Electrons hang ten on laser wake

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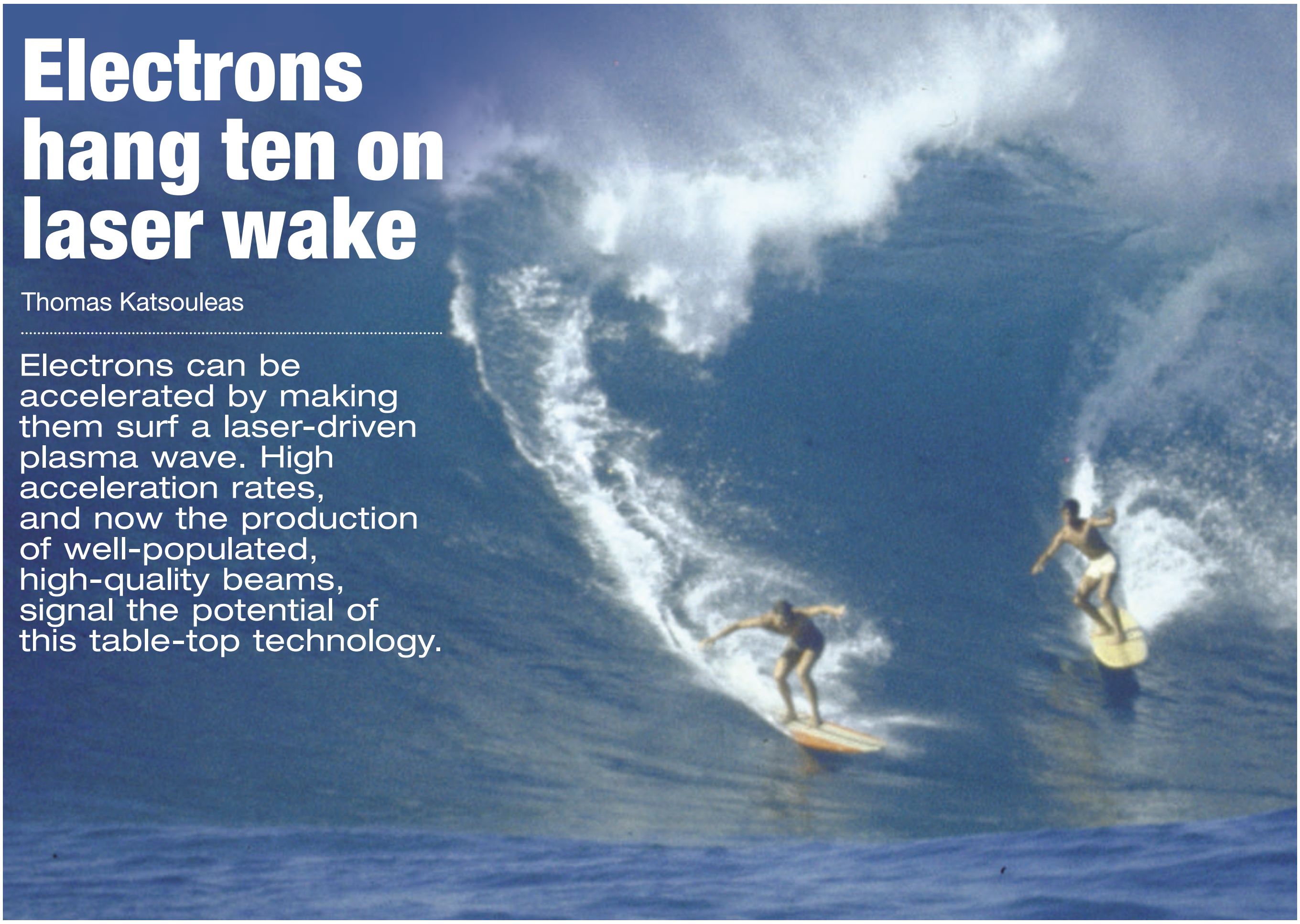
Electrons can be accelerated by making them surf a laser-driven plasma wave. High acceleration rates, and now the production of well-populated, high-quality beams, signal the potential of this table-top technology.



Huge particle accelerators have been at the vanguard of research in particle physics for more than half a century; through high-energy collisions of accelerated particles, the fundamental building-blocks and forces of nature have been revealed. The latest project, the Large Hadron Collider (LHC) currently under construction at CERN in Geneva, will attempt to find the Higgs boson, a particle associated with the mechanism through which all other known particles are thought to acquire their masses. But the size and cost of such machines — for the LHC, a 27-km circumference and several billion euros — are fuelling a serious effort to develop new and more compact accelerator technologies. Three reports[1–3] in this issue (from page 535) announce fresh progress, using a principle known as plasma wakefield acceleration.

Plasmas — gaseous 'soups' of dissociated electrons and ions — offer a means of acceleration that could be realized on a table top[4]. Waves can be generated in a plasma using short laser pulses; electrons or their antimatter counterparts, positrons, can then 'surf' the electric field of a wave's wake. Particles have been accelerated in wakefields at rates that are more than a thousand times higher than those achieved in accelerators based on conventional large-scale technology. However, whether plasma wakefield accelerators could produce the high quality of beam needed for applications in high-energy physics, and in other areas of research and medicine, remained in question. The results now presented by Geddes *et al.*[1], Mangles *et al.*[2] and Faure *et al.*[3] are a milestone in this regard. They provide the first demonstration that a beam of electrons can be accelerated in a wakefield to a single energy. Moreover, their beams are of high quality (having a small angular divergence) and significant charge (about 10^9 electrons).

In a conventional accelerator, charged particles such as electrons, protons or their antiparticles are accelerated by an alternating, radio-frequency electric field through long metallic cavities (around a metre long for medical applications, but several kilometres long for high-energy physics). The rate of acceleration is limited by the peak power of the radio-frequency source and, ultimately, by electrical breakdown at the metal walls of the accelerator. Laser-driven plasma waves overcome both of these limitations: the high peak power of lasers is unmatched, and the plasma, as it is already an ionized gas, is impervious to electrical breakdown. In 1995, Modena *et al.*[5] made clear the remarkable potential of this scheme, and it has been confirmed by subsequent experiments. Using the radiation pressure of a laser to drive a compressive oscillation in the plasma (like a sound wave, but with electrostatic repulsion rather than pressure as the restoring force), electrons have been accelerated from rest to an energy of 100 megaelectronvolts (MeV) within a distance of 1 mm — more than 5,000 times shorter than the distance required to reach that energy in a conventional accelerator.

But acceleration rate is only one measure of a good accelerator. The number of particles in a beam, and their spread in angle and energy, also matter. In 2002, Malka *et al.*[6] showed that well-collimated beams of 10^8 electrons could be produced within an angular spread of 3° by a laser-driven wakefield; in these experiments, however, the energy spread of the beams was 100%. This wide range of energies occurred because the particles were trapped from the background plasma — in much the same way that white-water gets trapped and accelerated in an ocean wave — rather than injected into a single location near the peak of the wave (as is done in a conventional accelerator). But injection is difficult in a wakefield accelerator because the wavelength of the plasma wave is tiny — typically 10,000 times shorter than the usual 10-cm wavelengths of the radio-frequency fields in conventional accelerators. Successfully injecting tightly packed bunches of particles near the plasma-wave

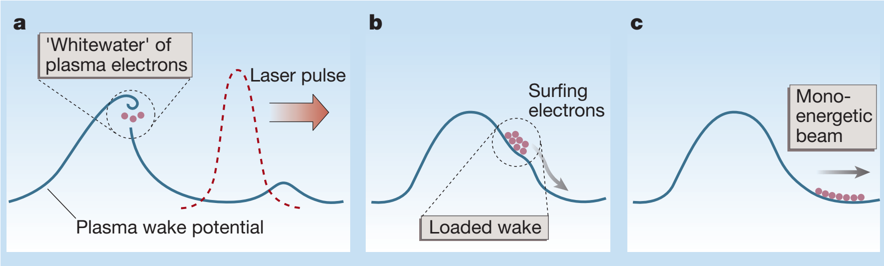


Figure 1 **Wakefield acceleration.** a, **In a plasma excited by a laser pulse, the wake potential rises until it steepens and breaks. Electrons from the plasma are caught in the 'whitewater' and surf the wave.** b, **The load of the electrons deforms the wake, stopping further trapping of electrons from the plasma.** c, **As the electrons surf to the bottom of the wake potential, they each arrive bearing a similar amount of energy.**

peak was expected to be a challenge for the field for several years to come.

Instead, the three groups reporting in this issue[1–3] have found a new physical regime, in which electrons are 'self-injected' in a narrow region of space and made to surf as a single group, all reaching the same energy (Fig. 1). The three experiments are similar in many ways. In each of them, 10–30 terrawatts of laser power, in pulses 30–55 femtoseconds long, is focused into an ionized jet of gas roughly 2 mm long and with a particle density of 2×10^{19} cm^{-3}; a nearly monoenergetic distribution of electrons is observed, with instrument-limited energy spreads of 2–24% at roughly 80–170 MeV. With up to a few times 10^9 electrons per beam, the energy densities in these experiments are a hundred to a thousand times higher than has previously been achieved. The angular spread of the beams is also about ten times tighter than before — comparable to the best of the beams produced by radio-frequency systems. Moreover, the pulse lengths of the beams are about 10 femtoseconds (10^{-14} s), making them attractive as potential radiation sources for ultrafast time-resolved studies in biology and physics.

Despite the similarities between the three experiments, it is the differences that have helped to identify the mechanisms responsible for their success. The three groups used different approaches to control what turns out to be a key factor — the interaction length in the plasma. The interaction length is the distance over which the particles surf the wake, and it is determined by either the end of the plasma or the weakening of the laser pulse through diffraction (the natural tendency of tightly focused light to spread). Geddes *et al.*[1] used a preformed plasma channel to guide the laser over several times the length that it would travel without diffraction in a vacuum; the groups of Mangles[2] and Faure[3] used a larger laser spot size (up to 24 micrometres) to increase the interaction length. The groups describe essentially the same physics: first, the laser pulse evolves to become shorter and narrower; this creates a large wake that traps electrons from the plasma; the loading of the wake with trapped particles turns off further trapping; and finally, 'dephasing' of the electrons as they outrun the wake creates a monoenergetic beam (basically, like marbles that roll to the bottom of a hill, they arrive at different times but end up at the same energy; Fig. 1).

Geddes *et al.*[1] emphasize the need for large interaction lengths to enable the electrons to dephase from the wave; their demonstration of guiding an intense laser in a plasma channel suggests a means of extending future wakefield accelerators beyond the millimetre scale. Mangles *et al.*[2], however, stress the need to reduce the interaction length to prevent the dephasing from becoming complete (the marbles reach the next hill and begin to slow down). Thus, as in the children's story *Goldilocks and the Three Bears*, the interaction length must be not too long, nor too short, but just right.

There is still a long way to go from these experiments in the 100-MeV range to the frontiers of high-energy physics (it's likely that considerably more than 100,000 MeV needs to be available in a particle collision to produce a Higgs boson). The shot-to-shot stability and efficiency of these schemes also need to be improved. Nevertheless, these results represent the most significant step so far for laser-based accelerators, and should stimulate further advances in the near future. In particular, developments in high-power laser technology and plasma-channel production (particularly lower-density channels to increase the wake speed and hence the dephasing length) could both lead to the generation of beams of up to a few thousand MeV from a single-stage table-top device. Such accelerators would not only be more compact but would also exceed conventional sources in peak current, brightness and shortness of pulse duration. Wakefield acceleration may one day change the way we approach the physics and applications of particle beams. ■

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