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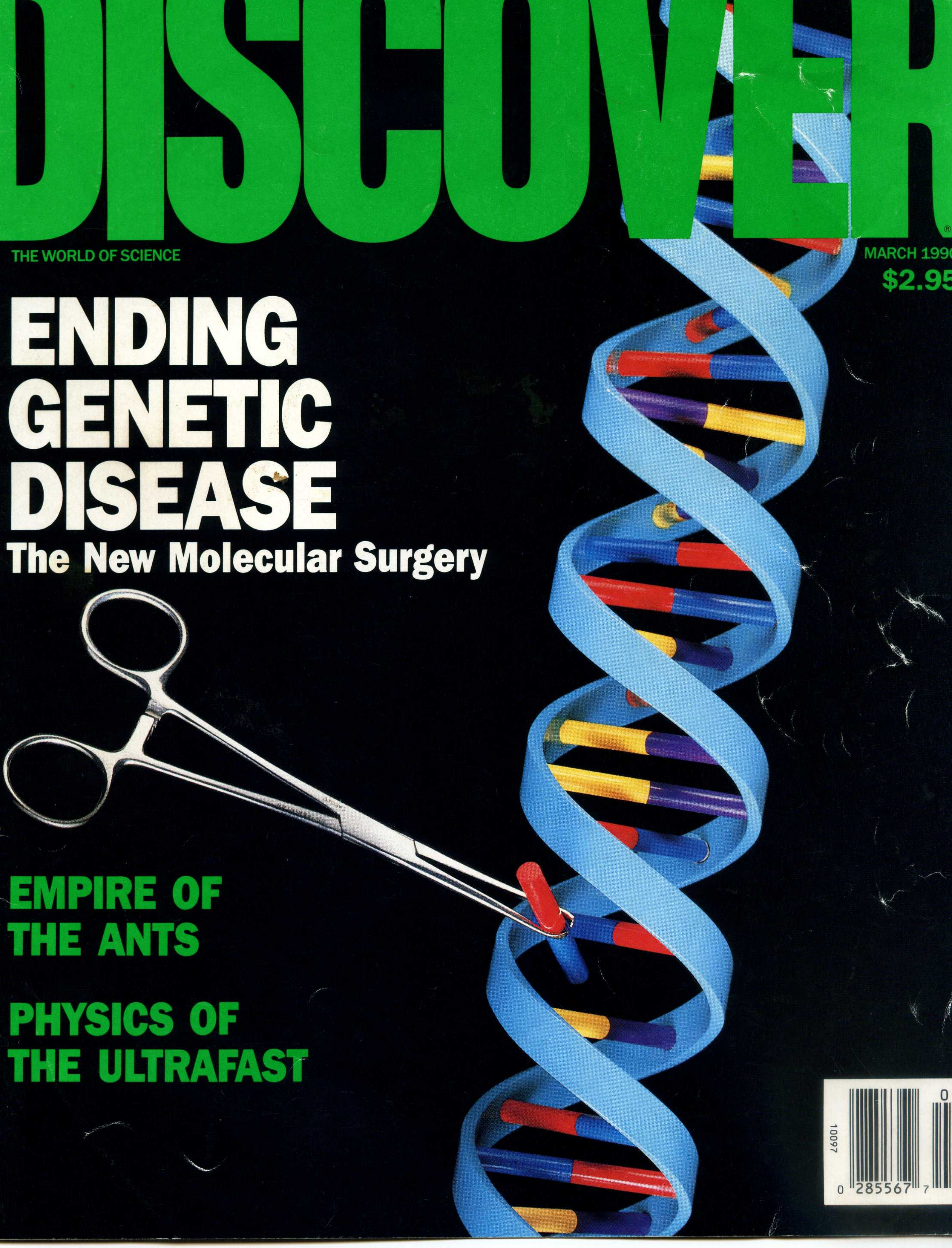

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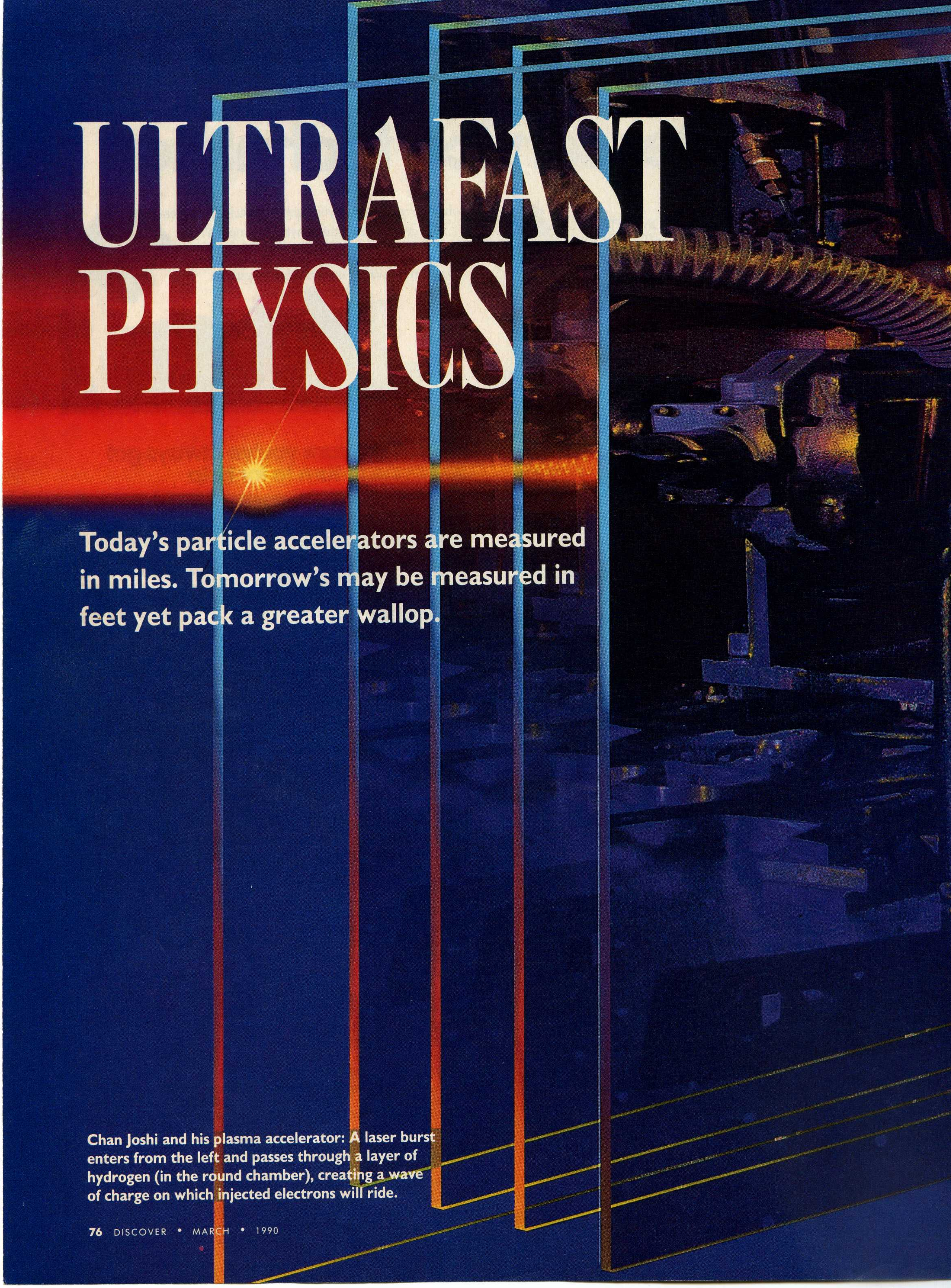
Today's particle accelerators are measured in miles. Tomorrow's may be measured in feet yet pack a greater wallop.



Chan Joshi and his plasma accelerator: A laser burst enters from the left and passes through a layer of hydrogen (in the round chamber), creating a wave of charge on which injected electrons will ride.

BY GARY TAUBES

Most people have never heard of Chan Joshi, and it's possible they never will. The 36-year-old physicist spends his days in a cramped laboratory in the basement of the UCLA engineering building, waist-deep in lasers, cables, mirrors, and optical lenses. To the untrained eye the lab looks less like a place where physics experiments are conducted than a chop shop for old *Star Wars* parts.

But Joshi's lab, built up from scratch over four years, represents several million dollars' worth of what could be called long-shot physics. In this little room Joshi and his colleagues hope to create a prototype of a plasma particle accelerator, a radically new type of machine that could represent the very future of particle physics. If Joshi succeeds, he could well become—by physics standards, at least—a household name.

But that's a considerable if; radical change isn't easily achieved in a world of billion-dollar machines. Particle accelerators have been with us now for more than six decades, and in all that time the technology of the machines has remained fundamentally the same. The generic accelerator is an extremely long, narrow tunnel charged with powerful electric and magnetic fields. When a subatomic particle—say, an electron or a proton—is fired into the tunnel, the fields cause the tiny

PHOTOGRAPH BY ERIC SANDER; PHOTOCOMPOSITION BY GUY FERY

projectile to accelerate to near-light speed; the longer the tunnel, the greater the acceleration and energy of the particle. Physicists then guide these particles along a path that ensures they will collide either with each other or with a stationary target. And the greater the energy released on impact, the greater the likelihood that the energy released will be converted into new particles. By studying the resulting subatomic shrapnel, physicists can gather information about the fundamental nature of matter and about the forms in which it arose during the incredibly energetic first instants of the universe's existence.

Unfortunately, to get closer and closer to the secrets of creation, physicists have needed ever more powerful—and ever bigger—machines. One of the first particle accelerators, designed in 1930 by California physicist Ernest Lawrence, was about the size of a bread box and was capable of cranking out 13,000 electron volts—barely a spark by today's standards. Today's top collider achieves energies 5 million times that and needs 14,000 times the elbow room to do it. The accelerators already planned for the next decade will be several times larger than that. "By thirty years from now," Joshi says, "physics machines will be getting too costly, too big, and some kind of new revolutionary approach will be required. This is what we're aiming at."

Today's colliders come in two basic shapes: straight and round. In the straight model—such as the linear collider at Stanford—oppositely charged particles speed together down an electromagnetic racetrack. At the end of the straightaway the two particle swarms are split and sent into opposite arcs that branch off from the tunnel like exit ramps off a highway. Curving back around through these semicircular arms, the swarms head straight for each other and slam together in a shrapnel-scattering collision.

In round models—like the new European ring collider outside Geneva—the end is the same, although the path to destruction is different. Particles are fired in opposite directions down a circular track and directed around and around the ring. With each trip they pick up a little more energy. Finally, after tens of thousands of revolutions, they are forcibly introduced to each other.

The laser beam is focused to one-fiftieth of an inch. Intense and dangerous, it is fired through two centimeters of hydrogen gas confined in a sealed chamber.

Although the technology of these machines hasn't changed very much, their size has—and so has their cost. The European collider can put out a prodigious 70 billion electron volts (70 GeV), but to achieve that energy level, it took a ring 16 miles around and a billion dollars. Like the 50-GeV Stanford linear collider, this machine accelerates electrons, which are the particles of choice for many physicists: electrons are lighter, more fundamental particles than protons, and the debris they yield is thus easier to predict and analyze. But electrons are not very easy to accelerate in rings because they radiate away energy as they round curves, and the European collider is already near the limit for such machines.

A second approach to particle collision, therefore, employs the relatively heavy protons, which round curves effortlessly and thus can be boosted to much higher energy levels. The proton-accelerating Tevatron at Fermilab in Batavia, Illinois, can get up to one trillion electron volts (one TeV). The Superconducting Supercollider, scheduled to be built in Texas during the 1990s, will also accelerate protons and will achieve an astounding 20 TeV. However, the Supercollider—assuming that it ever gets built—will have a 42-mile circumference and will probably cost much more than the $5 billion its proponents estimate.

Which brings us back to lighter, more easily accelerated electrons: True, we may not be able to build much bigger ring colliders for electrons, but couldn't we build longer linear colliders to reach higher and higher energy levels? Theoretically, yes, but even the Stanford accelerator needs a two-mile tunnel to get its electrons fired up to speed, and it cost more than $100 million to build in 1983. A linear accelerator that could achieve results comparable to those expected from the Supercollider would have to reach one TeV and accelerate its electrons through a tunnel more than 12 miles long. Within three decades, physicists predict, accelerators will have to be five to ten times that size.

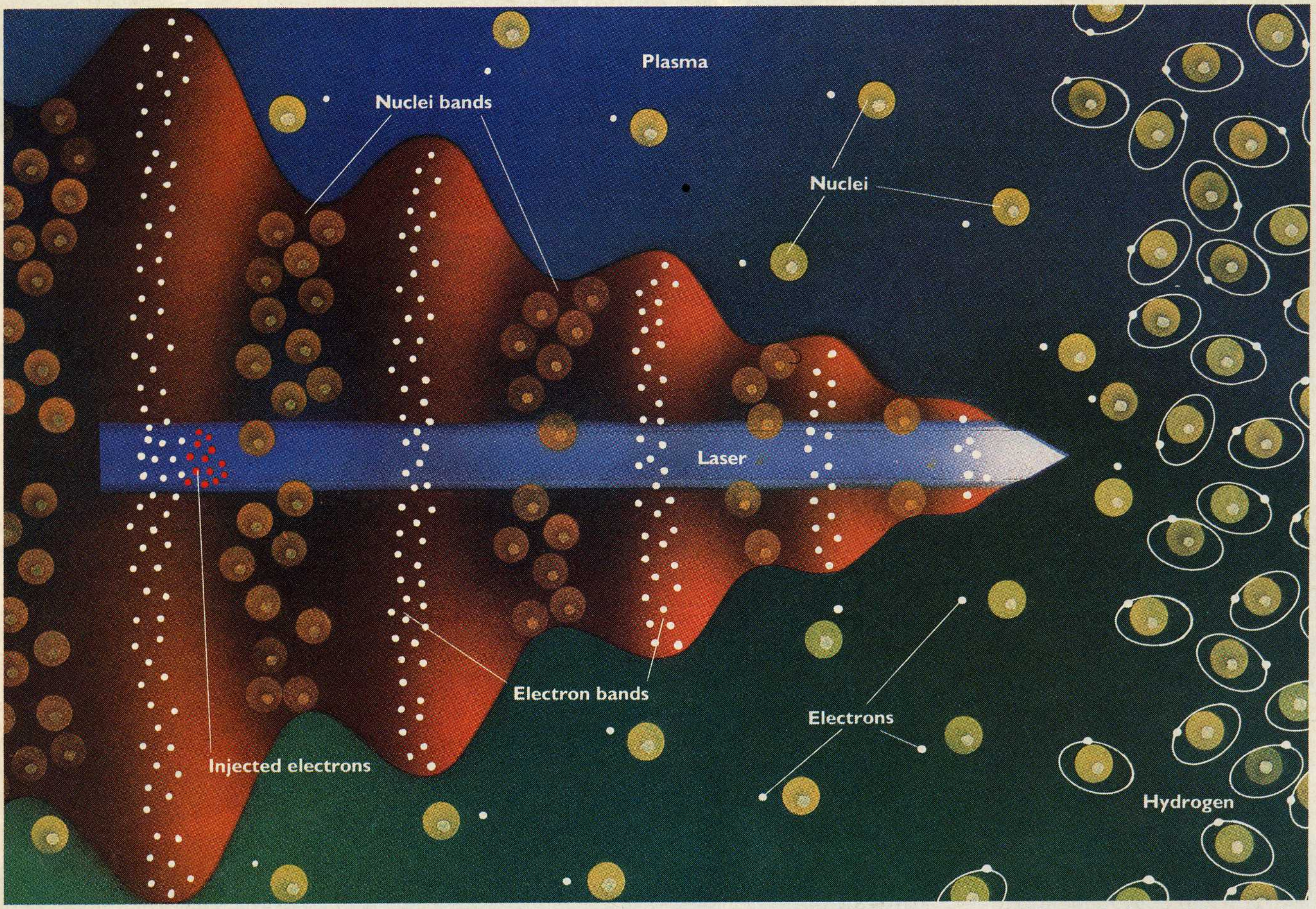
Joshi proposes to find a way out of all these size restrictions. The bits of equipment that clutter his lab represent a miniature prototype of a system that could become the accelerator of 30 years hence—a machine that will not only accelerate electrons to the incredible energy levels required by future physicists, but will do so in the space of just a few hundred feet.

The spark that drives the system is a single, powerful laser pulse. The flash of light originates in a projector at the front of the room as a pair of different laser frequencies combined into a single beam. At first, the beam is a weak one, about as big as a pinpoint and barely strong enough to scorch a piece of paper. Mirrors then bounce the beam through an array of amplifiers that boost it to 10,000 times its original power.

At this stage the laser packs a considerable energy wallop, but it is dispersed energy, spread across a beam with the circumference of a volleyball. The laser gets down to scientific business only after it is bounced through a maze of six mirrors and focused back down to one-fiftieth of an inch. Now, intense and dangerous, the beam is fired through two centimeters of hydrogen gas confined in a sealed chamber. Plowing through the gas, the laser pulse rips the hydrogen's electrons right off its atoms, creating what is known as a plasma—gaseous nuclei with no orbiting electrons.

Because the two laser frequencies alternately magnify and cancel each other, they create a repeating wavelike pattern of very high and very low light intensity. These areas, which can be thought of as a passing series of peaks and valleys, segregate the oppositely charged particles: As the high-intensity peak passes through the gas, it pushes away some of the lightweight, negatively charged electrons. Left behind in the low-intensity valleys is a higher concentration of heavier, positively charged nuclei.

As the peak passes, the electrons start



A laser pulse of two different frequencies is fired into hydrogen gas. The pulse rips electrons away from their nuclei, creating a plasma. Because the laser frequencies alternately magnify and cancel each other, they create a wave of high and low light intensity, or "peaks" and "valleys," that increasingly segregate the electrons and nuclei into bands of negative and positive charge. If other electrons are now injected between the bands, they will be carried along and accelerated to near-light speed.

rushing back toward the positively charged nuclei. Because they are moving so fast, they actually overshoot the nuclei, but they are soon met by the next high-intensity peak and given another shove. With each successive peak the electrons are, in effect, set vibrating back and forth like a plucked guitar string. Thus the laser begins to create band after band of electrons and nuclei, alternating down the entire length of the pulse.

As the thousands of peaks and valleys in a single laser pulse pass through any given region in the plasma, more and more electrons in that region are recruited into this back-and-forth movement, and the more completely the electrons and nuclei are separated. Thus, the farther back the band is from the leading edge of the laser pulse, the greater the overall magnitude of the vibration, and the greater the charge of the band—the effect is that of a steadily increasing wave of charge, moving through the plasma along with the laser.

At nearly the same instant the beam enters the gas, an injection gun fires a cluster of high-speed electrons into the wake of charged bands that follows. The electrons are aimed to land directly behind a band of protons and directly in front of a band of electrons. Attracted by the protons and repelled by the other electrons, they ride along on the wave, following the laser at near-light speed, picking up energy.

Einstein showed that as matter moves faster and faster, some of the energy of its acceleration is converted into mass. At relatively slow speeds the effect is not detectable; but as an object approaches the speed of light its increased mass becomes significant. With just two centimeters of plasma and a laser flash of less than a billionth of a second—"a long time in our business," says Joshi—researchers armed with energy detectors and particle detectors will, in theory, be able to observe the accelerated electrons gaining mass, and if they do, they'll know the prototype accelerator can work. "In another year," Joshi says, "we might have proof we can do it."

If they get that proof, Joshi's next step, of course, would be to build a bigger accelerator, for the longer a particle rides on a plasma wake, the more speed and mass it picks up. To whip electrons up to one TeV—nearly 15 times the energy produced by the electron accelerator in Geneva—the two-centimeter plasma layer would have to be replaced by a 300-foot tunnel. The scale of the machinery would be considerable, but it would still be compact compared with conventional colliders.

It's not just Joshi who's fomenting the collider revolution. Around the country more than 150 physicists at a dozen research centers, including Stanford, Cornell, Texas A&M, and the University of Maryland, are working to banish the Brobdingnagian accelerator and replace it with an affordable, down-size model.

ILLUSTRATION BY IAN WORPOLE

One of the first to look seriously into plasma and its accelerator applications was physicist John Dawson. Between 1958 and 1973, as head of Princeton's controlled-fusion energy project, Dawson investigated ways to harness the energy released in the fusion of different forms of hydrogen plasma. He then began toying with using plasma's wave-propagating ability to develop a new type of accelerator.

In 1979, after moving to UCLA, Dawson outlined the accelerator that would eventually inspire Joshi and others. Primarily a theoretician, Dawson never constructed the accelerator himself; he tested his ideas only on paper and in the brain of a computer simulator.

Dawson calculated that he would need a stretch of plasma roughly the length of a football field in order to get his electrons up to collision speed. Even in a chamber this long, however, he would focus his attention on a spot measuring barely a quarter inch. So easily do electromagnetic waves excite plasma that almost immediately after the laser wake forms it begins to break up into turbulent swirls. If the electrons cannot ride a straight, true wake, they cannot accelerate sufficiently. However, Dawson knew that just behind the laser things aren't so terribly turbulent.

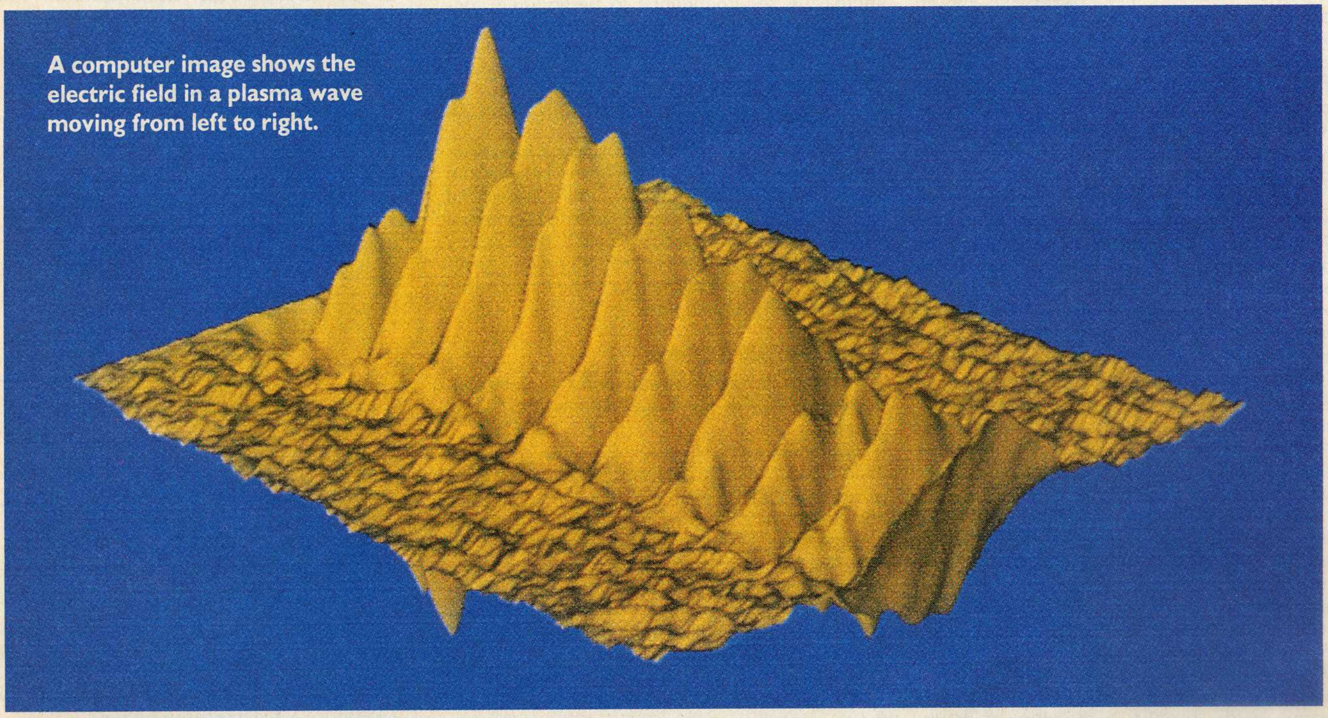
"There's the light wave, the plasma wake, and the electrons all chasing each other through so many meters of plasma," he says, "and somewhere in the back the whole thing breaks into turbulence. But just in that little region behind the light pulse, things are still calm because the wake hasn't yet had time to misbehave." In that tiny space, however, 10 billion electrons would be racing along—a more than ample particle sample.

One wondrous scenario has doctors placing dime-size particle accelerators inside the human body to photograph biochemical reactions.

Ultimately, the power that could be generated by plasma systems could help physicists re-create some of the particles that were produced in the first instants after the Big Bang. Theories suggest that at 10^{-43} second (about one ten-millionth of a billionth of a billionth of a billionth of a billionth of a second) after the birth-blast of the universe, the energy extant in what would become the cosmos was 10^{19} GeV (10 billion billion billion electron volts). An instant later, at 10^{-35} second, energy levels dropped to 10^{14} GeV, and the fundamental building blocks of matter—quarks and electrons—became distinct from each other. At 10^{-6} second, when energy had quieted to a few hundred million electron volts, quarks began coalescing into neutrons and protons. It wasn't until a comparative eternity later (about a minute) that the protons and neutrons began assembling themselves into simple elements like helium and lithium.

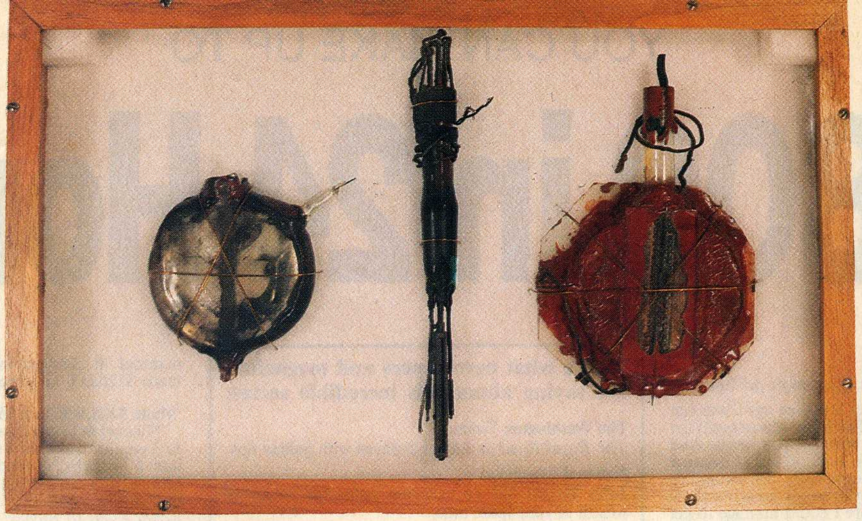
In order to test these cosmological theories, physicists have used particle accelerators to try to re-create the conditions that prevailed just after the Big Bang. But so far no colliders have ever topped the one TeV mark, an energy level that duplicates conditions only as far back as 10^{-12} second after the Big Bang. Even the planned 20 TeV Supercollider will go back only as far as 10^{-16} second. And the Supercollider, physicists think, is pretty close to the limit for proton-accelerating ring colliders. To get any nearer the ultimate moment of creation, physicists will need electron-accelerating linear colliders producing energies between 5 and 10 TeV.

But the first step for plasma researchers is the much more modest goal of building a one-GeV accelerator. The



A computer image shows the electric field in a plasma wave moving from left to right.

COMPUTER SIMULATION COURTESY WARREN MORI, D. W. FORSLUND, AND J. M. KINDEL, LOS ALAMOS NATIONAL LABORATORY



Two of the first particle accelerators, built in 1930, are preserved in a showcase at the University of California. Inside these vacuum chambers, radio waves accelerated hydrogen ions. The electric filaments that ionized the gas and carried the radio frequency for the unit on the left are also displayed.

PHOTOGRAPH COURTESY LAWRENCE BERKELEY LABORATORY, UNIVERSITY OF CALIFORNIA

machine would have only one-fiftieth the punch of the Stanford machine, but it would help prove that the plasma-wave concept is a viable one. Depending on how efficient it turns out to be, the plasma chamber could be from four inches to three feet long.

At the moment, though, even such a relatively modest accelerator is still physics fantasy. Joshi's two-centimeter system has not even had a first full-dress rehearsal, and may not until 1991. None of the other labs working on plasma systems is much further along.

For physicists with a bit less patience, there is a slightly more conservative route to the one-GeV goal: the dielectric accelerator, now being developed at Argonne National Laboratory outside of Chicago by physicist Jim Simpson. Like Joshi's approach, this technology also promises to bring accelerators down to size, but it does so without using plasma. The disadvantage of the dielectric technology is that, although it might produce accelerators much more powerful than conventional models, they would still be much less powerful than a plasma accelerator. The advantage is that a prototype might be completed relatively soon. Indeed, Simpson hopes to have a one-GeV model by 1995.

A dielectric is simply an insulating material like glass or plastic or ceramic. What makes dielectrics useful to particle physicists is that in the presence of a rapidly moving charged particle, the material will radiate electromagnetic energy.

Simpson and his colleagues use dielectric materials in the shape of a long, thin tube. When they fire a short pulse of electrons—known as the drive beam—down the tube at near-light speed, the particles cause the atoms in the tube walls to become polarized and radiate electromagnetic energy. The energy converges in the center of the tube as an electric field, which follows along after the drive beam, matching its velocity. The physicists then inject a smaller bunch of electrons—called the witness beam—into the moving field; these particles ride along with the field, also following the drive beam and also attaining near-light speed. As they go they pick up energy from the drive beam and from the dielectric material and convert it into mass.

The longer the dielectric tube is, the more energy the electrons can collect. Simpson estimates that for every three feet the electrons move down the tube, 100 million electron volts can be produced. In theory, the one-GeV goal could be attained in a ceramic tunnel as little as 30 feet long. Back in 1987 Simpson and company proved that their system was actually capable of accelerating electrons. Although this put them ahead of their UCLA competition, the technology is certainly not bug-free.

"This is a brand-new area," says Simpson. "At this point all we're trying to do is see if it works at all. Practical applications could be decades away."

Argonne physicist Paul Schoessow agrees: "When you're pushing technology to the limit," he says, "there's always something that's going to bite you."

Like Joshi, the Argonne researchers believe it will be a good 20 years before their technology stops biting. Full-scale dielectric accelerators, they believe, may not be a reality until the second decade of the next century. Until that time their work will have no real practical application. Plasma technology, however, may have a more immediate future. Joshi believes that even before the superpowered plasma accelerator is built—indeed, even if it never is—his group may find many ways to apply whatever technology they do develop.

"What we learn we could use to develop compact low-power and medium-power systems," he says. "These could be used by universities and other private groups who don't have access to giant colliders." Joshi believes that plasma technology could also be adapted for medical applications such as radiation therapy and diagnostic imaging.

Dawson agrees, suggesting that if engineers could make extraordinarily powerful accelerators that could fit in a room, they could also build moderately powerful ones the size of a football or smaller—perhaps even the size of a dime. He envisions medical accelerators that could actually be slipped inside the human body.

"Imagine if we could generate a million electron volts in a millimeter," Dawson says. "The X-rays would then be coming from inside out. You get a totally different view." He envisions plasma accelerators that would shoot what are called femtosecond X-ray pulses—X-rays a quadrillionth of a second long. "You could look at very fast phenomena," he says. "You could actually photograph chemical reactions as they take place—for instance, carbon combining with hydrogen. If we could perfect a way of making these pulses follow one right after the other, you could even take motion pictures."

As the man who hatched the whole scheme to begin with, Dawson is not reluctant to describe such wondrous scenarios. Plasma technology, he believes, is a research area whose potential has only begun to be explored. "This technology opens up whole new areas of things that people have never imagined," he says. "Plasma accelerators will allow us to explore both the nature of the universe around us and the basic processes of life within us. It is a technology that reveals both the infinitely vast and the infinitely small." ☐

Gary Taubes wrote the September cover story on cosmic rays.