Electrons surf to high energies on plasma waves

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THE accelerators used by particle physicists need to be many kilometres long to reach the energies at which new particles such as the Higgs boson are expected to be found. The particles are accelerated by electric fields, and accelerator designers are always looking for ways to increase the electric field strength since this will reduce the length of the machine. One possibility that has been investigated over the past decade is the use of plasma waves in laser-produced plasmas. The electric field in a large-amplitude plasma wave can be orders of magnitude stronger than the fields produced in conventional accelerators. The downside is that the plasma medium cannot be controlled as precisely as metal conductors, so replacing the large machines required for high-energy physics with plasma-based accelerators is still a distant dream.

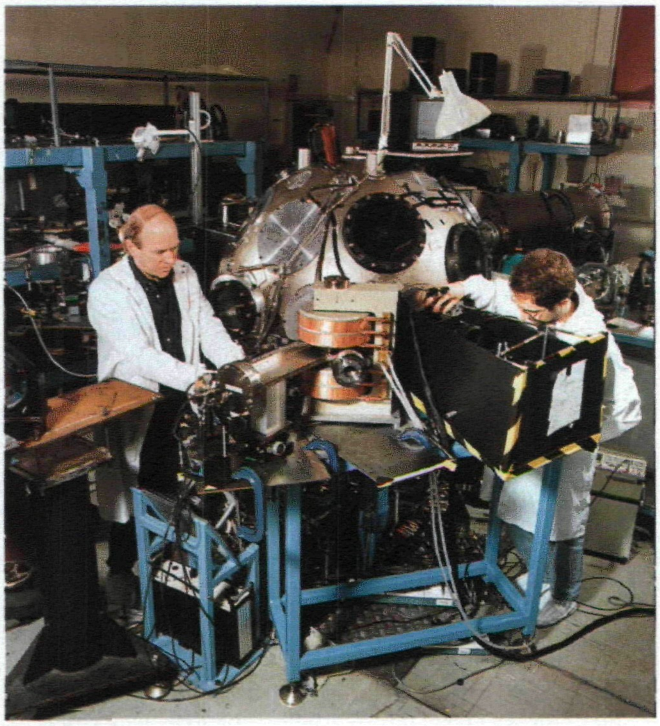
However, an important advance in particle acceleration to more modest energies has recently been demonstrated at the Rutherford Appleton Laboratory (RAL) in the UK (A Modena *et al.* 1995 *Nature* 377 606). A team from Imperial College in London, the University of California at Los Angeles, the Ecole Polytechnique in Palaiseau, France, the Lawrence Livermore National Laboratory in California and RAL used the VULCAN laser at Rutherford to accelerate electrons up to energies of 44 MeV in a well collimated beam. The electrons were accelerated by the plasma wave produced when a short, high-intensity laser pulse from VULCAN was focused onto a gas target.

The electric field in the plasma wave is produced by differences in the electron and ion charge densities in the plasma. The field is both periodic and parallel to the wave propagation direction (i.e. the wave is longitudinal). The plasma wave produced by a laser can have both a large amplitude and a phase velocity close to the speed of light, and a particle moving with the wave is accelerated by this field, rather like a surfer on a water wave.

So far, most discussion of plasma accelerators has focused on either "beat wave" or "wake field" schemes. In the beat wave scheme, two laser pulses that differ in frequency by the plasma frequency – the characteristic frequency of longitudinal oscillations in the plasma – interact as they propagate through the plasma. This generates a driving force at the beat frequency, which, being in resonance with the plasma wave, drives it up to a high amplitude. In the wake field scheme, a single laser pulse leaves a wake, consisting of a plasma wave, behind it. The laser pulse must be shorter than one wavelength of the plasma wave.

However, the present experiments used single-frequency pulses that were too long to generate a wake. Therefore the large-amplitude plasma wave producing the acceleration was attributed to a third mechanism: forward Raman scattering. This process involves the resonant excitation of a second or "decay" electromagnetic wave and a longitudinal plasma wave by an electromagnetic pump wave (such as a laser). Backward Raman scattering, in which the decay electromagnetic wave travels in the opposite direction to the incident wave, has been investigated in detail because it is thought to prevent effective energy absorption by the solid targets used in laser-fusion experiments.

In the less dense gas targets of the present experiments, forward Raman scattering occurs with the incident and decay waves parallel. The generated plasma wave has a high phase velocity, which can be close to that of light under suitable conditions. In essence, the process is similar to the beat wave scheme, with two electromagnetic waves interacting to drive up the plasma wave. The difference is that the second wave is driven up from noise rather than being generated externally. This has the advantage that the frequency difference of the waves automatically matches the plasma frequency, and thus the careful control of the plasma density that is needed for a successful beat wave experiment is not necessary.



Preparing a short-pulse electron acceleration experiment using the VULCAN laser at the Rutherford Appleton Laboratory.

The experiments used 25 TW, 0.8 ps pulses focused to a 20 μm spot on the edge of a 4 mm diameter plume of helium gas from a pulsed supersonic gas jet. The most important diagnostics measured the scattered wave spectrum and the electron energy spectrum in the forward direction. The best results were obtained at the highest gas density used, 1.5×10^{19} cm^{-3}, giving an electron energy spectrum essentially flat up to 30 MeV, falling off slowly up to the detector limit of 44 MeV. Although the higher value is the greatest energy claimed by the team, it seems reasonable to suppose that the spectrum continues up to substantially higher energies. This acceleration is accompanied by a tremendous broadening of the scattered wave spectrum.

The acceleration is likely to be the result of wave breaking. The wave grows until the potential wells associated with the longitudinal wave field become deep enough to trap particles in the main part of the thermal distribution of electrons. Substantial numbers of particles are then accelerated up to relativistic energies. At the same time the coherence of the wave is destroyed. The process is analogous to the familiar breaking of a water wave where liquid at the crest of the wave is thrown forward and the coherent wave breaks up.

Compared with a conventional particle accelerator, the system produces beams with a transverse emittence that matches those of photoinjector-based linacs, but with a current that is between 10 and 100 times less. However, the acceleration length is estimated to be only a few hundred micrometres, and the inferred peak electric field is of the order of 100 GV m^{-1}, the highest collective field produced to date in a laboratory. Although VULCAN is a large system, advances in laser technology make it possible to envisage compact laser-based accelerators producing electrons in the range from a few MeV to a few hundred MeV in the not too distant future. □