Imaging Catheter Gives Surgeons the Inside Picture

NOT so long ago, a blocked artery called for major surgery. That meant patients spent many hours under anesthesia, endured large and potentially traumatic incisions, and required months of recovery time.

Today, surgeons are using minimally invasive medical procedures that are less traumatic and more cost-effective. Most of these newer procedures incorporate thin catheters—hollow flexible tubes—that surgeons insert in small incisions in a major artery, such as the femoral artery in the thigh. The surgeon snakes the catheter through the arterial network to the problem area. Millimeter-size tools can then be guided through the tube to fix the medical condition.

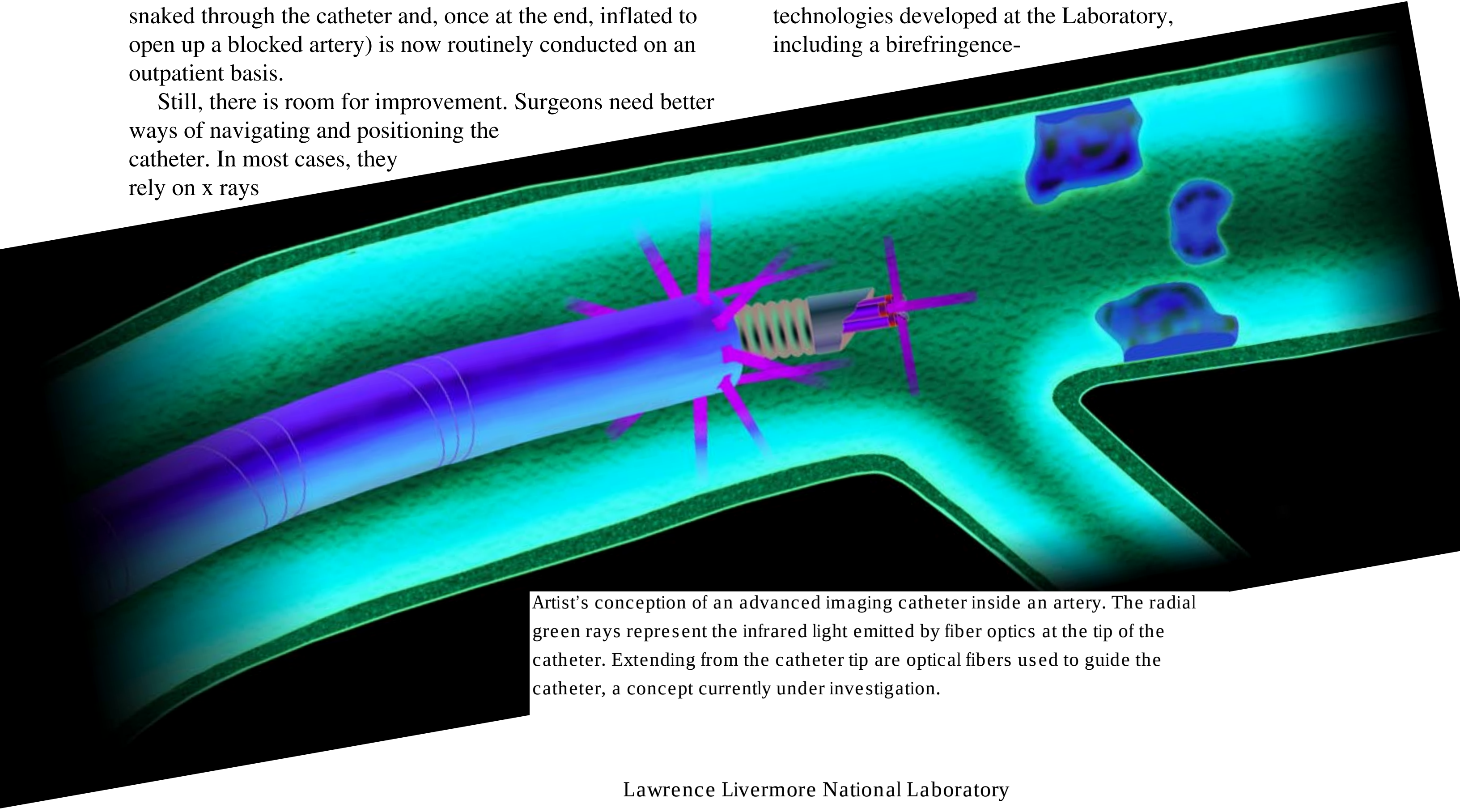
Use of catheter-based procedures is growing rapidly. In the United States alone, over 700,000 of these minimally invasive surgeries are performed annually. A key advantage of this technique is that patients recover in days, not months. For example, balloon angioplasty (in which a small balloon is snaked through the catheter and, once at the end, inflated to open up a blocked artery) is now routinely conducted on an outpatient basis.

Still, there is room for improvement. Surgeons need better ways of navigating and positioning the catheter. In most cases, they rely on x rays to provide a snapshot of the arterial system as they manually push and pull the catheter into position. In addition to this limited view, there's also the problem that the catheters can be 2 meters long and 800 micrometers across, and maneuvering these thin soft tubes of plastic is like pushing on a string.

At Lawrence Livermore, a team of researchers (backed by three directorates—Laser Programs, Engineering, and Defense and Nuclear Technologies—and by the Laboratory Directed Research and Development Program) has developed a prototype catheter that shows promise in meeting these challenges. The advanced imaging catheter, as envisioned by physicist Luiz Da Silva and his team, will have a number of optical fibers embedded in the catheter wall to produce a stream of images—essentially a video—of the surrounding fluid and arterial wall.

3D Brought Inside

The advanced imaging catheter builds on unique technologies developed at the Laboratory, including a birefringence-



Artist's conception of an advanced imaging catheter inside an artery. The radial green rays represent the infrared light emitted by fiber optics at the tip of the catheter. Extending from the catheter tip are optical fibers used to guide the catheter, a concept currently under investigation.

insensitive optical coherence tomography (OCT) system. OCT is a noninvasive, noncontact optical technique that uses infrared light to image through highly scattering media such as blood and the vascular wall. "OCT is similar to ultrasound imaging, but it can achieve significantly higher spatial resolutions and is sensitive to differences in optical rather than acoustic properties of tissue," explains Da Silva.

This same technology lies at the heart of an R&D 100 Award-winning system that images teeth and dental tissue with near-infrared light. (See *S&TR*, October 1998, pp. 10–11, for more information about OCT and the optical dental imaging system.)

The three-dimensional imaging makes it easier for the physician to identify the location of the medical condition in an artery and guide the catheter to it. For instance, the figure at bottom right shows an x-ray image of a cerebral aneurysm. Because an x ray is a two-dimensional image of a three-dimensional structure, its views often leave the surgeon unsure which way to navigate the catheter. Moreover, the amount of chemical dye injected to provide contrast in the x ray must be limited, so the dye is not used continuously and the surgeon at times must work "blind" without even this two-dimensional visual clue.

"I observed an operation where the surgeon refused to proceed because he was uncertain that the catheter was in the correct position," said Da Silva. "Physicians told us that if a compact catheter could produce three-dimensional images and allowed them to actively guide it in the body, these procedures would be quicker, less traumatic, and have a much higher success rate."

Three Areas to Tackle

The team is focusing on three areas of development for this next generation of catheters: the fabrication technology needed to place optical fibers within the thin polymer wall of a catheter, the materials and techniques required for actively controlling the catheter, and radiation transport modeling.

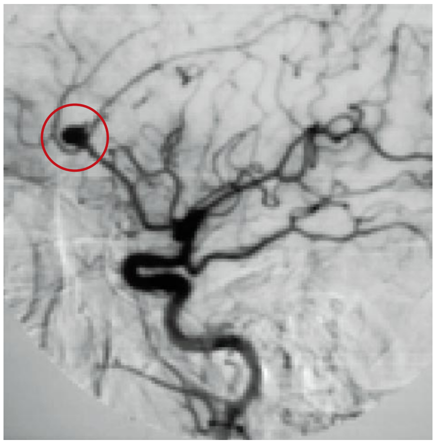
"There are two ways to place optical fibers in the walls of the catheter," says Da Silva. "One way is to embed the optical fibers into existing commercial catheters. A key question regarding this approach is how it would affect the flexibility of the catheter. Another possibility is to extrude the catheter polymer with the optical fibers already embedded in the walls. We're pursuing both possible solutions." Along with a commercial collaborator, the team has developed tubing that can hold 10 optical fibers and is 1.7 millimeters in diameter with a wall 0.2 millimeters thick.

To find a better way of "pushing on a string," the team looked at Laboratory-developed microactuators and so-called smart materials. One possible solution might come from a shaped-memory polymer material being investigated at Livermore that can be activated by optical heating. "By using multiple wavelengths and different polymers," says Da Silva, "it may be possible to actively control and manipulate the tip of the catheter." Alternatively, shaped-memory alloy materials that can be made to move when heated could be placed near the catheter tip. A surgeon could then guide or position the tip by altering the temperature of the shaped-memory alloy, causing the catheter tip to bend. A microrudder scheme has also been proposed, which would steer the catheter tip using blood flow as a means of propulsion.

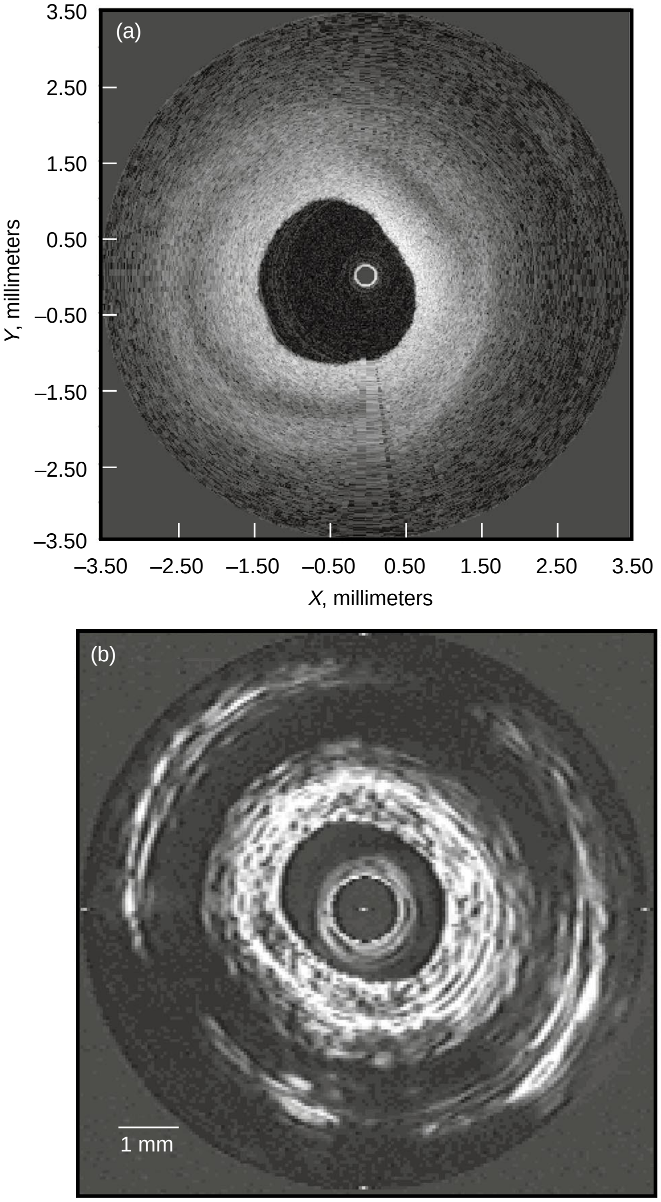
Radiation transport modeling is key to understanding OCT and developing simulation and analytical tools for optimizing the catheter's imaging system. Laboratory researchers recently adapted the Livermore-developed code LATIS (a two-dimensional laser–tissue interaction code) to simulate what occurs when photons from the fiber optics scatter from blood and biological tissue and return to the catheter's collecting lens. (For more information about LATIS, see *S&TR*, March 1999, pp. 23–25.) Besides helping in the design of the final system, the modified LATIS code can help researchers interpret OCT imaging in a variety of applications.

Results Are Promising

The team has manufactured and tested a prototype single-fiber catheter with encouraging results. "The OCT imaging system has an order of magnitude higher resolution than state-of-the-art ultrasound," says Da Silva. The team has also been working on miniaturizing the electronics and has managed to



Two-dimensional angiogram (x ray) showing a cerebral aneurysm (circled). An advanced imaging catheter would provide a perspective from inside the artery in three dimensions.



(a) Images obtained with optical coherence tomography (OCT), a technology developed at the Laboratory, can resolve details as small as 12 micrometers in size, whereas (b) state-of-the-art ultrasound systems can resolve features down to about 150 micrometers in size.

shrink the device from a large (60 by 90 by 90 centimeters) rack-mounted electromechanical device to a box about half a meter on each side—a size much more compatible with operating room conditions.

In the process, the team made significant improvements to the system, increasing its sensitivity by a factor of 30. It can now penetrate through 2 to 3 millimeters of biological tissue such as arteries.

The team sees other possible uses for the catheter as well. For instance, it could be used to examine the structures of composite materials and to search for signs of delamination in plastic explosives. The team is also evaluating whether the imaging catheter might be used to characterize wall- and ice-layer thickness in laser targets for the National Ignition Facility.

"The other challenge we must keep in mind, if our imaging catheter is to become a commercial reality, is cost." continues Da Silva. "The added cost of the device needs to be reasonable. Right now, we're looking at adding $10 or less to catheters that normally cost between $500 and $1,000. We're talking with the National Institutes of Health, industry, and physicians as we continue our development. Everyone's interested and sees cost-effectiveness as an important step toward the next-generation catheter."

—Ann Parker

Key Words: advanced imaging catheter, LATIS, medical technology, optical coherence tomography (OCT), radiation transport modeling.

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JanUSP Opens New World of Physics Research

A legacy from the Livermore lasers program of the 1970s is helping Laboratory researchers achieve the world's brightest laser, thereby making possible a new world of plasma physics experiments. In a project funded under the Laboratory Directed Research and Development Program, the Janus laser, a milestone in the Laboratory's development of glass lasers, has been incorporated in JanUSP (for Janus-pumped, ultrashort-pulse laser). This new instrument recently produced the highest irradiance (power per unit area) ever recorded: two sextillion (2×10^{21}) watts per square centimeter.

Achieving this long-sought level of brightness is a requirement for exploring plasmas present only in the interiors of stars and detonating nuclear devices. The characteristics of such extreme plasmas include electric fields 100 times stronger than those binding electrons to atomic nuclei, magnetic fields like those found on the surface of white dwarf stars, electron oscillatory ("quiver") energies similar to gamma-ray bursts, and pressures one trillion times that of Earth's atmosphere at sea level.

JanUSP is a significant upgrade to Lawrence Livermore's longstanding ultrashort-pulse laser facility. Research on ultrashort-pulse lasers (with pulse lengths lasting from a billionth to a trillionth of a second) has been the focus of intense activity at Livermore since the mid-1980s. The work arrived at a major milestone in the late 1990s when the Laboratory's Petawatt laser achieved record-breaking levels of power (more than a quadrillion, or 10^{15}, watts) and irradiance (approaching a sextillion, or 10^{21}, watts per square centimeter) at full energy of about 680 joules before it was shut down (see *S&TR*, March 2000, pp. 4–12).

At 200 terawatts (2×10^{14} watts) and 15 joules, JanUSP has a fraction of the power and energy, respectively, of the Petawatt. However, with its shorter pulse length (85 femtoseconds, less than a tenth of a trillionth of a second) and smaller spot size (2 micrometers), it can access much different regimes of matter.

The machine's front end is a commercial oscillator that produces 75- to 80-femtosecond pulses of 800-nanometer light. The low-energy laser pulses are passed through diffraction gratings, made by Livermore's Diffractive Optics Group. The gratings drastically stretch pulses out in time so that they do not distort and eventually damage the laser optics.

Laser Beam with Push

The stretched pulses are energized by a series of amplifiers using increasingly larger titanium-doped sapphire crystals. The final amplification stage features a 10-centimeter-diameter, 5-centimeter-thick, titanium-doped sapphire crystal, the largest in the world and one that required three years to be produced commercially. Energizing this crystal is 130-joule green light from the Janus laser. The fully amplified light is recompressed to its original duration and focused onto a target inside a 2-meter-diameter chamber.

"We want to use JanUSP to explore the uncharted regime of matter subjected to irradiance above 10^{21} watts per square centimeter," says physicist Paul Springer. To meet that goal requires heating a relatively thick (several micrometers) sample of metal extremely fast, and researchers are tapping the enormous pressure of JanUSP's laser light to do so. Physicist Jacques Denavit first proposed the technique of using light to literally push ions from an aluminum or gold foil some 500 nanometers thick onto a target of uranium or other dense metal. "We don't typically think of light as having a noticeable pressure, but JanUSP's laser beam is so intense that it can generate hundreds of petapascals of pressure at the surface of a target," observes physicist Scott Wilks, who has been using the two-dimensional Zohar computer code (written by physicist A. Bruce Langdon) to model JanUSP–plasma interactions.

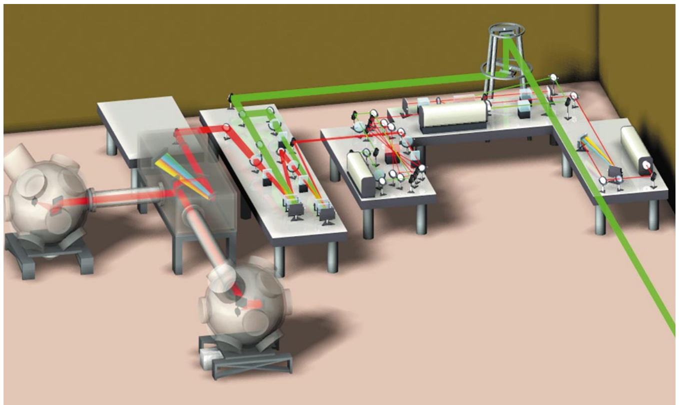
If all goes according to plan, later this summer a laser pulse from JanUSP will literally push electrons forward and out of the foil in less than a trillionth of a second. The negatively charged electrons, in turn, will drag positively charged protons and uncharged neutrons with them. The heavy ions, traveling at 8,000 kilometers per second (about 3 percent of the speed of light), will be deposited onto a target made of a heavy metal such as uranium.

In less than a billionth of a second, the impinging ions will travel 5 to 10 micrometers into the target, rapidly creating a superhot plasma of 1,000 volts (about 10 million kelvins). The ions, with about 1,800 times the mass of electrons, are much slower and therefore travel only one-thousandth the distance. As a result, the plasma they create will be confined to a thickness of several micrometers. The plasma will be in thermal equilibrium, meaning that all ions and electrons will radiate at the same temperature. "It's the same kind of plasma that is found at the center of a star or an exploding nuclear device," Springer says. In those cases, thermonuclear energy is transferred through ions, not electrons.

Heating Matter with Ions

Springer notes that although lasers have been used for years to create plasmas from solid targets, the interactions have been with targets' electrons, not their neutrons and protons. "Lasers with prepulse—the less intense, first part of a pulse—couple their energy to hot electrons, which heat up materials to lower temperatures than what we want," says Springer. "Heating with ions is a better way to create the high-energy-density plasmas we're looking for."

Typical laser pulses have what's known as a pedestal, or a slow rise time before the pulse achieves its full intensity. As a result, the prepulse boils electrons off the target's surface. This initial impact creates relatively low-density plasma that interacts with the main pulse, which arrives an instant later. The key to creating plasmas with ions is making the pulse rise time extremely fast. "You don't want the target to know the laser is there until the main pulse arrives," explains Wilks. "The main pulse can then couple its energy directly to the ions and not into the electrons."



JanUSP's front end produces 75- to 80-femtosecond pulses of 800-nanometer light. The low-energy pulses are passed through diffraction gratings that drastically stretch them out in time. The stretched pulses are energized by amplifiers using increasingly larger titanium-doped sapphire crystals, including the largest in the world. Energizing the final crystal is laser light supplied by Janus, built in the late 1970s. The fully amplified pulses are recompressed and focused onto a target inside a 2-meter-diameter chamber.

The Petawatt laser achieved its record power level with a much longer pulse length (440 femtoseconds) and a much larger aperture (57 centimeters). As a result, its prepulse was a million times larger than the one Livermore scientists hope to see with JanUSP. Indeed, the goal for the so-called pulse contrast (ratio between the main pulse and prepulse) is an unprecedented 10 billion.

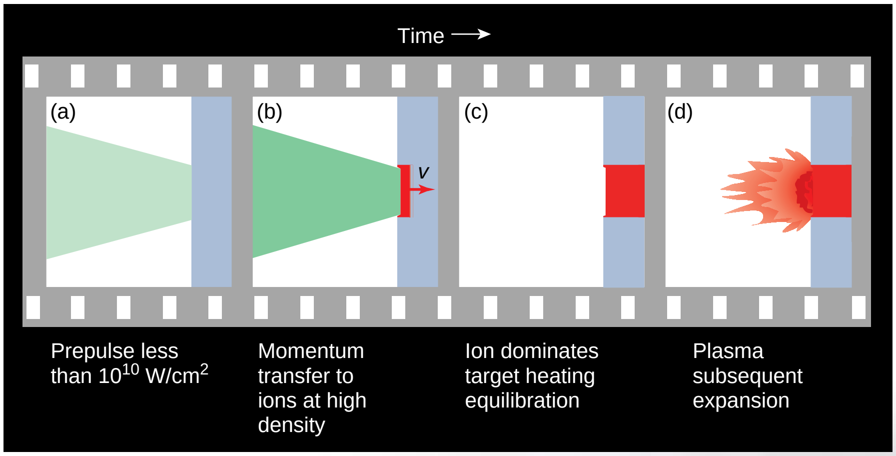
Alternatives for creating extreme states of plasma with ions don't exist. Gas guns are too slow by a factor of 1,000. Much more energetic lasers like the National Ignition Facility (now under construction at Lawrence Livermore) heat vastly more mass, but they were not designed to achieve the temperatures of JanUSP. And typical ultrashort-pulse lasers don't have the light intensity or pulse contrast necessary to couple energy to ions.

Springer also notes that the rapid time scales involved in JanUSP experiments are driving improvements in diagnostics for measuring the fleeting plasmas. The JanUSP team has improved upon the x-ray streak camera that was successfully used on Lawrence Livermore's Nova laser, which was decommissioned last year. The new camera achieves 50 times greater resolution than its predecessor. The techniques used to improve Nova's diagnostics can also be applied to those being built for the National Ignition Facility, Springer says.

New Plasma Regimes to Help Stockpile Stewards

JanUSP's high-temperature, high-density plasmas will shed new light on a wide range of astrophysical studies. Such plasmas, especially those caused by strong shocks in solid materials, are also important to the Department of Energy's Stockpile Stewardship Program to ensure the reliability and safety of the nation's nuclear arsenal. A major goal of the Stockpile Stewardship Program is gaining a better understanding of materials under extreme pressures and temperatures.

Another possible application for JanUSP is testing the concept of an ion "lens." The lens involves curving the foil target to focus ejected ions into a 0.3-micrometer-wide, intense beam at the back of the target. Wilks, who's done computer simulations on the concept, says the ion lens could be useful for radiation therapy and for integrated circuit manufacturing



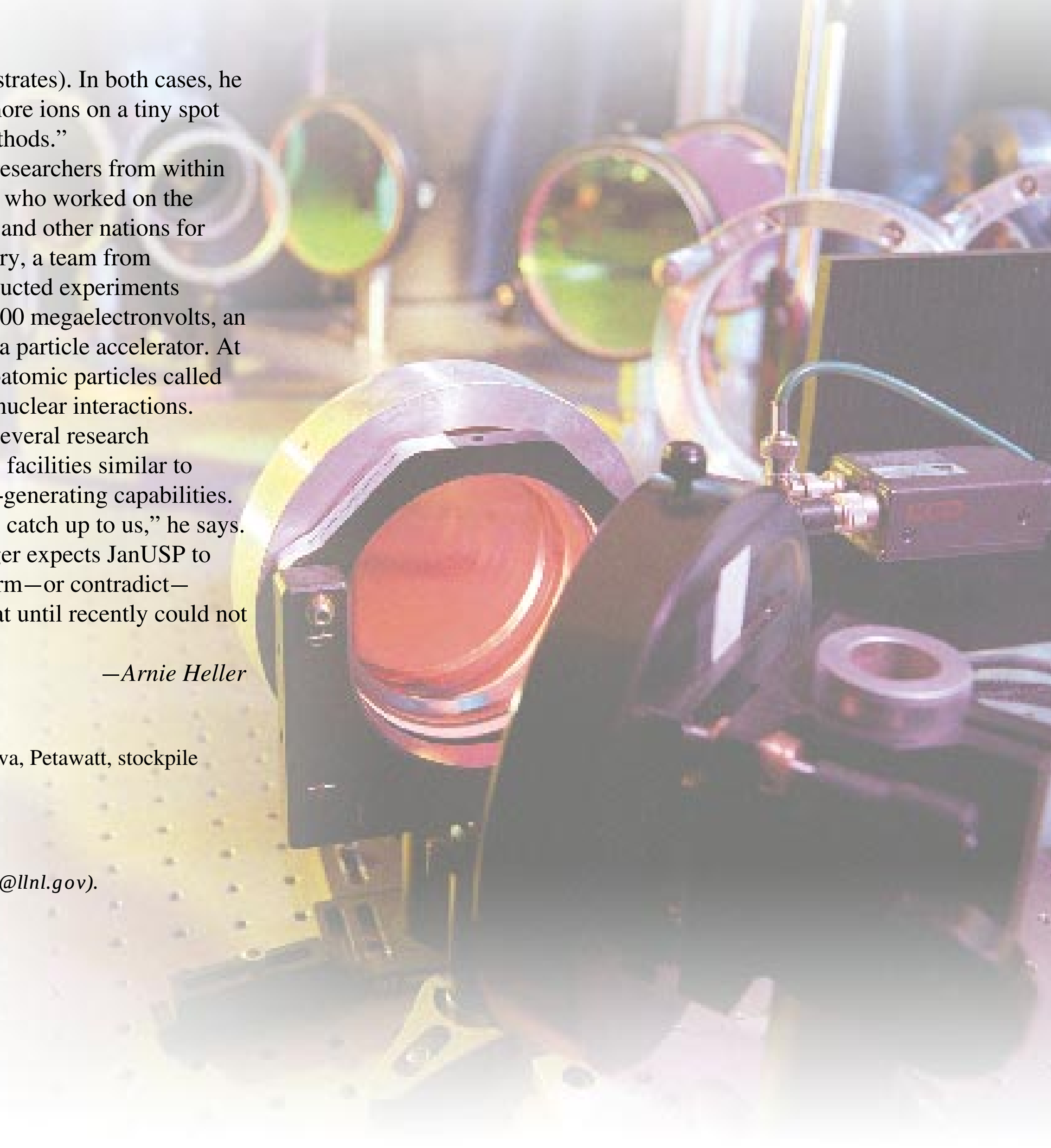
(a) JanUSP's laser pulse will have an extremely low prepulse to prevent low-energy plasma from interacting with the main laser pulse. (b) The main pulse will push electrons out of a thin metal foil. (c) The negatively charged electrons will drag positively charged protons and uncharged neutrons with them, depositing the ions onto a heavy metal target such as uranium. (d) The ions will travel several micrometers into the target, rapidly creating a superhot plasma.

(for doping materials onto silicon substrates). In both cases, he says, "you're focusing substantially more ions on a tiny spot than is possible with conventional methods."

The facility is currently attracting researchers from within Lawrence Livermore (including those who worked on the Petawatt), other national laboratories, and other nations for investigating new concepts. In February, a team from Germany's Max Planck Institute conducted experiments designed to accelerate electrons to 1,000 megaelectronvolts, an energy never before achieved outside a particle accelerator. At that energy, it is possible to create subatomic particles called pi-mesons, which are responsible for nuclear interactions.

Physicist Dwight Price notes that several research institutions worldwide are developing facilities similar to JanUSP because of its unique plasma-generating capabilities. "Other research centers are rushing to catch up to us," he says. For at least the next few years, Springer expects JanUSP to provide a wealth of new data to confirm—or contradict—models of extreme states of matter that until recently could not be tested in the laboratory.

—Arnie Heller



Key Words: ion lens, Janus, JanUSP, Nova, Petawatt, stockpile stewardship.

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