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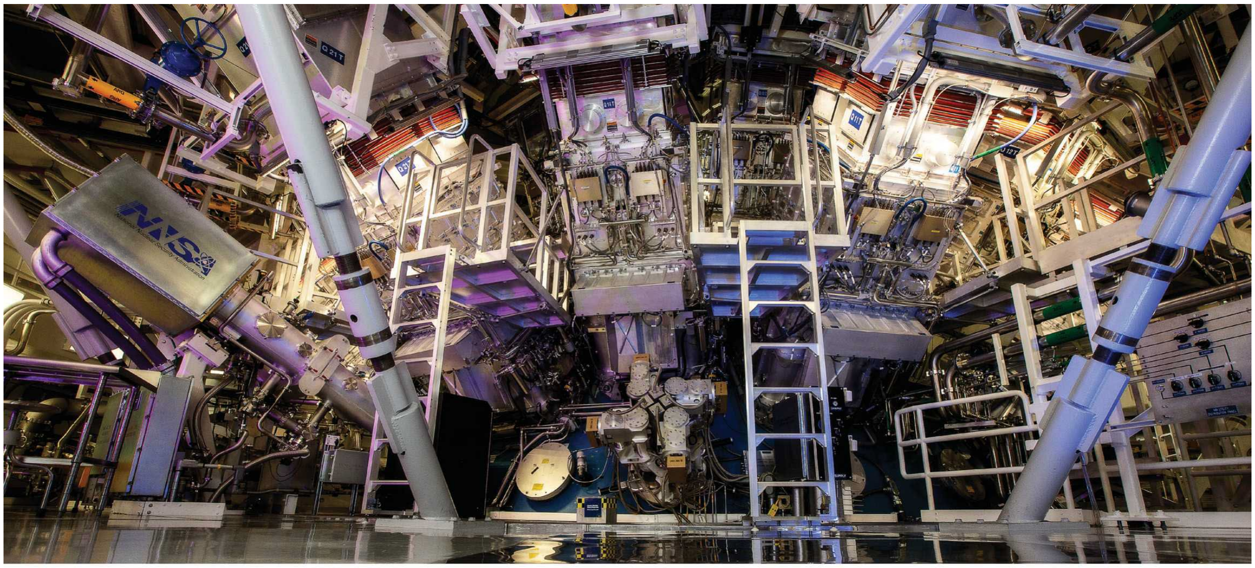

View of the NIF Target Chamber from the Target Bay. NIF's 192 laser beams converge at the center of the giant sphere to make a tiny hydrogen fuel pellet implode.
Credit: Jason Laurea

Fusion Ignition and the Path to Inertial Fusion Energy

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The achievement of fusion ignition at Lawrence Livermore National Laboratory's (LLNL) National Ignition Facility (NIF) in December 2022 was the culmination of more than 60 years of research and development in laser-driven inertial confinement fusion at LLNL. That historic scientific, engineering, and technological accomplishment, a prime example of the value of ingenuity and commitment in the face of a grand scientific challenge, marked a significant advance in LLNL's support of the National Nuclear Security Administration's science-based Stockpile Stewardship Program to maintain the reliability and security of the nation's nuclear deterrent without underground testing. It also furthered Livermore's research in high energy density science and established the fundamental scientific basis for inertial fusion energy (IFE), emboldening further public and private research into the development of IFE as a potential source of abundant clean, safe, and reliable energy. The U.S. government has funded a multi-disciplinary, multi-institutional program that LLNL is now leading to make inertial fusion energy a reality.

I. Introduction

The U.S. Department of Energy's (DOE) Lawrence Livermore National Laboratory made scientific history on December 5, 2022. An experiment at NIF achieved "target gain,"producing more energy from nuclear fusion (3.15 MJ) than the amount of laser energy delivered to the fusion target (2.05 MJ)—a metric for achieving a robustly ignited fusion plasma [1-3]. An international team of scientists, engineers, technicians, and support staff has compared the groundbreaking achievement to the first powered flight by the Wright Brothers. Four additional ignition shots followed the December experiment: July 30, 2023; October 8, 2023; October 30, 2023; and February 12, 2024. The most recent experiment produced an estimated 5.2 MJ—more than doubling the input energy of 2.2 MJ. Additional experiments using higher laser energies and producing even higher energy yields are expected in the coming months, further demonstrating that NIF can repeatedly conduct fusion experiments at multi-megajoule levels of energy output [4].

Nuclear fusion is the process that powers the sun and other stars, where gravitational forces provide the natural confinement, compression, and heating required for fusion. Other than at NIF, the world's largest and highest-energy laser, these conditions only occur on Earth in an exploding thermonuclear weapon. The results of NIF ignition experiments enable researchers to assess the performance of nuclear weapon systems and perform weapon science and engineering calculations. This is a key element in the DOE National Nuclear Security Administration's science-based Stockpile Stewardship Program to ensure the safety and reliability of the nation's nuclear deterrent in the absence of underground weapons testing [5].

Another important LLNL/NIF mission is to explore the possible use of nuclear fusion as a future energy source. By 2050, projections indicate a nearly 50 percent increase in worldwide energy consumption [6]. An energy technology revolution and breakthrough concepts are needed to decarbonize the world's energy system and stabilize the climate. Fusion has the potential to provide a reliable, abundant, safe, and clean source of electricity. The repeated achievement of fusion ignition at NIF has established the fundamental scientific feasibility of laser-driven inertial confinement fusion (ICF) as a path toward fusion energy—a potentially transformative technology that could produce electric power without carbon emissions, long-lived nuclear waste, or the risk of meltdowns. Fusion researchers around the world, in government laboratories and the private sector, are now working to develop the technology to generate electricity through fusion [7, 8]. The achievement of target gain at LLNL, along with overall progress in magnetic fusion and other confinement schemes, has set the stage for a national and international effort to move fusion energy from the laboratory to the marketplace. The lessons learned from LLNL's ignition experiments are helping lay the groundwork for constructing, in the foreseeable future, IFE-based power plants [9].

II. Achieving Fusion Ignition

Demonstrating, and then repeating, fusion ignition in the Laboratory arrived after six decades of research into laser-driven ICF at LLNL [10]. Following the invention of the laser in 1960, Livermore developed a succession of ever-higher-energy laser systems, culminating in the construction of NIF, a 192-beam laser system capable of exceeding the extremes of pressure and temperature that exist in the centers of stars [11].

Figure 1. LLNL has achieved fusion ignition on NIF five times to date.

Scientists, engineers, and technicians had to overcome a daunting array of challenges in designing and constructing NIF. Working closely with industrial partners, the NIF team found solutions for NIF's optics in rapid-growth crystals, continuous-pour glass, optical coatings, and new finishing techniques that can withstand NIF's extremely high fluences. The team also worked with vendors to develop pulsed-power electronics, innovative control systems, and advanced manufacturing capabilities. Known as "The Seven Wonders of NIF," the team introduced these enabling technologies as the facility was being built [12]. Similar technical breakthroughs will be required in the international effort to develop fusion energy power plants.

Expectations for ignition on NIF within a year or two of its dedication were high, but the first ignition experiments, beginning in 2011, fell well short of the predictions derived from computer models. The experiments produced only one to two kilojoules of energy which is a small fraction of the 1.8 MJ fired into the pencil-eraser-sized cylinders called hohlraums that held NIF's tiny plastic target capsules filled with frozen deuterium and tritium [13]. The implosions were unstable, asymmetric, and had a high level of energy-sapping laser-plasma interactions (LPI).

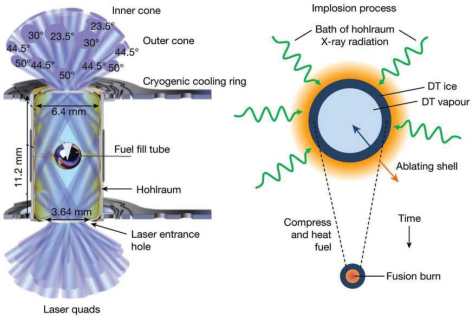

Figure 2. A typical NIF indirect-drive target configuration. At left, laser beams (blue) enter a pencil-eraser-sized cylinder called a hohlraum through laser entrance holes at various angles. At right, at the center of the hohlraum, the target capsule, filled with a thin layer of cryogenic deuterium-tritium (DT) fuel and a volume of DT gas, is bathed in X-rays. The X-rays heat and blow off, or ablate, the outer surface of the capsule, causing a rocket-like implosion that compresses and heats the fuel in the capsule's central "hot spot" to the densities and temperatures required to fuse the atoms. The resulting fusion reactions create high-energy alpha particles (helium nuclei) that accelerate into and heat the cold fuel surrounding the hot spot, generating an explosive, self-sustaining fusion reaction that leads to ignition.

Over the subsequent 10 years, the models and the ability to interpret them improved, and the researchers benefited from an ever-growing knowledge base provided by NIF's sophisticated diagnostic equipment, improvements in laser energy balance, optics, and targets, and new experimental designs based on lessons learned from earlier experiments. The impediments to successful implosions—asymmetries, LPI, fuel contamination by target capsule material, radiative losses, laser backscatter and hot-electron production, and other instabilities—were gradually overcome [14].

Reaching ignition was made possible by contributions from the NIF laser, operations, diagnostics, optics, and modeling teams and the Livermore and General Atomics target fabrication teams; scientists, engineers, technicians, and administrative and support personnel from throughout the Laboratory; and extensive collaborations with researchers in the world's fusion, plasma physics, and high energy density (HED) science communities in other national laboratories, universities, and industry. ICF researchers intend to build on the recent results by increasing energy coupling to the targets, and then understanding and correcting the limitations presently observed with respect to compression [15].

Achieving ignition, a case study in the value of innovation and persistence in the face of a demanding scientific challenge, garnered world-wide attention and excitement: the foundational basis for generating energy from controlled fusion had been demonstrated. To date, more than $6 billion of private funding has been invested in the global fusion industry, and the number of commercial fusion companies has grown to more than 40 [16]. But the question remains: When will fusion energy be available to power our homes and businesses? The answer depends on the level of resources brought to bear on the problem, the extent of worldwide public- and private-sector collaboration, the pace of technology development, and—as in the case of ignition—the dedication and creativity of the world's fusion community.

III. Fusion Energy Challenges

NIF is an experimental facility; it was not designed to be efficient or to produce power. The NIF laser architecture and target configuration were chosen to give the highest probability for fusion ignition for research purposes and were not optimized to produce net energy for fusion energy applications. For example, the fusion reaction produces only a fraction of the energy needed to fire the facility's 192 powerful laser beams.

Significant technical and political challenges remain, therefore, in translating fusion ignition from a laboratory experiment to a viable commercial power plant [17]. Fortunately, however, several components of the NIF laser system, as well as LLNL's expertise in other key aspects of ICF, can provide a kick-start for developing the technology for an integrated power plant (Figure 3). And the same fusion plasmas created on NIF for national security applications can also be exploited to be the basis of IFE physics.

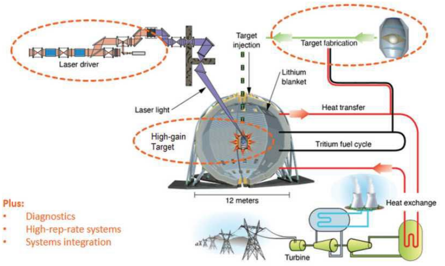

Figure 3. Schematic of a potential IFE power plant; the orange circles and text denote areas of LLNL expertise. A laser fusion power plant would use high-powered lasers to create continual fusion ignition reactions from a steady stream of hydrogen pellets. These pellets, which contain the hydrogen isotopes deuterium and tritium, would be fired into the plant at a rate of approximately 600 per minute. The plant's lasers would precisely converge on each pellet, causing them to ignite and give off 50 to 100 times more energy than went in. That excess energy could then be converted into a clean, abundant source of electricity and connected to the power grid. Laser fusion power plants would likely be about the size of a small football stadium, and just one could meet the energy needs of a city the size of Washington, D.C.

Developing an economically attractive approach to fusion energy is a grand scientific and engineering challenge that will require the same level of sustained commitment that characterized the quest for ignition. Fusion power plants will require the integration of multiple complex subsystems, as well as factoring in cost and efficiency into their design. Areas that will require significant additional technology development include:

- Efficient drivers capable of achieving net energy gain (more energy produced than the energy required to operate the reactor).
- The ability to fire the driver at a repetition rate of 10 Hz or more to provide a continuous stream of energy to the power plant.
- Enhancing understanding of the complex physics of burning plasmas.
- Designing high-gain targets capable of emitting 50 to 100 times the input energy.
- Mass-producing robust, high-quality, and inexpensive targets at a rate of nearly one million per day for a power plant shot rate of 10 Hz.
- Developing a lithium blanket for converting the heat from the fusion reactions into usable energy and for breeding tritium.
- Constructing materials able to withstand the reactor's intense radiation environment.
- Taking advantage of emerging technologies such as exascale computing, artificial intelligence, machine learning, and advanced manufacturing.
- Training the future workforce.
- Instilling public confidence in the benefits and safety of fusion energy.

These and other challenges were explored in a series of workshops and reports [18-23] that followed LLNL's breakthrough experiment on August 8, 2021, that moved NIF to the threshold of ignition [24].

IV. The Path Forward

Building on LLNL's demonstration of fusion ignition in a laboratory, the U.S. government is now taking concrete steps to make inertial fusion energy a reality. Achieving ignition gives the United States a "unique opportunity" to further lead the world scientific community's pursuit of developing fusion as a future source of clean energy, according to a February 2023 IFE Basic Research Needs (BRN) report from DOE's Office of Science. "The formidable scientific and technological challenges that lie ahead before fusion energy becomes fast, efficient, economical, and reliable enough can be overcome," the report said, "with expanded, coordinated research, development, and deployment programs and strategic public-private partnerships" [25, 26]. The BRN report provides a set of priority research opportunities that can inform IFE efforts.

Recognizing that the U.S. needs to capitalize on its current leadership in ICF to move from ignition to practical fusion energy, Livermore established a new IFE institutional initiative in 2022 to help support and grow the national program and community. The initiative also seeks to strengthen science, technology, and engineering capabilities through a strategy of multi-institutional partnerships [27].

In May 2023, DOE announced awardees to a $46 million milestone-based fusion development program that emphasizes public-private partnerships through government support and private company cost-share as a first step toward realizing the Biden administration's Bold Decadal Vision for commercial fusion energy [28]. Under this milestone program, private companies are leading the development of designs for fusion pilot plants.

And in December 2023, DOE announced awards in a $42-million program to establish three multi-institutional and multi-disciplinary hubs to advance foundational IFE science and technology. This effort, the Inertial Fusion Energy Science and Technology Accelerated Research (IFE-STAR) program, brings together expertise and capabilities across national labs, academia, and industry to address priority research opportunities for IFE [29].

IFE-STAR includes a four-year, $16 million project for LLNL to accelerate IFE science and technology through the IFE Science and Technology Accelerated Research for Fusion Innovation and Reactor Engineering Hub, or STARFIRE [30]. STARFIRE Hub partners are working together to develop systems-level laser architecture, plant-compatible target designs, and a plant-assessment framework.

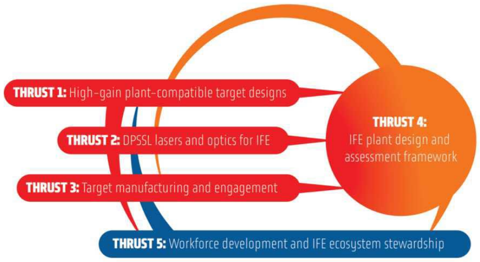

Figure 4. The IFE-STARFIRE hub will accelerate technology and workforce development to advance fusion energy research.

STARFIRE's efforts will develop foundational science and technology to support the growing public and private IFE communities. STARFIRE will accelerate the demonstration of high-gain target designs, target manufacturing, tracking, and engagement, as well as diode-pumped solid-state laser (DPSSL) technologies, with the development of these technologies guided through an IFE plant-modeling framework. The project will also begin developing the IFE workforce of the future through partnerships with leading universities and innovative curriculum development and implementation.

The hub consists of members from seven universities, four U.S. national labs, one international lab, three commercial entities, one philanthropic organization, and three private IFE companies. Two other hubs were also awarded, led by Colorado State University and the Laboratory for Laser Energetics at the University of Rochester. Together, the three hubs are helping to lay the foundational groundwork for laser fusion energy prototype plants in the coming decade in support of DOE's Bold Decadal Vision for Fusion Commercialization.

V. Summary and Conclusions

In collaboration with the international ICF, plasma, and HED research communities, Lawrence Livermore National Laboratory has successfully completed its 60-year pursuit of fusion ignition in a laboratory. Four subsequent experiments also succeeded in producing more energy from a laser-driven ICF implosion than the laser energy required to initiate the fusion reaction, enabling researchers to study new regimes in HED physics that are important to LLNL's stockpile stewardship mission.

For many decades, the running joke in fusion research was "fusion is 20 years away and always will be." Yet ICF researchers are now able to refer to the milestones of burning plasmas, fusion ignition, and target energy gain greater than unity, or "scientific breakeven," in the past tense. With proof of fusion ignition and scientific breakeven in the laboratory, Livermore's next challenge is to help lead a national and international effort to apply the lessons of ignition in the quest to make fusion a source of abundant clean, safe, and reliable energy. Inertial fusion energy has the potential to be a game-changing technology for deep decarbonization while bolstering American science and technology leadership, security, and energy independence. With funding from the U.S. government and in collaboration with the private sector, the prospect of powering the world's homes and businesses with fusion energy is no longer a distant dream. Substantial challenges remain, but the future of ICF and fusion energy could not be brighter.

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