Advanced Laser Promises EXCITING Applications

The extremely powerful High-Repetition-Rate Advanced Petawatt Laser System (HAPLS) is poised to be an important tool for scientific research.

Inside the European Union's Extreme Light Infrastructure (ELI) Beamlines facility in the Czech Republic, Livermore's High-Repetition-Rate Advanced Petawatt Laser System (HAPLS) will be available to the scientific user community for a broad range of research.

IN 1996, Lawrence Livermore scientists ushered in an age of new laser technology with the Nova Petawatt, the first system to generate a peak power greater than 10^{15} (1 quadrillion) watts. Livermore scientists quickly discovered they could use the machine to create a source of radiation and subatomic particles, such as high-energy x rays, gamma rays, electrons, and proton beams, for experiments that were the first of their kind.

Twenty years later, Livermore researchers set a world record for average-power lasers and delivered a system to the European community capable of firing petawatt pulses 10 times per second (10 hertz). The High-Repetition-Rate Advanced Petawatt Laser System (HAPLS) is a major advancement over current petawatt lasers, which cannot fire more often than once per second. (See *S&TR*, January/February 2014, pp. 4–11.) "The high repetition rate of the HAPLS system is a watershed moment for the research community," says Constantin Haefner, HAPLS project manager and the program director for Advanced Photon Technologies in Livermore's National Ignition Facility (NIF) and Photon Science Principal Directorate. "HAPLS is the first petawatt laser to provide application-enabling repetition rates."

HAPLS's pulses are designed to be of such intensity (up to 10^{23} watts per square centimeter) that laser–matter interactions can generate intense beams of radiation and subatomic particles. These laser-driven secondary energy sources are compact and versatile and, together with a high repetition rate, will enable many applications in physics, materials science, medicine, biology, and industry. (See the box on p. 11.) In addition, the technology will contribute to the Department of Energy's research portfolio and its National Nuclear Security Administration's (NNSA's) Stockpile Stewardship Program.

Haefner explains that while scientists are currently performing experiments with powerful single-shot lasers, the possibility of repeating experiments 10 times per

second—and for hours at a time—is unprecedented. "What the research community needs is reliable laser drivers that deliver the same precise performance pulse after pulse with high photon flux," says Haefner. Proof-of-principle experiments with single-shot lasers have provided a glimpse into new applications, but a high-repetition-rate petawatt laser with high pulse-to-pulse stability and minimal required maintenance is needed to explore these promising research areas and make possible transformative scientific discoveries.

Physicist Andy Bayramian, HAPLS systems architect, points out that researchers using single-shot systems must select experiments with anticipated high signal-to-noise ratios, since each shot is unique and the characteristics of the laser vary from one shot to another. In contrast, HAPLS is designed to repeat an experiment 10 times per second in a steady state mode and is automated to provide closed-loop stability. As a result, researchers can detect subtle reactions in a timely fashion that are typically overshadowed by other physics.

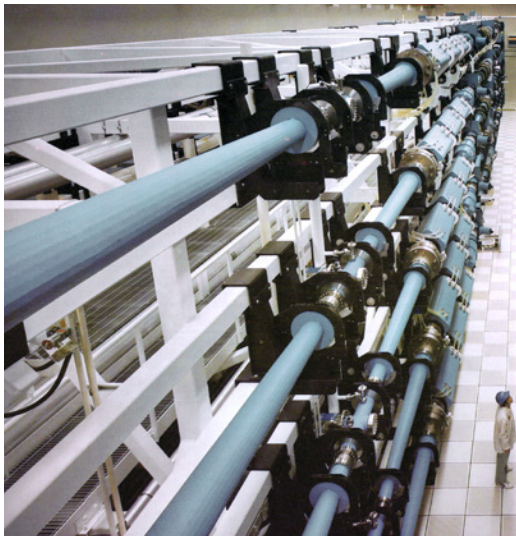
In 1996, Lawrence Livermore's Nova Petawatt became the world's first laser to generate a peak power greater than 10^{15} (1 quadrillion) watts.

Bayramian says, "HAPLS enables a truly exciting new regime in science and technology exploration."

A Record-Breaking Achievement

In 2013, the European Union's Extreme Light Infrastructure (ELI) Beamlines facility contracted with Lawrence Livermore National Security (LLNS), LLC, which manages the Laboratory for NNSA, to deliver a petawatt laser with performance far exceeding current lasers. The system had to be capable of firing at 10 hertz with each pulse delivering 30 joules of energy in less than 30 femtoseconds (quadrillionths of a second) for a peak power of 1 petawatt per shot. The system also had to have low power consumption. For comparison, a modern-day flashlamp-pumped laser system with similar specifications to HAPLS running at 10 hertz would draw 2.2 megawatts of electrical power. HAPLS consumes less than 130 kilowatts.

A team of researchers from Lawrence Livermore and the ELI Beamlines facility was at the Laboratory to mark HAPLS's milestone achievement. Researchers included (front left) Bedřich Rus from ELI Beamlines and (front right) Livermore's Constantin Haefner. (Photo by Jason Laurea.)



Conceptual work on HAPLS began in the fall of 2013. By 2016, an enterprising band of Lawrence Livermore physicists, engineers, materials scientists, and technicians, along with their visiting European colleagues, completed construction and final testing of HAPLS in a laboratory at Livermore. "HAPLS was a very fast-paced project," says Haefner. "In three years, we went from concept to a fully integrated and record-breaking system with unprecedented capabilities. During that time, we pushed the cutting edge in high-average-power petawatt lasers more than tenfold."

On November 29, 2016, HAPLS reached its first commissioning milestone and had set a world record for diode-pumped petawatt lasers, achieving 16 joules of energy and a 28-femtosecond pulse duration (equivalent to about 0.4 petawatts per pulse after compression) at a repetition rate of 3.3 hertz. The system was operated for more than 1 hour. An independent international committee reviewed the results and confirmed the record-setting performance. The test showed that the HAPLS design is sound and that the system can eventually be ramped to 10 hertz once installed at ELI Beamlines.

Following the historic test, Lawrence Livermore Director William Goldstein

said, "The Laboratory takes pride in pushing science and technology to new regimes." Goldstein noted that the Nova Petawatt was the first laser to achieve a peak intensity exceeding 10^{21} watts per centimeter (compared to HAPLS's expected intensity of 10^{23} watts per square centimeter). HAPLS's potential repetition rate is also substantially greater than the Nova Petawatt, which could fire only once every few hours.

HAPLS was disassembled in early 2017 and delivered in late June to the ELI Beamlines facility in Dolní Břežany near Prague in the Czech Republic. The laser will be integrated into the facility's laser beam transport and control systems. Both Livermore and ELI personnel will oversee ramping of the laser to design specifications. ELI Beamlines plans to make HAPLS available in late 2018 to the international scientific user community.

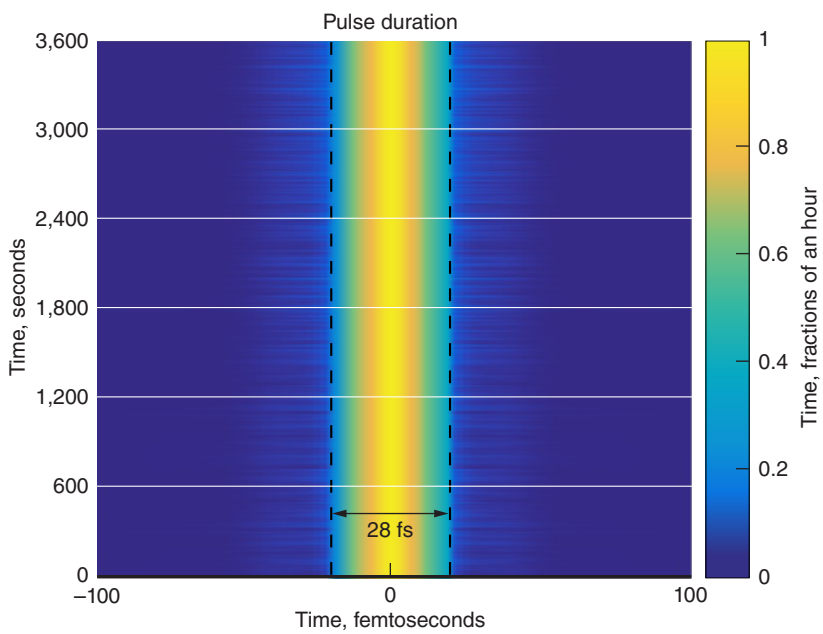
Showcase of Livermore Technology

HAPLS embraces a host of groundbreaking methods and technologies developed largely at Livermore, including arrays of laser diodes that replace less efficient and bulky flashlamps; advanced gratings for compressing high-peak-power and high-average-power laser light without damaging optics; automated control systems to continuously monitor components, minimizing the need for human intervention; and advanced optics and optical coatings. The system also uses a Livermore-developed helium-gas cooling method for laser amplifier components. Together, these advances contributed to making HAPLS the most compact petawatt laser ever built.

During HAPLS's development, Livermore personnel worked closely with industry to advance the state of the art. Several innovations driven by HAPLS's subsystem technology, including advanced laser diodes as well as industrial pump lasers and optical coatings, are already on the market. Roman Hvězda, the ELI Beamlines project manager, said, "Given the design requirements, nobody else could deliver this system in such a short time on schedule and on budget." He added that the venture with Lawrence Livermore "will be a basis for continued cooperation in the future."

Development of HAPLS's major systems was organized into several phases that were set forth in the ELI Beamlines–LLNS agreement. Performance milestones mimicked technical progress in research and development, integration, and commissioning, which provided ELI Beamlines with the confidence that the project was on track. The intermediate performance level, achieved in November, demonstrated that HAPLS's systems worked together and that the laser will meet its final design performance once installed at ELI Beamlines.

Chief mechanical engineer Dan Mason was responsible for delivery of laser hardware. "HAPLS required vast amounts of custom hardware that needed to be designed, fabricated, and assembled," he says. Engineers also conducted a great deal of thermomechanical analysis to ensure components and systems would not be unduly stressed. According to Mason, working on a first-of-a-kind laser typically



The exceptional stability of the diode-pumped HAPLS system is reflected in the measurement of the pulse duration. In one test, HAPLS fired 3.3 times per second for more than an hour, with the laser pulses (more than 12,000 total) showing remarkable uniformity. The average pulse duration was 28 femtoseconds (fs), well below the 40-femtosecond requirement. Colors depict the temporal pulse shape for all 12,000 pulses, with yellow and blue representing the highest and lowest peak power, respectively.

requires a laser technology development program, which leads to production of a prototype followed by additional testing. "For HAPLS, we had little prototyping. The schedule was extremely aggressive. We had to identify technology risks as early as possible and conduct thorough analyses up front to ensure success. We could not let the system fail in the integrated testing phase and have to start all over again."

> "HAPLS is the first petawatt laser to provide application-enabling repetition rates."

Working alongside ELI Researchers

In all, about 100 Livermore engineers, physicists, and technicians collaborated on HAPLS. Livermore laser physicists and engineers worked closely to design the system architecture and assemble it into an integrated system. Individual subsystems were developed and assembled by mechanical, electronic, optical, and control systems engineers. Approximately 10 scientists from ELI Beamlines and the Czech Academy of Sciences traveled to Livermore to train and collaboratively commission and operate this new complex machine.

"From the beginning, this collaboration provided hands-on training and expertise, helping to ensure operational success once the laser is installed at ELI Beamlines," said Bedřich Rus, scientific coordinator for laser technology at ELI Beamlines. "We never had a standard client–supplier relationship," he said. "It has been a great experience for our researchers and has supported their careers and professional development."

Bayramian observes, "Our Czech colleagues, mainly young scientists and technicians, saw how Laboratory personnel attacked problems and managed technical risk. They were introduced to our operations and safety culture and were attentive, inquisitive, and hardworking." Jeff Horner, HAPLS chief engineer and project manager for the system's installation at ELI Beamlines, remarks, "We trained ELI staff how to run high-average-power lasers. They were well educated in laser physics, but they had limited hands-on experience." Haefner comments, "Technology transfer does not happen through sharing of manuals, but through sharing of minds."

Laser Features Advanced Diodes

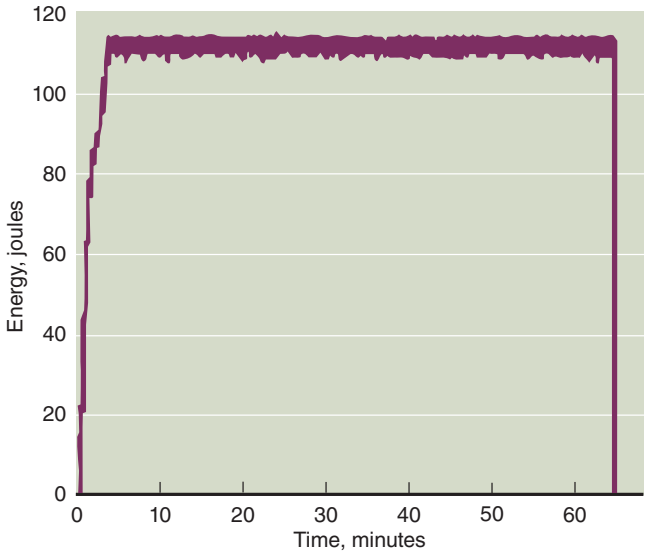
HAPLS consists of two interconnected Livermore-designed laser systems that require a combined space of about 4.6-by-17 meters, plus a 4-square-meter footprint for the laser pulse compressor. Horner says, "One of the great things about HAPLS is its compact design. Laser systems of much less capability exist that are several times larger." One of the keys to the compact size is Livermore inventions in beam transport and amplifier gain balancing.

The first system—a diode-pumped, solid-state pump laser—energizes the second system—a short-pulse laser. The pump laser is designed to deliver 200 joules of energy at a repetition rate of 10 hertz for an average power of 2 kilowatts. The pump laser incorporates many examples of Livermore intellectual property.

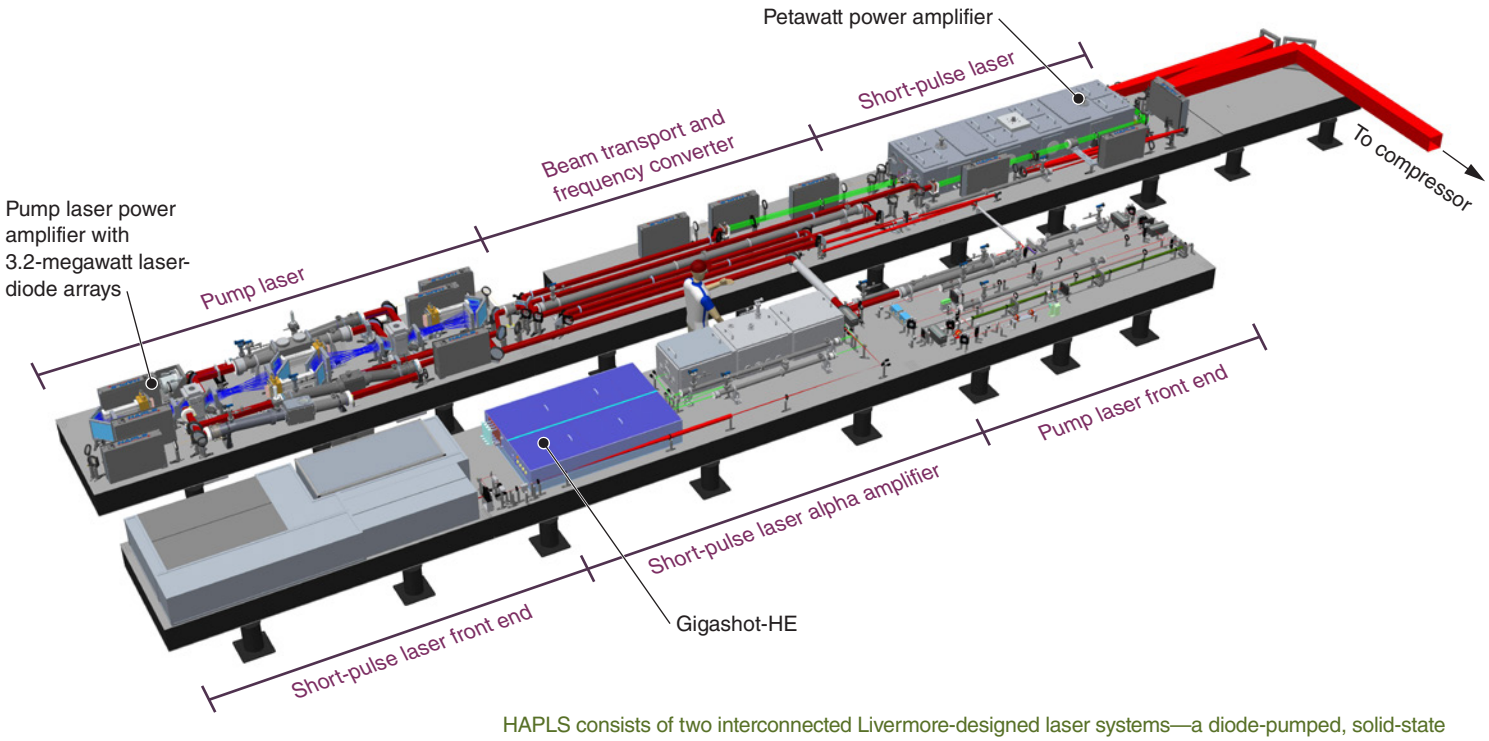
The pump laser's amplifier uses two amplifier heads containing many neodymium-doped glass slabs, similar to those used at NIF but much smaller. Helium gas streams through the gaps between the amplifier slabs at almost ultrasonic velocities to remove heat inherently deposited in the gain material as part of the pumping and lasing process. The gas is invisible to the laser beam because of helium's low refractive index, which is close to that of a vacuum. Helium-gas cooling was invented by Livermore scientists George Albrecht and Steve Sutton in the 1980s. This method is an established one for heat removal in Livermore's high-energy, high-average-power laser systems and has been adopted by other groups as well. Gas cooling allows HAPLS to run continuously, firing 36,000 times per hour with high repeatability and stability.

Current petawatt laser systems barely operate at 1 hertz because they use flashlamps to energize their amplifiers. "We are at the limits of flashlamp technology," says Bayramian. "Laser-diode arrays enable a far more capable class of high-energy laser systems." At the output end of the pump laser, a frequency converter doubles the pump laser frequency from infrared to green to match the absorption band of the short-pulse laser.

Essential to HAPLS's remarkable repetition rate are the highest peak-power



The pump laser that energizes the short-pulse amplifier delivers pulses with energy greater than 100 joules and an energy stability of 0.7 percent. As shown in this graph, during a test, the pump laser was ramped in energy to approximately 100 joules in less than 5 minutes and then operated for 1 hour.



HAPLS consists of two interconnected Livermore-designed laser systems—a diode-pumped, solid-state pump laser and a short-pulse laser. At the pump laser output, a frequency converter doubles the laser energy from infrared to green. The short-pulse laser features custom Livermore alpha and beta amplifiers. The Gigashot-HE laser is used as a pump source for the alpha amplifier and delivers 2 joules of green laser energy per pulse at a repetition rate of 10 hertz. The entire laser system measures just 4.6-by-17 meters, plus a 4-square-meter footprint for the laser pulse compressor. (Rendering by Paul Bloom.)

laser-diode arrays in the world. Diode technology was first demonstrated on Mercury, a high-average-power laser built by Livermore researchers in the late 1990s. For HAPLS, the team partnered with Lasertel, Inc., of Tucson, Arizona, to develop advanced arrays of laser diodes with an emitting area of 5.6-by-13.8 centimeters and that produce a peak power of 800 kilowatts each. Diodes are approximately 20 times more efficient than conventional flashlamps, consuming less electricity and generating less heat in the laser.

The Livermore–Lasertel team combined advanced laser diodes and a Livermore-designed pulsed-power system to produce the High-Power Intelligent Laser Diode System (HILADS). This system delivers two-to-threefold improvements in peak output power and intensity over flashlamp technology in a 10-times-smaller footprint. Four HILADS devices were integrated into the HAPLS pump laser. The four devices together contain more than 400,000 diodes, the largest number ever assembled, and produce a combined 3.2 megawatts of diode power. Extensive testing indicates that the HILADS lifetime will exceed 2 billion pulses. The HILADS development team won an R&D 100 Award in 2015. (See *S&TR*, January/February 2016, pp. 16–17).

"Combining Lasertel's diode technology with Livermore's highly compact and efficient pulsed-power system is the enabling technology to drive high-energy lasers at faster repetition rates," says Haefner. "Our collaboration has allowed several new benchmarks for laser performance to be set in a remarkably short period of time," says Lasertel President Mark McElhinney.

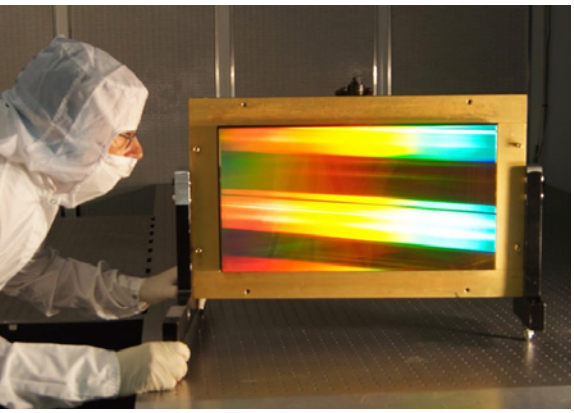
A Delicate Process

HAPLS's short-pulse laser converts the energy from the pump laser to 30-joule, 30-femtosecond pulses of 820-nanometer laser light with a peak power exceeding 1 petawatt. This laser uses titanium-doped sapphire (Ti:sapphire) as its amplification medium. For short-pulse laser systems, Ti:sapphire is a popular gain material because of its high optical quality, large bandwidth, and large crystal size (up to 20 centimeters in diameter). The 200-terawatt Callisto laser designed by Livermore scientists in the 1990s was used to generate intense beams of protons and is considered the grandfather of Ti:sapphire disk lasers. Although Ti:sapphire has a high thermal conductivity, it suffers from a large quantum defect, converting almost half of the pump power into heat. Thus, it also requires gas-cooling of the amplifier faces, similar to the method used in the pump laser. Mason says specially prepared slabs of Ti:sapphire for HAPLS's short-pulse power amplifier required more than two years to produce, including growing the boule (the initial crystal ingot), followed by months of machining, shaping, edge-cladding, and applying antireflection coatings. The slabs were then integrated into the gas-cooled

amplifier package for installation. "From start to finish, the process was an extremely delicate one," says Mason. "We had only one chance to get it right."

The short-pulse laser features two custom Livermore amplifiers, an alpha and a beta. The Gigashot-HE, a diode-pumped solid-state laser developed for HAPLS by Northrop Grumman Cutting Edge Optronics, is used as a pump source for the alpha laser. The Gigashot-HE laser delivers 2 joules of 532-nanometer (green) laser energy per pulse at a repetition rate of 10 hertz, with each pulse lasting less than 10 billionths of a second.

The short-pulse laser incorporates chirped-pulse amplification, a process pioneered at the University of Rochester in the mid-1980s. This technique first stretches a short pulse of light in time from femtoseconds to nanoseconds (10^{-15} to 10^{-9} seconds) by passing it through an optical device using finely etched diffraction gratings, thereby applying a frequency chirp. This "stretcher" converts the pulse into a lower intensity, nanosecond-long pulse in which shorter wavelengths lag behind longer wavelengths. "Without chirped-pulse amplification, the laser beam would very quickly destroy the short-pulse laser optics during this stage," says physicist David Alessi. Following amplification up to 10 billion times higher energy, the pulse is compressed in time by two pairs of diffraction gratings (the compressor), in which shorter wavelengths catch up with the longer wavelengths to achieve a cohesive, short-duration, high-peak-power pulse that can be focused at ultrahigh intensities onto a target. The Livermore-designed gratings for both the stretcher and compressor were manufactured in-house by physicists Hoang Nguyen and Jerry Britten. The gratings feature hundreds of kilometers of precisely inscribed gold-coated lines that measure less than a micrometer wide and feature a new design that enables these gratings to be operated at high-average power.



HAPLS's short-pulse laser incorporates chirped-pulse amplification, a process pioneered at the University of Rochester in the mid-1980s. This technique stretches a short pulse of light in time by passing it through a "stretcher" using finely etched diffraction gratings (shown here). The stretcher converts the pulse into a lower-intensity, longer pulse. Following amplification, two pairs of diffraction gratings are used to compress the pulse in time.

Control System Keeps Watchful Eye

HAPLS also features an automated, integrated control system such as the one operating at NIF. The control system features multiple ultrafast diagnostics that continuously monitor the health of the laser. "Each shot gives permission to the succeeding shot," explains Daniel Smith, a controls engineer for HAPLS. The sophisticated control system has a high level of automation including an auto-alignment capability and immediately stops the laser if any component is out of specification. Front-end processors are tied to 85 cameras, 24 motors, and numerous diagnostic instruments. The system's high level of automation is largely responsible for allowing the laser to be operated by as few as two people, meeting an operational requirement.

In addition, adaptive optics help produce a high-quality beam a few micrometers in diameter, which when focused on a target will eventually enable HAPLS to generate intensities of 10^{23} watts per centimeter. These optics correct for distortions in the laser beam, providing experimenters with the highest quality laser beam profile.

Samuel Buck from ELI Beamlines and Livermore's Shawn Betts monitor HAPLS's system function and performance during operations. HAPLS's high level of automation allows the laser to be run by as few as two people, which meets an operational requirement. (Photo by Jason Laurea.)

Pushing the Boundaries

"It has been an incredible experience pushing the boundaries of laser technology," says physicist Tom Spinka, commissioning manager of HAPLS's short-pulse laser. "The brief time from conceptual design to commissioned hardware was remarkable." Horner cites the support provided by groups throughout NIF and Livermore's Engineering Directorate, such as optics fabrication experts, who helped make HAPLS a reality.

"An incredibly committed team, working long days and weekends, pushed the state of the art by 10 times," says Haefner. "People were inspired by the idea and the technology. Every milestone was completed on schedule, on budget, and within specification. We started with an empty room and ended with a world-record product."

For the Laboratory, the HAPLS project provided several opportunities, including the ability to participate in an international effort to deliver a cutting-edge laser for a flagship research facility. "This project allowed us to advance Livemore knowledge and expertise and push the frontiers of science and technology," says

A New World of Applications at ELI Beamlines

The Livermore-designed High-Repetition-Rate Advanced Petawatt Laser System (HAPLS) will be a key component of the European Union's Extreme Light Infrastructure (ELI) Beamlines facility, which was built for the international scientific user community to study laser–matter interactions. Coordinated by the Czech Republic's Institute of Physics, Academy of Sciences, ELI Beamlines is the largest scientific project in that country. Construction of the facility began in October 2012 and was completed in early 2017, although key systems are still being installed. The first experiments are scheduled for late 2018.

Although ELI Beamlines will house at least two other large lasers, HAPLS is expected to be the "workhorse" laser and will be known as the L3 laser system. The facility will include seven experimental chambers located in the basement, including a large experimental chamber dedicated to academic research of laser plasma. Scientists will be able to direct the output from any laser to whichever experimental chamber is needed.

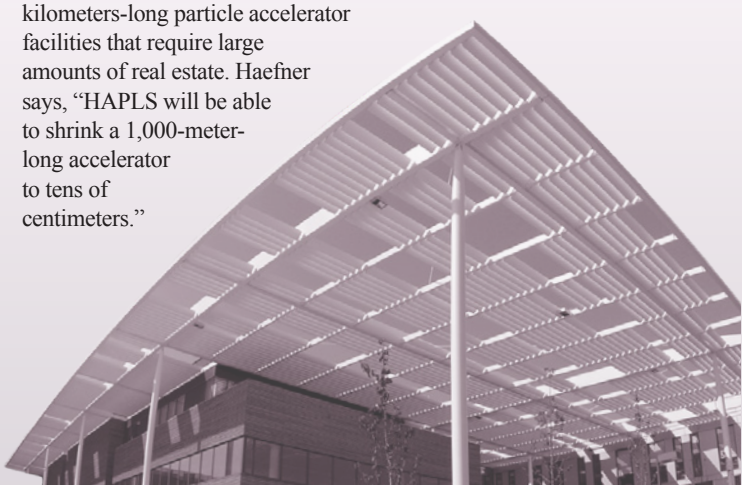
The facility was officially dedicated on October 19, 2016. Patricia Falcone, Lawrence Livermore's Deputy Director for Science and Technology, attended the ceremonies along with Constantin Haefner, HAPLS project manager and program director for Advanced Photon Technologies in Livermore's National Ignition Facility and Photon Science Principal Directorate. "We are excited to be working with our colleagues on realizing new capabilities for lasers and are also looking forward to great scientific results from this wonderful facility," says Falcone.

Other dignitaries described the aim of the facility as attracting the best scientists in the world to perform experiments at the frontier of science to make ELI Beamlines the "CERN of laser research." Bedřich Rus, scientific coordinator for laser technology at ELI Beamlines, noted that several world records already were broken during the development of the project's laser systems, including the world's highest-peak-power laser-diode arrays developed for HAPLS.

HAPLS is expected to drive laser-accelerated sources of electrons with energies of several tens of gigaelectronvolts, as well as protons and ions with energies reaching several megaelectronvolts. Such a capability will make possible new investigations into atomic physics, time-resolved proton and x-ray radiography, nuclear physics, high-energy-density physics, plasma physics, chemistry, biochemistry, and medicine.

As one example, extremely short and bright pulses of x rays are needed for exploring phenomena that take place over very short time and length scales. Streams of extremely bright and short x rays for imaging cells and proteins at unprecedented spatial and temporal resolution will be used to study biochemical reactions and the formation and dissolution of chemical bonds. ELI Beamlines has already established the ELIBIO center, which will exploit some of the world's most powerful photon beams to perform breakthrough studies in life sciences. HAPLS could also be applied to explore treatments for deep-seated tumors using high-quality beams of protons.

Secondary-source applications include advanced imaging and nondestructive evaluation of materials. Other industrial applications include laser peening, nondestructive evaluation of parts and products—for example, to identify defects in aircraft turbine blades—and generating drugs and tracers for medical diagnostics. HAPLS could also force scientists to radically rethink the need for kilometers-long particle accelerator facilities that require large amounts of real estate. Haefner says, "HAPLS will be able to shrink a 1,000-meter-long accelerator to tens of centimeters."



Haefner. Such knowledge can only serve to benefit the Laboratory and its missions.

Haefner is optimistic the project will also help energize U.S. short-pulse and high-average-power laser research efforts. He notes that several nations in Europe and Asia are planning advanced high-repetition-rate lasers such as HAPLS because of their potential to revolutionize fields ranging from medicine to clean energy. He adds that a valuable aspect of HAPLS's design is its scalability.

As Livermore scientists help to integrate the laser system into the ELI Beamlines facility, Haefner and other Laboratory researchers are looking to develop the next generation of HAPLS-type lasers and advance several technologies originally developed for the laser system. Haefner says, "We want to continue to engineer technologies important to U.S. economic competitiveness, national security, and entirely new applications."

—Arnie Heller

Key Words: chirped-pulse amplification; diffraction grating; Extreme Light Infrastructure (ELI) Beamlines facility; flashlamp; Gigashot-HE; High-Power Intelligent Laser Diode System (HILADS); High-Repetition-Rate Advanced Petawatt Laser System (HAPLS); laser diode; Lasertel, Inc.; Lawrence Livermore National Security (LLNS), LLC; Mercury laser; National Ignition Facility (NIF); Nova Petawatt laser; petawatt; titanium-doped sapphire (Ti:sapphire).

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