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Producing extreme ultraviolet laser pulses efficiently by wakesurfing behind electron beams

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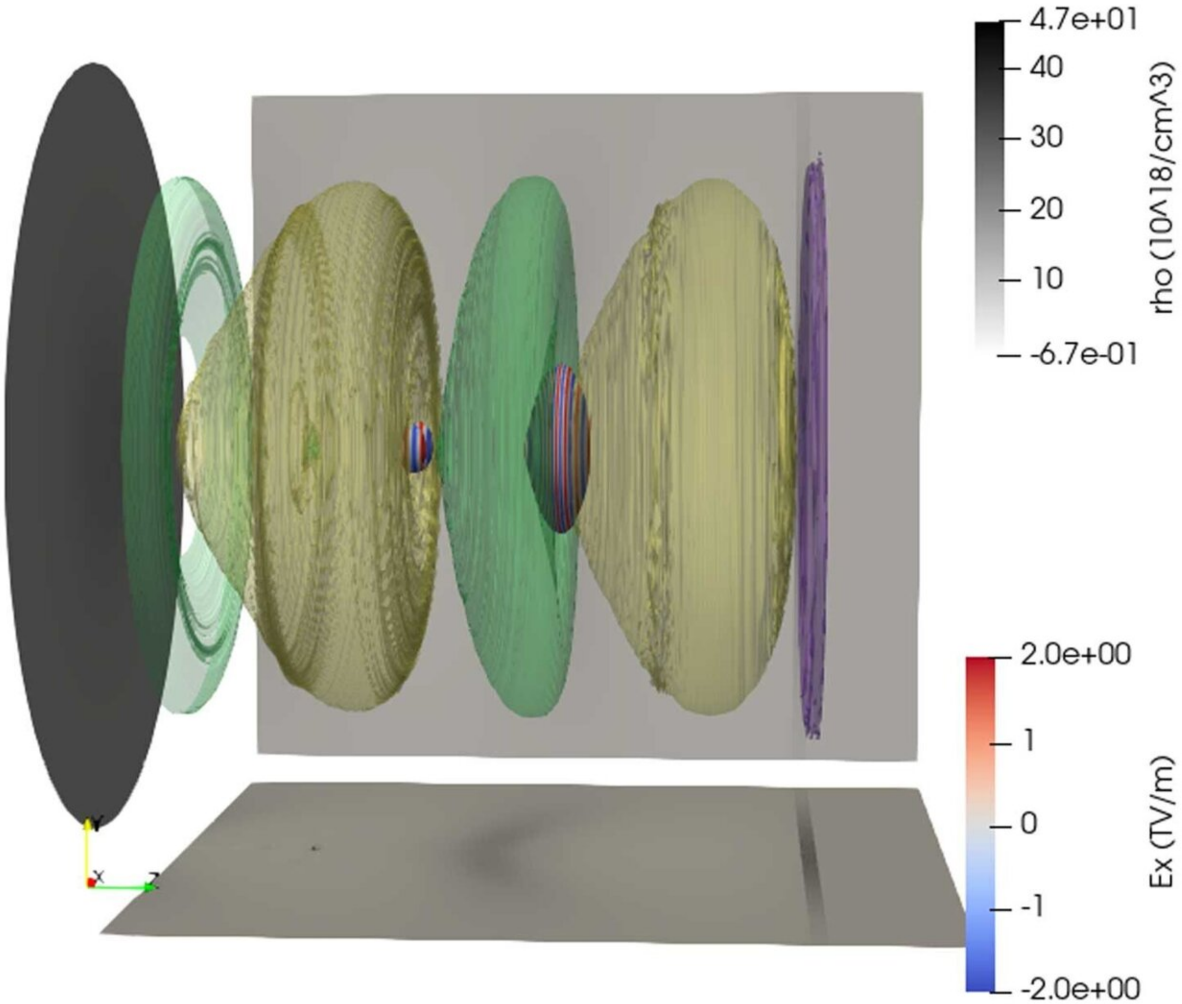


A 3D simulation of the wake behind the electron beam (purple) and how a light pulse (blue and red stripe) might surf behind it. The plasma wake is shown in alternating yellow for the absence of electrons and green for peaks in the electron density. When a light pulse sits on that boundary, it can continuously gain energy—the trick is keeping it there. Credit: Ryan Sandberg, High Field Science Group

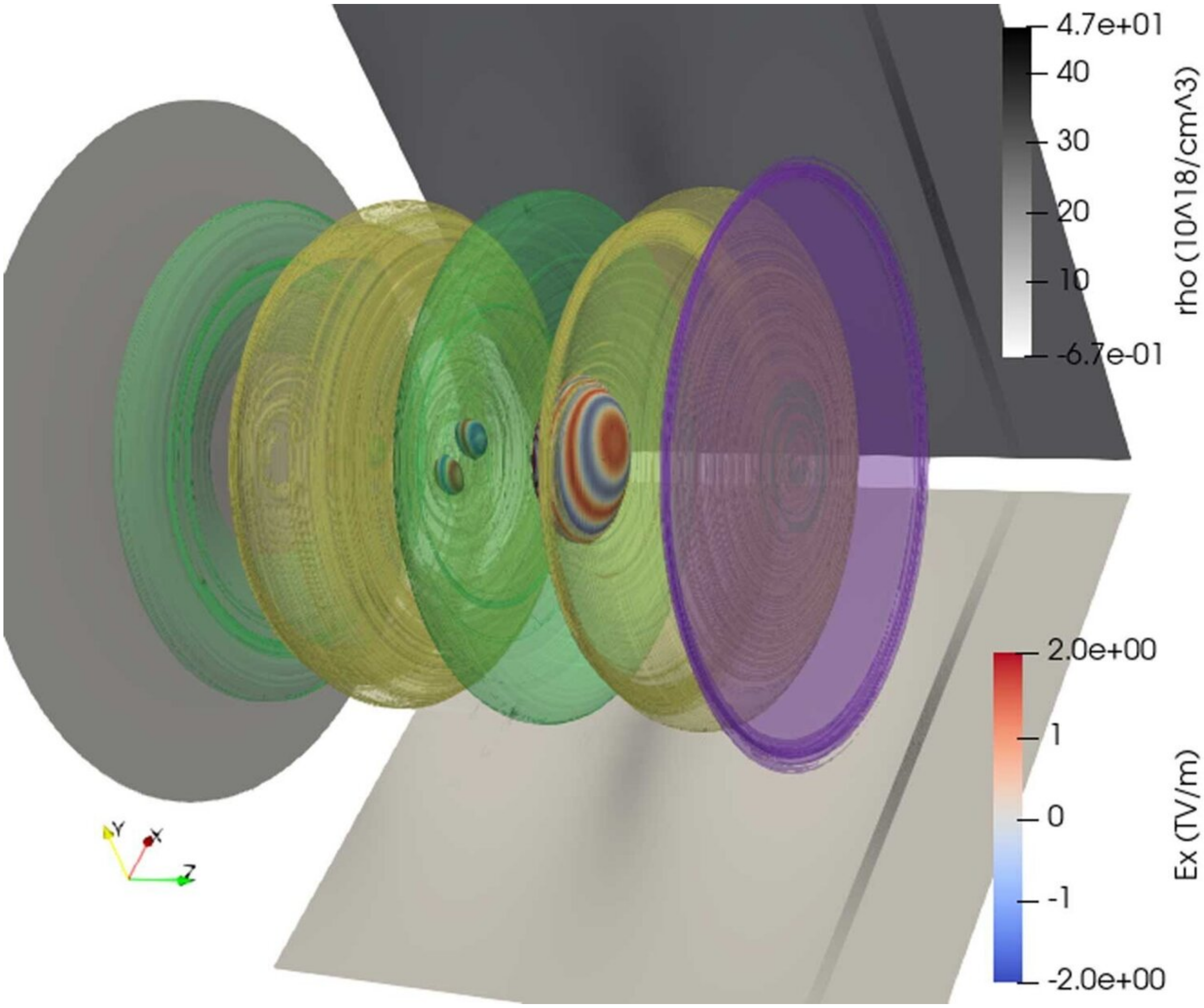
A laser pulse surfing in the wake of an electron beam pulse could get upshifted from visible to extreme ultraviolet light, simulations done at the University of Michigan have shown.

The approach could enable more efficient generation of high-energy laser light, perhaps even to X-rays. The 3D simulation showed up to a tenfold increase in the frequency of the light, while the 1D simulation went up to a 50-fold increase. In principle, the researchers say it is possible to continue amping up the energy of the laser pulse by extending the period of time that it can ride in the wake of the electron beam.

"Future lasers, potentially including those used to pattern semiconductor chips for computers, could take advantage of this effect to produce higher energy pulses more efficiently," said Alec Thomas, U-M professor of nuclear engineering and radiological sciences and corresponding author of the study in *Physical Review Letters*.

A tenfold increase in frequency is enough to turn visible light into extreme ultraviolet radiation, and the method also maintains the alignment of the waves in the initial laser pulse, known as coherence. In addition, the energy of the pulse rises with the frequency, enabling peak powers as high as a 100 trillion watts.

This is more than the output of the world's electrical generation capacity, for a fleeting quadrillionth of a second. The researchers anticipate that this phenomenon could save a significant amount of energy in semiconductor manufacturing and laser physics labs, although they prefer not to estimate how much until confirming the finding with experiments.



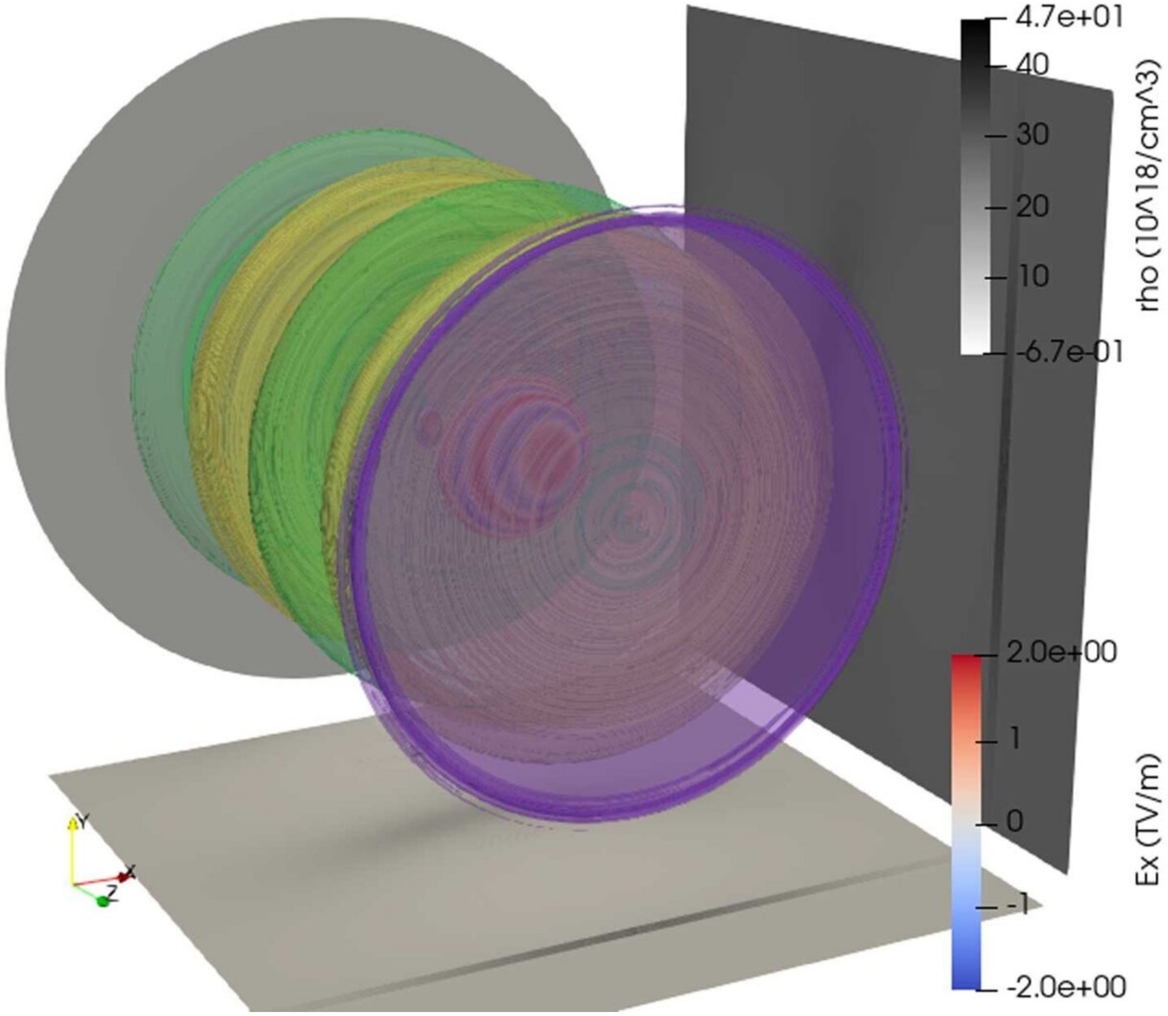
Side view of a 3D simulation of the wake behind the electron beam (purple) and how a light pulse (blue and red stripe) might surf behind it. Credit: Ryan Sandberg, High Field Science Group

Here's how it works:

Start with a short pulse of electrons traveling near the speed of light. When they travel through a gas, they tear it apart, or ionize it, creating a state of matter called plasma in which electrons are lifted off their atoms. As far as the electron pulse is concerned, the heavy, positively charged ions are stationary, but the loose electrons form a wake behind the electron pulse.

"It's kind of like a motorboat flying through the water, pushing the water behind it," said first author Ryan Sandberg, a U-M Ph.D. graduate in applied and interdisciplinary mathematics and scientific computing and now a research fellow at Lawrence Berkeley National Laboratory. "The electron pulse plows through, and the laser pulse is very similar to someone sitting behind the motorboat trying to surf this wake."

That wakesurfing laser pulse—sitting just ahead of the first wave of loose electrons trailing the electron beam—will pick up energy from the wake. It does this because the fairly high density of loose electrons, bordered by an area from which they are largely absent, creates a boundary where the laser light moves differently on either side. When the light waves exit the loose electrons, the peaks and troughs draw closer together, shifting the laser pulse to a higher and more energetic frequency of light.



End view of a 3D simulation of the wake behind the electron beam (purple) and how a light pulse (blue and red stripe) might surf behind it. Credit: Ryan Sandberg, High Field Science Group

This effect was first predicted in 1989 by researchers at the University of California, Los Angeles and Los Alamos National Laboratory, but at the time, only a 10% upshift seemed feasible before the laser pulse slipped out of position on the plasma wake. Still, the California team speculated that if it was possible to keep the light on that boundary between the electrons and the area absent of electrons, the pulse could continue to gain energy, even to a tenfold increase.

More than 30 years later, the Michigan team found a new way to make that happen. The trouble is that the electron beam, and hence the wake, is not going the same speed as the laser pulse—the light is slowed down slightly by the plasma even though it is gaining energy. To keep the laser pulse in the right spot, the boundary also needs to shift backward relative to the electron beam.

Sandberg and Thomas propose to accomplish this by varying the density of the gas that the electron beam travels through. As the gas becomes less dense, the wake extends further behind the electron beam.

"By doing that, Ryan managed to get frequency upshifts a hundred times beyond what anybody has done before," Thomas said.

Sandberg and Thomas think that it's possible to achieve a tenfold frequency increase using this method at laboratories like the Stanford Linear Accelerator Center and, in the future, the ZEUS laser facility at U-M. And in principle, they anticipate that as long as the light stays on the boundary, the wavelength of the light would continue to shorten, pushing to higher energies and frequencies.

More information: R. T. Sandberg et al, Photon Acceleration from Optical to XUV, *Physical Review Letters* (2023). DOI: 10.1103/PhysRevLett.130.085001

Provided by University of Michigan

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