Physics

VIEWPOINT

A Metamaterial for Next Generation Particle Accelerators

An experiment reveals the potential of custom-engineered metamaterials to yield higher accelerating gradients than current particle accelerator technology allows.

by Patric Muggli*

Particle accelerators are some of the biggest man-made machines, capable of endowing particles with tera-electron-volts (TeV) of energy. And yet, to discover new particles or to explore the conditions of the early Universe, we might ultimately need much higher energies. The expense and land requirements for such large machines have pushed scientists and engineers to explore alternative accelerator technologies, which can accelerate particles ever closer to light speed over shorter distances [1]. A promising option for a linear accelerator is wakefield acceleration, where the acceleration comes from the intense electric field produced in the wake of a relativistic electron bunch, or "drive," that travels through a cavity or plasma. A group led by Richard Temkin at the Massachusetts Institute of Technology, Cambridge, and colleagues has now designed and tested a structure made of steel and copper plates—a "metamaterial"—that offers potential advantages for wakefield acceleration [2].

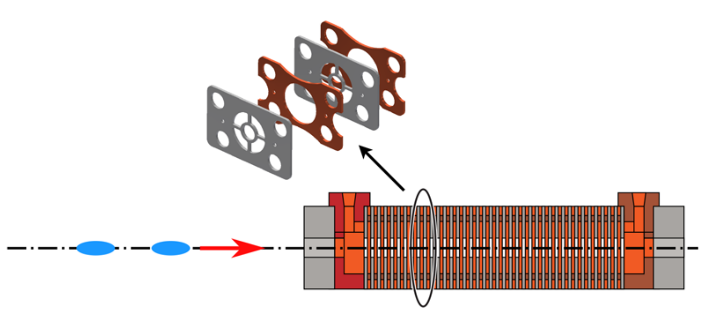

Figure 1: To accelerate particles to high energies, wakefield accelerators use the intense electromagnetic field that trails an electron bunch (blue) as it travels through a metal, plasma, or other material. Temkin and colleagues have designed an alternative wakefield material based on a metamaterial—a horizontal stack of copper and steel plates. This new material could allow for higher accelerating gradients than current technology permits [2]. (X. Lu *et al.* [2]; adapted by APS/Alan Stonebraker)

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The vast majority of accelerators elevate particles to high energies using intense electric fields, which are produced by driving a periodic metallic structure with microwaves. However, the resulting accelerating gradient—the energy gained by a particle over some distance—is limited to about 100 MeV/m, which is why accelerators need several kilometers to reach a tera-electron-volt. At higher gradients, the walls of most metallic structures can't sustain the microwave electric field and electrical breakdown occurs [3]. In the wakefield acceleration approach, the gradient limit can be much higher because the method typically makes use of dielectric materials with high breakdown fields, or plasma, which, in principle, has no breakdown limit. Here, the energy of the drive bunch is transferred into a short and intense microwave pulse (the wakefield), whose electric field can accelerate particles that directly trail behind. Alternatively, this pulse can be harnessed to energize particles in a different structure. Wakefield methods have reached gradients of 1 to 100 GeV/m [4, 5], but they have so far failed to reliably produce accelerated beams with a quality comparable to those made with metallic structures in traditional (non-wakefield) accelerators. Dielectrics and plasmas also have their own practical shortcomings and offer limited tunability.

Temkin and colleagues went a new route by engineering a metallic metamaterial—a periodic structure assembled from different parts—that combines the high gradient of wakefield accelerators and a high degree of tunability. Their metamaterial is an 8-cm-long structure made of 40 stainless-steel "wagon-wheel" plates alternating with copper spacer plates (Fig. 1). The plates are closely spaced with a 2-mm period, well below the wavelength of electromagnetic waves at typical operating frequencies. As a result, the electrons in the drive bunch don't "see" the individual plates but rather the composite effect of the entire structure: the metamaterial thus appears as a medium with novel electromagnetic properties. By varying the shape and geometry of the metamaterial, Temkin and his team could tune these properties such that the wakefield of the drive bunch was confined in a short and intense microwave pulse. This confinement minimizes the chance of electrical breakdown, which is less probable for shorter pulses. Also, the fields on the structure walls can be kept to a minimum and the accelerating field to a maximum via the metamaterial design. As a result, electrical breakdown is less of a limiting factor compared with conventional metallic structures, and a higher gradient can be achieved.

In a series of tests performed at the Argonne Wakefield Accelerator facility, Temkin and colleagues characterized the performance of the metamaterial. The team engineered the device to have a fundamental mode whose phase and group velocities were optimal for extracting power from the 65-MeV drive bunches available at Argonne. Moreover, the metamaterial was designed to have a negative group velocity, meaning that the wakefield energy travels backward relative to the bunch. The researchers confirmed this feature experimentally by showing that an overwhelming fraction of the emitted power exited through the back port of the structure. The metamaterial could extract more energy from the electron bunch than conventional metallic [6] or photonic band-gap [7] structures.

In their preliminary experiments, the researchers didn't try to accelerate a trailing bunch. However, from their measurements of the radiation produced by two electron bunches they estimated that the gradient available for acceleration would be 75 MeV/m. Simple scaling shows that 300 MeV/m could be attained with eight drive bunches. Moreover, it should be possible to achieve larger gradients in even smaller metamaterial structures by using higher energy, shorter electron bunches. Such bunches would be available at, for instance, FACET II, an accelerator testing facility that will soon be in operation at SLAC.

There is an intense and healthy competition in the accelerator community to reach the highest possible gradient and beam quality. One approach is to improve the existing metallic structures of traditional accelerators, which guarantees high beam quality but only a modest boost in accelerating gradient. Another option is to use new materials, such as plasma, which can handle much higher gradients, but beam quality is currently an issue. The approach of Temkin and colleagues is somewhere in between, in that it uses a new material that is nonetheless a metal. They have thus made a clever attempt to take the best of both worlds: the high accelerating gradient of new materials and the high beam quality of traditional structures. New materials have often changed the world—think of iron, plastic, and silicon. Whether metamaterials are a game-changer for accelerators remains to be seen—their ability to accelerate particles in high gradients and to meet other requirements still has to be tested. But the payoff for success would be high, which is why researchers are actively exploring this type of promising innovation.

This research is published in *Physical Review Letters*.

REFERENCES

[1] B. Cros and P. Muggli, "Towards a Proposal for an Advanced Linear Collider, Report on the Advanced and Novel Accelerators for High Energy Physics Roadmap Workshop," (CERN, Geneva, 2017); (PDF).

[2] X. Lu *et al.*, "Generation of high-power, reversed-Cherenkov wakefield radiation in a metamaterial structure," Phys. Rev. Lett. **122**, 014801 (2019).

[3] A. Grudiev, S. Calatroni, and W. Wuensch, "New local field quantity describing the high gradient limit of accelerating structures," Phys. Rev. ST Accel. Beams **12**, 102001 (2009).

[4] V. Malka *et al.*, "Electron acceleration by a wake field forced by an intense ultrashort laser pulse," Science **298**, 1596 (2002).

[5] I. Blumenfeld *et al.*, "Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator," Nature **445**, 741 (2007).

[6] C. Jing *et al.*, "Electron acceleration through two successive electron beam driven wakefield acceleration stages," Nucl. Instrum. Methods Phys. Res. Sect. A **898**, 72 (2018).

[7] E. I. Simakov *et al.*, "Observation of wakefield suppression in a photonic-band-gap accelerator structure," Phys. Rev. Lett. **116**, 064801 (2016).

10.1103/Physics.11.137

