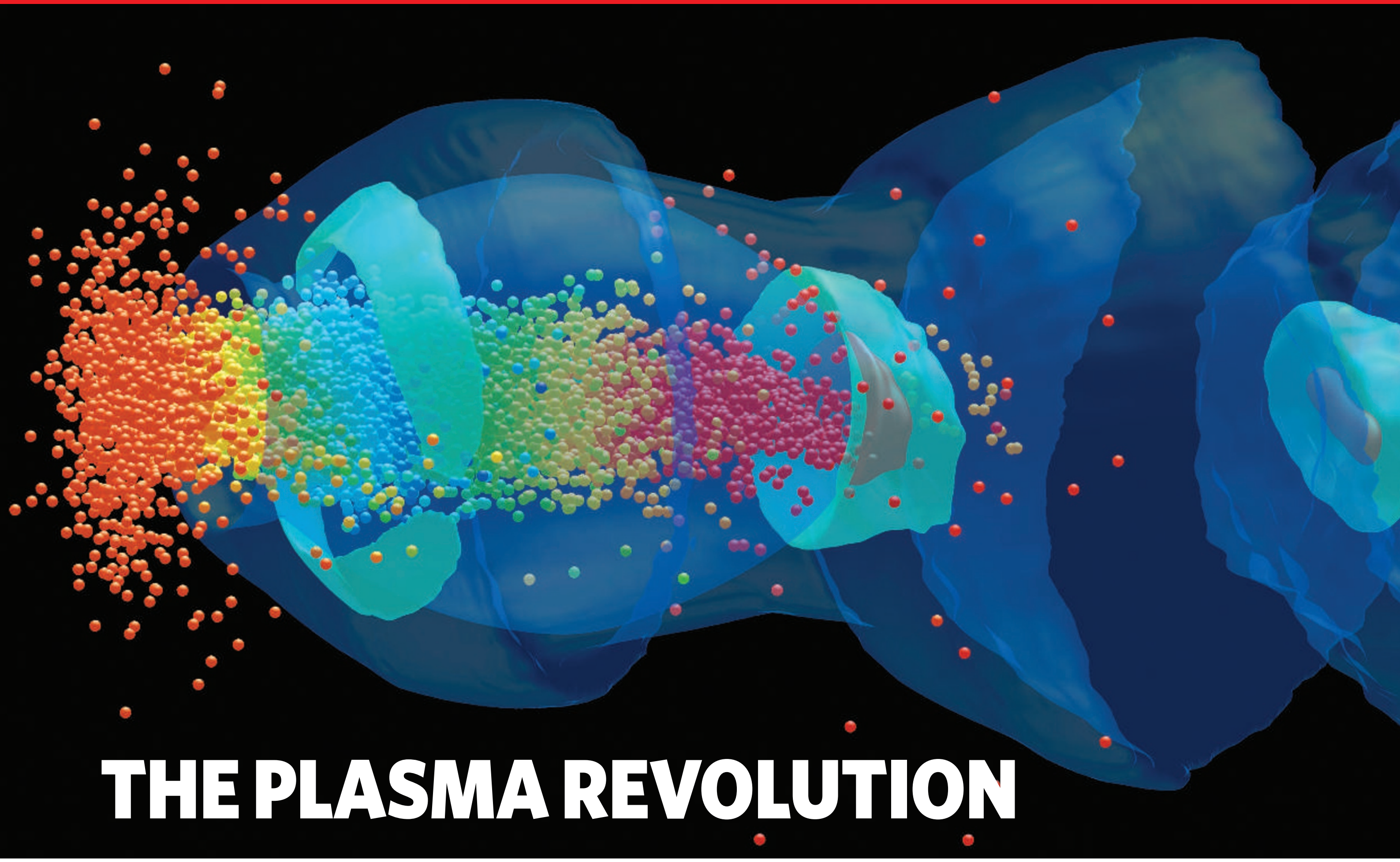


M. ZHOU/F. TSUNG

THE PLASMA REVOLUTION

Particle accelerators that use plasma technology promise to shake up the fields of high-energy particle physics and cancer treatment. Challenges remain, but smaller, cheaper machines are within reach. **Navroz Patel** reports.

Beyond the theoretical and engineering challenges of building particle accelerators, sheer cost is a concern for physicists whose work involves accelerating and smashing subatomic particles together at great speed. Many particle physicists think that if the planned International Linear Collider — a US$7-billion electron–positron collider that could begin operation within a decade — gets the go ahead, it may be the last large accelerator to be built for many decades as governments put a squeeze on funding.

The cost of accelerators is a concern not just for those who crave bigger and bigger machines to probe ever higher energy scales. Some oncologists think that proton beams could offer superior results to conventional X-ray treatment of some tumours, yet they say the size and cost of the accelerators has limited the number of studies into their clinical effectiveness.

"If we can reduce an accelerator's size, we can reduce the cost of proton therapy to something very small," says Charlie Ma, director of radiation physics at the Fox Chase Cancer Center in Philadelphia, Pennsylvania. Building a proton-treatment centre with conventional cyclotron or synchrotron accelerators costs between $100 million and $200 million, which explains why there are so few of these facilities (see 'Targeting tumours').

> **"Experiments over the next few years could make or break our field."**
> — Wim Leemans

But if accelerator research continues to progress at the rapid rate seen in recent years, the economics could be about to change for the better. A handful of groups are working on a new way to accelerate particles — known as wakefield acceleration — that should not only help push physicists towards the next energy frontier, but also provide affordable, table-top accelerators that could revolutionize cancer treatment.

The technique involves passing either a laser beam or a beam of particles through a plasma. The beam scatters electrons, causing an uneven distribution of charge between the scattered particles and the plasma ions. To restore an even distribution, the electrons are pulled back towards the positive plasma ions that have congregated towards the rear of the beam pulse. But the electrons overshoot their original positions, creating a wake-like disturbance called a wakefield oscillation. Within this wake are pockets of plasma ions, which physicists refer to as bubbles, thanks to their spherical shape.

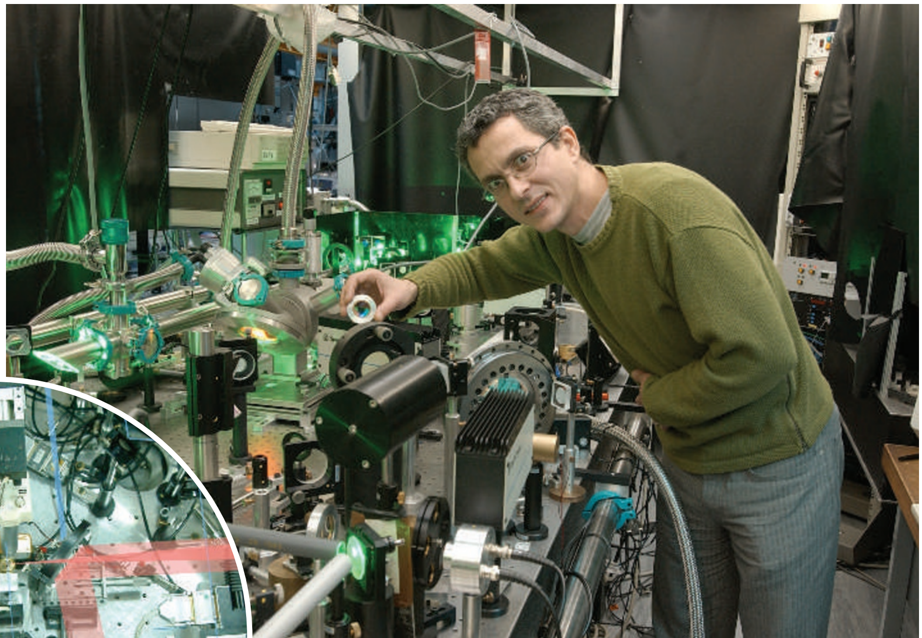
The wake of a breaking wave causes turbulence, and the wake generated in a plasma is no exception. But as surfers and boat owners know, if you hit the wave at just the right spot, you can be accelerated by its surf. So some electrons can surf the plasma wakefield, as can other particles, such as protons, injected into the beam, accelerating them to very high energies.

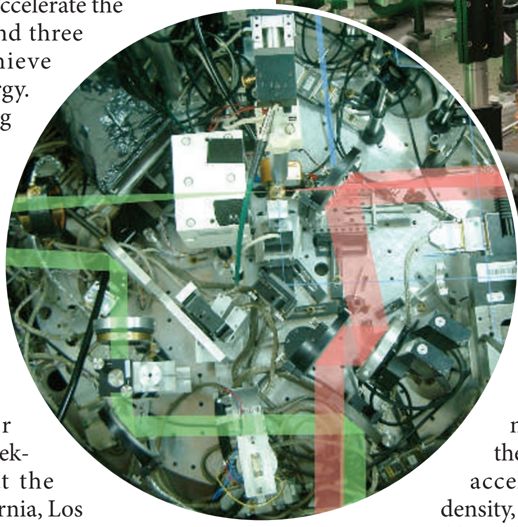
When particle beams are used to create the wake, it is often simply referred to as 'plasma wakefield acceleration', and the disturbance is created through electromagnetic repulsion between the beam and plasma electrons. For laser wakefield acceleration, the radiation pressure from the laser beam causes the wake formation.

Bubble effect

In the past three years, wakefield acceleration has generated its own bubble of excitement. Swapan Chattopadhyay, director of the Cockcroft Institute, a collaborative accelerator-research centre opened last year in Warrington, UK, says that a wakefield experiment at the Stanford Linear Accelerator Center (SLAC) in California this year has opened up a new chapter in accelerator physics.

Using a 400-metre extension of the 3.2-kilometre main accelerator at SLAC — the longest linear accelerator in the world — researchers have managed to double the energy of the electron beam over a distance of just 85 centimetres[1]. Much of the beam loses energy in setting up the plasma wakefield, but a few (just 0.02%) of the electrons were accelerated from 42 gigaelectronvolts to around 85 gigaelectronvolts. Conventional technology would have to accelerate the electrons for around three kilometres to achieve this pick-up in energy. "This trick of sending the SLAC's electron beam through a plasma jet to double its energy without having to double the size of the facility is truly remarkable," says Chattopadhyay.





Victor Malka uses a counterposing laser (inset) to control the injection of electrons into plasma fields.

One of the SLAC team, accelerator physicist Chandrashekhar Joshi based at the University of California, Los Angeles (UCLA), says that taking laser wakefield accelerator research to SLAC was the logical next step for the field. "Short-pulse lasers are powerful, but beams typically contain energies of tens of joules," he explains. The energies of particle beams, on the other hand, are of the order of kilojoules. In other words, particle-beam technology can reach much higher energies than contemporary reliable laser technology.

Splitting ions

In theory, there is no limit to the energies that plasma wakefield accelerators could reach. In conventional accelerators, particles are accelerated by an electric field — the steeper the electric gradient, the greater the acceleration. But the field can only increase so far before the surrounding cavity material, such as copper or a superconducting material, starts to break down as electrons are stripped from its atoms. Because plasma, although electrically neutral overall, is already broken down into its atoms and electrons, it can support much stronger electric fields.

J. FAN

The SLAC experiment was a breakthrough on several fronts. It showed that the technology can work at larger distances — reaching almost a metre, rather than the couple of centimetres previously achieved with laser technology. It also produced enough energy to be of interest in high-energy particle physics. But the energy of the accelerated electrons and the distance over which they continue to accelerate are not the only important properties of an accelerator. Other key factors also need to be addressed: the number of particles accelerated, or energy density, should be as high as possible, and the particles need to have a low energy spread, which means that they all have similar energies. With an energy spread of 100%, the SLAC experiment still has some way to go.

Experiments with laser wakefield accelerators, although operating at lower energies and over shorter distances than plasma accelerators, are making progress with these key factors. In 2004, three groups used lasers to accelerate electrons so that they had similar energies and reasonable energy densities, exceeding 10^9 electrons per beam. These experiments reinvigorated interest in wakefield acceleration, which was first proposed[2] by physicists Toshiki Tajima and John Dawson at UCLA a quarter of a century earlier.

"If we can reduce an accelerator's size, we can reduce the cost of proton therapy to something very small." — Charlie Ma

But to do particle collision experiments, such as those at SLAC, the beams need to reach energy densities of 10^{34} particles. The tiny fraction of electrons accelerated at SLAC is nowhere near enough for a collision experiment.

Late last year, researchers took wakefield acceleration a step further. The 2004 experiments had accelerated electrons over the 0.1 gigaelectronvolt range, but a collaboration between researchers at the Lawrence Berkeley National Laboratory in California and a team led by the University of Oxford's Simon Hooker in Britain has now boosted electrons to more than 1 gigaelectronvolt[3].

Small steps

This is not yet the high-energy frontier, which sits in the region of teraelectronvolts and beyond, but it is still a respectable gain on earlier experiments. "Our next goal is to go up to 10 gigaelectronvolts, for which we will need a bigger laser — around one terawatt," says Wim Leemans, head of the group at Lawrence Berkeley National Laboratory.

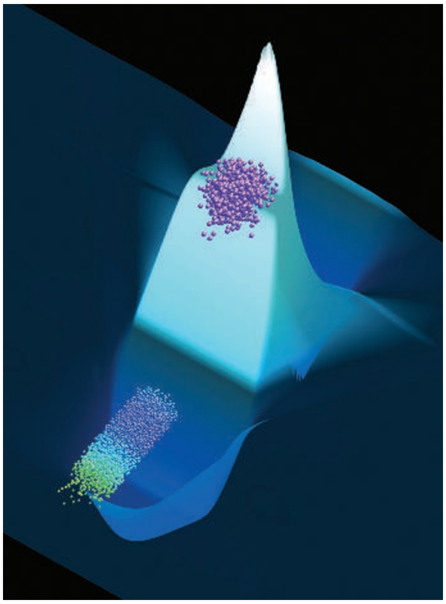
What's more, the researchers were able to create narrower particle beams with tight beam spreads — the energy spread divided by the peak energy. Tight spreads are essential in cancer treatment, as the energy determines how deeply the protons will deposit their maximum energy in the body. The researchers achieved a beam spread of less than 5%, compared with 10% in 2004 and 100% just a few years earlier. But there's still room for improvement. Karl Krushelnick, a wakefield accelerator physicist at the University of Michigan in Ann Arbor says: "For many processes that we would like to use these electron beams for, this figure needs to be well below 1%."

Also last year, Victor Malka and his team at the Ecole Polytechnique in Palaiseau outside Paris developed a technique that uses a second counterposing laser beam to create an electron beam that can have its energy changed on the fly[4]. The second laser beam is used to control the injection of the electrons that surf the wakefield. The resulting accelerated electrons had an energy spread of less than 10%, and by changing the way that the two lasers overlap the researchers could tune the energy of the beam from 15 megaelectronvolts to 250 megaelectronvolts. Importantly, the beam was much less prone to fail than in previous experimental set-ups.

Particles to the people

"We now have a good understanding and much of the science worked out," says Malka. "In a sense, what we are left with is the technological work needed to improve and stabilize the machines to create a commercial product." The commercial application that Malka has in mind for his group's research is cancer treament. Since 2004, he has been collaborating with a group led by oncologist Uwe Oelfke at the German Cancer Research Center in Heidelberg to perform rigorous simulations comparing proton therapy with X-ray therapy for targeting tumours[5]. The team hopes to apply its results to patients within the next 5 years.

If wakefield researchers make the advances they hope to over the coming years, then table-top accelerators could become much more powerful than they are now. Many



Particles can surf along giant plasma waves.

C. K. HUANG/F. TSUNG

experiments that are currently the preserve of relatively few, typically large and costly, facilities will be carried out in the basements of universities using compact and cheap technology. "Experiments over the next few years could make or break our field," says Leemans. "Still, I'm hopeful that we will be able to further address issues such as beam quality and that wakefield acceleration will really prosper."

Even at the high-energy frontier, the next generation of very large accelerators will probably incorporate plasma. According to Krushelnick, plasma wakefields are the only affordable way to achieve the very large acceleration gradients needed to get to extremely high energies, perhaps even the terascale. Plasma techniques may initially be used to boost existing accelerator technology, as with the SLAC experiment, or in the staging of multiple modules to build a plasma wakefield accelerator from scratch. The SLAC team is already trying to work out how numerous small plasma accelerators can be combined to create a reliable machine. And Joshi says that he hopes that he and his team can address all the remaining critical scientific issues and propose an accelerator that is entirely based on plasma within 10 years. ■

Navroz Patel is a writer based in New York City.

1. Blumenfeld, I. *et al. Nature* **445,** 741–744 (2007).
2. Tajima, T. & Dawson, J. M. *Phys. Rev. Lett.* **43,** 267–270 (1979).
3. Leemans, W. P. *et al. Nature Phys.* **2,** 696–699 (2006).
4. Faure, J. *et al. Nature* **444,** 737–739 (2006).
5. Glinec, Y. *et al. Med. Phys.* **33,** 155–162 (2006).
6. Slater, J. D. *et al. Int. J. Radiat. Oncol. Biol. Phys.* **59,** 348–352 (2004).

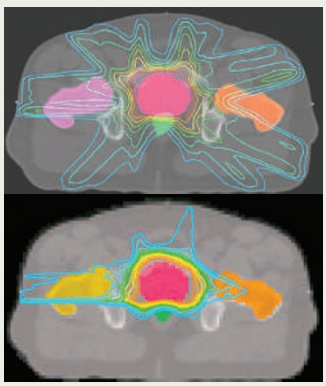
Targeting tumours

Standard radiotherapy can restrict tumour growth in many patients with cancer. It works by delivering high doses of X-rays into the body so that enough molecules are ionized to damage tumour cells. But because they are difficult to target precisely, X-rays often damage healthy tissue around the tumour, so doctors cannot use as high doses as they would like.

Proponents of proton therapy argue that the protons in a particle beam should be able to target tumours more precisely than X-rays do. This is because protons lose most of their energy just before coming to a standstill when travelling through matter. Maximum ionization will thus occur as the protons approach their targeted stopping point, which depends on the energy of the beam, leaving healthy tissue largely untouched. Computer simulations performed by oncologist Charlie Ma and his colleagues at the Fox Chase Cancer Center in Philadelphia support the idea that proton beams generated by wakefield accelerators can target tumours much more accurately than conventional radiotherapy techniques (see simulations, right).

Others argue that the radiation biology of proton therapy is poorly understood and the claimed superiority of particle beams over conventional radiotherapy has not been demonstrated sufficiently in the clinic. "Proton beams have favourable physical characteristics, but the question is: will that translate to improved clinical outcomes?" asks Steve Hahn, a radiation oncologist at the University of Pennsylvania's School of Medicine in Philadelphia. "Answering that is probably going to take randomized phase-III trials."

Ma says that he has some sympathy for this view but argues that costs have limited the acceptance of proton therapy, since it was first proposed in the 1940s. Existing proton-therapy machines use large and expensive conventional accelerators, and so need a lot of space. The radiation shielding alone can cost around US$40 million, according to Ma, with the total price tag for a proton-treatment centre reaching



The radiation dose (coloured lines) can be distributed more tightly around a prostate tumour (red) with proton therapy (bottom) than with conventional radiotherapy.

C. MA/FOX CHASE

$100 million or more.

With so few clinical facilities in the world, phase-III trials of the sort Hahn is asking for have been few and far between. In one of the largest clinical studies[6] reported so far, 1,255 men given proton therapy for prostate cancer had survival rates equal to those for conventional radiotherapy and surgery, but with fewer side effects. Ma thinks that affordable wakefield accelerators offer the best way to address concerns over clinical outcomes. Hahn agrees: "Wakefield acceleration promises to make the technology cheaper and widely available and so should help resolve the empirical controversy."

Ma is hopeful that the laser wakefield facility his group is developing in the lab will soon be converted into a clinical system. If all goes to plan, then the Fox Chase Cancer Center will start treating its first patients in the next 5–10 years, and become a prototype clinical facility for a new generation of compact proton-therapy centres.

In Germany, oncologist Uwe Oelfke at the Cancer Research Center in Heidelberg thinks that he could start using wakefield accelerators on patients with hard-to-treat eye cancers as soon as proton beams of 70 megaelectronvolts are available — some 12 megaelectronvolts more than has been achieved so far with laser wakefield acceleration. "If something like this could be built and operate reliably, it would be a huge step," he says. **N.P.**