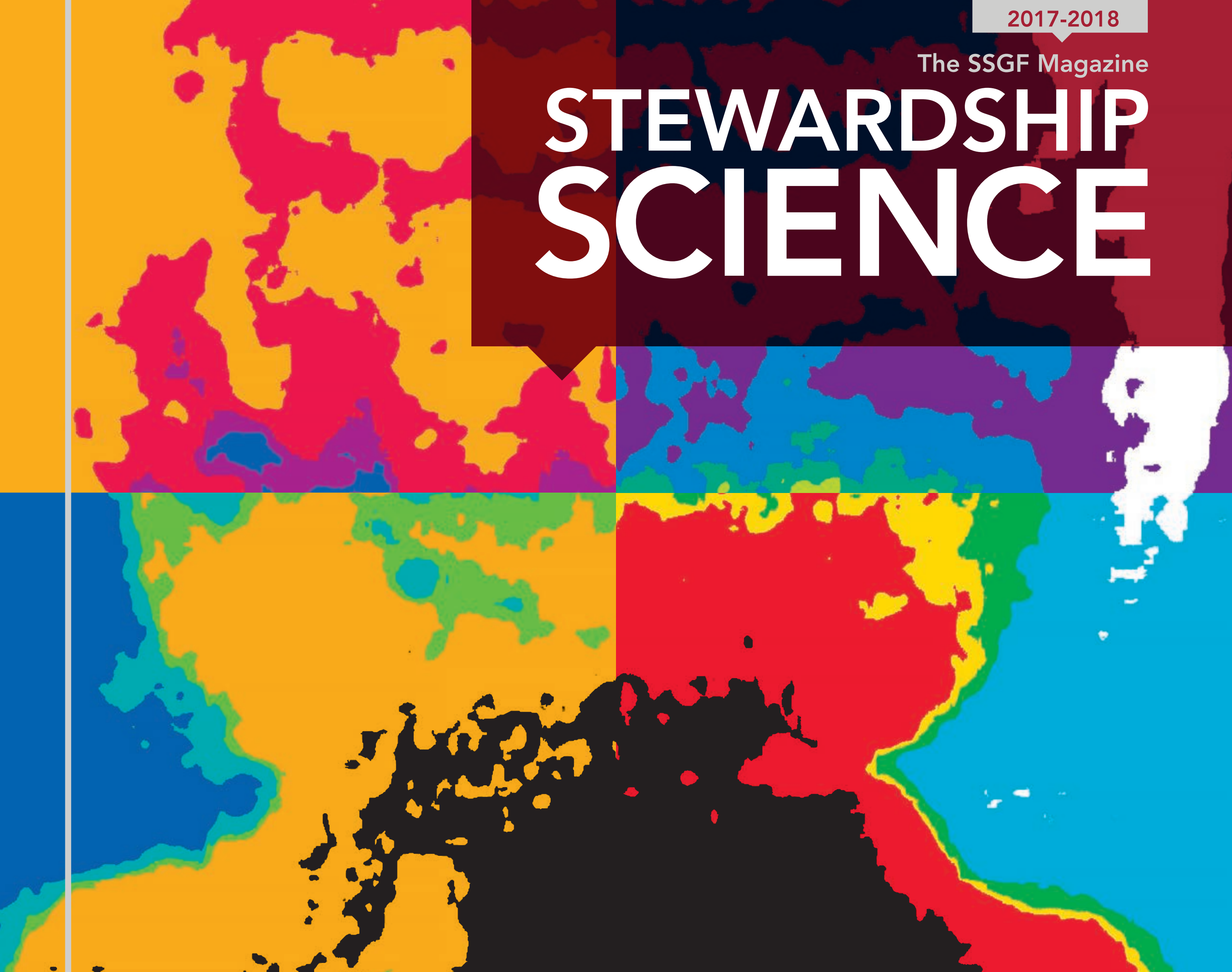

2017-2018

The SSGF Magazine

STEWARDSHIP SCIENCE

SPECIAL ISSUE:

ALUMNI AT THE LABS

Former fellows put their training to work at Los Alamos, Sandia and Lawrence Livermore national laboratories, where they explore fusion's nature and cosmic alchemy

Graduating fellows dive into atomic structure and warm dense plasma, and a program alumna discusses life in academia

Plus: explosions, mega-supercomputing and planetary defense.

Department of Energy
National Nuclear Security Administration

STEWARDSHIP SCIENCE
GRADUATE FELLOWSHIP

Courtesy of
Lawrence Livermore
National Laboratory

ANNOUNCING 2017'S INCOMING FELLOWS

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PAUL FANTO | Yale University

ERIN NISSEN | University of Illinois, UC

GABE SHIPLEY | University of New Mexico

GIL SHOHET | Stanford University

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The DOE NNSA SSGF program is open to senior undergraduates or students in their first or second year of graduate study. Access application materials and additional information at:

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The Department of Energy National Nuclear Security Administration Stewardship Science Graduate Fellowship (DOE NNSA SSGF) program provides outstanding benefits and opportunities to students pursuing a Ph.D. in areas of interest to stewardship science, such as properties of materials under extreme conditions and hydrodynamics, 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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LETTER FROM THE EDITORS

A Special Salute to Fellowship Alumni

MARKING ITS 11TH ANNIVERSARY THIS YEAR, the Department of Energy National Nuclear Security Administration Stewardship Science Graduate Fellowship has amassed an impressive collection of alumni. More than 30 graduates are building careers in critical NNSA stockpile stewardship areas: high energy density physics, nuclear science and materials under extreme conditions and hydrodynamics. A growing subset of that group, we're happy to report, work in the national laboratory complex, allowing us to devote this issue's features to alumni.

In particular, we sample the science of three former program fellows, one at each of the DOE NNSA national security labs: Forrest Doss at Los Alamos, where he studies physics shared by nuclear fusion and cloud-formation; not far down the road in Albuquerque, Matthew Gomez, who works on Sandia's famous Z machine and a project called MagLIF to understand other fusion phenomena; and Matthew Buckner, the most-freshly-minted of the featured alumni, whose research on an ancient phenomena – how elements were born in stars – set him on a path that has led from North Carolina to Northern California, at Lawrence Livermore.

Our Front Lines conversation is with an alumna who took a related but different path: Anna Erickson, now researching and teaching engineering at Georgia Tech. Also in Front Lines: profiles of two final-year fellows and lab research in brief.

Finally, we're sad to report the recent passing of a visionary, our friend and colleague James Corones. Jim founded the Krell Institute, which manages the fellowship behind this magazine. He was instrumental in creating the program – and this publication. He believed in the power of words and in the necessity for science storytelling to extend beyond the insular world of professional journals to reach a wider audience. The Essay Slam, our annual fellows' writing contest (this year's winning entry appears on page 24), was another of Jim's many inspirations. We will miss Jim's imagination and intellect, his warmth and ceaseless encouragement. Jim, this one's for you.

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

2017 2018

STEWARDSHIP SCIENCE

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ROSTER

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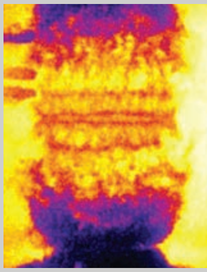

FUSION FORCES

An artist's embellishment of a color-enhanced X-ray radiograph (right) of Kelvin-Helmholtz instabilities – a feature that fusion-experiment shocks share with certain cloud formations and ocean waves. Our cover story starts on page 10.

Stewardship Science: The SSGF 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) program, which Krell manages for NNSA under cooperative agreement DE-NA0002135. Krell is a nonprofit organization serving the science, technology and education communities.

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FEATURES

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The Bomb-Shard Chase

Flash X-ray and high-speed camera equipment, foreground, are helping Sandia National Laboratories researchers study fragmenting explosives in ways that haven't been possible in the past.

Explosives research in stockpile stewardship spans decades, but there's little in the literature about an associated phenomenon known as fragmentation: the violent splintering of a bomb's casing after detonation. Fragmentation can send deadly pieces of an improvised explosive device – such as a pipe bomb or homemade land mine – helter-skelter at incredible speed.

To understand the nature and physics of IED fragmentation and its broader implications, a team of roughly two dozen researchers at the Department of Energy's Sandia National Laboratories in New Mexico is in the midst of a three-year DOE undertaking called the Fragment Tracking Project.

The goal is to gather otherwise unobtainable data from reactions that happen in millionths of a second. One hope in learning where the fragments end up is to mitigate damage, especially on battlefields, where IEDs have caused an estimated two-thirds of American casualties since 2001.

The team has tested explosive devices on a desert range and has developed diagnostic tools that include an array of high-speed digital cameras, a flash X-ray camera and constantly evolving computer models that both guide experiments and analyze the resulting data.

But there is no one-size-fits-all model, because how a device's casing fragments depends on a panoply of parameters. "An explosion is something you think of as a flash, a bang, the ground shakes and things disappear," says Mark Anderson, project lead. "But the dynamics of what occurs during that explosion vary drastically. We describe an explosion in terms of the rate of energy released. We think of an explosive as having stored potential energy that some chemist has developed, where the molecular bonds are broken during a detonation to release the kinetic energy. The more rapidly you can release the energy, the more work you can get from the explosive system."

The bomb fragment data are missing, diagnostic development team lead Phillip Reu notes. His group examines how the bomb casing fails, hoping to gain "the best understanding yet of how explosives operate and to provide data that we can actually work into our computer models. Eventually we'll turn over those data to our modelers, with whom we're tightly coupled, so they can improve simulation codes."

Reu's team aims to capture "the entire fragment story from fragment birth at the case to where it ends up and what effects the fragments have. We now have a suite of diagnostics that is very successful in getting data on velocities, shapes and movement, and that is where the discovery is in the project."

The team is particularly interested in how fragment shape influences flight, what energies fragments achieve and how their tumbling might affect distance traveled. It's possible that explosive fragments could fly a couple of miles from their source.

Typically, modelers will design a device, such as a 15-centimeter plate with an explosive weighing from 100 grams to 4 kilograms – from a few ounces to the weight of a small bowling ball. An up-close X-ray camera and three synchronized high-speed digital cameras capture the fireball.

A technique called digital image correlation lets researchers "actually look at the surface of a pipe bomb and see how the material comes apart in terms of strain rates or velocities on the surface," Reu says. The X-ray camera records the surface's early evolution as it comes apart in the fireball while the high-speed cameras see what happens when the fragments flee the smoke and flash and travel through the air.

Researchers are pursuing two ways to obtain X-ray motion pictures. One employs nine Marx generators to get nine distinct images that can be cobbled into a movie. The other, under development, is a single-source X-ray that provides a continuous stream of X-rays for imaging.

Anderson says the work is made possible through advances in high-speed computing that enable predictions and measurements of something that happens faster than the blink of an eye. "We couldn't have done this just eight years ago. It's a fascinating job."

– Tony Fitzpatrick

Fellows on Location

This year's two outgoing DOE National Nuclear Security Administration Stewardship Science Graduate Fellowship recipients share their research experiences.

SMALL PROBLEM, BIG IMPLICATIONS

As **Juan Manfredi** began graduate school in nuclear physics at **Michigan State University**, a professor gave him some advice: To succeed at scientific research, you must be interested in thinking about the broad theoretical concepts and engage in the day-to-day details of performing experiments.

"Most of what a nuclear physicist does isn't thinking about and figuring out problems of nuclear physics," says Manfredi, a Department of Energy National Nuclear Security Administration Stewardship Science Graduate Fellowship recipient. "It's setting up detector equipment. It's writing analysis software and that sort of thing."

Manfredi has adhered to both rules. "Nuclear physics is cool because the problem is so small. A nucleus is on the order of femtometers (10^{-15} meters) large but also extremely dense. There are a lot of protons and neutrons that fit into this tiny space, and how they organize is an interesting problem." Yet what happens in the nucleus can affect phenomena on a gargantuan scale, like supernovae and stellar reactions.

But Manfredi also has spent hours configuring vacuum pumps, detectors and data acquisition systems at MSU's National Superconducting Cyclotron Laboratory (NSCL). Now that he's run his experiments, "I have to write code to process the data and understand them. That can be frustrating, but I really like it."

Manfredi's research targets a mystery surrounding the spectroscopic factor (SF), a property that provides clues to the structure of an atom's nucleus.

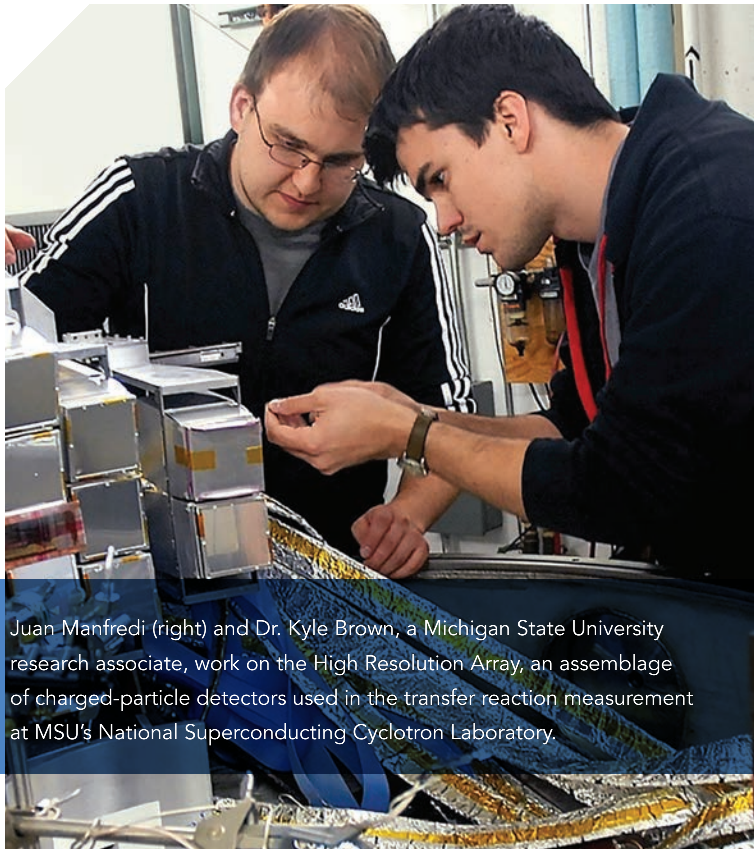
"In our theoretical model, the protons and neutrons in a nucleus can be in a bunch of orbitals that have different energy and different momenta or other properties," Manfredi explains. The SF quantifies the occupancy of an energy level held by a given nucleon – a neutron or proton. In other words, the SF is a measure of the probability that a certain nucleon is sitting in a certain orbital. Studying SFs provides valuable inputs and tests for nuclear structure models.

Two of the most common ways physicists study SFs are knockout reaction experiments (a particle launched at the atom punches out a nucleon) and transfer reaction experiments (a nucleon transfers to another nucleus).

The problem: For some isotopes – atoms with varying numbers of neutrons but identical numbers of protons – SFs obtained via knockout reactions are different from SFs obtained with transfer reactions. Scientists are "using two different reactions to measure this one fixed quantity and getting different answers," Manfredi says. "It's like two astronomers with two different telescopes looking at the same star and getting two different answers: either someone's telescope is broken or how someone's telescope works isn't fully understood."

Working with advisors Betty Tsang and Bill Lynch, Manfredi used rare isotope beams at the NSCL to study transfer reactions with argon 34, a proton-rich nucleus, and argon 46, a neutron-rich nucleus. Manfredi will compare SF analysis results from these reactions with knockout reaction results performed at the same beam energy and with results from transfer reactions performed at a lower beam energy.

Manfredi is analyzing his data with programming skills he improved during his 2014 Lawrence Livermore National Laboratory practicum. Under Rob Hoffman and Peter Anninos, he performed realistic nuclear equations of state in COSMOS++, a neutron star simulation code. The task helped Manfredi improve his coding skills and led him to take added courses in computational math, science and engineering when he returned to MSU.



Juan Manfredi (right) and Dr. Kyle Brown, a Michigan State University research associate, work on the High Resolution Array, an assemblage of charged-particle detectors used in the transfer reaction measurement at MSU's National Superconducting Cyclotron Laboratory.

HIGH HARMONIES

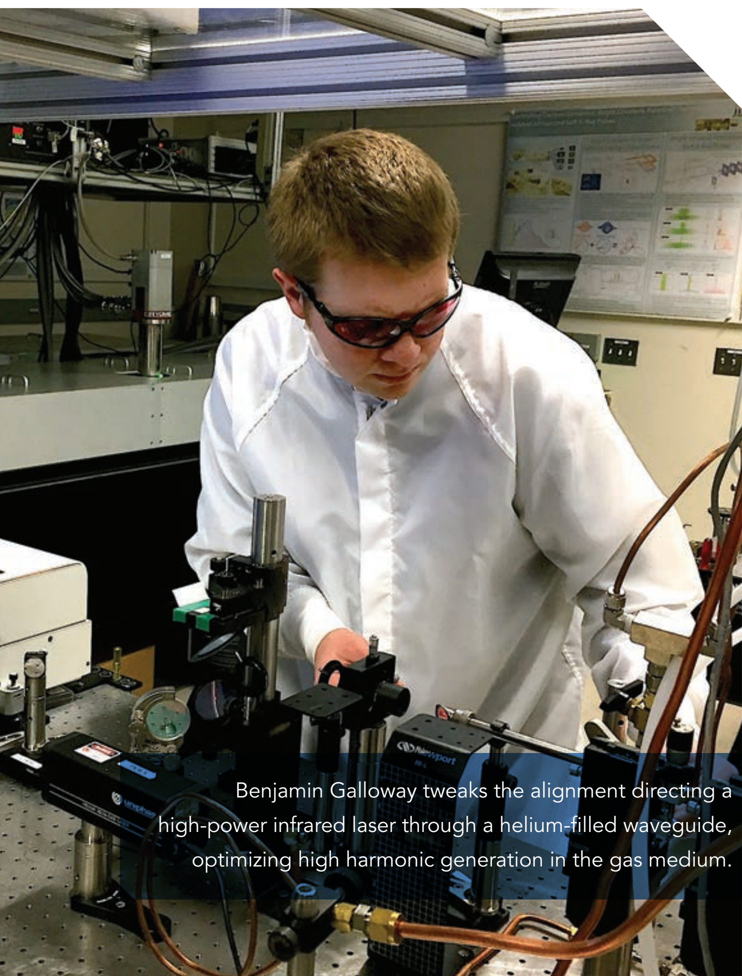
Benjamin Galloway loves surprises – in the lab, at least.

Galloway and his colleagues at the **University of Colorado, Boulder**, fire an exceedingly brief, intense laser pulse into a gas. Somehow, the pulse emerges even shorter and with more energy. For example, an infrared laser pulse measured in femtoseconds (10^{-15}) can transform into an X-ray-energy-boosted one just attoseconds (10^{-18}) long.

This high harmonic generation (HHG) phenomenon is understandable via science – which Galloway probes – but it amazes him nonetheless.

"This nonlinear physics is supercool because there's a lot of things happening that you wouldn't expect," says Galloway, a recipient of the Department of Energy National Nuclear Security Administration Stewardship Science Graduate Fellowship. "It almost seems like magic."

Also surprising: Table-top devices mostly made with off-the-shelf lasers and parts generate these abbreviated bursts. The instruments are hundreds of times smaller and less expensive than the linear accelerators and synchrotrons researchers typically use to produce intense X-rays for physics experiments.



Benjamin Galloway tweaks the alignment directing a high-power infrared laser through a helium-filled waveguide, optimizing high harmonic generation in the gas medium.

Galloway and his doctoral advisors, Henry Kapteyn and Margaret Murnane, want to use HHG X-rays to probe warm dense plasma found only in extreme conditions like nuclear fusion and star interiors. Little is known about this exotic state of matter. "Because of the super-high densities and high energies that are present, the assumptions (such as how particles act) we use in our models break down," Galloway says. The group also has used the technique to image materials at the nanometer scale, and HHG can produce X-ray frequencies useful for high-resolution spectroscopy.

In high harmonic generation, a high-intensity, short-pulse laser is fired at a gas target – usually argon or helium. The light ionizes the gas atoms, stripping away electrons.

"The electrons can move away and then back toward the atom," Galloway says. "As that electron recombines, it can emit an X-ray photon." In essence, the electron is "taking energy from the driving laser to create a secondary laser at a higher photon energy in the X-ray regime." In one case, the group drove HHG using light at a wavelength of 3.9 microns to reach a photon energy of 1.6 kilo-electron volts, corresponding to harmonics above the 5,000th order. "So we summed 5,000 driving photons to form a single X-ray photon."

Galloway wants to tune the X-ray laser so it produces desirable properties, like precise energies or pulse lengths. "All of these things can be controlled by changing the driving-laser parameters."

Galloway's 2014 practicum at Lawrence Livermore National Laboratory focused on much bigger lasers. With Bradley Pollock, he explored wakefield acceleration, which uses a high-energy laser pulse to create an electric charge in a cloud of ionized gas. As the charge moves through the gas, particles ride it like a surfer to near light speed. The accelerated electrons wiggle, producing X-rays.

Galloway helped set up wakefield experiments on Titan, a powerful laser at Livermore's Jupiter Laser Facility. He also simulated electron trajectories to correctly place instruments and ran other tests. He later analyzed diagnostic data and developed a computer code to track electron trajectories and calculate their energies and emission angles.

Deflecting Doom

Sixty-five million years ago, a 15-kilometer-wide asteroid crashed into Earth. The impact radically changed global climate, wiping out the dinosaurs.

Scientists have catalogued and mapped the orbits of other similar-sized asteroids, but they haven't tracked many smaller space rocks – up to a few hundred meters in diameter. An unexpected strike, though highly unlikely, could devastate a city or surrounding region.

Planetary-defense researchers are on the case, including Lawrence Livermore National Laboratory's Megan Bruck Syal. In an emergency, their work would help response teams make critical decisions about how to deflect or destroy an asteroid. Bruck Syal, a physicist, uses a combination of experimental data and sophisticated computational methods to study a variety of planetary scenarios.

Using an open-source code developed by Livermore's J. Michael Owen, Bruck Syal has built large-scale computer models of other collisions in our solar system, such as the impact that produced a colossal 9 km-wide crater on the Martian moon Phobos. She and her colleagues showed that a comet or asteroid 250 meters wide could have produced the crater, which extends over nearly half of the moon's surface.

Modeling such a large-scale three-dimensional problem is challenging, and the team was particularly excited that their results proved consistent as the simulation became more detailed. "Usually you don't have the computer resources necessary to throw enough processors at the problem to really demonstrate that your answer has converged," Bruck Syal says.

Another piece of planetary defense: understanding the composition and properties of the space rocks that pose a potential threat. Bruck Syal has been collaborating on experiments led by the University of Oxford's Laura Chen using the Janus laser at Livermore's Jupiter Laser Facility. The team carefully selected space rock samples, shaved them to a few hundred microns and blasted them with the laser. By monitoring the impacts as the wafers are vaporized, the team has extracted helpful information about the strength of these highly heterogeneous rocks. That data could support a NASA mission to test a kinetic impactor at the asteroid Didymos – DART, for the Double Asteroid Redirection Test. Besides Livermore, NASA is collaborating on DART and other work with researchers from Sandia and Los Alamos national laboratories.

Kinetic impact deflection – hitting an asteroid with another fast-moving object that would knock the space rock off course – is one of two primary strategies for dealing with a potentially Earth-endangering meteorite. Information about the strength of asteroids provides critical data for Bruck Syal's computational models. She recently used such simulations to portray how properties such as composition, porosity and strength affect how a kinetic impactor would divert an incoming asteroid. "In a realistic scenario," she says, "if an asteroid is headed our way, we're not going to have full information on it." Mission planners will need to understand that uncertainty to ensure the deflection's success.

But for scenarios involving large asteroids or short warning times, kinetic impactors might not be enough; planet protectors may have to use the nuclear option to deflect or disrupt an asteroid. Bruck Syal is now working on models that simulate a nuclear impactor scenario: how the energy from a nuclear explosion correlates with breaking up an incoming asteroid. Such calculations rely in part on the wealth of data and computational resources that Livermore employs in stockpile stewardship research to assure the safety, security and efficacy of the U.S. nuclear deterrent without live testing.

A critical question in planetary defense is ensuring that, in an asteroid emergency, planners would choose the right approach. Bruck Syal and others hope to continue studying the gray areas, to define just when a kinetic impactor plan would give way to a nuclear deflection.

– Sarah Webb

Booting Up Trinity

Trinity, Los Alamos National Laboratory's new supercomputer, is poised to advance the transition of high-performance computing (HPC) to the exascale, a million trillion operations per second. Trinity's components have been installed, tested, and accepted from the manufacturer, Cray. The first part of the system is in regular use and the full machine – a unique hybrid of traditional and experimental components – is on track for full operation in summer 2017.

Trinity is the first Advanced Technology System (ATS) provided by the DOE Advanced Simulation and Computing (ASC) program at Los Alamos. An ATS has a dual mission, says Bill Archer, ASC program director. First, the system must meet the simulation and computing needs of the DOE National Nuclear Security Administration's Stockpile Stewardship Program. Second, the system provides leading-edge technology to users.

ASC contracted with Cray in 2014 to design and build Trinity, based on input from the three national security labs – Los Alamos, Sandia and Lawrence Livermore. The New Mexico Alliance for Computing at Extreme Scale (ACES), a joint effort of Los Alamos and Sandia, is deploying the machine. With more than 760,000 cores on more than 19,000 nodes, Trinity will crunch numbers at a theoretical peak rate surpassing 40 petaflops (a million billion or quadrillion operations per second) and use more than 2 petabytes of aggregate main memory while exceeding 6 petabytes of memory bandwidth.

As a result, it will be able to handle two to four large simulations or computation projects of 750 trillion bytes at once. It occupies about 5,200 square feet and relies on a massive air and water cooling system to dissipate heat generated at its 10-megawatt peak power consumption.

Trinity is among the world's biggest and fastest machines. Its main distinction: It's specially designed as a training camp for new technologies and the computer scientists who will use them. Trinity is pioneering several new data storage technologies that are part of the exascale transition, says Scott Hemmert, a Trinity architect and Sandia staff member.

Based on the Cray XC40 architecture, Trinity is split into two parts. The first runs on Xeon v3 (codenamed "Haswell") processors, low-risk workhorses of today's most sophisticated and reliable codes. This part began doing classified work for the stockpile stewardship program in July 2016 and provides large-scale computational work for all three weapons laboratories.

The second part features Xeon Phi processors with next-generation capabilities. In February 2017, this part of the machine began a four-month tryout with unclassified codes to stress test it. Afterward, plans call for merging the two parts and returning Trinity to a fully classified system, giving stockpile stewardship application developers access to either processor type. "Typically, users will select one or the other processor type, depending on the application they are running," says Jim Lujan, Los Alamos Trinity project manager. "However, it will be possible for a code that has been rewritten to do so to actually use both types of processors together."

Trinity also breaks new ground with complementary technologies for data storage and use, relying on solid-state burst buffers instead of traditional disk drives to manage working data. The burst buffers' fast response and high bandwidth accelerate applications that require large numbers of small input-output (I/O) operations.

Trinity is advancing hardware technology toward the exascale. However, Archer says, "The most important advance is pushing the NNSA applications to use the emerging technologies."

– Andy Boyles

Conversation

Nuclear Physics, Policy and Engineering

Anna Erickson is an assistant professor in Nuclear and Radiological Engineering at the Georgia Institute of Technology. She was a DOE National Nuclear Security Administration Stewardship Science Graduate Fellowship recipient from 2008 to 2011. She served an internship, a practicum and a postdoctoral research fellowship at Lawrence Livermore National Laboratory.

Why are you interested in nuclear science?

The fascinating thing about nuclear science is it depends on both physics and mathematics, so you have to be good at both. We also use basic physics to create practical things, like nuclear reactors or medical devices or to enforce nuclear security at our borders. This practical application of fundamental physics drew me to the field.

What career did you foresee when you started graduate school?

I thought I would get a job at a national laboratory, and I interned at Argonne three times as an undergraduate. I focused on fast reactors and moved to MIT to complete my graduate degree. I loved the technology, but I was focusing on what I call paper reactors: In the U.S. at that time there was little chance the fast reactor programs would restart or that the plans themselves would be built.

I turned to something more hands-on – something I could build and focus on the actual physics of the research – and that was nuclear security and detection systems. That led me to internships at Lawrence Livermore National Laboratory and to the DOE NNSA SSGF.

The last year of my Ph.D., the chair of the mechanical engineering school at Georgia Tech emailed out of the blue asking if I was interested in academia. Livermore already had a spot for me as a postdoc after graduation, but I met with him. He listed reasons to teach that I never considered, especially shaping your research to influence the science but also to create the next generation of scientists. Georgia Tech also was willing to hold the position open while I completed my Livermore postdoc. That persuaded me to join academia. It also helped that the interview happened in February, during the worst snow year in Boston, and it was 75 degrees and sunny in Atlanta.

How did the fellowship influence your career?

Turning to issues of nuclear security, nonproliferation and stockpile stewardship helped me understand that nuclear engineering has a really intricate interplay between nuclear physics, policy and the actual engineering. Spending three years as a fellow also allowed me to meet people with various backgrounds who I've continued interacting with past graduation. The program shaped my career and my understanding of nuclear engineering, but also gave me some good friendships and it continues to do so.

Your research revolves around reactor design, especially as it pertains to national security and nuclear nonproliferation. What makes this important?

When I started my career, I focused on the safety aspects of nuclear reactor design. It never entered my mind that there's a nonproliferation aspect. When I switched to nuclear security, I focused on methods to find nuclear material and keep it from entering the country. People would say that's a disconnect from reactor design, but it turns out that separating nuclear power from proliferation is wrong.

The importance of my research is that it focuses on nuclear power that is economical, safe, efficient and reliable but also doesn't contribute to proliferation. The other aspect is understanding how to detect at a port or border any nuclear material from a reactor or enrichment facility. Nonproliferation is a multifaceted problem and just studying one side isn't enough. That's why my group focuses on the full picture, from the reactor all the way to identifying that (nuclear) material.

How can the sophisticated detectors you develop stop nuclear proliferation?

One aspect of our research is using detectors for active interrogation. That's a fancy name for combining an external source of radiation – X-ray or gamma radiation, for example – with a system to either image the material or just find and identify it. We deal with the challenges associated with this active interrogation environment, which tends to have high rates of radiation emission from the source. Transmitting that radiation through objects provides information to confirm the presence of special nuclear material.

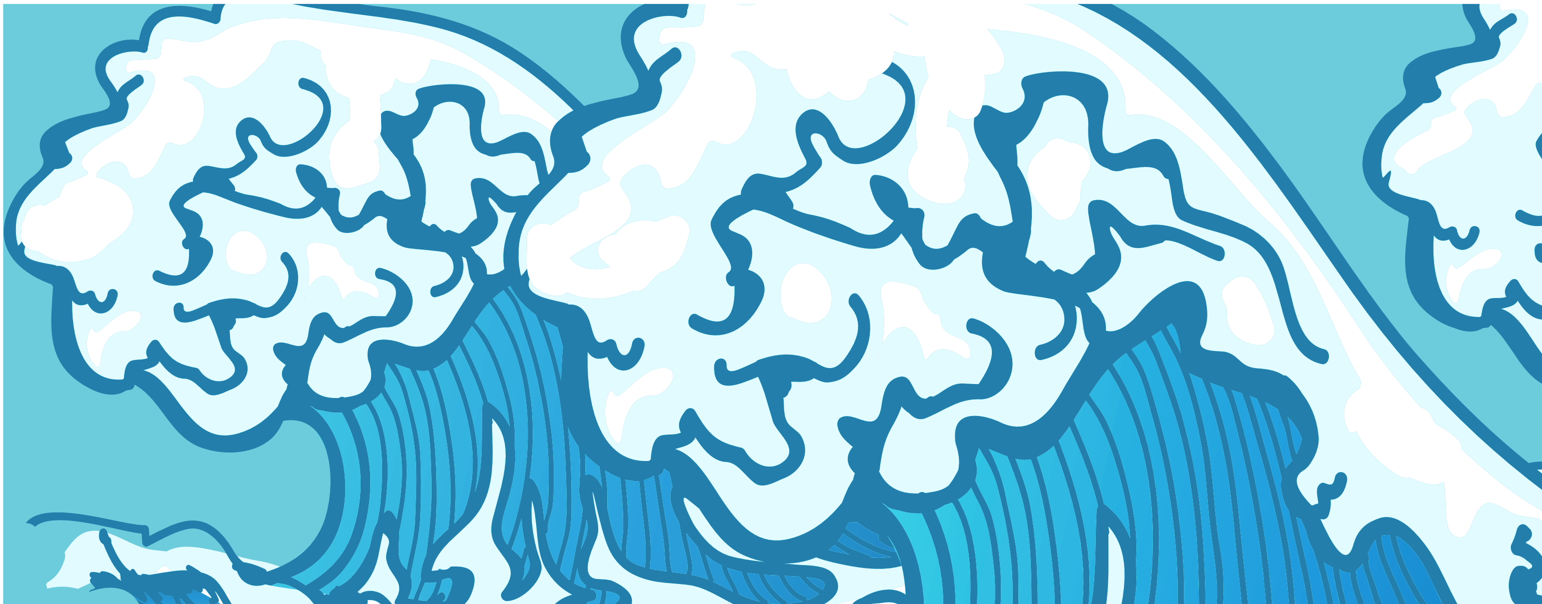
What role do you see the DOE NNSA SSGF playing in the nuclear energy arena?

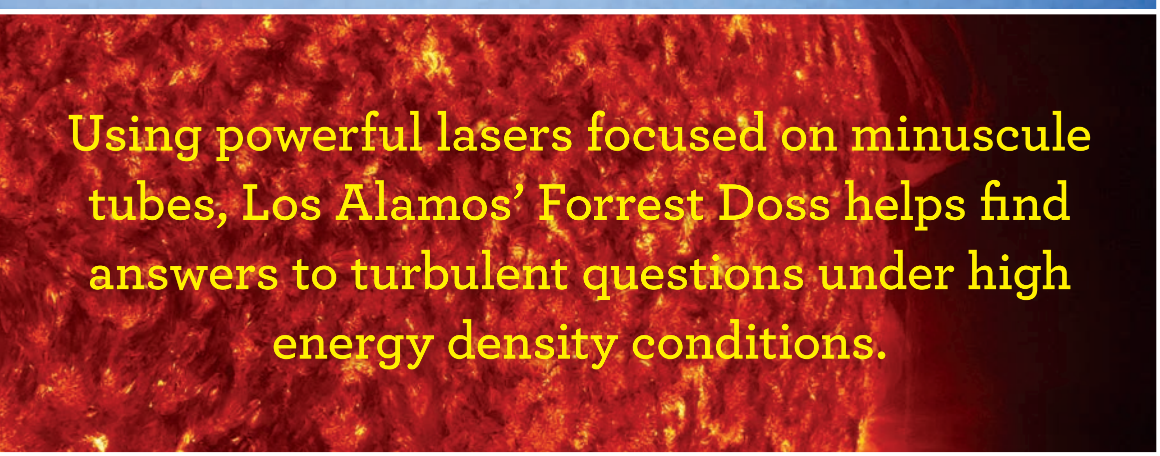
The fellowship invests in human capital needed to understand the physics behind the processes related to the stockpile, but it also has much a broader role. It's really invested in the fundamental physics of nuclear-related processes, whether it's fission or fusion. Those fundamental physics are the same regardless of the context. Instrumenting tomorrow's advanced reactors will require an understanding of coolants and fuels, changes to the fuel over time, and neutron radiation. Stewardship science addresses a lot of that through a different application.

COVER STORY

BY THOMAS R. O'DONNELL

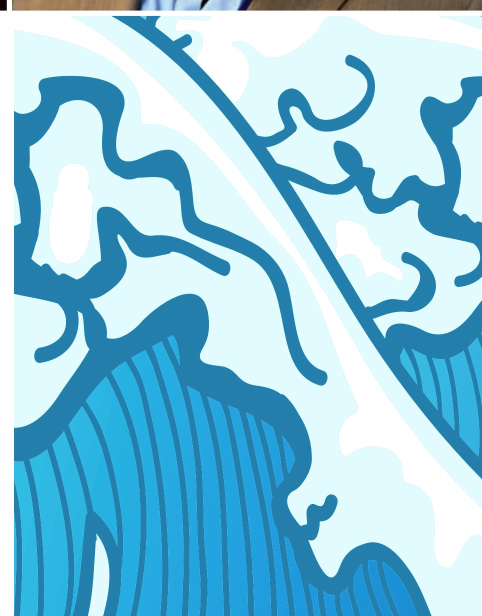
CLOUDY with a chance of FUSION





Using powerful lasers focused on minuscule tubes, Los Alamos' Forrest Doss helps find answers to turbulent questions under high energy density conditions.

TO A PHYSICIST it's clear what forces are at work when wind pushes the ocean into waves or air currents twist clouds into curlicues. For at least a century, scientists have studied these examples of turbulence from shear – two fluids flowing past each other like the blades of a scissors. They understand well what's happening where the moving layers meet. It's less obvious, however, whether shear turbulence works the same way under extreme pressures and in high-energy conditions. Specifically, physicists want to know how shear behaves in experiments designed to spark nuclear fusion, the process that powers the sun and other stars.



Answers are coming, thanks to surprising results from experiments designed by Forrest Doss, a scientist at the Department of Energy's Los Alamos National Laboratory in New Mexico and a DOE National Nuclear Security Administration Stewardship Science Graduate Fellowship (DOE NNSA SSGF) alumnus (2006 to 2010). He is working on experiments at the National Ignition Facility (NIF) at the Department of Energy's Lawrence Livermore National Laboratory (LLNL). His tests found unmistakable evidence that the shear physics developing in high-powered fusion experiments may be more familiar than strange.

Doss's experiments focus on inertial confinement fusion (ICF), in which hydrogen isotopes are compressed so tightly and quickly that their nuclei meld, releasing tremendous energy.

NIF researchers employ massive lasers to do the squeezing on a pea-sized ball filled with frozen hydrogen fuel. It's held in a gold tube called a hohlraum. Lasers enter each end in a brief burst, hitting the hohlraum walls and creating an X-ray bath that implodes and heats the capsule. If all goes well, the nuclei fuse.

"Fusion is going to be an enormous win whenever it can be achieved. Since it hasn't yet, there's a long list of things to check and find out what's tripping us up," Doss says. Near the top of that list: instabilities that develop in the hydrogen as the capsule collapses. If the pressure that maintains the orderly separation between fuel and imploding-capsule layers is even a little unbalanced, fluids slip past each other, causing turbulence that hinders the reaction. Material from the plastic capsule also can jut into the hydrogen like fingers, again spoiling conditions for fusion.

"All of our understanding of these sorts of instabilities and their transition toward turbulence have shear in them as a mechanism," Doss says, so it's important to insure it behaves the way researchers think it does, even under high pressures and energy densities.

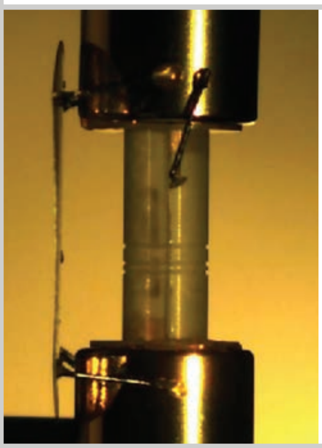
To understand and design ICF experiments, researchers create computer models based on the physics involved. By changing model parameters like capsule configuration or laser power, they get an idea of how the experiment will work. The models calculate what's happening inside the capsule as it's squeezed.

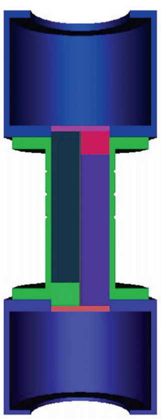
But the models are only as good as the physics that go into them. Scientists have studied shear since the early days of weather forecasting and airplane design and clearly understand how it works in standard, large-scale situations. They're less sure the same principles apply in tiny high energy density (HED) conditions, with pressures a million times that of Earth's atmosphere, temperatures in the tens of thousands of degrees and shocks moving at hundreds of kilometers per second.

"These are pretty extreme conditions," says Kirk Flippo, a Los Alamos scientist who oversaw the realization and execution of Doss' experiments. Scientists are asking standard hydrodynamics codes to model HED tests and it's "just not clear that those equations will hold together in such an environment."

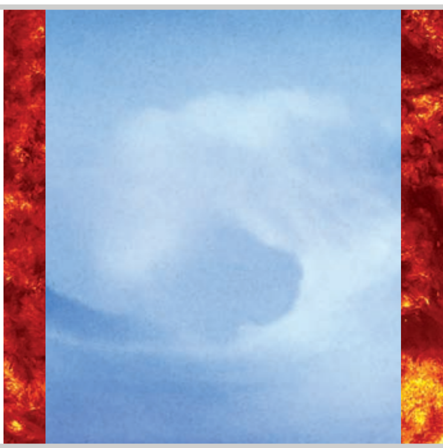
Doss' job: Design an experiment that isolates the effects shear has on mixing, producing data to improve and

Thomas R. O'Donnell is senior science editor for the Krell Institute. He has written extensively about research at the DOE national laboratories.





A shock tube for National Ignition Facility shear instability experiments. Powerful lasers generate X-rays that send opposing shocks down the foam-filled tube, producing shear effects that are captured with high-speed X-ray cameras. Near left: Schematic of a shock tube, seen split in half lengthwise, with a foil separating the halves. The halves are plugged at opposite ends.



validate ICF computer simulations. "In the actual system of the capsule, it's nearly impossible to figure out what's happening because it's a tiny thing that's converging inside of a hohlraum and trying to undergo nuclear burning," Doss says. Instead, in a larger experiment, "I tried to get rid of everything that's happening except the shear."

The first tests used the University of Rochester's OMEGA, one of the world's most powerful lasers. With multiple iterations and tests, Doss and his colleagues designed and made tubes just 1.6 mm long and under a millimeter in diameter – about the size of a mustard seed. An aluminum foil divided each tube down its length, creating top and bottom spaces. Each half was plugged at opposite ends, with the other end open. Researchers filled each half of the tube with a low-density carbon-hydrogen foam. Rapid X-ray imaging tracked what happened during the experiments.

OMEGA fired a 1-nanosecond, 5-kilojoule pulse onto plastic ablator materials at the tube's opposite ends. The materials vaporized, heating rapidly and launching shocks that turned the foam into a plasma. The shocks moved across each side of the foil from opposite directions at speeds of 110 km per second and pressures of around 5 million times Earth's atmosphere. "That gets flow going in opposite directions behind each shock. Where they cross, we get a tremendous amount of shear," Doss says.

As the shock passed, it also heated the foil to a plasma. The foil's heavier composition showed up well in X-ray images, letting researchers see how materials mix in the shear layer. The researchers mainly tracked the layer's width. If shear instability caused no mixing, Doss says, then after the shock passes the layer would puff out as it became a gas, then squeeze together as the shock rebounds. "It would rattle around a bit, but it wouldn't be able to grow continuously."

Researchers attribute any added growth past the initial shock to shear, letting them quantify its effects.

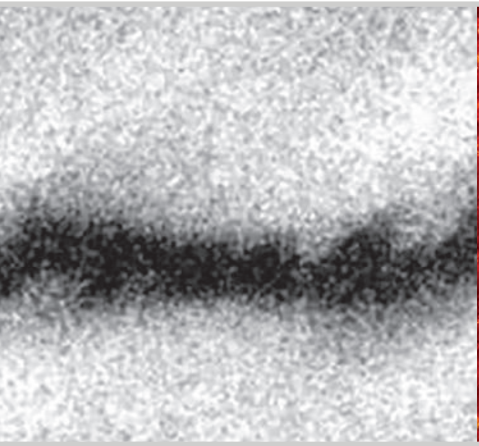
Results from the OMEGA experiments matched well with simulations run using RAGE, a radiation-hydrodynamics code developed at Los Alamos. The comparisons showed that mixing accounts for most of the layer's spread.

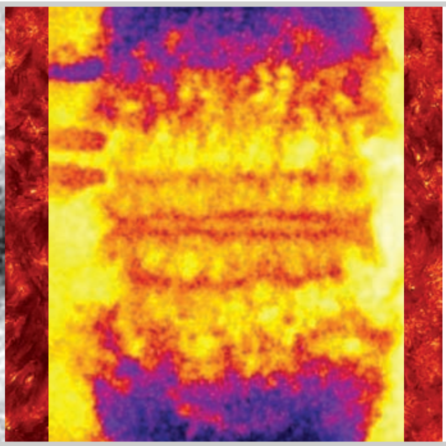
The OMEGA experiments, however, had limits. First, the shock tube's extraordinarily small size meant it suffered from boundary effects, with the walls influencing the shock and mixing. Images showed chaotic turbulence.

More importantly, OMEGA's pulse on the ablator is brief, hitting the carbon-hydrogen foam like a hammer blow to launch the shock. "The experiment can't last and get into the real developed shear kind of regime," Doss says. The shocks cross at about 7 nanoseconds and the experiment ends at about 16 nanoseconds. During the intervening 9 nanoseconds, when shear happens, energy in the system steadily declines.

"To learn more, we would need to get more separation between the layer's initial response to the shock and the shear layer's continued growth," Doss says.

To address these problems, Doss and his colleagues turned to NIF, with laser energy 100 times greater than at OMEGA. With more energy, the team could experiment with shock tubes roughly three times larger (almost 5 mm long and 1.5 mm in diameter) than those used at OMEGA, reducing edge effects. The NIF laser drive also is like a steady press, sustaining for 10 nanoseconds, rather than OMEGA's hammer-like, 1-nanosecond pulse. The opposing shocks don't cross the tube's center point until around 17 nanoseconds after the laser fires and the longer drive time sustains the pure shear environment for as long as 35 nanoseconds.





Far left: Cloud formations typical of Kelvin-Helmholtz (K-H) instability rollers. Center: A high-speed X-ray radiograph showing a side view of a NIF shock-tube experiment. Bumps in the dark layer of plasma indicate curls from K-H instability rollers. Near left: Overhead view of a colorized X-ray from a titanium foil shock-tube experiment, with well-defined horizontal rows of K-H rollers.

'Seeing (the rollers) show up so plainly here was a really great triumph.'

Beginning in late 2013, the NIF fired 300-kilojoule laser pulses into partial hohlraums at the ends of a series of shock tubes, producing X-rays that sent shocks down the tubes at speeds and pressures similar to those in the OMEGA experiments.

The resulting X-ray images thrilled the researchers. In a side view, they saw evidence of rollers – curlicues in the mixing layer characteristic of Kelvin-Helmholtz instability, a classical shear phenomenon. Viewed from above, the vortices lined up in filaments spanning the turbulent layer, like a series of ocean waves. "Those weren't put there. They aren't part of the foil" before the shock hits, Doss says. "These straight lines that appear in a system that would otherwise be totally chaotic is a great indication that you really got into a shear state and that's dominating everything."

Kelvin-Helmholtz instabilities and the resulting rollers are found in cloud formations, ocean waves and other everyday occurrences. The surprise is "we can get a picture of them at NIF that looks the same" as these large-scale phenomena, "but everything's happening a billion times faster and at one ten-thousandth the size," Doss says. "These rollers are some of the most studied structures in classical fluid mechanics, so seeing them show up so plainly here was a really great triumph."

It was the first time, Flippo says, anyone had seen "these coherent structures that you see almost everywhere in nature" but at tiny scales. Because that demonstrated that standard shear physics equations apply to HED scenarios, Doss could calculate the amount of energy in the experiment's mixing layer. The results, Flippo says, were nearly identical to mixing layer energies as predicted in simulations.

That "gives us a lot of confidence that the code is getting it right," Flippo says. "We can take these hundred-year-old fluid experiments and apply them to our data, which is really cool. And we're talking about eight orders of magnitude in scaling between (historic) fluid experiments and the NIF experiments. That's kind of mind-boggling."

It also means the researchers can tweak the experiments as they seek ways to control shear mixing. For example, they've shot shock tubes in which the aluminum foil is slightly roughened, on the scale of a few microns (millionths of a meter). The result: The instability layer is wider when viewed from the side, with a long-lasting chaotic structure that stops Kelvin-Helmholtz roller development. Roughness is a major specification for ICF capsule surfaces and researchers want to know how much an uneven finish could influence mixing in an implosion.

The researchers also have tested thinner, denser foils made of titanium to see how those factors affect shear mixing. Roller structures appeared, then merged as mixing grew later in the experiment than it did with aluminum foils.

"We're looking for more variables than just that width" of the mixing layer, Doss says. "Now that we have these connections with classical flow behavior, we're looking at other ways to take advantage of what people have spent almost a century thinking about in that system and finding more variables we can compare." As data come in, they'll assess "if we really do have predictive power" for experiments. The NIF experiments alone have led to nine published journal articles so far.

The shock tubes Doss designed and Flippo helped actualize and test also could be used to study other shocks. "The next evolution of this is to use the exact same setup but change the package around," Flippo says, so shocks go through the separating layer rather than parallel to it. That lets researchers study other kinds of instability, like Rayleigh-Taylor and Richtmyer-Meshkov.

Flippo is pleased with how the project progressed, from Doss's designs, to translating them into an experiment platform, to OMEGA tests and finally NIF shots. He credits Los Alamos project manager John Kline with pushing to get NIF access. "Because the team did a lot of engineering and homework, those (early) shots returned beautiful data. That's not something that's typical of these experiments," which often take months of precious shots to tune. "You could say we were lucky or you could say we were good," Flippo joked. "In either case, we were really happy to be able to get this off the ground and working as fast as we did."

Doss is thrilled, too. "It's been a great opportunity, being able to set up and design and own an experiment at this level." He'll soon move on to other possible fusion roadblocks – "the list of good things to go after and see where the smoking gun might be." SS

The Hydrogen Squish

To get the most bang out of a hydrogen fusion experiment, Matthew Gomez and colleagues at Sandia National Laboratories must carefully balance three competing properties.

BY ANDY BOYLES

Sandia National Laboratories scientists Matthew Gomez (left), Adam Sefkow (center) and Steve Slutz atop the Z machine.

HOW MANY NEUTRONS can you squeeze out of a wisp of hydrogen isotopes? That question drives Matthew Gomez, a physicist at Sandia National Laboratories in Albuquerque, New Mexico. His practicum at Sandia through the Department of Energy National Nuclear Security Administration Stewardship Science Graduate Fellowship (DOE NNSA SSGF) led to a permanent post at the lab. Now he's one of a handful of principal investigators who are advancing a new approach to nuclear fusion, in which atoms merge, releasing tremendous energy.

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Research teams around the world are going about fusion in many ways. A tokamak, for example, uses a mesh of powerful magnetic fields to contain a mass of plasma too hot for any solid material to contain. Researchers intend to trigger fusion reactions in the plasma, generating enough energy to reduce fossil fuel use.

Other teams trigger small, short-lived fusion reactions in laboratories. Their immediate goal is to yield the neutrons needed for stockpile stewardship research. Gomez works on such a project: MagLIF, which stands for magnetized liner inertial fusion. The approach traps, heats, and literally squeezes small amounts of hydrogen isotopes, forcing them to fuse and unleash several forms of radiation, including neutrons. To accomplish the feat, MagLIF marshals three components. The first is a magnetic field that helps trap hot, charged particles in the fuel, where they boost fusion reactions. The second is a laser that preheats the nuclear fuel.

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The third MagLIF component is Sandia's mighty Z machine, often called simply "Z." It stands 6 meters tall and 33 meters in diameter and combines electrical flows from banks of capacitors into a single current that can total as much as 26 million amperes – the world's most powerful jolt of electricity – for about 100 billionths of a second. For those 100 nanoseconds, the current creates a mighty magnetic grip called a Z pinch, crushing a small container of nuclear fuel. This implosion gives MagLIF the "inertial fusion" part of its name.

Gomez is team lead for integrating the three MagLIF components. To squeeze more neutrons out of the fuel, the team wants to "turn up the knob," he says, on all three components: magnetic field, laser preheating and Z pinch. But increasing the power of any one disrupts at least one of the others. Gomez wants to "understand the balances between them and try and determine what's the right direction to go in terms of optimizing as many of the parameters as you can."

Gomez couldn't have predicted his career would lead him to a project like MagLIF. With a lifelong love of math, he found most science courses to be fairly superficial until high school. "Every year, I took a new science class," he says, starting with biology, then chemistry, then physics. "And every year that I took a new class, that was what I knew I was going to do. I'm curious sometimes, if they had been in a different order, if I would've ended up where I did."

He ended up in physics and at the University of Michigan, partly because he liked the football team but mainly because it's one of the nation's top schools for his field. As an undergraduate, he was thinking generally of working in nuclear engineering, but a senior-year class in plasma physics gave him a new trajectory. "It was really interesting and different," he says. "It seemed like a very novel thing, something that you would just kind of hear a little bit about."

That led him into an internship at Sandia, helping put together a pulsed-power driver much smaller and less powerful than Z. Besides assembling and testing the device, he helped connect the systems that support it. Finally, he designed a transmission line to deliver the electrical jolt to the experimental targets and a vacuum system to isolate experiments from ambient air.

For his doctoral studies, also at the University of Michigan, Gomez turned to plasma physics. After his first year, he did another internship at Sandia, again working on a pulsed-power driver smaller than Z. Gomez toured the Z facility shortly after he arrived and the machine's power impressed him. It still does, especially if he happens to be in the building during an experiment. "When it fires, it's almost like a mini earthquake," he says.

Meanwhile, the university had invested in a device called a linear transformer driver. Eight hundred times less powerful than Z, the new technology can deliver a high-voltage, high-current load directly to a target, bypassing many complications inherent in Z and other pulsed-power drivers.

The Z machine's final optics assembly, which guides a laser into a target and heats fuel for MagLIF experiments.

Gomez helped assemble the device, including the infrastructure that supports it. He again designed a transmission line, the current-delivery hardware, and a vacuum system. "That was like a year of my grad school, just starting with a bunch of parts and putting everything together and making sure that it worked."

With that done, the experiments began. A typical test involves suspending a small array of ultra-thin wires or a tube of thin foil in the target position. When the device fires, a burst of electrical current flows through the target. Under the energy surge, the atoms comprising the wires or foil separate from one another and the electrons break free of the atomic nuclei. The result is a hot plasma that implodes on the target's central axis. As the implosion reaches its peak crushing force, the plasma emits various kinds of radiation.

Based on his experiences with three similar machines, Gomez saw that Sandia was the natural place for him to do his required DOE NNSA SSGF practicum. For his project, he settled on a long-standing problem with Z: Somehow, in a part of the machine where the currents converge on the target, part of the power always went missing. Gomez narrowed the glitch down to an errant plasma arising from trace contaminants at this juncture. He and others are working to learn how the plasma interferes with current flow.

By the time Gomez joined Sandia as a physicist, the machine and the MagLIF experiments were familiar territory.

To run a typical MagLIF experiment, the team places a small amount of deuterium into a can, or liner, about the size of a pencil eraser. Deuterium is a go-to hydrogen isotope for nuclear fusion. In addition to the single proton in a typical hydrogen nucleus, it also holds a neutron. As a result, the isotope is more susceptible to fusion reactions than garden-variety hydrogen. The team intends to add another hydrogen isotope, tritium, which bears one proton and two neutrons.

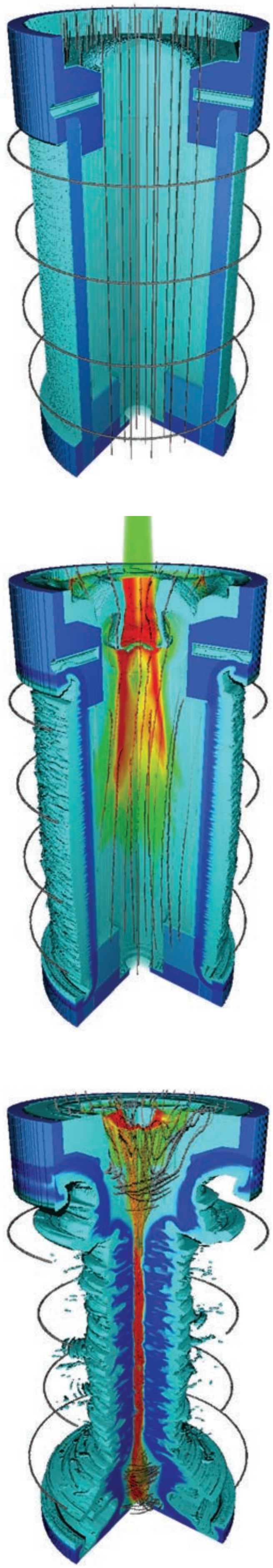
Instead of a wire array, the deuterium-filled liner is Z's target. The team sets up the machine to give the liner a multimillion-ampere shock (and Z pinch) lasting 100 billionths of a second. But Z's grip, powerful as it is, needs the help of another, smaller magnetic field to coax fusion reactions from deuterium. As Z crushes and heats the fuel, hot, charged particles begin to lose their heat to the liner's sides. To keep particles away from the liner, the team uses the Applied B-field on Z (ABZ), a device consisting of two circular magnetic coils, one above the liner and the other below. The coils set up field lines that run vertically through the fuel. Although many charged particles follow these lines to escape through the liner ends, the axial magnetic field retains enough particles for the tens of nanoseconds necessary to reach fusion temperatures.

In February 2013, the team had a surprising result when testing the newly installed ABZ for the first time. In a typical liner target implosion, frustrating instabilities create bulges and pinches along its length. The instabilities shut down fusion reactions and can even tear open the liner. But the axial magnetic field somehow kept the liner surprisingly uniform as it collapsed. "It was different from what we were expecting," Gomez says, "and that was really exciting."

Knowing that more heat spawns more fusion, the physicists added one more component to their approach. While the axial magnetic field was in place and just before the Z pinch, they shone a powerful laser into the top of the liner, instantly heating the fuel to 100 electron-volts (eV), more than 1 million degrees centigrade. At that moment, the Z pinch crushed the liner under 100 million to 200 million atmospheres of pressure, heating the fuel to 2,500 eV, more than 25 million degrees centigrade.

And deuterium nuclei fused.

The implosion emitted heat, charged particles and about 2 trillion of the sought-after neutrons. In fact, the target also gave off alpha particles (consisting of two neutrons and two protons) and 50 billion of the high-energy neutrons that form when deuterium fuses with tritium – although the MagLIF team had not added tritium to the fuel. The high-energy neutrons showed that some of the tritium that forms in deuterium-deuterium fusion reactions also fused with deuterium in secondary reactions. "Although we had predictions of the expected performance of this target



A schematic of the MagLIF concept: An axial current (top) creates force that implodes a gas-filled target in a pencil-eraser-sized can, or liner; (center) near the start of implosion, a laser heats the fuel; and the liner compresses (bottom), further heating the fuel to fusion-relevant conditions.

design, fusion is notoriously difficult, so many of us were pleasantly surprised by the outcome of the experiments," Gomez says with characteristic understatement. To the researchers' amazement, images of the implosion showed that the quarter-inch-long column of fuel was just twice the thickness of a human hair, 40 or 50 times smaller than the target's initial diameter. Before the experiment, they thought that anything exceeding a conversion factor of about 30 would be "so unstable that you wouldn't get anything useful out of it."

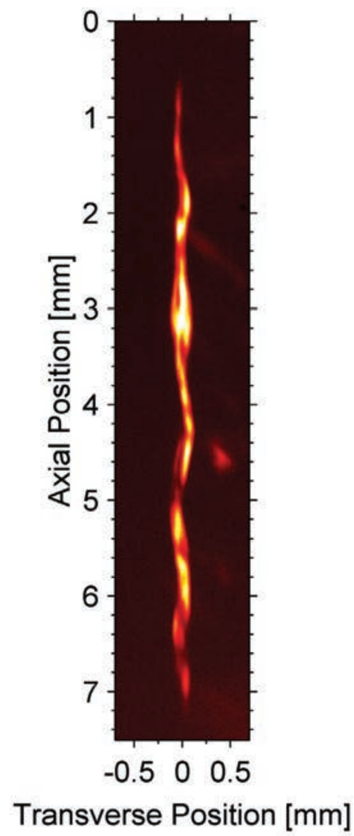
With that experiment, MagLIF ranked among a very few approaches that spark fusion by crushing nuclear fuel, a method called inertial confinement fusion (ICF). The most mature ICF technology operates at the National Ignition Facility (NIF) at DOE's Lawrence Livermore National Laboratory in Livermore, California. NIF uses the world's most powerful laser to start a cascade of events that result in ICF reactions. NIF lasers create X-rays, which converge on a spherical capsule containing deuterium and tritium fuel. The X-rays convert the capsule's surface into plasma, which shoots outward in all directions. The equal and opposite force exerted inward by the expanding plasma crushes the fuel and triggers fusion.

With four decades of development, NIF is more powerful than MagLIF and delivers larger neutron payloads. Eight-year-old MagLIF leapfrogs the energy-losing intermediate stages of converting laser energy into X-rays and then X-ray energy into the kinetic energy of expanding plasma. It draws less power and pours more of its total energy directly into the implosion. "We're kind of newcomers, but we're trying to catch up," Gomez says.

As a leader of the effort to maximize and balance the three MagLIF components, Gomez makes a lot of judgment calls, trying to focus on the most promising of team members' ideas. "We've optimized some of the materials that we put into the target," he says. "We've adjusted how our laser is configured. We've tried turning up knobs on the current and the magnetic field as well. We've played around with some of the dimensions of the targets." As a result, the team has achieved outputs as high as 3 trillion neutrons from deuterium-deuterium reactions.

To push the technology further, the team is developing diagnostics that will help them understand the plasmas themselves. That knowledge will inform the scientists' decisions. For example, does the axial magnetic field need to be almost perfectly uniform, or can it vary by as much as 15 percent? More wiggle room in this input would allow the team to crank up the Z-pinch current.

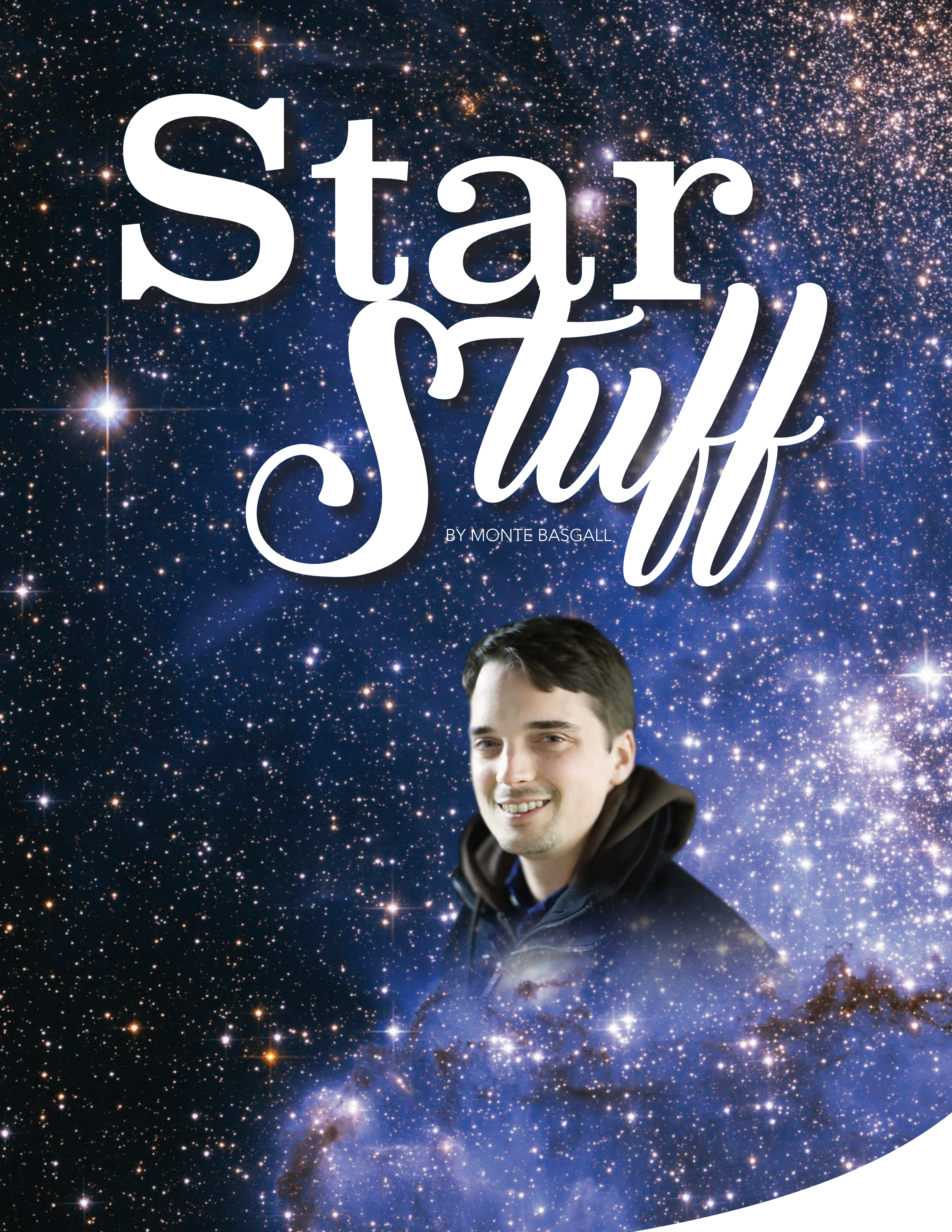
"We have this idea of where we want to be," Gomez says. "It's not obvious how you get there because you can probably get any one of those individual parameters up to that point. But can you get all three there at the same time?" SS



An X-ray emission image captures a 2-nanosecond snapshot of a 6-millimeter column, showing the hottest region of compressed fuel. The result was part of a series of experiments designed to validate key features of the MagLIF inertial confinement fusion concept.

Star Stuff

BY MONTE BASGALL



EARTHLY EXPERIMENTAL PLATFORMS LET LIVERMORE'S MATTHEW BUCKNER EXPLORE STARS' ELEMENT-MAKING MACHINERY.

THE CONCEPTS Matthew Buckner studies as a post-doctoral researcher at the Department of Energy's Lawrence Livermore National Laboratory are distant: the basics of how stars and elements are formed. Yet he tackles them with earth-bound experiments that satisfy his yen for tangible science.

As a University of North Carolina-Chapel Hill graduate student, Buckner tinkered with and ran tests at the Laboratory for Experimental Nuclear Astrophysics (LENA), part of the Triangle Universities Nuclear Laboratory (TUNL).

His time at LENA, Buckner wrote later, gave him the "analytical pedigree of a physicist, the maintenance toolkit of a technician, the hands-on experience and troubleshooting techniques of an engineer and the beam optics and beam transport skills of an accelerator operator."

By the time he'd graduated, Buckner was already tackling mysteries of the universe. One arose from the analysis of oxide grains recovered from primitive meteorites and interplanetary dust.

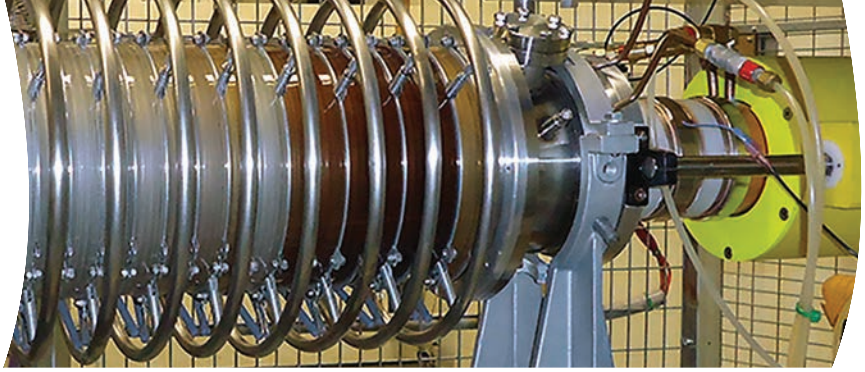
These strange particles have an odd deficit in the oxygen-18 isotope – an O-18 to O-16 ratio in those grains that differed so dramatically from the norm in our solar system that some scientists have surmised the grains may have migrated here from other stars.

One popular notion: They formed in the atmosphere of a star similar to our sun but near the end of its life, when it would have swollen into a red giant. This star might undergo an "extra mixing stage called cool bottom processing," says Buckner, who works on applied nuclear physics and energy applications. "Due to the temperatures in that region you could actually run through a chain of reactions that might produce these isotopic ratios."

Buckner was first author on a 2012 *Physical Review C* paper examining what he calls an "unobserved low-energy resonance" that would favor nuclear transformations from one nuclide to another. "It's supposed to be there," he says. "And that was the key measurement I was trying to make in the laboratory."

At TUNL, Buckner could probe what was happening in dying stars on an earthly platform by transmuting isotopes with a student-built electron cyclotron resonance (ECR) ion source. Duke University co-manages TUNL with North Carolina State University and the UNC, where Buckner was a Ph.D. student in nuclear astrophysics, with support from a DOE National Nuclear Security Administration Stewardship Science Graduate Fellowship (DOE NNSA SSGF). He credits the fellowship for four years of "very generous funding" and "getting my foot in the door" at Lawrence Livermore.

On LENA, Buckner and colleagues aimed proton beams of appropriately low energies at thin films of O-18-enriched tantalum oxide. Those beams could then excite the O-18, changing it into fluorine-19 and producing a characteristic cascade of gamma rays.



The ion accelerator at the Laboratory for Experimental Nuclear Astrophysics. The instrument, housed at Duke University, produces a high-intensity proton beam for measuring nuclear fusion reactions like those which happen in stars.

"I probed these reactions with protons because a stellar plasma is often primarily protons," he explains. "And the energies of that laboratory proton beam can be mapped to plasma temperatures in stars."

He and his co-experimenters positioned a high-purity germanium detector near the target to detect gamma rays emanating from excited nuclei. A second detector grouping made of sodium iodide was positioned nearby.

To weed out gamma signals produced when the proton beam encountered background contaminants, the two surveillance systems worked together as a "gamma-gamma coincidence detector." Only events logged by both at the proper time and energy intervals were considered valid.

Buckner also used a program developed at UNC to solve the thermonuclear reaction rate of the O-18 to F-19 transition. He used two other codes for calculating the direct capture of protons by the O-18. "You can think of them as calculating the cross section – the probability that a particular reaction will occur –based on underlying nuclear physics quantities."

After all that painstaking work, the researchers did not find the sought-after resonance that could be associated with cool bottom processing at the energy level they chose at LENA. But they set a new upper limit on its resonance strength and determined new reaction rates at that limit.

Buckner's doctoral dissertation studies, outlined in a Jan. 4, 2015, *Physical Review C* paper he also first-authored, used the same tools at LENA – upgraded over three additional years – to painstakingly probe a different kind of thermonuclear reaction that can lead to nuclear fireworks.

The sources are certain two-star binary systems. One component is a white dwarf: the burned-out corpse of a much larger body – often composed of oxygen, carbon, neon and magnesium – that has already completed its giant phase and "blown off all of its envelope," Buckner says. The second is a stellar neighbor that "could be similar to our sun or more massive. It's still burning hydrogen-to-helium in its core and is essentially a reservoir of protons."

The fuse is set when the white dwarf collects hydrogen-enriched matter on its surface from its companion. Pressures and reactions produce heat that drives a thermonuclear runaway on the surface of that oxygen-enriched, electron-degenerate stellar corpse.

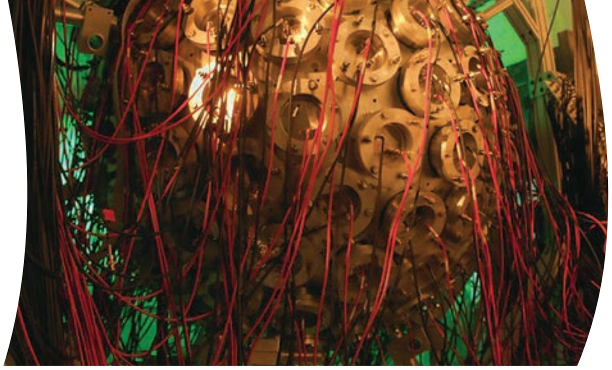
This explosive hydrogen-burning event is known as a classical nova, Buckner says. "And these phenomena are thought to be recurrent." That means the dwarf star "can eventually start accreting matter again from its companion. And the entire cycle will repeat itself."

His 2015 paper probed the rate at which a different isotope, O-17, is thought to transmute to F-18 during such eruptions. "That particular stellar phenomenon may be one of the primary sources of O-17 in the entire galaxy," Buckner says. On LENA's ECR ion source, Buckner's group was able to capture new energies for an electromagnetic interaction between the nucleus and the proton beam. The measured range fell between 170 and 530 kilo-electron volts – "relevant to the actual stellar phenomenon and the lowest in-beam measurement of this reaction."

Although the same gamma ray detector arrays were used for both his 2012 and 2015 papers, which acknowledge the fellowship for its support, the intricate coincidence detector analysis for the 2015 research was "a key triumph of this research and the thesis," he says. It involved extensive simulation of the entire detector system and the gamma cascade using GEANT4, a framework of software libraries the European accelerator lab CERN curates.

A 2015 DOE news release labeled their findings a breakthrough, saying such measurements "are extremely difficult because they occur at a tiny rate in the laboratory."

Among the co-authors of Buckner's 2012 and 2015 *Physical Review C* papers was Christian Iliadis, professor and chair of physics and astronomy at UNC. Iliadis served as his principal graduate school mentor, Buckner says, and wrote "the book on experimental nuclear astrophysics." Another coauthor and UNC professor, Arthur Champagne, currently directs TUNL and LENA.



The Detector for Advanced Neutron Capture Experiments (DANCE) at the Los Alamos Neutron Science Center. DANCE allows study of capture reactions on small quantities of radioactive isotopes for nuclear astrophysics and stockpile stewardship science.

Early on, Buckner says, his parents – both social workers – "gave me a free range to be creative. But they didn't put any sort of pressure on me to get good grades. They just really wanted me to get into all my interests, be it physics, art, music, mathematics competitions or the yearbook committee." After graduating as salutatorian from North Warren Regional High School in Blairstown, New Jersey, he started college as a film major at Boston University. When he decided film "just didn't have everything I was looking for," Buckner followed his North Warren physics teacher's recommendation and went to Lehigh University in Bethlehem, Pennsylvania. He graduated summa cum laude in astrophysics, with honors in physics and a stack of other honors and scholarships.

Buckner's ties to Lawrence Livermore began in his second year of graduate school, when he did a summer practicum there for the DOE NNSA SSGF program. "I was helping them design a gas ionization detector," he recalls. "I saw the whole thing through, start to finish."

Buckner formally joined Lawrence Livermore as a post-doctoral researcher in November 2014 and has since been involved in a number of neutron-capture experiments.

One *Physical Review C* paper, released in February 2017, measured neutron-induced reaction cross sections of metastable americium-242 at energies from 25.3 milli-electron volts (mEV) to 1 eV. Am-242's metastable version exists in an excited state and has a half-life of 141 years. Normal, or ground state, Am-242 has a half-life of just 16 hours, Buckner says. The metastable form also has "the highest measured thermal-fission cross section of any known nucleus," the authors say. That makes metastable Am-242 "an appealing nuclear fuel," potentially operating for long periods as a space reactor, nuclear engine, small core reactor or fission battery, the authors wrote. "For a spacecraft, the energy from 1 kilogram of metastable americium-242 is equivalent to 1,000 tons of conventional oxygen and hydrogen rocket fuel," Buckner adds.

An earlier *Physical Review C* paper, from 2016, addressed previously missing information about transmutations of the radioactive isotope plutonium-242 when bombarded with neutron beams at energies from 25.3 mEV to about 6 kilo-electron volts.

Determining such "neutron-capture cross sections" for Pu-242 "is particularly relevant for modeling reactor performance and the development of next-generation reactors because it has a long half-life (about 380,000 years)," the paper says, and improving the precision of such radioactive isotope information is a priority for NNSA's Stockpile Stewardship Program.

"There are a lot of open questions still out there in the nuclear data community that require experimental investigations," Buckner says. "It also depends on what facilities have the ability to make these measurements over wide energy ranges."

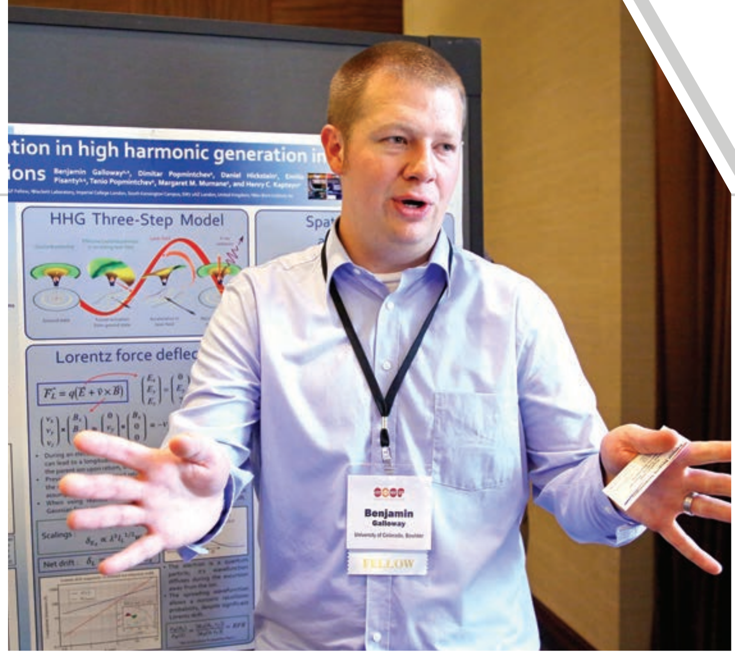
For the Pu-242 and the metastable Am-242 studies, he worked with Los Alamos National Laboratory's Lujan Neutron Scattering Center, which provided the necessary pulsed neutron beams. Those beams were aimed at the nearby Detector for Advanced Neutron Capture Experiments (DANCE). At the heart of DANCE, targets seeded with those isotopes interacted with the neutrons.

So-called parallel plate avalanche counters (PPACs) converted the energy from the resulting neutron fission fragments to electrons, which a cathode then collected for analysis. Because neutron beams also can induce fission reactions unconnected with the experiments, duplicate PPACs without radioactive targets were separately exposed to the neutron beams to weed out background contaminants.

Los Alamos scientists sent these data to Buckner for detailed signal processing. Those analyses are aided by his mostly self-taught knowledge of C++, a science-oriented computer programming language. Other cross-section studies he's done have involved collaborations with Argonne's National Laboratory's upgraded Compact Heavy Ion Counter (CHICO 2) as well as TRIUMF, Canada's national lab for particle and nuclear physics near Vancouver.

Says Buckner, "I'm very much indebted to the fellowship for providing me with so many resources and opportunities." SS

Monte Basgall is a freelance science writer and former newspaper reporter. He covered basic sciences, engineering and environmental sciences at Duke University for 17 years.



Laser Science Is Not Mad Science

BY BENJAMIN GALLOWAY

A blindingly bright laser shoots through a crowd of atoms. The laser is so bright that pieces of the atoms get ripped away, only to begin a performance of wiggling motions. While the tiny particles slosh to and fro, some of the atoms and their lost pieces rendezvous. There is a flash of invisible light – a signature of broken atoms made whole again – and it's all over. The dust settles. The world keeps rotating, the sun keeps burning, and people everywhere go about their lives without knowing there was a laser at all, let alone a turbulent sea of highly excited atom fragments in a laboratory somewhere.

What do scientists hope to achieve when they fire their powerful (and expensive) lasers at seemingly innocuous things, like the air? Who can benefit from their strange exploits? Who even cares? Indeed, the impact this research has on society is not clear at first glance. It may seem surprising that the process described above, called high harmonic generation (HHG), can help make computer chips smaller, medical X-ray exams less damaging to patients, and science research more efficient and accessible. That means smaller phones, less cancer risk and more clues to how the world works, which in turn leads to further advances to benefit society. HHG provides a means to achieve all of these goals by giving scientists and engineers a versatile tool: An X-ray laser.

To make an X-ray laser via HHG, scientists start with a more conventional laser with a reddish color. Firing this energetic light beam into a cloud of atoms causes those atoms to break into pieces, but it also gives them opportunities to reunite and release energy. As a result of these atom interactions, the red laser changes color drastically, from red to violet, and then hundreds or even thousands of times further, to outside the range of colors that the human eye can see. A far cry from where it began, the new X-ray laser can now pass through thick materials and reveal the fastest dynamics in the universe at the tiniest of scales.

It is difficult to grasp just how bizarre the HHG process actually is. Imagine a rainbow. Its beauty lies in all of the colors that it possesses – all of the colors that we can see. But the rainbow and its colors are really just an indication of what the sun provides. All of those colors were already present before water droplets redirected them toward our eyes, forming the rainbow. On the flip side, HHG allows us to start with light of a single color and make new colors that did not exist previously. Like a magician pulling a rabbit out of a hat – the rainbow represents a rabbit that was simply hidden until revealed, whereas HHG represents actually pulling the rabbit out of thin air.

In truth, magic and rainbows are glamorous analogies to HHG. The actual research laser scientists perform is challenging and sometimes messy. Numerous pieces of equipment must accompany a laser for it to work properly: water circulators, high-voltage power, vacuum pumps, gas lines – you get the picture. With so many working pieces, it's not uncommon for an experiment to halt because one of the components breaks down due to age, wear, contamination or electrical failure. Until all problems are fixed, no progress can be made. Laser scientists may be experts in laser science, but making repairs in a laboratory quickly teaches them to become proficient plumbers, machinists and electricians.

When every component functions and the X-rays shine bright, the real science can begin. By using such an exotic light source as a microscope, researchers can find new ways to examine and improve devices we interact with every day. The fundamental laws that govern nature can be investigated too – whether it's magnetism, heat transport, medicine, or chemistry, there's a chance to uncover something new, something never seen before, something worth writing about.

The beauty of nature can be seen outside in a rainbow or in the star-strewn sky at night, but it is also present in the mystery that governs atoms and light in a basement laboratory. As scientists, we are motivated not by some mad notion of world domination but by our pursuit of nature's beauty and its ability to improve the lives of others.

The author is a final-year fellow and the winner of the 2017 SSGF Essay Slam, an annual writing contest open to current and former fellows.

DOE NNSA SSGF FELLOWS ROSTER

OUTGOING CLASS

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JUAN MANFREDI
Michigan State University, physics (Betty Tsang); LLNL

FOURTH YEAR

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COLE HOLCOMB
Princeton University, physics (James Stone); LLNL

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California Institute of Technology, astronomy and astrophysics (Sterl Phinney); LLNL

CAMERON MEYERS
University of Minnesota, rock and mineral physics (David Kohlstedt); LLNL

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THIRD YEAR

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CHRISTOPHER MILLER
Georgia Institute of Technology, mechanical engineering (Min Zhou); LLNL

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University of Utah, nanotribology (Bart Raeymaekers); LLNL

ALISON SAUNDERS
University of California, Berkeley, warm dense matter (Roger Falcone); TBD

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Yale University, physics (Yoram Alhassid); TBD

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POOF OF CONCEPT

This fleeting 6-millimeter-high wisp demonstrates the promise of an inertial confinement fusion concept called MagLIF. For more, see the story starting on page 15.

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