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Electron Acceleration by Laser-Excited Plasmas

In 1979, Toshiki Tajima and John M. Dawson at UCLA suggested that electric fields generated within a neutral plasma could be used to accelerate charged particles to very high energies in a very short distance,[1] offering a revolutionary way to build particle accelerators much smaller than currently possible. This year, experimenters have reported the first conclusive evidence for significant acceleration of electrons by plasmas.

Although a neutral plasma has a net electric charge of zero, external disturbances such as laser or electron pulses can generate an electric field within it. Such disturbances can create plasma regions that are high in positive charge as well as regions high in negative charge.[2] The resulting electric field causes electrons in the plasma to oscillate about the positive ions; and the collective motion of the electrons leads to the creation of a "plasma wave" that propagates along the length of plasma. Accompanying this plasma wave is an electric field that can, if properly tailored, travel at velocities approaching the speed of light. Under the proper conditions, the electric field can add energy to an externally injected charged particle, thereby accelerating it.

Plasma waves can be excited (intensified) either by a short but powerful laser or electron pulse propagating through the plasma[3] or by combining two laser beams of slightly different frequencies such that their frequency difference (beat frequency) matches the plasma's natural frequency of oscillation.[3] Several laboratories around the world have studied the latter collective acceleration scheme, known as the Plasma Beat Wave Accelerator,[4] so-named because the interference between two laser beams causes a peak or "beat" in intensity at regular intervals, which then excites a strong beat-wave in the plasma. Over the years, many groups have reported success in exciting such plasma waves using the beat-wave technique.[5] However, it was not until this year that conclusive evidence for significant energy gain by electrons injected externally in such a plasma wave was demonstrated.

The UCLA experiments used a short but powerful CO_2 laser pulse containing two frequencies to excite the relativistically propagating-plasma beat wave. The plasma was created from H_2 gas that was ionized by the same laser pulse. The plasma wave has a wavelength of only 360 μm and a lifetime less than a billionth of a second. Studying the plasma and the plasma wave therefore required sophisticated light scattering techniques. Since such a plasma wave travels near the speed of light, it is necessary to inject pre-accelerated relativistic particles into the wave to gain energy from it.

The source of electrons for injection in the UCLA experiments was a small radio-frequency (RF) linear accelerator that produced bunches of electrons with 2 mega-electron-volts (MeV) of energy. In null tests, no accelerated electrons were observed when none were injected or when the laser was operated on a single frequency. However, accelerated electrons up to 9 MeV in energy were observed when the 2 MeV electrons were injected in a plasma wave excited by a dual-frequency laser beam.[6] The accelerated electron signal agreed well with indirect measurements of the strength of the plasma wave using optical tests. In more recent experiments the UCLA researchers have observed electrons with energies up to 25 MeV. They estimate the acceleration length to be approximately 1 cm which gives an acceleration gradient in excess of two giga-electron-volts (GeV) per meter. This gradient is 100 times greater than 20 MeV/m, the current standard for linear accelerators. This demonstration by the UCLA team[6] is a significant step forward in making plasma wave accelerators a reality as well as in advancing our understanding of relativistic wave-particle interactions in a plasma.

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