The threshold of ignition on the NIF and laying the path towards Inertial Fusion Energy (IFE)

Fusion Power Associates

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And the HED/ICF/NIF teams

LLNL-PRES-XXXXXX

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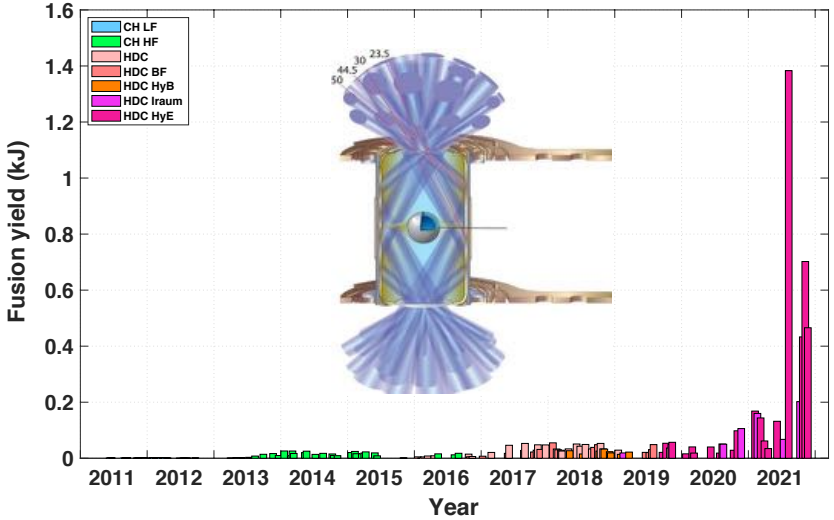
Lawrence Livermore National Laboratory

The August 8th, 2021 shot (N210808) on NIF marks a significant advance in ICF research, and lays the groundwork for IFE



- Spurred by advances in physics understanding, target designs, diagnostics, target fabrication, and the NIF laser, we've made exciting progress over the last two years
- N210808 produced 1.35 MJ of fusion yield
  - Used a design with smaller case-to-capsule ratio, and increased late-time x-ray drive
  - Achieved capsule gain (yield/capsule absorbed energy) ~5+, E_{cap} ~ 230 kJ
  - Achieved a laser gain ~0.7 (Fusion Energy/Laser Energy), equated with ignition by NAS 1997 committee
- 3 repeat experiments completed so far to assess the variability in this new regime
  - 430 kJ, 700 kJ, 480 kJ

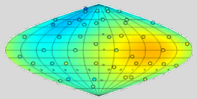
The time is right to restart an IFE program in the US – these promising results, decades of expertise in inertial fusion science and technology, combined with emerging technologies, can enable rapid progress

Diagnostic innovations, target quality advances, and laser improvements are all key to recent progress

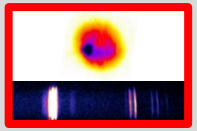
>120 Diagnostics now provide an unparalleled view into the implosion

- **DT Fuel Uniformity: Compton Radiography:** ~100keV x-rays produced by Advanced Radiography Source provide radiographs of DT fuel

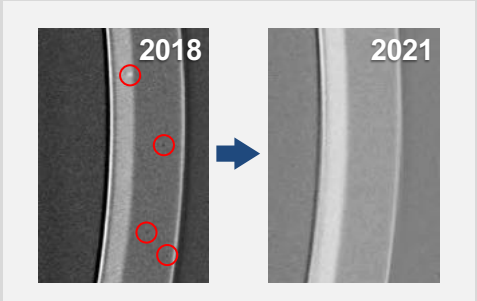
- **DT Yield Map/Fuel Uniformity:** 48 Real-Time Nuclear Activation (NAD)'s

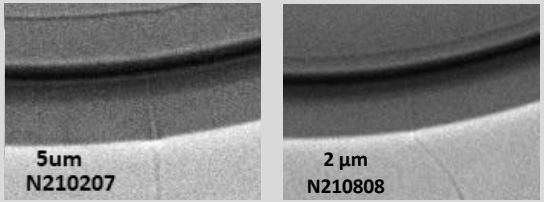


- **X-ray Imaging & Spectroscopy:** 3 x-ray imaging lines of sight; x-ray spectroscopy to characterize materials mixed into the hotspot



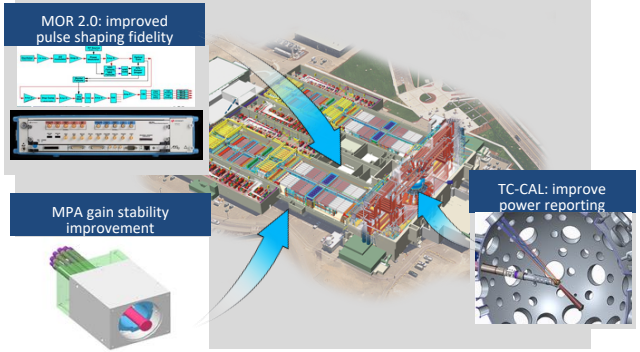
Capsule pits and voids reduced by~ 100x; 2 µm fill tube reduced perturbations





Laser operating at its highest sustained levels of energy and power to date

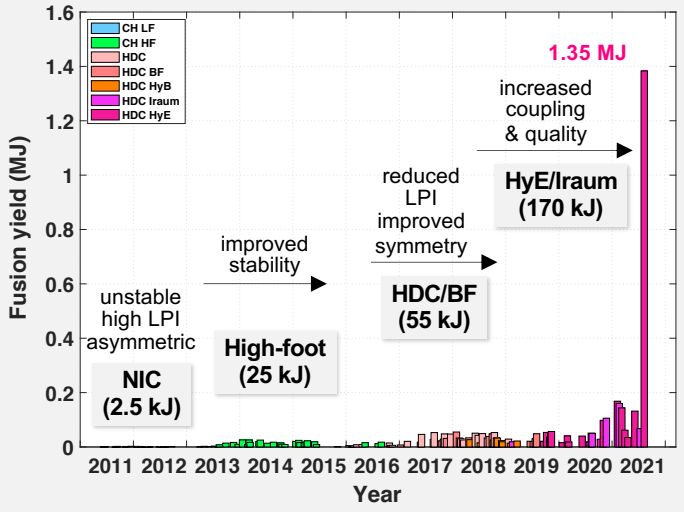
- Continued investments in optics and laser technology
- Fidelity of the laser models, accuracy of the laser diagnostic; beam quality, front-end performance and low-mode symmetry have been all improved



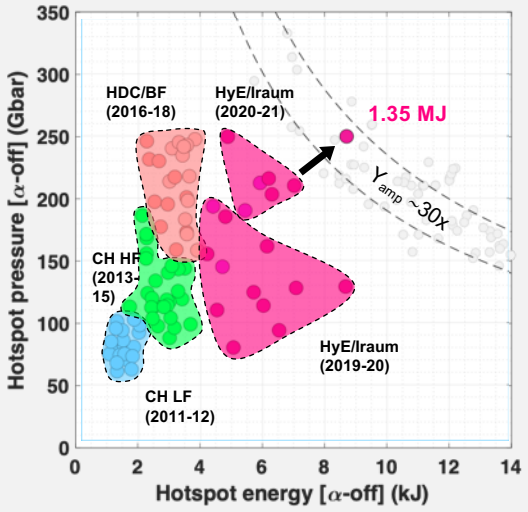
This accomplishment was built on decades of hard work and dedication by many people at LLNL, in partnership with the whole fusion, plasma, and High Energy Density Science (HEDS) community

With each major campaign on the NIF, hotspot pressure and energy were gradually increased

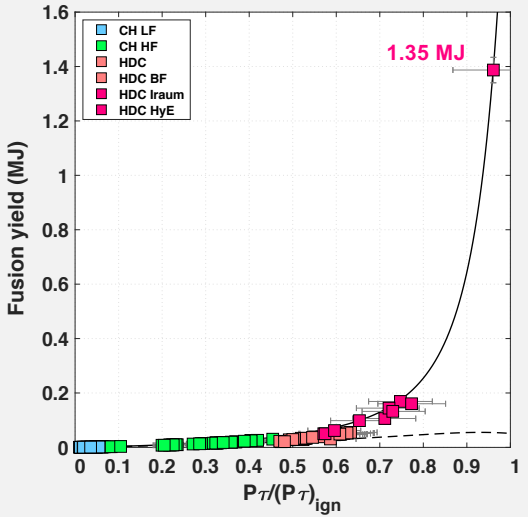
Fusion Yield



Hotspot pressure-energy [no-α]



Generalized Lawson Criterion

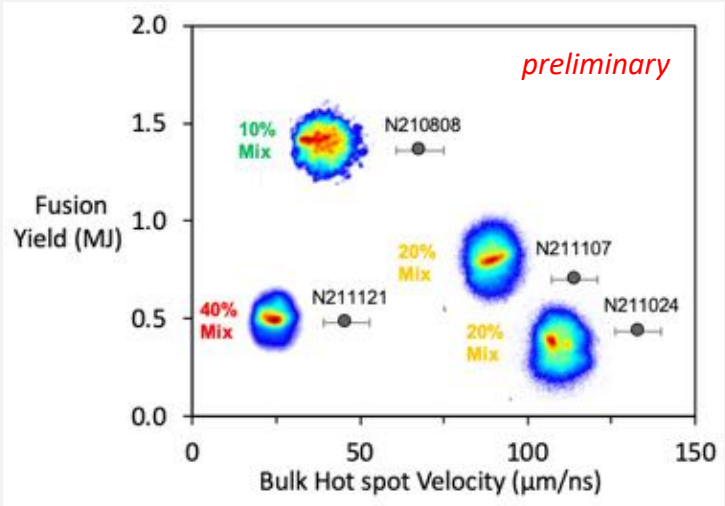


APS-DPP 2021: D. Callahan (AR01.00001), O. Hurricane (BI01.0001), P. Patel (CO04.00001), A. Christopherson (CO04.00005), A. Kritcher (GO04.00002), A. Zylstra (QI02.00001)

Capsule absorbed energy ~230 kJ ⇒ capsule gain > 5x
Hohlraum is driven by 1.9 MJ laser energy ⇒ target gain of 0.7

3 repeat shots so far to assess the sensitivity of the N210808 implosion to variability in the system and degradation mechanisms

N210808 and near-repeats



N211024: 430 kJ
- More particulates on capsule surface
- Laser delivery calculated to have resulted in deeper shock mergers
- CFT had gas leak

N211107: 700 kJ
- 5 µm fill tube
- More particles, with larger size
- Similar laser delivery to N211024

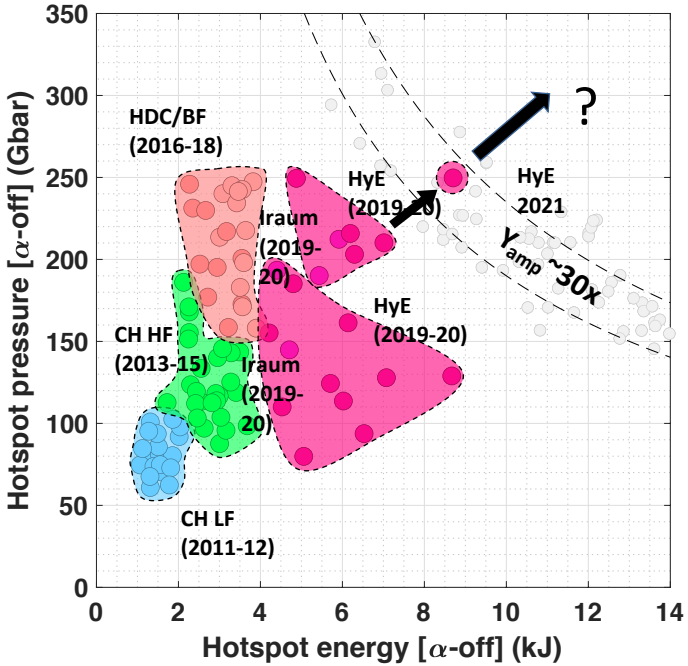
N211121:480 kJ
- 2 µm FT, but first to use a focused ion beam-drilled fill tube hole
- More particles on capsule surface
- Capsule has larger thickness asymmetry

The ±50% variability in yield on the ignition cliff appears correlated with measured relative Mode 1 asymmetry and hot spot mix levels

We have made much progress in the last few years but much work remains to be done

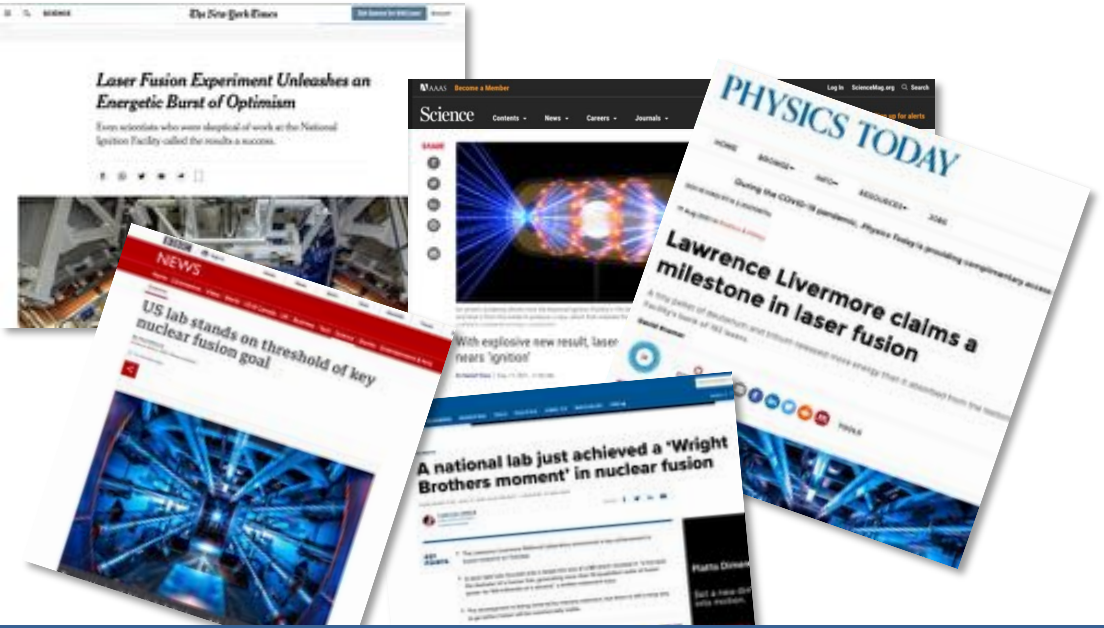
- Understand where we are
  - Assess variability
  - Assess sensitivity to input parameters
  - "Dudded" fuel to validate models in this Y_{amp} range
- Push to higher performance
  - Higher compression
  - Higher laser energy
  - Further improvements to hohlraum
- Use the current design for science experiments
  - Output from this implosion is most powerful/energetic driver that we have for HED
- Improve our simulation capabilities

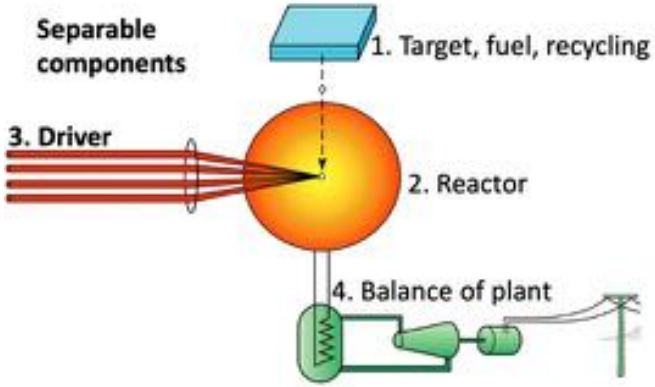
Ignition figure of merit $\sim (\rho R)^3 T^3 \sim E_{HS} P_{HS}^2$



This is a very exciting time for our field!

The recent NIF results establish the basic scientific feasibility of laser-driven inertial fusion energy (IFE)





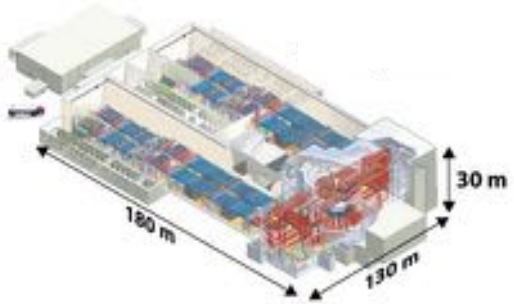
The demonstration of ignition threshold paves the way to a broad, national, coordinated plan to pursue IFE. The path forward for IFE research will require different, but synergistic, technologies from the NNSA Stockpile Stewardship Program

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

An electricity-producing IFE power plant would require:

- A more robust, high-margin ignition scheme likely different from what is pursued as part of the SSP
- A high-efficiency, high rep-rate driver
- 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
- …

NIF: Single Shot

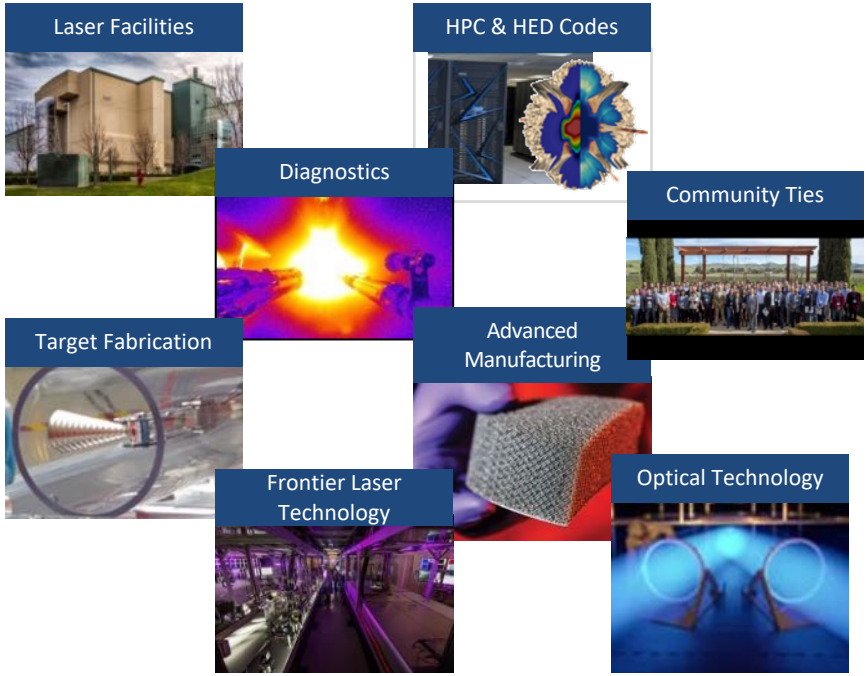


IFE plant: >10 Hz

NIF provides a unique opportunity to experiment at “fusion scale”

LLNL possesses many areas of expertise that can contribute to the national 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 currently being developed for a range of Stockpile Stewardship and DOE-Office of Science needs

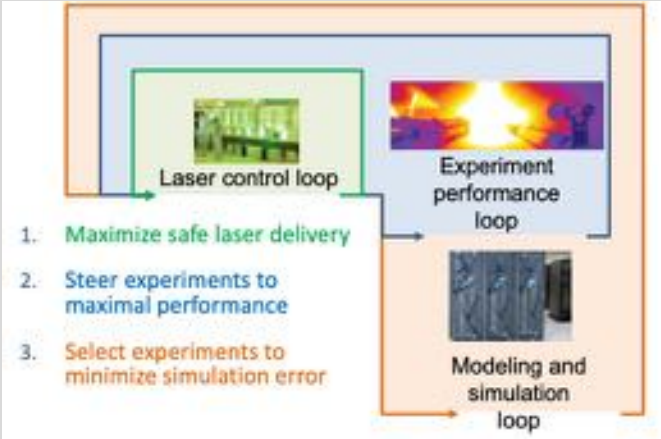
The SLAC MEC Upgrade project brings together cutting-edge laser and high-rep-rate technology necessary for pushing HED

U.S. DEPARTMENT OF ENERGY
Office of Science

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 HED studies of IFE processes or regimes

LLNL is both building the 10 Hz PW laser, and developing integrated systems and advanced component technologies for conducting HED experiments at high rep-rate



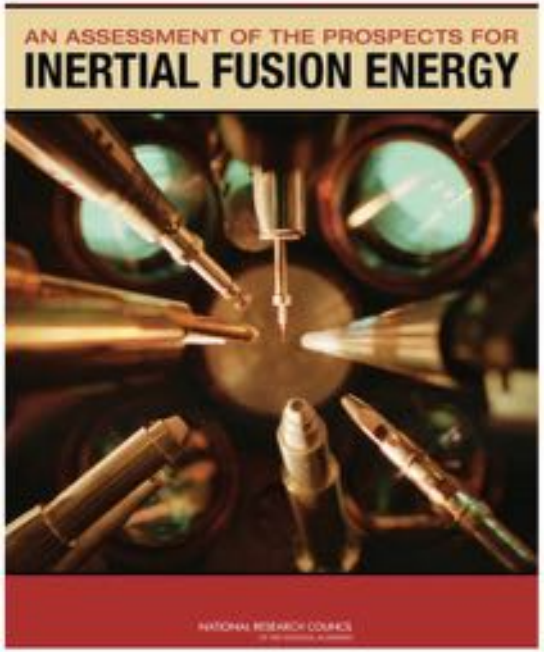
The MEC Petawatt Upgrade will be an unprecedented capability for HED science; many of these technological aspects are also relevant to IFE

We are working with partners to lead the effort 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 shown enormous support for IFE

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

"(d) INERTIAL FUSION RESEARCH AND DEVELOPMENT.—

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"(1) IN GENERAL.—The Director shall carry out a program of research and technology development in inertial fusion for energy applications, including ion beam, laser, and pulsed power fusion systems.

"(2) ACTIVITIES.—As part of the program described in paragraph (1), the Director shall support activities at and partnerships with universities and 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 (a), 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)

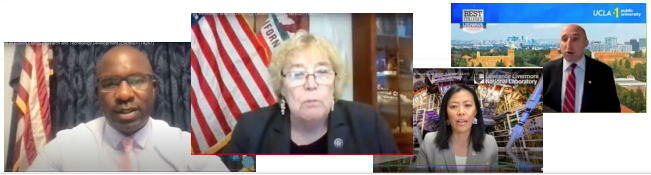
Congresswomen Johnson and Lofgren Congratulate National Ignition Facility on Major Milestone Toward Fusion Ignition

"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."

HSST Energy Subcommittee Hearing 11/17/2021:

FOSTERING A NEW ERA OF FUSION ENERGY RESEARCH AND TECHNOLOGY DEVELOPMENT

SUBCOMMITTEE ON ENERGY
DATE: WEDNESDAY, NOVEMBER 17, 2021
TIME: 10:00 AM



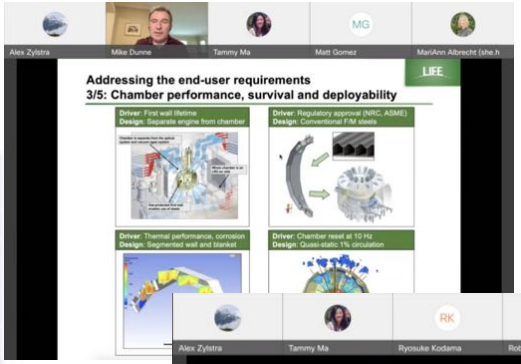
A series of community- and DOE-driven IFE workshops is in the works – aiming for a BRN report by end of summer

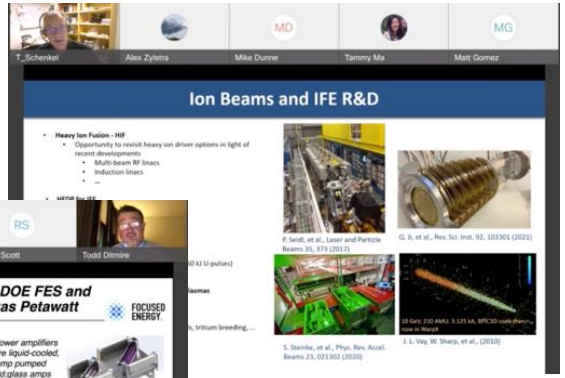
The IFE Community Workshop is designed to engage as many in the community as possible; the BRN will be invite-only

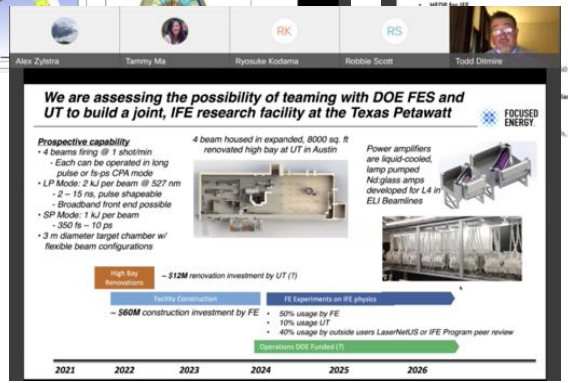
IFE Workshop Kickoff (Nov. 16, 2021) engendered a lot of excitement, >200 participants, including international + private

Agenda:

Start	End	Speaker	Topic
	8	8:15 Alex Zylstra	Kickoff / goals
8:15		8:45 Mike Campbell	IFE overview
8:45		9:15 John Perkins	IFE target designs
9:15		9:45 Steve Obenschain	HAPL
9:45		10:00 ----	break
10:00		10:30 Mike Dunne	LIFE
10:30		10:50 Matt Gomez	MagLIF
10:50		11:10 Thomas Schenkel	HIF
11:10		11:40 Omar Hurricane	N210808
11:40		11:50 ----	break
11:50		12:10 Robbie Scott	UK perspective
12:10		12:30 Ryosuke Kodama	Asia perspective
12:30		12:50 Todd Ditmire	perspective
12:50		13:00 Peter Seidl	Call for whitepapers







The full workshop will be held virtually Feb. 22-24, 2022.

A call for whitepapers has been issued, and the website will be launched this week.

These recent game-changing NIF results lay the groundwork to explore inertial fusion as a path for clean energy with the wider community

- With N210808, we achieved capsule gain ~5, burning plasma, and 0.7x “NAS ignition"
- The development of IFE is distinct yet highly synergistic with NNSA’s SSP mission through the ICF program
- 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
- IFE is a multi-decadal endeavor, and will require innovation to enable economical energy source
- We are working with partners to lead the effort to restart a funded, coordinated IFE program in the U.S.
- An IFE Community workshop and a DOE OFES Basic Research Needs workshop are being planned

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