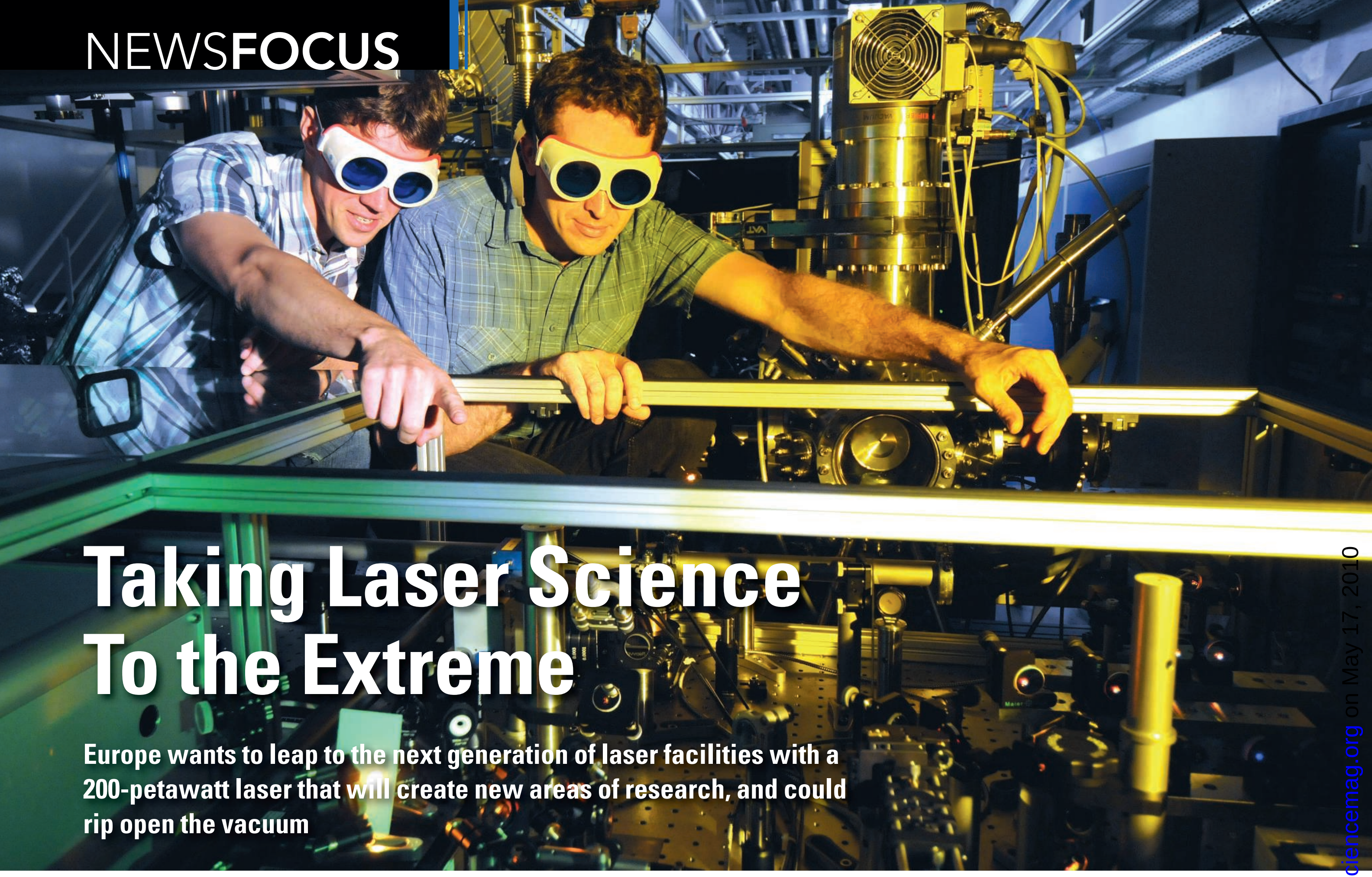

Taking Laser Science To the Extreme

Europe wants to leap to the next generation of laser facilities with a 200-petawatt laser that will create new areas of research, and could rip open the vacuum

CREDIT: THORSTEN NAESER/LABORATORY OF ATTOSECOND PHYSICS AT MPQ

THE FIRST HALF-CENTURY OF THE LASER'S history has seen a constant push for higher power. Today, the Vulcan laser at the Rutherford Appleton Laboratory (RAL) near Didcot, U.K., fires pulses that have 10,000 times the power of all of Britain's electricity-generating stations added together. One of the world's most powerful lasers, Vulcan doesn't black out the entire country because its pulses are very short, less than a picosecond (10^{-12} seconds) in duration, so the energy of each pulse is a moderate 0.5 kilojoules.

Vulcan is a large machine, but over the next few years a group of European countries wants to take lasers into the realm of international big science with a facility built around a device that can produce 200-petawatt (2×10^{17} watts) pulses, 200 times the power of today's best lasers. The Extreme Light Infrastructure (ELI) isn't yet a done deal, but there is considerable political and scientific momentum behind it. That's in part because the three countries leading the project are the Czech Republic, Hungary, and Romania—all recently joined members of the European Union. "There is political pressure from the new states and the E.U. to build [research facilities] in the new states," says Wolfgang Sandner, director of the Max Born Institute in Berlin.

If ELI goes ahead, it will be the most prominent science project in Eastern Europe since the fall of the Berlin Wall. Initially split into outposts in the three countries, leading up to one mammoth laser to be built by 2017, ELI will ultimately be the Swiss army knife of laser centers. Its superfast, high-power pulses will probe the atomic nucleus and watch electrons inside atoms and molecules. By colliding pulses with various targets, researchers plan to create other sorts of radiation—electrons, protons, ions, x-rays, and gamma rays—for use in everything from cancer therapy to nuclear physics.

The ultrahigh power and intensity of pulses of ELI's final laser will produce electric fields so strong that they may alter and sense the texture of the vacuum itself, opening up new research areas for astrophysicists and particle physicists. According to quantum electrodynamics (QED), the vacuum teems with pairs of electrons and positrons that pop fleetingly into existence, briefly separate, and then recombine and disappear. The electric fields of ELI's pulses may be strong enough to pull these pairs apart before they can recombine, or at least feel the texture of this sea of virtual particles and test QED in a very direct way. We want to "drill a hole in the vacuum," says ELI project coordinator Gérard Mourou, director of the Laboratory of Applied Optics (LAO) at Palaiseau, France.

The power of three

About 5 years ago, the E.U. called for ideas for international infrastructures to boost European research. Dozens of labs around the world already boast terawatt (10^{12} watts) lasers, and a handful, including Vulcan, can now reach petawatts (10^{15} watts). Mourou and others wanted to go even bigger. They put together a plan for a laser that would push current technology to its limits, into the hundreds of petawatts. Laser science "is ready to go to the next step, to a truly international laser infrastructure beyond the capability of a single nation," says Sandner.

Several European countries expressed interest in hosting ELI, but securing funding proved difficult until the three eastern countries realized they could apply for E.U. structural funds. These are grants given to less developed E.U. member states to build infrastructures such as roads, bridges, and hospitals, but they can equally well be spent on research facilities.

Last year, the Czech Republic, Hungary, and Romania came up with a novel plan: They would become equal partners in

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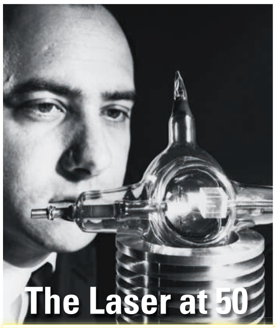
In a flash. Researchers prepare attosecond laser experiments at the Max Planck Institute of Quantum Optics.

the project and split it in three so that each would have a facility geared to a different branch of laser science. (Institutions in another 10 E.U. nations are also involved.) The three centers would have lasers with a range of powers between 1 and a few tens of petawatts; and the decision on where to put the final 200-petawatt laser would be put off for 2 years to give researchers more time to choose the best technology.

Although laser scientists acknowledge that this makes the project more complicated, there are benefits, too. “There will be a slight increase in cost but a huge boost to local scientists [in each country],” says Sandner. If the structural funds are approved by early next year as expected, the three countries could begin pouring concrete in 2011, with a total price tag of about €750 million. “This is very, very significant. It’s the first time a European infrastructure project has been built on the east side of the [former] Iron Curtain,” says physicist Marius Enachescu, who is deputy secretary of state in Romania’s research ministry.

The ELI facility in Hungary will focus on science using ultrashort laser pulses, just attoseconds (10^{-18} seconds) in length. Researchers began making attosecond pulses about a decade ago when they found that if they fired a femtosecond (10^{-15} seconds) laser pulse into a gas such as neon, they created higher order harmonics of the original frequency. By superposing these harmonics, they could create attosecond-scale pulses, which is just the time scale needed to discern the movement of electrons in an atom.

Researchers hope Hungary’s ELI facility will enable them to carry out “pump-probe” type experiments, in which one pulse sets an atomic process in motion, then a second snaps the action a moment later like a hyperfast camera. They say they will be able for the first time to image the position in time and space of both nuclei and electrons at the subatomic scale.



In May 1960, Theodore Maiman unveiled the first working laser. This package describes a small sample of current laser research.

CREDIT: © BETTMANN/CORBIS

The Czech branch of ELI will be a laser-based beamline facility. Many areas of science rely on beams of particles and high-energy photons from accelerators, synchrotrons, x-ray tubes, and radioactive sources. In 2000, researchers discovered that they could also generate many of these beams by firing high-intensity laser pulses into gas jets, thin foils, and other targets. This laser strategy can produce x-rays and gamma rays, as well as pulses of electrons, protons, and ions, with a brightness and pulse length that open up new experimental possibilities. “When a laser interacts with a target, all sorts of impressive things are created. The products often cannot be produced in any other way,” says John Collier, RAL’s head of high-power lasers.

One possible application this ELI branch plans to explore is cancer therapy with proton or ion beams. Such beams are extremely effective for treating deep-seated tumors, but to perform such therapy a hospital now needs a particle accelerator costing tens of millions of dollars—something few can afford. Laser physicists think they can accelerate particles in a much cheaper and more compact way. When they fire a high-intensity laser pulse into a plasma, the photons’ magnetic field kicks electrons in the plasma forward and these then strike a foil target. As they emerge from the other side, they drag positive ions in the pulse’s wake. Such acceleration works “much faster over a shorter distance” than traditional accelerators do, says Sandner. “It’s in its very early infancy, but it points a way to the next step.”

The third planned ELI facility, in Romania, aims to open up a new area of laser science by probing the atomic nucleus with beams that are ultraintense—focused so that they have the maximum power per unit area. “The laser power that exists now cannot be compared with the strength of the nuclear field,” says Enachescu. But he hopes that his nation’s ELI outpost can change that.

It’s not clear yet whether ELI’s laser beams alone will be able to excite a nucleus into higher energy levels, but physicists are developing other tricks that utilize those beams to accomplish the feat. One such scheme involves colliding a laser pulse head-on with an electron beam to produce an intense burst of gamma rays. “Then we will use that to disturb nuclei,” says Mourou.

Probing the vacuum

The fourth, and at the moment least-defined, part of ELI is the final 200-petawatt laser. The uncertainty is because planners are still weighing two rival methods to stretch current technology to this new power level. All high-power research lasers rely on amplifiers: pieces of an active lasing medium, such as glass doped with neodymium, that resemble a laser without the end mirrors. Just before a pulse is fired, the amplifier is pumped with light from another source to create a large number of excited atoms. When the pulse comes through, those atoms emit light in step with the pulse, amplifying it with extra photons. But at about a gigawatt, each pulse has so much power that it begins to damage the glass. Researchers got around this problem in the mid-1980s after Mourou and colleague Donna Strickland developed a technique called chirped pulse amplification (CPA), which reduces the peak power of a short, high-power pulse by stretching the pulse out in time, before amplifying it and compressing it again.

ELI may need additional strategies to increase laser power. “We’re getting to the limit of CPA,” says ELI Deputy Coordinator Georg Korn of the Max Planck Institute of Quantum Optics in Garching, Germany. The ELI team may consider an adaptation of CPA involving a special nonlinear crystal to transfer power from one stretched beam to another. This will be tested in a planned upgrade of Vulcan to 10 petawatts. Meanwhile, Mourou’s LAO and other French labs are testing a different amplifier material, titanium-doped sapphire, by building a 10-petawatt laser.

The ELI team must eventually decide which approach to back and whether to push for even higher power or simply build 20 10-petawatt lasers and combine the beams to make one of 200 petawatts. “We have to wait for this new technology to develop. Two-hundred petawatts is so advanced that there is a need for a demonstrator,” says Collier.

Even if researchers achieve that power, they will still need high-intensity beams before they can explore the vacuum. Theorists calculate that an intensity of 20^{29} watts/square centimeter (W/cm^2) will be needed to rend apart electron-positron pairs. ELI will likely be able to reach intensities of only about 10^{24} W/cm^2, but “there are some clever ideas around, some of them not yet published,” says Korn. These include using laser pulses to create intense gamma rays and probing the vacuum with them.

With enough funding, says laser scientist Donald Umstadter of the University of Nebraska, Lincoln, ELI should overcome any technical difficulties. “They’ve set ambitious goals to reach ideal conditions. If they do, it will be very exciting. Whenever you are going to the limits, you can expect interesting physics to emerge.”

–DANIEL CLERY

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