Surfing a Laser Wave

Toward a tabletop particle accelerator

By IVARS PETERSON

Particle accelerators are the behemoths of physics. The Stanford Linear Collider, for example, hurls electrons and positrons down a 2-mile-long tunnel before steering the particles into head-on collisions in the middle of a massive detector.

It's difficult to imagine shrinking this kind of machine to fit on top of a bench in a university laboratory. Advances in laser technology, however, have opened up the possibility of building a tabletop accelerator.

Researchers can now generate and manipulate extremely short, immensely powerful laser pulses that instantly strip electrons from atoms to produce a plasma of charged particles. As demonstrated in recent experiments, the same pulses create electric fields strong enough to organize some of these electrons into a tight beam and accelerate them to high energies in just a few centimeters.

"We have shown for the first time that a beam of electrons comes out of this laser-plasma interaction," says Donald P. Umstadter of the University of Michigan's Center for Ultrafast Optical Science in Ann Arbor.

"That's very exciting," says Toshiki Tajima of the University of Texas at Austin. "It's an extremely important result."

Once the Michigan findings are firmly established, researchers believe that new devices built to take advantage of the observed effects may ultimately develop into tabletop particle accelerators.

The availability of such compact, relatively inexpensive laboratory machines could reduce the need for major facilities like the Stanford Linear Collider. It would also make possible the generation of extremely short X-ray pulses for probing materials in unprecedented detail.

The idea of a laser electron accelerator goes back to 1979, when Tajima and John M. Dawson of the University of California, Los Angeles, proposed firing intense laser light into a gas to create a plasma of electrons and positively charged ions. They postulated that, just as a motorboat racing across a lake leaves a wake, the laser pulse would generate a disturbance in the plasma as it traveled through the gas.

Additional electrons injected into the plasma could then surf the laser pulse's wake, draining energy from the plasma wave as they steadily picked up speed.

Development of the wakefield accelerator was initially stymied by the lack of powerful lasers capable of delivering short pulses of light. In 1987, Gerard A. Mourou, then at the University of Rochester in New York and now director of Michigan's optical science center, led a team that, to generate high-power laser pulses, invented a technique called chirped pulse amplification.

Researchers now have laser systems that produce light in bursts as short as 100 femtoseconds and with peak powers as high as 100 trillion watts.

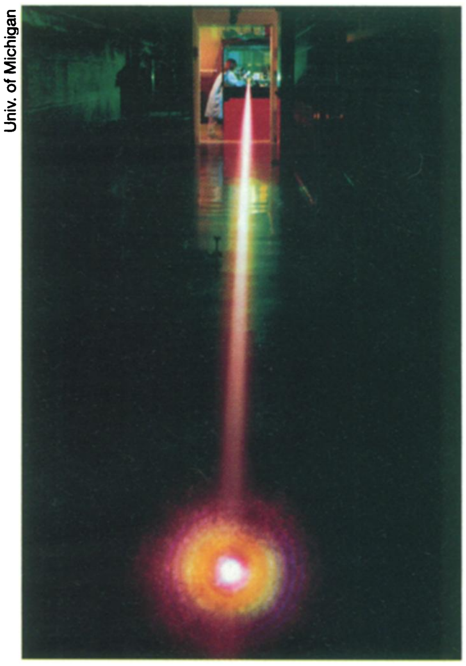
Umstadter and his colleagues have discovered that such powerful laser pulses are strong enough to create a plasma wave in a stream of argon gas and that the wave, in turn, actually accelerates electrons.

"Normally, plasma-wave electrons can't be accelerated by the plasma wave itself," Umstadter says. "We suspect we're generating additional electrons that are out of phase with the plasma wave's electric field, and these electrons get caught by the wave."

Moreover, the accelerated electrons, traveling at nearly the speed of light, appear to be automatically focused into a narrow beam. "You need a certain level of laser power to get this effect," Umstadter remarks. His team has produced electrons with an energy of 1 gigaelectronvolt after about 1 centimeter of acceleration.

These findings have encouraged the Michigan team to design an all-optical laser electron accelerator. One laser pulse creates the plasma wave. A second pulse travels the same route to push extra electrons into the wave.

"We're pushing the laser technology to its limits at the same time as we're exploring new approaches to plasma wave generation and the injection of electrons," Umstadter notes.



Univ. of Michigan

A laser pulse traveling down a laboratory hallway bores a plasma channel through the air.

Researchers have also made progress in another facet of laser acceleration. Ordinarily, a focused laser beam travels only a short distance into a gas before fanning out. Moreover, as the light ionizes gas atoms to create a plasma, the beam spreads out even more quickly.

It turns out that, under the right conditions, light and plasma can interact to keep the light focused into a beam as it travels through the gas. "It's what I would call a self-organizing tendency of laser [light] and plasma to produce the effect we want," Tajima says.

The Michigan group has generated such a plasma channel, 80 micrometers wide and more than 20 meters long, through air by sending pulses from a low-energy laser down a laboratory hallway.

"Once we discover how to use these optical channels to accelerate electrons over longer distances, it may be possible to generate energies equivalent to [those of] today's most powerful conventional particle accelerators," Umstadter notes.

The Michigan effort isn't the only one devoted to developing a wakefield accelerator. Groups at the University of Texas, UCLA, the Naval Research Laboratory, and the Argonne National Laboratory and several teams in Japan, France, and elsewhere are all pursuing various schemes aimed at achieving this goal.

"We have a spectrum of different methods, and we have promising results," Tajima says. "It's an exciting time right now." □