

Plasma wakefield acceleration shows promise

When electrons are precisely positioned in a region of high electric field, they can pick up a lot of energy in a small space.

In their quest to test the standard model and search for new physics beyond it, particle physicists have sought ever larger and more powerful facilities for accelerating and colliding charged particles. Conventionally, accelerators rely on metal plates and resonators to generate electric fields and RF waves. The magnitude of those fields is limited to tens of megavolts per meter, so to accelerate particles to 125 GeV (the energy of the Higgs boson) or more requires a path of many kilometers. Protons and heavier particles can be accelerated in circles, but electrons and positrons must be accelerated in straight lines, lest they lose all their energy to synchrotron radiation. The 3-km linear accelerator at SLAC is currently the world's longest; reaching the high energies relevant to particle physics with a conventional electron accelerator would require a much larger, costlier facility.

Accelerators based on plasmas, which can sustain electric fields up to

tens of gigavolts per meter, have the potential to be a smaller and cheaper alternative. An electron-density wave in a plasma, co-propagating with a charged-particle bunch, can keep the bunch in a high-field region over a path of a meter or more, thereby imparting a lot of energy to the particles in a compact space. But the precision engineering required to accelerate particles efficiently and uniformly has been a challenge.

Now Chandrashekhar Joshi (at UCLA), Michael Litos, Mark Hogan (both at SLAC), and their colleagues have taken a leap forward.¹ In their plasma wakefield accelerator, the plasma wave is created by a 20-GeV electron bunch from SLAC's linac. A second bunch of equally energetic electrons follows close behind. With SLAC's purpose-built Facility for Advanced Accelerator Experimental Tests,² the researchers could place the trailing bunch at just the right spot in the plasma wave to increase the bunch energy by 1.6 GeV over just 30 cm of plasma.

Energy boost

Plasma acceleration schemes, first proposed by John Dawson in the 1970s, come in two basic types. (See the article by Joshi and Thomas Katsouleas, *PHYSICS TODAY*, June 2003, page 47.) In laser

wakefield acceleration, the plasma wave is created by the radiation pressure of an intense laser pulse. Because the wave can accelerate particles almost from rest, the scheme offers a way to create self-contained tabletop accelerators for moderate-energy applications, such as medicine and materials science. (See the article by Wim Leemans and Eric Esarey, *PHYSICS TODAY*, March 2009, page 44.)

In plasma wakefield acceleration, on the other hand, one bunch of fast-moving particles drives the plasma wave that accelerates another bunch. Both bunches must start out at ultra-relativistic energies, traveling so close to the speed of light that their separation doesn't change even as the first bunch loses energy and the second gains energy. The scheme is therefore not suitable for free-standing accelerators; instead it is being developed as a way to boost the energy of large linacs. (For the same reason, it's far better suited to accelerating electrons than protons, which would need 2000 times as much energy to reach the ultrarelativistic starting point.)

Litos likens the plasma wakefield accelerator to an electrical transformer converting a large bunch of moderate-energy electrons into a smaller bunch at higher energy. That capability would be useful for particle-physics experiments, in which high collision energies are critical in the search for new physics. It also has the potential to reduce the size and cost of x-ray free-electron lasers. The Linac Coherent Light Source at SLAC, currently the only operating XFEL, uses electrons accelerated over 1 km of the linac. (See *PHYSICS TODAY*, August 2009, page 21.) Plasma wakefield boosters on a smaller linac could, says Litos, "make XFELs more palatable to universities rather than just national labs."

Riding the wave

Figure 1 shows a simulation of the process under the conditions used in the new experiment. The drive bunch pushes away the plasma electrons, leaving a region of net positive charge in its wake. (The plasma ions, not shown in the figure, are heavy enough to be unaffected.) At the back of the wake, the longitudinal electric field E_z is strongly negative, capable of accelerating electrons in the direction of travel.

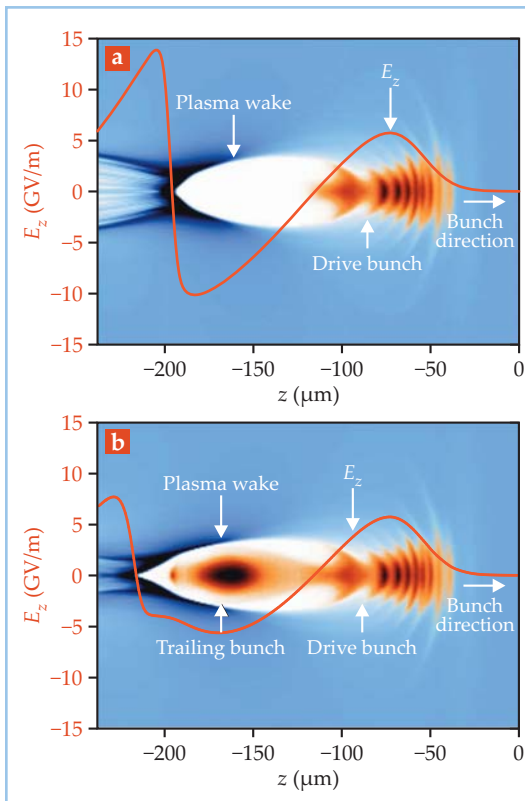


Figure 1. Simulations of a plasma wakefield interaction, with beam density shown in orange, plasma-electron density in blue, and the longitudinal electric field E_z as an orange curve. (a) The drive bunch clears away the plasma electrons, leaving a region of strong but inhomogeneous electric field in its wake. (b) If the trailing bunch is large enough and positioned in the right spot, it can flatten the electric field so that the trailing bunch is uniformly accelerated. (Adapted from ref. 1.)

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Figure 2. Two bunches from one. An electron bunch from the SLAC linear accelerator is dispersed according to its energy—here, the high-energy end of the bunch is shown in red and the low-energy end in blue. The bunch is then allowed to collide with a thin tantalum bar, which scatters the middle portion of the bunch out of the beam. (Adapted from ref. 1.)

But the field in the wake of the drive bunch alone, shown in figure 1a, is far from homogeneous. Electrons separated by just a few microns would gain energy at vastly different rates. That's bad for collider experiments, which require particles as close to a single energy as possible.

Fortunately, if the trailing bunch is large enough, its own effect on E_z can be significant. As shown in figure 1b, E_z is reduced in magnitude, but also flattened, to a near constant -5 GV/m. Using a denser plasma would yield a stronger E_z . But it would also reduce the size of the wake and make positioning the trailing bunch more difficult.

Beam gymnastics

Earlier proof-of-principle plasma wake-field experiments have used, instead of a pair of electron bunches, a single elongated bunch. The physics is the same—the electrons at the back of the bunch are accelerated by the wake produced by those at the front. But to achieve the desired small energy spreads, it's necessary to use two discrete bunches separated by about $100\ \mu\text{m}$, or 300 fs. The only way to make such closely spaced bunches is by crafting them out of a single linac bunch.

To accomplish that, the researchers first used magnets to elongate the bunch to about 2 mm, with the highest-energy electrons in the front. Then, as shown in figure 2, they rotated the bunch and allowed it to collide with a thin tantalum bar. Electrons that struck the bar were scattered and removed from the beam, whereas those on either side kept going. Rotating the bunch again and compressing it down to submillimeter size gave the desired two-bunch structure.

The plasma was created from a chamber full of lithium vapor; 100 ps before the electrons' arrival, the researchers shot a laser pulse through the vapor to ionize the Li atoms and create a 1-mm-wide tunnel of plasma, which remained ionized for several nanoseconds, plenty of time for the plasma wake to do its work.

The researchers then measured the outgoing electrons to see what had happened. Figure 3 shows the energy spectrum of one of their trials compared with the outcome of the simulation from figure 1b. In each case, both bunches started at 20.35 GeV; the drive bunch lost energy and broadened, whereas the trailing bunch gained energy and remained sharply peaked. The red dashed line shows a fit to the energetic core of the trailing bunch, with an energy spread of 2%.

What lies ahead

Clearly, much work remains to be done: An energy gain of less than 10% is hardly going to revolutionize high-energy physics. Furthermore, of the 800 pC that started out in the trailing bunch, only 74 pC remained in the accelerated core. Better preservation of the beam is a priority for the SLAC team's future work.

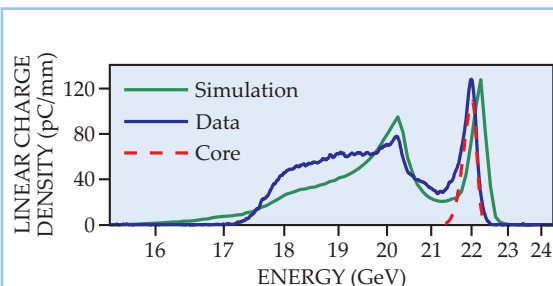


Figure 3. Energy profiles of the simulated and actual electron bunches after they interact with the plasma. In both cases, the drive bunch, which begins with an energy just above 20 GeV, loses energy and broadens. The trailing bunch gains energy and is dominated by the sharply peaked core. (Adapted from ref. 1.)

One way to reach higher energies is simply by making the plasma chamber longer. With the setup as it is, plasma wakefield acceleration can continue for several meters before the drive bunch runs out of energy. The researchers are working on ways to daisy-chain several plasma accelerators together to pass the same trailing bunch from one to the next but use a fresh drive bunch each time.

A high-energy collider experiment would need not just accelerated electrons but also positrons of equal energy. Plasma wakefield acceleration of positrons is tricky because of their positive charge: They draw the plasma electrons toward them rather than clearing them away, and the resulting wake structure is much less conducive to accelerating a trailing bunch. "But we've been making progress," says

Litos, "and we hope to publish some results soon."

Some simulations of plasma wakefield acceleration have predicted a phenomenon called the hosing instability, in which the electric field perpendicular to the direction of travel causes the trailing bunch to wobble back and forth with increasing amplitude and eventually break apart. But not only did the researchers see no sign of the hosing instability in their experiments, they couldn't produce it even when they tried. "That was an interesting surprise, and rather encouraging," says Litos. "The hosing instability had been predicted to be a potential show stopper."

Johanna Miller

References

1. M. Litos et al., *Nature* **515**, 92 (2014).
2. M. J. Hogan et al., *New J. Phys.* **12**, 055030 (2010).

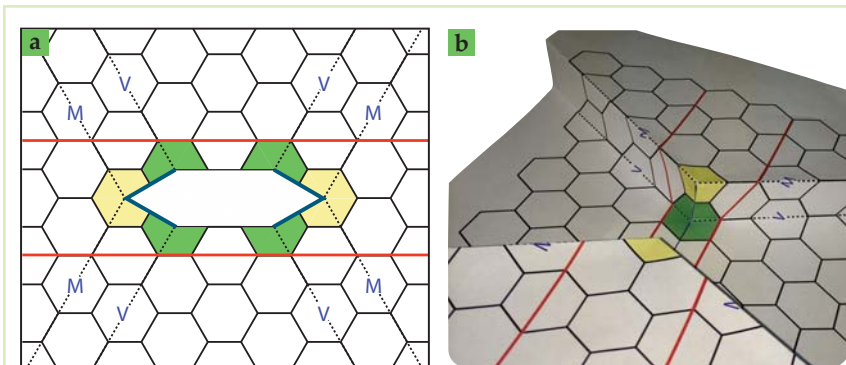
Rewriting the rules of kirigami

Practiced on a lattice instead of paper, the art of cutting, folding, and pasting takes on new scientific significance.

All origami artists should have in their repertoire certain basic folds—the petal, the crimp, the rabbit ear, to name just a few. Skillfully deployed, those basic folds can serve as building blocks for intricate, original creations. Now Randall Kamien, Shu Yang, and coworkers at the University of Pennsylvania have used concepts from condensed-matter theory to identify fundamental elements in a related

art form: kirigami, the art of cutting, folding, and pasting.¹

The Penn group specifically considered kirigami on a honeycomb lattice—a choice inspired by the prospect of fashioning three-dimensional nanostructures from self-assembled DNA networks and from graphene and graphene-like materials. The researchers impose constraints designed to mimic the bond networks in those materials:



In lattice kirigami, holes in a two-dimensional structure can be repaired only with certain folds. For the template shown in panel a, for instance, mountain (M) and valley (V) folds simultaneously close the hole and pop portions of the surface out of the plane, as shown in panel b. The resulting lattice can be characterized by its topological defects: Two cells (yellow) have five neighbors instead of the usual six, and two (green) have seven. The red lines, bent in the folded structure, illustrate the distortion of the original lattice. (Adapted from ref. 1.)



Thomas Hellerer, Consulting

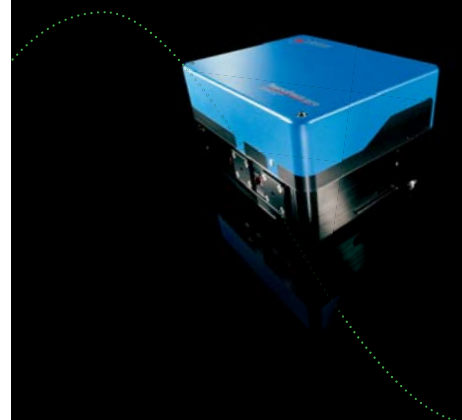
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