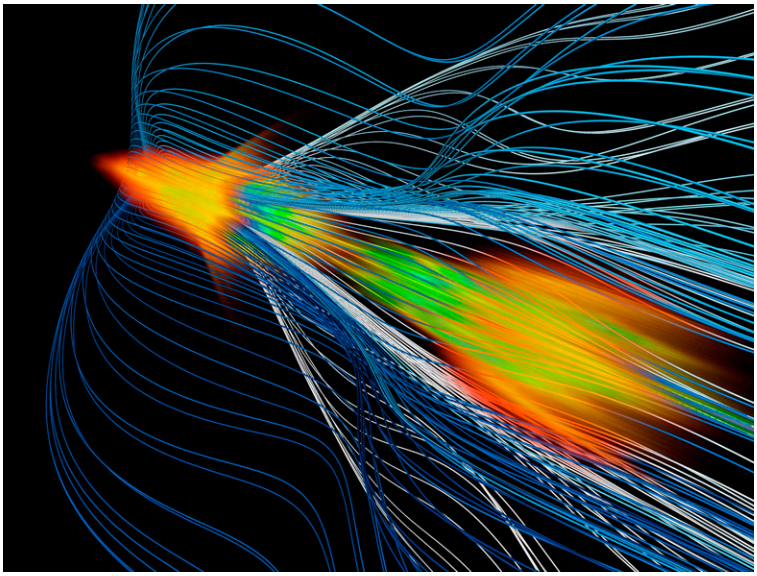
Building accelerator afterburners with plasma

David J. Harris, *Science Writer*

Particle colliders are pushing the limits of economic and political feasibility. Already, the next generation of planned linear colliders is tens of kilometers long; a planned circular collider is 100 kilometers in circumference. Such massive projects will take years to build and strain government purse strings. And yet, scientists are intent on pursuing even higher energies to reveal more of the universe's secrets by smashing together fundamental particles.

Unable to increase the size of their machines much more, scientists are turning to alternate particle-accelerating methods. Among them is plasma wakefield acceleration, an approach that has shown particular promise in recent experiments. The results suggest that plasma wakefield acceleration could serve as an energy booster to a linear collider, doubling collision energies from 500 gigaelectronvolts to 1 teraelectronvolt, thus allowing much higher energies in the same distance. Although these experimental results unexpectedly stretched the limits of what the best-available simulations had predicted, big technological hurdles remain before plasma wakefield-based devices are ready for prime time.

"We're not trying to save a factor of two in size," says Mark Hogan, head of the plasma acceleration group at SLAC National Accelerator Laboratory. "We're really trying to make improvements that are thousands of times better."



A new particle collider approach accelerates high-energy positrons in an ionized gas or plasma. Here, a simulation shows the formation of a high-density plasma (green/orange color) around a positron beam moving from the bottom right to the top left. Plasma electrons pass by the positron beam on wave-like trajectories (lines). Image courtesy of Weiming An (University of California, Los Angeles, CA).

Positrons and Possibilities

Plasma wakefield accelerator technology itself is not new. The idea has been around since 1979 (1), and experimental implementations have been able to accelerate electrons for nearly 20 years (2, 3).

But recent experiments (4) have shown how similar technology can work for accelerating the electron's antimatter counterpart, the positron. In a collider, the positrons annihilate along with the electrons, leaving only the sought-after newly created particles born of the fiery collision. Physicists theoretically predicted that the electron technique would work for positrons but, for reasons that had initially been mysterious, simulations didn't show the desired accelerating mechanism.

Experiments revealed the keys to the mechanism's success. Preaccelerated positron bunches from a conventional linear accelerator, about 1-kilometer long, at the Facility for Advanced Accelerated Experimental Tests at SLAC, were injected into a custom-built, meter-long, high-density plasma chamber. The bunches of high-energy positrons essentially carve their own path through the plasma, attracting plasma electrons as they go.

But rather than just scattering those electrons out of the way, the positron bunches "capture" the plasma electrons, which begin to propagate alongside the positrons. This electron propagation helps contain and focus the positrons, keeping them in tight bunches as they pass through more plasma.

"What we saw shooting out of the plasma was very, very surprising," says Hogan. Previous experiments with nonuniform plasmas, expected to be more appropriate for the task, had led to de-focused bunches of positrons, not at all useful for an accelerator.

One of the secrets to the mechanism is that not all of the positrons make it through the plasma as part of the bunches. The leading positrons annihilate or are scattered out of the bunches; but, in the process, they set up the copropagating electrons to do their job. Those leading positrons give up their energy to the electrons, which then transfer it back to the trailing positrons in the bunches, accelerating those positrons to higher energy. And this, in principle, provides a turbo boost of sorts that could allow for the exploration of fundamental particles without colliders tens of kilometers long.

One criticism of the plasma wakefield acceleration technique had been that, although researchers can achieve high energies, not enough electrons or positrons were being accelerated, leading to an intensity that was too low to be useful. That's less of an issue with the new technique.

You could tell the simulators were almost giddy.

—Mark Hogan

From Experiment Back to Theory

So why was this such a surprise to those conducting the computer simulations? The process of setting up an equilibrium in which the captured electrons are in copropagating states takes about 40 centimeters, which is much farther than available computing power allows simulations to run. Many particle-scale behaviors typically seen in particle accelerators occur over a length scale of micrometers or less. The simulations just saw the early positrons being annihilated and scattered, with no accelerating potential forming in the distances they could simulate. Upon hearing the result, "you could tell the simulators were almost giddy," says Hogan.

With this result, plasma wakefield acceleration takes a step closer to being part of a chain that accelerates electrons and positrons to record energies.

The accelerator chain would still consist of a conventional, relatively long superconducting linear accelerator that would get particles to perhaps 20 gigaelectronvolts. The plasma wakefield stages would then be chained after each other to give a boost of 20–25 gigaelectronvolts per stage over a distance of tens of meters per stage.

Still, Brian Foster of the University of Oxford and Deutsches Elektronen-Synchrotron warns that using plasma wakefield acceleration as an "afterburner" on a linear collider "really is the most difficult imaginable application," because of the focusing and alignment constraints. He suggests that there are plenty of other interesting accelerator applications for the technology, such as replacing conventional linear accelerators in medical and manufacturing applications.

Foster anticipates that creating a realistic conceptual design for these afterburners might be a possibility in about 10 years, once the technology is more refined. In that case, plasma wakefield acceleration modules could easily substitute for in-place linear collider acceleration modules without significant design changes to the linear collider, and would be a first step to making very high-energy accelerators using the technology.

But even with this new technology, linear colliders for electrons and positrons face a fundamental limit of about 5 teraelectronvolts as the electron and positron beams start interacting with each other via the creation of photons at that energy, and the beams can no longer be focused to the very small regions required.

Because of that limit, accelerator physicists are already thinking about what is beyond this energy frontier, with proposals for radically different machines that collide different types of particles, such as muons, heavier cousins of the electron. "To get much beyond 5-teraelectronvolt lepton collisions," says Foster, "the only way is to build a circular muon collider, something even further beyond the horizon than a plasma wakefield accelerator linear collider!"

1 Tajima T, Dawson JM (1979) Laser electron accelerator. *Phys Rev Lett* 43(4):267–270.
2 Rosenzweig JB, et al. (1988) Experimental observation of plasma wake-field acceleration. *Phys Rev Lett* 61(1):98–101.
3 Leemans WP, et al. (2006) GeV electron beams from a centimetre-scale accelerator. *Nat Phys* 2(10):696–699.
4 Corde S, et al. (2015) Multi-gigaelectronvolt acceleration of positrons in a self-loaded plasma wakefield. *Nature* 524(7566):442–445.