2022 DOE Basic Research Needs for Inertial Fusion Energy (IFE)

ARPA-E Workshop: Enabling Technologies for Improving Fusion Power Plant Performance and Availability

March 7, 2023

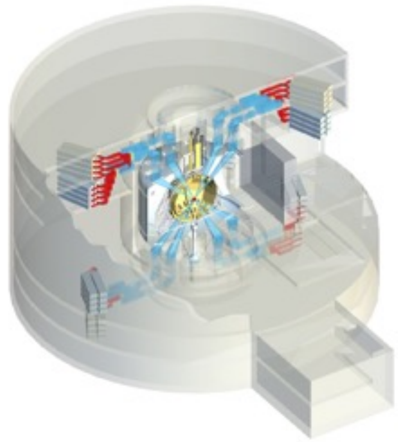
Tammy Ma, BRN Chair

Fusion energy may be the ultimate clean and limitless energy source

Desirable features for future energy sources

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

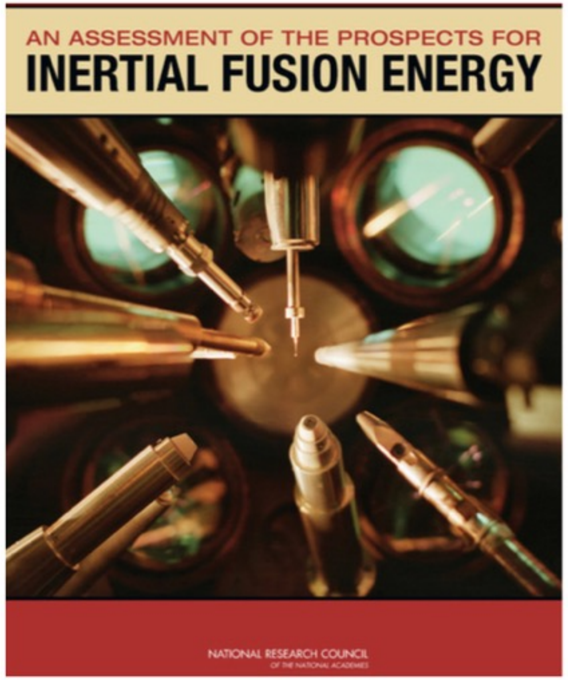
Fusion has the potential to meet all of these!



Advantages of the inertial fusion energy (IFE) concept:

- Scientific energy gain has been demonstrated
- Significantly different technological risks than MFE
- Separable components / Highly modular
- Multiple target concepts with same driver
- Reduced tritium inventory
- Attractive development path
- Technology and science spin-offs
- Multiple sponsors for key technologies (e.g., laser diodes, high neutron yield sources)

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



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

Progress across multiple laser drive and magnetic drive approaches

Private sector interest and investment

Sustained advocacy

New legislation

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

Over 2022, the US DOE held a Basic Research Needs in IFE to define a new national IFE program

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

Process:

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

The workshop report was released in Jan 2023

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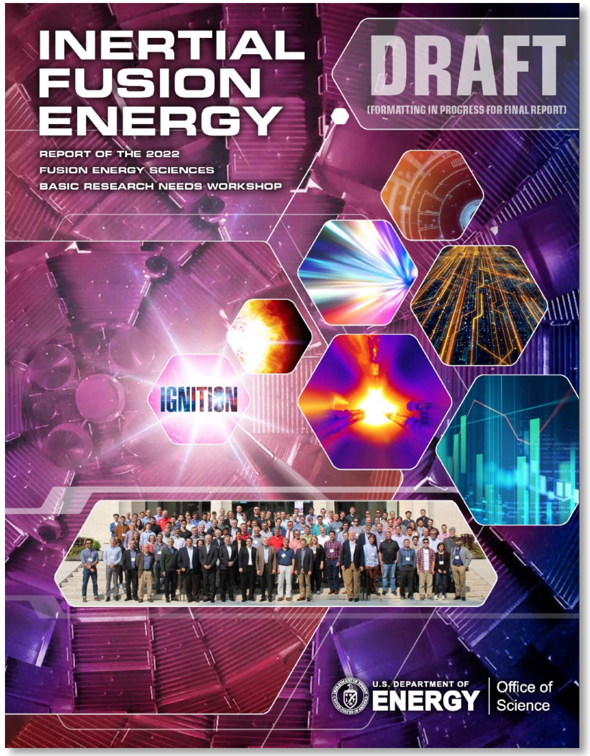


Report released Jan 2023

Final editing in progress. Aiming for mid-March for final product

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

BRN Charge

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

Department of Energy
Office of Science
Washington, DC 20585

5/27/2022

Dear Colleagues:

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

Charge:

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

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

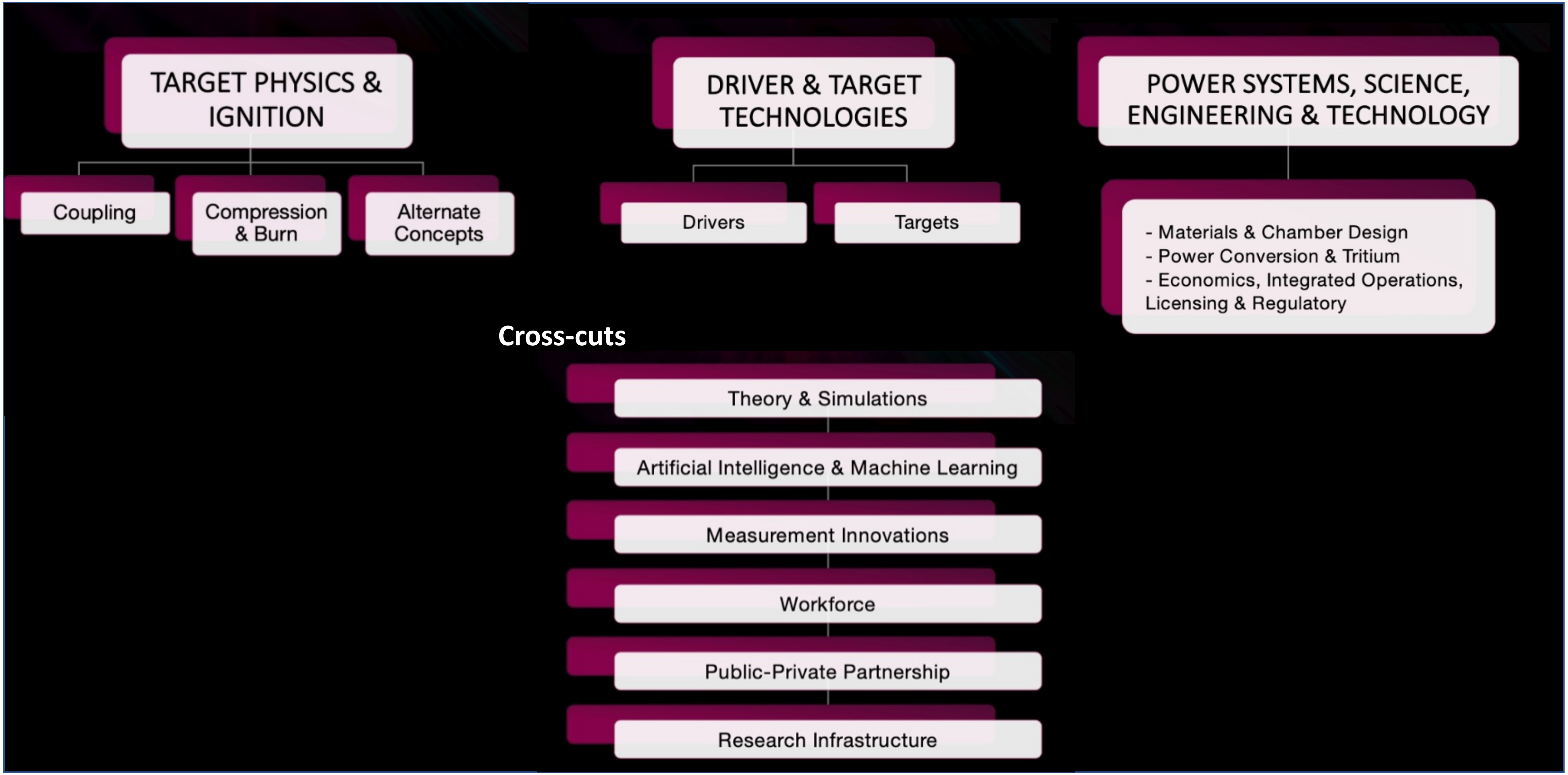
A website for the workshop is planned to keep the community informed on the progress and matters relating to the workshop.

Sincerely,

James W. Van Dam

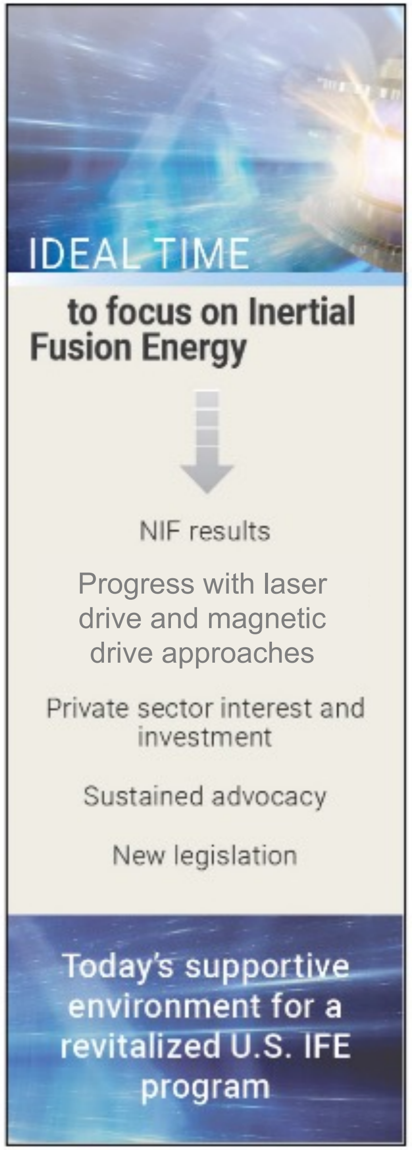
James Van Dam
Associate Director, Office of Science
Fusion Energy Sciences

Fostering a New Era of Inertial Fusion Energy S&T



Overarching Findings

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



Overarching Priority Research Opportunities

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

Overarching Structural Concepts

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

> "The 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)

PRO's from each Subpanel (1/2)

- **Coupling Physics:** 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 MagLIF and PP coupling.
- **Compression and Burn:** Identify the underlying physics limiting the convergence/areal density required for high gains (all concepts).
- **Alternate 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).
- **IFE 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 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.

PRO’s from each Subpanel (2/2)

- **Modeling and Simulations:** 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) - Machine Learning (ML):** Take advantage of AI-ML for data analysis of next generation of high rep 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 rep 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:** Facilitate partnerships between private IFE companies and government labs and universities to leverage substantial public sector capabilities towards joint development and acceleration of IFE commercialization, and to aid private companies to capture 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.

Driver PRO’s

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

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

PRO 4-3: Increase the damage threshold 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

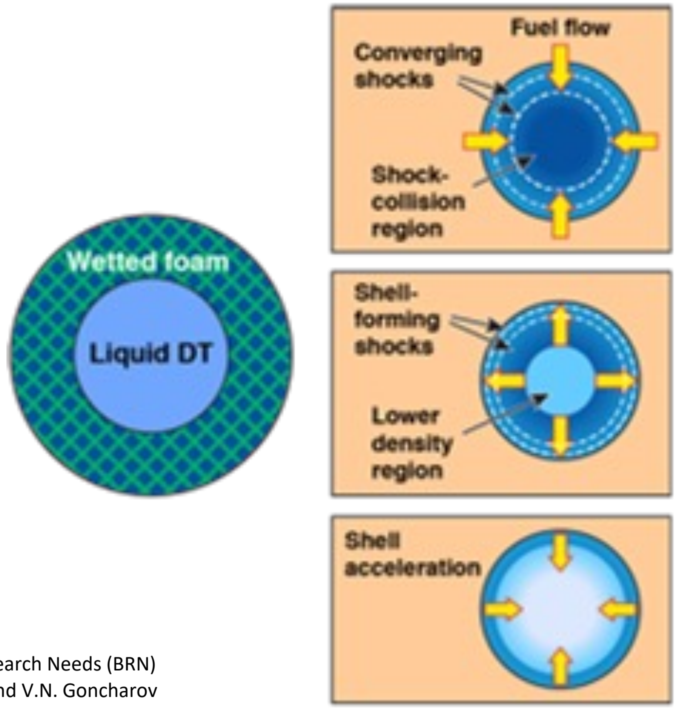
***Fig. 4.1**: The High Repetition Rate Advanced Petawatt Laser System (HAPLS) architecture is based on eight major key laser technology leaps that enable high peak power pulses with 10Hz repetition rate.*

Target Manufacturing PRO's

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



OR ~1700um

CH foam ~0.1gm/cc

Wall ~500 um

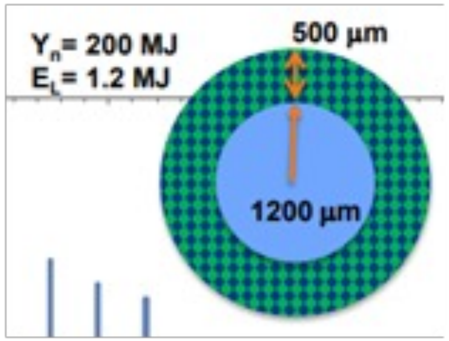


Figure 5.3: *Laser direct drive target, wetted foam with liquid DT layer formed dynamically by laser pulse shaping while target is on-the-fly toward chamber center. Target is completely full of liquid DT prior to the pulse shaping[1]*

[1]E.M. Campbell talk,"Overview of ICF History, Challenges Prospects for Driver-target Concepts", to Basic Research Needs (BRN) Workshop, June21-23, 2022; and adapted from V. N. Goncharov, et al, Phys. Rev. Lett. 125, 065001 (2020), and V.N. Goncharov talk, "Interial fusion Energy Target Designs with Advanced Laser Technologies", to IFE Science & Technology Community Strategic Planning Workshop, 22-24 February 2022, https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/agenda

Power Systems Science, Engineering, & Technology PRO's

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 RD&D program

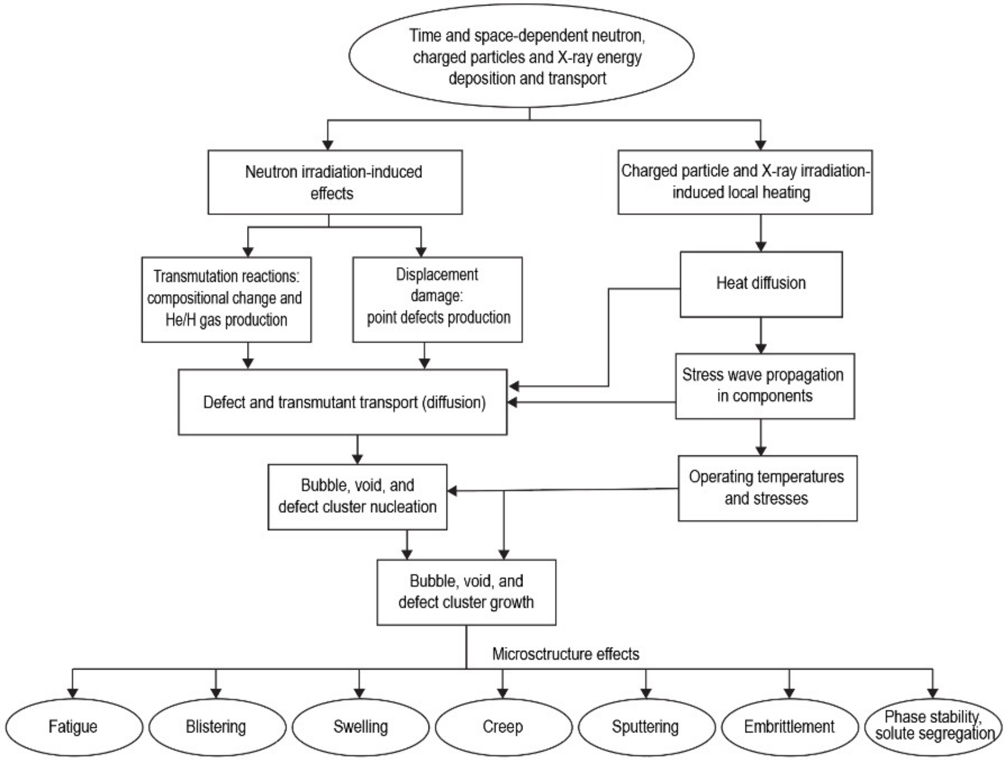


***Figure 6.2.** Overview of the radiation damage processes and ensuing effects in pulsed fusion reactor systems. This diagram is modified from Ref* to better illustrate the neutron-irradiation effects.*

Ref*: S. Zinkle et al. Annu. Rev. Mater. Res. 44, 241 (2014)

A Technical Readiness Level (TRL) evaluation was completed for five target-driver systems

		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	Proof-of-Concept	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.
	Proof-of-Concept	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	Proof-of-Principal	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.
	Proof-of-Principal	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).
	Proof-of-Performance	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	Proof-of-Performance	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.

The 5 driver-target systems

(1) Laser Indirect-Drive
(2) Laser Direct-Drive, including Shock Ignition
(3) Fast Ignition
(4) Heavy Ion Fusion
(5) Magnetically-Driven Fusion

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

Short term initiatives: carry out scoping studies of the different IFE concepts

OVERARCHING PRO#3. Develop scoping studies to evaluate the various IFE concepts. With input from the energy industry and fusion science and technology experts, identify the most promising concepts to guide downselection and to inform directions of technological development.

- There are five major IFE concepts currently under development at very different levels of effort

(1) Laser Indirect-Drive	High
(2) Laser Direct-Drive, including Shock Ignition	Moderate
(3) Fast Ignition	Low-Moderate
(4) Heavy Ion Fusion	Low
(5) Magnetically-Driven Fusion	Moderate

- Not enough resources to advance all concepts if IFE has to play a role in the energy portfolio in the non too distant future

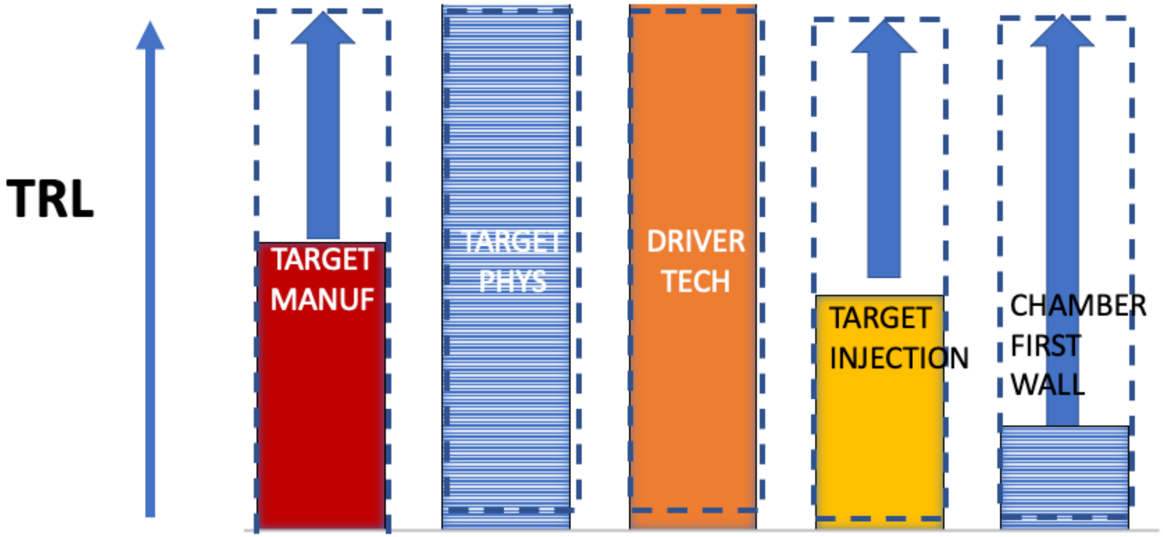
- More effective to assess the viability of each concept and downselect to a few

The scoping studies should utilize systems integration as the principle guiding the development of an IFE concept

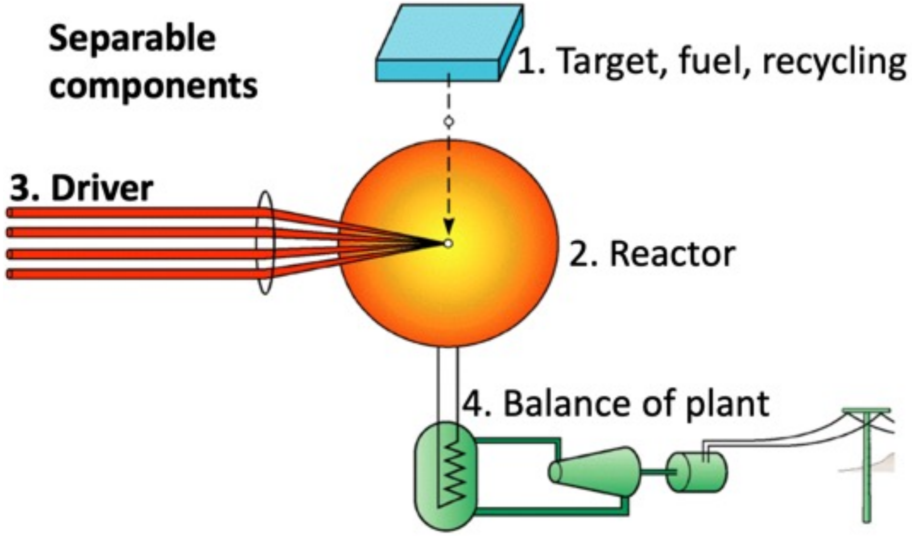
- Each concept has potential showstoppers that need to be assessed for viability of paths forward. For instance:
  - Magnetic drive → cost of recyclable transmission lines
  - Laser direct and indirect drive → chamber clearing, injection and tracking at ~ 10 Hz
  - Fast Ignition → same issues as laser drive + target complexity + two lasers instead of one
  - Heavy ion fusion → Final focusing, accelerator size and complexity, no implosions to date

OVERARCHING PRO#2. Employ system-level integrated studies to guide the IFE R&D in a coordinated fashion with the objective to advance the different areas of IFE science and technology towards the goal of building and operating an FPP.

- To make tangible progress towards a FPP requires that a systems level view be utilized to define requirements and necessary technology development



The path forward for IFE research diverges from that for NNSA's weapons research program because technologies specific to IFE will require development



The top-level technical challenges for fusion energy are well known:

1. Ignition and fusion energy gain
2. Fuel system delivery and cost
3. Lifetime of the fusion chamber and optics
4. Safety and licensing
   - Tritium and any activated materials
5. High availability plant operations

from NAS 2013

Inertial Fusion Energy is a grand scientific and engineering challenge with enormous potential energy and climate security payoffs.

The time is now to capitalize on the momentum for IFE!

BRN Charge

Department of Energy
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Washington, DC 20585

5/27/2022

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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.

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Sincerely,

James W. Van Dam

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

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)									