creating uniform solid fuel layers in capsules by rolling capsules down a cryogenic spiral tube. They are developing superconducting electromagnetic injectors for layered capsules using a sabot [5]. They have demonstrated the ability to layer fuel, with layer thickness dependent on capsule dimensions and material, layering tube details, and allowable non-uniformity of the layer. They have also shown fuel layer smoothness improvements by adding impurities to the fuel (e.g., neon)[6, 7].

IFE Target Types

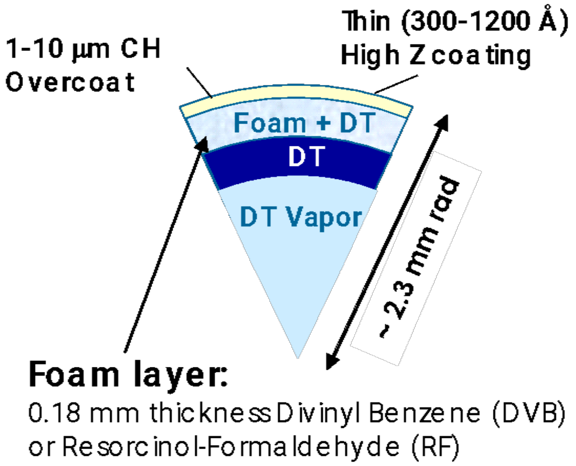


Figure 5.1. Laser direct-drive (LDD) target with solid deuterium-tritium (DT) ice layer developed by the HAPL program (Adapted from Sethian et al., 2010 [8]).

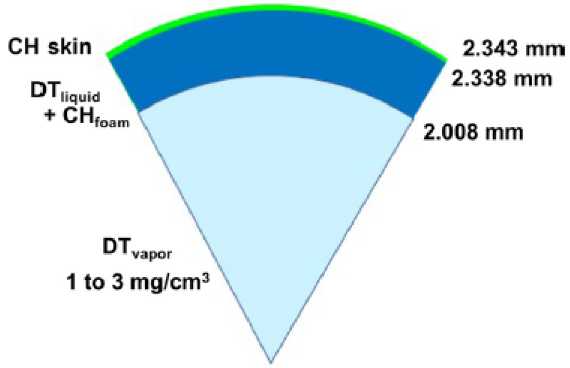


Figure 5.2. Laser direct-drive (LDD) target utilizing deuterium-tritium (DT) wetted foam. The liquid DT layer is formed by wicking DT into a polymer foam layer.

Laser Direct-Drive (LDD) Targets. LDD targets typically consist of a thin spherical shell or capsule containing a uniform layer of solid deuterium-tritium (DT) ice **(Figure 5.1** [8]**)**. Often a polymer foam lines the interior of the capsule, intermixed with the outer portion of the DT ice, to improve opacity or pre-heat characteristics of DT that will be ablated to implode the more interior DT. The typical approach to fill these targets with DT is to slowly diffuse DT gas through the capsule wall to high pressure, followed by cooling to cryogenic temperatures to freeze the DT. This is a slow process, which leads to simultaneous filling of large batches of targets. Larger batches lead to a need for a larger DT inventory. After filling, the DT needs to be formed into a uniform layer. This may be accomplished via beta-layering or, for layers of moderate thickness, by rolling down a spiral channel to fast-freeze the layer onto the capsule wall. Beta-layering is a slow process (e-folding time to uniform symmetry of 26 minutes) with implications for DT inventory. Several proposed IFE target designs put forth between 1987 and recent times have suggested using liquid DT wetted into foam on the interior of the capsule [10, 12, 13] (**Figures 5.2 and 5.3** [9-11]). These “wetted foam” designs offer the prospect of simplified and faster DT filling and layering. All DT is sustained/wicked into foam. Immersion into liquid DT to wicking through holes and into foam would simultaneously fill and layer the capsule. This process should be dramatically faster than the gas permeation fill and beta-layering route and hence should significantly reduce the DT inventory required for filling and layering the targets. The outer surface of the target is typically coated with a very thin infrared reflective coating to reduce thermal radiation heat load on the target while injecting the target into the reactor target chamber. Note that from a target-fabrication perspective, SI and hotspot ignition LDD targets are very similar. We can also shape such targets to compensate for low mode drive nonuniformity and can readily vary DT ratios.

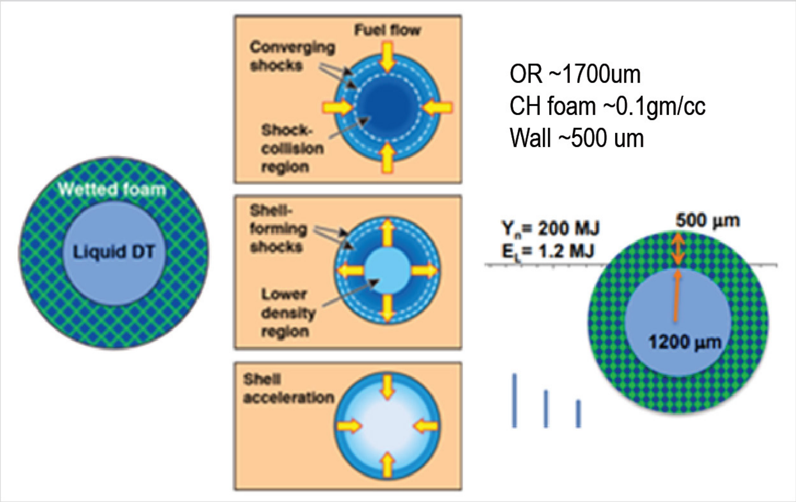


Figure 5.3. Laser direct-drive (LDD) target, wetted foam with liquid deuterium-tritium (DT) layer formed dynamically by laser pulse shaping while target is on the fly toward chamber center. Target is completely full of liquid DT prior to the pulse shaping [9-11].

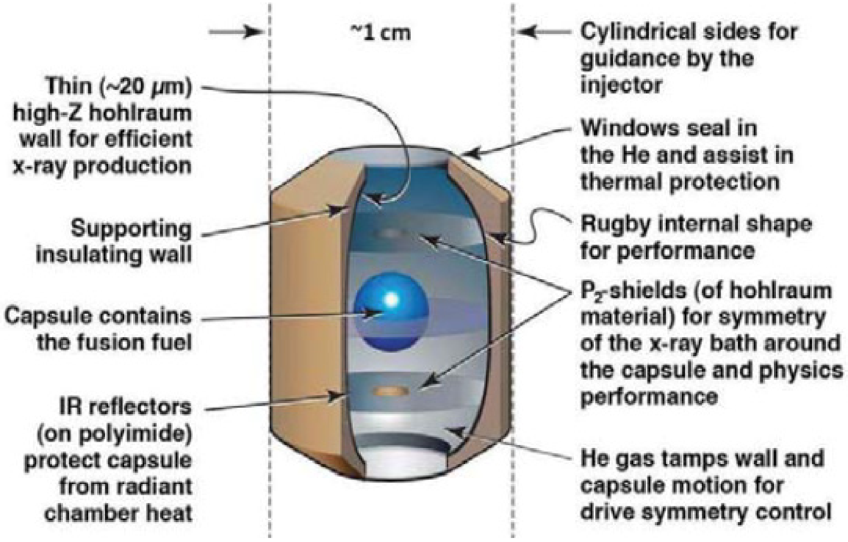


Figure 5.4. Laser indirect-drive (LID) target developed by the LIFE program (adapted from Miles et al. (2014) [14]).

Laser Indirect-Drive (LID) Targets. LID targets typically place a spherical capsule in the center of a cylindrically symmetric high-Z enclosure known as a hohlraum (**Figure 5.4** [14]). Very thin film with an infrared reflective coating typically covers the ends of the hohlraum. The coated film windows reduce heat load to the capsule during injection into the reactor target chamber by reflecting away thermal radiation from the reactor target chamber and diverting hot residual gas/plasma in the chamber to keep it from reaching the capsule. Lasers are shone in through the hohlraum end windows (laser entrance holes), illuminating the hohlraum inner wall whilst missing the capsule. This generates x-rays used to implode the capsule. For high-efficiency x-ray generation, the entire hohlraum, or at least a few tens of µm of the inner surface of the hohlraum, is made of high atomic number (Z) materials, such as lead or tantalum. The hohlraum material should be removable from the reactor chamber so, for liquid first-wall chambers, using a hohlraum material that is a component of the liquid wall is convenient. Sometimes, small shields are placed inside the hohlraum to alter or improve the symmetry of the radiation field inside of the hohlraum. Both these shields and the capsule can be suspended in the hohlraum using thin films. These films should have high strength to be thin enough to have minimal effect on the target implosion and yet be strong enough to allow the target to be accelerated to high speed for injection into the reactor target chamber, using an injector of reasonable length.

Since x-rays rather than laser light implode the capsule, the capsule ablator is thicker than in LDD. The capsule wall may also be doped with higher-Z elements for radiation preheat protection. We can fuel the capsule with DT via a slow ramping of DT pressure on the target to diffuse (permeate) DT into the capsule. However, this leads to high DT inventories because of the extra dead space between the capsule and the hohlraum. We can use beta-layering to layer the DT fuel as solid ice by imposing a non-uniform temperature profile on the exterior of the hohlraum, with the temperature profile designed to produce a spherical isotherm at the position of the capsule. This is how layering for NIF targets currently works. Filling and layering the capsule separately and then assembling the capsule into the hohlraum cryogenically is conceivable but complicated. Alternatively, a lower DT inventory method to fill and layer the capsule is to use a wetted foam fuel layer on the interior of the capsule and fill via wicking DT into the foam layer through a small hole, laser-drilled through the capsule wall. Ultimately, we will need automated assembly of all the target parts, with a precision level at the ten to tens of micrometers.

Fast Ignition (FI) Targets. FI targets are driven using two types of laser pulses. First, an array of lasers compress the target using a long-duration, nanosecond pulse. Then an ultra-short-pulse, picosecond laser(s) is (are) focused onto the side of the target to ignite the compressed target fuel. Specifically, the ultra-short laser pulse generates an electron or proton beam, depending on target design, to initiate ignition and burn. For a plain spherical capsule, the coronal plasma ablated off the target during the first pulse, causes the electron or proton beam to be generated too far away from the compressed fuel core to effectively ignite the core. This issue has led to the addition of a hollow cone to the capsule of the FI target (Figures 5.5 and 5.6). The cone prevents ablated plasma

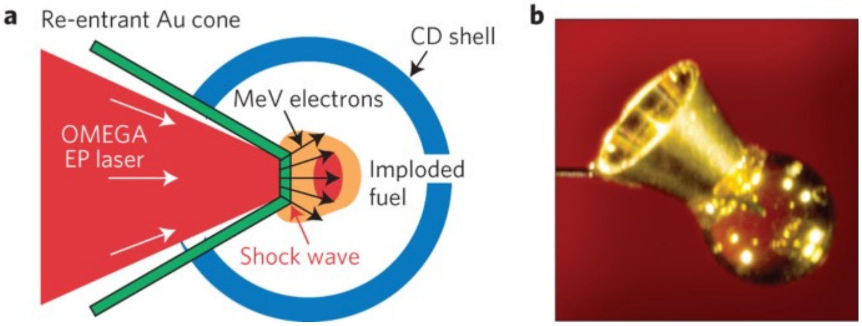


Figure 5.5. (a) Schematic and (b) assembled target of an electron fast ignition (FI) target, driven by long and short laser pulses (adapted from Betti and Hurricane (2016) [15]).

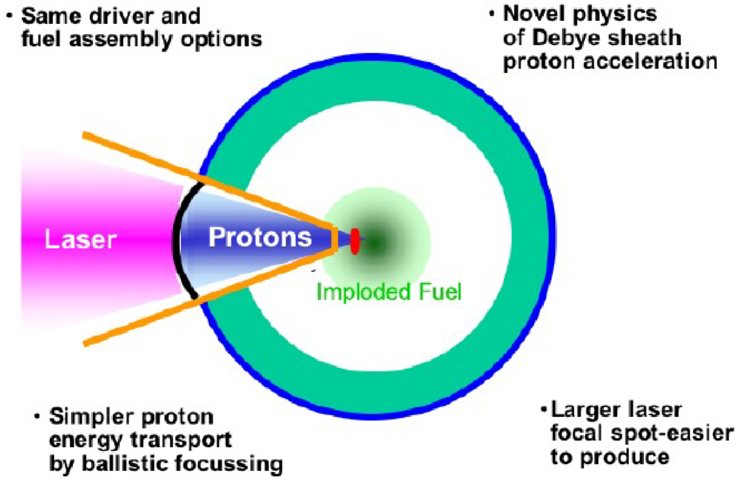


Figure 5.6. Schematic of a proton fast ignition (FI) target, driven by long and short laser pulses (adapted from Ditmire et al (2021) [16]

from the first laser pulse from reaching the interior of the cone. The electron or proton beam can thus be generated at the cone tip (electrons, **Figure 5.5** [15]) or near the cone tip (protons, **Figure 5.6** [16]), much closer to the compressed fuel core. For proton FI, a thin foil is added inside the cone for proton generation (**Figure 5.6**). The target may be fueled with DT via a slow ramping of DT pressure on the target to diffuse (permeate) DT into the capsule. This leads to high DT inventories, due to the slow pressure ramp required to avoid crushing the capsule. We can use beta-layering to layer the DT fuel as solid ice by imposing a non-uniform temperature profile on the exterior capsule using shaped cavities clamped around the target and/or heaters. Alternatively, a method of filling and layering the capsule using a wetted foam fuel layer on the interior of the capsule requires a lower DT inventory. As described for LID targets, filling is possible via wicking into the foam layer through a small hole, laser-drilled through the capsule or cone wall. Also as with LID, we will ultimately need automated assembly of all the target parts, with the precision level at the ten to tens of micrometers.

Indirect-drive heavy-ion fusion (HIF) targets. Indirect-drive HIF targets are often similar to LID targets. **Figure 5.7** [17] shows a hotspot ignition target with distributed radiators. From a target-fabrication perspective, this target is similar to the LID target but differs in several important ways. The heavy ions used to drive the fusion target have very long penetrating power into the target materials, whereas laser light has very little. This means that the ends of the heavy-ion fusion hohlraum have solid walls, not thin windows. This makes the heavy-ion fusion target more thermally robust against DT fuel-layer degradation due to the reactor chamber thermal threat. The hohlraum is lined with high Z foams of various densities. These are the distributed radiators. They generate Bremsstrahlung x-rays upon deposition of ion-beam energy as the beams pass through the foams. Use of foam provides more spatially uniform x-ray production using lower-energy ions. Designs for direct-drive HID targets also exist [18, 19]. While these are spherical-like laser-driven direct-drive targets, their outer layers are thick metal layers compared to thin low atomic number (Z) layer(s) in LDD.

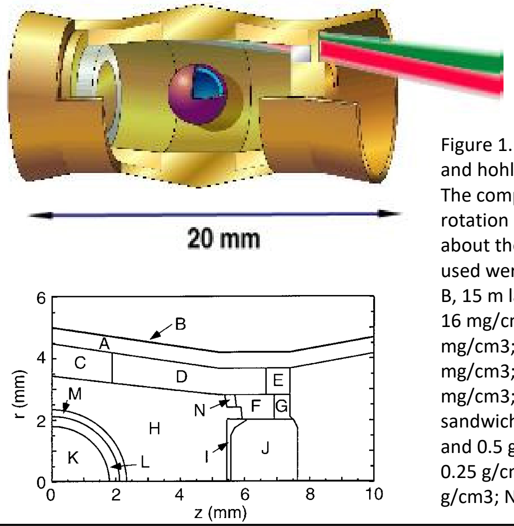


Figure 1. Diagram of a quarter of the capsule and hohlraum for the close coupled target. The complete target can be formed from a rotation about the z axis and a reflection about the r axis. The materials and densities used were as follows: A, AuGd at 0.1 g/cm3; B, 15 m layer of AuGd at 13.5 g/cm3; C, Fe at 16 mg/cm3 ; D, (CD2)0:97Au0:03 at 11 mg/cm3; E, AuGd at 0.11 g/cm3; F, Al at 70 mg/cm3; G, AuGd at 0.26 g/cm3; H, CD2 at 1 mg/cm3; I, Al at 55 mg/cm3; J, AuGd sandwich with densities 0.1 g/cm3, 1.0 g/cm3 and 0.5 g/cm3; K, DT at 0.3 mg/cm3; L, DT at 0.25 g/cm3; M, Be0:995Br0:005 at 1.845 g/cm3; N, (CD2)0:97Au0:03 at 32 mg/cm3.

Figure 5.7. The distributed radiator target irradiated in an indirect-drive geometry with heavy ions (adapted from Callahan-Miller and Tabak (1999) [17]).

Another type of HIF target is the ion-beam FI "X" target (**Figure 5.8** [20]). This target uses a high-density tungsten cylindrical case as a tamper. The cylindrical case has re-entrant conical end walls at each end and is lined with a cylindrical shell of polymer (CH) for use as a propellant. The long-duration ion drive pulse(s) interact with the propellant layer. Just inside the propellant layer is an aluminum layer as a pusher/propellant/tamper layer. The remaining cavity is fully filled with DT fuel. The short-duration ion-ignition pulse strikes the target on axis once the fuel has been compressed; the target and implosion are cylindrically symmetric. Note that this target does not require any DT layering process. Rather, we can fill the target by dispensing liquid DT into the target, sans one end-

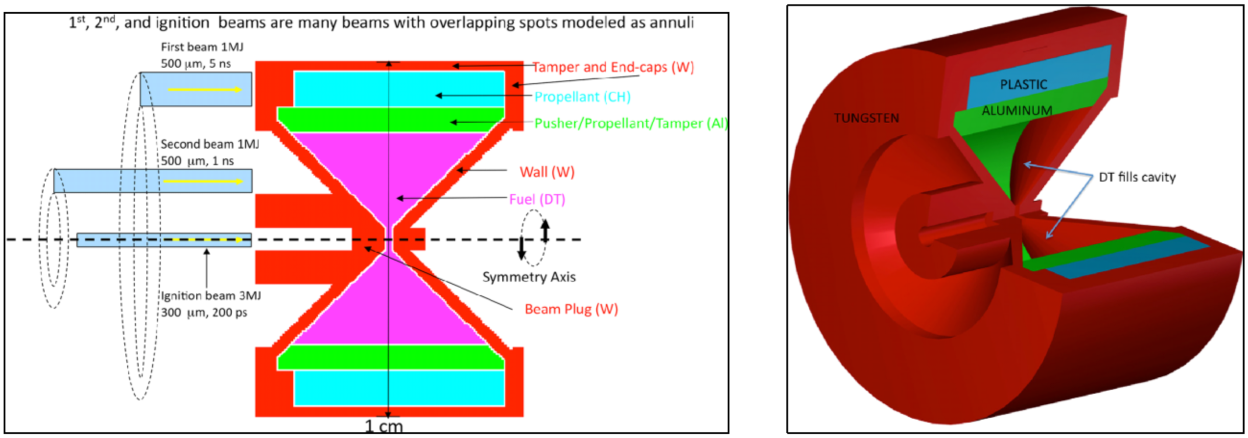


Figure 5.8. X-target, irradiated with indirectly driven, long combined with short-pulse heavy ions (adapted from Henestroza and Logan (2012) [20]).

wall, and then fasten the missing end-wall to complete the target. Size and lack of a precision-formed DT layer both make this target thermally robust to the reactor chamber thermal threat. Thus, the X-target does not require a capsule.

Pulsed-Power Targets. Pulsed-power targets come in different types. The most recently studied pulsed-power IFE scheme uses the magnetized liner inertial fusion (MagLIF) approach. Figure 3.4 shows a MagLIF-type target for magnetically driven implosions. In the MagLIF target, coils (not shown in Figure 3.4) first generate a seed axial magnetic field on the target. A large current is driven through a low-Z liner (e.g., a beryllium or aluminum can), and the resulting magnetic force implodes the liner, compressing its contents. The bottom end of the can is fully enclosed, whereas a thin window film covers the top end of the can to hold in the enclosed fuel gas. As the liner is imploding, a several nanosecond laser is shone on-axis through the window to pre-heat the gaseous fuel. We can use cryogenic temperatures to increase the density and hence the amount of fuel in the target. We can accomplish higher gains/yields by having a foam layer on the inside of the liner so that liquid fuel can be wicked up into a layer along the liner's inner surface.

Summary of Target Types. Scaling present day manufacturing processes to economically mass produce targets for IFE will require considerable relaxation of today's target specifications and simplification of target design. The additional components of indirect drive, FI, and pulsed-power targets (relative to the capsule of direct drive and SI targets) add complexity to the target fabrication process. The additional parts also generate more waste in the reactor that we must recover and potentially recycle. For all target types, we will need to develop rapid target characterization methods for sorting and measuring production-process witness targets for proofing and maintaining process parameters in target-fabrication production equipment. Emerging manufacturing technologies, such as additive manufacturing, are promising; however, they are at very early stages both in technology maturation and in understanding process controls and mass-production scaling. As a primary focus area, all IFE concepts should capitalize on other commercial high-volume industries to drive technology and adoption for target designs of interest.

Target Injectors

Several institutions have developed experimental target injectors using gas guns and electromagnetic launchers for both direct- and indirect-drive targets. Institutions have also pursued target tracking.

- In *Japan*, EX-Fusion has developed a 10-Hz-capable target dropper and tracker for 1-mm-diameter polymer beads [21]. While beads are not targets of the type considered in this report, it does demonstrate high-rate operation in a non-cryogenic system.
- In *Russia*, the Lebedev Physical Institute is developing an electromagnetic launcher for direct-drive targets based on high-temperature superconducting sabots and permanent magnet guideways. They have achieved sabot levitation and low-speed sabot propulsion (~1 m/s) [5]. They have published design calculations for achieving 200+ m/s target launches. They do not appear to have launched targets from their prototypes yet.
- In *Europe*, the HiPER program considered a gas gun with a subsequent magnetic levitation stage acting on an SI target (similar in shape to a direct-drive target) held in a sabot; they also considered the system being developed by the Lebedev Physical Institute [22]. HiPER did not build prototype target injectors.
- In the United States, General Atomics developed a helium gas gun for launching direct-drive targets protected by a sabot [23]. This gun demonstrated reactor compatible target launch velocities, up to 400 m/s. General Atomics also developed a linear induction accelerator (LIA)-based target injector for launching indirect-drive targets [24] or sabot launching of direct-drive targets. This LIA injector demonstrated reactor-compatible target launch velocities of up to 57 m/s, as well as 80 revolutions/s target spin. (Cylindrically symmetric target surrogates require spin to be stable in flight.) They operated the gas gun and the LIA, both room temperature devices, in single-shot mode. However, future generations of these devices were expected to be upgradeable to cryogenic operation and continuously operated at reactor-relevant shot frequencies. **Table 5.1** gives the accuracy achieved in the gas gun and the LIA. General Atomics improved the accuracy of the LIA by adding both active and magnetic lenses after the exit of the LIA barrel to correct the trajectory of the target in flight. The target-injector accuracy achieved can help inform the beam-steering requirements for drivers.

Thus, target injector development has shown the ability to reach reactor-relevant velocity and accuracy in single-shot mode at room temperature. However, target injectors still need considerable development. In particular, target injectors need target loaders that operate at reactor shot-frequency and need to be capable of cryogenic operation, as will be needed for the DT fuel-layered cryogenic targets used in most reactor concepts. We will also have to demonstrate long life (i.e., low wear, low maintenance).

We must accurately hit the injected target on the fly. Carlson *et al.* (2010) [25] demonstrated this capability with direct-drive targets at low speed (5 m/s) using a single, small-diameter, low-power laser beam; they were able to hit the targets with an accuracy of 28 µm (one sigma precision). Any future IFE integrated activity should include developing and demonstrating target-tracking and beam-steering for full-power, full-sized laser beams or full-current ion beams to accurately hit a target on the fly at full reactor velocity.

Table 5.1: Accuracy achieved by target-injector demonstrations at General Atomics

INJECTOR	REPEATABILITY 1 σ (mm)	REPEATABILITY 1 σ (mRad)
Gas gun with two-piece sabot, 400 m/s, and 1-mg direct-drive target	10	0.59
Gas gun barrel with one-piece shuttle, mechanically driven, 50 m/s, and 1-mg direct-drive target	4	0.24
Linear induction accelerator (LIA) with indirect-drive target surrogate – no steering – horizontal	5.97	2.5
LIA with indirect-drive target surrogate – passive steering – horizontal	0.6	0.3
LIA with indirect-drive target surrogate – active steering – horizontal	0.24	0.1
LIA with indirect-drive target surrogate – no steering – vertical	5.42	2.3
LIA with indirect-drive target surrogate – passive steering – vertical	0.68	0.3
LIA with indirect-drive target surrogate – active steering – vertical	0.24	0.1

Commonalities between ICF and IFE targets

ICF and IFE target fabrication processes have many aspects in common: capsule and capsule mandrel production; shimming of capsules; use of foam shells, foam density profile (radial) control, and foam shells with seal coats (conversely thin shells with inner foam layer); infrared reflective layers; solid DT layering; wetted foam liquid layering; diagnostics of pits; protrusions/dust; cracks; inclusions (e.g., high Z materials); and three-dimensional inspection. However, compared to ICF, we must be able to manufacture all IFE targets at a much lower cost (roughly 10–20% of the electricity value of the target's yield; e.g. ~$0.26 to $0.51 each for 400 MJ target yield in a 33%-efficient reactor where electricity value is 7 cents/(kW*hr)) and in much higher quantities (typical reactor rates range from 0.1 to 15 Hz continuous production). An IFE power plant system must accommodate target manufacturing variation while still achieving the average neutron output flux required for the reactor. Thus, we must demonstrate mass production of a single target design at high rate, low cost, and with high manufacturing yield. Absent the detailed ICF metrology techniques used today, inspection yields must be high or have significantly relaxed specification compared to ICF targets. We expect that IFE target metrology will utilize traditional quality-sampling protocols for qualified manufacturing processes to maintain the process controls of the manufacturing parameters and tolerances.

Target transportation to high-speed injection into the reactor chamber at reactor shot frequency will require an injection technology that does not destroy fragile targets and is accurate enough to be compatible with the beam-steering slew rate and slew range of the driver beams.

Most IFE concepts utilize target tracking for accurately determining target position in the chamber so that we can steer driver beams to precisely hit the target (with the exception of pulsed-power targets and possibly some HIF targets). A key challenge here is the interdependence of the target chamber neutron shielding and volumetric environmental (debris) mitigation to allow implementation of such a tracking system within a dynamic and harsh reactor environment.

5.2 Priority Research Opportunities (PROs)

PRO 5-1: ***Demonstrate high-volume techniques for spherical capsule or wetted-foam capsule fabrication***

This PRO applies to LID, LDD, FI, SI, and HIF approaches since there are target designs in all these IFE schemes that use a spherical capsule or part thereof to contain the target fuel.

Capsules and wetted-foam capsules need to be highly spherical, and the degree of sphericity and deviation from sphericity at various length scales is target-design specific. The wall thickness must be highly uniform and is also target-design specific. Diameters needed for the various IFE designs should fall within the 2–10-mm range. Fabrication techniques must project to produce capsules at an affordable cost when scaled to reactor levels. This depends on design parameters including target yield, target shot rate, reactor efficiencies, and reactor capital cost. We anticipate that the capsule cost needs to be under about 10–20% of the electricity value of the targets' yield, produced at rates between about 0.1 and 15 Hz, continuously, dependent on reactor design.

Wetted-foam capsules add manufacturing complications because of the double-layer structure (the outer capsule plus an inner foam layer). The wetted-foam capsule can be made inside out (foam shell first, then creating a capsule layer on the foam shell) or outside in (outer capsule layer first, then lining with a foam layer) or both layers simultaneously (e.g., with additive manufacturing). The foam layer should have uniform density and should require less than ~1/20th of solid density, with foam-cell sizes of less than ~1 µm.

We encourage manufacturing methods that broaden the exploration of target-design space, which can lead to better performing targets. Examples include a radial gradient in the foam layer or specific deviations from spherical symmetry to match non-spherical illumination.

The microencapsulation technique can produce uncured capsules or foam shells at the required rate. The challenge is in curing the capsule while maintaining sphericity and wall uniformity. Curing in small, flask-sized, containers with appropriate agitation produces quality shells. Approaches to the fabrication challenges include but are not limited to (1) scaling up the curing of microencapsulated shells to large-scale containers (drum size) with high yield; (2) utilizing deterministic methods to center the inner surface to outer surface of the shell and cure rapidly while centered (e.g., use dielectrophoresis to force centering, then cure with an ultraviolet (UV)-light-curing polymer formulation); and (3) increasing the production rate of high-resolution additive manufacturing systems (e.g., 2-photon polymerization printers). Additionally, high speed screening techniques may be useful for removing out-of-specification shells, thereby improving yield, as well as characterization of process-witness targets to maintain production process parameters.

PRO 5-2: ***Demonstrate accurate on-the-fly engagement of IFE targets by a driver beam***

This PRO applies to the LID, LDD, FI, SI, and HIF approaches since they all plan to inject targets into the reactor chamber.

To successfully ignite the target, we must accurately hit (engage) it. The precision required is target/driver-design dependent, but we expect the required engagement precision to be ~<25 µm. For the target to survive the thermal threat of the reactor environment (temperatures ~1000 °C), we must inject the target at high speed. While the required target speed is reactor- and target-design-specific, we anticipate it will be in the 50–200-m/s range. The challenge of this PRO is to accurately hit (engage) targets or target surrogates traveling at reactor-relevant velocity, primarily a demonstration of the integration of the target-tracking system and a system for steering the driver beams. Target surrogates enable us to use non-prototypic target injectors. Using targets will entail integration of prototypic target injectors, as well. We may need different target tracking for different types of targets due to their varying shapes. We will also need a diagnostic for determining engagement accuracy. Beam steering must accommodate the full aperture expected of the reactor-sized driver beam. While initially we could employ a low power/energy/current beam to engage the target, ultimately we should integrate an IFE reactor-level, full-power/energy/current beam into the demonstration.

PRO 5-3: ***Develop an IFE target injector for cryogenic IFE targets capable of reaching reactor-relevant velocity without damaging the target or its fuel layer***

This PRO applies to the LID, LDD, FI, SI, and HIF approaches since they all plan to inject (shoot) the targets into the reactor chamber.

Target injector prototypes capable of reactor-relevant velocities and acceleration profiles have been built and were used to assess target-injection accuracy. Accuracy requirements will depend on the slew range through which the driver beam-steering system can deflect the beam, which will be driver- and beam-steering-specific. We will likely need accuracy to be better than 0.5 mrad. Reactor-relevant velocities and accelerations are reactor- and target-design-dependent. We anticipate that required velocities will be ~50–200 m/s, with acceleration of less than ~1000 g. However, the previously built target injectors were single-shot, room-temperature devices. The challenge is developing a target injector that incorporates a target loader capable of reactor-relevant loading rates (~1–10 Hz) and continuous 24/7 operation. We should design the loader to have an appropriate interface for receiving cryogenic targets from a target-fill and -layering station, and it should be gentle enough not to damage targets as it handles them. Initial injector development and prototypes may be at room temperature, but ultimately the injector should operate at cryogenic temperatures.

Injectors shooting cylindrically symmetric targets (such as hohlraums) will need to spin the target about the cylinder axis, as well as axially accelerate the target, to prevent tumbling of the target during flight. Injectors shooting spherically symmetric targets do not need to spin the target but do need to account for the complex aerodynamic response within the fusion chamber that can lead to unpredictable deflection in a non-vacuum environment. We can use sabots to protect the target from mechanical or thermal damage while it is in the injector and in transit across the chamber and to aid in the aerodynamic performance—much like a hohlraum. If we use a sabot, we must employ a mechanism to remove the sabot in-flight to keep it from reaching the reactor chamber. Ideally, we would recover sabots without damage and reuse them. However, where we expect sabot damage to occur, we would include the cost of recycled, refurbished, or new sabots as a penalty on the cost of each target or an additional operating cost for the reactor. Long life and low-maintenance operation are ideal characteristics for an injector.

Assessment of items affecting these characteristics during injector operation is appropriate (e.g., barrel wear, accuracy degradation with shots). Injectors should include a provision for preventing any gas used or present in the injector from reaching the reactor chamber if that gas is incompatible with the reactor chamber. An example of this would be installing differential pumping along the flight path between the injector and the reactor chamber to remove helium propellant gas used in a gas gun–style injector. Prior injector prototypes have been built using gas guns and various electromagnetic architectures (e.g., LIA). We expect these architectures to be suitable for IFE injectors, but others may also work as well.

References

1. M. Tolley, et al. *HiPER targetry: production and strategy*. 2011. SPIE; http://dx.doi.org/10.1117/12.891879.

2. J. P. Perin, *Cryogenic systems for LMJ cryotarget and HiPER application.* Laser and Particle Beams, 2010. **28**(1): p. 203-208, 10.1017/s0263034610000091.

3. J. Li, et al., Continuous and scalable polymer capsule processing for inertial fusion energy target shell fabrication using droplet microfluidics. Sci Rep, 2017. **7**(1): p. 6302, 10.1038/s41598-017-06746-3.

4. Kai Du, et al., *Recent progress in ICF target fabrication at RCLF.* Matter and Radiation at Extremes, 2018. **3**(3): p. 135-144, 10.1016/j.mre.2017.12.005.

5. I. V. Aleksandrova, E. R. Koresheva, and E. L. Koshelev, A high-pinning-Type-II superconducting maglev for ICF target delivery: main principles, material options and demonstration models. High Power Laser Science and Engineering, 2022. **10**, E11. doi:10.1017/hpl.2022.1.

6. E. R. Koresheva, Cryogenic Target Factory for IFE Reactor: Conception & Pop Experiments, in 7th IAEA. 2015.

7. I. V. Aleksandrova, et al., *An efficient method of fuel ice formation in moving free-standing ICF/IFE targets.* Journal of Physics D: Applied Physics, 2004. **37**(8): p. 1163, https://doi.org/10.1088/0022-3727/37/8/004.

8. J. D. Sethian, et al., *The Science and Technologies for Fusion Energy With Lasers and Direct-Drive Targets.* Ieee Transactions on Plasma Science, 2010. **38**(4): p. 690-703, 10.1109/Tps.2009.2037629.

9. E.M. Campbell, Overview of ICF History, Challenges Prospects for Driver-target Concepts. 2022: Basic Research Needs (BRN) Workshop.

10. V. N Goncharov, et al., Novel Hot-Spot Ignition Designs for Inertial Confinement Fusion with Liquid-Deuterium-Tritium Spheres. Physical Review Letters, 2020. **125**(6), 10.1103/physrevlett.125.065001.

11. V. N. Goncharov, et al., Inertial Fusion Energy Target Designs with Advanced Laser Technologies, in NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

12. R. A. Sacks and D. H. Darling, *Direct Drive Cryogenic Icf Capsules Employing D-T Wetted Foam.* Nuclear Fusion, 1987. **27**(3): p. 447-452, Doi 10.1088/0029-5515/27/3/009.

13. R. E. Olson, et al., A polar direct drive liquid deuterium-tritium wetted foam target concept for inertial confinement fusion. Physics of Plasmas, 2021. **28**(12), 10.1063/5.0062590.

14. Robin Miles, et al., *Thermal and Structural Issues of Target Injection into a Laser-Driven Inertial Fusion Energy Chamber.* Fusion Science and Technology, 2014. **66**(2): p. 343-348, 10.13182/fst14-779.

15. R. Betti and O. A. Hurricane, *Inertial-confinement fusion with lasers.* Nature Physics, 2016. **12**(5): p. 435-448, 10.1038/nphys3736.

16. T. Ditmire, et al., Focused Energy Perspective on Inertial Fusion Energy. 2021: IFE Workshop.

17. D. A. Callahan-Miller and M. Tabak, *Increasing the coupling efficiency in a heavy ion, inertial confinement fusion target.* Nuclear Fusion, 1999. **39**(11): p. 1547, 10.1088/0029-5515/39/11/306.

18. B Badger, F Arendt, and K Beckert, *A Conceptual Heavy Ion Beam Driven Fusion Reactor Study.* UWFDM-450 and KfK, 1981. **3202**,

19. Shigeo Kawata, Direct-drive heavy ion beam inertial confinement fusion: a review, toward our future energy source. Advances in Physics: X, 2021. **6**(1): p. 1873860, 10.1080/23746149.2021.1873860.

20. Enrique Henestroza and B. Grant Logan, *Progress towards a high-gain and robust target design for heavy ion fusion.* Physics of Plasmas, 2012. **19**(7): p. 072706, 10.1063/1.4737587.

21. Kazuki Matsuo, Yoshitaka Mori, and Koichi Masuda, EX-Fusion's challenge for the realization of laser fusion system, in NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

22. HiPER Project Team, *HiPER Preparatory Phase Study: Final Report (Grant Agreement Number 211737)*. 2013 (https://cordis.europa.eu/docs/results/211/211737/final1-hiper-final-report.pdf).

23. D. T. Frey, et al., *Rep-rated target injection for inertial fusion energy.* Fusion science and technology, 2005. **47**(4): p. 1143-1146, https://doi.org/10.13182/FST05-30.

24. Ronald Petzoldt, et al., *Linear induction accelerator with magnetic steering for inertial fusion target injection.* Fusion Science and Technology, 2015. **68**(2): p. 308-313, https://doi.org/10.13182/FST14-915.

25. Lane C. Carlson, et al., Completing the Viability Demonstration of Direct-Drive IFE Target Engagement and Assessing Scalability to a Full-Scale Power Plant. IEEE transactions on plasma science, 2010. **38**(3): p. 300-305, 10.1109/TPS.2009.2037423.

SECTION THREE

FUSION PILOT POWERPLANT INTEGRATED SYSTEMS

Chapter 6: Power Systems, Science, Engineering & Technology

6.1 Introduction

This chapter covers the technical challenges that are inherent to the power systems required within an operating inertial fusion energy (IFE) plant—tritium fuel cycle systems, structural and first wall materials, and breeding and cooling blanket systems. It also provides a framework for how to structure a broad-based approach to IFE technology development in the context of a set of self-consistent, integrated power plant concepts.

The development of IFE plant technologies and the associated testing, licensing, and safety assurance programs are clearly long-lead-time challenges. Different IFE approaches impose a wide range of nontrivial requirements on the target-physics solutions, and there are many complex cross-dependencies between individual subsystems. Thus, we must, from the earliest phase of this program, cultivate a set of integrated plant models and quantitative point-design parameters alongside the development of individual subsystem technologies, ensuring that these models appropriately inform decision makers regarding the tradeoffs between specific solutions. This allows us to evaluate the impact of pursuing different technical paths in a self-consistent manner, quantifying the benefit to be gained by advancing the performance of any given area and determining the knock-on impact to the risk/stress placed on adjoining subsystems and overall plant viability. In this way, we can assess the relative merits of advances in physics performance and different technologies and materials. The end-product is a risk/performance/integration framework to inform a balanced program.

We can derive a quantitative evaluation of options for an IFE technology-development program by working backward from the integrated requirements of a pre-commercial, utility-scale pilot plant and assessing the technical viability of combining different subsystem solutions [1, 2]. Such an evaluation can also help motivate the need for early-stage (low technology readiness level (TRL)) research and development (R&D) in areas where step-changes in performance can unlock otherwise intractable problems or greatly advance the overall attractiveness of a given approach. Many of these activities

SUMMARY

A viable IFE-development program must incorporate a set of system-level design activities early on to provide guidance throughout the life of the program. In particular, we must design **three key sub-systems,** as well as system integration. **Selection of the chamber materials and component fabrication** will be highly specialized with extensive component evaluation and lifetime testing. We must **optimize tritium** extraction, confinement, containment, and processing technologies and materials, as well as understand the impact of tritium on base materials and component structures. The **integrated chamber solution** needs to enable target/driver delivery, efficiently capture and transmit thermal power, resist damage, breed sufficient tritium, remove residual target debris, reset for the next pulse, and maintain sufficient longevity for sustained multi-year operation. Finally, we need an unbiased, **integrated system model and point-design framewor**k to inform technology-development priorities, assess tradeoffs, and evaluate plant-level performance characteristics. Many of these activities are synergistic with ongoing work in the inertial confinement fusion and magnetic fusion energy communities, as well as the fission power sector.

are synergistic with ongoing work in the inertial confinement fusion (ICF) and magnetic confinement fusion (MCF)/magnetic fusion energy (MFE) communities, as well as in the fission power sector.

A high-level summary of the power-systems scope in this chapter is as follows:

- Advanced material development and testing (in section 6.2, see "Fusion Materials" sub-section)
  - **Objectives:** Selection of the chamber materials and component fabrication will be highly specialized (e.g., low impurity steels or composites in conventional or complex advanced manufactured forms), with extensive component evaluation and lifetime testing to demonstrate the ability to fabricate the material into necessary shapes with practical joining processes. We will need to support qualification of components by comprehensive material modeling, requiring a program that closely couples material development and modeling and characterization over multiple length-scales for irradiated materials. We will need test-validated models to quantify resistance to radiation damage, including swelling and helium embrittlement, high-temperature strength and resistance to creep, and resistance to corrosion and environmental cracking at high-temperature. Of paramount importance is the effect of 14-MeV neutron transmutation on material performance. We need a comprehensive, model-guided material development and irradiation-materials science program, linking microstructure and modeling utilizing 14-MeV neutrons, mixed spectrum/fission spectrum test reactors, and surrogate ion beams. We need to understand the unique IFE issues of pulsed irradiation and pulsed high heat-flux thermomechanics to realize accelerated development of next-generation materials.
  - *PRO 6-1:* ***Develop a modeling-informed, experimentally verified understanding of IFE structural materials at the macro- and microscopic levels when subjected to a pulsed, fusion-relevant spectrum (neutrons, ions, neutrals/debris, x-rays, thermal).***
  - *PRO 6-2:* ***Develop models and experimental data to inform damage thresholds in transmissive and reflective final optics and establish solutions that enable sufficient longevity in a fusion environment.***
- Tritium-processing system development and testing (in section 6.2, see "Fuel-Cycle Technologies" section)
  - **Objectives:** We must optimize tritium extraction, confinement, containment, and processing technologies and materials, consistent with an on-site inventory that fits within a regulatory regime for predictable licensing and the high-throughput needs of continuously operating plants. Understanding the impact of tritium on base materials and component structures is critical to enabling design and testing of prototypes for chamber exhaust systems, blanket systems, and tritium-processing systems.
  - *PRO 6-3:* ***Develop synergistic target/fuel cycle co-design between the plasma physics community and the fuel-cycle teams and chamber design teams to develop target designs and identify target materials and processing methods that have minimum impact on the fuel cycle and allow for inventory reduction.***

- Fusion engine (chamber) design, manufacture, and testing (in section 6.2, see "Fuel-Cycle Technologies" section)
  - Objectives: The integrated chamber solution is perhaps the single most difficult element to develop in the absence of an integrated pilot plant. The chamber needs to enable successful target and driver delivery; capture and transmit thermal power with high efficiency; be resistant to activation, decay heat, radiation damage, and corrosion; breed sufficient tritium; remove residual target debris; reset for the next pulse; withstand the peak stresses of each pulse along with time-averaged creep and degradation; and maintain sufficient longevity and availability for sustained multi-year operation. For laser-based systems, the chamber systems needs to enable the required intensity on target, which can range from modest levels (10^{14}–10^{15} W/cm^2 for central hotspot (CHS) and magnetized liner inertial fusion (MagLIF) designs) to more challenging levels (10^{16} and 10^{19} W/cm^2 for shock ignition (SI) and fast ignition (FI), respectively). We need high heat-flux component and heat-transfer loop designs, supported by validated codes, with construction and testing of scaled prototypes. To inform choices in coolant materials and overall plant design and safety analysis, we need to optimize for safety and performance of the integrated engine system, including testing key sub-systems—such as the primary heat-transfer loop—and extracting data on corrosion, chemical reactivity, and thermomechanical and nuclear performance.
  - *PRO 6-4:* ***Develop a test facility with a neutron source to evaluate blanket technologies and to test fuel-cycle components and systems at scale, including tritium extraction and transport, and the potential for direct internal recycle (DIR).***
- Integrated power-plant design (in section 6.2, see "System Integration and Design" section)
  - Objectives: We need to establish a robust, quantifiable basis for overall plant requirements and design optimization. This basis needs to combine physics and technology performance terms with operating characteristics (e.g., the impact of failure modes on downtime and component health), licensing requirements (e.g., material qualification, waste disposal, safety performance), economic terms (e.g., capital, operations- and management-dependency), and supply chain considerations (e.g., ability to deliver repetition-rated targets). We need an unbiased, integrated system model and point-design framework to inform technology-development priorities, assess tradeoffs, and evaluate plant-level performance characteristics.
  - *PRO 6-5:* Undertake a series of system-design studies to establish a suite of self-consistent, quantitative IFE plant models, and use these to guide each aspect of the R&D program.

Overlap with ICF Programs

ICF and IFE share a number of important connections in the area of power systems:

- Systems engineering and integration experience from the largest-scale ICF facilities provides invaluable insight into the structure and depth of analysis needed in comparison to more traditional "laboratory physics-scale" facilities (e.g., the transition from NOVA to NIF).

- We must learn target characteristics that are adaptable to IFE. We must identify targets for IFE that have sufficient gain and thermomechanical integrity that we can rapidly and cheaply manufacture and insert into the chamber. We can identify some of these characteristics in ICF research.
- ICF physics developments can provide new information for incremental or revolutionary changes in IFE system-design options (e.g., details of ignition threshold parameters, gain-scaling, margins, and potential high-efficiency physics schemes).
- Conversely, requirements for IFE effluent management (gas-exhaust processing, tritium inventory, chamber chemistry, etc.) impose strict limitations on target materials and thermomechanical performance. We need to test some subset of these on ICF facilities (e.g., impact of tolerances of mass-manufactured targets, any yield modifications due to wetted foams, etc.).

A wide range of distinct challenges in the power-systems area also require unique R&D *outside* of the ICF program. We explore these further below, including the following elements that are critical to IFE but largely irrelevant to ICF:

- Lifetimes and disposal pathways of chamber materials, final optics, and consumables
- Tritium breeding and extraction from blanket materials and subsequent purification and delivery in closed-cycle continuous flow systems
- Reactor coolant options, material compatibility, corrosion, and tritium affinity
- Regulatory and safety implications of the above

Overlap with MFE Programs

IFE has many helpful commonalities with MFE in power-systems areas, both domestically and internationally, and we should pursue deep partnership in developing technical options, manufacturing infrastructure, regulatory engagement, and workforce. Examples include:

- Materials and irradiation-materials science modeling
  - Fundamental modeling and data on cascade damage and transmutation effects to fusion materials, with testing in existing facilities and construction of new facilities of common need
  - Development of a wide range of first-wall, blanket, blanket structural, and functional materials [3]
- Tritium systems and safety
  - Fuel-cycle design and testing, including inventory monitoring and safety assessment
    - Note that the target environment of IFE reactors drives unique effluent handling requirements
- Economics, integrated operations, and licensing and regulatory concerns
  - IFE has many commonalities with MFE in the regulatory space (NRC, ASME, EPA, etc.) and utility solutions

- The regulatory stance for IFE could offer substantial advantages over some MFE designs because of its lower tritium inventory and its segregated distribution and because of the separability of systems allowing offsite manufacture and test

Overlap with Fission Programs

Fission has several key technology areas that overlap with IFE:

- Molten salt and liquid metals/liquid alloy technologies for the coolant cycles
- Molten salts, fluorides, and chlorides are being developed for use as thermal transport and fuel solvents for Generation IV advanced nuclear reactors [4-8]; FLiBe (a molten salt made from a mixture of lithium fluoride and beryllium fluoride) is of particular interest to IFE because of its high tritium-breeding ratio attributed to neutron multiplication from Be
- The fission community is already driving commercialization of FLiBe; for example, Kairos Power, LLC submitted a construction permit application to the Nuclear Regulatory Commission (NRC) in 2021 to build a 35-MW, FLiBe-based test reactor near Oak Ridge, TN, and Aberdine Christain University's NEXT lab has filed a permit with the NRC as well to build the FLiBe-based Molten Salt Research Reactor (MSRR)
- Many private sector companies already manufacture commercially available pumping, piping, and storage equipment for molten salts used in the nuclear and solar industries
- Material compatibility and chemistry control with molten salts at high temperatures [7], coupled to databases of thermophysical and thermochemical properties backed by modeling and testing
- Purification and handling of Be-containing salts [7]
- Separation and purification of lithium isotopes
- Purified lithium-7 is needed for fission applications to minimize tritium production, and purified lithium-6 may be needed for some fusion applications to maximize tritium production [5]
- Methods for tritium extraction from salts, such as FLiBe (smaller scale for fission but necessary as some lithium-6 will inevitably be in the salt) [5, 8]
- Irradiation material science and certain material development
- Material testing in mixed-spectrum fission reactors and the need for fast reactor tests
- Metal corrosion data and test apparatus
- Radiation transport and neutronics modeling
- Nuclear fission has driven development of powerful radiation-transport models that are well validated and have been used widely in fusion applications
  - For example, MCNP (Monte Carlo N-Particle) is a neutron, photon, and electron transport code developed for fission that has already been extended for use in MFE and high-energy-density (HED) science
- The greater demands on nuclear analysis for fission and fusion has stimulated development of simulation acceleration techniques (so-called “variance reduction”), such as ADVANTAG, MS-, and FW-CADIS; these permit simulations to be run in a reasonable time

- The shielding design of a fusion device is more complex than that for fission reactors because of the need for many penetrations through the shielding to accommodate additional heating systems (e.g., lasers) and diagnostics; as a result, very large models with extensive detail have been developed, and the codes and the computer architecture on which they run have greatly advanced in recent years [9]

6.2 Priority Research Opportunities (PROs)

Fusion Materials

The intrinsic separability of IFE's major systems, such as target and driver, and its relaxed geometric design flexibility as compared with MFE will aid its development. Moreover, we can develop critical IFE systems independently as prototypic demonstrations in an informed fashion. We can then draw these together, both physically and through rigorous design activity, by a Chamber Technology and Design Activity. Beyond integration, such a design activity must advance a range of practical but fundamentally challenging scientific and engineering activities, such as development and engineering application of materials in extreme environments. Each of these areas is necessarily supported by modeling, ranging in scale from the atomistic length, which allows us to understand evolving microstructure, to continuum modeling, which is required to validate design codes that ultimately describe the system. **Figure 6.1** provides elements of a holistic material-development program spanning from our current TRL *proof of concept* through the TRL maturation ladder to realize a validated chamber design.

The literature has discussed an array of potential IFE systems, as defined by choice of driver, target, chamber wall, repetition rate, fusion performance, and blanket/cooling system [10-12], each of which represents a trade of increased chamber/material performance for reduced design complexity (see **Table 6.1** below following the National Academy of Sciences Report, "An Assessment of the Prospects for IFE" (2013)[10]).

The development path of materials supporting inertial fusion is inextricably linked to the design choice. However, given the relatively low TRL of IFE materials irradiation science, the challenges and priorities necessary to support reactor design are very similar across different design choices, as outlined in the subsequent sections of this chapter.

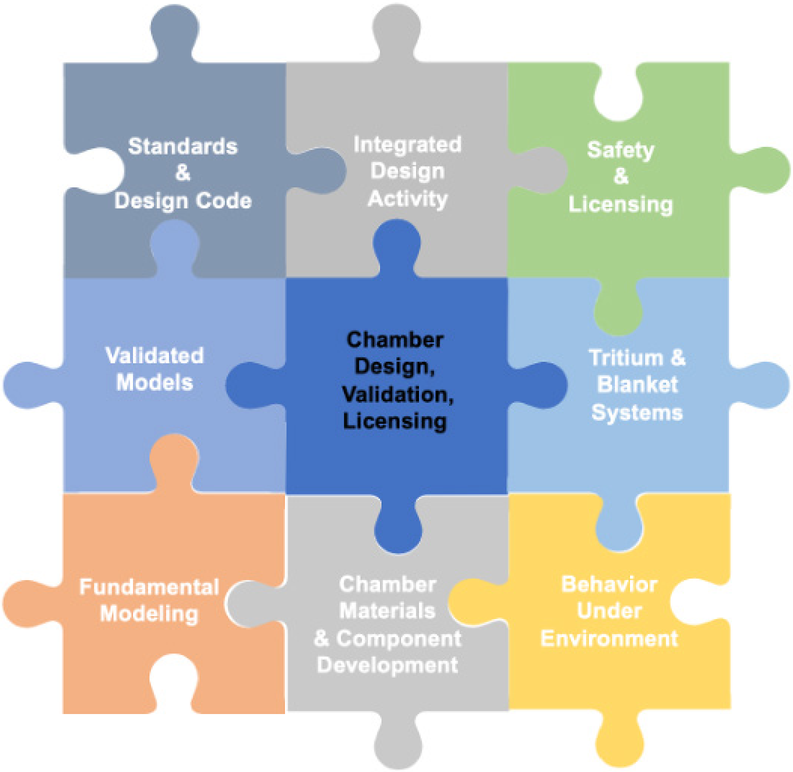


Figure 6.1. Relationship of material development, modeling, data, design, and engineering activities toward the realization of a validated IFE component.

Table 6.1: High-level description of the advantages and challenges of IFE chamber and wall concepts.

Concept Wall/chamber	Advantages	Challenges
Solid Wall/Vacuum	• Simplest chamber • Easier laser/target issues	• Material survival
Magnetic Intervention/Vacuum	• Smallest chamber • Mitigates first-wall thermal load	• Ion dumps
Replaceable Solid Wall/Vacuum	• Easier laser/target issues	• Operational complexity
Solid Wall/Gas in Chamber	• Smaller chamber	• Laser/target issues (hot gas/residual plasma)
Thick Liquid Walls	• Much reduced materials and neutronics issues	• Chamber recovery • Droplet formation • Difficult to modify

Performance of Structural and First Wall Materials

PRO 6-1: **Develop a modeling-informed, experimentally verified understanding of IFE structural materials at the macro- and microscopic levels when subjected to a pulsed, fusion-relevant spectrum (neutrons, ions, neutrals/debris, x-rays, thermal)**

Associated Facilities: Fusion Prototypic Neutron Source (FPNS), MEXT upgrade for pulsed ions, and high thermal-heat-load facility. These will all complement pulsed-neutron, FI, and mixed-spectrum fission materials test reactors, as well as current and future ICF/IFE/MFE facilities.

Neutron Damage to Materials in the Steady State: Cascade Damage and Transmutation. Neutrons are the primary products of fusion reactions in deuterium-tritium (DT)-based fusion reactors. Neutrons carry approximately 80% of the DT reaction energy as kinetic energy, which is then deposited as heat utilized to produce electricity. In this process, these neutrons cause significant changes in component-material properties, which may greatly limit the lifetime of a fusion power plant. For this reason, we need a thorough understanding of material behavior under irradiation to allow us to develop higher-performance materials and, ultimately, to validate components for reactor use. This scientific challenge is common across MFE, IFE, and fission power communities. The pulsed nature of repetition-rated IFE is an additional challenge.

While the average displacement damage rates in the first wall of IFE systems are comparable to those for corresponding MFE systems [13-15] (on the order of 3×10^{-7} to 6×10^{-7} dpa/s), the instantaneous damage rates are typically 6–7 orders of magnitude larger in IFE systems [16, 17]. In the IFE regime, the dynamic response of the exposed materials and the subsequent microstructure evolution are largely unknown. We should invest key efforts to identify the microstructure damages that are sensitive to the displacement rate and pin down potential nonlinear effects accompanying the extremely high displacement-damage rate. The resultant information will inform the specific needs in material development for sustaining the pulsed-radiation environments of IFE facilities.

The expected damage rate in the SOMBRERO design [18] is ~15 dpa/FPY (displacements per atom per full power year) at the first wall and is associated with ~3800 appm (atomic parts per million) of helium generation in its C/C structure. Although this average displacement damage rate is attainable in present-day fission reactors, the instantaneous damage rate and associated helium production rate are not, and we have yet to develop a physically informed model for the difference. The higher instantaneous damage rate in IFE is expected to promote rate-sensitive microstructure processes, such as point-defect recombination, homogeneous cluster nucleation, etc., while the short downtime between pulses may affect temperature-sensitive microstructure processes, dependent on the repetition-rate (e.g., annealing and general kinetics). Limited guidance exists in the literature on how to extrapolate fission reactor and ion irradiation effects to these unique conditions of IFE. Sorting out the contributions of cascade-induced damage, fusion-specific transmutations, and the effect of pulsed irradiations is paramount, as described below.

Figure 6.2 presents the phenomenology of pulsed-radiation damage and the ensuing effects in IFE-relevant reactor systems [16]. Neutron irradiation has two primary effects: displacement damage and transmutations. The former effect results from high-energy collision cascades initiated by the 14-MeV neutron bombardment, which will generate point defects, such as vacancies and interstitials. This cascade damage is virtually the same for a 14-MeV fusion neutron as it is for an ~1-MeV fission-born neutron. For this reason, we may use fission reactors in our fusion-materials research programs, as fission and IFE reactors will share common underlying material-development paths.

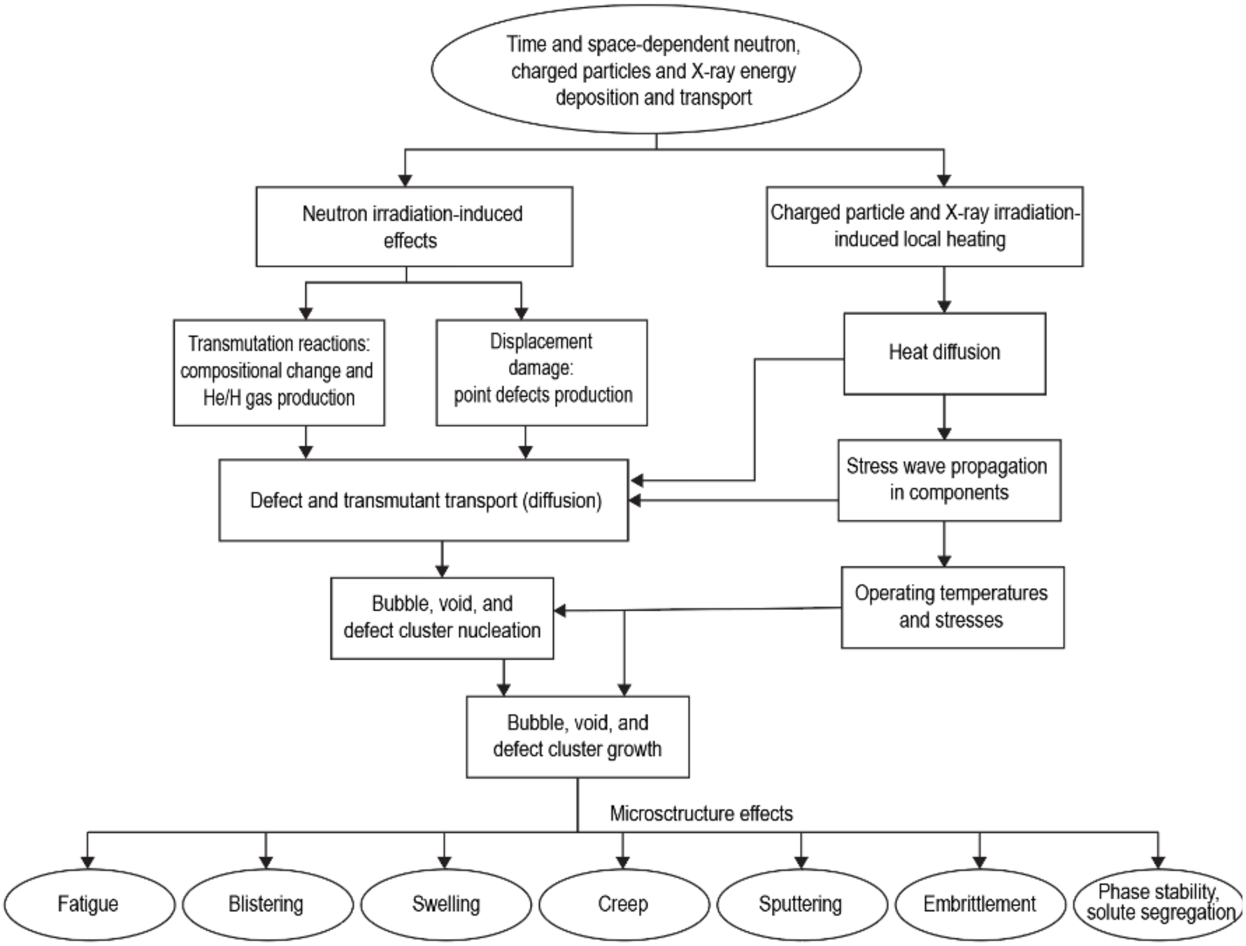


Figure 6.2. Overview of the radiation damage processes and ensuing effects in pulsed fusion reactor systems. This diagram is modified from Zinkle and Snead (2014) [13] to better illustrate the neutron-irradiation effects.

The defects resulting from the neutron cascade will undergo recombination, migration, and agglomeration into microscopic clusters. The accumulation of single and clustered defects can also result in microstructure changes, including swelling, creep, blistering, embrittlement, loss of ductility, phase instabilities, and solute segregation. The ultimate life of the first wall and, to a large degree, the economics of fusion reactors are determined by the degradation of mechanical and physical properties caused by these phenomena.

The second primary effect of neutron irradiation, neutron-induced transmutations, are equally important in determining the suitability of a given material for nuclear applications and more so for fusion systems (than for fission systems), given their higher transmutation yield. Such transmutations can change the chemical composition of the irradiated materials through a range of nuclear reactions. For instance, transmutation calculations using neutron spectra obtained with the ANISN code (for ITER structure design) show that pure tungsten (W), the plasma-facing material for ITER and DEMO fusion reactors, transmutes into a W-18Re-3Os alloy after 50 dpa of irradiation [19]. This dpa level equals the accumulated damage near the surface of the tungsten first wall over 10 years of operation in the DEMO reactor, for a damage rate of 5 dpa/year [20]. Transmutation products not only affect the performance of tungsten (i.e., increase its hardness [21] and lower its thermal conductivity [22]), they also change the retention property of hydrogen particles [23].

An even bigger issue from neutron-induced transmutation is generation of helium and hydrogen gas atoms via (n, α) and (n, p) reactions. While these reactions occur less frequently than the major (n, ϒ) reactions, they pose a much more significant impact on material properties. For instance, helium is not soluble in metals or alloys. Therefore, the generated helium atoms tend to cluster and accumulate at defects, dislocations, and grain boundaries, resulting in bubble formation, swelling, or embrittlement. The need for a concerted modeling and experimental effort to understand transmutation irradiation science, while known to be a significant issue for many decades, has recently risen to the very highest priority in the MFE community, as called out in the recent National Academies of Sciences, Engineering, and Medicine (NASEM) [24] and Fusion Energy Sciences Advisory Committee (FESAC)[25] reports. Such urgency is shared as a priority research direction in this report.

These damage processes (displacement damage and transmutations) do not occur independently from the thermodynamic state of the material since the local temperature and stress state strongly influence the defect dynamics, including transport, nucleation, and growth (**Figure 6.2** [13]). The energy deposition time and the thermal response of the material determine the ultimate temperature history, and an equilibrium operating temperature is approached following each energy pulse. Similarly, the rate of energy deposition and the elastic response of the material determine the stress history.

The last decades have experienced substantial progress in terms of the accuracy, scale, and relevance of material modeling under fusion-reactor operation. We can now simulate increasingly more complex and realistic material microstructures under fusion-representative conditions, complementing experiments and solidifying our understanding of material behavior under meaningful dose rates, temperatures, gas atom to dpa ratios, and spectral details. Further, while many challenges remain, the experience acquired by modeling teams over the last few decades has now resulted in a set of “best-practices” supported by a relatively wide community consensus, with applications in a wide range of different operational scenarios. Current models can effectively capture irradiation-damage buildup coupled to microstructural evolution, dose-rate- and temperature-dependent regimes, nuclear transmutation and gas atom evolution, solute mobilization by radiation-enhanced diffusion, and the change in derivative quantities, such as hardening, swelling, or creep. While important gaps in our understanding remain (particularly in terms of high-dose and high-temperature material behavior, synergistic helium/hydrogen effects in ferritic materials, pulsed irradiation, and chemical effects), the modeling is presently in a good position to issue qualified material-behavior predictions in the anticipated operational range gap between a fusion facility and a pulsed FPNS. Hence the need for such a pulsed FPNS facility to be built as a matter of urgency.

Pulsed Neutron Damage to Microstructure and Properties. There has been considerable interest in the pulsed irradiation effect on microstructure evolution since the 1970s [16, 24, 25], mostly driven by the understanding of discontinuous events in magnetic fusion reactors. However, there is still a lack of experimental studies on pulsed irradiation effects relevant to future inertial fusion devices. Previous experiments had found that the influence of pulsed irradiation is sensitive to temperature, dose, pulse period, and duty factor, and that the pulsed effects can significantly alter microstructure damages, including dislocations, voids, and phase evolution.[25] In particular, the most crucial issues when considering irradiation in a pulsed irradiation device are (1) understanding the impact on materials of ultra-short, ultra-intense neutron discharges and (2) looking at the potential differences in helium- and hydrogen-to-dpa ratios between steady irradiation and pulsed regimes. The first point pertains to how switching from a low–dose rate, high–accumulated damage scenario to a very high–dose rate, very small–total dose scenario changes our understanding of irradiation damage processes, particularly as they relate to the possibility of cascade overlap and defect relaxation times in between discharges. The second point addresses the potential differences in transmutation rates between both regimes, leading to chemical composition inventory changes and helium and hydrogen production. We must carefully weigh the potential implications of pulsed irradiation, as well as transmutation-induced gas production and compositional changes, on swelling, creep, and mechanical-property degradation in structural materials.

While no operational-appropriate pulsed-neutron sources exist at the moment, several efforts in the past have sought to develop inertial fusion–based concepts to produce fast neutrons for high-burnup of spent nuclear fuel. **Figure 6.3** shows representative neutron spectra and primary knock-on atom (PKA) distributions in iron for a conceptual fusion pulsed-irradiation engine (known as the Laser

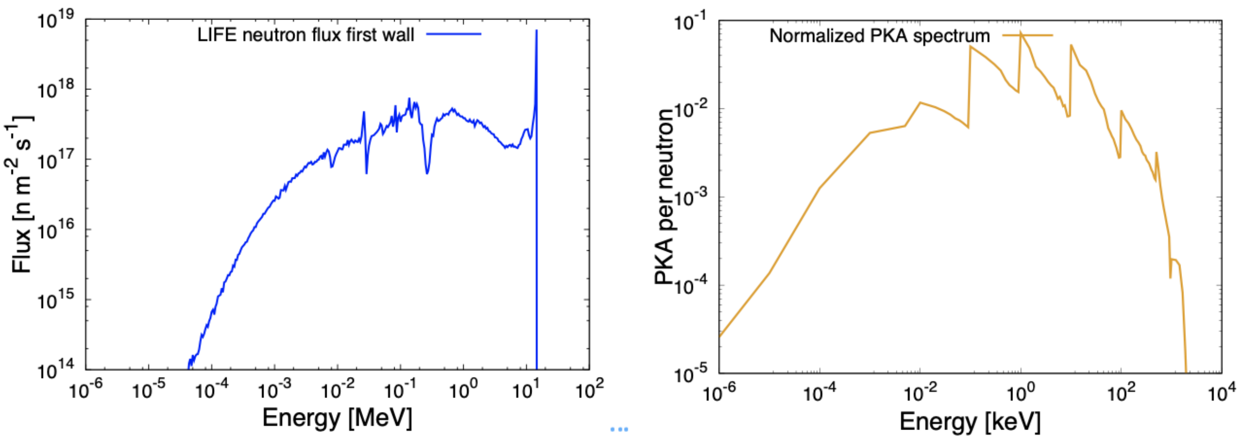


Figure 6.3. *(a) Nominal neutron flux in a pulsed fusion reaction chamber first wall (iron as reference material) based on the LIFE concept. (b) Associated PKA distribution at beginning of lifetime.*

Inertial Fusion Energy, or "LIFE" concept), with its typical 14-MeV peak and average PKA energies of several tens of keV.

Pulsed X-Ray and High Energy Ion Effects on Surface Ablation. In addition to steady-state and pulsed neutrons, the IFE device must withstand high heat fluxes emanating from the DT reaction and, depending on the cooling system used, large temperature excursions. As many of these same conditions are similar those in MFE, as discussed in a review by Alvarez *et al.* (2011) [17], potential facility and fundamental research collaboration opportunities exist. As one might certainly expect however, the pulsed nature of an IFE device is a considerable complication and presents issues (discussed later in this section) that are distinct from those in MFE.

As discussed previously, different concepts have been proposed for the chamber walls, involving both solids [11] and liquids [12]. The solid first-wall concepts are more mature, in part due to extensive R&D from within the nuclear materials and MFE communities, which has provided insight into the mechanisms governing material degradation. Implantation of energetic ions can lead to formation of point defects (vacancies) and extended defects (dislocation loops and bubbles). In the case of helium in metals, Hammond (2017) [26] recently published an excellent review on this topic from an MFE perspective. As Hammond highlighted, one of the main consequences of this implantation of energetic ions is nucleation of small high-pressure bubbles that grow to several nanometers in diameter. As they grow, these bubbles can displace material toward the exposed interface, causing changes in surface morphology. Note that the growth rate and evolution of these defects, among other things, depends strongly on the helium concentration within the material, as well as the temperature. For a pulsed device, we need R&D to better understand how these quantities vary on a shot-to-shot basis.

Implantation of hydrogen isotopes can likewise result in larger-scale structures, such as blisters. The detailed mechanisms of defect nucleation and growth, however, can differ considerably from helium implantation. The issues of tritium retention and permeation through chamber wall materials will closely couple with formation of defects. As Meier *et al.* (2014) [11] discussed, vaporization of the hohlraum and target are expected to create atomic-level debris in an IFE device, rather than macroscopic fragments. Over time, redeposition of this material on the interior surfaces of the chamber, as well as on optical or diagnostic ports (and possible co-deposition with tritium), could be a concern [27].

Neutron damage of the chamber wall remains a critical issue and can impair structural integrity. The LIFE design expected a 6.0-m target chamber to have to be able to withstand up to 10–20 dpa before requiring replacement (at intervals of 2–4 years). While the neutron fluence for an IFE system may be comparable to that of an MFE system, its neutron flux will reach a much higher peak value. The resulting damage structure could vary considerably between pulsed and steady-state operation. Recent experimental research at LLNL with pulsed ion beams has provided evidence of this effect, illustrating how damage accumulation in silicon carbide (SiC) materials can be sensitive to the time constant associated with defect relaxation [28]; however, modeling of these effects was less conclusive for iron [29]. In general, further study of these dynamic effects in materials could greatly enhance our understanding of the material response to irradiation/neutron damage on very short timescales. Beyond this, the lack of a high-flux source that can provide a representative energy spectrum of 14-MeV fusion neutrons remains an obstacle to further progress for both the MFE and IFE communities. Such a device would be necessary for testing and qualifying new materials intended for the chamber wall and received high prioritization in the recent FESAC and APS-DPP reports.

The chamber materials will also be exposed to intense x-ray pulses, which are absorbed within the first few microns of the chamber wall (as compared with neutron irradiation, which affects the entire bulk [30]). Without any countermeasures, the energy deposited by these materials is sufficient to melt reduced-activation ferritic/martensitic (RAFM) steel [11]. We can avoid this problem by using a low-density gas to protect the chamber walls for some designs—although this also requires close attention to the start-up phase of a reactor and to the dependency on repetition rate. Such gas may compromise the delivery of high intensities on targets (e.g., for FI and SI). Even with this countermeasure, however, pulsed operation can still lead to thermal expansion/compressive stresses near the surface and potentially to recrystallization, leading to crack formation and growth. We will need to take this issue into consideration when assessing the resilience of materials used for the chamber wall.

Liquid metal walls are an intriguing concept that could potentially mitigate some of the issues mentioned above. Since they could be replenished, liquids would be less susceptible to the effects of neutron damage. Most of these designs are still at a conceptual level, and we must resolve questions regarding their feasibility.

The qualities of final optical components are very sensitive to x-ray ablation from the surface since non-uniform removal of <3 nm will adversely impact laser-light focusing. However, the x-ray energy deposition pulses expected in IFE will be below the threshold for ablation. The essential question is whether there is a credible mechanism for ablation by repetitive sub-threshold energy deposition? Fundamental, variable-controlled experiments performed to very high cycles on facilities could prove valuable for understanding the underlying phenomenon behind high-cycle loading. Moreover, if rapid heat deposition dominates the ablation mechanism, we need to determine if using much cheaper infrared lasers or other heat sources for the simulation is more sensible.

Fatigue and Synergistic Neutron and Thermomechanical Damage to Structural Components. Irrespective of the IFE design, cyclic thermal loading will translate into structural thermal fatigue issues. As recognized in Raffray (2002, 2003) [31, 32], while IFE operation is cyclic and MFE is largely steady state, there is considerable overlap, not only in the materials and high-heat-flux components contemplated, but also with regards to the cyclic loading. This latter recognition focuses on transients, such as MFE edge-localized modes (ELMs). These transients, while only within an order of magnitude in energy density, frequency, and maximum particle fluxes, are from a materials-science and structural-engineering standpoint, a strong threat in their encouragement of failure due to materials crack formation and propagation.

Performance of Functional Materials

PRO 6-2: ***Develop models and experimental data to inform damage thresholds in transmissive and reflective final optics and establish solutions that enable sufficient longevity in a fusion environment***

Developing laser optics that can survive the severe operational environment over an economically attractive lifetime is vital to laser IFE systems. This environment involves the interaction of laser light, ionic and neutral debris, and short-duration neutron pulses. As a result, the quality and integrity of laser optics degrade over a limited number of pulses. Generation of near-surface defects (point defects and dislocation loops) by intense laser energy (as well as by neutrons and energetic particles) leads to surface deformation and loss of focusing quality. The reflectivity and optical qualities may substantially degrade after only a few thousand shots as a result of plastic slip steps propagating to the surface and the internal defect strain field. The experimental database for multi-shot laser damage of optical quality materials is scarce and extends only to 10,000 shots for only a few materials [33]. However, there is a clear trend of a decreasing laser damage threshold with increasing number of shots.

Irradiation-induced defects in transmissive optics have been previously investigated. Very low neutron and gamma fluences will produce defects to sufficiently impair the optical transmissivity of common windows, such as glass. One of the proposed design approaches anneals these color centers by raising the temperature of the final optics element. This scheme's soundness depends on the ability of these color centers to migrate without agglomeration in the lattice. It is also assumed that gaseous nuclear products will not stabilize these color centers and impede their migration. We need to verify these scenarios, both experimentally and at a fundamental theoretical level.

Studies have noted the existence of transient absorption effects, with lifetimes from a few tenths to a few hundred seconds, exhibiting values as much as two orders of magnitude higher than the residual long-term absorption. For example, pulsed neutron work on fused silica suggests that the bulk of the prior research using post-irradiation absorption measurements may be significantly underestimating the degradation expected for IFE, in which the radiation pulse rate will be on the order of a few hertz. At such a repetition rate, the transient absorption effects will essentially present a steady-state condition during power-plant operation.

Determining the most appropriate experimental approach to studying radiation effects in optics is complex. Post-irradiation studies are essential and have led to considerable understanding of radiation effects *in silica*. *In situ* measurements tend to be much more complicated and limit the available radiation sources, especially for neutron irradiation. However, *in situ* measurements are essential if the data obtained are to be relevant to IFE conditions. In addition to developing an understanding of the transient damage structures that result in this temporarily increased absorption and the kinetics of the radiation-induced processes, we need to consider the temperature dependence, dose-rate dependence, and possible saturation of these effects.

Further, we need to determine the correct balance between *in situ* and post-irradiation measurements. Is it sufficient to irradiate optical materials at temperatures below the application temperature and simulate actual conditions through annealing? We may find comparisons with optics protection mechanisms used in other systems to be informative (e.g., extreme ultraviolet (EUV) lithography and some directed energy systems).

Fuel-Cycle Technologies

In the lead up to a fusion pilot plant (FPP), the fuel cycle for an IFE power plant will need to have demonstration facilities that align with reports from the FESAC committee and from the NASEM Study "Bringing Fusion to the U.S. Grid"[24]. These test facilities would carry out demonstrations of blanket technologies and DT fuel and exhaust processing. These facilities need to allow testing of systems up to TRL 6 or 7. Currently, no such infrastructure exists anywhere in the United States for validation and integrated system testing for either blanket or fuel-cycle technology in a radiation or non-radiation environment.

In the fusion-blanket community, discussions continue whether a blanket test facility should utilize only a thermal source without a neutron source or if the facility needs to contain a neutron source to capture all the relevant physics and material-degradation mechanisms that would occur in a blanket. A thermal-blanket test facility would have lower cost and be faster to construct. A blanket test facility with a neutron source would cost more but would allow testing of critical phenomena like tritium extraction, tritium production, effectiveness of multipliers, and material degradation with chemical, neutron irradiation, and tritium effects.

A DT fuel and exhaust processing facility would need to define whether it focuses on the main closed-loop fueling cycle or includes technologies for overall facility tritium management. A demonstration plant for DT fuel and exhaust processing would likely include testing of a full-scale system with non-radioactive simulants (e.g., protium and deuterium) followed by an engineering-scale (1/10- to 1/4-scale) up to a full-scale demonstration with tritium. Because the fuel cycle for IFE shares similarities with MFE fuel-cycle technologies, the demonstration facilities will be applicable to both, and where necessary can be modified to vet both IFE and MFE.

This Basic Research Needs (BRN) panel focused on the unique needs of the fuel cycle for IFE, but notes that the fuel cycle needs defined by the MFE community and identified as being common needs are still critical to the IFE fuel cycle. View this report as amplifying those needs because they are critical to both fusion approaches. Only a limited number of MFE-specific fuel-cycle technologies, such as pellet injection, are not applicable to IFE applications.

Fuel and Exhaust Processing

PRO 6-3: ***Develop synergistic target/fuel cycle co-design between the plasma physics community and the fuel-cycle teams and chamber-design teams to develop target designs and identify target materials and processing methods that have minimum impact on the fuel cycle and allow for inventory reduction***

Development of a sustainable DT fuel cycle for IFE presents distinct challenges specific to its operation and approach. Each target inserted into the chamber will introduce impurities, such as carbon, hydrogen isotopes, metals, and other elements (e.g., N, O, Pb), depending on target composition. Exhaust processing and other fuel-cycle processes will need to remove these impurities and provide a pure DT mixture to inject back into new targets. Additional impurity elements or increases in impurity quantities can require addition and resizing of unit operations within the fuel cycle that increase operating expenditure (OPEX) and capital expenditure (CAPEX) costs, tritium inventory, and waste-processing considerations. Therefore, collaborative design between fusion target performance and the fuel cycle will be essential in developing an integrated IFE plant concept that can produce fusion energy at competitive costs.

Partners working on NIF and the LIFE project developed preliminary fuel-cycle designs specific for IFE [34-36]. **Figure 6.4** illustrates a simplified version of the fuel-cycle design developed for LIFE. This design and modeling included creation of a fuel-cycle simulation to assess the impact of design changes on the inventory, footprint, and technology choices for fuel-cycle processes. The LIFE partners based their design and modeling on a relatively modest pre-conceptual effort.

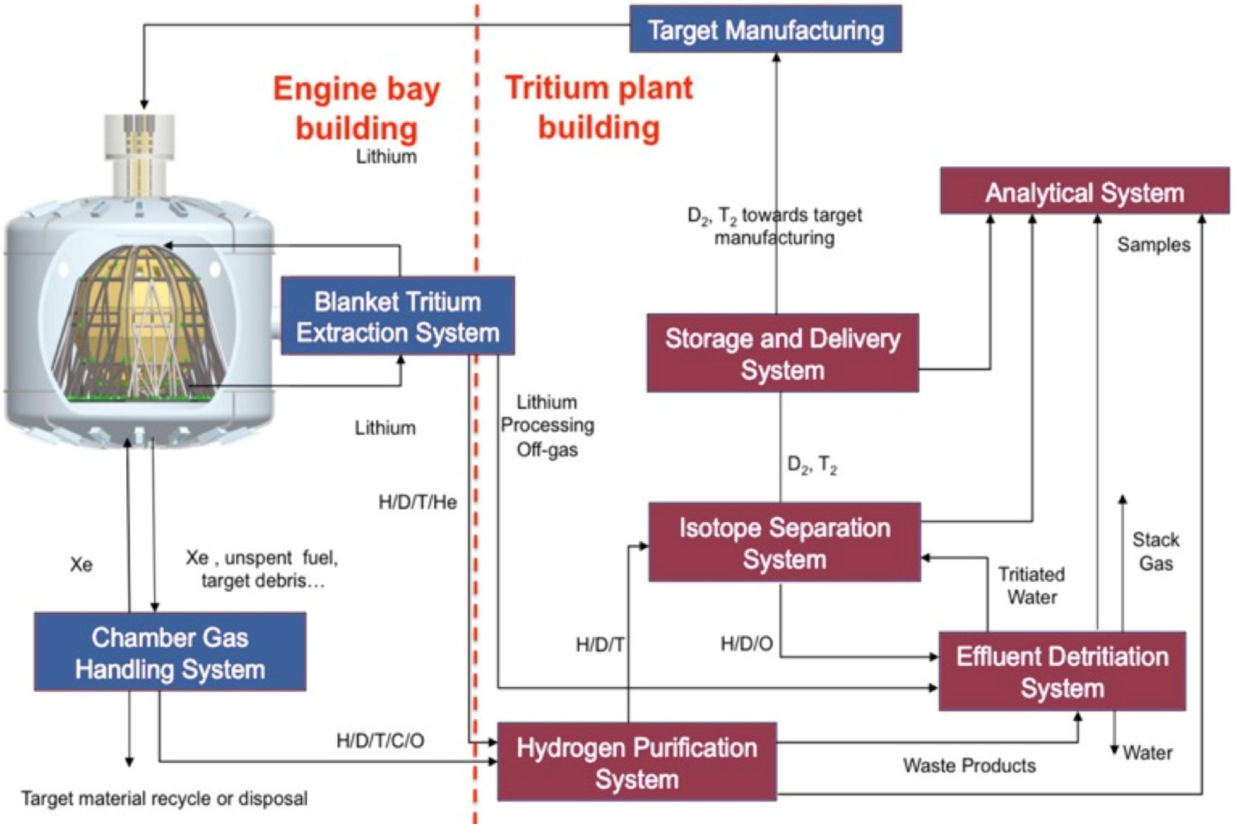


Figure 6.4. Simplified fuel cycle for an IFE system.

We need significantly more detail to support the fuel-cycle design for an IFE pilot plant. The fuel processing illustrated in an early version of the LIFE program to utilize plastic-backed hohlraums for indirect-drive fusion provides an example of the importance of design decisions. Specifically, processes to remove the plastic byproducts (protium and carbon) would have dominated the fuel cycle, given the proposed target compositions, process separation efficiencies, and recycle requirements. Those gases would have been several orders of magnitude higher than the fuel (DT) needed for fusion. The impact of plastic-backed hohlraums on the fuel cycle ruled out their use. While this topic is not specifically under debate today, encapsulants, foam layers, heat shields, hohlraums, sabots, sweep gases, or air in-leakage throughout the system can all introduce impurities into the IFE DT fuel cycle, which need to be processed. Such impurities may include gaseous products, such as ammonia, tritiated water, tritiated hydrocarbons, or other compounds. These impurities need to be decomposed to recover tritium before we can release them to the environment. We need to design and adapt tritium-cleanup systems for the impurity profiles that will be encountered in an IFE system. In addition to impurity processing and removal, we will likely need to scale and adapt other tritium-processing components, such as isotope separation and confinement systems, to IFE requirements. We expect this will be an ongoing, iterative process led by modeling and IFE community engagement.

The fuel's burn fraction in the fusion engine is a fundamental fuel-cycle parameter. Among a variety of other factors, the burn fraction directly relates the required fuel input to the net power generation rate. IFE has a distinct advantage over MFE due to its intrinsically higher burn fraction for an optimized design (20–30% compared to 1–5%). This point is important since, as the burn fraction decreases, the flow of fuel increases, as does the exhaust from the reactor. This increases the size of every section of the fuel cycle, which has four critical outcomes:

1. The larger sections require more energy to operate, so fuel flow must be further increased to maintain the specified net-power generation rate
2. Inventory increases directly with the size of the plant
3. Increased inventory (or residence time of tritium) also increases tritium decay, requiring an increased tritium breeding ratio (TBR)
4. Changes in the fuel cycle composition can have non-linear effects on fuel-cycle processes, possibly exacerbating effects of modifications

The trade-offs in target design and operating conditions needed to achieve high burn-up fractions will need to be factored into the fuel-cycle design.

Tritium Breeding

PRO 6-4: ***Develop a test facility with a neutron source to evaluate blanket technologies and to test fuel-cycle components and systems at scale, including tritium extraction and transport, and the potential for direct internal recycle (DIR)***

Development of fuel-cycle technology for IFE shares many challenges and could share similar solutions with MFE [10, 24, 37-40], with some exceptions. Examples include:

- Tritium breeding and extraction of tritium from blankets are both at a low TRL.
- Most IFE approaches do not utilize magnets, so some of the blanket concerns in the MFE community, such as magneto-hydrodynamics (MHD) in lithium or lithium alloy blankets, do not apply to IFE. This provides alternate breeder blanket approaches to the IFE community.
- Fuel cycle challenges—such as real-time accountancy for tritium and tritium clean-up from effluents—will be similar, but implementation may differ because tritium injection into targets and storage and movement of targets in an IFE plant differ from MFE needs.
- As in the case of MFE, IFE fusion plants will need to achieve and sustain TBRs greater than 1 to ensure tritium self-sufficiency.

ITER and DEMO are considering many tritium breeding-blanket test concepts, which provide a good technical basis for developing breeding-blanket technologies for IFE [41, 42]. Reviews of these tritium-breeding methods show that the main functions of a breeding blanket are (1) to breed tritium from lithium and (2) to employ neutron multipliers where necessary [43, 44]. While there are several options for multiplying neutrons, beryllium and lead are effective and do not produce significant quantities of long-lived radioisotopes [43, 44]. There are two main classes of breeding technologies: solid ceramic breeders and liquid breeding blankets. Liquid breeding blankets can also be subdivided into liquid metals and molten salts, which behave fundamentally differently [43, 44]. Several good reviews summarize the technical challenges in developing blanket technologies related to ITER [38, 42, 45-48]. Commercial fusion companies have also had renewed interest in using FLiBe as a breeding blanket material [49, 50]. Corrosion, tritium extraction, and other issues associated with FLiBe are areas of active research in both the fusion and advanced fission communities [5, 51].

The need for lithium-6 enrichment in blankets depends on the approach. Tritium can be bred from lithium-7 in addition to lithium-6, but it is an endothermic process that would decrease total fusion power. The complications associated with enriching lithium-6 and the availability of enriched lithium-6 is pushing some companies to utilize natural lithium. Many members of the fusion community would welcome increased availability of enriched lithium-6. Research into environmentally friendly lithium-6 enrichment concepts that do not rely on mercury would be of potential interest.

We will need to replenish blanket materials in a power plant. Thus, we need to define replacement cycle times, design components for easy replacement, and develop blanket maintenance schedules for any blanket and reactor combination.

The APS CPP report [39] recommended several basic research needs related to tritium breeding:

1. Initiate small-scale tests for a variety of functional breeder blanket materials to advance blanket concept designs
2. Test the compatibility between breeder media and structural materials
3. Develop models and multi-physics models to enable integrated blanket designs

Several leading blanket-system concepts have been proposed: helium-cooled pebble bed (HCPB), water-cooled lead-lithium (WCLL), helium-cooled lead-lithium (HCLL), dual-coolant lead-lithium (DCLL), and single-coolant molten salt (SCMS). Each concept presents challenges to address. Selecting the correct breeding blanket technology requires a better understanding of material properties and interactions in an integrated system at relevant temperatures [42].

A blanket test facility with a neutron source can also be used to build up tritium inventory for startup reactors. CHIMERA [52] in the United Kingdom is a thermal-blanket test facility. The U.S. IFE/MFE programs would benefit from a partnership with CHIMERA, allowing a domestic test facility to leapfrog the need for a thermal test facility to focus on a facility that includes a neutron source. The MFE community is supporting fission-neutron material testing with the option of using a fusion neutron source for testing if one becomes available. However, no one has put forward proposals to construct such a facility.

A neutron test facility can provide added benefits:

1. Assisting the NRC in defining regulatory guidance for future facilities
2. Helping the private sector get better guidance from the NRC on future facilities
3. Reducing the burden on private sector investments (and liability), allowing them to focus on reactor technology
4. Developing tritium-handling expertise

The more relevant the test facility (neutron source for blankets) becomes, the better the opportunity for engaging the private sector in unified standards for safe and effective operation of tritium systems.

Tritium Extraction. Tritium extraction is a research need that accompanies tritium breeding [37, 38]. Tritium that cannot be extracted from the blanket due to diffusion, permeation, or molecular combination reduces the total TBR of the system. A thorough understanding of the usable TBR for each blanket system is necessary for system design. Additionally, efficient tritium extraction lowers the tritium concentration within the breeding material to minimize tritium transport through undesirable pathways, such as diffusion through process-containment materials [48]. Methods of tritium extraction depend on the breeding blanket medium. Tritium extraction techniques proposed for use in lithium and lead-lithium blankets include permeation against vacuum (PAV), the Maroni process, and direct lithium tritide (LiT) electrolysis [53-56].

Idaho National Laboratory is conducting the Tritium Extraction Experiment (TEX) at the Safety and Tritium Applied Research (STAR) facility. These experiments are focusing on tritium extraction from lead lithium in DCLL breeder systems. TEX can be altered to use helium purges. This facility will produce results for HCPB, WCLL, HCLL, and DCLL blankets. The Massachusetts Institute of Technology (MIT) is planning to construct a facility (LIBRA) able to test different tritium-extraction methods from FLiBe. Fusion blankets using FLiBe can potentially draw on technologies being developed for advanced fission reactors. A finding in the report “Bringing Fusion to the U.S. Grid”[24] found that “advanced fission reactors that use lithium-bearing fluoride salts (such as FHRs) may provide a bridge source of tritium and demonstrate tritium control and recovery applicable to fusion power.” We may need additional research on FLiBe-extraction technologies for fusion because the desire in fission is to suppress tritium production in contrast to fusion needs. These differences may drive different development paths but could leverage similar innovations.

The APS CPP report [39] recommended a basic research need related to tritium extraction that we reiterate and amplify in the above PRO: “Construct bench-scale experiments to test tritium extraction concepts and transport in breeder and structural blanket materials.”

Heat Transfer. Ultimately, the heat generated in the reactor needs to be circulated to a generator for electricity production. The first wall and blanket system will be the primary receivers of the heat generated in the reactor. Efficient removal and transfer of this heat to a generator, as well as materials that safely operate in these conditions, are essential to the viability of a power plant. Blanket concepts need a viable heat-extraction method. Blanket systems are categorized by cooling methods: helium-cooled, water-cooled, dual-cooled, and molten salt–cooled.

We need to demonstrate the relative heat transfer efficiencies of each blanket system concept to provide power-plant and reactor designers with system-design metrics.

Neutron Shielding. Breeder-blanket concepts are meant to provide neutron shielding. Reactor architectural choices will determine what percentage of neutrons the blanket will shield, with the reactor facility shielding the remainder. No domestic facilities are currently set up for testing and verifying the shielding capability of breeder blanket systems for fusion-relevant neutrons.

In MFE, ~80% of the reactor area is covered by the blanket and available for tritium breeding. Different IFE-concept architectures will have different percent area coverages and may require a higher TBR blanket material if lower area is available for elements such as beam paths. Reactor architecture will thus have a direct impact on breeding-blanket material selection. A test facility should focus on developing a database of blanket-material properties and make it available to system architects.

Direct Internal Recycle (DIR). A concept within the MFE community that has gained increasing traction as a way to increase fuel cycle efficiency and decrease the tritium inventory within a fusion energy system is direct internal recycle (DIR) [57]. DIR is a concept that comes from the preference of the divertor in MFE to exhaust hydrogen isotopes relative to helium ash, thereby making it advantageous to have a method to directly recycle a part of the DT from the exhaust back to the feed without isotopic rebalancing. Implementations of DIR utilizing metal foil pumps to help recover DT from the exhaust have been proposed, and research on those concepts is ongoing for MFE [58, 59]. While DIR has gained significant traction within the MFE community, the IFE community has not yet explored a similar concept in detail for IFE due to the focus on achieving ignition. Direct recycling for IFE would need to reinject and create targets from the recycled DT mixture.

System Integration and Design

System Design Studies

PRO 6-5: ***Undertake a series of system-design studies to establish a suite of self-consistent, quantitative IFE plant models, and use these to guide each aspect of the research, development, and demonstration (RD&D) program.***

As noted in the introduction to this chapter, many prior studies have shown a very high degree of coupling between IFE sub-systems (from target design to target survival, chamber lifetime, system performance, scale of the fuel cycle, etc.). A viable IFE-development program must incorporate a set of system-level design activities whose outputs are models of the integrated operation of a set of characteristic IFE plants.

This approach will demonstrate to all stakeholders the potential benefits, challenges, and operating characteristics of an IFE reactor and will provide quantitative guides for developing component technologies, concepts, and plant designs.

We can use these plant-level models to stress-test different physics and technology options in a quantitative, self-consistent manner. We can also use them to indicate where there are mismatched requirements between sub-systems, where there is a lack of alignment in sub-system TRL maturity, and where there is a challenge to the viability of a given approach and to quantify the impact of proposed advances in the performance of a given parameter.

This approach will help modulate inappropriate claims of the ease or difficulty of a path to market, bolstering the overall credibility of our community and avoiding overselling and underappreciation of the technical development needs.

A systems code that includes sufficient detail to inform the many technological trade-offs is an important program element. IFE reactor-systems design efforts need to incorporate a wide range of considerations (see [1, 2] and references therein), including pursuing the following tasks:

- Identify the R&D pathways that provide the greatest set of opportunities for a given concept (reducing risk) and which can bridge between concepts (reducing overall investment costs)
- Identify potential show-stoppers (or the need for a fundamentally new approach) in specific sub-systems and integrated concepts
- Quantify the requirements from a concept of operations (CONOPS) that delivers high-availability, high -performance plant operations, including the impact of different design choices (e.g., yield, repetition-rate, materials choices, etc.).
- Inform economic models and investment options, including options for co-generation and process-heat applications for thermochemical industrial applications

As an example, many aspects of the fuel cycle and chamber performance can have a direct impact on the design requirements for an IFE target, quite different from those associated with the “single-shot” ICF program. This includes the following:

- The use of some common target materials (e.g., CH or CD) can drive an untenably large isotope separation system
- The presence of carbon-based compounds can compromise the efficient working of the chamber gas-handling system (e.g., via creation of long-chain molecules that lead to blockages), necessitating consideration of chamber chemistry in the high temperature gas
- Beta-layering approaches to forming the DT layer are incompatible with maintaining a low tritium inventory in the plant, necessitating the exploration of wetted foams or other fast-filling techniques
- Tritium implantation and co-deposition of vaporized target materials on the chamber walls and exhaust systems can lead to an unworkable solution; for example, hohlraums and direct-drive shielding layers cannot tolerate high-melting-point metals, such as gold or uranium, necessitating the adoption of materials such as lead
- Manufacturing tolerances for mass manufacture need to be consistent with fusion performance sensitivities (noting that there is a system-level trade-off with driver energy, which typically leads to more robust performance)
- Considerations of target survival (via the thermomechanical insult upon injection and traversal of the chamber) impose strict constraints on target designs (e.g., the need to shield the cryogenic DT layer or the need to ensure suitably thick hohlraum windows and tents)
- Considerations of chamber survival from the x-ray, ion, and neutron output of the pellets impose the need for a solution that is self-consistent with the target injection survival constraints, chamber gas density, debris management (e.g., sabots), and chamber gas dynamics (e.g., clearing)

As a result, we need to provide input from “day-one” on acceptable materials choices and target configurations to inform the likely viability of different schemes. We will thus need an experimental test program to assess these dependencies (e.g., the impact of wetted foams, or low melting point metals).

6.3 Conclusions

In summary, as noted by the IFE community workshop, the formation of system design teams should be one of the very first activities of a new IFE program. This is an activity that provides guidance throughout the life of the program and needs to be of sufficient scale and capability to be able to adapt to emerging R&D breakthroughs or showstoppers from each area.

Finally, to enable timely and balanced progress, we should select an FPP design based on IFE as an option in DOE’s recently announced Milestone-Based Fusion Development Program, as long as there is a suitably qualified submission.

References

1. Mike Dunne, Tom Anklam, and Wayne Meier, *Inertial Confinement Fusion Power Plants*, in *Encyclopedia of Nuclear Energy*, E. Greenspan, Editor. 2021, Elsevier: Oxford. p. 807-821.

2. E. Michael Campbell, et al., *Overview of IFE Key Power Plant Technologies∗*, in *Encyclopedia of Nuclear Energy*, E. Greenspan, Editor. 2021, Elsevier: Oxford. p. 751-794.

3. UK Atomic Energy Authority, *UK Fusion Materials Roadmap 2021-2040*. (2021) https://www.royce.ac.uk/content/uploads/2021/09/UK_Fusion_Materials_Roadmap_Interactive.pdf.

4. R. Roper, et al., *Molten salt for advanced energy applications: A review.* Annals of Nuclear Energy, 2022. **169**: p. 19, 10.1016/j.anucene.2021.108924.

5. C. W. Forsberg, et al., Tritium Control and Capture in Salt-Cooled Fission and Fusion Reactors: Status, Challenges, and Path Forward. Nuclear Technology, 2017. **197**(2): p. 119-139, 10.13182/nt16-101.

6. H. E. McCoy, et al., *New Developments in Materials for Molten-Salt Reactors.* Nuclear Applications and Technology, 1970. **8**(2): p. 156-169, 10.13182/NT70-A28622.

7. Mark Anderson, et al., *Heat Transfer Salts for Nuclear Reactor Systems - Chemistry Control, Corrosion Mitigation, and Modeling*. 2015 (https://www.osti.gov/biblio/1169921): United States.

8. Paul W. Humrickhouse and Thomas F. Fuerst, *Tritium Transport Phenomena in Molten-Salt Reactors*. 2020 (https://www.osti.gov/biblio/1777267): United States.

9. R. Juarez, et al., *A full and heterogeneous model of the ITER tokamak for comprehensive nuclear analyses.* Nature Energy, 2021. **6**(2): p. 150-157, 10.1038/s41560-020-00753-x.

10. National Research Council of the National Academies of Science Engineering and Medicine, *An Assessment of the Prospects for Inertial Fusion Energy*. 2013, Washington, DC: The National Academies Press (doi: 10.17226/18289); https://nap.nationalacademies.org/catalog/18289/an-assessment-of-the-prospects-for-inertial-fusion-energy.

11. W. R. Meier, et al., *Fusion technology aspects of laser inertial fusion energy (LIFE).* Fusion Engineering and Design, 2014. **89**(9-10): p. 2489-2492, https://doi.org/10.1016/j.fusengdes.2013.12.021.

12. W. R. Meier, *Liquid Wall Chambers*. 2011 (https://www.osti.gov/biblio/1021070): United States.

13. S.J. Zinkle and L.L. Snead, *Designing Radiation Resistance in Materials for Fusion Energy.* Annual Review of Materials Research, 2014. **44**(1): p. 241-267, 10.1146/annurev-matsci-070813-113627.

14. J. Knaster, A. Moeslang, and T. Muroga, *Materials research for fusion.* Nature Physics, 2016. **12**(5): p. 424-434, 10.1038/nphys3735.

15. Kai Nordlund, et al., *Primary radiation damage: A review of current understanding and models.* Journal of Nuclear Materials, 2018. **512**: p. 450-479, https://doi.org/10.1016/j.jnucmat.2018.10.027.

16. N. M. Ghoniem and G. L. Kulcinski, A critical assessment of the effects of pulsed irradiation on the microstructure, swelling, and creep of materials. Nuclear Technology-Fusion, 1982. **2**(2): p. 165-198, 10.13182/fst82-a20749.

17. J. Alvarez, et al., *Potential common radiation problems for components and diagnostics in future magnetic and inertial confinement fusion devices.* Fusion Engineering and Design, 2011. **86**(9): p. 1762-1765, https://doi.org/10.1016/j.fusengdes.2011.01.080.

18. Wayne R. Meier, *Osiris and SOMBRERO inertial fusion power plant designs–summary, conclusions, and recommendations.* Fusion Engineering and Design, 1994. **25**(1): p. 145-157, https://doi.org/10.1016/0920-3796(94)90060-4.

19. Tetsuji Noda, Mitsutane Fujita, and Masatoshi Okada, *Transmutation and induced radioactivity of W in the armor and first wall of fusion reactors.* Journal of Nuclear Materials, 1998. **258-263**: p. 934-939, https://doi.org/10.1016/S0022-3115(98)00088-9.

20. M. R. Gilbert, et al., An integrated model for materials in a fusion power plant: transmutation, gas production, and helium embrittlement under neutron irradiation. Nuclear Fusion, 2012. **52**(8): p. 12, 10.1088/0029-5515/52/8/083019.

21. R. G. Abernethy, *Predicting the performance of tungsten in a fusion environment: a literature review.* Materials Science and Technology, 2017. **33**(4): p. 388-399, 10.1080/02670836.2016.1185260.

22. T. Tanno, et al., Effects of transmutation elements on the microstructural evolution and electrical resistivity of neutron-irradiated tungsten. Journal of Nuclear Materials, 2009. **386-88**: p. 218-221, 10.1016/j.jnucmat.2008.12.091.

23. V. K. Alimov, et al., Surface morphology and deuterium retention in tungsten and tungsten-rhenium alloy exposed to low-energy, high flux D plasma. Journal of Nuclear Materials, 2014. **454**(1-3): p. 136-141, 10.1016/j.jnucmat.2014.07.064.

24. National Academies of Sciences Engineering and Medicine, *Bringing Fusion to the U.S. Grid*. 2021, Washington, DC: The National Academies Press. https://doi.org/10.17226/25991.

25. R. Maingi, et al., *Summary of the FESAC Transformative Enabling Capabilities Panel Report.* Fusion Science and Technology, 2019. **75**(3): p. 167-177, 10.1080/15361055.2019.1565912.

26. Karl D. Hammond, *Helium, hydrogen, and fuzz in plasma-facing materials.* Materials Research Express, 2017. **4**(10): p. 104002, 10.1088/2053-1591/aa8c22.

27. J. L. Bourgade, et al., Diagnostic components in harsh radiation environments: Possible overlap in R&D requirements of inertial confinement and magnetic fusion systems. Review of Scientific Instruments, 2008. **79**(10): p. 5, 10.1063/1.2972024.

28. J. B. Wallace, et al., *Time constant of defect relaxation in ion-irradiated 3C-SiC.* Applied Physics Letters, 2015. **106**(20): p. 202102, 10.1063/1.4921471.

29. J. M. Perlado, et al., *Multiscale modeling study of pulsed damage accumulation in α-Fe under inertial fusion conditions.* Journal of Nuclear Materials, 2002. **307-311**: p. 907-911, https://doi.org/10.1016/S0022-3115(02)01018-8.

30. R. M. Hunt, et al., *Fatigue cracking of a bare steel first wall in an inertial confinement fusion chamber.* Fusion Engineering and Design, 2013. **88**(5): p. 311-316, https://doi.org/10.1016/j.fusengdes.2013.03.017.

31. A. R. Raffray, et al., *Dynamic chamber armor behavior in IFE and MFE.* Fusion Engineering and Design, 2002. **63-64**: p. 597-608, https://doi.org/10.1016/S0920-3796(02)00138-2.

32. A. R. Raffray, D. Haynes, and F. Najmabadi, *IFE chamber walls: requirements, design options, and synergy with MFE plasma facing components.* Journal of Nuclear Materials, 2003. **313-316**: p. 23-31, https://doi.org/10.1016/S0022-3115(02)01328-4.

33. J. D. Sethian, et al., *The Science and Technologies for Fusion Energy With Lasers and Direct-Drive Targets.* Ieee Transactions on Plasma Science, 2010. **38**(4): p. 690-703, 10.1109/Tps.2009.2037629.

34. S. Reyes, et al., *Overview of the LIFE fuel cycle.* EPJ Web of Conferences, 2013. **59**, 10.1051/epjconf/20135911002.

35. S. Reyes, et al., *LIFE Tritium Processing: A Sustainable Solution for Closing the Fusion Fuel Cycle.* Fusion Science and Technology, 2013. **64**(2): p. 187-193, 10.13182/FST12-529.

36. Susana Reyes, et al., *Recent developments in IFE safety and tritium research and considerations for future nuclear fusion facilities.* Fusion Engineering and Design, 2016. **109-111**: p. 175-181, https://doi.org/10.1016/j.fusengdes.2016.03.034.

37. M. E. Sawan and M. A. Abdou, *Physics and technology conditions for attaining tritium self-sufficiency for the DT fuel cycle.* Fusion Engineering and Design, 2006. **81**(8-14): p. 1131-1144, 10.1016/j.fusengdes.2005.07.035.

38. M. Abdou, et al., Physics and technology considerations for the deuterium-tritium fuel cycle and conditions for tritium fuel self sufficiency. Nuclear Fusion, 2021. **61**(1): p. 50, 10.1088/1741-4326/abbf35.

39. Scott Baalrud, et al., *A community plan for fusion energy and discovery plasma sciences.* arXiv preprint arXiv:2011.04806, 2020, https://doi.org/10.48550/arXiv.2011.04806.

40. T. Carter, et al., *Powering the Future: Fusion & Plasmas*. 2020 (https://science.osti.gov/-/media/fes/fesac/pdf/2020/202012/FESAC_Report_2020_Powering_the_Future.pdf), Fusion Energy Sciences Advisory Committee.

41. C. P. C. Wong, et al., *Overview of liquid metal TBM concepts and programs.* Fusion Engineering and Design, 2008. **83**(7-9): p. 850-857, 10.1016/j.fusengdes.2008.06.040.

42. L. V. Boccaccini, et al., *Status of maturation of critical technologies and systems design: Breeding blanket.* Fusion Engineering and Design, 2022. **179**: p. 17, 10.1016/j.fusengdes.2022.113116.

43. M. Aristova and C. A. Gentile, *COMPARATIVE STUDY TO EVALUATE CANDIDATE MATERIALS FOR TRITIUM PRODUCTION IN A DIRECT DRIVE IFE REACTOR.* Fusion Science and Technology, 2009. **56**(1): p. 475-477, 10.13182/fst09-a8948.

44. F. A. Hernández and P. Pereslavtsev, First principles review of options for tritium breeder and neutron multiplier materials for breeding blankets in fusion reactors. Fusion Engineering and Design, 2018. **137**: p. 243-256, https://doi.org/10.1016/j.fusengdes.2018.09.014.

45. Mohamed Abdou, et al., *Blanket/first wall challenges and required R&D on the pathway to DEMO.* Fusion Engineering and Design, 2015. **100**: p. 2-43, https://doi.org/10.1016/j.fusengdes.2015.07.021.

46. M. Rubel, Fusion Neutrons: Tritium Breeding and Impact on Wall Materials and Components of Diagnostic Systems. Journal of Fusion Energy, 2019. **38**(3-4): p. 315-329, 10.1007/s10894-018-0182-1.

47. S. Smolentsev, et al., *Dual-coolant lead-lithium (DCLL) blanket status and R&D needs.* Fusion Engineering and Design, 2015. **100**: p. 44-54, 10.1016/j.fusengdes.2014.12.031.

48. C. E. Kessel, et al., *Critical Exploration of Liquid Metal Plasma-Facing Components in a Fusion Nuclear Science Facility.* Fusion Science and Technology, 2019. **75**(8): p. 886-917, 10.1080/15361055.2019.1610685.

49. A. J. Creely, et al., *Overview of the SPARC tokamak.* Journal of Plasma Physics, 2020. **86**(5): p. 25, 10.1017/s0022377820001257.

50. C. Forsberg, et al., Fusion Blankets and Fluoride-Salt-Cooled High-Temperature Reactors with Flibe Salt Coolant: Common Challenges, Tritium Control, and Opportunities for Synergistic Development Strategies Between Fission, Fusion, and Solar Salt Technologies. Nuclear Technology, 2020. **206**(11): p. 1778-1801, 10.1080/00295450.2019.1691400.

51. Charles W. Forsberg and Per F. Peterson, *FHR, HTGR, and MSR Pebble-Bed Reactors with Multiple Pebble Sizes for Fuel Management and Coolant Cleanup.* Nuclear Technology, 2019. **205**(5): p. 748-754, 10.1080/00295450.2019.1573619.

52. T. R. Barrett, et al., *A New Facility for Combined-Load Testing of Fusion Reactor In-Vessel Components.* Ieee Transactions on Plasma Science, 2020. **48**(6): p. 1432-1438, 10.1109/tps.2020.2968405.

53. Victor A. Maroni, Raymond D. Wolson, and Gustav E. Staahl, Some Preliminary Considerations of A Molten-Salt Extraction Process to Remove Tritium from Liquid Lithium Fusion Reactor Blankets. Nuclear Technology, 1975. **25**(1): p. 83-91, 10.13182/NT75-A24351.

54. H. Moriyama, et al., *Tritium Recovery from Liquid-Metals.* Fusion Engineering and Design, 1995. **28**: p. 226-239, https://doi.org/10.1016/0920-3796(95)90043-8.

55. P. W. Humrickhouse and B. J. Merrill, *VACUUM PERMEATOR ANALYSIS FOR EXTRACTION OF TRITIUM FROM DCLL BLANKETS.* Fusion Science and Technology, 2015. **68**(2): p. 295-302, 10.13182/fst14-941.

56. Joseph A. Teprovich, et al., *Electrochemical extraction of hydrogen isotopes from Li/LiT mixtures.* Fusion Engineering and Design, 2019. **139**: p. 1-6, https://doi.org/10.1016/j.fusengdes.2018.11.018.

57. C. Day and T. Giegerich, *The Direct Internal Recycling concept to simplify the fuel cycle of a fusion power plant.* Fusion Engineering and Design, 2013. **88**(6-8): p. 616-620, 10.1016/j.fusengdes.2013.05.026.

58. S. Hanke, et al., *Progress of the R&D programme to develop a metal foil pump for DEMO.* Fusion Engineering and Design, 2020. **161**: p. 6, 10.1016/j.fusengdes.2020.111890.

59. B. J. Peters, S. Hanke, and C. Day, *Metal Foil Pump performance aspects in view of the implementation of Direct Internal Recycling for future fusion fuel cycles.* Fusion Engineering and Design, 2018. **136**: p. 1467-1471, 10.1016/j.fusengdes.2018.05.036.

SECTION FOUR

CROSS-CUTTING AREAS

Chapter 7: Theory & Simulation

7.1 Introduction

Predictive capability for inertial confinement fusion (ICF) yield is critical for reliable inertial fusion energy (IFE)-gain predictions. The system-wide design of a power plant relies on the target design and its predicted gain. For example, lower driver efficiencies can be tolerated if capsule implosions result in higher gain. Gamma- and x-ray-flux, as well as neutrons (for deuterium-tritium (DT) fuel), can influence the choice of chamber wall materials. The choice of materials included in capsule design is also driven by the need for IFE-relevant gains and the need to mitigate physics that can potentially compromise target performance. The ICF program is pursuing several IFE approaches for high yield—each defined by its unique set of driver parameters and target material choices and, therefore, its unique developmental path. An accurate first-principle predictive capability for the different IFE concepts is not yet available. To identify the most promising IFE approaches, we must continue to develop these tools across the broad range of driver and target parameters applicable to the different approaches. This section focuses on improving physics modeling with broad relevance to all the IFE approaches, including laser- or ion-driven direct- and indirect-drive, as well as magnetized liner inertial fusion (MagLIF).

IFE-relevant designs require computational tools that simulate integrated capsule implosions and a related suite of models that address the range of multi-scale, multi-physics plasmas, with details that may vary from one approach to another. Predictive capabilities of fusion yield require funding in the priority research opportunities (PROs) listed in this section. Use of institutional codes through multi-institutional collaborations is also important for accelerating progress toward identifying favorable IFE approaches. Advancing toward a complete IFE modeling ecosystem necessitates developing and adopting data standards for code inputs and outputs to enable complex multi-physics workflows. Ultimately, the community should strive to develop an integrated ecosystem of codes with on-the-fly tunability of physics and numeric complexity. Finally, the suite of IFE-relevant codes should exploit exascale-era

SUMMARY

Improved prediction is key to IFE. We must improve both the physics models and the algorithms that implement them. For example, we must **develop theoretical and simulation models of the detailed physics of LPI evolution.** In addition, a number of unexplored instabilities will require integrating disparate physics packages into a unified framework that includes accurate kinetic descriptions of high-energy density plasmas. The predictive capabilities of target- and machine-scale simulations also closely tie to the accuracy of underlying material properties. Thus, we must **improve predictive calculations of static and transport material properties under IFE-relevant extreme conditions.**

Finally, we need to **improve our predictive capability for magnetized IFE plasmas,** as magnetization of an inertial fusion fuel is a potential path to high gain. Because IFE modeling tends to be computationally intensive, we must enable these algorithms to use the latest hardware. Since some algorithms can make effective use of sizable speedups on GPUs, while others cannot, we need a mix of heterogeneous architectures. Ultimately, the community should develop an integrated ecosystem of codes with on-the-fly tunability of physics and numeric complexity, through which the user can select the physics fidelity, dimensionality, and algorithmic accuracy.

computer architectures to increase the accuracy of the physics models and the turnaround of high-fidelity simulations.

Science and Technology Challenges

Radiation hydrodynamic codes are typically used to design and guide experiments on implosion facilities. However, implosions occur across a range of scales beyond those well-modeled by the fluid-approximation (**Figure 7.1**), and different ICF target designs access a wide range of conditions at stagnation (for example, laser-driven ICF stagnation reaches >300-Gbar pressures on nanosecond timescales, while magnetized plasmas operate at lower pressures and longer timescales). In addition, the range of conditions accessed during implosions and relevant to whole IFE systems is large—varying from fractions of solid density to many hundred times solid density and temperatures up to ~a few hundred million degrees. To bridge the gap between the length and timescales of implosions and those of other relevant phenomena, reduced models are used in radiation hydrodynamic codes. For laser-driven approaches, depending on the design and the approach, laser intensities ranging from ~3 × 10^{14} W/cm^2 to ~10^{20} W/cm^2 are used to set these conditions in implosions.

Different physics can dominate the interaction of the laser with the plasma depending on the laser intensity. Plasma effects related to energy deposition, back-scatter, and hot-electrons are included in codes using approximations or semi-empirically (PRO 7-1a). Related kinetic effects (PRO 7-1b) like non-local heat transport are also approximated with simplified models. Verifying these models against more exact, targeted physics codes and validating them in experiments is important for predicting IFE-gains. Similarly, implosion simulations include properties of materials with a range of atomic numbers varying from that of hydrogen to gold under weakly/strongly coupled conditions at varying levels of degeneracy. As indicated in PRO 7-1c, calculations of material properties under these conditions are challenging. Validating these models is also important for gain predictions. Finally, improved modeling of magnetic fields can reduce the required driver energies by the suppression of heat in the compressed hotspot or, in the case of MagLIF, can better predict target designs through improved modeling of the current flow (PRO 7-1d).

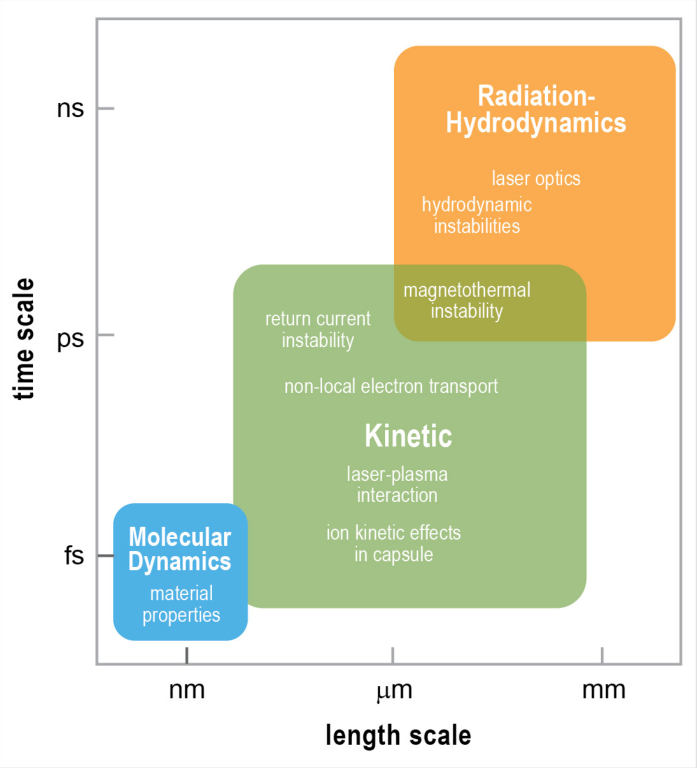


Figure 7.1. IFE is an inherently multi-scale and multi-physics problem. Typical time and length scales covered by various simulation methods as well as some of the relevant processes are listed.

Finally, ICF and therefore IFE simulation tools were developed for use with CPU architectures. Heterogeneous architectures, including GPUs, are the basis of current and upcoming exascale systems. Modernizing simulation codes to exploit these platforms, including developing new and potentially more accurate algorithms, can significantly impact IFE target-physics modeling. This is a challenging task, calling for collaborations between computer scientists, mathematicians, physicists, and data scientists (PRO 7-2).

Knowledge Gaps

Improvement in ICF implosion performance is typically achieved through a combination of simulations that identify performance trends and semi-empirical tuning of experimental parameters. We have made significant progress in lower-compression implosions in direct- and indirect-drive laser-driven implosions. However, high-compression IFE-relevant implosions, less robust to uncertainties in the physics and the experimental parameters, deviate significantly from simulation predictions. Differences between simulation and experiment have been attributed to inaccuracies in the reduced models, omission of key physics, and differences in the assumed and as-shot experimental parameters (such as as-shot amplitudes of nonuniformity sources, as-shot target quality, and as-shot driver parameters).

Where Does IFE Overlap with Inertial Confinement Fusion (ICF) and Where is it Unique?

Many tools exist to simulate implosions and guide the design of ICF experiments, which will be critical for an IFE program. These tools include integrated implosion-physics radiation-hydrodynamic codes and physics-specific codes used to study laser-plasma interactions, kinetic effects, and material properties under high-energy-density physics (HEDP) conditions. Some areas where reliable predictions of an IFE-relevant design can be accelerated include improving models of driver-target coupling in implosion codes (e.g., the interaction of the laser with the coronal plasma for laser-driven and MagLIF approaches); coupling kinetic descriptions into radiation-hydrodynamic codes, which may potentially require new algorithms; and calculating static and transport properties of materials across a broader IFE-relevant range of density and temperature parameters than those accessed in ongoing ICF experiments. Separate from integrated implosion codes, detailed physics codes that study a specific aspect of an IFE implosion (e.g., codes used to calculate static and transport properties of materials, the interaction of drivers and targets, or modeling kinetic physics) are critical to accelerate the path toward an IFE-relevant design. These codes have a broad development base beyond the national laboratories. They are very important for exploring and understanding fundamental phenomena, verifying reduced models used in implosion codes, and identifying the optimal parameter space for target design, as well as strategies for mitigating effects that might compromise target performance. Improved targeted physics codes through better physics models, modern algorithms, and access to newer computing architectures can significantly improve predictive capability.

Unraveling IFE-relevant implosion physics on existing ICF facilities requires detailed, high-quality measurements and analysis techniques (for example, an innovative diagnostic would infer spatially and temporally resolved density profiles in experiments). These types of measurements would play a significant role toward validating codes. Onsite analysis of diagnostics with edge-computing facilities—particularly on intermediate IFE-relevant facilities—would accelerate the rate of validation of codes. Capabilities to produce synthetic diagnostics are already part of the ICF program but should continue to be emphasized as part of an IFE program. Access to existing compression facilities including OMEGA, NIF, and Z and to university-scale facilities through, for example, LaserNetUS and ZNetUS are important for providing the larger community access to validation platforms for codes.

An IFE program can also take advantage of ICF simulation tools being adapted to exploit heterogeneous architectures (PRO 7-2). Modern architectures have transformed high-performance computing (HPC) through the use of hybrid CPU/GPU systems. The suite of IFE-relevant codes should exploit these architectures to increase the accuracy of the physics models and the turnaround of high-fidelity simulations. The IFE community should leverage the large body of software and expertise from the DOE Exascale Computing Project and the SciDAC collaborations.

Increasing use of the artificial intelligence (AI)/machine learning (ML) to design targets, interpret diagnostics, and analyze experiments on existing relatively low-repetition-rate compression facilities will accelerate improvements toward predictable simulations. AI/ML has the potential to significantly enhance the rate of learning related to IFE. It will continue to play an important role in target design (the increased throughput potentially available through modern HPC machines will permit exploration of a larger target physics parameter space), model development, diagnostic selection, experimental analysis, and uncertainty quantification for predictions. Collaborations with industry workshops that broaden the base of researchers using these techniques can lead to faster progress in understanding and to reliable code predictions for IFE-relevant target designs. The converse also holds true: an intermediate repetition-rate IFE facility can improve ICF target performance with its increased rate of data-taking, permitting a wider exploration of the ICF parameter space.

Developing the range of codes with improved algorithms that we can use efficiently on modern architectures or improving the fidelity of the physics models requires complementary skill sets, including those of physical scientists, computer scientists, programmers, mathematicians, and data scientists. Programs that train students within academia or through interactions with the national laboratories and collaborations with industry offer a route to building this needed workforce.

IFE-relevant target-design codes face unique challenges in that they have been developed for ICF and are used within controlled environments. Providing the larger community, including universities and private industry, access to use these codes and related HPC resources will accelerate the path toward an IFE demonstration plant. We also need to develop processes by which a group outside of the National Nuclear Security Administration (NNSA)-funded national laboratories could develop the relevant parts of an integrated code and use it to identify IFE-related designs. This process may take the form of a formal collaborative research and development agreement (CRADA). Sharing restricted data, such as equations of state (EOS) and opacities, outside the NNSA complex is another aspect that requires agreements amongst the national laboratories, NNSA, and the Office of Science. Finally, access to HPC facilities for groups that develop IFE-relevant models and codes beyond the national laboratories would accelerate the path toward reliable IFE-relevant designs.

Where Does IFE Overlap with Magnetic Fusion Energy (MFE) and Where is it Unique?

IFE overlaps with MFE include, among others, development and optimization of particle-mesh codes on heterogeneous platforms [1, 2], connections to DOE Office of Science’s Advanced Scientific Computing Research (ASCR)-supported low-level software tools and libraries (e.g., the Extreme-Scale Scientific Software Stack, E4S [3]), development of the common electromagnetic Particle-In-Cell (PIC) codebase [4], and modeling of ion sources for MFE and heavy-ion fusion (HIF).

We need to both improve physics modeling and leverage modern simulation hardware to accelerate reliable IFE-relevant target-design predictions. While physics models are critical, without the benefits of accelerating the numerical algorithms, improved models may remain intractable. Thus, both the main PROs listed below are equally important for developing predictable codes. Within PRO 7-1, related to physics models, the sub-PROs are listed in order of their priority.

7.2 Priority Research Opportunities (PROs)

PRO 7-1: ***Develop an ecosystem of simulation and modeling tools to predict the gain in IFE-relevant target designs through integrated implosion physics and targeted physics codes***

PRO 7-1a: ***Improve the theory and develop the simulation tools to accurately model and to enable control of laser plasma instabilities (LPIs) in IFE-relevant regimes***

Crucial for the success of any laser-based IFE scheme is the predictable delivery of laser energy to the target, with LPI control. LPIs can non-uniformly scatter laser energy away from the target and can produce suprathermal electrons that preheat the fuel and impede compression. Ideally, an optimal IFE design would include control of the long-time evolution of LPIs in IFE plasmas, using fine-scale sculpting of laser profiles, both temporally and spatially on the instability growth timescale and speckle-width length-scale. Such modulations are meant to curtail plasma self-organization of parametric instabilities throughout the under-dense coronal plasma of a laser fusion target without deleteriously affecting the implosion. Mitigating LPI can considerably expand the parameter space in laser intensity and choice of target materials for laser-driven targets.

The goal of this PRO is to develop theoretical and simulation models that can access the detailed physics of the evolution of LPIs from the single laser hotspot limit to two interacting adjacent hotspots to multiple (statistical limit) interacting hotspots and from a sub-picosecond timescale to 100s of picoseconds and from the sub-micrometer length-scale to 100s of micrometers. This capability will lead to advanced laser manipulation technology for laser-pulse shaping that is common in the telecom industry and that we must bring to the high-energy, high–average power IFE regime.

A number of schemes have been proposed to control or tame LPIs (e.g., large laser bandwidths [5-7], STUD pulses [8, 9], shorter laser wavelengths [10]). Detailed models with which to compute the kinetic non-linear regime of LPIs are limited because of the assumptions made to make the complex absorption physics problem tractable. We need fully kinetic and nonlinear models of LPI, including laser modulation. Integrated models that can capture the physics of the long-time evolution of multiple interacting LPI processes with a large number of crossing beams would constitute such an advance.

The art of integrating computational models that span length- and timescales from micrometers and femtoseconds to 100s or 1000s of micrometers and nanoseconds requires meshing kinetic nonlinear plasma models with reduced-moment models and phenomenological rate-equation models. It requires full electromagnetic wave propagation with scalar, paraxial, and geometrical optics descriptions. Such integration technology using AI and ML tools to the maximum will also enable other elements of IFE. In particular, designing optimized pulse shapes with sub-picosecond features and lasting on the order of 200–2000 ps will require ML tools that ought to have use in areas such as target design, manufacturing, laser-pulse amplification, and propagation.

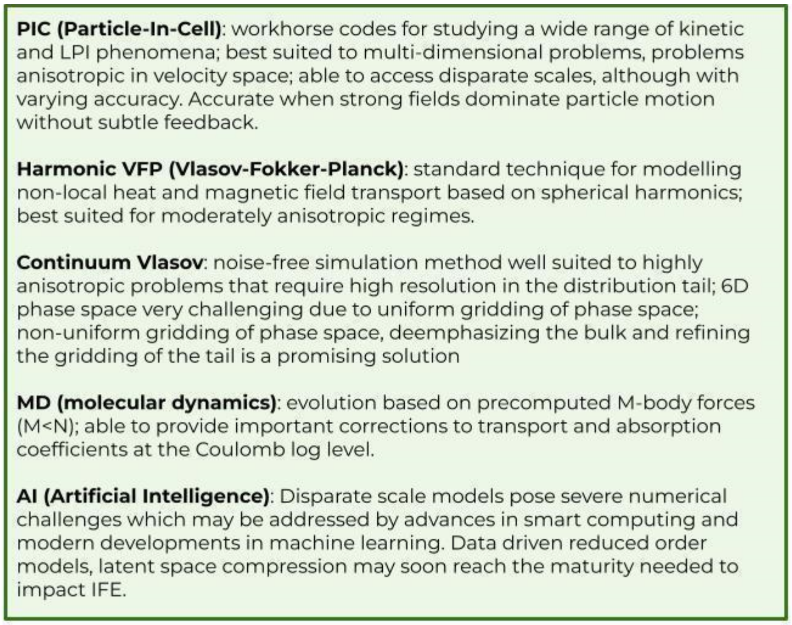
IFE-relevant laser schemes require energy to be delivered to the ablation front cleanly, uniformly, without hot-electron preheat or asymmetry, and thus predictably. Smart computing innovations, such as novel ways of efficiently searching and representing phase-space for kinetic simulations of LPIs, may play a major role in grappling with these complexities. The advent of high-repetition-rate lasers, ML techniques for optimization, and advanced pulse-shaping techniques, such as STILLETTO [11], make it imperative to follow through with this approach now. STUD pulses to modulate the laser on very fast (sub-picosecond) timescales and scrambling hotspot patterns on that timescale is another approach to controlling LPI. Broadband lasers have also been proposed for controlling LPI.

The following numerical models are currently used to model LPI phenomena:

1. Particle-In-Cell (PIC) codes: These codes are able to simulate LPI at the kinetic level, including multi-speckle effects. Their usefulness is currently limited due to their inability to resolve certain regions of phase-space, such as the tail of the distribution function, and inability to properly capture the spectrum of waves in the non-linear regime due to particle noise.
2. Vlasov models: These continuum models are also able to simulate LPI processes at the kinetic level, without noise. However, they are often more expensive than PIC due to the use of uniform gridding in phase-space, and they often need to be used in a reduced number of dimensions (typically only two dimensions in velocity space).
3. Reduced models: A number of reduced models have been incorporated into radiation hydrodynamic codes, but these are based largely on linear theory and require *ad hoc* multipliers, limiting their range of applicability in the broad parameter space required by IFE.

PRO 7-1b: ***Develop the next generation of computational tools capable of simulating kinetic effects in thermal and magnetized plasmas***

The physics models used in IFE research are multi-scale, meaning they contain physics packages that describe processes that occur on different temporal and spatial scales. Current computational models for IFE can be split into three broad categories: (1) radiation-hydrodynamics and magnetohydrodynamics (MHD) for target implosion dynamics and for z-pinch physics; (2) PIC codes for simulating short-pulse laser-plasma interactions, including relativistic intensity, non-linear wave-particle interactions, ion-beam transport, and kinetic effects in thermal and magnetized transport of electrons and ions [12]; and (3) Vlasov-Fokker-Planck (VFP) codes, which grid phase-space uniformly, for modeling intricate coherent structures, self-organization in IFE plasmas, thermal and magnetic transport, anisotropy, and non-local interactions in phase space [13]. VFP codes based on spherical harmonic expansions in velocity space are particularly efficient when simulating non-local electron transport in which the velocity distribution function is close to isotropic. Figure 7.2 lists these broad categories of computational models.



PIC (Particle-In-Cell): workhorse codes for studying a wide range of kinetic and LPI phenomena; best suited to multi-dimensional problems, problems anisotropic in velocity space; able to access disparate scales, although with varying accuracy. Accurate when strong fields dominate particle motion without subtle feedback.

Harmonic VFP (Vlasov-Fokker-Planck): standard technique for modelling non-local heat and magnetic field transport based on spherical harmonics; best suited for moderately anisotropic regimes.

Continuum Vlasov: noise-free simulation method well suited to highly anisotropic problems that require high resolution in the distribution tail; 6D phase space very challenging due to uniform gridding of phase space; non-uniform gridding of phase space, deemphasizing the bulk and refining the gridding of the tail is a promising solution

MD (molecular dynamics): evolution based on precomputed M-body forces (M<N); able to provide important corrections to transport and absorption coefficients at the Coulomb log level.

AI (Artificial Intelligence): Disparate scale models pose severe numerical challenges which may be addressed by advances in smart computing and modern developments in machine learning. Data driven reduced order models, latent space compression may soon reach the maturity needed to impact IFE.

Figure 7.2. The broad categories of computational models for IFE and their uses.

In addition to the key physics of LPIs and non-local transport, a number of unexplored instabilities driven by transport phenomena operate in the kinetic regime (e.g., thermomagnetic instabilities [14], collisional-Weibel [15], return-current instability [16], magnetothermal instability [17]). The physics of these instabilities is intimately related to kinetic processes operating in the non-linear regime and should be studied in conjunction with LPI effects, such as filamentation.

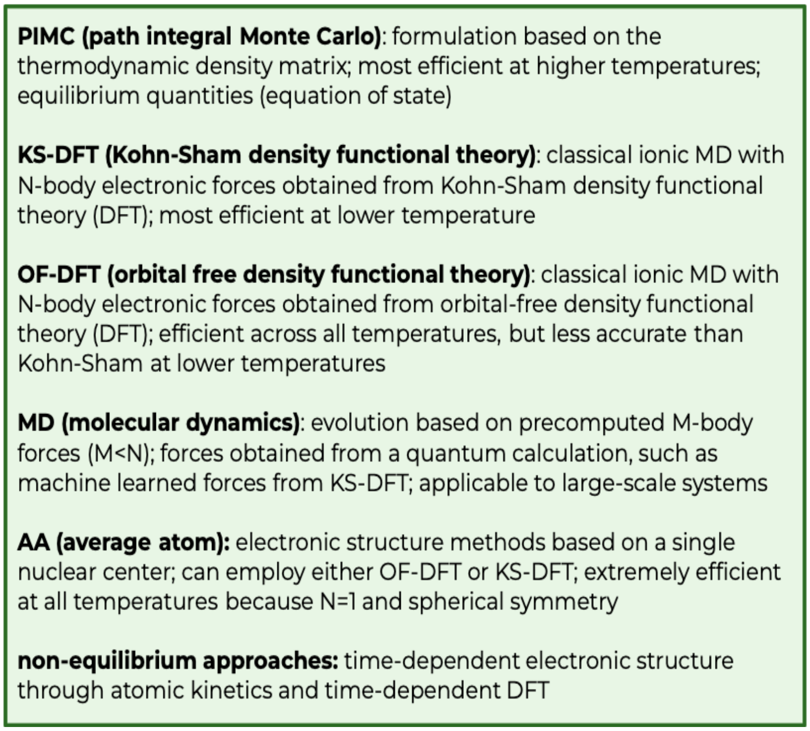
Recent experiments on NIF generating record yield have highlighted anomalies in our understanding of ion dynamics in the hotspot, inferred from neutron measurements [18]. While there is currently no evidence the overall yield is affected, the trend suggests that ion kinetic effects increase with increasing yield. Our lack of understanding of what causes this trend suggests a deficiency in our ion-modeling capability of dense fuel assembly, which we could remedy by applying 1- and 2-D multi-ion-species VFP simulation tools with a kinetic calculation of reactivity coupled to synthetic neutron time-of-flight (nToF) diagnostics.

The aforementioned models are well established and work well within their regime of applicability. However, no model alone can accurately capture all the relevant processes and scales of IFE. Most of the current developments focus on refining existing algorithms or adding additional physics packages that attempt to account for kinetic effects with reduced models. A challenge facing the community is the integration of disparate physics packages into a unified framework that includes accurate kinetic descriptions of high-energy density (HED) plasmas. This will require establishing reduced/subgrid models for the dominant physical processes and developing new methods for merging these models that operate in different regimes. Prime examples include the following:

- Improve the modeling of non-local electron transport by developing better reduced models and/or coupling harmonic electron VFP with radiation-hydrodynamic codes
- Improve the modeling of LPI (e.g., parametric instabilities and particle acceleration) and transport by developing better reduced methods and/or coupling collisional-PIC with multi-physics ICF codes
- Explore AI and ML methods for bridging the gap between processes that operate on disparate scales (e.g., long-term behavior of the laser speckles with the plasma with the aim of mitigating asymmetry and hot electrons)
- Improve current algorithms via adaptive phase-space methods, mesh refinement where appropriate, methods to appropriately relax the solution of kinetic models to classical models in regimes of classical applicability (e.g., asymptotic preserving schemes); these methods are essential for increasing model accuracy and would also enable us to apply these models to regimes that are currently inaccessible by improving efficiency

PRO 7-1c: ***Improve predictive calculations of static and transport material properties under IFE-relevant extreme conditions***

Material properties, including EOS, transport coefficients, and the emission, absorption, and scattering of radiation, are input data for hydrodynamic simulations of inertial fusion experiments. The predictive capabilities of target- and machine-scale simulations are closely tied to the accuracy of the underlying material properties. For example, the EOS determines the compressibility of materials; thermal conductivities can influence instability growth in implosions; stopping powers determine how much energy is recaptured from initial fusion products; and radiation physics is integral to hohlraum physics, energy-loss rates, and x-ray diagnostics, such as imaging and spectroscopy. Ensuring common material properties (e.g., sharing of material property tables) is a necessary step in comparing predictions from different radiation-hydrodynamics codes.



PIMC (path integral Monte Carlo): formulation based on the thermodynamic density matrix; most efficient at higher temperatures; equilibrium quantities (equation of state)

KS-DFT (Kohn-Sham density functional theory): classical ionic MD with N-body electronic forces obtained from Kohn-Sham density functional theory (DFT); most efficient at lower temperature

OF-DFT (orbital free density functional theory): classical ionic MD with N-body electronic forces obtained from orbital-free density functional theory (DFT); efficient across all temperatures, but less accurate than Kohn-Sham at lower temperatures

MD (molecular dynamics): evolution based on precomputed M-body forces (M<N); forces obtained from a quantum calculation, such as machine learned forces from KS-DFT; applicable to large-scale systems

AA (average atom): electronic structure methods based on a single nuclear center; can employ either OF-DFT or KS-DFT; extremely efficient at all temperatures because N=1 and spherical symmetry

non-equilibrium approaches: time-dependent electronic structure through atomic kinetics and time-dependent DFT

Figure 7.3. Some of the physical models used in the atomic-scale codes that compute material properties.

The physical models used in the atomic-scale codes that compute material properties vary widely in their sophistication, physical fidelity, and computational expense (see **Figure 7.3**). Models range from density-functional-theory molecular dynamics (DFT-MD), path-integral Monte Carlo (PIMC), kinetics models, and average-atom DFT-based models to highly distilled models parameterized by quantities like the mean ionization state. Most of these models assume local thermodynamic equilibrium (LTE), which enables tabulation on simple grids of material temperature and density, but many IFE-relevant plasmas access non-LTE regimes that are difficult to tabulate (e.g., hohlraums, high-Z diagnostic tracers, magneto-inertial fusion), and hydrodynamic simulations therefore default to less sophisticated models in those regimes. Predictions from this wide variety of models can vary by orders of magnitude, especially for transport properties (see [19-21]). Compounding this uncertainty is the fact that there are very few experiments—especially for transport and radiation physics and non-LTE plasmas—that are of sufficient quality to benchmark these critical material properties.

Thus, knowledge of material properties is (1) essential for predictive ICF design and diagnostics and (2) presents enormous research challenges and opportunities for both theory and experiment. In theory and computation, modern hardware capabilities and ML techniques offer opportunities for unprecedented accuracy and efficiency in generating and using material properties data for IFE. These opportunities include using new computing architectures to accelerate the most sophisticated models, including PIMC and time-dependent DFT; ML methods that can learn multi-body interatomic potentials from these models and use them to generate accurate ionic transport coefficients like diffusivity and viscosity; surrogate models that offer improvements over traditional interpolation methods used in hydrodynamics codes; tabular non-LTE data schemes that can increase both accuracy and speed in IFE simulations; and ML-informed methods for uncertainty quantification.

Beyond the basic computation of material properties across vast physical regimes, two additional issues greatly increase the challenges. The first issue is the treatment of mixtures. Many materials are composed of several elements with varying degrees of stoichiometry. For codes that can (currently) only simulate a few dozen particles, this causes severe statistical problems. Furthermore, one quickly faces the curse of dimensionality in terms of organizing and tabulating the results; ML can have a huge impact here. Moreover, not all of the methods discussed above can compute all of the properties; while PIMC can compute the EOS, it cannot provide ionic transport coefficients due to its lack of dynamics. Stitching together such data from multiple methods introduces a lack of consistency. The second issue is that not all materials are in LTE, particularly high-Z elements at high temperatures. While molecular dynamics (MD) codes are capable of handling any degree of non-equilibrium for the ions, far fewer techniques exist for electrons, especially partially degenerate electrons. Further investment in techniques such as time-dependent DFT and non-LTE methods for atomic physics is greatly warranted.

Finally, we need benchmark-quality experimental measurements. These are difficult to obtain in the plasma regimes of interest to IFE because one must not only prepare and probe a relatively uniform sample of material at extreme conditions but must also independently characterize its composition, temperature, density, and radiation field. A fairly large number of such experiments have measured EOS quantities up to pressures of 1 Gbar, but only a handful have accurately measured transport properties, such as conductivities, stopping powers, opacities, and the detailed emission line profiles and charge state distributions that are essential to x-ray diagnostics, especially in non-LTE regimes. While flagship experimental facilities like NIF, OMEGA, Z, and SLAC's Linear Coherent Light Source provide access to extreme material conditions, it is notable that warm dense matter *(WDM)*, one of the most theoretically challenging regimes of interest to IFE, is relatively accessible on smaller-scale facilities and could benefit from university partnerships. Advances in probe capabilities (e.g., tabletop x-ray sources, both broadband and monochromatic) and diagnostics (including time-dependent detectors and improved analysis techniques) are also critical opportunities for progress in this area. **Figure 7.4** shows the temperature and density space relevant to fusion physics and the models we can use to accurately simulate those plasma regimes.

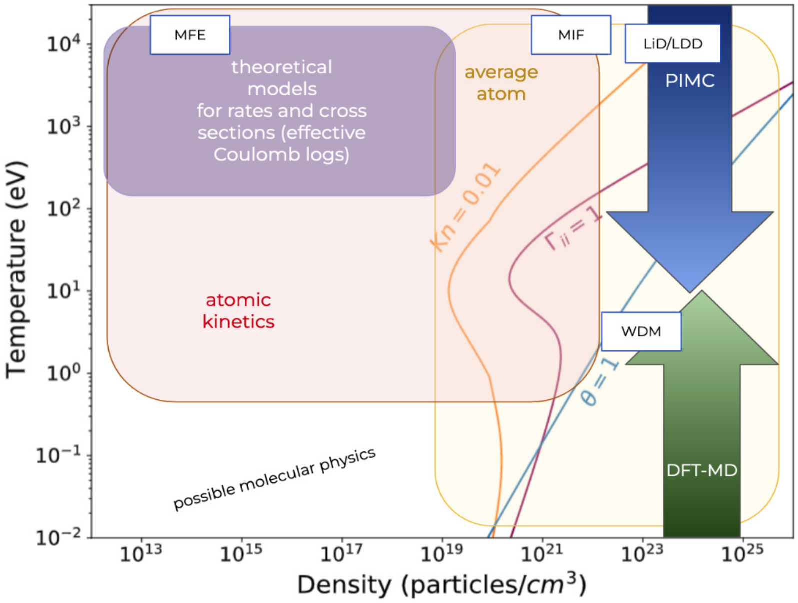


Figure 7.4. *The vast temperature and density space of relevance to fusion physics requires a range of modeling techniques to accurately capture these physical regimes.*

Improving our understanding and implementation of material properties will have a profound impact on the reliability and usefulness of IFE simulations, both at present ICF and future IFE scales. In the immediate term, extending the predictive capabilities of our best atomic-scale models, applying data science and ML tools to material properties and uncertainty quantification, and working toward rigorous experimental benchmarks will help increase our understanding of the complex, integrated, experimental ICF plasmas we are creating today. For future IFE, better knowledge of material properties will directly lead to increased predictive capability for driver-target coupling, fuel assembly, and energy balance and burn.

PRO 7-1d: ***Improve modeling of magnetic fields to enable better predictions of current flow in the MagLIF approach and develop detailed numerical treatment of magnetic fields in integrated radiation-hydrodynamic codes, including models for non-local heat and alpha transport with the goal of identifying IFE designs that can reduce driver energy and efficiencies for IFE-relevant gains***

Magnetization of an inertial fusion fuel provides a mechanism to suppress electron thermal conduction—one of the main energy-loss mechanisms that make ignition harder to achieve and limit fusion performance. Magnetization of electrons in fusion fuel requires fields of many thousand tesla, far beyond what we can apply directly. The implosion of the fuel, however, compresses the magnetic flux within it, meaning that more modest initial fields of a few 10s of tesla are required. With still higher fields, alpha particles become magnetized and remain in the fuel for longer, boosting the ignition process. Multiple experiments in direct drive and more recently with indirect drive have demonstrated increased ion temperatures and fusion yields using applied magnetic fields. The extra boost to fusion yield provided by magnetization may be sufficient to achieve more robust or reliable ignition in current designs or to allow the ignition of lower-temperature, higher–areal density targets. This approach therefore represents a potential path to high-gain designs for IFE.

Accurate prediction of the magnitude of the compressed magnetic fields and therefore the increase in fusion performance remains extremely challenging. The way in which the magnetic field modifies the transport of heat through the plasma is intrinsically linked to the way in which the heat flow redistributes the field. A complete numerical treatment requires the solution of an extended Ohm’s law for magnetic and electric fields, as well as accompanying magnetized heat transport effects. While a number of HEDP codes contain some extended MHD effects, only a limited number contain this complete treatment. The well-studied effects tend to be those that lead to improved performance, such as magnetic-flux compression and magnetized electron-heat flow, whereas other terms that offset some of the gains are less well studied. These include the Nernst effect by which the electron-heat flow removes the very magnetic field that is being used to suppress it. The extension of these effects into regions where the electron transport is non-local and the electron distribution function is non-Maxwellian is a key area of research. This has been an area of intense study for thermal conduction but is also needed for all the transport terms in a complete extended MHD treatment.

Suppression of electron-heat flow using magnetic fields is by no means a universal panacea, particularly where heat flow is an important requirement, such as in the ablation phase of a direct-drive implosion, hohlraum heating in indirect drive, and burn propagation. Applied magnetic fields introduce an intrinsic anisotropy with different heat flows parallel and perpendicular to the field, which results in shape asymmetries. Note that magnetization effects can be important even without applied magnetic fields due to the so-called Biermann Battery effect in which density and temperature gradients can spontaneously generate magnetic fields.

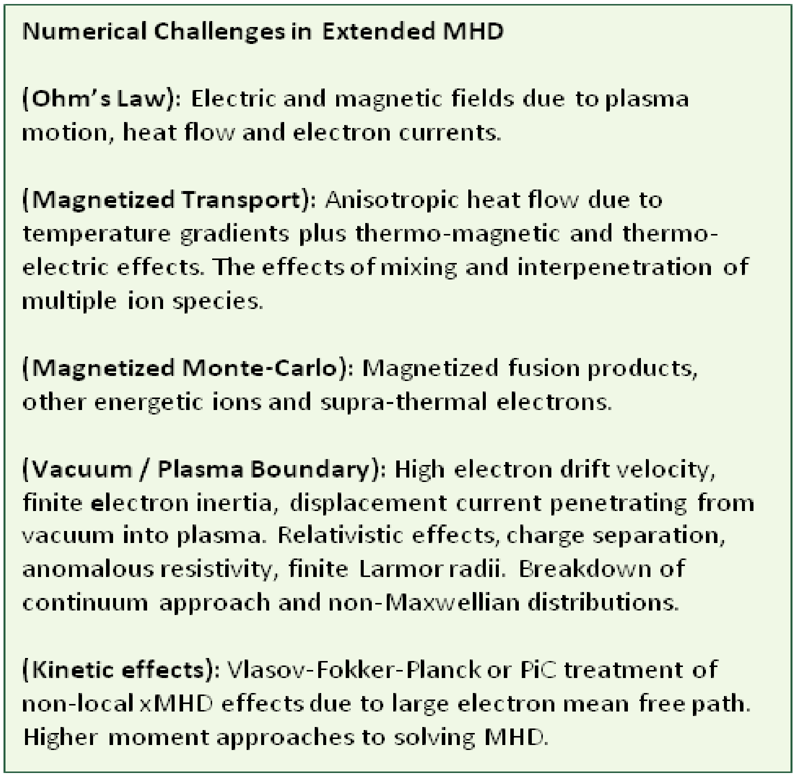
We need to improve our predictive capability for magnetized IFE plasmas. We can achieve this feat through cross-code comparisons, development of theoretical bench test problems, and access to well-constrained experimental data.

Magnetically driven implosions, such as on the Z machine, have additional complexities associated with predicting and controlling the applied fields. A principal challenge associated with modeling these implosions is accurately predicting the flow of electric current through the entire system. As the current flows through the convolute and into the load (which are initially surrounded by vacuum), a certain amount of gas molecules absorb onto the surfaces of these current-carrying structures. These gas molecules outgas and are ionized and form a very low-density plasma, one that is too low density to be modeled well using the standard single fluid formulation. For example, the Alfven velocity diverges in these very low-density plasmas in the strong magnetic field. These near-vacuum regions extend all the way to the exterior of the physics target. Modeling this near-vacuum plasma with a fluid code generally involves introducing a mass density floor and setting the electrical conductivity to zero below a certain density. The aforementioned low-density plasmas cause parasitic currents to flow outside of the electrodes, redirecting current they carry. The result is reduced current and thus reduced energy delivered to the physics target, which impairs the ability to predict overall system performance. We can model the physics target largely independently of the system if we use the measured current delivered. Predicting the current flow into the system in a new facility is difficult given the significance of these parasitic currents.

Simulations of magnetically driven implosions at Z are currently performed in 2D and 3D, employing MHD, and can include all the terms in Ohm’s law. Complex circuit models, such as the generalized Spice network, dynamically solve for external circuits self-consistently. Anisotropic thermal conduction is employed with the choice of several anisotropic conductivity models. We can perform burn physics using a Monte Carlo method for charged particle transport, which includes the effect of magnetic fields on the particle orbits. MagLIF simulations employ a 3D ray-tracing model. Sefkow *et al.* (2014) used simulations extensively to design and model MagLIF experiments [22]. Through focused physics experiments, scientists have tested the ability to model laser propagation into MagLIF-like gas-filled targets[23]. Researchers have also used high-resolution simulations to examine the ability of dielectric coatings to mitigate the electrothermal instability [22-24].

As we develop designs for magnetically driven devices intended to reach ignition and high yield, improved modeling of the overall current flow through the system is imperative. We can achieve improved modeling using an extended MHD formulation or through hybrid kinetic methods. Extended MHD involves generalizing the standard single fluid equations to include electron inertial and displacement current terms, both of which become important in the very low-density plasmas outside the electrodes. By including these terms, we can model the plasma dynamics over a wider range of densities and without the need to introduce zero-conductivity plasma regions or density floors. Extended MHD may require smaller time steps than the standard equations but should still be less computationally expensive than fully kinetic approaches. Incorporating a multispecies formulation of the equations, such as a 13-moment model, allows us to model effects that cause species separation and mixing. As computing resources become more capable and kinetic algorithms improve, hybrid fluid kinetic methods become more practical. Extremely low-density plasma regions are treated with kinetic methods, such as PIC or VFP, while the higher density plasma regions in the fluid regime, such as in the target, are treated with MHD. Various approaches have been applied to join these plasma regions together self-consistently.

Figure 7.5 shows some of the numerical challenges in extended MHD, which are areas of ongoing research. Further research will help to improve predictive capability for ignition and high-yield machines.



Numerical Challenges in Extended MHD

(Ohm's Law): Electric and magnetic fields due to plasma motion, heat flow and electron currents.

(Magnetized Transport): Anisotropic heat flow due to temperature gradients plus thermo-magnetic and thermo-electric effects. The effects of mixing and interpenetration of multiple ion species.

(Magnetized Monte-Carlo): Magnetized fusion products, other energetic ions and supra-thermal electrons.

(Vacuum / Plasma Boundary): High electron drift velocity, finite electron inertia, displacement current penetrating from vacuum into plasma. Relativistic effects, charge separation, anomalous resistivity, finite Larmor radii. Breakdown of continuum approach and non-Maxwellian distributions.

(Kinetic effects): Vlasov-Fokker-Planck or PiC treatment of non-local xMHD effects due to large electron mean free path. Higher moment approaches to solving MHD.

Figure 7.5. *Numerical challenges in extended MHD*

PRO 7-2: ***Develop modern simulation tools that leverage heterogeneous hardware to accelerate the path toward reliable IFE designs***

Prediction and understanding are keys to mature IFE research and technology to the point of proposing IFE demonstrations and power plants. Improving the computer modeling tools can lead to big boosts for IFE. Improvements to existing physics models or inclusion of additional physics, continuous advances in algorithms (e.g., high-order solvers, mesh refinement), the advent of the latest computing technologies (latest CPUs, GPUs, exascale supercomputers), and exponential progress in AI and ML do all contribute, and we should leverage these advances to push IFE computer modeling tools to the next level.

With current simulation tools, the zoning requirements to resolve ablation, hydrodynamic instabilities, Marshak waves, etc. are well understood. With this resolution, existing algorithms have demonstrated an ability to model reasonably well the growth of hydrodynamic instabilities in the ablation front of relevant capsule ablators [25-27]. Improving accuracy and reducing uncertainty in simulations will come largely from new physics models that offer higher fidelity, are more accurate, or model effects not previously included. We identified several priority research areas earlier in this chapter.

In conjunction with improving the physics models, we need to continue to improve or reassess the algorithms that implement these models on computers; we can adjust them to be more physically accurate, to bring additional numerical capabilities (e.g., spatial zooming with adaptive mesh refinement), or to fit new hardware architectures better. These include the use of data-driven and other approaches from AI/ML to, for example, improve accuracy or speed of the algorithms or replace them with a surrogate.

Because IFE modeling tends to be very computationally intensive, we must enable these algorithms to take advantage of the latest hardware. The first "true exascale" supercomputer, Frontier (hosted at Oak Ridge National Laboratory (ORNL) in the United States), has recently taken the #1 spot in the top 500 list of supercomputers [28], primarily due to over 37,000 Advanced Micro Devices (AMD)

Instinct MI250X GPU accelerators. We conceived the simulation tools used for IFE modeling at a time that did not involve the type of specialized programming needed to run efficiently on these platforms. Hence, very few of these models are able to use the latest hardware efficiently, if at all, even at the level of a single or a few CPU or GPU, let alone at the scale of many thousands to tens or hundreds of thousands of them. The challenge is that special expertise is required to port the portions of the codes that can benefit from these architectures, and there are a very large number of lines of code to port overall. Yet, the potential speedup and increased computational powers that these architectures provide could be significant. Examples of new capabilities obtained by applying GPUs include inline non-LTE kinetics models with ~100 times as many configurations as previously used. These models incorporate substantially more of the physics available in the best offline models. Two-dimensional hohlraum simulations performed on LLNL's Sierra machine used this capability to model millions of configurations per zone per species, delivering unprecedented fidelity. An Implicit Monte Carlo radiation transport algorithm has been developed that makes use of both GPUs and CPUs simultaneously. Since some algorithms can make effective use of both types of processors, while others do not lend themselves to sizable speedups on GPUs, we need a mix of heterogeneous architectures. To exploit these, the IFE community should leverage the large body of software and expertise that the DOE Exascale Computing Project (ECP) [29] and Scientific Discovery through Advanced Computing (SciDAC) collaborations [30] developed and continue to maintain. In addition, access to HPC facilities for groups beyond the national laboratories that develop IFE-relevant models and codes would accelerate the path toward more credible IFE-relevant designs.

We should also leverage and incorporate the exponential progress in AI/ML into all IFE theory and modeling activities that can benefit from them. In addition to the above-mentioned algorithm improvements and use of surrogates, AI/ML methods can help us scope out a multi-dimensional parameter space to optimize a target design, while intelligent sampling methods can help the scan to converge on an optimum faster. Collaborations with industry workshops that broaden the base of researchers using these techniques can lead to faster progress in understanding and improving code predictions for IFE-relevant target designs.

7.3 Conclusions

Predictive modeling tools for IFE require an "all-hands-on-deck" approach with the community working together and incorporating all the relevant tools. This demand imposes development and adoption of data standards for code inputs and outputs (e.g., openPMD) to enable complex multiphysics workflows. These standards will also streamline access to massive amounts of simulation or experimental data for surrogate model training or other AI/ML data-based operations with out-of-the-loop coupling. Ultimately, the community should strive to develop an integrated ecosystem of codes with *on-the-fly* tunability of physics and numeric complexity, through which the user can select the degree of physics fidelity, dimensionality, space and time resolution, and algorithmic accuracy.

Through increased support under its Theory and Simulation program, DOE Office of Science's Fusion Energy Sciences (FES) program can specifically accelerate development of IFE by supporting improvement of physics modeling that has broad relevance to all IFE approaches. We can also leverage common modeling platforms, software tools and libraries, and relevant codebases between MFE and IFE.

We need multidisciplinary teams that include theoretical and computational plasma physicists, applied mathematicians, computer scientists, data scientists, and software engineers to develop the next generation of IFE modeling tools. These tools will need to implement better algorithms of higher fidelity physics models that take advantage of the latest computing hardware and AI/ML advances. Further, these new breeds of tools will have complexity that is on par with the fusion devices they model and should be treated as such, with proper planning, maintenance, user support, and training. Programs that train students within academia or through interactions with the national laboratories and collaborations with industry offer a route to building this needed workforce.

References

1. S. Ku, et al., *A new hybrid-Lagrangian numerical scheme for gyrokinetic simulation of tokamak edge plasma.* Journal of Computational Physics, 2016. **315**: p. 467-475, 10.1016/j.jcp.2016.03.062.

2. A. Myers, et al., *Porting WarpX to GPU-accelerated platforms.* Parallel Computing, 2021. **108**: p. 102833, https://doi.org/10.1016/j.parco.2021.102833.

3. M. A. Heroux, S. Shande, and J. Willenbring. *The Extreme-scale Scientific Software Stack*. 2023; Available from: https://e4s-project.github.io/.

4. Jean-Luc Vay and Eric Sonnendrucker, *AMR-PIC Simulations for ITER "[White paper]"*, in *U.S. ITER Research Program: 2022 Fusion Energy Sciences Research Needs Workshop*. 2022 (https://drive.google.com/file/d/1CUdTOESC34lCifGj-n2O9EmgSDiAdHLb/view).

5. R. K. Follett, et al., *Thresholds of absolute instabilities driven by a broadband laser.* Physics of Plasmas, 2019. **26**(6): p. 10, 10.1063/1.5098479.

6. J. W. Bates, et al., Mitigation of cross-beam energy transfer in inertial-confinement-fusion plasmas with enhanced laser bandwidth. Physical Review E, 2018. **97**(6): p. 061202, 10.1103/PhysRevE.97.061202.

7. A. G. Seaton, et al., *Cross-beam energy transfer in direct-drive ICF. I. Nonlinear and kinetic effects.* Physics of Plasmas, 2022. **29**(4): p. 10, 10.1063/5.0078800.

8. B. Afeyan and S. Huller, *Optimal control of laser plasma instabilities using Spike Trains of Uneven Duration and Delay (STUD pulses) for ICF and IFE.* Ifsa 2011 - Seventh International Conference on Inertial Fusion Sciences and Applications, 2013. **59**, https://doi.org/10.1051/epjconf/20135905009.

9. B. J Albright, L. Yin, and B. Afeyan, Control of Stimulated Raman Scattering in the Strongly Nonlinear and Kinetic Regime Using Spike Trains of Uneven Duration and Delay. Physical Review Letters, 2014. **113**(4), https://doi.org/10.1103/physrevlett.113.045002.

10. S. P. Obenschain, et al., *Direct drive with the argon fluoride laser as a path to high fusion gain with sub-megajoule laser energy.* Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 2020. **378**(2184): p. 20200031, 10.1098/rsta.2020.0031.

11. D. E. Mittelberger, et al., *Programmable, direct space-to-time picosecond resolution pulse shaper with nanosecond record.* Optics Letters, 2021. **46**(8): p. 1832-1835, 10.1364/ol.417080.

12. A. J. Kemp, et al., *Laser-plasma interactions for fast ignition.* Nuclear Fusion, 2014. **54**(5): p. 23, 10.1088/0029-5515/54/5/054002.

13. M. Sherlock, J. P. Brodrick, and C. P. Ridgers, *A comparison of non-local electron transport models for laser-plasmas relevant to inertial confinement fusion.* Physics of Plasmas, 2017. **24**(8): p. 9, 10.1063/1.4986095.

14. D. A. Tidman and R. A. Shanny, *Field-generating thermal instability in laser-heated plasmas.* Physics of Fluids, 1974. **17**(6): p. 1207-1210, 10.1063/1.1694866.

15. E. M. Epperlein and A. R. Bell, *Non-local analysis of the collisional Weibel instability in planar laser-ablated targets.* Plasma Physics and Controlled Fusion, 1987. **29**(1): p. 85-92, 10.1088/0741-3335/29/1/007.

16. D. W. Forslund, *Instabilities associated with heat conduction in the solar wind and their consequences.* Journal of Geophysical Research (1896-1977), 1970. **75**(1): p. 17-28, https://doi.org/10.1029/JA075i001p00017.

17. J. J. Bissell, C. P. Ridgers, and R. J. Kingham, *Field Compressing Magnetothermal Instability in Laser Plasmas.* Physical Review Letters, 2010. **105**(17): p. 175001, 10.1103/PhysRevLett.105.175001.

18. E. P. Hartouni, et al., *Evidence for suprathermal ion distribution in burning plasmas.* Nature Physics, 2022, 10.1038/s41567-022-01809-3.

19. J. A. Gaffney, et al., *A Review of Equation-of-State Models for Inertial Confinement Fusion Materials.* High Energy Density Physics, 2018. **28**: p. 7-24, 10.1016/j.hedp.2018.08.001.

20. P. E. Grabowski, et al., *Review of the first charged-particle transport coefficient comparison workshop.* High Energy Density Physics, 2020. **37**, 10.1016/j.hedp.2020.100905.

21. S. B. Hansen, et al., *Review of the 10th Non-LTE code comparison workshop.* High Energy Density Physics, 2020. **35**, 10.1016/j.hedp.2019.06.001.

22. A. B. Sefkow, et al., *Design of magnetized liner inertial fusion experiments using the Z facility.* Physics of Plasmas, 2014. **21**(7): p. 15, 10.1063/1.4890298.

23. M. R. Weis, A. J. Harvey-Thompson, and D. E. Ruiz, *Scaling laser preheat for MagLIF with the Z-Beamlet laser.* Physics of Plasmas, 2021. **28**(1): p. 17, 10.1063/5.0029850.

24. K. J. Peterson, et al., Electrothermal Instability Mitigation by Using Thick Dielectric Coatings on Magnetically Imploded Conductors. Physical Review Letters, 2014. **112**(13): p. 5, 10.1103/PhysRevLett.112.135002.

25. B. A. Remington, et al., *Single-mode and multimode Rayleigh-Taylor experiments on Nova.* Physics of Plasmas, 1995. **2**(1): p. 241-255, 10.1063/1.871096.

26. M. M. Marinak, et al., *Nonlinear Rayleigh-Taylor evolution of a three-dimensional multimode perturbation.* Physical Review Letters, 1998. **80**(20): p. 4426-4429, 10.1103/PhysRevLett.80.4426.

27. R. S. Craxton, et al., *Direct-drive inertial confinement fusion: A review.* Physics of Plasmas, 2015. **22**(11): p. 153, 10.1063/1.4934714.

28. *Top 500*. Available from: https://www.top500.org/.

29. *Exascale Computing Project*. Available from: https://www.exascaleproject.org/.

30. Department of Energy. *Scientific Discovery through Advanced Computing*. Available from: https://www.scidac.gov/.

Chapter 8: Artificial Intelligence and Machine Learning

8.1 Introduction

Vision: Artificial Intelligence (AI)/Machine Learning (ML)-Enabled Integrated Power Plant Operation

Imagining a possible inertial fusion energy (IFE) power plant in operation is helpful for understanding the many ways in which machine learning (ML) and artificial intelligence (AI) could provide key capabilities in operating an energy-production complex. Such a high-repetition-rate facility would manufacture targets on site and on demand and launch them in rapid succession into a target chamber. A confluence of laser beams, their pulse shape optimized to ensure robust ignition and burn, would vaporize each target, sending successive pulses of neutrons into the surrounding walls to be converted to heat. The automated control system would evacuate and reset the chamber between each implosion, with a multitude of sensors continuously monitoring the intricate coordination, providing rapid feedback to the system.

For such a facility to use hundreds to thousands of targets per day, we will need cheap, fast, and reliable production. Targets must undergo quality control, and advances in computer vision enabled by ML could provide, not only rapid classification (accept/reject), but also characterization from which optimized, target-specific pulse designs would be chosen. Advanced computer-vision algorithms will be critical in target tracking and targeting. Rapid, physics-based inference engines could be able to adjust laser-pulse timings, laser-plasma instability (LPI)-mitigation techniques, and intensities based on targeting data, target characterization data, and yield of other targets from the same production batch. An abundance of sensors, providing the diagnostics necessary for the feedback to the AI control of the entire system, will generate a large volume of data to be reduced and processed as it is streamed from these sensors to the control system.

ML and AI will also play a pivotal role in laying the scientific groundwork for a production IFE facility. The science basis for an operational IFE reactor still requires a great deal of research and development (R&D) into, not only the

SUMMARY

ML and AI have great potential to shape IFE, but we must address several key areas.

(1) Data-driven models will require large amounts of well-curated data. Thus, the IFE community must **develop unified data and code management standards and infrastructure.**

(2) ICF and IFE have historically been data poor, with experimental campaigns numbering in the dozens of shots. Higher shot rate experiments would accelerate progress toward IFE milestones by rapidly exploring concepts. Thus, we must **develop or upgrade facilities to take advantage of necessary advances in drivers, targets, diagnostics, and AI/ML.**

(3) High-repetition-rate experiments and eventual reactor operation are not feasible without automated data analysis. **Fast, physics-constrained ML surrogate models for data inference and AI-controlled analysis workflow** can address these new challenges.

(4) Improved predictive capabilities will inform roadmap decisions for all IFE concepts and accelerate design optimization. **AI/ML could ultimately provide real-time, fast emulation to inform target and driver shaping.** Such models could also lead to more predictive simulation.

(5) IFE will clearly benefit from the application of AI/ML; however, the IFE community currently lacks sufficient AI/ML expertise. **Efforts should focus on training existing IFE researchers in AI/ML techniques.**

technologies involved, but also how we deploy them to reach robust ignition and burn. High-repetition-rate facilities will accelerate the pace of this development by providing a deluge of data that the community has not yet had to handle. Because of its ability to rapidly process and understand these data—even to the extent that experiments are self-driven—ML and AI will be essential to accelerating exploration and discovery. Laser controls with more sophisticated pulse patterns, optimized to improve implosion efficiency, could be encoded in data-driven models trained on experimental and simulation data. Similarly, we can use AI to rapidly explore design space using modeling and simulation, both at the high level—executing automated inverse design or design optimization searches—and in simulation algorithms themselves, either incorporating higher-fidelity modeling at reduced cost or accelerating forward simulation through intelligent *in situ* data analysis and adaptive, intelligent algorithms.

Background and Current State of the Field

Over the last decade, AI and ML have experienced a renaissance that has catapulted them into the forefront of consideration across scientific and engineering domains. These topics are not new, but the increasing volumes of data and computational power have made concepts like artificial neural networks useful in commercial applications, such as social networking, advertising, image recognition, and natural language processing. Increasingly, scientists and engineers are trying to adapt the successes of the commercial sector to address challenges in technical applications. While they unarguably have a great deal of hype, AI and ML will be important new tools the IFE community can harness to realize fusion energy power plants.

ML and AI are often used interchangeably, but they are distinct concepts. ML—in particular the subset of deep learning (DL) in which the underlying model is a neural network—is a pathway to AI, but not all AI uses ML. Intuition about ML is possessed by anyone who knows linear regression. In linear regression, one seeks to fit the best line, $y = mx + b$, to a set of data given by (x_i,y_i) pairs of data $(2 < I < = n)$. “Best” is typically defined through an optimization process to minimize the distance between each point and the line (i.e., least squares). Here, we have the major components of ML: a set of data, an assumed model that maps an input x to an output y with unknown parameters (m,b), and a constraint that defines a mathematical optimization problem. Modern ML methods are data-driven models that map one or more inputs to one or more outputs, in which the “assumed form” is a more complicated, often nonlinear, representation like a neural network with up to billions of unknowns, “trained” to satisfy one or more constraints. If the outputs are known, the training method is supervised, and if they are not known, the training is unsupervised; in the latter, the ML method seeks to identify internal structure, such as clusters or latent spaces. There are many more considerations and complications in practice, but this basic analogy is a useful model to keep in mind.

For our purposes, we will distinguish between ML and its use in AI by whether the system can take action. For instance, the difference between image recognition, which has been a cornerstone of ML research, and computer vision, which is an AI technology, is the difference between identification (“that is an intersection with a red light”) and action or control (“stop the car at the intersection”). AI systems (e.g., virtual agents, speech recognition, and recommendation systems) are typically active learning systems (i.e., they are continuously learning from new data).

While ML and AI have made great strides in recent years, one cannot merely adopt the methods used in commercial applications and apply them to science. In many commercial applications, “good enough” is sufficient and “why” is irrelevant. As identified in the 2019 DOE Office of Science

Advanced Scientific Computing Research (ASCR) report [1], scientific ML requires a higher degree of rigor and confidence. Unfortunately, practice is far ahead of theory in ML, so we do not yet have the same degree of mathematical underpinnings in ML as we do in numerical analysis. How to properly design a neural network is still more art than science (the number of levels, i.e., depth; the number of unknowns in each level, i.e., breadth; the connectivity patterns between nodes and the functional form at each node, e.g., the activation function). The explainability (or interpretability) of an ML model is important, not only to ensure that the model has identified meaningful correlations in the data, but also to serve as a source of hypothesis-generation for scientific discovery and to maintain generalizability of the models. Adherence to physical constraints is by no means guaranteed, and methods to ensure this are still under investigation, whether weakly through optimization constraints (e.g., PINNs, physics-informed neural networks [2]) or more strongly through the neural network structure and perhaps learning the lower-dimensional invariant manifold. It is believed that ML techniques that respect physics will be better at generalization (i.e., extrapolation or prediction) outside of the domain of the training dataset, and ML methods that concurrently quantify uncertainty in predictions could help establish confidence in a prediction and suggest data needed to improve the model [3]. Many ML approaches are not robust, meaning that small perturbations in data or even just changing the order of training data can result in vastly different predictions. For these reasons, AI and ML as applied in scientific applications are at a very low technology readiness level (TRL), making them still very much a subject for basic research.

Despite not yet having rigorous underpinnings, ML and AI still have great potential to shape IFE and are already being investigated for use with magnetic fusion energy (MFE) and inertial confinement fusion (ICF), as well as other scientific and engineering domains. Following the analogy above, a common application is to use ML to produce a generative model for physical phenomena for which predictive models are too expensive or for which no suitable governing equations exist. The data used to train such models can be experimental, observational, numerical, or a combination. Examples include intermolecular force models in classical molecular dynamics (MD) trained from *ab initio* simulations (see, e.g., [4, 5] and references therein), turbulence subgrid models [6-9], and the modeling of kinetic effects in macroscopic material models through data-driven coefficients and/or terms [10]. In some sense, this is the “engineering” use of ML to close models for practical approximation, like fitting a curve to experimental data to produce a phenomenological model. A more “science” approach is to use ML to help identify governing equations from data (i.e., symbolic regression, such as the sparse identification of nonlinear dynamical systems (SINDy) efforts [11, 12]).

With sufficiently large amounts of data—DL models need significant amounts of data for training—we can use generative models of complex systems as fast surrogates for sensitivity studies, design optimization, and ultimately control. Indeed, the most well-known fusion applications of ML are the preliminary MFE control studies conducted by DeepMind (Google Research) [13] and the ICF pulse-design studies that favored an ovoid implosion for greater robustness [14]. The 2020 DOE Fusion Energy Sciences (FES)/ASCR Basic Research Needs (BRN) workshop report [15] and recent summary article, “Data-Driven Plasma Science” [16], provide good reviews of recent attempts to use ML and AI to address challenges in modeling, design, and control in MFE and ICF. Further, current DOE FES and Advanced Research Projects Agency – Energy (ARPA-E) projects are looking at ML models for controlling high-repetition-rate lasers [17] and plasma detachment in tokamaks [18].

Note that in fusion applications, generating well-characterized and curated training data is much easier through simulation than through experiment, and low-fidelity simulations can provide much more data than high-fidelity simulations. Thus, transfer learning—by which presumably fundamental behavior is learned from dense data and the model is then partially retrained on sparse, higher-fidelity or experimental data—is an active approach to data-poor problems. While MFE has historically been able to produce more experimental data (though perhaps without the curation necessary for use in ML training), now that the IFE community has more high-repetition-rate laser capabilities, it has an opportunity to create the experimental data it will need to use ML models and AI agents.

With these ideas in mind, we organized the remainder of this chapter around how AI and ML will contribute to the understanding and engineering we need to realize an IFE power plant. In addition to using modeling and simulation (mod/sim) and experimental facilities as sources of data, AI and ML will also further enable these resources as we study and explore IFE design choices. Data-driven approaches have the potential to greatly accelerate progress in realizing IFE, but to do so will require investments in data management and engineering. Finally, in this chapter we envision how these capabilities can all come together to enable IFE power generation.

Artificial Intelligence (AI)/Machine Learning (ML)-Enabled Modeling and Simulation

With limited experimental data, mod/sim has been a key component in developing IFE-relevant high energy density physics (HEDP). Even with the significant increase in the volume of data from high-repetition-rate experiments, mod/sim will continue to play an important role for inference and design, as well as being a critical component of self-driven experiment control loops. HEDP requires challenging multi-scale, multiphysics models, and direct modeling from first principles cannot reach the engineering scales of IFE, even with the most powerful supercomputers. Moderate-fidelity radiation hydrodynamic simulations, which are the primary tool, still take hours to days to reach final solutions and consume millions of compute hours annually. Still these radiation hydrodynamic models lack all the fast timescales and short length-scale phenomena to make them fully predictive. The holy grail of mod/sim is to increase fidelity (improved material models, laser-plasma interactions, and other kinetic-scale effects) while simultaneously decreasing the time-to-solution. AI/ML have the potential to do just that.

The primary role of ML in IFE mod/sim right now is in mapping input parameters directly to a set of observables [19]. Once trained, ML models provide extremely fast surrogates, making sensitivity and design searches much more efficient. For example, Humbird *et al.* (2021) [20] used tens of thousands of radiation hydrodynamic simulations of an indirect-drive implosion to provide data to train an ML model to predict yield based on an initial configuration and laser drive. They then “transfer learned” the resulting ML model to assimilate a much smaller set of experimental data and used the model to investigate the design space for the laser drive. Models of this type could also be fast methods for data inference by which, ideally, measured quantities can be mapped to a self-consistent plasma state. Models built in this way have much less constraint on the mapping that would ensure physical consistency with the dynamic evolution, and surrogates for control will need to be able to predict dynamics. An alternative is dynamically evolving surrogates (or “model order reduction”), which evolve a lower-dimensional representation of the solution. Traditional linear projection methods, such as “proper orthogonal decomposition,” fall into this category, and newer classes of methods combine these ideas with neural networks and constraints provided directly by the “full order model” that generates training data [19]. Still, it is important to realize that the ML models require Herculean efforts to produce training data that do not even possess higher-fidelity effects like kinetic features. Afeyan *et al.* (2022) [21] proposed that, by using a hierarchy of self-consistent models of increasing fidelity and a transfer-learning approach, we can use more runs of lower fidelity and fewer runs of higher fidelity to more efficiently train a DL model.

To improve the physical fidelity of moderate- or low-fidelity models without significantly increasing their cost, ML models have the potential to provide fast but higher fidelity alternatives to the closure models currently used [19, 22, 23]. Hydrodynamic-scale codes require many closures and source terms, particularly for material properties and effects that are difficult to model at a macroscale (for example, nonlinear kinetic effects, such as trapping). Often these closures involve simplifications, but we could train ML models on high-fidelity, subgrid data to provide better representations of under-resolved physics. Even the codes we use to generate these material models could benefit [5]: whereas *ab initio* calculations are often intractable for large systems of atoms, we could use *ab initio* simulation results to train the more sophisticated, data-driven intermolecular potentials used in more efficient classical MD models.

ML models will not provide high-fidelity estimates without high-fidelity training data, so the potential benefits already discussed will still present significant challenges unless we reduce the time-to-solution for high-fidelity simulations. AI-enhanced numerical algorithms have the potential to do exactly this, ushering in a new paradigm of intelligent computing [24]. Every time-step or iteration of a simulation provides information about the mapping of the input state to the output state, but we seldom use this information in numerical algorithms to guide the solution process. Even most solution-adaptive algorithms, like common adaptive mesh refinement strategies, are governed by instantaneous heuristics and not by information about the discrete map between time-steps. For example, as Joglekar and Thomas discussed [23], learning from step to step could generate fast ML update operators, which could significantly accelerate implicit time-stepping. Taking this observation one step further, we often compute ensembles of entire forward solutions and yet ignore this prior knowledge of nearby solutions to compute each solution as if we have never seen samples of the solution-space before. If we can efficiently compress or encode this information [19, 24], we can re-use it to "precondition" the solution process very effectively; the NSCAR (Nearby Skeleton Constrained Accelerated Recomputing) formulation [24] added nearby solutions as a variational constraint that helps the algorithm find the solution faster.

Data generated by AI-enhanced numerical methods, combined with lower fidelity data and increasing amounts of experimental data, will be the foundation for intelligent design and discovery automated through continuously improving AI models. We could use an AI agent to drive the sampling strategy for design optimization, using ML surrogates to rapidly interrogate parameter space and monitor the uncertainty in estimates (due to sparsity in the training data in that region or when going beyond the domain of the training data). In regions where uncertainty is deemed too large, we could launch new forward simulations or high-fidelity subgrid simulations to generate new samples, and the ML surrogates could improve themselves by incorporating this new information. Di Natale *at el.* (2019) [25] demonstrated a concrete example of such an intelligent simulation workflow in their multiscale simulation of the RAS-protein cancer pathway.

To enable this future vision of mod/sim for IFE, we will need a great deal of infrastructure. Of course, as discussed below, we will also need community standards for mod/sim data formats and management [26]. In addition, each data-driven model will itself be a product for use by the community, and managing the well-characterized data and data-driven models is another application for AI automation. One could imagine a community recommendation system that identifies models or even datasets that could be found on demand, reducing duplication of work and accelerating progress.

Artificial Intelligence (AI)/Machine Learning (ML)-Enabled Experiments

Applying AI/ML to the analysis of experiments relevant to IFE is quite challenging because of the scarcity of data available from current IFE-relevant experiments. Opportunities exist for us to develop AI/ML techniques that operate in this severely data-starved environment; for example, a statistical model recently led to record direct-drive ICF yields on the OMEGA Laser Facility [27, 28]. However, accessing the full potential of AI/ML algorithms requires large datasets, which in practice can only be collected with higher-shot-rate experiments (HSR, i.e., more than 10 shots per hour) [29]. At such rates, these experiments can generate data at 10–10,000 times the current rate and volume. As discussed below, this volume of data will enable development of ML-based models that we can use to predict new optima, and integrating AI into these HSR platforms will enable unprecedented rates of progress in IFE research.

HSR experiments can make use of closed-loop feedback control architectures in which controls, diagnostics, analysis, AI/ML codes, and simulations are all connected in a “self-steering” experiment [17, 30]. We could configure closed-loop experiments to explore a large complex parameter space using a Markov Chain Monte Carlo (MCMC) algorithm or to optimize a quantity of interest (e.g., fusion yield or instability growth). Studies have already employed this methodology to optimize the properties of particle beams accelerated by either target normal sheath acceleration (TNSA) or laser-plasma wakefield accelerators [31, 32]. A control loop for an integrated IFE experiment would allow us to incorporate measurements from multiple diagnostic sources to make adjustments (e.g., correcting systematic target and/or laser misalignment in ICF implosions based on inferred hotspot velocities). These types of self-correcting control systems will make HSR experiments more robust against shot-to-shot variability, increasing the quality and repeatability of measurements. Further, by utilizing high-speed ML-based surrogate models to navigate high-dimensional IFE parameter space, we would be able to accelerate the rate of scientific learning while simultaneously searching for optimal performance.

HSR experimental technologies have advanced considerably in the past two decades. HSR drivers >1 kJ are now operating [33-36], and we could feasibly scale them up to an integrated implosion driver. Efforts are already underway to develop targets [37, 38], diagnostics [30, 39-43], and ML-based data-processing algorithms [40, 44] for IFE-relevant HSR experiments. Importantly, we must be able to distill highly complex diagnostic data into key physics-relevant metrics at a rate greater than four orders of magnitude from the current state-of-the-art to enable active feedback from experimental outputs to driver and target inputs. The commercial success of HSR liquid-tin-jet laser-plasma extreme ultraviolet (EUV) light sources for lithography exemplifies the technological feasibility of an integrated complex HSR experiment [45]. AI/ML will enable, as well as benefit from, HSR experiments; for example, control loops could automatically adjust laser-pulse shapes, correct optical alignment, automate target positioning, and perform target quality control to deliver more precise and repeatable performance. We will also need AI/ML to be able to automatically preprocess and reduce large datasets, as discussed further in the next section. However, conducting IFE-relevant HSR experiments (especially integrated implosions) still presents challenges.

Much of the technology required to conduct HSR experiments (HSR lasers, targets, diagnostics) is ultimately required for generating power with IFE [46]. Development of HSR experimental facilities could de-risk these technologies by enabling us to demonstrate key technology needs and, ultimately, to inform power-plant design elements. In addition, conducting IFE-relevant HSR experiments could accelerate scientific progress toward IFE [22, 47, 48]. HSR experiments are also well-suited for studying many IFE-relevant topics, especially highly nonlinear and parametric processes, such as hydrodynamic instabilities and laser-plasma interactions [49]. For example, we could use high-flux, HSR laser-driven neutron sources for materials damage testing, which will be necessary for all fusion concepts [50, 51].The higher volume of shots (and lower cost per shot) of HSR experiments would lower the cost of exploring innovative concepts and would also make an HSR facility an ideal platform for training early-career scientists and students in applying advanced computational technologies to difficult scientific problems. Relative to the extremely low shot rate of current IFE-relevant experimental platforms (one or a few shots per day), even a modest increase in repetition rates would be transformative. However, AI/ML will be vital underpinnings for utilizing these facilities to their full potential and ultimately achieving robust IFE.

Data Management and Engineering

Many AI/ML algorithms are most powerful when applied to large datasets (“big data”), such as databases of experimental measurements or simulation outputs. In practice, to apply these algorithms, we need some standardization of the dataset format and contents. However, in many IFE-relevant fields (e.g., plasma physics), data are commonly stored in idiosyncratic formats unique to the facility or code that created it. Furthermore, little infrastructure exists to aggregate and sustainably archive these data. As a consequence, we do not extract the full value from costly simulations or experimental data, which could even, in the worst case, lead to unnecessary duplication of experiments or simulation runs.

The FAIR (Findable, Accessible, Interoperable, Reusable) guiding principles for scientific data management and stewardship [52] provide a blueprint for addressing these problems. Developing open and shared data formats that conform to these principles will allow the IFE community to share data between institutions, improving cooperation between facilities and public-private partnerships (PPPs). Improved data formats will also enable more generalizable analysis codes (increasing the effectiveness of scientists by reducing duplication of effort) and encourage the application of AI/ML techniques to large datasets. Investing at the beginning of an IFE program in developing these standards and updating existing data to conform with them will produce compounding benefits.

We need to prioritize data standardization for experiments and simulations to further increase our ability to share and collaborate between groups. The ability to quickly share data will be vital to progress in IFE research. By standardizing data and communication protocols, we may be able to enable multi-facility, multi-scale experiments in which lower-power drivers can develop models that we can validate at larger-scale facilities, which could then lead to further speed increases in learning for IFE.

The IFE-relevant HSR experiments described in the “AI/ML-enabled Experiments” section will also come with data management challenges. Even with conservative estimates of ~200 shots/day and 5 GB/shot, such experiments could easily produce more than 1 TB/day. In addition to requiring significant storage, we must make these data available to researchers, including collaborators around the world. Experiments with significantly higher shot rates will generate orders of magnitude larger volumes of data at rates that exceed the speed with which we can record those data. In this regime, we must reduce data on the fly prior to storage, including through low-power computing located near data sources ("edge computing"). These processes inherently rely on AI/ML algorithms to reduce data in quasi-real time. Additionally, practical processing and analysis of datasets containing hundreds or thousands of shots or simulations will also require application of AI/ML techniques.

Several scientific fields have already confronted and met the challenge of collecting big data. Particle physics experimentalists routinely create, store, and analyze petabytes of raw data [53-55]. Beamline accelerator experiments within the high-energy physics (HEP) community already incorporate edge computing techniques to allow data collection on 1-MHz experiments. Researchers working on next-generation HSR IFE experimental facilities could partner fruitfully with these other communities.

Each of the preceding topics will rely on advanced computational algorithm development and utilization of the best available hardware to eventually integrate experiments and simulations to fully realize autonomous discovery. We may also be able to realize further enhancements in experimental operation speed (analysis, targeting, data handling) through edge computing.

Artificial Intelligence (AI)/Machine Learning (ML) on the Road to a Power Plant

Currently, there are no well-developed efforts to apply AI in IFE pilot-plant design; however, we can learn a lot from fission plant design and AI/ML. Gomez-Fernandez *et al.* (2019) [56] summarize the status of R&D of learning-based approaches in nuclear science and engineering, finding applications to reactor health and monitoring, radiation detection, and optimization, and summarizing all the techniques currently in use. Sobes *et al.* (2021) [57] developed an AI-based algorithm for designing and optimizing a nuclear reactor core based on a flexible geometry and demonstrated a 3x improvement in the selected performance metric. They recognized that a primary challenge of a vast design space with an arbitrary geometry is that it requires computational evaluation of many candidate designs and multiphysics simulation of nuclear systems, which are time-intensive. Therefore, they developed an ML-based multiphysics emulator and evaluated thousands of candidate geometries on Summit, Oak Ridge National Laboratory's (ORNL) leadership-class supercomputer. **Figure 8.1** shows the workflow of the AI/ML that includes surrogate models.

Woodruff Scientific (WS) is working on the cost and design of fusion power plants (FPPs)—currently supported by ARPA-E [58]—by combining look-up tables with a flexible costing code and neutronics analysis and is exploring the use of AI with SapientAI. Historically, the method for designing a fusion energy plant has been to consider a physics design point for a realistic plasma configuration and then build the technologies around it, making decisions informed by the state-of-the-art in materials, manufacturing, and current literature (e.g., ARIES [59]). WS will enhance their design workflow using AI/ML tools. These tools will consist of an open-source library utilizing

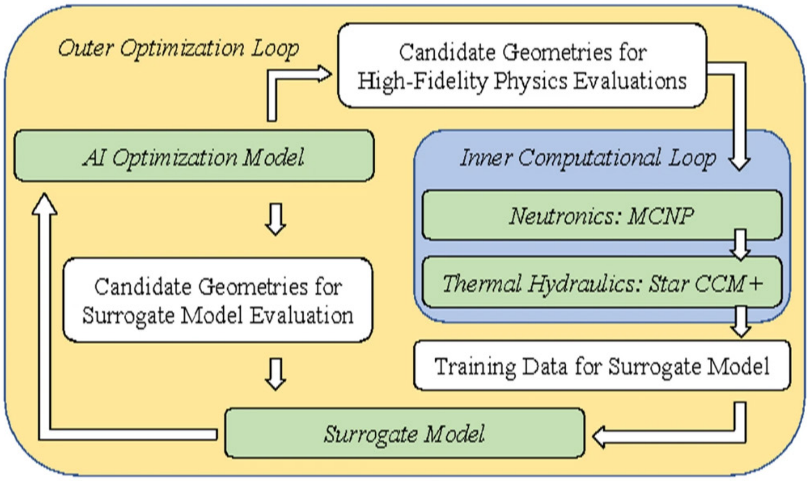


Figure 8.1. *From Sobes et al., 2021 [57], illustrating the AI optimization workflow.*

state-of-the-art deep neural networks, random forests, and gradient-boosting technologies, which WS will apply to subcomponents of their digital twin workflow to develop an additional optimization capability. This optimization capability will allow for predictive sampling relative to quantities of interest to explore and optimize reactor and plant configurations via customized cost functionals. For example, they will be able to predict configurations that are most cost efficient relative to other configuration parameters of interest. In addition, once they have developed and streamlined the optimization workflow, they will further containerize their modelization workflow within a surrogate model (e.g., autoencoder) to dramatically reduce the computational burden of running forward-model predictions when performed within the parameter limits of the previously explored space.

We can place the modeling framework for target design in similar optimization loops, passing information from one model to another, starting with look-up tables for design points, passing to computer-aided design (CAD) and meshing tools, and following with a topology optimization step, before handing the design to a finite element method (FEM) code to assess performance of the target under compression. We can automate each loop within an information management system and use the results to train a surrogate to speed up the search for an optimization.

8.2 Priority Research Opportunities (PROs)

At the IFE BRN workshop, our subpanel identified five priority research opportunities (PROs) necessary to realize the promise of AI/ML in accelerating design and deployment of IFE power plants.

PRO 8-1: ***Develop and employ common interoperable metadata standards built upon modern data formats like HDF5 and following the FAIR principles across all public, private, and academic participants in the IFE community.***

Wherever possible, we should share data freely between institutions and leverage existing data-management standards from other scientific communities. Data-driven models will require large amounts of well-curated data, and data re-use will accelerate discovery and design. However, heterogeneous metadata formats for experimental data and simulation outputs, as well as institutional barriers on sharing data, are barriers to compiling large IFE-relevant datasets for AI/ML. Data will be a valuable commodity, and effective public/private/academic partnerships will need to proactively address data-sharing concerns. Furthermore, export control and classification concerns complicate the assembly of large datasets for AI/ML applications, especially for PPPs. The outset of a national IFE program is the right time to solve this problem. The IFE community must develop unified data and code management standards and infrastructure for simulations and experiments.

PRO 8-2: ***Develop or upgrade experimental facilities to take advantage of advances in drivers, targets, diagnostics, and AI/ML to conduct IFE-relevant higher shot rate (HSR) experiments.***

Designed for flexibility, HSR experiments would accelerate progress toward IFE milestones by rapidly exploring concepts and allowing further exploration of challenging non-linear regimes. Research in this area would advance TRLs for high-repetition-rate drivers, targets, and diagnostics that are compatible with real-time control. Larger experimental datasets could transform the field of IFE-relevant HEDP and are needed to fully utilize the potential of AI/ML. ICF and IFE have historically been data poor, with experimental campaigns numbering in the dozens of shots and diagnostics providing limited characterizations. Even the current data rates in IFE-relevant experiments are too slow to collect the large datasets required for many AI/ML applications. Furthermore, human-in-the-loop is rate limiting for experimental data analysis. AI could be an enabling technology for controlling high-repetition-rate drivers, analyzing results, and even automating experiments. Finally, more small-to-medium-scale university resources will not only provide opportunities to generate data and refine control systems but will also develop a much-needed IFE workforce with AI/ML expertise.

PRO 8-3: ***Develop AI/ML techniques to automate and improve data processing and analysis.***

Rapid and robust data analysis is a prerequisite for even a modest repetition-rate facility, so the need for and associated impact of this capability could be immediate. More data will require improved and automated data analysis, which AI/ML can enable. Experimental measurements are rarely direct and require inference to obtain quantities of interest. Human intervention in this process introduces both bias and delay. Currently, data pre-processing and analysis for IFE-relevant experiments is human labor intensive and will not scale to the shot rates required for IFE operations; high-repetition-rate experiments and eventual reactor operation are not feasible without automated data analysis. Fast, physics-constrained ML surrogate models for data inference and AI-controlled analysis workflow can address these new challenges. Unified metadata standards will enable standard community analysis routines to work on different datasets.

PRO 8-4: ***Develop and deploy AI/ML-enabled autonomous, multi-scale, multi-physics simulations.***

Improved predictive capabilities will inform roadmap decisions for all IFE concepts and accelerate design optimization. AI/ML could ultimately provide real-time, fast emulation to inform target and driver shaping to be included in diagnostics design for real-time controls. To execute this ambitious goal, the community will need more AI/ML expertise and more data, as well as the cycles to generate these data. High-fidelity simulation codes are very expensive; however, we must capture and curate data from such simulations for use by the community, perhaps in fast, community-curated, data-driven models. Such models could also lead to more predictive simulation, including turning data-driven models of higher-fidelity physics (non–local thermodynamic equilibrium (NLTE) kinetics, LPI, material heterogeneity, extended magneto-hydrodynamics (MHD)) into lower-fidelity codes. In addition to improving models, AI/ML augmentation can improve numerical algorithms, helping to accelerate solutions by adapting work to regions of greatest significance while also using prior knowledge (e.g., solutions from nearby calculations) to reduce effort and accelerate time-to-solution. Full-physics surrogates can bridge the gap between experiment and simulation and provide fast approximate predictions for specific problem classes, enabling exploration of design space to identify better target and driver designs (e.g., higher yield, more robust to perturbations and instabilities). Furthermore, we have opportunities to explore and/or influence private sector ML/compute accelerator hardware development via shared IFE benchmark workloads. AI/ML-enabled computational simulation could transform the field of IFE-relevant HEDP and is needed to fully utilize the potential of AI/ML.

PRO 8-5: ***Allocate workforce development funding (e.g., fellowships and grants) to support the development of ML-enabled HED science and to help retain talent in the field.***

Recruiting and retaining an IFE workforce with AI/ML skills is a significant challenge given the economic value of these skills. IFE will clearly benefit from the application of AI/ML; however, the IFE community currently lacks sufficient AI/ML expertise, both in the current workforce and in pipelines (training programs). Many aspects of IFE (especially HSR facilities) will require AI/ML to replace human-labor-intensive analysis and control, but automation is also a force multiplier on the workforce, freeing up scientists to focus on science. Unfortunately, we face difficult competition with industry for AI/ML talent and, further, AI/ML experts with the physics knowledge required to ensure physically relevant models are difficult to find. However, our data-starved and scientifically challenging problems can be a unique attractor for AI/ML experts. In five years, we predict we will need an IFE workforce with AI/ML knowledge at a scale similar to our need for modeling and simulation expertise in the community. Efforts should focus on increasing the overlap between AI/ML and FES specialists, particularly by training existing IFE researchers in AI/ML techniques.

8.3 Conclusions

The renaissance for AI/ML, driven by the scales of data and compute available today, is occurring at a particularly opportune time for IFE. AI/ML, through automation and rapid inference, promise to accelerate progress in scientific discovery, engineering design, and operational control—at a time when IFE can greatly benefit in all three areas. However, the promise of AI/ML will not be realized in IFE in the short-term without intentional investments in workforce development, data generation, community data management and standardization, and research into AI/ML techniques developed specifically for IFE application. Advances in any of these areas will benefit not only IFE but also communities with nearby physical domains and application problems, including MFE and HED.

References

1. Nathan Baker, et al. *Workshop report on basic research needs for scientific machine learning: Core technologies for artificial intelligence*. 2019. US DOE Office of Science (SC), Washington, DC (United States), doi: 10.2172/1478744; (https://www.osti.gov/biblio/1478744) 10.2172/1478744.

2. Maziar Raissi, Paris Perdikaris, and George E Karniadakis, *Physics-informed neural networks: A deep learning framework for solving forward and inverse problems involving nonlinear partial differential equations.* Journal of Computational physics, 2019. **378**: p. 686-707, https://doi.org/10.1016/j.jcp.2018.10.045.

3. Silviu-Marian Udrescu and Max Tegmark, *AI Feynman: A physics-inspired method for symbolic regression.* Science Advances, 2020. **6**(16): p. eaay2631, https://doi.org/10.1126/sciadv.aay2631.

4. Oliver T Unke, et al., *Machine learning force fields.* Chemical Reviews, 2021. **121**(16): p. 10142-10186, https://doi.org/10.1021/acs.chemrev.0c01111.

5. M. S. Murillo, *IFE Material Properties "[White paper]"*, in *IFE BRN* 2022 (see Accepted White Papers at https://events.bizzabo.com/IFEBRN2022/page/2133559/white-papers).

6. Fabrizio Sarghini, G De Felice, and Stefania Santini, *Neural networks based subgrid scale modeling in large eddy simulations.* Computers & fluids, 2003. **32**(1): p. 97-108, https://doi.org/10.1016/S0045-7930(01)00098-6.

7. Masataka Gamahara and Yuji Hattori, *Searching for turbulence models by artificial neural network.* Physical Review Fluids, 2017. **2**(5): p. 054604, 10.1103/PhysRevFluids.2.054604.

8. Stephan Rasp, Michael S Pritchard, and Pierre Gentine, *Deep learning to represent subgrid processes in climate models.* Proceedings of the National Academy of Sciences, 2018. **115**(39): p. 9684-9689, https://doi.org/10.1073/pnas.1810286115.

9. Shawn G Rosofsky and EA4103118 Huerta, *Artificial neural network subgrid models of 2D compressible magnetohydrodynamic turbulence.* Physical Review D, 2020. **101**(8): p. 084024, https://doi.org/10.1103/PhysRevD.101.084024.

10. G Kluth, et al., *Deep learning for NLTE spectral opacities.* Physics of Plasmas, 2020. **27**(5): p. 052707, https://doi.org/10.1063/5.0006784.

11. E Paulo Alves and Frederico Fiuza, *Data-driven discovery of reduced plasma physics models from fully kinetic simulations.* Physical Review Research, 2022. **4**(3): p. 033192, https://doi.org/10.1103/PhysRevResearch.4.033192.

12. Steven L Brunton, Joshua L Proctor, and J Nathan Kutz, *Discovering governing equations from data by sparse identification of nonlinear dynamical systems.* Proceedings of the national academy of sciences, 2016. **113**(15): p. 3932-3937, https://doi.org/10.1073/pnas.1517384113.

13. Jonas Degrave, et al., *Magnetic control of tokamak plasmas through deep reinforcement learning.* Nature, 2022. **602**(7897): p. 414-419, https://doi.org/10.1038/s41586-021-04301-9.

14. Jayson L Peterson, et al., *Zonal flow generation in inertial confinement fusion implosions.* Physics of Plasmas, 2017. **24**(3): p. 032702, https://doi.org/10.1063/1.4977912.

15. David Humphreys, et al., *Advancing fusion with machine learning research needs workshop report.* Journal of Fusion Energy, 2020. **39**(4): p. 123-155, https://doi.org/10.1007/s10894-020-00258-1.

16. Rushil Anirudh, et al., *2022 Review of Data-Driven Plasma Science.* arXiv preprint arXiv:2205.15832, 2022, https://doi.org/10.48550/arXiv.2205.15832.

17. Tammy Ma, et al., *Accelerating the rate of discovery: toward high-repetition-rate HED science.* Plasma Physics and Controlled Fusion, 2021. **63**(10): p. 104003, 10.1088/1361-6587/ac1f67.

18. Ben Zhu, et al., *Data-driven model for divertor plasma detachment prediction.* Journal of Plasma Physics, 2022. **88**(5): p. 895880504, https://doi.org/10.48550/arXiv.2206.0996.

19. W. E. Lewis, P. F. Knapp, and K. Beckwith, *Key challenges in adapting data-driven approaches to modeling of inertial fusion concepts "[White paper]"*, in *IFE BRN* 2022 (see Accepted White Papers at https://events.bizzabo.com/IFEBRN2022/page/2133559/white-papers).

20. Kelli D Humbird, et al., *Cognitive simulation models for inertial confinement fusion: Combining simulation and experimental data.* Physics of Plasmas, 2021. **28**(4): p. 042709, https://doi.org/10.1063/5.0041907.

21. Bedros Afeyan, et al., *Using STUD pulses to Control LPI Adaptively in Space and Time, Using Machine Learningand High Rep Rated Lasers: The Green Option for IFE "[White Paper]"*, in *IFE BRN*. 2022 (see Accepted White Papers at https://events.bizzabo.com/IFEBRN2022/page/2133559/white-papers).

22. V. Gopalaswamy, et al. *Validating IFE Concepts with Machine Learning Driven Design Optimization*. in *NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop*. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

23. A.S. Joglekar and A. G. R. Thomas, *Improving Inertial Fusion Energy Modeling Using Machine Learning "[White paper]"*, in *IFE BRN Workshop*. 2022 (see Accepted White Papers at https://events.bizzabo.com/IFEBRN2022/page/2133559/white-papers).

24. Bedros Afeyan, et al., *Accelerating Ensembles of Plasma Kinetic Simulations through Adaptive Learning: NSCAR, BARS, mini-BARS, TPOR and all that "[White Paper]"*, in *IFE BRN*. 2022 (see Accepted White Papers at https://events.bizzabo.com/IFEBRN2022/page/2133559/white-papers).

25. Francesco Di Natale, et al. *A massively parallel infrastructure for adaptive multiscale simulations: modeling RAS initiation pathway for cancer*. in *Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis*. 2019 (https://doi.org/10.1145/3295500.3356197).

26. J. L. et al. Vay, *Integrated ecosystems of advanced simulation tools for plasma modeling "[White paper]"*, in *BRN IFE*. 2022 (see Accepted White Papers at https://events.bizzabo.com/IFEBRN2022/page/2133559/white-papers).

27. Varchas Gopalaswamy, et al., *Tripled yield in direct-drive laser fusion through statistical modelling.* Nature, 2019. **565**(7741): p. 581-586, https://doi.org/10.1038/s41586-019-0877-0.

28. CA Williams, et al., *High yields in direct-drive inertial confinement fusion using thin-ice DT liner targets.* Physics of Plasmas, 2021. **28**(12): p. 122708, https://doi.org/10.1063/5.0069372

29. P. V. Heuer, et al., *Preface to special topic: The High Repetition Rate Frontier in High-Energy-Density Physics.* Physics of Plasmas, 2022. **29**(11): p. 110401, 10.1063/5.0130801.

30. G.G. Scott, et al., *High repetition rate diagnostics with integrated machine learning analysis for a new paradigm of actively controlled Inertial Fusion Energy experiments "[White Paper]"*, in *NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop*. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

31. SJD Dann, et al., *Laser wakefield acceleration with active feedback at 5 Hz.* Physical review accelerators and beams, 2019. **22**(4): p. 041303, https://doi.org/10.1103/PhysRevAccelBeams.22.041303.

32. R. J. Shalloo, et al., *Automation and control of laser wakefield accelerators using Bayesian optimization.* Nature Communications, 2020. **11**(1): p. 6355, 10.1038/s41467-020-20245-6.

33. A Bayramian, et al., *The Mercury project: A high average power, gas-cooled laser for inertial fusion energy development.* Fusion Science and Technology, 2007. **52**(3): p. 383-387, https://doi.org/10.13182/FST07-A1517

34. MC Myers, et al., *Repetitively pulsed, high energy KrF lasers for inertial fusion energy.* Nuclear fusion, 2004. **44**(12): p. S247, https://doi.org/10.1088/0029-5515/44/12/S16

35. Jan Pilar, et al. *Characterization of Bivoj/DiPOLE 100: HiLASE 100-J/10-Hz diode pumped solid state laser*. in *Solid State Lasers XXVII: Technology and Devices*. 2018. SPIE; https://doi.org/10.1117/12.2290290.

36. E Sistrunk, et al. *All diode-pumped, high-repetition-rate advanced petawatt laser system (HAPLS).* in *CLEO: Science and Innovations*. 2017. Optica Publishing Group; https://doi.org/10.1364/CLEO_SI.2017.STh1L.2

37. IV Aleksandrova and ER Koresheva, *Review on high repetition rate and mass production of the cryogenic targets for laser IFE.* High Power Laser Science and Engineering, 2017. **5**, https://doi.org/10.1017/hpl.2017.9

38. DT Goodin, et al., *Demonstrating a target supply for inertial fusion energy.* Fusion science and technology, 2005. **47**(4): p. 1131-1138, https://doi.org/10.13182/FST05-A838

39. MJ-E Manuel, et al., *Enhanced spatial resolution of Eljen-204 plastic scintillators for use in rep-rated proton diagnostics.* Review of Scientific Instruments, 2020. **91**(10): p. 103301, https://doi.org/10.1063/5.0014949

40. DA Mariscal, et al., *Design of flexible proton beam imaging energy spectrometers (PROBIES).* Plasma Physics and Controlled Fusion, 2021. **63**(11): p. 114003, https://doi.org/10.1088/1361-6587/ac234a

41. DA Mariscal, et al., *Enhanced analysis of experimental x-ray spectra through deep learning.* Physics of Plasmas, 2022. **29**(9): p. 093901, https://doi.org/10.1063/5.0097777.

42. Edison Liang, et al., *A scintillator attenuation spectrometer for intense gamma-rays.* Review of Scientific Instruments, 2022. **93**(6): p. 063103, https://doi.org/10.1063/5.0082131

43. J.A. Frenje, et al. *γ-ray spectrometry for diagnosing high-repetition-rate Laser Direct-Drive Inertial-Fusion-Energy implosions "[White Paper]"*. in *NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop*. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

44. RA Simpson, et al., *Development of a deep learning based automated data analysis for step-filter x-ray spectrometers in support of high-repetition rate short-pulse laser-driven acceleration experiments.* Review of Scientific Instruments, 2021. **92**(7): p. 075101, https://doi.org/10.1063/5.0043835

45. PAC Jansson, et al., *Liquid-tin-jet laser-plasma extreme ultraviolet generation.* applied physics letters, 2004. **84**(13): p. 2256-2258, https://doi.org/10.1063/1.1690874

46. National Research Council of the National Academies of Science Engineering and Medicine, *An Assessment of the Prospects for Inertial Fusion Energy*. 2013, Washington, DC: The National Academies Press (doi: 10.17226/18289); https://nap.nationalacademies.org/catalog/18289/an-assessment-of-the-prospects-for-inertial-fusion-energy.

47. Peter Heuer, et al. *Accelerating the science, technology, and workforce base for inertial fusion energy with a proposed high repetition rate facility "[White Paper]"*. in *NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop*. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

48. D.A. Mariscal, et al., *Accelerated Scientific Discovery with AI-driven Experiments in support of IFE*, in *NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop*. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

49. Donald A Haynes. *Addressing common technical challenges in inertial confinement fusion*. 2016. Los Alamos National Lab.(LANL), Los Alamos, NM (United States); https://doi.org/10.2172/1327991

50. Franziska Treffert, et al., *Towards High-Repetition-Rate Fast Neutron Sources Using Novel Enabling Technologies.* Instruments, 2021. **5**(4): p. 38, https://doi.org/10.3390/instruments5040038.

51. G. J. Williams, et al., *Spinoff Technologies from the Development of Short Pulse Lasers for Fast Ignition IFE "[White Paper]"*, in *NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop*. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

52. Mark D Wilkinson, et al., *The FAIR Guiding Principles for scientific data management and stewardship.* Scientific data, 2016. **3**(1): p. 1-9, https://doi.org/10.1038/sdata.2016.18.

53. Pamfilos Fokianos, et al. *CERN Analysis Preservation and Reuse Framework: FAIR research data services for LHC experiments*. in *EPJ Web of Conferences*. 2020. EDP Sciences; https://doi.org/10.1051/epjconf/202024506011

54. CERN. *CERN-OpenData-Portal*. Available from: http://opendata.cern.ch/.

55. Luca Mascetti, et al. *Cern disk storage services: report from last data taking, evolution and future outlook towards exabyte-scale storage*. in *EPJ Web of Conferences*. 2020. EDP Sciences; https://doi.org/10.1051/epjconf/202024504038.

56. Mario Gomez-Fernandez, et al., *Status of research and development of learning-based approaches in nuclear science and engineering: A review.* Nuclear Engineering and Design, 2020. **359**: p. 110479, https://doi.org/10.1016/j.nucengdes.2019.110479.

57. Vladimir Sobes, et al., *AI-based design of a nuclear reactor core.* Scientific reports, 2021. **11**(1): p. 1-9, https://doi.org/10.1038/s41598-021-98037-1.

58. ARPA-E Project. *Fusion Costing Study and Capability*. Project Term: 2020-2023; Available from: https://arpa-e.energy.gov/technologies/projects/fusion-costing-study-and-capability.

59. ARIES Program. *Archival Information Site*. Accessed 2023; Available from: http://qedfusion.org/bib.shtml

Chapter 9: Measurement Innovations

9.1 Introduction

Science and Technology Challenges

Substantial science and technology challenges remain on the road to inertial fusion energy (IFE) that will require measurement innovation. While diagnostics for IFE will build heavily on baseline capabilities that exist for today's inertial confinement fusion (ICF) and magnetic fusion energy (MFE) experiments, notable gaps remain. For example, in terms of ICF, a number of "zeroth order" diagnostics exist, capable of observing fundamental parameters (e.g., areal density). Pushing measurements to inform physics models to know *why* observable parameters are what they are is a key remaining challenge. Further, IFE will require measurements at an unprecedented repetition rate (10 Hz) and at scale. This is uncharted territory for current ICF diagnostics and will certainly require innovation. Another potential challenge is that diagnostics for glass lasers ($\boldsymbol{\lambda}$ ~ 350–1600 nm) are currently more abundant than diagnostics for any other drivers/concepts. Given the diverse set of ideas for how to achieve IFE and depending on the direction research takes, we are guaranteed to need more measurement innovations. Ultimately, the need to retain flexibility for things we do not yet know we need (e.g., measurement innovations in materials, chamber, power conversion, etc.) is an additional consideration every step along the way from current experiments to the IFE-plant level.

Knowledge Gaps

As is clear from the science and technology challenges discussion above, we are still missing substantial measurement capabilities in our push toward a commercial IFE facility. We have identified four primary areas with substantial knowledge gaps and will discuss each in more detail in our priority research opportunities (PROs) which we have priority ranked. First, there is a significant remaining foundational physics knowledge gap in how to go from the current best performing inertial fusion experiments to the gain-producing scale we will need for IFE. Diagnostics will be essential in bridging this gap. Based on current understanding, measurements at interfaces (gas/ice, fuel/ablator) will be required to inform codes and modeling

SUMMARY

IFE has distinct challenges that call for dedicated diagnostics research and development. We focus on four key areas.

(1) Power plants must operate at high gain for economical power output. **Measurement innovations can shine a light on areas currently hindering high gain.** Further, we must **push techniques to higher resolution across multiple domains and build multi-modality single-experiment diagnostics.**

(2) To support high-repetition-rate data acquisition, analysis, and optimization, we will need to **develop detectors compatible with high-repetition rate operation, coupled with rapid ML-based analysis and diagnostic modeling.**

(3) As we progress toward higher fusion yields and increased bombardment with neutrons and electromagnetic pulses, **electronic acquisition will require shielding and standoff to remain functional.** Furthermore, damage to the diagnostics themselves will require monitoring, repair, and replacement.

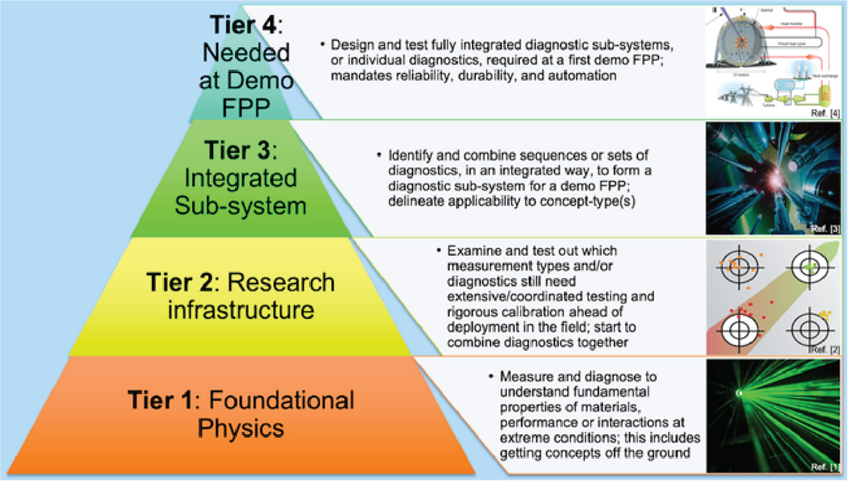
(4) We will need specialized diagnostics to **monitor any facility structural vulnerabilities that are uniquely challenging for IFE, such as high-energy radiation damage to reinforced concrete, steel structures, or vacuum vessels.**

Finally, measurement innovations on the road from ICF to IFE will involve a paradigm shift from maximizing diagnostics designed to enable understanding to minimizing diagnostics in order to maximize power output.

to push toward high gain; more broadly, diagnostics will be essential in determining which quantities limit gain. We will need to focus on achieving unprecedented temporal, spatial, and energy resolution in 3D to capture, understand, and improve performance of inertial fusion experiments geared toward achieving higher gain. In this context, note that there is significant overlap with efforts within current ICF programs; thus, we need to take care to balance efforts specifically targeting IFE with efforts already undertaken for ICF under the National Nuclear Security Administration (NNSA) umbrella, avoiding duplication of work and leveraging outputs across the two enterprises. After the foundational-physics stage, the ability to operate diagnostics at high repetition rate and in a severe radiation environment will also be essential. Note that improved measurement resolution and ability to operate diagnostics at high repetition rate will also benefit high energy density physics (HEDP) and basic science efforts. Finally, an operating plant, even at sub-scale prior to power production, will have substantial infrastructure diagnostic needs, including those for laser delivery, target tracking, and wall monitoring.

Identifying Overlap with Inertial Confinement Fusion (ICF) Versus Where Inertial Fusion Energy (IFE) Is Unique

A significant development effort exists within the national laboratories, universities, and industry for detecting missing fundamental ICF physics and for developing the required diagnostic capabilities for ICF/HEDP (**Table 9.1**). A primary example is the National Diagnostics Working Group (NDWG), which is a unique group of subject matter experts in the field of ICF/HEDP diagnostic development. The group includes scientists, engineers, and technicians from the United States and abroad. The transformative diagnostics these groups are developing, which have been identified as pivotal for ICF in the next decade, will also be key in advancing IFE Tier 1 goals (see **Figure 9.1** [1-4]). These diagnostics could be deployed for IFE investigations without additional investment to start, essentially a dual-use diagnostic opportunity. However, it is not clear whether the new capabilities



- Design and test fully integrated diagnostic sub-systems, or individual diagnostics, required at a first demo FPP; mandates reliability, durability, and automation
- Identify and combine sequences or sets of diagnostics, in an integrated way, to form a diagnostic sub-system for a demo FPP; delineate applicability to concept-type(s)
- Examine and test out which measurement types and/or diagnostics still need extensive/coordinated testing and rigorous calibration ahead of deployment in the field; start to combine diagnostics together
- Measure and diagnose to understand fundamental properties of materials, performance or interactions at extreme conditions; this includes getting concepts off the ground

Evaluation Criteria for Measurement Innovations: Progress Assessment

Experimental techniques, capabilities, infrastructure and measurement innovations for IFE will improve and evolve over time as transformative technologies come online and mature. The complexity and level of integration for measurements will also evolve over time. To capture this sequencing of diagnostic development goals and needs, we establish a tiered system: Tiers 1–4.

The criteria prioritize reproducibility of measurements and science quality. In Tier 1 for foundational physics measurements, there is ample opportunity tor workforce development connectivity and leveraging existing experimental infrastructure, e.g., LaserNetUS, DOE lightsources, academia and industry (Image shown: example laser scatter (1)). Tier 2, leverages what was learned in Tier 1, but moves the end goal into starting to consider direct applications for an FPP, e.g., measurement effectiveness, diagnostic reliability and maintenance (Image shown: emphasis on accuracy and precision measurements (2)). Once successful in Tier 2, a diagnostic/measurement approach can advance to Tier 3 to be considered as part of an integrated platform. This will also require extensive testing (Image shown: example of multiple diagnostic ports available making simultaneous measurements (31). Tier 4 diagnostics are geared towards what is likely needed for a Demo FPP (Image shown: schematic of possible IFE plant design [4]). These Tiers are also aligned with Technical Readiness levels (TRL) for a Demo FPP: Tier 1 covers TRLs 1-2; Tier 2 covers TRLs 2-3-4; Tier 3 covers TRLs 4-5; and Tier 4 covers TRls 6-7. Annual evaluation by an expert community will be required to assess whether diagnostics/measurements are progressing as needed in the timeframe for a Demo FPP.

Figure 9.1. Four-tiered evaluation criteria for progress assessment of measurement innovation [1-4].

already proposed will be enough to address the fundamental questions we must answer to move inertial fusion implosions from the current performance at ignition to the high gain needed for IFE.

Table 9.1: The ten transformational diagnostics identified by the National Diagnostic Working Group (NDWG) and their capability [5].

TRANSFORMATIVE DIAGNOSTIC	NEW CAPABILITY
Single LOS imaging (SLOS or DIXI-SLOS)	Multi-dimensional shape and spectra with unprecedented time and space resolution for fusion, Pu strength, and radiation effects sources.
Ultraviolet Thomson scattering (UVTS)	Localized plasma conditions and turbulence in hohlraums and laser direct drive (LDD) ablation plasma. Additional uses include plasma conditions at low density for rad flow studies and many discovery science applications.
3D n/gamma imaging (NIS)	3D shape & size of both burning and cold compressed fuel, as well as remaining carbon ablator.
Gamma spectroscopy (GCD)	Fusion burn history allowing inferred pressure with increased precision and measured truncation of burn from degradation mechanisms such as mix and loss of confinement.
Time resolved neutron spectrum (MRS-time)	Time evolution of the fusion burn temperature and areal density.
Hard x-ray imaging (Wolter)	High energy source distribution and space-resolved plasma conditions in the hot plasma. Also enables high spatial and temporal resolution for radiography to infer material strength.
Time resolved diffraction (XRDt)	Time evolution of material structure (including weapon materials) and compression at high pressure. Also enables more efficient facility use through multiple measurements on a single shot.
High-resolution velocimeter (HRV)	Higher accuracy (<1%) time evolution of material EOS at high pressure. Also enables more efficient facility use through multiple high-fidelity measurements on a single shot.
>15-keV x-ray detection (DHEX)	Multiple-frame time resolved detection of high energy (>15 keV) x-rays with high detection efficiency.
hCMOS	Multi-frame, burst mode imaging sensor capable of capturing images on the nanosecond timescale.

Despite sharing some diagnostics needs with ICF, IFE has distinct challenges that call for dedicated diagnostics research and development (R&D). This includes adapting the necessary diagnostics for high-repetition-rate operation (~10 Hz), sub-batch target metrology (see also Chapter 5), and optics maintenance. In most designs, the targets will be injected into the reactor vessel and will need to be tracked by diagnostics at the required repetition rate (see also Chapter 5). We will need to first demonstrate this capability with a proof-of-principle tracking system operating at relevant repetition rates, potentially leveraging expertise from previous work performed at General Atomics on their target test stand.

The harsh radiation environment in an IFE facility is challenging for diagnostics, and we will need to mitigate the effect of radiation on diagnostics by, for example, sufficient shielding and deployment of radiation-hardened electronic components. High neutron yield is already an issue for NIF, where the radiation pulse from threshold of ignition shot disrupted or degraded facility systems, such as room lighting and fiber optics. This was in a single-shot with a low gain value at around unity; the radiation situation in a high-gain, high-repetition-rate IFE facility will be considerably more challenging. This calls for a dedicated effort to develop radiation-hardened diagnostics that will allow us to diagnose the status of the fueling system, tritium breeding, and at-scale tritium handling. We will need to orchestrate hot-swapping (i.e., replacing a damaged instrument while not shutting down operation) of diagnostics more frequently, including merging multiple ICF diagnostics onto single lines of sight for ease of access, similar to the highly engineered diagnostic modules that ITER has built into the wall.

In general, moving from ICF to IFE will require a paradigm shift in diagnostics. While ICF is maximizing different particle, x-ray, and optical diagnostics to capture the full picture for improving our physics understanding of implosions, IFE will tend to minimize the footprint of diagnostics in the facility in order to maximize the power output of the system, due to the need for wall-area neutron absorption. Every additional solid-angle steradian that is covered by a diagnostic is one less steradian for power output.

Further thinking is required *to identify* the diagnostics we will need at higher technology readiness levels (TRLs); *to determine* how to integrate diagnostics into subsystems and, ultimately, into a fusion pilot plant (FPP); and even *to recognize* what future diagnostics issues will require further investigation.

Identifying Overlap with Magnetic Fusion Energy (MFE) Versus Where Inertial Fusion Energy (IFE) Is Unique

Despite the large discrepancies in parameter space between IFE and MFE (e.g., 12 orders of magnitude in confinement time and 11 orders of magnitude in plasma density but similar temperatures), their diagnostic communities have synergistic overlaps [6]. Conventional diagnostics and their absolute calibrations are being developed in both IFE and MFE, including spectroscopy and polarimetry (x-ray, optical, electron, neutron, and magnetic), scattering (Thomson and particle), and fast-ion diagnostics. IFE diagnosticians are authorities in fast measurements; these skills could be brought to bear in MFE to measure instability evolution or performance dynamics on nanosecond timescales. Similarly, the MFE community has decades of experience implementing magnetic diagnostics; we can adapt these techniques as IFE begins exploring externally applied magnetic fields in high energy density (HED) plasmas. High-resolution x-ray spectroscopy is a well-established diagnostic in MFE for identifying and calibrating high-Z impurities in the plasma and can be adapted to IFE for monitoring impurities and wastes. As the national fusion energy sciences (FES) community moves toward burning plasmas, understanding and quantifying self-heating from alpha particles is essential. An already-established technique is measuring the signature alpha knock-on neutron (AKN) tail in neutron spectra.

In the step from present and planned fusion facilities to any demonstration fusion power plants, the measurement philosophy will reverse. Measurements needed for plasma control toward optimal reactor performance and machine protection will take precedence over measurements aimed at physics studies. We will need significant measurement innovations to adapt conventional standard diagnostics to the core essential diagnostics for fusion power plants. The diagnostics should be able to function in the extremely harsh environment caused by high fluxes of neutrons, x-rays, gamma rays, etc. and should ideally be remotely maintainable. IFE could also benefit from the experience and investments of the worldwide MFE program in developing state-of-the-art radiation-hardened detector technology, including sensors, light extractors, and associated electronics [7]. Diagnostics for ITER can provide guidance for instrument development at IFE facilities.

While their configurations and constraints may differ significantly, MFE and IFE share many common issues and interests, such as performance of materials in a fusion environment; tritium breeding blankets; and tritium concerns, including recovery, processing, accountability, and inventory minimization; in particular, IFE will greatly benefit from the long experience and large investments being made worldwide on tritium breeding and handling [8].

Owing to the pulsed nature of IFE, there are critical differences between IFE and MFE in the capture and control of x-rays, energetic particles, and neutrons in the surrounding materials and the subsequent damage and response. IFE will require modified testing and irradiation facilities. Moreover, IFE's unique target-injection scheme will require fabrication, characterization, and supporting diagnostics for target and metrology. As available, the IFE community should coordinate with fusion prototypic neutron source (FPNS) facilities [9] (e.g., Oak Ridge National Laboratory (ORNL))—which leverage spallation neutron generation—to test IFE diagnostics, materials, and perform needed calibrations.

9.2 Priority Research Opportunities (PROs)

PRO 9-1: ***Leverage and develop diagnostics to assess factors limiting gain***

PRO 9-1a: Diagnose which quantities are critical to propel implosions toward high gain

Power plants must operate at high gain, which is fundamental for economical, net power output. Generally, we would like to see gains in the range 10–100x. The challenge is that, at present, world-leading gains are ~1–2 orders of magnitude lower than this requirement. Fortunately, this underlying need for high-gain implosions has large overlap with NNSA's ICF mission space and a drive to higher yield. Measurement innovations can shine a light on areas hindering high gain and can help remediate them, thereby propelling us along the roadmap to IFE. Of note, diagnostic development intended to quantify gain-limiting phenomena must be tightly coupled to recommendations from the Coupling (Chapter 1) and Compression and Burn (Chapter 2) sections of this report.

Effective, near-term measurements will not only diagnose the symptoms of failed gain attempts but also the causes of these failures. For example, a leading hypothesis is that small-scale hydrodynamic instabilities arise when implosion convergence nears that needed for high gain and that these instabilities actually stymy the compression needed for high gain. At present, we do not directly diagnose this instability growth. ICF facilities have excellent diagnostics that identify the post-shot symptoms of poor compression (e.g., increased x-ray emission due to mix, fuel-shell ρR asymmetries, etc.), but the root causes limiting high-gain remain unclear. This PRO would shine a light on these causes, so we may better understand and remediate them.

Several specific areas for diagnostic development supporting high gain have already been identified. Note that we mean these examples to be suggestive rather than proscriptive. Prime among desired new diagnostics is the ability to diagnose the converging ρR as a function of both space and time. Similarly, direct measurement of the (in-flight) fuel adiabat would also be highly valuable. Of note, neutron-backscatter techniques could provide a direct measure of the burn-averaged fuel adiabat, which might serve as an initial benchmark for model verification and validation. As ICF facilities begin driving toward high gain, we will need diagnostics with temporal resolutions $\mathcal{O}$(ps) since implosion conditions change drastically when moving from smoldering to burning to fully ignited plasmas.

Another area that will promote understanding of gain-limiting effects is diagnosing the interfaces between materials in imploding plasmas. The importance of these diagnostics is twofold: (1) they may directly measure instability growth at density and material interfaces and (2) they can provide better benchmarks for our computational models at the multi-scale, multi-physics boundaries (see also Chapter 7). Innovations that diagnose material interfaces (e.g., solid-plasma interfaces, materials of different compositions, dopant levels) could have high impact on understanding present limiting factors in reaching high gain.

The push to high gain is presently being undertaken by national ICF facilities, such as the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL). Diagnostic development in this area would benefit from coordinating and leveraging efforts at existing facilities and avoiding duplicating efforts.

PRO 9-1b: Improve measurement resolution across energy, space, and time for key diagnostics

The dynamical evolution of inertial fusion materials, processes, and systems is intrinsically multiscale in nature. The need to fill Tier 1 foundational physics knowledge gaps (from **Figure 9.1**) in IFE and to enable future systems control for pilot plants, demands development and implementation of novel multi-fidelity, multi-resolution experimental diagnostics. In particular, pushing techniques to higher resolution across multiple domains (energy, space, and time) and building multi-modality single-experiment diagnostics (i.e., being able to measure more than one parameter at a time with high fidelity for each parameter) will establish technique architecture for future *in situ* IFE measurements. However, diagnostic research and development is required to achieve this goal. For instance, different aspects of the IFE process—from laser-plasma instability (LPI) visualization, mitigation, and control to troubleshooting the best target design for performance, materials, and delivery optimization to structural materials for optics and chamber components for survivability to fuel systems materials—each necessitate new high-performance diagnostics with sensitivities across disparate length- (sub-µm to m), time- (ps to ms), and energy-scales (eV to MeV).

Innovations in measurement multi-modality and resolution will address the most outstanding knowledge gaps we must bridge to first understand and then control IFE. For instance, current diagnostics only provide measurements to ~10s of micrometers and ~10s of picoseconds in an ICF experimental environment (e.g., short-pulse laser-driven). Conversely, at 4th generation light sources, like x-ray free-electron lasers (XFELs), where measurement fidelities are on the order of sub-micrometer and femtoseconds, the dynamic drivers currently available are incapable of generating the needed extreme states of matter. Of particular importance is moving in a diagnostic-development direction, which enables space- and time-resolved measurements to address inadequacies in Tier 1 studies of burning plasmas. For instance, this includes but is not limited to (1) 2D spatially and temporally resolved ion temperatures to few micrometers and nanoseconds over 0.5 eV to evaluate hotspot symmetries and mixing, (2) simultaneous energy-flow and loss measurements within a burning plasma down to a few picoseconds resolution, (3) simultaneous ion and electron temperatures with time resolution down to few picoseconds for physics-model validation, 4) burn wave time-resolved tracking with picosecond accuracy to identify degradation mechanisms, (5) 3D electron temperatures measurements over 10s of micrometers with sub-micrometer spatial-resolution, and (6) ρR(x,t) as influenced by capsule inhomogeneities require a few picoseconds temporal resolution over 10s of nanoseconds timescales combined with sub-micrometer 3D spatial resolution over the entirety of a capsule. In the context of addressing gaps in diagnostic needs for power plants, the range of resolution needs will become much larger (e.g., target positions, laser alignments, etc). Ultimately, this thrust for higher resolution and multi-modal diagnostic suites is to enable Tier 1 foundational physics objectives as a necessity to advance to higher Tiers 2 and 3.

The community will need to consider what combinations and types of novel multi-probe/multi-resolution techniques can be coupled together to provide *in situ* measurements for Tier 1 tasks. The IFE diagnostics thrust should coordinate with the ICF community's NDWG. Addressing technical gaps in physical hardware capabilities—for instance, microelectronics advancements (e.g., large area-, gapless-, high-speed complementary metal-oxide-semiconductor (hCMOS)-cameras with effective pixel size ≥ 10s of nanometers), fast-feedback readouts and field-programmable gate arrays (FPGAs) for onboard computing, and enhanced survivability of delicate diagnostic components in harsh environments—will provide transformative detector technologies. Coordination between the ICF and IFE diagnostics communities (leveraging the NDWG) will be key; suggested research approaches for high-resolution measurement and diagnostic development can start from concepts outlined in Table 9.1.

PRO 9-2: ***Develop high-repetition-rate diagnostics, transformative for IFE (and ICF) research***

Any viable approach to IFE will need to operate at a high-repetition rate compared to present-day ICF experiments (on the order of 10 Hz versus a few shots per day). As such, diagnostic development to sustain data acquisition at this level is important. Although some laser drivers are now capable of operating at a repetition rate desirable for IFE (see Chapter 4), our ability to diagnose target physics experiments at high-repetition rate is still lagging within the IFE and ICF community. We will need an integrated diagnostic-development approach, combining offline diagnostic development, experiments at existing facilities, and integration of modeling and machine learning (ML)-based analysis, to successfully diagnose IFE-relevant physics and experiments.

Detector media, such as image plate, film, or CR-39 detectors, have long recovery and processing timescales. Hence, to develop diagnostics to support high-repetition-rate data acquisition, analysis, and optimization, we will need to use appropriate detectors coupled with rapid ML-based analysis and diagnostic modeling. Key detector development in this context will include an assessment of current scintillator materials, development of fast scintillator materials, absolute diagnostic calibration, design of novel optical signal transport systems, and development of fast, temporally resolving electronic detectors at the picosecond to nanosecond timescale.

Conventional data analysis often relies on time-intensive processes that are heavily human-operator-dependent and are thus subject to individual biases and systematic errors. Even auto-analyzed data, from NIF for example, take minutes to process, which is a paradigm that cannot realistically scale to high-repetition-rate experiments operating at several hertz. ML algorithms are widely used to identify and extract measurable quantities from large datasets of diverse types, including images and time-series data, and we can develop these techniques for use with specific diagnostics to vastly increase the data processing rate and allow for real-time feedback (see also Chapter 7). In the laser-driven plasma-accelerator community, several groups have made progress in using AI and ML in conjunction with high-repetition-rate diagnostics [10-12]. They have demonstrated, for example, that Bayesian optimization can be used to optimize the quality and stability of an electron beam for 24 hours at 1 Hz by adjusting, in real-time, the laser and plasma parameters. In this case, high-repetition-rate electron spectrometers measured the energy and energy spread of the accelerated electrons and fed that information back to the computer. Leveraging detector edge-computing via FPGAs or similar will also enable auto-analysis/rapid pre-processing, as is done in high-energy physics (HEP) communities and at collider labs, such as ATLAS and CERN.

Synthetic diagnostic modeling will also be a keystone of this PRO. We can use codes, such as GEANT4 and MCNP, to model detector response—including spectral sensitivity, energy resolution, and signal-to-noise ratio—for a range of detector media of interest. Through these efforts, we can generate realistic synthetic diagnostic response data for a range of simulated experimental conditions. We can then tailor these data with well-defined signal-to-noise ratios or unexpected spectral shapes, for example, to test the robustness of the algorithms. We can also use them to train the algorithms for data processing and error recognition.

To develop high-repetition-rate ICF diagnostics, we can also leverage the current research infrastructure. Within LaserNetUS, several university-scale facilities have high-repetition-rate drivers that are already successfully executing experiments in which neutrons, x-rays, electrons, and protons are acquired at repetition rates ranging from a few hertz to a shot every few minutes. The IFE program should prioritize dedicated high-repetition-rate diagnostic development at LaserNetUS facilities. In addition to using LaserNetUS facilities, we could enhance high-repetition-rate diagnostic development by engaging with the conventional particle-accelerator and light-source communities, already able to acquire, store, and analyze large datasets in real time. XFELs and synchrotrons routinely operate at 100s of hertz to megahertz repetition rates, and their infrastructure is well adapted to test potential IFE-relevant diagnostics. At these data-collection rates, exascale computing will become paramount. As indicated in PRO 9-4, for high-repetition-rate diagnostics, we also need uniformity across control systems; protocols for saving, file-naming, archiving, and extracting data; and computational architecture.

PRO 9-3: ***Develop radiation-hardened diagnostics critical for IFE power plants; leverage MFE and high-yield NNSA efforts***

As we make progress toward higher fusion yields, diagnostics will be subjected to harsh bombardment of neutrons and electromagnetic pulses. Substantial background problems will develop even on passive detectors, such as image plate and film. Electronic acquisition will require shielding and standoff to remain functional. Furthermore, materials subjected to high yields are damaged over time, and thus the ability to shield or otherwise protect diagnostics will directly determine the diagnostic lifecycle. Damage of the diagnostics themselves will require monitoring, repair, and replacement. For the pulsed-power path toward fusion, debris will further complicate the diagnostic stations.

Intense radiation environments are already a primary consideration for diagnostics in existing ICF facilities. In high-yield experiments at both OMEGA and NIF, while the high-voltage pulse modules of framing cameras are sufficiently hardened for operation, the images register on film rather than CCD cameras to minimize neutron impact and allow high-yield operation. To avoid noise in acquired images, optics such as grazing incidence curved mirrors or spherical crystals are often used to deflect signals out of the line of sight so that heavy shielding can reduce noise on the detector. Similarly, crystal spectrometers are designed to incorporate line-of-sight shielding. The diagnostics for a fusion plant will require careful down-selection to just the key measurements needed for various stages of development and plant operation. The ICF community will largely face and address the challenges for diagnostics development at lower repetition rates. Thus, IFE programs can focus efforts on hardening the measurements that are critical to power plants. Forming this list itself will require conceptual studies in the coming years. An example of one such unique challenge is hardening (and developing) the measurements to study impurities in cooling fluids that may arise from contaminants in the first wall.

Different approaches will be relevant depending on the measurement. In the case of electronics, we can build designs of circuits and protective stations based on knowledge from the NNSA laboratories and space physics (e.g., NASA). The signals themselves should be maximally transported from the fusion reaction (e.g., via optical fibers, x-ray, or optical relays). Even pinhole imagers will require flexible designs to accommodate varying yields or modes of operation, such as a large stand-off integration mode as compared to a closer "single-shot" arrangement. Analogous to what is currently done for laser optics, we will need to design some measurement devices for monitoring damage and subsequent "hot" swapping. For instance, to increase distance to hot/harsh environments, we may find remote measurements, such as laser probes, particularly practical for environmental monitoring by techniques such as laser-induced breakdown spectroscopy (LIBS). For all approaches, we should design, develop, and test shielding to further mitigate the radiation environment.

PRO 9-4: ***Adapt critical infrastructure diagnostics to IFE power-plant environment***

The buildings housing the first generation of IFE power plants are likely to look similar to conventional fossil-fuel or nuclear-fission plants in terms of the engineering required to ensure safe and efficient delivery of power to the electrical grid. IFE plants will need to be operational as close to 100% of the time as possible to be commercially viable, leaving much less time for maintenance shutdowns than we have with demonstration reactors or ICF research facilities. This requirement places stringent demands on support systems. As noted previously, by investing in the fundamental science (e.g., accelerators), the fission power, medical, defense, ICF, and space exploration sectors have established significant understanding of the problematic effects of radiation on electronics and structural components; developing partnerships with experienced groups in these sectors will be very valuable.

Where an IFE plant differs, and where innovation in diagnostics is certainly required, is in the nature of the radiation environment that it will generate during operation. IFE plants will operate at much higher peak outputs than nuclear fission or conceptual MFE fusion plants, with a high repetition rate and a distinct output spectrum of charged and neutral radiation. We will need specialized diagnostics to monitor any identified vulnerabilities that are uniquely challenging, such as high-energy-radiation damage to reinforced concrete, steel structures, or vacuum vessels; the accumulation of radioactive target/chamber debris; and contamination of vacuum or heat-exchange systems. Further, we will need bespoke diagnostics to enable and validate repairs and maintenance. Restrictions on material choices due to problematic nuclear reactions may force re-engineering of existing basic commercial off-the-shelf (COTS) instruments and could present challenges for the underlying supply chain. Choices of materials will also impact the type and quantity of radioactive waste generated by a fusion plant through its operational life [13].

Engineering fusion plants to contain the core's hazardous radiation will be possible as far as human exposure is concerned; however, in some cases completely shielding the drivers and other facility-level components will not be possible. Increasing the stand-off distances through signal relays and improving shielding and the survivability of diagnostics will all help, but many diagnostics will be required to operate for long periods—probably without easy access for maintenance—in high-dose, high-peak-power radiation environments. Long-term R&D considerations must include the routine devices found in many industrial settings, which we may need to re-engineer for this environment. We may also need to modify power supplies, oxygen monitors, temperature sensors, personnel access controls, facility services (e.g., water, HVAC), lighting controls, and fire-suppression systems if we cannot sufficiently isolate them from the core. These demands also apply to more specialized diagnostics, such as leak sensors (especially for the tritium that most conceptual IFE plants will need to breed to fuel themselves), electromagnetic pulse (EMP) monitors, contamination/activation sensors, and the suite of instruments required to keep the driver at optimum performance.

IFE plant designs are conceptually diverse, and the development priorities will vary depending on the driver used; for example, some concepts do not require tritium as a fuel, others do not use lasers. Looking across the whole range of proposed facilities, however, we can see plenty of common ground in the need for improved diagnostics at the plant-infrastructure level:

- Hardened driver-specific diagnostics with enhanced hands-off reliability for extended periods, including for associated power supplies and data connections, must address the following issues:
  - Degradation of structural (e.g., steel) and functional (e.g., fiber optics) materials under irradiation
  - EMP and radiofrequency noise sensitivity
  - Rapid impact assessment of batch variations in COTS components
  - Development of novel pre-installation testing/on-line non-destructive evaluation techniques
- Robust automated metrology and inspection, delivery, and positioning diagnostics for targets; these diagnostics must have unimpeded performance in their extreme environments [14] and must provide the following capabilities:
  - Target quality and assurance (Q&A)
  - Real-time cryogenic status diagnostics
  - In-flight target positioning and trajectory measurements via scatter light analysis
  - Target-interaction pointing-accuracy diagnostics
- Longer-term (Tier 2–3) critical facility services—such as fire suppression, data network hardware, electrical distribution, water flow sensors/valves (etc.), gas handling systems, and HVAC—must be tested in and adapted to the expected radiation environments through the following activities:
  - Planning for obsolescence and upgrade of IT hardware
  - Maintaining and monitoring access to replace/repair services in high-radiation environments—diagnostics to monitor system health, leaks, etc.
  - Implementing redundancy of key systems—need more than one type of diagnostic solution to avoid common-mode failures
  - Ensuring interaction of emergency systems (e.g., sprinklers) with operational facilities—what diagnostics are required to ensure the facility is always safe?

- Adaptation of existing diagnostic systems will need to eliminate problematic materials with the following potential issues:
  - Sensitivity to radiation environment
  - Accidental accumulation of hazardous/proliferant materials—active monitoring or periodic inspection/assay will both need specialist instrumentation
  - Generation of radioactive waste—to reduce this issue, we will need to optimize and highlight required monitoring measurements to guide maintenance/replacement cycles for facility subsystems/infrastructure
- Use of simulations to explore the impact of modifications at a facility level, which would allow us to do the following:
  - Develop tools to make quick and robust assessments, *c.f.* ITER (for which diagnostics form an integral part of the overall facility shielding)
  - Choose and maintain appropriate diagnostics to validate simulations on a routine basis

9.3 Conclusions

From the measurement-innovations perspective, the near-term science priority should be developing diagnostics to support achieving high gain. That said, this goal also falls under NNSA's priorities. Thus, to maximize the impact of FES contributions, the measurement innovations BRN panel suggests focusing on high-repetition-rate and radiation-hardened diagnostics, which, longer-term, will be just as essential for achieving the final goal of IFE. FES can execute on repetition-rated and radiation-hardened diagnostic development by leveraging existing facilities, including LaserNetUS, which can already execute experiments at modest repetition rates, and NIF, where radiation-hardened diagnostics are starting to play an essential role (see Chapter 10). University principal investigators (PIs) are also particularly well-placed to contribute to this effort, playing into the other long-term goal of IFE workforce development.

Leveraging Connections and Workforce Development

All diagnostic development efforts will also benefit from public-private partnerships (PPPs) (see Chapter 11). Examples of successful partnerships of this type already exist, including in the development of fast photomultiplier gating and pulse dilation technologies. We should engage existing ICF diagnostic-development groups to help coordinate this effort, including the ICF NDWG, the High Temperature Plasmas Diagnostics community, the Innovation Network for Fusion Energy (INFUSE), and Advanced Research Projects Agency – Energy (ARPA-E) programs. A unique thrust along which an IFE program could contribute is engaging non-traditional partners to develop diagnostics that identify gain limitations. Private fusion companies are particularly aggressive in their pursuit of high gain and, as such, would make highly motivated partners in diagnostic development.

Involving university programs leads to a virtuous cycle, in that we could fund small university groups to develop novel, semi-portable diagnostics to diagnose gain limitations. These diagnostics could then be prototyped or "ride along" on national facilities and be ported to different private fusion companies. These efforts will naturally form thesis projects for a new generation of graduate students whose thesis projects, as well as labor, will be necessary for IFE and ICF. The public efforts should maximally leverage the private sector, which may identically support small university groups for targeted challenges in radiation hardening diagnostics. Identifying infrastructure needs for Tier 1 and 2 activities will be critical. We can and should develop a large amount of this work “off-line” at smaller facilities in academia or by leveraging LaserNetUS and DOE Lightsource and Fusion facilities. In particular, we can learn from other communities already facing exascale computing challenges, such as HEP, astronomy, and accelerator designers, to optimize handling of high-repeptiton-rate diagnostics and analytics for IFE.

Any efforts to further research toward achieving high gain will also critically depend on close communication between the diagnostic and theory and simulation communities to validate the simulation tools (see Chapter 7) and will tie in closely with the research directions described in the Coupling (Chapter 1) and Compression and Burn (Chapter 2) sections of this report. In terms of the radiation hardening (*PRO 9-3*) and infrastructure (*PRO 9-4*) diagnostic priorities, there is significant overlap with the needs of the MFE community [6], which we should leverage going forward.

Finally, measurement innovations on the road from current ICF efforts to IFE will involve a paradigm shift from maximizing diagnostics to maximize understanding (and achieve gain) to minimizing diagnostics to maximize power output. This evolution is tied to progress along the Tier scale as illustrated in **Figure 9.2**, where the measurement innovation PROs are also indicated in terms of when in the progression we will need them.

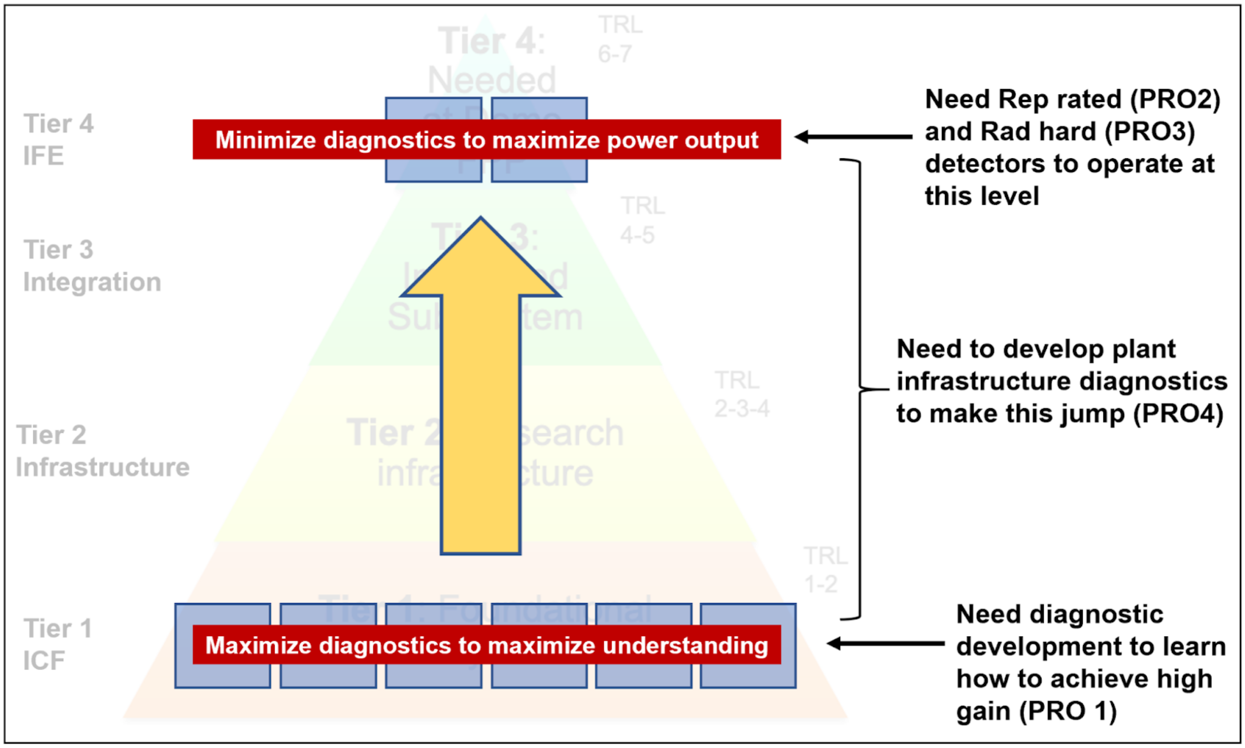


Figure 9.2. Going from fundamental ICF research to an IFE power plant will require a paradigm shift from many to minimal diagnostics. The PROs identified by the measurement innovations BRN panel represent essential efforts that will be required as part of this transition.

References

1. LLNL: National Ignition Facility and Photon Science. *DOE Workshop Examines Inertial Fusion Energy Research Needs*. 2022; Available from: https://lasers.llnl.gov/news/doe-workshop-examines-inertial-fusion-energy-research-needs.

2. LLNL: National Ignition Facility and Photon Science. *Photo Gallery: History - Omega (Photo # NIF-1109-17880)*. Accessed 2023; Available from: https://lasers.llnl.gov/media/photo-gallery/history&id=26.

3. Artel. *Lab Report 4: Defining Accuracy, Precision and Trueness*. 2019; Available from: https://www.artel.co/learning_center/defining-accuracy-precision-and-trueness/.

4. University of Bonn. *Physicists make laser beams visible in vacuum*. 2021; Available from: https://phys.org/news/2021-08-physicists-laser-visible-vacuum.html.

5. S. Ross, *The National Diagnostic Plan (NDP) for HED Science September 2021*. (2021) (https://www.osti.gov/servlets/purl/1823688), Lawrence Livermore National Laboratory (LLNL), Livermore, CA (United States).

6. J. L. Bourgade, et al., Diagnostic components in harsh radiation environments: Possible overlap in R&D requirements of inertial confinement and magnetic fusion systems. Review of Scientific Instruments, 2008. **79**(10): p. 5, 10.1063/1.2972024.

7. L. F. Delgado-Aparicio, et al., *Burning-plasma diagnostics: photon and particle detector development needs.* Princeton Plasma Physics Lab technical report PPPL-5388, USA https://bp-pub.pppl. gov/pub_report/2017/PPPL-5388-abs. html, 2017, https://bp-pub.pppl.gov/pub_report/2017/PPPL-5388-abs.html.

8. National Research Council of the National Academies of Science Engineering and Medicine, *An Assessment of the Prospects for Inertial Fusion Energy*. 2013, Washington, DC: The National Academies Press (doi: 10.17226/18289); https://nap.nationalacademies.org/catalog/18289/an-assessment-of-the-prospects-for-inertial-fusion-energy.

9. Brian Egle, Phillip Ferguson, and James D. White, *US Fusion D-Li Neutron Irradiation Facility: Fusion Prototypic Neutron Source (FPNS) Technology Study*. 2019 (https://doi.org/10.2172/1649392), Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States); https://www.osti.gov/biblio/1649392.

10. S. Jalas, et al., *Bayesian Optimization of a Laser-Plasma Accelerator.* Physical Review Letters, 2021. **126**(10): p. 6, 10.1103/PhysRevLett.126.104801.

11. G.G. Scott, et al., High repetition rate diagnostics with integrated machine learning analysis for a new paradigm of actively controlled Inertial Fusion Energy experiments "[White Paper]", in NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

12. R. J. Shalloo, et al., *Automation and control of laser wakefield accelerators using Bayesian optimization.* Nature Communications, 2020. **11**(1): p. 6355, 10.1038/s41467-020-20245-6.

13. UK Atomic Energy Authority, *UK Fusion Materials Roadmap 2021-2040*. (2021) https://www.royce.ac.uk/content/uploads/2021/09/UK_Fusion_Materials_Roadmap_Interactive.pdf.

14. Neil B. Alexander, et al., Target injection, and engagement for inertial fusion energy "[White Paper]", in NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

Chapter 10: Research Infrastructure

10.1 Introduction

DOE has created infrastructure to develop inertial confinement fusion (ICF) and, more broadly, to advance understanding of high energy density physics (HEDP). Research in HEDP is fundamental to both ICF and inertial fusion energy (IFE). International activities in HEDP add to those in the United States, and there is both global competition and cooperation as the world explores frontiers and applications in this field.

The research infrastructure needed to fully demonstrate the feasibility of IFE for power generation does not exist today. Infrastructure required to meet that need includes upgraded and new facilities, a skilled workforce, scientific and technological knowledge, theory and modeling codes, commercial engagement, and an enabling policy environment. This chapter addresses the current state of infrastructure for studying IFE, the means by which we can better use and improve this existing infrastructure, and a path forward to develop IFE—from concept to proof of principle to demonstration to fusion pilot plant (FPP).

The existing infrastructure for IFE supports basic research, and modest upgrades of that infrastructure would accelerate progress on key issues. Current facilities are critical for engaging the IFE community and for progress in the next several years. However, they are insufficient to support the needs of a serious IFE program, as is made clear by the fact that IFE is not currently part of the mission of any U.S. facility or research program.

Beyond near-term basic research at existing facilities, a successful IFE program will require several major new facilities:

- **“Proof-of-Principle” facility:** At least one new facility to prove the effectiveness of an efficient driver technology that is scalable to the required repetition rate, operates in a realistic fusion environment, and integrates many of the component technologies
- **“Demonstration” facility:** A new facility to demonstrate high fusion gain, with a plausible pathway to scale to high repetition rate and sufficient energy extraction
- **FPP facility:** A pilot facility with net generation of electric power

SUMMARY

The community continues to consider multiple driver technologies and target implosion and ignition modes for IFE. While this multiplicity of options is exciting and important, it is unlikely that a public program can carry them all to maturity in parallel. Thus, we need to answer the question, what specific infrastructure will best enable IFE? While the current infrastructure around ICF is insufficient to demonstrate the feasibility of IFE today, it does support basic IFE research. Thus, we should **increase the number of experiments at existing large-scale facilities and utilize and upgrade relevant existing mid-scale facilities.** Further, we should **form at least one national IFE team or partnership that is focused on best use of existing facilities and on continued research and design for developing future IFE infrastructure.**

In pursuit of this goal, calls for proposals that encourage IFE partnerships could help enable major collaborative efforts that would drive IFE forward by coordinating research and development and design of future IFE facilities. Ultimately, an IFE program will need to **pursue detailed concepts for an integrated system design generated by public-private partnerships that will lead to construction of a proof-of-principle facility, then a demonstration facility, and finally an FPP that proves efficacy of IFE for commercial use.**

The community continues to consider multiple driver technologies and target implosion and ignition modes for IFE. While this multiplicity of options is exciting and important, it is unlikely that a public program can carry them all to maturity in parallel. Thus, we need to answer the question, what specific infrastructure will best enable IFE?

The National Academy of Sciences (NAS) report “An Assessment of the Prospects for Inertial Fusion Energy (2013)” [1] identified multiple drivers and endorsed a “parallel development approach” to hedge against “uncertainties in the future availability of alternatives.” A community-based workshop led to the “IFE Science & Technology Community Strategic Planning Workshop Report (2022) [2],” capturing developments since the NAS report and including new approaches, but did not select or rank-order them. Finally, the DOE Fusion Energy Sciences (FES) long-range plan, “Powering the Future: Fusion & Plasmas (2020),” [3] also cited several options and noted, “Inertial fusion energy (IFE) utilizes advances in lasers, pulsed-power technology, and other innovative drivers to achieve fusion at high fuel density. The enormous progress made with indirect drive at the National Ignition Facility (NIF), direct drive, magnetic-drive inertial confinement fusion (ICF), and heavy-ion fusion (HIF) underpin the promise of IFE. An IFE program that leverages U.S. leadership and current investments should be targeted.”

A key question for the fusion community, which includes academic institutions, national laboratories, government funding agencies, and the private sector, remains: Given the potential resources available from government and the private sector and the knowledge gained over the last two decades, what development paths are possible and optimal?

Background

The following observations of the status of IFE inform our list of priority research opportunities (PROs):

- Currently envisioned resources are insufficient to address all the critical issues of all of the suggested technical approaches to IFE
- Both government and private resources will be necessary for realizing IFE
- Much of the expertise for IFE is found in the public sector; public-private partnerships (PPPs) involving the government and universities working together with companies are expected to be very effective in developing IFE
- Developing a methodology for assessing and down-selecting the various technical approaches for IFE will be important for optimally utilizing funding

A variety of venues currently study nuclear fusion in dense plasmas, which underpins the IFE concept, and their studies include theory, modeling, and experiment. The work of the nuclear-weapons community in developing fusion-based weapons since 1949 and during the last two decades under the National Nuclear Security Administration (NNSA)’s Stockpile Stewardship Program has increased fundamental understanding of fusion in dense plasmas. Through theory, modeling, and experiments, as well as workforce and facility development, these efforts in ICF have revealed and addressed many of the challenges also associated with IFE. Aspects of NNSA programs that will continue to be relevant to IFE include the quest for shots with higher gain and consistently high yields (e.g., using more powerful lasers), precision target manufacturing, optimized diagnostics, dynamic radiography, and validated modeling codes. In addition to work in the nuclear-weapons community, discoveries and studies involving nuclear processes in gravitationally confined astrophysical environments (in the Sun and other stars) have increased understanding of fusion burn under dense and hot-plasma conditions.

National and global HEDP programs have developed capabilities relevant to IFE development:

- Compression of matter at conditions of high density, temperature, size, and timescales associated with the Lawson criterion for ignition
- High temporal and spatial resolution measurement of igniting plasmas, including energy-resolved neutron and x-ray emissions
- Data synthesis, analysis, and reconstruction techniques to infer derived plasma properties
- Specialized targets with associated high-resolution diagnostics and analysis techniques to investigate aspects of fusion target behavior
- Capability to build, measure, and implement suitable targets with tritium
- Laser and pulsed-power driver technologies with repeatable, precision pulse-shaping, energy delivery and associated diagnostics
- High-repetition-rate laser drivers
- Sophisticated simulation tools, high-performance computing (HPC), and associated material databases for driver-target interaction and fusion target implosion and burn

The various approaches to fusion energy have important differences but also share commonalities, implying potential synergies for research and development (R&D). Technical components of the various proposed IFE system designs are at different technology readiness levels (TRLs), including differences in workforce availability, facility availability, and government agency and commercial interest. The commonalities among the different approaches to IFE and other proposals for fusion energy (such as magnetic fusion energy (MFE)) include first-wall interactions, tritium breeding, diagnostics, etc. Further, hot and reactive environments are found in all fusion systems. The common issues just within the various IFE approaches include that any driver scheme must address energy delivery to the capsule in an environment that is complex for both optics and beam propagation.

Synergies that we can exploit using the capabilities of existing infrastructure include the following:

- *Chamber materials:* Oak Ridge National Laboratory (ORNL) supports research facilities for materials in extreme conditions, and DOE Virtual Laboratories for Technology (VLTs), whose objective is to develop radiation-hardened structural materials suitable for tokamaks, support other related materials programs [4]. These materials may be suitable for IFE reactor chamber walls. The pulsed nature of IFE introduces unique material requirements; examples include rate-dependent effects (time-dependent flux of photons, neutrons, charged particles) or thermal/mechanical shocks.
- *Energy conversion and first wall:* Research facilities exploring liquid metals or molten salt technology for tritium breeding, etc.
- *Particle-beam optics:* Superconducting magnet technology for MFE overlaps with focusing magnets for heavy-ion drivers.
- *Accelerator-based particle collisions:* Experiments measure energy-dependent, binary collision cross-sections and other parameters associated with fusion processes.

- *Laser-plasma interactions:* Experiments that address challenges for IFE include dynamics of hot and dense environments with intense electromagnetic fields, particle generation in high-power laser interaction with plasmas, and control of laser coherence and bandwidth to mitigate effects that are detrimental to precise control of energy flow.
- *Research infrastructure:* FES is developing the Materials Plasma Exposure eXperiment (MPEX), Fusion Prototypic Neutron Source (FPNS), and Matter at Extreme Conditions-Upgrade (MEC-U). For example, the MEC-U facility [5] will leverage the diagnostic power of the Linac Coherent Light Source (LCLS), together with a kilojoule nanosecond-long pulse and 10-Hz, 150-J petawatt lasers, to provide a facility with capacity for upgrades pursuant to IFE-relevant science, such as multi-kilojoule colliding shocks, capacity for continuous 10-Hz experiments, high-brightness pump-probes for materials studies, and dynamic tomography.
- Computing resources and code development

10.2 Priority Research Opportunities (PROs)

We identified three PROs that address basic research needs in research infrastructure for IFE. The IFE community would use integrated systems studies of IFE options, as described in the Executive Summary (Overarching PROs 2 and 3), to determine detailed activities.

PRO 10-1: ***Increase the number of experiments at existing large-scale facilities***

This PRO would directly address critical issues for IFE, including exploring driver and target designs for high gain, and is the only near-term extant means of testing at or near IFE scale. This effort would require collaboration among federal agencies and programs.

Experiments at NNSA's major laser facilities—NIF at Lawrence Livermore National Laboratory (LLNL), Z Pulsed-Power Facility at Sandia National Laboratories, and OMEGA at the Laboratory for Laser Energetics (LLE) at the University of Rochester—enable fusion science at the high energy and density scales needed for IFE-relevant integrated experiments. Synergistic advances in research at these facilities would benefit both DOE Office of Science FES and NNSA missions. FES partnerships with NNSA and DOE Basic Energy Sciences (BES) and High-Energy Physics (HEP) (for access to its facilities and people) would accelerate IFE research. Such access is critical for progress until new facilities are available.

Perhaps the most important aspect of better access is the availability of more shots. The advances leading to the August 2021 shot on NIF that reached threshold of ignition were built on just 171 cryogenic deuterium-tritium (DT) shots (supported by several hundred more "tuning" shots) over a period of a decade. We could dramatically accelerate our rate of learning with more experiments; more shots means more feedback on the precision required in target construction and laser performance.

In large part, the shot rate (of high energy shots required for integrated ICF implosions) on NIF is currently limited by the growth rate of damage on the optics. Such damage is typically due to debris and shrapnel resulting from vaporizing and exploding the target material or from tiny inclusions in the optics materials that can cause damage when the laser passes through. While the NIF facility has carried out a sustained effort to continuously improve optics recycling processes and rates, further improvements to the efficiency of this optics loop and/or repair and installation of new optics would allow NIF to run at a higher shot rate. Furthermore, reliability and efficiency improvements in experimental operations, such as for laser gain amplification and target and beam alignment, will support operational robustness at a faster shot tempo. In the near-term, we may be able to explore partnerships between the agencies or with private industry to fund incremental improvements at existing facilities (e.g., NIF) to increase shot rates, with the goal of supporting dedicated experiments for IFE.

Although OMEGA operates at substantially lower total energy (30 kJ versus the 2 MJ of NIF), it is a world leading facility in the study of direct drive and advanced-concept fusion schemes. Again, more shots can greatly propel development. In the case of OMEGA, we might be able to obtain a substantial increase in available shots by adding more shift time. Similarly, improvements to operational efficiency may enable an increase in shots that would allow us to explore benefits to IFE.

PRO 10-2: ***Utilize and upgrade, in the near-term, relevant, existing mid-scale facilities***

This PRO would enhance our ability to make progress on those technical issues and novel ideas for IFE that do not require operation at full-scale to advance understanding and identifies examples of such instances that are possible at modest cost.

We can address critical work for IFE at mid-scale facilities (especially those in FES's LaserNetUS network of high-power lasers; Figure 10.1), including the MEC end-station at LCLS and the Jupiter Laser Facility. These facilities provide capabilities for understanding issues such as laser plasma interaction (e.g., on an imploding target for direct-drive concepts), fusion ignition (including laser particle generation), high-repetition-rate target and experimental cycle development, etc. Allocation of time specifically for IFE experiments at these mid-scale facilities would accelerate IFE research. IFE-specific instruments and techniques brought by IFE researchers would then augment the capabilities and resources already existing at these facilities, thus also benefitting the LaserNetUS facilities' HED and other fundamental science experiments.

Although they do not operate at scale, mid-scale facilities provide a unique opportunity to advance IFE due to their relative low-cost, high-repetition rate, and the speed with which they can be upgraded. Mid-scale facilities also tend to be less restricted by programmatic requirements, giving them flexibility that permits them to be agile in the range of scientific questions they can explore if given DOE support. For example, we might explore plasma and debris damage to the final optics of an IFE plant and possible mitigation strategies at sub-scale by scaling the sample in size and volume to achieve similar irradiation fluences. Similarly, some aspects of laser propagation in a chamber environment can be studied at sub-scale. Some studies at these mid-scale facilities have already begun exploring the problem of targetry (injection, tracking, and placement), and we can greatly expand these studies. Developing machine learning (ML) algorithms for rapid analysis of the large amounts of data produced by fusion-relevant diagnostics and the use of this analysis to devise rapid control loops should be a high priority for the high-repetition-rate-capable facilities. Effective training of deep-learning (DL)-based systems requires large datasets that only such facilities can currently provide.

Mid-scale facilities supporting IFE may be upgraded (e.g., as part of LaserNetUS). Upgrades in these directions that are possible at potentially modest cost and speedy implementation include a higher bandwidth (>1%) laser concept for improved coupling on OMEGA [6], new vacuum chambers for

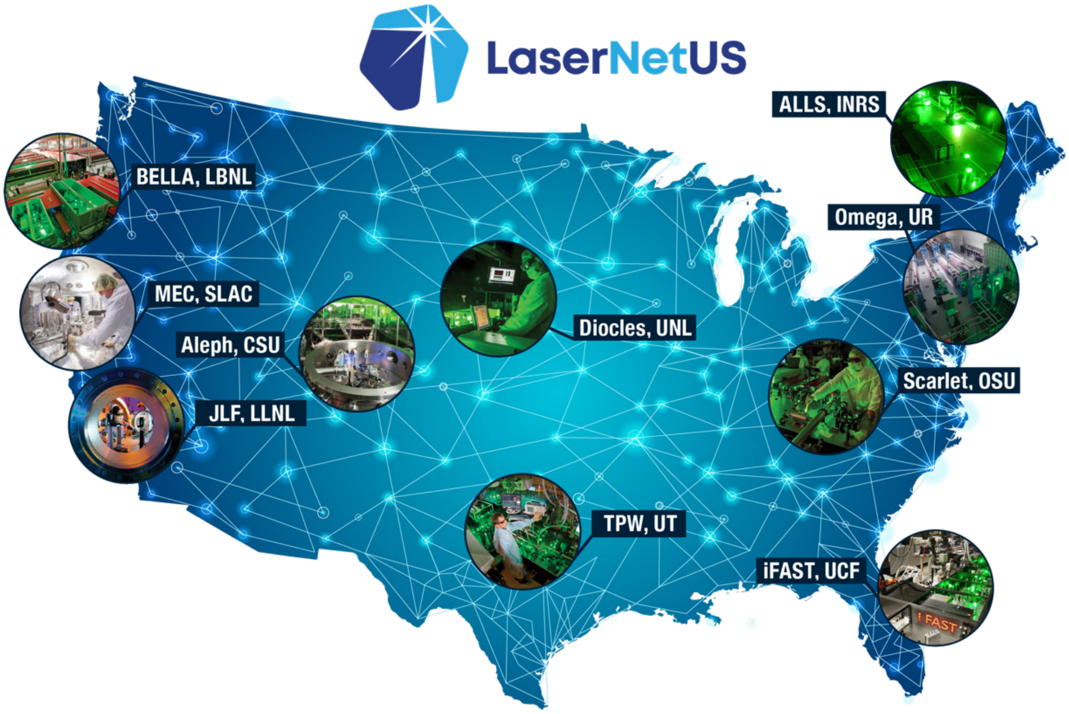


Figure 10.1. The mid-scale laser facilities that make up the LaserNetUS network.

exploring challenging plasma and debris environments without risk to the laser systems, increased repetition rate, higher pulse energy, backlighter-based diagnostics employing secondary beam lines, high-repetition-rate operation, and more.

We can address important issues for heavy-ion-driven fusion at existing and upcoming high-intensity particle accelerator facilities, including the Facility for Antiproton and Ion Research (FAIR; GSI, Germany) [7], the Facility for Rare Isotope Beams (FRIB) [8], the Spallation Neutron Source (SNS) [9], and the Proton Improvement Plan-II accelerator (PIP-II) [10] in the United States (supported by DOE Nuclear Physics (NP), HEP, BES, and NNSA). For example, experiments addressing beam control and target interactions, with multi-kilojoule pulses are possible. We should leverage talent and capabilities from various programs—including DOE offices with accelerator expertise—and hold joint agency workshops; such efforts would reveal synergistic interests.

PRO 10-3: Form at least one national IFE team or partnership that is focused on making best use of existing facilities, as well as continued R&D, for developing future infrastructure to demonstrate IFE

Establishing PPPs to develop and prove relevant technologies demonstrates the commitment of the government and the readiness of the private sector to invest in IFE and further mature advanced concepts. Such partnerships would involve DOE, private companies, universities, and national laboratories. Raising the TRL of relevant technologies (e.g., develop repetition-rated, high-power lasers; advance particle accelerator technology; fabricate targets that could be manufactured at low cost; develop tritium-handling solutions; etc.) will be a goal of PPPs.

A call for proposals requesting support to develop detailed reports on IFE concepts could provide a path to encourage IFE partnerships. The scientific and engineering community could organize into teams, involving broad sets of interested partners, to respond. Teams would prepare proposals for specific, integrated IFE design concepts. As a key component, the proposals should include an evaluation of the available driver technology and diagnostics, target manufacturing, and computational infrastructure that either exists or that would be needed to support experimental efforts. At the end of these grants, teams would report on readiness of their IFE concept. The IFE community could use these public reports to better understand possible paths forward to IFE and to identify commonalities between the various proposed design concepts.

A second call for proposals could encourage teams with proven readiness, for example based on the work funded by the prior call, to propose a path forward. To review proposals from these teams, DOE could assemble an expert assessment group that would analyze concept-readiness for multi-year funding. This process could result in a down-selection and formation of several IFE partnerships. **These organizations would be major collaborative efforts, involving universities, national laboratories, and the private sector; they would drive IFE forward by coordinating research and development and designing proof-of-principle and demonstration facilities.**

The resulting IFE partnerships would be expected to address the challenges to PPP, as well, to develop mechanisms to best take advantage of the opportunities of PPP. Existing facilities are a primary developer of the workforce needed for private-sector success in IFE. **We should explore new avenues for exchanging ideas and personnel between the national laboratories, universities, and the private sector,** including instituting supportive mechanisms for training personnel from the private sector in developing targetry, diagnostics, and ML techniques currently only available at the national laboratories or midscale facilities, such as those of LaserNetUS. Further, we could support scientists at the labs and universities to bring technology to the private sector. We would need to explore how to engage these communities as much as possible within the confines of existing law and the sometimes-conflicting requirements of these communities. We expect DOE would be an active partner in this work.

Overall, this path forward allows us to prioritize development of integrated power-plant system studies for relevant concepts and will expose science and technology gaps with TRL assessments. This effort would provide roadmaps to understand risks for each concept and to uncover common technology needs that benefit from early investments.

Such IFE partnerships would accelerate the path to an integrated system design for IFE and to eventual development of a proof-of-principle facility, a demonstration facility, and a pilot-plant facility. This recommendation builds on the development path suggested in the 2013 National Academies assessment of IFE [1]. A proof-of-principle facility would demonstrate an IFE-enabling and efficient driver technology, with capability for target manufacturing and injection. A demonstration facility would demonstrate high gain under conditions relevant to achieving required repetition rates. An FPP would have high gain and the required repetition rate, energy extraction, efficiency, and reliability and would implement the other crucial subsystems, such as tritium handling and remote operations.

10.3 Conclusions

The current infrastructure around ICF, built to support the Stockpile Stewardship Program and HEDP and to improve our fundamental understanding of extreme environments, is insufficient to demonstrate the feasibility of IFE today. A dedicated IFE program is necessary to push for improved utilization of existing infrastructure by increasing the shots available to IFE research. Moderate upgrades to existing infrastructure could efficiently advance the state of critical technical questions across the modes of IFE. Ultimately, an IFE program will need to pursue detailed concepts for an integrated system design from PPPs that will lead to the construction of a proof-of-principle facility, then a demonstration facility, and finally an FPP, proving efficacy of IFE for commercial use.

References

1. National Research Council of the National Academies of Science Engineering and Medicine, *An Assessment of the Prospects for Inertial Fusion Energy*. 2013, Washington, DC: The National Academies Press (doi: 10.17226/18289); https://nap.nationalacademies.org/catalog/18289/an-assessment-of-the-prospects-for-inertial-fusion-energy.

2. A. Zylstra, et al., *IFE Science & Technology Community Strategic Planning Workshop Report*. 2022 (https://lasers.llnl.gov/content/assets/docs/nif-workshops/ife-workshop-2022/IFE-Workshop-Report.pdf).

3. T. Carter, et al., *Powering the Future: Fusion & Plasmas*. 2020 (https://science.osti.gov/-/media/fes/fesac/pdf/2020/202012/FESAC_Report_2020_Powering_the_Future.pdf), Fusion Energy Sciences Advisory Committee.

4. *The Virtual Laboratory for Technology, ORNL*. 2022 8/22/2022]; Available from: https://web.ornl.gov/sci/vlt/mission.shtml.

5. Gilliss Dyer and Alan Fry, *Matter in Extreme Conditions Upgrade (Conceptual Design Report)*. (2021) (doi: 10.2172/1866100), SLAC National Accelerator Lab: Menlo Park, CA, United States (https://www.osti.gov/biblio/1866100).

6. J. D. Zuegel and C. Dorrer, *PolyKrōm: Two New Broadband Laser Architectures for Laser Direct-Drive Inertial Fusion Energy (LDD-IFE) "[White paper]"*, in *IFE BRN*. 2022 (see Accepted White Papers at https://events.bizzabo.com/IFEBRN2022/page/2133559/white-papers).

7. K. Schoenberg, et al., High-energy-density-science capabilities at the Facility for Antiproton and Ion Research. Physics of Plasmas, 2020. **27**(4): p. 12, 10.1063/1.5134846.

8. J. Wei, et al., Accelerator commissioning and rare isotope identification at the Facility for Rare Isotope Beams. Modern Physics Letters A, 2022. **37**(09): p. 11, 10.1142/s0217732322300063.

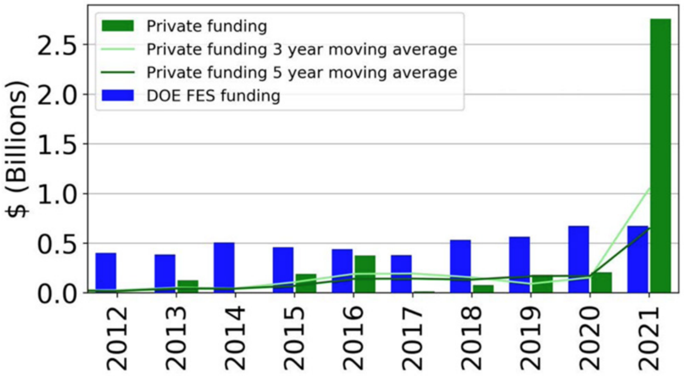
9. V.S. Morozov and S.M. Cousineau, Benchmarking and Validation of IFE Driver Technology, in NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

10. Vladimir Shiltsev, *Improvement Plans of Fermilab's Proton Accelerator Complex.* Journal of Physics: Conference Series, 2017. **888**(1): p. 012043, 10.1088/1742-6596/888/1/012043.

Chapter 11:
Public-Private Partnership

11.1 Introduction

Public-private partnerships (PPPs) have the opportunity to play a critical role in inertial fusion energy (IFE) research and development (R&D), as well as its potential commercialization. Although nearly all prior IFE-related science and technology has been government sponsored, the private sector has expressed significant interest in IFE startups over the last several years. Total private investment in IFE currently sits at ~$180 million (nearly all in the past few years), and this investment is likely to grow, given the trend of escalating investments in the larger private fusion industry, which has already surpassed $4.7 billion [1]. Many of these startups are foreign-based or have both a U.S. and foreign presence [1]. **Figure 11.1** summarizes current private and public-sector investment in fusion. At the same time, public-sector investment into IFE is ramping up. The recent Congressional authorization and appropriations to restart a U.S. IFE program and the White House's announcement of a "Bold Decadal Vision" for accelerating the commercialization of fusion energy have both highlighted this public sector interest. These efforts will be coordinated between DOE's Office of Science Fusion Energy Sciences (FES) program, the National Nuclear Security Administration (NNSA), the Advanced Research Projects Agency – Energy (ARPA-E), and the Office of Nuclear Energy (NE) [2]. We should further consider these developments



Plot credit: Sam Wurzel, Technology-to-Market Advisor, ARPA-E

Figure 11.1. Summary of private and public sector fusion funding. In 2022, we saw the addition of ~$2.3B to private sector totals.

SUMMARY

Any revitalized U.S. IFE program must help the community develop mutually beneficial public-private partnerships (PPPs). Although nearly all prior IFE-related science and technology has been government sponsored, the private sector has recently expressed significant interest in IFE startups. **DOE should facilitate PPPs to enable R&D of critical IFE system/component science and technology, modeling and simulation capabilities, and design/construction of next-generation IFE test and support facilities, as well as supporting cultivation and sustainment of a diverse workforce.** However, current mechanisms and funding support for partnerships are insufficient.

Since IFE is just ramping up in both the public and private sectors, we have an opportunity to **form the right consortia to jointly advance the foundational science, technology, and engineering (STE) needed across the industry, in a pre-competitive manner that allows the entire community to benefit.** DOE should consider programs that help establish and support appropriate multi-party, PPP consortiums for IFE in areas with broad, prioritized STE R&D needs from both the public and private sector. Further, DOE should implement contractual mechanisms that streamline partnership formation and are consistent across the DOE complex. Finally, we should **identify and communicate clear guidelines for international partnerships.**

within the context of the ongoing DOE NNSA inertial confinement fusion (ICF) and high-energy density (HED) program. This program has sustained R&D at the level of hundreds of millions of dollars per year over two decades in many science and technology areas that are synergistic with IFE needs. This NNSA investment has resulted in unique IFE-relevant R&D capabilities, such as OMEGA at the Laboratory for Laser Energetics (LLE) at the University of Rochester, the Z facility at Sandia National Laboratories, and the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL), as well as target fabrication capabilities at General Atomics. These investments have enabled significant advancements relevant to and now being leveraged for IFE, including ignition defined by the Lawson criterion on NIF [3]. DOE FES has also funded a modest program (~$20M/year) that has supported related HED science R&D.

For the purposes of this chapter, “public sector” implies organizations, programs, and capabilities that have been dominantly U.S. government-funded, such as at the national laboratories and academia but also at private companies that have long-term contracts with DOE to support the ICF and HED programs. This ICF/HED public sector has traditionally been aligned with long-term government programs in basic HED plasma science and stockpile-stewardship mission areas. However, this sector has a growing IFE mission area likely to focus on foundational and broad-based science, technology, and engineering (STE) for enabling a commercial IFE industry versus having a goal of a dominantly government-funded prototype power plant that would then be transitioned to industry. Note that opportunities also exist for partnerships with allied government-funded efforts, and they would fit under a broader definition of “public sector.” For clarity, here we will be specific when we refer to these efforts.

In contrast, our use of “private sector” here denotes companies, or efforts within companies, that are currently dominantly funded through private investment, such as venture capital, with the primary goal of developing prototype fusion power plants or the components needed for them. This sector includes the venture capital firms currently investing in these IFE startups. No definitions are exact, and the overall situation is rapidly changing. We should note that some private sector companies (e.g., established commercial companies in the nuclear sector and companies relevant to IFE supply chains, such as laser-diode companies) are observing the IFE space with interest but are not currently players. Additionally, certain philanthropic organizations are funding fusion research at academic institutions.

The above is, of course, a summary of the current situation, and these definitions should be adjusted in the future as appropriate. Here we use PPP to denote a range of possible collaborations between the public and private sector, from efforts in one sector that produce capabilities, knowledge, or results that are then explicitly transitioned to and leveraged by the other sector, to efforts that integrate teams from both sectors for joint R&D. PPPs and joint projects between these sectors to advance IFE could be funded through private and/or government funding or through combined funding, such as from government-sponsored, cost-shared, milestone-based IFE programs [4].

Any revitalized U.S. IFE program must help the community develop appropriate and mutually beneficial PPPs. This is especially true given the private and public landscape described above and the low technology readiness level (TRL) of many of the envisioned required IFE technologies. Further, developing these PPPs is also critical because much of the difficult-to-replicate capabilities needed to advance IFE presently reside in government-funded national laboratories, select universities, and industry and are designed to support the U.S. ICF and HED programs. Public and private sector IFE programs are all currently early stage. This environment creates a unique, time-urgent opportunity to form PPPs and efficient, streamlined partnership programs and structures to enable and sustain PPPs in a broad, community-inclusive manner to maximally accelerate IFE. These partnerships will need to address R&D in all the following categories:

- IFE science, technology, and engineering (STE)
- Next-generation test and support facilities
- Staffing requirements
- Licensing and regulatory environment

Further, they will need to address these topics in the context of currently developing roadmaps and private-sector needs that are centered around company-specific IFE concepts. Meanwhile, the public sector will need to focus more on foundational and base-building R&D and workforce development for the entire IFE and ICF/HED community.

11.2 Priority Research Opportunities (PROs)

The following sections summarize the panel's findings and opportunities. We have divided these PROs into three categories:

- Undertaking overall joint STE and facility development
- Improving partnership models and structures
- Developing and sustaining a diverse, inclusive workforce for the entire community

The diverse membership of the panel informed these findings and recommendations, as well as individual and group interviews with multiple IFE startups and IFE-relevant component companies, venture capital firms currently in the fusion space, large private companies in the nuclear sector, and national laboratory groups. Private companies interviewed included Breakthrough Energy Ventures; EX-Fusion; First Light Fusion; Focused Fusion; Leonardo Electronics U.S. Inc.; Marvel Fusion; Prime Movers Lab; Westinghouse Electric Company, LLC; and Xcimer Energy Company. We also incorporated input from members of the IFE Virtual Collaboratory [5].

Overall Joint Science, Technology, and Engineering (STE) and Facility Development

PRO 11-1: ***DOE should facilitate PPP structures and programs that enable public sector capabilities to be appropriately leveraged for accelerating IFE R&D.***

PPP can play a crucial role in enabling and guiding IFE R&D with the anticipated advent of large private sector investments in IFE. In fact, investments both in private and public sectors are ramping up. Thus, significant opportunity exists now to accelerate the development and potential commercialization of IFE by creating appropriate PPP structures and programs that are mutually beneficial to both public- and private-sector needs. Current mechanisms and funding support for partnerships are insufficient.

DOE should facilitate PPPs to enable R&D of critical IFE system/component science and technologies, modeling and simulations capabilities, and design and construction of next-generation IFE test and support facilities, as well as supporting cultivation and sustainment of a diverse, inclusive workforce. Appropriate joint road-mapping activities facilitated by PPPs are useful for guiding investments for both the public and private sectors.

Needs of the Public and Private Sector and Opportunities for PPPs. We found that there are significant opportunities for PPPs that serve the needs of both the public and private sector and that can accelerate the development of IFE.

Private sector. The goals and needs of private sector companies typically center around rapid execution of work closely focused on advancing their particular IFE concept. This work centers on R&D milestones that motivate the next round of investments and intermediate experimental facilities that ultimately culminate in a fusion pilot plant (FPP). Potential spinoff technologies are an important, but usually secondary, part of a company's valuation and mission. All these companies have R&D needs that align with capabilities in the public sector, even for companies focusing on more exotic fuel cycles than the deuterium-tritium (DT) cycle or driver approaches. Many are already leveraging expertise in the public sector, either through directly hiring staff from the public sector or by leveraging capabilities through small PPPs, work for others, and experiments on existing facilities.

The IFE companies we interviewed have all been capitalized at various levels for them to assemble teams to work on initial R&D and detailed roadmaps toward an FPP. Many are also focusing on the next-step experimental facility required to advance their concepts. These planned facilities typically center around particular target-driver concepts. DOE should consider these facilities to be PPP opportunities as it thinks about the next-generation suite of experimental facilities for ICF, HED, and IFE. These opportunities are particularly important since the construction and operating costs of any substantial next-generation facility able to conduct sophisticated experiments will likely be in the $100s of millions to billions level. Some of these private sector–led facilities, especially given the international nature of the IFE-startup landscape, might also garner partnerships with allied governments, as in MFE (e.g., as described in this U.K Atomic Energy Authority (UKAEA) press release [6]). In the meantime, companies are leveraging existing facilities, such as those in LaserNetUS, including OMEGA, to conduct initial experiments in a limited fashion, constrained by machine availability. Note that with respect to near-term full- or near-full-scale experiments, such as ones we can only do on NIF, access is extremely limited. For example, with the exception of NIF's Discovery Science program, which traditionally has not conducted IFE-related experiments, there is currently no avenue for a private sector entity to propose and be granted IFE shots on NIF.

Public sector. The goals and needs of the public sector primarily focus on developing and sustaining capabilities—including the workforce and new facilities—that can serve multiple missions, covering the current ICF and HED programs, as well as a growing IFE program. The public-sector federal government (as well as performer) perspective holds a strong interest in enabling PPPs that strengthen foundational STE and capabilities required for these mission spaces, while also supporting private industry's drive toward IFE.

Opportunities for public-private partnerships (PPPs): science, technology, and engineering (STE). As noted, the private sector is already leveraging public-sector capabilities. For example, IFE startups are conducting experiments at public facilities, such as the Texas Petawatt, Colorado State University's ALEPH laser, and OMEGA. They are also leveraging existing target fabrication capabilities and contracting work to the public sector for simulations to refine a target design. Companies have also already reached out to the public sector to discuss potential partnerships for designing and constructing driver facilities. DOE's INFUSE program (the Innovation Network for Fusion Energy; covered in the next section) has facilitated some of these activities. The public-sector capabilities (and associated facilities) that are of interest for the IFE startup companies we interviewed unsurprisingly cover many topics that would be important to any IFE program, public- or private-led:

- Simulation and modeling capabilities
- Advanced diagnostics
- Advanced driver technologies, target-driver architectures, and associated chamber technologies
- Foundational target fabrication capabilities
- Radiation-resistant materials R&D
- Tritium breeding and handling and blankets
- Systems engineering (for example, for repetition-rated operations) and road-mapping
- ICF and HED experimental facilities for conducting experiments and existing datasets from these facilities
- Independent testing and verification
- Continued support for supply chains relevant to ICF, HED, and IFE

Moreover, the companies we interviewed collectively emphasized tritium breeding, processing, handling, recovery, and associated blanket technologies; advanced radiation-resistant materials; and balance of plant as areas where they preferred and desired government and public-sector leadership. Pointedly, these are also topics that have foundational R&D needs, including new research facilities, and that can span both IFE and MFE domains, making them reasonable candidates for government-led community partnerships.

The list above is not exhaustive and represents opportunities for public-sector investment that would serve the entire community, with opportunities for private-sector-funded work to feed back into base capabilities for all, including the supply chain. For example, a private-sector-funded project at a national laboratory to simulate a particular target design using a long-established code might require the addition of a physics package that would remain part of the code and add to public-sector capabilities. In this particular example, it might be further possible to set up a consortium or hub (see next section) centered around advanced modeling capabilities. Each hub member would contribute to the base code with no intellectual property (IP) constraints and would be motivated to participate in the consortium for access to the latest capabilities and for sustaining their staff's access to it. Applications of the code and the resultant answers to a particular company's concept might have IP constraints and could be protected appropriately. Similarly, continual development and deployment of advanced diagnostics from the public sector to private experiments would reinforce diagnostic capabilities for the entire community.

Opportunities for public-private partnerships (PPPs): facilities. The public sector should consider PPPs to help with both constructing and operating private-sector-led next-generation facilities that could serve the entire community. For example, this partnership might center around a new repetition-rated, high-energy laser facility, where a set fraction of shots are made available for the community in exchange for public-sector support for construction and/or operations [7]. In some scenarios, these facilities might be outside the United States and/or led via PPPs that involve allied governments; DOE should consider participating in and supporting IFE-relevant situations that are mutually beneficial (e.g., similar to current NNSA partnerships with the United Kingdom and France in nuclear security [8]). DOE should explore mutually beneficial partnerships in facilities between the ramping U.S. IFE program and the established U.S. ICF and HED programs. Through combined program and PPP resources, we might be able to, for example, increase capabilities and shot rates at existing unique facilities like OMEGA and NIF in the near-term, allowing for increased private-sector access and acceleration of synergistic, community-wide ICF, HED, and IFE goals.

Tritium processing and handling was an area in which private industry collectively desired government leadership. Discussions with public-sector experts and stakeholders indicated that this area required significant additional R&D, as current capabilities are insufficient for the scale of processing and handling envisioned, including throughput and recovery fraction. We will need a research facility similar to the prior Los Alamos National Laboratory (LANL) Tritium Systems Test Assembly facility; such a facility could be a good opportunity for a potential public-sector-led PPP, perhaps formulated as a tritium R&D consortium or innovation hub. With regards to blanket technologies and radiation-resistant materials, the focal point for potential joint efforts here is the need for a steady-state, high-flux neutron-source exposure facility, such as the Materials Plasma Exposure eXperiment (MPEX). Further, we also need efforts to understand additional material development and testing needs that are more IFE-specific, such as those centered around IFE's much higher peak-radiation and energetic-ion outputs. **In all cases, private-sector involvement in these publicly led efforts will be important to ensure capabilities and results can be applied to each company's IFE concept.**

Balance of plant and related system engineering, as well as safety and overall public outreach, are areas where capabilities exist in public national laboratories, academic sectors, and the nuclear-reactor industry. We interviewed established large companies in the nuclear-energy sector who are observing the ramping interest and startup activities in IFE. They believe this is an area to which they would naturally contribute expertise once the TRL of the core technologies at the startups passed a sufficient level to enable partnership between the startups and these larger established companies. They indicated such partnerships would serve to move toward prototype plants and full commercialization. On the public-sector side, the current national laboratory infrastructure can also provide construction and operational experience of large-scale experimental facilities.

One unique aspect of the current PPP landscape is the expected role for independent testing and verification. Leveraging advanced diagnostic capabilities in the public sector, startup companies see independent testing and verification of private sector results as important for helping to verify key milestones for investors and for building credibility with the wider community. This effort could leverage existing facilities, such as those within LaserNetUS. Further, this effort could follow some prior INFUSE and ARPA-E examples in which they deployed portable diagnostics from a national laboratory to a private company to conduct independent measurements—such as neutron yields—from their machines during an experiment.

In conclusion, there are significant opportunities for PPPs to jointly develop STE that would accelerate IFE. DOE, in partnership with the private sector, should further identify and prioritize areas of foundational, pre-competitive R&D that serve the overall IFE community. They should also plan appropriate programs, resources, facilities, and streamlined community access for these areas in the context of the decadal vision for accelerating fusion commercialization.

PRO 11-2: ***DOE should further identify and prioritize areas of foundational, pre-competitive R&D that serves the overall IFE community.***

The public sector has significant capabilities and experience that the private sector wants to leverage for R&D efforts specific to each company's concept. The private sector has also identified areas of R&D that serve and benefit the overall community and would be more suitable for the public sector to lead, such as tritium breeding and handling and independent testing and evaluation. A significant amount of the needed R&D would be pre-competitive science and technology, allowing the public sector to help advance individual company concepts (such as modeling and simulations of specific concepts) while sustaining and growing foundational capabilities that serve the entire community. We can leverage lessons from broader fusion programs and other energy programs as we ramp up IFE PPPs.

DOE should plan appropriate programs, resources, and streamlined community access for areas of pre-competitive R&D in the context of the decadal vision for accelerating fusion commercialization. DOE should identify these areas in collaboration with the private sector, with the expectation of private-sector engagement in the pre-competitive R&D. We identified several areas of particular interest to start-up companies in the section above titled “Opportunities for public-private partnerships (PPPs): science, technology, and engineering (STE).”

PRO 11-3: ***DOE should consider joint funding and partnerships for construction, modification, and/or operation of private sector or ally government-led facilities.***

Advancing IFE will require new component and integrated test and demonstration facilities with significant construction and/or operating costs. These facilities form a part of current roadmaps in both private and public sectors. Some of these facilities could be constructed and operated outside of the United States, with sponsorship from other governments. The accessibility and availability of current mid-to-larger-scale experimental facilities, like OMEGA and NIF, are presently limited for private sector-led IFE experiments.

Joint funding and partnerships for private-sector- or ally-government-led facilities (especially ones that would serve significant community needs) in exchange for access to experiments and development of foundational, pre-competitive science and technology would be of significant value. DOE should consider leading the development and construction of such new experimental facilities that serve the overall community, such as neutron sources that are centered around advanced radiation-resistant material development or facilities that further the technology of tritium processing. Further, DOE should consider the possibility of augmenting existing experimental facilities for additional IFE R&D capabilities in the near-to-midterm, in the context of synergistic STE goals across the ICF, HED, and ramping-up IFE programs. Finally, DOE should consider increasing accessibility and availability of current DOE-funded experimental capabilities for private sector-led experiments.

Improving Partnership Models and Structures for Effective Public-Private Partnerships (PPPs)

The fusion community currently uses several models for PPPs, and several legal contractual mechanisms form the underlying agreements between parties using these models. Overall, DOE and the community should consider improved models and legal mechanisms, including consortium and hub approaches, to effectively accelerate the commercialization of IFE. Moreover, to help form PPPs, DOE and the community should facilitate forums for exchanging information concerning available public and private capabilities and priorities.

Current Common Public-Private Partnership (PPP) Mechanisms. The current federal-government-enabled PPPs in fusion energy center around the INFUSE model and individual project-focused programs, such as those from ARPA-E. The newly announced DOE Milestone-Based Fusion

Development Program is modeled after elements of NASA's Commercial Orbital Transportation Services (COTS) and NE's Advanced Reactor Demonstration programs (ARDP). This new program aims to encourage the growing fusion private sector to partner with the public sector to accelerate R&D toward an FPP. Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs and individual agreements, such as Cooperative Research and Development Agreements (CRADAs) between private companies and public sector entities like the national laboratories, also play a role in forming PPPs in fusion. Given the nascent and growing nature of DOE's IFE program, the few existing PPPs in IFE are conducted either through the INFUSE program or through individual agreements. The following summarizes the details and feedback from interviews we conducted about these PPP arrangements:

- With INFUSE, modeled off DOE NE's Gateway for Accelerated Innovation in Nuclear (GAIN) program, a company in partnership with a national laboratory or a university submits a proposal for joint work with an 80 (national laboratory or university)/20 (company) cost-share to the program and, if accepted, DOE funds the national laboratory or university directly to conduct its portion of the work, while the company executes its part of the work through its own funds. The underlying legal mechanism is a two-party CRADA.

The feedback was consistent that, although INFUSE was considered a success in earlier cycles and a welcomed program, the size and duration of the grants (1 year, $250k or 2 year, $500k) were too small and CRADAs took too long to execute (anywhere from 6–12 months) due to negotiations with individual laboratories and required DOE approvals. Additionally, CRADAs were not consistent across different national laboratories. **Opportunities exist to augment the INFUSE program and also to potentially make more consistent use of DOE's short-form CRADA, for which contract execution time can be shortened to 6–8 weeks or less, assuming neither party alters the standard terms. INFUSE should also examine the possibility of other contractual mechanisms that might be more efficient.**

- ARPA-E-like programs follow the standard approach of setting up targeted programs with focused technical goals and metrics and required cost-share. These programs encourage the community to organically form public-private teams across the community to respond. Moreover, additional forums and federal-program-manager-led program activities to facilitate team formation, investor engagement, commercialization, and transition are part of the standard approach. The teams involved might consist of private companies, national laboratories, and academia, with a lead that handles the subcontracts to the rest of the team.

The contractual mechanisms employed here—from the government to a private sector lead—are typically a cooperative agreement or could potentially be an "other transaction authority" (OTA), which can be faster. The lead then uses standard vendor contracts for its subcontracts and, in cases when a national laboratory is a subcontractor to a private-sector lead, a strategic partnership project (SPP) agreement.

The community appreciated this program structure and approach, and this model appears to be similar to what might be used for the upcoming milestone-based FPP program and other component-development efforts. **One potential concern expressed for a traditional milestone-based program under this model is the need for the team lead, potentially a start-up, having to front the costs of any public-sector portion of the team that must operate under a cost-plus accounting model, such as a national laboratory. DOE should explore a hybrid fixed-price and cost-plus approach in these situations.**

- SPPs/work for others (WFO) and CRADAs between a private company and a DOE national laboratory are long-enduring mechanisms for PPPs and technology transfer between the national laboratories and private companies across technology areas. An SPP project initiated from the private sector for a national laboratory must be complementary to the mission of the DOE facility, not adversely impact current DOE programs, not place the facility directly in competition with the private sector, and not create a detrimental future burden on DOE resources. Typically, a project will include as-needed licensing of laboratory technologies, and IP terms are dependent on a myriad factors, including the source of the sponsor funds. A challenge associated with this model is that private companies need to have sufficient knowledge of capabilities and priorities of the public-sector counterpart to formulate mutually beneficial projects or to even approach the public-sector entity. The length of time to execute the agreements is dependent on the complexity of the project and the extent of required DOE reviews; a foreign-entity-funded SPP requires DOE review that could take anywhere from 2–6 months.
- SBIR and STTR programs remain enduring funding mechanisms for small U.S. companies, with STTRs enforcing collaboration between the proposing company and public sector non-profits, such as a national laboratory. Limitations of the SBIR and STTR programs include the significant work involved in preparing proposals for the small initial investments in the $100–150K range. Given that the established government-wide structure of SBIRs and STTRs will likely remain static, within the context of IFE, DOE should tailor its norms with respect to the program to help accelerate IFE commercialization. For example, DOE could consider more “direct-to-phase-2” efforts, which would allow $1M-scale government investments to be made as the first allocation, skipping the initial ~$150K ceiling for Phase 1.

Improving Current Approaches and Implementing Underutilized Approaches. An underlying theme from private sector feedback on current PPP mechanisms is the general need to execute contracts more quickly, both for contracts from the federal government to private companies, such as OTAs, and for contractual mechanisms between companies and the national laboratories. In particular, respondents desired to have the latter be streamlined and made consistent across the national laboratories. The international nature of IFE will compound these challenges, specifically for technologies that are export controlled or could be and for the many capabilities in the public sector that exist in the national security arena. DOE should consider, for allied nations and countries, provisions or master agreements that might reduce the time it takes to complete partnerships on individual projects.

Another underlying theme and finding is that there are currently no streamlined mechanisms or programs for multi-party PPPs, such as consortium or hub approaches as seen in other areas of research. Since IFE is just ramping up from both a public- and private-sector point of view, we have an opportunity to form the right consortia or hubs to jointly advance the foundational STE that is commonly needed across the industry, in a pre-competitive manner that allows the entire community to benefit from these efforts. Individual companies, who could be either part of or outside of the consortium, could build upon and leverage these foundational efforts for their unique IFE concept. These consortia or hubs that address broad foundational STE—such as in areas covered in the prior section (e.g., tritium processing and handling, advanced materials, or advanced modeling and simulation capabilities leveraging DOE’s major investment in high-performance computing

(HPC))—would be complementary to any government milestone FPP programs, which would be more focused on advancing individual company IFE concepts.

Tang (2022) [9] summarizes the history of relevant PPP consortium approaches, which we can leverage for IFE, ranging from SEMATECH to a Virtual National Lab (VNL) for extreme ultraviolet (EUV) to more recent examples of the ATOM Research Alliance (ARA). Although details of the consortiums differ, many have the common theme and mission of working to develop foundational technologies for their field, with the consortium members helping to determine areas of highest priority. They are also typically led by a single entity, usually a non-profit, that exists solely to conduct and execute the business of the consortium (under various oversight arrangements). This set-up side-steps the need for cumbersome and slow multi-party CRADAs. These features potentially streamline the ability of the consortium to receive and commit research funding from multiple public and private sources to its members and other groups, as well as execute new contracts and partnerships with appropriate IP considerations. DOE should consider programs that help establish and support appropriate multi-party, PPP consortiums for IFE in areas that have broad, prioritized STE R&D needs from both the public and private sector.

In addition to the need for improved PPP models and mechanisms, the community also noted that public and private parties often struggle to understand in detail what actual capabilities are available on both sides, including facility availability and access and projects that might be of mutual interest. Often both parties lack visibility into the goals and needs of potential partners, stymying the formation of potential partnerships. Opportunities exist here for DOE, the national laboratories, the existing ICF/HED community, and the wider public sector to streamline PPP formation in a consistent manner, offering fair opportunity for the private sector to propose partnerships leveraging public-sector capabilities. We could achieve this endeavor through mechanisms like requests for information (RFIs), industry days, and/or centralized websites that provide continuous two-way updating of capabilities and opportunities for partnership, suitable for the full range of possible funding sources. These mechanisms would serve to highlight IFE areas in which collaborations between public and private sectors could be fruitful.

PRO 11-4: ***The public sector, through DOE and/or its contractors, should continue engagement with the private sector to increase awareness and opportunities for mutually beneficial partnerships.***

Significant public-sector capabilities exist for the private IFE sector to leverage. Conversely, private-sector capabilities that could benefit the public sector are also emerging. However, the details of these capabilities and their availability can be difficult to find. Further, existing mechanisms for collaboration, such as traditional (versus short-form) CRADAs and SPPs, can be cumbersome and time-consuming to finalize (recognizing that the private sector is generally more agile and can move more quickly than federal agencies and national laboratories). Additionally, the global nature of the IFE private sector complicates the environment for partnerships, particularly given the notable public capabilities that primarily reside in the U.S. national security infrastructure.

The public sector can increase private-sector awareness of partnership opportunities, in a fair, transparent, and consistent manner. DOE should implement contractual mechanisms that streamline and reduce the time to form partnerships, such as OTAs and short-form CRADAs, that are consistent across the DOE complex. Further, we should identify and communicate clear guidelines for international partnerships. The community should also consider creating consortia and innovation hubs that can streamline the above for multi-party partnerships holistically.

Developing and sustaining an ICF, HED, and IFE community workforce via PPPs

The emergent and growing IFE public and private sectors, along with continuing needs of international ICF and HED programs, will create new workforce demands but also opportunities for the community. Specifically, IFE PPPs could help retain and grow the workforce and enlarge its pipeline in a diverse, inclusive manner for the entire community.

The ramping up of IFE as a revitalized goal for both the public and private sectors can be highly motivating in terms of sustaining and retaining the current workforce, since many in the current ICF and HED workforce entered the field motivated by the possibility of fusion energy. This is also a significant motivating factor for the emerging and next-generation workforce, given the overall increasing recognition of climate-change challenges and the need for enduring, clean sources of energy. The addition of IFE as a resourced mission space within the HED science and fusion STE community thus has the potential to increase the vitality, size, diversity, and inclusiveness of the workforce to the benefit of all mission spaces served by the community.

The rapid infusion of new demands on the workforce presents near-term challenges for the community and the established programs that have long sustained it. These challenges should motivate broader thinking on PPPs that would provide the public-sector workforce opportunities to contribute to the emergent IFE industry and private-sector needs while sustaining core public-sector capabilities that are needed by all, including the ramping private IFE sector. The establishment of joint IFE research, development, and demonstration (RD&D) public-private-sector projects as discussed in the prior sections is clearly a primary path forward. Additional opportunities include the potential establishment of formal government and industry workforce rotation programs, potentially modeled on the current Intergovernmental Personnel Act (IPA) program that allows employees to be loaned to the federal government from federally funded research and development centers (FFRDCs) for fixed terms. Sabbatical and entrepreneurial leave programs could be strengthened and leveraged for the same purpose, with the overall goal of helping to retain and develop the overall public sector workforce while enabling the private sector.

From a pipeline perspective, new, jointly public- and private-sector-funded IFE programs targeted at universities and academia should be considered to increase the workforce pipeline in a diverse and inclusive manner and in a manner consistent with the staffing needs of an emergent IFE industry and its supply chains, as well as existing ICF and HED programs. PPP-driven academic centers and innovation hubs are one potential path forward. Current models in the community that serve a similar purpose, such as NNSA’s academic programs designed to develop the next generation workforce and augment fundamental science needed for its core mission should be studied and leveraged for IFE appropriately.

Lastly, the growing international nature of ICF, HED, and IFE implies a larger community to draw from for U.S. program needs, but also greater competition for that talent pool. To accelerate development and commercialization of IFE and to develop and sustain the associated U.S. industry and public sector, DOE should consider mechanisms to accelerate visas, immigration, and permanent residency for workers with skills needed for IFE, while setting guidelines that account for U.S. and allied-partner national security interests.

PRO 11-5: ***DOE and the public sector, in partnership with U.S. and international private industry, should consider workforce exchange and rotation programs.***

Growth in IFE coupled with the continued needs of ICF and HED programs will increase strain on the existing workforce. Opportunities exist for PPPs that could help retain and grow the workforce and enlarge its pipeline in a diverse, inclusive manner for the entire community.

Workforce exchange and rotation programs could allow staff to join a partnering organization for a fixed term while retaining their position at the home organization. We could model these programs on the current IPA program, which allows FFRDCs to loan employees to the federal government. Further, we could strengthen existing sabbatical and entrepreneurial-leave programs. Both of these approaches would help retain and develop the overall public-sector workforce while enabling the private sector.

We should also consider new, jointly public- and private-sector-funded IFE programs targeted at universities and academia to increase the workforce pipeline in a diverse and inclusive manner that is consistent with the staffing needs of an emergent IFE industry and its supply chains, as well as with existing ICF and HED programs.

Finally, the growing international nature of ICF, HED, and IFE implies both a larger community to draw from for U.S. program needs and also greater competition for that talent pool. Thus, to accelerate development and commercialization of IFE and to develop and sustain the associated U.S. industry and public sector, DOE should consider mechanisms to accelerate visas, immigration, and permanent residency for workers with skills needed for IFE, while setting guidelines that account for U.S. and allied-partner national security interests.

References

1. Fusion Industry Association. *The global fusion industry in 2022*. 2022; Available from: https://www.fusionindustryassociation.org/about-fusion-industry.

2. The White House. *Readout of the White House Summit on Developing a Bold Decadal Vision for Commercial Fusion Energy*. 2022; Available from: https://www.whitehouse.gov/ostp/news-updates/2022/04/19/readout-of-the-white-house-summit-on-developing-a-bold-decadal-vision-for-commercial-fusion-energy/.

3. H. Abu-Shawareb, et al., *Lawson Criterion for Ignition Exceeded in an Inertial Fusion Experiment.* Physical Review Letters, 2022. **129**(7): p. 19, https://doi.org/10.1103/PhysRevLett.129.075001.

4. DOE Office of Science. *Milestone-Based Fusion Development Program, Funding Opportunity Announcement Number: DE-FOA-0002809*. [Funding Opportunity Announcement] 2022 09/22/22; Available from: https://science.osti.gov/grants/FOAs/-/media/grants/pdf/foas/2022/SC_FOA_0002809.pdf.

5. IFE Collaboratory for Public-Private Partnerships. Accessed 2023; Available from: https://events.bizzabo.com/RFI-IFE/home.

6. UK Atomic Energy Authority;. *General Fusion to build its Fusion Demonstration Plant at UKAEA's Culham Campus*. [News Story] 2021 06/17/2021; Available from: https://www.gov.uk/government/news/general-fusion-to-build-its-fusion-demonstration-plant-at-ukaeas-culham-campus.

7. University of Texas Austin, *Workshop on Laser Facility for Inertial Fusion Energy (IFE) and High Energy Density Laboratory Plasmas (HEDLP) Research*. 2022 (https://drive.google.com/file/d/1iq-yjtx3hAxqbLeGkdWqW2-RgWkiUGl3/view), University of Texas Austin.

8. Department of Energy;. *US–UK Mutual Defense Agreement Marks 60 Years*. 2018 06/26/2018; Available from: https://www.energy.gov/articles/us-uk-mutual-defense-agreement-marks-60-years.

9. Vincent Tang, Initial Thoughts on Public Private Partnerships and Consortium Models for IFE "[White Paper]", in NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop. 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

Chapter 12: Workforce

12.1 Introduction

Once established, a DOE Inertial Fusion Energy (IFE) program has the potential to catalyze rapid growth in public- and private-sector funding toward IFE development. The recent achievement of ignition—the first demonstration of a net target energy gain—may further stimulate growth of IFE sciences and technologies to the point that the current traditional IFE-related fields of high-energy-density physics (HEDP) and inertial confinement fusion (ICF) are no longer equipped to meet IFE workforce needs. While some of the IFE technologies are shared with magnetic fusion energy (MFE), the majority of IFE research and development (R&D) needs require a workforce with unique skills, knowledge, and abilities that must be built from the ground up. At this time, the IFE Basic Research Needs (BRN) panel did not coalesce on a pathway forward to develop the requisite workforce, however we recognize the importance of devising a workforce-development plan when critical needs arise. The IFE BRN leadership proposes the steps below.

> Harnessing a broad range of views, expertise, and experiences drives scientific and technological innovation and enables the Office of Science community to push the frontiers of scientific knowledge for U.S. prosperity and security.
>
> —**Fusion Energy Sciences RENEW**
> Funding Opportunity Announcement

***PRO 12.1:* In anticipation of a possible growth of the IFE workforce, the Office of Fusion Energy Sciences(FES) should closely monitor the state of the field (including efforts in the private sector) to identify the right time for initiating a workforce-development study.**

Such a study should include workforce-development experts and representatives from organizations and institutions involved in IFE, ranging from private-sector companies to national laboratories and academia. Based on the substantial needs for an increased workforce with specific skills in various science and technology discipline areas, an IFE program should be organized to proactively promote training and recruiting from all backgrounds, recognize the benefits of a diverse workforce, and facilitate the search for talent to include minority-serving institutions and underrepresented groups.

***PRO 12.2:* A future IFE workforce-development action plan should be coordinated with established DOE initiatives promoting diversity, equity, inclusion, and accessibility.**

The new Reaching a New Energy Sciences Workforce (RENEW) initiative [1] within the DOE Office of Science is an example of an existing effort that can be engaged when developing workforce-building strategies.

References

1. DOE Office of Science. *Reaching a New Energy Sciences Workforce (RENEW)*. Accessed 2023; Available from: https://science.osti.gov/Initiatives/RENEW.

SECTION FIVE

ANALYSIS OF THE INTEGRATED TARGET-DRIVER APPROACHES

Chapter 13: Analysis of the Integrated Target-Driver Approaches

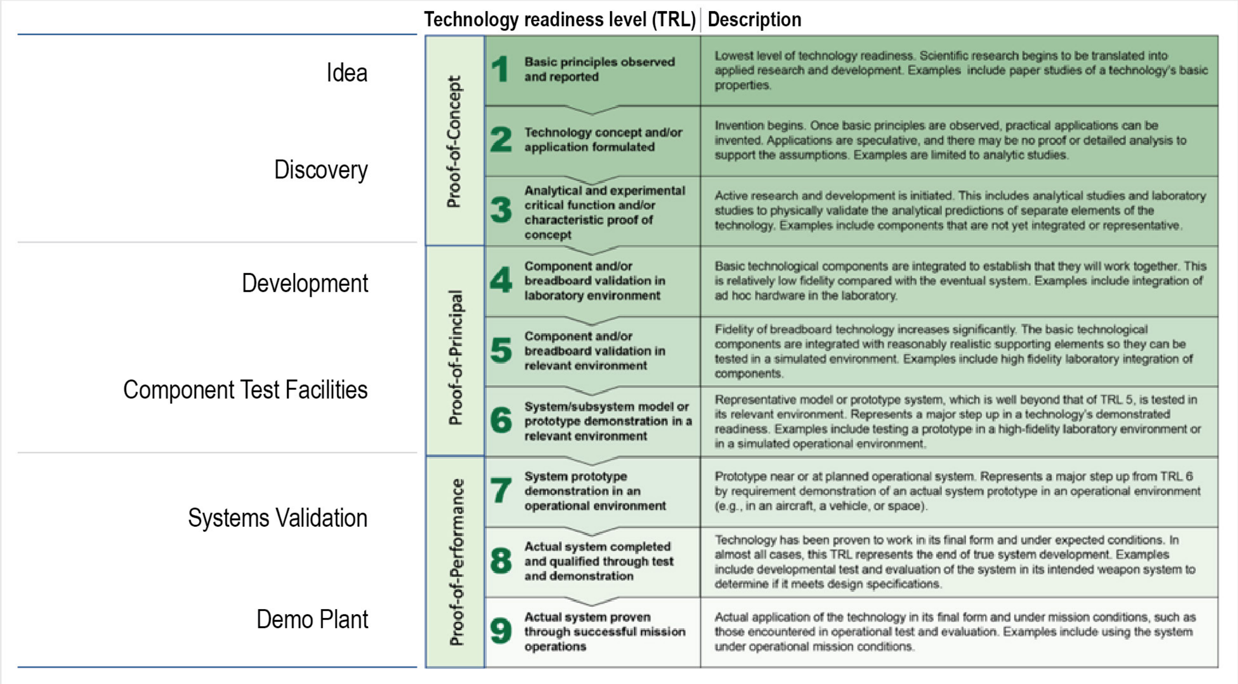
In response to the charge letter, we carried out a preliminary technology readiness assessment of the different fusion concepts to determine their potential and maturity as candidates for a fusion pilot plant (FPP). All existing fusion energy concepts, whether inertial or magnetic, have mostly developed around the physics of the fusion fuel rather than the technology required for a functional, reliable, and economically viable power plant. Historically, fusion energy development has been characterized by setting milestones on the plasma physics with the promise that a major technology development would follow once the physics milestones were met. One of these physics milestones is demonstrating a burning and/or ignited deuterium-tritium (DT) plasma. Such a demonstration instills confidence in the fusion community and its stakeholders that DT fusion reactions can be self-sustaining, thereby amplifying the fusion energy outputs well above the input to the plasma, a prerequisite for any fusion concept based on DT fuel.

> In the research and development world, ideas are like schoolchildren. All new technologies must pass through a number of grades before they are declared ready for graduation. […] Each TRL represents the evolution of an idea from a thought, perhaps written on a cocktail napkin or the back of an envelope, to the full deployment of a product in the marketplace.
>
> —Jim Banke
> “Technology Readiness Levels Demystified”[1]

Demonstrating a burning plasma is the main goal of the ITER tokamak for magnetic fusion energy (MFE) and a necessary requirement for achieving high neutron yield on the National Ignition Facility (NIF) for inertial confinement fusion (ICF). While ITER is scheduled to test DT fuels and explore burning plasma regimes late in the next decade, NIF has already demonstrated burning plasmas [1] and achieved Ignition [2]. The recent NIF results validate the plasma physics principles of laser fusion and form the basis for a future technology-development effort. Since fusion research has thus far focused on the plasma physics, efforts in fusion technology have been modest and the technology readiness of all fusion concepts is low. We made an attempt to assess the technology readiness of the different inertial fusion concepts during this workshop. Our assessment is intended to be preliminary and far from conclusive.

Our assessment followed the nine technology readiness levels (TRL) originally developed for NASA and formulated by Blanke in 1989 [3]. TRL assessment is widely used in industry and in federal procurement for research and development (R&D) programs. Publications by DOE [4] and the U.S. Government Accountability Office (GAO) [5] provide guidance on TRL applications. Specific applications of TRLs can be found for nuclear fission [6], magnetic fusion [7-11], and IFE [12].

Figure 13.1 [5] describes the nine TRLs from the original NASA formalism [3]. TRLs can be used for readiness assessment of either integrated systems or individual subsystems. The highest level (TRL 9) is applicable to a fully functional subsystem including its integration or, in the case of IFE, the fully operational IFE reactor.



		Technology readiness level (TRL)		Description
Idea	Proof-of-Concept	1	**Basic principles observed and reported**	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples include paper studies of a technology's basic properties.
Discovery		2	**Technology concept and/or application formulated**	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
		3	**Analytical and experimental critical function and/or characteristic proof of concept**	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
Development	Proof-of-Principal	4	**Component and/or breadboard validation in laboratory environment**	Basic technological components are integrated to establish that they will work together. This is relatively low fidelity compared with the eventual system. Examples include integration of ad hoc hardware in the laboratory.
Component Test Facilities		5	**Component and/or breadboard validation in relevant environment**	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include high fidelity laboratory integration of components.
		6	**System/subsystem model or prototype demonstration in a relevant environment**	Representative model or prototype system, which is well beyond that of TRL 5, is tested in its relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.
Systems Validation	Proof-of-Performance	7	**System prototype demonstration in an operational environment**	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requirement demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, a vehicle, or space).
		8	**Actual system completed and qualified through test and demonstration**	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
Demo Plant		9	**Actual system proven through successful mission operations**	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.

Figure 13.1. Description of the nine technology readiness levels (TRLs) adapted from the U.S. Government Accountability Office (GAO) [5]. The leftmost column was added to characterize the different stages of an IFE development path up to a demonstration power plant (DEMO).

While many IFE concepts have been proposed over the years, we only considered five to be sufficiently developed to be reviewed with respect to their technology readiness.

1. Laser Indirect-Drive (LID)
2. Laser Direct-Drive (LDD, including Shock Ignition (SI))
3. Fast Ignition (FI)
4. Heavy-Ion Fusion (HIF)
5. Magnetically Driven Fusion (MDF)

Five subpanels, each devoted to a specific fusion concept, first developed the fusion concept assessment. Subsequently, the entire panel evaluated and voted on each subpanel assessment. The subpanels carried out their assessments with respect to the following scientific milestones and system developments, critical for any IFE-development path:

- Demonstration of ignition and reactor-level gain
- Manufacturing and mass production of reactor-compatible targets
- Driver technology at reactor-compatible energy, efficiency, and repetition rate
- Target injection, tracking, and engagement at reactor-compatible specifications
- Chamber design and first-wall materials
- Maturity of theory and simulations
- Availability of diagnostic capabilities for critical measurements

As shown in **Figure 13.1**, the nine TRL levels are divided into the following three groups:

- TRLs 1–3; Concept Exploration
- TRLs 4–6: Proof of Principle
- TRLs 7–9: Proof of Performance

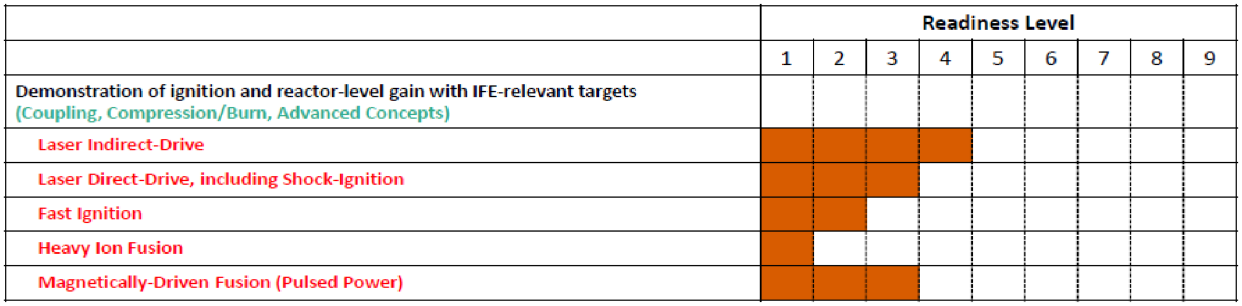
The three groups correspond to the science and technology maturity levels ranging from the formulation of the fusion concept and exploration of its feasibility (TRL 1-3) to the demonstration of the basic physics and engineering principles (TRL 4-6) to the achievement of reactor-relevant performance levels for each component and ultimately for the integrated system (TRL 7-9).

Note that readiness levels identify R&D gaps between the present status and any level of achievement for a particular concept. They help to identify which steps are needed next. TRLs provide an objective, integrated self-consistent, and design-independent procedure that is understandable and usable by the full range of stakeholders in fusion, including governments, R&D providers, private-sector developers, and end-users. The utility of TRLs is their ability to identify elements of the program for discussion that are underdeveloped, potential show-stoppers, or may impact schedule due to lack of resources or current capabilities.

In the formalism we use here, we do not consider “system integration” to be a separate issue; rather, each and every technology issue must progress through TRLs requiring increasing levels of system integration. We interpret TRL 9 to be a fully functioning demonstration power plant. This assessment is only a starting point, and we will require additional effort to evolve this methodology and evaluate readiness through broader community participation.

Assigning TRL levels requires interpreting the precise meaning of the language in the definition of TRLs, as well as judging the relevance of existing facilities and R&D programs throughout the world. Thus, assigning TRLs includes an element of subjectivity. The charts below show the results of our TRL assessment with respect to the scientific milestones and system development paths listed above for each of the five categories of IFE concepts also given above.

Demonstration of Ignition and Reactor-Level Gain



	Readiness Level								
	1	2	3	4	5	6	7	8	9
Demonstration of ignition and reactor-level gain with IFE-relevant targets **(Coupling, Compression/Burn, Advanced Concepts)**									
Laser Indirect-Drive	■	■	■	■					
Laser Direct-Drive, including Shock-Ignition	■	■	■						
Fast Ignition	■	■							
Heavy Ion Fusion	■								
Magnetically-Driven Fusion (Pulsed Power)	■	■	■						

Manufacturing and Mass Production of Reactor-Compatible Targets

	Readiness Level								
	1	2	3	4	5	6	7	8	9
Manufacturing and mass production of reactor-compatible targets (Targets)									
Laser Indirect-Drive	🟧	🟧							
Laser Direct-Drive, including Shock-Ignition	🟧	🟧							
Fast Ignition	🟧	🟧							
Heavy Ion Fusion	🟧	🟧							
Magnetically-Driven Fusion (Pulsed Power)	🟧								

Driver Technology at Reactor-Compatible Energy, Efficiency, and Repetition Rate

	Readiness Level								
	1	2	3	4	5	6	7	8	9
Driver technology at reactor-compatible energy, efficiency, and repetition rate (Drivers)									
Laser Indirect-Drive	🟧	🟧	🟧	🟧					
Laser Direct-Drive, including Shock-Ignition	🟧	🟧	🟧	🟧					
Fast Ignition	🟧	🟧	🟧						
Heavy Ion Fusion	🟧	🟧							
Magnetically-Driven Fusion (Pulsed Power)	🟧	🟧	🟧						

Target Injection, Tracking, and Engagement at Reactor-Compatible Specifications

	Readiness Level								
	1	2	3	4	5	6	7	8	9
Target injection, tracking and engagement at reactor-compatible specifications (Targets)									
Laser Indirect-Drive	🟧	🟧							
Laser Direct-Drive, including Shock-Ignition	🟧	🟧							
Fast Ignition	🟧	🟧							
Heavy Ion Fusion	🟧	🟧							
Magnetically-Driven Fusion (Pulsed Power)	🟧								

Chamber Design and First-Wall Materials

	Readiness Level								
	1	2	3	4	5	6	7	8	9
Chamber design and first wall materials (Power Systems, SE&T)									
Laser Indirect-Drive	🟧								
Laser Direct-Drive, including Shock-Ignition	🟧								
Fast Ignition	🟧								
Heavy Ion Fusion	🟧								
Magnetically-Driven Fusion (Pulsed Power)	🟧								

Maturity of Theory and Simulations

	Readiness Level								
	1	2	3	4	5	6	7	8	9
Maturity of Theory & Simulation (Theory & Simulation)									
Laser Indirect-Drive	■	■	■						
Laser Direct-Drive, including Shock-Ignition	■	■	■						
Fast Ignition	■	■							
Heavy Ion Fusion	■	■							
Magnetically-Driven Fusion (Pulsed Power)	■	■							

Availability of Diagnostic Capabilities for Critical Measurements

	Readiness Level								
	1	2	3	4	5	6	7	8	9
Availability of diagnostic capabilities for key measurements (Measurement Innovations)									
Laser Indirect-Drive	■	■	■						
Laser Direct-Drive, including Shock-Ignition	■	■	■						
Fast Ignition	■	■							
Heavy Ion Fusion	■	■							
Magnetically-Driven Fusion (Pulsed Power)	■	■							

Relative to the other concepts, we ranked laser indirect- and direct-drive at a higher readiness level. This higher readiness is in large part a consequence of the extensive development of laser fusion within the National Nuclear Security Administration (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 in this analysis. This means that, although some component validation has occurred in laboratory environments, these components are still “low fidelity” compared to the eventual system (TRL 4) 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 need to emphasize that the aforementioned assessment is a preliminary step and is by no means exhaustive or conclusive. Thus, view this assessment as a starting point for a more comprehensive assessment that should follow from an FES-sponsored scoping study, as stated in the following high-level opportunity:

High-Level Opportunity: Develop scoping studies to evaluate the various IFE concepts with a comprehensive system-engineering approach. The objective is to identify the most promising concepts via integrated design activities toward an FPP and to inform directions of technological development.

References

1. A. B. Zylstra, et al., *Burning plasma achieved in inertial fusion.* Nature, 2022. **601**(7894): p. 542-548, 10.1038/s41586-021-04281-w.

2. Lawrence Livermore National Laboratory: News. *Lawrence Livermore National Laboratory achieves fusion ignition*. 2022; Available from: https://www.llnl.gov/news/lawrence-livermore-national-laboratory-achieves-fusion-ignition.

3. J. Banke *Technology Readiness Levels Demystified*. 2010 (https://www.nasa.gov/topics/aeronautics/features/trl_demystified.html).

4. U.S. Department of Energy, Technology Readiness Assessment Guide (G 413.3-4). 2009.

5. U.S. Government Accountability Office, GAO Technology Readiness Assessment Guide: Best Practices for Evaluating the Readiness of Technology for Use in Acquisition Programs and Projects (GAO-16-410G). 2016, U.S. Government Accountability Office; https://www.gao.gov/assets/gao-16-410g.pdf.

6. J. Carmack, *Technology Readiness Levels For Advanced Nuclear Fuels and Materials Development*. (2014), Idaho National Laboratory; https://inldigitallibrary.inl.gov/sites/sti/sti/5935853.pdf.

7. M.S. Tillack, et al., *Issues and R&D Needs for Commercial Fusion Energy (UCSD-CER-08-01)*. 2008, University of California, San Diego; https://cer.ucsd.edu/_files/publications/UCSD-CER-08-01.pdf.

8. M. Tillack, Technology Readiness Evaluations for Fusion Materals Science and Technology, in International Conference on Fusion Reactor Materials 11. 2011: Charleston, SC.

9. N.K. Prinja and S.M. Gonzalez, *Fusion Specific Technology Readiness Levels*, in *28th IAEA Fusion Energy Conference*. 2021 (https://conferences.iaea.org/event/214/contributions/17443/attachments/10545/15274/Fusion_Specific_Technology_Readiness_Levels.pdf).

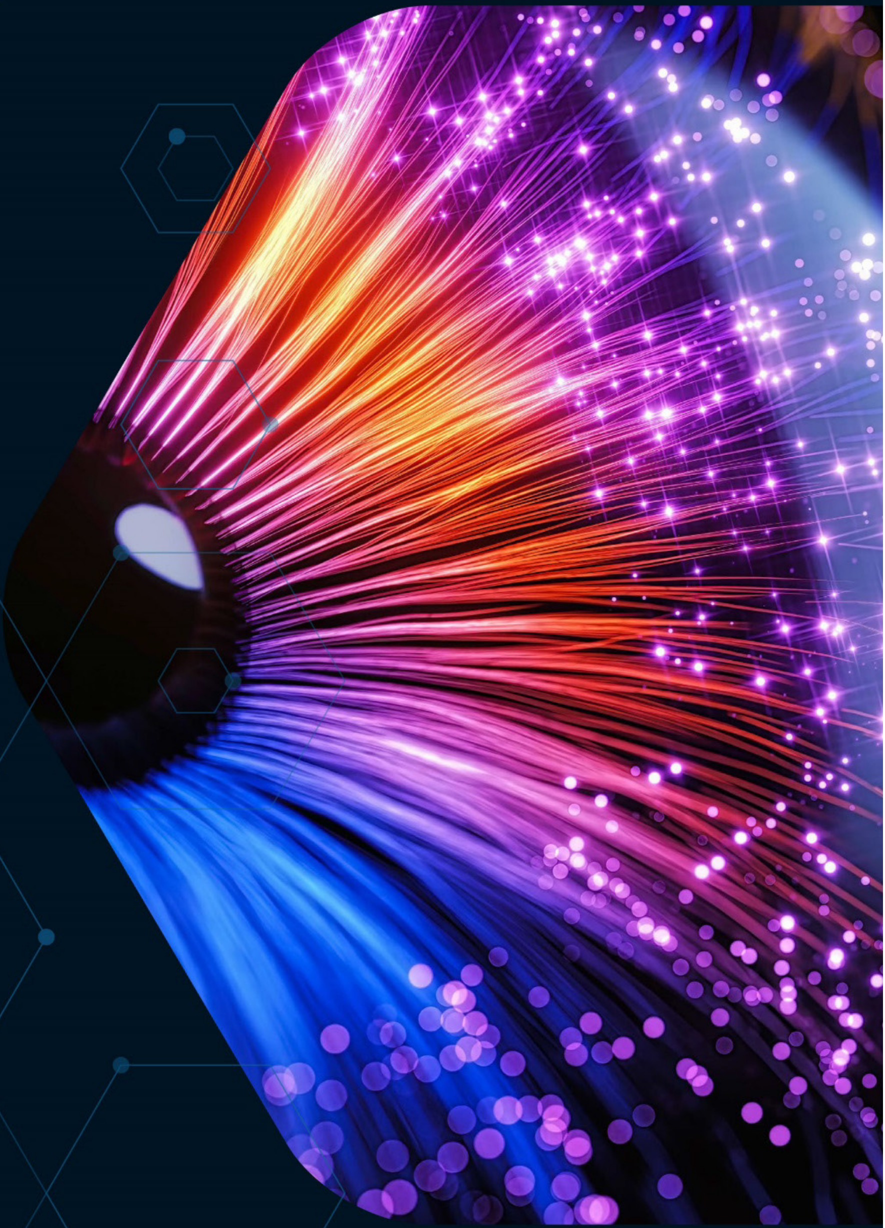
10. R. Maingi, et al., *Summary of the FESAC Transformative Enabling Capabilities Panel Report.* Fusion Science and Technology, 2019. **75**(3): p. 167-177, 10.1080/15361055.2019.1565912.

11. A. Sagara, R. Wolf, and H. Nielson, Technological readiness comparison for Helical and Tokamak DEMO, in 3rd IAEA "DEMO Programme Workshop”. 2015: Hefei, China.

12. National Research Council of the National Academies of Science Engineering and Medicine, *An Assessment of the Prospects for Inertial Fusion Energy*. 2013, Washington, DC: The National Academies Press (doi: 10.17226/18289); https://nap.nationalacademies.org/catalog/18289/an-assessment-of-the-prospects-for-inertial-fusion-energy.

SECTION SIX

CONCLUSION



CONCLUSIONS

Harnessing fusion energy on earth is a grand scientific and technical challenge with monumental payoff—the prospect of unlimited, safe, carbon-free energy. Inertial Fusion Energy (IFE), in particular, has enormous potential, has had significant recent progress, and can build off its substantial achievements. Furthermore, IFE allows for an attractive development path with modular technology development that also lends itself to spin-out technologies.

After demonstrating ignition on the National Ignition Facility (NIF), we are at a critical juncture in IFE research. As a community, we can exploit the growing scientific basis of fusion ignition, burn, and energy gain for practical applications. We have the opportunity now to incorporate and integrate multiple emerging technologies to make rapid progress. We can overcome the technology challenges associated with high-repetition rate and efficient, economical, and reliable energy systems with expanded, coordinated research, development, and deployment programs and strategic public-private partnerships (PPPs).

The United States is the current leader in high-energy-density (HED) and inertial confinement fusion (ICF) research and must capitalize on its decades of expertise and skilled workforce in this arena to lead the way in IFE. We have a unique opportunity right now to grow the national program by nourishing and leveraging our leadership in ICF with unique and world-leading competencies in the science and technology that underpins IFE.

The NIF results, progress with the laser direct-drive and magnetic-drive approaches, private sector interest, sustained advocacy, and new legislation have created a supportive environment today for a revitalized U.S. IFE program. This Basic Research Needs (BRN) workshop report has laid out priority research opportunities (PROs) to help the United States drive forward the science and technologies crucial to successfully realizing IFE on a relevant timescale.

The fusion energy industry and landscape is evolving—it is a unique and exciting time. Now is the moment to start a robust IFE program in the United Sates under the auspices of the DOE Office of Science – Fusion Energy Sciences (FES).

SECTION SEVEN

APPENDICES

APPENDIX I: WORKSHOP CHARGE

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.

Fusion, the process that powers the Sun, has the potential to provide a reliable, limitless, safe, and clean energy source. The development of fusion energy is a grand scientific and technical challenge that requires diverse approaches and paths to maximize the likelihood of success. Currently, the main approach pursued by the U.S. Fusion Energy Sciences program is that of magnetic fusion energy (MFE). Another approach is known as inertial fusion energy (IFE). The 2013 National Academy of Sciences report entitled "An Assessment of the Prospects for Inertial Fusion Energy" 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". In 2021, the National Ignition Facility achieved a record gain of more than 1.3 megajoules (MJ) from fusion reactions. This breakthrough result, coupled with recommendations in the recent Fusion Energy Sciences Advisory Committee Long-Range Plan to establish an IFE program, as well as Congressional authorization, provides a motivation for a BRN Workshop to assess the status of IFE and outline science and technology priority research opportunities.

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:
    ∀ Demonstration of ignition and reactor-level gain
    ∀ Manufacturing and mass production of reactor-compatible targets
    ∀ Driver technology at reactor-compatible energy, efficiency, and repetition rate
    ∀ Target injection, tracking and engagement at reactor-compatible specifications
    ∀ Chamber design and first wall materials
    ∀ Self-consistency of the proposed concepts regarding an integrated power plant design, to inform the formation of a balanced IFE program
4. Identify magnetic fusion energy (MFE) efforts in the United States and abroad

that could be leveraged to advance IFE (e.g., blanket, structural, and plasma-facing materials development, deuterium-tritium fuel cycle processing, remote handling technology, safety analysis tools, waste stream management, modeling and simulation, etc.), and identify where there are substantive differences in these systems that require IFE-specific development.

5. Assess the role of the private sector, including public-private partnerships in a national IFE Program and design of a fusion pilot plant.

Assessment of IFE research opportunities should span experiments, theory and simulation, artificial intelligence and machine learning, diagnostics, drivers, targets, target delivery, integrated plant design, and systems engineering.

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

APPENDIX II: WORKSHOP PARTICIPANTS

Workshop Leadership at DOE

Kramer Akli (SC/FES)

James Van Dam (SC/FES)

Chair and Co-Chair

Tammy Ma

Riccardo Betti

Coupling Physics

Max Karasik (panel lead)

Siegfried Glenzer (panel lead)

Bedros Afeyan

Dustin Froula

Pat Knapp

Yin Lin

Pierre Michel

Jason Myatt

Sean Regan

Robbie Scott

Yasuhiko Sentoku

Compression and Burn

John Kline (panel lead)

Omar Hurricane (panel lead)

Stefano Atzeni

Jason Bates

Alison Christopherson

Valeri Goncharov

Ryosuke Kodama

Carolyn Kuranz

Steve Slutz

Cliff Thomas

Alex Zylstra

Alternate Concepts

Cameron Geddes (panel lead)

Pravesh Patel (panel lead)

Brian Albright

Ken Anderson

Farhat Beg

Tom Mehlhorn

Peter Norreys

John Perkins

Scott Wilks

Drivers

Constantin Haefner (panel lead)

Steve Payne (panel lead)

Colin Danson

Todd Ditmire

Conner Galloway

Ryan McBride

Steve Obenschain

Jorge Rocca

Thomas Schenkel

Tom Spinka

Jon Zuegel

Targets

Mike Farrell (panel lead)

Dave Harding (panel lead)

Neil Alexander

Mark Bonino

Eric Duoss

Yongfeng Lu

Wendi Sweet

Ying Tsui

Power Systems, Science, Engineering, and Technology

Lance Snead (panel lead)

Walter Shmayda (panel lead)

Mike Dunne (panel lead)

Dave Babineau

Dave Crandall

Brenda Garcia-Diaz

Erik Gilson

Rob Kolasinski

Kevin Kramer

Harry McLean

Mianzhen Mo

Mike Tobin

George Tynan

Jeff Ulreich

Bruno Van Wonterghem

Steve Zinkel

Theory and Simulations

Radha Bahukutumbi (panel lead)

Jean-Luc Vay (panel lead)

Jerry Chittenden

Frederico Fiuza

Stephanie Hansen

Marty Marinak

Michael Murillo

Andrew Schmitt

Mark Sherlock

Artificial Intelligence and Machine Learning

Jeff Hittinger (panel lead)

Simon Woodruff (panel lead)

Ryan Coffee

Varchas Gopalaswamy

Peter Heuer

Derek Mariscal

Chris Orban

Luc Peterson

Brian Spears

Measurement Innovations

Maria Gatu-Johnson (panel lead)

Arianna Gleason (panel lead)

Félicie Albert

Lan Gao

Matthew Hill

David Schlossberg

Rahul Shah

Wolfgang Theobald

Research Infrastructure

Douglass Schumacher (panel lead)

Roger Falcone (panel lead)

Gilliss Dyer

John Edwards

Li Fang

Alan Fry

Rick Kraus

Sam Morse

Marius Schollmeier

Peter Siedl

Jackson Williams

Public-Private Partnership

Vincent Tang (panel lead)

Mike Campbell (panel lead)

Cris Barnes

Ahmed Diallo

Andrew Holland

Mario Manuel

Matthew Moynihan

Christophe Simon-Boisson

Workforce

Mingsheng Wei (panel lead)

Arturo Dominguez (panel lead)

Richard Buttery

Frank Graziani

Mark Koepke

Special thank yous to Chandra Curry, Leilani Conradson, Jessica Troxel, and Brittany Lemesh of SLAC for hosting the BRN website and coordinating the zoom and virtual meeting logistics for the virtual BRN.

Thank you also to Optica and David Lang for hosting the BRN chairs to run the virtual BRN from Optica headquarters in DC.

Credit for report cover page and section break artwork goes to Janelle Cataldo and Brian Chavez, LLNL.

Editing and formatting of the final report was done by Katie Lindl, Melanie Mendez, Janelle Cataldo, and Jeannette Yusko, LLNL.

APPENDIX III: WORKSHOP PROGRAM

This BRN occurred over several months of 2022. The Covid pandemic occurring at this time thus required that all activities related to the BRN occur virtually.

Prior to the 3-day workshop, the panels were convened and commenced work on information gathering, and tackling portions of the charge in pre-BRN meetings.

2022 IFE Basic Research Needs Workshop

all sessions held virtually over Zoom

Day 1: June 21, 2022		
Open Session		
Plenaries		
Welcome & Review Charge	*Riccardo Betti*	11:00 – 11:10 am (ET)
FES Welcome	*Jim Van Dam*	11:10 – 11:20 am
SC3 Deputy Director Remarks	*Harriet Kung*	11:20 – 11:30 am
Representative Zoe Lofgren Remarks	*Zoe Lofgren (recorded)*	11:30 – 11:40 am
Staff, Energy Subcommittee; Committee on Space, Science, and Technology, U.S. House of Representatives	*Adam Rosenberg & Daniel Dzaidon*	11:40 – 11:50 am
Accelerating fusion RD&D via public-private partnerships	*Scott Hsu*	11:50 am – noon
Overview of IFE history, challenges, and prospects for driver-target concepts	*Mike Campbell*	12:00 – 1:00 pm
Break: 1:00 – 2:00pm		
Leveraging ICF to propel IFE	*John Edwards*	2:00 – 2:30 pm
Privately funded fusion companies	*Andrew Holland*	2:30 – 2:45 pm
BRN marching orders, deliverables, schedules	*Tammy Ma*	2:45 – 3:00 pm
Open Session		
Committee Discussion	*Committee*	3:00 – 6:00 pm

Post BRN-workshop, the panels continued to meet in their small groups to develop content and write up their findings and PRO's.

Day 2: June 22, 2022		
Closed Session		
Committee Discussion	*Committee*	11:00 am – 6:00 pm

Day 3: June 23, 2022		
Closed Session		
Committee Discussion	*Committee*	11:00 am – 5:30 pm
Writing assignments, due dates, report structure	*Tammy Ma & Riccardo Betti*	5:30 – 5:45 pm
Final wrap-up	*Tammy Ma & Riccardo Betti*	5:45 – 6:00 pm

Post BRN-workshop, the panels continued to meet in their small groups to develop content and write up their findings and PRO's.

APPENDIX IV: ACRONYMS APPEARING IN THE REPORT

AI	Artificial Intelligence
AKN	Alpha Knock-On Neutron
AMD	Advanced Micro Devices
appm	Atomic Parts Per Million
APS	American Physical Society
AR	Anti-Reflection
ARA	ATOM Research Alliance
ARDP	Advanced Reactor Demonstration Programs
ArF	Argon-Fluoride Laser
ARPA-E	Advanced Research Projects Agency – Energy
ASCR	DOE Office of Advanced Scientific Computing Research
ASE	Amplified Stimulated Emission
BES	DOE Office of Basic Energy Sciences
BRN	Basic Research Needs
CAPEX	Capital Expenditure
CBET	Crossed Beam Energy Transfer
CHS	Central Hotspot
COE	Cost of Electricity
CONOPS	Concept of Operations
COPA	Collinear Optical Parametric Amplification
COTS	Commercial Off-the-Shelf
COTS	NASA’s Commercial Orbital Transportation Services (*Ch. 11 only*)
CPA	Chirped Pulse Amplification
CPP	Community Planning Process
CR	Convergence Ratio
CRADA	Cooperative Research and Development Agreement
D	Deuterium
DCLL	Dual Coolant Lead Lithium
DFT-MD	Density-Functional-Theory Molecular Dynamics
DIR	Direct Internal Recycle
DL	Deep Learning

DOE	Department of Energy
dpa	Displacements Per Atom
DPP	Division of Plasma Physics
DPSSL	Diode-Pumped Solid-State Laser
DT	Deuterium-Tritium
ECP	Exascale Computing Project
ELI	Extreme Light Infrastructure
ELMs	Edge-Localized Modes
EMP	Electromagnetic Pulse
EOS	Equations of State
EUV	Extreme Ultraviolet
FAIR	Findable, Accessible, Interoperable, Reusable
FAIR Facility	Facility for Antiproton and Ion Research
FES	DOE Office of Fusion Energy Sciences
FESAC	Fusion Energy Sciences Advisory Committee
FFRDC	Federally Funded Research and Development Centers
FI	Fast Ignition
FPGA	Field-Programmable Gate Arrays
FPNS	Fusion Prototypic Neutron Source
FPP	Fusion Pilot Plant
FPY	Full Power Year
FRIB	Facility for Rare Isotope Beams
FWHM	Full-Width at Half-Maximum
GAIN	Gateway for Accelerated Innovation in Nuclear
GAO	U.S. Government Accountability Office
HAPL	High Average Power Laser (referring to the DOE-funded program 2000-2008)
HAPLS	High Repetition Rate Advanced Petawatt Laser System
HCLL	Helium Cooled Lead Lithium
HCPB	Helium Cooled Pebble Bed
HED	High Energy Density
HEDS	High Energy Density Science
HEDP	High Energy Density Physics
HEP	High Energy Physics
HIF	Heavy-Ion Fusion

HiPER	High Power Laser Energy Research
HPC	High-Performance Computing
HR	High Reflection
HSR	Higher Shot Rate
HTI	Healthy to Innovative (Framework)
ICF	Inertial Confinement Fusion
ID	Indirect Drive
IFE	Inertial Fusion Energy
INFUSE	Innovation Network for Fusion Energy
IP	Intellectual Property
IPA	Intergovernmental Personnel Act
ISI	Induced Spatial Incoherence
KrF	Krypton-Fluoride Laser
LBNL	Lawrence Berkeley National Laboratory
LCLS	Linac Coherent Light Source
LDD	Laser Direct-Drive
LFEX	Laser for Fast Ignition Experiment, Osaka University
LIA	Linear Induction Accelerator
LIBS	Laser-Induced Breakdown Spectroscopy
LID	Laser Indirect-Drive
LIDT	Laser-Induced Damage Threshold
LIFE	Laser Inertial Fusion Energy (referring to the LLNL program 2008-2013)
LiT	Lithium Tritide
LLE	Laboratory for Laser Energetics, University of Rochester
LLNL	Lawrence Livermore National Laboratory
LMJ	Laser Megajoule
LPI	Laser-Plasma Instability
LTD	Linear Transformer Driver
LTE	Local Thermodynamic Equilibrium
MagLIF	Magnetized Liner Inertial Fusion
MCMC	Markov Chain Monte Carlo
MCNP	Monte Carlo N-Particle
MD	Molecular Dynamics
MDD	Magnetic Direct Drive

MDF	Magnetically Driven Fusion
MEC-U	Matter at Extreme Conditions-Upgrade
MFE	Magnetic Fusion Energy
MHD	Magnetohydrodynamic
MIT	Massachusetts Institute of Technology
ML	Machine Learning
MLD	Multi-Layer Dielectric
Mod/sim	Modeling and Simulation
MPEX	Materials Plasma Exposure eXperiment
MSI	Minority Serving Institution
MSIPP	Minority Serving Institution Partnership Program
MSRR	Molten Salt Research Reactor
MTTF	Mean Time to Failure
NAS	National Academies of Sciences
NASEM	National Academies of Sciences, Engineering, and Medicine
NE	Office of Nuclear Energy (DOE)
NIF	National Ignition Facility
NNSA	National Nuclear Security Administration (DOE)
NOPA	Noncollinear Optical Parametric Amplification
NP	DOE Office of Nuclear Physics
NRC	Nuclear Regulatory Commission
NRL	Naval Research Laboratory
NSCAR	Nearby Skeleton Constrained Accelerated Recomputing
nToF	Neutron Time-of-Flight
OPEX	Operating Expenditure
OPA	Optical Parametric Amplification
ORNL	Oak Ridge National Laboratory
OTA	Other Transaction Authority
PAV	Permeation Against Vacuum
PDD	Polar Direct Drive
PIC	Particle-in-Cell
PIMC	Path-Integral Monte Carlo
PINN	Physics-Informed Neural Network
PIP-II	the Proton Improvement Plan-II

PKA	Primary Knock-on Atom
PPP	Public Private Partnership
PPPL	Princeton Plasma Physics Laboratory
PRO	Priority Research Opportunity
Q&A	Quality and Assurance
R&D	Research and Development
RAFM	Reduced-Activation Ferritic/Martensitic
RENEW	Reaching a New Energy Sciences Workforce
RFI	Request for Information
RTL	Recyclable Transmission Line
SBIR	Small Business Innovation Research
SBS	Stimulated Brillouin Scatter
SC	DOE Office of Science
SciDAC	Scientific Discovery through Advanced Computing
SCMS	Single Coolant Molten Salt
SFG	Sum Frequency Generation
SI	Shock Ignition
SINDy	Sparse Identification of Nonlinear Dynamical Systems
SNS	Spallation Neutron Source
SPP	Strategic Partnership Project
SRS	Stimulated Raman Scatter
SRRS	Stimulated Rotational Raman Scattering
SSD	Smoothing by Spectral Dispersion
SSS	Strong Spherical Shock
STAR	Safety and Tritium Applied Research
STTR	Small Business Technology Transfer
STUD	Spike Train of Uneven Duration and Delay
T	Tritium
TBR	Tritium Breeding Ratio
TEX	Tritium Extraction Experiment
TNSA	Target Normal Sheath Acceleration
TPD	Two Plasmon Decay
TRL	Technology Readiness Level
UHI	Ultra-High Intensity

UKAEA	U.K Atomic Energy Authority
UV	Ultraviolet
UVTS	Ultraviolet Thomson Scattering
VFP	Vlasov-Fokker-Planck
VLTs	(DOE) Virtual Laboratories for Technology
VNL	Virtual National Lab
WCLL	Water Cooled Lead Lithium
WDM	Warm Dense Matter
WFO	Work for Others
WS	Woodruff Scientific
XFEL	X-Ray Free-Electron Laser