THE AGE OF IGNITION

INSIDE LAWRENCE LIVERMORE NATIONAL LABORATORY'S FUSION BREAKTHROUGH

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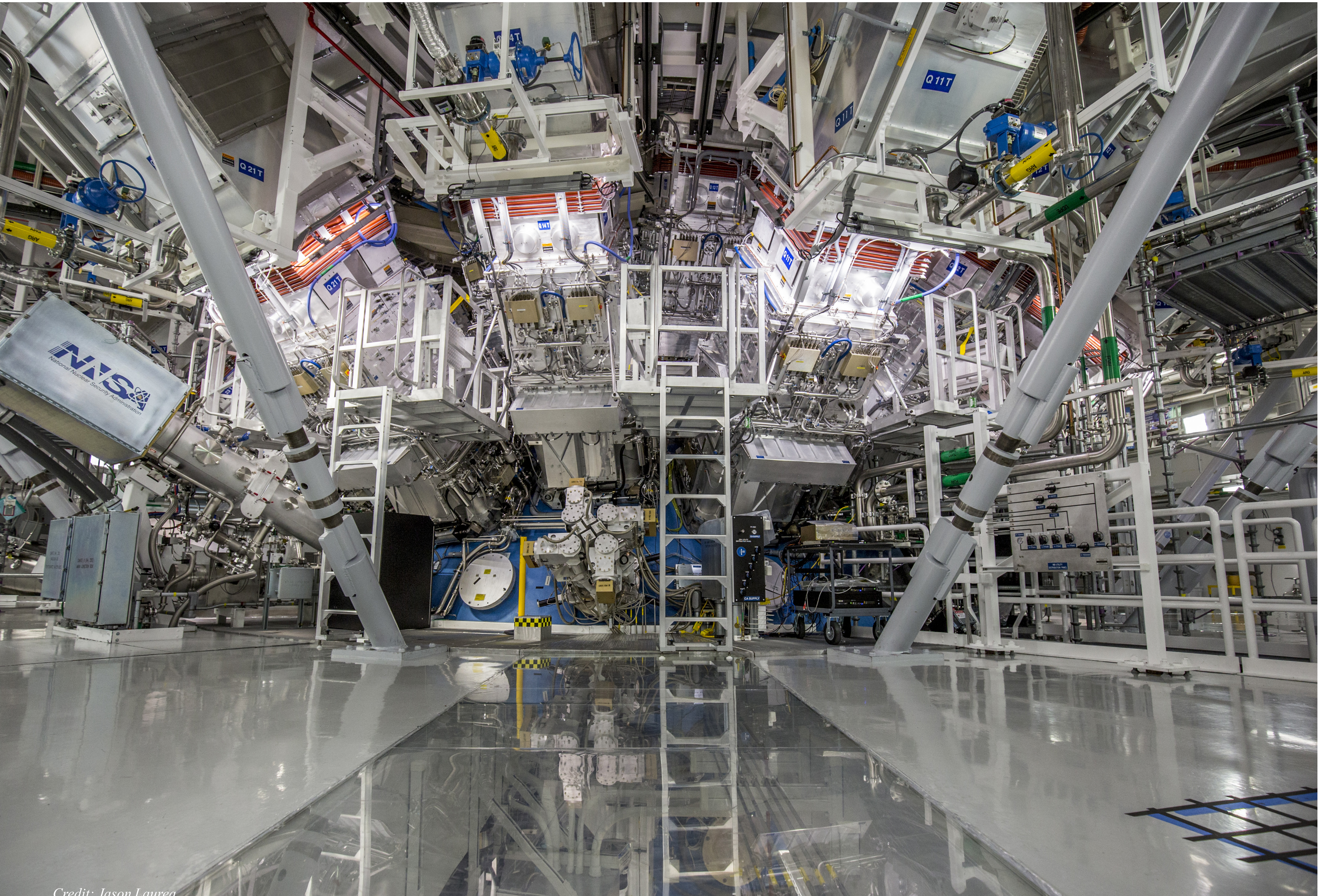
Inside Lawrence Livermore National Laboratory's Fusion Breakthrough

Foreword by LLNL Director Kim Budil

On the morning of Dec. 5, 2022, researchers at Lawrence Livermore National Laboratory (LLNL)'s National Ignition Facility (NIF) achieved one of the great scientific accomplishments in history—fusion ignition.

Our pursuit of this incredibly ambitious technical goal began more than 60 years ago when John Nuckolls and his team made the audacious proposal that lasers could be used to produce fusion ignition in the laboratory. Many said it was not possible—the NIF laser was not energetic enough, the targets would never be precise enough, our modeling and simulation tools were just not up to the task of this complex physics. But, over the decades, we steadily built our understanding and developed the technology to make this "impossible" task possible. This is what national laboratories are for—taking on the most difficult challenges and persistently following the science where it leads.

This achievement opens new realms for us to explore—advancing our capabilities for national security missions and sustainment of our nuclear deterrent without nuclear testing, generating the most extreme conditions ever created in a lab, and laying the groundwork for inertial fusion energy. This truly monumental first step sets the stage for a transformational decade in high energy density science and fusion research, and I cannot wait to see where it takes us!



Credit: Jason Laurea

STAR POWER:
Blazing the Path to Fusion Ignition

It was the middle of the night on Dec. 5, 2022, and anticipation was building among the handful of researchers and technicians in the National Ignition Facility (NIF) Control Room. A set of pre-shot simulations had predicted a slightly better than 50-50 chance that the impending nuclear fusion experiment would reach or exceed "break-even"—producing as much or more energy than it used to drive the fusion reaction.

The shot had been delayed for the completion of optics installations and other tasks from the weekend's facility maintenance period. Finally at 1:03 a.m., the computer-controlled countdown reached zero, shot director Joseph Griffo pronounced, "Shot!" and NIF's 192 powerful lasers fired 2.05 megajoules (million joules) of ultraviolet energy into the ends of a pencil eraser-sized cylinder holding a tiny capsule of hydrogen fuel.

Radiation alarms sounded in unoccupied areas of the facility as the heavily shielded Target Chamber was flooded with 1.12×10^{18} (1.12 quintillion) high-energy neutrons—the equivalent of 3.15 megajoules of fusion energy—produced by an explosive, self-sustaining thermonuclear reaction. Monitors began to display the unprecedented neutron yield captured by an array of diagnostic instruments, and the broad smiles and hearty high-fives around the Control Room told the story:

After 12 years of sustained and often frustrating effort and hundreds of experiments, Lawrence Livermore National Laboratory (LLNL) had achieved ignition—meeting a milestone that tantalized the inertial confinement fusion (ICF) community for more than 60 years and launching the age of controlled fusion ignition in the laboratory.

"This was only the second NIF shot to deliver more than two megajoules of ultraviolet energy to an ICF target," said NIF Operations Manager Bruno Van Wonterghem. "This shot is just the beginning of a whole new level of ICF operations."

Physicist Alex Zylstra, who was the shot's principal experimentalist, was waiting at home for news of the result. "As the data started to come in," he said, "we saw the first indications that we had produced more fusion energy than the laser input. One of the first things I did was call one of the diagnostic experts to double-check the data, and we kind of went from there."

That expert was Dave Schlossberg, science lead for the NIF Nuclear Diagnostics group, who had asked Zylstra to call him if anything interesting happened.

"My phone rang at about 1:30 a.m. and it was Alex, quite excited," Schlossberg said. "The first neutron data was rolling in, and it indicated higher performance than we'd ever seen before.

"In the pitch black of my living room from 2 to 4 a.m. Monday morning," he said, "I quickly confirmed the validity of these results and continued communicating with Alex. More data rolled in from other diagnostics, and we excitedly realized this was a momentous event."

The preliminary data were quickly shared with Zylstra's colleagues. Annie Kritcher, the experiment's lead designer and team lead for integrated modeling, had gone to bed and was having "vivid dreams of all possible outcomes from the shot. This always happens before a shot," she said, "from complete success to utter failure.

"Thankfully, Alex had sent me a message, so by the time I woke up, I saw that it wasn't a failure. You see one diagnostic and you think, 'Well, maybe that's not real.' And then you start to see more and more diagnostics rolling in pointing to the same thing, and it's just a great feeling."

Later that morning, members of the NIF management team could barely contain their excitement as they waited for the diagnostic data to be processed. They were overjoyed when the initial analysis confirmed that NIF had lived up to the promise of its middle name.

Over the next few days, the data were carefully analyzed by NIF's nuclear diagnostics group, x-ray group, and other target diagnostic experts, and peer-reviewed by outside consultants. The validated results were announced to the rest of the NIF & Photon Science (NIF&PS) team on Dec. 9, and to the world through a U.S. Department of Energy (DOE) news conference on Dec. 13.

"The pursuit of fusion ignition in the laboratory is one of the most significant scientific challenges ever tackled by humanity. Achieving it is a triumph of science, engineering, and most of all, people."

LLNL Director Kim Budil

The historic achievement, which more than doubled NIF's previous energy record, marked a significant advance in LLNL's support for the National Nuclear Security Administration (NNSA)'s science-based Stockpile Stewardship Program to maintain the reliability and security of the nation's nuclear deterrent without underground testing. It also furthered LLNL's research in high energy density science and demonstrated the fundamental science basis for inertial fusion energy (IFE), emboldening further research into the development of IFE as a potential source of clean, safe, and limitless energy.

What's more, the Dec. 5 experiment was only the first of several experiments that achieved ignition during the following months. On July 30, 2023, the NIF laser again delivered 2.05 MJ of energy to the target, resulting in 3.88 MJ of fusion energy output, the highest yield achieved to date. On Oct. 8, 2023, NIF achieved fusion ignition for the third time with 1.9 MJ of laser energy resulting in 2.4 MJ of fusion energy yield.

And on Oct. 30, 2023, NIF set a new record for laser energy, firing 2.2 MJ of energy for the first time on an ignition target. This experiment resulted in 3.4 MJ of fusion energy yield, the second-highest neutron yield ever achieved on NIF.

These results demonstrated NIF's ability to consistently produce fusion energy at multi-megajoule levels.

Reaching ignition was made possible by contributions from the Laboratory's NIF&PS, Strategic Deterrence, Physical and Life Sciences, Engineering, Computing, and Operations 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 science communities in other national laboratories, universities, and industry.

LLNL Director Kim Budil also credited "the many supporters and stakeholders in the National Nuclear Security Administration, the Department of Energy, and in Congress, who've ensured we could reach this moment, even when the going was tough.

"The pursuit of fusion ignition in the laboratory is one of the most significant scientific challenges ever tackled by humanity," Budil said. "Achieving it is a triumph of science, engineering, and most of all, people."

Among the key factors enabling the breakthrough:

- Creative experimental designs informed by steady increases in the scientific understanding of the complex physics of inertial confinement fusion.
- Record levels of energy generated by NIF's lasers.
- Increasingly damage-resistant optics that enable the laser system to operate at energies and powers well beyond its design specifications.
- Terabytes of data from NIF's suite of more than 100 state-of-the-art nuclear, x-ray, and optical diagnostics.
- Enhanced experiment-based modeling and simulation that helped shape the new experimental designs.
- Advancements in the metrology and fabrication of custom-made targets.

Ignition on NIF, the world's largest and highest-energy laser system, means the nuclear fusion reactions sparked by the lasers produce as much or more energy than the laser energy delivered to the target—the definition of ignition used by the National Academy of Science in a 1997 review of NIF.

In NIF ICF experiments, a target capsule containing two forms of hydrogen, deuterium (D) and tritium (T), is suspended inside the cylindrical x-ray "oven," called a hohlraum. On the capsule's inside surface is a thin layer of cryogenically cooled DT and a volume of DT gas. When the hohlraum is heated by NIF's laser beams to temperatures of more than three million degrees Celsius, the resulting x rays heat and blow off, or ablate, the outer surface of the capsule, called the ablator. This causes a rocket-like implosion that compresses and heats the DT fuel.

In this "indirect-drive" process, the shape of the imploding fuel must remain as spherical as possible to maximize compression and form a stable central "hot spot." Ignition occurs when the energy from a self-sustaining fusion reaction overcomes the cooling effects of x-ray losses, electron conduction, and implosion expansion.

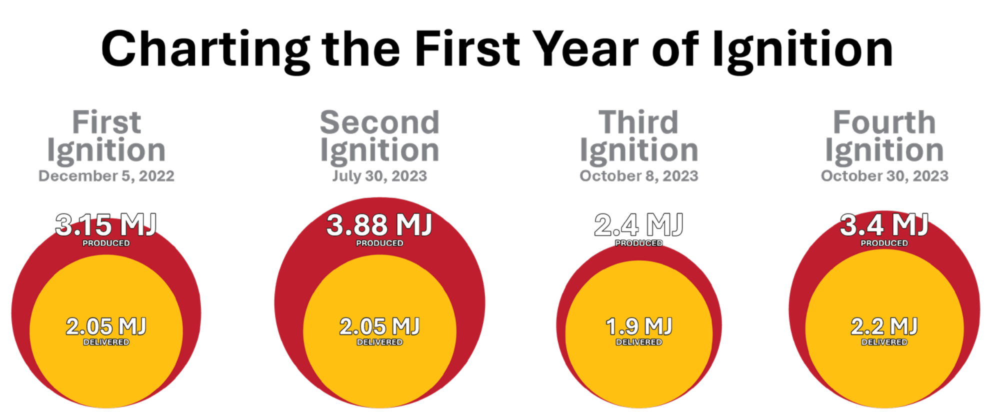
Reaching ignition crowned six decades of research and development of the world's highest-energy lasers at LLNL, all working toward the goal of creating in the laboratory the temperatures and pressures found only in the center of stars and giant planets and in exploding nuclear weapons.

And it fulfilled the vision of the Laboratory's fusion pioneers, such as former LLNL Director John Nuckolls, who first proposed using lasers to create the power of the stars in a laboratory; John Emmett, the first leader of the Laboratory's consolidated laser programs; and former NIF Chief Scientist John Lindl, who literally wrote the book on the physics of indirect-drive ICF in 1998.

Nuckolls recalled that when he first conceived of using lasers to create the power of the stars in a laboratory, "I said, 'We have two problems: How am I going to get a million-joule laser?' because that's what I calculated we would need. The next problem was, 'I don't think I'm going to live long enough.'

"I lucked out," he said, "and here I am, and here's this wonderful program. Incredible, it's beyond belief."

Lindl, who joined the ICF program in 1972 and became the leader of the Laser Target Design Group in 1978, presented the original proposal for NIF to the National Academy of Science in 1989. He



LLNL has achieved fusion ignition on NIF four times to date. Credit: Brian Chavez

Jill Hruby, DOE under secretary for Nuclear Security and administrator of the National Nuclear Security Administration (NNSA), discusses NIF's fusion breakthrough at the DOE news conference in Washington, D.C. Hruby said LLNL researchers have "opened a new chapter in NNSA's science-based Stockpile Stewardship Program." Hruby is flanked by, from left, LLNL Director Kim Budil, Energy Secretary Jennifer Granholm, White House Office of Science and Technology Policy Director Arati Prabhakar, and NNSA Deputy Administrator for Defense Programs Marvin "Marv" Adams. Credit: DOE

Physicists John Emmett (left) and John Nuckolls, early LLNL pioneers in laser and ICF technology.

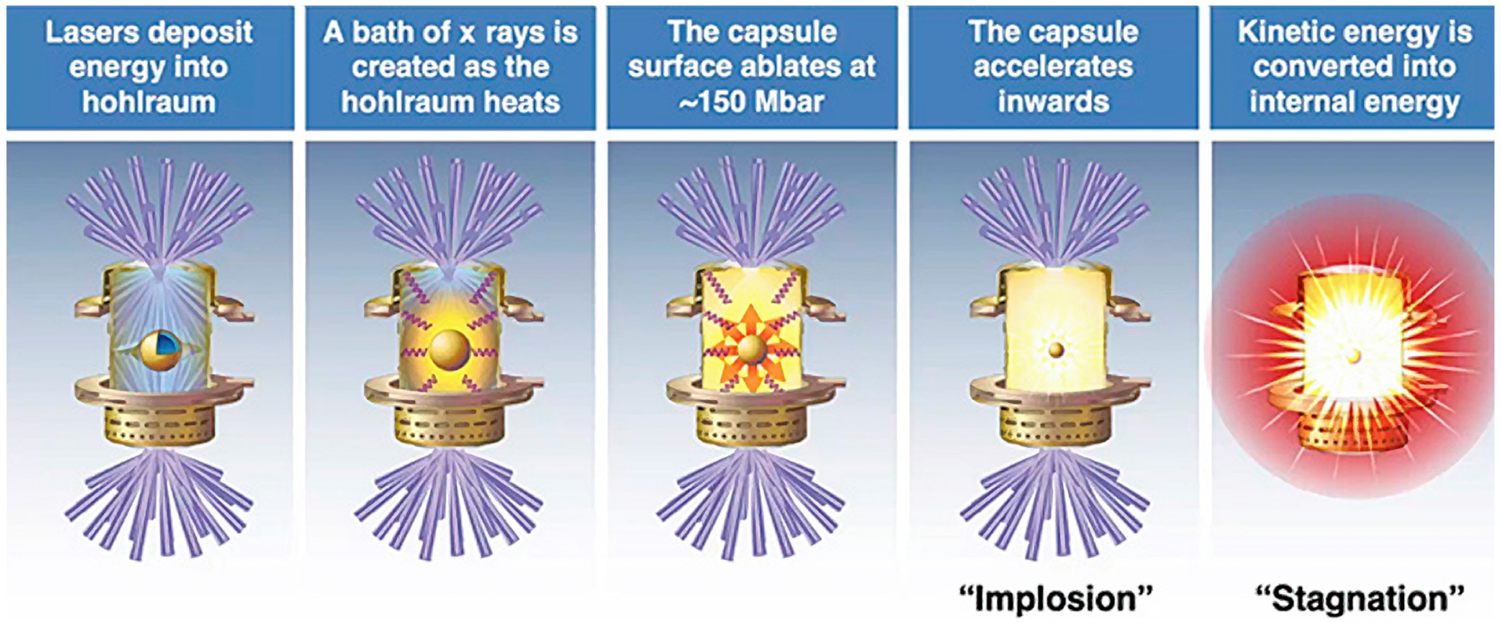


Illustration of laser-driven inertial confinement fusion. In ignition experiments, the implosion crushes the capsule to smaller than the width of a human hair, impelling the fuel to temperatures and densities exceeding those found in the sun. Achieving the conditions for ignition demands precise control of design, laser, and target parameters.

said the academy gave the project only a 50-50 chance of achieving ignition.

"I would say that, by far, the majority of the scientific community was very skeptical, if not downright dismissive, of the likelihood that we would succeed," Lindl said. "But there have been enough people who believed we could do it and sustained the support for what we've been doing that got us to this point.

"Fortunately, we were on the positive side of the 50-50 proposition."

To get to ignition, LLNL researchers confronted and overcame a wide variety of issues: implosion asymmetries and hydrodynamic instabilities; fuel contamination by material from the target capsule; radiative losses: laser backscatter; and perturbations caused by the ultra-thin "tents" holding the capsule inside the hohlraum and the tiny tubes used to fill the capsule with fuel.

The researchers met in an auditorium almost every week to review the results and implications of the previous week's experiments—doing their best to tease out the subtle nuances of one of history's toughest scientific quests.

They adjusted the energy and timing of the laser pulses, experimented with new target designs and materials, found ways to couple more laser energy to the target to boost the hot-spot pressure and temperature, and made NIF's optics more resistant to laser damage.

Nino Landen, the ICF Experiments Program group leader, noted that the road to ignition also represents "the culmination of developing and refining state-of-the-art diagnostics and active probe techniques over several decades by hundreds of scientists, engineers, and technicians" at NIF's predecessor, the Nova Laser at LLNL, the Omega Laser Facility at the University of Rochester, and NIF.

> *"We knew we were moving in the direction where things should start working better."*
>
> **ICF Chief Scientist Omar Hurricane**

"These allowed us to measure and understand hohlraum and capsule conditions and sensitivities, and ultimately adjust the input laser and target parameters for optimizing implosion performance," Landen said. "The experimental developments led notably over decades by Mike Campbell (former Laser Programs associate director) and Joe Kilkenny (former ICF Program leader and current chief systems engineer for Measurement Systems) to advance ICF have also proved useful for a broader set of high energy density science experiments."

The researchers knew they were on the threshold of ignition when an Aug. 8, 2021, experiment produced 1.35 megajoules (MJ) of energy, about 70 percent of the 1.92 MJ of laser energy absorbed by the target. That experiment incorporated several design changes that boosted the energy reaching the fuel.

The resulting fusion reactions propelled almost 500 quadrillion energetic alpha particles (helium nuclei) into the cold fuel surrounding the hot spot, igniting a self-sustaining "burn wave" of additional reactions that consumed about 2 percent of the fuel.

The Aug. 8 result, as well as NIF shots in 2020 and 2021 that produced a burning plasma for the first time, "showed an existence proof that ignition was possible," said ICF Chief Scientist Omar Hurricane. "We knew we were moving in the direction where things should start working better."

The Dec. 5 ignition shot was the second in a modified experimental campaign, called "Hybrid-E High Energy" (HyeHE), that built on earlier Hybrid designs but included design improvements for higher fusion energy output: about 8 percent more laser energy (2.05 MJ), a longer pulse, and a thicker (by 6 microns) target capsule (a micron is one-millionth of a meter).

The higher-energy shot was enabled in part by implementing several technologies to protect NIF's optics from damage. They included the installation of 80 additional high-quality fused silica debris shields, for a total of 128 of NIF's 192 beamlines, to protect the final optics from debris generated by less-durable disposable shields.

The HyeHE campaign's goal was to overcome variations that had stymied several earlier efforts to replicate the 2021 results, such as implosion asymmetries and fuel contamination by capsule material, that were linked to microscopic defects in the capsules.

> *"In the future, the NIF laser could produce even higher energies and power and promise larger target gains."*
>
> **Co-Program Director of Laser Science and Systems Engineering Jean-Michel Di Nicola**

"The whole point behind this new design change—higher energy and a thicker ablator—was to have more margin against needing to have a very pristine capsule," Kritcher explained. "The thicker capsule also lets us burn up more of the DT fusion fuel."

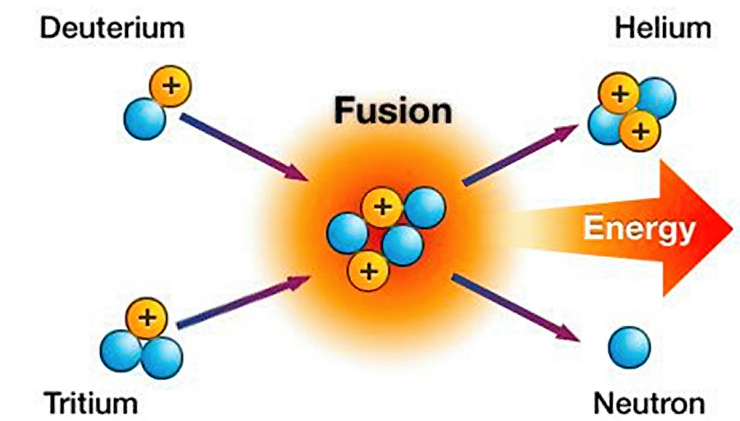
The first shot in the new campaign, on Sept. 19, produced about 1.2 MJ of energy, falling just short of the 2021 result primarily because the implosion was driven oblate, leading to a pancake-shaped hot spot that wasted some of the additional laser energy.

To improve symmetry for the December shot, the researchers adjusted the balance of energy among the laser beams, both at the start and in the main part of the pulse. At the peak of the pulse, this was achieved by wavelength tuning—slightly changing the wavelength of one or more sets of beams to control the exchange of energy as the beams crossed in the laser entrance holes.

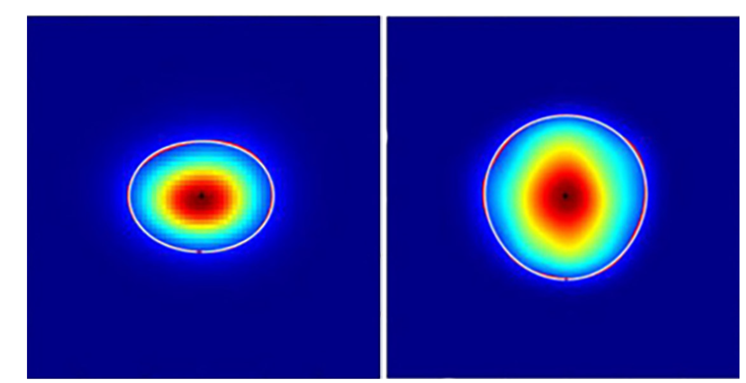
This rebalancing of the laser energy helped equalize the x-ray drive so energy was evenly distributed throughout the hohlraum, producing a more symmetric implosion that burned about 4 percent of the fuel and resulted in ignition (see Page 10: "Designing for Ignition: Precise Changes Yield Historic Results").

Significantly, the ignition experiment used a target capsule with many more surface and subsurface defects and high-Z (high atomic number) "inclusions" than the 2021 experiment that moved NIF to the threshold of ignition.

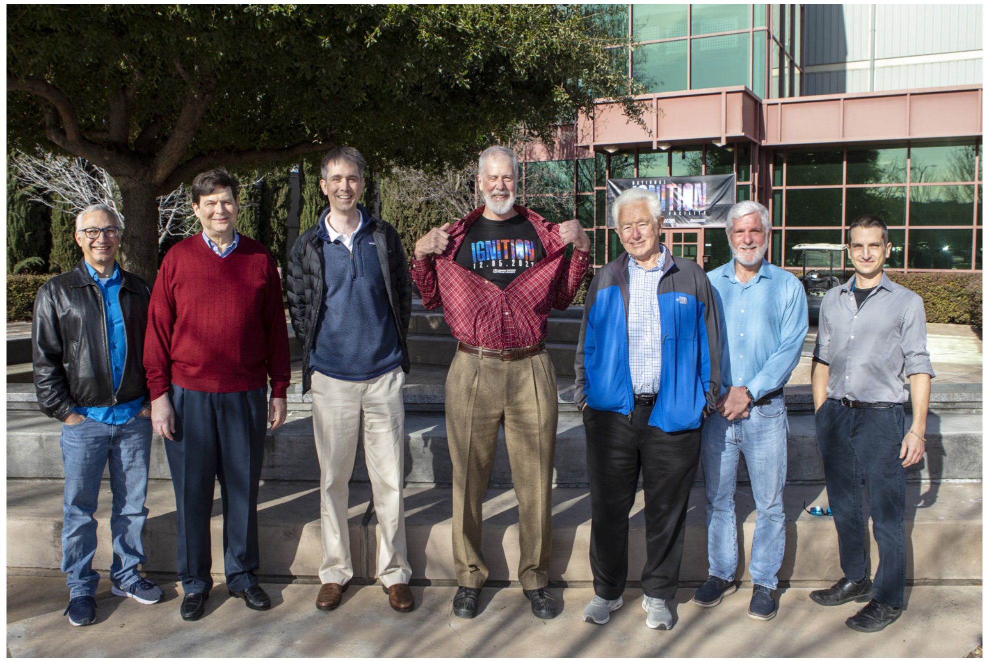
The new design was shared with LLNL's cognitive simulation team, and they concluded that "we had a greater than 50 percent probability of achieving the National Academy of Science's definition of ignition," said LLNL design physicist Kelli Humbird. "This was the first time we've attempted this kind of prediction, and our current data-driven model indicated there was a substantially higher chance of achieving ignition with this design when compared to the August 8 design."



In a fusion reaction, nuclei of the two isotopes of hydrogen, deuterium (containing one neutron and one proton) and tritium (two neutrons and one proton), are forced together by extremes of temperature and pressure and fuse to form a helium nucleus. In the process, some of the mass of the hydrogen is released as energy.



Primary neutron imaging by the NIF neutron imaging spectrometer developed by Los Alamos National Laboratory shows the implosion shape of the Sept. 19 experiment (left) and the Dec. 5 shot that achieved ignition. The September implosion was slightly oblate, or pancake-shaped, while the December shot was more symmetric.



Among the many researchers who contributed to NIF's groundbreaking ignition experiment were (from left): Omar Hurricane, Nino Landen, Michael Stadermann, John Lindl, Joe Kilkenny, Doug Larson, and Dave Schlossberg. Credit: Jason Laurea

Target Fabrication Program Manager Michael Stadermann said the fact that the capsule was flawed was "very encouraging" for the team. "This gives us confidence that we can make shells of equal quality or even better quality in the future—that we'll be able to reproduce this experiment or even improve on it," he said.

Accessing the energies of fusion ignition will enable stockpile stewardship experiments at a new level of high energy density conditions. Ignition will also help weapons scientists test and refine the computer models they use to better understand and assess the performance of the stockpile's aging nuclear weapons.

"Fusion ignition is a key process in our thermonuclear weapons," said Mark Herrmann, LLNL's program director for weapons physics and design. "The very extreme environments created when the fusion plasma ignites enables testing that ensures that we can maintain and modernize our nuclear deterrent."

Added Budil: "Our leadership in science and technology helps to build strong relationships with our allies and partners and to demonstrate our capabilities to our adversaries."

Ignition experiments also will help assess the survivability of nuclear weapon components and other weapon-relevant materials important to national security.

The Dec. 5 shot was the first experiment "where we put the ignition platform to work for stewardship," said now-retired NIF Director Doug Larson. The experiment fired a blast of neutron radiation on depleted uranium samples and test objects, a step toward eventually conducting enriched uranium and plutonium survivability experiments.

"Nobody else can do that," Larson said. "Nobody else has an intense pulsed source of 14 MeV (14 million electron-volt) neutrons to assess stockpile survivability questions. Right now, it's (about) survivability, but as we attain even higher yield, it'll broaden to other (stewardship) applications."

The data and insights from ignition experiments also will help evolve inertial fusion energy, or IFE, as a viable technology for future power plants.

Achieving ignition "demonstrates the basic scientific feasibility" of IFE, said Tammy Ma, lead for LLNL's Inertial Fusion Energy Institutional Initiative.

"Developing an economically attractive approach to fusion energy is a grand scientific and engineering challenge," she said. "Without a doubt, it will be a monumental undertaking. However, the potential benefits are enormous: clean, carbon-free, abundant, reliable energy capable of meeting the world's energy demands, and furthermore, providing for the energy sovereignty and energy security of the U.S."

Having blazed the path to ignition, ICF researchers and their collaborators quickly implemented plans for sustained, and even higher, yields to enable new stockpile stewardship and basic science applications at NIF.

"To quote Winston Churchill," said NIF Director Gordon Brunton, "'Now is not the end. It is not even the beginning of the end. But it is, perhaps, the end of the beginning.'

"With more than 20 years invested in getting NIF to the starting block," Brunton said, "we must prioritize restoring the workforce and facility to sustainably continue to maximize the recent outstanding results for the Stockpile Stewardship Program.

"Beyond the near-term sustainment of NIF," he said, "our modest plans for further upgrades will extend our worldwide leadership in high energy density physics and keep NIF as a flagship scientific capability of the nation for decades to come."

Improving the Targets

As a step toward this vision, experiments later in 2023 used a new set of target capsules carefully manufactured to reduce the defects that limited the performance of earlier shots.

In addition, said Jean-Michel Di Nicola, co-program director for NIF's Laser Science and Systems Engineering, boosting the laser's power by another 8 percent would provide more margin for ignition. "In the future, with a (facility) sustainment and upgrade investment," he said, "the NIF laser could produce even higher energies and power and promise larger target gains."

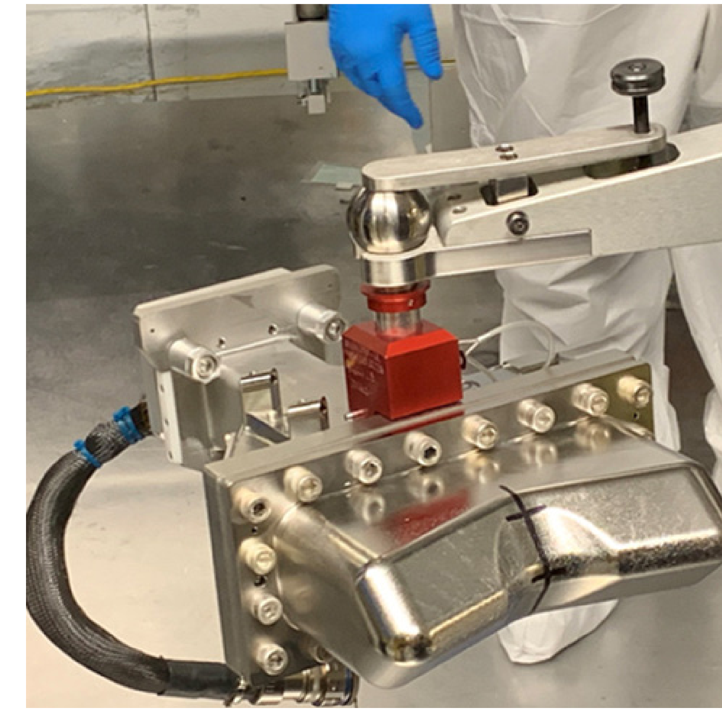
Laser upgrades and additional optics improvements enabled NIF to reach 2.2 MJ of energy and nearly 450 trillion watts of peak power in October, facilitating additional ignition experiments with fusion yields even higher than the Dec. 5 shot. Researchers believe the laser could potentially deliver as much as 2.6 to 3 MJ later this decade.

"Little changes can make a big difference" in the outcome of an experiment—both positive and negative, Herrmann noted. He said LLNL's goal moving forward is to control the "inherent variabilities" in fusion implosions and continue to consistently produce results in the multi-megajoule range.

Achieving ignition "was a long, difficult journey," said Budil, "but NIF started full-scale experimental operations in 2009 and hasn't looked back since. In the end, the laser has exceeded all of its performance goals and opened whole new areas of high energy density science to exploration."

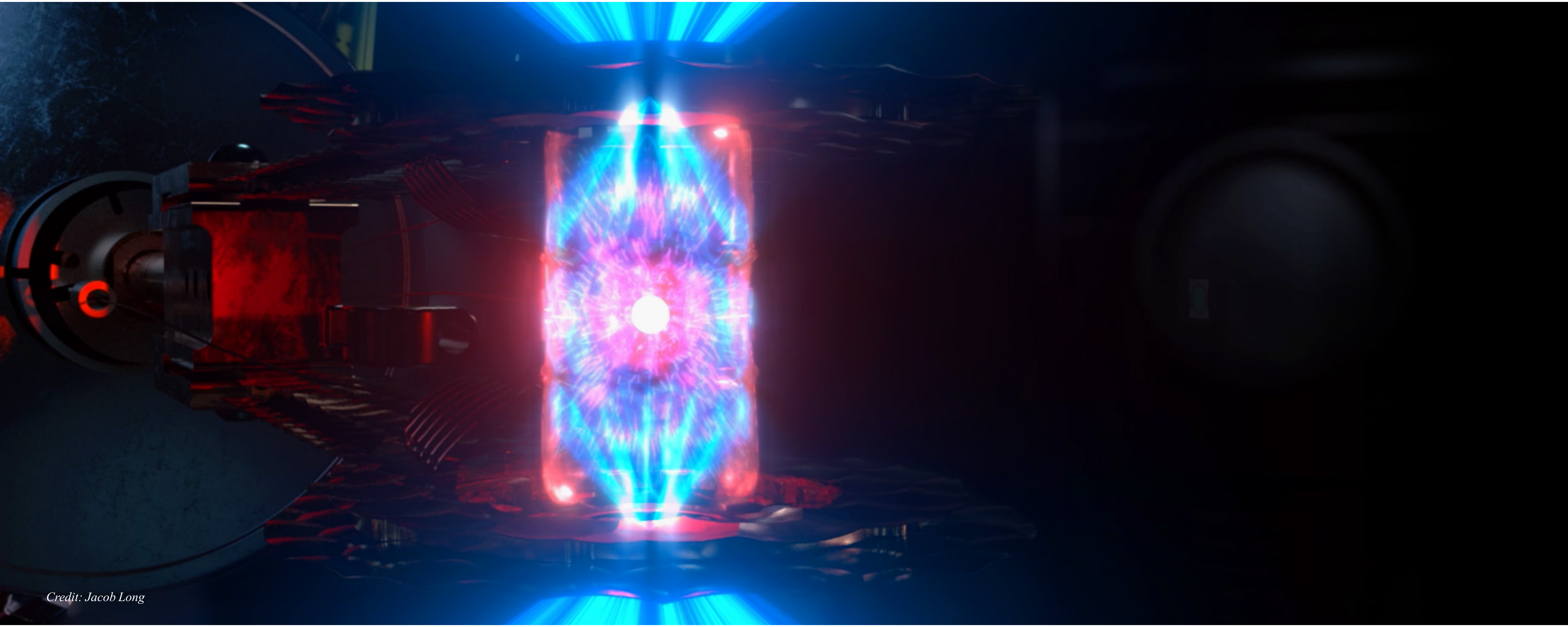
Along with the LLNL participants, the researchers credited the experiment's success to collaborators from Los Alamos and Sandia national laboratories, the Nevada National Security Site, General Atomics, Diamond Materials, the Laboratory for Laser Energetics at the University of Rochester, the academic community including the Massachusetts Institute of Technology, the University of California, Berkeley, and Princeton University, and international partners including the United Kingdom's Atomic Weapons Establishment and the French Alternative Energies and Atomic Energy Commission.

—*Charlie Osolin*



The cryogenic-compatible x-ray, neutron, and blast snout (XNBS) used in the first high energy density neutron survivability test on Dec. 5.

Researchers and technicians in the NIF Control Room react to U.S. Secretary of Energy Jennifer Granholm's Dec. 13 announcement that NIF had achieved fusion ignition for the first time. Granholm likened ignition to the Wright Brothers' first flight and called it "one of the most impressive scientific feats of the 21st century." Credit: Jason Laurea



Credit: Jacob Long

DESIGNING FOR IGNITION:

Precise Changes Yield Historic Results

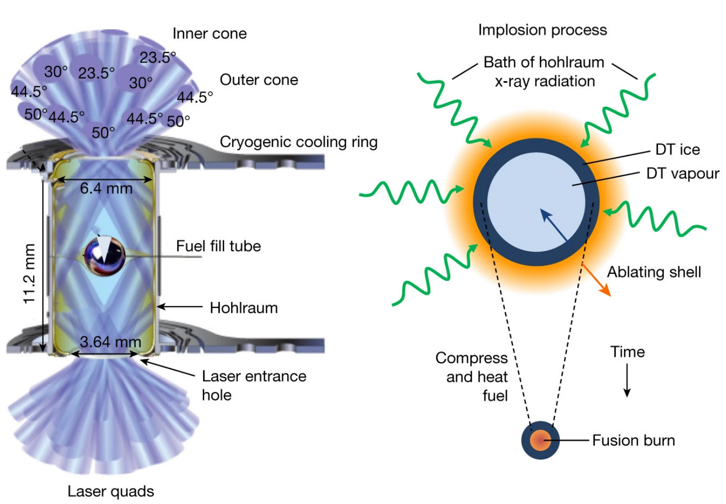
Three football fields could fit inside the National Ignition Facility, but it's what happened in a capsule the size of a peppercorn that made scientific history on Dec. 5, 2022.

The LLNL experiment that made news headlines around the world was anything but an overnight success. The accomplishment was the result of decades of research to determine the laser requirements and target conditions it would take to create a fusion reaction that produced more energy than it consumed.

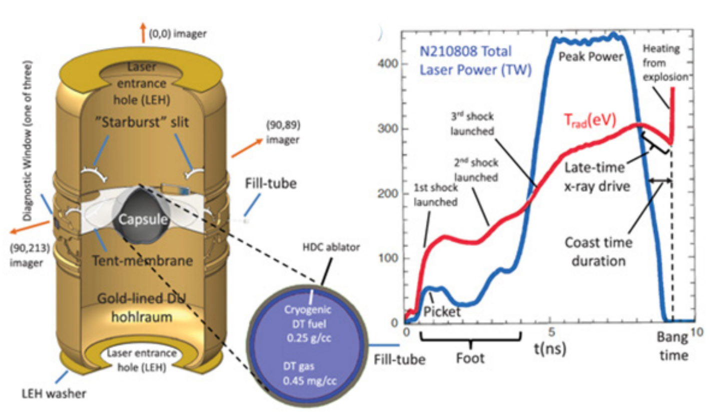
NIF's progress from a few kilojoules of energy yield when the facility began ignition experiments in 2011 to the December breakthrough was due in large part to the steady evolution of experimental designs—closely coupled with continuous improvements in diagnostic, optics, and modeling and simulation technology, target quality, and the energy, reliability, and energy balance of NIF's 192 laser beams.

"The last 10 years have been tough; we were counted out so many times," said ICF Chief Scientist Omar Hurricane. "But it has also been steady progress to get to this point; 10 years is a relatively short time for such a hard scientific challenge."

To put the many doubts to rest, the researchers modified the elements of NIF's experiments—the size, shape, and composition of the targets,



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.



Increased hot-spot energy (red line at right) and pressure was achieved in the Aug. 8, 2021, experiment by increasing the radius of the target capsule, reducing the apertures of the laser entrance holes, and lowering and extending the duration of the peak power to reduce the coast-time duration.

the shape and energy of the laser pulse, the timing of the implosions—as they gradually gained more understanding of the inertial confinement fusion (ICF) physics that could enable a self-sustaining "burn wave" of fusion reactions that would lead to ignition.

Improvements in Steps

Annie Kritcher, the experiment's lead designer and team lead for integrated modeling, said the experimental design process has involved "many years of building up understanding and developing models and cross-checking those models against experimental data, and then using those calibrated models together with semi-analytical models and theory to make design improvements."

> *"Achieving ignition requires a great deal of finesse. Although these changes seem small, they make all the difference."*
>
> ***Lead Designer Annie Kritcher***

The key steps along the path to ignition included:

- Designing and experimenting with the energy, shape, and duration of the laser pulse to improve the stability and velocity of NIF implosions.
- Changing the composition of the target capsule, the ablator, from polymer (CH) to high-density carbon (HDC), or diamond, to improve energy efficiency and ablation pressure.
- Launching a series of "Hybrid" (high-yield big-radius implosion design) experiments that coupled the best elements of previous high-yield experiments with new understanding of the implosion process provided by rapid advances in diagnostic and modeling technology.
- Increasing the size of the diamond capsules and modifying the size and configuration of the hohlraums to deliver more energy to the hot spot in the center of the capsules where the fusion reactions begin.
- Modifying the design to enable the target changes with the same laser driver capability while maintaining high hot-spot energy density.
- Reducing the amount of helium gas in the hohlraums to inhibit backscatter losses and energy-robbing hot-electron production.
- Improving energy distribution and implosion symmetry by adjusting the balance of energy among the laser beams, both at the start of the laser pulse and when the beams cross in the laser entrance holes.

"Controlling the symmetry in these implosions is like trying to compress something the size of a basketball down to the size of a pea and keep it looking like a sphere to the percent level," Kritcher said. "This lets us squeeze the hot-spot plasma (a mixture of ions and free electrons) to conditions more extreme than the sun's core.

"We're trying to do this in a very harsh environment," she added, "where the target is filling with plasma and it's difficult to get all the laser beams where you want them to go to create a uniform x-ray oven."

In the end, it was vanishingly small, intentional energy-balance adjustments, coupled with a 6-micron (millionth of a meter) increase in the thickness of the capsule and a .13-megajoule (8 percent) boost in the lasers' energy, that resulted in the first ICF reaction to achieve ignition—producing 3.15 megajoules (MJ) of fusion energy from a laser input of 2.05 MJ.

"Achieving ignition requires a great deal of finesse," Kritcher said. "Although these changes seem small, they make all the difference."

"We had a debate over a laser setting equivalent to five trillionths of a meter going into this experiment," added principal experimentalist Alex Zylstra. "We had a discussion with the laser science team over a timing discrepancy of 25 trillionths of a second. Small timing errors, a billionth of a second, would be an eternity for us in this experiment."

"What ended up working was not some dramatic departure from what we had been doing," Hurricane said. "It was much more incremental—thinking about these incremental changes and making improvements that moved us in the right direction."

On the Threshold

LLNL's first major breakthrough in energy yield came on Aug. 8, 2021, when a Hybrid-E experiment produced about 1.35 MJ of fusion energy—about 70 percent of the 1.92 MJ of laser energy delivered to the target—putting NIF at the threshold of ignition. That accomplishment came just a few months after NIF for the first time achieved a "burning plasma"—when the fusion reactions are the primary source of heating in the plasma.

To reach the 1.35 MJ milestone, the researchers shrank the aperture of the hohlraum's laser entrance holes to prevent energy from escaping during the experiment; re-adjusted the x-ray oven symmetry; reduced defects in the target capsule that contributed to "mix," or contamination of the central hot spot by capsule material; decreased the size of the tube used to fill the capsule with hydrogen fuel from five to two microns; and extended the laser pulse to effectively hold the implosion together longer and concentrate more energy in the hot spot.

Experimental Design Team members discuss the results of the Dec. 5 ignition experiment. From left: Annie Kritcher, Chris Young, Kelli Humbird, Omar Hurricane, and Chris Weber. Credit: Jason Laurea

Creating a NIF ICF implosion is a highly inefficient process; normally only 10 to 15 percent of the initial infrared laser energy reaches the capsule. About half of the energy is lost when the infrared light is converted to higher-energy ultraviolet; half of the remainder is used to create x rays in the hohlraum; and much of the rest is dissipated when x-ray energy escapes through the laser entrance holes or is lost to laser-plasma interactions, backscatter, and other factors.

Doubling the hot-spot energy had been shown to increase NIF's energy yield by a factor of four; that's why finding ways to increase the energy absorbed by the hot spot was a key element of the experimental designs that produced both the 2021 result and fusion ignition in 2022.

"By increasing the amount of energy delivered to the hohlraum from the laser," Hurricane said, "we are reducing the implosion's coast time (the time between maximum compression and the end of the laser pulse). That's a very strong lever.

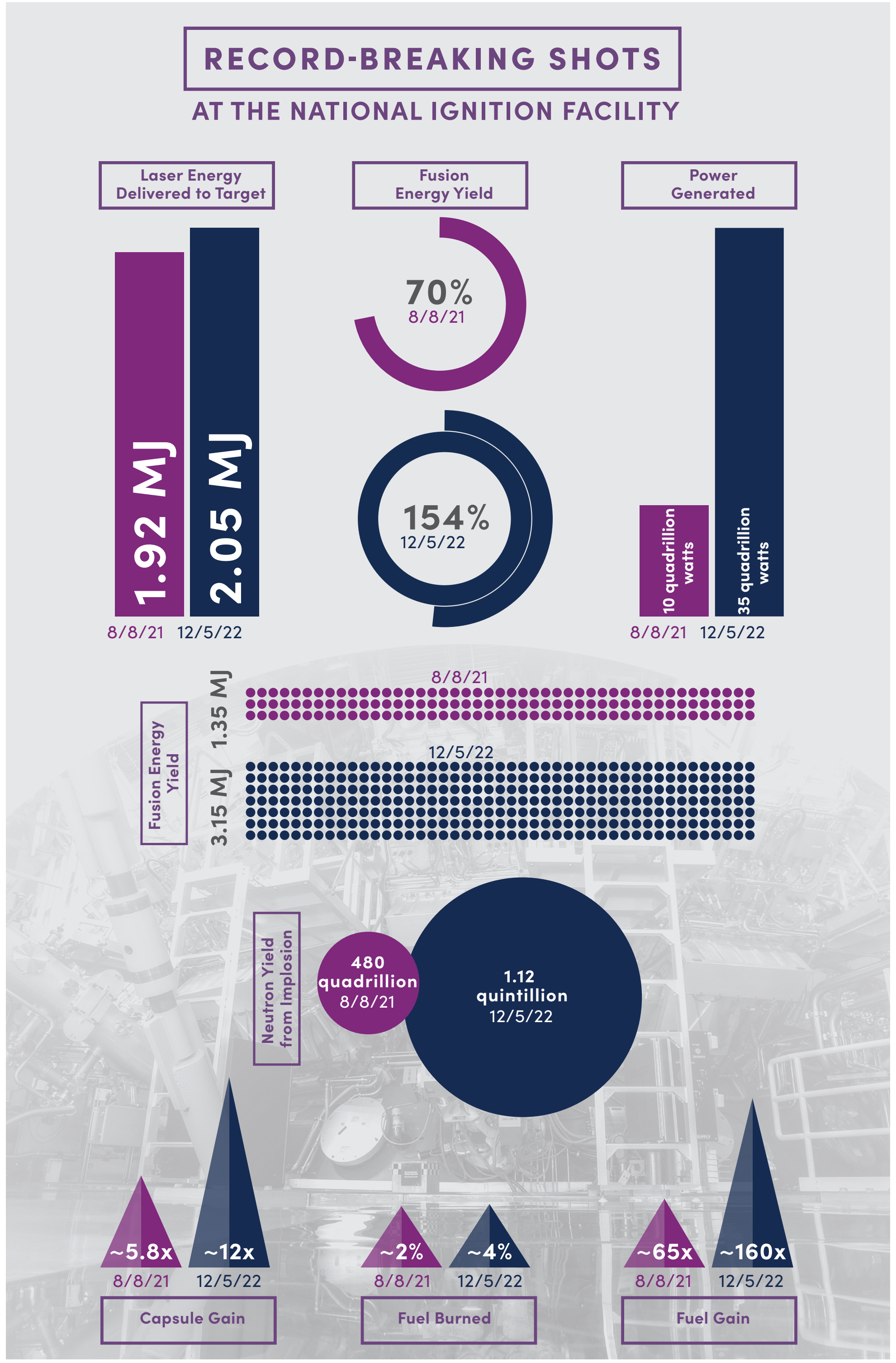
"The radiation temperature in the hohlraum stays higher at late time than it would have if we had a very long coast time," he said. "That helps keep the implosion compressed. It's a really good benefit."

The 2021 shot was the scientific equivalent of reaching the red zone on a football field. The drive to the goal line, however, stalled during the following year; several follow-up experiments were unable to replicate the Aug. 8 result.

To gain a better understanding of the origins of the "inherent variations" that were hindering NIF's performance, LLNL researchers and their colleagues from the ICF community convened a series of workshops to examine the results of the follow-up experiments.

A careful analysis of those experiments, including a statistical analysis of the data, enabled the team to quantify the degradation mechanisms and identify the sources. The leading degradation mechanisms were implosion asymmetries and microscopic defects in the capsules that caused the capsule material to mix into the fuel.

"Asymmetries in the implosion reduce the transfer of energy from the (capsule) shell to the reacting plasma," said Arthur Pak, team lead for stagnation science. "This reduces the temperature and compression that can be



Comparison of key parameters between the NIF "threshold" experiment in 2021 and the 2022 ignition shot. "Gain" refers to the difference between the energy delivered to the capsule and the fuel and the fusion energy output. All these energy gain metrics increased by about 5,000 times over the past decade. Credit: James Wickboldt

achieved in the DT plasma, making it more difficult to ignite. Likewise, ablator material that mixes into the plasma increases the radiative loss, cooling the plasma and making it harder to ignite.

"Minimizing these degradations was critical to achieving ignition," Pak said.

> *"Even when we had struggles with the engineering, the physics, and the perceptions—just having the grit to stick with it really paid off."*
>
> *ICF Chief Scientist Omar Hurricane*

LLNL computational physicist Marty Marinak, leader of the HYDRA multi-physics radiation hydrodynamic code used to design and model ICF experiments, added that high-resolution 3D capsule simulations "indicated it was essential that we develop a more robust design to achieve ignition. This code, assisted by theoretical and data-driven models, was used to optimize the new target design to achieve greater robustness."

To deal with the variability issues, the researchers modified the Hybrid-E design by increasing the laser power by 8 percent, to 2.05 MJ. The new "Hybrid-E High Energy" (HyeHE) design also called for an 8-percent thicker capsule that could effectively use the extra energy and better protect the fuel from instability growth.

Kritcher said the design was generated using "a combination of complex radiation hydrodynamic simulations using the HYDRA code, analytical scaling, and semi-analytical models that were benchmarked against experimental data." These were used to determine how much thicker to make the capsule with a given laser energy upgrade as well as how to improve the symmetry.

"Using the extra laser energy to drive thicker capsules is better for stability and more fuel burn-up," she said.

"A key understanding from the variability study," said LLNL senior physicist Laurent Divol, "was that all the measured degradations were roughly equivalent to losing 10 percent of the energy in the hot spot just before it could ignite.

"This gave us confidence that we could return to yields above 1 MJ if NIF could deliver 10 percent more energy—and that energy coupled well to the hotspot. Simple scaling and simulations predicted that combining more NIF energy with a good quality implosion should produce an even higher yield ... and it happened on the second try!

"Future work is focused on further improving the energy coupling and compression of the implosions," Divol said, "which will make the experiments more robust and less sensitive to these degradations."

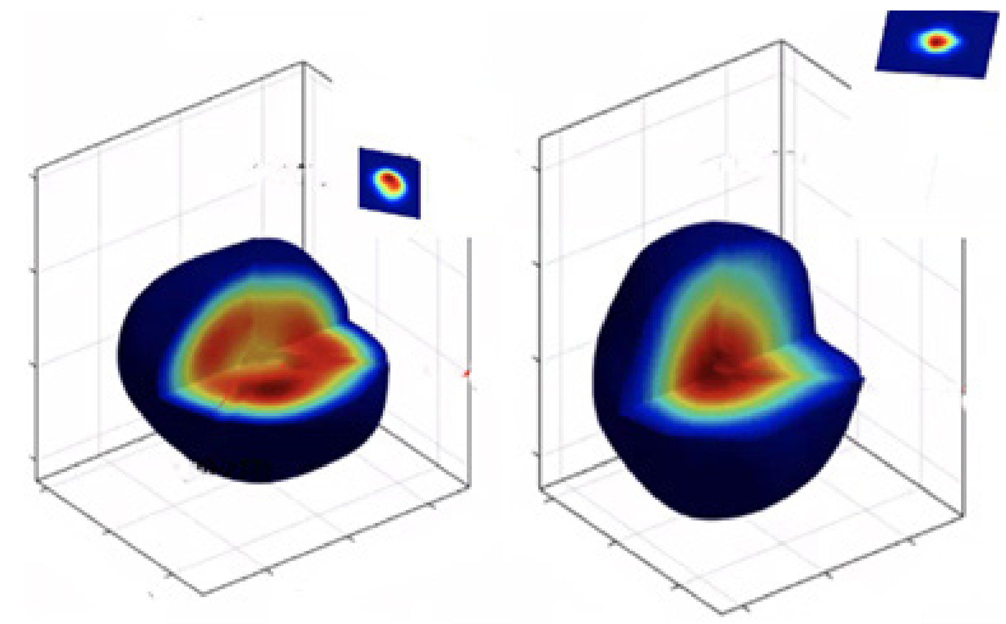
But boosting NIF's energy even further beyond its design specification of 1.8 MJ (the "threshold" shot had reached 1.92 MJ) was not without risk—such as possible damage to the laser system by light backscattered from the target.

Risk Management

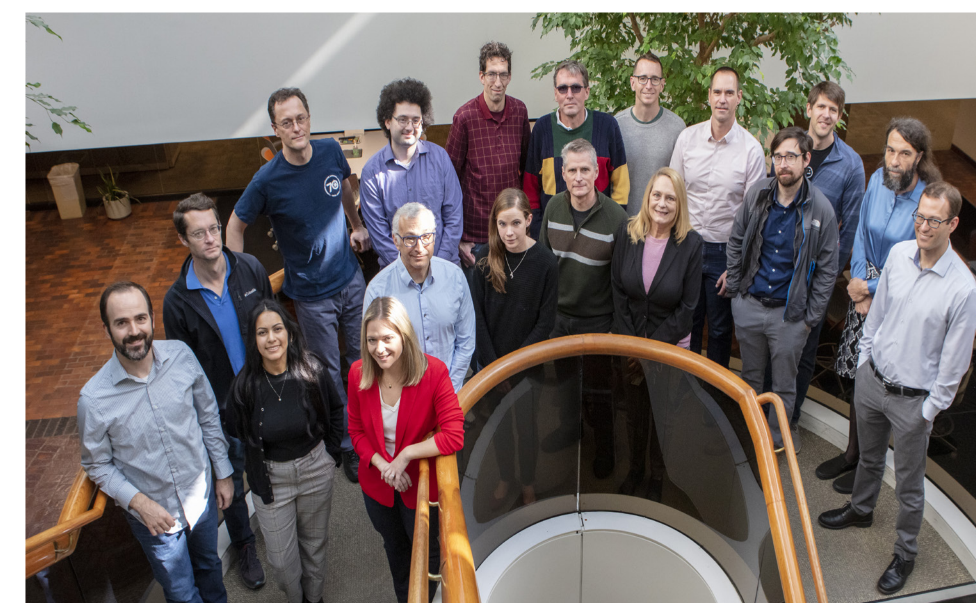
"To date, the highest-performing NIF shots have leveraged wavelength tuning that modifies where laser power is deposited within the target and controls implosion symmetry," said design physicist Tom Chapman. "This technique can further raise the potential of producing damaging levels of scattered light—but, utilizing recent facility upgrades, can also be used to rebalance power away from damaging areas.

"Careful risk management has allowed us to safely perform experiments in these new (energy) regimes," Chapman said, "and the current data make us optimistic that we can safely push even further forward."

The first HyeHE experiment on Sept. 19, 2022, delivered 7 percent more energy at the end of the laser pulse than the previous follow-up shots—increasing compression, concentrating additional energy in the hot spot, and producing more fusion reactions that led to higher energy yield—about 1.2 MJ—than the earlier repeat experiments. The yield still fell short of ignition, however, because of pancake-shaped implosion symmetry.



Time-integrated 3D neutron imaging shows the symmetry improvement from the Aug. 5, 2021, experiment (left) to the Dec. 5, 2022, ignition shot, made possible by an experimental design that balanced the energy throughout the laser pulse. The December experiment consumed about 4 percent of the fuel, compared to about 2 percent in the 2021 shot.



Members of the NIF design and experimental teams (front row, from left): Chris Weber, Rocio Madriz Ledezma, Annie Kritcher, Omar Hurricane, Kelli Humbird, Steve Maclaren, Denise Hinkel, Arthur Pak, and Chris Young; (back row, from left): Dan Clark, Bogdan Kustowski, Eugene Kur, Tom Chapman, Laurent Divol, Jim Gaffney, Brian Spears, Ryan Nora, and Michael Kruse. Not shown: Marty Marinak, Scott Sepke, and Alex Zylstra. Credit: Jason Laurea

The Age of Ignition

Designing for Ignition

Fortunately, the follow-up experiments gave the experimental and design teams a chance to gather and use new tuning data, "which really helps us get a better picture for benchmarking the codes," Kritcher said. "The data helped improve our modeling and was used to improve symmetry throughout the entire pulse."

For the Dec. 5 experiment, "we designed very specific laser-power changes at very specific times for all of the laser beams to improve symmetry compared to the September experiment," Kritcher said.

"We set the design parameters and then we worked with our AI (cognitive simulation) team; they took that information and came up with an independent assessment that confirmed what we had predicted—that we'd achieve a gain of more than one."

To reach their goal, the researchers readjusted the energy balance, or "cone fraction," of the inner and outer cones of the laser beams early in the laser pulse. At the pulse's peak, when the laser beams entered the hohlraum, "we changed the design of the laser wavelength so that some beams could 'give' more energy to other beams, creating symmetry for ignition," Kritcher said.

In this wavelength tuning, or cross-beam energy transfer, technique, the wavelength of the laser light on a subset of inner and outer cone beams is changed by a few angstroms (an angstrom is one-tenth of a billionth of a meter) as the beams cross in the hohlraum's laser entrance holes. This adjusts the balance of energy reaching the inner walls of the hohlraum.

For the ignition shot, the researchers increased the difference in the beams' wavelength, known as the "delta lambda," from 2.50 to 2.75 angstroms—a change equivalent to about one-fourth the diameter of an atom.

"It's amazing how sensitive (wavelength tuning) is," Hurricane said. "It's a very nonlinear process. A small change can shift a lot of energy into the beam, and that's how we can control the symmetry.

"The takeaway here," Hurricane said, "is if you just stick with it, and you keep chipping away at the problem, a lot of these hard problems can be solved.

"It's a good life lesson, and it was really important in this case, even when we had struggles with the engineering, the physics, and the perceptions—just having the grit to stick with it really paid off."

—Charlie Osolin

LLNL SCIENTISTS CHEER DAWN OF THE 'ERA OF IGNITION'

LLNL's historic fusion ignition experiment generated awe, pride, and bright optimism about the future among Lab employees.

A crowded internal staff meeting held a few days after the potentially world-changing fusion energy breakthrough erupted in jubilant applause and shouts of joy when the gathering kicked off with a short video announcing NIF had indeed lived up to its middle name—"Ignition."

"I feel fantastic, I'm just so proud of all these people," said Tayyab Suratwala, program director for Optics and Materials Science & Technology. "To me, ignition is like an accumulation of a hundred miracles. There's so many technological advancements and ingenuity that help make it happen."

The excitement in the air was still palpable more than a week later as scientists, researchers, engineers, and support staff gathered in Lab auditoriums to watch the live video feed of the Dec. 13, 2022, news conference as Energy Secretary Jennifer M. Granholm made the public announcement that ignition and energy gain had been achieved at LLNL.

The audience burst into cheers when Granholm made the announcement and introduced LLNL Director Kim Budil, and applauded again when a panel of Lab experts talked about the results.

"It's phenomenal excitement—it's incredible," said Thomas Spinka, program element leader for laser development in the NIF & Photon Science (NIF&PS) Directorate's Advanced Photon Technologies Group. "It's what we've all hoped and worked hard towards for decades, and in some cases, for entire careers."

"We have taken the first step into the fusion age," said a smiling Vincent Tang, NIF&PS principal deputy director. "Congratulations to all of us. This is a monumental achievement by the team. When I got out of grad school in magnetic fusion, I worried I wouldn't see this moment or something like it until I was near retirement. I am grateful to be here when it happened."

The ignition shot followed some six decades of work by generations of scientists who steadfastly pursued the goal of inertial confinement fusion.

"To answer that old question of, over those 60 years, what team would be the modern Prometheus to bring star fire to the Earth, and when would that time be—and it's you and it's now," NIF&PS Principal Associate Director Jeff Wisoff said.

Outwardly, physicist Annie Kritcher, the experiment's lead designer, seemed calm. But on the inside, she was jumping for joy.

"I couldn't personally be happier," Kritcher said. "I don't even know how to really express my happiness. I'm a reserved person, so this is like my '10' level of happiness.

"I feel kind of like I met my personal goals for my career," she said. "All of these years, there's been so many people who have dedicated their lives to this. It's just so gratifying to check all the boxes and to achieve this official goal.

"And it's big science, so to be able to do this with all the pieces pulling together is amazing. It's like lighting the fusion match, and I just can't wait to see where we and others take it in a year or two and to be a part of it."

Physicist Alex Zylstra, who was the lead experimentalist, appreciated the implications of the moment. "We'll see where the future takes us, but we're all hopeful that at some point, there will be fusion on the (electric) grid providing power," he said.

NIF Operations Manager Bruno Van Wonterghem said during the staff meeting that he had been waiting for this moment for his entire 30-year Lab career.

"Even though I never doubted LLNL was going to reach ignition, all along we'd heard 'Ignition is 50 years away, it will always be 50 years away,'" Van Wonterghem said. "And this is the first time we can say ignition is five days behind us. It is the start of a whole new era, it is the era of ignition."

The ignition shot "celebrates the unique talent and the capabilities that only the Lab can bring to bear to make the impossible possible," he said.

Tammy Ma, who leads the Lab's Inertial Fusion Energy Institutional Initiative, said she was about to board a plane at San Francisco International Airport the morning after the shot to attend an annual fusion industry meeting.

"I got a call from my boss saying, 'I think we got ignition,' and I burst into tears," Ma said. "I was jumping up and down in the waiting area. After all these years, every time I walk into the National Ignition Facility, I still get goosebumps. It's a wonderful place to work and I'm so proud of this team."

Ellie Tubman, a postdoctoral researcher who worked on backscatter diagnostics and other HED experiments at NIF, said she couldn't believe it when she first heard the preliminary results.

"I even wondered if it was just a fluke and perhaps one diagnostic had read higher neutron counts in error," she said. "But as the analysis of other diagnostics confirmed high neutron readings confirming it was real, it was amazing."

Tubman said she was very honored to be part of such a passionate team, noting she joined the fusion effort because she loved both the challenge and opportunities the underlying science offered. "I hope this sparks more curiosity and interest from the wider community, bringing even more new faces and ideas to the team," she said.

NIF & Photon Science staff members listen to an internal presentation about NIF's history-making Dec. 5 experiment. Credit: Mark Meamber

Félicie Albert, now the director of LLNL's Jupiter Laser Facility, said she was "super proud, super excited" by the news.

"I cannot think about a better place to be than at the Lab," she said.

And former NIF Director Doug Larson, who retired from LLNL on Nov. 30, 2022, called it the "best retirement gift ever!

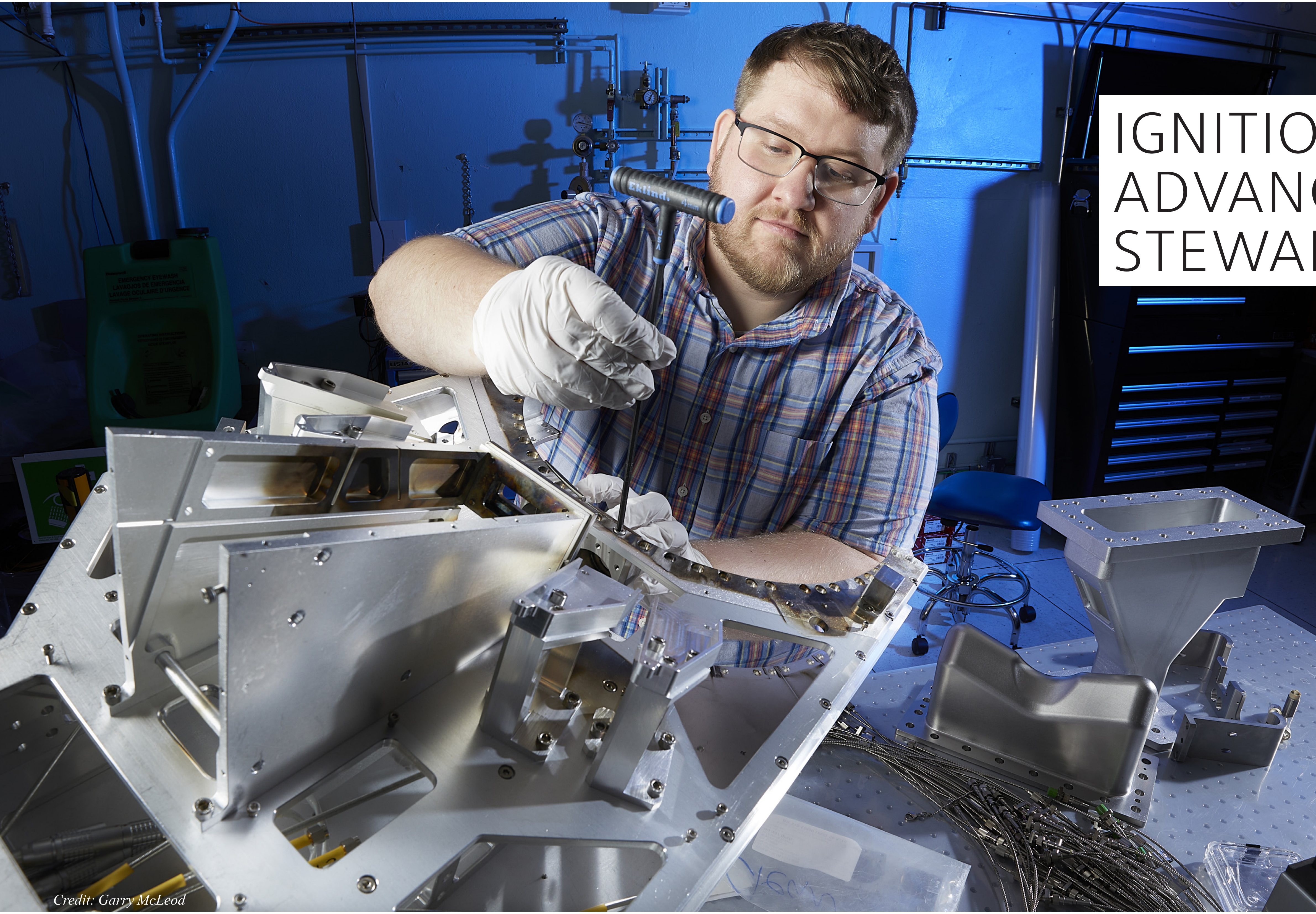
"The result certainly shows that a little more laser energy can go a long way," Larson said, "and gives some strong motivation for NIF's energy and power upgrade (to as much as 2.6 to 3 MJ later this decade) that is planned after we finish the NIF sustainment effort (a five-year plan to refurbish and upgrade critical NIF systems to sustain the facility through 2040)."

And, as Tang added, "There's so much left to do. This is the end of the beginning, not the beginning of the end."

—Benny Evangelista, Jon Kawamoto, and Charlie Osolin

The Age of Ignition

Ignition Experiment Advances Stockpile Stewardship Mission



Credit: Garry McLeod

IGNITION EXPERIMENT ADVANCES STOCKPILE STEWARDSHIP MISSION

The primary mission and driving goal behind LLNL's breakthrough fusion ignition experiment was stockpile stewardship science.

LLNL is one of two National Nuclear Security Administration (NNSA) laboratories that certify the safety, security, and effectiveness of the nuclear explosives packages in the U.S. nuclear stockpile. As part of that work, the weapon survivability program develops the innovative computational capabilities and experimental platforms to design and certify the nation's nuclear deterrent to survive and still perform as expected in a variety of extreme environments, including hostile radiation effects or a nearby nuclear detonation.

"A big part of our science-based Stockpile Stewardship Program is making sure we have experimental access to methods for weapons testing that allow us to test our calculations, check our simulations, develop our intuition, and test the understanding we have from the nuclear tests we did during the underground testing era," said Mark Herrmann, program director for Weapon Physics and Design at LLNL.

Igniting inertial confinement fusion (ICF) capsules at NIF simulates aspects of the conditions that exist in an exploding nuclear weapon—producing intense radiation and providing a unique ability for LLNL to test in a pulsed thermonuclear neutron environment.

"The inertial confinement fusion program has been working for many years to demonstrate higher megajoule yields and ultimately reach ignition," said Laura Berzak Hopkins, associate program director for Integrated Weapon Science. "But that's not the end in and of itself. The goal of the December shot was really twofold. Not only did we achieve ignition, which is really a remarkable achievement, but we also commissioned a new set of fielding hardware engineered to survive megajoule environments."

Designed and built by the NIF Materials and Radiation Effects group, the u-shaped hardware, called the cryogenic-compatible x-ray, neutron, and blast snout (Cryo XNBS), was inserted into the NIF Target Chamber

and situated approximately 10 to 12 centimeters from the target, allowing researchers to expose various weapon-relevant samples, such as uranium or other materials, as well as electronics, to the highest possible thermonuclear fusion neutron fluences available.

To protect the material contained inside, the snout utilized a 22-kilogram (or 50-pound) steel case to protect against the destructive force from significant amounts of x-rays and debris wind generated by megajoule-class ICF experiments. The snout is configurable, depending on the samples, materials, or diagnostics used in future experiments.

The LLNL team in December successfully qualified the Cryo XNBS fielding hardware, as well as the *in-situ* diagnostics, demonstrating that the snout can survive the extreme environment and perform according to expectations, Berzak Hopkins said.

"From the stockpile stewardship perspective, reaching ignition is a real testament to the enabling capabilities that help us assure the safety, reliability, and resilience of our nuclear arsenal," Berzak Hopkins said. "And from an energy standpoint, this demonstration of proof of principle is groundbreaking.

Members of the LLNL Strategic Deterrence Directorate work on the fielding hardware commissioned for weapons survivability experiments. The steel case protects against the destructive force from significant amounts of x rays and debris wind generated by megajoule-class ICF experiments. Credit: Garry McLeod

Coupling those two together, it's an inspirational moment, as it opens the door for an entirely new experimental capability that will now be enabled at NIF."

In developing this integrated capability, NIF engineers built diagnostics into the Cryo XNBS to get real-time data from the samples situated in the snout.

One of the first indications that ignition may have been reached during the December shot came from the diagnostics connected to the survivability experiment in the fielding hardware, said Brent Blue, National Security Applications program manager at NIF.

"It takes some time for the data to get pulled off the various NIF diagnostics in the Target Chamber, then move through the control system, and eventually get pushed to the viewers," Blue said, noting that the diagnostics hooked up to the experiment in the Cryo XNBS gave the groundbreaking data almost instantly.

"We knew right away that something big had just happened," he said. "We got a very good measurement, so we were very excited for the result."

In addition to real-time diagnostics, the team can retract the snout to outside the Target Chamber after a shot, disassemble it, and complete post-test examination of samples. The team is working on developing additional types of post-test analyses that will inform their understanding of how materials behave under extreme environments produced by a detonating nuclear weapon.

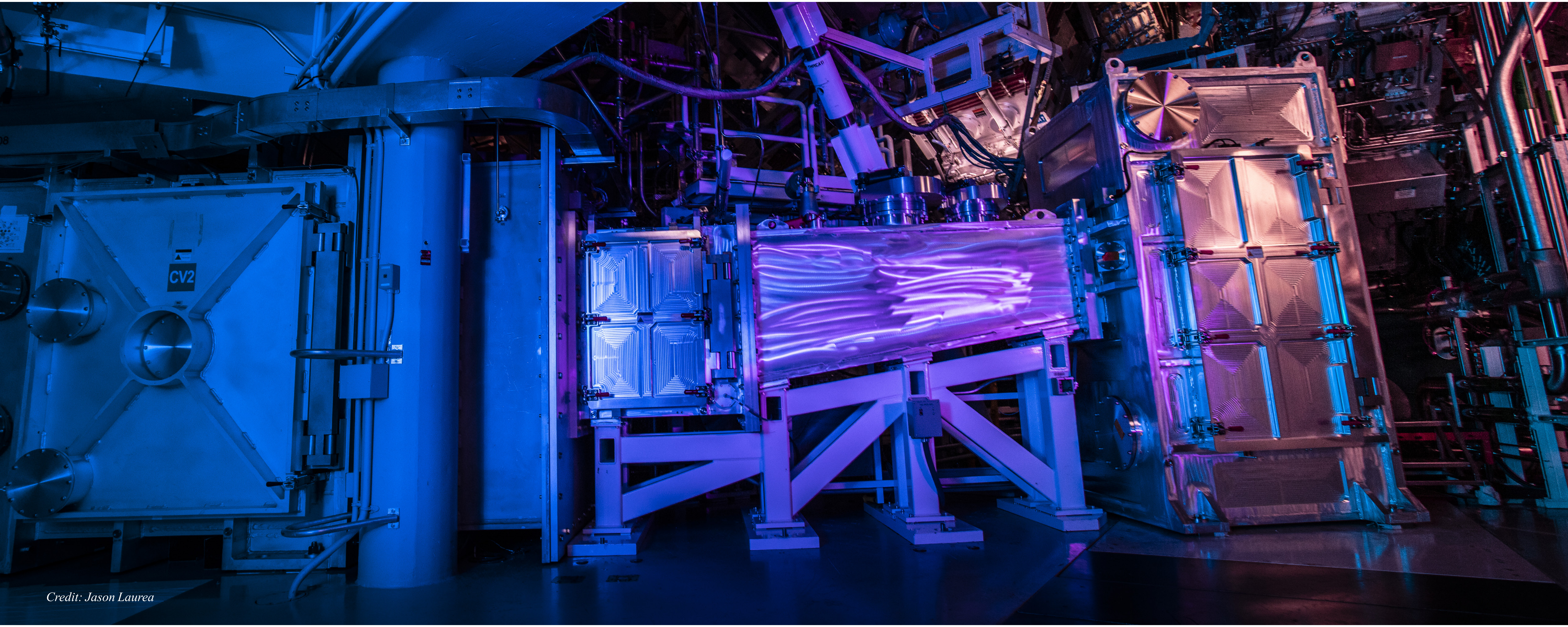
Following the successful qualification of the snout hardware in December, future experiments are planned at NIF to assess the response of a range of NNSA and Department of Defense stockpile components and subsystems to the threat-relevant environment created by igniting ICF capsules. Researchers are also planning to steadily expand the type of materials used in survivability experiments, placing more complex samples into the snout.

"Developing this capability is critical for stockpile stewardship," Blue said, "but it's really a unique scientific capability that doesn't exist anywhere else in the world to be in such close proximity to these very high neutron flux environments. We are just on the cusp of discovering what we can do with this new capability."

—Paul Rhien

NIF operators examine the Cryo XNBS hardware after the ignition shot. Credit: Charles Yeamans

The Age of Ignition
Laser Focused



Credit: Jason Laurea

LASER FOCUSED:
Power and Finesse Drove LLNL's Fusion Ignition Success

To achieve fusion ignition, NIF's laser system needed to operate flawlessly at both ends of the performance spectrum, delivering immense energies while controlling the energy balance across all 192 laser beams with extreme precision.

LLNL scientists took advantage of a modest increase in NIF's laser energy output to 2.05 megajoules (million joules, or MJ) of ultraviolet energy. This was 8 percent more than the 1.9 MJ that was available for the August 2021 experiment that brought NIF to the threshold of ignition.

The designers were also able to further fine-tune how this energy interacted with the peppercorn-sized target capsule through meticulous adjustments in the laser beams' wavelengths.

"NIF is a big hammer, it's extremely energetic," said Jean-Michel Di Nicola, NIF's co-program director of Laser Science and Systems Engineering. "But brute force alone is not enough. We need to have finesse and make sure that we deliver that energy with exquisite accuracy."

This impressive combination of power and finesse, built and refined over several decades of effort by generations of NIF&PS laser scientists and engineers, gave LLNL the capability to achieve its long-sought goal

of conducting a thermonuclear fusion experiment that reached ignition and exceeded scientific "break-even"—producing as much or more fusion energy than the amount of laser energy used to drive the target.

"It's quite a grand challenge to do that because the laser architecture is extremely complex and a marvel of laser physics, engineering, and optics manufacturing," Di Nicola said.

From their inception as a single weak pulse of light in the Master Oscillator Room (MOR), NIF's high-energy laser beams travel nearly 5,000 feet in just five microseconds, bounding along a route that crisscrosses the length of three football fields

"Not only is NIF an amazing high-energy, high-power laser, but it's also a very precise pulse-shaping laser."

Experimental physicist Joe Ralph

Master Oscillator Room staff members Chris Kinsella (left) and Matt Prantil (right) install hardware as part of an upgrade that improved the fidelity of NIF's pulse-shaping capabilities. Credit: Tyler Dumbacher

before emerging as a powerful blast of energy when they impact the target.

Along their journey, the beams pass through about 7,500 large half-meter-sized optics and 26,000 smaller ones that amplify their energy and direct them to a pencil-eraser-sized target, called a hohlraum, inside the Target Chamber. Opened for experiments in 2009, NIF's original design specification was to deliver 1.8 MJ of ultraviolet energy with a peak power of 500 terawatts (TW).

"Since the completion of the National Ignition Facility Project in March 2009," said NIF Operations Manager Bruno Van Wonterghem, "we have continuously increased the energy and power to make sure that we were obtaining the regime where implosion experiments could take place in relevant conditions. And in July 2012, we shot the first hohlraum at 1.9 MJ and 430 TW. This started a decade of inertial confinement fusion (ICF) research that finally enabled us to demonstrate burning plasmas and approach ignition."

"Being part of this human and scientific adventure is really rewarding."

Jean-Michel Di Nicola

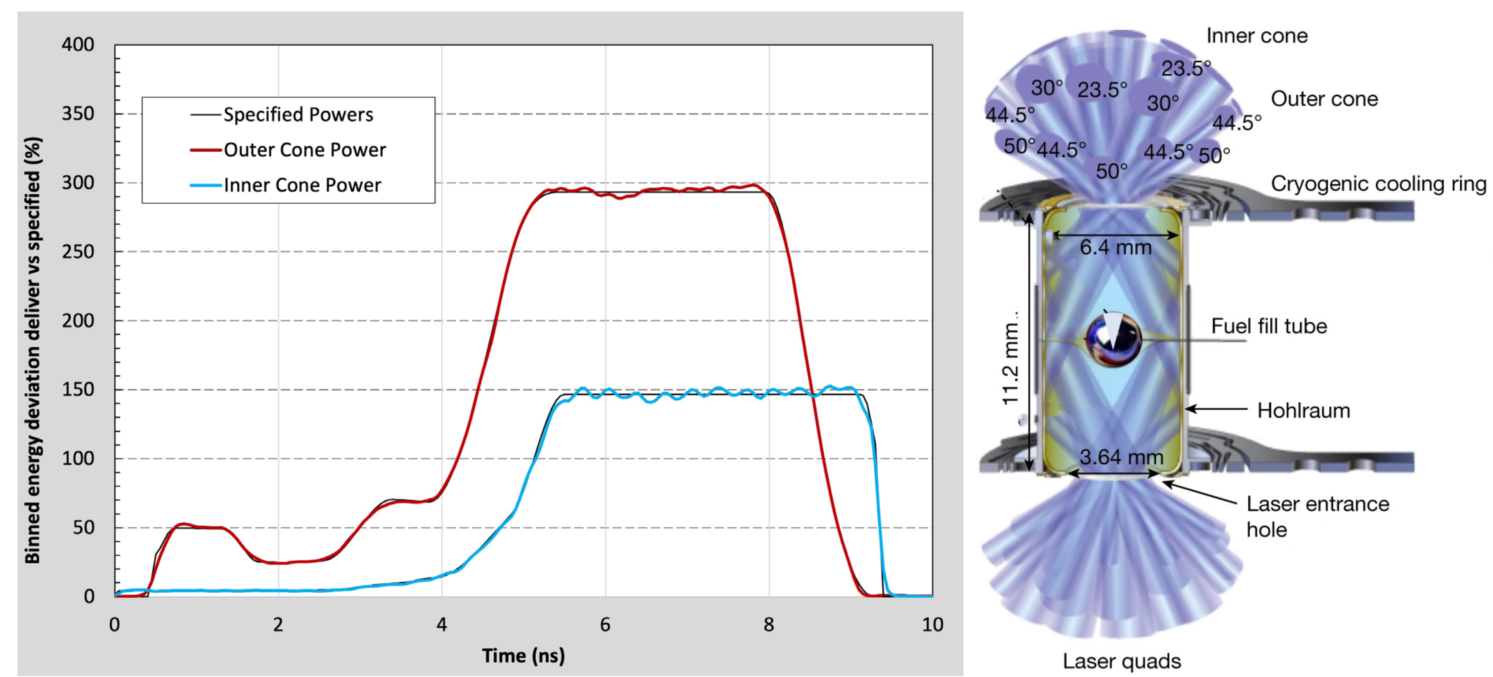
The August 2021 experiment reached a significant milestone, but LLNL's experimental designers were stymied in their attempts to repeat the result, chiefly because subsequent target capsules were not as perfectly constructed as the one used that day.

Even the tiniest imperfections—such as microscopic pits and voids in the capsule and perturbations initiated by the fuel fill tube—caused implosion asymmetries that led to degraded implosions and limited the neutron yield.

By the summer of 2022, NIF's laser and optics teams implemented advances in optics science and engineering to turn up the laser energy to 2.05 MJ while increasing the thickness of the capsule. This boost proved to be a game-changer for the "layered" implosion performance (NIF capsules contain a thin layer of cryogenically cooled deuterium (D) and tritium (T) along with a volume of DT gas).

"Wonderfully, fantastically, we had a new option available to us, made available by increasing the laser energy delivery to the target," said Richard Town, associate program director for ICF science. "This motivated capsule design changes to use the new 2.05 MJ laser capability to drive heavier, more stable capsules."

Town said the experimenters were able to "thicken up" the fuel capsule by 6 to 8 percent to make it less susceptible to degradations from imperfections. "And it worked," he said. "Basically, that extra energy—that bigger hammer—hitting a slightly thicker target brought us in a more favorable regime, and we achieved ignition."



To provide the laser energy conditions required for ignition, NIF's laser system was able to meet the requests of experimental designers within a pointing accuracy level of 50 microns and a timing level of 30 picoseconds (trillionths of a second). The red line shows the pulse for outer cone beams and the blue line shows the pulse for beams aimed at the inner cone.

Fine-Tuning Finesse

Still, even with the increased energy, more fine-tuning of the laser wavelengths was needed to balance the new recipe of laser energy and capsule thickness. This was where finesse—delivering the laser beams into the hohlraum and around the fuel capsule at just the right time, power profile, and at the correct wavelengths to drive a near round, highly symmetrical implosion—was crucial.

"The laser itself also has to be perfectly balanced," Town said. "If you drive (the capsule) harder from the top than the bottom, you'll introduce thin spots and you'll see jetting of the fuel, the first degradation mechanism."

In addition, driving the laser energy too hard from the top and the bottom of the hohlraum produces a flat pancake-shaped implosion, while pushing too hard from the sides produces a prolate, or sausage-shaped, implosion. "Both of those degrade the performance," Town said.

The capability to adjust laser wavelengths was built into NIF when it originally opened and was refined over time. A key three-year project completed in the summer of 2022 modernized the MOR—known as the "heart of the laser"—from the oscillator to the pulse-shaping system input.

Imagine, Di Nicola said, holding a standard low-power laser pointer used in classrooms and in presentations, but with a special button that allowed you to alternate between brighter and less bright light. Then imagine standing on the other end of the beam watching waves of laser light coming at you.

Similarly, he said, "If you were at the middle of the Target Chamber, you would see a wave coming at you," taking about 8 billionths of a second. "Initially, you would be on the low burner at 50 terawatts of power and then you would feel a little bit of a dip, going lower, then going up, and finally having a big push and (experiencing) 300 terawatts for the outer cone of beams."

Even with the new laser energy boost and thicker capsule, a Sept. 19, 2022, NIF shot produced 1.2 MJ of energy, falling just short of the August 2021 mark. The imaging data from NIF's diagnostics suggested that some of the laser's energy was wasted because the implosion was observed to be oblate, or significantly out-of-round.

Putting the 'I' in NIF

For the December shot, the team made a tiny change, measured in angstroms, in the relative wavelength of the inner and outer cone of beams hitting the middle of the hohlraum wall. To put this in context, one angstrom is 10^{-10} of a meter and one-ten thousandth of the fundamental wavelength of the NIF laser.

"We changed the wavelength separation—a one-fourth angstrom difference between the outer and inner cones—so that we diverted some of the energy to the equator, and that led to a round implosion," said experimental physicist Joe Ralph. "So we went from an oblate implosion to a round implosion, and that essentially got to our 1.5x gain. At this point, we put the 'I' in NIF.

"Not only is NIF an amazing high-energy, high-power laser, but it's also a very precise pulse-shaping laser," Ralph said.

NIF Director Gordon Brunton praised literally thousands of scientists, engineers, and staff from LLNL and other national laboratories, universities, and industry who contributed over the last six decades to the laser advances that made ignition possible.

"I'm proud being part of this team," Di Nicola said. "Being part of this human and scientific adventure is really rewarding."

—Benny Evangelista

NIF: AN ENGINEERING MARVEL

NIF is a remarkable engineering and technology success story. Materials scientists and laser physicists, working with engineers, designed a facility that contains 7,500 large (meter-scale) optics, 26,000 small optics, and 66,000 control points. The optics and other components are contained in approximately 6,200 complex modular devices called line replaceable units (LRUs), which can be replaced quickly when necessary to ensure continuous operation of the facility.

The NIF laser pulses travel one kilometer from initial pulse formation in the Master Oscillator Room to the target in 4.5 microseconds, arriving at the Target Chamber center within 30 picoseconds of each other with an accuracy of 50 microns. Achieving this level of pointing stability and absolute accuracy on target was an engineering challenge of the first order, requiring rock-solid stability in the optics support systems, precise placement and alignment of components—despite a multitude of opportunities for errors to creep in—and a rigorously accurate computer timing system.

To meet these challenges, all of the structures holding NIF's mirrors and lenses were carefully designed with extreme stability in mind. At the beginning of the project—before any hardware had been designed—precise vibration measurements of the ground at the site were made.

The engineering team characterized every local vibration source including pumps, motors, and transformers, and estimated their effect on each of the most sensitive laser components—generally the laser mirrors. The budget for vibration (>1Hz) and drift (<1Hz) was met using this detailed model, and tests on the prototype beamline demonstrated performance at or better than the 50-micron requirement. In addition, to ensure beamline components do not infringe on the laser clear aperture, precision survey techniques were employed for a rigid survey network and well-controlled physical placement for all beamline components. All beam enclosures, support systems, and the Target Chamber are located to an accuracy of one-fourth of a millimeter.

This information was then provided to the design team, which engineered structures that were both stiff enough and had sufficient damping that the response of the structures to ground vibration and the anticipated vibration from building equipment would meet overall stability requirements. The design solutions included thick concrete foundations, lightweight steel platforms, and extensive vibration isolation mechanisms at all sources of vibration. Exhaustive structural analyses were conducted to convince the engineers of the feasibility of the design, and a comprehensive construction plan was executed to assure that all design details were meticulously implemented. As a result of this integrated and comprehensive end-to-end program, NIF has been able to achieve all of its stability requirements on a routine basis.

Ensuring that all 192 beams arrive within 30 picoseconds of the prescribed arrival time is achieved by using a precise timing system which is constantly updating its internal clocks using the GPS satellite system. Integrated software and hardware constantly monitor and update the timing to maintain accuracy. LRUs can be readily exchanged to maintain the timing accuracy through design tolerances of better than 300 femtoseconds (three-tenths of a trillionth of a second) for each mechanical interface. In addition, tightly controlled procedures maintain system timing for each LRU.

—Charlie Osolin

Inside one of NIF's two switchyards. These highly stable 10-story structures contain beam enclosures with turning mirrors that redirect the beams to the upper and lower hemispheres of the Target Chamber. The switchyards convert the parallel laser beam layout to the spherical configuration of the Target Chamber, as the beams need to enter the chamber along radial lines to converge on the target.

The Age of Ignition

Optics Meet the Demands of Increased Laser Energy

Credit: Jason Laurea

OPTICS MEET THE DEMANDS OF INCREASED LASER ENERGY

If NIF were a race car, it would run at the redline most of the time.

"NIF is the only laser system that intentionally operates above the laser damage growth threshold," said Tayyab Suratwala, Optics and Materials Science & Technology program director. "We operate the laser at a power and energy level for which we can repair the optics at an acceptable rate."

Pushing that envelope was an important enabler for LLNL to achieve ignition. Since NIF became operational in 2009, the LLNL optics team has persisted in hardening the optics to withstand ever-increasing laser energy, as NIF routinely exceeded its design specification of 1.8 megajoules, and the debris that results from every experiment.

"Working in optics on NIF is like peeling an onion that is always growing," Suratwala said. "Each time we overcome a challenge, we turn up the laser energy and create new challenges."

The latest solution to the challenge of higher laser energy—a then-record 2.05 megajoules delivered in the ignition shot—is the fused silica debris shield or FSDS.

A Shield for the Shield

About five years ago, LLNL solved one intractable problem when researchers discovered that the disposable debris shield (DDS), which protects more valuable optics in the final optics assembly from debris, was itself a source of debris. After considering several possible solutions, including changing the DDS material, the scientists landed on adding the FSDS to the final optics assembly.

The FSDS became a shield for another shield—in this case, for the grating debris shield (GDS), which is so valuable it is repeatedly repaired to extend its life as much as possible. With the optics recycling loop strategy, debris-induced laser-damaged GDSs and the wedged

focus lens optics are removed, repaired, and returned to NIF at a pace of about 40 optics a week.

"The FSDS reduced the number of damage sites on the GDS by 98 percent," said staff scientist Chris Miller. "Our installed optics are lasting three times longer. And it allows us to use a thorough recycle process."

Before, the team only repaired GDS damage sites that were 50 microns or larger. With less damage overall, they can repair sites as small as 10 microns.

"With our optics lasting longer, we are better able to operate the laser at higher energy levels," said Optics Damage S&T Group Leader Wren Carr.

A Complex Implementation

Adding the first major optic to NIF was no simple task. Ramping up production of the FSDS brought together many specialties including optical scientists, engineers, programmers, and procurement. The team tackled challenges like developing image analysis software to evaluate damage on the new optic and increasing throughput in the Optical Processing Facility (OPF).

"Thanks to the booming semiconductor industry, there is more demand for fused silica," said materials scientist Lana Wong. As the component engineer for the DDS and FSDS, she led the effort to identify and qualify multiple fused silica vendors to ensure an adequate supply chain.

The FSDS was initially installed on 48 beamlines in 2021 and on 80 more a year later. Before that transition, the OPF processed four optics a week.

"We tripled production, adding another eight FSDS optics per week to our regular workload," said process engineer Diana VanBlarcom. "It meant reworking recipes for cleaning and coating, re-engineering equipment to hold multiple FSDS optics instead of one, and updating control systems, to name a few (upgrades)."

Installing the FSDS into NIF affected every area of operation. It required reprogramming NIF's control system, the complex software that orchestrates some 66,000 control elements; designing and executing an efficient install and de-install process; and developing processes for *in-situ* monitoring and removal criteria.

The FSDS went into a slot that had previously housed a metal shutter. Before each shot, this tray was moved out of the laser path.

"It was a huge change, telling the laser to shoot through an area that previously it was told never to shoot through," said Nathan Ruiz, FSDS system manager. "Every technician working on NIF is now well-versed in the FSDS."

The operation brought together all the facility teams: Facility and Infrastructure Systems (FinS), Laser-Alignment System Engineering (LASE), Laser Science and Systems Engineering (LSSE), the Optics Assembly Building (OAB), Optics & Materials Science & Technology (OMST), NIF&PS Control Systems (NCS), Radiation Operations, Shot Operations, and Total Online Procurement Systems (TOPS).

Alex Maroudas removes a clean fused silica debris shield from the optics washer in the Optics Processing Facility. Credit: Jason Laurea

"On NIF, there is no margin for error. There were multiple layers of checks and balances," Ruiz said. "And we did it right every time."

The FSDS Implementation Team was recognized for its effort with a Department of Energy Secretary's Honor Achievement Award for the successful implementation and production operation of FSDS optics.

More Optics Improvements

The FSDS built on earlier advances like the Advanced Mitigation Process (AMP), a chemical-etching method that removes damage precursors. AMP was first deployed in 2014 and revamped in 2017. Also in 2017, the optics team began using an anti-reflective coating on the GDS to prevent it from reflecting excess light back to other optics.

"From investigating a problem to deploying a solution on the NIF optics, it's about a five- or six-year process," Suratwala said. "We are seeing these solutions pay off in a big way."

Another problem under investigation is the pedestal beams, the 32 beams along the bottom of NIF's Target Chamber.

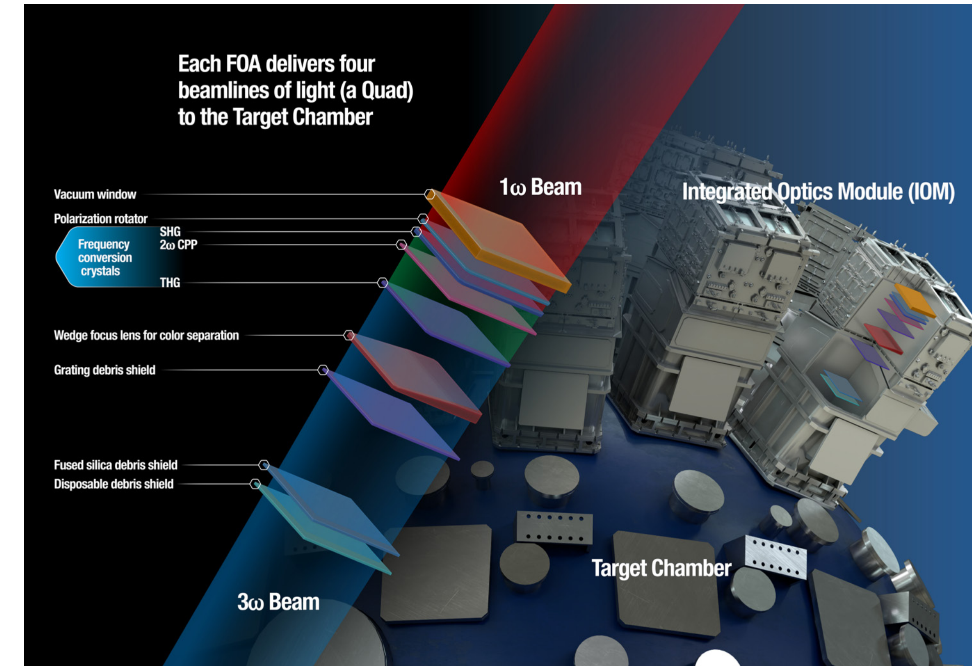
"The optics in those lower beamlines experience more debris damage, which we can attribute to some degree to gravity," Carr said. "As the debris trickles down to the pedestal beams, it slips into small openings and finds its way through cracks and gaps."

The FSDS won't be installed in the pedestal beams until the NIF operations teams can significantly bring down the damage rate. They are working on mechanical debris shielding, which has been partially deployed on the 32 lower beamlines.

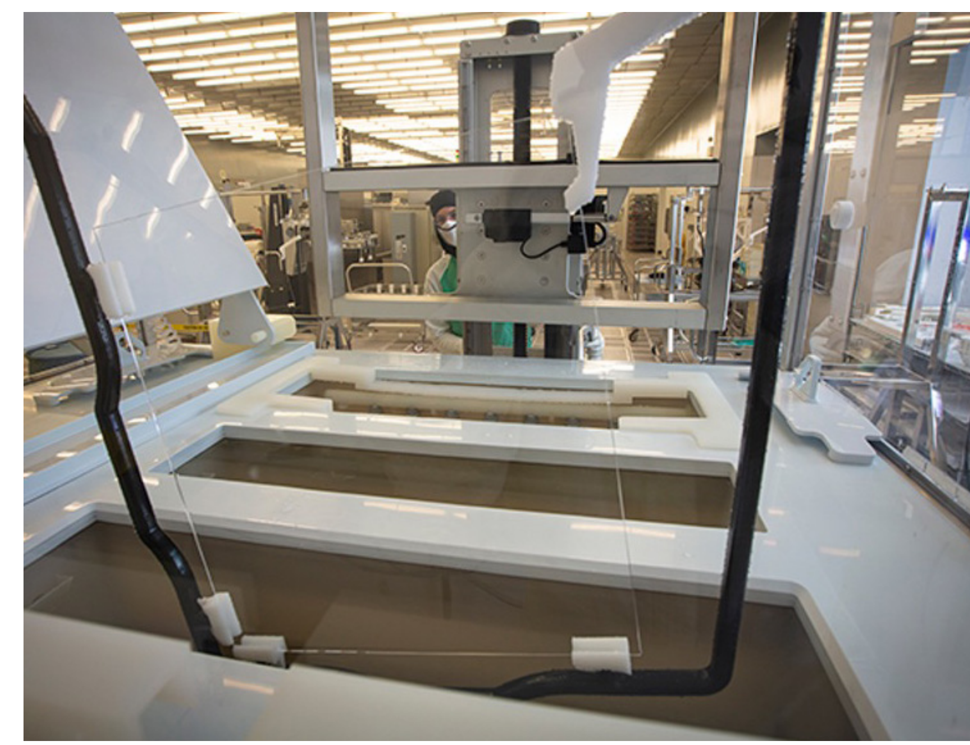
Carr is confident that the team will continue to make progress with the mechanical debris shielding and against other challenges, such as how to make coatings stick better to the GDS and why debris damage is also higher on the upper 32 beams of NIF.

"Our job is never done, but that's what makes it exciting," he said.

—Patricia Koning



In the Final Optics Assembly, the FSDS (not shown in this image) sits between the DDS and the GDS to protect the valuable GDS from debris generated from the DDS.



The new FSDS optic, shown here being processed through the Advanced Mitigation Process to improve its laser damage resistance, was a critical factor in NIF's ability to deliver more than two megajoules of laser energy in ignition experiments. Credit: Jason Laurea

The Age of Ignition
Computing Codes, Simulations Helped Make Ignition Possible

Credit: Randy Wong

COMPUTING CODES, SIMULATIONS HELPED MAKE IGNITION POSSIBLE

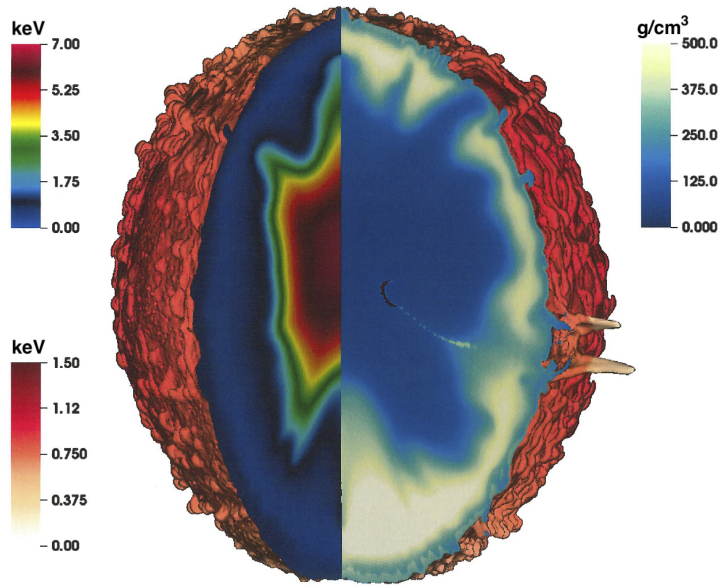
For LLNL physicist George Zimmerman, and for the hundreds of physicists, computer scientists, and code developers who have worked on fusion for decades, computer simulations have been inexorably tied to LLNL's quest for ignition.

Harkening back to the genesis of LLNL's ICF program, codes have played an essential role in simulating the complex physical processes that take place in an ICF target and the facets of each experiment that must be nearly perfect.

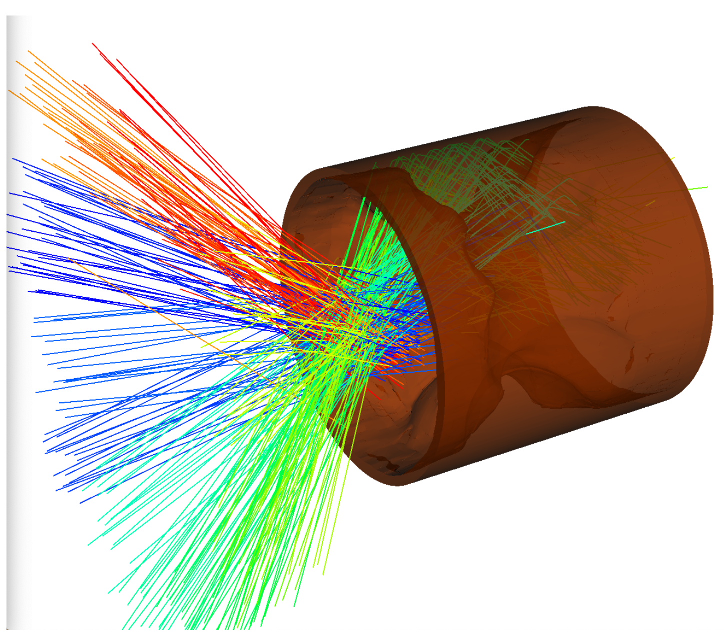
Many of these processes are too complicated, expensive, or even impossible to predict through experiments alone. With only a few NIF laser shots per year to test target and experimental designs, computer modeling provides designers with valuable insights into which ideas are more likely to work.

Zimmerman's one- and two-dimensional ICF code LASNEX was the first computer code to incorporate all the required physics for ICF and served as the foundation for the advanced high-resolution 3D codes that followed and are used to model all aspects of ICF today.

Those range from the specifications of the hohlraum—the cylindrical housing for the deuterium-tritium (DT) capsule that generates the thermonuclear reaction—to the behavior of the x rays produced



This graphic shows a high-resolution 3D HYDRA capsule simulation of a June 2017 NIF shot. The spherical contour surface shows the ablation front colored by ion temperature. The cutaway view shows density on the right where the capsule shell contains the hot spot. The jet from the fill tube is visible near the equator. Ion temperature is shown on the left. Credit: Marty Marinak.



The multiphysics code KULL simulates laser beams shooting into the laser entrance hole of a gold hohlraum during an ICF experiment. Credit: Branson Stephens

when the lasers hit their target, to implosion dynamics and the physics of a burning plasma.

Codes provide valuable information that can be used to analyze data and extrapolate predicted results.

"I think they're instrumental, not only in bringing in funding, but also in guiding the design work in the right direction," he said. "If a simulation says a design won't work, you can probably count on that. If a simulation is very difficult, that might be a hint to pursue a different path."

LASNEX was first introduced in a celebrated 1972 *Nature* paper that presented the original concept that hydrogen fuel pelted with a high-powered laser could produce the elusive fusion burn. LASNEX was key to establishing funding for the numerous LLNL laser systems and became an essential tool on the path to ignition, helping scientists and target designers better understand increasingly complicated ICF experiments and the vital importance of implosion symmetry, stability, and timing to a successful ignition.

Zimmerman won the 1997 Edward Teller Award for his work on LASNEX. He and his team—including longtime physicists David Bailey and Judy Harte and computer scientist Lee Taylor—actively maintain LASNEX today and are currently developing new models to assess remaining experimental anomalies. The code continues to be fundamental for target designers to "try things out," and provides insights into which designs could be successful.

Many Knobs to Turn

"LASNEX has been benchmarked against laser and ICF experiments for 50 years, so there's some validity to the results," Zimmerman said. "Because it's been through all that, we know that it is reasonably complete. The code has lots of knobs, so we can turn a process on or off and ask, 'Did that matter?' We have also implemented many potentially important processes just to see if they matter. This is very useful information for other ICF code developers as they prioritize the implementation of various models."

To many, including Lab computational physicist Michael "Marty" Marinak, the ignition achievement is all the evidence needed to prove codes were sufficiently "close" to reality to enable designers—working with the target fabrication team, experimentalists, and the laser team—to guide the ICF program to success.

Marinak—the lead developer for HYDRA, the principal ICF code used today—said the exponential growth in high performance computing (HPC) at LLNL, along with improvements to HYDRA, allowed the first high-resolution fully spherical 3D simulations of ICF implosions.

In the run-up to ignition, LLNL physicist Dan Clark applied full-sphere simulations to ICF targets, giving scientists a much clearer understanding of what problems needed to be fixed to make ignition happen, including the relative impacts of various asymmetries and miniscule details of engineered features on the capsule, Marinak said.

In 2019 and 2020, a series of simulations performed with HYDRA told scientists that several sources of asymmetry in the implosion were acting in concert to limit performance and prevent ignition.

"When we started generating diagnostics from full-sphere 3D simulations, a lot of the mysteries went away," Marinak said. "The simulations told us if you fixed just one of those issues, you probably wouldn't be able to measure an improvement. Even if you fixed all of them to within target fabrication's abilities, you still wouldn't get the capsule to ignite. That was the turning point. We couldn't just fix the sources of asymmetry. We needed a more robust target."

HYDRA takes advantage of massively parallel computing, where large numbers of processing nodes work on pieces of a computational problem in parallel, allowing them to handle massive datasets and provide faster solutions. Imbued with decades of knowledge about ICF targets and all the physics scientists know how to model, HYDRA is used to simulate the entire ICF implosion in 3D.

The code models every aspect of the hohlraum, including up to 100 specifications for each target—the capsule's dimensions and thickness, the smoothness of the ablator surface, and the diameter of the fill tube used to inject the hydrogen fuel into the target. HYDRA is also used across the national fusion program to model various types of ICF targets, including direct-drive, heavy ion, and magnetically driven targets.

Designers used HYDRA to make the target more robust, changing the hohlraum's size and making the capsule thicker to take advantage of the boost in energy gained from bumping the NIF laser from 1.9 to 2.05 megajoules (MJ). They also reduced the laser entrance hole size to make the target more efficient—the fewer x rays that escape the hohlraum, the more energy would impact the capsule. They called the target "Hybrid-E High-Energy (HyeHE)."

> "We promised that we could do this thing that no one else has done before for stockpile stewardship and for other purposes, and it was greatly rewarding to finally see that we helped to make that happen."
>
> **Computational physicist Marty Marinak**

"The idea was to make a bigger target, but we had to make it bigger in a way that optimized all the desired properties—a task where simulations excel," Marinak said. "The code was telling us, along with theory, that reducing the time between when the laser goes off and the capsule reaches peak compression velocity was the best place to use that (additional) energy. Then you've got to make the capsule thicker because you're burning off more of it. So how much thicker do you make it?"

HYDRA simulations provided an answer. With the new target specs and laser energy accounted for, and small adjustments to improve implosion symmetry, the ICF team made an integrated prediction—an ensemble of target simulations showing probabilities of the resultant energy yield. For the first time, the predictions told scientists that the likelihood the shot would achieve the elusive breakeven point was slightly greater than 50 percent.

Lead experimental designer Annie Kritcher also forecast a doubling of the 1.2 MJ yield that had been obtained from the first shot using the HyeHE design on Sept. 19, 2022. Both outcomes were as the code had predicted.

Based on the knowledge gained from HYDRA and other codes, Marinak was confident target design was "moving in the right direction" and would eventually result in higher yields.

"I always thought we would make it, but ignition is difficult and was harder to accomplish than we had thought, and that's probably why there's no one else in the world that has done it," Marinak said. "Now we have a much clearer understanding of the behavior of these implosions and the challenges that must be overcome.

"We promised that we could do this thing that no one else has done before for stockpile stewardship and for other purposes, and it was greatly rewarding to finally see that we helped to make that happen."

Cavalcade of Codes

With the road to ignition beset with multiple hurdles, a host of codes (and codes within codes) were brought to bear on the problem. Codes have been ingrained in the overall NIF design loop. They're used to help design the experiment, to model the target capsule and iterate on designs, to answer questions from experimentalists, and to understand what occurred post-experiment. The knowledge gained from each shot goes back into the codes to improve them.

The codes use material models and libraries to account for fundamental material properties and are essential to the success of the ICF models. In every case, the codes use high-fidelity equation of state (EOS) and opacity tables created by multi-disciplinary teams across the Lab. Further developing scientists' understanding of material properties and improving these models is another necessary research and development activity to support ICF, requiring a strong partnership between the ICF designers and code teams.

"There are a lot of physics that go on in an ICF experiment, and a lot of it's highly nonlinear and it's very tightly coupled, so that makes it a complicated problem," said Doug Miller, project manager for the ICF-related code KULL. "It has to work all together at the same time to get a pretty good approximation to reality. And it's got to run fast enough so the designers can come up with an idea, try a simulation, and get an answer in a day or a couple of days so they can iterate quickly before they try and build an experiment."

KULL has made unique contributions to ICF and ignition through its three different methods for simulating radiation transport, as well as hydrodynamics, thermonuclear reactions, nonlinear thermal equilibrium (non-LTE) properties and turbulence, and by modeling the lasers' ability to deposit energy in a realistic way. Capabilities originally spearheaded in KULL are being transferred to LLNL's next generation effort, MARBL.

With its unique attributes, KULL can handle the turbulent fluid flows encountered in ICF experiments, making it a valuable computational tool for ICF.

In Miller's view, the impact of codes on ignition has been "extremely large," at times providing the only hint that there were many more puzzles to be solved before ignition could be realized.

"Codes were overpredicting performance for a long time, and the 'why' was an important mystery; it really let us know that there's a lot going on here that we don't understand," Miller said. "The ideas for a long time came fast and furious, and without the codes to weed out the ones that obviously didn't work, we wouldn't have gotten anywhere. It's been very hand-in-glove with the design staff. It was a big shock to discover that all the little things needed to be modeled, and that it really did make a big difference."

Other factors that needed to be accurately modeled were the behavior of the NIF laser and the fusion plasma. PF3D, a massively parallel specialized code developed by computational physicist Steve Langer and team, simulates the interaction between NIF's high-intensity laser and the burning plasma that contains the fusion reactions. The interaction can scatter laser light in directions that experimentalists don't want. PF3D can model an entire laser beam as it hits the plasma as well as cross-beam energy transfer, which is used to control the beams' energy balance.

Predicting Plasma Behavior

CRETIN, developed as an astrophysics code to calculate the spectra coming from accretion disks around black holes, also proved extremely beneficial, predicting what the plasma inside the NIF target would do and what it would look like. The code has allowed researchers to improve the physics in the simulation codes and better match experimental results.

Capable of running in one, two, and three dimensions, CRETIN is one of only a few codes in the world that can perform atomic physics and radiation transport under non-LTE conditions, such as the low-density, high-temperature and radiation environment found in the NIF Target Chamber. CRETIN evaluates atomic structure and transitions between atomic states during ICF experiments using atomic data.

"To do that in detail accurately is an immensely large problem, which is difficult to do a single time," said Lab physicist Howard Scott, lead developer of CRETIN. "It's not something that we can afford to do in the middle of another calculation. ICF needs good, but not highly detailed, atomic models which can be used a very large number of times during the ICF simulation, and that's what CRETIN is providing and using during the simulations."

In recent years, the improved atomic physics from CRETIN informed researchers that "we really needed to step up our game" and adapt, Scott said. Besides predicting radiation coming off the hohlraum walls, CRETIN has provided scientists with more detailed atomic data to model spectroscopic diagnostics. The atomic modeling code in CRETIN sits inside several radiation-hydrodynamic codes, including HYDRA and KULL and another core ICF code called ARES.

LLNL physicist and computer scientist Brian Pudliner, who served as a member of the ICF "red team," leads the ARES project. The code was first used for ICF in 2005, and its unique ability to capture turbulent fluid mixing and its impact on physics has made it an invaluable resource for designing and analyzing HED and ICF experiments at LLNL. It is also applied to magnetically driven fusion in experiments at Sandia National Laboratory's Z machine and to model debris within the NIF Target Chamber.

Pudliner said ARES has been working to extend its capabilities to model how the laser deposits the energy inside the hohlraum, where matter is driven to extreme states, investigating a complex interplay of multiphysics to capture how the energy is transported within the hohlraum.

"You have to be able to do that coupling between the plasma and the radiation field to model these experiments, and it's very challenging for the simulation," Pudliner said. "ICF experiments start off at cryogenic temperatures and then very quickly, you have lasers turning things into plasmas and metal of the hohlraum heating up to high temperatures and emitting x rays, and to simulate that you really have to capture extremes of the conditions."

> *"I thought, 'Wow, that's progress. That's the kind of thing that you call a breakthrough.' "*
> ***Physicist and computer scientist Brian Pudliner***

While ARES didn't directly model the capsule used in the Dec. 5 fusion shot, it did impact the processes behind the experiments and will continue to be used heavily as scientists test different capsule designs to increase energy yield. When he heard about the historic ignition shot, Pudliner said he was excited that ICF scientists had finally overcome daunting challenges.

"When you have spent time listening to all the struggles and the scientific uncertainty of what's going on (in ICF), when you get to the other side of that, it feels like, 'We solved it. We got around those issues,'" Pudliner said. "That is just a very satisfying turn of events. There are some scientific problems that just persist forever, and you just feel like you never make any progress, and this was one where you could win. I thought, 'Wow, that's progress. That's the kind of thing that you call a breakthrough.'"

Pudliner led an effort to port ARES over to graphics processing units (GPUs) on LLNL's current flagship Sierra supercomputer and is enthusiastic for the potential of the upcoming exascale-class (10^{18} floating-point operations per second) El Capitan for future HED and ICF experiments. Scheduled for production in 2024, El Capitan's ability to run more computationally expensive multiphysics than ever before, like those needed to model hohlraums or design experiments, will provide even more insight for ICF researchers, he said.

"There are areas that we haven't really been able to make work on the GPU because there just hasn't been enough memory; El Capitan is going to change that," Pudliner said. "There have been classes of problems that have worked very well on Sierra—we've seen enormous performance gains, and that's changed how people work on those types of problems. With El Capitan, we're going to see that happening in more application spaces related to NIF and high energy density physics."

Another Lab scientist thrilled to work on El Capitan is Rob Rieben, a computational physicist who helped develop the ARES and ALE3D codes before beginning his own code, a next generation multiphysics (magneto-radiation hydrodynamics) pulsed-power code known as MARBL.

For ICF applications, MARBL adds multi-material hydrodynamics, equations for fusion reactions, and tracking temperatures for radiation, ions, and electrons. What really sets the code apart from its predecessors is its higher-order algorithms, in which mesh elements have multiple degrees of freedom to "curve," whereas low-order algorithms run with straight-edged elements.

Solving conservation laws on a mesh that moves with the fluid has potential advantages for modeling ICF because when a capsule implodes, it is squeezed by about a factor of 30 in radius, according to Rieben. Higher-order moving-mesh algorithms can model the resulting extreme fluctuations, turbulent flow, and fluid instabilities with higher resolution and accuracy, Rieben said. In general, the more mesh elements in a simulation, the better the simulation can reflect reality. High-order mesh elements also can converge faster, resulting in quicker solutions than lower-order methods, he said.

Better Resolution

"Think of your mesh as a bunch of Legos," Rieben said. "A traditional Lego just has straight edges; it doesn't bend. But our elements have curvature built into them. They have more resolving power; they track more features per element than a lower-order code."

Rieben and his multidisciplinary team of physicists, computer scientists, engineers, and mathematicians have been working to port MARBL and its million-plus lines of code to run on GPUs, first with Sierra, and now for the upcoming exascale El Capitan.

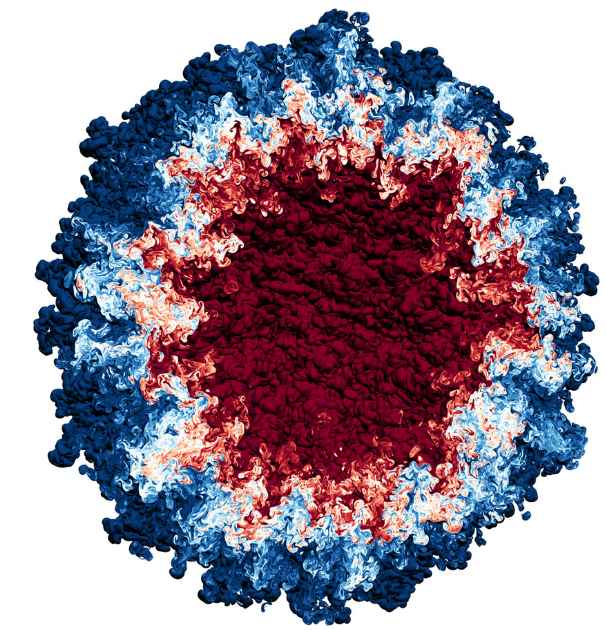
"What we consider heroic today will be commonplace on El Capitan," Rieben said. "That's one of our goals—that thing that maybe only one person could do over the course of a long period of time, now a lot more people can do in a very short time."

Other implications for ICF will be the ability to run high-fidelity 3D ensembles (collections of simulations) to answer multiple scientific questions at once and perform unprecedented uncertainty quantification and machine learning (ML) studies, Rieben said. The capability opens the door to ML-backed design optimization, giving researchers an expanded design space exploration tool to create more robust targets.

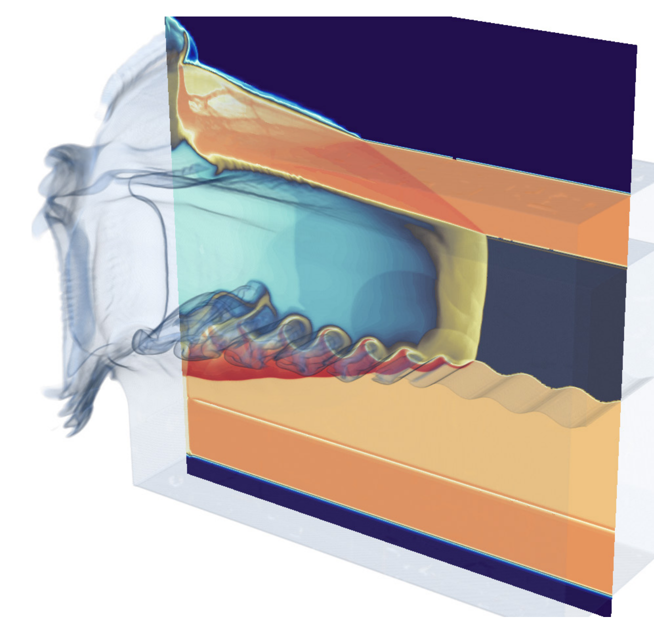
For the first time, scientists also could create 3D ML surrogate models, trained on thousands of ICF simulations, to perform "inverse design" of target capsules, where AI techniques are used to back-engineer optimal target initial conditions and drives based on the desired yield output.

"I'm really excited about the idea of inverse design for multiphysics simulation," Rieben said. "MARBL is extremely well-suited for this work, and we've already got some examples of doing this at small scale, and we're looking forward to scaling that up."

—*Jeremy Thomas*



Researchers in 2018 used the code ARES and the Ascent library to perform a 98-billion-zone capsule instability calculation on LLNL's Sierra, one of the world's most powerful supercomputers. This image shows turbulent fluid mixing in a spherical geometry—part of a simulation of an idealized ICF implosion. Credit: Brandon Morgan



A MARBL 3D ALE radiation-hydrodynamics simulation of a laser-driven high energy density physics experiment. The model consists of 600 million quadrature points and ran on LLNL's El Capitan Early Access System-3 computer RZVernal. Credit: Rob Rieben and Thomas Stitt

ENGINEERING DIVISIONS PROVIDE EXPERTISE TO SUPPORT FUSION ENERGY'S FUTURE

In the 2000s, LLNL engineer Steve Hunter was asked to work on the concept of a laser fusion ignition power plant, not because of his laser or electronics knowledge, but because of his firearms expertise. He needed to figure out how to inject a stream of targets into the Target Chamber, so that a constant source of fuel was available.

"The targets were a bit delicate, so they could only withstand a certain amount of acceleration," Hunter said. "I calculated that we would need a 10-meter-long barrel to keep the acceleration within limits, and I designed an air gun based on the Gatling gun with a special rotary valve. Then I built a Plexiglas prototype in my garage and powered it with a shop vacuum."

National security and energy needs go hand in hand, but typically, not this directly.

While those initial plans for achieving a commercially viable fusion energy plant were eclipsed by LLNL's ignition achievement, the Lab's National Security Engineering Division (NSED) and Defense Technologies Engineering Division (DTED), both part of the Engineering Directorate, have long histories of providing infrastructure for NIF's operations and for the pursuit of fusion energy.

This history is partly due to the expertise of these divisions' engineers in handling volatile and rare materials. But it's also attributable to the link between national security and energy production: Energy dependencies make countries susceptible to each other's priorities, and climate change threatens national ecosystems and economics. Inertial fusion energy (IFE) pursues a clean-energy solution that could easily power the world through fusion-fueled power plants.

Hunter—who has been embedded at NIF off and on since 2004—had previously worked on a system that projects dark spots into each laser beam to minimize optics damage. Since defects in the optics absorb more energy, thereby causing damage sites to expand during subsequent full power shots, projecting dark spots into the beams blocks the defects from absorbing their energy. Optics need to be replaced when the damage grows too large, and since there are five final optics in each of 192 beams, each costing approximately $50,000, it can be an expensive problem.

The team had to develop a special liquid crystal using a material that was in such short supply that they bought nearly the entire world's stock, and Hunter was responsible for the electronics that projected an image of the dark spots onto this liquid crystal.

"This was a very difficult project, and NIF wouldn't work without it," Hunter said. "But one thing I learned while working on this project was that there are many groups working on difficult problems, and all of them are required for NIF to function. I came to appreciate what an incredible science and engineering achievement NIF is."

Another example of rarefied engineering expertise that quietly keeps the facility running is that of the team mitigating electromagnetic interference (EMI). Charlie Brown has been in NSED for the 20 years he's been at the Lab, working mainly at NIF in the context of EMI.

Brown consults with NIF teams to characterize and help mitigate EMI that occurs in NIF due to the motion of charged particles when the lasers hit the target and when ionizing radiation strikes objects in and around the Target Chamber. In such interactions, charged particles, like electrons, are spewed everywhere, and when they're violently put in motion, electromagnetic fields are generated. Even some of the diagnostics generate their own EMI.

"That's a bad thing in a facility where many diagnostics rely on electrical cables," Brown said. "You get interference, and it obscures the actual signal that you're looking for, damages your instruments, or maybe worse—it perhaps gives you physics that aren't real."

Those diagnostics include x-ray streak and framing cameras that look at the target, acting as the eyes of the physicists. These diagnostics are crucial because they give the physicists the feedback that allows them to tune their models and get NIF to ignition.

Since EMI is sneaky—high-frequency EMI in particular is hard to defend against—Brown is highly alert to gaps or seams where metal surfaces are bolted together, and he is keenly attuned to the engineering trade-offs that come with EMI-prevention designs. No matter how well-designed an aspect of NIF is, it may require additional shielding based on simulations that show how much interference to expect from different leakage points.

While Brown and his team attempt to mitigate EMI in the existing fusion set up, NSED engineers led by John Moody are contributing to a Laboratory Directed Research and Development-funded project that harnesses the power of magnetic fields, called MagNIF. As the name suggests, MagNIF involves magnetizing the fusion fuel at NIF to reduce heat loss from the compressed fuel core by constraining the motion of electrons and fusion-generated alpha particles.

The capability, when completed, could be one tool to help increase fusion yields by a factor of two or more, and increase the types of fusion experiments that can be done on NIF. In addition to potential yield enhancements, magnetic fields may also reduce the effect of key implosion degradations such as ablator-fuel mix and hot spot asymmetries leading to a more robust implosion design.

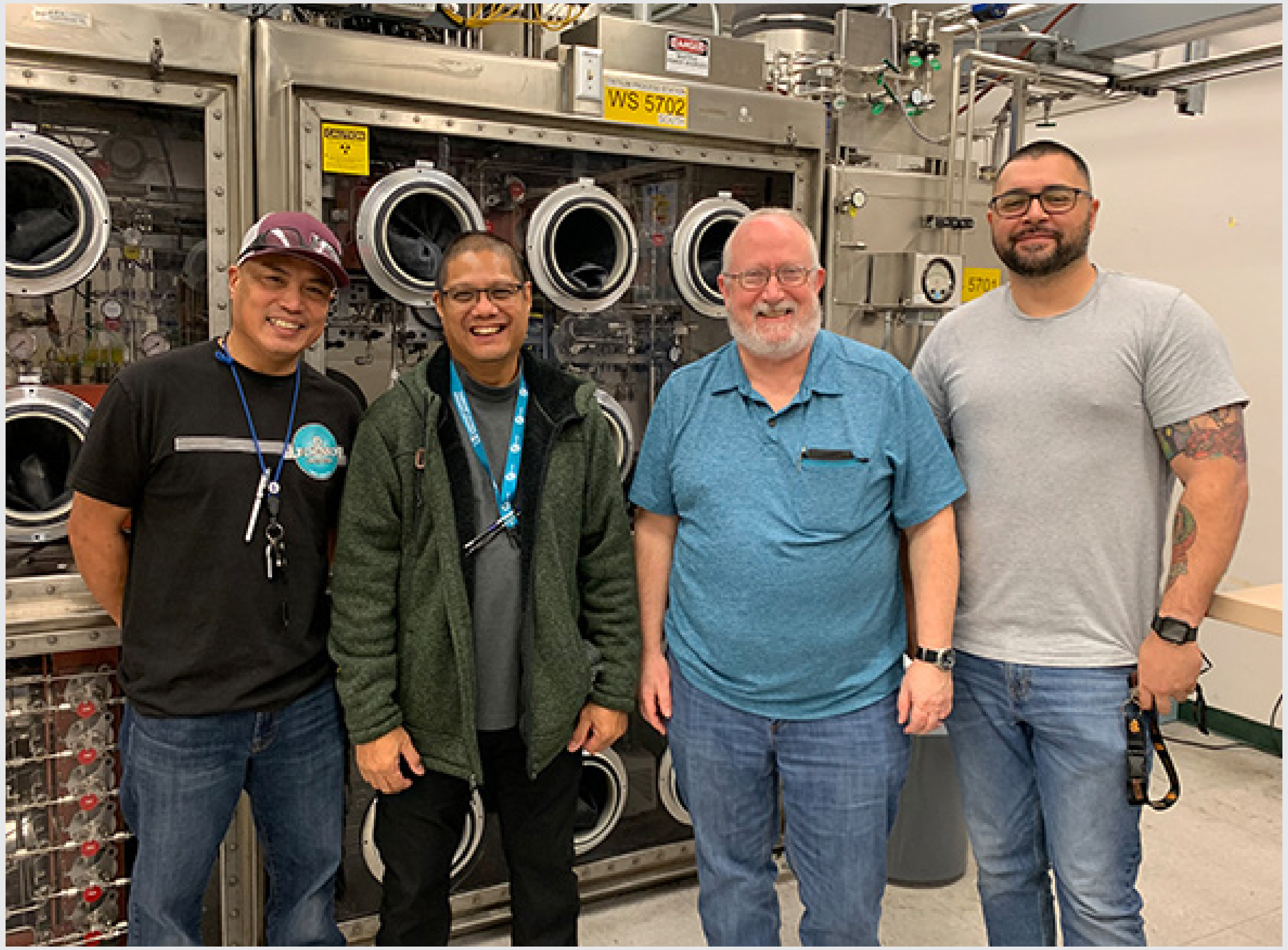
DTED also is in the business of enhancing the power of reactions and viability of shots. The Tritium Team supervised by Clint Byington calibrates and delivers the tritium-deuterium gas that surrounds the target. The gas has long been used in nuclear experimentation and design.

"Tritium is a constant in fusion experiments because of its reaction with deuterium," Byington said. "Combined, the two gases produce a large amount of energy, amplifying the fusion potential between nuclei in inertial confinement fusion reactions."

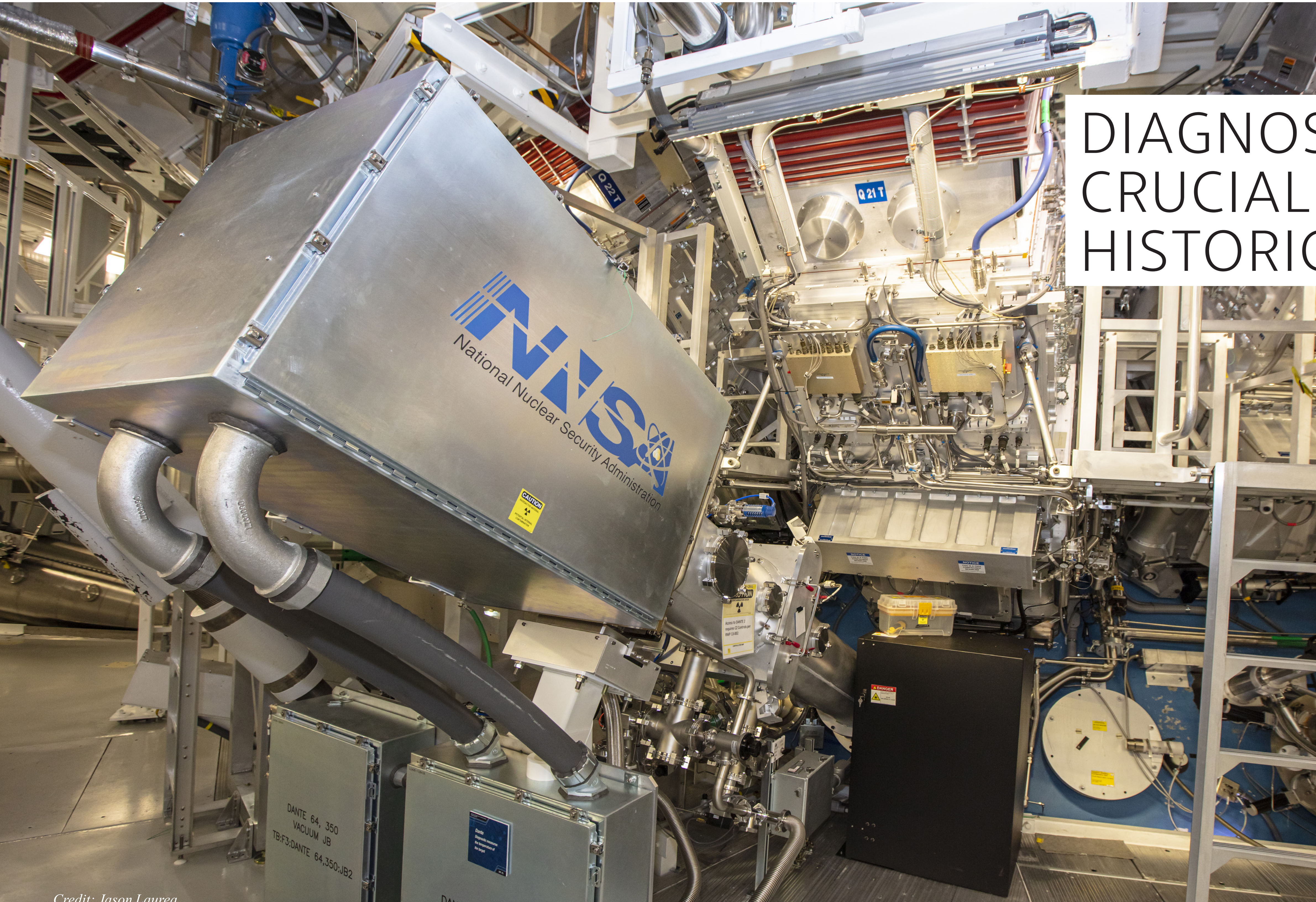
While some of the team's requested fills get quite exotic and held to tight tolerances, the gas fill that Byington's team delivered to NIF for the December fusion ignition shot was considered a "standard fill" at 50 percent tritium, 50 percent deuterium. Standard or not, each fill involves a dynamic process whereby extreme, repeatable precision is challenging because of constant fluctuations in the percentages of the product maintained on the team's storage beds.

"It is incredibly satisfying to have played a role in this milestone, and we are increasingly motivated to continue providing precision gas mixtures and to ensuring that our contribution is consistently excellent," Byington said.

—Aimee Fountain



Defense Technologies Engineering Division (DTED) technologists fill the NIF targets with tritium and deuterium required for ignition experiments. From left, DTED staff members Chris Padagas, Joseph Advincula, Steven Keesee, and Aaron Torres stand in front of the Tritium Process Station (not pictured: Supervisor Clint Byington).



Credit: Jason Laurea

DIAGNOSTICS WERE CRUCIAL TO LLNL'S HISTORIC IGNITION SHOT

Diagnostics—specialized, state-of-the-art measuring instruments—played an essential role in LLNL's fusion ignition milestone.

The data collected from NIF diagnostics were "really critical for our progress," said Arthur Pak, team lead for stagnation science.

"They've helped to identify, quantify, and mitigate degradations or loss mechanisms, which have impeded our progress," Pak said. "They allow us to test hypotheses and design changes to understand the conditions of the fusion plasma and the sensitivities of the system."

According to Andrew MacKinnon, former lead scientist for NIF diagnostics, the approximately 20 instruments used to diagnose the ignition shot were essentially the same as those used on the Aug. 8, 2021, experiment when LLNL achieved a then-record 1.35 million joules (MJ) of fusion energy. These optical, x-ray, and nuclear diagnostics continued to play key roles in measuring the performance of experimental campaigns leading up to the fusion ignition shot.

NIF's diagnostics have been developed over decades of ongoing collaborations with national and international partners, including Los Alamos and Sandia national laboratories, the University of Rochester's Laboratory for Laser Energetics, the Massachusetts Institute of Technology, UC Berkeley, the Nevada National Security Site, National Security Technologies, LLC, the Atomic Weapons Establishment (AWE) in the UK, and the French Alternative Energies and Atomic Energy Commission (CEA) in France. Industrial and commercial partners included General Atomics, Kentech Instruments Ltd., Sydor Technologies, Spectral Instruments Imaging, Keysight Technologies,

NIF Target Area Operator Henry Deras services the Dante diagnostic, one of the first diagnostics to be installed at the National Ignition Facility. Dante is involved in virtually every NIF shot. Credit: Jason Laurea

Tektronix, Photek Ltd., AMETEK, Teledyne Princeton Instruments, Artep LLC, Inrad Optics, and Saint-Gobain.

The contributions of NIF's venerable Dante diagnostic were emblematic of the instruments employed in the historic shot.

Dante is actually two diagnostics—Dante 1 and Dante 2—that are involved in nearly every shot. Dante 1 was one of the first diagnostics installed in the late 2000s and is "a workhorse," according to Mike Rubery, the NIF nuclear physicist in charge of Dante.

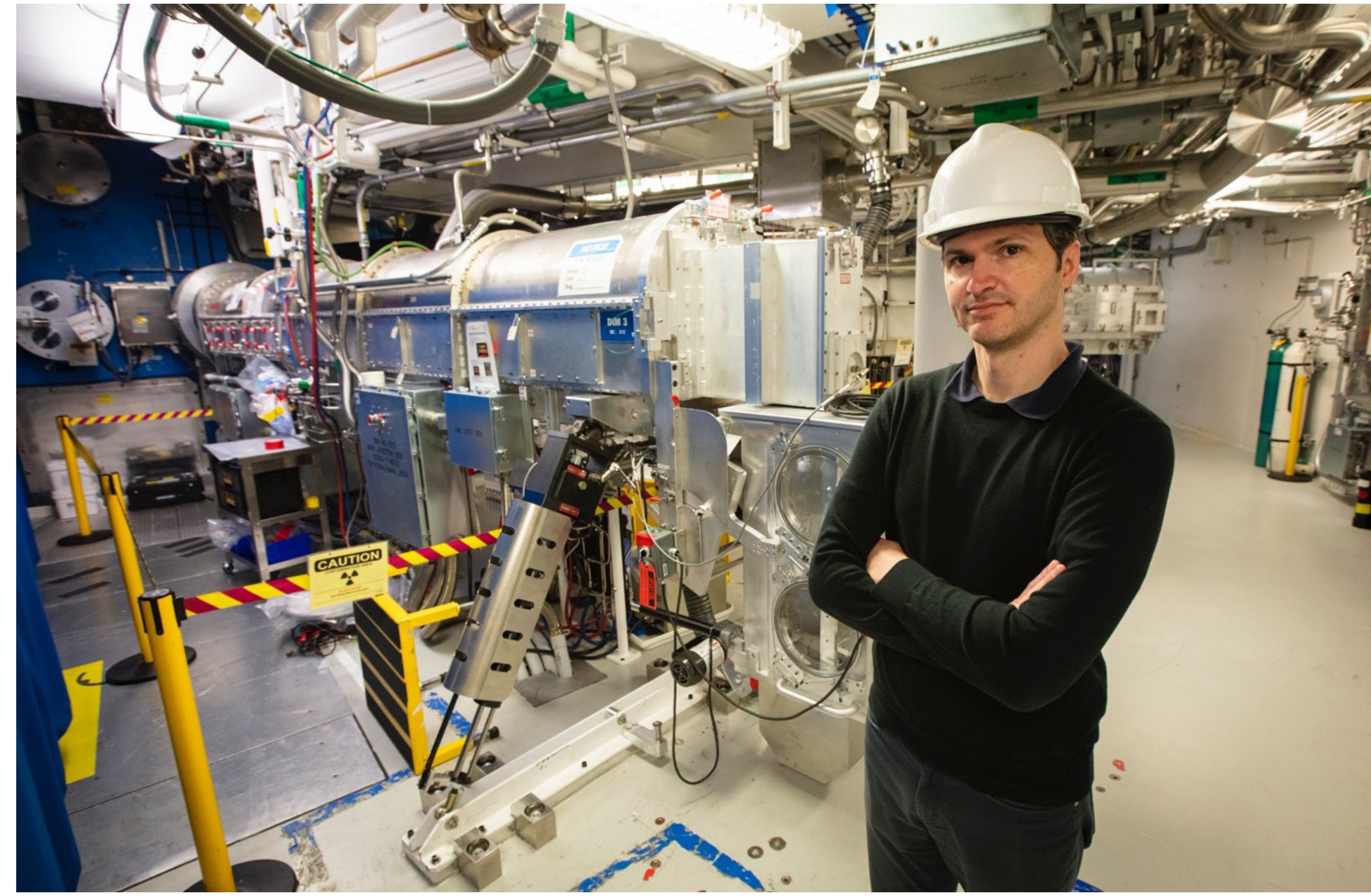
These broadband, time-resolved x-ray spectrometers measure the time-dependent soft x-ray power and temperature produced when NIF's 192 lasers are fired into a hohlraum, the tiny gold cylinder that holds the peppercorn-sized target capsule. NIF, the world's largest and highest-energy laser, is capable of producing temperatures of more than 3 million degrees Kelvin inside the hohlraum. This creates pressures of hundreds of billions of Earth atmospheres that implode the capsule and fuse the hydrogen fuel.

Dante measured the energy produced in the target capsule's "hot spot" during the ignition shot, said MacKinnon, now the leader of NIF&PS High Energy Density Science and Technology organization. The inertial confinement fusion (ICF) experiment was the first to generate more energy—3.15 megajoules—from the fusion reaction than the laser energy (2.05 MJ) delivered to the hohlraum, thus achieving ignition.

"We had seen indications of this in some of the higher-yield shots since Aug. 8, 2021, but nothing as clear as (the Dec. 5 shot)," MacKinnon said. "It was initially disbelief that gradually morphed into astonishment that we had achieved ignition."

Since 2021, NIF has added a new diagnostic, the Polar Dilation X-ray Imager (Polar DIXI), that can obtain time-resolved x-ray images at MJ-plus yields, MacKinnon said.

The Target Area Science and Engineering (TASE) team, part of the Lab's Laser Systems Engineering & Operations (LSEO) program, has developed a comprehensive suite of 140 optical, x-ray, and nuclear diagnostics that help measure the performance of every NIF shot.



Clement Trosseille, lead scientist for NIF's Single-Line-of-Sight (SLOS) and framing camera diagnostics, stands in front of the SLOS. Credit: Jason Laurea

The diagnostic suite measures the characteristics of each implosion: the amount of laser energy that gets coupled to the target; the uniformity of the capsule compression; the amount of capsule ablator/fuel mix; the total fusion energy released; and more. This information is fed to computer models to improve researchers' understanding of the implosion and inform future experimental designs.

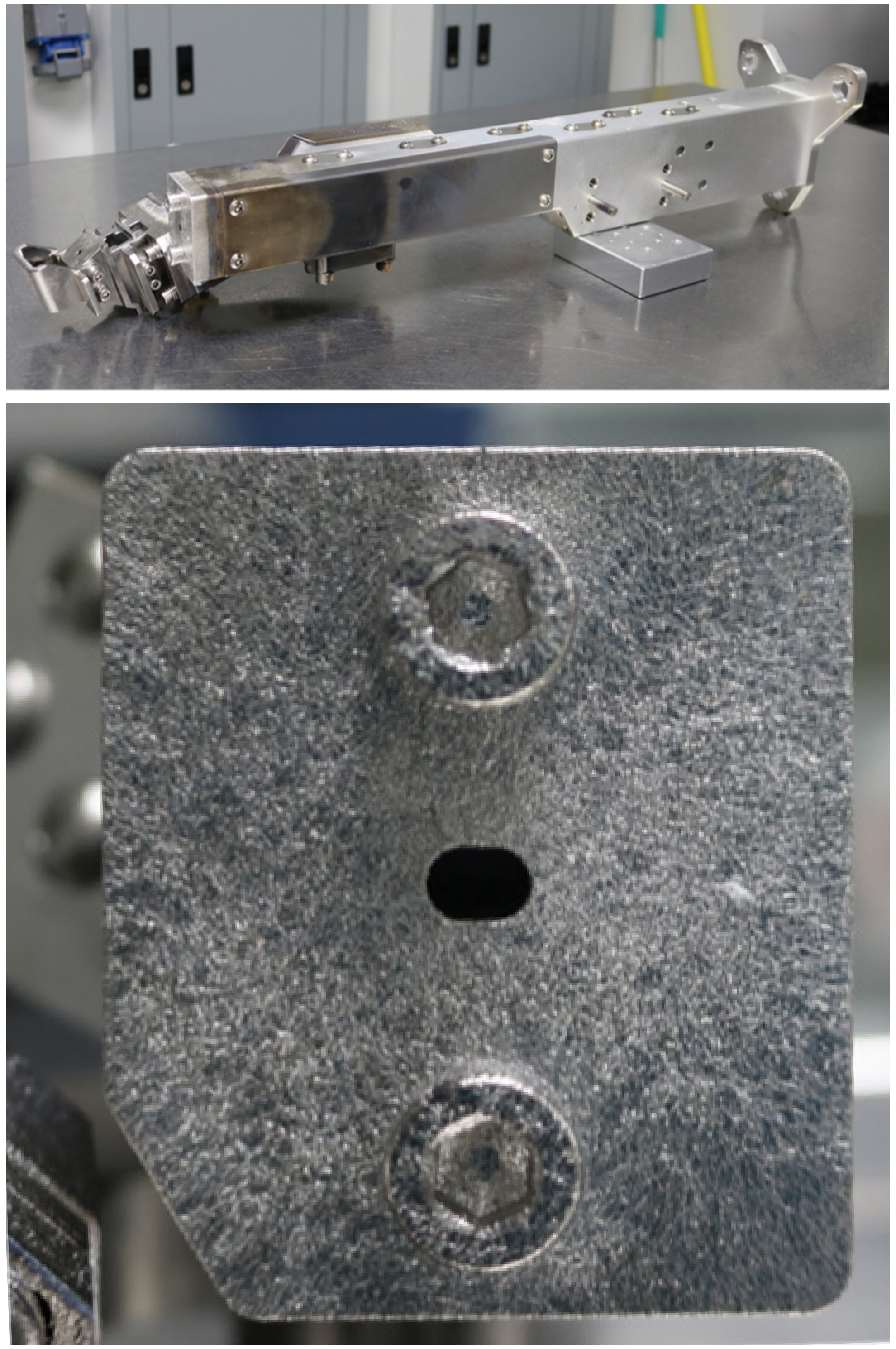
The LSEO engineering team is constantly upgrading existing diagnostics while creating new diagnostics in parallel, said Nuclear Diagnostic Engineering Lead Cory Waltz. One example of diagnostic evolution is the Neutron Imaging System (NIS), which was fielded on NIF in collaboration with Los Alamos National Laboratory. The first NIS on NIF was deployed in 2011 and provided a single 2D image of where neutrons are emitted from the hot spot of an implosion.

> *"Success like this drives more developments in the instrumentation."*
>
> ***Nino Landen, ICF experiments group leader***

Since then, Waltz said, the Lab has added two more NIS lines-of-sight (LOS) allowing for the 3D reconstruction of the neutron emitting volume. The design has also evolved to add the ability to image gamma rays on two of the three LOS.

These data, combined with x-ray diagnostic data, can show how items like the capsule fill tube affect the symmetry of the implosion. For the Dec. 5 shot, two of the LOS NIS imagers were fielded and collected data, with initial analysis showing a highly symmetric implosion.

Some diagnostics use snouts to hold equipment that's inserted into the Target Chamber on diagnostic instrument manipulators (DIMs). These snouts must survive the extreme environment created by a NIF shot. Recently, NIF has been increasing the laser energy delivered to targets from a maximum



(Top) The Neutron Imaging System 1 (NIS1) snout holds the NIS pinhole assembly about 32 centimeters from the target. (Bottom) Blast shield on the front of the NIS1 snout. High x-ray flux from the target is absorbed in the stainless-steel shield, heating it up and causing it to melt and eject material before resolidifying. Credit: Cory Waltz

of about 1.9 MJ to the 2.05 MJ used in the ignition shot.

This higher laser energy results in an increased x-ray flux emitted by the target. The surfaces of the diagnostic snouts with a direct line of sight to the target absorb the energy and become superheated, which melts and ablates metal that is ejected before the surface resolidifies; the resulting impulse force recoils down the snout.

The Target Diagnostic engineering team uses a LS-DYNA computer model to determine the expected forces along the snout from this recoil, allowing every snout to be engineered to withstand these forces.

> *"It's kind of life changing. I consider myself incredibly lucky to be here at this moment."*
>
> ***Nuclear physicist Mike Rubery***

One key diagnostic measurement from the ignition shot was the total fusion energy yield, indirectly determined by measuring the number of neutrons emitted from the capsule.

Each deuterium-tritium (DT) fusion reaction emits one neutron, one alpha particle, and 17.6 million electron-volts (MeV) of kinetic energy shared between the two particles. Determining the number of neutrons emitted gives the number of fusion reactions that occurred, and multiplying this number by the energy per fusion provides the total fusion yield.

According to Waltz, the official yield measurement on Dec. 5 came from two absolute yield diagnostics: the Magnetic Recoil Spectrometer (MRS), which was developed in collaboration with MIT, and the zirconium Neutron Activation Detector (NAD).

The zirconium-90 isotope within the NAD sample becomes activated when it reacts with neutrons above energies of 12.1 MeV, allowing it to be a good measure of the 14 MeV neutron flux emitted from the target while not measuring lower-energy background neutrons. The activated zirconium decays, emitting gamma radiation with a known half-life that is measured after

the experiment to determine the total initial activation from the shot. This can then be correlated to the neutron yield the shot had to produce to create the initial activation.

The ignition shot was just a few hours old when ICF Experiments Group Leader Nino Landen was already focused beyond the historic event and excited about the possibilities that had suddenly opened up.

"I tend to look to the future," he said, "and I was thinking, 'Wow, what does it mean for going further?' Because this shot exceeded my expectations relative to Aug. 8, 2021; this provided an opportunity to refine our extrapolations."

Landen recalculated extrapolations that day based on anticipating more NIF laser energy and a more efficient hohlraum in the future. "That, to me, is the most exciting part that visually shows that with both the existing NIF and a slightly upgraded NIF, the potential has gone up in terms of what it can do," he said.

"The good news is that success like this drives more developments in the instrumentation. We really want to look for 'gotchas' and are trying to stay a little bit ahead of the game by adding instrumentation to look at why things maybe don't perform as we expect."

Landen likened the ignition achievement to rungs on a ladder. "We didn't know if there was another rung on the ladder—and now we know there is," he said. "We're moving up the ladder faster and faster in terms of the yield. It's progressing more quickly, which is just what you'd expect once you get ignition. Things can get easier post ignition."

Rubery echoed Landen's excitement over the ignition breakthrough.

"It's kind of life changing," Rubery said. "I consider myself incredibly lucky to be here at this moment."

—Jon Kawamoto

Justin Jeet, Shaun Kerr, and Eddie Mariscal are inside the North Pole neutron time-of-flight (nTOF) enclosure that detects and records neutrons released during NIF's laser-driven implosions. Credit: Jason Laurea

IGNITION GIVES U.S. 'UNIQUE OPPORTUNITY' TO LEAD WORLD'S IFE RESEARCH

LLNL's achievement of fusion ignition at NIF positions the United States with 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 U.S. Department of Energy (DOE) Office of Science report.

Capitalizing on that opportunity will require a renewed, robust, and rapidly paced program of inertial fusion energy (IFE) research that coordinates efforts from the public, private, and academic sectors. This conclusion comes from the DOE Office of Science-sponsored IFE Basic Research Needs (BRN) report, from the result of a three-day workshop in June 2022, and many months of work by a panel of experts.

"There is a huge amount of momentum in the fusion field right now, which gives us a very special opportunity to grow the national IFE program and accelerate the development of fusion energy by leveraging our leadership in inertial confinement fusion (ICF), developing new collaborations through public-private partnerships, and working closely with DOE and the community," said LLNL physicist Tammy Ma, the lead for the Laboratory's Inertial Fusion Energy Institutional Initiative.

The virtual Basic Research Needs workshop, chaired by Ma and Professor Riccardo Betti of the University of Rochester, brought researchers and IFE supporters together to explore the science, technology, and investments needed to realize IFE's potential.

The workshop was convened as momentum for IFE accelerated in the wake of the Aug. 8, 2021, experiment that brought LLNL to the threshold of ignition.

During the months both before and following the workshop, 120 panelists invited by DOE worked together to author the Basic Research Needs report, which will become a foundational guide for DOE to establish a national IFE program.

The report was basically completed by Dec. 5, 2022. But on that day, LLNL provided IFE an even bigger shot of momentum by achieving fusion ignition in an ICF experiment, a feat that supplied the "unique opportunity right now to grow the national program by nourishing and leveraging our (US) leadership in ICF," the 250-page report said.

"With the demonstration of ignition on the NIF, we are at a critical juncture in IFE research," the report said. "As a community, we can exploit the growing scientific basis of fusion ignition, burn, and energy gain for practical applications. We have the opportunity now to incorporate and integrate multiple emerging technologies to make rapid progress."

But the current infrastructure around ICF, which supports the National Nuclear Security Administration (NNSA)'s Stockpile Stewardship program, and high energy density (HED) physics, designed to improve fundamental understanding of extreme environments, "is insufficient to demonstrate the feasibility of IFE today," the report said. "A dedicated IFE program is necessary to push for improved utilization of existing infrastructure by increasing the shots available to IFE research."

The formidable scientific and technological challenges that lie ahead before fusion energy becomes fast, efficient, economical, and reliable enough "can be overcome with expanded, coordinated research, development, and deployment programs and strategic public-private partnerships," the report said.

The BRN report's findings are:

- IFE and magnetic fusion energy (MFE)—which uses powerful magnetic fields—are two main approaches that have different technical risks and benefits. Both should be considered important parts of the DOE's Fusion Energy Sciences research and development portfolio. Creating and growing a healthy new national IFE program will require the IFE and MFE sectors collaborating to take advantage of technological developments to address common issues.
- LLNL's demonstration of thermonuclear ignition "constitutes a pivotal point in the development of inertial fusion energy."
- Ignition and other major advances in IFE-relevant physics and technology during the past several decades were mostly funded under the nation's national security mission, an investment that makes the United States "the recognized leader in IFE science and technology."
- With private industry driving the commercialization of fusion energy in the United States, "public-private partnerships could greatly accelerate the development of all fusion energy concepts."
- "Accelerating IFE will require a suite of dedicated, new, and upgraded facilities to increase the rate of learning and test new technologies."
- ICF computer modeling codes primarily reside at NNSA national laboratories, including LLNL. The codes were "built on decades of investment and expertise and constitute a valuable resource for advancing IFE science and technology," the report said. An assessment of how to access ICF codes optimally and securely for IFE development should be carried out with NNSA.
- Improved diversity, equity, and inclusion measures are needed to enhance the climate and culture of the broader field of fusion and plasma research.

Additionally, the report said one national IFE team or partnership should be formed to focus on "making the best use of existing facilities." The report notes that an IFE science and technology push could leverage existing resources such as LaserNetUS, a broad network of university and government laser research facilities that includes LLNL's Jupiter Laser Facility.

The report acknowledged that developing a fusion pilot plant still faces challenges that could take years or decades to surmount. Accelerating progress toward building those pilot plants will require evaluating and identifying the most promising concepts and taking advantage of emerging technologies such as exascale computing, artificial intelligence, machine learning, advanced manufacturing, and high-rep-rate laser systems.

"We have a unique opportunity right 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 report said.

LLNL has already been out in front in helping spur development of IFE, including sponsoring a community workshop in February 2022 on the potential for ICF research to generate commercially viable IFE, participating in multiple DOE workshops centered around fusion energy, and establishing IFE as an LLNL Institutional Initiative.

The Lab is also helping to drive a newly formed "IFE Collaboratory" effort that brings together 11 U.S. national laboratories and institutions to facilitate public-private partnerships. In the autumn of 2022, LLNL organized a two-day conference with collaboratory members and private companies working on various aspects of fusion energy development in attendance to form new partnerships and jointly respond to DOE calls.

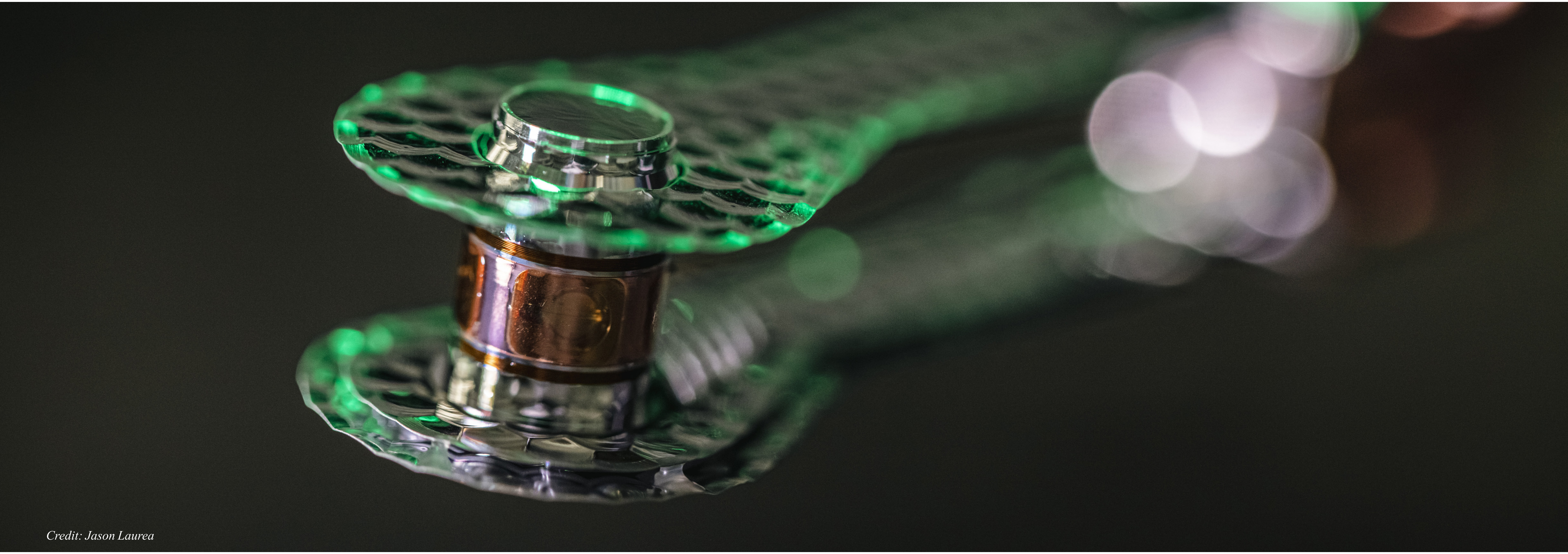
LLNL Director Kim Budil said the achievement of ignition signals the time is now for a major push to make IFE a reality.

"This report provides an important roadmap to tackle the significant scientific and engineering challenges that still lie ahead on the path toward a fusion energy future," Budil said. "The report outlines exciting opportunities for LLNL to partner with the entire fusion energy community as we work together to accelerate the development of IFE during what promises to be a transformational decade of high energy density science and fusion research."

—Benny Evangelista

Attendees of one of the LLNL-organized inertial fusion energy "collaboratory" conferences met in November 2022 at the University of California Livermore Collaboration Center just outside the Lab's gates. LLNL organized a series of meetings to facilitate public-private partnerships with national labs, academic institutions, and private companies working on various aspects of fusion energy development. Credit: Jason Laurea

The Age of Ignition
Target Evolution Is a Key to NIF's Continued Success



Credit: Jason Laurea

TARGET EVOLUTION IS A KEY TO NIF'S CONTINUED SUCCESS

The intricate, delicate targets used in NIF experiments are marvels of design, engineering, and precise manufacturing.

"We've been working over the last 16 years on continuously improving the quality of these targets," said NIF Target Fabrication Program Manager Michael Stadermann. "That effort has been based on decades of prior target development activities at Livermore and elsewhere."

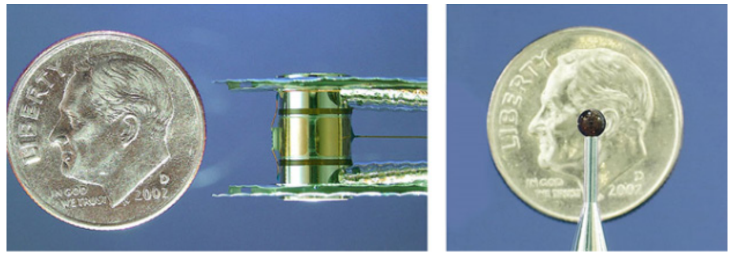
And, he added, the BB-sized synthetic diamond fuel capsules at the heart of NIF's targets are "almost perfectly round" with a surface 100 times smoother than a mirror.

But for NIF to continue to match and exceed December's milestone ignition shot, an even higher level of perfection—or even a different capsule material—may be needed.

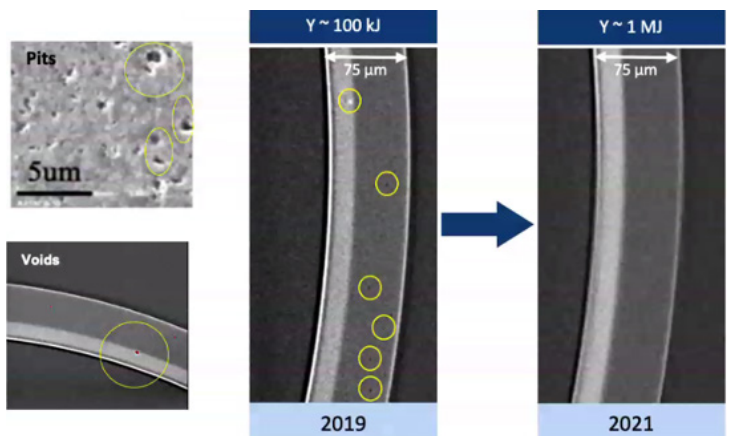
"Perfection is really hard, so we've yet to get there," Stadermann acknowledged. "We still have tiny flaws on our (capsule) shells smaller than a bacterium, and despite their small size, these flaws still have the potential to affect the experiment."

In fact, inertial confinement fusion (ICF) researchers have determined that capsule defects were a chief cause of the implosion degradations that foiled their initial efforts to repeat the Aug. 8, 2021, experiment that brought LLNL to the threshold of ignition. "Microscopic capsule imperfections amplified by hydrodynamic instabilities (were) the dominant degradation mechanism," said Richard Town, associate program director for ICF science.

The tiny imperfections in the capsule can grow into large distortions of the implosion at peak compression, the researchers found. Along with the pits, voids, and foreign material impurities, or "inclusions," in NIF's diamond capsules, a recent study showed that low levels of non-uniformity (about 0.7 percent) in capsule thickness can grow



NIF, the world's largest and highest-energy laser system, focuses 192 laser beams into a centimeter-scale hohlraum (left) containing a millimeter-scale fusion capsule (right), which is then compressed by a factor of 30 to a diameter the size of a human hair.



Left: Examples of microscopic defects in NIF's high-density carbon (HDC), or diamond, target capsules: "pits" on the capsule surface and subsurface "voids." Right: Tomographic images show the dramatic reduction in voids in the capsule used in NIF's Aug. 8, 2021, "threshold" experiment that achieved 1.35 megajoules of fusion energy—a level of capsule quality that was not matched in either the same or subsequent batches.

Researchers have identified capsule defects, along with perturbations caused by the tiny tube used to fill the capsule with hydrogen fuel (top left), as the primary causes of the three main sources of degradations that have dampened the deuterium-tritium (DT) fusion yield in NIF experiments: hot-spot drift, known as Mode 1 or P1; implosion asymmetries, or Mode 2; and hot-spot contamination from capsule material, or "mix."

into approximately 25 percent variations in the fuel areal density and produce hot-spot drift at velocities of about 100 kilometers per second.

"This result is significant because if we know the causes for these asymmetries in ICF implosions, we are better able to predict them and understand their impact," said LLNL physicist Dan Casey. "Perhaps most important, if we know the causes, we can work on fixing them."

In an effort to overcome the capsule issues, the researchers last year boosted the laser's energy to 2.05 megajoules and increased the capsule's thickness by about 8 percent—changes that helped enable the ignition shot that produced more fusion energy than the laser energy absorbed by the target, despite a lower-quality capsule.

The quality of the capsule used in August 2021, however, convinced former NIF Target Fabrication Manager Abbas Nikroo that "getting ignition was inevitable at that point.

"It indeed only took a little over a year to achieve ignition," said Nikroo, who worked on target development at General Atomics (GA) of San Diego as well as NIF from the early 1990s to March 2022, and now serves as NIF's deputy director for physics integration.

Nikroo said his first reaction to the news of ignition "was to think of all those who had worked toward this effort, including some who never got to see it—and I was glad I was here when it happened. The next thought was that this was just the beginning since, as usual, this program pushes the limits continually."

Seeking Solutions

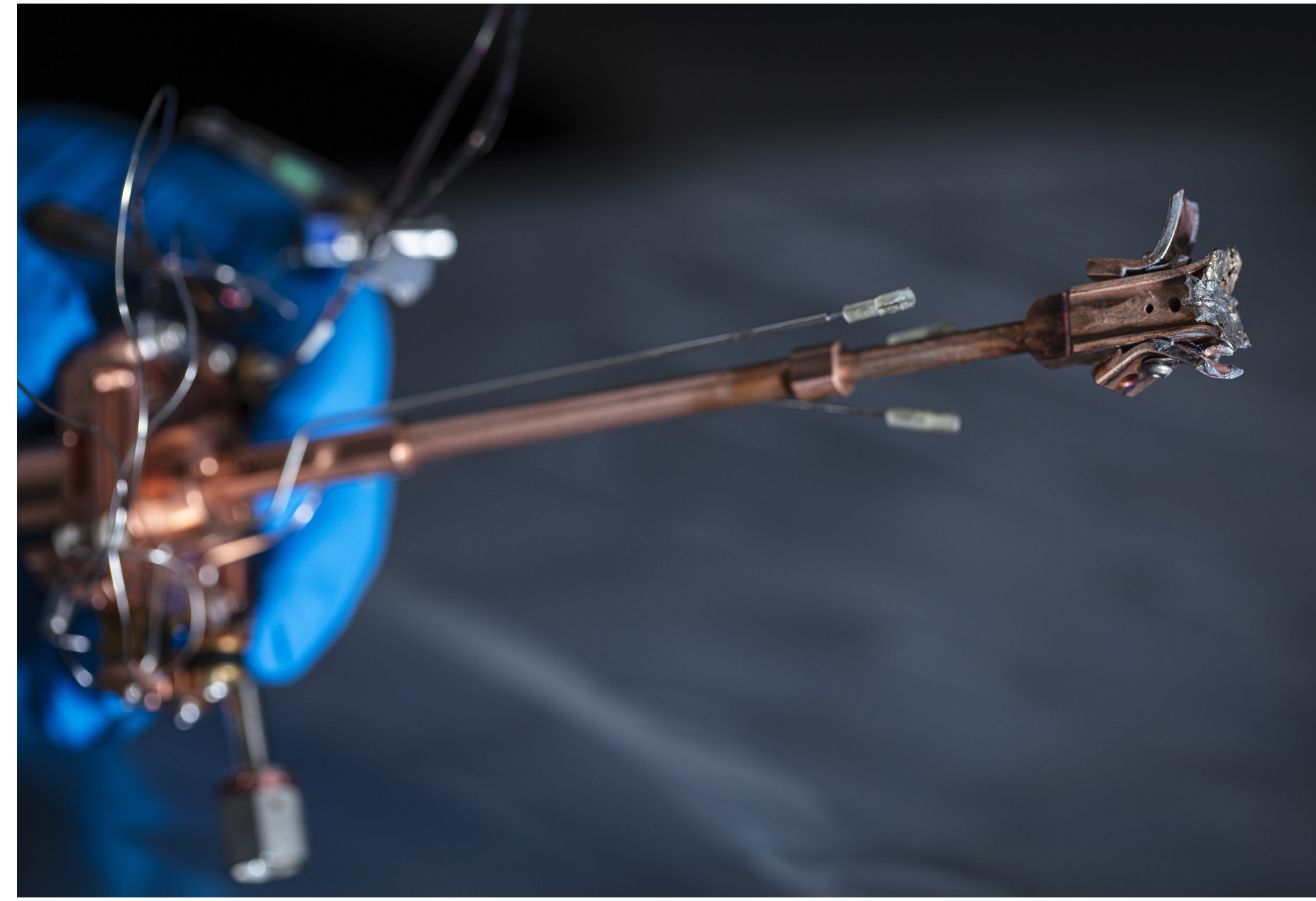
Diamond is the current material of choice for NIF capsules, called ablators, because its higher density enables it to outperform previous target materials such as plastic in terms of implosion velocity and ablation pressure. Problems arose in 2017, however, when a series of "hybrid" (high-yield big-radius implosion design) experiments called for larger capsules, which turned out to exhibit more pits and smaller, harder-to-detect voids than their predecessors.

"Implosion physics and target fabrication play hand-in-hand," said Deputy Target Fabrication Program Manager Salmaan Baxamusa. "There's an interplay between what they've learned and what we can do that helps drive forward target technology.

"We try to make (the targets) as good as we can—even measuring these defects is a challenge—and we rely on the physics team to tell us what they care about."

Fabrication of diamond capsules is a multi-step procedure that uses plasma-assisted chemical vapor deposition on silicon mandrels, followed by polishing, microfabrication of the fill-tube hole, and removing the mandrel through the micron-scale hole by a chemical leaching process. The capsules are produced in batches of 20 by a partnership involving LLNL, Diamond Materials GmbH of Freiburg, Germany, and GA.

"The demands on the capsules are very high," said Christoph Wild, managing director of Diamond Materials, who leads a 25-person team along with his partner Eckhard Wörner. "We collaborate closely with Lawrence Livermore and try to minimize defects like impurities, cavities, or uneven walls."



The target after NIF's milestone ignition shot. Credit: Jason Laurea

"Once the HDC coatings on a spherical mandrel are complete, nearly every subsequent step in the process is performed by GA staff in San Diego or at LLNL," said GA's Jared Hund. "Having a close working relationship with LLNL is critical to being responsive to the experimental needs as a unified team."

Stadermann noted that minimizing defects is a two-step process, beginning with characterizing the extent of the flaws using x-ray tomography. "We have to be able to actually see them, measure them, and quantify how many are on a shell," he said.

For the second step—improving capsule quality—LLNL and Diamond Materials are "working as a team to isolate the problem to machining, operations, or surroundings," Stadermann said. "This process has been very fruitful for narrowing down a set of conditions that has allowed us to improve the target beyond where we are today."

> "The demands on the capsules are very high."
> **Christoph Wild, Diamond Materials**

Some shells produced at LLNL have displayed fewer defects than the Diamond Materials capsules, so the team developed a "traveling shells" fabrication process to produce five batches of "hybrid" shells. LLNL's diamond-coating capability was used to create the layer in which the shells are doped with a small amount of tungsten (the tungsten absorbs x rays that could heat the fuel's cryogenic ice layer during the implosion).

The shells started at Diamond Materials with the deposition of the base layer, then were sent to Livermore for deposition of the doped layer. From here, they went back to Germany for polishing and another diamond layer, and then final polishing. Finally, they were sent to GA to assess their quality and to attach the micron-sized fill tubes, then returned to Livermore for insertion into hohlraums.

Those shells are now "working their way through the system," Stadermann said. The first hybrid capsule was used in a high-peak-power

experiment on April 16, while other hybrid capsules were used in higher-energy experiments later in the year.

"We have improved inclusions substantially with these traveling batches," he said, while noting that only some of the shells are meeting tightened specifications for wall-thickness uniformity and pit size established by the physics team.

"Thickness uniformity drives hot-spot velocity, or Mode 1," Stadermann said. "Of all the degradations, we think we understand Mode 1 the best. For pits, there is no real hard spec other than we don't want to see any. But for Mode 1, I think physics is pretty certain that it's bad and they can quantify that; that's why it's a firmer spec."

> "We have to be able to work (the problems) all at one time."
>
> **Salmaan Baxamusa**

Even as they work to minimize defects in the diamond shells, the Target Fabrication Team is studying other, non-crystalline materials as possible long-term substitutes for diamond.

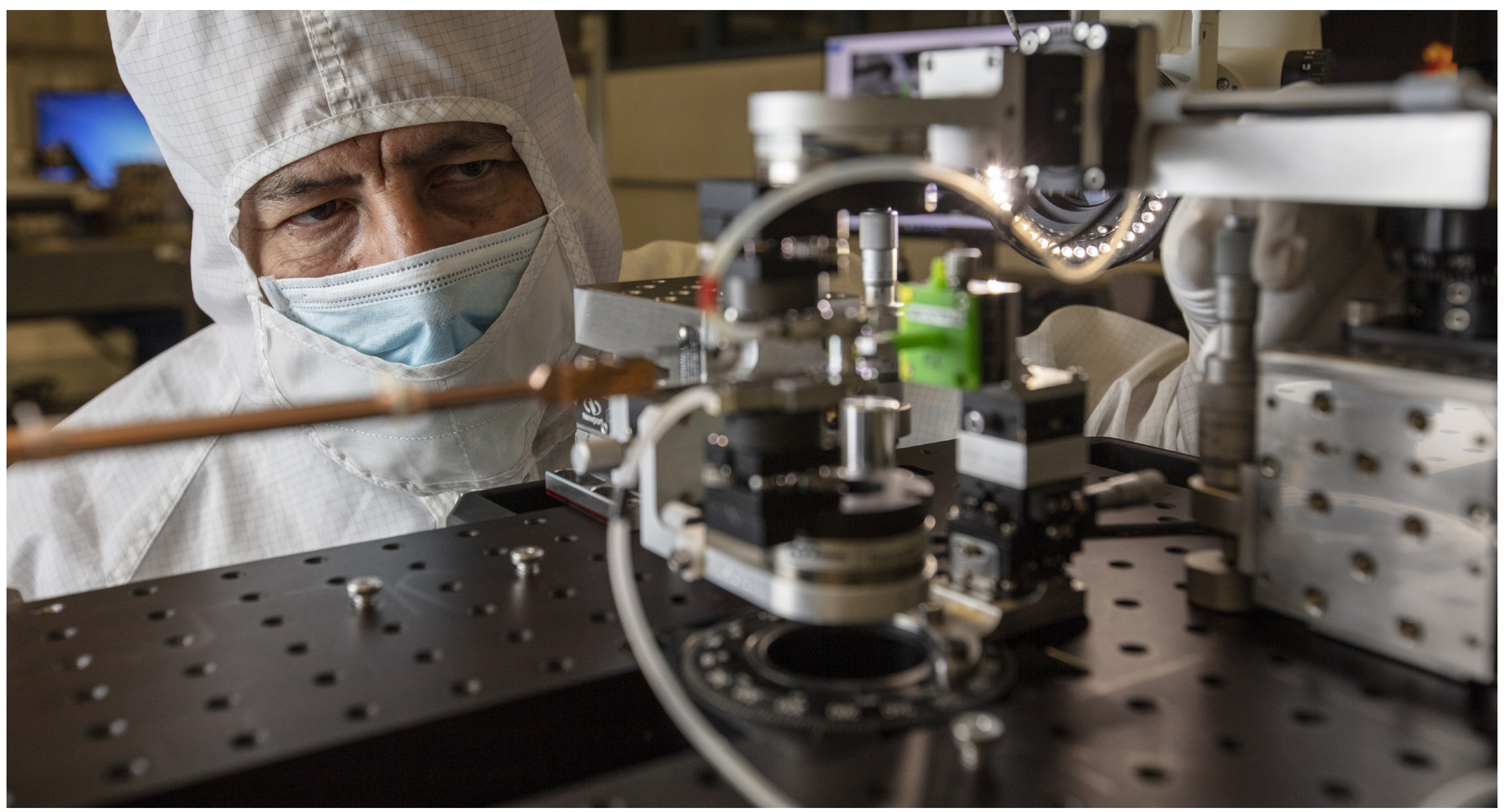
A strong initial laser pulse is needed to melt diamond's crystal structure and minimize hydrodynamic instabilities during an ICF implosion, but that pulse shape increases the fusion fuel's adiabat, or resistance to compression, making ignition more difficult.

Hoping to find alternatives that could enable a lower adiabat, researchers are looking at next-generation ablator materials with good density, such as boron carbide (B_4C) and diamond-like carbon (DLC), according to LLNL material scientist Sergei Kucheyev.

"Both of these materials form stable amorphous phases—glassy, lacking long-range crystalline order," Kucheyev said. "These materials have an attractive combination of properties for ICF, such as low atomic mass, high density, good density uniformity, excellent chemical resistance, and mechanical robustness.

"I call both B_4C and DLC 'futuristic' ablators," he said, "since we have not yet been able to demonstrate B_4C or DLC ablator shells with the desired properties despite several previous attempts both at GA and LLNL over the past decades. It's a major technical and scientific challenge that we're getting close to solving.

"We're using vapor phase plasma-assisted vacuum deposition for both B_4C and DLC," he said. "We've made good progress over the past three years in understanding the deposition process and developing recipes for the deposition of ultrathick B_4C coatings with close-to-zero residual stress and desired uniformity. Our work on DLC is more recent, but early results are promising."

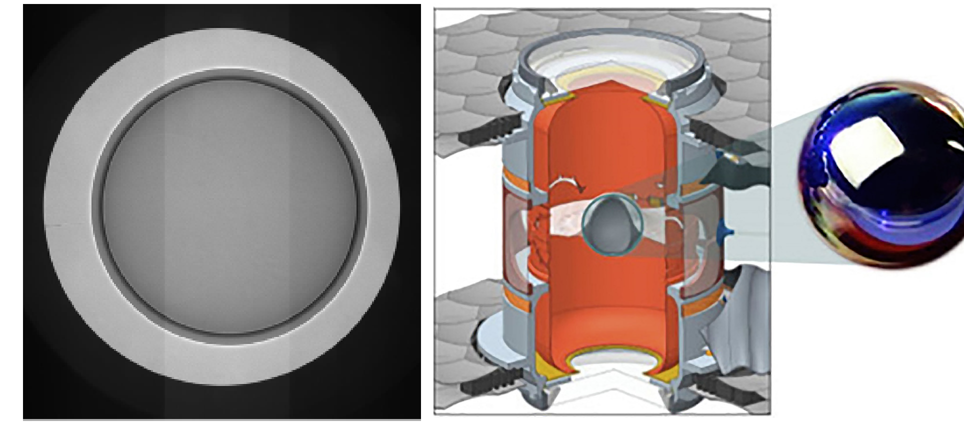


Technician Silverio Diaz assembles a target at the final cryogenic target assembly station in LLNL's Target Fabrication facility. The facility is a "class 100" cleanroom, allowing the entire NIF cryogenic target assembly process to take place in a clean environment. Credit: Jason Laurea

"We work on today's problems so we can deliver a target," Baxamusa said. "We work on tomorrow's problems so that we can improve the current technology, and then we work on next year's problems, because all those are going to be important. We have to be able to work them all at one time."

"With improved targets and with (planned) NIF upgrades," Nikroo added, "we have confidence that we can get into the 10s of megajoules range (of fusion energy) and make significant contributions to both stockpile stewardship and inertial fusion energy (IFE)."

—*Charlie Osolin*



Left: X-ray transmission image of a "hybrid" capsule in a finished target for an upcoming ICF experiment. Right: Illustration of a diamond capsule suspended in a hohlraum.

Among the many members of the LLNL/General Atomics Target Fabrication Team who help develop NIF's precision targets: (from left) Jared Hund from General Atomics and LLNL's Salmaan Baxamusa, Suhas Bhandarkar, and Sergei Kucheyev. Credit: Jason Laurea

The Age of Ignition
High Performance Computing, AI, and Cognitive Simulation Provided 'Crystal Ball'

Credit: Tanya Quijalvo

HIGH PERFORMANCE COMPUTING, AI, AND COGNITIVE SIMULATION PROVIDED 'CRYSTAL BALL'

For hundreds of LLNL scientists on the design, experimental, and modeling and simulation teams behind ICF experiments at NIF, the results of the now-famous ignition shot didn't come as a complete surprise.

The "crystal ball" that gave them increased pre-shot confidence in a breakthrough involved a combination of detailed high-performance computing (HPC) design and a suite of methods combining physics-based simulation with machine learning. LLNL calls this "cognitive simulation," or CogSim.

The detailed HPC design uses the world's largest supercomputers and its most complicated simulation tools to help subject-matter experts choose new directions to improve experiments. CogSim then employs artificial intelligence (AI) to couple hundreds of thousands of HPC simulations to the set of past ICF experiments.

These CogSim tools are providing scientists with new views into the physics of ICF implosions and a more accurate predictive capability when considering parameters such as laser energy and target design specifications.

“It’s almost like looking into the future based on what we’ve seen in the past about what might happen,” said Brian Spears, LLNL’s deputy modeling lead for ICF. “Our traditional design tools and experts say, ‘These are the knobs that you should adjust,’ and then the new CogSim tools say, ‘Given those adjustments and patterns from prior experiments, that looks like it’s going to be really successful.’ ”

Because of the cost and complexity of ICF experiments at NIF, LLNL researchers rely heavily on HPC modeling and simulation to design new high-performing and symmetrical implosions and predict results in advance. Developed at LLNL over the past several years, CogSim methods such as deep neural networks and “transfer learning”—which conveys knowledge gained from solving one problem to a different, related problem—can learn from multiple fusion experiments at NIF, improving in accuracy as more data is acquired. And the methods are spreading across the Lab’s core mission areas.

“The CogSim tools are adding to our programmatic toolbox, giving us new methods to measure our uncertainties and helping us combine experiments and simulation in new ways,” said physicist Richard Town, who leads the ICF science program.

Swinging for the Fences

CogSim has grown into an important tool for the ICF program, providing detailed post-shot analyses of NIF experiments and helping to quantify sources of degradation that the DT target experiences during a shot, such as implosion asymmetries and the unwanted mixing of materials caused by tiny defects on the capsule’s surface, according to Kelli Humbird, NIF design physicist and CogSim researcher.

“Our team has been pioneering the use of AI and CogSim in ICF and high energy density research for several years,” Humbird explained.

Applying CogSim techniques to ICF research on HPC machines including LLNL’s flagship Sierra and its unclassified companion Lassen, the Lab’s Jade, Magma, Corona, and Pascal systems, and Trinity at Los Alamos National Laboratory, has resulted in faster, better-performing models that can predict outcomes with higher confidence than simulations alone, researchers said.

While Spears cautioned this predictive capability “doesn’t mean that you hit a grand slam every time and these techniques still have much to prove,” it does give researchers a good idea of whether the next ICF experiment will be a home run or a strikeout.

“After the traditional design work and subject matter experts tell the team what changes to make, we can expose that new design to expected real-world variations to ask, ‘Is this going to stand up to the conditions of NIF?’ ” Spears said. “The new thing that CogSim methods bring is a more quantitative understanding of which physics degradations are at play and the way they’re correlated. It essentially says, ‘Look, I’ll tell you the probability of whatever physics quantity you want to know.’ ”

After LLNL’s promising record-breaking shot in August 2021, which yielded 1.35 MJ of fusion energy and put LLNL on the threshold of ignition, the CogSim team “did something a little different,” Humbird said. Based on data from a series of “repeat” experiments with the same target design, the team discovered ways to quantify how a given target design’s performance could vary from shot-to-shot—a difficult prospect using only traditional design work because targets and laser energy delivery differ with each shot.

By leveraging large ensembles of the hydrodynamics simulation code HYDRA and statistical inference methods, the team modeled degradations the target could be exposed to during the experiment and how they might affect the energy yield.

In September 2022, LLNL teams began a new ICF campaign with an upgraded capability—bumping the laser’s energy up from 1.9 megajoules to 2.05 MJ. LLNL’s design teams, led by Annie Kritcher, modeling lead for integrated experiments, devised ways to improve on the early results and effectively use the additional laser energy. Simulations run using HYDRA showed Kritcher that making the surface of the target capsule—called the “ablator”—thicker would create a more favorable “hot spot” in the implosion and reduce contamination from outside the target.

The integrated design team passed along its target specifications to the CogSim team, which ran a suite of tools—Bayesian inference, neural networks, and transfer learning. By integrating the modified design, higher laser energy, and adjustments to implosion symmetry with a wealth of knowledge from past NIF experiments, and applying the degradation distribution that it learned from previous shots, the team predicted how the new design would react to the conditions.

Based on the higher-energy laser shots and the integrated HPC-based design adjustments, LLNL scientists were “already ramping up for something to happen” when the CogSim team completed its analysis in late November, Spears said.

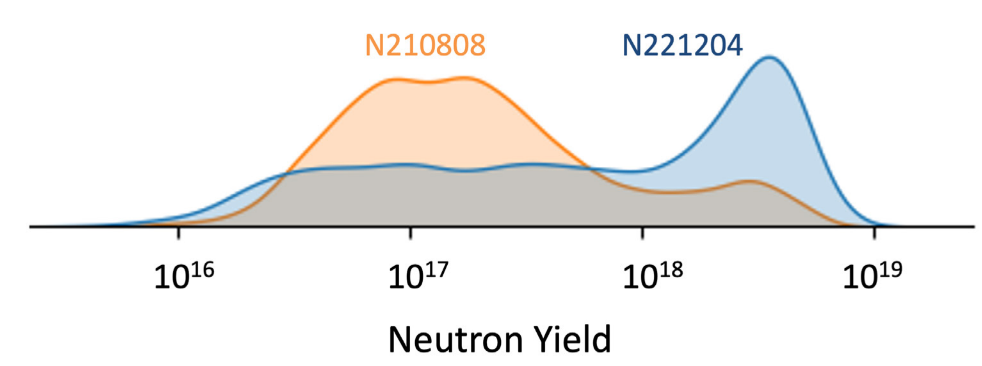
The models showed the probability for exceeding “break-even” (as much or more energy out than laser energy in) was essentially a coin flip—just a shade over 50 percent—with a projected yield of two to three times more than the record 2021 shot. The team produced graphs of the distribution probabilities and presented them to Lab senior leadership a few days before the experiment.

“We got an answer that said, ‘OK, this design shrugs off lots of things that looked damaging to previous designs, so it’s far more robust,’ ” Spears said. “When we asked the model the important question—‘How likely is it that we’ll get more energy out than the laser put in?’—for the first time ever, the answer was more likely than not. When we saw that, it felt very significant. This was the first time that the models, the experiments, the expert design sensibility, and our CogSim techniques were all saying this was going to be a big deal. It just felt like a green light popped on the dashboard.”

The predictions were “exciting and a little nerve-wracking,” Humbird said.

“This was the first time we’d had such a credible—as in, a highly data-informed, with uncertainties that were well quantified—(ignition) prediction ahead of time,” Humbird said. “We really hoped we would be correct.”

Expectations ran high for the shot, which took place a little after 1 a.m. on Dec. 5. More



This graph shows the CogSim model’s predicted probability distributions for neutron yield for experiments on Aug. 8, 2021 (labeled N210808 in orange), and Dec. 5, 2022 (labeled N221204 in blue). The N221204 design had a significantly higher chance, at 50.2 percent, of achieving ignition when compared to the previous record experiment, N210808, at 17.3 percent. Credit: Kelli Humbird.

than 1,000 scientists in total eagerly waited for the preliminary yield numbers to roll in. Spears awoke early and was checking emails by 6 a.m. He spotted a message from lead experimentalist Arthur Pak, who had been reviewing initial counts of neutrons produced by the experiment.

“We had a CogSim prediction sitting there with a probability distribution over the yields, and the number popped up,” Spears recalled. “In a flash, I could see that it was in the right-hand tail of that 50-percent probability region. I was more or less paralyzed for a few seconds—I had to look at the exponent and the number to figure out if it actually said what it looked like it said—that it was really what our whole design team predicted and hoped for, and to make sure we weren’t making a mistake or that it was an order of magnitude lower than what it was. Then I was going to pop the champagne.”

Thrilled but cautious, Spears and Humbird began exchanging texts and plotted the initial data onto their laptops.

“It takes you a minute to do the quick mental math to convert (the neutron count) to the approximate energy in megajoules,” Humbird said. “Once I did that, I thought, ‘Oh man, this one might be break-even.’ The data is preliminary though, so you don’t want to get too excited right away, but the measurements were falling right within our expectations.”

For members of the CogSim ICF team—which also includes researchers Luc Peterson, Jim Gaffney, Rushil Anirudh, Ryan Nora, Eugene Kur, Peer-Timo Bremer, Brian Van Essen, Michael Kruse, and Bogdan Kustoswki—ignition is just the beginning.

“The tools are really starting to reach a level of maturity that’s making them practical for use on the timescale consistent with the NIF shot rate,” Humbird said. “With the upcoming arrival of (the exascale supercomputer) El Capitan and the corresponding increase in compute power, we see these tools playing a pivotal role in ICF design exploration and optimization. And of course, one good prediction doesn’t validate a model. We’re hoping to do this again for the next several experiments and really put our tools to the test.”

An Expanding Role

For LLNL, ignition is a testament to decades of tireless work by hundreds of scientists, engineers, designers, and modeling/simulation teams in laser-driven fusion. For Spears, it also represents a culmination of his 18 years in data science for ICF and the CogSim approaches he and LLNL Deputy Associate Director for Computing Jim Brase have co-developed over the past six years. And ignition lends credence to the use of CogSim in other Lab efforts including stockpile stewardship, “self-driving” lasers, and predictive biology.

The Cognitive Simulation Institutional Initiative, led by Spears, is funded through the Laboratory Directed Research and Development (LDRD) program. The initiative is part of a broader effort by DOE and NNSA to incorporate emerging AI and machine-learning techniques into mission-relevant projects, with a goal of advancing AI technologies and computational platforms to improve scientific predictions.

The same predictive CogSim capabilities used to drive NIF are being applied by Spears, Timo Bremer in the Center for Applied Scientific Computing, and Tammy Ma, lead for LLNL’s Inertial Fusion Energy (IFE) Institutional Initiative, to invent new methods for “self-driving” laser operations.

Ignition is still just a first step toward a fusion energy future that scientists hope will become much cheaper, easier, and more efficient over the coming decades. To develop feasible fusion power plants, scientists will need to accomplish ignition many times per second, making a high repetition rate critical, according to scientists.

Using CogSim tools, researchers could perform fusion experiments, compare them to simulations from real-time data and decide autonomously and on-the-fly how the next experiment should run while performing the necessary adjustments in a matter of milliseconds—far faster than any human could, Spears said.

CogSim is also being used for molecular design across many Lab core mission areas, including biodefense, public health, advanced materials, and manufacturing.

According to Brase, the tools are improving simulations of cancer-causing protein interactions in pilot projects with the National Cancer Institute (NCI) and for the Accelerating Therapeutic Opportunities in Medicine consortium—with NCI’s Frederick National Laboratory for Cancer Research and the University of California, San Francisco—leading to better efficacy and safety predictions for new molecules and targets for drug development.

And LLNL's Program Lead for Predictive Design of Biologics Dan Faissol and his team are finding success in optimizing designs for antibody therapies for the evolving SARS-CoV-2 virus and its many variants.

Brase began coupling machine learning with simulations a decade ago, beginning with cybersecurity applications. He connected with Spears to bring the ideas to ICF research and expanded CogSim to biology through the Biological Applications of Advanced Strategic Computing (BAASiC) initiative. Brase said CogSim has improved science across the Lab by providing faster, bigger, and more efficient models, enhancing predictive power and "steering" simulations to accomplish desired objectives.

In the case of molecular drug design, CogSim is deployed in a multiscale approach, where machine-learning models select areas of interest in macroscale simulations of protein-lipid interactions for further inquiry at a more detailed atomistic level. The approach allows researchers to lengthen the simulated time duration of the interactions by a factor of a million—from nanoseconds to milliseconds—to better examine biological interactions.

Additionally, CogSim can improve a model's predictive power when experimental data is limited, Brase said. In drug design, CogSim tools can learn from the protein binding of similar molecules to predict binding of novel molecules using only a few experimental measurements. AI models also can direct the overall design process by proposing variations on the molecular structures for the next optimization round.

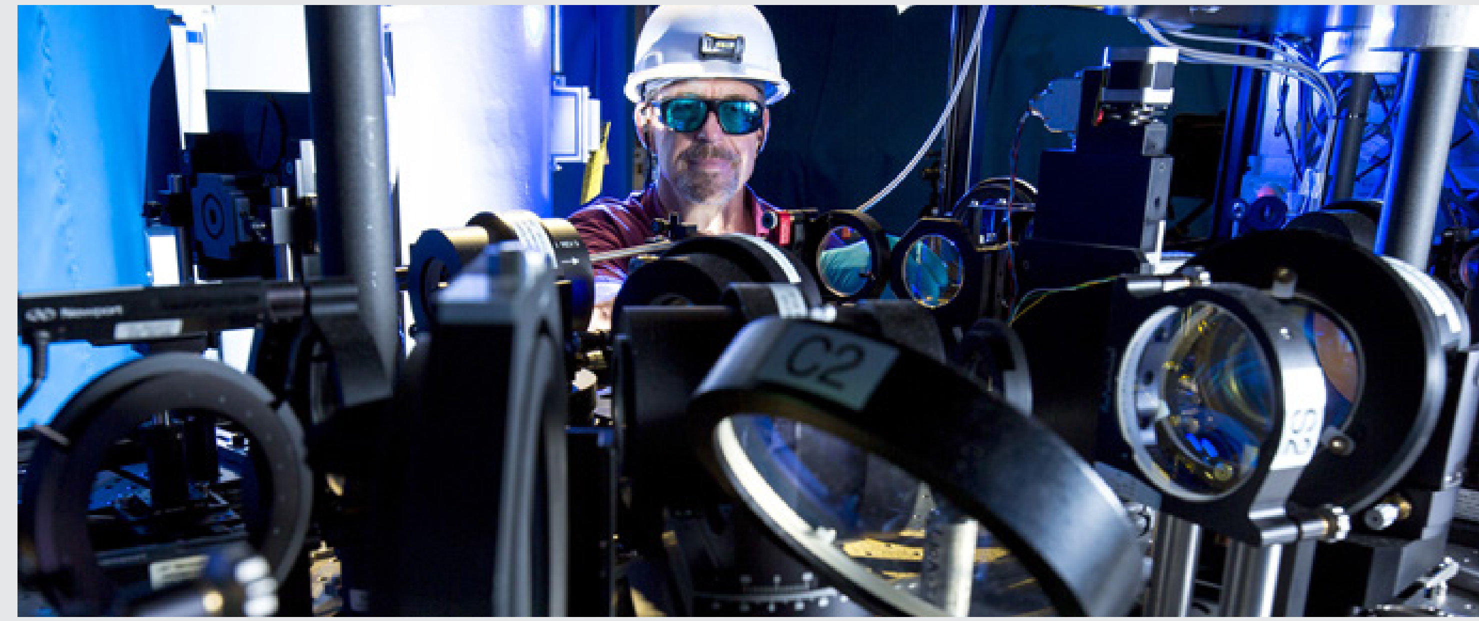
"Not only can we use CogSim to steer simulations, but we can also use it to determine the best experiments to do to reach a design or modeling goal," Brase said. "Essentially, we use the CogSim model to design the next experiment, then bring that data back into the models to improve their performance and then repeat the cycle. This 'active learning' loop will enable integrated computing and lab automation to make the whole process of building models and designing complex systems for biology or energy 'self-driving.' This is an exciting frontier and an area we're focusing on for the future."

As CogSim matures and LLNL scientists look to incorporate AI for science methods even more in the coming years, Spears envisions an acceleration in scientific discovery never imagined before.

"It's great what we just did (with ignition), but the way that this Laboratory operates is that we're looking 10 years into the future, and we can already see what the next 10 years is," Spears said. "It's doing this thing (ignition) that we did once but doing it faster and in a self-driving way that is so quick that discovery happens. It feeds scientists and engineers with the things that they need to know, without them having to labor over setting up the diagnostics. These kinds of things become automated in a way that frees us up to think faster and dream bigger."

—Jeremy Thomas

PHYSICAL AND LIFE SCIENCES INNOVATIONS THAT ENABLED LLNL'S FUSION IGNITION BREAKTHROUGH



Responsible system engineer Gene Frieders inspects the VISAR (Velocity Interferometer System for Any Reflector), an ultrafast optical diagnostic that uses a pulsed laser and interferometry to measure shock waves. One of NIF's most versatile and frequently used diagnostics, VISAR provides vital information for future experiment design and calibration. Credit: Jason Laurea

While the experiment that achieved LLNL's historic ignition breakthrough took only a fraction of a second, it was the result of work performed over several decades by numerous LLNL staff, including dozens of scientists from the Physical and Life Sciences (PLS) Directorate.

PLS staff played key roles in enabling this first-ever demonstration of fusion ignition. Building on more than 60 years of foundational research in physics, laser science, materials science, and nuclear science at LLNL, they developed innovative solutions in areas such as target design and fabrication, optics, experimental design, and diagnostics.

For example, a team of PLS experts spent the last two decades focusing on refining the design of NIF targets. The targets are composed of more than 100 specialized components, including the tiny, fuel-filled capsules at their core, which each measure only 2 millimeters in diameter. The group's recent accomplishments include analyzing and refining design of:

- Hollow capsules specifically for fusion experiments. The team continually revamps capsule design in response to experimental results, identifying ways to mitigate imperfections that can cause implosion instabilities.
- The complex micro-assembly process used to fabricate targets, which focuses on creating capsules that can achieve precision performance under cryogenic conditions, as well as continually reducing the time needed to produce the targets.
- Materials that are strong enough to suspend the capsule inside a slim tube, yet cause minimal experimental interference.
- Glass tubes used to inject hydrogen fuel into target capsules through a tiny hole drilled into the capsule's shell. Reducing the size of fill tubes to just 2 microns in diameter, much smaller than a human hair, minimizes damage to the capsule.
- The cryogenic hydrogen fuel used in LLNL's fusion experiments, including efforts to tune the fuel's chemistry so that it forms a smooth, uniform layer on the capsule's inside surface and remains frozen at the density required for ignition.

PLS employees also made noteworthy contributions by developing computational models of matter under extreme conditions and sophisticated diagnostics that enable scientists to analyze experimental data, refine the models, and improve experimental design. For example, they developed:

- Opacity and equation-of-state models capable of simulating ultra-fast processes that occur during an ignition experiment, such as conversion of laser light to x rays and the compression of capsule walls, which ultimately causes the fuel to ignite.
- An optical diagnostic known as VISAR, which is used to measure velocities and tune the timing of shocks produced by NIF lasers that compress capsules to a very high density.
- X-ray diagnostics that measure how capsules respond to pressure, including whether capsules can maintain their shape under extreme pressure.
- X-ray spectroscopy techniques used to measure the amount of ablator material that mixes with the fuel—which can make it more difficult to compress the capsule.
- Narrowband radiography that uses a crystal backlighter imager coupled to a special camera, enabling scientists to capture a backlit radiograph of the target as it implodes.

For more than a decade, experts at LLNL's Nuclear Counting Facility (NCF) have used neutron-yield diagnostics to assess NIF shots. Following each fusion experiment, NCF staff analyze coupons retrieved from NIF's Target Chamber, using gamma spectrometry to quantify the number of neutrons emitted by the target. This reliable benchmark diagnostic was deployed the day after the Dec. 5, 2022, ignition experiment, with NIF leaders waiting only an hour after handing off the coupons to NCF to obtain an initial assessment of the shot's yield.

In addition, PLS materials scientists and engineers helped develop a strategy to ensure that LLNL has ongoing access to high-quality optics, capable of withstanding the increasing laser energy used in fusion experiments—including delivering 2.05 megajoules of energy to the target in the ignition experiment. Even the tiniest flaws, defects, and contaminants can absorb the laser light and initiate damage that can degrade the optic's performance.

This multidisciplinary team developed:

- An optics recycling process in which experts inspect, clean, and repair damage to lenses and debris shields, avoiding the more expensive and time-consuming process of fabricating and installing new optics. Over the last 12 years, they have recycled more than 10,000 optics.
- Fused silica debris shields that reduce damage to optics during NIF experiments. A relatively new technique uses cone-shaped surface features to produce shadows that inhibit the growth of damage on the optic's exit surface.

We are fortunate to have such a talented, dedicated team of experts in the PLS Directorate who have explored fusion ignition from a variety of angles and contributed to the fusion breakthrough.

—Glenn Fox

HOW NIF WORKS

What happens when 192 of the world's highest-energy lasers converge on a target the size of a peppercorn filled with hydrogen atoms? Answer: the same thing that happens inside the Sun and the stars: fusion! NIF's laser beams can create nuclear fusion in the laboratory by generating the same temperatures and pressures that exist in the cores of stars and giant planets and inside nuclear weapons.

We use NIF's lasers for several specific missions: Stockpile Stewardship, high energy density science, Discovery Science, energy security, and building future generations of scientists. And we're researching more types of applications, including advanced lasers and photonics, additive manufacturing, and missile defense.

At the outset of a NIF experiment, a weak laser pulse—about 1 billionth of a joule—is created, split, and carried on optical fibers to 48 preamplifiers that increase the pulse's energy by a factor of 10 billion, to a few joules. The 48 beams are then split into four beams each for injection into the 192 main laser amplifier beamlines.

Guided by laser mirrors, each beam zooms through two large glass amplifiers, first through the power amplifier and then into the main amplifier. In the main amplifier, a special optical switch called a plasma electrode Pockels cell (PEPC) traps the light, forcing it to travel back and forth four times, while special deformable mirrors, spatial filters, and other devices ensure the beams are high quality, uniform, and smooth.

From the main amplifier, the beam makes a final pass through the power amplifier. By now, the beams' total energy has grown from 1 billionth of a joule to 4 million joules—all in a few millionths of a second.

The 192 beams proceed to two 10-story switchyards on either side of the Target Chamber and split into quads of 2×2 arrays by a series of transport mirrors. Just before entering the Target Chamber, each quad passes through a final optics assembly, which converts the laser pulses from 4 million joules of infrared to more than 2 million joules of ultraviolet energy and focuses them onto the target. NIF's 192 laser beams travel about 1,500 meters from their birth to their destination at the center of the spherical Target Chamber. Yet the journey from start to finish takes only about 5 microseconds.

How NIF's Lasers Work

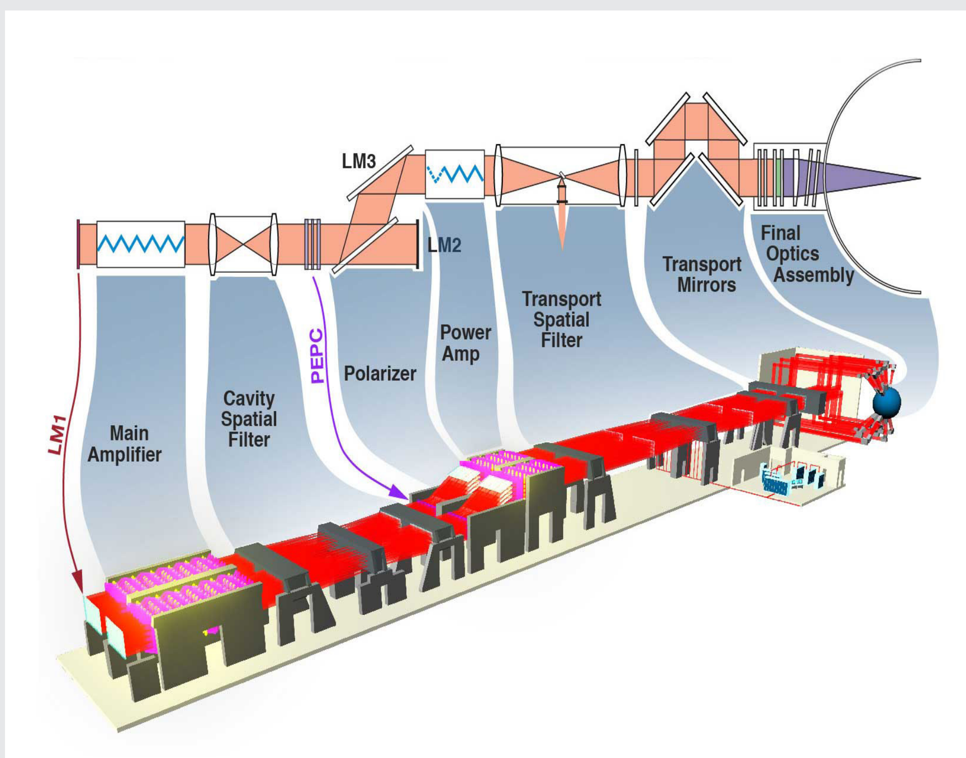
In a sense, NIF, the world's largest and highest-energy laser system, is one big laser amplifier. As with most large lasers, NIF uses intense flashes of white light from giant flashlamps to "pump" electrons in big slabs of laser glass to a higher-energy state that lasts only about one-millionth of a second.

A small pulse of laser light "tuned" to the excited electrons' energy is directed through the glass slabs. This laser pulse stimulates the electrons to drop to their lower, or ground, energy states and emit laser photons of exactly the same wavelength.

This process produces huge numbers of photons of the same wavelength and direction—an extremely bright and straight beam of light. The initial low-energy pulse is amplified by more than a quadrillion times to create 192 highly energetic, tightly focused laser beams that converge in the center of the Target Chamber.

How NIF Targets Work

In a NIF ignition experiment, a tiny capsule containing two forms of hydrogen, deuterium (D) and tritium (T), is suspended inside a cylindrical x-ray "oven" called a hohlraum. When the hohlraum is heated by NIF's powerful lasers to temperatures of more than 3 million degrees Celsius, the resulting x rays



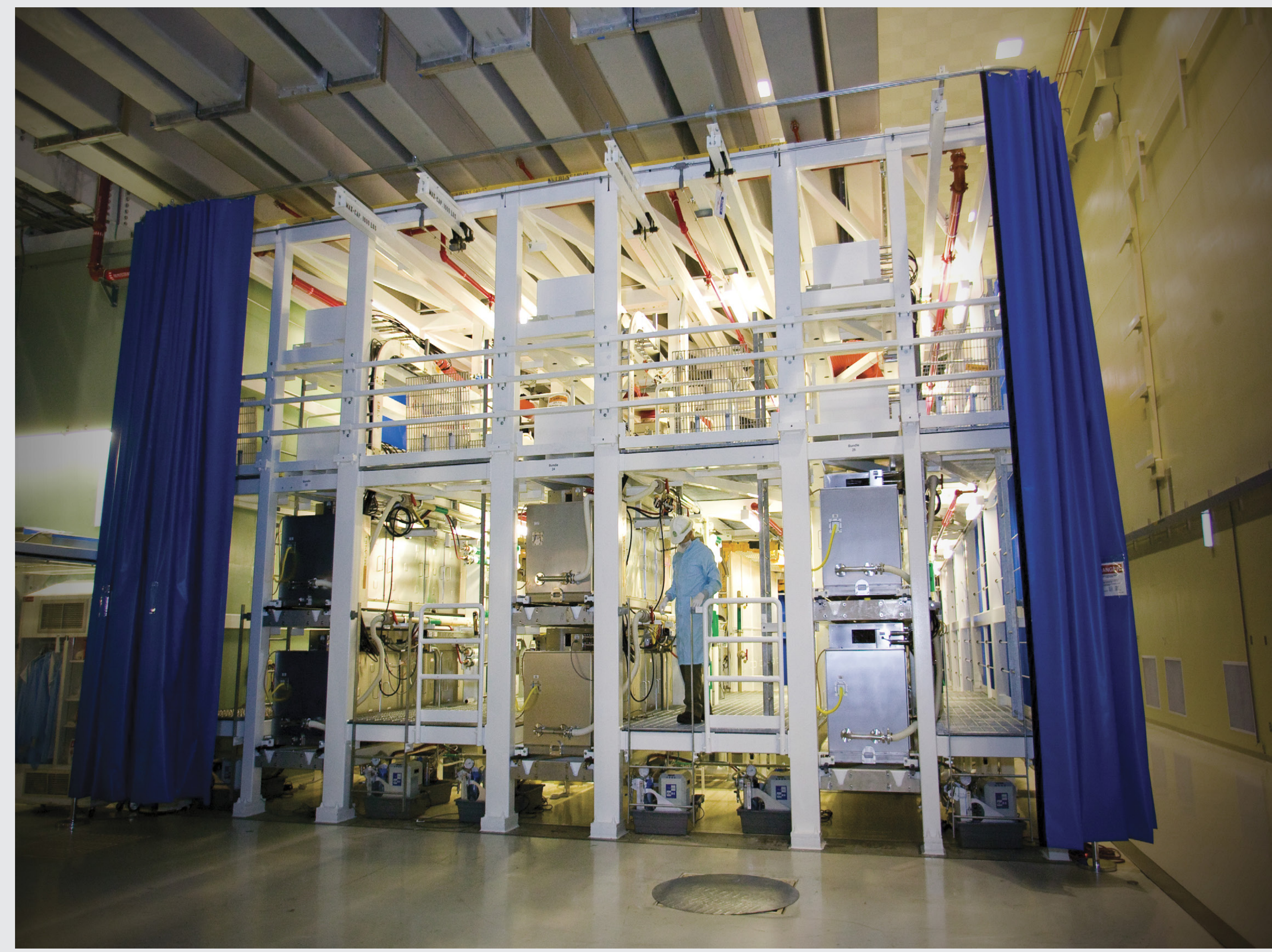
heat and blow off, or ablate, the surface of the target capsule, called the ablator. This causes a rocket-like implosion that compresses and heats the DT fuel to extreme temperatures and densities until the hydrogen atoms fuse, creating helium nuclei (alpha particles) and releasing high-energy neutrons and other forms of energy.

If the implosion is symmetrical and compression and temperature in the "hot spot" at the center of the capsule are sufficient, the resulting alpha particles spread through and heat the surrounding cold fuel, triggering a self-sustaining fusion reaction. This process can generate energy equaling or exceeding the energy delivered to the target, a condition known as ignition.

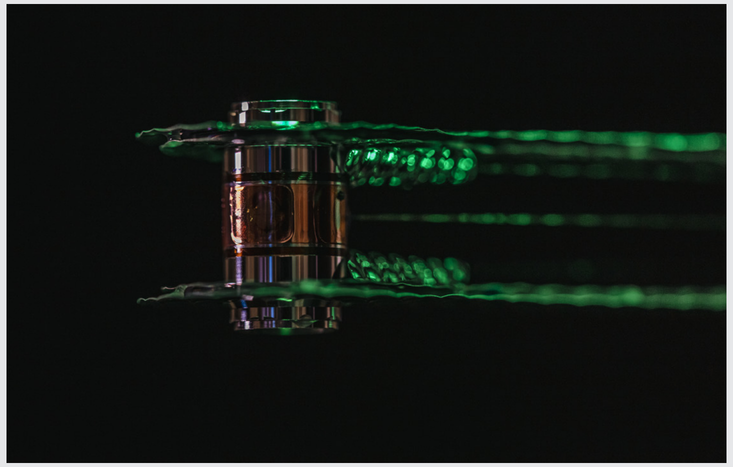
The Seven Wonders of NIF

LLNL's achievement of ignition would not have been possible without the dedication of the scientists, engineers, and technicians who overcame 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 energies. The team also worked with vendors to develop pulsed-power electronics, innovative control systems, and advanced manufacturing capabilities.



NIF's preamplifier modules are unique and complex lasers in themselves. They take the nanojoule-level laser light from the master oscillator, amplify it more than a billion times, and set its spatial profile before injecting it into the main laser beampath.



NIF targets are precisely controlled in a cryogenic cooling system that keeps the deuterium-tritium fuel frozen inside a millimeter-sized capsule.

Laser Glass

Laser glass is the heart of the NIF laser system; it's the material that amplifies the laser light to the very high energies required for experiments.

NIF's laser glass is a phosphate glass that contains neodymium atoms (Nd:glass). Neodymium-doped laser glass is the preferred gain medium for use in high-peak-power lasers for fusion energy research.

The NIF laser system uses about 3,070 42-kilogram plates of laser glass. Each glass plate measures 3.4 by 46 by 81 centimeters (about 3 feet long and about half as wide). If stacked end-to-end, the plates would form a continuous ribbon of glass 1.5 miles long. The glass slabs are set on edge at a specific angle, known as Brewster's angle, so that the laser beams have very low reflective losses while propagating through the glass.

To produce this glass quickly enough to meet construction schedules, Hoya Corporation, USA, and SCHOTT North America developed a new production process that melts raw materials into one continuously flowing strip of high optical-quality laser glass. Once cooled, the glass is cut into pieces as it leaves the production system; the segments are then polished to the demanding NIF specifications. This novel, continuous melting process makes meter-sized plates of laser glass at a rate 20 times faster, 5 times cheaper, and with 2 to 3 times better optical quality than with previous processes.

Each NIF beamline contains two large amplifier sections designed to efficiently amplify the 1-joule input pulse from the injection laser system to each of the 192 beams to the required power and energy while maintaining high beam quality. The amplifiers, with 16 glass slabs per beam, are arranged in two amplifier sections—the main amplifier and the power amplifier. Together, these amplifiers provide 99.99 percent of NIF's energy and power.

The amplifier slabs are surrounded by vertical arrays of flashlamps. Measuring nearly 180 centimeters (6 feet) of arc length, NIF's 7,680 flashlamps are the largest commercial units ever made. Each is driven with about 50,000 joules of electrical energy. The flashlamps excite the neodymium in the glass slabs to provide optical gain at the infrared frequency of 1,053-nanometer wavelength, also referred to as 1ω, or "one omega," light. Some of the energy stored in the neodymium is released when the laser pulses from the injection laser system pass through the amplifier slabs.

Optical Switch

A key component in the laser chain, an optical switch called a plasma electrode Pockels cell (PEPC), was invented and developed at LLNL. A Pockels cell rotates the polarization of a laser beam when a voltage is applied across an electro-optic crystal. Depending on the voltage applied, the Pockels cell either allows light to pass through or to reflect off a polarizer, creating an optical switch.

For each of NIF's 192 beamlines, a PEPC allows the laser pulse to make four passes through the main amplifier, building up its energy with each pass. Without this multi-pass configuration, NIF's beamlines would have to be much longer than they are.

Preamplifier Modules

NIF's master oscillator generates a very small, low-energy laser pulse. The pulse may range from less than 100 trillionths to 25 billionths of a second long and has a specific temporal shape as requested by NIF experimenters. The low-energy pulse is split and carried on optical

The fabrication of melted and rough-cut blanks of laser glass amplifier slabs needed for NIF's construction (3,072 pieces) was completed in 2005. The amplifier slabs are neodymium-doped phosphate glass manufactured by Hoya Corp. USA and SCHOTT North America.

fibers to 48 preamplifier modules (PAMs) for initial amplification and beam conditioning and shaping. The PAMs increase the energy by a factor of 10 billion to about 10 joules.

PAMs perform three kinds of precision beam shaping:

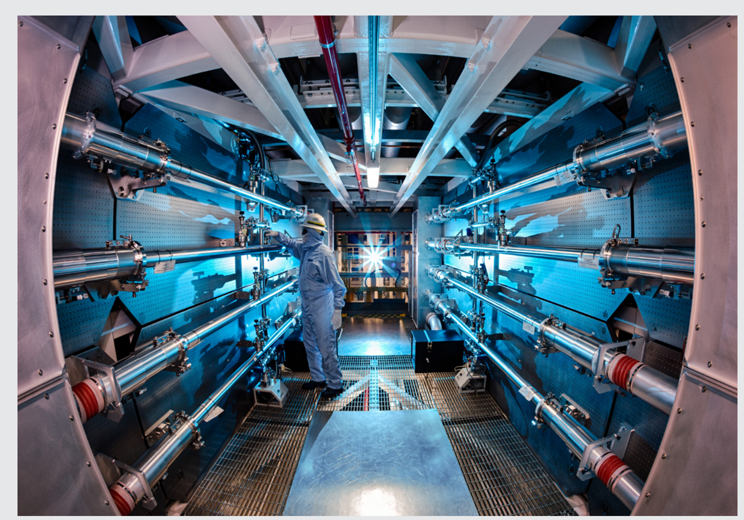
- Spatial shaping to make the square beam more intense around the edges to compensate for the higher gain profile in the center of the large amplifiers.
- Spectral shaping and beam smoothing to eliminate both hot spots and dark spots at the focus by manipulating the focal beam pattern with fast changes in wavelengths.
- Temporal shaping to ensure that the laser pulse delivers energy to the target at precisely prescribed times to control compression and ignition.

Deformable Mirror

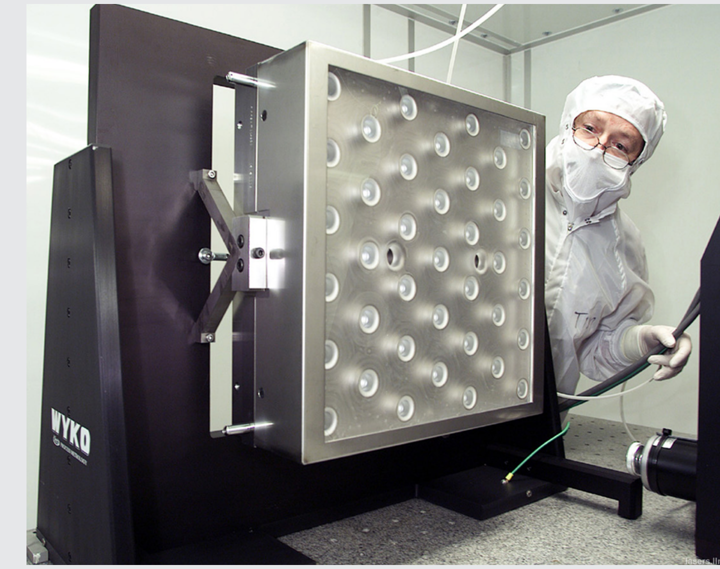
In planning NIF, engineers knew that as the beams made four passes through the amplifiers they would accumulate wavefront aberrations due to distortions in the amplifier glass and other optics. They needed to develop a way to compensate for these distortions to produce a well-controlled, focused beam.

The answer lay in the deformable mirror, an adaptive optic that uses an array of actuators to bend its surface to compensate for those wavefront errors. There is one deformable mirror for each of NIF's 192 beams. Each mirror is located at the end of the main amplifier.

The computer-controlled mirrors serve as the eyeglasses of NIF. Thirty-nine actuators are attached to the back of the mirror. These mirrors push or pull the optical surface to correct optical distortion in the beam from residual thermal distortion, imperfect optical materials and surface flatness, and amplifier distortion due to flashlamp heating.



Color-enhanced image of the inside of a NIF preamplifier support structure. Credit: Damien Jemison



Deformable mirrors, located at the ends of the NIF main amplifiers, use an array of 39 actuators to create a movable surface that corrects aberrations in a beam due to minute distortions in the optics.

By correcting each beam, a smaller spot size can be achieved, producing higher power density or better-controlled focal spots at the target. Deformable mirrors help beams reach the required spot size of about 100 microns or smaller. That's about the diameter of an average human hair.

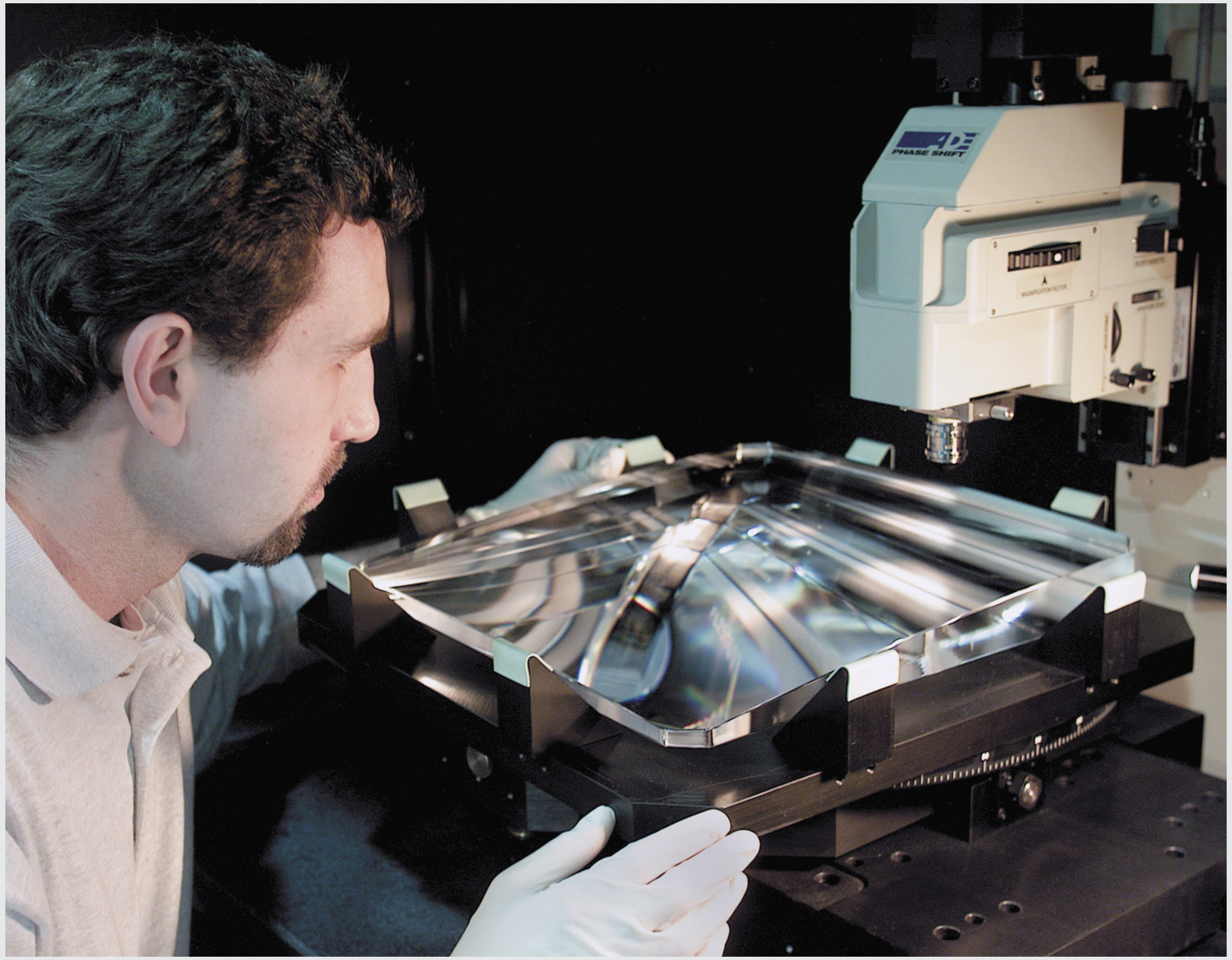
Rapid-Growth Crystals

NIF requires some 480 optics produced from large single crystals of potassium dihydrogen phosphate (KDP) and deuterated KDP (DKDP). These crystals have special optical properties, like prisms, that transmit, refract, and break light up into its colors like those in a rainbow.

The crystals serve two functions: polarization rotation and frequency conversion. KDP crystals are used in the plasma electrode Pockels cells. Inside NIF's final optics assemblies, KDP and DKDP crystals convert the beams' infrared (1ω) light into 3ω (ultraviolet) light. The interaction of the beams with the fusion target is much more favorable if the beams are ultraviolet.

The development of the technology to quickly grow high-quality crystals was a major undertaking and is one of the most highly publicized technological successes of the NIF construction project. The rapid-growth process, first pioneered in Russia, was perfected at Livermore to keep up with NIF's aggressive construction schedule.

With this method crystals that would have taken up to two years to grow by traditional techniques take only two months. In addition, the size of the rapid-growth crystals—up to 800 pounds—is large enough that more plates can be cut from each crystal, so a smaller number of crystals can provide NIF with the same amount of optics. About 75



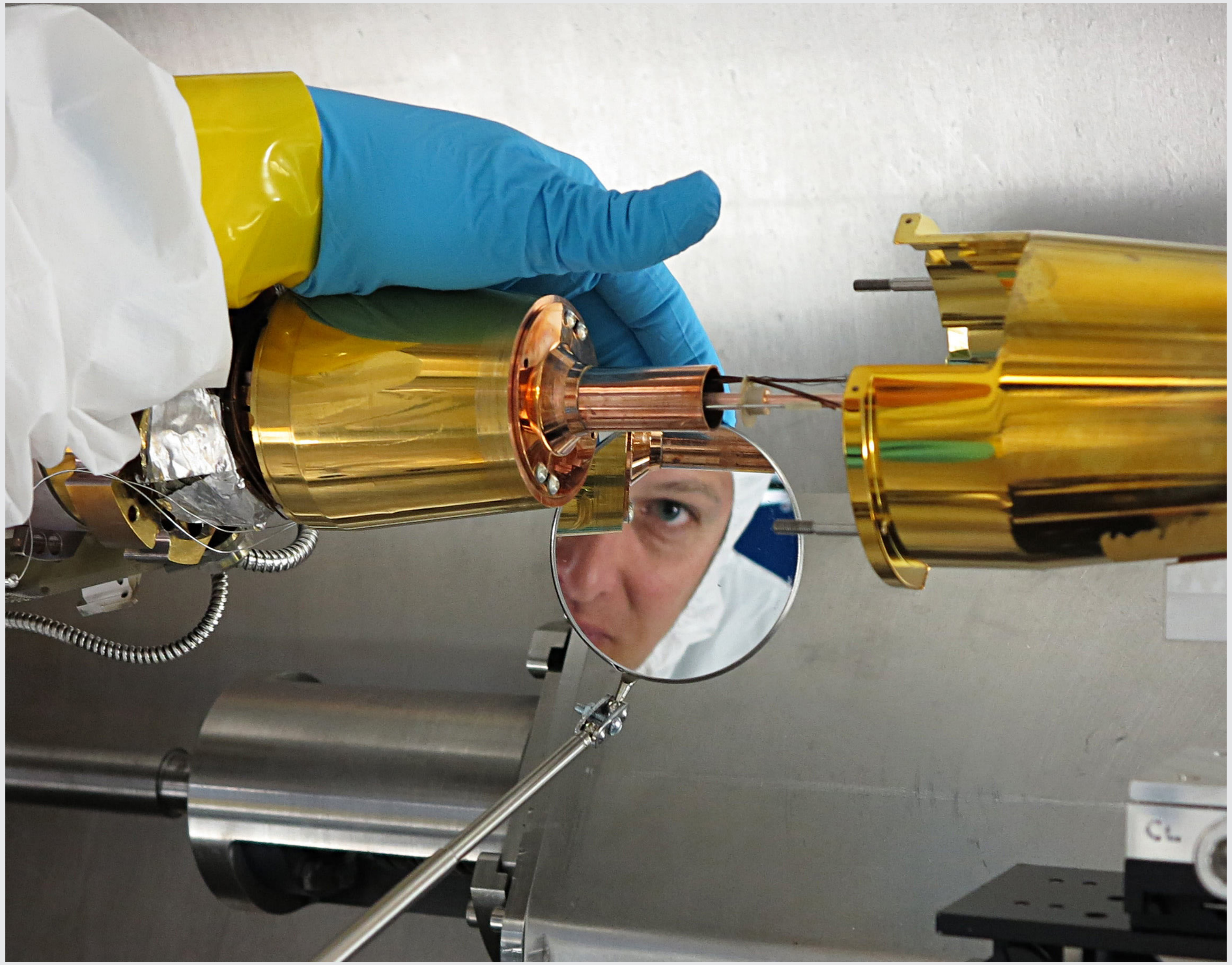
The NIF final optics assembly uses plates cut from large KDP crystals to convert laser light from infrared to ultraviolet, which is a more favorable wavelength for fusion experiments.

production crystals were grown with a total weight of nearly 100 tons.

Computer Control System

A NIF target shot requires all 192 laser beams to arrive within 10 trillionths of a second of each other and to be aligned within 50 microns—half the diameter of a strand of human hair—all with the right frequency and energy level. It takes more than 66,000 control points to achieve this precision, as well as one of the world's most sophisticated computer control systems. More than 2,000 computers running 5 million lines of code make it possible to align and fire the 192 NIF laser beams with some 800 channels of target diagnostic data efficiently and reliably several times a day. The control system uses predetermined set-up and alignment scripts with operator oversight while test and full-shot countdown sequences are fully automated.

The NIF control room is inspired by the National Aeronautics and Space Administration's Mission Control room in Houston, Texas. Control room operators access data through a hierarchy of on-screen graphics menus. Operators can also view videos of the laser beams and target from



NIF targets are complicated engineering marvels in tiny packages.

camera sensors incorporated into the beampath and Target Chamber.

Target Fabrication

Creating targets for NIF requires interplay among target designers, materials scientists, precision engineers, and a precision fabrication and assembly complex. The laser drives a target capsule inward at nearly a million miles an hour. Because the targets are subjected to extreme temperatures—greater than those in the Sun—and pressures similar to those found in the core of Jupiter during experiments, the targets must be designed, fabricated, and assembled with extreme precision and demanding materials requirements in a clean environment.

For example, components must be machined to within an accuracy of 1 micron (1 millionth of a meter). Many material structures and features can be no larger than 100 nanometers, which is just 1/1,000th the width of a human hair. And a capsule must have a smoothness tolerance approaching 1 nanometer—equivalent to removing all features on the Earth's surface taller than 60 meters (about 200 feet)—and be as free as possible from defects. Each target is characterized using an array of specialized optical, x-ray, and mechanical inspection systems.

–Charlie Osolin

Credit: PBS

FROM ‘60 MINUTES’ TO ‘SNL,’ FUSION IGNITION NEWS THRUSTS LLNL INTO THE ZEITGEIST

The headlines told the story:

“Scientists Achieve Nuclear Fusion Breakthrough With Blast of 192 Lasers,” *The New York Times*.

“U.S. announces milestone on fusion energy, sparking hopes for clean power,” *The Washington Post*.

“Breakthrough in nuclear fusion technology could dramatically alter clean energy landscape,” *PBS NewsHour*.

The official announcement on Dec. 13, 2022, that LLNL achieved fusion ignition with an experiment at NIF generated a media blitz, with tens of thousands of news stories that reached billions of people around the globe.

“Scientists reveal ‘holy grail’ breakthrough to create ‘limitless clean energy,’ ” *The Mirror*.

“Breakthrough in nuclear fusion energy announced,” *BBC News*.

“Could nuclear fusion energy help fight climate change?” *France 24*.

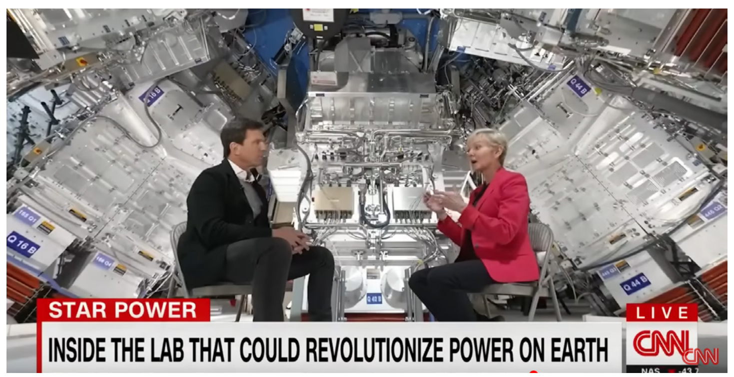
For months afterwards, hardly a day went by without a story published somewhere in the world mentioning the historic milestone. The news was covered by national and local print, digital, and broadcast media outlets, science magazines, technology sites, and various industry publications.

During the first week alone, media tracking data showed the announcement generated more than 103,000 mentions in print and digital news stories that had a combined audience reach of about 57.6 billion, and an additional 3,000 TV spots with a potential viewership of 2.7 billion.

“This is extremely exciting, it’s a major breakthrough,” MIT plasma physicist Anne White told *Science* magazine.

“It’s like the fire has been lit,” Steven Cowley, director of the Princeton Plasma Physics Laboratory, told *IEEE Spectrum*. “This

“60 Minutes” host Scott Pelley introduces a segment on the ignition milestone. Credit: 60 Minutes.



CNN Chief Climate Correspondent Bill Weir interviews Energy Secretary Jennifer Granholm inside the NIF Target Bay. Credit: CNN.

Vincent Tang, principal deputy principal associate director of the NIF & Photon Science Directorate, is interviewed by RTV Slovenija’s Adrijan Bakič in the Target Bay for a documentary produced by the Slovenian network. Credit: RTV Slovenia.

is the first controlled fusion ignition that we’ve ever seen, and that’s spectacular.”

“So it’s probably premature for anyone to dance around the house in their bathrobe, singing ‘Clean, green energy for everyone!’ but … nope, actually, going to do the happy dance anyway,” wrote *Washington Post* opinion columnist Megan McArdle. “Scientists have accomplished a net energy gain from a fusion reaction. This is potentially the biggest news of the decade.”

Meanwhile, an editorial in *The Independent* newspaper based in Livermore congratulated the many LLNL “scientists, engineers and technicians who made history.

“NIF won’t be the instrument to pursue fusion power,” *The Independent* wrote. “Maybe that will happen in future decades, maybe not. In the meantime, NIF has strengthened our national defense program and opened a door to further scientific advances. That’s a great contribution for a major research facility, and we are proud that it happened in our backyard.”

The science behind the breakthrough is complicated to explain to general audiences, so the network news shows called on popular science pundits like Bill Nye “The Science Guy” and astrophysicist Neil deGrasse Tyson to break down why this was a big deal.

“If this is a harbinger, if this is really the beginning of something huge,” Nye told the audience on CNN, “it would change the world.”

“I see it akin to the transition from horses to automobiles,” Tyson said on *Fox Business*. “It’s a pivot in civilization.”

Bloggers and YouTube content creators amplified the news coverage, which further fueled the social media buzz. LLNL’s social media platforms gained 20,000 new followers within a matter of days, and traffic to Lab websites, including NIF’s pages, spiked with visits from 199 different countries.

“Livermore looks nothing like the center of the sun, but this East Bay city, surrounded by pastoral vineyards and ranches, is where scientists have re-created the production of energy the way the sun does: through nuclear fusion,” said the *San Jose Mercury News*.

News this monumental was hard to keep under wraps. Word began to circulate through the world’s scientific community soon after the Dec. 5 shot, but LLNL scientists wanted to first verify the data obtained by NIF diagnostics to make absolutely certain the results were what they appeared to be. Once the data were verified, the official news was announced Dec. 13 by Energy Secretary Jennifer Granholm, NNSA Administrator Jill Hruby, LLNL Director Kim Budil and NNSA Deputy Administrator for Defense Programs Marvin “Marv” Adams in a Washington, D.C., news conference.

News outlets, however, had picked up on that early buzz and published speculative stories in the days before the official announcement.

So by the time the official news conference was ready to start, more than 20,000 people were in the queue waiting and more than 227,000 watched. About 387,000 viewers watched the video stream of a subsequent panel discussion by LLNL scientists.

Across all DOE, LLNL, and NNSA platforms, the announcement had about 11 million views. An LLNL ignition video garnered about 3.5 million views.

In the weeks and months that followed, news media interest remained elevated. LLNL was inundated with requests for interviews and visit requests, including from countries such as Japan, South Korea, Taiwan, Finland, Portugal, France, Slovenia, Austria, Germany, and the United Kingdom. The media sought to learn from Lab scientists what would come next.

In January, a crew from *CBS-TV’s* “60 Minutes” visited NIF. Scott Pelley, one of the news magazine’s hosts, interviewed Budil and several scientists who worked on the ignition campaign. Pelley also received what he described as “the first look at what’s left of the target assembly that changed history, an artifact like Bell’s first phone or Edison’s light bulb.

“We liken the first ignition to the first Wright brothers flight which covered only 120 feet,” Pelley said in the broadcast. “It was 44 years from a puddle jump to supersonic flight. Whether fusion power is 10 or 50 years away is now mainly an engineering problem. Lawrence Livermore has proven that from a machine, a star is born.”

In April, *Time* named design physicist Annie Kritcher to the news magazine’s annual Time 100 most influential people in the world. In July, Fast Company named Budil one of the magazine’s “Most Creative People in Business” for 2023.

The news coverage thrust LLNL, NIF, and fusion ignition into the cultural zeitgeist so much that the venerable *NBC-TV* comedy show “Saturday Night Live” mentioned ignition in its Weekend Update segment.

Also, an SNL sketch that was cut for time (but posted online) featured actor Austin Butler portraying a NIF fusion scientist.

The news even topped a sports column posted on *ESPN.com*.

“Last week, scientists studying fusion power at the National Ignition Facility of the Lawrence Livermore National Laboratory in California announced they’d finally made a breakthrough,” the story read. “I wonder, though, if any of the scientists have ever tried converting all of the power put into another seemingly renewable and insatiable energy resource: The debate on the Internet about whether Lionel Messi or Cristiano Ronaldo is better at soccer.”

And naturally, the satirical outlet *The Onion* had to weigh in by posing and answering questions in its own inimitable style:

Q: What’s the primary benefit of nuclear fusion?

A: We can finally declare victory over the sun.

Representatives from media outlets from around the world continue to visit LLNL to learn more about the next steps for fusion research and fusion energy, and requests for interviews with Lab experts remain high. For example, a crew from *RTV Slovenija* included NIF as part of a documentary on U.S. decarbonization efforts that aired in Slovenia in May.

Even the youth-oriented TV network *Nickelodeon* brought the news to its audiences with a segment on its “Nick News” program that covered emerging clean energy technologies.

“Wave, solar, and fusion are game changers that could be the keys to saving our environment,” Nick News correspondent Tejas Hullur said after touring NIF.

And several local and national media outlets came to the Lab on May 8 to cover an ignition celebration. One story by public broadcasting outlet KQED noted that while commercial fusion energy may still be decades away, achieving ignition has already paid benefits to the nation.

“NIF’s ignition discovery simulates the uncontrolled fusion of a nuclear bomb explosion,” the KQED story said, “and researchers hope doing this in a controlled lab setting can corroborate their computer models, which they use instead of the live test explosions.”

—*Benny Evangelista*

MSNBC’s Ali Velshi congratulates LLNL Director Kim Budil during the news program “Velshi.” Credit: MSNBC.

Science communicator Bill Nye (right) explains the impact of LLNL’s fusion ignition breakthrough on “CNN Tonight” with CNN’s Bill Weir, Laura Coates, and Alisyn Camerota. Credit: CNN.

The Age of Ignition
Hundreds Gather to Celebrate Historic Fusion Achievement

HUNDREDS GATHER TO CELEBRATE HISTORIC FUSION ACHIEVEMENT

On a day certain to rank in the upper echelon of LLNL's historical milestones, DOE and NNSA officials, members of Congress, past Lab directors, employees, and partners gathered on May 8 to celebrate the Lab's 2022 fusion ignition achievement.

Even a light shower couldn't dampen the enthusiasm for the celebration, as the hundreds in attendance honored the researchers, stakeholders and supporters that made the successful shot possible.

Distinguished speakers at the celebration lauded the achievement as a "remarkable breakthrough" for stockpile stewardship and national security, and the start of what they hope will open the floodgates to developing fusion as a viable, carbon-free energy source.

With NIF serving as a backdrop, LLNL Director Kim Budil welcomed the audience and the many more employees watching online to an "extraordinary class reunion" of fusion's luminaries, sponsors, and supporters.

Energy Secretary Jennifer Granholm called fusion the "holy grail" of clean energy, and honored the countless scientists, researchers, target fabrication experts, and operations teams who contributed to ignition over the past 60-plus years, including fusion pioneer and former Lab Director John Nuckolls, who was in attendance.

"Today isn't just a celebration of what we've achieved with ignition; it's a declaration of all that still to come," Granholm said. "Thank you all for joining us, for all the tireless work that I know you put into getting us into this exciting moment, and for all the invaluable contributions I know you'll be making in the months and the years ahead, because once you have harnessed the power of the stars, I imagine there is no limit to how bright we can shine."

Granholm, who stressed the importance of public-private partnerships with industry to developing commercial fusion energy, announced a new Inertial Fusion Energy Science & Technology Accelerated Research (IFE-STAR) funding opportunity from DOE's Office of Science to support creation of innovation hubs combining expertise from DOE national laboratories, academia, and industry to advance inertial fusion research.

"You can already see the impact (fusion energy investment) is making on the surrounding community and the potential it has to create new jobs and grow the economy," Granholm said. "Folks are traveling down that magnetic (fusion) pathway, but we don't have to worry about a road not taken. Thanks to this ignition achievement, we can, and we will see what both pathways hold …. We believe that public-private partnerships will be key to getting inertial fusion to that next level."

DOE Under Secretary for Nuclear Security and NNSA Administrator Jill Hruby thanked the "thousands of employees and partners who've dedicated their careers to making this achievement

Even a light shower couldn't dampen attendees' enthusiasm. Credit: Blaise Douros.

possible." Hruby said ignition has opened new chapters in NNSA's science-based Stockpile Stewardship Program and heralds a key step toward "unlocking the potential for a clean energy source that could revolutionize the world.

"Reaching ignition in a controlled fusion experiment was an achievement that took six decades to realize, from the notional idea discussed here just after the invention of the laser, and involved development, engineering, experimentation, and partnerships. It also confirmed something important—that the U.S. still leads big science and knows how to turn ideas into reality," Hruby said. "It has given us so much hope for the future."

NNSA Deputy Administrator for Defense Programs Marvin "Marv" Adams praised Lab computer scientists, diagnostic teams, and designers for overcoming the array of challenges to accomplish the "remarkable" feat.

"It's very important for our national security," Adams said. "The achievement we celebrate today illustrates that big, important accomplishments often take longer and require more effort than originally predicted, but that big, important accomplishments are often more than worth that time and effort."

U.S. Rep. Zoe Lofgren (D-CA18), a longtime NIF supporter, recalled past battles for funding of fusion ignition experiments dating back to the 1990s. Lofgren stressed the value of supporting ongoing fusion research as a potential clean energy source to help combat climate change, and said the Lab's achievement has ignited Congressional support to appropriate additional funding for fusion as recommended by the Fusion Energy Sciences Advisory Committee (FESAC).

"Now is the time to move aggressively towards the deployment of fusion energy," Lofgren said. "We are so used to people who scoff at that concept, but we all know because of your efforts, we're closer than ever."

Several hundred employees from across the Laboratory viewed the festivities either in-person or online. John Ruiz, a mechanical designer in the Laser Systems Engineering and Operations Division supporting NIF, said he had to see the celebration.

"I wanted to come out and celebrate with everybody else," said Ruiz, a Lab employee since 2016. "We're very proud to be a part of this whole endeavor. It feels really great to know that we're being recognized for all the hard work we put in."

Florinda Santos, an LLNL custodian, said she felt "blessed" to be able to personally take part in a momentous milestone.

"The new future that's going to be coming up for us is going to be really challenging and really good," Santos said. "It's going to be exciting to see what comes forth after this. It's just awesome to be part of this event and be here with everybody today."

Sarah Kennedy, a Strategic Defense office manager, added: "This is just such a huge deal, and it's such an exciting thing for the Lab and for our country, so I wanted to be a part of it. It's incredible what they've been able to accomplish; this once-in-a-lifetime thing. It's really neat to see that they're celebrating it as much as it deserves to be celebrated."

As the skies cleared, many Lab employees enjoyed special "ignition-edition" cookies strategically placed at stations across the Lab.

Tim Cunningham from the NIF Target Diagnostics Factory wore his commemorative ignition T-shirt while sampling each cookie flavor at the Central Café. He called the celebration "incredible.

"I loved it; it was good to be part of it," Cunningham said. "Just to hear what the secretary of energy and the head of the NNSA said about this—the accolades. It was amazing."

Cunningham said his whole team, which builds and processes the data from the diagnostics used at NIF, sat together at the ceremony to listen to the speeches. "How many jobs can you go to where they've been trying something for 60 years and we just proved it? Not many," he said.

Nick Lewis, who noshed on a honey-orange cookie, joined the Lab five months ago as ignition was being achieved. Lewis said "it was just starting to get more interesting" as he was beginning his Lab career, and that "this celebration is pretty awesome. Very clearly, there's a new stepping stone to bigger and bigger things. And that's exciting."

Randy Strauser, lead technician in Target Fabrication, has worked for General Atomics for 23 years, the last 13 of them at LLNL, and was pleased with the event.

"The Lab is really good at doing a celebration of milestones," he said, adding that this was the one "everybody's been waiting for.

"I didn't want to retire until they got ignition," Strauser said. "It's history in the making and now it's going to be exciting to see what's going to go on next."

—Jeremy Thomas and Benny Evangelista

Past Lab directors and fusion science luminaries were among the guests of honor in attendance for LLNL's May 8 celebration. Credit: Jason Laurea.

Lab Director Kim Budil embraces former Lab Director and inertial confinement fusion pioneer John Nuckolls as U.S. Rep. Zoe Lofgren (left), and Energy Secretary Jennifer Granholm look on. Credit: Jason Laurea.

NNSA Livermore Field Office Manager Janis Parenti, NNSA Deputy Administrator for Defense Programs Marvin "Marv" Adams, Energy Secretary Jennifer Granholm, DOE Under Secretary for Nuclear Security and NNSA Administrator Jill Hruby, LLNL Director Kim Budil, and U.S. Rep. Zoe Lofgren joined in a May 8 ignition celebration at LLNL. Credit: Blaise Douros.

The Age of Ignition Meet the People Behind the Scenes of LLNL's Historic Ignition Shot

Credit: Jason Laurea

MEET THE PEOPLE BEHIND THE SCENES OF LLNL'S HISTORIC IGNITION SHOT

The essential contributors to LLNL's fusion ignition milestone included hundreds of Lab employees who work diligently behind the scenes and often out of public view.

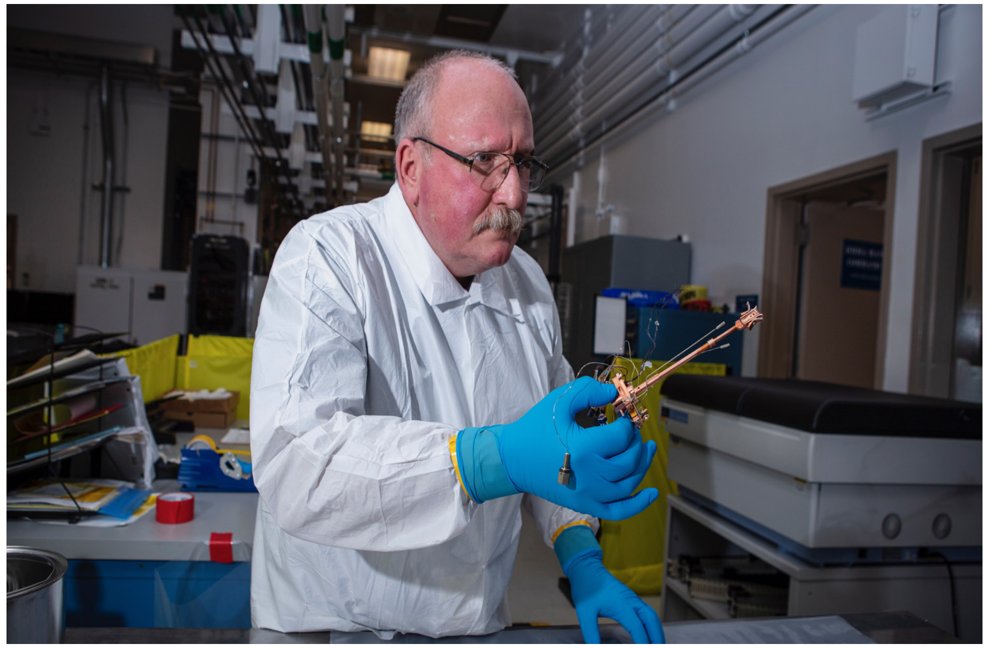
"The NIF Operations teams in the Target Bay and Control Room did an incredible job working meticulously through the long preparation to get the laser, diagnostic systems, and the DT (deuterium-tritium) fuel layered target ready for the Control Room to start the shot sequence," said Bruno Von Wonterghem, NIF's longtime commissioning and operations manager. "The team worked diligently through all issues and successfully fired all 192 beams with all systems participating.

"The best reward was that they were the first people to know that this shot was very different, as the alarms started sounding," Von Wonterghem said. "They made history happen."

Here are profiles of just a few of the key workers who played a crucial role in the groundbreaking experiment—and who will continue to perform essential duties at the Lab:

Stephen Moyle, Hazardous Material Management Area (HMMA) Manager, Radioactive Waste Manager

Job responsibilities: "I'm responsible for the safe and compliant management of the volumes of radioactive waste generated at NIF, which is the largest generator of such waste at the Lab. Although there are certainly more important and flashy jobs at NIF, I'm proud of what I do.



Stephen Moyle, Hazardous Material Management Area (HHMA) manager and NIF radioactive waste manager, is "handling history" by holding the target stalk used in the Dec. 5, 2022, experiment that produced fusion ignition at LLNL. Credit: Jason Laurea

"With the help of Tim Fuller, my indispensable and dedicated Radioactive and Hazardous Waste Management (RHWM) technician, and our partners at RHWM, we have been able to manage this vast amount of waste for 12-plus years safely, without incident. This also speaks volumes about the entire workforce at NIF. We could not be as successful with waste management without our professional workforce who know the importance of properly handling radioactive waste. It's a great pleasure to work with them daily.

"Another important aspect of my job is waste minimization. Over the years, the policies and procedures I have put in place have led to NIF greatly reducing its amount of waste generated even with an increased shot schedule.

"As HMMA manager, I supervise a user facility that various work groups use to work on diagnostics as well as any other contaminated equipment. I also have the equipment, procedures, and experience to decontaminate any items that are required to be transferred to any facility which is not authorized to handle radioactive material, on site or off."

Career and background at the Lab: "I spent 20 years in the U.S. Navy operating nuclear power plants on submarines. I always knew I would work at the Lab because both of my parents retired from here and my former high school girlfriend and current wife has worked here for 30-plus years. I started working at the Lab in 2005 with a short stint as a health and safety technician and was promoted to safety officer for the Physical and Life Sciences (PLS) Directorate in 2007. Started at NIF in 2009; have been here ever since. Greatest job at NIF."

Role in the Dec. 5 shot: "My role in the historic shot came after the shot was completed. I was asked to decontaminate the actual target stalk that held the target for the first fusion shot ever! It's a very humbling job; I'm handling history. I get to make this historic item safe for the public to view and enjoy in whatever venue it ends up in."

Reaction to the fusion ignition milestone: "As I'm working on this target stalk in the HMMA, I think of direct parallels to the Wright brothers flight (in 1903).

"The Wright brothers first flight took less than a minute and was less than 1,000 feet in length, but it was the first time in history it had ever been accomplished. Moreover, there were a lot of smart people at the time that said it would never happen.

"Within 25 years of the Wright brothers first flight, Charles Lindbergh was flying across the entire Atlantic Ocean all by himself. What a difference 25 years makes in the history of aviation.

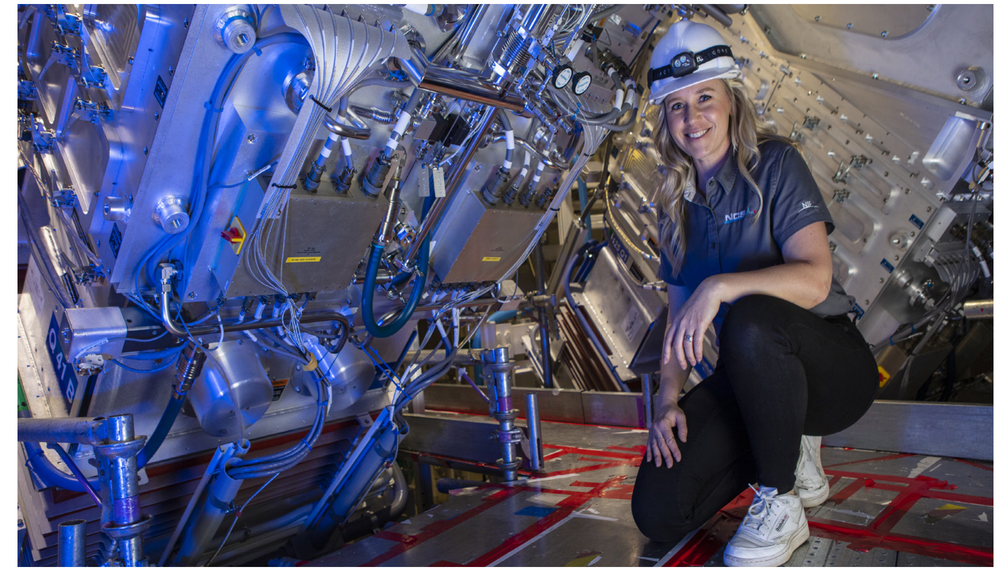
"If you think of this target stalk as the first flight of fusion energy, where will we be in 25 years? I find it very cool and exciting to think about what the fusion energy equivalent of Lindbergh's flight is going to look like not that far in the future. The possibilities are limitless and it's a very exciting and rewarding time to work at NIF."

Jessica Vaher, Engineering Technical Associate and Team Lead for Control System Electronics Technologists (E-Techs)

Job responsibilities: "My responsibilities include scheduling and coordinating E-Tech resources to perform controls hardware reactive/preventative maintenance tasks, configure new hardware for upgrades, and test controls as additional laser and diagnostic systems are commissioned. In parallel, as a senior E-Tech and part of the on-call controls hardware team, I work with the E-Techs to maintain the NIF control system and support shot operations 24/7. This involves testing, troubleshooting, and replacing controls hardware for the Integrated Computer Control System (ICCS), the Industrial Control System (ICS), and the Safety Interlock System (SIS)."

Career and background at the Lab: Vaher earned her B.S. in computer engineering technology from DeVry University and began her career at LLNL in 2005. She has worked in Lasers Systems Engineering and Operations (LSEO) at NIF for 18 years.

From 2005 to 2006, in the NIF controls hardware group as an E-Tech, she built, configured, calibrated, and tested the front end processors for alignment control, wavefront control, laser energy, timing, and diagnostic video.



Jessica Vaher works with the NIF control system electronics technologists (E-Techs) to maintain the NIF control system and support shot operations. Credit: Jason Laurea

From 2006 to 2014, in the NIF control room as a duty engineer for shot operations, she monitored and maintained the processes running within ICCS, executed software deployment plans, queried and updated the ICCS database, and analyzed software issues while gathering data for developers.

From 2014 to 2015, as a target area coordinator for shot operations, she aligned high-precision diagnostics and targets within the Target Chamber, documented component issues and inconsistencies, and operated ICS to pump and vent vessels in support of diagnostic and target exchanges.

She became an electronics technologist in 2015 and senior electronics technologist in 2019. She became E-Techs team lead the following year and added her current role as engineering technical associate in 2021.

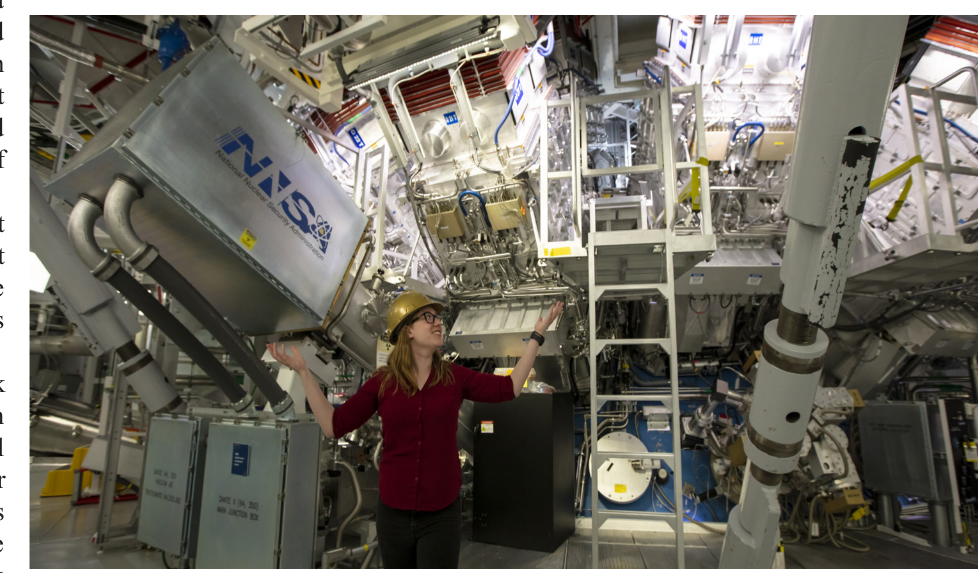
Role in the Dec. 5 shot: "In the week leading up to the Dec. 5 shot, I worked with my team to resolve outstanding control system issues to help ensure that the laser and diagnostics systems on all 192 beamlines would be available for the experiment. In the hours leading up to the system shot, I was standing by as part of the controls hardware on-call team to support shot operations and resolve any potential control system issues during the shot cycle."

Reaction to the ignition milestone: "When I joined NIF in 2005, I knew this was a unique facility with impressive goals. I was excited to contribute and be part of a project found nowhere else on Earth. In conversations with friends outside of work over the years, the topic of moving inevitably comes up and when asked if I'd ever move out of California, I respond with, 'But there's no NIF!'

"I remember working in the Control Room on Owl shift when we were taking system shots on the first commissioned bundle (of laser beams), Bundle 31. I remember when we were still counting and increasing the number of commissioned line replaceable units (LRUs), which were represented by a growing stack of wooden blocks in the strategy room. With the achievement of fusion ignition, we've come so far since those first system shots on just one bundle, and NIF still has untapped potential. I can't wait to see what challenges we overcome next."

Kelsey Wilson, Laser, Engineering, and Optics Technician on the Beam Control/Target Area Alignment Team

Job responsibilities and role in the Dec. 5 shot: "As an alignment operator on these teams, we're in charge of aligning the target inside the Target Chamber to within a few microns and making sure that all 192 NIF beams are going to land correctly on the target, as well as making sure that all of the diagnostics that the scientists need for the shot are aligned so they actually collect all the data they need for each shot."



Kelsey Wilson helps align the target inside the Target Chamber. Credit: Jason Laurea

Career and background at the Lab: "I've been at NIF on the alignment teams for two-and-a-half years now. Before that, I was working as a quality assurance inspector at a company that makes the aluminum parts for companies like Alcon and Newport while I was finishing my laser technology and electronics technology degrees at Irvine Valley College and Pasadena City College.

Reaction to the fusion ignition milestone: "As far as the shot goes, it's so cool to know that I'll be able to look back on this in the future and be able to say, 'Oh yeah, the first time humanity created ignition? Yeah, I was totally there. I helped do that.'

Wilson is part of the behind-the-scenes team that helps make the NIF magic happen.

"We're a 24/7 facility, we work 13-hour days to be able to do the science that we do. We're always up here working away, doing our thing."

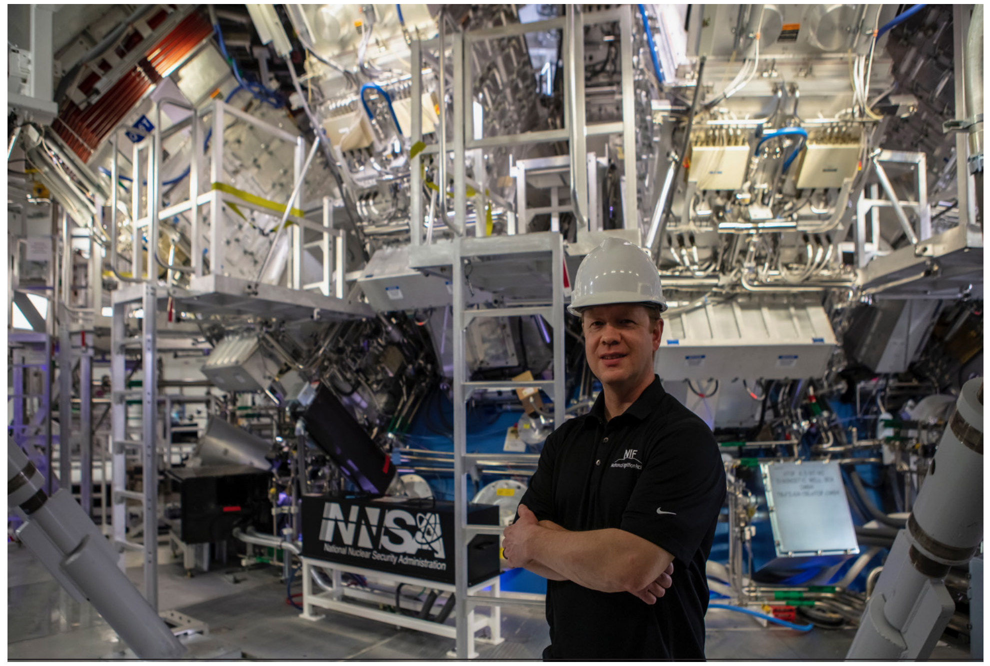
Matt Cohen, Deputy Section Leader for Target Experimental Operations (TEXOPS)

Job responsibilities and role in the Dec. 5 shot: Cohen assisted in the planning and execution of the setup and recovery of diagnostics before and after the shot.

Matt Cohen.

Career and background at the Lab: Cohen served as an electronics technician and nuclear reactor operator in the U.S. Navy Submarine Service from 1996 to 2002. He began at the Lab and at NIF in 2004 as an instrument calibration technician. He spent several years helping to commission NIF utility systems before becoming a work center supervisor and eventually moving to his current role.

Reaction to the fusion ignition milestone: "I feel extremely lucky to be part of this NIF team. It's humbling to think about how many people's entire careers were devoted to get us to this milestone. I'm looking forward to the challenge of what's in store over the next decade and hope I can contribute to future successes."



Daren Hart, lead operator for NIF shot operations, fondly remembers his many colleagues who contributed to the ignition achievement. Credit: Jason Laurea

Daren Hart, Shot Operations Lead Operator

Job responsibilities: Hart is responsible for the coordination and management of all NIF operations and supporting staff.

Background and career at the Lab: Hart's NIF roles have included serving as alignment operator from 2006 to 2015, Target Area coordinator from 2015 to 2017, and lead operator from 2017 to the present.

Role in the Dec. 5 shot: "In support of the shot that resulted in the ignition milestone, I coordinated facility preparations, executed preliminary laser performance checks, and verified that all experiment prerequisites were completed."

Reaction to the fusion ignition milestone: "Achieving ignition has brought on a bit of nostalgia for me.

"I remember the excitement when I started working here in the commissioning phase of NIF. Many times, conversations would focus on the anticipation of ignition. Some wanted to see the black hole it made. Others couldn't wait to find out what superpower they got. So on and so forth. The essence of those jokes was that people wanted to be there when it happened.

"Most of all, the accomplishment reminds me of the many people I have worked with here over the years. Several NIF veterans continue going strong and a few of the legends are still around. But many faces have come and gone for a multitude of reasons. Thankfully, the new generations that fill those voids always bring new perspective and fresh ideas to further advance the project.

"There are times that a topic will come up and I will remember a face and situation, but the names occasionally elude me. I wish we had a NIF yearbook, mostly to acknowledge all the people that have contributed toward the ignition milestone.

"Overall, I take pride in knowing that I played my part in the historical achievement."

Jaclyn Guzman is a multi-system operator, responsible for the operation and maintenance of a wide variety of auxiliary shot support systems. Credit: Mark Meamber

Jaclyn Guzman, Industrial Controls Team, Engineering Technologist and Facility Infrastructure Maintenance Technician

Job responsibilities: Guzman is a multi-system operator, responsible for the operation and maintenance of a wide variety of auxiliary systems, including Vacuum, Argon, HVAC, System Cooling, Tritium Processing, and other systems during and outside of the shot cycle.

Career and background at the Lab: Guzman spent eight years in the U.S. Army Military Police Corps Protective Services Battalion assigned to high-value targets. She has always had an interest in nuclear advancements and, after obtaining her degree in engineering technology, she joined the NIF team two years ago and "love(s) every second of it."

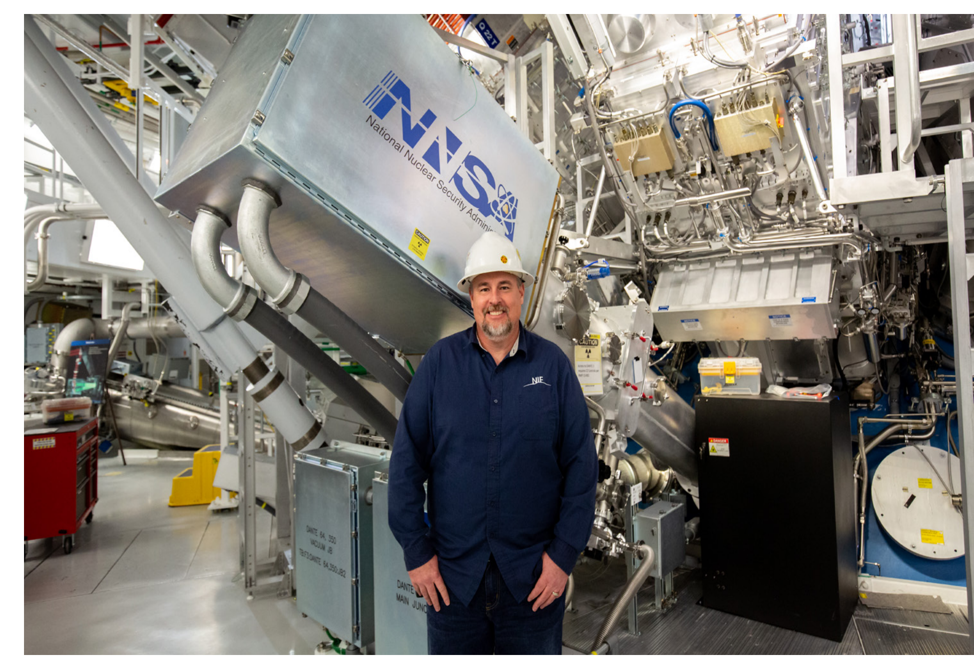
Role in the Dec. 5 shot: Guzman was focused on making sure all auxiliary shot support systems were operating effectively enough to ensure smooth execution of the high-yield shot.

Reaction to the fusion ignition milestone: "I feel honored to be a part of such a tremendous scientific breakthrough. This is world history at its finest, working with some of the most brilliant and inspiring people from around the world. I look forward to witnessing how the insight and understanding we have gleaned from this momentous experiment will help us usher in a new era of energy technology."

Shannon Sauers, Radiation Safety Officer

Job responsibilities and role in the Dec. 5 shot: Before the shot, Sauers was responsible for planning post-shot diagnostic recovery to maximize efficiency and maintain worker doses at ALARA (As Low as Reasonably Achievable) levels in anticipation of high yield.

After the shot, his duties included radiological control oversight of the NIF Target Bay reentry and recovery of diagnostics, utilizing high-radiation-area controls.



Shannon Sauers, NIF radiation safety officer, has seen NIF achieve "many important milestones." Credit: Mark Meamber

He also calculated expected dose rates of diagnostics based on yield and typical half-life, and worked with Operations to arrange the recovery schedule based on when individual diagnostics would meet radiological work permit limits. In addition, he managed individual worker doses, ensuring that recovery exposure limits were not exceeded.

Career and background at the Lab: "I've worked in radiological control for 18 years. Have been at LLNL for 12 years, all at NIF. Prior to LLNL, I worked at the Nevada Test Site and the Hanford Site."

Reaction to the fusion ignition milestone: "Based on Target Bay dose rates (from neutron activation) immediately following the shot, we knew we had likely achieved a record yield. There was immediate excitement in the facility and high expectations as we waited for the official yield number. I've been at NIF long enough to see many important milestones, including producing the first detectable neutrons, and now through ignition. Being a part of the journey and seeing all the hard work come to fruition is extremely gratifying."

Priscilla Yung, Industrial Hygienist

Job responsibilities and role in the Dec. 5 shot: "As a certified industrial hygienist and safety professional, I provide primary industrial hygiene oversight to the NIF as part of a multi-disciplinary Integrated Safety Team.

"My job is to ensure that NIF personnel do not get exposed to hazardous substances during the course of their work so they can focus on the cutting-edge science and innovation that is needed to make the world a safer place through its stockpile stewardship mission and unlimited sustainable energy mission.

"My job entails a weekly review of all the constituents that comprise the targets scheduled to be shot the following week, including the target used in the historic Dec. 5 shot, to ensure that any potential contamination that may be produced and subsequently expose workers during Target Chamber entry, diagnostic handling, and maintenance/repair/configuration activities are within acceptable limits and properly controlled to prevent overexposures.

"Among other duties, I also ensure that proper safe entry procedures are followed when entering the NIF beampath, where physical hazards such as lasers and atmospheric hazards such as oxygen-displacing inert gases are present."

Career and background at the Lab: "I joined the Lab seven years ago, first supporting Operations & Business, then Physical and Life Sciences, and for the past two years, NIF & Photon Science."

Reaction to fusion ignition milestone: "When I heard the news about ignition, on CNN of all places, I was on a vacation with my family. My first reaction was one of surprise, followed by gratitude. Gratitude for the fact that I got to play a small, but nonetheless important, role in such a historic, world-changing event. Gratitude for my team, which included two colleagues—Anni Mai and Sam Paik—who provided seamless backup for me while I was away on a vacation. And gratitude for the privilege of helping improve the world that my daughter will be inheriting, one full of hope and endless possibilities."

Priscilla Yung, NIF&PS industrial hygienist.

Miguel Castro, Integrated Safety Team Leader

Job responsibilities and role in the Dec. 5 shot: "I work with programmatic personnel to identify and manage risks associated with mission work. My role on Dec. 5 was limited. Most of the analysis and decision-making had already been completed in anticipation of the results."

Career and background at the Lab: "I have worked at LLNL for almost 21 years. I began my career as a Health & Safety tech. The Lab helped me by paying for my graduate study in health physics and I filled that role for a decade with half of that time served at NIF. In 2019, I went into Environment, Safety, & Health management.

Reaction to the fusion ignition milestone: "I realize my role is small in this big achievement, but it reminds me of a story from NASA where President John F. Kennedy asks a janitor what he does (for the agency) and he responds that he is helping put a man on the moon. That sentiment echoes in my mind because I believe that paramount to this achievement was the commitment from many different individuals to contribute as best they can to a common goal."

Alexander Yang, Health Physicist

Job responsibilities: As the health physicist, Yang anticipates, identifies, and evaluates radiological hazardous conditions resulting from program activities. He develops and implements policies, procedures, and standards to ensure those hazards are managed to ensure proper and safe working conditions.

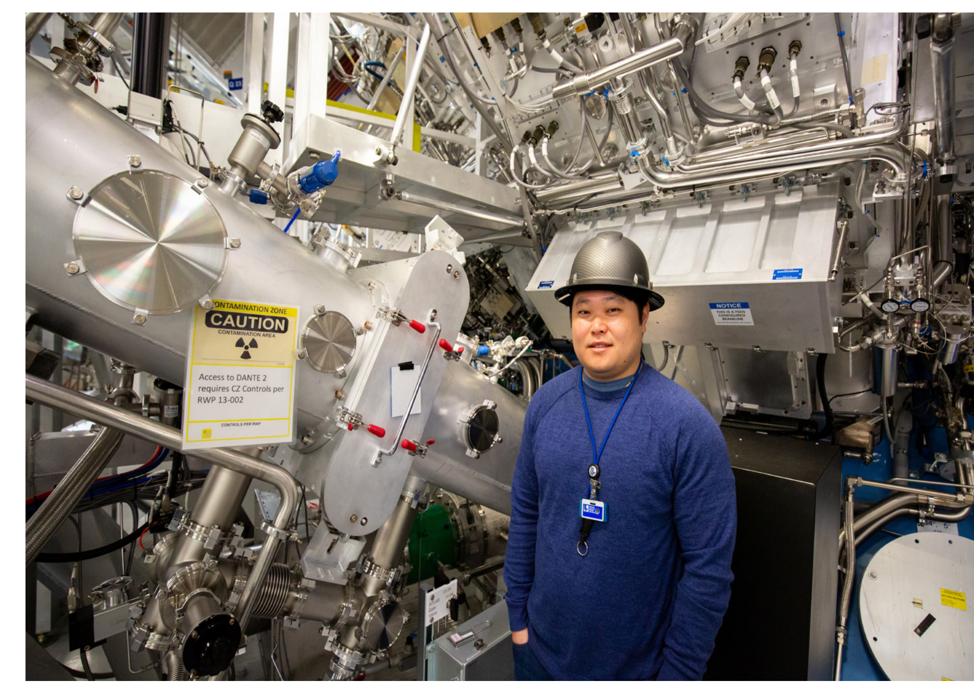
Career and background at the Lab: Yang has worked for seven years as a health physicist and has been at the Lab for two years. Before arriving at LLNL, he worked five years at Pearl Harbor Naval Shipyard in Honolulu, Hawaii, in dosimetry, environmental monitoring, and as a radiation safety officer.

Role in the Dec. 5 shot: "Most of our team's responsibility for the Dec. 5 milestone was in preparation and anticipation of the conditions in the Target Bay. Following a high-yield experiment at NIF, the Target Bay becomes heavily activated by the neutrons produced. My team and I worked to develop a robust radiological control program to manage exposure from ionizing radiation to the radiological workers who must enter the Target Bay to begin recovery operations."

Reaction to the fusion ignition milestone: "It's incredibly exciting to be working for an organization that is pushing the boundaries of science every day. The ignition shot on Dec. 5 puts a lot of what we do into perspective and I'm thankful I was able to be a part of it. I think people were proud to work at NIF before, but after the ignition milestone, spirits are especially high now. I haven't seen people, not just my team, this excited about anything since I've been at the Lab."

—Jon Kawamoto

Miguel Castro, NIF&PS integrated safety team leader, stands in front of the N41 direct drive port, where the Lab previously deployed metal coupons to indirectly characterize the induced radioactivity of all metallic equipment in the Target Bay. This methodology was briefly used at NIF before higher yields forced the Lab to abandon it. Credit: Jason Laurea



Alexander Yang, NIF&PS health physicist, and his team worked on anticipating and preparing for hazardous radiological conditions in the Target Bay to ensure safe working conditions. Credit: Jason Laurea

MILESTONES ON THE PATH TO IGNITION

Over the decades since the first laser was demonstrated in 1960, LLNL researchers have designed and built a remarkable succession of lasers—each bigger, more complex, and more powerful than the last. Extraordinary challenges entice and inspire great people, and the work the Laboratory and its laser, optics, inertial confinement fusion, and diagnostics pioneers did to optimize laser performance and measurement techniques, past and present, help make today's laser research possible at LLNL and around the world.

Following the lead of visionaries like John Nuckolls, Ray Kidder, John Foster, John Emmett, Carl Haussman, and John Lindl, the Lab's laser scientists and engineers constructed a series of record-setting lasers. These groundbreaking technologies—from the single-beam, 10-joule Janus laser in 1974 to today's 192-beam, two-megajoule National Ignition Facility—have been applied to Laboratory mission areas ranging from stockpile stewardship and national security to Discovery Science, energy security, and national competitiveness, while attracting a steady stream of world-class inventors and innovators.

These unprecedented projects were the basis for numerous collaborations with universities, other laboratories, outside industry, and the larger fusion research community—collaborations which made possible the construction of NIF, the world's largest and highest-energy laser system, some 20 years after Janus. Concurrently, researchers also developed increasingly sophisticated optics, targets, modeling and simulation tools, and diagnostic instruments needed for measuring and observing what was happening in the laser systems and their experiments—advancements that enabled LLNL's historic fusion breakthrough in December of 2022.

Thanks to the hard work and innovation of the members of the LLNL team, our collaborators and industrial partners, and our partners in ICF and high energy density (HED) science research, NIF is now helping the nation maintain its credible nuclear deterrent by conducting ignition experiments to study the conditions found in exploding nuclear weapons and providing experimental access to user communities for national security, Discovery Science, and the quest for clean fusion energy. None of this would have been possible without the creativity and dedication of LLNL's laser and fusion pioneers and their successors. We truly do stand on the shoulders of giants.

A Legacy of Lasers

The long path to NIF presented many obstacles, faced much skepticism, and was never certain until the lasers actually began to fire. Meeting those tests demonstrated a particular strength of LLNL and its people: surmounting setbacks and technical challenges. Here is a summary of the major steps leading to NIF's dedication in 2009 and the Laboratory's achievement of fusion ignition in 2022:

1917:

Albert Einstein lays the foundation for the laser by introducing the concept of stimulated emission: a photon interacts with an excited molecule or atom and causes the emission of a second photon having the same frequency, phase, polarization, and direction.

1957:

Edward Teller and colleagues at LLNL begin to explore peaceful applications of nuclear explosives, including the use of nuclear technology as a source of energy.

A view between two banks of the 10 beamlines in the laser bay of the Nova laser, NIF's predecessor, shortly after the laser's completion in 1984. The blue boxes contained the amplifiers and their flashtube "pumps." The tubes between the banks of amplifiers were the spatial filters.

The first working laser, constructed by Ted Maiman in 1960. Credit: HRL Laboratories, LLC

1960:

LLNL's John Nuckolls proposes an inertial fusion energy scheme to implode a milligram of deuterium-tritium (DT) fuel to super-high densities by a radiation implosion in a miniscule shell called a hohlraum. In Nuckolls' early 1960s calculations—which are met with surprise and criticism—the implosion ignites a 50-megajoule (MJ) thermonuclear explosion, energized by several MJs of radiation from a non-nuclear radiation energy source—a "driver"—outside the tiny hohlraum. Jets, particle beams, plasma guns, hypervelocity pellets, pulsed-power machines, and other sources are evaluated.

Nuckolls and his colleagues are "astonished" when Ted Maiman at Hughes Research Labs in California announces the first working laser—an acronym for light amplification by stimulated emission of radiation—in July of 1960.

1961-62:

LLNL's Ray Kidder and others make calculations with weapons design codes in which the surface of a fusion capsule is ablated directly by a high-power pulse of spherically symmetric laser light. The calculations show that "energy gain"—generating more fusion energy than the energy required to initiate a fusion reaction—would require the fuel to be compressed to about 1,000 times its liquid density (200 grams per cubic centimeter).

1962-63:

Livermore Director John Foster, along with Associate Director Teller, start a small experimental laser fusion program directed by Kidder to study the possibility of using lasers to compress fuel to the density required for energy gain. Nuclear experiments are also initiated to explore ignition of small DT masses and to test the stability of implosions driven by strong pulse shapes.

1970-71:

A new generation of computer calculations by Nuckolls, Lowell Wood, George Zimmerman, and Ron Thiessen show that interesting laser fusion experiments could be done with lasers as small as 10 kilojoules and that target gains of 100 could be achieved with a megajoule-size laser. Skeptics, however, question the feasibility of multi-megajoule, hundred-terawatt lasers.

1972:

LLNL Director Mike May and Associate Director Carl Haussman consolidate the Laboratory's experimental laser efforts into a single focused program known as Y Division on July 10, 1972, with Haussman as associate director of the Laser Program, John Emmett, a laser scientist from the Naval Research Laboratory, as Y Division leader, and Bill Krupke as Emmett's deputy. In the ensuing 50 years, increasingly complex and energetic laser systems, each with five to 10 times more energy than its predecessor, enable cutting-edge research in inertial confinement fusion (ICF), high energy density science, nuclear weapons stockpile stewardship, Discovery Science, and laser fusion energy.

1973:

Led by Laser Programs Associate Director Jim Davis, the uranium Atomic Vapor Laser Isotope Separation (U-AVLIS) Program begins; its goal is to help maintain the U.S. market share of supplying the world's

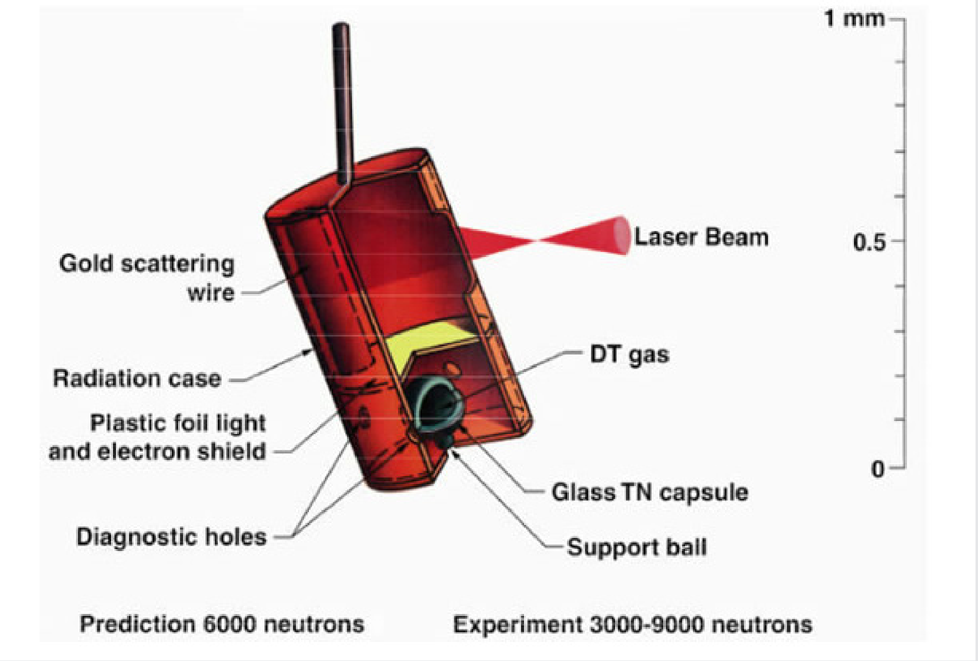
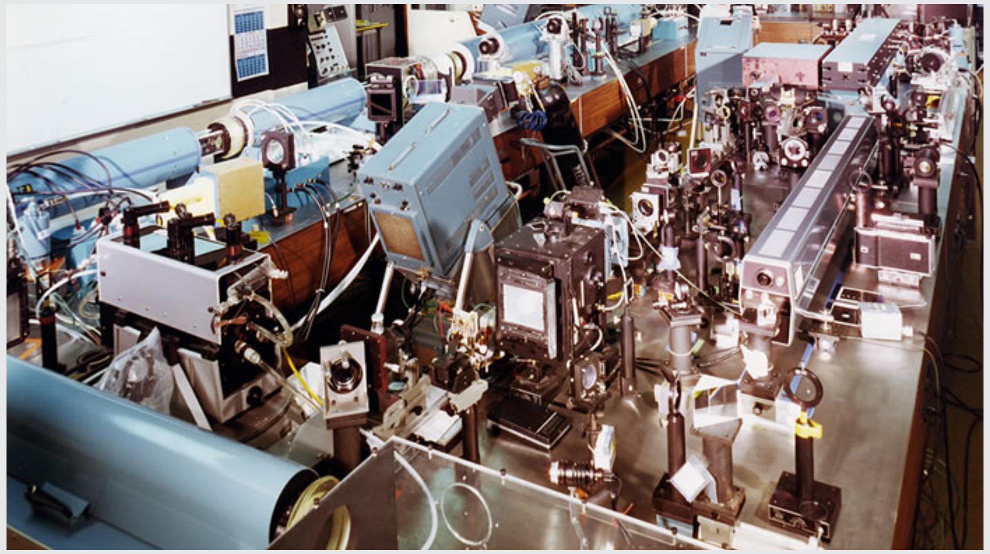


Illustration of the target for the first laser-driven radiation implosion experiment. Credit: John Nuckolls



The Janus Laser as it looked in 1975. Janus spurred the development of many important diagnostic techniques, including a method for obtaining a high-resolution image of an imploded target and measuring its temperature, which led to better-characterized experiments.

uranium enrichment services. The process uses copper vapor and liquid dye lasers as well as solid-state lasers.

1974:

The one-beam, 10-joule Janus laser, built in 1974 to conduct target compression experiments, carries out the first fusion experiments at the Laboratory.

1976:

Janus demonstrates the first controlled thermonuclear reaction in laser-imploded deuterium-tritium fuel capsules. Physicist Mordy Rosen is hired by Nuckolls into X-Division (ICF design). Rosen goes on to lead X-Division during the 1990s when the Nova Technical Contract is completed, leading to DOE's final approval of NIF construction. Other key members of X-Division include John Lindl, Bill Kruer, and Claire Max.

1977:

Under the leadership of ICF Program Director John Holzrichter, the 20-beam Shiva laser delivers 10.2 kilojoules of infrared laser energy in less than one-billionth of a second in its first full-power firing, becoming the world's most energetic and highest-power laser.

1985:

The 10-beam Nova laser produces 40 kilojoules of ultraviolet energy in its 4.5-meter-diameter Target Chamber. Nova includes optical elements to convert infrared light to ultraviolet and provides the physics basis for proceeding with a 1- to 2-megajoule laser designed to demonstrate thermonuclear ignition and propagating plasma burn in the laboratory.

1992:

The last of 1,032 nuclear tests carried out by the United States, a 20-kiloton underground test code-named Divider, is conducted at the Nevada Test Site on September 23. On October 2, President George H.W. Bush signs Congressional legislation mandating a nine-month moratorium on U.S. nuclear weapon testing. The moratorium is subsequently extended by President Bush's successors.

1993:

On January 15, as his last official act in office, Secretary of Energy James Watkins signs Key Decision 0, which affirms the mission need for the National Ignition Facility. The justification states that NIF is being proposed to support the inertial confinement fusion program requirement to achieve ignition and propagation of thermonuclear fusion and burn.

Victor Reis, the Assistant Secretary for the Department of Energy's Defense Programs, played a key leadership role in the 1990s in defining the emerging Stockpile Stewardship Program and the need for the National Ignition Facility.

LLNL Director Bruce Tarter (left), Energy Secretary Federico Peña, and U.S. Rep. Ellen Tauscher participate in the ceremonial groundbreaking on May 29, 1997.

In June 1999, after careful preparation, a rotating crane hoisted the target chamber and gently moved it to the Target Bay, a breathtaking event that took only about 30 minutes.

1994:

Congress establishes the science-based Stockpile Stewardship Program, which combines advanced scientific and experimental capabilities with high-performance supercomputing to help scientists and engineers understand and resolve issues in the nation's nuclear deterrent. On October 21, Energy Secretary Hazel O'Leary verifies the mission need for NIF and identifies LLNL as the preferred site for the facility. The mission areas identified for NIF are nuclear weapons physics, inertial fusion energy science and technology, and other applications. The nuclear weapons physics discussion states that, "In the absence of underground testing, the NIF would be a critical tool for the Department's Science-Based Stockpile Stewardship Program."

Building NIF

1997:

After extensive planning beginning in the early 1990s, ground is broken for the National Ignition Facility on May 29, 1997. The facility construction challenges are enormous, particularly in managing such a large and technically complex project under intense scrutiny, developing unique laser and optical technologies, and building and aligning the super-clean environmental enclosures containing the laser beams (see Page 26, "An Engineering Marvel"). Many components are obtained thanks to significant technology advancements made to bring the vision of NIF to fruition (see Page 61, "The Seven Wonders of NIF").

Laser Programs (later NIF & Photon Science) Associate Directors Mike Campbell, George Miller, and Ed Moses, along with NIF Project Director Ralph Patterson and Commissioning Manager Bruno Van Wonterghem, lead the team of scientists, engineers, technicians, and government, academic, and industrial partners that bring the NIF construction project to a successful conclusion.

Technicians John Hollis (right) and Jim McElroy install a SIDE camera in the Target Bay. The camera was the last of NIF's 6,206 various opto-mechanical and controls system modules called "line replaceable units" or LRUs to be installed.

1999:

On June 17, 1999, the 287,000-pound, 10-meter-diameter Target Chamber is hoisted by one of the world's largest cranes. Previously used at the Nevada test site to lower nuclear weapons for underground tests, the giant crane lifts the Target Chamber and gently lowers it inside the NIF Target Bay so the NIF building can be completed around it.

2001:

The main NIF building is completed in September 2001. Spanning the width of three football fields and standing 10 stories tall, the facility requires more than 55,000 cubic meters of concrete, 7,600 tons of reinforcing steel rebar, and 5,000 tons of structural steel.

2003:

All 192 support structures and clean enclosures for the laser beams are completed.

2008:

Special equipment installation and commissioning of the second of NIF's two laser bays is completed.

2009:

The final NIF line replaceable unit (LRU) is installed on January 26, 2009, bringing the total to 6,206 LRUs installed since 2001 and marking the final major special equipment installation milestone. On March 31, 2009, the U.S. Department of Energy announces that the National Nuclear Security Administration (NNSA) has certified the completion of "the historic effort to build the world's largest laser."

With thousands in attendance, including California Gov. Arnold Schwarzenegger, NIF is officially dedicated on May 29, 2009. The laser system demonstrates the precision, flexibility, and reliability required for repeated ignition experiments and shows the capability to create sufficient x-ray energy to drive fuel implosion, an important step toward the ultimate goal of fusion ignition. NIF's dedication marks the latest incarnation of LLNL's rich legacy of lasers and sets in motion the next chapter of one of the nation's greatest scientific assets.

2010:

The NIF Project Team's groundbreaking technical achievement, exemplary management, and spirit of innovation win NIF the Project Management Institute's 2010 Project of the Year Award, and this spirit continues to guide thousands of dedicated LLNL employees during NIF's first decade of operations.

Pursuing Ignition: A Decade of Progress

NIF's final path to ignition was built on a decade of advances by LLNL researchers and their collaborators under the leadership of ICF Program Director John Edwards, Associate Program Director for ICF Science Richard Town, ICF Chief Scientist Omar Hurricane, former ICF Program Associate Division Leader Debbie Callahan, and ICF Experiments Program Group Leader Nino Landen, along with many others.

They guided the team to address and gradually solve a wide range of challenges that had limited NIF's implosion performance. Edwards and his team worked in lockstep with a NIF leadership team that included NIF directors Ed Moses, Mark Herrmann, and Doug Larson, Commissioning and Operations Manager Bruno Van Wonterghem, Target Fabrication Program Manager Abbas Nikroo, and many others.

2011-12:

Ignition experiments begin as part of NNSA's National Ignition Campaign (NIC), which ends on Sept. 30, 2012. The campaign has two principal goals: developing a platform for ignition and HED

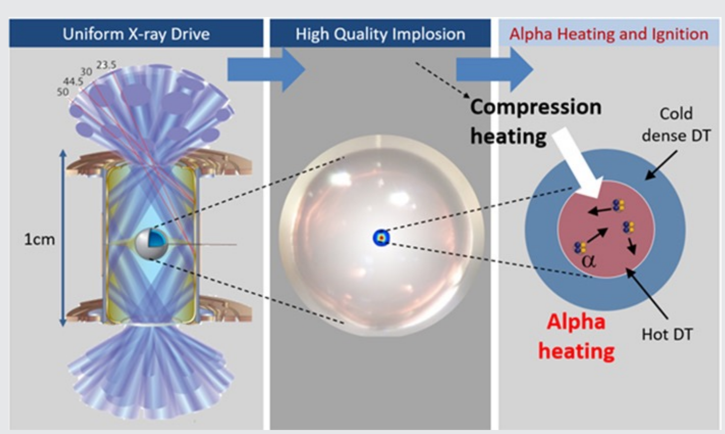
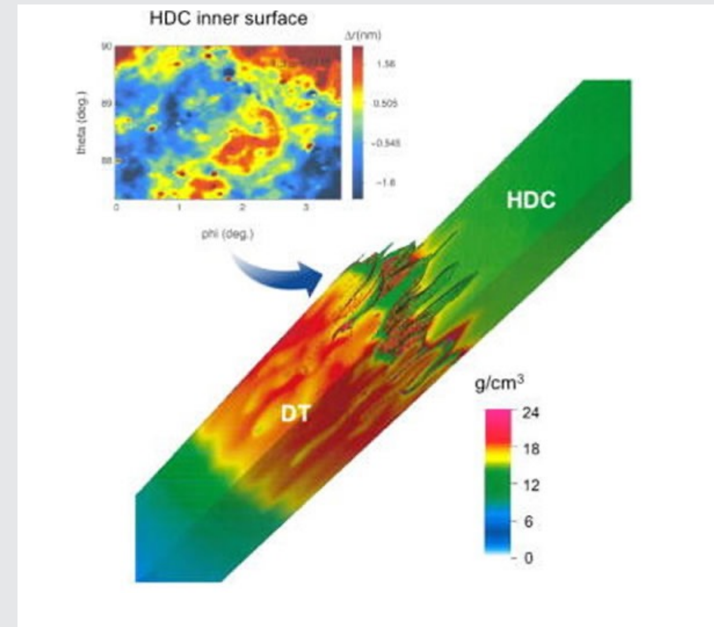
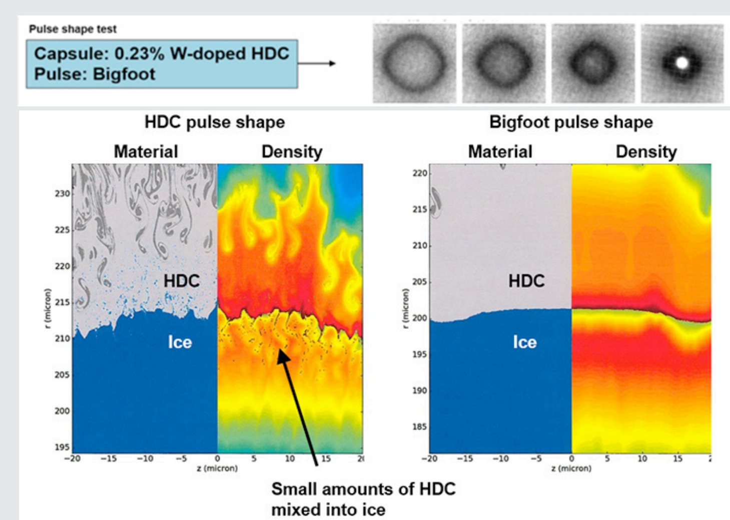


Illustration of alpha heating in a standard NIF target.



A high-resolution 3-D simulation of a 2017 NIF shot at the time of peak implosion velocity showing the effects of capsule surface roughness. Significant mixing between the high-density carbon (HDC) ablator, or target capsule, and deuterium-tritium (DT) fuel has occurred by this time, including long fingers of hot HDC that have penetrated halfway through the DT.



(Top) CBI/SLOS radiographs from an experiment in July 2020 during a "Bigfoot" implosion of a tungsten (W)-doped HDC capsule. The experiment was designed to test simulations (below) suggesting that the rapid acceleration provided by the "Bigfoot" pulse shape stabilizes the implosion against early-time instabilities, reducing mix.

science applications (including target and diagnostic fabrication) and transitioning NIF to routine operations as the world's preeminent HED science user facility.

Over the course of the campaign, LLNL researchers steadily increase the laser's energy and power, culminating on July 5, 2012, when the laser system's 192 beams deliver more than 1.8 megajoules of ultraviolet light and more than 500 trillion watts of power to the center of the Target Chamber.

NIC experiments, however, produce fusion yields of only a few kilojoules, far less than computer models predict. The implosions are unstable and asymmetric, with a high level of energy-sapping laser-plasma interactions (LPI). Although ignition is not achieved, a large body of scientific knowledge and major new experimental, diagnostic, modeling, and target fabrication capabilities are developed and validated that help guide subsequent experiments.

For example, researchers find that slightly tweaking the wavelength of certain laser beams can control the exchange of energy between the beams as they enter the laser entrance holes, an effect known as cross-beam energy transfer (CBET), a major cause of asymmetry. Key diagnostics, such as the velocity interferometer system for any reflector (VISAR), the streaked x-ray spectrometer (NXS), and the dilation x-ray imager (DIXI) capable of acquiring 200 billion images a second, are fielded to capture every detail of NIF implosions, with many more state-of-the-art diagnostics to follow.

> *"All of this work was only possible because of the efforts and accomplishments of the amazing teams that designed and built NIF and laid the scientific groundwork for this advance."*
>
> **Mark Herrmann**

2013-2015:

With the introduction of the "high-foot" design—which increases the power in the first stage, or foot, of the laser pulse and shortens the pulse duration—stability is improved and the mixing of capsule material with the fusion fuel is reduced, but at the cost of lower compression. Still, the high-foot implosions are the first to demonstrate significant alpha heating—where the energy generated through fusion reactions exceeds the amount of energy deposited in the fusion fuel and hot spot by the implosion, a condition known as fuel gain.

In alpha heating, alpha particles (helium nuclei) produced in the target capsule's central hot spot deposit their energy in the cold deuterium-tritium (DT) fuel surrounding the hot spot, heating the fuel, increasing the rate of fusion reactions, and producing more

The exterior of NIF as seen from the rooftop of a building across the street. Credit: Mark Meamber

alpha particles. This "bootstrapping" process is the mechanism required to accelerate the DT fusion burn rate to eventual self-sustaining fusion burn, known as a "burning plasma," and ignition. The high-foot experiments achieve about 25 kilojoules of yield, double the yield that would have resulted without alpha heating.

2016-2018:

Hurricane and Callahan, co-leaders in the high-foot campaign, are installed as co-leads for Integrated Experiments. Researchers begin to use high-density carbon (HDC), or diamond, capsules instead of the plastic capsules previously used; HDC and "Bigfoot" experiments with these capsules reduce laser-plasma interactions, improve symmetry, increase implosion velocity, and more than double energy yield to about 55 kilojoules.

The Target Fabrication team works to shrink the size of the tubes used to fill the capsules with fuel and to find replacements for the ultra-thin "tents" that support the capsule inside the hohlraum. Researchers lower the amount of helium gas in the hohlraums to boost the energy absorbed by the target capsule and the central hot spot by reducing backscatter losses and hot-electron production. This requires them to learn about laser energy coupling symmetry control in a new hohlraum regime. Studies also begin on the use of different hohlraum shapes, such as the Rugby, I-Raum, and Frustraum, intended to improve implosion symmetry and increase energy coupling.

To build understanding, NIF's diagnostics, coupled with rapid advances in computer modeling and simulation, provide detailed information on all aspects of the implosion, from incident and backscattered laser light to the x-ray drive provided by the hohlraum. The timing of the shocks to compress the target, the uniformity of the capsule as it's being imploded, and the plasma conditions as it approaches decompression or stagnation provide key insights into experimental results.

> "This is a Wright Brothers moment. Our result is a significant step forward in understanding what is required for (fusion) to work."
>
> **Omar Hurricane**

In 2017 researchers, led by Callahan and Hurricane, launch a series of "hybrid" experiments labeled Hybrid-B, C, D, and E. The experiments combine aspects of the most successful previous experimental designs and new understanding with new target designs that pair larger capsules with smaller or reconfigured hohlraums, along with new laser pulse shapes aimed at enhancing the radiation temperature in the hohlraum.

The hybrid experiments benefit greatly from continuous improvements in laser technology, including steady increases in laser energy and power made possible by years of work to harden NIF's optics against laser damage. The development of the Virtual Beam Line++ code, which calculates the light diffraction, amplification, and other behavior of the laser light, enables scientists to calibrate for distortions in the laser beams and deliver the precise pulse shape required by experimenters. Other upgrades, such as automation of time-consuming manual activities, an advanced laser alignment system, an integrated suite of online tools, and methods for gleaning more data from a shot, steadily increase the rate of data generation.

2019-2020:

With the beginning of the "Hybrid-E" program in 2019, led by lead designer Annie Kritcher and lead experimentalist Alex Zylstra, researchers make significant progress in coupling more energy to the target to improve compression and hot-spot pressure and temperature. An experiment in June 2019 tests large diamond capsules in compact hohlraums under ignition-relevant conditions (high laser energy and implosion velocity). The shot uses CBET, once a liability, to control asymmetries caused by the larger capsule and low gas-fill. The experiment significantly betters the capsule absorbed energy of NIF's record-setting shots from the summer of 2017—from 150-200 kilojoules to more than 270 kilojoules—while maintaining the good symmetry and high velocity needed for a successful implosion. Similar but slightly lower coupling gains are achieved in the I-Raum campaign testing smaller-scale implosions.

Advanced diagnostic and simulation technologies substantially improve understanding of the sources of implosion degradations, especially asymmetries and fuel contamination, or "mix." A series of experiments conducted in 2019 test the theory that including different types and amounts of dopants in the capsule shell could help control instability and reduce mix. The results are recorded using NIF's CBI/SLOS "Super Camera"—the crystal backlighter imager (CBI) paired with the single line of sight (SLOS) camera.

In addition, the Target Fabrication team develops new metrology and manufacturing tools and tests different carbon crystalline structures in a drive to substantially reduce the surface and subsurface defects, called "pits" and "voids," and thickness variations in the larger diamond target capsules needed for the hybrid experiments.

Progress accelerates in November 2020, when Hybrid-E and I-Raum experiments achieve a burning plasma state for the first time, producing an energy yield of about 100 kilojoules, nearly double the previous record. A high-velocity Hybrid-E implosion with an extended laser pulse generates hot-spot pressures of about 300 gigabars (300 billion atmospheres).

2021:

On Feb. 7, 2021, a Hybrid-E experiment achieves a fusion yield of 6×10^{16} (60 quadrillion) neutrons and 170 kilojoules of fusion energy output, a 70 percent increase over the November results. Experiments using the I-Raum achieve similar yields.

On Aug. 8, 2021, NIF stuns the world's scientific community by achieving a yield of more than 1.35 MJ, putting researchers at the threshold of ignition and opening access to a whole new experimental regime. In the experiment, alpha heating ignites fusion reactions that spread through the fuel in a self-sustaining thermonuclear burn wave, consuming almost 2 percent of the fuel.

The shot produces an unprecedented 4.8×10^{17} (480 quadrillion) neutrons and more than 10 quadrillion watts of power for about 100 trillionths of a second. The fusion energy generated is about five times the energy absorbed by the capsule and about 70 percent of the laser energy shot at the target. The 1.35 MJ of fusion energy yield is eight times more than the February experiment and 25 times the record set in 2018.

Key factors in the experiment's success include shrinking the apertures of the hohlraum's laser entrance holes to curb energy losses; substantially reducing the defects in the target capsule; decreasing the size of the fill tube from five to two microns; and extending the laser pulse to effectively hold the implosion together longer and concentrate more energy in the hot spot.

2022-2023:

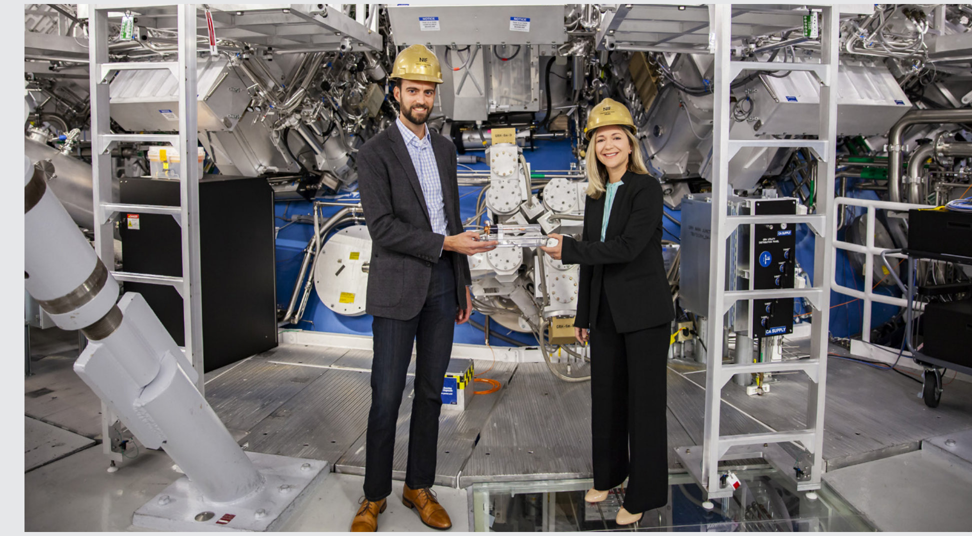
The Aug. 8, 2021, result is carefully analyzed and further experiments are conducted in the fall of 2021 and into 2022. The goals are to improve researchers' ability to predict future performance and to assess increases in NIF's energy and power to drive even higher yields.

Those efforts pay off with the Dec. 5, 2022, ignition shot that produces 3.15 MJ of fusion energy from a laser energy input of 2.05 MJ, more than doubling the yield from the Aug. 8 experiment. Several subsequent experiments in 2023 also achieve ignition and target gain, demonstrating NIF's ability to consistently perform at the multi-megajoule level.

"This has been an incredible challenge," Edwards said. "So many extremely hard problems had to be understood and overcome across the entire system to get to this point. Pretty much at every step we were pushing and expanding the envelope of the possible.

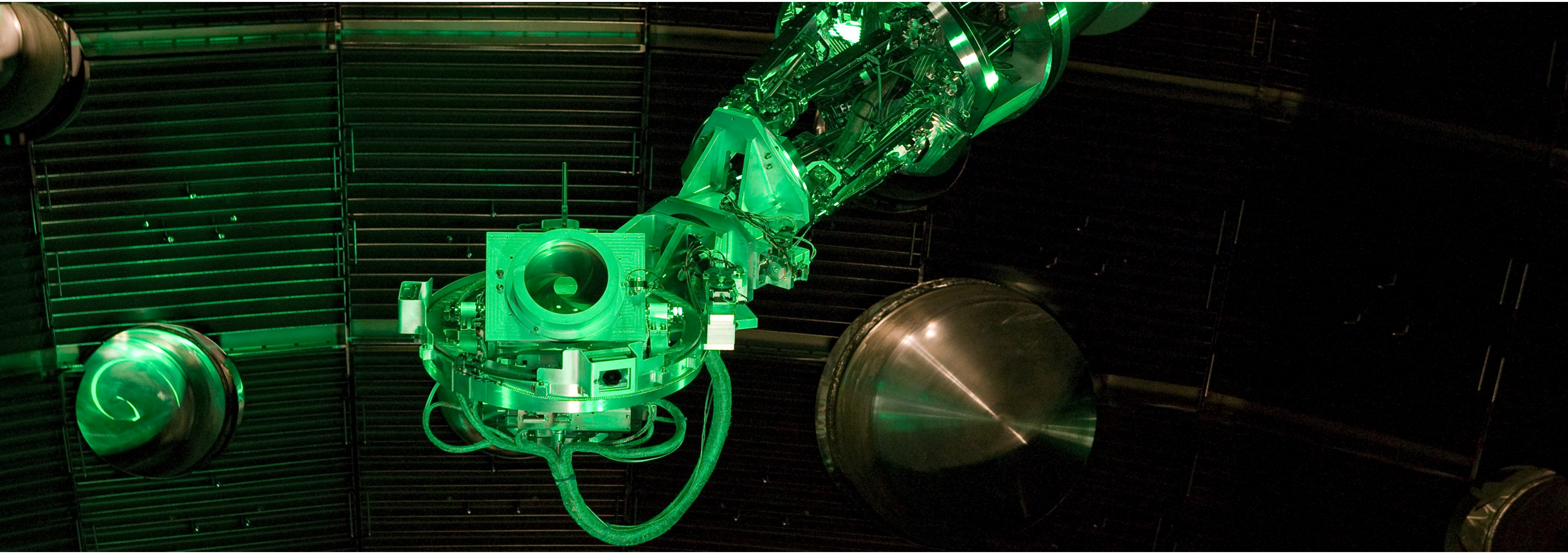
"The inventiveness and commitment of the many people over decades who made this happen never ceases to amaze me," he added. "It's been a privilege to share such a remarkable journey."

—Charlie Osolin



Alex Zylstra and Annie Kritcher in the NIF Target Bay holding a NIF target. Credit: Mark Meamber

The Age of Ignition
NIF Sustainment



NIF SUSTAINMENT: ENSURING THE NEXT 20 YEARS OF PROGRESS

Having blazed the path to fusion ignition at NIF, LLNL researchers and their collaborators are now making plans for sustained, and even higher, nuclear yields to enable and expand applications for stockpile stewardship and basic science research.

Achieving these goals will require sustained high availability of NIF, which was designed and built beginning in the mid-1990s. Much of the facility is more than 20 years old and many critical support facilities are in buildings approaching 40 years of age.

"NIF is a marvel of engineering, but it's an aging marvel," said NIF Director Gordon Brunton.

Since experiments began in 2009, NIF has been exceptionally productive and reliable. It has an experiment success rate of over 95 percent and fewer than 30 days of unplanned downtime in more than 2,400 days of shot operations.

"With more than 20 years invested in getting NIF where it is today," Brunton said, "we must prioritize restoring the workforce and facility to sustainably continue to maximize the recent outstanding results. Building on a sustained NIF, our plans for further upgrades will extend our worldwide leadership in high energy density physics and keep NIF as a flagship scientific capability of the nation for decades to come."

Deferred maintenance, obsolescence, and aging issues are pushing NIF beyond its designed operating point, which is beginning to affect performance and increasing the risks of a significant stoppage or slowdown in experimental operations. As the premier tool of the science-based Stockpile Stewardship Program (SSP) for performing experiments in the high energy density (HED) regime, this outcome would have unacceptable consequences.

To assure that NIF continues to deliver for the SSP through its design lifetime of 2040, LLNL developed a five-year Sustainment

Parts of NIF and its support facilities are decades old, including the 10-meter-diameter Target Chamber, shown being lowered into place in 1999.

Plan that identified urgent refurbishments, recapitalization, and improvements that must be addressed to sustain NIF.

"We identified 30 key refurbishment and recapitalization activities," said Jeff Horner, NIF & Photon Science chief engineer and project manager for NIF Sustainment. "Work in some areas, mostly in planning, procurement, and hiring staff is already underway. We will replace obsolete components and do some equipment hardening to tolerate the more extreme radiation environment (in high-energy-yield shots).

"Among the improvements will be simplifying the removal and replacement of components for high-yield shots to restore lost efficiency. We are in a new regime of high-yield shots that these sensitive components were not designed for," he said.

The first year, already underway, is focused on shovel-ready procurements and adding the necessary additional staff required to execute on the project scope. The second year, in fiscal year 2024, will consist mostly of planning and designing the large-scale projects. For the last three years of the plan, anticipated from fiscal years 2025 to 2027, all sustainment activities will be executed and completed.

To make this possible, there will be more dedicated maintenance time on NIF. Currently, NIF experiments are conducted five days a week, with two days devoted to maintenance and facility reconfigurations for the next week of experiments. Three times a year, longer maintenance periods are held, typically lasting two weeks.

"Maintenance of NIF has been an ongoing priority since the NIF became operational," said Brianna Arth, a deputy project manager for NIF Sustainment. "But now after 14 years of full operation, the facility has reached the age that major maintenance and refurbishment is needed."

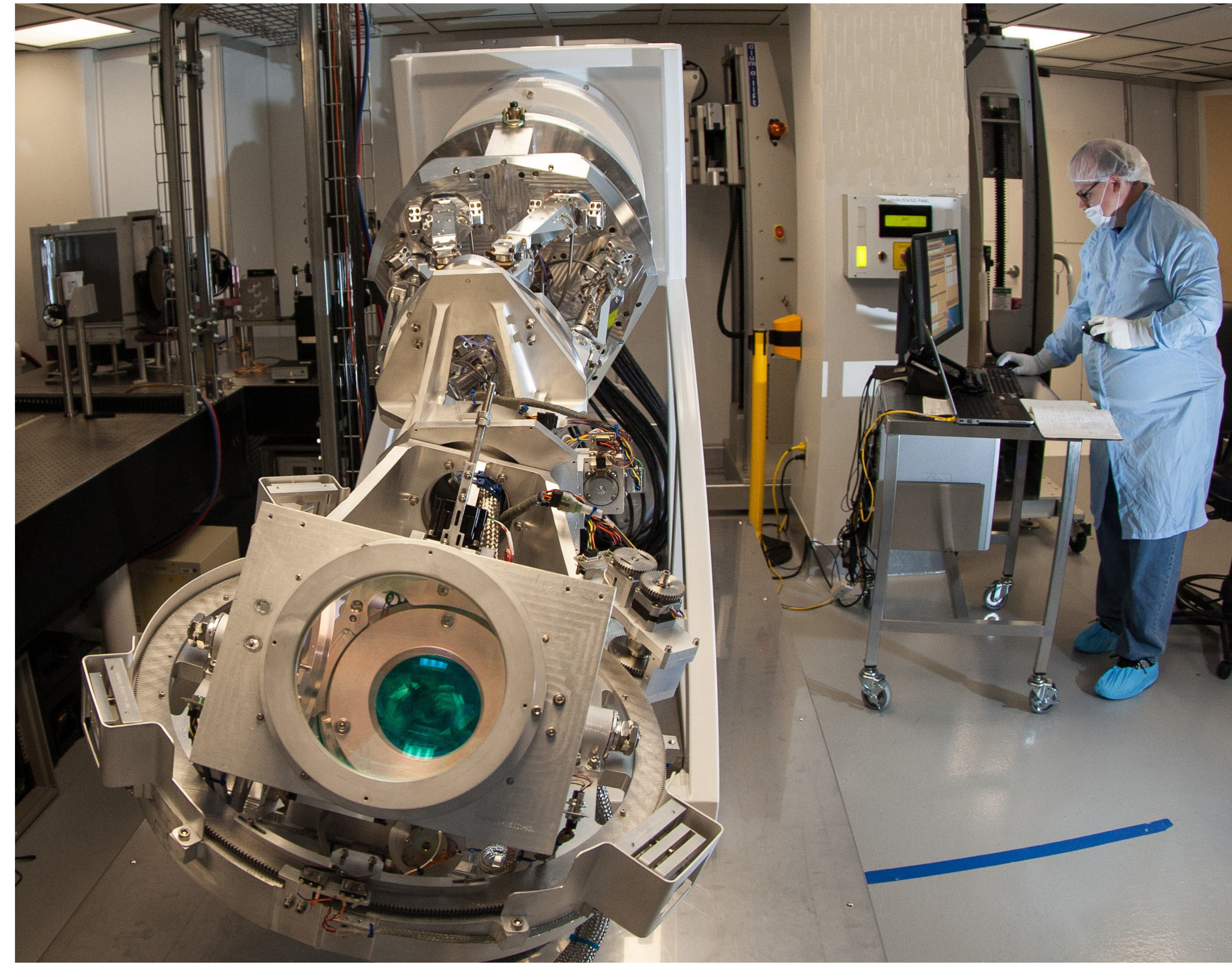
During the execution phase, additional facility maintenance time will be necessary for Sustainment Project activities that range from swapping optics to upgrading the complex control and data system. The team is currently developing plans for how much time will be necessary and to minimize the overall impact on the experimental data rate that NIF provides.

More Maintenance Time

"It's a real shift in mindset," Arth said. "For so many years, we've been focused on the shot schedule and maximizing experimental time. Now we need to find a balance that addresses the current needs of the facility. It's about setting ourselves up for success in the future, to continue doing higher- and higher-yield shots."

One of the biggest and most urgent projects on the sustainment list is amplifier refurbishment. As the world's largest optical instrument, debris is a perpetual problem for NIF. Debris can lead to increased light scatter and laser-induced damage, limiting optics lifetimes.

Of particular concern are NIF's main laser amplifiers, which serve as NIF's engine, delivering the very high infrared, or 1ω, laser energy required for every shot. The main



One planned sustainment activity will refurbish the Final Optics Damage Inspection (FODI) system to make it more radiation-tolerant and robust and to enhance performance. FODI, a complex, precision opto-mechanical telescope that examines optics between shots, can inspect optics up to 7 meters away and detect damage sites as small as 10 microns in diameter. With obsolete cameras and motion-control components and limited spares, FODI remains an ongoing single-point failure in NIF operations, resulting in more than 200 hours of delays annually. Credit: James Pryatel.

amplifiers multiply the energy of the small seed pulse that starts each experiment to an energy in the range of the 10,000 to 20,000 joules needed to convert the beams' 1ω light to 3ω (ultraviolet, or UV) light that ultimately drives the NIF targets.

"The amplifiers are essentially untouched since they were installed on NIF 15 to 21 years ago," said Harpreet Juneja, amplifier refurbishment project manager.

Each time the NIF lasers fire, flashlamps in the beamlines are energized, emitting light that is absorbed by the amplifier glass. After 4,000 shots and counting, sealant on the amplifier blast shields, which separate the amplifier slabs from the flashlamps, has begun to degrade and is depositing debris on the amplifier optics. If left unchecked, this could cause permanent damage to these unique optics.

"Elimination of the debris must be addressed in the near term to avoid the possibility of having to reduce the operating point of the NIF," Juneja said. "We're going to remove, refurbish, and replace each of the laser glass slabs. We have extra slabs in inventory, but no way to procure more of these glass slabs. So, we will be creating a recycling loop."

In addition, the blast shields will be removed and replaced. This entails purchasing

NIF's original laser glass, shown here in 2005, has not been touched since it was installed. A recycling loop for the laser glass slabs used in the amplifiers is being created to refurbish this important component.

raw material for the blast shields and coating them using an in-house technique. Work is underway on a new cleanroom facility for processing the blast shields and cleaning the amplifier glass slabs.

This is no small undertaking in a facility with 192 beamlines. Approximately 772 laser glass slabs and 1,728 blast shields need to be removed for refurbishment or replacement. Staff will work its way through the bundles of eight beamlines each over a multi-year period.

"One challenge is the volume of work. We need all hands on deck to do the removal and replacement or refurbishment," Juneja said. "Another is that much of the equipment and vendors that we used to build NIF simply don't exist anymore."

For example, the order of installing the amplifiers on NIF doesn't work as well for removing amplifiers. One project underway is to redesign and streamline the automated system that swaps line replacement units containing the amplifier blast shields.

Sustainment will also provide new opportunities for the engineering staff to shift from operations to design. The overall project will take an estimated 50 to 70 additional staff members. About half will be new hires and about half will be redeployed from existing projects.

"This is as much about staff sustainment as it is about NIF sustainment," Horner said. "I'm excited for our newer generation of engineers to have this opportunity to design and execute. I was the design engineer for the integrated optics module and had the opportunity to work on a lot of this equipment during NIF construction, and now it is their turn to deploy new and revitalized equipment."

Completion of the NIF sustainment scope over the next five years will ensure NIF can continue to operate at its current performance through the 2030s.

"NIF sustainment will lay the foundations, for both the facility and our staff, on which we plan to further extend the performance of the laser over the next decade, and push to even high nuclear yields, opening up new relevant physics and fundamental science regimes," Brunton said. "The future is bright—literally!"

—*Patricia Koning*

Afterword by Brad Wallin, Deputy Director, Strategic Deterrence

Nearly 60 years ago, John Nuckolls' vision of inertial confinement fusion set Lawrence Livermore National Laboratory (LLNL) on the course to pursue one of the greatest scientific challenges of the century. These pages detail that journey in the context of our ultimate success. It's a story about LLNL's technical excellence and perseverance achieving a truly historical breakthrough.

The achievement of fusion ignition is the pinnacle of why the Stockpile Stewardship Program was established—to advance the frontiers of our nation's science and technology capabilities to ensure the safety, security, and reliability of the U.S. nuclear deterrent. I'm incredibly excited to see how this new era of ignition will inform the future of our stockpile modernization efforts.

LLNL was founded on bold visions and the willingness to take on the toughest challenges. I want to thank all that were involved—thousands of individuals—who ensured we could reach this long-held goal. We have shown the world our fortitude and will continue to make the impossible possible.

Afterword by Jeff Wisoff, Principal Associate Director, NIF & Photon Science Directorate

I hope you are inspired by these stories about how LLNL achieved fusion ignition at NIF. These stories are only a summary of all the hard work and perseverance of many generations of scientists, researchers, and engineers who brought their diverse set of talents together to work on a greater mission that serves our nation.

I grew up in an era when our country was striving to be the first to land on the moon, another once seemingly impossible feat. The space program was very inspirational to me, and it helped bring our country together. I believe the inspirational story behind NIF's pursuit of one of the hardest engineering and scientific challenges can also become a unifying force in that it shows how working together with dedication, determination, and grit, we can accomplish amazing things.

I am proud that our teams here at NIF, in collaboration with many partners, have become the modern Prometheus, bringing the fire of the stars to Earth. But this story isn't over; we still have much more work to accomplish. It is only the end of the beginning.

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