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Big Physics Gets Small

Tabletop Accelerators Make Particles Surf on **Plasma Waves**

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TABLETOP ACCELERATORS producing electron beams in the 100- to 200-million-electron-volt (MeV) range are just one type of machine made possible by plasma acceleration.

PLASMA ACCELERATORS

A new method of particle acceleration in which the particles “surf” on a wave of plasma promises to unleash a wealth of applications

By Chandrashekhar Joshi

CHIP SIMONS

Physicists use particle accelerators to answer some of the most profound questions about the nature of the universe. These gargantuan machines accelerate charged particles to nearly the speed of light and then smash them together, re-creating the conditions that existed when our universe was cataclysmically born in the big bang. By analyzing the debris of the collisions, physicists hope to understand how the seemingly disparate forces and particles that exist in our universe are all connected and described by a unified theory. Unfortunately, as they get closer and closer to solving this mystery of creation, physicists need particle accelerators of ever greater power (and expense).

The most powerful particle accelerator, now under construction at CERN, the European laboratory for particle physics on the French-Swiss border, is the 8.6-kilometer-diameter Large Hadron Collider (LHC). After the LHC is completed in 2007, the collisions of its two seven-trillion-volt proton beams should tell us what gives particles their mass [see "The Mysteries of Mass," by Gordon Kane; Scientific American, July 2005]. Other currently operating machines are attempting to explain why the universe contains more matter than antimatter and are giving us a peek into the primordial state of matter called a quark-gluon plasma. All these colliders are based on a bulky decades-old technology in which microwaves accelerate the particles.

Over the past 75 years these machines and their predecessors have produced remarkable discoveries about the nature of fundamental particles and the behavior of nuclear matter. Advances in the science and engineering of particle accelerators made that continual stream of revelations possible by allowing scientists to build machines whose energy was greater by roughly a factor of 10 every decade. Will such advances continue? The microwave-based machines may well be approaching the limits of what is technologically and economically feasible. In 1993 Congress canceled the $8-billion Superconducting Super Collider project, a 28-kilometer-diameter accelerator that would have had more than twice the power of the LHC. Many particle physicists now hope to follow the LHC with a 30-kilometer-long linear collider, but no one can predict if that proposed multibillion-dollar project will fare better than the Super Collider.

Perhaps just in time, new approaches to particle acceleration, using the fourth state of matter (after solid, liquid and gas) called a plasma, are showing considerable promise for realizing an accelerator for physics at the highest energies (100 billion electron volts and up). This plasma-based approach might dramatically reduce the size and cost of such an accelerator.

Giant accelerators operating near the high-energy frontier for physics research are just one part of the story. In addition, people use smaller machines for materials science, structural biology, nuclear medicine, fusion research, food sterilization, transmutation of nuclear waste, and the treatment of certain types of cancer. These smaller machines produce electron or proton beams with relatively low energy—in the 100-million- to one-billion-volt range—but still occupy large laboratory spaces. Extremely compact, or "tabletop," plasma accelerators promise to provide electron beams in this energy range.

TABLETOP PLASMA ACCELERATORS promise to provide electron beams for lower-energy APPLICATIONS.

Overview/*Surfing on Plasmas*

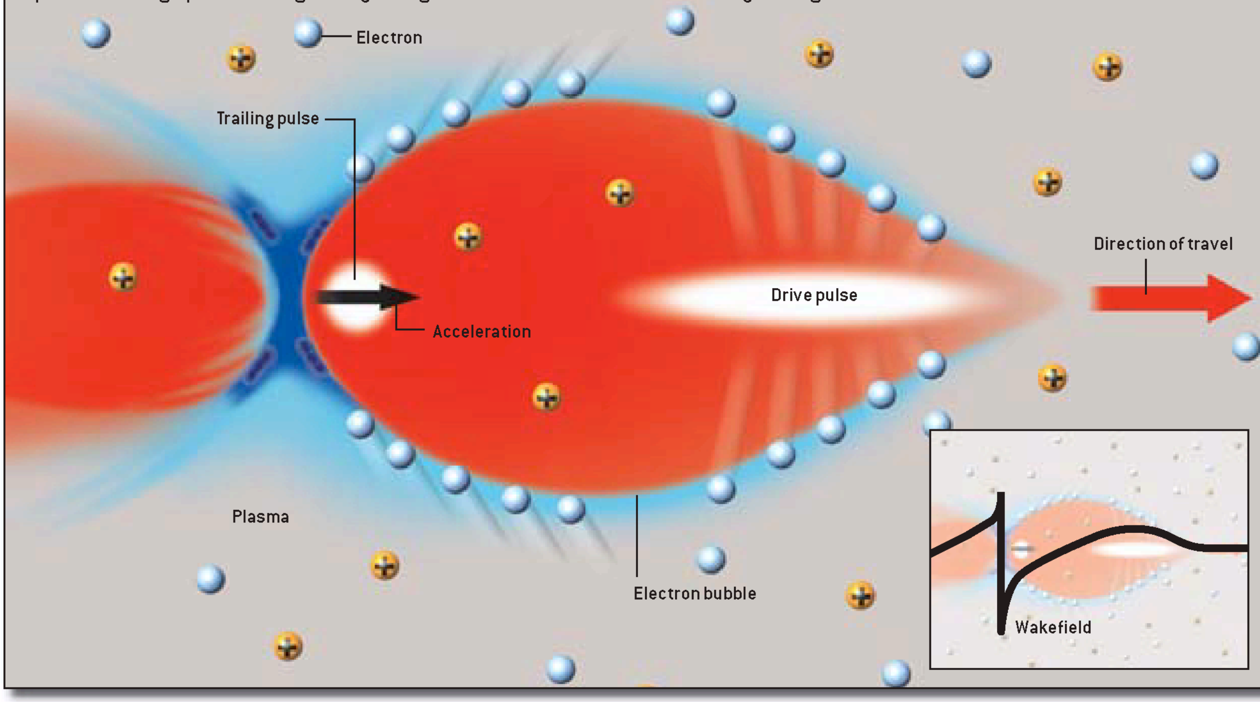
- For decades, particle colliders have used microwave cavities to propel particle beams to nearly the speed of light. That approach, exemplified by the 8.6-kilometer-diameter Large Hadron Collider, is reaching its technological and economic limits.
- A new technique, in which electrons or positrons gain energy by surfing on a wave in an ionized gas, or plasma, promises to slash the size and expense of these high-energy accelerators used by particle physicists to study questions such as the origins of mass in the universe. So far the method has been demonstrated in small laboratory experiments.
- The plasma machines will also enable construction of tabletop accelerators for a wide range of lower-energy applications, including materials science, structural biology, nuclear medicine and food sterilization.

Microwaves vs. Plasma

Before I detail the new technology, it helps to review some accelerator basics. Accelerators come in just a few broad types. First, they propel either lighter particles (electrons and positrons) or heavier ones (such as protons and antiprotons). Second, they can accelerate the particles in a single passage along a straight line or in many orbits around a circular ring. The LHC, for example, is a ring that collides two proton beams. The collider that physicists hope to build after the LHC will be a linear collider of electrons and positrons. The energy at the collision point will initially be in the neighborhood of one-half TeV (trillion electron volts). At such energies, electrons and positrons must be accelerated in a straight line; accelerating them in a ring would result

THE BUBBLE REGIME

Wakefield accelerator relies on a charge disturbance known as a wakefield to provide the driving force. The drive pulse, which can be a short pulse of either a laser or an electron beam, blows the electrons (*blue*) in an ionized gas, or plasma, outward—leaving behind a region of positive charge (*red*). The positive charge pulls the negatively charged electrons back in behind the drive pulse, forming an electron bubble around the positive region. Along the axis that the beam propagates, the electric field (*plotted below*) resembles a very steep ocean wave about to break. This field—the wakefield—causes a trailing pulse of electrons caught near the rear of the bubble to feel a very strong forward acceleration.



in excessive energy loss from a process called synchrotron radiation. Linear acceleration of electrons and positrons is what plasma-based accelerators are most suited for.

A conventional linear collider accelerates its particles with an electric field that moves along in synchrony with the particles. A structure called a slow-wave cavity (a metallic pipe with periodically placed irises) generates the electric field using powerful microwave radiation. The use of a metallic structure limits how large the accelerating field can be. At a field of 20 million to 50 million volts per meter, electrical breakdown occurs—sparks jump and current discharges from the walls of the cavities. Because the electric field has to be weaker than the threshold for breakdown, it takes a longer acceleration path to achieve a specific energy. For example, a trillion-volt beam would require an accelerator 30 kilometers long. If we could accelerate particles far more quickly than is allowed by the electrical breakdown limit, the accelerator could be made more compact. That is where plasma comes in.

In a plasma accelerator, the role of the accelerating structure is played by the plasma, an ionized gas. Instead of being a problem, electrical breakdown is part of the design because the gas is broken down to begin with. The power source is not microwave radiation but is either a laser beam or a charged particle beam.

At first sight, laser beams and charged particle beams do not seem well suited for particle acceleration. They do have very strong electric fields, but the fields are mostly perpendicular to the direction of propagation. To be effective, the electric field in an accelerator has to point in the direction that the particle travels. Such a field is called a longitudinal field. Fortunately, when a laser or charged particle beam is sent through a plasma, interaction with the plasma can create a longitudinal electric field.

The process works in this way: A plasma as a whole is electrically neutral, containing equal amounts of negative charge (electrons) and positive charge (ions). A pulse from an intense laser or particle beam, however, creates a disturbance in the plasma. In essence, the beam pushes the lighter electrons away from the heavier positive ions, which in turn get left behind, creating a region of excess positive charge and a region of excess negative charge [*see box above*]. The disturbance forms a wave that travels through the plasma at nearly the speed of light. A powerful electric field points from the positive to the negative region and will accelerate any charged particles that come under its influence.

A plasma medium can support accelerating electric fields of fantastic

GEORGE RETSECK

magnitude. A plasma containing 10^{18} electrons per cubic centimeter (an unexceptional number) can generate a wave with a peak electric field of 100 billion volts per meter. That is more than 1,000 times more intense than the accelerating gradient in a typical conventional accelerator powered by microwaves. Now the catch: the wavelength of a plasma wave is only 30 microns, whereas the typical microwave wavelength is 10 centimeters. It is very tricky to place a bunch of electrons in such a microscopic wave.

The late John M. Dawson of the University of California, Los Angeles, first proposed this general method of using plasmas to accelerate particles in 1979. It took more than a decade before experiments demonstrated electrons surfing plasma waves and gaining energy. Three different technologies—plasmas, accelerators and lasers—had to be tamed and made to work together. My group at U.C.L.A. accomplished that feat unambiguously in 1993. Since then, progress in this field has been explosive. Two techniques in particular, called the laser wakefield accelerator and the plasma wakefield accelerator, are showing spectacular results. The laser wakefield looks promising for yielding a low-energy tabletop accelerator, and the plasma wakefield has the potential to produce a future collider at the energy frontier of particle physics.

Pulses of Light

TABLETOP PLASMA accelerators are made possible today by intense, compact lasers. Titanium-sapphire lasers that can generate 10 terawatts (trillion watts) of power in ultrashort light pulses now fit on a large tabletop [see "Extreme Light," by Gérard A. Mourou and Donald Umstadter; SCIENTIFIC AMERICAN, May 2002].

In a laser-powered plasma accelerator, an ultrashort laser pulse is focused into a helium jet that is a couple of millimeters long. The pulse immediately strips off the electrons in the gas, producing a plasma. The radiation pressure of the laser bullet is so great that the much lighter electrons are blown outward in all directions, leaving behind the more massive ions. These electrons cannot go very far, because the ions pull them back inward again. When they reach the axis that the laser pulse is traveling along, they overshoot and end up traveling outward again, producing a wavelike oscillation [*see box on preceding page*]. The oscillation is called a laser wakefield because it trails the laser pulse like the wake produced by a motorboat.

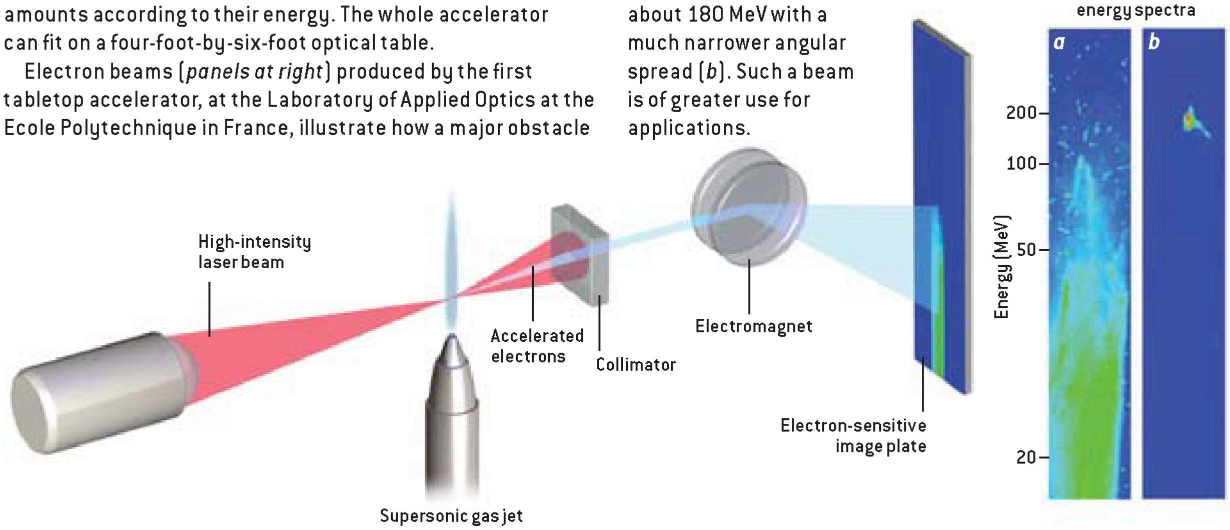
The electrons actually form a bubblelike structure. Near the front of the bubble is the laser pulse that creates the plasma, and inside the rest of the bubble are the plasma ions. This bubble structure is microscopic, about 10 microns in diameter. The electric field in the bubble region resembles an ocean wave but is much steeper. Although other structures are also possible, using the bubble regime appears to be the most robust way to accelerate electrons.

If a device such as an electron gun introduces an external electron close to where there is an excess of electrons in the plasma, the new particle will experience an electric field pulling it toward

LASER WAKEFIELD ACCELERATOR

A tabletop plasma accelerator consists of a high-intensity laser beam focused on a supersonic jet of helium gas (*left*). A pulse of the beam produces a plasma in the gas jet, and the wakefield accelerates some of the dislodged electrons. The resulting electron pulse is collimated and passed through a magnetic field, which deflects the electrons by different amounts according to their energy. The whole accelerator can fit on a four-foot-by-six-foot optical table.

Electron beams (*panels at right*) produced by the first tabletop accelerator, at the Laboratory of Applied Optics at the Ecole Polytechnique in France, illustrate how a major obstacle was overcome. Although some electrons were accelerated to 100 MeV, the electron energies ranged all the way down to 0 MeV (*a*). Also, the beam diverged by about a full degree. In contrast, the results from the recently discovered "bubble" regime showed a monoenergetic beam of about 180 MeV with a much narrower angular spread (*b*). Such a beam is of greater use for applications.

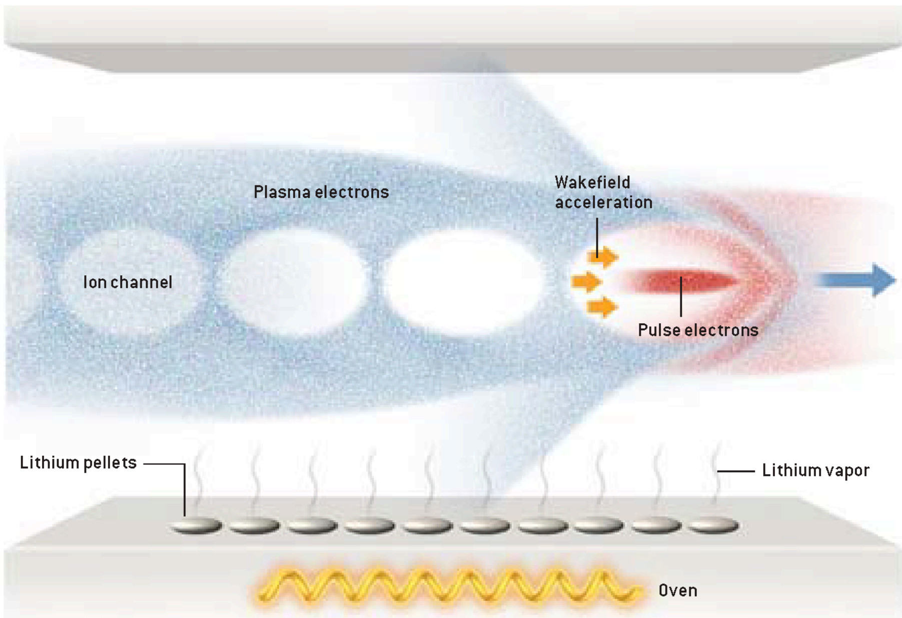


GEORGE RETSECK (*illustration*); SOURCE: VICTOR MALKA (*spectra*)

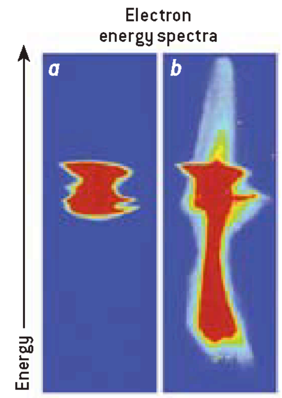
PLASMA AFTERBURNER

Plasma wakefield acceleration was recently demonstrated in an experiment using a beam of the Stanford Linear Collider (SLC). The accelerator added 4 GeV of energy to an electron beam in just 10 centimeters—an energy gain that would require a 200-meter section of a conventional microwave accelerator.

In the experiment, an oven vaporized lithium pellets. An intense electron pulse (*red*) ionized the vapor to produce a plasma. The pulse blew out the plasma electrons (*blue*), which then set up a wakefield, or a charge disturbance, behind the pulse. Electrons located in that wakefield experienced powerful acceleration (*orange arrows*).



In the absence of the lithium (*a*), SLC's 30-GeV beam was quite mono-energetic (energy is plotted vertically). After passing through 10 centimeters of lithium plasma (*b*), most of the beam particles lost energy in generating the plasma wakefield (*red tail*). The wakefield accelerated a small number of electrons that happened to be at the back of the pulse to higher energy (*blue region at top*).



the positive charges inside the bubble. The wave moves along at light speed, so the electron has to be injected close to this velocity to catch the wave and gain energy from it. We know from the theory of relativity that any further increase in the electron's energy mostly comes from an increase in the mass of the particle and not its speed. The electron therefore does not significantly outrun the plasma wave. Instead it surfs the wave, gaining energy all the way. Some of the electrons from the plasma itself are also trapped and accelerated in this way, like foam caught on a cresting ocean wave.

In 2002 Victor Malka and his group at the Ecole Polytechnique's Laboratory of Applied Optics in France showed that a beam of 10^8 electrons could be generated using a laser-driven wakefield. The beam was well collimated, that is, tightly focused. Unfortunately, the accelerated electrons had a very wide range of energies—from one to 200 million-electron volts (MeV). Most applications require a beam of electrons that are all at the same energy.

This energy spreading occurred because the electrons were trapped by the wakefield wave at various locations and at different times. In a conventional accelerator, particles to be accelerated are injected into a single location near the peak of the electric field. Researchers thought that such precise injection was impossible in a laser wakefield accelerator because the accelerating structure is microscopic and short-lived.

Serendipity came to the rescue. In 2004 three competing groups from the U.S., France and the U.K. simultaneously stumbled on a new physical regime in which self-trapped electrons surf as a single group, all reaching the same energy. The three groups each used a higher-power laser than before—10 terawatts and above. When such a powerful laser pulse propagates through the plasma, it becomes both shorter and narrower, creating a large electron bubble that traps electrons from the plasma. These self-trapped electrons are so numerous that they extract a significant amount of energy from the wake and thus turn off further trapping. Those electrons with the highest energy begin to outrun the wake. Thus, higher-ener-

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GEORGE RETSECK (*illustration*); STANFORD LINEAR ACCELERATOR CENTER, UNIVERSITY OF CALIFORNIA, LOS ANGELES, AND UNIVERSITY OF SOUTHERN CALIFORNIA (*spectra*)

gy electrons in the front begin to lose energy even as lower-energy electrons in the back are still gaining energy.

The result is a beam of electrons with a narrow energy spread. In Malka's experiments, for example, the energy spread was reduced from 100 percent to only 10 percent with up to 10^9 electrons per beam. The angular spread of the beam was also much narrower than in earlier experiments—comparable to the best beams produced by conventional microwave linear accelerators. The resulting electron beam (actually a pulse) had a length of only 10 femtoseconds (10^{-14} second), the shortest ever produced by an accelerator, making it attractive as a potential radiation source for resolving ultrafast chemical and biological processes. The electron pulse could be directed onto a thin metal target to produce a correspondingly short x-ray pulse. In the next year or two, I expect to see applications of x-rays from tabletop accelerators demonstrated.

How might one further increase the energy of the electron beam to produce a billion-electron-volt (GeV) laser wakefield accelerator? One needs to create a plasma wave that persists over a distance of about one centimeter instead of just a couple of millimeters. The laser beam that excites the wave therefore must be kept intense in the plasma for a longer time by guiding it in what is called a plasma fiber. A particularly promising approach is the use of a preformed plasma fiber, which researchers at Lawrence Berkeley National Laboratory are pursuing. In this method the electrons have a lower density along the plasma's axis. This causes the plasma channel to have a higher refractive index along its axis than at its edges—just the right condition for the channel to act like an optical fiber to guide the laser beam. The Berkeley experiments have already shown that such channels generate monoenergetic electron beams. Further improvements in this approach are likely to produce the first GeV-class tabletop plasma accelerator in the very near future.

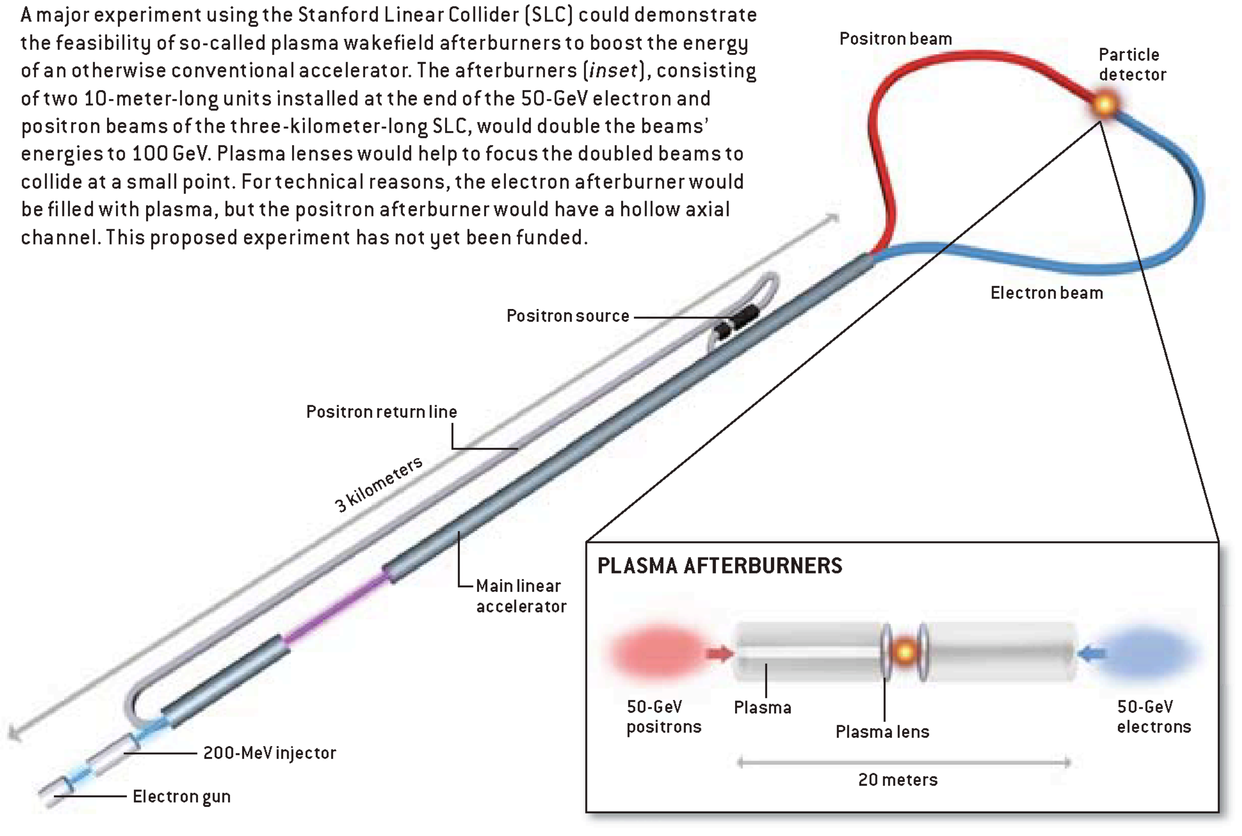
Scaling Up to the Energy Frontier

HOW CAN THESE centimeter-scale laser-driven plasma accelerators be extended to generate the TeV energies that are of interest to particle physicists? One approach would be to string together hundreds of compact laser-plasma acceleration modules, each providing a net energy gain of a few GeV. This design, called staging, is how microwave accelerators are combined to produce high energies. The problems associated with staging of plasma accelerators, however, are enormously complicated.

Instead the approach currently favored is the so-called plasma afterburner, in which a single plasma wakefield accelerator stage doubles the output en-

BOOSTING A CONVENTIONAL ACCELERATOR

A major experiment using the Stanford Linear Collider (SLC) could demonstrate the feasibility of so-called plasma wakefield afterburners to boost the energy of an otherwise conventional accelerator. The afterburners (*inset*), consisting of two 10-meter-long units installed at the end of the 50-GeV electron and positron beams of the three-kilometer-long SLC, would double the beams' energies to 100 GeV. Plasma lenses would help to focus the doubled beams to collide at a small point. For technical reasons, the electron afterburner would be filled with plasma, but the positron afterburner would have a hollow axial channel. This proposed experiment has not yet been funded.



GEORGE RETSECK

ergy of a conventional accelerator. In this approach, a conventional accelerator raises two electron or positron pulses to several hundred GeV. The first pulse (called the driver) contains three times as many particles as the second, trailing pulse. Both the driver and the trailing pulses are typically only 100 femtoseconds long and are separated by about 100 femtoseconds. As in a laser wakefield accelerator, when the driver pulse is focused into the plasma, it produces a wakefield bubble (provided that the beam is denser than the plasma). The process is the same as in the laser wakefield case, except now the particle beam's electric field does the pushing instead of the laser beam's radiation pressure. The electron bubble encloses the trailing beam, which is rapidly accelerated by the longitudinal component of the resulting electric field.

The plasma wakefield accelerator is causing a great deal of excitement among physicists who are working on advanced acceleration techniques. Three critical advances have made this scheme extremely attractive. These advances came from a team of scientists at U.C.L.A., the University of Southern California and the Stanford Linear Accelerator Center (SLAC) using the beams from the Stanford Linear Collider.

First and foremost, these scientists got around the problem of laser-driven plasma accelerators being only a few millimeters in length: they made a meter-long plasma accelerator for both electrons and positrons. It took great skill to keep the driver beams stable over such a length. Second, they demonstrated greater than 4 GeV of energy gain for electrons in just 10 centimeters. This energy gain was limited only by practical considerations and not by any scientific issues, which means that it can be increased simply by elongating the plasma.

Finally, they showed that plasma could further sharpen an already focused electron or positron beam by a factor of at least two. The improvement is significant for a collider, in which the accelerated particles must be focused to a very small spot. The more tightly focused the beams are, the more collisions the collider produces. For a collider, the rate of collisions is as vital a parameter as the total energy.

These breakthroughs have fueled speculation about the scalability of the plasma scheme to the energy frontier, but first the technique must be tested using a currently available accelerator as the first stage. For example, a pair of plasma wakefield devices could be installed on either side of the collision point of the Stanford Linear Collider. That would double the energies of the beams from the present 50 GeV to 100 GeV. Each plasma afterburner would be about 10 meters long. Although such a project is not yet funded, SLAC is proposing to the Department of Energy construction of a high-energy beam line called SABER to further this research.

I have described these plasma accelerators solely in terms of electron acceleration. To accelerate positively charged particles, such as positrons, the electric field must be reversed. The easiest way to do this is to use a positron driver beam. The positive charge of this beam draws the electrons of the plasma inward, and similar to before, they overshoot the central axis and form a bubble. The direction of the electric field is flipped compared with the electron-beam configuration I described earlier, as is required to accelerate a trailing beam of positrons.

In addition, these plasma-based machines can accelerate heavier particles such as protons. The one requirement is that the injected particles must be already traveling at nearly the speed of light, so they are not left behind by the plasma wave. For protons, that means an injection energy of several GeV.

Physicists are making rapid progress in the quest for a plasma accelerator. Although many of the fundamental physics issues are solved, the making of practical devices still poses formidable challenges. In particular, beam engineers must achieve adequate beam quality, efficiency (how much of the driver beam's energy ends up in the accelerated particles), and alignment tolerances (the beams must be aligned to within nanometers at the collision point). Finally, the repetition rate of the device (how many pulses can be accelerated each second) is important.

It took conventional accelerator builders 75 years to reach electron-positron collision energies in the range of 200 GeV. Plasma accelerators are progressing at a faster rate, and researchers hope to provide the new technology to go beyond the microwave systems for high-energy physics in just a decade or two. Much sooner than that, the companion laser wakefield technology will result in GeV tabletop accelerators for a rich variety of applications.

Surf's up! SA

The ACCELERATOR demonstrated greater than 4 GeV of energy gain for electrons in just 10 CENTIMETERS.

MORE TO EXPLORE

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Accelerator Physics: Electrons Hang Ten on Laser Wake. Thomas Katsouleas in *Nature,* Vol. 431, pages 515–516; September 30, 2004. Also three research reports in the same issue.

The Lasers, Optical Accelerator Systems Integrated Studies (L'OASIS) Group at the University of California, Berkeley: **http://loasis.lbl.gov/**

Stanford's Plasma Wakefield Accelerator Experiment: **www.slac.stanford.edu/grp/arb/e164/index.html**