

January/February 2014

# Science & Technology

REVIEW

## International Collaboration Sparks a Laser Revolution



*Also in this issue:*

**Tabletop High-Energy X Rays**

**Superstrong Nanotwinned Metals**

## About the Cover

As described in the article beginning on p. 4, Lawrence Livermore and European scientists are constructing the High-Repetition-Rate Advanced Petawatt Laser System (HAPLS), a laser designed to generate a peak power greater than 1 petawatt. Each pulse will generate 30 joules of energy in less than 30 femtoseconds. The laser system will deliver these light pulses 10 times per second, making possible new scientific discoveries in the areas of physics, medicine, biology, and materials science. HAPLS will be built at Livermore for the Extreme Light Infrastructure Beamlines facility, currently under construction near Prague in the Czech Republic (shown in the cover rendering).



Cover design: George A. Kitrinios

## 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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### Artificial Retina: Invention of the Year

A Department of Energy–funded project resulted in the first-ever retinal prosthesis—or bionic eye—approved in the U.S. by the Food and Drug Administration for blind individuals with end-stage retinitis pigmentosa, a group of degenerative diseases that affects two million people worldwide. The artificial retina has enough resolution for people to see the lines of a crosswalk, find objects, and read letters a couple of centimeters tall. The invention, in which Lawrence Livermore played a prominent role, earned a place in the top 25 best inventions of 2013 from *Time Magazine*. The artificial retina also garnered a 2013 best innovation designation from *Popular Science*.

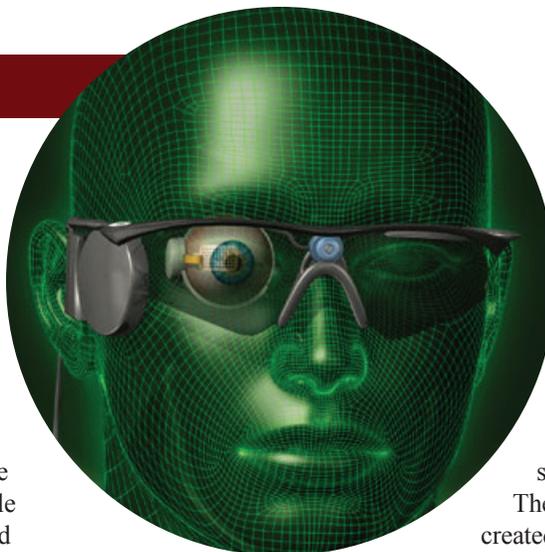
The invention was commercialized by Second Sight Medical Products, Inc., and is now called the Argus II Retinal Prosthesis System, which gives sight to the blind. The device consists of a miniature video camera that is mounted on a pair of glasses and sends footage to a microprocessor worn on a person's belt. The processor converts the visual data to electronic signals, which are transmitted wirelessly to a 60-pixel electrode array implanted in the back of the eye. The optic nerve picks up these signals and sends them to the brain, where they are interpreted as rudimentary gray-scale images.

The Livermore team contributed three major components to the artificial retina project: the thin-film electrode array that contains the neural electrodes, the biocompatible electronics package that stimulates the retina and powers the wireless communication, and an ocular surgical tool that enables the replacement of the thin-film electrode array. In addition, Livermore was responsible for the system integration and assembly of the next-generation artificial retina system with 240 stimulating electrodes. Future trials are planned to test for the treatment of macular degeneration, the most common cause of blindness in Americans over the age of 60.

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### Examining the Origins of Life on Earth

Shock-compression experiments by a team of international scientists have provided the first confirmation that life on Earth may come from out of this world—a prediction made by Livermore physical chemist Nir Goldman. (See *S&TR*, June 2011, pp. 13–15.) Supercomputing simulations that Goldman ran in 2010 and again in 2013 indicate that the impact of icy comets crashing into Earth billions of years ago could have produced a variety of prebiotic or life-building compounds, including amino acids. His work predicted that the simple molecules found in comets (such as water, ammonia, methanol, and carbon dioxide) could have supplied the raw materials for prebiotic chemistry, and the impact with early Earth would have yielded an abundant supply of energy to drive the reactions.



In an effort to examine Goldman's predictions, collaborators from Imperial College in London and the University of Kent designed a series of experiments that mimicked the simulations. Using a light-gas gun, they fired a projectile into an icy mixture similar to the molecules found in comets.

The shock compression of this mixture created several types of amino acids, confirming that the impact itself can yield life-building compounds. As a result, says Goldman, "This phenomena increases the probability of life originating and being widespread throughout our solar system." The research was published in the September 2013 online edition of *Nature Geoscience*.

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### Human Activity Affects Atmospheric Vertical Temperature

Scientists from Lawrence Livermore and six other scientific institutions reported that human influences have directly affected the latitude and altitude pattern of atmospheric temperature. Their research compares multiple satellite records of atmospheric temperature change with results from a large, multimodel archive of simulations. "Human activity has very different effects on the temperature of the upper and lower atmosphere, and a very different fingerprint from purely natural influences," says Benjamin Santer, the lead researcher in a paper appearing in the *Proceedings of the U.S. National Academy of Sciences* online edition September 16, 2013. Observational satellite data and the computer-model-predicted response to human influence have a common latitude–altitude pattern of atmospheric temperature change. The key features of this pattern are global-scale tropospheric warming and stratospheric cooling over the 34-year satellite temperature record.

Natural internal fluctuations in climate are generated by complex interactions of the coupled atmosphere–ocean system, such as the well-known El Niño Southern Oscillation. External influences include human-caused changes in well-mixed greenhouse gases, stratospheric ozone, and other radiative forcing agents, as well as purely natural fluctuations in solar irradiance and volcanic aerosols. Each of these external influences has a unique "fingerprint" in the detailed latitude–altitude pattern of atmospheric temperature change. Fingerprint information has proved particularly useful in separating human, solar, and volcanic influences on climate.

"The pattern of temperature change that has been observed vertically in the atmosphere, from ground level to the stratosphere, fits with what is expected from human-caused increases in greenhouse gases," says Santer. "The observed pattern conflicts with what would be expected from an alternative explanation, such as fluctuations in the Sun's output." Coauthor Celine Bonfils adds, "In contrast to volcanic influences, human-caused atmospheric temperature changes affect all latitudes and last longer."

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# Making Possible the Century of Photonics

**F**OR more than four decades, Lawrence Livermore has been at the forefront of laser technology. Our laser scientists and engineers push the limits of what is possible in their drive for ever-higher peak power and intensities, ultrashort pulses, and especially, average power. The Laboratory's development of high-peak-power, short-pulse laser systems began in the mid-1980s, resulting in a 10-terawatt laser in 1989. Further efforts culminated in the kilojoule-class Nova Petawatt, achieving for the first time a peak power exceeding  $10^{15}$  watts in 1996. Livermore's development of high-peak-power, short-pulse laser systems continued in the 21st century with Falcon, Titan, and Callisto. Furthermore, the Advanced Radiographic Capability, currently under construction at the National Ignition Facility (NIF), will be the most energetic short-pulse laser in the world.

Now Livermore researchers have joined with European colleagues to build the High-Repetition-Rate Advanced Petawatt Laser System (HAPLS). As described in the article beginning on p. 4, this instrument is designed to reach a peak power exceeding 1 petawatt at a repetition rate of 10 times per second to deliver intensities on target up to  $10^{23}$  watts per square centimeter. HAPLS is based on diode-pumped, solid-state laser technology, which ensures reliable delivery of this peak power at a high-repetition rate and at much-reduced electrical power consumption—a major advancement over current petawatt systems.

Following a worldwide assessment by the European laser community, Lawrence Livermore was chosen as the only organization qualified to build HAPLS. The laser system will be built and tested at the Laboratory to a predetermined set of project completion criteria and then delivered and commissioned at the Extreme Light Infrastructure (ELI) Beamlines facility, now under construction in the Czech Republic. HAPLS will be the highest average-power petawatt laser installed at the ELI Beamlines facility, which is the first in a series of advanced facilities comprising the ELI project. Scientists from the Czech Republic's Institute of Physics are already working alongside Livermore physicists and engineers.

HAPLS embraces a host of groundbreaking technologies developed at Livermore. These technologies include helium-gas cooling of key components, advanced gratings that enable amplification of high-peak-power laser light without damaging optics, systems that constantly monitor themselves to minimize the need for human intervention, arrays of laser diodes that replace less efficient and bulky flashlamps, and advanced optics and optical finishing technologies.

The system's pulses will be used to generate extremely bright and short x-ray pulses for imaging cells and proteins at unprecedented spatial and temporal resolution. Another application is generating bunches of protons or ions for medical therapy and materials science research. Scientists will also study the interaction of intense laser light with matter to improve prospects for laser fusion energy.

Our selection is a great honor and a testament to Livermore's expertise in laser design, technology development, and record of successfully delivering projects that push the limits of existing technology. The award also is a testament to the confidence in our capabilities by the Board of Governors of Lawrence Livermore National Security, LLC. Because no precedent existed for this international partnership, the board agreed to underwrite any contract liabilities.

The Laboratory's success in winning the HAPLS contract is due in large part to the long history of strategic investment in key capabilities through Livermore's Laboratory Directed Research and Development (LDRD) Program and other internal funding mechanisms. The core competencies developed in optics, materials, and lasers through LDRD investments have resulted in the Laboratory's unique capability to succeed on a project such as HAPLS. This project is proof that strategic investments can pay big dividends. The highlight beginning on p. 16 presents another example in which a modest investment has a high-payoff potential. A Livermore team is focusing ultrahigh-intensity light from Livermore's Callisto laser on various gases to produce ultrashort x-ray pulses. This tabletop system produces the same x rays that typically require vastly larger particle accelerator and synchrotron facilities.

Building HAPLS with our European colleagues is surely one of the most exciting laser projects in the world and permits our researchers to continue to hone their craft. While the 20th century has been described as the Century of Electricity, this age may well prove to be the Century of Photonics. I expect to see lasers play an increasingly important role in our society, from medicine to industry to energy. I look forward to Lawrence Livermore contributing even more to this new era of light.

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■ Jeff Wisoff is acting principal associate director for NIF and Photon Science.

# Lighting a New Era of Scientific Discovery



*A groundbreaking agreement unites Lawrence Livermore and European scientists to deliver a laser with performance far in advance of any in the world.*

**S**INCE the founding of its Laser Program in the mid-1970s, Lawrence Livermore has become the global leader in the design and operation of high-energy and high-power lasers as well as the supporting science, engineering, and technology development. The Laboratory's 192-beam National Ignition Facility (NIF) is the most energetic in the world, and Livermore has achieved numerous records for peak-power and high-average-power performance on a host of other lasers. Last year, the European scientific community turned to the Laboratory for the design and construction of an extraordinarily powerful laser. Called the High-Repetition-Rate Advanced Petawatt Laser System (HAPLS), the instrument will be key to the world's new preeminent, high-intensity laser science facility in the Czech Republic.

HAPLS is designed to ultimately generate a peak power greater than 1 petawatt ( $10^{15}$  or 1 quadrillion watts), with each pulse delivering 30 joules of energy in less than 30 femtoseconds (trillionths of a second or 0.00000000000003 seconds)—the time it takes light to travel a fraction of the width of a human hair. The laser system will deliver these pulses of light at 10 hertz (10 repetitions per second).

Delivering more than 1 petawatt at this extreme repetition rate is a major advancement over current petawatt systems, which cannot fire more often than once per second. "HAPLS's high repetition rate will make possible new scientific discoveries," says Livermore physicist and HAPLS project manager Constantin Haefner. While scientists have long performed experiments with powerful single-shot lasers, they have never had an opportunity to repeat experiments at 10 times per second.

HAPLS will deliver ultrashort, high-energy laser pulses for generating secondary sources of electromagnetic radiation (such as high-brightness x rays) and accelerating charged particles (electrons, protons, or ions). The laser technology will enable many applications in physics, medicine, biology, and materials science. In addition, the technology will contribute to the development of laser-driven fusion power plants, which will require repetition rates of at least 10 hertz. Because high-average-power lasers demand extremely high reliability and maintainability, HAPLS will also test a number of concepts for industrial applications. (See the box on p. 6.)

The High-Repetition-Rate Advanced Petawatt Laser System (HAPLS) is being developed, assembled, and tested at Lawrence Livermore. In 2016, HAPLS will be transferred to the European Union's Extreme Light Infrastructure (ELI) Beamlines facility (shown in this artist's rendering), currently under construction in the Czech Republic. Here, the laser will be commissioned for use by the international scientific community. The building in the center background will house HAPLS and other laser systems.

HAPLS will be a flagship machine for the European Union's Extreme Light Infrastructure (ELI) project, which is designed to explore fundamental physics under extreme conditions. The laser system will be located at ELI Beamlines, currently under construction in Dolní Břežany near Prague. ELI Beamlines is the first of three laser facilities to be constructed under the European project. ELI Attosecond will be

located in Hungary for the investigation of natural phenomena on ultrashort timescales (into the  $10^{-18}$  seconds regime), while ELI Nuclear Physics will be located in Romania and dedicated to the new field of photonuclear physics.

Coordinated by the Czech Republic's Institute of Physics, Academy of Sciences, ELI Beamlines is the largest scientific project in that country. Construction

began in October 2012 and is scheduled for completion in 2017. Although ELI Beamlines will house four lasers, HAPLS is expected to be the "workhorse" system.

HAPLS will be constructed and tested to an intermediate level of performance at Lawrence Livermore by a team of scientists from the Laboratory's NIF and Photon Science (NIF&PS) Principal Directorate in collaboration with researchers from the

## Broad Range of Experiments Planned for European Laser Facility

Extreme Light Infrastructure (ELI) Beamlines is a European Union project in the Czech Republic designed to transform laser science by building advanced lasers to study laser-matter interactions, laser-driven secondary sources, and fundamental physics at ultrahigh light intensities. When fully implemented in 2017, ELI Beamlines will contain the world's most powerful lasers for use by the international scientific community. The project represents a joint investment of nearly 300 million euros on behalf of the European Union and the Czech Republic government.

Lawrence Livermore scientists, working with their European colleagues, will design and construct the High-Repetition-Rate Advanced Petawatt Laser System (HAPLS) for the ELI Beamlines facility. The system's high repetition rate will enable a generation of laser-driven secondary sources with a brilliance unmatched worldwide, allowing researchers to probe the fundamental properties of light-matter interaction at extreme intensities and on ultrashort timescales. HAPLS will provide laser-accelerated sources of electrons with energies of several tens of gigaelectronvolts as well as protons and ions with energies achieving a few gigaelectronvolts. The production of electrons and particles in the gigaelectronvolt regime will make possible new investigations in atomic physics, nuclear physics, high-energy-density physics, particle physics, plasma physics, cosmology, astrophysics, chemistry, biochemistry, and medicine.

For example, scientists anticipate using streams of extremely bright and short x rays for imaging cells and proteins at unprecedented spatial and temporal resolution to study the time history of biochemical reactions and the formation and dissolution of chemical bonds. In studies to improve oncology treatments, HAPLS could be used for producing high-quality beams of protons or ions to treat deep-seated tumors.

Livermore's Michael Dunne, director of Laser Fusion Energy for the Laboratory's National Ignition Facility and Photon Science (NIF&PS) Principal Directorate, explains that HAPLS could attain intensities of  $10^{23}$  watts per square centimeter, a long-standing performance goal and 100 times greater than the  $10^{21}$  watts per square centimeter first achieved with Livermore's

Nova Petawatt laser 18 years ago. An intensity of  $10^{23}$  watts per square centimeter combined with a repetition rate of 10 hertz or greater would permit experiments of light-matter interaction that have never been attempted. Chris Barty, chief technology officer for NIF&PS, notes that achieving this intensity would open up entirely new areas of laser-matter investigation, enable new applications of laser-driven x rays and particles, and for the first time allow researchers to study laser interactions with the sea of virtual particles that comprise a vacuum. Livermore physicists also are looking forward to astrophysics experiments performed with HAPLS. These experiments are expected to address questions such as how cosmic rays and solar systems form.

Dunne foresees several critical HAPLS applications. First, the system will greatly enhance new industrial processes, such as laser peening, that require nearly continuous pulses of laser light. Another application, centered on HAPLS's pump laser, is important for advancing laser fusion. Low-cost, high-energy, high-efficiency lasers with repetition rates of many times a second are required for a commercial laser fusion power plant. Secondary sources of neutron streams could also be used to test the strength and longevity of candidate materials for a fusion-energy power plant. Furthermore, by functioning similar to an incredibly compact particle accelerator, HAPLS could elucidate the mechanisms involved in the aging of materials in existing nuclear reactors and aid in the development of new methods to process nuclear waste.

Finally, a large fraction of scientific studies, such as those involving hot, dense matter, are performed in low signal-to-noise environments. "We want to build up data continuously to improve the signal-to-noise ratio," says Dunne. Livermore physicist Andy Bayramian explains, "With a low-petawatt repetition rate, researchers can perform only basic physics experiments. They are not able to ferret out low signal-to-noise environments to see the signal, because each shot is unique as a result of the beam's changing characteristics. At 10 hertz and with mechanisms to provide feedback, this laser system will provide stability and repeatable beam quality, allowing scientists to see what is actually occurring."

Czech Academy of Sciences. When the ELI Beamlines facility is ready to accept the laser system (anticipated in spring 2016), it will be shipped to the Czech Republic and reassembled. The laser system will then be integrated with the facility and gradually ramped to its design specifications. Members of the international scientific community should conduct their first experiments using the laser in 2018. The conceptual design of HAPLS is complete and has undergone extensive review. The development team has begun procuring components and finalizing engineering designs.

### International Competition

Following an international competition to build a laser that would meet the needs of ELI Beamlines, the Laboratory was chosen as the only qualified supplier. An agreement for \$46 million was signed September 16, 2013, after more than a year of contract negotiations between ELI Beamlines and Lawrence Livermore National Security, LLC (which manages Lawrence Livermore for the National Nuclear Security Administration). Members of NIF&PS, led by physicist Michael Dunne, program director for HAPLS, took part in the negotiations.

“We are proud and excited to be working with Lawrence Livermore, which is an internationally recognized center of excellence in high-performance lasers,” says Jan Ridky, director of the Czech Republic’s Institute of Physics, Academy of Sciences. Ed Moses, director of Fusion Science and Applications at Livermore, says, “This agreement is a great honor and a testament to our world-leading expertise in laser design, development, and operation as well as our track record of successful project delivery.” Moses notes that the agreement marks a new phase in the long-standing relationship between Lawrence Livermore and the European laser community.

While satisfying the technical needs of the ELI Beamlines project, the HAPLS effort is also important to meeting key



Livermore and ELI Beamlines scientists (left to right) Andy Bayramian, Tomas Mazanec (ELI), Steve Telford, Jack Naylor (ELI), and Constantin Haefner discuss the laser control system interface document for HAPLS.

goals for the Department of Energy (DOE). “Developing advanced short-pulse laser technology is key to many DOE missions,” says Haefner, who is optimistic the project will help energize the U.S. short-pulse and high-average-power laser research efforts. Several nations in Europe and Asia are planning advanced short-pulse laser facilities because of their potential to revolutionize fields ranging from clean energy to defense. “This is the age of the photon,” says Haefner.

According to Dunne, the requirements set by the ELI Beamlines project for HAPLS are well aligned with previously developed Livermore lasers. The Laboratory has extensive experience in the research and engineering of high-average-power and high-peak-power laser systems, including the world’s first petawatt laser, demonstrated in 1996 as part of Livermore’s Nova laser. In all, the HAPLS design builds on Livermore expertise in high-energy lasers (Janus, Shiva, Nova, and NIF),

high-average-power lasers (Atomic Vapor Laser Isotope Separation, Solid-State Heat Capacity Laser, and Mercury), and high-peak-power lasers (Falcon, Nova Petawatt, and Callisto).

Haefner points out that Livermore is currently building two unique high-intensity petawatt lasers. The first is HAPLS, the highest average-power petawatt laser in the world. The second is the Advanced Radiographic Capability (ARC), the world’s most energetic petawatt laser. ARC will operate in single-shot mode and will produce up to 4 petawatts and 13 kilojoules to generate more penetrating, higher energy x rays than is possible with conventional radiographic techniques. (See *S&TR*, December 2011, pp. 12–15.)

### Combining Two Livermore Designs

HAPLS will consist of two interconnected Livermore-designed laser systems that, when set up at ELI Beamlines, will require a combined

space of about 4.6 by 17 meters, plus 4 square meters for the final laser pulse compressor. The first system—a diode-pumped, solid-state laser—will energize or “pump” the second system—a chirped-pulse-amplification, short-pulse laser. The pump laser’s power amplifier will use neodymium-doped glass amplifier slabs, such as the ones used on NIF, and is designed to deliver 200 joules of energy at a repetition rate of 10 hertz for an average power of 2 kilowatts. At the output end of the pump laser, a frequency converter will double the pump laser frequency from infrared to green to match the absorption band of the short-pulse laser.

HAPLS’s short-pulse laser will use titanium-doped sapphire (Ti:sapphire) as its amplification medium. This laser is designed to convert the energy from the pump laser to 30-joule, 30-femtosecond pulses for a peak power exceeding 1 petawatt. The Laboratory has extensive experience with Ti:sapphire lasers. One example is Callisto, an ultrahigh-intensity

laser that has been used to generate intense beams of protons. (See pp. 16–19 in this issue; *S&TR*, January/February 2009, pp. 11–15.)

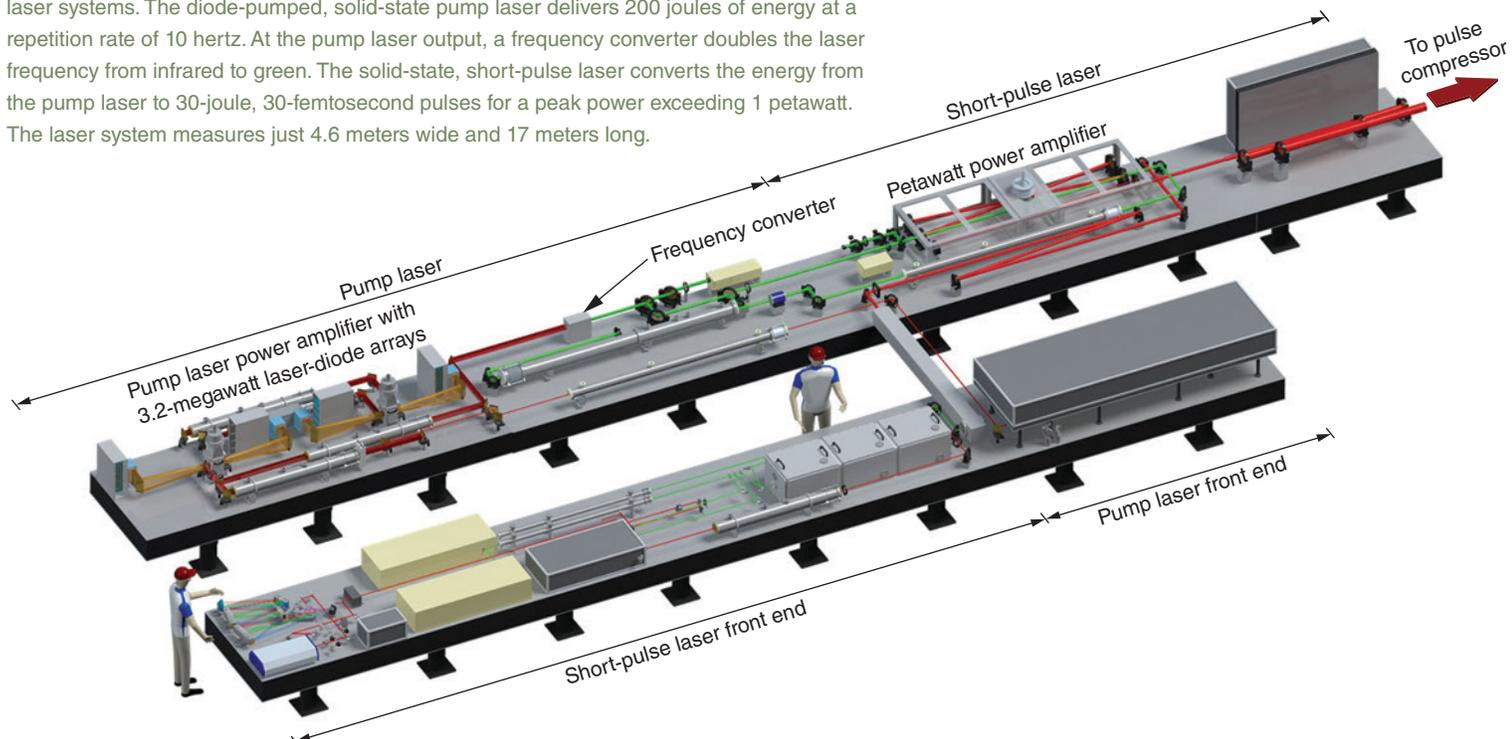
The short-pulse laser will build on Livermore’s expertise in chirped-pulse amplification, a common architecture for short-pulse lasers. An ultrashort laser pulse, only picoseconds to femtoseconds ( $10^{-12}$  to  $10^{-15}$  seconds) long, is first stretched to reduce its intensity. The pulse’s frequency content is distributed over time to create a nanosecond-long ( $10^{-9}$ -second), frequency-swept (chirped) pulse that can be amplified without generating intensities above the damage limit of laser glass and optics. After amplification, the chirped pulse is passed through an arrangement of diffraction gratings (called the pulse compressor) to undo the frequency sweep and re-create the initial short pulse, thus producing a high-energy, high-power laser pulse.

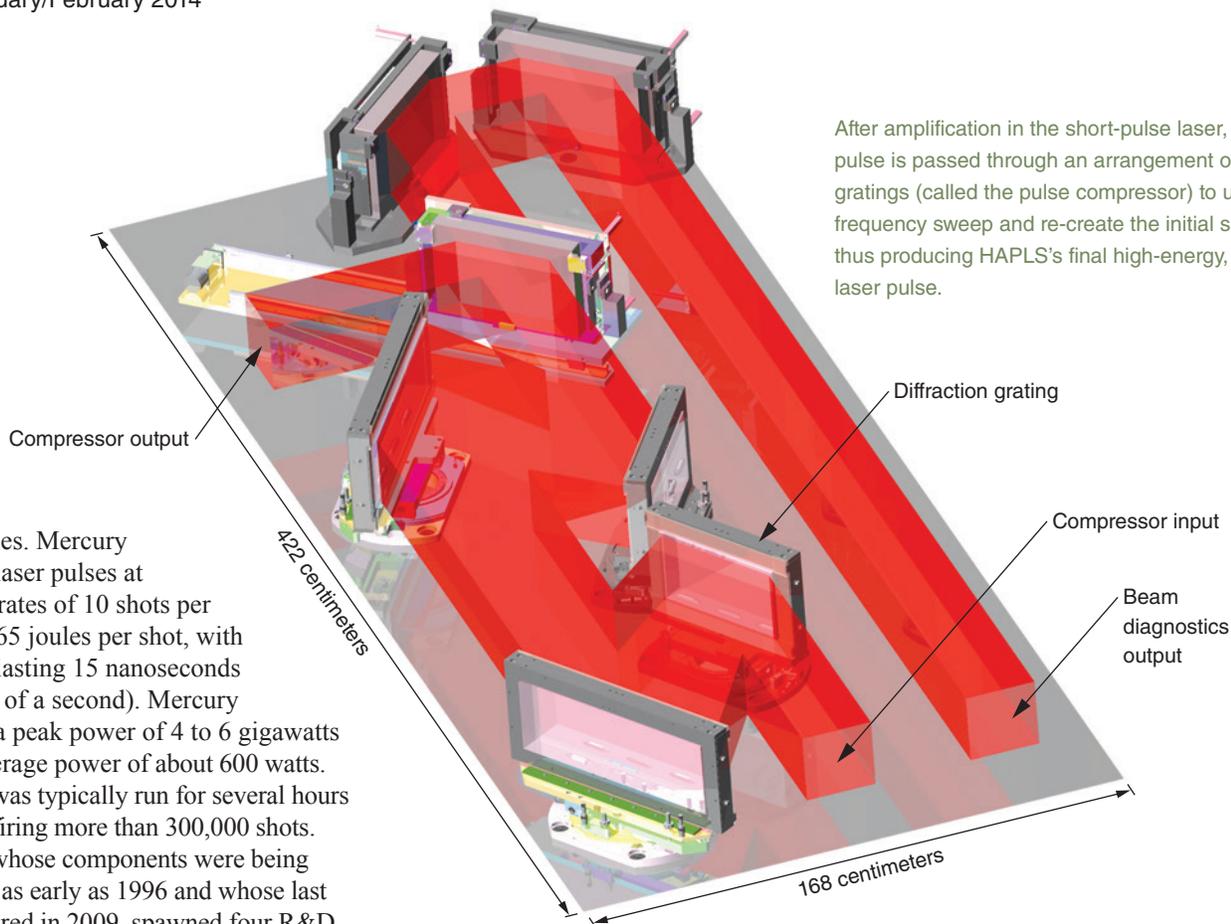
Physicist Andy Bayramian, member of the HAPLS development team, notes

that current high-power laser systems barely operate at 1 hertz, a repetition rate unchanged for more than a decade, because these systems use flashlamps (similar to those in operation at NIF) to energize their amplifiers. Laser diodes, just 100 micrometers long, are 20 times more efficient than conventional flashlamps found in typical petawatt and other types of lasers. They also generate substantially less waste heat. Laser diodes on the HAPLS pump laser are key to firing 10 times a second for hours at a time. Five arrays containing more than 500,000 diodes, the largest number ever assembled, will be used for a combined total of 3.2 megawatts of diode power. The pump laser’s diode arrays will be commercially manufactured to Livermore specifications.

Diode technology for lasers was demonstrated on Mercury, a high-average-power, solid-state laser system Livermore researchers built to develop and demonstrate laser fusion-energy

This computer-aided design shows HAPLS’s two interconnected Livermore-developed laser systems. The diode-pumped, solid-state pump laser delivers 200 joules of energy at a repetition rate of 10 hertz. At the pump laser output, a frequency converter doubles the laser frequency from infrared to green. The solid-state, short-pulse laser converts the energy from the pump laser to 30-joule, 30-femtosecond pulses for a peak power exceeding 1 petawatt. The laser system measures just 4.6 meters wide and 17 meters long.





After amplification in the short-pulse laser, the chirped pulse is passed through an arrangement of diffraction gratings (called the pulse compressor) to undo the frequency sweep and re-create the initial short pulse, thus producing HAPLS's final high-energy, high-power laser pulse.

technologies. Mercury produced laser pulses at repetition rates of 10 shots per second at 65 joules per shot, with each shot lasting 15 nanoseconds (billionths of a second). Mercury produced a peak power of 4 to 6 gigawatts and an average power of about 600 watts. The laser was typically run for several hours at a time, firing more than 300,000 shots. Mercury, whose components were being developed as early as 1996 and whose last shot was fired in 2009, spawned four R&D 100 awards. It still holds the world record for pulse energy from a diode-pumped laser system.

Chris Barty, chief technology officer for NIF&PS, first suggested in 2001 that a laser system similar to HAPLS could be constructed using Livermore technology as a pump source. At the time, the notion of creating a 10-hertz petawatt laser was considered audacious. "Mercury was a great demonstration," says Barty, "but we didn't do anything with the 65 joules of infrared light it produced 10 times per second." Barty proposed using the light from Mercury to energize a second laser designed to produce 15-femtosecond petawatt pulses at 10-hertz repetition rates, a rate more than 10,000 times higher than previously achieved. In 2007, Livermore designed and began construction of the 10-hertz petawatt laser. Despite those technical successes, the project was discontinued before the petawatt system could be completed, and the laser serves as the basis for the HAPLS design.



Laser diodes on the pump laser for HAPLS are key to firing 10 times a second for hours at a time. Diode technology was first demonstrated on Mercury (shown above), a high-average-power, solid-state laser system that Livermore researchers built in the late 1990s to develop and demonstrate laser fusion-energy technologies.

### Keeping Things Cool

Bayramian, former lead scientist on Mercury, notes that in addition to diodes, HAPLS will incorporate other advances developed on Mercury. For example, a key challenge for high-average-power operations is preventing damage to optical components. To that end, Livermore scientists have developed several technologies to increase the damage resistance of critical optics, such as superior manufacturing methods and advanced optical coatings. This effort is evident on NIF's 192 laser beamlines, which operate at 10 times higher intensity than typical commercial laser systems. In the 1980s, Laboratory scientists developed a method for continuously

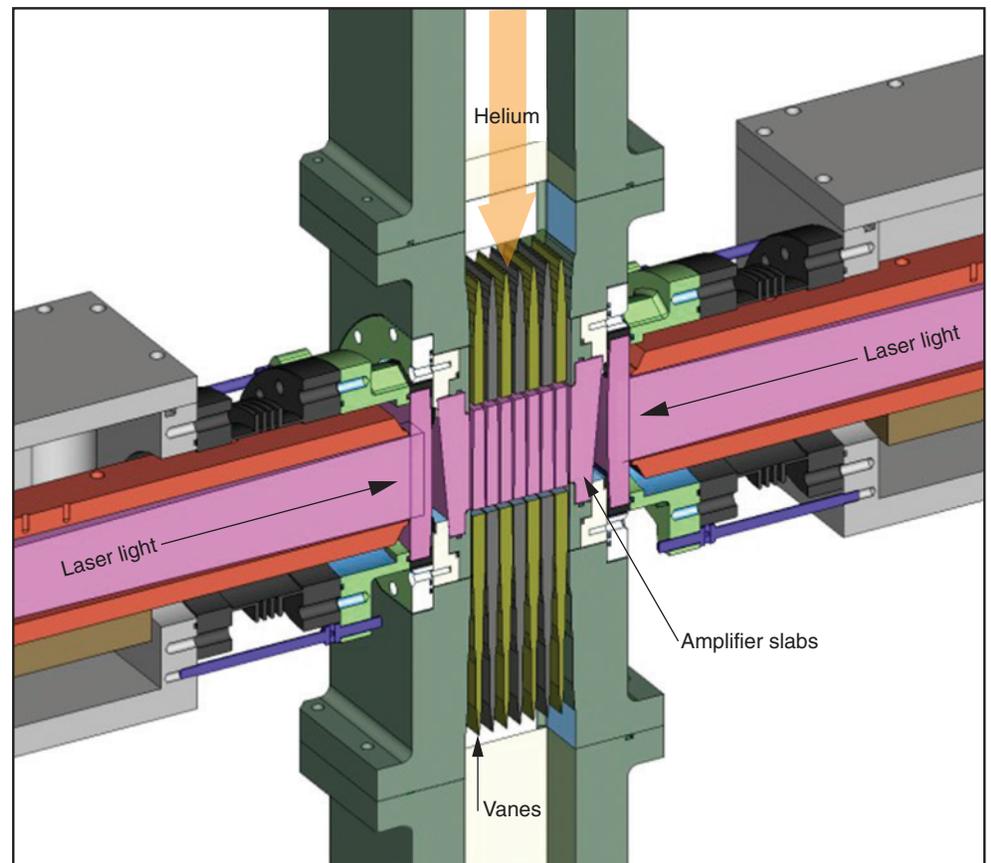
cooling critical optics to permit a laser to safely fire at 10 hertz. This technology, adopted by Mercury designers, propels high-velocity helium gas across components, in particular the laser amplifiers, to keep them cool. HAPLS will feature helium-gas cooling for both the pump and short-pulse lasers.

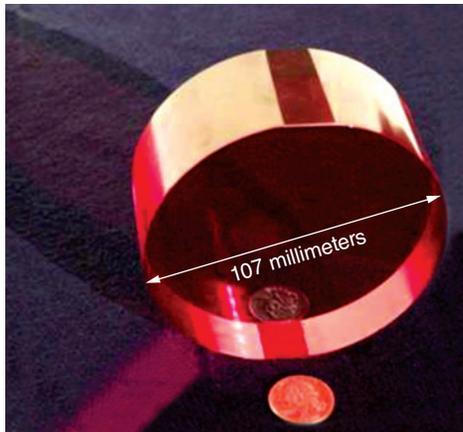
The cooling process requires removing heat from the face of the glass in the same direction that the laser beam propagates. Normally, heat removal drives thermal gradients, which can induce wavefront aberrations on the beam. With the Livermore method, all portions of the laser beam travel through the same gradients in the same directions, so wavefront aberrations are

minimal. In the HAPLS design, room-temperature helium gas, pressurized to 3 atmospheres, will travel about 100 meters per second (Mach 0.1 in helium at those conditions). The gas will be invisible to the laser beam because of helium's low refractive index, which is close to that of a vacuum.

For a 10-hertz repetition rate, an automated integrated control system is required. HAPLS will use an advanced version of the one developed for Mercury, which is similar to the system that operates on NIF. As part of the HAPLS control system, multiple ultrafast diagnostics will continuously monitor the laser's health. As a result, HAPLS will be capable of nonstop shot monitoring and control of most

HAPLS will feature helium gas cooling for both the pump and short-pulse lasers. Developed by Livermore scientists in the 1990s, this technology continuously cools critical optics to permit safe 10-hertz operation. The pump laser's amplifier glass is embedded in metal "vanes" to help circulate the helium gas flowing from above. Light from the laser diodes and the pump laser converge on the amplifier before being redirected to the short-pulse laser.





HAPLS's short-pulse laser will use (a) titanium-doped sapphire crystals as its amplification medium. (b) This polished boule measures 107 millimeters in diameter and 46 millimeters thick. (c) After the boule is sliced, it is precision cut to the desired shape, and an edge cladding is applied to suppress parasitic lasing.

operations, including precise alignment of key components.

Even with the best quality-control mechanisms, HAPLS's laser light will still exhibit some aberrations that require correction. Static wavefront correctors, successfully fielded on Mercury and NIF, and dynamically controlled deformable mirrors, a form of adaptive optics, will be deployed to correct these aberrations. Each deformable mirror has an array of actuators that can bend the mirror's surface to compensate for wavefront errors in the laser beam. Other adaptive optics will help maintain beam quality by continuously correcting for beam distortions in the amplification chain of both the pump and short-pulse lasers. Says Barty, "With adaptive optics in place, the system will be able to sense and correct any distortions at 10 hertz." In essence, the laser will learn to "heal" itself through nearly instant feedback.

In addition, HAPLS will feature mechanisms to largely mitigate a phenomenon called parasitic lasing, the inadvertent and unwanted propagation of spurious laser light that can develop in any laser system. Parasitic lasing can emit light in unexpected directions and reduce

the energy that can be extracted from the amplifier, which can in turn affect the amplifier's reliability and efficiency. The Livermore solution, embodied in Mercury, is to bond specialized glass edge cladding to absorb parasitic lasing. This cladding, a proprietary formulation, contains an absorption material carefully matched to the emission of the laser light.

Haefner plans to thoroughly test and validate every subsystem as it is built. The many systems will then be integrated, followed by gradual ramping of the laser to its full capability. The effort will take advantage of Livermore's suite of two- and three-dimensional computer codes to model the functioning of components and the behavior of laser light at extreme intensities. HAPLS is designed to allow for future upgrades and scaling to even higher energies and repetition rates, which will ensure the longevity and scientific competitiveness of the ELI Beamlines facility.

### Enduring Collaboration

In remarks last year, U.S. Ambassador to the Czech Republic Norman Eisen said, "I am happy to see that American scientists at Lawrence Livermore National Laboratory—working with

Czech partners—will design and build the one-of-a-kind laser system that will be at the heart of ELI Beamlines. I'm looking forward to hearing the first news reports about Czech and American researchers making scientific breakthroughs at ELI Beamlines."

Judging from three decades of success in developing breakthrough laser designs, components, and manufacturing techniques, Livermore scientists are poised to succeed, not only with HAPLS but also in establishing an enduring scientific collaboration with the Czech Republic. What's more, Lawrence Livermore researchers are looking forward to being of service to their colleagues planning the other two ELI facilities in Hungary and Romania.

—Arnie Heller

**Key Words:** Advanced Radiographic Capability (ARC), Callisto laser, chirped-pulse amplification, Extreme Light Infrastructure (ELI) Beamlines High-Repetition-Rate Advanced Petawatt Laser System (HAPLS), laser diodes, Mercury laser, National Ignition Facility (NIF), parasitic lasing, petawatt.

**For further information contact Constantin Haefner (925) 422-1167 (haefner2@llnl.gov).**

# In Metals

## Not All Twins Are Identical

**F**ROM the steel used in construction to the copper in circuit boards, most metals are made of closely packed crystallites, or grains, which can range in size from nanometers to millimeters ( $10^{-9}$  to  $10^{-3}$  meters). For many applications, shrinking the grain size of these materials can confer notable macroscale performance benefits. For instance, smaller grains have more surface area in contact with neighboring grains, which can make a metal stronger. When metal is compressed, twisted, or stretched, atoms move out of position in the crystal structure, producing dislocations that deform the material. Just as a retaining wall holds the soil on a steep hillside in place, the interfaces, or boundaries, between grains help limit the formation and motion of dislocations. Generally, the greater the number of boundaries, the better a material is at halting dislocations.

Material scientists have more recently turned their focus to another type of boundary, found within the crystalline structure of ordinary metals such as silver, copper, and gold. This interface is called a coherent twin boundary (CTB) because one side is a mirror image, or twin, of the other. “Twin boundaries have emerged as the second most important interface in materials



science, after grain boundaries,” says Lawrence Livermore materials scientist Morris Wang. “They can affect many fundamental applications and projects.”

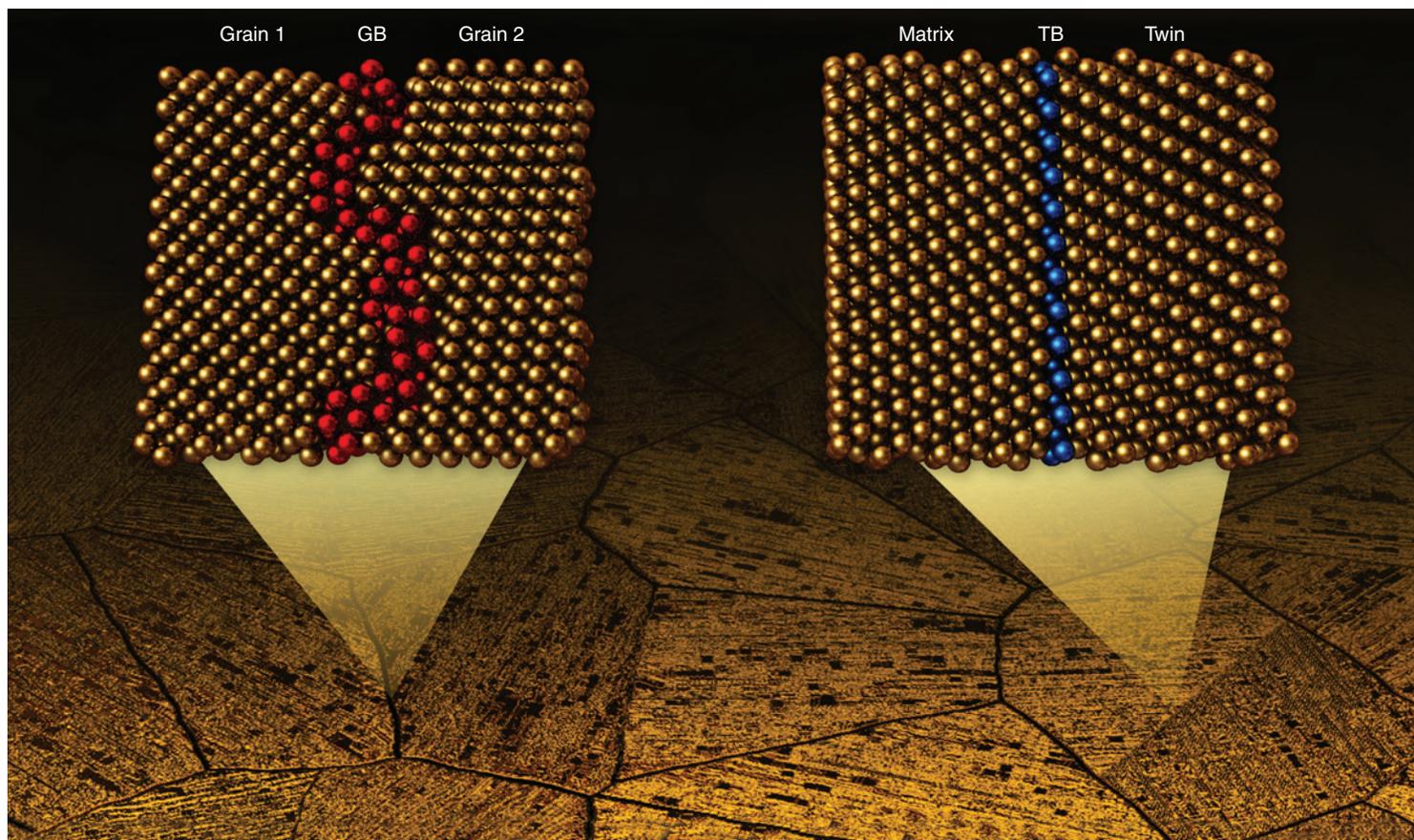
Nanotwinned metals, featuring CTBs spaced less than 100 nanometers apart, hold several advantages in strengthening metals compared with grain boundaries. Most very hard metals are also brittle, but nanotwinned metals gain strength while remaining ductile. This characteristic makes them particularly attractive for structural applications. Also, electron transmission is much easier through twin boundaries, an important property for computer manufacturing and other electronics applications. Pure copper, for instance, is nearly as soft as butter but with very high thermal and electrical conductivity. Nanotwinned pure copper boasts comparable conductivity but 10 times the strength.

Most research into CTBs and the properties they imbue in metals has relied on the assumption that CTBs are a smooth, flat, one-atom-thick plane. However, experimental and computational

research by Wang and several colleagues has shown that CTBs in nanotwinned copper are not perfect planar interfaces but instead are riddled with tiny steplike features and curvatures. Indeed, these defects are largely responsible for the desirable mix of properties in nanotwinned metals.

### Surprisingly Dynamic Behavior

Livermore scientists have conducted several experiments over the past few years to better understand the nanoscale features of nanotwinned copper and how they correlate with macroscale properties. Together with Ames Laboratory researcher Ryan Ott, they examined the mechanical properties of nanotwinned copper samples using in situ synchrotron x-ray diffraction (SXRD) at Argonne National Laboratory’s Advanced Photon Source. The synchrotron’s intense x rays allowed the researchers to track material response to applied stress at a microstructural level, both at room temperature and at 180°C.



The mechanical properties of nanotwinned metals depend on both the size of crystals, or grains, and the spacing between twin boundaries (TBs). Two types of interfaces in a nanostructured crystalline metal are shown in two dimensions: (left) a typical grain boundary (GB) and (right) a coherent TB.

The material deformed far more readily at the higher temperature. When samples were examined with a transmission electron microscope (TEM), the heated metal exhibited more dislocation movement and twin boundary separation, consistent with its ease of deformation. At both temperatures, though, the movement and separation were more extensive than anticipated. Materials scientist Thomas LaGrange explains, “The in situ deformation experiments displayed an anomalous drop in strength along a particular crystal direction. Twin boundaries that we thought to be stable and stationary were moving.” The team began to suspect that twin boundaries might be less reliable than assumed.

Using fresh nanotwinned copper samples, the Livermore researchers characterized the material’s nanoscale structure. They used a new electron-diffraction crystal orientation mapping method, called inverse pole figure orientation mapping (IPFOM), that works with a TEM. IPFOM collects and organizes up to 250,000 frames of nanodiffraction patterns at a time and then accurately determines how each region is oriented, or misoriented, with respect to the surrounding crystal structure.

The typical mapping technique, scanning electron microscopy–based electron backscatter diffraction, resolves features roughly 50 nanometers or larger. By pushing the limits of the IPFOM device, the team was able to capture features as small as a nanometer—a mere five atoms wide. The images enabled them to identify previously unseen features and gather statistics on twin and grain interfaces. At moderate resolution, the metal appeared to contain mostly “normal” CTBs, interspersed

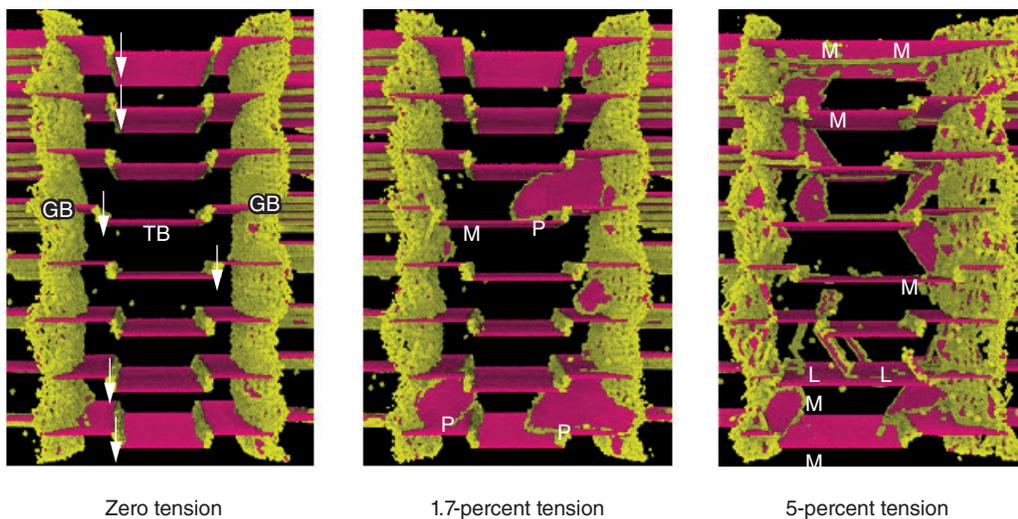
with a few defective, or incoherent, twin boundaries. However, at high resolution, the researchers could see that most of the seemingly perfect twins had many steplike incoherent segments, which ranged from 1 to 5 nanometers in height. Although the placement of these imperfections varied, their concentration was remarkably consistent, indicating that twin boundaries might be intrinsically defective.

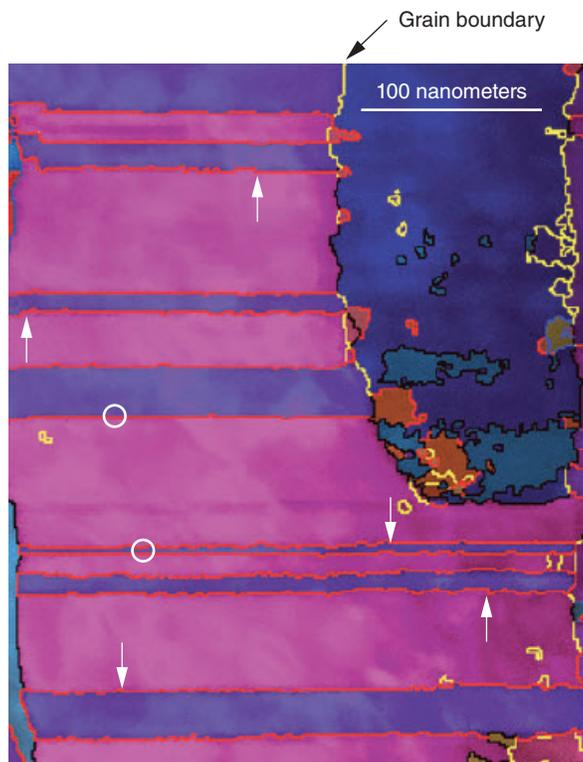
### Building a New Theoretical Foundation

At the atomic level, nanotwinned copper structure is clearly more heterogeneous and its deformation more complex than materials scientists had assumed. To better understand the experimental results, the Livermore researchers, together with University of Vermont professor Frederic Sansoz, performed molecular dynamics simulations at the Vermont Advanced Computing Center. In a series of scenarios, they compared how perfect and imperfect twin and grain boundaries responded under loading conditions similar to those in the SXRDR investigations.

The researchers found that copper modeled with defective twin boundary segments more closely matched experimental observations. In fact, the defective twin regions were largely responsible for the combination of strength and ductility observed in nanotwinned metals. Simulations showed that when nanotwinned copper was stretched, the imperfect twin boundaries initially pinned the dislocations in place, strengthening the material. Continued stress caused the areas to de-pin and the

A molecular dynamics simulation illustrates the evolution (left to right) of the microstructure within a grain of nanotwinned copper subjected to uniaxial tension. Both defective GBs and stepped (defective) TBs are shown in different stages of deformation. Vertical arrows indicate the positions of migrating stepped imperfections. The locations where step migration and partial dislocation from GBs occur are marked M and P, respectively. L indicates locked, or pinned, regions.





High-resolution inverse pole figure orientation mapping provides essential information about the microstructure of nanotwinned copper, including grain boundary defects. In this edge-on image, a GB is indicated by the yellow and black line segments. The white circles mark a defect-free TB region, while the white arrows mark the location of selected TB defects.

material to soften and flow. When the metal was twisted, the stepped regions of twin boundaries migrated and separated, or detwinned, rather easily. Detwinning removes a supportive interface, which can make the material more ductile but less strong, because fewer interfaces are available to impede dislocation motion.

The researchers also found that even in CTB-strengthened metals, grain boundaries greatly influenced material behavior. Simulations showed that less defective grain boundaries enhanced structural stability, but more defective grain boundaries made the material deform much more easily. The proximity of a grain boundary to a twin boundary also seemed to affect the susceptibility of that interface to detwinning.

### From Aberration to Asset

Livermore modeling results revealed that the material properties of a nanotwinned metal are dictated to a great extent by the concentration, placement, and type of twin and grain boundaries in the microstructure. Given these variables, not every nanotwinned metal sample will behave uniformly. Says Wang, “We need to redefine the concept of twin boundaries. A variety of grain boundaries exist, and now we know that twin boundaries also vary.” Twin-boundary diversity could be advantageous, potentially enabling material scientists to formulate and fabricate a microstructure tailored to meet a specific macroscale need. For example, researchers could develop a material that would reduce the likelihood of stress cracks in a nuclear reactor pressure vessel.

A daunting amount of work remains, but as Livermore researchers endeavor to develop metals with superior strength—work directly relevant to many of the Laboratory’s missions—they will be aided by a first-of-its-kind capability that enables them to map strain on a nanometer scale during TEM-based deformation experiments. LaGrange notes that one of the first applications of the new strain-mapping capability will be to study the role of triple junctions, places where twin boundaries and grain boundaries meet, in accommodating stress and influencing deformation behavior.

In addition, Ames Laboratory scientists, in collaboration with Wang, plan to examine whether doping enhances the strength of nanotwinned silver, the most electrically conductive metal. If effective, nanotwinned silver may eventually be used to make cheaper and sturdier transparent conductive electrodes, which are key components in both solar panels and the light-emitting diode displays found in cellular phone and television screens. With a greater understanding of their formation and properties, material scientists, designers, and manufacturers will soon begin viewing “defective” twin and grain boundaries as potential assets.

—Rose Hansen

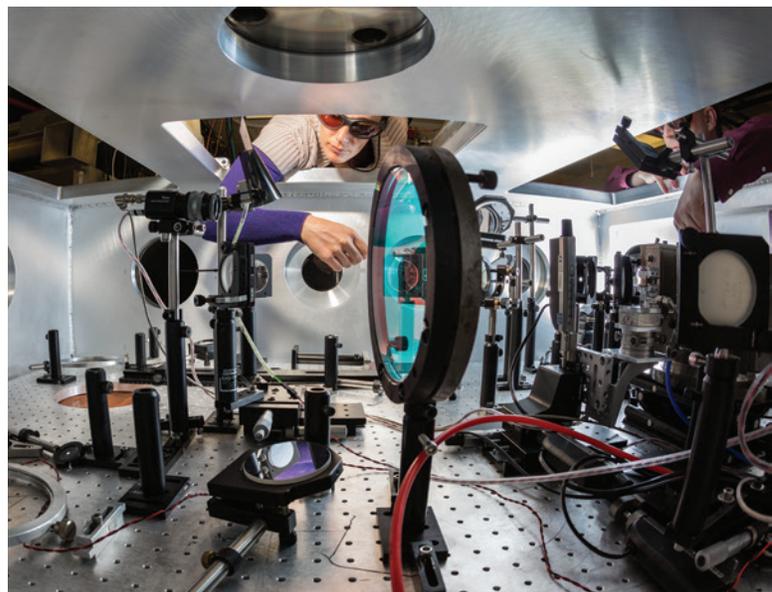
**Key Words:** coherent twin boundary (CTB), detwinning, grain boundary, high-strength metal, inverse pole figure orientation mapping (IPFOM), material property, materials science, nanotwinned metal, strain mapping, synchrotron x-ray diffraction (SXR), transmission electron microscope (TEM).

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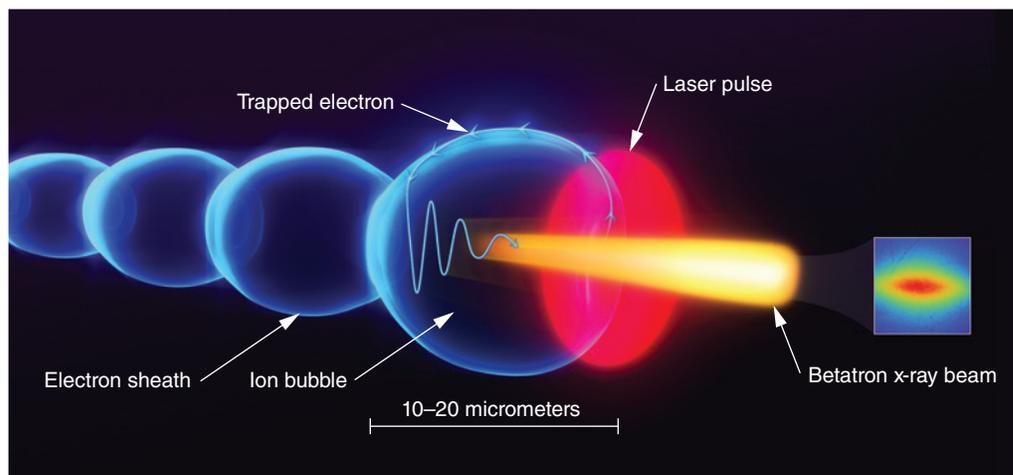
# Betatron X Rays Bring Focus to a Very Small, Very Fast World

**S**HORTER duration and brighter—these are the desired qualities of x-ray pulses for exploring phenomena over very short time and length scales. The shorter the pulse, the better its ability to capture events occurring on ultrashort timescales, such as changes in atomic configuration. The brighter the x ray, the stronger the signal, which allows a researcher to conduct multiple experiments in a single shot and provides a better signal-to-noise ratio. This latter quality is a major benefit when probing dense plasmas and other phenomena that naturally emit x rays or visible light. Producing pulses that have both characteristics is not trivial and typically requires expensive, kilometer-long particle accelerator facilities.

A Livermore team led by Félicie Albert, along with researchers from the University of California at Los Angeles (UCLA) and SLAC National Accelerator Laboratory, has produced x-ray pulses with all the characteristics users desire, with the added benefit of being generated on a system the size of a large tabletop. Pulses from Livermore's Callisto laser are focused onto various gases, generating relativistic electrons—oscillating similar to those first created in betatrons in the 1940s—that, in turn, produce high-energy x rays in the femtosecond ( $10^{-15}$ -second) regime. The compact size of the Callisto system makes it possible for scientists



Livermore researchers Félicie Albert (center) and Bradley Pollock (far right) prepare the tabletop-sized Callisto laser system for laser-wakefield betatron x-ray experiments at the Laboratory's Jupiter Laser Facility.



During Livermore's laser-wakefield betatron x-ray experiments, an intense laser pulse strips electrons off gas atoms, forming ions and free electrons. The electrons are pushed away by the intense laser light, and some circle back behind the pulse to be captured in the positively charged ion bubble in the pulse's wake. As the electrons accelerate through the positively charged ion bubble, they wiggle, emitting betatron x rays.

to contemplate routinely using these betatron x rays in applications such as radiography; phase-contrast imaging; and spectroscopy for materials research, high-energy-density (HED) studies, and nondestructive characterization.

### Hit 'Em with Your Best Shot

At the heart of the betatron x-ray experiments are Livermore's 200-terawatt Callisto laser and a cell (just a few millimeters long) filled with a gas. Callisto uses chirped-pulse amplification to produce a 60-femtosecond-long pulse of ultrahigh intensity light. The laser's 13-centimeter-diameter beam is focused under vacuum onto the cell's 500-micrometer entrance pinhole within a spot diameter of 12 micrometers and up to intensities of  $10^{19}$  watts per square centimeter. The cell is typically filled with helium, although Albert's team has also experimented with nitrogen, carbon dioxide, argon, and neon.

As the leading edge of the pulse encounters the edge of the gas cloud, the pulse strips electrons from the gas molecules, creating a plasma of positively charged ions and free electrons. The pulse creates a plasma cloud as it continues to travel through the gas. The light pressure of the pulse's peak pushes the free electrons in the cloud away from the laser pulse, similar to how the prow of a boat pushes water away from the bow. The ions, which are about a thousand times heavier than the free electrons, are too heavy to be moved by the light pressure. Thus, as the pulse passes by, it leaves a positively charged "bubble" populated only by ions in its wake.

Just as some of the water displaced by the boat prow will circle around and be trapped by the boat's wake, some of the electrons shoved aside by the light pulse will circle back and be drawn into the wake of the pulse, that is, the ion-filled bubble. The "wakefield" electrons accelerate through the positively charged bubble,

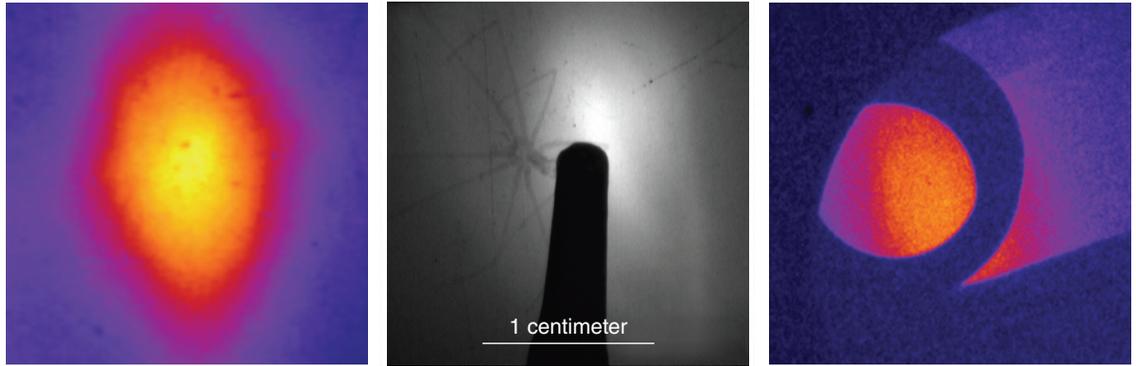
oscillating rapidly in a sinusoidal path and emitting x rays. These laser-wakefield betatron x rays are synchronous with the initial laser pulse on the femtosecond timescale.

### Achieving a Trifecta

Using Callisto to generate laser-wakefield betatron x rays sidesteps some of the drawbacks of producing high-energy x rays with other sources, such as synchrotrons and free-electron lasers. In a synchrotron system, such as the one at Argonne National Laboratory's Advanced Photon Source, electrons from a storage ring are wiggled by undulator-produced alternating magnetic fields. The oscillating motion causes the electrons, which are traveling at close to the speed of light, to release broadband or monochromatic hard x rays of extreme brightness. These x rays are picoseconds in pulse length, slower than the femtosecond-long pulses and the motion of atoms in molecules and plasmas that might be studied with bright x rays. Free-electron lasers, such as SLAC's Linac Coherent Light Source, produce coherent, femtosecond x-ray pulses with high brightness but in narrow spectral and energy bands. These pulses are also typically in the soft x-ray regime (about 8 kiloelectronvolts).

Another drawback with other x-ray sources is that the systems require massive facilities, and the complex machines are expensive and kilometers in length. In addition says Albert, "Relatively few of these facilities exist worldwide. Potential users must compete for time with each other, and experiment schedules can fill up years in advance." The betatron x rays produced with laser wakefields achieve the perfect trifecta: hard x rays (potentially up to 100 kiloelectronvolts) of high brightness and femtoseconds in length. Plus, these x rays have some degree of spatial coherence and can be produced on a tabletop-sized system.

Betatron x-ray radiographs obtained at the Jupiter Laser Facility reveal images of (left) a beam profile, (center) a spider, and (right) a gold ignition hohlraum.



### Probing the Nature of Matter

In the first year of a Laboratory Directed Research and Development project to explore the nature and applications of laser-wakefield betatron x rays, Albert and her team at Livermore, including Lawrence Fellow Bradley Pollock, characterized the experimental source and benchmarked results against numerical particle-in-cell simulations. In collaboration with UCLA professor Chan Joshi and his group, the Livermore researchers also produced betatron x rays among the highest ever demonstrated—up to 80 kiloelectronvolts—and performed preliminary imaging experiments. In addition, they measured for the first time the angular dependence of betatron x-ray spectra in a laser-wakefield accelerator. “These data will help in designing future HED science experiments using this kind of source,” says Albert.

The project is now focused on applications, particularly those involving single-shot, ultrafast absorption spectroscopy—a powerful tool for studying the local atomic structure in materials. Says Albert, “Here at Livermore, femtosecond betatron pulses could eventually take ultrafast snapshots of National Ignition Facility experiments. They could also be used for nondestructive imaging and for a wide range of HED science experiments.”

The beauty of laser-wakefield betatron x rays is that they allow scientists to take femtosecond-long snapshots of ultrafast electronic and molecular changes in materials and possibly uncover details that have been previously unseen. The team also plans to use the source to perform optical pump and x-ray probe experiments for HED studies. “We hope to gain information on plasma temperature, density, and ionization-state dynamics,” says Albert. “In addition, we will have the opportunity to explore the poorly understood properties of warm, dense matter at the atomic level with femtosecond resolution.” Albert notes that this remarkable x-ray tool could potentially be used to discover new physical properties of materials at the high pressures and temperatures found only in planet interiors and fusion plasmas.

### Future Looks Bright for Betatron Rays

In experiments scheduled for the summer of 2014 at the Astra Gemini laser in the United Kingdom, the researchers, in collaboration with scientists from Imperial College London, will use betatron x rays to probe shocks and dense, transient states of matter. The initial optical laser pulse will shock iron samples and create the betatron x rays for imaging how those iron molecules relax back to an equilibrium state. “For the first time, we will be able to shock an iron sample and view the shock wave’s propagation through the sample with femtosecond precision,” says Albert. Because the betatron x rays and the pump are produced by the same laser, the optical and x-ray pulses will be perfectly synchronized.

Albert hopes to conduct other experiments using x-ray pump and probe. “Pumping a sample with x rays will allow us to observe different phenomena,” she says. “It’s an exciting possibility that we are still exploring.” Albert anticipates that the source will be further developed for future high-energy, high-repetition-rate laser systems such as the High-Repetition-Rate Advanced Petawatt Laser System currently being built at Livermore for the Czech Republic (see the article beginning on p. 4). “Such sources will facilitate application experiments by providing higher repetition and more stable betatron x rays,” says Albert.

More applications beckon on the horizon, as these x rays could be used in any research involving ultrashort synchrotron radiation. At the femtosecond timescale, delivered with a compact source, the sky looks to be the limit for laser-wakefield betatron x rays.

—Ann Parker

**Key Words:** Callisto laser, chirped-pulse amplification, femtosecond laser, high-energy-density (HED) experiment, Jupiter Laser Facility, laser-wakefield betatron x ray, National Ignition Facility, x-ray pump and probe.

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*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.*

### Patents

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#### **Methods for Tape Fabrication of Continuous Filament Composite Parts and Articles of Manufacture Thereof**

**Andrew H. Weisberg**

U.S. Patent 8,545,657 B2

October 1, 2013

This method for fabricating a composite structure includes forming two layers and placing the second above the first. For each layer, a bonding material is applied to a tape made of a fiber and a matrix. The bonding material has a curing time of less than about 1 second. The tape is added to a substrate to form adjacent tape winds with an approximately constant distance between. Additional systems, methods, and articles of manufacture are also presented.

#### **Systems Having Optical Absorption Layer for Mid and Long Wave Infrared and Methods for Making the Same**

**Paul J. Kuzmenko**

U.S. Patent 8,545,995 B2

October 1, 2013

An optical system according to one embodiment includes a substrate and an optical absorption layer coupled to the substrate. The optical absorption layer comprises a layer of diamondlike carbon and absorbs at least 50 percent of mid-wave infrared light (3 to 5 micrometers) and at least 50 percent of long-wave infrared light (8 to 13 micrometers). An optical system according to another embodiment includes depositing a layer of diamondlike carbon as an optical absorption layer above a substrate using plasma-enhanced chemical vapor deposition. The optical absorption layer absorbs at least 50 percent of mid-wave infrared light and at least 50 percent of long-wave infrared light. Additional systems and methods are also presented.

#### **High Power Density Fuel Cell Comprising an Array of Microchannels**

**Jeffrey D. Morse, Ravindra S. Upadhye, Christopher M. Spadaccini,**

**Hyung Gyu Park**

U.S. Patent 8,557,480 B2

October 15, 2013

A fuel cell according to one embodiment includes a porous electrolyte support structure with an array of fuel and oxidant microchannels. Fuel electrodes form along some of the microchannels, and oxidant electrodes form along others. The array of porous walls is formed using at least one of the following methods: molding, stamping, extrusion, injection, or electrodeposition. In another embodiment, anode electrodes form along some of the microchannels, and cathode electrodes form along others. Additional embodiments are also disclosed.

#### **Method for Manufacturing Solid-State Thermal Neutron Detectors with Simultaneous High Thermal Neutron Detection Efficiency (>50%) and Neutron to Gamma Discrimination (>10<sup>4</sup>)**

**Rebecca J. Nikolic, Adam M. Conway, Daniel Heineck, Lars F. Voss,**

**Tzu Fang Wang, Qinghui Shao**

U.S. Patent 8,558,188 B2

October 15, 2013

Solid-state thermal neutron detectors can be manufactured with simultaneous high thermal neutron detection efficiency (>50 percent) and neutron-gamma

discrimination (>10<sup>4</sup>). A structure includes a p+ area on the first side of an intrinsic region and an n+ area on the second side. The thickness of the intrinsic region is minimized to achieve a desired gamma discrimination factor of at least 1.0 × 10<sup>4</sup>. Material is removed from the p+ or the n+ area and placed into the intrinsic layer to produce pillars with open space between each pillar. The open space is filled with a neutron-sensitive material. An electrode is placed in contact with the pillars, and another electrode is placed in contact with the side that is opposite the intrinsic layer with respect to the first electrode.

#### **System and Method of Modulating Electrical Signals Using Photoconductive Wide Bandgap Semiconductors as Variable Resistors**

**John Richardson Harris, George J. Caporaso, Stephen E. Sampayan**

U.S. Patent 8,563,930 B2

October 22, 2013

This system and method produce modulated electrical signals using a variable resistor with a photoconductive wide-bandgap semiconductor. The conduction response changes in amplitude of incident radiation and is substantially linear throughout a nonsaturation region, thus enabling operation in nonavalanche mode. The system also includes a modulated radiation source, such as a modulated laser, to produce amplitude-modulated radiation. This radiation is directed on the variable resistor to modulate the resistor's conduction response. A voltage source and an output port are connected to the variable resistor so that an electrical signal can be produced at the output port via the resistor. In this method, the variable resistor modulates the electrical signal, creating a waveform substantially similar to the amplitude-modulated radiation.

#### **Photoconductive Switch Package**

**George J. Caporaso**

U.S. Patent 8,563,957 B2

October 22, 2013

A photoconductive switch is made of a substrate with a center consisting of a photoconductive material such as silicon carbon. The outer substrate consists of diamond produced with chemical vapor deposition or another suitable material. Conducting electrodes are formed on opposing sides of the substrate. These electrodes extend beyond the substrate's center, with their edges lying over the outer substrate. Thus, any high electric fields produced at the edges of the electrodes remain outside the substrate's center and do not affect the active switching element. Light is transmitted through the outer substrate to the substrate's center to actuate the switch.

## Awards

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A new record for a high-performance computing calculation set on the Laboratory's Sequoia supercomputer was awarded the **Gordon Bell Prize** for peak performance at the SC13 Conference in Denver, Colorado, last November. Scientists at ETH Zurich and IBM Research, in collaboration with the Technical University of Munich and Lawrence Livermore, performed the largest simulation ever in fluid dynamics using 6.4 million threads on the 96-rack Sequoia, an IBM BlueGene/Q machine. The prize was awarded for an 11-petaflops (quadrillion floating-point operations per second) simulation of cloud cavitation collapse (shown at right). Livermore computer scientists **Adam Bertsch** and **Scott Futral** were members of the winning team. Named for C. Gordon Bell, one of the founders of supercomputing, the Gordon Bell Prize is awarded to innovators who advance high-performance computing. The prize is administered by the **Institute of Electrical and Electronics Engineers**.

In another announcement at the conference, the 20-petaflops **Sequoia** retained its **No. 1 ranking** on the **Graph 500 list**, which ranks the world's most powerful computer systems for data-intensive computing. The list gets its name from graph-type problems, or algorithms, that are a core part of many analytics workloads. Sequoia traversed more than 15,363 billion graph edges per second. **Dave Fox**, systems lead for Sequoia, led the Livermore work on the Graph 500 calculation, and **Fabrizio Petrini** led the IBM team. Data-intensive computing, also called "big data," has become increasingly important to Laboratory missions as high-performance computing platforms have become increasingly powerful, producing enormous quantities of information.

The **National Nuclear Security Administration (NNSA)** recognized three of Lawrence Livermore's projects with **2013 Sustainability Awards**. The **National Ignition Facility (NIF)** received a **Best in Class Award** for waste reduction and pollution prevention. The NIF and Photon Science Principal Directorate has implemented numerous program improvements that have significantly reduced low-level radiological waste generation, product use, and costs and time spent managing hazards. In addition, the **Laboratory** garnered a **Best in Class Award** for its holistic waste reduction program and an **Environmental Stewardship Award** for sustainable landscape.

The **Federal Laboratory Consortium's (FLC) Far West Region competition** honored four **Lawrence Livermore** teams for outstanding technology development, outstanding partnerships, and outstanding commercialization. FLC is a nationwide network of federal laboratories and provides a forum to develop strategies and opportunities for linking laboratory mission technologies with the marketplace.

A team of scientists and engineers received an **Outstanding Technology Development Award** for developing DNA-Tagged Reagents for Aerosol Experiments (DNATrax), a safe and versatile material that can be used to reliably and rapidly diagnose airflow patterns and problems in both indoor and outdoor venues. (See *S&TR*, October/November 2013, pp. 4–5.) The Livermore scientists who developed DNATrax include team lead **George Farquar, Elizabeth Wheeler, Ruth Udey, Beth Vitalis, Roald Leif, Brian Baker, Christine Hara, Cindy Thomas, Maxim Shusteff, and Sally Hall**.

Scientists from Lawrence Livermore and the Environmental Protection Agency (EPA) garnered an **Outstanding Partnership Award** for developing a rapid method for detecting viable anthrax-causing spores. The collaboration team includes **Staci Kane, Sonia Letant, Gloria Murphy, and Teneile Alfaro** of Lawrence Livermore and **Sanjiv Shah** of EPA.

Another collaboration was honored with an **Outstanding Partnership Award** for developing the Earth System Grid Federation (ESGF), which serves the data-driven needs of the climate research community. The collaborative team includes Livermore's **Dean N. Williams**, principal investigator for ESGF, and 11 partner institutions.

Finally, in 2008, QuantaLife, Inc., a Pleasanton, California, startup company, licensed a Laboratory technology called digital polymerase chain reaction (PCR). The technology is a refinement of real-time PCR that allows researchers to quantify and amplify nucleic acids, including DNA and RNA. Livermore Business Development Executive (BDE) **Catherine Elizondo** and former BDE **Ida Shum** worked with Laboratory researchers and QuantaLife to negotiate and manage the license agreement and business relationships. The work of the Laboratory's Industrial Partnerships Office, QuantaLife, and its successor company received an **Outstanding Commercialization Success Award**. The founder of QuantaLife and the co-inventor of the technology is **Bill Colston**, a former Livermore employee.

Two Laboratory scientists were selected as 2013 **fellows** of the **American Physical Society (APS)**. **John Moody** of the NIF and Photon Science Principal Directorate was cited in the plasma physics category for "pioneering experiments contributing to understanding propagation, scattering, transmission, and redirection of high-intensity laser beams in large-scale plasmas for inertial confinement fusion." **Pravesh Patel** of the Physical and Life Sciences Directorate was cited in the plasma physics category for "pioneering contributions in the science of ultraintense laser-matter interaction and particle acceleration and applications for creating and probing high-energy-density plasma states, and for his leadership in advancing the fast-ignition concept for inertial confinement fusion."

## Lighting a New Era of Scientific Discovery

Lawrence Livermore and European scientists and engineers are constructing the High-Repetition-Rate Advanced Petawatt Laser System (HAPLS), a laser designed to generate a peak power greater than 1 petawatt. Each pulse of light will deliver 30 joules of energy in less than 30 femtoseconds at a repetition rate of 10 hertz (10 pulses per second). HAPLS builds on two interconnected Livermore-designed laser systems. A diode-pumped, solid-state laser will energize a second short-pulse laser that uses titanium-doped sapphire glass as an amplification medium. HAPLS will deliver ultrashort high-energy laser pulses for generating secondary sources of electromagnetic radiation and accelerating charged particles for applications in physics, medicine, biology, and materials science. The laser system will be delivered to the Extreme Light Infrastructure (ELI) Beamlines facility, currently under construction near Prague in the Czech Republic.

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# Innovations in Radiochemistry



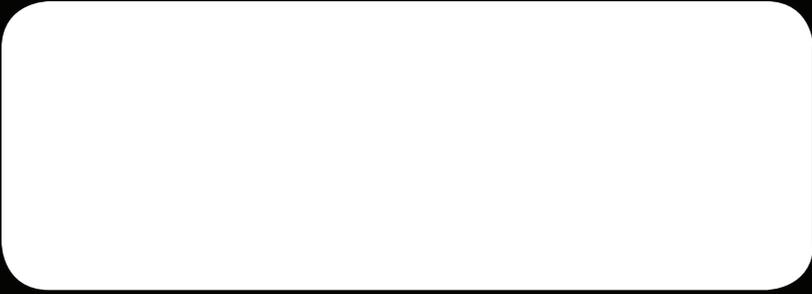
From forensics to fission and beyond, Livermore's nuclear and radiochemistry experts explore an array of scientific and national security challenges.

### *Also in March*

- *A compact and efficient neutron detector promises to strengthen neutron detection for nonproliferation and homeland security.*
- *An investigational platform using human tissue could speed development of medical countermeasures for biosecurity applications and improve drug discovery.*
- *Research on high-burnup fuels for nuclear power plants helps to affirm Livermore as a leader in actinide science.*

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