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Clever ways of choreographing lasers, plasmas and electron beams could transform particle physics. But as **Keay Davidson** and **Justin Mullins** report, it's very early days...

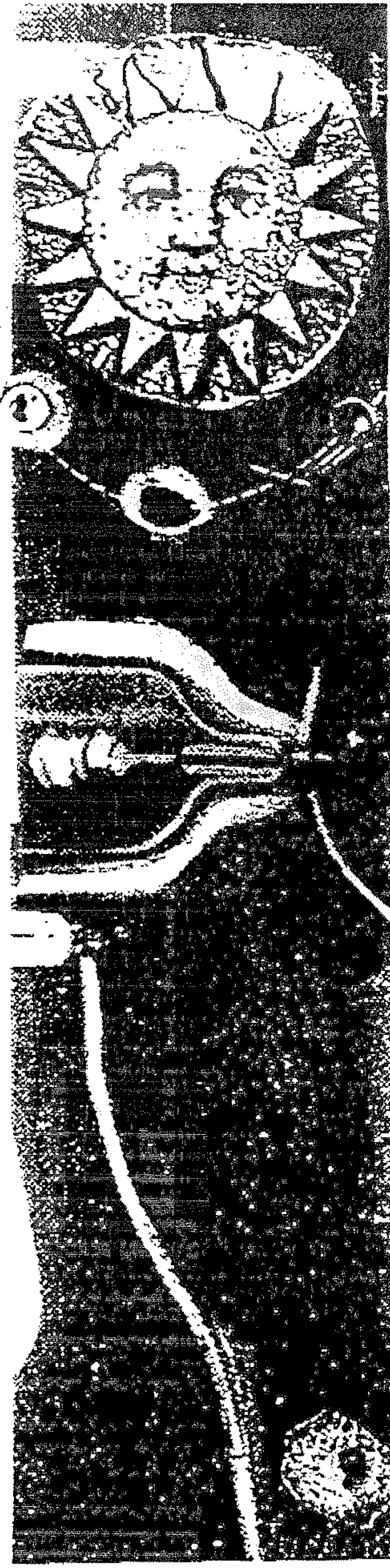
AS SURFERS ride the waves along the coastline of southern Californian, scientists nearby are creating waves of a different sort. Their waves are formed in high temperature plasmas and the charged particles that surf on them approach the speed of light. The technique, researchers say, could lead to a new generation of smaller and more powerful particle accelerators than the giant machines running today.

The largest accelerators are tens of kilometres long. The world's longest, at the particle physics laboratory at CERN near Geneva, is circular and measures 27 kilometres round. And the Superconducting Supercollider would have been 87 kilometres in circumference, if it had been built in the US. Why so big? Accelerators work on the principle that charged particles speed up in an electric field. The stronger and longer the field, the more energy it can pass to a particle. But the fields in today's machines cannot be made any stronger without ripping electrons from the fabric of the apparatus, causing sparks which prevent the accelerator from working. So, using conventional technologies, the only way to accelerate particles to the high energies physicists want is to make the electric fields, and hence the machines, longer.

Plasma wave accelerators work differently. Inside them a powerful laser beam heats a thin pencil of gas in a larger chamber to form a plasma. At

Illustrations: Gary Powell

accelerator on benchtop?



temperatures of about 100 000 kelvin, the atoms in the gas dissociate into positive ions and a sea of free electrons. The plasma waves are created in this sea by laser light. The alternating electric and magnetic fields that are part of the laser beam's electromagnetic wave together force electrons out of their path when the intensity is at a maximum. But they allow the electrostatic repulsion between the electrons to force them back when the intensity falls to zero.

The crests and troughs of these waves correspond to regions of high and low electron density. This variation creates powerful electric fields which sweep through the plasma approaching the speed of light. The fields exist over distances of a few ten millionths of a metre. Confined to such a scale, the electric fields can be extremely powerful without affecting the apparatus and can accelerate the particles surfing on these waves to very high energies.

The bigger the plasma waves, the stronger the electric fields. To make them as powerful as possible, physicists rely on the phenomena of resonance. There is a certain frequency at which the electrons in a plasma move back and forth naturally. When the frequency of the light matches this, the plasma waves are at their largest.

Find the beat

Unfortunately, a plasma reflects light that exactly matches its own natural frequency. So, in 1979, John Dawson, a physicist at the University of California in Los Angeles, and Toshiki Tajima at the University of Texas in Austin, proposed generating plasma waves using two laser beams of higher but slightly different frequencies that could pass through the plasma. When these overlap they interfere to form a "beat wave" of a lower frequency which matches the natural frequency of the plasma.

Initially, physicists found it extremely difficult to accelerate particles using the beat wave technique. The intensity of laser light must be extremely uniform to create plasma waves and this can only be achieved when it is precisely focused. One of the main problems facing physicists is creating long enough waves: the waves last only for the very short distance over which the beam is precisely focused. Scientists have found, however, that the plasma itself can focus light, extending the region of uniform intensity by seventy times. But there is a long way to go. The best experiments have achieved a uniform intensity over distances of no more than a centimetre or so.

Short but strong

Physicists need to increase this to a few metres to get the best performance out of their machines. This is the maximum length for a plasma accelerator. Although they are extremely powerful, the electric fields are very short, stretching from the crest of the plasma wave to the trough. When an electron has surfed into the trough it cannot gain any more energy. In practice, this happens after the wave has travelled a few metres. To reach very high energies physicists expect to build future machines in short stages, accelerating the electrons more at each stage.

Turbulence is also a problem. The ions in a plasma are heavier than electrons and so take longer to react to light passing through. At the head of the plasma-wave train, the light beam is constantly plunging into fresh plasma so any movement of ions here is insignificant. But the waves behind begin to interact with these ions causing the plasma to become

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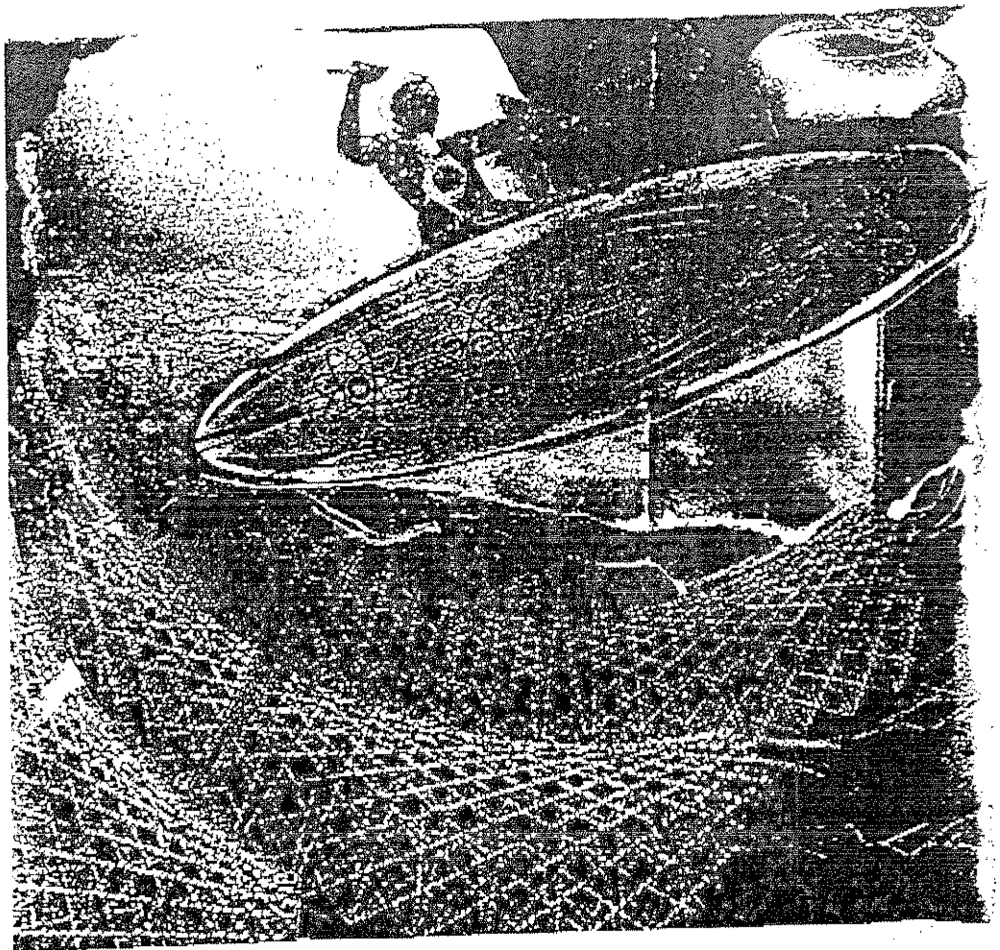

energetic electrons can travel faster than light in certain gases and liquids. At these speeds the particles emit bluish light, known as Cerenkov radiation, in a cone about their path, rather like the shock waves created by a supersonic jet. In doing this, the particles lose energy and slow down.

Physicists can accelerate electrons by reversing the process. A beam of particles gains energy if light hits them at the Cerenkov angle—the angle subtended by the cone of Cerenkov radiation. The technique is known as inverse Cerenkov acceleration.

No comparison

Using this method, scientists at the Brookhaven National Laboratory in New York have accelerated electrons to 3·7 MeV over a distance of 12 centimetres. This may not be as much as the beat wave or wakefield techniques generate, but Wayne Kimura, the physicist in charge of the experiment, says the comparison is unfair. Kimura achieved his result with a 700 megawatt laser while Joshi used two lasers, both about a thousand times more powerful.

Back in Oxfordshire, however, Bingham believes that inverse Cerenkov techniques do not offer the potential of plasma wave accelerators. Although it is inherently less complex because there is no plasma to sustain, the technique is less efficient because the laser has to illuminate a larger region and is therefore less intense. Kimura is continuing his experiments. In the next part of his project he hopes to reach 100 MeV.

While 1000 MeV energies are theoretically possible with benchtop-sized accelerators, physicists want teraelectronvolt (TeV) accelerators which are at least a thousand times more powerful, to carry out their experiments. Such machines will be built in stages with each section accepting electrons from the previous one and accelerating them to higher energies. The sections may have to contain progressively denser plasmas. The greater the density, the larger the plasma waves they can support but these have to be driven by more powerful lasers. To reach such energies, scientists believe that plasmas might have to exist in solid form and the plasma waves be driven by X-ray lasers. TeV accelerators may be less than a kilometre long although Bingham cautions that the technology is still many years away—if it is possible at all.

The research shows that lasers can accelerate electrons but producing a well-focused beam that physicists can use is difficult. The plasma itself can help. The waves create magnetic as well as electric waves and these act to pinch the electrons into a tightly packed beam. Nevertheless, Robert Cahn, a physicist at the Lawrence Berkeley Laboratory, believes these methods are unlikely to lead to accelerators that will be useful for probing the heart of matter in the next twenty years. "When high temperature superconductors were discovered, some physicists wanted to redesign the SSC to include them. But fundamental advances cannot always be applied immediately in the way you want."

Others agree. A recent report on the future of high-energy physics commissioned for the American government found that although some ingenious ideas had been put forward, none of these were yet suitable for a high-energy physics accelerator.

Silicon sculpting

But physicists are not the only people to use accelerators. The high-energy electrons from plasma-wave accelerators could be fired into a target to produce X-rays. This would have applications in the semiconductor industry, for example, where the small wavelength of X-rays makes them ideal for etching fine detail onto silicon chips.

An important feature of plasma-wave accelerators is that they produce small bunches of electrons separated by the wavelength of the plasma. In turn, these produce small, rapid bursts of X-rays which could be extremely useful in examining structures such as chemical bonds and muscle tissue that would be destroyed or damaged by a continuous beam. According to Bingham, these accelerators could be ready in ten years and would be much smaller than existing X-ray sources which fill a small room.

Much depends on the success of the next generation of experiments. At the Rutherford Appleton Laboratory, Bingham hopes to collaborate with Joshi and a team from Imperial College in London to accelerate electrons to 100 MeV in about a centimetre using plasma-beat wave techniques. If all goes to plan, they hope to start producing results within a year. "Once the experiments have been done, it's amazing how quickly industry can pounce on technology like this, improve it and turn it into a viable product." Chip manufacturers, chemists and biologists may have to wait only ten years to see the fruits of plasma-wave accelerators. High-energy physicists, however, are destined to wait much longer.

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turbulent and the waves to decay. The solution is to fire the lasers in pulses with enough time between each to allow any turbulence to settle down.

The lasers that heat the plasma cause their own set of problems. In the early 1980s, their optics were not good enough produce a uniform plasma. This lead to plasmas in which the density of electrons varied from place to place. As the density changes, so does the resonance frequency making plasma waves difficult to sustain for more than a fraction of second. And because of imperfections in laser optics, the intensity of the beam along its cross section could vary—also producing variations within the plasma. By the end of the decade, scientists were able to solve both these problems as more powerful lasers with better optics became available.

The first breakthrough in plasma wave acceleration came in 1992 when a team at UCLA led by the physicist Chandrashekar Joshi accelerated electrons to 9 million electronvolts (MeV) over a distance of only 1 centimetre. They found that the waves were unable to pick up slow moving electrons. In order to catch the waves in the way surfers have to paddle to catch ocean waves, Joshi had to inject an electron beam into the plasma that had already been accelerated to 2·8 MeV. In April this year the team announced that they had reached 30 MeV—using fields that were thirty times larger than those possible in conventional accelerators. If they can make their design work over ten centimetres, they could reach 300 Mev.

Robert Bingham at the Rutherford Appleton Laboratory in Oxfordshire is confident of further success. "There is no reason why physicists cannot accelerate electrons to energies greater than 1000 MeV over about ten centimetres," he says. To produce these energies with current techniques requires accelerators about a kilometre long. Bingham says a similarly powerful plasma-wave accelerator would fit on a benchtop although a rather large one.

'These accelerators could be ready in ten years and would be much smaller than existing X-ray sources which now fill a small room'

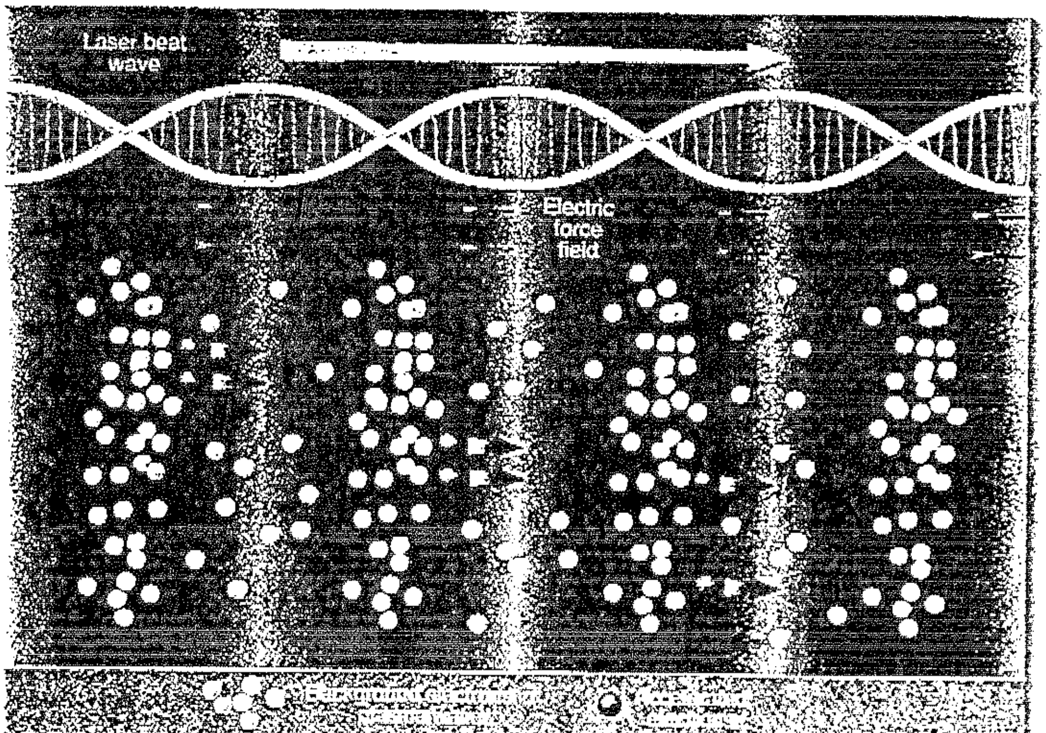
Other ways of producing plasma waves may be even more promising. Instead of matching the natural frequency of the plasma to a beat wave, it is possible to create waves using one intense pulse of light from a single laser. Such a pulse pushes electrons out of the way as it travels through the plasma. When it has passed, the electrons spring back. To produce the waves at the natural frequency of the plasma, the pulse must be half as long as those waves. The accelerated electrons surf in electric fields created in the wake of these pulses—hence the name wakefield accelerators.

The most impressive new work involving wakefield accelerators has been carried out in Japan. A 19-strong team of physicists led by Kazuhisa Nakajima based at the KEK particle physics laboratory in Tsukuba, has accelerated electrons to 18 MeV over a distance of only 0·6 millimetres. Although this may not be as high as the energies achieved with the beat wave technique, the electric fields were ten times stronger. Bingham is cautious about future applications, however. He says that the laser pulse can be so intense that it can push the electrons out of the plasma thus destroying the waves.

Andy Sessler, a physicist at the Lawrence Berkeley Laboratory in California, is more upbeat however. He points out that if this technique worked over a distance of a metre it would reach energies of 30 GeV—about a third of the energy possible with the 27-kilometre Large Electron Positron collider at CERN.

One problem with both beat wave and wakefield accelerators is that they accelerate very few electrons at a time. The main reason for this is that the lasers work only in short bursts at a time, releasing so much energy that they must cool down for twenty minutes between pulses. So wakefield techniques, for example, involve electrons surfing behind a single pulse of light. To make the most of the energy, scientists hope to use the same pulse more than once by piping it back to the beginning or by reflecting it into another accelerating chamber.

One new accelerating method does not rely on plasmas at all. Instead, it exploits the fact that highly



The laser beat-wave creates waves of high and low electron density in the plasma. These produce electric fields between the crests and troughs which accelerate "surfing" electrons to high energies