# STEWARDSHIP SCIENCE

2024-2025

THE SSGF/LRGF MAGAZINE

## FELLOWS IN FUSION

Program alumni take part in ignition milestones at Livermore's NIF

Los Alamos: A close look at crunched crystals

Sandia: The stuff of black holes

Plus: A new way to X-ray, pressurized diamonds, microlasers on a chip; Fellows on Location; life at PNNL after the fellowship; and how playing with Play-Doh paid off

# DOE NNSA FELLOWSHIP OPPORTUNITIES

## BENEFITS

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The Department of Energy National Nuclear Security Administration Stewardship Science Graduate Fellowship (**DOE NNSA SSGF**) provides outstanding benefits and opportunities to students pursuing degrees in stewardship science areas, such as **materials under extreme conditions, nuclear science or high energy density physics.**

The fellowship includes a 12-week research experience at Lawrence Livermore National Laboratory, Los Alamos National Laboratory or Sandia National Laboratories.

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# COMPLEX SCIENCE, PLAIN LANGUAGE

WITH THIS ISSUE, *STEWARDSHIP SCIENCE* magazine celebrates its 15th birthday. When we started in 2010, the idea was to showcase nuclear stockpile-related research at the Department of Energy National Nuclear Security Administration laboratories. Although that focus hasn't changed, it has shifted over the years as the fellowships have grown. The magazine still chronicles the work at Sandia, Los Alamos and Lawrence Livermore national laboratories but is now more fellow-centric.

Volume 1, No. 1.

This shift has been made possible by the proliferation of fellowship alumni at the labs and the success of current fellows' research residencies and practicums. To wit: Our cover story, "Their Best Shot," captures the excitement and achievements of former fellows behind one of the most prominent scientific milestones in recent years: the fusion net-energy gains at Livermore's National Ignition Facility. That story begins on page 9.

That piece and the rest of the articles assembled here — and in every issue — address what *Science V. Story* (University of California Press, 2024) author Emma Frances Bloomfield describes as "a common problem for science communications." Namely, "how to make complex, technical, or otherwise restricted information accessible and relevant for public audiences."

That's precisely the philosophy behind the fellow-written essays we've included since the beginning, in which we ask writers to describe their research in a way that any curious person could understand regardless of scientific or technical acumen. In "From Play-Doh to Printed Polymers," SSGF recipient Sofia Gomez of the University of Texas at El Paso strived to do just that, drawing a direct line from child's play to her current pursuit: printing super-strong materials and analyzing them via an electron microscope. You'll find Sofia's essay on page 8.

– *The Editors, Stewardship Science: The SSGF/LRGF Magazine*

# STEWARDSHIP SCIENCE

*Stewardship Science: The SSGF/LRGF Magazine* showcases researchers and graduate students at U.S. Department of Energy National Nuclear Security Administration (DOE NNSA) national laboratories. *Stewardship Science* is published annually by the Krell Institute for the NNSA Office of Defense Program's Stewardship Science Graduate Fellowship (SSGF) and its Laboratory Residency Graduate Fellowship (LRGF), both of which Krell manages for NNSA under cooperative agreement DE-NA0003960. Krell is a nonprofit organization serving the science, technology and education communities.

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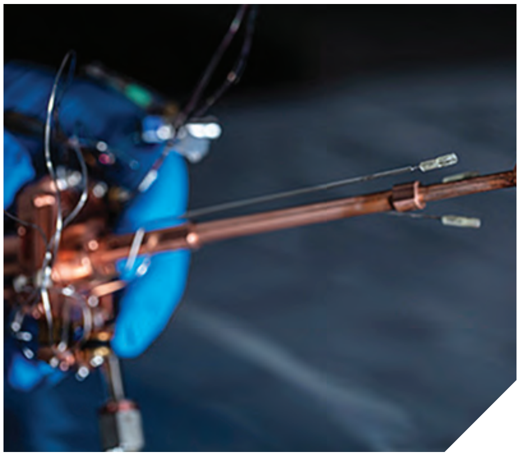
## FEATURES



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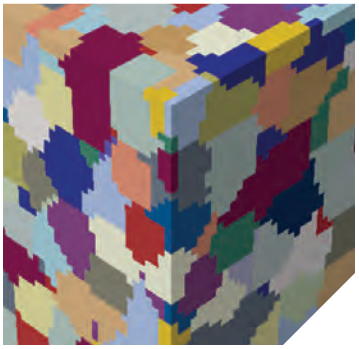

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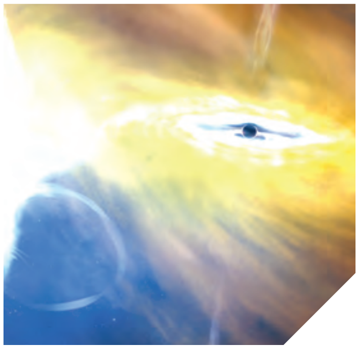

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*By Sofia Gomez*

Our 2024 Essay Slam winner studies how tiny bubbles confer great strength in 3D-printed materials.

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### OF SPLASHY LASERS AND GASES WITH PIZZAZZ

What a diverse group of fellows finishing the programs learned from working at the labs.

## ON THE COVER

An artistic rendering of 192 laser beams converging to heat a cylindrical gold hohlraum, which emits X-rays and implodes a fuel capsule to produce a fusion reaction. In December 2022, researchers at the National Ignition Facility achieved their long-sought goal: fusion ignition, where the energy produced exceeded the amount of laser energy used to heat the capsule. NNSA DOE SSGF and LRGF alumni at Lawrence Livermore National Laboratory contributed to this breakthrough and continue to pursue this work for national security and fusion energy applications.

*John Jett and Jake Long, LLNL.*

## A SHARPER IMAGE FOR X-RAYS

A new X-ray spectrometer that microscopically analyzes material samples promises advances in nuclear safety, semiconductor design, geology, environmental science, forensics and materials engineering.

Developed at Los Alamos National Laboratory to sniff out uranium and other actinides, the tool, a detector called HXI (for hyperspectral X-ray imaging), can sharply delineate and spatially map each element. It's also the first detector to perform chemical state analysis, or how atoms are bound together into molecules.

What's more, HXI can identify a greater range of elements than the two most widely used X-ray device types: wavelength-dispersive spectrometers (WDS) and energy-dispersive spectrometers (EDS).

The advances landed Los Alamos and the detector a prestigious 2023 R&D 100 Award.

Matthew Carpenter, a Los Alamos staff scientist and HXI team leader, explains the novelty of the instrument. "So not just seeing that there are peaks from uranium but being able to look at small changes in their heights and ratios, and those are tied to the chemical state of the uranium that gave those peaks."

Researchers using HXI, for example, can observe uranium and oxygen in a sample, suggesting the presence of uranium oxide — a capability that offers potential for detecting compounds associated with nuclear weapons development. "We can see the difference between, say, $UO_2$, $UO_3$, $U_3O_8$, and so on," Carpenter says. "That's why it's such a powerful tool."

Many approaches destroy their samples, but HXI leaves even the tiniest samples intact for further study. "We get information from the sample," Carpenter says, "but then you can pull it out and you still have the sample."

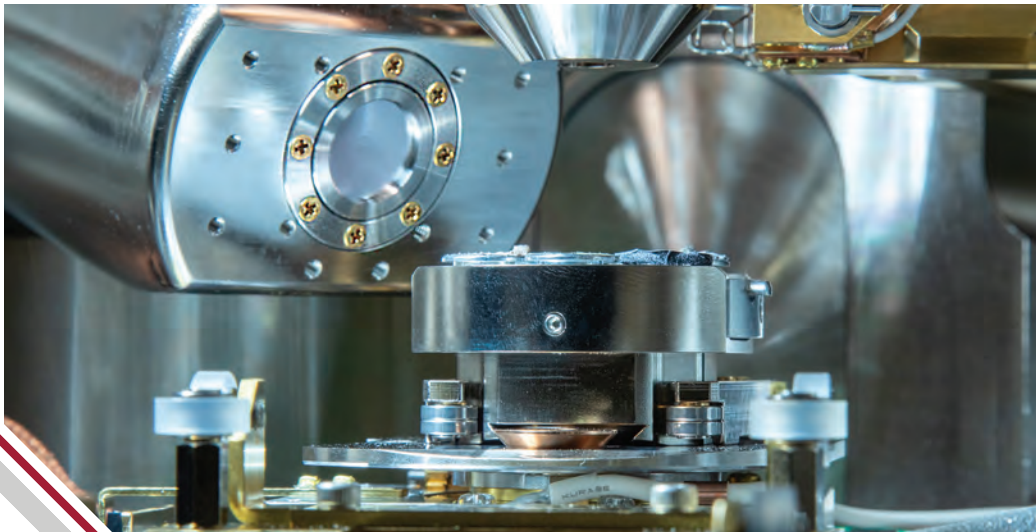
Like WDS and EDS, HXI operates with a scanning electron microscope (SEM), a combination that could fit in a two-car garage. To use each type of spectrometer, researchers place a sample under the SEM, which bombards it with electrons. Atoms in the sample undergo excitation as they absorb energy from the incoming electrons, then re-emit that energy as X-ray photons. Spectrometers use detectors of various designs to capture spectra of the X-rays, yielding information about the sample's composition.

HXI avoids the limitations of WDS and EDS. WDS renders an X-ray spectrum of sharp peaks and valleys, clearly indicating each element's presence but only in a narrow band of that spectrum. EDS captures a broad swath of the X-ray spectrum but yields rounded peaks that bury distinctions among key elements and chemical species. HXI offers the best of both approaches, delivering sharp peaks and valleys across the full X-ray spectrum.

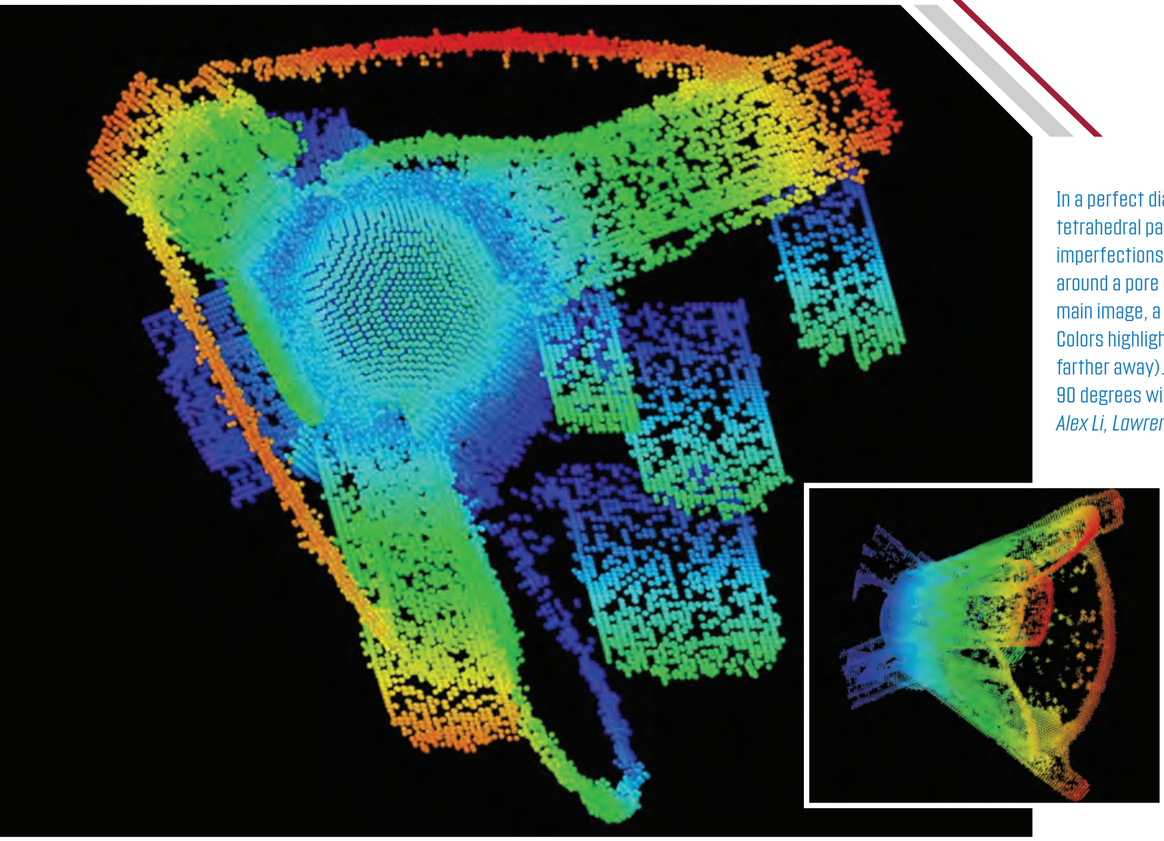
HXI accomplishes this feat with an array of microcalorimeters called transition edge sensors (TES). The name refers to the fact that each sensor is a superconductor whose temperature is held at the edge of the transition between superconductivity and normal conduction. Each sensor can detect a single X-ray photon as one photon raises its temperature above the transition edge, causing the sensor to stop superconducting and deliver an electrical signal proportional to the X-ray's energy.

Los Alamos developed HXI in collaboration with the National Institute of Standards and Technology and the University of Colorado Boulder. The team worked for years to build an array of 256 sensors, achieving the best combination of high-energy resolution and efficiency through the most compact array of microcalorimeters so far. Because TES must be repeatedly cooled to a precise temperature, a unique challenge was the design of a cryostat that doesn't require downtime to reset and stands mechanically independent of the SEM so that its vibrations do not shake the sample or sensors.

Now the team is looking for new stakeholders who may have uses for HXI, Carpenter says. "It's a question of what problems people have and what answers can we provide to them, especially on a nanoscale, that are otherwise unreachable."
– *Andy Boyles*



The hyperspectral X-ray Imaging (HXI) detector. The HXI provides ultra-sensitive elemental and chemical composition analysis for a variety of materials. *Los Alamos National Laboratory.*



In a perfect diamond crystal, carbon atoms line up in tetrahedral patterns. The colored dots highlight imperfections where carbon bonds broke and reformed around a pore defect (circular area center left). In the main image, a shock wave moves toward the viewer. Colors highlight layers of depth (red is nearby, blues farther away). The inset shows the same 3D data rotated 90 degrees with the shock wave moving left to right. *Alex Li, Lawrence Livermore National Laboratory*.

## STRESSED DIAMONDS ▸

Although diamonds are super-strong, even these crystals have limits under extreme conditions. And that feature happens to make them useful for fusion experiments and other high-energy physics applications, says Rob Rudd, a computational materials scientist at Lawrence Livermore National Laboratory. “Diamond is really interesting because it’s so hard,” he says. “It’s not a metal, but if you exert enough stress on it, it does deform.”

Today, laser windows and ablators are made from manufactured diamonds. At Livermore’s National Ignition Facility, diamond encapsulates deuterium-tritium fuel for fusion experiments. As lasers heat a walled cavity, or hohlraum, housing the diamond, the capsule absorbs laser energy, heating and pressurizing the fuel inside to drive ignition. Manufactured diamond crystals can include defects that alter the material’s shock response, Rudd notes, and these incredibly small pores can disrupt the symmetry of fusion implosions, leading to less-than-optimal results.

To better understand diamond’s behavior at pressures near its elastic limit, or a million or so times atmospheric pressure, graduate student Alex Li from the University of California San Diego carried out detailed simulations of diamond under these conditions. Previously, researchers observed that diamond’s shock response varied depending on the direction of the incoming shock wave. In this study, they added tiny pores and examined the impacts of shockwaves at different orientations. “Voids can act as stress concentrators,” Li says, “and that leads to these dislocations forming earlier than you would have expected.”

They simulated three different shock orientations and observed that 70 gigapascal shocks in one orientation led to a variety of dislocations, including rectangular ones emanating from the void and a cone-shaped area of maximum shear stress. Similar shocks in other orientations never exhibited cracking at all or only fractured at significantly higher pressures.

The simulations helped identify the amount of stress required to make compression irreversible and damage the diamond. They confirmed those results with experiments at the University of Rochester’s Omega Laser Facility. Their results were published in the journal *Matter* in September 2023.

Li continues to explore how void size affects how dislocations form in diamonds, and the results could contribute to a predictive model of the material’s plasticity under extreme conditions. The ongoing work is funded by a Livermore laboratory directed research and development grant examining materials dynamics, especially using X-ray free-electron lasers, such as those at the Linac Coherent Light Source at the SLAC National Accelerator Laboratory, Rudd says. “I’m hoping that Alex’s simulations are going to inform some very exciting experiments.”
– *Sarah Webb*

## ILLUMINATED DATA ▸

After a long effort that surmounted technical obstacles, researchers at Sandia National Laboratories have fabricated novel microchips that use light to move data more quickly than possible with the usual electrons.

This could lead to futuristic, fast and energy-efficient microscale devices, says Ashok Kodigala, a Sandia staff scientist and co-inventor of a patented heterogeneous integration process for combining multiple materials and classes of devices into optical microchips, or photonic integrated circuits.

"If you have a lot of information that you want to get across from one place to another, then you're going to use photonics," Kodigala says. That's because conventional microelectronics have intrinsic speed limits in the movement of information along highways made of copper wires.

But fiberoptic cables — the superhighway equivalent available in photonics — have fewer such barriers. So, he notes, "there's really nothing stopping you."

Unlike electrons, light can multiply the information it carries because it can simultaneously exist as many different color frequencies in the same fiber pipeline. "If you have three channels available for electronics you may have 100 channels for photonics, with each channel at faster data rates."

The practical implications: future data centers that operate at optimal energy efficiency, super-portable biochemical sensors, and versatile radars and other advanced defense technologies. Coaxing integrated circuits to process light adds manufacturing challenges, says Patrick Chu, co-leader of the National Security Photonics Center, housed within Sandia's Microsystems Engineering Science and Applications Complex in New Mexico.

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This is because microelectronic circuits are built on wafers made of silicon atoms, which unfortunately are very poor light emitters, Kodigala says. "Figuring out the fabrication processes for that was the challenging part."

To add light-friendly materials, his team had to fuse or bond-in semiconducting compounds having different properties from silicon. This began with the light sources — tiny but powerful lasers made from both silicon and other semiconductors such as indium gallium arsenide phosphide or indium phosphide.

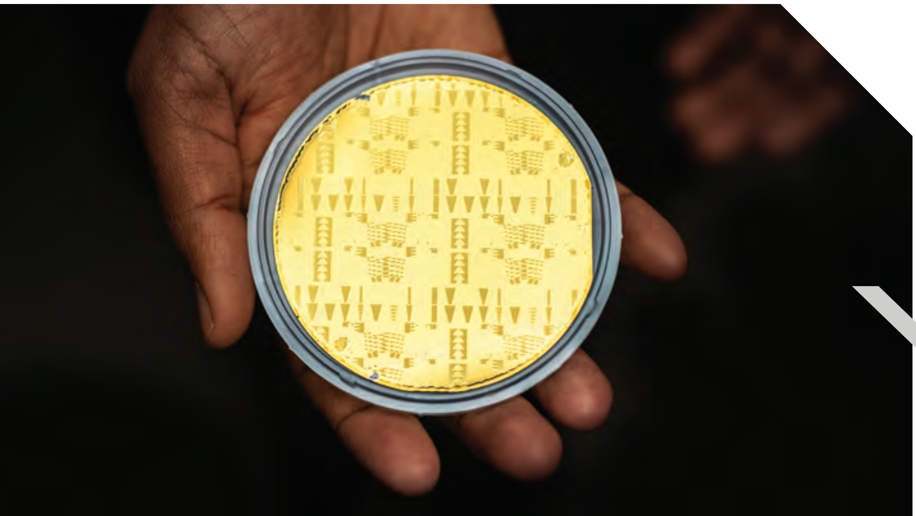
Such hybrid microlasers can function by generating coherent light inside their cavities, Kodigala says. "That's really why this heterogeneous approach exists, so you have the best of all worlds, filling in for all the weaknesses."

Kodigala's team has also developed other components needed for a working photonic circuit to help embedded lasers operate at high data-transfer rates. One is an amplifier, also made of indium phosphide, that can boost the light source, Kodigala says.

The laser beam carries the encoded information. That's done with another device called a modulator, made of another material such as lithium niobate. Modulators, Kodigala says, can "shutter the light on and off in a variety of schemes, like in Morse code fashion. That has to be at high speed. And the faster it goes the more information gets encoded or the higher the data rate."

A third device is a photon-absorbing detector, made of materials like germanium and designed to keep pace with the modulator. "If it can't keep up then that information is lost," Kodigala says.

Not least, a fourth vital part — the low-loss acousto-optic isolator — is what Kodigala describes as a one-way traffic stop for the light that keeps backscatter from getting into the laser. "It's typically a bulky device not integrated on a chip; however, we have fully integrated this device such that it is compatible with other photonic components developed here."
*– Monte Basgall*



More than a thousand experimental lasers and amplifiers adorn a three-inch, gold-electroplated silicon wafer made at Sandia National Laboratories' Microsystems Engineering, Science and Applications complex. *Craig Fritz, Sandia National Laboratories*.

# A MEETING CALLED WANDA

*Stephanie Lyons (SSGF, 2010-2014) is a Pacific Northwest National Laboratory physicist specializing in radiation detection, with applications in astrophysics and nuclear nonproliferation. Before moving to Richland, Washington, to join PNNL in 2019, she got her Ph.D. at the University of Notre Dame (2016) and was a postdoctoral researcher at Michigan State University's National Superconducting Cyclotron Laboratory. Her conversation with* Stewardship Science*'s Sarah Webb has been edited for space.*

What is your day-to-day work like?

My work, in the ultra-low background detection group, varies dramatically, from writing papers or development documents for new projects to hands-on work testing equipment and characterizing detectors. Sometimes I'm building partnerships with other laboratories to work on solving some of the most difficult problems we face.

How has your training supported your career?

During my graduate work, I learned a lot about making nuclear data measurements and working with different types of radiation detectors to understand astrophysical data. And as a postdoc, I worked with short-lived isotopes, doing beta decay and indirect methods for neutron-capture measurements, and I still collaborate with that group today. There, I applied my graduate work to a new problem set. And that has been the key at PNNL, adapting my knowledge to multiple multifaceted problems and working with chemists, physicists, environmental scientists and more every day to solve complex national security problems.

What are some of those PNNL projects?

One is stewarding detector capability in our Shallow Underground Laboratory, which is unique in the DOE complex. The facility shields experiments from cosmic rays and neutrons, reducing backgrounds at these levels. One of the first things I started working on was liquid scintillation counting, in which samples are mixed with a liquid that reacts with radioactive elements to produce light. Detecting that light enables us to measure the radioactivity. I'd never done this before but enjoyed developing our low-background liquid scintillation counter.

With an upcoming project, we'll be studying isotopes within the First Foods of Indigenous people (or what pre-European-contact ancestors in eastern Washington grew and ate). Researchers will take cactus samples and nearby soil samples, and we'll look at the strontium-90 content via liquid scintillation counting to improve transport models for environmental contaminants.

We also work across multiple different national security spaces, mainly nonproliferation but also nuclear explosion monitoring and nuclear forensics. With radiation detection, there are many applications.

Describe your involvement with the Nuclear Data Working Group.

In the mid-2000s, DOE researchers at the national labs and at headquarters realized that many people don't understand the importance of nuclear data and how intertwined it is with national security. Even if you're not aware of it, data get pulled from these databases all the time. The group includes representatives from any national lab that wants to participate, and we have points of contact for the various sectors or area leads at headquarters within the DOE.

Every year we gather in Washington, D.C., for a meeting called WANDA, the Workshop for Applied Nuclear Data Activities, to discuss the federal government's interests. What do they not understand? What are their nuclear data needs this year in an area such as fusion? Where are there holes in that knowledge? The working group discussions can lead directly to funding announcements for future research. It's nice to feel very integrated into that entire process.

You've also been a U.S. delegate to the International Conference on Women in Physics. How did you get started?

I'm one of a group that has ranged from five to about 12 delegates interested in advancing participation of women in physics. At the International Conference on Women in Physics, many countries' representatives might be the only female physics professor in the country. I've always been very passionate about advocacy for women in physics. When I was in graduate school, I helped found a chapter of the Association for Women in Science at Notre Dame, which remains a thriving chapter. I continued in that same vein through my postdoc and served as the postdoc representative for the diversity and inclusion committee at NSCL. More recently, my work has evolved into a more general advocacy for underrepresented groups and communities. That work boosts my performance and my morale; it makes you keenly aware that you're not alone.

How has the SSGF shaped your career and what would you advise future fellows?

First and foremost, it got me through grad school, and the opportunities and connections have sustained me. I continue to see and reconnect with colleagues from the program at conferences. The practicum experience really helped inform my next-step career decisions. It provided a specific understanding of the type of work that is done at the national labs and the pros and cons of that career path versus an academic one.

I would advocate for the approach I took: Try out a project with no relevance to your thesis work. The practicum is so short and such a unique opportunity to get the experience and learn something totally new. It will benefit you, and you will grow and become more flexible. You'll gain a better understanding of yourself and what you like to do.

# From Play-Doh to Printed Polymers

*By Sofia Gomez*

Sofia Gomez, seen here at her lab's 3D printer, won the 2024 Essay Slam contest with the accompanying piece. The author is an SSGF fellow and a Ph.D. student in mechanical engineering at the University of Texas at El Paso. *Sofia Gomez.*

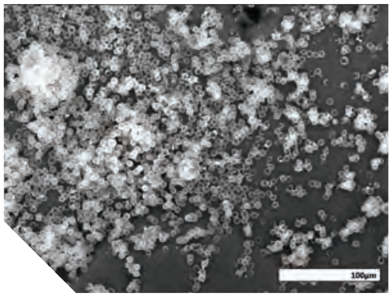
When I was in kindergarten, I made my first 3D model using the most incredible and innovative material: Play-Doh. I used my creativity to invent a very rare-looking flower, as my teacher described it. As a four-year-old, my world revolved around coloring inside the lines and snack time. Fast forward 20 years and now my world is doing a Ph.D. in mechanical engineering, and I am still creating 3D models. Except this time, I am designing them using software and building them with 3D printers, a technique known as additive manufacturing, or AM for short.

As the artist Theo Jansen has said, "The walls between art and engineering exist only in our minds." When I first started studying mechanical engineering as an undergraduate, I didn't realize that creativity would become an integral part in innovation. It wasn't until my junior year, during an undergraduate research assistantship, that I began to ask questions about the world around us, especially about the materials that have built it up. For instance, how do metals, polymers and ceramics differ in their material properties and why? I want to understand the integrity of materials — how they break and how that correlates with what they're made of.

To gain a deeper understanding of materials, I gravitated toward theoretical physics and computational science. It was a steep learning curve because I was used to courses that emphasized experiments. As it turned out, though, simulating the vibrational energies of metal alloys and observing how they were created through interatomic forces helped me understand how materials function at the atomic scale. The experience kindled a passion for materials engineering and supplied the motivation to pursue a subset of this research in graduate school.

There, I had the liberty to devise my own hypotheses and design experiments to test them. I wanted a project that included making materials from scratch, forming them, testing them and 3D-printing them — specifically, a class of materials called polymer syntactic foams. The material is of interest for its high-energy-absorbing properties, with applications in defense and aerospace. Think of syntactic foams like any household sponge but one whose pores are filled with hollow particle reinforcements, tiny thin-walled bubbles that compress when the material is squeezed and help mitigate the effects of shocks and vibrations. The pores in these polymer syntactic foams are about 20 microns across and visible only through what became my favorite piece of equipment, a scanning electron microscope.

Traditional fabrication of polymer syntactic foams is intricate and requires a mold. The microscopic bubbles are extremely brittle, so the utmost care is essential to ensure that they stay intact. This fabrication method takes about two weeks. A 3D-printing process requires no mold and can cut fabrication time in half. I can create a digital model and transfer the design to a 3D printer in a readable format. Next, I modify the file and choose the desired layer thickness and printing speed. The material, in this case liquid polymer, is extruded through a nozzle and onto a substrate. The prototype is built up layer by layer from the bottom up until it is complete. Then I heat the freshly printed structure in an oven to solidify it.



A scanning electron micrograph of the author's printed polymer. *Sofia Gomez.*

Besides learning to use 3D printers as a tool to create our components, my research has also focused on understanding the material properties of the syntactic foams before 3D-printing them. I have looked at how different hollow microspheres' volumes affect their strength. When I compared the energy absorbance of polymer structures without hollow particle reinforcements to syntactic foams, I saw that the increase in energy absorbance was over 500%. I find it incredible that these tiny spheres have such a big impact on these polymer structures.

Research to me is much more than completing experiments and documenting my findings. It has changed my way of thinking. It's made me realize that my ideas can be turned into things that are impactful to stewardship science. In graduate school, I have used my creativity to spark innovation and fill in scientific gaps. I have found a passion not only in understanding and making materials but also fabricating them using AM technologies. AM has enabled me to bring my computer models to life, not unlike my kindergarten flower — just a bit more sophisticated.

# Their Best Shot

*By Sarah Webb*

## Fellowship alumni played important roles in Livermore's ignition breakthrough and continue to drive NIF fusion research.

NIF's preamplifier support structure, colorized. *Damien Jemison.*

Just after midnight on Monday, Dec. 5, 2022, physicist Alex Zylstra was sitting on his living room sofa, waiting for results. As lead experimentalist for the Department of Energy's National Ignition Facility (NIF) shot that had been scheduled for Sunday afternoon, he had been awake since 6 a.m. working on experimental details from home.

After rounds of checks and delays, he passed time by emailing research team members, many of whom were resting for a few precious hours. Down the hall, his 5-month-old daughter snoozed in her crib.

Finally, just after 1 a.m., the shot went off. And then a setback. One of the instruments that usually reports first didn't work. "My first thought is 'oh, we messed something up,' but the initial neutron numbers looked promising," he recalls. Fusion reactions combine hydrogen isotopes to produce helium and neutrons. More neutrons mean more atoms are fusing.

Zylstra, who from 2009 to 2013 was a DOE National Nuclear Security Administration (NNSA) Stewardship Science Graduate Fellowship (SSGF) recipient, called nuclear diagnostics lead Dave Schlossberg. "I woke him up." Zylstra was nervous and wanted to make sure that the information was consistent before the team saw it later that morning. Next, he texted lead designer Annie Kritcher. "Looks like we got target gain," shorthand for more fusion energy produced than the laser put in. Then he emailed the rest of the team.

Zylstra then poured himself a celebratory glass of wine and attempted to sleep. Forty-five minutes later his daughter woke up. He suspected she was excited, too.

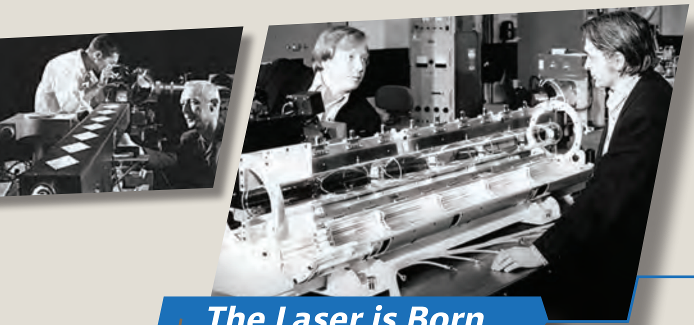
That was just the beginning of a whirlwind week of meetings, discussing data and diagnostics, and working with scientists inside and outside Livermore's fusion team to check the results.

The next week, Zylstra was in Washington for Secretary of Energy Jennifer Granholm's announcement that Lawrence Livermore National Laboratory, where NIF is based, had achieved the first experimental fusion ignition. Soon he was in a roomful of reporters talking about the results.

In that shot, NIF's cavernous laser facility centered X-ray pulses from 192 lasers — 2.05 megajoules of energy — on a cylindrical gold vessel, a hohlraum the size of a pencil eraser. Inside a tiny spherical diamond capsule filled with hydrogen fuel, a mixture of deuterium and tritium isotopes, was heated and compressed (imploded) until it ignited, burned and exploded. The fusion reaction produced 3.15 MJ — 1.5 times the energy delivered from the lasers.

Ignition — defined as more fusion energy released than the lasers put in — culminated decades of physics research. Even once NIF was

## IGNITION: A BRIEF HISTORY



### The Laser is Born

*In **1958**, Arthur Schawlow and Charles Townes publish the first detailed proposal for a laser, then called an optical maser. In **1960**, a small group led by Livermore physicist and future director John Nuckolls use computer codes to outline the basics of inertial confinement fusion, showing that radiative heating of deuterium-tritium fuel could initiate a small-scale fusion explosion.*

### Stating Fusion Ignition's Case

*In **1972**, Nuckolls and colleagues published a Nature paper, describing fusion ignition via laser compression, a chain reaction where alpha particles reheat the fuel and continue the process. LLNL soon developed major laser systems such as Janus, Argus, Shiva and Nova, predecessors to NIF.*

completed, the research took more than a decade of twists and turns. Thousands of people have worked on NIF programs, hundreds have supported the recent experiments that led to this result, and scores of scientists, engineers and technicians were involved directly in the historic experiment.

Zylstra represents a subset of NIF researchers: DOE NNSA SSGF alumni and others from its newer, sister program, the Laboratory Residency Graduate Fellowship (LRGF). The work continues as program alumni contribute to support the NNSA's national security mission and research toward building fusion energy plants.

NIF's work to achieve fusion ignition has been both a scientific and a national security grand challenge. In 1997, NIF construction began to study high energy density physics and support stockpile stewardship, a program to maintain the safety and effectiveness of nuclear weapons after the nuclear test moratorium in 1992. NIF experiments are thermonuclear reactions in a laboratory — an important tool in maintaining the country's nuclear deterrent.

Fusion reactions combine the positively charged nuclei of smaller atoms to make heavier elements. Electrostatic forces tend to drive like charges apart, but with enough kinetic energy to smash them together, the nuclear force binds the nuclei together and releases energy. With enough energy output, the process can sustain a chain reaction, which can produce an explosion or be harnessed to produce electricity.

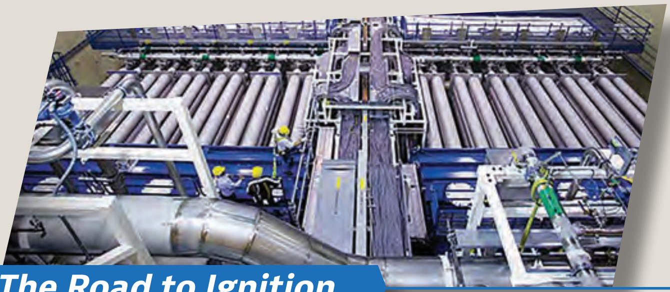
NIF's method is inertial confinement fusion (ICF), in which a powerful driver heats and compresses fuel-filled targets to drive fusion reactions. It's just one of a suite of physics approaches for carrying out fusion reactions.

Optimizing ICF experiments is an exercise in balancing pros and cons. Maximizing energy can mean having less control over where it's deposited. For example, one ICF approach is direct drive, aiming lasers directly at a fuel-filled capsule, which maximizes energy transfer but requires narrow lasers with impeccable aim.

NIF uses indirect drive, which reduces energy efficiency because a heavy metal hohlraum encases the capsules and initially absorbs the laser energy until it emits X-rays to heat the fuel. NIF also uses hot-spot ignition, a process of carefully balancing laser pulses and shock waves to produce symmetrical implosions where energy is concentrated at a central point in the fuel capsule. Indirect drive produces a bath of X-rays that are more symmetrical.

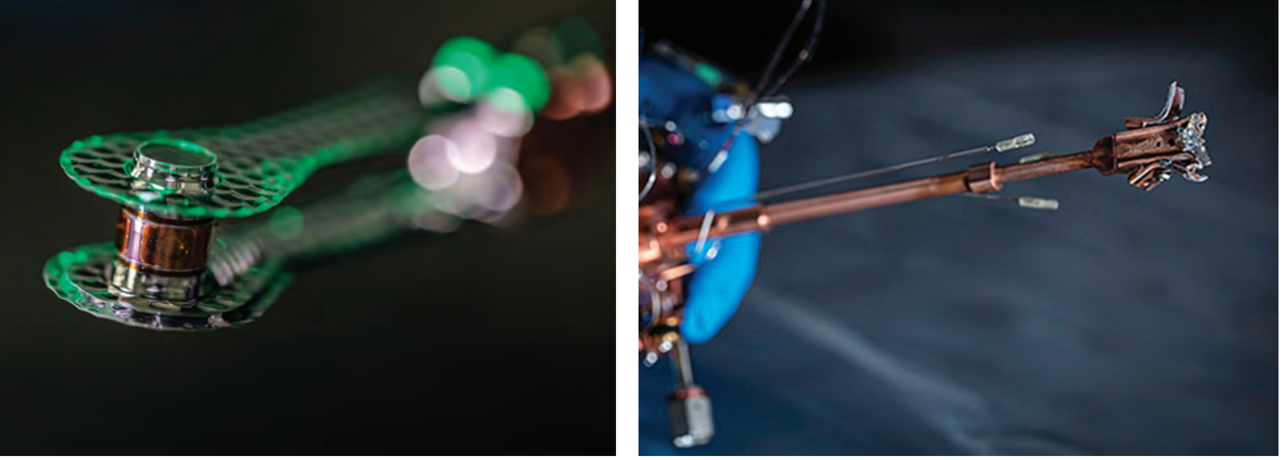
## NIF's Conception

*In **1994**, two years after the nuclear test moratorium, a National Ignition Facility is proposed as part of the Stockpile Stewardship and Management Program. The facility, says its advocates, will carry out experiments to confirm data from large-scale computer simulations.*



## The Road to Ignition

*In **2009**, a dozen years after NIF's official **1997** groundbreaking, NIF is completed and its first test shots are fired. On **August 8, 2021**, NIF achieves an energy yield of 1.3 MJ, 25 times more than previously observed. This experiment was widely reported at the time as near-ignition. **Dec. 5, 2022**: the historic ignition shot that produced more energy than the lasers supplied.*



A NIF target (left) before an experimental shot and (right) after the facility's milestone ignition shot. The cylinder is a centimeter-wide hohlraum that contains a fuel capsule just millimeters in diameter. *Lawrence Livermore National Laboratory.*

NIF researchers often describe their work as a juggling act, adjusting to maximize energy yield, a process that has been honed since the facility became operational in 2012. As NIF designer Chris Young (SSGF 2011-2016) says, "A ton of my time, thought and effort right now just goes into understanding how do we walk that tightrope of balancing all the different factors to make sure the fuel still ignites, while pushing things right up to the edge of failure to get the highest possible performance out of the ICF targets."

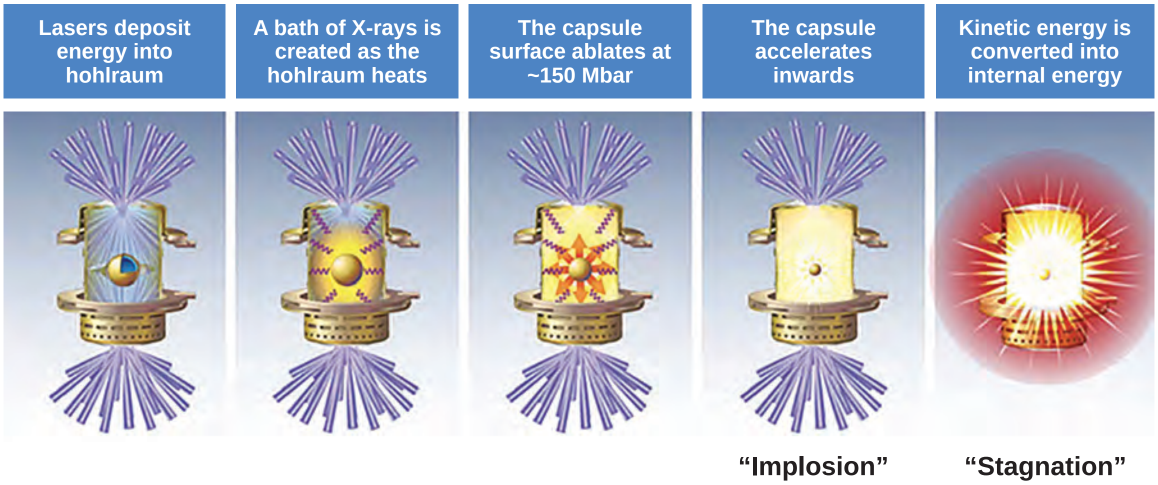
Leading up to 2017, changes in hohlraum design, laser pulse design and target materials contributed to improved performance. With target modifications and shorter laser pulses, researchers could maintain symmetry, allowing more laser energy to be absorbed by the target. Through improved production processes, high-density carbon capsules — the manufactured diamond used today — also had sufficiently smooth surfaces to be used in ICF experiments. That innovation has carried through to today's target designs. Former NIF designer Laura Berzak Hopkins (SSGF 2006-2010) had a key role in that work. (See sidebar, "Designer Targets.")

Zylstra came to Lawrence Livermore National Laboratory in 2018 after several years at Los Alamos National Laboratory, but he'd been working on NIF in various roles since 2009, while he was in graduate school. One of his initial projects was to work on the Hybrid E campaign, which explored early diamond capsules and the parameters needed to manage the implosions. They employed laser beams at different wavelengths, which helped control implosions. But these capsules were larger than later designs and could have many small defects that could affect implosion quality.

Fellow SSGF alumnus Young joined the ICF program in late 2016 just after completing his Ph.D. at Stanford University. He became part of Kritcher's design team in 2019. Designers combine complex plasma physics simulations and theory with data from experiments to engineer the extreme conditions that can support fusion. Their team helps to define the parameters that experimentalists like Zylstra and the facility engineers use to carry out NIF shots.

In November 2020, Young designed a shot that briefly held the facility record for energy released at approximately 100 kilojoules. In that experiment, the team achieved burning plasma for the second time in a few weeks. A burning plasma is one where the fusion reaction itself becomes the primary reaction heat source. Less than a year later, in August 2021, the team hit a yield record: 1.3 MJ from a laser input of 1.9 MJ. This result crossed an important physics threshold known as the Lawson Criterion and was described in the media as "near-ignition." The team had yet to reach ignition as defined by the National Academy of Sciences: one that produces more energy than the laser delivers.

But they were close. The team focused on exactly what it would need to pass the ignition threshold, Zylstra says. They started with the lasers. "Can you give us a little more?" Zylstra asked the laser team.



How laser-driven inertial confinement fusion works at NIF. Purple lines represent laser beams that produce X-rays within the cylindrical gold hohlraum. The implosion process produces conditions like those at the center of the sun and other stars. *Lawrence Livermore National Laboratory.*

Kritcher, Young and the design team had to figure out how to use that extra energy. They zeroed in on testing thicker capsules to help with confinement. In these experiments, the goal was to compress symmetrically, ignite the fuel and hold it together long enough so it could burn up in a runaway process before exploding. “Just tiny, tiny bits matter,” Kritcher says. “Getting a little bit more confinement actually helps you burn up quite a bit more fuel.”

With thicker capsules, they reasoned, the added laser energy could couple more energy to the implosion and harness its kinetic energy “like a spherical rocket,” Young says. But a thicker capsule also made maintaining the spherical symmetry more challenging and slowed the implosion, which could decrease the yield.

Using those thicker capsules, a second shot in September 2022 exceeded 1 MJ. But the symmetry of the implosion was flattened rather than spherical. “We didn’t quite get the shape,” Zylstra says. “We knew we could fix that.” Another shot was added to the schedule for the first week in December — the shot heard ’round the fusion world.

Berzak Hopkins suggests that NIF earned its middle name because of another “I” word: integration, of laser beamline technology, optics assembly materials, facility diagnostics, high-performance computing and codes, and target fabrication. “Ignition to me represents this grand integration of knowledge, skills and capabilities.”

Now that NIF has achieved ignition, it is fulfilling its original promise and its NNSA mission of, as Kritcher puts it, “bringing our A-game to the stockpile stewardship program effort.”

Berzak Hopkins, who is now Livermore’s associate program director for integrated weapons science, says that studying how neutrons with ignition-level energy interact with various materials, components and structures is helping with the lab’s weapons-survivability mission. “As we continue to push ignition to higher levels, we increasingly open space to a broad range of weapons science and material and physics processes accessible in no other facility.”

Four subsequent experiments — one in July 2023, two in October 2023 and one in February 2024 — have achieved ignition either by repeating the first ignition experiment or with design changes. The first shot repeated the December 2022 experiment and increased the target yield to 3.88 MJ. In early October 2023, the team carried out a shot using less laser energy (1.9 MJ) and a capsule design closer to the 2021 then-record shot. By optimizing the compression, Kritcher notes, their team achieved 2.4 MJ. Later that same month, the team used higher energy, 2.2 MJ, and achieved 3.4 MJ. The February shot used that higher laser energy to achieve an even greater yield: 5.2 MJ.

## DESIGNER TARGETS

When Laura Berzak Hopkins (SSGF 2006-2010) joined Livermore’s NIF ICF team in 2012, she says, “I dove right into design work, and one of my initial projects focused on shock timing.” Shock timing determines the level of compression achievable in the capsule implosion, a feature that researchers want to keep as close to spherical as possible. It also helps control an implosion’s performance.

Berzak Hopkins also supported neutron diagnostics development, designing a new NIF target — the indirect drive exploding pusher (IDEP) — that minimized neutron scattering from the capsule itself and improved diagnostics calibration and scattering-measurement accuracy in high-compression targets.

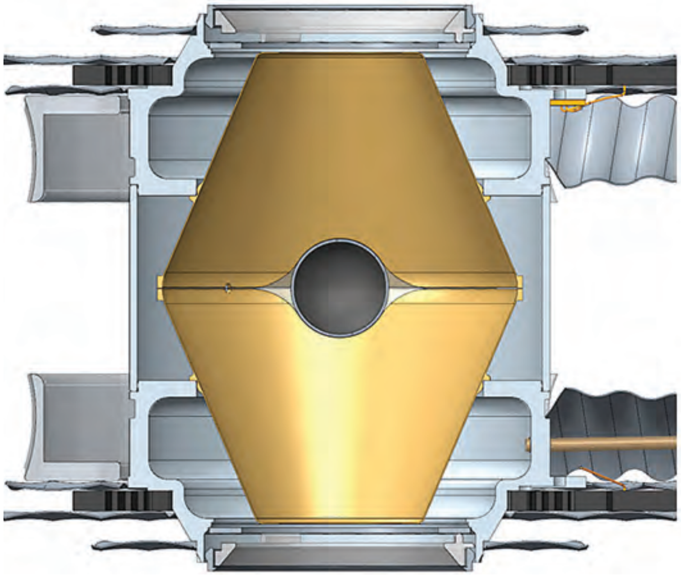
ICF teams had used designs that jammed hohlraums with gas — helium — at high pressure to help maintain the laser propagation. The IDEP target had a thin plastic shell and used just a little gas. The shell was ablated using nanoseconds-long laser pulses. It turned out that low helium increased the laser-target efficiency by 20% and produced results that better matched simulations. The results led to reduced gas use.

Target development research also had advanced so that manufactured diamonds, or high-density carbon (HDC), were now smooth enough and their crystals could be grown to the right size and thickness for capsules. Because diamond’s density is three times higher than plastic’s, the team could wed this new material with the strategy of lower hohlraum gas-fill densities and short laser pulses. With more energy available, maintaining implosion symmetry became challenging, and Berzak Hopkins developed time-dependent strategies for balancing laser power at different intervals during the laser pulse. In 2017, a record-breaking shot Berzak Hopkins designed exceeded $10^{16}$ neutrons in yield. Products from the fusion reaction were now heating the capsule fuel directly, a benchmark known as alpha heating.

Berzak Hopkins recalls that time before HDC capsules became standard as one of angst and frustration about the progress toward fusion. “That was really an incredibly exciting shot. My baby was the low-fill hohlraums and HDC capsules, and now my baby is all grown up.”

Above: The graph shows how today's energy yields from NIF are already advancing the understanding of radiochemistry and X-ray effects (left) with ignition (golden orb, center). Higher yields (upper right) will offer unprecedented opportunities to test materials and explore physical phenomena under conditions that researchers previously could not achieve. *Lawrence Livermore National Laboratory.*

Below: The frustraum is an advanced hohlraum design that researchers are testing at NIF. The wide-bodied shape makes it more energy-efficient than a cylinder with more wall area. It also can hold a larger fuel capsule (central dark sphere) than current designs. This and other new designs could help boost fusion-experiment energy yields. *Scott Vonhof/Lawrence Livermore National Laboratory.*



That press forward has left little time to relax, Kritcher says. "The call is always for more energy." Nearer term goals are to push the energy yields into the tens, eventually hundreds, of megajoules, an arena that could yield insights about dense plasma physics, weapons science, astrophysics and more.

Many factors drive successful ICF implosions, but the upper limit is set by the amount of laser energy NIF can provide. Researchers also can increase yields through energy-efficiency gains, with advanced hohlraum designs or even incorporating magnetic fields.

Livermore scientist Hong Sio (SSGF 2012-2016) is working on some of these strategies. For example, he's part of a team studying an advanced hohlraum design, the frustraum, that replaces the traditional gold cylinder with a tapered shape that widens at the center. With less wall area than its predecessors, the shape is more energy efficient and can accommodate a larger capsule. If this or other advanced designs could boost efficiency by even 15%, Sio notes, it effectively increases NIF laser energy by as much.

Adding magnetic fields to ICF experiments also could boost energy yields by trapping charged particles inside the implosion, which would slow heat loss. With extra thermal energy in the hot spot, the fuel would more readily ignite. The magnetic field also traps the deuterium-tritium alpha particles generated from the fusion reaction, which in turn adds their energy to the hotspot, making the reaction hotter still.

To test how this might work on NIF, Sio and his colleagues have run room-temperature magnetized ICF experiments. Applying a strong magnetic field, around 25 tesla, to these so-called warm implosions, the fusion yields increased up to three-fold and the ion temperature was 40% higher, Sio says. They published their findings in the journals

*Physical Review Letters* and *Physics of Plasmas*. The results support further research to build a new magnetic target that can be cryogenically cooled to NIF's far-chillier 18 degrees kelvin.

Besides supporting stockpile stewardship and basic high energy density physics research, ignition has nudged fusion energy from the realm of science fiction toward a new grand challenge: commercial inertial fusion. An energy plant would need to fire shots up to 10 times per second, round-the-clock, a feat far beyond today's technology.

Public and private funds are being invested in energy projects, at Livermore and elsewhere. In May 2023, DOE pledged $46 million for eight companies working on designs for fusion energy power plants. Two of them are focused on inertial fusion. Later that year, DOE announced another $42 million for three multi-institutional and multidisciplinary research centers in inertial fusion energy science and technology at Livermore, Colorado State University and the University of Rochester. According to a 2023 report, fusion energy companies' funding now exceeds $6 billion, with more than 90% coming from private sources. In fact, in late 2023, Livermore's Zylstra took a research position at a fusion-energy startup company, Pacific Fusion. Recent LRGF alumni Will Riedel and Raspberry Simpson — each finished the fellowship in 2022 — are working on fusion energy at Livermore. (See sidebar, "A Path To Power.")

When Simpson wrote her winning Lawrence Fellow research proposal in 2021, she included many different applications of laser-driven proton sources. One was heating fusion fuel for a power plant, which even that recently seemed like a far-off idea. "This would be cool if there's interest around fusion energy," she recalls thinking. Ignition changed the game. Simpson's postdoctoral advisor, Tammy Ma, now leads Livermore's Inertial Fusion Energy Program, and Simpson is actively working on this project.

The fast shift highlights both the challenges and opportunities that come in a post-ignition research landscape. Planning fusion's future will involve new questions for the incoming generation of plasma physicists, says Pacific Fusion's Nathan Meezan, a former LRGF steering committee member and 18-year NIF veteran. Instead of pushing toward the ignition goal, the question becomes "okay, well, what do we do now?"

To reach higher energies, will the next generation of fusion scientists upgrade NIF, build a bigger NIF or propose other fusion approaches? "We need them to help us figure out what to do next," Meezan says. "It's actually a different problem, and I find that really exciting." SS

## A PATH TO POWER

NIF can fire several shots a day. But to sustain a fusion energy power plant, implosions must happen about 10 times each second nonstop. With a laboratory directed research and development grant, Livermore is self-funding several ways to tackle this challenge, from improving hohlraums and implosion schemes to designing cheaper targets.

One possible approach for a fusion plant is to use fast ignition, a concept developed at Livermore by Max Tabak in the early 1990s, instead of hot-spot ignition, currently used on NIF. "You can think of the differences like the differences between a spark plug versus a diesel engine," says Raspberry Simpson. Fast ignition uses separate lasers (the equivalent of a spark plug) to heat the fuel (like a gas engine) while NIF's hot spot ignition relies on compression heating (similar to a diesel engine).

Simpson worked on laser-driven proton acceleration with Livermore's Tammy Ma during her LRGF residencies (see 2022-2023 *Stewardship Science*, "Laser Focused"). Now as a Lawrence Fellow, she's applying that work to fusion energy, as part of a laboratory-directed research and development strategic initiative. NIF's hot spot ignition requires aiming large lasers with nanosecond pulses to heat and compress the fusion capsule simultaneously. Fast ignition separates the heating and compression steps. Simpson's part of the problem is how to use laser-driven proton sources to heat compressed deuterium-tritium fuel.

Negatively charged electrons also could be useful for fast-ignition heating, and Livermore postdoc Will Riedel is working on that part of the puzzle. He specializes in simulating heat transport in fusion plasmas, and he's been examining whether electrons could be used as the charged particle source instead of protons. He's also looking at innovative ways to control those beams.

"There's still a huge ocean of work between where we are now and some hypothetical fusion energy power plant," Riedel says. "But it's really exciting to show that it's doable."


John Shimanek.

# YIELD SIGNS

Working at Sandia and Los Alamos, a fellow searches the atomic scale for clues about how crystals deform.

*By Mike May*

A mechanical engineer designing a girder for a structure ensures that it won't yield under the anticipated stress and strain. John Shimanek, a doctoral student in materials science and engineering at Pennsylvania State University, wants to know more. "We're concerned about what happens past yield — when the component starts to deform in a way that it won't spring back from," he says. "There's a lot of complex physics going on, and we wanted to get some insight into that."

Now in his final year of a Department of Energy National Nuclear Security Administration Stewardship Science Graduate Fellowship (DOE NNSA SSGF), Shimanek explains some of his approach to exploring what happens after a material yields. "We use a very low-level technique to get very accurate atomic-level information about the nature of how things deform in an ideal sense," he says. "Then we use some elastic arguments to try to scale that up to how it would deform in a realistic sense."

As part of his fellowship, Shimanek participated in two practicums: 2021 at Sandia National Laboratories and 2022 at Los Alamos National Laboratory, a collaboration that continues. He calls both practicums a great experience. "The main benefit is that it really closely connects you to work going on in the national labs, and I wouldn't have been supported to do that without the fellowship."

Shimanek takes various approaches to understanding the atomic-scale behavior of materials. Working with Ph.D. advisors Allison Beese and Zi-Kui Liu, both Penn State professors of materials science and engineering, Shimanek modeled the plasticity of single-crystal, nickel-based alloys.

One way to look at this is through slip systems, which Shimanek says is "a common view to take when you're talking about how deformation happens at a lower length scale, like microns." At that scale, metal has wood-like grains. "All of the atoms are oriented in a certain way, and in the next grain they might be oriented in a different way." Within any one grain in a metal, some planes made up by the atoms deform more easily than others. That's a slip system.

For simplicity, imagine two sheets of atoms as one carpet lying on top of another, with bonds connecting them. To slide one carpet over the other, all of the bonds could break at once, allowing the carpets to move — or slip — and then new bonds would form. "That's really hard to do," Shimanek says.

Instead, the top carpet could be moved over the other incrementally. A little roll in the top carpet — a place where bonds broke and the carpets separated — could push from one side of the top carpet to the other, like a wave moving in the ocean. "That little roll would be analogous to a crystal dislocation," Shimanek says. "It's not the whole thing slipping, but one little band breaking at a time and going through the material on that plane." That's how grains move relative to each other in a crystal.

To find out more about slip in crystals, Shimanek took a first-principles approach using density functional theory (DFT), which is a method of modeling the ground-state electronic structure of a material. Later, he applied a variety of approaches to simulate mechanisms of yield across a range of scales.

"I started off with atomistic simulations — almost the smallest scale you can go to," he says. "Then you try to build that up from a single crystal, which is about a one-micron scale, to multigrain things, which are around a few hundred microns."

A slip system links information across all of these scales and explains what features of the material determine when it will yield. As one example, Shimanek and his colleagues found that features of the atoms, such as size and electronic properties, strongly impact when a material will shear, which is basically one layer sliding over another.

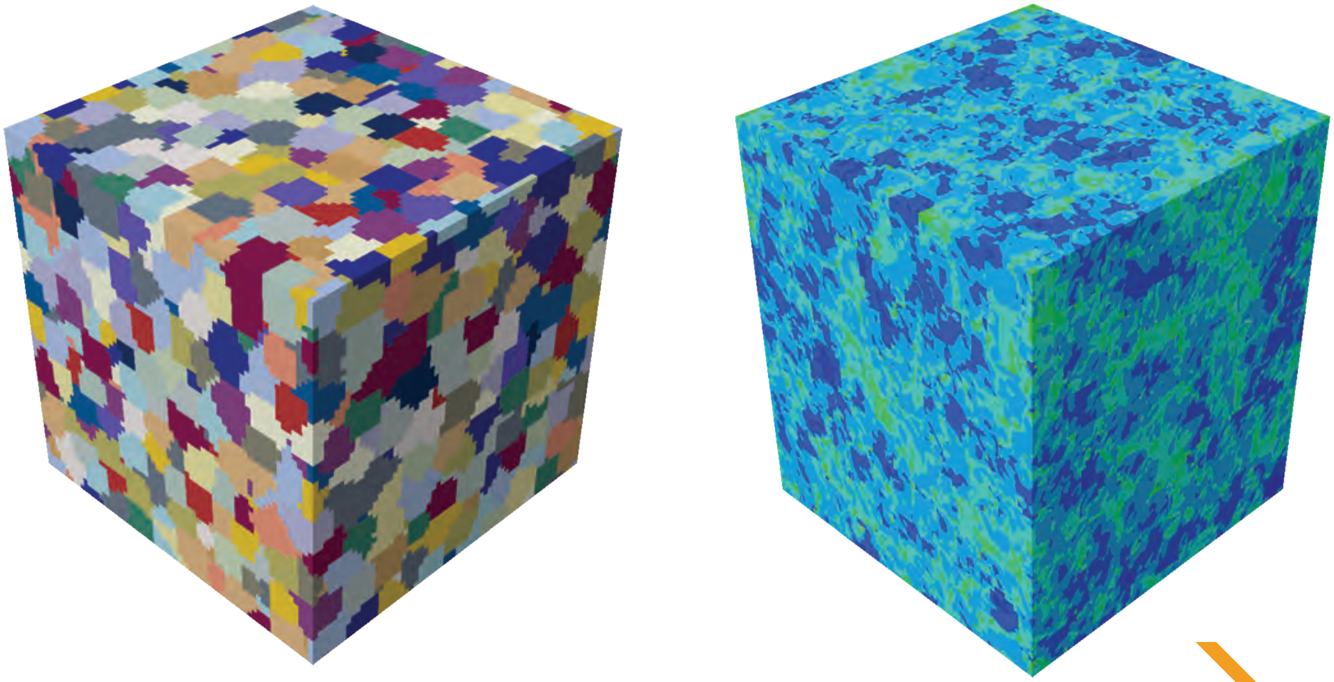
For dilute alloys — materials in which the added element is at a low concentration relative to the overall mixture — Shimanek expanded on the impact of electronic structures. “If you’re talking about the middle length scale, people don’t consider electronic structures very often,” he says. Those structures impact the atomic volume of an element, and Shimanek studied the connection between atom size and the mechanical properties of alloys. By looking at more than two dozen dilute nickel-based alloys, he showed that combining nickel with larger atoms decreased the shear strength in an alloy. Even one larger atom in a lattice can destabilize it during deformation, because the atoms don’t pack as well. In addition, combining nickel and atoms with a higher electronegativity — the ability to attract electrons — increased an alloy’s resistance to shear.

Such results reflect the basis of Shimanek’s approach: start at a small scale and work up. “You can decide what are the most important features that you can get from that lower length scale.” Then those features can be incorporated in models at longer scales.

Nonetheless, running such simulations depends on what Shimanek calls “expensive DFT calculations.” Shimanek ran most of these simulations on Penn State’s Roar supercomputer. During his practicum at Sandia, Shimanek also used that lab’s Sky Bridge supercomputer. Even with all of Shimanek’s DFT algorithms and lots of supercomputer power, he says, “there’s a long way to go if you want to consider the really fundamental nature of these things.”

Shimanek has already started to go further in modeling the plasticity of crystals. A big part of this involves incorporating more features of physical experiments in the models. “We want to make sure that we’re parameterizing the crystal-plasticity models correctly,” Shimanek says.

Imagine running an experiment that pulls on an alloy to measure its plasticity. Here, it matters how the alloy’s crystals are organized and how it’s pulled. “You have these atoms stacked a certain way, and you have something that describes their orientation,” he says. Think of that orientation as the grain of the alloy. “When you pull the alloy in an experiment, you’re going to have some uncertainty — one degree, two degrees, five degrees. That’s pretty reasonable experimentally, depending on how careful you are.” That uncertainty comes from the direction that a scientist means to pull on the alloy relative to its grain and the actual direction. The difference might be small, even fractions of a degree, but that can create a big impact at the atomic level. In some simulations, for example, being off just 0.3 of a degree changed the predicted strength of an alloy by 15%.



This simulation of a polycrystal depicts grains with different colors (left). Simulating the application of tension in the vertical direction (right) produces a landscape of changes in stress from low (blue) to high (green), which correlates with some of the boundaries between the grains. *John Shimanek.*

So when comparing results of simulations with experimental results, the uncertainty in performing the experiments must be considered. “Our models should account for that,” Shimanek says. “As we translate what we see from experiments to a model form, we want to make sure that the link is pretty solid.”

But what parameters should be used in a model? “There’s always assumptions in the model,” Shimanek says. “You’re building up from nothing, and then adding behavior.” Picking the best parameters to add, though, is a tricky process. “If you start adding everything that you can think of, you could get to this state where you don’t know what’s having the biggest effect.”

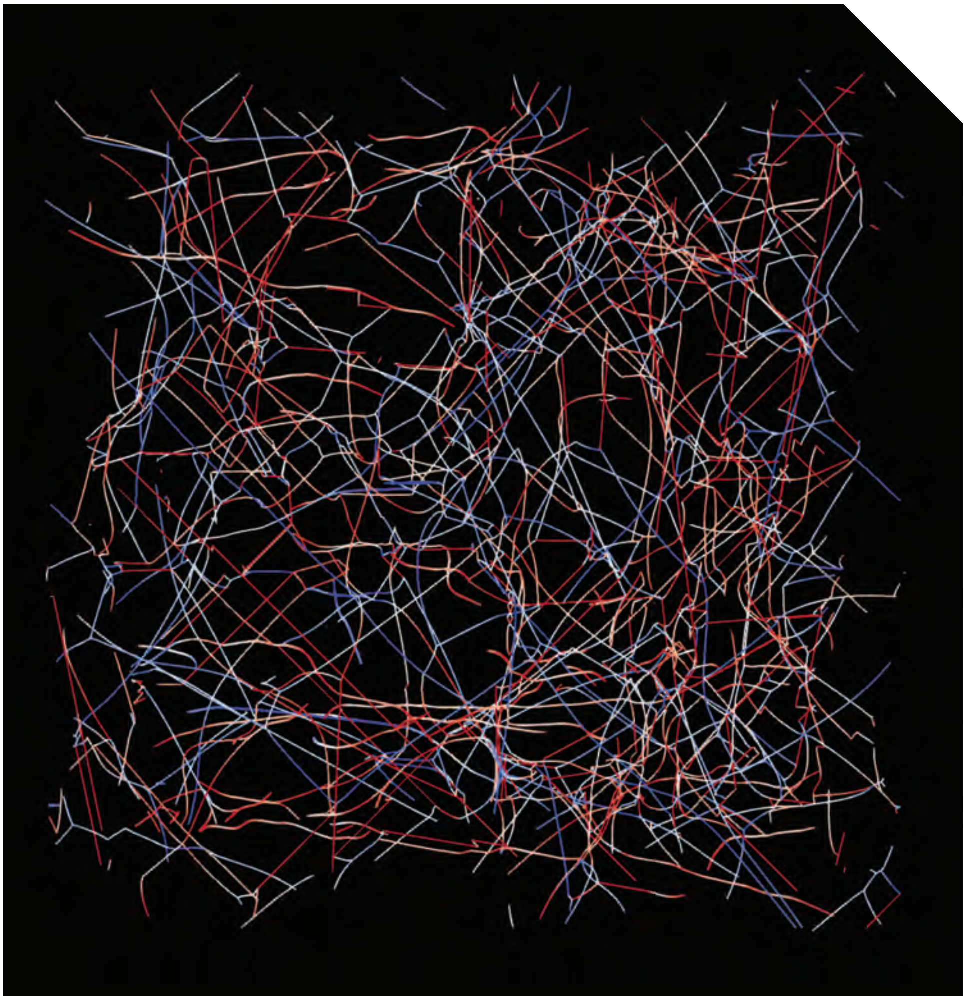
Part of the process comes from what Shimanek calls physical intuition. Some of that is pretty easy. For example, the kinds of atoms in an alloy will affect its plasticity. “But you also want to be open to the nonobvious things.”

In Shimanek’s ongoing collaboration with researchers at Los Alamos, he’s looking at dislocation dynamics. Here, the slip-system roll of carpet is modeled as a micron-scale, three-dimensional volume where changes in the arrangement of the atoms — dislocations — can be simulated directly as a material is manipulated. “You have a bunch of dislocations interacting from different systems,” he explains. From this, “you can start to say something about taking information from the atom-scale as input and try to say something about emergent properties, like the motion of these dislocations that affects the crystal plasticity.”

Shimanek is still checking the simulations that incorporate dislocation dynamics. For these models, which can run for months at a time, Shimanek has been using the Pittsburgh Supercomputing Center’s Bridges-2.

With this work, even getting to the simulations took a lot of time, he says. “We needed some custom output, which meant going back to the computer science — lots of writing in Fortran. It took me a while to get up to speed enough to make the changes that I needed to get this sort of data.” Shimanek envisions the results from his work on dislocation dynamics as a nice tie-in to his DFT and crystal-plasticity work across various length scales.

In thinking about the parameters and processes that a model should include, Shimanek says “everything should have some effect, but you want to build up the model in the right way, so that you’re getting the most important effects.” Only then will scientists develop a clearer view — from atoms to girders — of what happens to a material as it approaches and passes its point of mechanical yield and potential ways to prevent such failures. SS

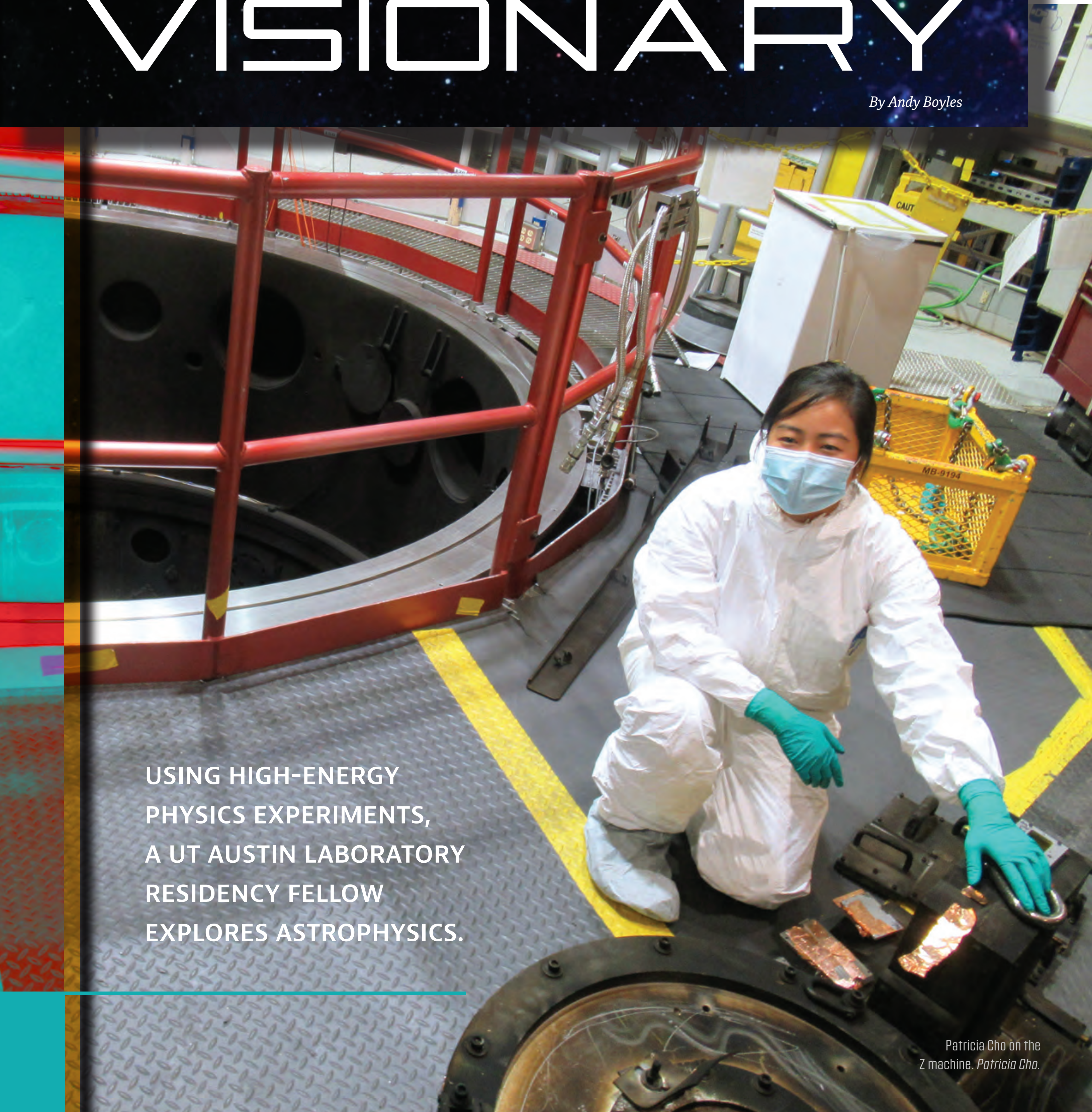


Using discrete dislocation dynamics code developed at Los Alamos National Laboratory, this simulation shows atoms out of arrangement in a crystal. The color indicates the angle of a dislocation from zero (blue) to 90 (red) degrees. *John Shimanek.*

# AN X-RAY VISIONARY

By Andy Boyles

**USING HIGH-ENERGY PHYSICS EXPERIMENTS, A UT AUSTIN LABORATORY RESIDENCY FELLOW EXPLORES ASTROPHYSICS.**



Patricia Cho on the Z machine. *Patricia Cho.*

Shortly after Patricia Cho began her astronomy Ph.D., her advisor came to her with an unusual request. He had misplaced his lecture notes for a graduate course she had taken the previous year. Could he borrow hers?

“And her notes were much better than my lecture notes, unsurprisingly when I thought about it,” says the advisor, Don Winget of the University of Texas at Austin. “But at the time, I was quite shocked. I realized that when she doesn’t understand something, she goes and figures out what’s going on and explains it in writing to herself, which then re-explains it to you, and you see it through new eyes.”

Helping others see familiar subjects through new eyes is a gift and long-term goal of this Department of Energy National Nuclear Security Administration Laboratory Residency Graduate Fellowship (DOE NNSA LRGF) recipient.

At Sandia National Laboratories in New Mexico, Cho’s research has yielded insights into a long-standing question: Are astrophysical models correct about the chemical composition of black hole accretion disks, the dust and other gravity-captured material that turn into plasma, which is ionized gas, as it spirals inward? Her new benchmarks for iron X-ray emission suggest the models are off, results that have yet to reach parts of the astronomy community. She is helping to spread the word that high-energy physics experiments can answer stubborn questions.

“I would like to continue to build connections between the astrophysics community and the laboratory community to flesh out these ideas,” Cho says.

Winget adds: “Patty is rightfully at the forefront of that work. She’s such a good spokesperson for the cause because she can also break down really complex ideas very clearly, and so that makes her a great ambassador for the field.”

Cho’s wide-ranging interests brought her to science in a roundabout way. Growing up in the southeastern suburbs of Los Angeles, she wanted to be either a cardiologist or an astronaut. By the end of high school, however, her love of reading had drawn her into the liberal arts. In 2010, she received a bachelor’s degree in Asian studies and applied linguistics from Williams College in Williamstown, Massachusetts. She was a fixture on the dean’s list and received the Linen Senior Prize in Asian Studies.

Cho remembers having no sense “of what I wanted to do ultimately.” She tried office work but didn’t like it. “So I set off and wound my way through the Pacific Northwest, working at a smattering of organic farms.”

Still dissatisfied, she returned to an earlier interest in math. At Columbia University, working toward a second undergraduate degree, she plowed through calculus, physics and computer science. She tried electrical engineering and considered mechanical engineering and pure physics. “I just on a whim took an astronomy course and then decided that was the way to go.”

As an undergrad at Columbia, she worked with astrophysicist Jules Halpern, who enabled her to take several trips to the MDM Observatory in Arizona. There, she trained a 1.3-meter optical telescope on so-called redback millisecond pulsars to study their poorly understood light fluctuations.

In these binary star systems, an ordinary star revolves around a supernova remnant called a pulsar. These pulsars rotate once every few milliseconds. The pairs are named redback millisecond pulsars after Australia’s redback spider; just as the female spider kills the male with a shower of digestive juices during mating, the pulsar slowly consumes its smaller companion through an accretion disk. A byproduct of the destruction is a charged-particle wind traveling near lightspeed.

Cho’s findings suggest that fluctuations in the system’s light emissions might be due to the repeated breakage and reconnection of magnetic field lines that channel the pulsar wind onto localized regions of the companion star as it continues to be consumed. Cho was first author on the team’s 2018 paper in *The Astrophysical Journal.*

When she was accepted into the UT Austin astronomy Ph.D. program, she expected to do more observational astronomy. Then she discovered the laboratory astrophysics center program led by Winget. “They told me what they were involved in with the experiments at Sandia, and I just thought it was so cool. So I signed on, and here I am.”

Her presence was felt immediately, Winget says. She loved theoretical astrophysics and elevated undergrads to a graduate level on difficult subjects. He recalls a colleague saying that graduate school is where scientists learn their limitations. “I don’t think Patty ever discovered her limitations because she was good at everything she tried,” he says. “Every once in a generation you run into somebody like that.”

After Cho completed her coursework, she applied for the fellowship and was accepted. She combined the program’s two residencies into one long Sandia research experience. Guillaume Loisel, her main advisor there, says she was a hard worker, fast learner and adept presenter. “I had no doubt she could succeed based on those qualities.”

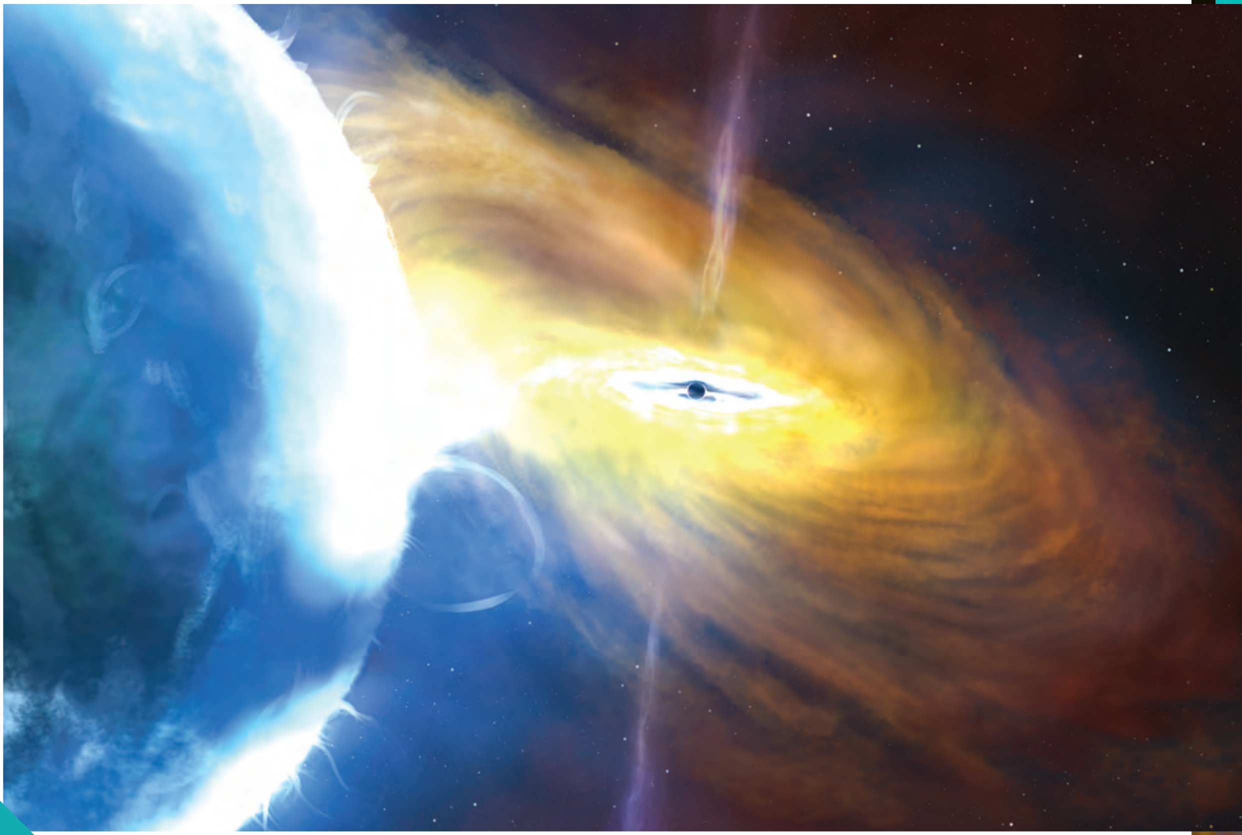
Cho joined Sandia’s Z Astrophysical Plasma Properties (ZAPP) collaboration, led by Loisel, James Bailey and Taisuke Nagayama.

The group uses the massive and massively powerful Z Pulsed Power Facility, or Z machine, to replicate and study some of the most exotic materials, called plasmas, in which intense heat and pressure — or, in the case of Cho's experiment, intense X-rays — lead atoms to lose electrons and re-emit X-rays of various wavelengths.

The Z machine is the world's most powerful pulsed-power device. Thirty-six massive electrical generators surround a central staging area where they unleash millions of amps into experimental targets, typically smaller than 5 centimeters in diameter. The current transforms the target into a super-hot plasma. Simultaneously, it exerts a powerful squeeze on the plasma with a force called the azimuthal magnetic field, like a fist that clenches around the sample at tremendous pressures. The plasma emits X-rays, which are used in a wide range of experiments.

Soon after joining ZAPP, Cho took over iron experiments Loisel had begun. The work centers on whether black hole accretion disks house as much iron as observations suggest. Current theory says the proportions of iron everywhere should roughly match the sun's. But X-rays from material surrounding certain black holes and neutron stars bear evidence of five to 20 times more iron than expected. Called the super-solar iron abundance problem, the contradiction has stumped astrophysicists. Do some regions have more iron than others? Or do the iron X-ray models need to be revised?

To establish benchmarks for iron X-ray emissions, Cho produces iron plasmas at black hole accretion disk conditions. She starts planning each experiment two to four months ahead. Working with highly trained Sandia technicians and engineers, she provides details on any parts that need to be specially designed.



An artist's rendering of a black hole in the Cygnus X-1 system. The immense gravity of the black hole (center) pulls material off its companion star (left), forming an accretion disk around the black hole. *NASA/John Paice.*

On the day of an experiment, she arrives by 6 a.m. The technicians set the target — an array of thin tungsten wires — in the center of Z. She watches as a Sandia collaborator mounts a small piece of thin iron foil in the path of X-rays that will flood out of the target. Beyond the foil are instruments that will capture the X-rays coming from the iron foil once it also forms a plasma. These instruments are dispersive crystals — prisms for X-rays. One captures spectra of tungsten X-rays absorbed by the iron. Another collects X-ray spectra emitted by the iron.

At the same time, other ZAPP researchers oversee the setup of their own experiments. The group has only a handful of shots a year for their work, and they place several experiments around and above the target to get the most out of each shot.

There's no mistaking when the shot goes off. The floor and windows shake, and Cho hears the explosion, the equivalent of three sticks of TNT. In billionths of a second, the tungsten becomes plasma and so does the iron foil. The iron plasma enters the same photoionization regime seen in black hole accretion disks: X-rays are ripping more electrons from the nuclei than electron collisions are. Afterward, the spectra recorded on the film in Cho's diagnostics reveal that the iron is ionized down to the L-shell level — some with 10 electrons (neon-like), some with 9 electrons (fluorine-like), and others with 8 electrons (oxygen-like).

The ions gave off high levels of X-rays. In October 2023, Cho presented her findings in an invited talk at the American Physical Society. She concluded: "Iron L-shell spectra from laboratory photoionized plasmas suggest astrophysical models may significantly underpredict absolute emission intensity."

She says it's highly unlikely that there's that much iron. "The question is, what is the theory that's going wrong there? This experiment can actually say something about that." She is preparing these and subsequent studies for publication.

Cho feels the pull of stewardship science and plans to pursue a career at the national labs. She also remains committed to building bridges between laboratory astrophysics and other fields of astronomy. "What else can we probe in the lab?" she says. "How else can we advance the fundamental physics that all of astrophysics rests on?" SS

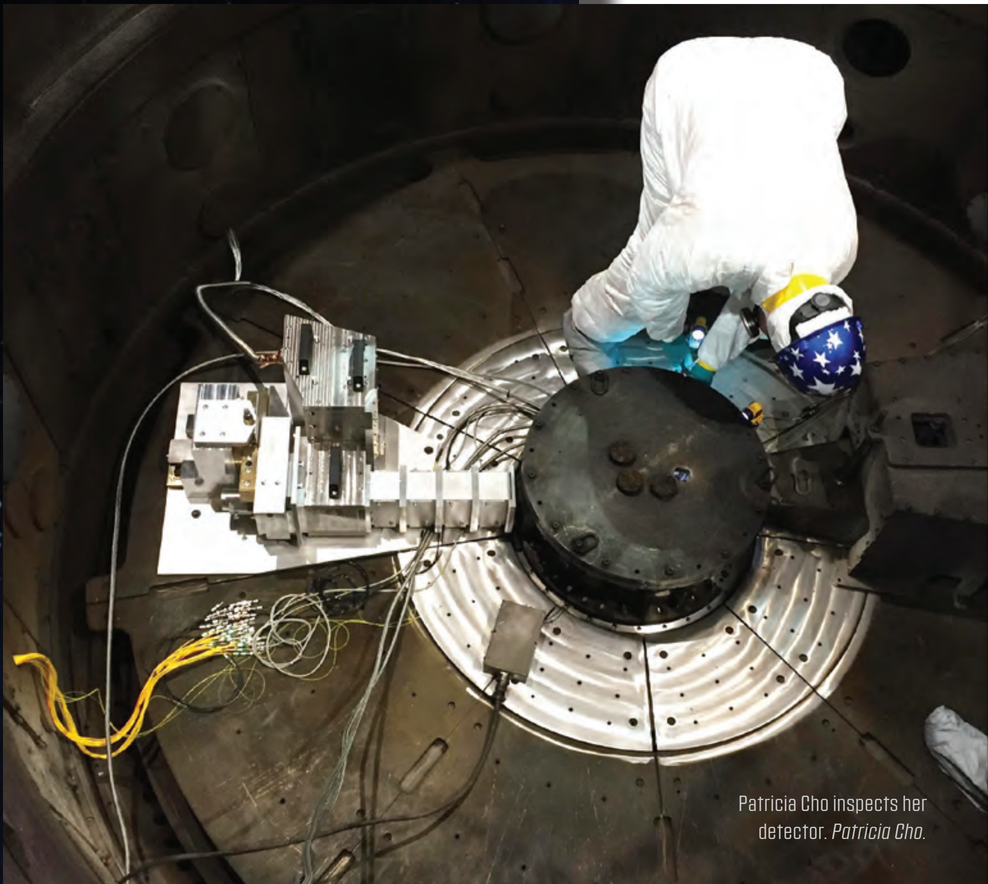
## SURVIVING CRUNCH TIME

As part of her Ph.D., LRGF recipient Patricia Cho developed a way to deploy a digital data-collection method that withstands Z-machine explosions.

Most researchers use film to capture spectra from Z's short-lived plasmas. The machine's 26 million-amp pulse puts out a pressure wave, debris and an electromagnetic pulse that can destroy a typical electronic detector. In fact, her early designs didn't last past the blast. The latest iteration holds up and retains its data.

"It's just a lot of shielding, really," Cho says. "Thick blocks of tungsten along with a diagnostic redesign that reroutes much of the pressure wave." She credits Sandia's skilled engineers and colleagues who gave input into the design.

Sandia collaborator Guillaume Loisel credits Cho with the clever shielding solutions that ultimately succeeded. "Patty definitely led," he says. "She had the ideas and led the resolution."



Patricia Cho inspects her detector. *Patricia Cho.*

*Outgoing fellows describe their research experiences. (Abbreviation key: SSGF/LRGF = DOE NNSA Stewardship Science Graduate Fellowship/Laboratory Residency Graduate Fellowship.)*

## CONNECTING THE DOTS

An invitation to study tiny particles during a summer at Los Alamos National Laboratory kicked off what has become nearly a decade of experimenting for LRGF recipient Kevin Kwock at the lab.

Kwock first went there as an undergraduate to study quantum dots, a nanomaterial recognizable in everyday life as the “Q” in QLED TVs. He returned years later after joining James Schuck’s Columbia University engineering group and entering the fellowship, partaking in three residencies at Los Alamos to build equipment and study what makes each nanosized material unique.

Quantum dots and other nanoparticles’ light-emitting properties strongly depend on what surrounds them. “Their environment, their substrates, their ligands, their neighboring nanoparticles — they all influence the ultimate optical emission,” Kwock says. But individual nanomaterial particles are quite different from one another. Like any two given snowflakes, he says, “no two nanoparticles are alike.”

Kwock and his Columbia colleagues recently discovered that certain nanoparticles produce a behavior called photon avalanching, where they absorb a single photon that triggers the emission of many. Kwock wondered if exposing these so-called upconverting nanoparticles to a strong magnet could change the threshold at which their photons began avalanching. This change in the properties not only would illustrate each nanoparticle’s differences but also would allow researchers to magnetically tune nanoparticles for practical applications, such as ultrasensitive magnetometers and enhanced navigation technologies.

To study how such particle distinctions originate, Kwock spent two years creating a chamber of extreme conditions, one that could chill particles to 4 degrees kelvin yet hold the magnetic energy of 7 tesla. Then he placed a microscope inside to observe connected particles and their photon-avalanching behavior. Kwock was surprised there were no observed changes in the nanoparticles’ photon-avalanche thresholds. Still, as his graduate studies conclude, he’s made a unique magneto-optical machine at Los Alamos that’s well-suited for other nanomaterials experiments.

Back at Columbia, he’s also become adept at using ultrafast probes and engineering nanoscale devices, collaborating on work that’s been published in his field’s top journals.

## MICROSTRUCTURAL INTEGRITY

Materials researchers are synthesizing a variety of new inorganic-organic hybrid materials with potentially useful properties. But some can only produce powder-grain-sized crystals. Such microcrystals are difficult to characterize with traditional X-ray crystallography because radiation can destroy them before researchers can gather the data needed to decipher their structures.

SSGF recipient Elyse Schriber and her Lawrence Berkeley National Laboratory colleagues Aaron Brewster and Dan Paley have developed a new approach called small-molecule serial femtosecond X-ray crystallography (smSFX) to address this problem. The method singles out individual crystals with narrow, super-short X-ray pulses, just millionths of a billionth of a second long. The technique requires the bright light produced by X-ray free electron lasers (XFEL), which are produced at only five facilities in the world, including the SLAC National Accelerator Laboratory.

Working with her Berkeley Lab colleagues and University of Connecticut Ph.D. advisor J. Nathan Hohman, Schriber probed the structures of crystals of a previously characterized inorganic-organic hybrid material, mithrene. They then determined the structures of two other materials, thiorene and tethrene, that had frustrated previous characterization efforts. They published these results in *Nature* in January 2022.

Since then, Schriber and colleagues have examined 18 more microcrystalline materials, acquiring data on as many as seven different substances in a single beamtime. The group is developing the approach as a high-throughput mail-in service so that other researchers can use the technique.

Schriber’s 2023 Lawrence Livermore National Laboratory practicum with Matthew Coleman drew on her experiences with XFELs. She defended her dissertation in November 2023 and joined SLAC as a postdoctoral scholar in photon science.

## DESIGNING FOR IMPACT

LRGF recipient Brianna MacNider wants to build resilient materials and structures that don’t exist in nature but are useful to humans. In her aerospace engineering research, the University of California San Diego Ph.D. student is designing new geometries that can be used in materials that absorb shock and tension, such as helmets or cars’ crumple zones. “The possibility of having designer materials is the long-term goal,” she says.

During her 2022 and 2023 residencies at Los Alamos National Laboratory, MacNider tested how her own materials and others performed under extreme stress, such as the way body armor might deform when hit with a bullet. Working with LANL’s Dana Dattelbaum, MacNider created 3D-printed polymers, each about 6 millimeters wide, with geometrical lattice patterns that compress under stress. She tested how different patterns — cross-hatched diamonds, for instance, or wiggly lines — collapse when hit with pulsed energy waves.

Her research found that some materials, like soft polymers printed in diamond patterns, absorbed the stress, suggesting they would effectively protect whatever was on the other side. Hard, brittle materials shattered under the impact, whereas magnesium materials stretched beyond their limit when shock waves passed through them and then bounced back.

MacNider is particularly interested in these materials' quasi-static properties: the way they behave when put under increasing pressure for a long time. Understanding the specific patterns of shock waves as they move through different materials, she says, could lead to other applications such as the transmission of acoustic signals through a structure. Her work at LANL has already led to one paper, and she hopes to continue researching quasi-static and dynamic effects after she graduates, she says. "I very much enjoy the fundamental aspect of discovering something and then getting to share it with people."

## SPLASHY LASERS

Stanford University Ph.D. student and SSGF recipient Griffin Glenn uses lasers to accelerate ion beams in ways he hopes will advance cancer therapies, particle physics and fusion power. Until a few years ago, the high-intensity lasers used for laser-driven ion acceleration created so much heat they needed an hour or more to cool down between shots. But newly invented equipment has allowed the lasers to be shot more than once each second, inspiring physicists like Glenn to try previously unimagined experiments.

But the speedy shots created a new problem for Glenn and his group, supervised by Siegfried Glenzer. The lasers destroy whatever they're fired at, and it takes much longer than a second to reach into the vacuum chamber and place a new laser target. To solve this problem for other experiments, SLAC's Sample Environment and Delivery Group had developed glass nozzles that produced thin sheet-like liquid jets. Since the sheets were continuously replenished after each laser shot, these targets were also perfectly suited for laser-driven ion acceleration. Glenn and colleagues refashioned these devices out of tungsten and stainless steel so they wouldn't be destroyed by their proximity to the high-power lasers.

A liquid jet. *Franziska Treffert and Griffin Glenn.*

In recent experiments, they have used their liquid jet targets to accelerate beams of protons and other ions at up to 5 hertz repetition rates. Glenn's work could help shrink particle accelerators from the massive instruments like those used at CERN and other facilities to devices that could fit inside a single room. This approach also could help advance inertial fusion energy.

In his SSGF practicum at Sandia, he worked with John Porter and Mark Kimmel to measure properties of laser pulses in the lab's petawatt laser.

Glenn has published papers on his Stanford research and presented his Sandia findings at the International Conference on Ultrahigh Intensity Lasers in Korea. When he's not plumbing particles and plasmas, he plays double bass in a Stanford orchestra.

## QUBIT WRANGLER

Reliable, large-scale quantum computers don't exist yet. But once the hardware is ready, Lawrence Livermore National Laboratory scientists want to immediately start using quantum computers to solve complex equations for fusion experiments at the National Ignition Facility (NIF).

First, however, they will need to figure out how to access a quantum computer's data, a far more complex task than opening a file on a classical computer. That's where Caltech SSGF recipient Christopher Yang comes in. In his 2022 practicum, Yang helped LLNL's Frank Graziani design algorithms that combine classical and quantum computing in the most efficient way.

When it comes to quantum computers, Yang says, "the rules and the coding language and everything are very, very different." Classical computers process bits of information in a binary fashion: each bit either contains an electrical current (one) or it doesn't (zero). A quantum computer, by contrast, processes information in a three-dimensional qubit that stores orders of magnitude times more information than a classical bit.

But due to the laws of physics, retrieving quantum information collapses the qubit into a simplistic one or zero, destroying much of the information it originally stored. One way to extract more information, Yang says, would be to simulate each calculation thousands of times and obtain the probability that a qubit will end up at either zero or one. Such simulations would allow researchers to run some classical computer algorithms on quantum computers, but repeating calculations would often require an impossible amount of work.

So Yang is looking for ways to match components of NIF's computing problems with the optimal platform, quantum or classical. That will allow researchers to design hybrid algorithms.

Yang is tackling similar quantum problems in his doctoral studies of laser interactions with subatomic matter. Doing this kind of math is much like working in a lab, he says. "It's like you have knobs that you can turn and manipulate, but these knobs are fundamental principles of physics that you can selectively use to induce very cool phenomena."

## 'GASES WITH PIZZAZZ'

Solids, liquids and gases can all be measured with equations that rest on centuries of experimentation and math. But plasmas — or, as LRGF recipient Logan Meredith calls them, "gases with some pizzazz"— are in a class all their own. These charged ion clouds are used in astrophysics experiments and nuclear fusion, yet studying their physical behavior is surprisingly hard.

In his 2020 and 2021 residencies at Sandia National Laboratories in New Mexico, the University of Illinois at Urbana-Champaign Ph.D. student developed computer simulations of plasmas and their interactions, such as what happens when researchers shoot a beam of electrons into a cloud of positively charged ions. "It's a delicate process of finding a version of an experiment that you can simulate with your code," he says.

A snapshot of electron density for a simulated cross-section of a tokamak. *Logan Meredith.*

Theoretically, a computer program could simulate each individual ion's speed, movement and charge as it traverses the system. But that calculation quickly becomes so large that it can crash even a supercomputer. Another option is to treat the whole system as a fluid, a simplification that makes the math easier but can yield inaccurate results.

Meredith wants to split the difference. Working with Sandia's Richard Kramer, he simulated millions of particles, each representing billions of real particles in a plasma system. He then sampled these theoretical plasma ions' movement at different stages like frames in a video.

Because many factors can affect ions' speed, syncing them required some complex math. But once he figured that out, Meredith could predict when the particles began to behave similarly enough for the simulation to treat them like a fluid instead of a gas.

Meredith says these simulations can help researchers trying to optimize or diagnose problems with equipment such as Sandia's Z machine, which is used in fusion research. At Illinois, he's modeling plasma ions in various ways to understand how they act in alternative scenarios. "The fact that we can do any of this is crazy to me," he says.

## FROM JAZZ TO JOLTS

After completing undergraduate jazz studies, upright bassist, LRGF recipient and recently minted University of New Mexico electrical engineering Ph.D. Maren Hatch had realized she missed science and math. She'd gone back to community college and eventually found herself at UNM as an undergraduate researcher on HELCAT, a plasma physics device. She soon set her sights on working at nearby Sandia National Laboratories, and when a research opportunity on electrothermal instability became available in 2018, she jumped at the chance. She's been working in that area ever since.

Metals inherently have tiny inclusions and voids, and when intense currents travel through them, such as in fusion research, current must divert around them, like water in a creek flowing around stones. Those changes can lead to fusion-energy-limiting nonuniform heating and instabilities. "I'm studying why this happens and how some of these larger instabilities happen," she says.

She has machined voids into ultrapure aluminum rods and studied how those materials responded to the high currents in a Z-pinch configuration. Ultra-fast pictures enable her to monitor electrothermal instabilities and to develop mitigation strategies such as epoxy or metallic coatings.

While interning at Sandia, Matt Gomez (SSGF 2007-2011) encouraged her to apply for the LRGF. For her 2022 residency, she chose to learn more about simulation and worked with Chris Rousculp at Los Alamos National Laboratory on the FLAG hydrodynamics code. There she modeled instabilities she'd been studying on Sandia's Mykonos, a smaller pulsed-power facility. For her 2023 residency, she returned to Sandia to complete her perturbation experiments with Tom Awe.

Hatch recently received Sandia's James Clerk Maxwell postdoctoral fellowship and will continue her work on electrothermal instabilities and study inertial confinement fusion. Outside research, she performs with the local band Entourage Jazz and is president of the Sandia Civitan Club, which serves meals, builds mobility ramps and does other service projects in greater Albuquerque.

## HOW ALLOYS ARE MADE

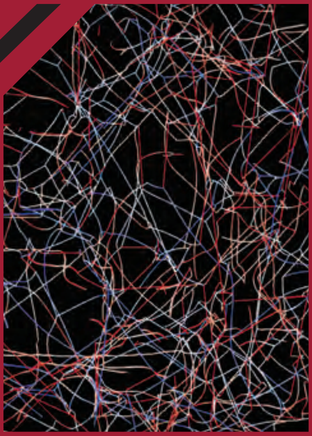
SSGF recipient Chris Jasien grew up watching the Discovery Channel's *How It's Made*. By his college years, he'd graduated to being a maker himself. Now, completing his doctorate in metallurgical and materials engineering at the Colorado School of Mines, he's become a titanium alloy expert. He specializes in a type of beta-titanium that's used across the aerospace, medical and defense industries.

Beta-titanium is extremely heat resistant, strong and anticorrosive. The metals were developed in the 1960s for use in airplanes and nuclear power plants. But they're also expensive and difficult to manufacture. An enduring challenge to metallurgists: creating a beta-titanium variation that is as strong as but lighter than the commercial alloys. Jasien focused on manufacturing and exploring one candidate alloy during his Sandia National Laboratories practicum.

He turned to a technique called additive manufacturing (AM), also known as 3D printing. AM works by selectively melting layers of metal powder with a laser to create the final part. But heating and cooling candidate metals can force them into a so-called intermediate phase, which can make them very brittle.

With Sandia advisor Jessica Buckner, he's written a paper detailing a beta-titanium alloy, absent the intermediate phase, with the strength and weight desired by various industries. He also presented those findings at the Stewardship Science Academic Programs Symposium in Washington.

Harkening back to his *How It's Made* days, Jasien's excited to now be like the engineers the series spotlighted. "You don't necessarily get to see from the outside what type of work goes on in these labs," he says.



## ABSTRACT EXPRESSIONISM OR DISCRETE DISLOCATION?

It's the latter, produced by SSGF fellow John Shimanek using Los Alamos National Laboratory's discrete dynamics code to study crystal deformation. Depicted here are atoms out of arrangement, ranging from zero degrees dislocation (blue) to 90 degrees (red). For more on his work, see "Yield Signs" on page 16.

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# MEET THE NEW DOE NNSA GRADUATE FELLOWS

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STEWARDSHIP SCIENCE GRADUATE FELLOWSHIP

Matthew Armbrust
*University of Nevada, Reno*
Materials

Matthew Cufari
*Massachusetts Institute of Technology*
High Energy Density Physics

Carter Fietek
*Ohio State University*
Materials

Isabel Hernandez
*University of California, Berkeley*
Nuclear Science

Julian Kinney
*University of Michigan*
High Energy Density Physics

Eliana Krakovsky
*Stanford University*
Materials

Sean Peyres
*University of Illinois, Urbana Champaign*
Nuclear Science

Steven Renfroe
*Georgia Institute of Technology*
Materials Science

### LRGF
LABORATORY RESIDENCY GRADUATE FELLOWSHIP

Danielle Brown
*Stanford University*
Physics, SNL-NM

Skylar Dannhoff
*Massachusetts Institute of Technology*
Plasma Physics, LLNL

James Nichols
*University of Colorado, Boulder*
Fluids, Structures, Materials, LLNL

Athena Padgiotis
*Texas A&M University*
Aerodynamics and Propulsion, SNL-C

Adria Peterkin
*Massachusetts Institute of Technology*
Nuclear Materials, LANL

Kate Sturge
*University of Maryland, College Park*
Material Physics, LANL

**Residency Locations**
**SNL-NM** = Sandia National Laboratories – New Mexico
**SNL-C** = Sandia – California
**LLNL** = Lawrence Livermore National Laboratory
**LANL** = Los Alamos National Laboratory
**NNSS** = Nevada National Security Site

For the complete listings of current fellows and alumni, please visit the fellowship websites.

https://www.krellinst.org/ssgf/ | https://www.krellinst.org/lrgf/

For more information, contact program coordinator Kris Moran, kmoran@krellinst.org, (515) 956-3696.