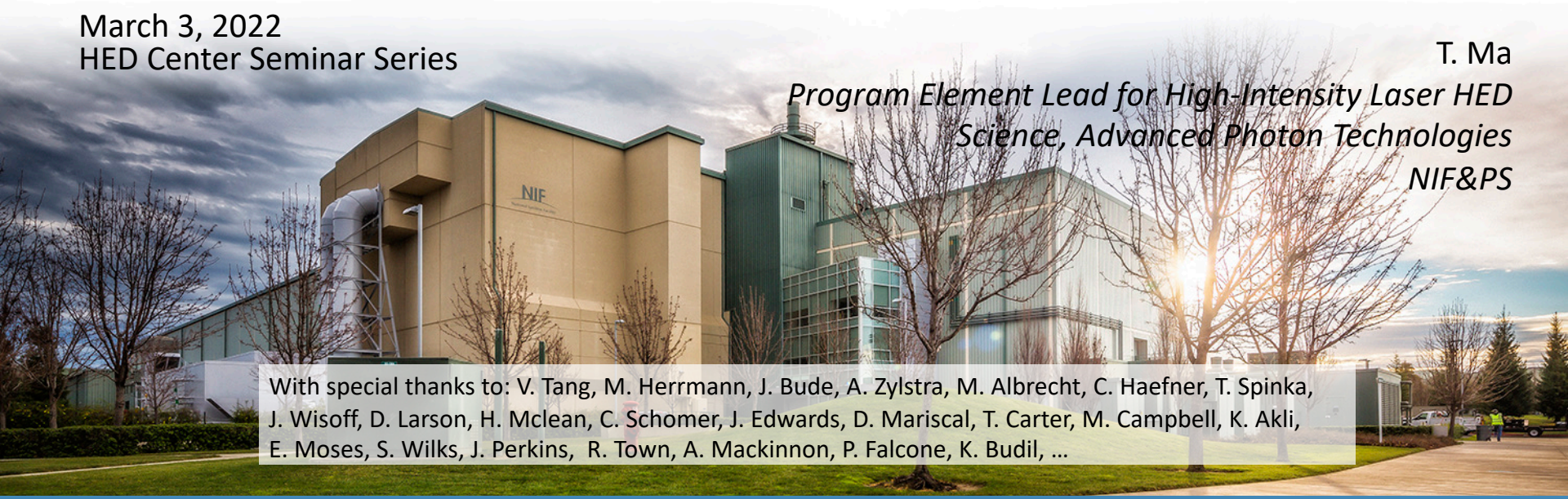
Inertial Fusion Energy: Plans and Progress for Reestablishing a National Program

March 3, 2022
HED Center Seminar Series

T. Ma
Program Element Lead for High-Intensity Laser HED Science, Advanced Photon Technologies
NIF&PS



With special thanks to: V. Tang, M. Herrmann, J. Bude, A. Zylstra, M. Albrecht, C. Haefner, T. Spinka, J. Wisoff, D. Larson, H. Mclean, C. Schomer, J. Edwards, D. Mariscal, T. Carter, M. Campbell, K. Akli, E. Moses, S. Wilks, J. Perkins, R. Town, A. Mackinnon, P. Falcone, K. Budil, …

LLNL-PRES-832330
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

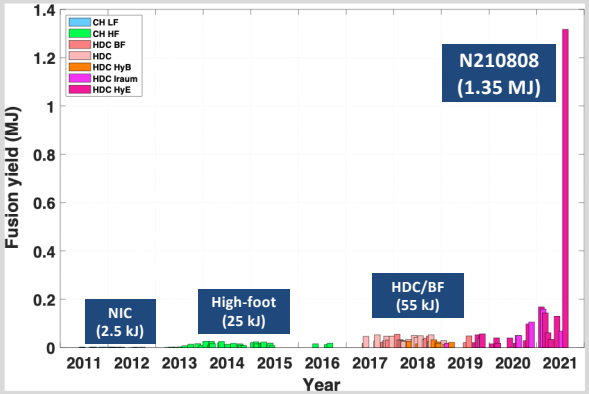
Game-changing ICF results on the NIF re-energize interest in Inertial Fusion Energy (IFE)

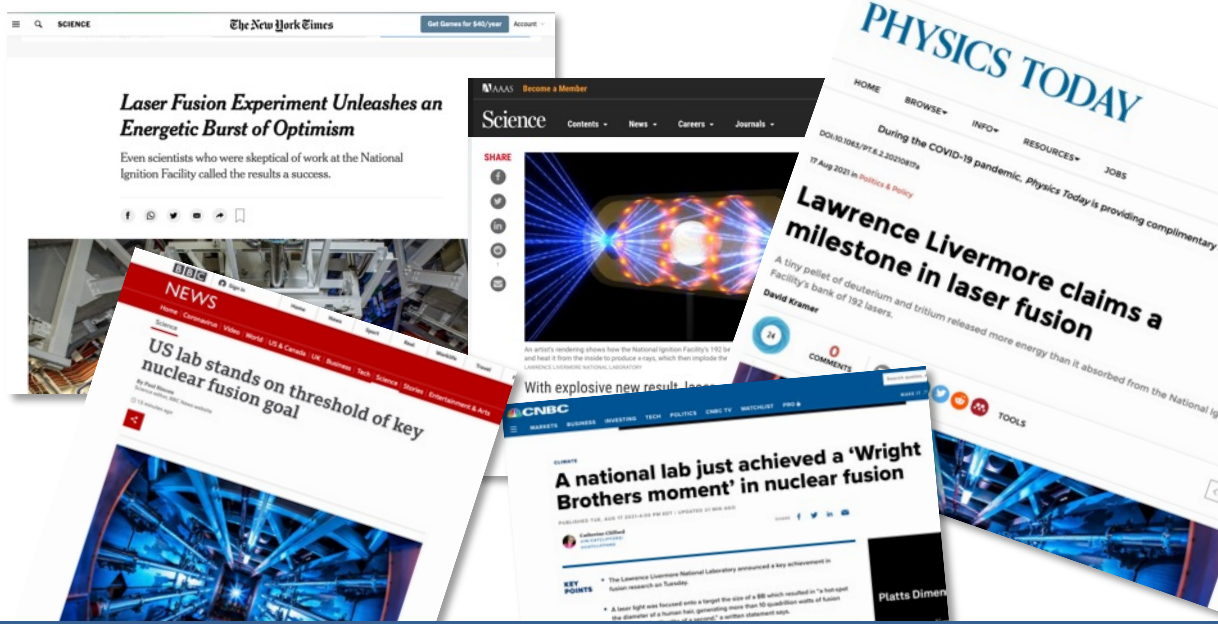
- There is currently no IFE program in the U.S.
- IFE and ICF via NNSA's SSP mission are highly synergistic, however IFE will require a different technology development path
- The time is right to restart an IFE program in the U.S. – decades of expertise in ICF combined with emerging technologies can enable rapid progress
- LLNL possesses many areas of key expertise that can contribute to the national effort
  - e.g., leveraging MEC-upgrade and high rep rate HED science to develop IFE-relevant technologies
- Through the recent 2020 FESAC Long Range Strategic Plan, the community strongly endorsed the re-establishment of an IFE program. A DOE BRN in IFE will be held this year.

In partnership with the wider community, LLNL's experience and expertise can support the reestablishment of a vibrant national IFE program and help to establish the technology basis for a credible development path towards clean fusion energy

The recent NIF results establish the basic scientific feasibility of laser-driven inertial fusion energy (IFE) – but a lot more to do!

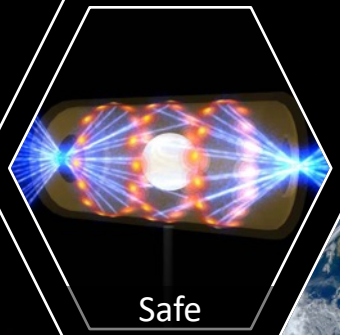
NIF Fusion Yield

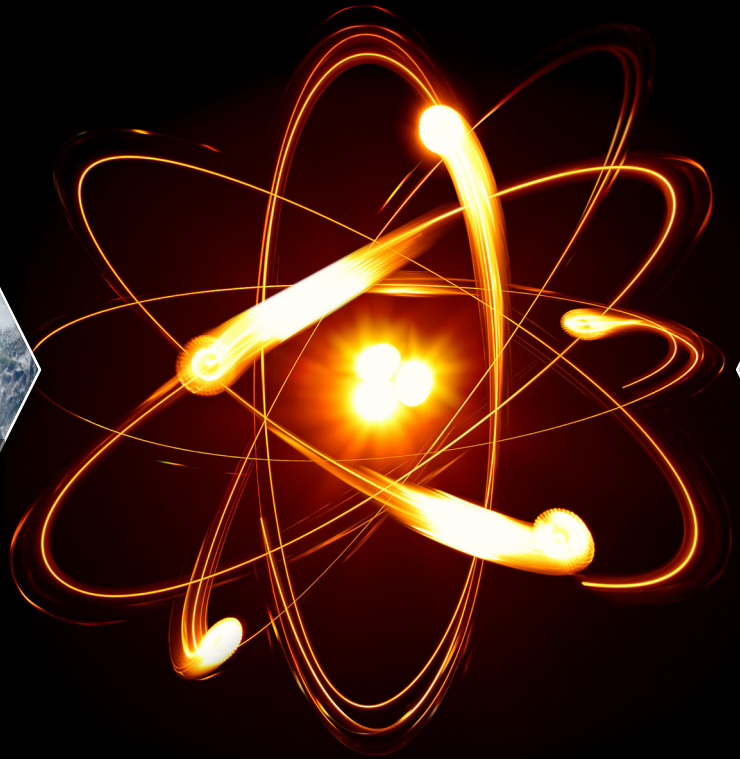


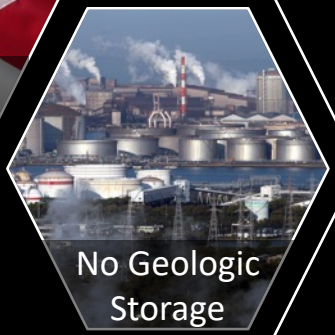


The excitement around the world (and immediate extrapolation to energy) was invigorating to see! The demonstration of ignition threshold paves the way to a broad, national, coordinated plan to pursue IFE

Fusion energy is attractive for many reasons

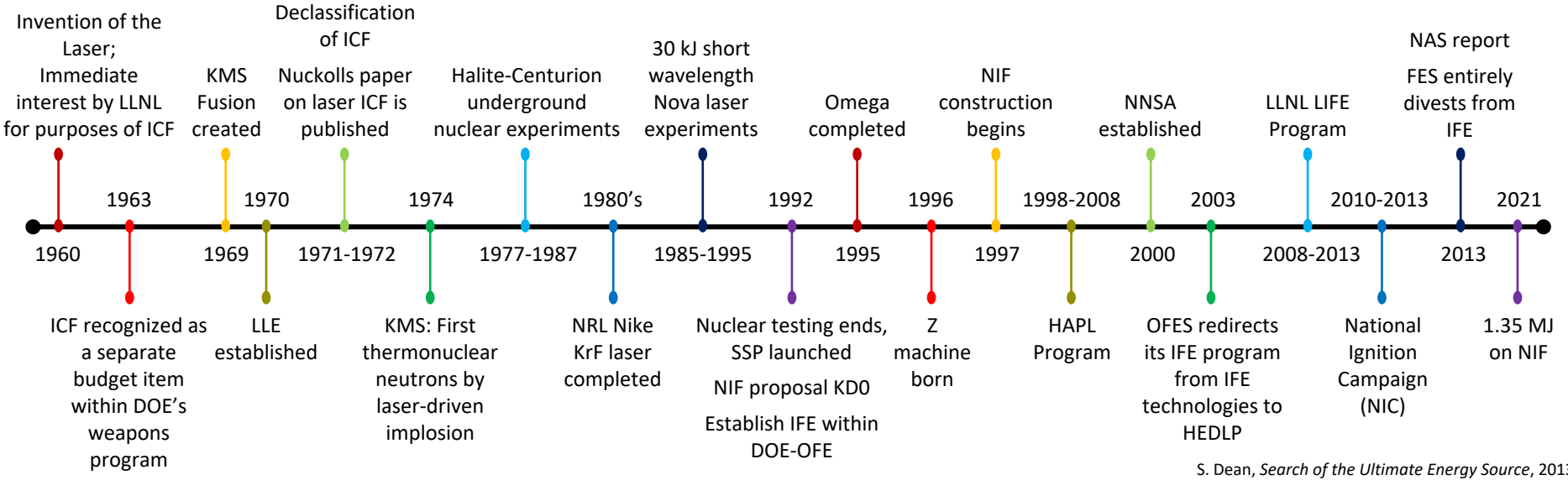






IFE offers a potential solution to help address the urgent issue of climate change while providing domestic energy security, and serves as a critical recruitment and training tool for DOE

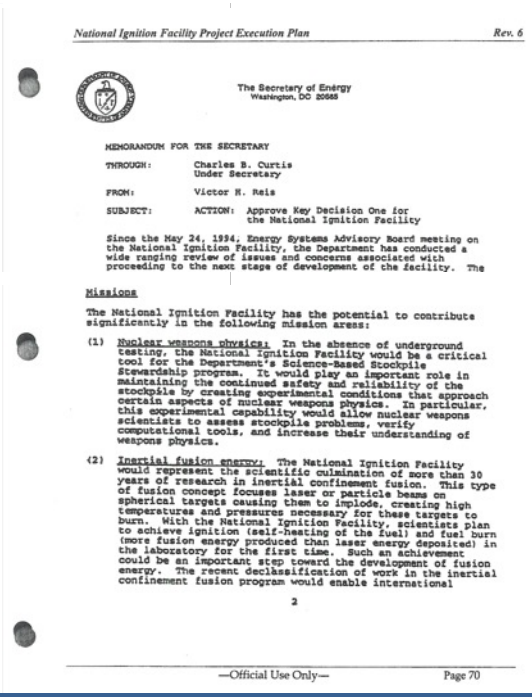
There is currently no IFE program in the U.S., and historically has largely been funded by Congressional add-ons and LDRD



S. Dean, *Search of the Ultimate Energy Source*, 2013
& Wikipedia

NNSA (primary funding source for inertial fusion) is focused on single-shot facilities and technologies; OFES is focused on fusion "science" and not currently energy development
→ DOE policy has had the effect of holding back IFE development

Today, IFE is not part of the current long-term energy R&D portfolio of the U.S. and is not being researched at LLNL



National Ignition Facility Project Execution Plan *Rev. 6*

The Secretary of Energy
Washington, DC 20585

MEMORANDUM FOR THE SECRETARY

THROUGH: Charles B. Curtis
Under Secretary

FROM: Victor H. Reis

SUBJECT: ACTION: Approve Key Decision One for the National Ignition Facility

Since the May 24, 1994, Energy Systems Advisory Board meeting on the National Ignition Facility, the Department has conducted a wide ranging review of issues and concerns associated with proceeding to the next stage of development of the facility. The

Missions

The National Ignition Facility has the potential to contribute significantly in the following mission areas:

(1) Nuclear weapons physics: In the absence of underground testing, the National Ignition Facility would be a critical tool for the Department's Science-Based Stockpile Stewardship program. It would play an important role in maintaining the continued safety and reliability of the stockpile by creating experimental conditions that approach certain aspects of nuclear weapons physics. In particular, this experimental capability would allow nuclear weapons scientists to assess stockpile problems, verify computational tools, and increase their understanding of weapons physics.

(2) Inertial fusion energy: The National Ignition Facility would represent the scientific culmination of more than 30 years of research in inertial confinement fusion. This type of fusion concept focuses laser or particle beams on spherical targets causing them to implode, creating high temperatures and pressures necessary for these targets to burn. With the National Ignition Facility, scientists plan to achieve ignition (self-heating of the fuel and fuel burn (more fusion energy produced than laser energy deposited) in the laboratory for the first time. Such an achievement could be an important step toward the development of fusion energy. The recent declassification of work in the inertial confinement fusion program would enable international

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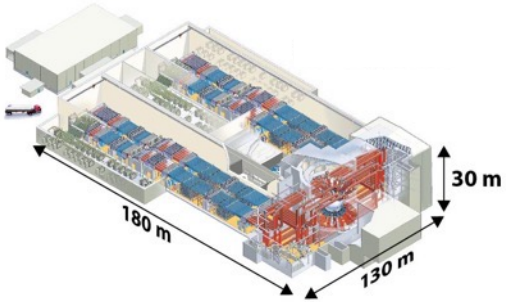
—Official Use Only— Page 70

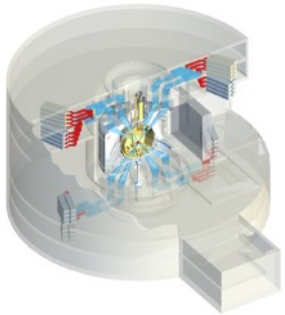
Developing IFE for civilian power production was one of the original mission needs in the NIF KD0, however the difficulty of achieving ignition compelled us to focus on SSP

The NIF is a scientific exploration facility, and very different from what would be needed for an IFE power plant

NIF: Single Shot



IFE plant: >10 Hz

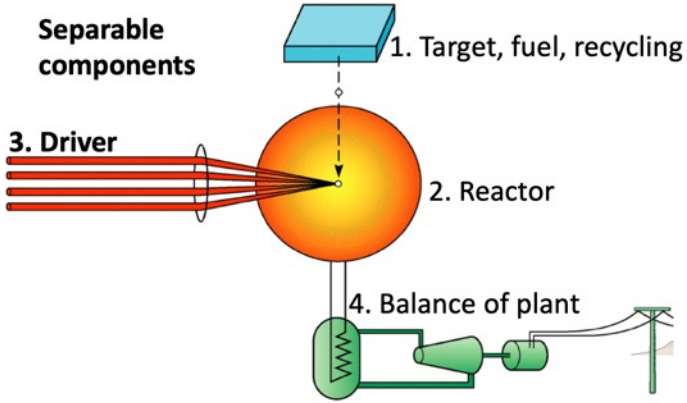


An electricity-producing IFE power plant would require:

- A more robust, high-margin ignition scheme
- A high-efficiency, high rep-rate driver
- Mass-production of robust targets
- High rep-rate target injection and tracking
- Energy conversion system
- Robust first walls and blankets for wall protection
- Tritium processing and recovery
- Remote maintenance systems
- Viable economics

The same fusion plasmas that we create for national-security applications can also be exploited to be the basis of IFE

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:

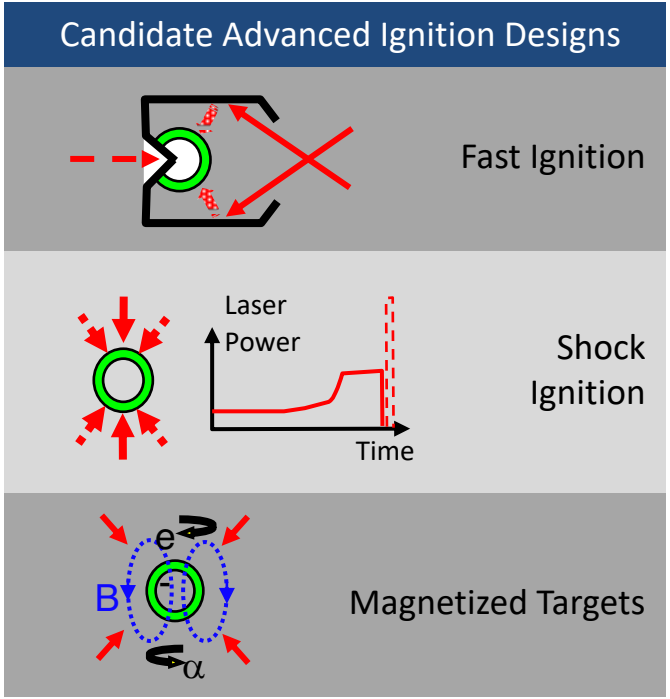
1. Ignition and fusion energy gain
2. Fuel system delivery and cost
3. Lifetime of the fusion chamber and optics
4. Safety and licensing
   - Tritium and any activated materials
5. High availability plant operations

from NAS 2013

We can take advantage of current ICF research on NIF and the opportunity to experiment at "fusion scale," while continuing to push IFE-relevant technologies (high avg power lasers, rep rate technologies, AI, targets) to advance the science and technology of IFE

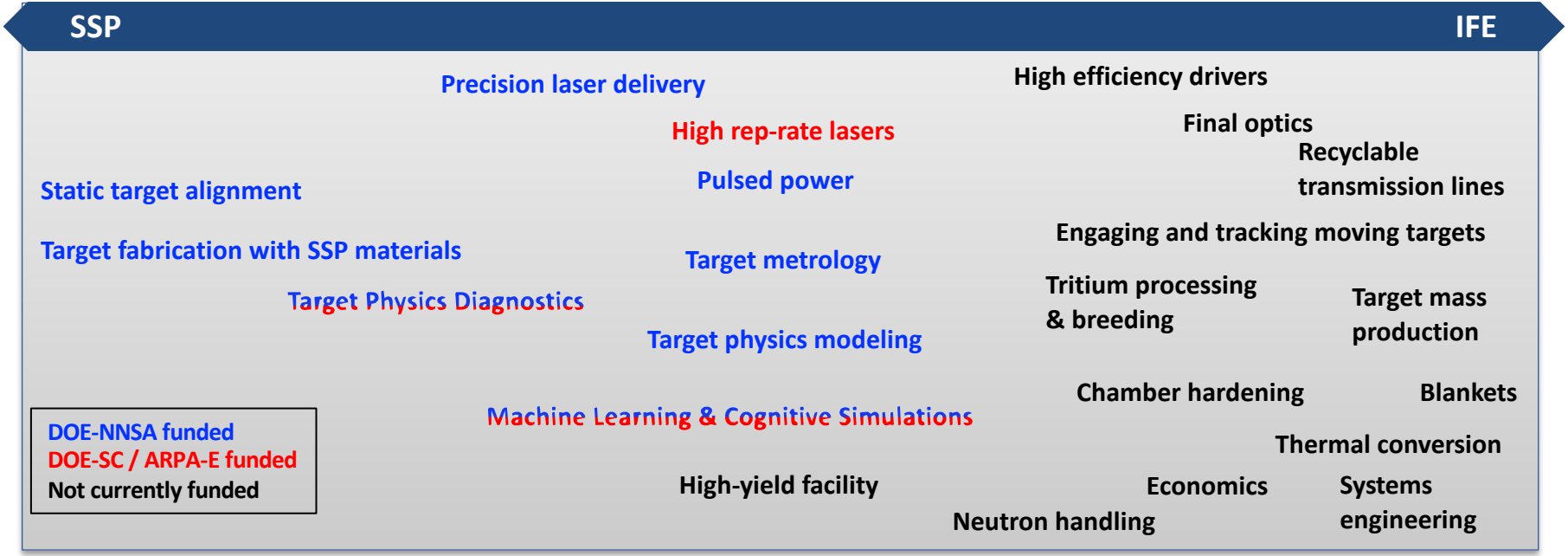
The synergies between IFE and ICF are many and mutually beneficial

- Advanced targets that could provide high gain for IFE could similarly produce high neutron yield for ICF applications
- Improvements in driver cost and repetition rate for IFE could similarly mean more HED experiments for SSP
- Simulation codes that guided us to 1.35 MJ can now be used to evaluate other schemes
- IFE offers a long-term solution for climate change and energy security – important factors in the overall national security landscape
- The exciting vision of IFE serves as an important recruitment and training tool for many DOE missions



LLNL has a special role to play: we can leverage our decades of expertise in ICF, and combine with new emerging technologies to enable rapid progress in IFE

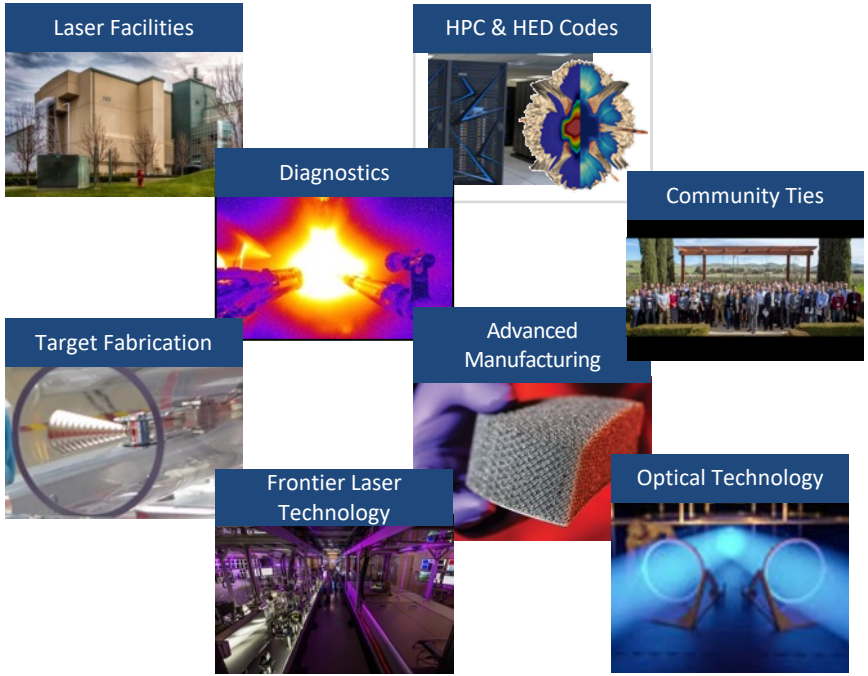
Many technologies are of interest to both SSP and IFE priorities, providing opportunities for partnership



"NNSA acknowledges there are areas of potential mutual interest for shared or aligned research, development, testing, and experimentation investments"

LLNL possesses many areas of expertise that can contribute to the national IFE effort

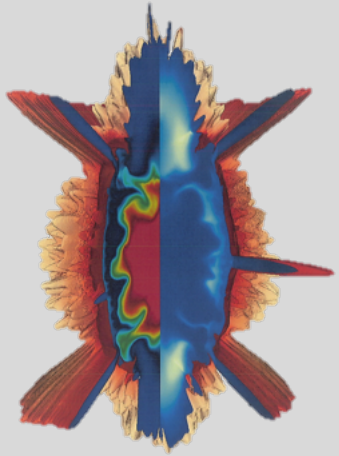
- Integrated experiments on NIF, Z, Omega + high-gain target physics
- Alternative concepts (HIF, FI, MagLIF)
- Advanced laser drivers
- Target fabrication & advanced manufacturing
- High-fidelity modeling and novel cognitive simulation
- Diagnostics & enabling technology
- Fundamental HEDP science and HED materials
- “Leapfrog” technologies such as plasma optics, heavy-ion beams
- Full systems engineering & modeling
- Expertise in transitioning technologies to industry



Many of the key technologies are uniquely brought together here

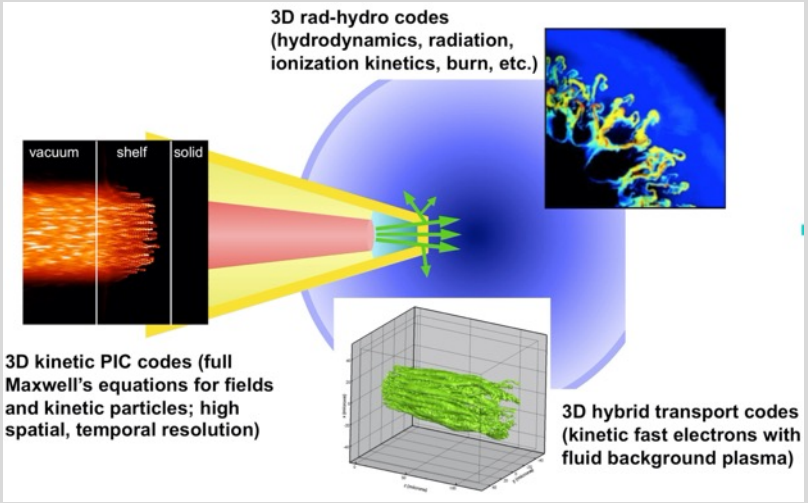
The increased physics understanding and refinement of codes over the past decade enables new evaluation of promising schemes

Central Hot Spot Ignition



Clark, et al IWPCTM, 2018

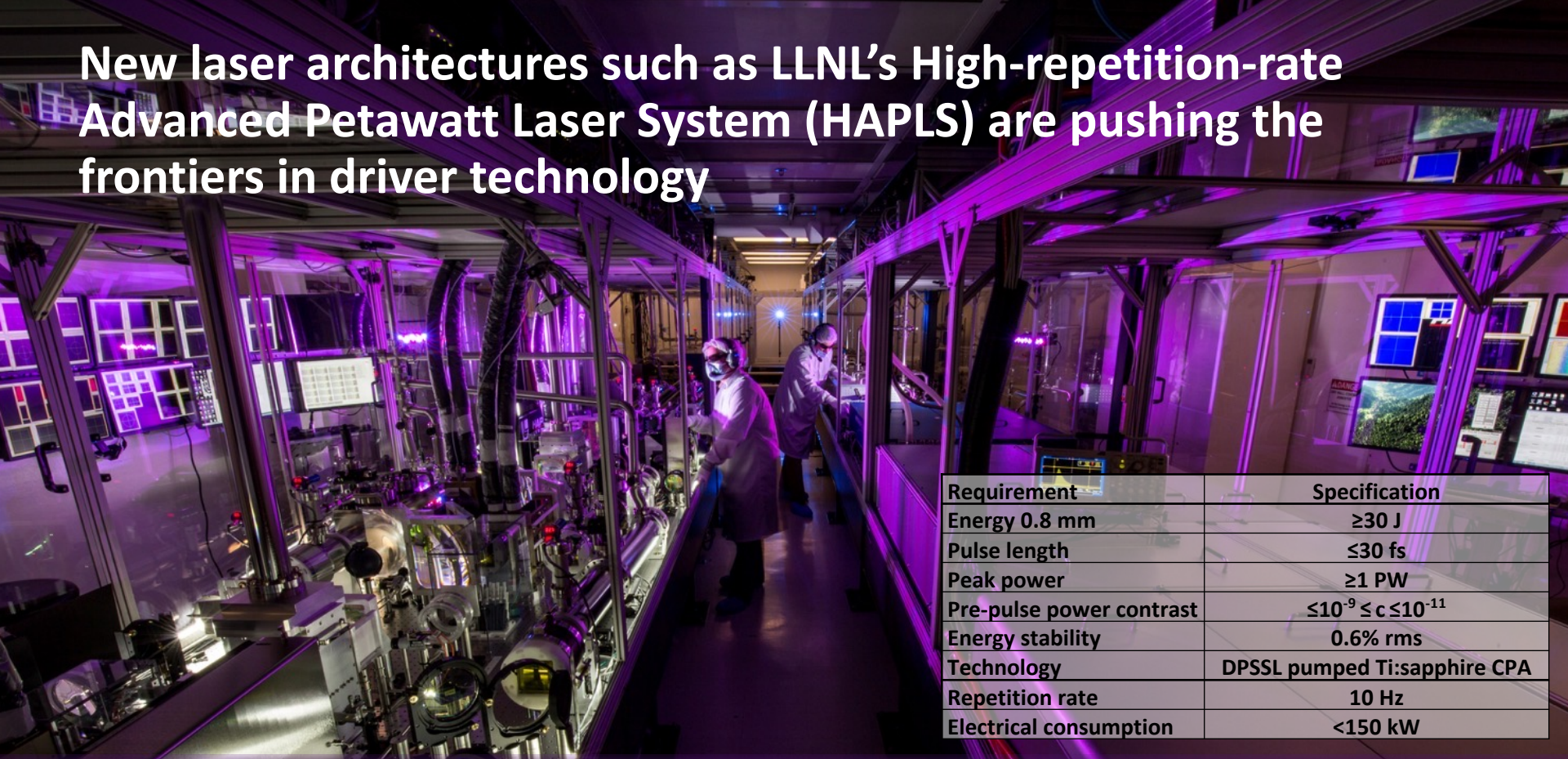
Fast Ignition



P. Patel, A. Kemp, D. Larson, M. Tabak

N210808 demonstrates that our codes were not so far off → the ability to predict the multi-scale physics now allows us to assess other advanced schemes in-silico

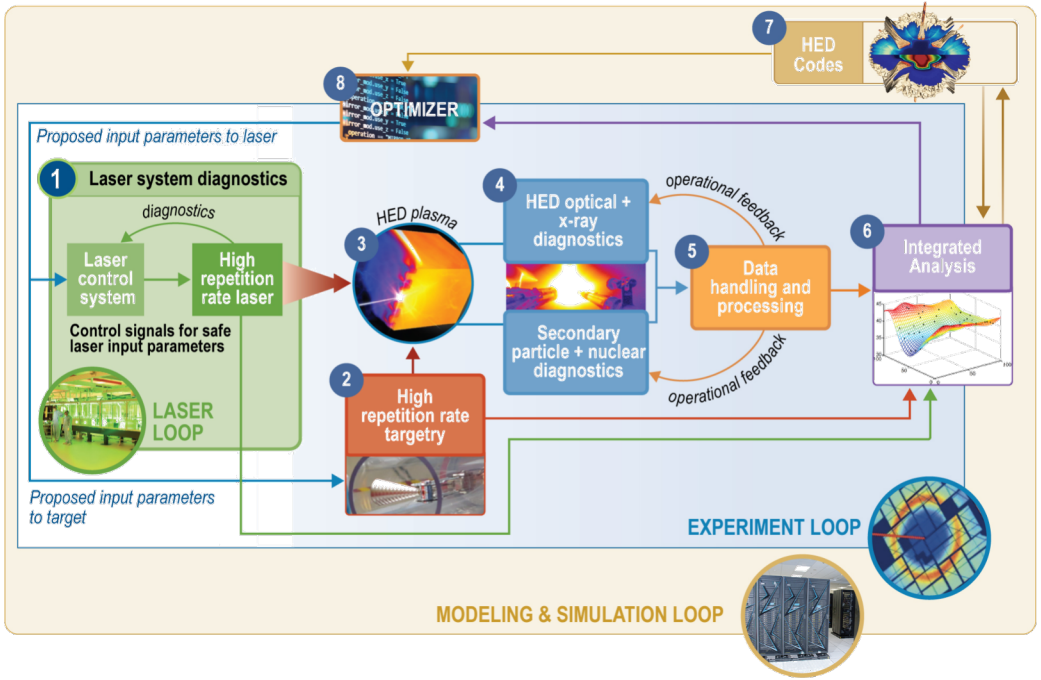
New laser architectures such as LLNL's High-repetition-rate Advanced Petawatt Laser System (HAPLS) are pushing the frontiers in driver technology



Requirement	Specification
Energy 0.8 mm	≥30 J
Pulse length	≤30 fs
Peak power	≥1 PW
Pre-pulse power contrast	$\leq 10^{-9} \leq c \leq 10^{-11}$
Energy stability	0.6% rms
Technology	DPSSL pumped Ti:sapphire CPA
Repetition rate	10 Hz
Electrical consumption	<150 kW

HAPLS is a scientific laser that advanced several technologies critical to future IFE laser drivers

High-rep-rate laser science is an opportunity to accelerate the rate of HED knowledge acquisition, while developing critical subsystems for IFE



T. Ma, et al., "Accelerating the rate of discovery: toward high-repetition-rate HED science". PPCF, (2021)

- Can accelerate scientific discovery by several orders of magnitude
- Exploits the synergies and builds connections between design – theory – experiments
- HRR HED supports our SSP mission to make impactful assessments utilizing HED capabilities on an ever-faster timescale

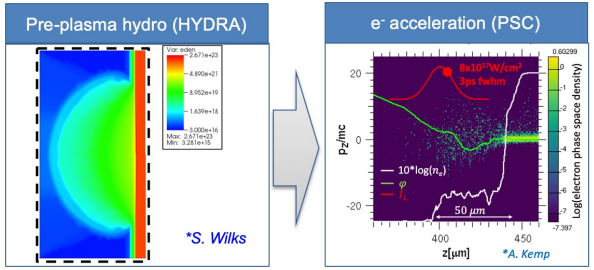
The "self-driving laser" not only allows for real-time experimental optimization, it is a testbed for massive increases in speed of key IFE facility components (like targets)

Machine learning/artificial intelligence is an enabling technology that revolutionizes the fusion energy landscape

Ongoing needs:

Simulations

Multi-physics, multi-scale

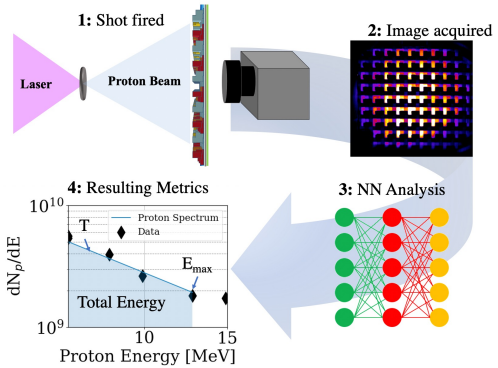


Multi-fidelity

- Low = 1,000's
- High = 10's

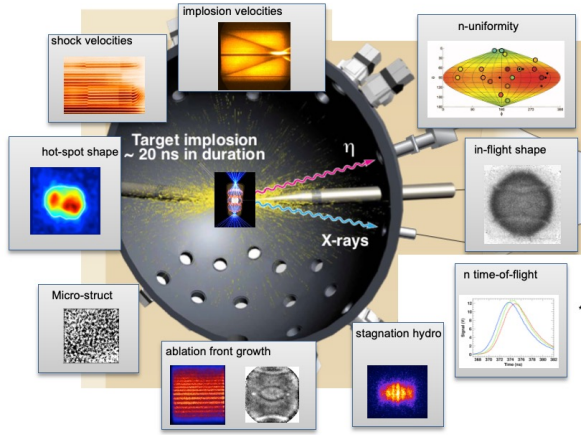
Connect multi-physics, multi-scale, multi-fidelity models

Experiments



Rapid, accurate, heterogeneous data analysis → compared to simulation models

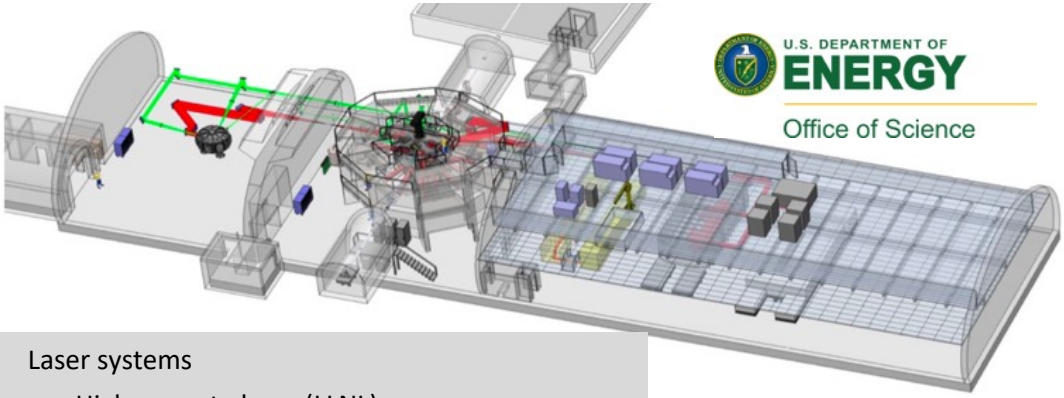
Data Handling



Pipelines/filtration/storage

ML must be leveraged to directly connect experiments with simulations now; and later to exquisitely control IFE power plant

The SLAC MEC Petawatt Upgrade project represents one opportunity to bring together cutting-edge laser and high-rep-rate technology necessary for IFE



U.S. DEPARTMENT OF ENERGY
Office of Science

Laser systems

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

CD1 achieved late 2021
Project completion 2026

Key Technical Opportunities

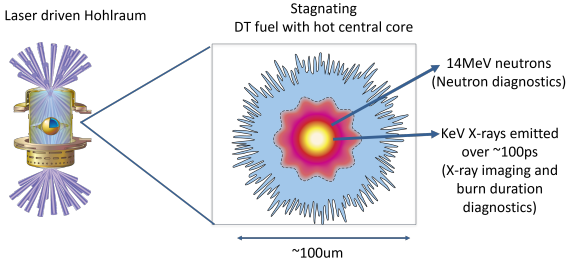
- Advanced high average power laser architectures
- 10 Hz operations
- High-throughput targetry
- Rep-rate and hardened diagnostics
- Compute on time scales commensurate with experiment
- Optimization strategies to seek out desired performance
- Focused IFE-relevant HED studies

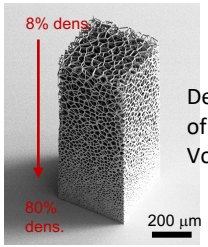
MEC-U feeds both our NNSA mission and IFE development

Much more R&D innovation needed! ENG, NIF&PS, PLS, WCI held a joint LDRD Townhall for High-Yield & IFE

3 example areas of interest:

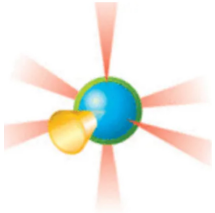
- Diagnostics for high yield
- Target manufacture methods which increase manufacturing yield and reduce production times and cost
- High yield, high margin ICF concepts





Design and TPL-Fabrication of Gradient Density Voronoi Microlattices

Izard & Xia
LDRD 22-ERD-004

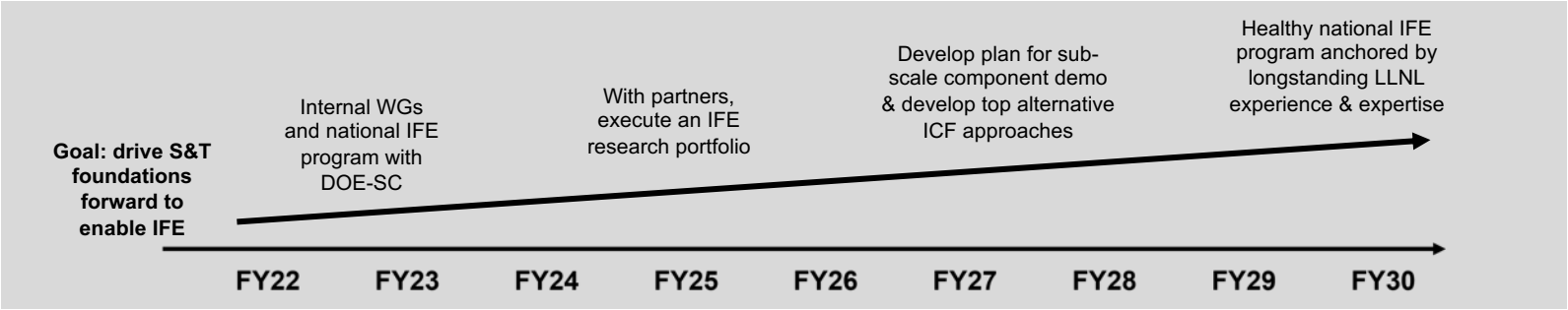


LDRD POCs:
- ENG: Rob Sharpe
- NIF&PS: Jeff Bude
- PLS: Tony Van Buuren
- WCI: Jim McCarrick

These organizations have committed to co-endorsing and co-funding FY23 LDRD starts for good S&T proposals which align to the goals, enhance our core competencies, and are consistent with budgets

LLNL is helping to facilitate a revitalized IFE program, starting with small internal investments and growing the national effort

- As an inception to a robust LLNL IFE program, start in technical areas synergistic with SSP and high yield facility needs (e.g. high margin, high yield target designs, novel target fab, high yield diagnostics, next generation laser drivers) → FY23 LDRD Townhalls for High Yield and IFE
- Help establish appropriate community-wide public-private partnership model for foundational IFE R&D
- Articulate and communicate the value of IFE to NNSA/DOE/DOD, congressional stakeholders, and the community. Facilitate partnerships between NNSA and DOE-FES



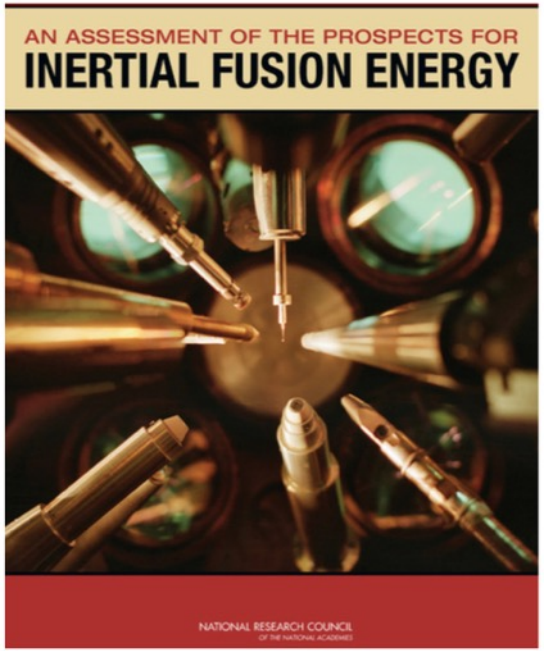
IFE will be an institution and community-wide undertaking, building on decades of advances. We are working on a Director's Initiative for IFE

On the national scene, we are working with partners to restart a funded, coordinated IFE program in the U.S.

NAS 2013 Study “An Assessment of the Prospects for Inertial Fusion Energy”* had a number of conclusions and recommendations including:

- “The appropriate time for the establishment of a national, coordinated, broad-based inertial fusion energy program within DOE would be when ignition is achieved.”
- “The potential benefits of energy from inertial confinement fusion … also provide a compelling rationale for including inertial fusion energy R&D as part of the long-term R&D portfolio for U.S. energy.”

**An Assessment of the Prospects for Inertial Fusion Energy*, Committee on the Prospects for Inertial Confinement Fusion Energy Systems, NRC (National Academies Press, Washington, D.C., 2013)



This is the time to begin as we stand at the threshold of ignition

Through the 2020 FESAC Long Range Strategic Plan, the community endorsed the re-establishment of an IFE program

FESAC Long Range Strategic Plan

Recommendation: Strengthen the innovative and transformative research that offers promising opportunities for fusion energy commercialization: stellarators, liquid metal plasma facing components, inertial fusion energy and alternate concepts

"Inertial fusion energy (IFE) utilizes advances in lasers, pulsed power technology, and drivers to achieve fusion at high fuel density. Progress with indirect drive at NIF, direct drive, magnetic drive ICF, and heavy ion fusion underpin promise of IFE. **An IFE program leveraging US leadership & current investments should be targeted."**

Portfolio Elements	Scenarios		
	Constant Level of Effort Significant loss of US leadership & significant missed opportunities	Modest Growth Loss of US leadership & missed opportunities	Unconstrained
Research, Operations, and Small Scale Construction			
FM&T Programs	Yes, enhance	Yes, enhance	Yes, enhance
US Tokamak Operations and Research	Yes, but reduce	Yes, but reduce	Yes
Stellarator and Alternates Operations and Research	Yes, but flat	Yes	Yes, enhance
IFE program	Yes, but limited	Yes, but limited	Yes
FPP Design Effort	Yes, but limited	Yes	Yes, enhance
GPS Program	Yes, but reduce modestly	Yes	Yes, enhance
HEDP Program	Yes, but reduce modestly	Yes	Yes, enhance

Even under a no growth budget scenario, it is recommended that an IFE program be restarted in the U.S.

Congress has directed DOE to support IFE

Energy Act of 2020 (enacted 12/28/2020):

25 "(d) INERTIAL FUSION RESEARCH AND DEVELOP-
26 MENT.—

December 21, 2020 (7:54 a.m.)

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1 "(1) IN GENERAL.—The Director shall carry
2 out a program of research and technology develop-
3 ment in inertial fusion for energy applications, in-
4 cluding ion beam, laser, and pulsed power fusion
5 systems.
6 "(2) ACTIVITIES.—As part of the program de-
7 scribed in paragraph (1), the Director shall support
8 activities at and partnerships with universities and
9 the National Laboratories to—

"(A) develop novel target designs;

"(B) support modeling of various inertial fusion energy concepts and systems;

"(C) develop diagnostic tools; and

"(D) improve inertial fusion energy driver technologies.

"(3) AUTHORIZATION OF APPROPRIATIONS.—Out of funds authorized to be appropriated under subsection (o), there are authorized to be appropriated to the Secretary to carry out the activities described in subsection (d) $25,000,000 for each of fiscal years 2021 through 2025.";

Build Back Better Act:

(5) INERTIAL FUSION RESEARCH AND DEVELOPMENT.—$140,000,000 shall be used to carry out the activities of the program of research and technology development in inertial fusion for energy applications authorized in section 307(d) of the Department of Energy Research and Innovation Act (42 U.S.C. 18645(d)).

U.S. HOUSE OF REPRESENTATIVES COMMITTEE ON
SCIENCE, SPACE, & TECHNOLOGY
Eddie Bernice Johnson, Chairwoman

For Immediate Release
August 17, 2021
Catherine Anderson
Ally Kehoe (Lofgren)

Congresswomen Johnson and Lofgren Congratulate National Ignition Facility on Major Milestone Toward Fusion Ignition

"I would like to congratulate the dedicated researchers at the Department of Energy's Lawrence Livermore National Laboratory, as well as their partners at Los Alamos and Sandia National Laboratories, the University of Rochester, General Atomics, and others throughout the country who worked to support this effort over several decades," **said Chairwoman Eddie Bernice Johnson (D-TX).** "This result is an astounding achievement for the U.S. fusion research community, and it did not happen overnight. It is a testament to the breakthrough possibilities that can be reached through patient, diligent adherence to the scientific process and through steady, substantial investments in the people that carry out this work. While there was very good reason to do this sooner, I hope that the Department will now take this opportunity to fully implement the fusion research provisions recently authorized in the Energy Act of 2020, and before that in the Department of Energy Research and Innovation Act. Among other important provisions, these laws include direction to the Department to establish an inertial fusion research program for energy applications, which would leverage the expertise developed at the National Ignition Facility and elsewhere to explore the potential for significant new pathways to our clean energy future."

House Science, Space & Technology Committee (HSST) Energy Subcommittee held a hearing on Fusion Energy, Nov. 2021

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FOSTERING A NEW ERA OF FUSION ENERGY RESEARCH AND TECHNOLOGY DEVELOPMENT

SUBCOMMITTEE ON ENERGY
DATE: WEDNESDAY, NOVEMBER 17, 2021
TIME: 10:00 AM
LOCATION: ONLINE VIA VIDEOCONFERENCING

OPENING STATEMENTS

Chairman Jamaal Bowman (D-NY) of the Subcommittee on Energy

Chairwoman Eddie Bernice Johnson (D-TX)

WITNESSES

Dr. Troy Carter, Director, Plasma Science and Technology Institute, University of California, Los Angeles and Chair, Fusion Energy Sciences Advisory Committee Long Range Planning Subcommittee

Dr. Tammy Ma, Program Element Leader for High Energy Density Science, Lawrence Livermore National Laboratory

Dr. Robert Mumgaard, CEO, Commonwealth Fusion Systems

Dr. Kathryn McCarthy, Director, U.S. ITER Project Office

Dr. Steven Cowley, Director, Princeton Plasma Physics Laboratory

Chairman Bowman: "But we now have new reasons for hope…On August 8th this past summer, the NIF produced the first so-called "burning plasma" in a man-made experiment."

Lofgren: "Fusion is essential to our energy future…What will you need from NNSA to optimize science at NIF?"

Ma: "Now is the time to reestablish a vibrant national IFE program and ignite a credible development path towards clean fusion energy."

The NIF results were widely heralded, and the bipartisan committee was overwhelmingly supportive of fusion energy and IFE

Even the White House is getting excited about fusion energy!

OFFICE OF SCIENCE AND TECHNOLOGY POLICY

EVENTS & WEBINARS

Upcoming Events

White House Summit: Developing a Bold Decadal Vision for Commercial Fusion Energy

Thursday, March 17, 2022 at 10:00 AM to 1:00 PM ET

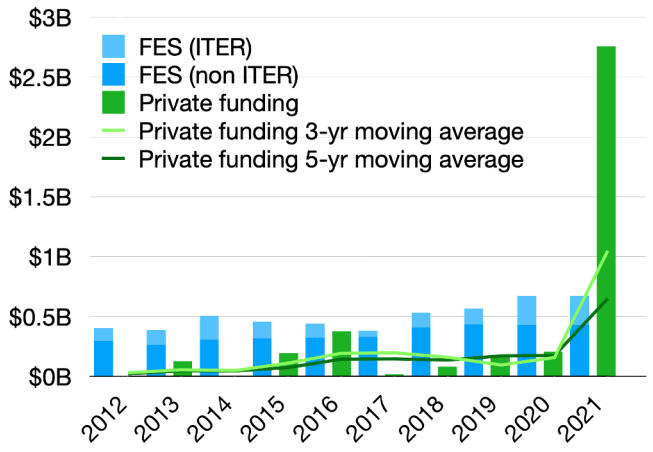
Watch live as the White House Office of Science and Technology Policy (OSTP) and the U.S. Department of Energy (DOE) host a summit on Developing a Bold Decadal Vision for Commercial Fusion Energy. This summit will convene fusion energy leaders from government, industry, academia, and other stakeholder groups to showcase progress made and have inclusive conversations about an updated fusion strategy.

The event will be led by White House and DOE leaders, including:

- Jennifer Granholm, U.S. Secretary of Energy
- Gina McCarthy, National Climate Advisor
- Dr. Alondra Nelson, Head of OSTP and Deputy Assistant to the President
- Brenda Mallory, Chair of Council on Environmental Quality
- Dr. Geraldine Richmond, DOE Under Secretary for Science and Innovation
- Shalanda Baker, DOE Secretarial Advisor on Equity and Deputy Director for Energy Justice in the Office of Economic Impact and Diversity
- Dr. Sally Benson, OSTP Deputy Director for Energy and Chief Strategist for the Energy Transition

Event will be livestreamed from the White House on March 17, 2022

There is enormous energy in the community right now, and we seek to focus the energy and enthusiasm for IFE constructively



Public and private funding for fusion science and technology.

- Private industry can play an important role in accelerating fusion commercialization
- We are frequently approached to partner (DOE-INFUSE, ARPA-E, venture capital activities) → how best to balance multiple companies?
- To partner in a productive way, S&T developments should be mutually beneficial and aligned with our core mission
- We support innovation and risk-taking, as long as approaches are credible
- We want to be a trusted agent, known as thought-leaders and a great partner for the entire national community in HED/ICF physics

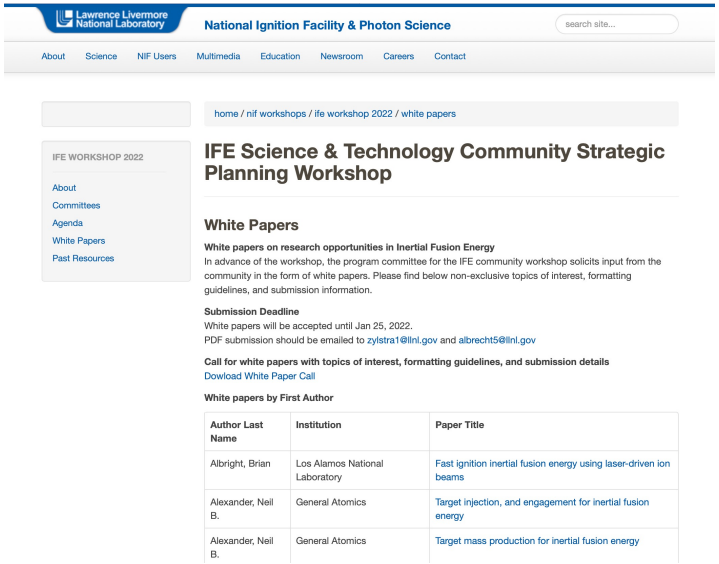
We are starting to work with other national labs/institutions to establish a framework to support IFE R&D by the wider community and private industry

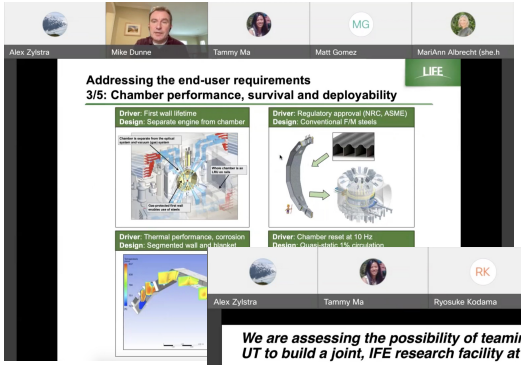
LLNL hosted IFE community workshops[1], and Office of Fusion Energy Sciences is sponsoring a Basic Research Needs (BRN)[2] for IFE

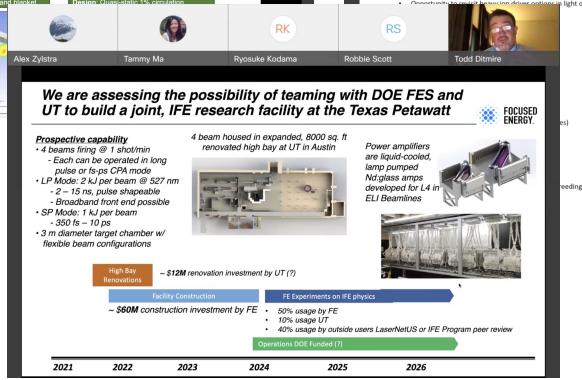
The BRN will lay out priority research opportunities to inform future efforts in IFE and build a community of next-generation researchers in this area

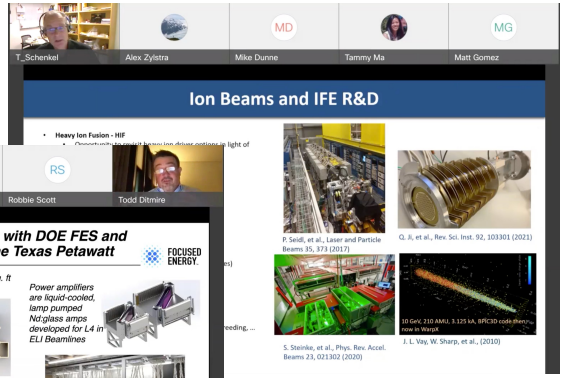
[1]Led by A. Zylstra (LLNL)
[2]chaired by T. Ma (LLNL) & R. Betti (LLE)

IFE Workshop engendered a lot of excitement, >80 white papers, >200 participants, including international + private









https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/

Whitepapers and talks are posted to the website

Inertial Fusion Energy is a grand scientific and engineering challenge with enormous potential clean energy payoff

- The U.S. is the current leader in HED/ICF. We are well-poised to lead and reap the benefits of IFE
- IFE is a multi-decadal endeavor, and will require audacious innovation to enable an economical energy source
- We are working with partners to restart a funded, coordinated IFE program in the U.S.
- LLNL possesses many areas of key expertise that can contribute to the national effort
- A White House Fusion Summit and DOE OFES Basic Research Needs workshop are being planned

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


Lawrence Livermore
National Laboratory