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Sculpting Light in Space and Time with the Flying Focus

A high-power laser pulse can move its brightest point over a long distance at an engineered speed, opening new ways to control the production of energetic particles and radiation.

CHICAGO—Recent advances in optical science allow for the longitudinal position of a laser's focus to move in space over the pulse duration. Using this technique, coined the "flying focus," researchers are seeking to overcome the dephasing limitations within laser-plasma interactions. This could enable unprecedented efficiencies in the production of laser-plasma produced electrons and terahertz radiation. Recent experiments have demonstrated that using a flying focus has led to the acceleration of electrons over longer distances and the production of more intense terahertz radiation than experiments conducted with conventionally-focused laser beams.

The flying focus works by making the brightest point of a laser pulse move at a precisely controlled speed. This capability has long been predicted to enable new ways of using powerful lasers to produce radiation and charged particles by matching the motion of the focal point to the motion of the generated radiation or particle beam. Despite these predictions, experiments demonstrating these applications have remained elusive because of the difficulty of producing a powerful flying focus in the laboratory.

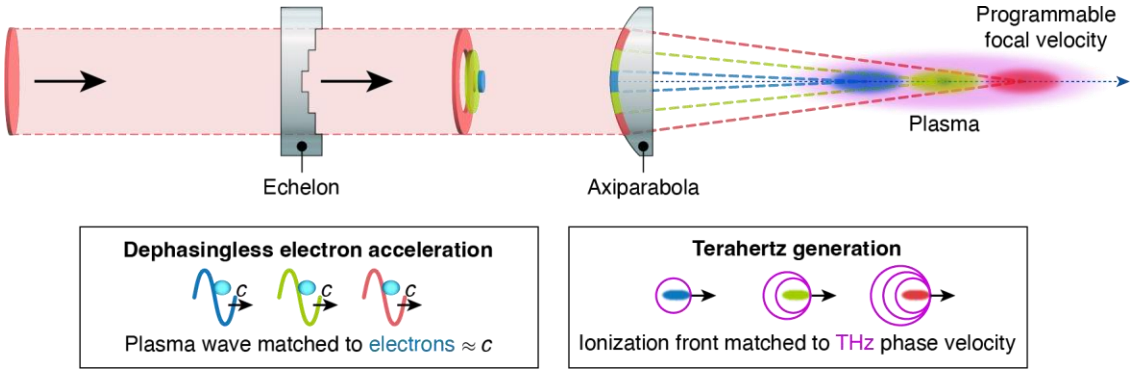


Figure 1: A laser pulse with a "flying focus" is produced using a combination of a radially-stepped echelon and an axiparabola. The focal velocity of the flying focus can be precisely controlled, allowing scientists to synchronize the motion of the focal point with the acceleration of electrons and the production of terahertz radiation. This provides a new way to control the properties of particles and radiation produced by high-power lasers.

Advances in optical fabrication and measurement at the University of Rochester's Laboratory for Laser Energetics have now made it possible to create a high-power flying focus, leading to two recent experiments demonstrating its potential (Figure 1). A normal

lens gathers light into one bright spot. The flying focus uses two special optics instead. One focuses different rings of the laser beam at different distances, stretching the focus into a long line. The other is stepped like a staircase and delays each ring by just the right amount so that the brightest point sweeps along the line at a chosen speed. By adjusting these delays, the researchers can precisely control how quickly the focal point moves along the line. That speed can be slower than the speed of light, equal to it, or even faster.

In one experiment, the laser pulse drove a wave through a plasma, and electrons rode that wave like surfers. Normally, the electrons eventually outrun the wave and stop gaining energy, like the surfer reaching the bottom of the wave. With the flying focus set to the speed of light, the wave kept pace with the electrons, allowing them to continue gaining energy.

In a second experiment, the team used the flying focus to generate terahertz radiation, an invisible form of light with a frequency between microwaves and infrared radiation. In the conventional approach, the laser creates an ionization front that moves faster than the speed of light and generates a terahertz wave much like a sonic boom, but at terahertz frequencies. This produces a hollow, ring-shaped beam. By slowing the flying focus to just below the speed of light, the researchers mitigated this effect and filled in the center of the beam, allowing the terahertz radiation to be focused to a spot roughly half as wide. Changing the speed of the flying focus also changed the frequencies contained in the terahertz radiation.

Both results were published this year in *Nature Physics* and *Nature Communications*. Together, the experiments demonstrate how controlling the motion of a laser's focal point can provide a new way to control the particles and radiation produced by high-power lasers. Next, the team will test a single optic that combines the functions of the two current optics, providing even finer control over the focal speed. They also plan to conduct experiments on NSF OPAL, a much more powerful laser facility being designed at the University of Rochester's Laboratory for Laser Energetics. Looking ahead, laser wakefield acceleration using a flying focus with NSF OPAL could produce electrons with energies comparable to those reached in CERN's 27-kilometer-long Large Hadron Collider, but in less than a meter.

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Abstract

FI01/6 Experimental control of terahertz radiation with an ultrashort flying focus

Session FI01: Plasma Optics and Structured Light

9:30 AM–12:30 PM, Tuesday, November 3, 2026

Room: Hilton Chicago, International North, Second Floor