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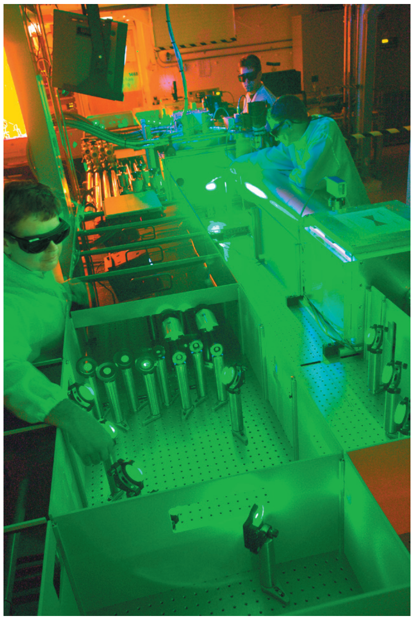
BELLA: The Next Stage in Laser Wakefield Acceleration

Contact: Paul Preuss, paul_preuss@lbl.gov

For over a year, the LOASIS group led by Wim Leemans, of Berkeley Lab's Accelerator and Fusion Research Division (AFRD), has held the world record for laser-wakefield acceleration, accelerating high-quality electron beams to energies exceeding 1 GeV, a billion electron volts, in a distance of just three centimeters. Now Leemans and his colleagues are poised to achieve energies an order of magnitude higher still, with BELLA, the BErkeley Lab Laser Accelerator.


From left, Csaba Toth, Joseph Wallig, and Wim Leemans of the LOASIS group work with the 40-terawatt laser. (Photo Roy Kaltschmidt)

"The first step for BELLA is to develop a 10-GeV laser-wakefield accelerator module," says Leemans. "With it we'll be able to address some of the most interesting scientific questions recently posed by the National Academies—everything from cosmology to extreme physics. How do the natural accelerators in the cosmos work? Is the theory of quantum electrodynamics adequate at the highest energies? We'll also get answers to exciting practical questions about using lasers to build the high-energy particle colliders of the future."

The energy an accelerator adds to a particle for each unit of distance it travels is called the accelerating gradient; electron and positron machines like the proposed International Linear Collider (ILC), plus other accelerators now in the planning stage, will add 25 million volts each meter. With that kind of gradient—strong for a conventional accelerator—beam energies of 250 GeV, needed to achieve the ILC's goal of smashing electrons and positrons together at center-of-mass energies of half a trillion electron volts, will require a linear collider at least 30 kilometers long.

But with billion-electron-volt beams in just three centimeters—so short that laser-wakefield acceleration has sometimes been called "tabletop" acceleration—Leemans's LOASIS group (LOASIS stands for Laser Optics and Accelerator Systems Integrated Studies) has already demonstrated an accelerating gradient a thousand times greater.

BELLA's 10-GeV accelerator module will provide powerful, intense electron beams with pulses as short as a femtosecond (a quadrillionth of a second, 1×10^{-15} sec) for research in materials science, life sciences, physics, and chemistry—an extraordinary facility in its own right—but that's just the beginning. By stringing a hundred or so of BELLA's 10-GeV modules together, intense colliding beams of electrons and positrons with center-of-mass energies of 1 TeV, a trillion electron volts, or more, could be created in just a few hundred meters. That's twice the energy of a conventional 30-kilometer collider—if not exactly on a tabletop, still in only about the dimensions of a typical sports arena.

The science that a 10-GeV BELLA module will be able to explore stretches the imagination. An electron accelerated in a very strong electric field can gain energy equivalent to its own rest mass while moving the distance of its Compton wavelength: that means moving the electron just 2.4 trillionths of a meter (2.4×10^{-12} m) in an electric field of 30 quintillion volts per meter (3×10^{18} V/m), the so-called Schwinger limit. Imagine a runner whose mass doubles with every six feet he or she runs!

In a vacuum, electron-positron pairs are always blinking into and out of existence as virtual particles; usually they don't stick around long. But a field strong enough to exceed the Schwinger limit can create stable particles from nothing, which is known as "boiling" or "snapping" the vacuum. Indirect, proof-of-principle experiments have been done with conventional accelerators, but vastly stronger fields could be produced by bouncing a petawatt laser beam (a quadrillion watts, 10^{15} W) off a 10-GeV electron beam accelerated by BELLA.

With this kind of power, conditions like those inside an exploding star could be recreated; cosmology would come into the laboratory.

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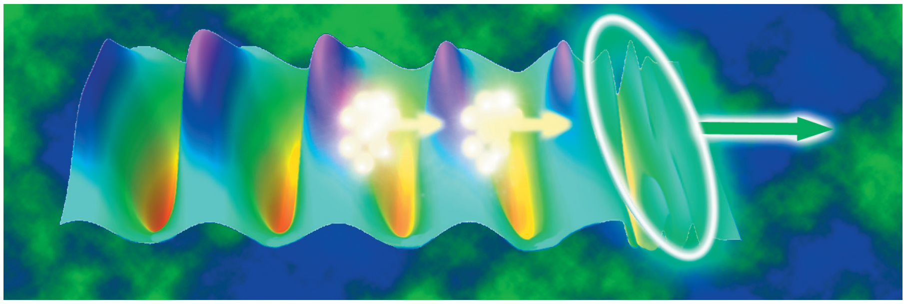
What it will take

Laser-wakefield acceleration begins with a plasma—a state of matter in which positively and negatively charged particles are dissociated, typically protons (hydrogen nuclei) and electrons. A laser pulse driven through the plasma creates a wake that traps some of the free electrons and carries them along like surfers riding a wave. But sooner or later, when the electrons outrun the wake, acceleration stops.



A laser pulse traveling through a plasma, indicated by the ellipse at right, accelerates bunches of free electrons (center) in its wake.

To lengthen this so-called "dephasing length" requires a more tenuous plasma and a laser beam collimated over a longer distance. Most experimenters have tried to achieve this by using a large laser spot size, which requires a much more powerful laser for a relatively modest gain in acceleration.

The LOASIS group, by contrast, developed the method of drilling a long focusing channel through the plasma, thin at the center, dense at the walls—a plasma channel with focusing geometry analogous to the optical fibers used in long-range communications. A laser drive pulse is sent through this channel to form a wake that can maintain its accelerating power over fairly long distances, and for a long enough time to generate multi-GeV electron beams.

BELLA's research and development will begin with facilities already in place at the LOASIS laboratory, where record-breaking 1-Gev electron beams were created using a 40-terawatt laser (40 TW, or 40 trillion watts) and a three-centimeter capillary carved in a block of sapphire. High-quality beams were created by first filling the capillary with hydrogen gas, then discharging a 1-joule capacitor through it to turn the gas to plasma and form the focusing channel guide, and finally by sending the 40-TW laser's drive pulse through the channel to accelerate free electron bunches.

The challenges for BELLA include devising a way to stage accelerating modules so that accelerated electron bunches from each stage are passed to the next for added acceleration. This in turn requires controlled, periodic, rapid plasma formation via discharge and laser-pulse injection into each stage. The LOASIS capillary-discharge technology will be extended to create plasma focusing channels up to tens of centimeters in length. Progress also requires diagnostic techniques and powerful computer simulations for fine-scale characterization and modeling of the beams.

To achieve BELLA's main objective of 10-GeV electrons, a new and much more powerful laser will have to be put in place, a state-of-the-art laser that can fire a 40-joule pulse in a brief 40 femtoseconds, then build up to fire again and again, once every second, a repetition rate of one hertz (1 Hz). Such a laser will have an average power of 40 W and a peak power of a quadrillion watts—a petawatt, 1 PW.

"Since the time we designed and built the LOASIS 40-TW laser ourselves, there has been a revolution in the field of laser technology," Leemans says. "Advances are now driven by commercial companies, and by military requirements, and we have been talking with two companies who want to build a laser for BELLA under our supervision."

Given Berkeley Lab's already substantial commitment to LOASIS, BELLA initially needs only modest funding for additional staff and equipment. In addition, sections of the HILAC and SuperHILAC accelerators for which Building 71 was built (and which now houses the LOASIS laboratory) must be removed and the building seismically retrofitted to prepare for the BELLA infrastructure. Completing BELLA will require a 1-Hz, 1-PW laser—the highest average power (40 W) petawatt-class laser in the world.

"With the support of DOE, which has already given its approval of BELLA's mission need, we plan to have a 10-GeV acceleration module in place and working within five years," Leemans says. "This will provide a unique user facility for scientists who need advanced light sources and free-electron lasers. Meanwhile, we'll be on the way to designing a new generation of powerful accelerators and colliders based on laser-wakefield acceleration technology. BELLA will help insure that the unique science DOE has made possible through its leadership in advanced accelerator research will go forward into the future with laser-based technologies."

The BELLA project will be carried out by the LOASIS Program staff led by Wim Leemans, presently including Eric Esarey, William Fawley, Cameron Geddes, Anthony Gonsalves, Nicholas Matlis, Estelle Cormier-Michel, Dmitriy Panasenko, Carl Schroeder, and Csaba Toth of AFRD, with Donald Syversrud and Nathan Ybarrolaza of Engineering and support from AFRD's Olivia Wong and Martha Condon. BELLA will involve collaboration with Berkeley Lab's Physics, Engineering, Advanced Light Source, and National Energy Research Scientific Computing Center Divisions, with academic institutions including Oxford University, the University of Colorado, the University of Nevada at Reno, and the University of Texas at Austin, with other DOE laboratories including the Lawrence Livermore National Laboratory, and with private industry.

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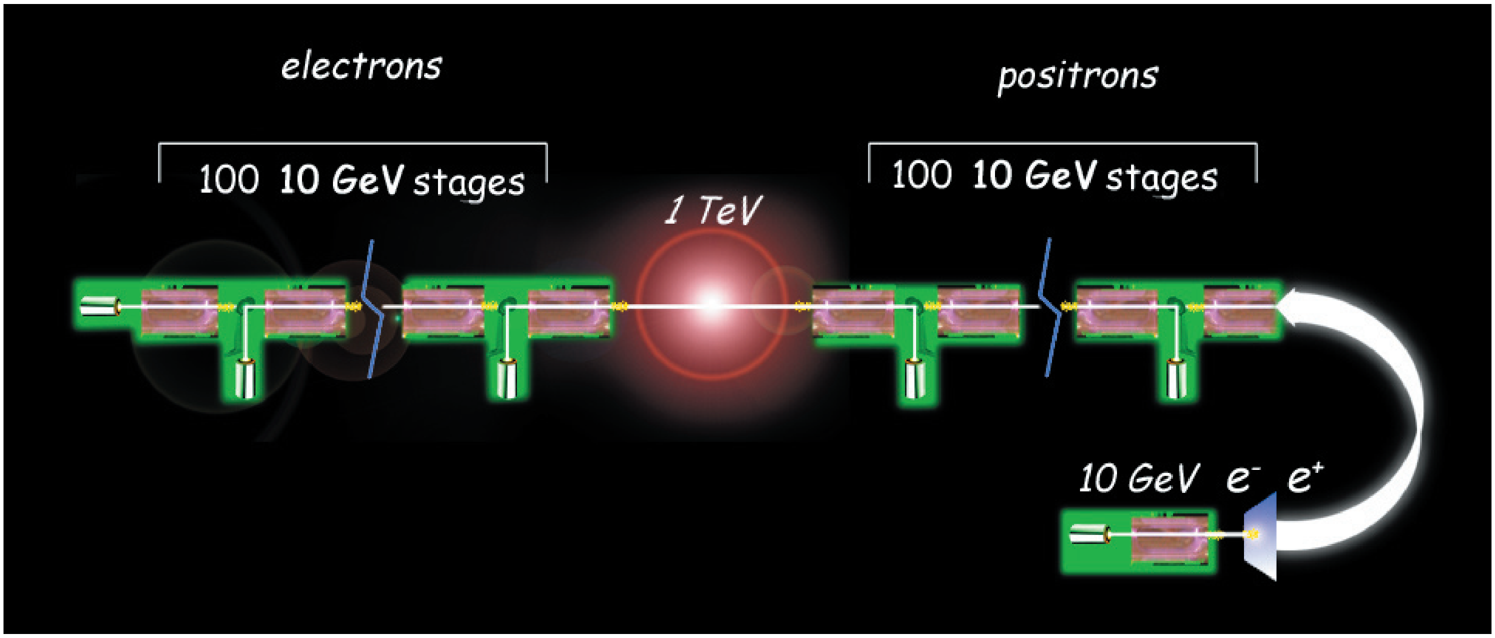

A collider with 100 or so 10-GeV stages in each beam could accelerate electrons in one beam and positrons in the other to center-of-mass energies of 1 TeV or more in just a few hundred meters.

Additional information

For more about LOASIS, visit http://loasis.lbl.gov/main.html.

For more about the world record laser-wakefield accelerator, one billion electron volts in three centimeters, go to http://www.lbl.gov/Science-Articles/Archive/AFRD-GeV-beams.html.

For more about "Dream Beams," the first high-energy, high-quality beams from a laser-wakefield accelerator, go to http://www.lbl.gov/Science-Articles/Archive/AFRD-laser-wakefield.html.