Lawrence Livermore National Laboratory

Science & Technology Review

April/May 2018

CELEBRATING Accelerator Science

Also in this issue:

Livermore Teams Win 3 R&D 100 Awards

Collaborations Garner R&D 100 Recognition

Building Next-Generation Diagnostics

About the Cover

For 30 years, Lawrence Livermore's Center for Accelerator Mass Spectrometry (CAMS) has been operating as a unique, safe, and reliable midsize user facility for isotopic measurement and analysis. As the article beginning on p. 4 describes, today the center is a resource for a broad user base of academic and commercial collaborators and provides a wide range of capabilities. Shown on the cover is CAMS's FN tandem Van de Graaff accelerator, the center's principal instrument, which provides high-precision, high-energy analysis of multiple isotopes. (Photo by Randy Wong.)

Cover design: Alexandria Diaz

About *S&TR*

At Lawrence Livermore National Laboratory, we focus on science and technology research to ensure our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. *Science & Technology Review* is published eight times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments in fulfilling its primary missions. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

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Plasma Optic Combines Lasers into Superbeam

A team of researchers at Lawrence Livermore has successfully combined 9 of the National Ignition Facility's (NIF's) 192 laser beams lasers into a superbeam by adding a plasma—a charged mixture of ions and free electrons—to the concept. The team used a Livermore-designed plasma optic to create the superbeam, which produced a directed pulse of light that was nearly four times the energy of any of the individual beams. The research was published in the journal *Nature Physics* on October 2, 2017.

Plasma generally creates instabilities when combined with intense laser beams. However, the researchers overcame this obstacle by controlling an instability that causes the transfer of energy when beams cross. "We've known that plasma can deflect light and change the direction of energy flow, but it has been difficult to do it in a very precise way," says Livermore physicist Robert Kirkwood, the lead author on the paper and the programmatic lead for the campaign. "Our results show that by using our new plasma optic, we can now control and predict what the plasma does quite accurately."

In certain experimental configurations, targets can only be driven by a single beam, which can deliver a limited amount of energy. By combining multiple beams into one, Livermore's plasma beam combiner can break through that limit and push these experiments into new physics regimes. Beams with high energy and fluence are expected to advance a range of applications including advanced x-ray sources and studies of physics processes occurring at extreme intensities. Looking forward, the team plans to scale up the experiment to 20 beams.

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Big, Bad, Martian Volcanoes Unveiled

In collaboration with the Scottish Universities Environmental Research Centre, the University of Glasgow, the University of St. Andrews, and the Natural History Museum in London, Livermore researchers have revealed the growth rate of a Martian volcano by dating six meteorites, which formed 1.3 billion to 1.4 billion years ago. The results of the research, which were published online in *Nature Communications* on October 3, 2017, indicate that the volcano grew exceptionally slowly—about 1,000 times more slowly than volcanoes on Earth.

Martian volcanoes are the largest in the solar system, and although their size indicates continued activity over billions of years, their formation rates are poorly understood. Using isotopic measurements, the research team, which includes Livermore cosmochemist Bill Cassata, determined that the meteorites are derived from a single volcano and represent at least four eruptions that spanned 90 million years. "The data are consistent with Martian volcanoes being active for much longer than those on Earth, which are typically active for only a few million years," says Cassata.

The new findings are the first detailed analysis of the eruption rates of volcanoes on Mars using Martian meteorites, which were ejected from the planet by asteroid impact events. The team used recent remapping of the Martian surface by NASA to identify the source of the meteorites and calculate the volcanic growth rate. The research supports evidence that Martian volcanoes date back more than 3.5 billion years and were much more active in the past. Says Cassata, "For Martian volcanoes to get so large, they must have been far more volcanically active earlier in planetary history."

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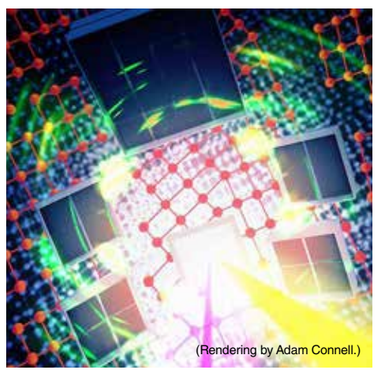
Revealing Material Changes during Shock Compression

The study of a material's plasticity (shape) at the most fundamental level rests on understanding how its lattice structure changes during deformation. In a research paper published online October 25, 2017, in the journal *Nature*, a team of researchers from Lawrence Livermore, the University of Oxford, Los Alamos National Laboratory, the University of York, and SLAC National Accelerator Laboratory reported in situ diffraction experiments measuring deformation twinning at the lattice level during shock compression.

Dislocation-slip (where lattice dislocations are generated and move) and twinning (where sub-grains form with a mirror-image lattice) are the basic mechanisms of plastic deformation. However, until now, diagnosing the active mechanism during the shock has been elusive. In the experiments, the team used a laser to launch a shock wave, in which a laser-heated plasma creates an opposing pressure in the sample. The researchers then probed the state of the sample with an x-ray beam. (See image below.) "The x rays scatter off the sample at specific angles, forming diffraction rings. The scattering angle provides information on the materials' structure," says Livermore physicist and lead author Chris Wehrenberg.


(Rendering by Adam Connell.)

By analyzing the changes of signal distribution within the lines, the team could detect changes in the lattice orientation, or texture, and show whether a material was undergoing twinning or slip. In addition, the team could demonstrate whether the sample twins or slips when shock compressed for most of the entire range of shock pressures. Wehrenberg says, "Our work highlights an untapped area of study, the distribution of signal within diffraction rings, which can yield important information for a variety of applications."

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Investing in Research Frontiers

ACROSS Lawrence Livermore, including in the Physical and Life Sciences Directorate, we must anticipate the future of science and technology and be bold in our investments to pursue cutting-edge advances. The Laboratory consistently promotes prominent programs, facilities, and capabilities that benefit our nation and help to address the pressing challenges we face. This issue of *Science & Technology Review* showcases several remarkable examples of how Laboratory support of promising research keeps us moving forward.

As the article beginning on p. 4 describes, we celebrate the longevity and ongoing service of Livermore's Center for Accelerator Mass Spectrometry (CAMS). Since its inception 30 years ago, CAMS has supported scientific research for a diverse range of disciplines. This premier user facility is home to a variety of instrumentation, including multiple accelerators, ion implantation beamlines, and specialized ion sources. Working with colleagues both internally and externally, CAMS staff address challenges in nuclear forensics, chemistry, physics, biomedicine, climate science, geology, and other Earth sciences.

As a microcosm of Lawrence Livermore, CAMS embodies the collaborative, multipurpose pursuit of the Laboratory's missions. From collecting specimens in the field to preparing samples in a laboratory and running measurements on accelerators, CAMS scientists embrace all facets of their work. A common refrain among the center's staff is appreciation for access to top-tier colleagues, to world-class facilities, and to mission-driven investments. Enthusiasm is contagious at CAMS, right down to its flamingo mascot.

Three decades along, CAMS continues to conduct unique, forward-looking research. The center is an exceptional example of multidisciplinary science in action, attracting academic and industry collaborators and providing a hiring pipeline for the Laboratory. As CAMS pushes scientific advancements in environmental research and for human health, opportunities arise to bring evolving technology, such as CAMS's laser-based system for radiocarbon analysis, to the marketplace. Through its emphasis on both applications and technology development, CAMS continues to be one of the world's most versatile and productive user facilities.

Livermore's research investments have also propelled the advances of technologies that promise to improve the state of the art. *R&D Magazine*'s annual R&D 100 awards salutes noteworthy scientific advances worldwide, and Livermore has gained a reputation for leading winning projects—many with technology-transfer potential. The 2017 awards ceremony brought a number of accolades to our scientists and engineers. Collectively, Laboratory staff were the lead developers on three winning innovations and also codeveloped four other recognized technologies. The highlights beginning on p. 12 showcase these notable inventions: the Radiation Field Training Simulator, the Earth System Grid Federation, the Applied Biosystems™ Axiom™ Microbiome Array, geometrically enhanced photocathodes, an aluminum–cerium superalloy, a new hydrogen safety sensor, and the National Risk Assessment Partnership Toolset.

The goal of science and technology advancement and the importance of long-term investment can also be seen in recent work at the National Ignition Facility, where experimenters are developing and implementing new diagnostic capabilities. The final highlight beginning on p. 21 describes two advanced diagnostic instruments, one of which is still under development, that will help scientists design new experiments and investigate implosion processes and material phase changes.

In reflecting on the value of CAMS and these other important projects, I am struck by the breadth of work at the Laboratory aimed at making the world a better place. We achieve this goal through more versatile research, more precise detectors, more accessible data, more practical training, more efficient devices, more durable materials, more secure fuels, more accurate predictions, and more scientific progress. Our talented staff—truly a worthy investment—make these scientific and technological innovations possible.

■ Glenn A. Fox is associate director for Physical and Life Sciences.

Renowned Accelerator Facility TURNS 30

Livermore's Center for Accelerator Mass Spectrometry celebrates a milestone anniversary with wide-ranging new research endeavors.

Livermore scientist Jessica Osuna (left) and former colleague Alexandra Hedgpeth monitor gas emissions from a soil column at a Minnesota peat bog. Sample analysis is done at Livermore's Center for Accelerator Mass Spectrometry (CAMS).

DURING autumn of 1989, scientists at Lawrence Livermore's Center for Accelerator Mass Spectrometry (CAMS) were mystified. Electrical systems connected to the center's premier accelerator system, the high-precision instrument at the heart of CAMS's radiocarbon work, were intermittently going offline, bringing experiments to frequent, frustrating halts. At the time, the Laboratory's reputation for Earth science and biomedical research was gaining momentum. Any hiccup in the center's ability to analyze samples from national laboratories, universities, and other institutions was unwelcome.

After some investigation, the source of the problem was identified—a power coil had shifted slightly, which in turn affected the electrical grounding within the accelerator. The culprit was the 6.9-magnitude Loma Prieta earthquake, whose epicenter had been just 96 kilometers south of the Laboratory. "Until then, none of us had needed to debug the equipment after an earthquake," remembers Jay Davis, CAMS's founding director. "We did not expect to have to troubleshoot that kind of problem." The response to the challenge was exemplary of the center's overarching methodology. Since CAMS opened in 1988, problem solving, insistence on accuracy, and adaptation to change have been integral to facility operations, including for experiments and technology development, and have helped make it a reliable facility for supporting Livermore's national security mission.

Similar to many other nascent efforts at the Laboratory, accelerator mass spectrometry (AMS) was initially used for nuclear technology research. (See *S&TR*, December 2013, pp. 16–19.) However, since Livermore's leadership in fundamental science was growing into more areas of physics, chemistry, and materials science, early plans for an AMS-focused facility concentrated on anticipating future needs and providing service to a wide community of user. CAMS originally supported only radiocarbon and tritium analysis—with separate handling protocols and preparation laboratories to avoid contamination. A major goal was to expand capabilities for measuring other isotopes. Davis says, "CAMS opened the door to exploration. Scientists started to ask themselves what could be done with this technology."

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In the beginning, resources were modest. CAMS staff assembled the first accelerator by combining new and used equipment. Davis recalls, "The ion source was purchased new, but we harvested the magnets from other laboratories. We built a machine we could not afford to buy." The team set about constructing instrumentation safely and inexpensively with next-generation computer systems. "Measuring isotopes at 1 radioactive atom per 1 quadrillion atoms is difficult to achieve. One big challenge was setting up the computer-controlled instrumentation that makes these measurements possible," continues Davis.

CAMS's focus has been guided over three decades by attention to both applications and technical development. "We have achieved a balance between internal and external users and

between fundamental basic science and Laboratory programmatic work," explains CAMS director Graham Bench. Today, the center houses multiple AMS instruments including the 10-megavolt FN tandem Van de Graaff accelerator, a heavy-element beamline for analysis of plutonium and uranium isotopes, a beamline for ion implantation experiments, and finely tuned devices for ion and neutron production. (See the box on p. 7.) A dedicated biological accelerator mass spectrometry (bioAMS) resource leverages high-performance liquid chromatography for specialized measurements. (See *S&TR*, December 2012, pp. 18–20.)

Built for Change

Although many similarly sized user facilities around the nation specialize in one research area, CAMS supports multidisciplinary goals and technologies with fewer than 30 full-time staff. Bench attributes the center's longevity to its scientific diversity. "We have always had a broad viewpoint. CAMS is unique because of our wide scope of work," he says. Ken Turteltaub, the Laboratory's Biosciences and Biotechnology Division lead, agrees, "We wanted to create an environment that brought different types of scientists together."

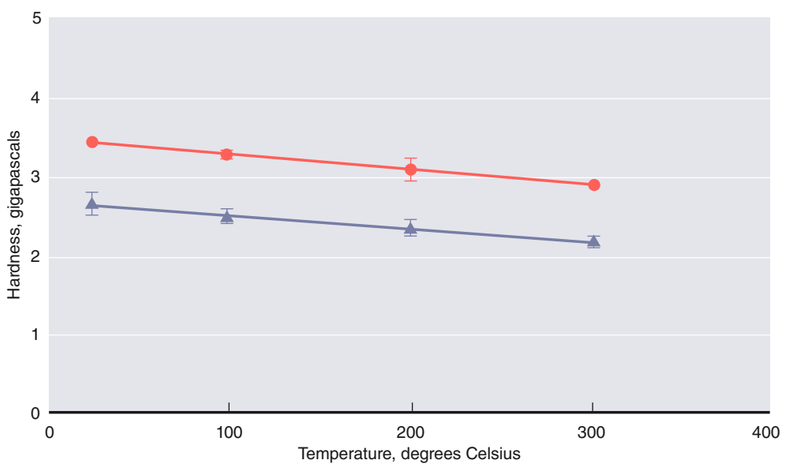
CAMS staff routinely measure a bevy of long-lived radioisotopes, including tritium; carbon-14 (^{14}C, in both liquid and solid forms); cosmogenic nuclides such as beryllium-10 (^{10}Be), aluminum-26 (^{26}Al), and chlorine-36 (^{36}Cl); nuclear fission decay products such as iodine-129 and strontium-90; and rare-earth metals and actinides including uranium-233 and -236 and plutonium-230 and -240. From studies of Earth system processes, atmospheric chemistry, and drug metabolism to assessments of radiation damage and materials modification, CAMS scientists have produced more than 1,000 peer-reviewed publications.

This range of expertise enables the center to support a broad user base of academic and commercial collaborators. (See the box on p. 10.) In addition, several U.S. agencies rely on CAMS, including the Department of Energy (DOE), the National Institutes of Health (NIH), and the National Science Foundation.

Building on CAMS's 30-year legacy of scientific achievements, the center's leaders emphasize the importance of persistent innovation and forward-looking research. "Our latest accomplishments are as important as what we have done in the past," states Bench. Davis adds, "CAMS was built for change." Recent work in four research areas showcases the breadth and depth of the center's capabilities: unique solutions for nuclear science challenges; studies of the terrestrial carbon cycle; geochronological and paleoclimatological research with cosmogenic nuclides; and laser-based ^{14}C analysis of biomedical samples.

Nuclear Science on a Mission

CAMS's highly sensitive instrumentation and nuclear science expertise are essential to Livermore's mission work. (See *S&TR*, September 2011, pp. 4–10.) Researchers such as deputy group leader Scott Tumey use high-energy ion implantation to study radiation damage. By accelerating ions into a target to change its properties, Tumey's team can study how tolerant materials are to radiation damage, and thus determine their utility in nuclear reactors. "The key to using ions for studying radiation damage is understanding the fundamental differences between how ions and neutrons interact with matter," explains Tumey. The higher the energy used in the irradiation process, the deeper the ions can penetrate the target material. For Tumey, a CAMS research scientist since 2004, this capability is invaluable. "We can produce samples on



A research team led by Livermore scientist Scott Tumey compared unirradiated (purple line) and ion-irradiated (pink line) steel alloys to characterize how indentation depth affects a material's hardness. The graph shows that at a depth of 200 nanometers, the effect was less pronounced after irradiation and at higher temperatures.

Safely Separating Ions and Counting Atoms

Lawrence Livermore's Center for Accelerator Mass Spectrometry (CAMS) occupies approximately 929 square meters and encompasses a dozen experimental and preparation laboratories. The FN tandem Van de Graaff accelerator is the center's principal instrument and can run a single radiocarbon sample in about 15 minutes. The 10-megavolt device provides high-precision, high-energy analyses of multiple isotopes with the sensitivity to detect 1 radioactive atom among 1 quadrillion atoms. Annually, CAMS's instruments average a combined 25,000 isotopic measurements.

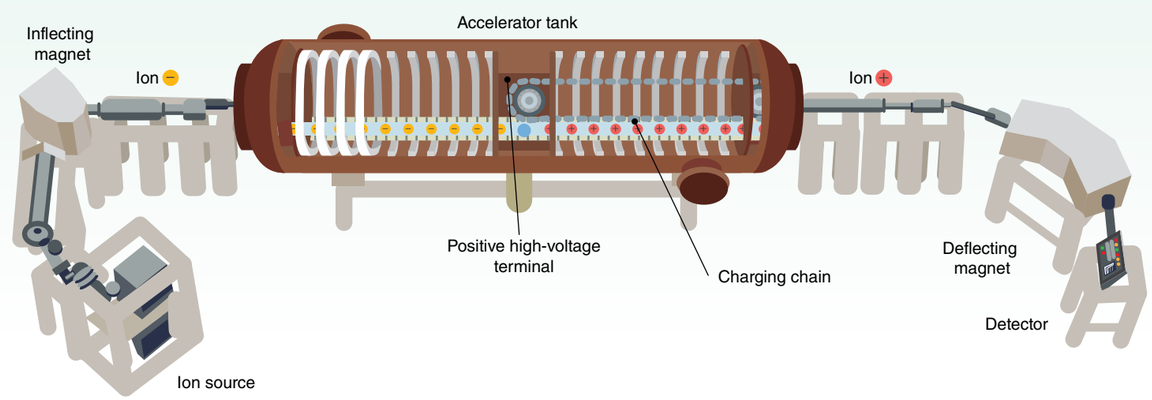
CAMS director Graham Bench stresses the importance of vigilance and safety in the center's research activities. "One can never be too careful when working with high-voltage machines and radioactive materials," he says. Tom Brown, CAMS's deputy director, ensures all new staff undergo safety training for using accelerator mass spectrometry (AMS). He notes, "High voltage, asphyxiating gas, and ionizing radiation are the main operational hazards. We follow several levels of controls to ensure personnel safety and environmental protection."

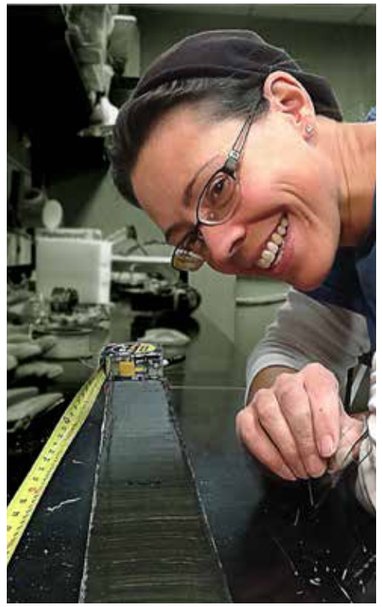
CAMS complies with both Lawrence Livermore's and the Department of Energy's safety procedures, and its laboratories are equipped with numerous safety features. Although most AMS operations do not produce substantial radiation, monitoring systems continuously run to enable automatic shutdown of a system if radiation levels exceed a certain limit. Power supplies are surrounded by grounded shields, and special sensors detect gas leaks and low oxygen levels. "We have never had a significant gas leak, nor have we needed the oxygen monitoring system to trigger for an actual dangerous event," emphasizes Brown, who joined CAMS 24 years ago.

With safety protocols in place, CAMS staff perform routine maintenance on all instrumentation. If a component malfunctions, Bench explains, "We fix it ourselves. We do as much as we can onsite." Replacement parts can be ordered from manufacturers, yet the CAMS team assumes responsibility for installation, configuration, and associated mechanical and computerized tasks. For instance, inside the FN's tank, acceleration is achieved by moving chains that maintain a constant positive charge on a high-voltage terminal. The chains' plastic and metal parts and the bearings around the chains' wheels can wear down and must be replaced. To access these components, the team must first pump sulfur hexafluoride—an insulating gas commonly used in high-voltage particle accelerators—into a storage container and then fill the tank with breathable air. According to Brown, staff develop do-it-yourself skills through their own experiences at CAMS and through dialogue with colleagues at other accelerator facilities.

High demand for CAMS's capabilities means accelerators must run all day and sometimes overnight, so the center's safety track record is crucial to its success. Brown says, "We all understand that we must control the hazards we encounter while conducting our work."

In a typical radiocarbon experiment, samples loaded into the accelerator's ion source are bombarded by negatively charged cesium ions to produce carbon ions. A magnet is set to select the atomic mass of interest. Inside the main tank, the particles are accelerated in two stages to separate the interfering molecular ions from their constituent atomic ions. A deflecting magnet then separates the ions by atomic mass and charge. A detector counts the ions of interest, and isotopic ratios are calculated to reveal the ions' relative abundance.





CAMS staff scientist Susan Zimmerman shows a core sample of mud retrieved from the bottom of Mono Lake. Radiocarbon dating of the sediments is done with the CAMS accelerator, and results help determine the environmental history of the lake basin.

which physical properties such as tensile strength and hardness can be directly measured rather than inferred from microstructural examination," he says.

In 2017, CAMS joined the Nuclear Science User Facilities network. Funded by DOE's Office of Nuclear Energy, this group of experimental laboratories provides facility access and technical proficiency to researchers tackling nuclear energy challenges. CAMS provides a unique opportunity to study the effects of neutrons on various nuclear materials, such as fuels. Tumey says, "With our high-energy accelerator, we can irradiate samples over a much larger range than other ion beam facilities, thus producing specimens suitable for the direct measurement of physical property changes associated with radiation damage."

In addition, AMS complements other analytical techniques to advance the Laboratory's nuclear forensic capabilities. "Our tandem accelerator effectively removes all molecules that have the same mass as the isotopes of interest. This feature provides an incredibly high degree of selectively and sensitivity," notes Tumey. For example, ^{26}Al and ^{10}Be can reveal information about materials used in a nuclear device, and thus Tumey's team is developing these isotopic signatures for post-detonation nuclear debris. He says, "Our methods are robust and rapid so that they can be successfully applied to any possible debris matrix and executed within the stringent timelines of a nuclear forensic response."

Seeing the Forest and the Trees

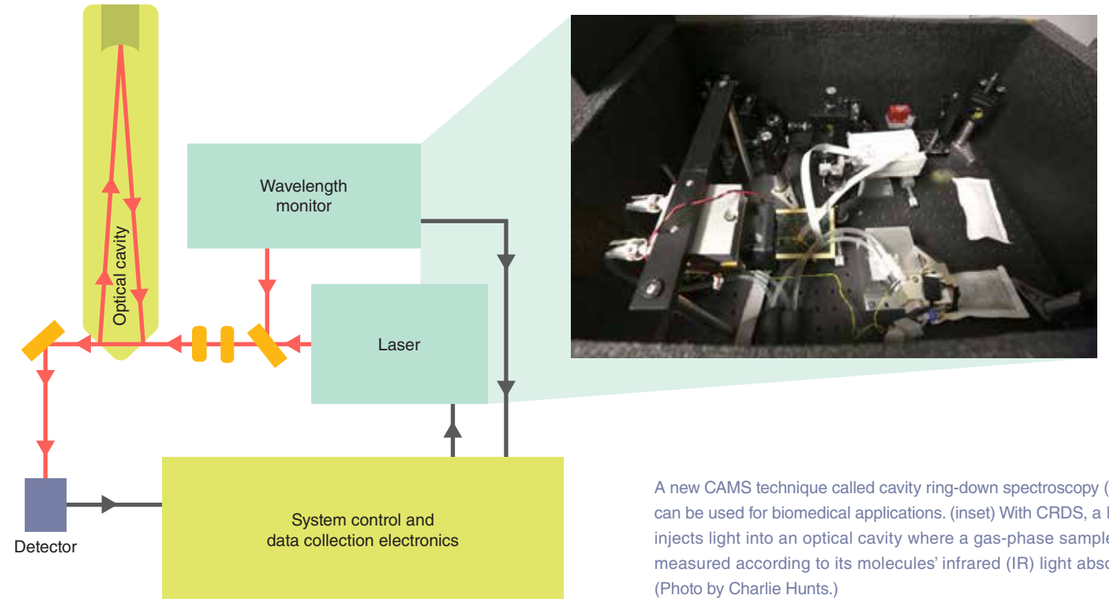
CAMS scientists conduct extensive radiocarbon analysis for multiple environmental science applications. Since joining the center in 2007, Earth scientist Karis McFarlane has studied carbon cycling in terrestrial ecosystems such as forests, wetlands, grasslands, and tundra. She works closely with DOE's Biological and Environmental Research (BER) Program on experiments that inform Earth system models. "We use radiocarbon analysis to track carbon as it moves through plants, soil, and the atmosphere," says McFarlane.

Through BER and the Laboratory Directed Research and Development Program, McFarlane and colleagues participate in a project called Spruce and Peatland Responses Under Changing Environments (SPRUCE). The multi-institutional study leverages CAMS's radiocarbon capabilities to measure ^{14}C and stable isotopes in carbon dioxide (CO_2) and methane emissions from a Minnesota peat bog. Scientists pump CO_2 and heat into enclosed sections of the peatland to simulate Earth's warming climate, testing the rates of carbon uptake, peat decomposition, and carbon release. "We see evidence that elevated temperatures increase both carbon uptake by vegetation and emissions, but in the short term we do not see losses of old peat carbon with warming," explains McFarlane. The rapid carbon cycling demonstrated by SPRUCE experiments help advance DOE's ability to predict and respond to climate change.

McFarlane's latest BER project—thanks to a DOE Early Career Research Program award—sends her to southern latitudes to better understand the role of moisture in carbon storage. For five years, her team will contribute to DOE's Energy Exascale Earth System Model (E3SM), a project that investigates complex processes such as the global water cycle and greenhouse gas fluctuations. (See *S&TR*, December 2017, pp. 4–11.) Soil samples from tropical forests in Puerto Rico, Cameroon, Indonesia, and several Latin American countries are being analyzed at CAMS for this project. "The tropics are chronically understudied along with ecosystem processes occurring below ground," notes McFarlane. "Tree root systems, for example, are not represented well in models. As a result, the models may have vertical inputs for roots going down only 20 centimeters, missing important soil carbon input patterns below that depth. Our soil profiles can help develop E3SM."

The Past Is Prologue

In addition to carbon-based studies, CAMS instruments are uniquely adapted for analysis of cosmogenic nuclides—the rare isotopes created in the atmosphere and terrestrial materials from cosmic ray collisions. With AMS, scientists can measure traces of these nuclides in rock, sand, sediment, and other natural



A new CAMS technique called cavity ring-down spectroscopy (CRDS) can be used for biomedical applications. (inset) With CRDS, a laser injects light into an optical cavity where a gas-phase sample is measured according to its molecules' infrared (IR) light absorption. (Photo by Charlie Hunts.)

materials to investigate the timing of processes such as glacial movement, landscape formation, tectonic motion, and climate change. For staff scientist Susan Zimmerman, an 11-year CAMS veteran, understanding these Earth system processes requires reconstructing the past. She says, "The goal is to bring the finest possible time resolution to the largest swath of Earth's history. This work is like flipping backward through a book to determine when events occurred and how fast changes have happened in the past."

"Fast" is a relative term to a geochronologist, and different cosmogenic nuclides provide specialized information about a specimen's historical surface exposure. For instance, ^{10}Be has a half-life of 1.4 million years, which makes it useful for analyzing old rock. Conversely, the half-life of beryllium-7 (^{7}Be) lasts only 53 days, leaving scientists with a fleeting measurement window before the isotope completely decays. Evaluating multiple isotopic signatures across a variety of sample materials helps Zimmerman piece together a more accurate picture of Earth's response to historical climate change. In one recent study, she was part of a team that measured aluminum and beryllium isotopes to chart erosion of the Greenland ice sheet as far back as 7.5 million years.

CAMS houses one of only two accelerators in the United States that routinely measures certain cosmogenic nuclides (^{26}Al, ^{10}Be, and ^{36}Cl), keeping staff busy running external users' samples as well as their own. Zimmerman, along with many CAMS scientists, often thinks about ways to expand the center's isotopic measurement capabilities to increase throughput as well as to extract more data from smaller sample sizes. She is working with staff scientist Alan Hidy and other Livermore colleagues to improve the efficiency of ^{7}Be measurement. Zimmerman says, "We can run a larger number of samples per day with greater sensitivity than before, so researchers can detect new patterns more quickly in the landscape they are studying."

Innovation with a Laser Focus

Since 1999, NIH has tasked CAMS with developing technology, analyzing samples, and interpreting data for the bioscience community. "Animal studies do not reveal everything about, for instance, how a drug will metabolize within a human. AMS's sensitivity allows us to quantify low-dose exposure," explains Turteltaub. "With consistent funding, we can move into the next phase as a user facility for bioAMS technology."

A laser-based system known as cavity ring-down spectroscopy (CRDS) is the newest tool in the bioAMS arsenal. CAMS staff scientist Daniel McCartt applies his engineering expertise to design and build better instrumentation. When McCartt was a Ph.D. student at Stanford University, he worked with CAMS and a commercial company, Picarro, Inc., to develop CRDS. He states, "Building a new instrument is not easy. At CAMS, I have access to analytical chemistry experts who can validate this new technology."

With CRDS, a laser injects light into an optical cavity where a gas-phase sample is measured according to its molecules' infrared (IR) light absorption. McCartt describes the cavity as a literal hall of mirrors. "When the laser is switched off, the light 'rings down' inside the cavity. We measure the light absorbed by the sample during this process," he explains. "The technique leverages the 'fingerprint region' of the mid-IR spectrum, where molecules are resonant with mid-IR light." The mirrors provide high sensitivity in a compact space, and the laser's specific wavelength required by the cavity length helps ensure high-fidelity measurements. Successful isotopic measurements include carbon-12, -13, and ^{14}C as well as the compound nitrous oxide.

The first-generation CRDS prototype garnered a patent and is undergoing testing. The system can record measurements every 2 to 15 minutes depending on isotopic concentration, and McCartt's team has achieved a run rate of more than 80 samples per day. McCartt is building a second-generation device to fit on a 0.60- by 1.82-meter tabletop. He states, "Our biggest challenge when trying to make a highly sensitive measurement is eliminating signal interference. The second CRDS version will use different spectroscopic techniques to better address these interferences."

The Next 30 Years

As CAMS embarks on its fourth decade of research, Bench predicts that AMS technology will become smaller, cheaper, and easier to use. He says, "We started biomedical work on tennis-court-sized instrumentation, and now we have a tabletop device." The center's efforts to make a resource more accessible over its lifespan mean that an AMS or CRDS device could one day be located where fieldwork is taking place or in a clinical setting. The bioAMS resource could be coupled with diagnostic imaging tools such as computed tomography and magnetic resonance imaging to provide a better understanding of disease trajectory and the effects of therapeutics on the body. Engineered human systems such as the Livermore-developed iCHIP (in vitro chip-based human investigational platform) present another valuable opportunity. (See *S&TR*, March 2014, pp. 16–19.) Turteltaub notes, "AMS has a role in addressing measurement challenges posed by these new technologies."

McFarlane looks forward to advances in radiocarbon extraction processes. "We are investigating simpler organic chemical extraction methods for natural abundance radiocarbon samples," she states. Tumey's group has begun developing additional nuclear forensic signatures. He says, "We want to structure sample-preparation protocols so that all isotopes relevant to AMS can be measured from a single, small aliquot of dissolved debris."

As technologies advance, CAMS is sure to retain its vibrant, innovative culture. Nanette Sorensen, the center's administrator since 1991, observes, "Something new is always happening. Our scientists like what they do." McFarlane confirms that research aimed at improving national security is "never boring," while Zimmerman underscores the interdisciplinary nature of the center's work. She explains, "We grow scientifically by working together, and this integrated view is exciting. We are all studying the same Earth."

—Holly Auten

Key Words: acclerator, accelerator mass spectrometry (AMS), biological accelerator mass spectrometry (bioAMS), carbon cycle, cavity ring-down spectroscopy (CRDS), Center for Accelerator Mass Spectrometry (CAMS), climate change, cosmogenic nuclide, Energy Exascale Earth System Model (E3SM), environmental science, geochronology, infrared (IR) light, ion implantation, ion source, isotope, nuclear forensics, Nuclear Science User Facilities, paleoclimatology, radiocarbon, Spruce and Peatland Responses Under Changing Environments (SPRUCE).

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A Reputation for Collaboration and Outreach

Over three decades, Lawrence Livermore's Center for Accelerator Mass Spectrometry (CAMS) has built a reputation for high-throughput analyses performed by staff with a wide knowledge base. A significant factor in the center's success is its emphasis on collaboration. "To be a credible user facility, it must be accessible and functional for external users," says founding director Jay Davis.

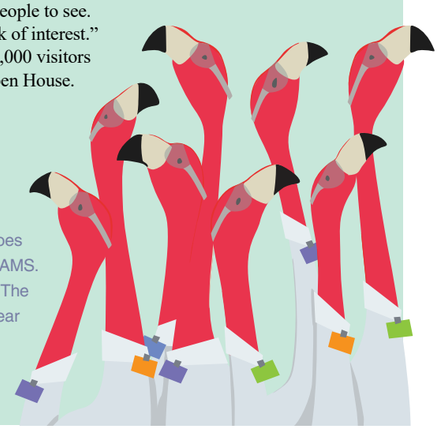
This open-door approach has helped CAMS secure multiple funding streams. The staff manage more than 200 work-for-others contracts and have participated in hundreds of national and international collaborations. Internal funding sources include projects underwritten by the Laboratory Directed Research and Development Program. "Lawrence Livermore is invested in codevelopment of novel technologies at CAMS because collaboration frequently leads to new ideas," explains CAMS director Graham Bench.

The center sees a steady influx of user-centered work from academic; commercial; and government partners, including other national laboratories. For some projects, external researchers send field-collected samples to CAMS for processing and data analysis. For other projects, scientists visit Livermore to observe their samples being processed with accelerator-based techniques, often relying on CAMS staff to help prepare specimens and interpret the data. In a third type of collaboration, CAMS scientists work with onsite Laboratory staff for specific projects, such as isotope production for the National Ignition Facility.

Initially conceived as the Multi-User Tandem Laboratory, the center was designed to be operated by scientists conducting research. According to Davis, many young researchers discover their potential through hands-on work at CAMS. He says, "This technology is sought after by the brightest students in the country." Ken Turteltaub, who arrived at the Laboratory in 1987 as a postdoctoral researcher and now leads the Laboratory's Biosciences and Biotechnology Division, notes, "At CAMS, scientists can work on scientifically risky problems and experiment with different technical approaches to solving them."

Over the years, CAMS has hosted approximately 1,300 faculty and students, becoming a gateway for potential employment at the Laboratory. Bench first worked with Livermore scientists as a graduate student in 1990. After seeing CAMS's capabilities up close, he asked for a job. More than two dozen Livermore careers began with similar stories at CAMS.

The center is also accessible to the public. In the past 2 years, staff have conducted more than 85 tours of the main accelerator facility for adults and regional schoolchildren. Nanette Sorensen, CAMS's administrator, states, "Our scientists volunteer as tour guides, which is exciting for young people to see. Engaging with a scientist could ignite a spark of interest." In October 2017, CAMS welcomed nearly 1,000 visitors during the Laboratory's 65th anniversary Open House.



The flamingo became CAMS's mascot after a series of practical jokes that began in the 1980s. From lawn ornaments and inflatable birds to plush toys and other trinkets, flamingoes inhabit the offices and laboratory spaces at CAMS. A bird even forms the "S" in the center's logo. The flamingoes shown here, wearing protective gear like their human counterparts, appeared on a flyer distributed at Lawrence Livermore's 65th anniversary Open House.

Prior to analysis, materials must undergo an extensive chemical pretreatment process to convert samples into a state of matter appropriate for the type of instrument used. Shown here, Livermore geologist Alan Hidy loads a sample into a centrifuge to separate its contents for future experiments. (Photo by Randy Wong.)

ENHANCED RADIATION Detection Training

THE U.S. government and many state and local agencies have spent billions of dollars fielding radiation detection equipment, both stationary and mobile, at border crossings and shipping ports and in cities. Millions of additional dollars have been dispersed on training emergency responders and law enforcement personnel to operate the equipment. However, typical training does not allow participants to use their own radiation detection gear against scenarios and radiation sources that would be involved in incidents of most concern—those involving high-intensity radiation sources or wide-area contamination following a nuclear or radiological event.

To help ensure that the nation is prepared to effectively respond to these threats, a Livermore team of scientists and engineers developed the Radiation Field Training Simulator (RaFTS)—a 2017 R&D 100 Award–winning technology. RaFTS dramatically reduces the cost of realistic training exercises by enabling trainees to actually use their own radiation detection equipment at their home locations and to train as if dangerous sources were present. "An important role of government is to ensure we have emergency responders adequately trained to deal with true radiation hazards, whether they are generated through accidents or acts of terrorism," says Steven Kreek, leader of Livermore's Nuclear Detection Research Program. RaFTS realistically represents potential hazards' locations, identities, and strengths without requiring any radioactive material to be in the training area. RaFTS controls the instrument, and the collected data can be analyzed just as if real sources were present. (See *S&TR,* July/August 2016, pp. 4–11.)

A Radiation Field Training Simulator (RaFTS) unit is shown secured to an Ortec Detective. The smaller enclosure holds the RaFTS battery, while the larger one next to it houses the electronics.

RaFTS Fills a Need

Experts increasingly recognize the importance of field exercises for training response personnel to operate radiation detection equipment. These exercises are designed to qualify individuals and teams to search for and identify radioactive materials, such as uranium or plutonium, in a terrorist nuclear or other radiological device or those from an accident involving radioactive contamination.

For health and safety reasons, agencies cannot conduct training by spreading high-intensity radioactive materials in their locales. Instead, training is done using tiny pinpoint radiation sources or virtual simulators. However, neither of these methods provides a fully realistic user experience, and each has fundamental limitations. For example, exercises wherein weak radiation sources are placed in an area require authorized controllers—individuals running the exercise who protect the sources from loss—to remain with the sources. The radiation is too low for instruments to see at range, and so trainees often home in on the controllers, which prevents them from experiencing that nuclear radiation and radioactive contamination are invisible and the signals could appear to come from all directions. During an actual event, only the instrument responses would be available to them, not artificial visual clues.

RaFTS is an externally mounted device that, in its final form, is expected to be the size and weight of a small mobile phone. During a training exercise, the RaFTS unit injects electronic pulses, or signals, into a trainee's radiation detector (which can vary by type and manufacturer). These signals exactly replicate all the physics of real hazard-level radiation sources. The unit provides real-time intensity levels and detailed energy spectra depending on the location of the detector relative to the source location and technology in use. RaFTS eliminates the safety, security, and cost concerns of using physical radiation sources (especially for special nuclear materials such as uranium and plutonium) while enabling fully realistic, physics-based scenarios.

Development team for RaFTS: (from left) Josh Oakgrove, Dan Bower, Greg White, Mark Cunningham, Steve Kreek, Dave Trombino, T.R. Koncher, and Bill Dunlop. (Photo by George Kitrinos.)

The training scenario defines the boundaries of the exercise as well as the location and details of point sources and distributed sources. The training coordinator determines the source locations within the exercise area and the types and intensity of radioactive materials. The location of the detector within the scenario is determined by a global positioning system or other device. Based on this input data, RaFTS calculates the dose rate and can feed in the source's energy spectrum at that location, commensurate with how the user is operating the detector. If operated correctly, RaFTS's outputs are of sufficient quality that the detection instrument behaves exactly as it would with real radioactivity, producing spectra that can be analyzed in detail and providing radiation intensity levels dependent on the trainee's location. The physics of the radiation detection process, including time- and location-varying sources, statistical randomness, and user instrument proficiency, are strictly maintained throughout the exercise. After training, the RaFTS device is simply detached from the detector, returning the instrument to normal function.

Technology with Further Possibilities

RaFTS technology can be applied to the entire community of radiation detection instruments such as radiation pagers, handheld spectral devices, and specialized search instruments. The team has demonstrated the technology with two different detectors in widespread use. The first was a Livermore-developed radiation detector licensed to Ortec, Inc., and marketed as the Detective. This detector, used to characterize complex radiation sources (or mixtures of sources), is based on high-purity germanium. The second was a sodium-iodide-based detector commonly used by law enforcement to search, and sometimes identify, radiation sources. This detector type is commonly used in backpack-based or compact handheld devices.

Kreek asserts that adoption of RaFTS across the entire user community of instrument manufacturers and emergency response personnel would greatly enhance training effectiveness, efficiency, and overall preparedness. "There is nothing like it," he says. "This technology dramatically improves responder preparedness for the scenarios of most concern." Kreek notes that the RaFTS concept could also be applied to chemical, biological, and other hazards.

—Arnie Heller

Key Words: emergency response, Ortec Detective, R&D 100 Award, radiation, Radiation Field Training Simulator (RaFTS), radiation source.

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HIGH-THROUGHPUT Pathogen Detection

ANYONE who has been sick knows the uncertainty that comes with trying to determine the cause of the illness. In cases of bacterial, viral, and other infections, the microbes responsible could be difficult to identify. Pathogen identification is important for determining whether a condition may be life-threatening and establishing effective treatment options. Thus, diagnostic platforms that can rapidly detect and characterize microbial agents are becoming a vital tool for protecting human health and safety.

In 2008, a team of Livermore biologists and informatics specialists developed the Lawrence Livermore Microbial Detection Array (LLMDA) to simultaneously identify up to 6,000 pathogens from known viruses and bacteria within 24 hours. (See *S&TR*, December 2010, pp. 19–21; and *S&TR*, April/May 2013, pp. 4–11.) Recently, through a technology-transfer partnership with Affymetrix and its parent company Thermo Fisher Scientific, the Livermore team helped transform the LLMDA platform into the Applied Biosystems™ Axiom™ Microbiome Array (ABAMA), which has a higher throughput. The technology earned the development team a 2017 R&D 100 Award.

ABAMA is the first high-throughput pan-microbial detection device. It can analyze 96 samples in parallel and detect more than 12,000 unique microbial species, including all known bacteria, viruses, fungi, archaea (primitive bacteria), and protozoa. In situations as diverse as battlefield medicine, analysis of suspected bioterrorism, and cancer screening, ABAMA's breadth and accuracy is becoming indispensable.

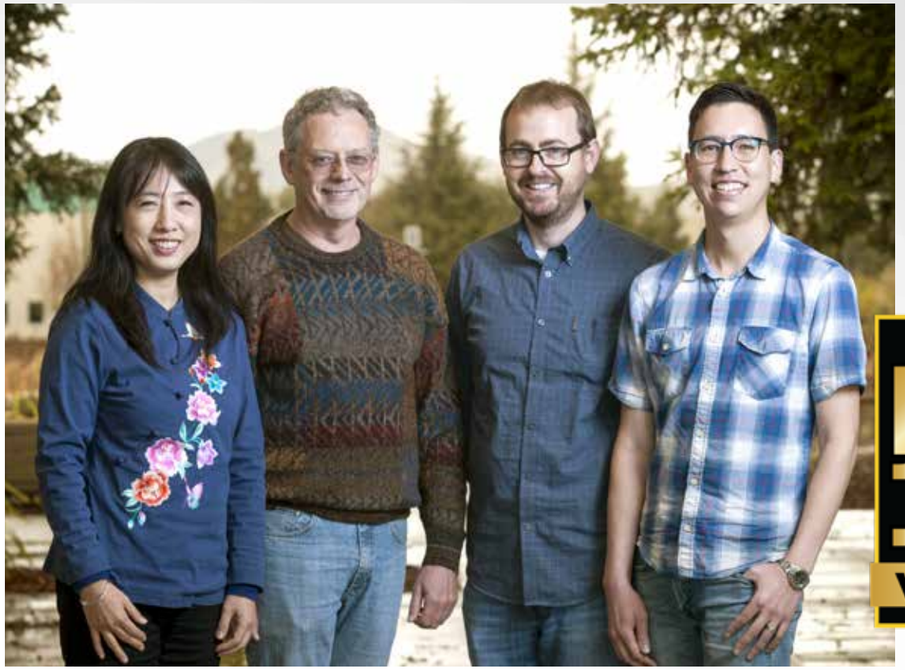
Each square on the Applied Biosystems™ Axiom™ Microbiome Array (ABAMA) represents 1.4 million probes—fragments of DNA that complement the isolated genetic markers of sequenced microbes. The array analyzes 96 samples in parallel, allowing scientists to run more tests simultaneously at much lower cost per test.

Array of Sunshine

The discovery of DNA in the 19th century paved the way for many scientific advances, including microbial detection. In particular, it became the basis for polymerase chain reaction (PCR)—a relatively inexpensive, fast, and sensitive way to detect known organisms in a sample. However, PCR can typically detect no more than about 50 different organisms at one time. Full-genome sequencing is the most accurate identification method, but the technique is time-consuming and expensive. Alternatively, ABAMA is a quick, accurate, and inexpensive technology that provides genome-level resolution for identifying all sequenced microbes present in a sample.

Individual samples assayed by ABAMA are exposed to 1.4 million different DNA probes—short stretches of DNA that complement the isolated genetic markers of sequenced microbes. Each probe is designed to be definitive at one of three taxonomic levels (genus, species, or strain). The probes are then synthesized on a small, square plastic surface (called a "chip") that is replicated 96 times, allowing as many samples to be tested in parallel. During processing, fragments of DNA from each sample are circulated over one array for several hours, allowing sample regions to "hybridize" or bond with their corresponding probes on the array. "If a DNA sequence from the sample matches a sequence on the array, the target DNA will bind to the array and that spot will fluoresce, or light up," says Laboratory biologist and ABAMA codeveloper Crystal Jaing.

Data analysis is performed with Applied Biosystems™ Axiom™ Microbial Detection Analysis Software (MiDAS) from Thermo Fisher Scientific. Using a composite likelihood maximization algorithm, the software successfully chooses the sequenced microbe that most closely matches the probe signals. In addition, since the ABAMA chip only corresponds to microbial DNA, the new array safely disregards the genetic material from the host organism, such as the 3 billion base pairs of human DNA. As a result, scientists can know which microbes, pathogenic or not, are present in the sample, typically within 24 hours.



Development team for ABAMA: (from left) Crystal Jaing, Kevin McLoughlin, James Thissen, and Nicholas Be. (Not shown: Shea Gardner, who passed away in 2016, and Tom Slezak.)

Parallel and Versatile Analysis

ABAMA's efficiency is causing the scientific community to rethink the way it conducts microbial analysis. The array can run 96 samples simultaneously, which presents a new challenge for scientists, many of whom have never had cause to prepare that many samples at once. Most other array methods can analyze up to 12 samples at a time, giving ABAMA a substantial advantage over its predecessors and at a much lower cost per test. Tom Slezak, who led the Livermore development team, says, "When you develop a big breakthrough technology, the world takes a while to catch up."

Since LLMDA was initially conceived in 2003, Slezak says, its development has been "a huge team effort," drawing from biology, computer science, chemistry, and genetics. The initial array's versatility and affordability has led to more than 40 collaborations around the world. In 2010, it was used to identify a pig virus (later determined to be benign) unknowingly present in a pediatric rotavirus vaccine, and more recently, it was used to look into the dangers of pathogens in microgravity aboard the International Space Station (see *S&TR*, January/February 2018, pp. 12–15). Other collaborations and sponsorships have included the Department of Defense, the Department of Homeland Security, the Centers for Disease Control and Prevention, and the Food and Drug Administration. The technology was even used to detect the bubonic plague in a 700-year-old tooth found in a medieval London cemetery.

ABAMA went into the market in August 2016, and today the device is offering an award-winning, revolutionary new screening method to scientists and researchers worldwide. For a growing array of scientific, governmental, and medical fields, ABAMA is shedding much-needed light on a challenging microbial problem.

—Ben Kennedy

Key Words: Applied Biosystems™ Axiom™ Microbiome Array (ABAMA), DNA, full-genome sequencing, Lawrence Livermore Microbial Detection Array (LLMDA), microbial detection, Microbial Detection Analysis Software (MIDAS), pathogen screening, R&D 100 Award.

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S&TR April/May 2018

INTERCONNECTING
A World of Petabytes

As the demand for global, broad-based climate change projections has grown, effectively managing the vast accompanying volumes of data represents a major challenge for computational scientists. In the area of understanding and predicting climate change and extreme weather events, advanced tools are required to securely store, manage, access, analyze, visualize, and process enormous and distributed data sets.

In 2017, Lawrence Livermore researchers received an R&D 100 Award for their work on the Earth System Grid Federation (ESGF)—a virtual, collaborative environment that links climate centers and users around the world to models and data via a computing grid powered by the world's supercomputing resources and the Internet. ESGF facilitates Earth system science and also provides an essential infrastructure for scientists to evaluate models through a common interface, regardless of the data's location. Although many large-scale data management systems exist, none rival ESGF's global accessibility and scientific capability.

The Earth System Grid Federation (ESGF) enables users to access global atmospheric, land, ocean, and sea-ice data generated by satellite, and in situ observations and complex computer simulations. Using modeling and data centers worldwide, ESGF forms a collaborative and interactive network for sharing massive amounts of data from climate and other science domains.

Welcome to the Federation

ESGF's roots go back nearly two decades, when Livermore computer scientist Dean N. Williams collaborated with Argonne National Laboratory's Ian Foster and Steve Hammond at the National Center for Atmospheric Research to apply grid computing to climate science applications that required quickly transferring massive amounts of data. The result was a climate-dedicated cyber environment called the Earth System Grid (ESG), which they used to move data among Department of Energy (DOE) sites.

Before ESG, the climate community comprised various groups and organizations, each with its own methods for creating workflows, generating data file formats and conventions, and storing information. If researchers wanted to study the results from other groups, they first had to spend significant resources converting the data into formats with which they were familiar. This task was no less daunting for Livermore's Program for Climate Model Diagnosis and Intercomparison (PCMDI), which had been evaluating dozens of climate models from institutions all over the world since 1989.

Using grid computing to facilitate PCMDI activities, the ESG team was able to unify data formats and conventions, collect the standardized climate models, and disseminate the information throughout the climate community. Advancements in data management, distributed data sharing, and model archiving led to the full integration of ESG into PCMDI's Coupled Model Intercomparison Project Phase 3 (CMIP3), which was extensively used in the fourth assessment report by the Intergovernmental Panel on Climate Change (IPCC). The 2007 Nobel Peace Prize was co-awarded to IPCC for this work.

"CMIP3 was originally thought to consist of 1 terabyte of data. Ultimately, it was 35 times larger. The next phase, which was slated to be 100 terabytes, turned out to be nearly 2 petabytes," says Williams. "To retrieve data for CMIP3, we sent out massive disk file systems to the climate community that they then shipped back to us. Since this process was not scalable for petabytes of data, we sent our collaborators software rather than disks." Thus, in 2011, ESGF was born—a federated, distributed archive for Earth system data.

A Prospering Federation

ESGF has become the largest-ever platform for collaborative data on Earth system science. At its heart is a peer-to-peer network of nodes distributed across several countries and united by common protocols and interfaces. Node sites span the globe including at NASA, the National Oceanic and Atmospheric Administration (NOAA), and Lawrence Livermore in the United States; the German Climate Computing Centre, the Institut Pierre Simon Laplace, and the Centre for Environmental Data Analysis in Europe; as well as institutions in Australia, China, and elsewhere abroad.

The federation's interoperability enables users to access global atmospheric, land, ocean, and sea-ice data generated by satellite, and in situ observations and complex computer simulations. With ESGF's networks, computers, and software, scientists can access and manage Earth system data more efficiently and robustly through newly developed user interfaces, distributed or local search protocols, federated security, server-side analysis tools, direct connections to high-performance networks, an open computation environment, and other community standards.

To guarantee data validity, ESGF uses quality control algorithms to ensure that the proper formats, units of measure, and conventions are used. Data are also given unique digital object identifiers so information can be tracked back to the source. Making the data easily traceable means researchers can reproduce the models of other researchers to test their repeatability. As models are rerun under different conditions, all variations of the output can be published concurrently to ESGF. The environment also uses versioning, which enables any updates to model data to supersede previous output while at the same time preserving the output history. As a result, data comparisons are possible between various outputs. Williams says, "Now that all these disparate data sets are in one place, scientists can for the first time do comparisons between observations, simulations, and reanalysis data. They can also utilize the data right away."

Federation of the Future

Today, ESGF serves more than 25,000 users, including scientists and policymakers, and provides them access to a staggering 5 petabytes of data—and this number is continually increasing. Aside from work performed for IPCC, ESGF also supports at least 25 other projects, including DOE's new Energy Exascale Earth System Model (E3SM)—the most advanced Earth system model ever created. E3SM is designed to run on future exascale computing systems.

Expanding upon ESGF's capabilities, developers are now looking into machine learning as a way of searching for important connections, patterns, and occurrences, including those associated with naturally occurring climate oscillations such as an El Niño or La Niña, buried deep within the vast petabytes of data available. Another feature under development would allow ESGF to include other science domains. In a prototype version, ESGF has incorporated epidemiology and hydrology data, enabling researchers to study how changes in climate may affect the spread of disease in certain regions. Williams says, "Putting together these different data sets provides a bigger picture of the world and the potential challenges we face. Economic models and other types of models could also be used in this way. The future of ESGF and this type of modeling are promising."

—Dan Linehan

The ESGF development team is led by Laboratory scientist Dean N. Williams and brings together an international cadre of experts in high-performance computing and climate science to deliver globally accessible Earth system data. (Photo by George Kitrinos.)

Key Words: climate science, Coupled Model Intercomparison Project Phase 3 (CMIP3), data sets, Earth System Grid (ESG), Earth System Grid Federation (ESGF), Energy Exascale Earth System Model (E3SM), federated distributed archive, grid computing, Intergovernmental Panel on Climate Change (IPCC), large-scale data management system, petabyte, Program for Climate Model Diagnosis and Intercomparison (PCMDI).

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TEAM SCIENCE REAPS International Recognition

LAWRENCE Livermore has always been an institution that stresses the importance of collaboration. Researchers work closely with colleagues throughout the Laboratory, industry, other national laboratories, and academia to develop advanced technologies and achieve scientific breakthroughs that might otherwise remain undiscovered.

This year, Livermore was a codeveloping organization for four R&D 100 Award–winning technologies. One research effort led to the development of geometrically enhanced photocathodes that stand to radically improve the performance of time-resolved x-ray detectors. Another focused on creating an aluminum–cerium (ACE) "superalloy" with reduced cost and superior performance. A third award was given for a hydrogen safety sensor that could help make hydrogen-fueled vehicles commonplace. Finally, the National Risk Assessment Partnership (NRAP) Toolset won an award for its suite of computer models that can help assess the environmental risk of potential carbon dioxide (CO_2) sequestration sites.

Photocathodes Increase Detector Efficiency

Livermore researchers, partnering with colleagues at the Nevada National Security Site (NNSS); Lawrence Berkeley National Laboratory; and NanoShift, LLC, have developed geometrically enhanced photocathodes to improve energy efficiency in time-resolved x-ray detectors such as streak cameras and dilation cameras. The team was led by NNSS scientist Yekaterina Opachich. Livermore codevelopers Andrew MacPhee, Perry Bell, David K. Bradley, Otto Landen, and Sabrina Nagel contributed to the initial concept and preliminary photocathode designs.

Photocathodes—devices containing photoemissive material that gives off electrons when exposed to light or other radiation—are used to convert incident photons into electrons, which can be manipulated by electric and magnetic fields to record the time and spatial evolution of the incoming signal. Applications include laser-driven plasma imaging, radiography, spectroscopy, and diffraction measurements. An x-ray detector containing conventional photocathodes has a limited quantum efficiency (how well it converts photons to electrons), as the escape depth for secondary electrons from the most efficient photocathode materials is only a few tens of nanometers. The development team broke this longstanding barrier by creating photocathodes with an innovative pyramid array configuration. The new design increases the surface area of the photocathode's exit face compared to its input face, resulting in a quantum efficiency three times that of traditional photocathodes at 7.5 kiloelectronvolts.

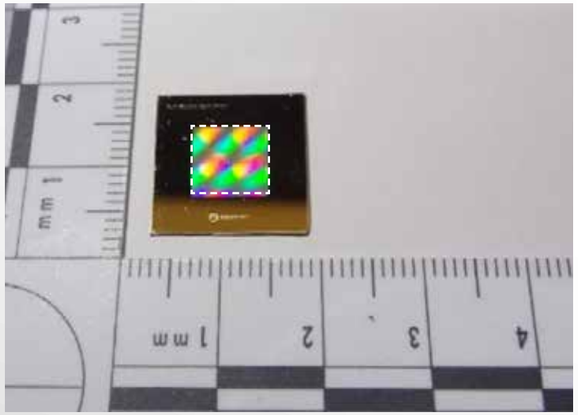
The geometrically enhanced photocathodes are adaptable to any x-ray detector, allowing for ease of use without compromising performance parameters such as spatial and temporal resolution. The new technology stands to revolutionize the design of photocathodes for x-ray streak cameras, extending the cameras' application to new regions of the electromagnetic spectrum. The advance also supports several Livermore core competencies, including nuclear science.

Aluminum's First "Superalloy"

The R&D 100 Award–winning ACE superalloy has mechanical properties that are two to three times better than standard aluminum alloys at temperatures above 250°C. The ACE development effort was led by the Department of Energy's (DOE's) Critical Materials Institute and included Livermore team members Scott McCall, Tony Li, Jon Lee, Alex Baker, Joshua Hammons, Patrice Turchi, and Aurélien Perron, along with researchers from Eck Industries, Ames Laboratory, and Oak Ridge National Laboratory.

ACE exhibits high castability—a measurement of how well the alloy can fill a mold without defects—and costs less to manufacture compared to other competitive alloys. In addition, it does not require heat treatment or "preconditioning" to impart properties such as hardness. "ACE is ideal for high-temperature applications, such as pistons in high-performance gasoline and diesel engines and new, lighter rotors for rotary engines," explains McCall. At operating temperatures of 200°C, ACE's yield strength is 220 percent that of the more expensive aluminum 2618 alloy, which is typically used in high-performance pistons in race cars. If ACE replaced traditional aluminum in pistons and cylinder heads, users could run engines at higher temperatures, increasing combustion and operational efficiencies. Also, ACE's inherent high strength allows complex net shape parts to be cast that would normally be susceptible to warping during traditional thermal processing or heat treatments.

As part of the development effort, Livermore researchers performed microstructural characterization studies using transmission electron microscopy and advanced synchrotron techniques, such as small- and ultrasmall-angle x-ray scattering and x-ray computed tomography, to measure ACE's response to high temperatures and mechanical loads. Livermore researchers also developed a materials design simulator to predict the alloy's phases, phase stability, and property diagrams.



The geometrically enhanced photocathode, which can be adapted to any x-ray detector, uses an innovative pyramid array configuration to increase the measured total electron yield up to three times over that of traditional x-ray photocathodes at 7.5 kiloelectronvolts.

The aluminum–cerium (ACE) "superalloy" is a major departure from aluminum alloy compositions developed over the last century. Components made from ACE could allow engines to run at higher temperatures, increasing combustion and operational efficiencies.

Sensor Boosts a New Energy Economy

Researchers from Los Alamos and Lawrence Livermore national laboratories worked with testing partner H2 Frontier, Inc., to develop a hydrogen safety sensor and demonstrate its efficacy for real-life applications, which includes meeting necessary performance and safety standards. This sensor, which earned the team a 2017 R&D 100 Award, paves the way for ensuring the safety of vehicles powered by hydrogen-based fuel cells, making hydrogen filling stations as safe as conventional gasoline stations. The work was done in support of the Laboratory's efforts to reduce the environmental impact associated with the nation's energy use.

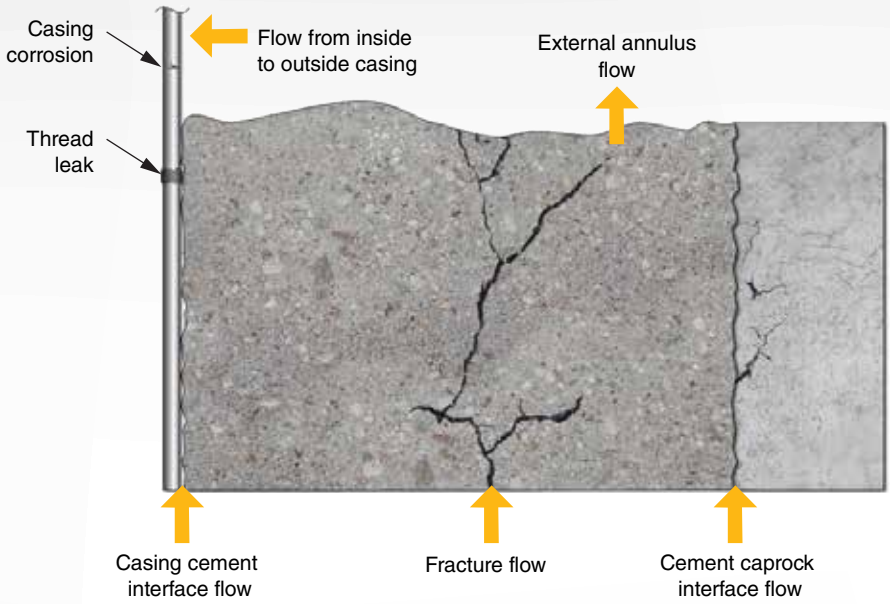
Vehicles powered by hydrogen-based fuel cells combine the performance of electric vehicles with the driving range and fueling time of conventional fossil fuel–powered vehicles. Until recently, a principal drawback of these cells has been hydrogen's perceived safety risks—it disperses quickly when released into the air and is highly flammable, colorless, and odorless. The advanced hydrogen safety sensor addresses this concern with a technology that is both simple and inexpensive. It also meets more of DOE's performance

This simple and inexpensive solid-state, electrochemical hydrogen safety sensor was tested at a hydrogen fueling station run by H2 Frontier, Inc. The device meets more of the Department of Energy's performance targets than all other commercial platforms, while operating under an extreme range of ambient temperatures.

targets than all other commercial platforms for sensitivity, selectivity, response time, stability, and insensitivity to humidity and barometric pressure, while operating under an extreme range of ambient temperatures.

The solid-state, electrochemical hydrogen safety sensor is built on a zirconium oxide-based platform with electrodes containing a tin-doped indium oxide (ITO) film and another film made of dense platinum. Livermore chemist Bob Glass, now retired, identified the benefits of using ITO as an electrode over a decade ago. Based on this research, ITO became an excellent candidate for the sensor because the material is fairly unresponsive to water vapor, allowing the sensor to be used in humid environments.

Livermore materials scientist Amanda Wu, project lead for the Livermore work, and the development team have spent the last several years testing their new sensor technology. Says Wu, "The point of field trials is to demonstrate the ability of our sensors to detect hydrogen consistently and reliably." A complete prototype sensor unit was installed at one of H2 Frontier's hydrogen stations to analyze the device's overall performance and effectiveness. The new sensors can be placed anywhere in the hydrogen supply chain for hydrogen production and distribution, and as a critical component in filling stations and in hydrogen-powered vehicles such as cars, buses, trucks, fork lifts, and even submarines.



The National Risk Assessment Partnership (NRAP) Toolset includes computational tools developed by Livermore researchers to examine the integrity of wellbores, especially the coupled chemical and mechanical processes governing flow in a well's damaged zones.

Adding Certainty to Carbon Storage

The use of fossil energy resources is expected to extend decades into the future to meet demands for affordable energy and drive economic development. Reducing carbon emissions from such resources requires capturing and storing large amounts of CO_2. Geologic formations deep underground are promising as repositories for storing this gas byproduct. However, geologic systems are inherently variable and often poorly characterized, making it difficult to know with certainty how a system will respond to large-scale injection and storage of CO_2.

In response to this challenge, a multilaboratory team developed a suite of computational tools to inform decision making for CO_2 sequestration sites. The DOE NRAP Toolset was developed by the National Energy Technology Laboratory in collaboration with Lawrence Livermore, Los Alamos, Lawrence Berkeley, and Pacific Northwest national laboratories. The Livermore team includes Susan Carroll, Joshua White, Yunwei Sun, Harris Mason, Wyatt Dufrane, Yue Hao, Stuart Walsh, and Kayyum Monsoor. The easy-to-use toolset combines 10 science-based prediction and design tools for assessing the geological integrity and environmental risk related to potential fluid leaks and ground motion at possible storage sites. Carroll says, "Livermore provided the scientific base for risks to induced seismicity, well integrity, and groundwater quality. We also developed a reduced order model to help assess impacts to drinking water aquifers." The NRAP Toolset can be downloaded for free and is currently being used for projects around the globe, including in Asia and Australia.

—Ann Parker

Key Words: aluminum–cerium (ACE) alloy, carbon dioxide (CO_2), carbon sequestration, hydrogen fuel cell, hydrogen safety sensor, geometrically enhanced photocathode, National Risk Assessment Partnership (NRAP) Toolset, R&D 100 Award, tin-doped indium oxide (ITO), x-ray detector.

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Instruments Peer Deeply into Laser Experiments

At the National Ignition Facility (NIF), more than 70 diagnostics are located inside and outside the target chamber (blue sphere) to collect data on laser experiments. (Photo by Damien Jemison.)

INSIDE the 192-beam National Ignition Facility (NIF)—the world's largest and most energetic laser—researchers study materials under extreme pressures, temperatures, and densities and capture the resulting data with high-resolution diagnostic instruments. NIF provides an unprecedented capability for conducting such experiments, which help to validate simulations of nuclear weapons performance and explore a range of scientific fields, from astrophysics and materials science to nuclear science and national security applications. In addition, many NIF shots focus on advancing the prospect of inertial confinement fusion (ICF).

Experimenters rely on an array of nuclear, optical, and x-ray diagnostic instruments to record vital data from NIF shots at micrometer length scales and picosecond (trillionths of a second) timescales. In addition, a suite of diagnostics provides critical data on the laser facility's performance. Diagnostics are either deployed to a fixed location in the target chamber or fielded on a diagnostic instrument manipulator (DIM), a telescopic device for inserting, retracting, and positioning instruments inside the target chamber.

More than 70 diagnostic systems are available to experimenters, according to Livermore physicist David Bradley, who leads a group focused on developing and deploying advanced diagnostics and measurement techniques at NIF. Indeed, the necessity for accurate and reliable diagnostics continues the motivation to create ever-better instrumentation. Bradley notes that experimental results and new types of experiments can suggest improvements to existing diagnostics or the need for entirely novel devices that take advantage of electronic and optical advancements.

Making the Grade

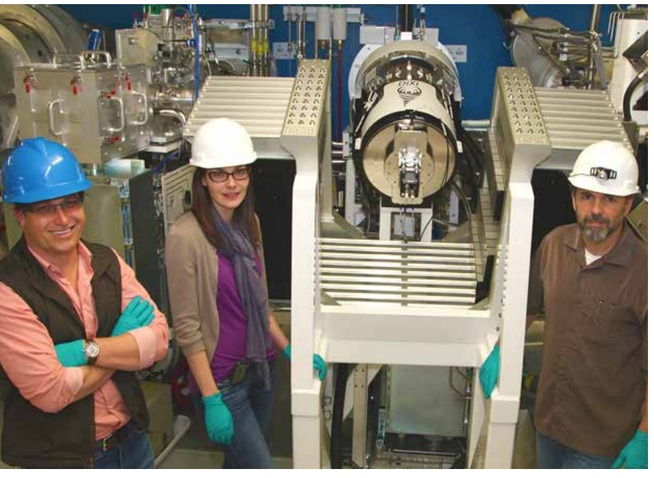
The National Diagnostic Working Group involves more than 100 researchers from Lawrence Livermore and Sandia national laboratories, the University of Rochester's Laboratory for Laser Energetics (LLE), the Massachusetts Institute of Technology, General Atomics, Princeton University, and other leading research centers that design and build advanced diagnostics. Initial tests of a new device are first tested at facilities smaller than NIF, such

as LLE's Omega Laser Facility or the Jupiter Laser Facility at Livermore. In addition, all instruments must undergo a series of design and safety reviews at NIF before their construction begins. Diagnostic development is so important that despite fierce competition among scientists worldwide for experimental time on NIF, the facility reserves laser shots solely for this purpose. As with other shots, these tests must be scheduled 6 to 12 months in advance.

X-ray diagnostics, in particular, provide experimenters with data at the spatial (micrometer) and temporal (picosecond) resolution needed to observe important phenomena that occur during a shot. These instruments measure target self-emission or use x rays generated by a backlighter to probe or radiograph dense matter. As demonstrated by the efforts of two NIF physicists—Sabrina Nagel and Laura Robin Benedetti—designing, building, and testing an x-ray diagnostic is often measured in years, but the payoff is well worth it. Improved diagnostics are key to advancing scientific understanding of how materials respond to high-energy-density environments.

Capturing ICF Implosions

Beginning in 2011, Nagel, an experimental physicist, spent her first three years at Livermore characterizing and calibrating the Dilation X-Ray Imager (DIXI), now used routinely in



(from left) Livermore engineer Jay Ayers, physicist Sabrina Nagel, and engineer Ken Piston stand next to the installed Dilation X-ray Imager (DIXI), which sits outside the NIF target chamber. DIXI is the world's fastest x-ray camera, producing images of an imploding target capsule with 10 times faster temporal resolution than previous systems.

Joe Kilkenny and Terance Hilsabeck, both from General Atomics, inspect the drift tube, a critical component of the single-line-of-sight x-ray diagnostic. The drift tube is analogous to the slow-motion feature on a standard camera. (Photo by Ken Piston.)

ICF experiments. DIXI relays information on the temperature, shape, and time history of the central hot spot within the fuel capsule as well as hot-spot nonuniformities during implosion. The instrument was developed by Livermore in collaboration with General Atomics and Kentech Instruments, Ltd., in the United Kingdom.

Located just outside the target chamber, DIXI records x-ray emissions at less than 10-picosecond temporal resolution, making it the world's fastest x-ray camera. Using an array of pinholes, DIXI converts x-rays generated by ICF experiments to electrons. The electronic signal is "stretched" and then recorded by a conventional shuttered electron camera. The key to the instrument's extraordinary temporal resolution is this stretching (also called pulse dilation) of the electronic signal. In addition, DIXI can operate under 10 times higher neutron backgrounds than conventional x-ray cameras. (See *S&TR*, January/February 2016, pp. 18–20.) "DIXI captures details of NIF implosions never before seen with slower cameras," says Nagel. Lower resolution instruments, for instance, might miss the movement of hot spot features that DIXI captures during the implosion process.

Based on DIXI's stellar performance, Nagel has also been helping to develop the single-line-of-sight (SLOS) x-ray diagnostic—a DIM-based instrument that will be located inside the target chamber. This device uses a similar pulse dilation concept to DIXI but features a sensor that contains an extremely fast response CMOS (complementary metal-oxide semiconductor) chip under development at Sandia National Laboratories. The

chip allows multiple images to be recorded from a single line of sight compared to the individual image captured by DIXI using pinhole optics. Nagel says, "By coupling SLOS with the Crystal Backlighter Imager (a diagnostic instrument that acts as a narrow-band filter), we expect to see the evolution of the fuel capsule's shell closer to 'bang time' (moment of peak x-ray emission)."

Studying Diffraction over Time

X-ray diffraction experiments probe the atomic structure of a material to see how atoms rearrange when they shift from one phase to another and how fast that transformation occurs. Improved time-resolved x-ray diffraction capabilities could enable new materials science experiments that provide information on the phase changes of materials under high pressures. Physicist Benedetti explains that Livermore scientists are interested in phase changes for materials important to stockpile stewardship. The research team will develop the new experimental platform by documenting the transformation of iron's crystal structure under high pressures, which is particularly relevant to geophysical research. The team includes Benedetti and about 10 other physicists and engineers.

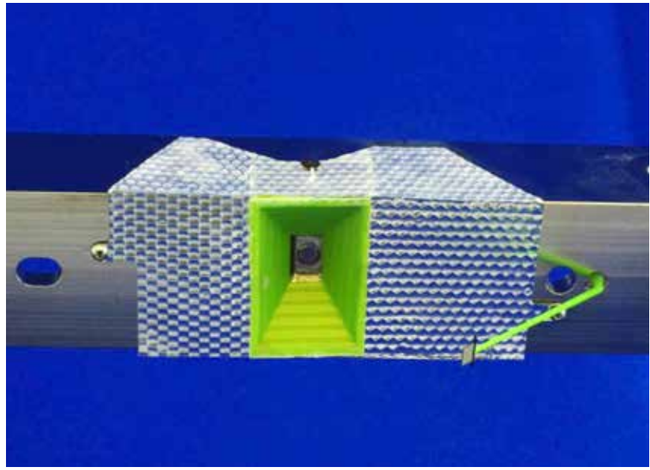
The proposed instrument builds on the success of x-ray diffraction experiments using Target Diffraction In Situ (TARDIS), the first device to include a NIF target and diagnostic instrument on a single, integrated platform. "As I investigated possible strategies for collecting time-resolved diffraction data, I realized we needed something entirely new," says Benedetti. She decided to adopt a "direct detection" design to capture data using both a streak camera and a time-resolved imaging sensor incorporating four of Sandia's proposed CMOS chips. The sensors will collect a series of six images to capture phase changes with less than 1-nanosecond temporal resolution. Together, the two instruments will eliminate the need for several NIF shots on the same material by taking multiple measurements within one experiment.

In December 2017, the team conducted a series of proof-of-concept experiments at the Omega Laser Facility that provided information on to how best shield the diagnostic in future design iterations from unwanted background electromagnetic pulses. The team has scheduled an experiment at NIF for September 2018, which will test the latest diagnostic design incorporating the CMOS-based sensor. Benedetti acknowledges that plenty of work needs to be done before the test is conducted.

Scientists at several National Nuclear Security Administration (NNSA) laboratories are following Benedetti's progress closely. The instrument is considered "transformative" by the National Diagnostic Working Group, meaning it has the potential to transform the experimental capability for critical NNSA needs.

Detailed Data Means Discovery

Whether a principal investigator for a study is from a national laboratory, an international research facility, or a leading university,



The TARDIS (Target Diffraction In Situ) package is an integrated platform that contains a target and a diagnostic. The package houses a material sample, an x-ray backlighter mounted on a stalk, and a cartridge containing an image plate to capture the x-ray diffraction pattern of the sample.

becoming qualified to conduct an experiment on NIF involves classwork, online guides, and shadowing experienced Livermore colleagues. In many cases, researchers from the Laboratory's weapons program design the experiments, often focusing on computer simulations to guide the setup and predict results, while physicists from other Livermore organizations focus more on target and diagnostic development.

The efforts of physicists such as Nagel and Benedetti underscore the dedication of experimenters to precisely document the fleeting events taking place during NIF shots to enhance understanding of complex processes and improve scientific capabilities. The richly detailed data that are acquired often lead to important discoveries about the nature of materials under pressure, which in turn strengthen national security and fundamental science and help researchers make further progress toward ignition.

—Arnie Heller

Key Words: CMOS (complementary metal-oxide semiconductor), diagnostic, diagnostic instrument manipulator (DIM), Dilation X-Ray Imager (DIXI), ignition, inertial confinement fusion (ICF), Jupiter Laser Facility, National Ignition Facility (NIF), Omega Laser Facility, single-line-of-sight (SLOS) diagnostic, Target Diffraction In Situ (TARDIS), time-resolved x-ray diffraction.

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Patents and Awards

In this section, we list recent patents issued to and awards received by Laboratory employees. Our goal is to showcase the distinguished scientific and technical achievements of our employees as well as to indicate the scale and scope of the work done at the Laboratory. For the full text of a patent, enter the seven-digit number in the search box at the U.S. Patent and Trademark Office's website (http://www.uspto.gov).

Patents

Nitrogen-Doped Carbon Aerogels for Electrical Energy Storage
Patrick Campbell, Elizabeth Montalvo, Theodore F. Baumann, Juergen Biener, Matthew Merrill, Eric W. Reed, Marcus A. Worsley
U.S. Patent 9,776,156 B2
October 3, 2017

Passive Magnetic Bearing Systems Stabilizer/Bearing Utilizing Time-Averaging of a Periodic Magnetic Field
Richard F. Post
U.S. Patent 9,777,769 B2
October 3, 2017

Metal-Dielectric-CNT Nanowires for Surface-Enhanced Raman Spectroscopy
Tiziana C. Bond, Ali Altun, Hyung Gyu Park
U.S. Patent 9,778,197 B2
October 3, 2017

Flexible Neural Interfaces with Integrated Stiffening Shank
Angela C. Tooker, Sarah H. Felix, Satinderpall S. Pannu, Kedar G. Shah, Heeral Sheth, Vanessa Tolosa
U.S. Patent 9,788,740 B2
October 17, 2017

Methods for the Selective Detection of Alkyne-Presenting Molecules and Related Compositions and Systems
Carlos A. Valdez, Alexander K. Vu
U.S. Patent 9,791,463 B2
October 17, 2017

Mechanically Stiff, Electrically Conductive Composites of Polymers and Carbon Nanotubes
Marcus A. Worsley, Sergei O. Kucheyev, Theodore F. Baumann, Joshua D. Kuntz, Joe H. Satcher, Jr., Alex V. Hamza
U.S. Patent 9,793,026 B2
October 17, 2017

Awards

Lawrence Livermore physicist **Félicie Albert** was awarded the 2017 **Edouard Fabre Prize** for her contributions to the physics of laser-driven inertial confinement fusion (ICF) and laser-produced plasmas. Albert, an experimental plasma physicist at the National Ignition Facility, shares this year's award with collaborator Alexis Casner, who is a research director of the French Alternative Energies and Atomic Energy Commission. Sponsored by the **European Cooperation in Science and Technology Network for Inertial Confinement Fusion**, the Edouard Fabre Prize is named for one of the founders of ICF in Europe and is awarded to active researchers within 15 years of their doctoral degree.

Laboratory researchers **John Heebner** and **Constantin Haefner** have been elected **fellows** of the **Optical Society of America**. Heebner was cited for his "numerous innovations, achievements, and technical leadership in high-energy laser systems and integrated optics including nonlinear optical microresonators and ultrafast light deflectors." Heebner leads the Ultrafast Optical and Electronics Systems Group, which supports multiple Laboratory programs. The group is pioneering diagnostic techniques that bridge the gap between ultrafast optics and high-bandwidth electronics.

Haefner is the program director for Advanced Photon Technology at the Laboratory and was recognized for "pioneering next-generation, high-average-power petawatt laser systems enabling a new arena of applications and sustained advancement of state-of-the art technologies in large-scale, high-intensity, peak-power laser systems." As program director, Haefner leads the research and development of advanced laser systems and technologies in support of national security missions as well as scientific and industrial applications.

Livermore engineer and computational mechanics expert **Jerome Solberg**, along with collaborators at Argonne National Laboratory and Texas A&M University, won a **Best Paper Award** at the **17th International Topical Meeting on Nuclear Reactor Thermal Hydraulics**. Their paper, entitled "High-Fidelity Simulation of Flow Induced Vibrations in Helical Steam Generators for Small Modular Reactors," details how the team created simulations to study the effects of vibrations caused by water (used as coolant) flowing over steam generator tubes in nuclear reactors. The capability could have benefits to design schedule, cost, and risk analysis, and could improve the ability to evaluate replacing or retrofitting such generators.

Abstract

Renowned Accelerator Facility Turns 30

Since beginning operations in 1988, Lawrence Livermore's Center for Accelerator Mass Spectrometry (CAMS) has made a name for itself as a unique, safe, and reliable midsize user facility. The center's multiple accelerator mass spectrometry (AMS) instruments, biological AMS resource, and new cavity ring-down spectroscopy technology enable a range of isotopic measurements. CAMS staff regularly work with a broad user base of academic and commercial collaborators while hosting hundreds of students and visitors. Recent work in four research areas showcases the breadth and depth of the center's capabilities. Highly sensitive instruments help address nuclear science challenges; studies of the terrestrial carbon cycle provide insight into carbon dioxide and methane emissions; geochronological and paleoclimatological research with cosmogenic nuclides allows scientists to reconstruct historical climate-altering events; and biomedical sample analysis enters a new era thanks to compact, laser-based technology developed at the Laboratory. As CAMS celebrates its 30th anniversary, scientists continue to focus on innovation and forward-looking research in service to Livermore's national security mission.

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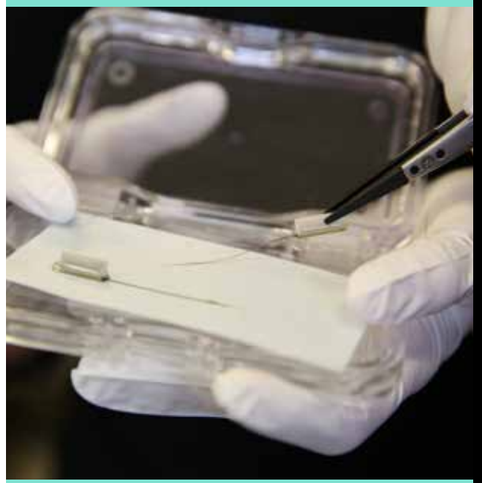
Coming Next Issue

Studying the Brain with Neurotechnology



Tiny biocompatible microelectrode implants promise greater understanding of how the brain functions and new treatments for neurological disorders.

Also in June

- *Imbuing a system of mobile, networked platforms with distributed intelligence and decision-making capability is the next cybernetic frontier.*
- *Livermore's Computation Directorate is taking advantage of collaboration and creativity across the entire Laboratory to facilitate world-class research.*
- *Scientists studying how different elements condense from plasma in the laboratory gain valuable insight into debris formation in nuclear fireballs.*

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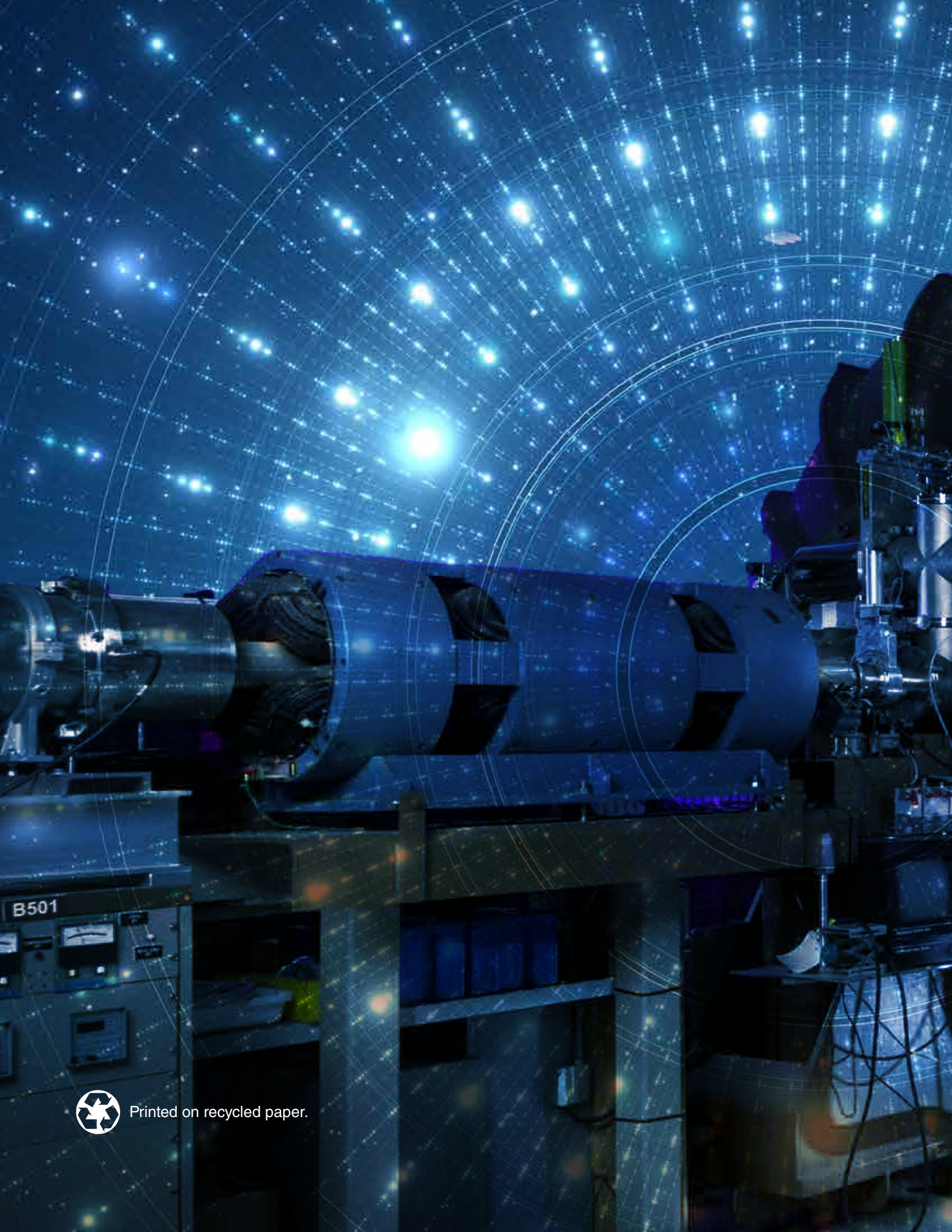

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