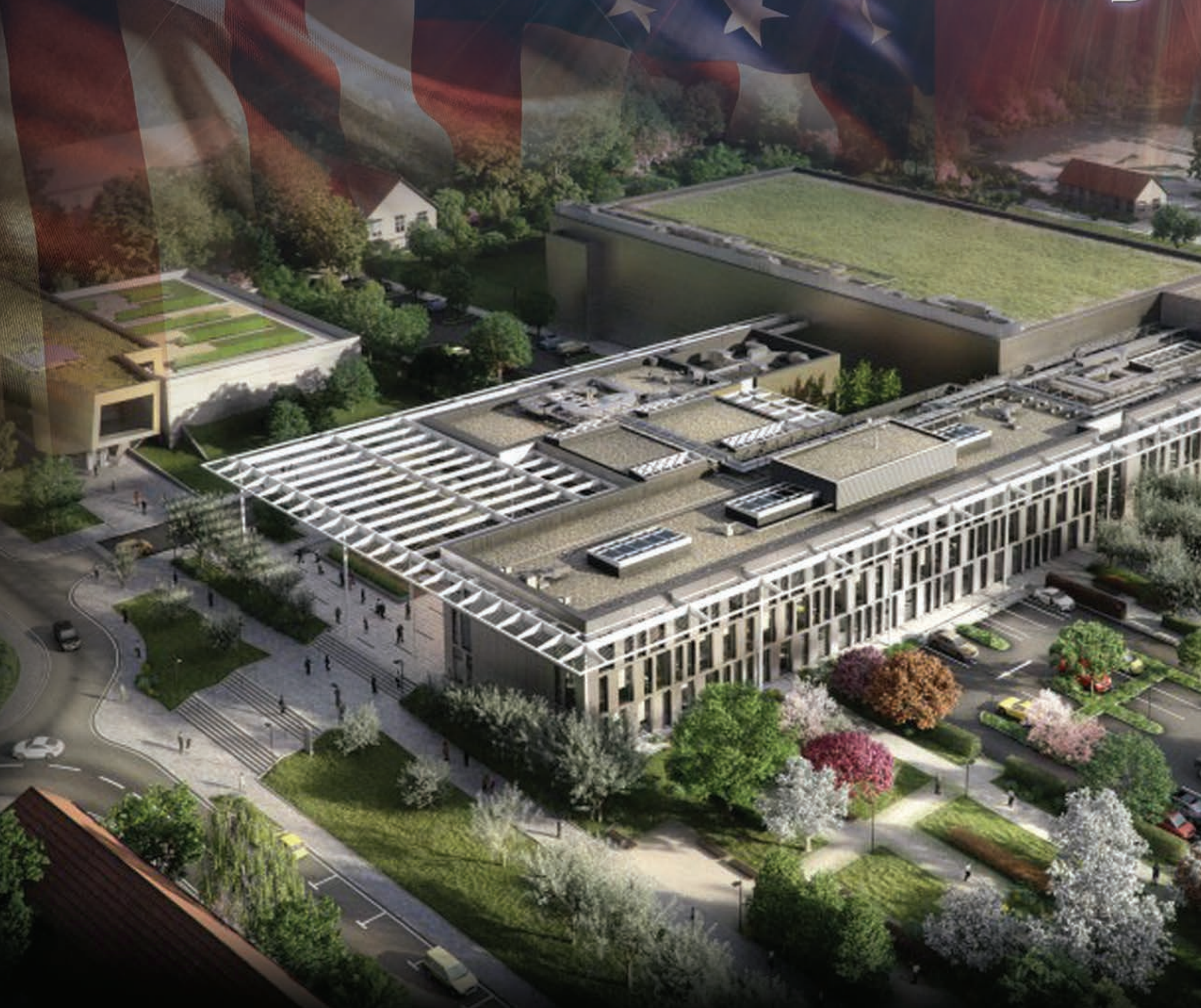
Lighting a New Era of Scientific Discovery



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

SINCE 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 in Dolní Břežany near Prague. ELI Beamlines is one of three laser facilities currently under construction as part of the European ELI project. ELI Attosecond is located in Hungary for the investigation of natural phenomena on ultrashort timescales (into the 10^{-18} seconds regime), while ELI Nuclear Physics is 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. HAPLS could also be used to explore the science of possible future oncology treatments for deep-seated tumors by studying how high-quality beams of protons or ions interact with tissue.

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.

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

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 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

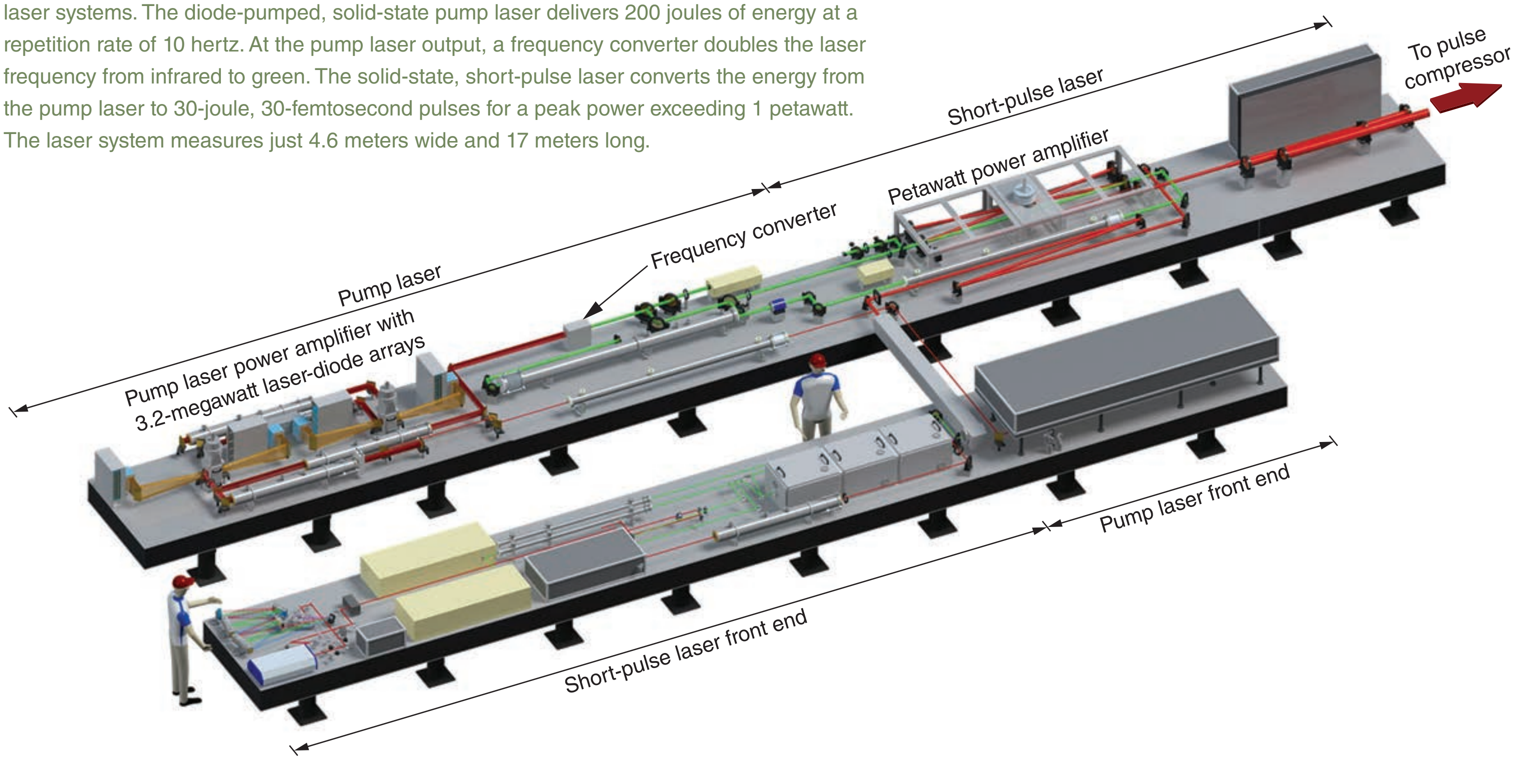
HAPLS will consist of two interconnected Livermore-designed laser systems that, when set up at ELI Beamlines, will require a combined space of about 4.6 by 17 meters, plus 4 square meters for the final laser pulse compressor. The first system—a diode-pumped, solid-state laser—will energize or "pump" 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.)

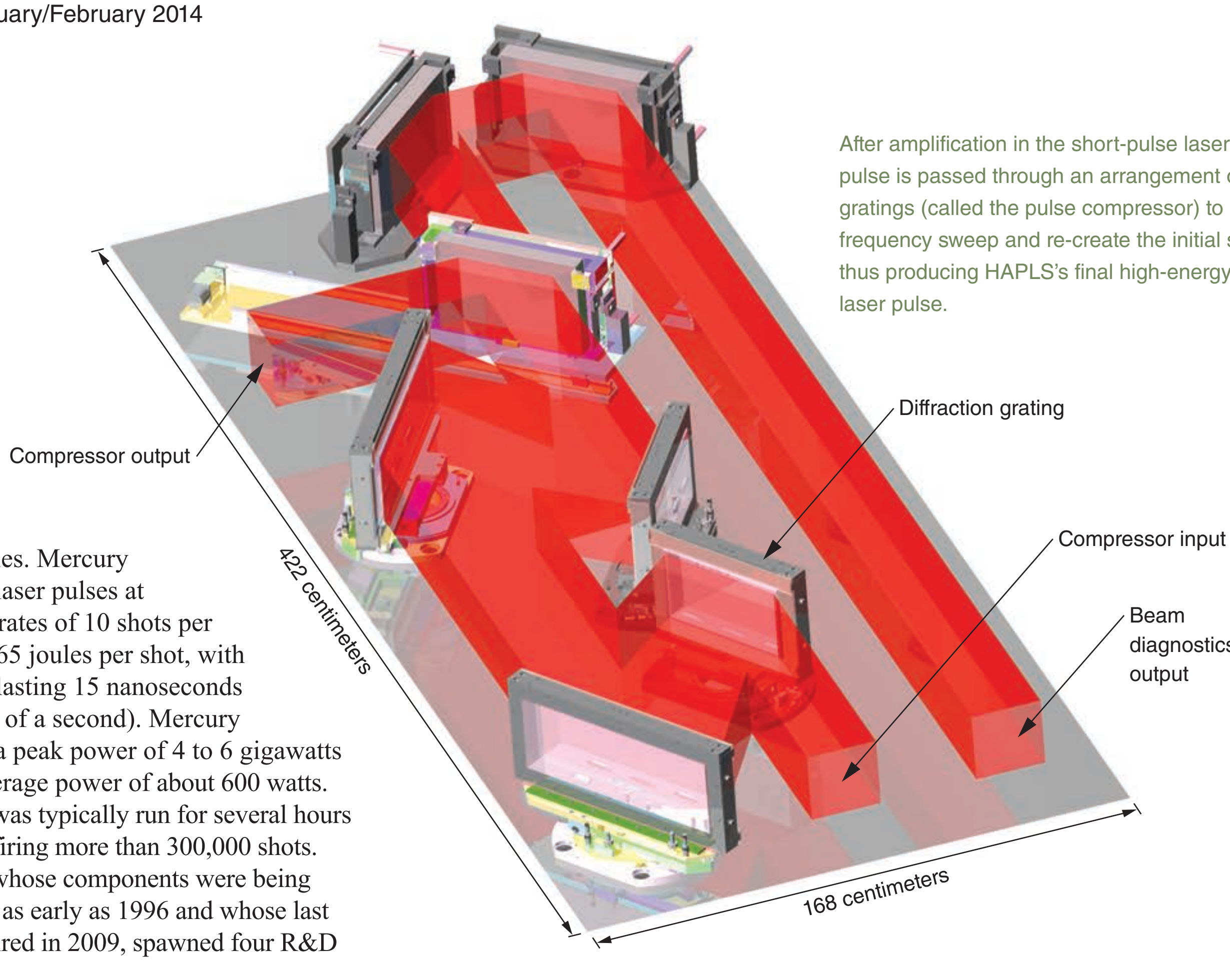
The short-pulse laser will build on Livermore's expertise in chirped-pulse amplification, a common architecture for short-pulse lasers. An ultrashort laser pulse, only picoseconds to femtoseconds (10^{-12} to 10^{-15} seconds) long, is first stretched to reduce its intensity. The pulse's frequency content 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.

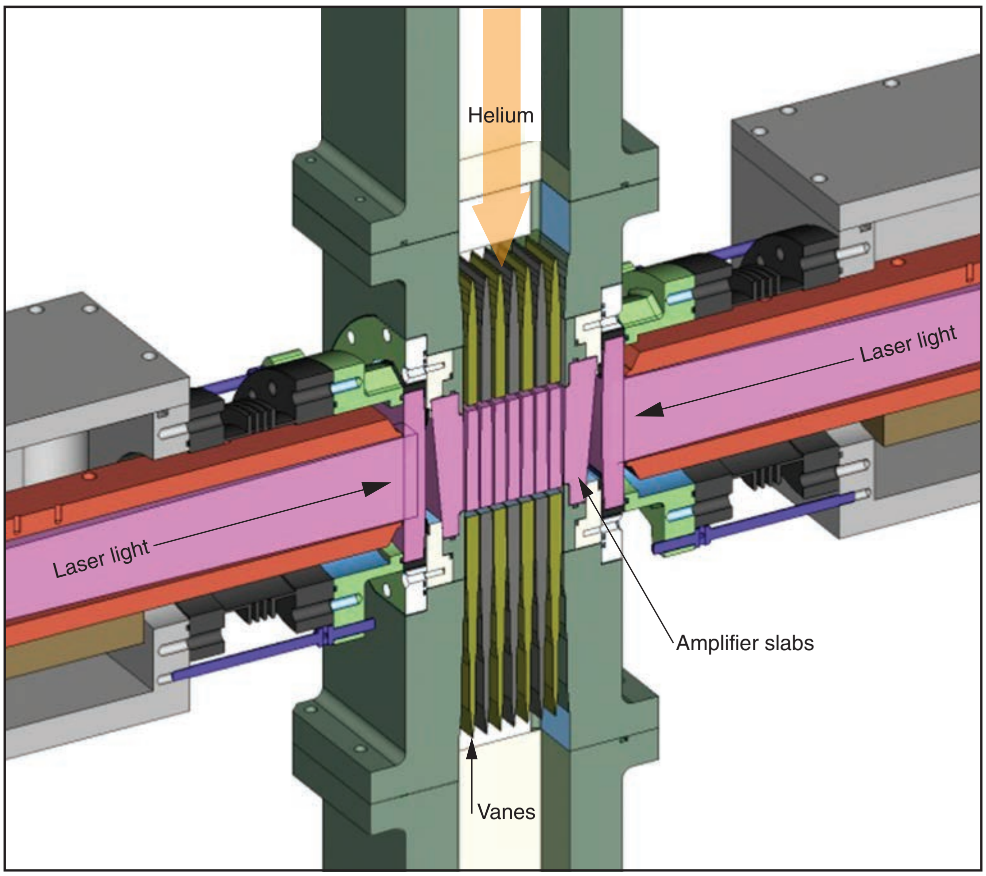
Laser diodes on the pump laser for HAPLS are key to firing 10 times a second for hours at a time. Diode technology was first demonstrated on Mercury (shown above), a high-average-power, solid-state laser system that Livermore researchers built in the late 1990s to develop and demonstrate laser fusion-energy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

Keeping Things Cool

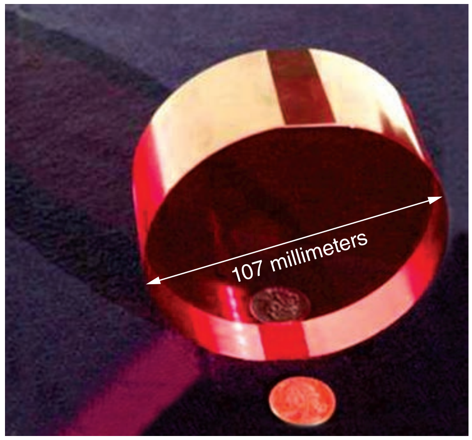
Bayramian, former lead scientist on Mercury, notes that in addition to diodes, HAPLS will incorporate other advances developed on Mercury. For example, a key challenge for high-average-power operations is preventing damage to optical components. To that end, Livermore scientists have developed several 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.

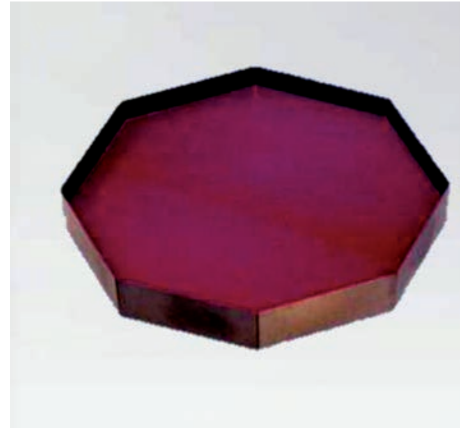
The cooling process requires removing heat from the face of the glass in the same direction that the laser beam propagates. Normally, heat removal drives thermal gradients, which can induce wavefront aberrations on the beam. With the Livermore method, all portions of the laser beam travel through the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

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