Upgraded laser facility paves the way for next-generation particle accelerators

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(Left): Two deformable mirrors. In addition to arrival time and pulse length control of both beam lines, these mirrors allow for independently shaping the focal spot mode, which is critical for optimized staged acceleration. (Right) In the newly-commissioned second beam line, the laser beam travels through the large white tubes into the laser-plasma accelerator vacuum system. Marlene Turner (foreground) and postdoctoral scholar Alex Picksley check for alignment. Credit: Marilyn Sargent/Berkeley Lab

Researchers at Lawrence Berkeley National Laboratory (Berkeley Lab) have completed a major expansion of one of the world's most powerful laser systems, creating new opportunities in accelerator research for the future of high-energy physics and other fields. The expansion created a second beamline for the petawatt laser at the Berkeley Lab Laser Accelerator (BELLA) Center, enabling the development of next-generation particle accelerators for applications in science, medicine, security, and industry. The second beamline came online this summer and is the culmination of several years of planning, design, and engineering by the BELLA and engineering teams.

"We are happy to see construction completed and are very eager to begin the wide variety of exciting experiments that are enabled by the second beamline," said Eric Esarey, Director of the BELLA Center.

Using light to move particles

Traditional accelerators use radio-frequency electromagnetic fields to gradually speed particles up over distances of tens of kilometers and tend to be huge and very expensive as a result. For example, the Large Hadron Collider at CERN, the famous international particle accelerator, accelerates particles along a circular path over 16 miles long, a monumental achievement costing billions of dollars to build and operate.

At the BELLA Center, scientists accelerate charged particles with electric fields generated by a high-powered laser interacting with a plasma, creating what's known as a laser-plasma accelerator (LPA). The team uses a one-petawatt laser that produces a beam of very short pulses or "bullets" of light, one per second, each of which is about a hundred times more powerful than a typical lightning bolt. When the laser beam passes through plasma (a gas-like soup of charged particles), it sets up a moving wave, and a charged particle placed in that wave is then propelled forward, like a surfer on an ocean wave. This "wakefield" approach can produce rates of acceleration up to one thousand times greater than conventional accelerators, making LPAs a promising candidate for the next generation of smaller, less expensive accelerators.

A powerful tool for accelerator technology development

The second beamline was designed to be highly tunable, able to produce a wide range of laser-spot sizes, with pulse durations and pulse energies that can be varied independently. The two beamlines are intended to be used in tandem, making the system a powerful and versatile tool for science and accelerator technology development. To create the new beamline, the team split off a portion of the main laser beam and ran it through a series of optics to generate a second beam of short, powerful pulses of light that can create a second wakefield.

In particular, the system was designed to enable the team's vision of staging multiple LPA modules in order to reach the high electron-beam energies needed for particle colliders, using the wakefield of the second beamline to further accelerate particles coming off the first. Initial experiments to achieve this goal are currently underway. In their longer-term vision, the team proposes stacking additional laser-powered modules to create accelerators of extremely high energies, enabling the next generation of physics discoveries at a fraction of the cost and size.

As an example, methods to enhance the energy efficiency of LPAs can also be explored with the dual beamlines. The second beamline laser pulse can be configured to absorb any leftover energy in the first beamline plasma that is unused by the acceleration process and then sent to an energy recovery system. Marlene Turner, a scientist in the BELLA Center, received a prestigious early career award from DOE to work on this concept. "Without the second beamline, my research, which aims to decrease the power consumption and environmental impact of future plasma colliders, would not be possible," said Turner.

The dual beamlines can be used in other configurations as well. For example, the second beamline can be used to accelerate particles to scatter off those from the first beamline, enabling physicists to probe the exotic physics that arise.

"The precision that these two laser beamlines bring, combining femtosecond timing and micron-scale spatial accuracy, is unprecedented at petawatt-class peak power levels, and will enable experiments on LPA staging as well as other advances in plasma acceleration such as laser tailoring of plasma accelerating structures, laser-based methods of particle injection, high energy photon production by laser scattering, and fundamental studies in high field quantum electrodynamics, " said Tony Gonsalves, the lead scientist on the BELLA petawatt team. "It's a big deal."

The power of team science

Berkeley Lab is known as a powerhouse of team science, and this new BELLA project exemplified this ethos. At any one time, the core team working on this project includes ten to fifteen mechanical engineers, electrical engineers, and research scientists, as well as a rotating cast of other key players, including radiological safety specialists and seismic engineers. This has ensured that the two-laser-beamline upgrade not only creates state of the art science, but is executed in a safe, well-engineered, and durable manner that will enable continued productivity for many years to come.

The team encountered their fair share of challenges due to the COVID-19 pandemic, which temporarily shut their facility down. After it reopened, the team had to work in shifts, using a ticketing system to maintain safe density of workers. Just bringing in a team of French engineers to install a compressor chamber took the better part of a year due to pandemic-related restrictions.

"It's been a long road to get this going, and a much longer road because of COVID," said Gonsalves. "If you were to count how many people have touched this project, it'd be a very large number. We're lucky to have this impressive infrastructure of people at the Lab to make a project like this possible."

Exotic physics and every-day applications

Particle colliders are discovery tools that scientists use to probe the structure of matter by smashing particles together with enough energy to break them apart, helping us understand what the universe is made of and the forces that hold it together. The ultimate goal of the new beamline is to develop a new accelerator technology that will enable colliders to reach higher energies. These questions go way beyond examining visible matter, which actually makes up a small fraction of the universe. There is five times more invisible dark matter in the universe than visible matter, and higher energy accelerators may be able to produce heavy dark matter particles so their properties can be studied.

The national security field is also paying attention to these developments in novel accelerator technology. Current technologies to screen for nuclear materials at ports, for nuclear treaties and other applications, are limited in precision. Laser-based accelerator technology, however, could be used to produce the tunable gamma rays or high energy muons needed to accurately detect nuclear compounds or other materials, and the technology could fit into a small, portable unit.

Basic studies in material science would also benefit greatly from the development of compact sources of short wavelength light, such as X-rays, driven by LPAs. Since the LPA intrinsically produces short electron bunches, on the order of femtoseconds, they are ideal to probe materials on ultrafast time scales.

Another exciting application of laser acceleration is in cancer radiation therapy, where the medical community is finding that shorter doses of stronger radiation do less damage to healthy tissues, known as the "flash effect." These laser systems could revolutionize radiation therapy.

"I am very excited to see the wide variety of science and applications that are enabled by the BELLA second beamline. These are cross-cutting and can impact a number of programs in the Office of Science, the Department of Defense, the National Institutes of Health, as well as in industry," said Cameron Geddes, Director of Accelerator Technology and Applied Physics Division of Berkeley Lab.

Provided by Lawrence Berkeley National Laboratory