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Hearing on *Fostering a New Era of Fusion Energy Research and Technology Development*
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Chairman Bowman, Congressman Weber, and Members of the Committee, thank you for the opportunity to testify before you today about fusion energy. My name is Tammy Ma, and I am currently the Program Element Leader for High-Intensity Laser High Energy Density Science at the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL). I have been involved in inertial confinement fusion (ICF) experiments on the NIF since experimental campaigns commenced on the facility in 2009, and I currently serve on the DOE Office of Science's Fusion Energy Sciences Advisory Committee (FESAC). I want to stress that today I am presenting my own opinions and not necessarily those of LLNL.

With my testimony, I hope to convey several points:

- Recent breakthrough results from National Ignition Facility (NIF) inertial confinement fusion (ICF) experiments have demonstrated capsule gain and burning plasmas; they have placed us on the threshold of fusion ignition where energy gain from nuclear fusion in the capsule exceeds the laser energy delivered.
- Achieving fusion ignition is the first major hurdle in efficiently harvesting fusion energy through inertial fusion energy (IFE), an innovative approach that is complementary to mainstream magnetic fusion energy (MFE) research. Currently, IFE is not part of the long-term energy R&D portfolio of the U.S. and is not part of the research being pursued at LLNL.
- The United States is the world leader in high energy density science which underpins the physics of fusion ignition, thanks to investments by the National Nuclear Security Administration (NNSA) and the DOE Office of Science. We are exploiting these extraordinary capabilities to perform world leading science and develop advanced technology. However, the U.S. lead is being challenged and competition is fierce.
- NIF's mission is scientific research of ICF to support the Stockpile Stewardship Program (SSP). It differs from what is needed for an IFE power plant. Developing IFE toward the goal of a clean energy source is a distinct challenge, yet one that is highly synergistic with NNSA's SSP mission under the ICF program.
- The time is right to restart an IFE program in the U.S. – decades of expertise in ICF which has brought us to the threshold of ignition combined with advances in our computing modeling capabilities and new emerging technologies such as novel laser architectures of relevance to IFE, machine learning, innovative diagnostics, and a growing community of skilled researchers can enable rapid progress.
- Through the recent 2020 FESAC Long Range Strategic Plan, the fusion community strongly endorsed the re-establishment of an IFE program.

The National Ignition Facility (NIF) Achieves the Threshold of Ignition

This past August, a breakthrough fusion experiment achieved a yield of 1.35 megajoules on the National Ignition Facility (NIF), more than two-thirds of the 1.9 megajoules of laser energy deposited on the target, and eight times more than the previous record (see Figure 1). This result places NIF on the threshold of fusion ignition for the first time, and demonstrates the feasibility of laboratory-scale laser driven inertial confinement fusion to achieve high-yield conditions.

The NIF is a football-stadium-sized facility that houses the world's largest, most energetic laser (approximately 60 times more energetic than any other laser in the world when it was completed in 2009). The precision and repeatability of this laser system are unprecedented in the world. NIF's 192 laser beams are guided and amplified through thousands of optical elements and then focused onto a miniature, highly engineered target the size of a BB. Inside this target is a spherical capsule containing the fusion fuel. The result is a hotspot the diameter of a human hair that creates conditions hotter and denser than those found at the center of the sun.

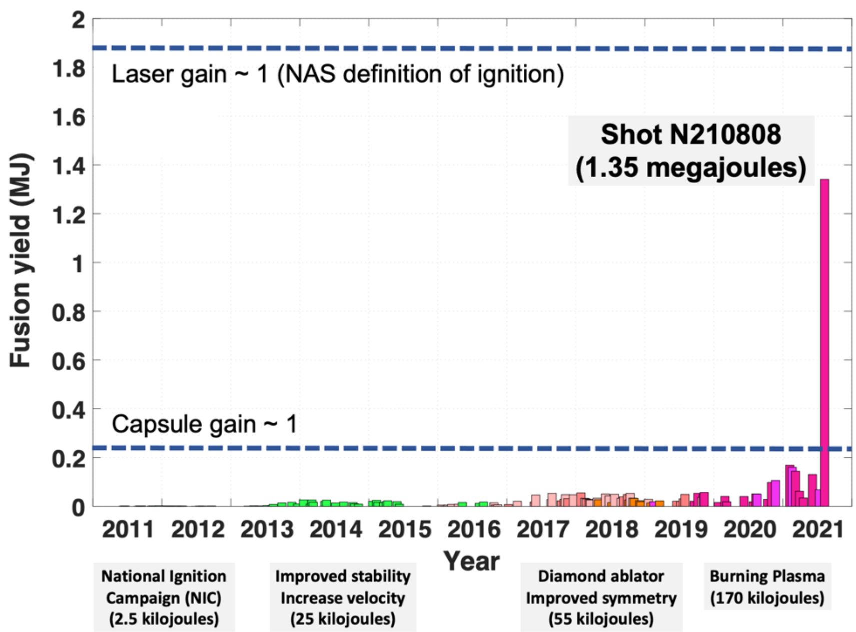

Figure 1. Shot N210808 on NIF produced more than 1.35 megajoules of fusion yield and marks a significant advance in ICF research. The histogram shows the progress over a decade of dedicated research and development on the NIF.

The central mission of the NIF is to provide experimental insight and data for the National Nuclear Security Administration (NNSA)'s science-based Stockpile Stewardship Program (SSP). Experiments in pursuit of fusion ignition are a vital part of this effort. They provide data in an important experimental regime that is extremely difficult to access, furthering our understanding of the fundamental processes of fusion ignition and burn, and enhancing the simulation tools that support our stockpile stewardship mission. Fusion ignition is the gateway toward even higher fusion yields in the future.

While full scientific interpretation of these latest results is still ongoing and will be vetted through the scientific peer-reviewed process, initial analysis shows that this experiment generated more than 10 quadrillion watts of fusion power for 100 trillionths of a second from a 50 micron-size burning plasma. This equates to an improvement of eight times over experiments conducted in the spring of 2021 and a 25-fold increase over the yield from a year ago. This shot also achieved capsule gain (defined as the ratio of energy released over the energy absorbed by the capsule) exceeding a factor of five. By the National Academy of Sciences 1997 definition of ignition (wherein the energy out of the target is equal to the total laser energy incident on it), the gain was 70% of that needed for ignition.

The experiment built on several advances gained from insights developed over the last few years by the NIF team, including new diagnostics; fabrication improvements in the target that include the hohlraum, capsule shell (which contains the deuterium and tritium fuel), and fill tube (by which the capsule is filled with the fusion fuel); improved laser precision; and design changes to increase the energy coupled to the implosion and the compression of the implosion.

These recent results now also open a vast new frontier for scientific exploration and exploitation. The same fusion plasmas that we create for ICF national security applications can also be exploited to become the basis of a future clean nuclear power source, which will also contribute to domestic energy independence and security.

Progress in Inertial Confinement Fusion (ICF) lays the groundwork for Inertial Fusion Energy (IFE)

As we approach inertial confinement fusion (ICF) ignition on the NIF, this will represent the first time in the laboratory that a fusion reaction will release more energy than was used to generate the reaction. This breakthrough 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 magnetic fusion energy. To be clear, however, NNSA does not have an energy mission and, therefore, no NNSA resources are being used for inertial fusion energy (IFE) research at LLNL.

It must be acknowledged that, like all approaches to fusion energy, there are many scientific, technological, and engineering challenges to IFE. An IFE system would work by using a driver (such as a laser) to implode an injected target to fusion ignition and high energy gain conditions many times per second. Net electrical energy gain should be possible when the ratio of fusion energy released to input driver energy is on the order of 100 times the input energy. To make this possible, significant technological hurdles need to be overcome: ignition schemes with high yield and robust margin must be developed; drivers must be developed that have high efficiency and that can be operated at repetition rates of several times per second; ignition-quality targets must be economically mass produced, efficiently driven, and stably imploded that yield high gain at the rate of many times per second; optics and hardware produced that can withstand continual exposure to both high optical irradiance and fusion radiation; and reactor chambers must be designed to contain the micro-explosion products and adequately protect the driver. Furthermore, each of these systems will have to be engineered with cost, operability, and maintainability in mind required for economical energy production.

The National Academy of Sciences studied this problem and released an excellent report in 2013 entitled "An Assessment of the Prospects for Inertial Fusion Energy." A number of findings and conclusions were made, including one that "The potential benefits of energy from inertial confinement fusion (abundant fuel, minimal greenhouse gas emissions, and limited high-level radioactive waste requiring long-term disposal) 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. A portfolio strategy hedges against uncertainties in the future availability of alternatives such as those that arise from unforeseen circumstances." The report was also clear in concluding 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] This is the time to begin as we stand at the threshold of ignition.

Fusion energy research is a high-stakes endeavor, and as such, technological diversity is always a good strategy. NNSA has made a significant investment in ICF, NIF, and other ICF-relevant facilities such as the Z Pulse Power Facility at Sandia National Laboratories, and the Omega Laser Facility at the University of Rochester. The DOE Office of Science Fusion Energy Sciences program can and should leverage this to help establish the IFE path forward.

The U.S. is the world leader in high energy density science, although that lead is being challenged

The study of the extreme density, temperature, and pressure conditions like those found in ICF plasmas is called high energy density (HED) science. U.S. investments supported by NNSA and the DOE Office of Science have made the U.S. the world leader in this area of science, giving the U.S. a competitive advantage. As an example, when completed in 2009, NIF operated with 60 times more energy than the next biggest laser in the world, which was the Omega Laser Facility, also in the U.S. Now, nearly a decade later, NIF operates with 10 to 20 times the energy of the next most energetic laser, which is in China. There are few fields of science today where the U.S. has had, and currently maintains, such a large lead over the rest of the world. This lead exists not only in facility capabilities but also in diagnostics, targets, simulations, and scientific output and publications. This world leadership along with the compelling scientific opportunities – especially the grand challenge of inertial confinement fusion ignition and the potential of a path to inertial fusion energy – has been a magnet for the best and brightest scientists and engineers to pursue research in HED science and to work as part of the SSP.

The world leading nature of NNSA's ICF facilities requires cutting edge science and technology that in turn leads to many spinoff benefits. For example, NIF requires unique capabilities in lasers, optics, precision target fabrication, diagnostics, and computer controls. Developments in these areas have led to a large number of R&D 100 awards over the years and a proliferation of ideas that support our national security (e.g., directed energy weapons) and our economic competitiveness (e.g., extreme ultraviolet lithography, an approach to help extend Moore's law in chip making, is a spinoff of inertial confinement fusion laser research).

While historically we have had an impressive lead in HED science, it is clear today that the rest of the world is aggressively focusing on catching up. Currently, megajoule (NIF) scale lasers are under construction in both France and Russia. The Chinese have completed and are operating the second most energetic laser in the world and are publishing papers with designs for lasers 50% to three times the size of NIF. Having more energy makes achieving inertial confinement fusion ignition easier.

The area of high intensity lasers is a particularly noteworthy example. Researchers in the U.S. pioneered the field of high intensity lasers. These lasers reach more extreme conditions not by increasing the energy delivered, but by reducing the duration of the laser pulse, achieving higher and higher powers as the duration is reduced. In the 1990s, LLNL broke the petawatt (10^15 watts) barrier with the construction of the Nova Petawatt. A number of novel and important new

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

properties emerged at the high intensities that these new lasers enabled, and since then dozens of petawatt class lasers have been built and thousands of publications about the exciting science in this area were published over the next 20 years. In 2017, the National Academy of Sciences published a report on "Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light." A key conclusion from this report is that:

> "The U.S. has lost its previous dominance. The United States was the leading innovator and dominant user of high-intensity laser technology when it was developed in the 1990s, but Europe and Asia have now grown to dominate this sector through coordinated national and regional research and infrastructure programs. In Europe, this has stimulated the emergence of the Extreme Light Infrastructure (ELI) program. At present, 80 to 90 percent of the high-intensity laser systems are overseas, and all of the highest power (multi-petawatt) research lasers currently in construction or already built are overseas."[2]

The DOE Office of Science's Fusion Energy Science Program has since started to respond, and we applaud them for pushing forward the Matters at Extreme Conditions (MEC) Upgrade project at SLAC National Accelerator Laboratory's Linac Coherent Light Source (LCLS), which recently achieved Critical Decision 1 (CD1) in the project stage. This project will integrate state-of-the-art high-energy, high-repetition-rate lasers with SLAC's x-ray light source to provide an unprecedented HED science platform (see Figure 2). Leveraging these advanced laser systems and reaping the potential rewards for HED science, however, also requires commensurate investment and development in massively parallel target fabrication and characterization, target debris management and mitigation, electromagnetic pulse (EMP) and radiation hardened diagnostics, and real-time data management and analysis coupled to sophisticated simulation codes. These capabilities are crucial for enabling the next frontier in data-driven HED science and are also key to advancing IFE.

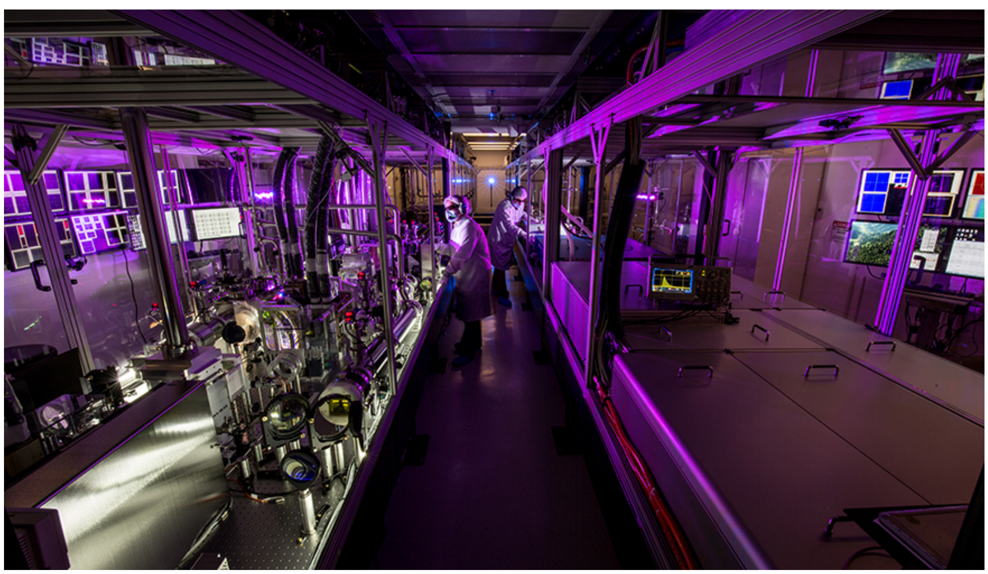

Figure 2. The High-repetition-rate Advanced Petawatt Laser System (HAPLS) is the world's most advanced, highest average power, diode-pumped laser system. It was designed, developed, and built by LLNL for the Extreme Light Infrastructure Beamlines (ELI-Beamlines) in the Czech Republic. A higher energy version is planned for the new MEC-Upgrade project at SLAC National Accelerator Laboratory, ensuring an unprecedented HED science capability for the U.S.

[2] *Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light*, Committee on Opportunities in the Science, Applications, and Technology of Intense Ultrafast Lasers; NAS (National Academies Press, Washington, D.C., 2017).

The synergies between IFE and ICF are many and mutually beneficial

The NIF is a marvel of science and engineering, allowing for research at the cutting edge of the most extreme conditions in the universe. However, it is exactly that – a scientific exploration facility, and very different from what would be needed for an inertial fusion energy power plant. As briefly touched on above, an electricity-producing IFE power plant would also require, for example, a more robust, high-yield ignition scheme likely different from what is pursued as part of the SSP; a driver, target injection, and tracking system, all operating at high repetition rates; an energy conversion system; robust first walls and blankets for wall protection, tritium processing and recovery, remote maintenance systems, and more.

The development of IFE towards the goal of a clean energy source, is distinct yet highly compatible with NNSA's SSP mission through the ICF program. The synergies between IFE and ICF are many and mutually beneficial; for example, advanced targets that could yield high gain for IFE could similarly produce high neutron yield for ICF applications, while improvements in driver cost and repetition rate for IFE could similarly mean more HED experiments for SSP. Furthermore, 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 also serves as an important recruitment and training tool for many DOE missions. Generations of laser and plasma physicists, scientists and engineers, have been drawn to the field for the opportunity to be involved with the big science and challenging problem of fusion. The current U.S. leadership in HED/ICF research stems, in part, from the historical pursuit of IFE and as such, we must continue to take a leading role in IFE to maintain preeminence in this arena. The U.S. 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 underlying science and technology that underpins IFE.

The time is right to restart an IFE program in the U.S.

The DOE is in an excellent position to make rapid progress in this area by leveraging the large investment being made in many emerging technologies and by the NNSA in ICF research. Many institutions already active in HED research would be well-positioned to contribute to this activity.

A number of promising technologies key to eventual IFE systems are making steady progress. In particular, exciting advances in repetition-rated high-energy laser technology and repetition-rated pulsed power technology in the U.S. over the last few years potentially lower the cost of a future driver for an IFE system. Additive manufacturing and other automated manufacturing techniques are becoming more cost-effective and are being used as part of the current target fabrication effort on NIF. Artificial intelligence and machine learning are being deployed to train large-scale, high-performance, high-speed models, improve predictive simulation models, and quantify uncertainties.

Many countries are ramping up efforts in IFE alongside magnetic fusion energy. EUROFusion, a consortium of nine European nations, is working on a Roadmap for an Inertial Fusion European Demonstration Reactor, and China and Russia are already building "NIF-like" lasers. The fusion energy industry is rapidly growing, already seeded by more than $2 billion of investment. The competition is substantial, but significant potential for productive partnerships and progress in fusion energy abound. For example, while public and private strategies differ in technical focus and deliverables, significant overlaps exist that are beneficial to both parties. Strategically partnering the public and private sectors can result in rapid enhancements in scientific and technological capabilities.

IFE is a multi-decadal endeavor and will require innovation to enable an economical energy source. This is an opportune time to move aggressively toward developing fusion energy as the world pushes toward decarbonization to mitigate the effects of climate change. Unlike other renewable energy sources, IFE would be both high-yield and extremely reliable, not susceptible to variables such as the weather or extended supply-chains. Future energy sources such as IFE will help make the nation more robust to potential geopolitical complications and alleviate our dependency on foreign energy providers.

The recent 2020 FESAC Long Range Strategic Plan endorsed the re-establishment of an IFE program

I had the honor of serving on the subcommittee that authored the 2020 FESAC Long Range Strategic Plan "Powering the Future: Fusion and Plasmas."[3] The report provides a decade-long vision for the field of fusion energy and plasma science and presents a path to a promising future of new scientific discoveries, industrial applications, and, ultimately, the delivery of fusion energy. The research community worked for more than a year to develop a wealth of creative ideas designed to accelerate fusion energy and advance plasma science, culminating in a consensus Community Planning Process Report. The FESAC report drew heavily on that report, to identify critical areas for research and development and prioritized investment.

Among the recommendations was to "strengthen the innovative and transformative research program elements that offer promising future opportunities for fusion energy commercialization: stellarators, liquid metal plasma-facing components, IFE, and alternate concepts… An IFE program that leverages U.S. leadership and current investments should be targeted."

Under the charge for the report, the committee was to determine a prioritization of projects and research programs under a number of different budget scenarios. Even at the constant level of effort budget scenario (flat funding relative to FY2019 budget levels), the committee recommended supporting a modest IFE program, focused on developing enabling technologies, through redirection of existing funds. The return on investment with even just modest funding for IFE is substantial, accelerating the fusion energy mission and providing excellent science, and aiding in the development of emerging technologies and innovative R&D. This underscores the community's commitment to the re-establishment of a robust IFE program in the U.S.

With the recent game-changing results on the National Ignition Facility bringing us to the threshold of ignition, and our decades of expertise in inertial confinement fusion science and technology, the U.S. is well-poised to make significant advances toward an inertial fusion energy future. IFE can enable a route towards clean and commercially viable power as well as unraveling mysteries of plasmas in our universe and developing technologies with broad societal impacts.

[3] *Powering the Future: Fusion and Plasmas,* A Report of the Fusion Energy Sciences Advisory Committee, U.S. Department of Energy, Office of Science, Fusion Energy Sciences (2020)