Unprecedented plasma lensing for high-intensity lasers

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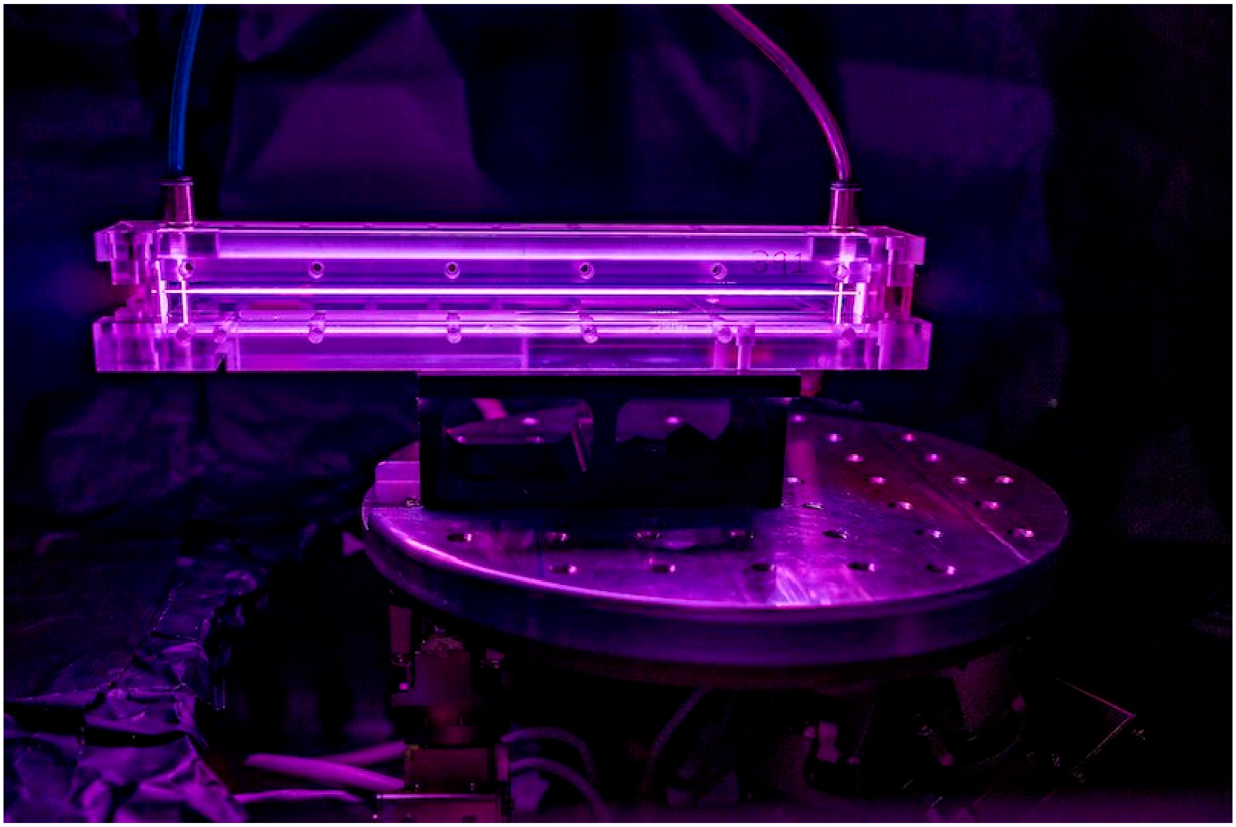


A 20-centimeter-long capillary discharge waveguide, used at BELLA Center to guide high-intensity laser pulses, and applied to set their record thus far for accelerating electrons: 8 billion electron volts (GeV). Credit: Thor Swift/Berkeley Lab

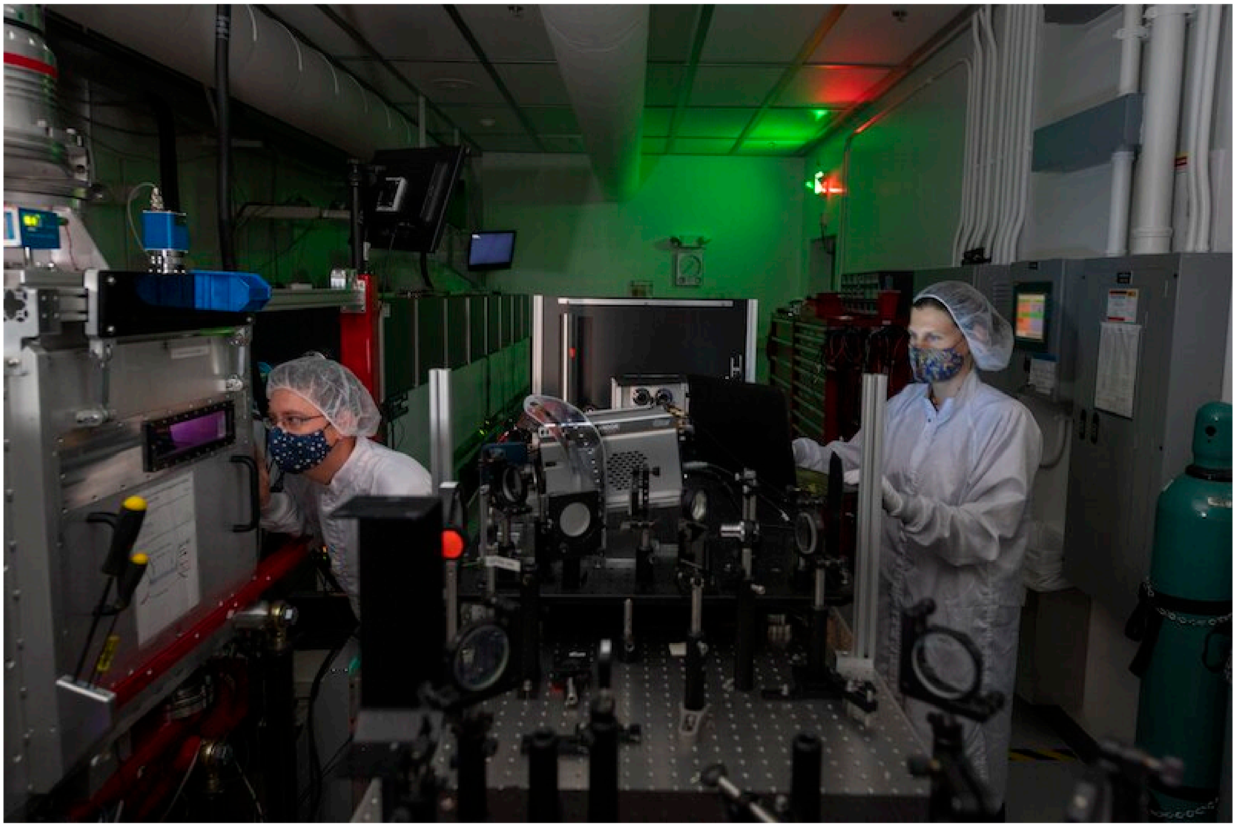
High-power laser pulses focused to small spots to reach incredible intensities enable a variety of applications, ranging from scientific research to industry and medicine. At the Berkeley Lab Laser Accelerator (BELLA) Center, for instance, intensity is key to building particle accelerators thousands of times shorter than conventional ones that reach the same energy. However, laser-plasma accelerators (LPAs) require sustained intensity over many centimeters, not just a spot focus that rapidly expands because of diffraction.

To achieve sustained intensity, the BELLA Center, at the Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab), uses thin hollow structures, or "capillaries," containing a plasma to transport the pulses of light. BELLA Center scientists have been pushing toward longer and longer capillaries as they strive for higher beam energies with their LPAs.

Their latest work shows, with higher precision than ever before, that these plasma waveguides are extremely stable and of reproducibly high quality, and that these characteristics can be maintained over distances as long as 40 centimeters. It confirms that this key technology for LPAs can be scaled up as the BELLA Center pushes toward higher energies, benefiting potential applications that range from biomedical research and treatment to free-electron-laser light sources for research facilities.

The work—led by postdoctoral scholar Marlene Turner, working with staff scientist Anthony Gonsalves—is described in a study published in the journal *High Power Laser Science and Engineering*.

"This work shows that capillaries can produce extremely stable plasma targets for acceleration and that observed variations in accelerator performance are primarily laser fluctuation driven, which indicates the need for active laser feedback control," said Cameron Geddes, director of the Accelerator Technology and Applied Physics Division, parent organization of the BELLA Center.



Marlene Turner (right) collaborating under COVID precautions with Anthony Gonsalves. Credit: Thor Swift/Berkeley Lab

Plasma channels give consistent guidance to powerful pulses

Fiber optics can transport laser beam pulses over thousands of kilometers, a principle familiar in modern computer networks. However, with the high laser intensities used at BELLA Center (20 orders of magnitude more intense than the sunlight on the Earth's surface), electrons would be near-instantaneously removed from their parent atoms by the laser field, destroying solid materials such as glass fibers. The solution is to use plasma, a state of matter in which electrons have already been removed from their atoms, as a "fiber."

The BELLA Center has used plasmas to guide laser pulses over distances as long as 20 centimeters to achieve the highest laser-driven particle energies to date. The plasma is created by an electrical discharge inside the capillary. This is where electrons "surf" a wave of ultrahigh electric field set up by the laser pulse. The longer the sustained focus, the faster they are going at the end of the ride.

However, the gas breakdown in an electrical discharge is a violent and largely uncontrolled event (imagine a tiny, confined lightning strike). Charting a path forward to ever higher energies and precision control at the BELLA Center, researchers needed to know how reproducible the wave-guiding characteristics are from one laser pulse to another, and how well each laser pulse can be guided.

In order to give wave-guiding results analogous to a fiber optic, the plasma density should be lowest in the center, with a profile mathematically described as parabolic. "We showed, with unprecedented precision, that the plasma profiles are indeed very parabolic over the laser pulse spot size they are designed to guide," said Gonsalves. "This allows for pulse propagation in the waveguide without quality degradation."

Marlene Turner inspects a 40-centimeter-long capillary. Credit: Thor Swift/Berkeley Lab

Other types of plasma waveguides (there are several ways to create them) can also be measured with high precision using these methods.

The measurement precision was also ideal for investigating how much the density profile changes from one laser shot to another, since although the capillary is durable, the wave-guiding plasma within it is formed anew each time. The team found outstanding stability and reproducibility.

"These results, along with our ongoing work on active feedback aided by machine learning techniques, are a big step to improving the stability and usability of laser-plasma accelerators," said Eric Esarey, director of the BELLA Center. (Active feedback to stabilize laser fluctuations is also the subject of research and development at the BELLA Center.)

Guided laser pulses illuminate a path toward progress

Laser-plasma acceleration technology could reduce the size and cost of particle accelerators—increasing their availability for hospitals and universities, for instance, and ultimately bringing these benefits to a next-generation particle collider for high-energy physics. One of the keys to increasing their particle-beam energy beyond the present record of 8 billion electron volts (GeV) is the use of longer accelerating channels; another is "staging," or the use of the output of one acceleration module as the input to another. Verifying the quality of the plasma channel where the acceleration takes place—and the consistency and reproducibility of that quality—gives a vote of confidence in the technology basis of these plans.

Aside from showing that this capillary-based waveguide is of high and consistent quality, this work involved waveguides twice as long as the one used for achieving record-breaking energy. "The precision 40-centimeter-long waveguides we have now developed could push those energies even higher," said Turner.

More information: M. Turner et al, Radial density profile and stability of capillary discharge plasma waveguides of lengths up to 40 cm, *High Power Laser Science and Engineering* (2021). DOI: 10.1017/hpl.2021.6

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