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Particle physics: Positrons ride the wave

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Particle accelerators and colliders have been the backbone of research into elementary particle physics for almost a century. The next generation of colliders must be able to generate collision energies for lepton particles, such as electrons and positrons, in the teraelectronvolt range (1 TeV is 10^{12} electronvolts). This will complement discoveries being made by the Large Hadron Collider at CERN, Europe's particle-physics laboratory near Geneva, Switzerland. On page 442 of this issue, Corde *et al.*[1] report a system for accelerating positrons — the antimatter counterparts of electrons — that might enable such instruments to be realized.

An experimental configuration of choice for colliders consists of smashing electrons (e^-) into positrons (e^+). The two particle beams are accelerated in two linear accelerators pointing towards each other, to collide head-on. The designs of e^+–e^- linear colliders have mostly been based on conventional accelerator technologies that use devices known as radiofrequency resonators. But these have allowed accelerating gradients of no more than about 100 MeV per metre. The TeV-energy colliders are therefore expected to be large and costly — for example, the proposed 0.5-TeV International Linear Collider is expected to be about 30 km long[2].

Alternative acceleration methods have been sought since the early 1980s (ref. 3). One class of such methods is plasma wakefield beam-driven acceleration (PWFA), in which the accelerating medium is an electrically neutral plasma composed of positively charged ions and highly mobile free electrons. As a group of electrons called the drive bunch travels through the plasma, it repels the plasma electrons. This leads to spatial modulation of the plasma's electronic density, which in turn induces a strong electric field commonly called a wakefield. When another group of electrons — the witness bunch — travels at an appropriate distance behind the drive bunch, it interacts with the wakefield. This interaction causes the witness bunch to accelerate rapidly.

The PWFA method proposed[4] in the mid-1980s for electron acceleration was initially developed in the linear regime, in which the electron beam has a lower particle density than the plasma. It was subsequently realized that this approach could also operate in a nonlinear regime (in which the electron beam has a higher particle density than the plasma), giving rise to sharp transitions in the plasma-density modulations that could support higher accelerating fields[5]. Using the latter mechanism, often referred to as a blowout regime, accelerating gradients of about 52 GeV m^{-1}have been attained for electron bunches[6].

Application of the PWFA technique to accelerate positrons over a short distance is a prerequisite for a plasma-based e^+–e^- linear collider. Previous work[7] in this area

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demonstrated energy modulation of a positron bunch with a peak accelerating gradient of the order of 50 MeV m^{-1}. The possibility of accelerating positrons in the nonlinear regime with high acceleration has long been contemplated, but not achieved. The main hurdles arise because the dynamics of plasma electrons under the influence of a positron drive bunch are different from the dynamics induced by an electron drive bunch, and because electron bunches are not suitable for driving plasma waves that can accelerate positron bunches.

Corde *et al*. now demonstrate positron acceleration with accelerating gradients of about 5 GeV m^{-1}, which is about 100 times higher than the gradients previously reported for positrons[7]. In brief, the authors used a conventional accelerator to produce a positron bunch, and sent it through a metre-long cell of lithium plasma.

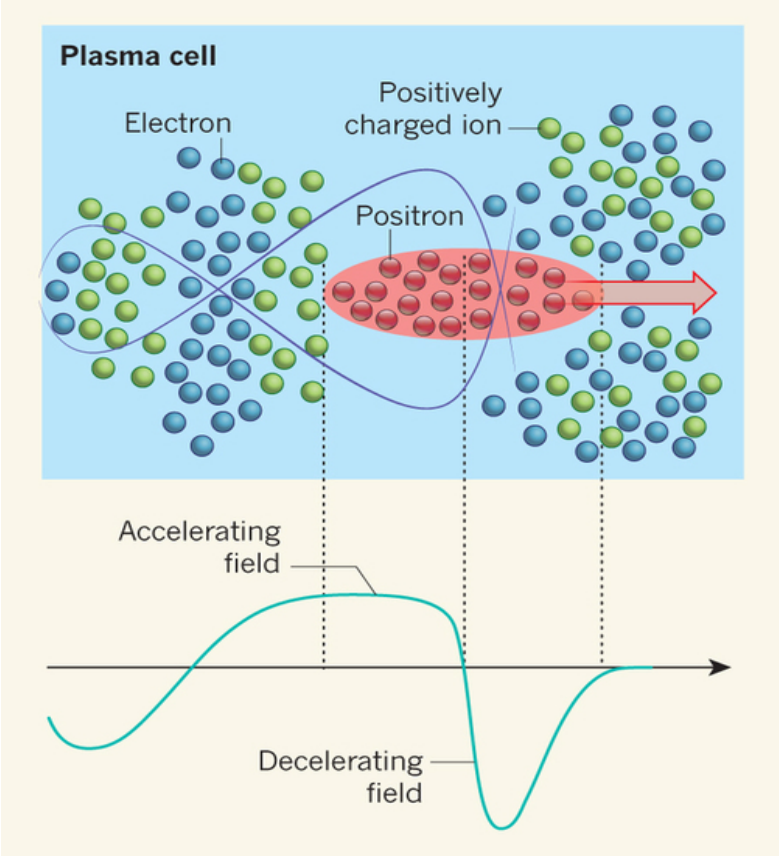
The plasma-density wave formed using positrons is different from that produced using electrons because the positron bunch attracts plasma electrons inward. As electrons flow through the bunch, the positrons gain or lose energy depending on their axial locations within the bunch (Fig. 1). At a particular plasma density, the wakefield can be tailored to switch polarity within the positron bunch, thereby decelerating the head of the bunch while accelerating positrons in the tail, effectively transferring energy from the head to the tail.

Corde *et al*. observe that the large positron population (about 1 billion positrons) experiencing the accelerating field effectively 'loads' the wakefield and affects its shape, leading to an approximately uniform energy gain for the accelerated positrons. The experiment therefore demonstrates that, by using appropriate operating parameters, only one positron bunch is needed for acceleration: part of its trailing population is 'trapped' and accelerated quasi-uniformly to higher energies, and so splits from the initial bunch. The authors observe that the newly formed and the accelerated positron bunches are quasi-monoenergetic — the positrons in the accelerated bunch have almost the same energy as each other. This is essential if the bunches are to be further transported and manipulated along an accelerator without substantial degradation of quality, for example before injection into a subsequent stage of a plasma wakefield accelerator.

Several challenges must be addressed to prove the overall suitability of a PWFA-based e^+–e^-linear collider. First, several of Corde and colleagues' PWFA modules must be concatenated to reach the desired final energy. The quasi-monoenergetic bunch formed in the first module would have to be used as a witness bunch by subsequent modules, and so the related synchronization issue — how to delay the witness bunch behind the drive bunch with sub-picosecond accuracy so that it interacts properly with the wakefield — would have to be investigated. It will also be important to understand and mitigate possible beam-quality degradation during the acceleration process as particles in the accelerated bunches scatter against the plasma electrons (and ions).

Several groups are already vigorously investigating these issues; Corde and colleagues' results provide further impetus to these studies.

Figure 1: Mechanism for positron acceleration.



Corde *et al.*[1] report that positrons can be accelerated in a lithium plasma composed of positive ions and free electrons; only some of the ions and electrons are shown. As the positron bunch moves from left to right, the electrons move towards it because of charge attraction; the blue line indicates a sample electron trajectory. This movement organizes electrons and ions into 'layers' behind the bunch, generating an electric field called a wakefield (depicted as a cyan trace on the lower plot). The positrons at the head of the bunch decelerate in response to the negative region of the wakefield, but positrons in the bunch's tail accelerate in an approximately uniform, positive region of the field.

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