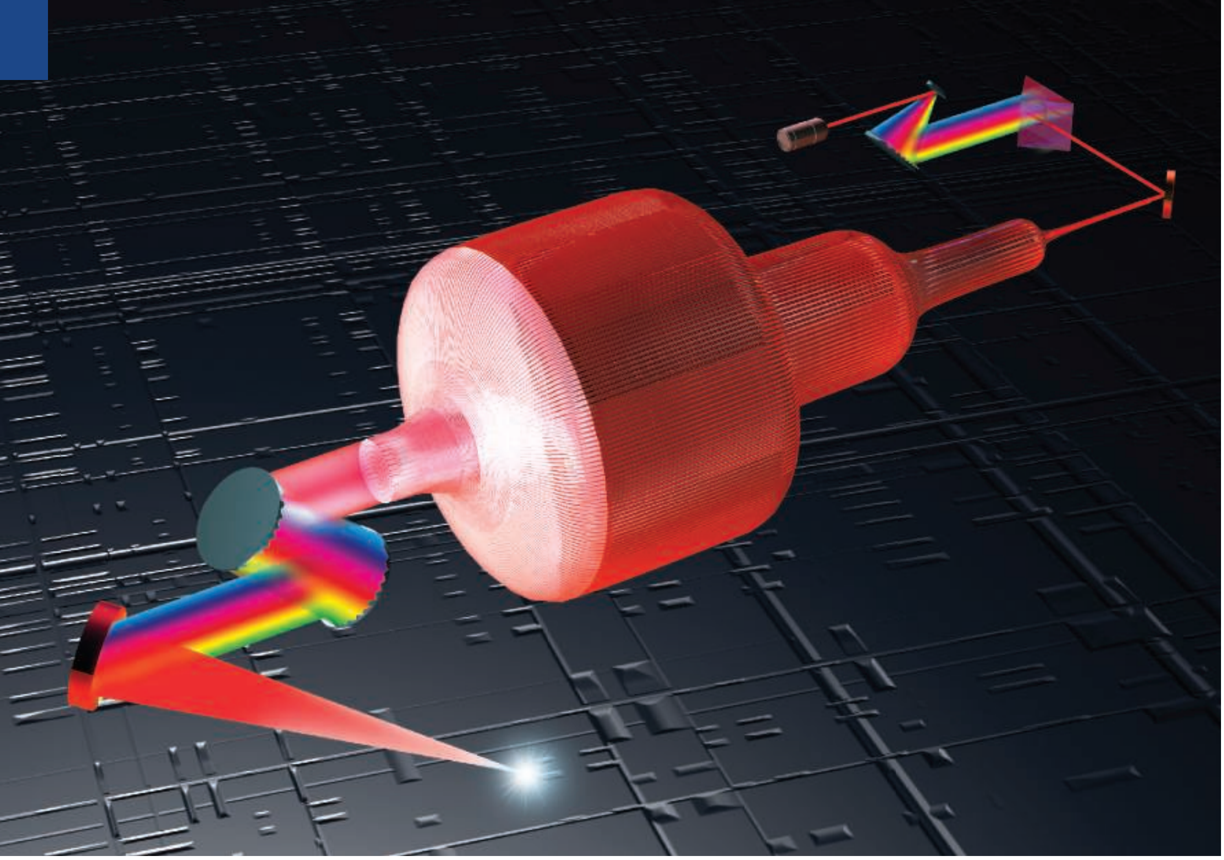

All for one. The ICAN laser would use thousands of fiber lasers to boost power before recombining their beams.

PARTICLE PHYSICS

Europe Aims for a Cut-Rate Superlaser To Power Future Particle Accelerators

Could the light at the end of high-energy physics' increasingly long tunnels be … light? The field's appetite for ever more powerful accelerators is running up against society's willingness to pay. The Large Hadron Collider (LHC) at CERN, the European particle physics laboratory near Geneva, Switzerland, with its 27-kilometer circular tunnel and detectors the size of cathedrals, cost close to $10 billion. Next, physicists want to build the 31-kilometer-long International Linear Collider at up to $25 billion, and they are talking about even bigger machines and longer tunnels. Sooner or later, these ambitions will be stymied—unless some new, radically cheaper accelerator technology succeeds. A team of European physicists sees hope in the light of simple fiber-optic lasers.

Researchers have known for decades that laser pulses can accelerate charged particles, but only in the past few years have they produced beams of high enough quality for particle physics. The remaining stumbling block is quantity: Lasers that can produce sufficiently intense pulses at high enough repetition rates with reasonable efficiency just don't exist.

"People said it was crazy."

—GÉRARD MOUROU
ÉCOLE POLYTECHNIQUE, PALAISEAU, FRANCE

Now, a consortium of European physics labs says that it can meet the necessary spec without building a new superlaser. The trick is to take fiber lasers—a workhorse of the telecommunications industry—and combine their output into a superbeam. In an 18-month pilot project funded by €500,000 from the European Union, the labs coaxed 64 fiber lasers to merge their beams smoothly. If the European Union's next 7-year research budget allows—it is now being finalized—they hope to scale up to a full-size demonstrator with thousands of fibers.

Physicists are reaching the limits not only of national budgets, but also of technology. To search for new physics, they would ultimately like to accelerate leptons, such as electrons and positrons, to energies in excess of 5 trillion electron volts (5 TeV). But doing so with today's technology would consume hundreds of megawatts (MW) of electricity—the entire output of a medium-sized power station. "There is no technology for over-5-TeV lepton colliders," says Roy Aleksan of France's Atomic Energy Commission lab at Saclay. The problem is that the radio-frequency waves now used to accelerate particles don't give them a very big kick, so it takes a lot of microwave cavities in a row to reach high energies. The cavities are also not very efficient at converting wall-plug electricity into beam power.

More than 30 years ago, John Dawson and Toshiki Tajima of the University of California, Los Angeles, proposed a radically different strategy: accelerating particles in a plasma stirred by a laser. A plasma is essentially a gas of charged particles: ions, and electrons stripped from them. If a high-powered pulse of laser light is fired into a plasma, the transverse electric field of the light pushes the featherweight electrons out of the way but barely budges the much heavier ions, leaving in its wake an electron-deficient bubble of positive charge followed by a region of negative charge that forms as electrons rush back in. The result is a powerful electric field parallel to the pulse's direction of travel. This "wakefield" can give a huge boost in speed to electrons, either those from the plasma or bunches of electrons specially injected to take advantage of it.

When Dawson and Tajima proposed this wakefield-acceleration technique, laser pulses could not be made short enough and powerful enough. In the mid-1980s, however, Gérard Mourou and Donna Strickland of the University of Rochester devised chirped pulse amplification (CPA). This takes a moderately powered short laser pulse and stretches it out into a longer, lower-powered one. Passing this elongated pulse through laser amplifiers boosts its energy, and so when it is recompressed to its original length it has greatly increased power. Almost all of the world's highest-power lasers use CPA to produce petawatt (10^{15} watt) pulses.

With such pulses, researchers could produce accelerating wakefields as strong as 10 billion to 100 billion volts per meter (GV/m), three orders of magnitude higher than conventional radiofrequency accel-

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eration (10-50 MV/m). But particle physicists didn't take the technique seriously because it produced particle beams of poor quality and low luminosity—too few particles per second.

"They need to develop an accelerator. Then people can say 'This is something we can use.' "
—ROY ALEKSAN
CEA SACLAY

The skeptics started to sit up and take notice in 2006, however, when researchers at Lawrence Berkeley National Laboratory in California created a high-quality 1-GeV electron beam in a tube of plasma just 3.3 centimeters long. In 2009, the International Committee for Future Accelerators and the International Committee on Ultra-High Intensity Lasers set up a joint task force to investigate how these new laser techniques could help accelerator development. Its report, published in 2011, sketched out a plan for an electron-positron collider with hundreds of laser plasma modules lined up to accelerate particles. The machine would be far smaller than current accelerators—no more than a couple of kilometers long—and potentially much cheaper. Yet it would reach an energy of between 1 and 10 TeV.

But the necessary lasers still don't exist. Although CPA lets researchers create pulses with sufficiently high peak power, such lasers typically fire just once a second, a pace far too slow to generate an intense particle beam. The lasers for a TeV-scale accelerator would need to produce thousands or even millions of pulses per second and, to avoid huge energy costs, would need a high wall-plug efficiency, too. "This is what you have to shoot for overall: high peak power and average power and efficiency," Aleksan says.

The report proposed a long-term R&D program to develop the necessary lasers. But Mourou, now at the École Polytechnique near Paris, had a better idea: use a common and inexpensive tool of the telecommunications industry, the fiber laser—little more than an optical fiber doped with ytterbium. Pumped with light from another source, fiber lasers can produce beams at high repetition rates and with high efficiency. What they lack is the ability to produce ultrashort, high-power pulses.

So Mourou proposed combining the output of many thousands of fiber lasers to create a beam that could drive a TeV accelerator. The system would work by taking short pulses from a seed laser, stretching them out, and then amplifying them in a large number of fiber lasers. The pulses would then be recombined into a single beam and compressed to produce short, high-power pulses. The hitch comes in the penultimate step: recombining the output of thousands of fibers into a single beam. All the beams have to be precisely in phase, otherwise some will destructively interfere with others to reduce the power of the final beam. "People said it was crazy," Mourou says.

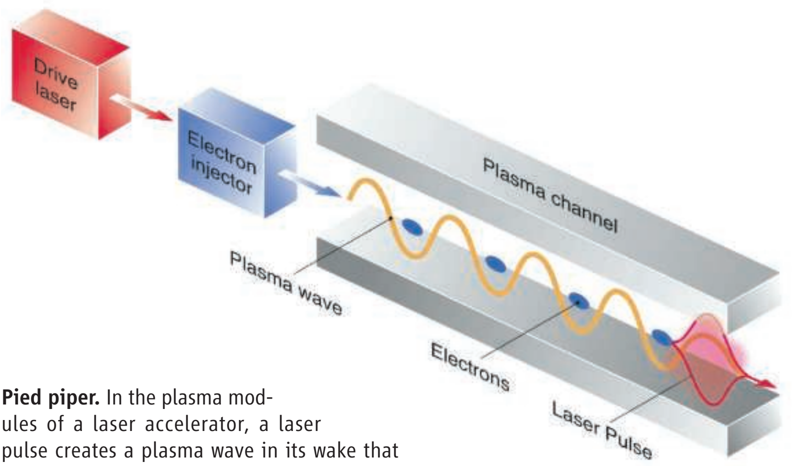
Mourou formed the International Coherent Amplification Network (ICAN) in collaboration with colleagues at CERN, the University of Southampton in the United Kingdom, and Germany's Fraunhofer Institute in Jena. After a year and a half of research, they showed that coherent combination could work. In their final demonstration, completed earlier this year, they fed the 64 fiber lasers into an 8-by-8 lattice so that their beams emerged in parallel. Allowing the beams to overlap slightly, the researchers could observe interference patterns between each beam and its four nearest neighbors. A camera recorded the patterns, detecting any differences in phase, and then a feedback loop would go back to the fiber laser in question and tweak its phase back into line in real time.

To monitor and adjust the roughly 30,000 fiber lasers needed for a particle accelerator would be a much more daunting task—one that Mourou likens to the challenge of designing the European Extremely Large Telescope, a 40-meter behemoth in which 6000 actuators will compensate for atmospheric distortion by reshaping a deformable mirror a thousand times a second. But the ICAN demonstration proved the principle.

The ICAN project drew attention from other communities that see the promise of a high-peak-power, fast-pulsing laser. The same technology could provide a low-cost source of electron beams for a type of x-ray light source called a free-electron laser; proton beams for cancer therapy; or medical isotopes. "ICAN heralds a revolution in laser-plasma-based acceleration," says Alexander Pukhov of the Skobeltsyn Institute of Nuclear Physics at Lomonosov Moscow State University.

Even if ICAN's laser scales up successfully, physicists will not build an all-out TeV-scale electron-positron collider anytime soon. But the ICAN team was intrigued by a proposal for a more modest machine: a Higgs factory. Now that researchers at CERN have discovered the Higgs boson, the last missing piece in their standard model, physicists want to make more of them to study their properties. One way of doing that is by colliding high-energy photons called gamma rays. A team at the Fermi National Accelerator Laboratory in Illinois, in collaboration with Mourou and Tajima, has proposed building a conventional accelerator producing two counter-rotating beams of electrons in the tunnel of the retired Tevatron collider at Fermilab. The electron beams—with the relatively low energy of 80 GeV—would be collided with photons from ICAN-style lasers, resulting in back-scattered 63-GeV gamma rays; beams of those photons would then be collided to produce Higgs bosons. The researchers estimate that such a gamma-gamma collider could produce 10,000 Higgs bosons per year, several times the number made by the LHC.

Before any of that can happen, Mourou and his team need to show that they can build a full-scale laser with the required capabilities. If the next E.U. research budget provides the €3 milllion they need, they may be able to show whether their proof-of-principle heralds a bright future for particle physics or is just a flash in the pan. "They need to develop an accelerator," Aleksan says. "Then people can say 'This is something we can use.' " **—DANIEL CLERY**



Pied piper. In the plasma modules of a laser accelerator, a laser pulse creates a plasma wave in its wake that drags along and boosts electron bunches.

CREDIT: W. P. LEEMANS AND E. ESAREY, *PHYSICS TODAY* **62**, 44 (2009)