The mechanism of cosmic magnetic fields explored in the laboratory

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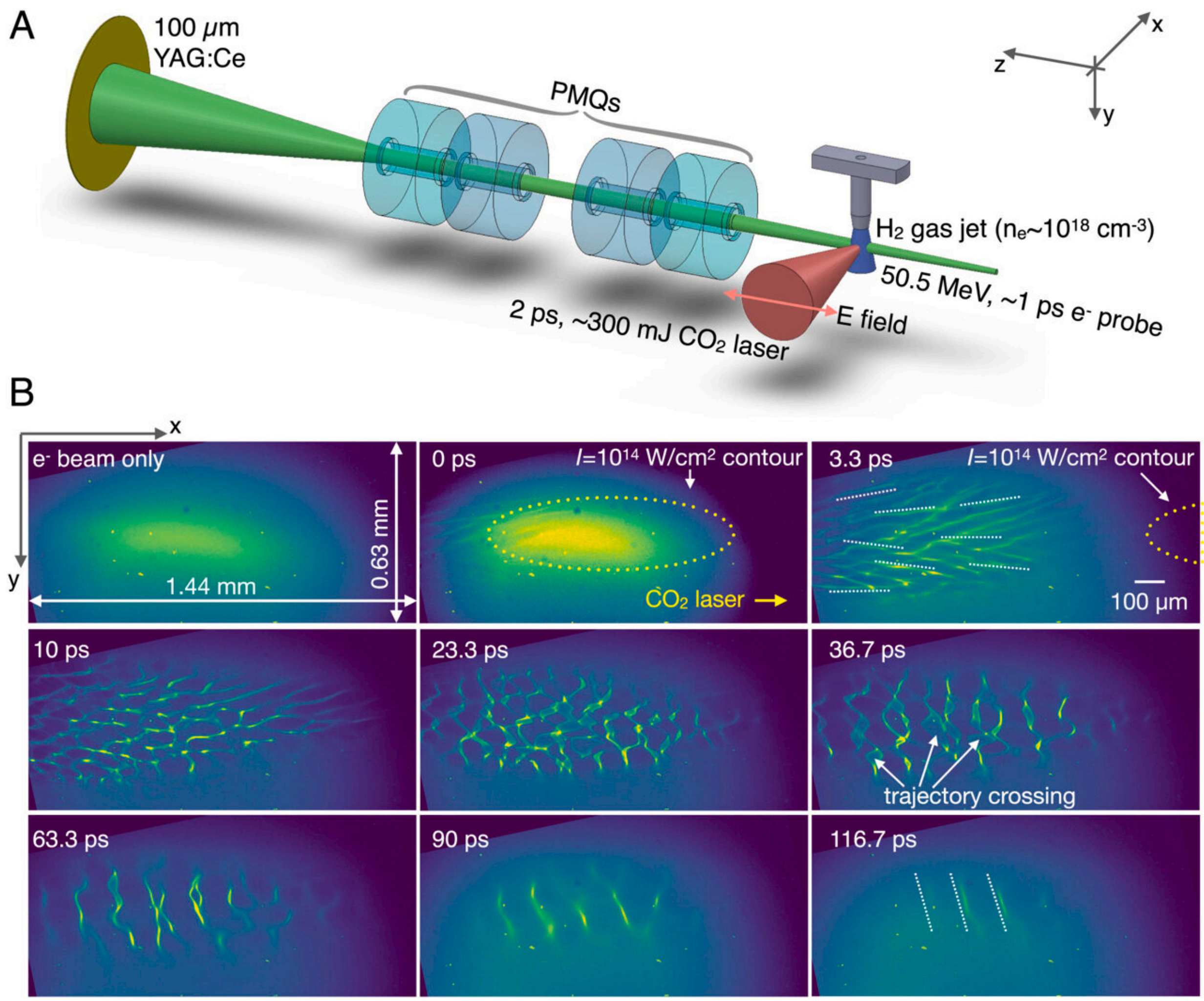
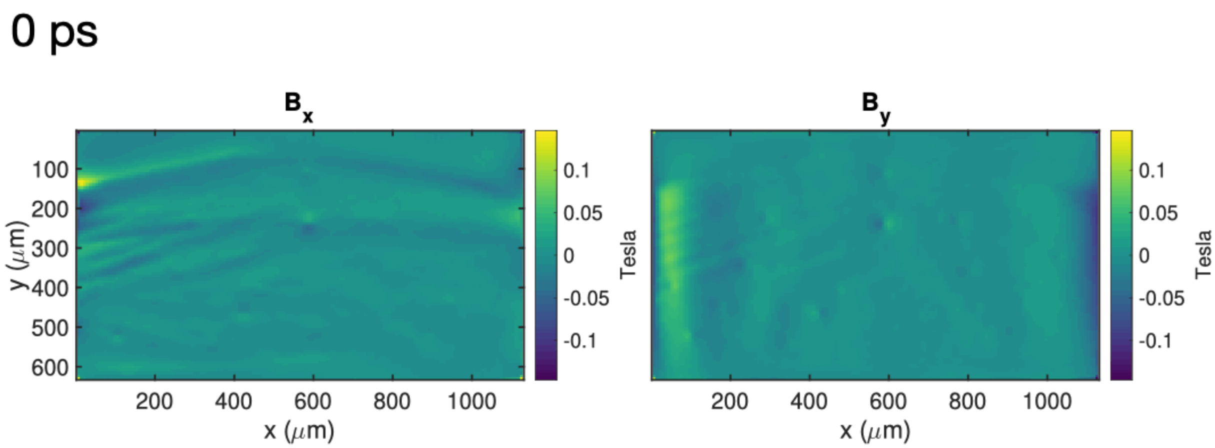


Experimental setup and representative snapshots of self-generated Weibel magnetic fields. (*A*) Sketch of the experimental layout. (*B*) Representative frames from the movie of the electron beam deflection by fields in the plasma. The first frame shows the e⁻ beam profile with no laser. The following frames show the evolution of the self-generated fields in the plasma. The yellow dotted ellipse on the 0 ps frame outlines the estimated 10^{14} W/cm^2 (ionization threshold) intensity contour of the CO_2 laser. The dotted white lines on the 3.3 ps and 116.7 ps frames are added to highlight the orientation of selected density strips. On the 36.7 ps frame, the white arrows mark structures caused by the trajectory crossing of the probe electrons which shift the effective object plane closer to the plasma. All images were rotated counterclockwise by 12° to correct the PMQ-induced slant and put the longer dimension of the elliptical plasma parallel to the laser propagation direction. Credit: *Proceedings of the National Academy of Sciences* (2023). DOI: 10.1073/pnas.221171311.

Plasma is matter that is so hot that the electrons are separated from atoms. The electrons float freely and the atoms become ions. This creates an ionized gas—plasma—that makes up nearly all of the visible universe. Recent research shows that magnetic fields can spontaneously emerge in a plasma. This can happen if the plasma has a temperature anisotropy—temperature that is different along different spatial directions.

This mechanism is known as the Weibel instability. It was predicted by plasma theorist Eric Weibel more than six decades ago but only now has been unambiguously observed in the laboratory. New research, now published in *Proceedings of the National Academy of Sciences*, finds that this process can convert a significant fraction of the energy stored in the temperature anisotropy into magnetic field energy. It also finds that the Weibel instability could be a source of magnetic fields that permeate throughout the cosmos.

The matter in our observable universe is plasma state and it is magnetized. Magnetic fields at the micro-gauss level (about a millionth of the Earth's magnetic fields) permeate the galaxies. These magnetic fields are thought to be amplified from weak seed fields by the spiral motion of the galaxies, known as the galactic dynamo. How the seed magnetic fields are created is a longstanding question in astrophysics.

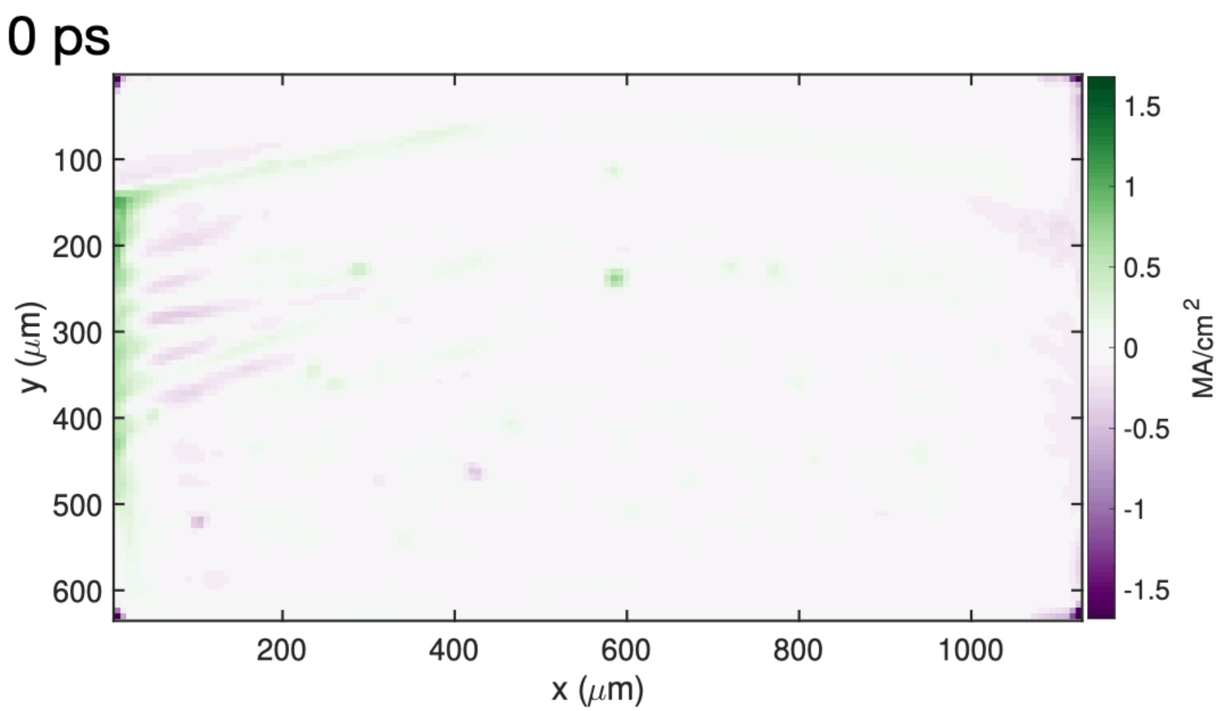


Evolution of the measured bunching of electron probe. Credit: *Proceedings of the National Academy of Sciences* (2023). DOI: 10.1073/pnas.221171311

This new work offers a possible solution to this vexing problem of the origin of the microgauss level seed magnetic fields. The research used a novel platform that has great potential for studying the ultrafast dynamics of magnetic fields in the laboratory plasmas that are relevant to astro- and high-energy density physics.

First theorized six decades ago, the Weibel instability driven by temperature anisotropy is thought to be an important mechanism for self-magnetization of many laboratory and astrophysical plasmas. However, scientists have faced two challenges in unambiguously demonstrating the Weibel instability. First, until recently, researchers were not able to generate a plasma with a known temperature anisotropy as initially envisioned by Weibel. Second, researchers had no suitable technique to measure the complex and rapidly evolving topology of the magnetic fields subsequently generated in the plasma.

This work, enabled by the unique capability of the Accelerator Test Facility, a Department of Energy (DOE) user facility at Brookhaven National Laboratory, employed a novel experimental platform that allowed the researchers to create a hydrogen plasma with a known highly anisotropic electron velocity distributions on a tens of trillionth of a second timescale by using an ultrashort but intense carbon dioxide laser pulse.



Evolution of the retrieved magnetic field components. Credit: *Proceedings of the National Academy of Sciences* (2023). DOI: 10.1073/pnas.221171311

The subsequent thermalization of the plasma occurs via self-organization of plasma currents that produces magnetic fields driven by Weibel instability. These fields are large enough to deflect relativistic electrons to reveal an image of the magnetic fields a certain distance from the plasma. The researchers obtained a movie of the evolution of these magnetic fields with exquisite spatiotemporal resolution by using an one picosecond relativistic electron beam to probe these fields.

More information: Mapping the self-generated magnetic fields due to thermal Weibel instability, *Proceedings of the National Academy of Sciences* (2023). DOI: 10.1073/pnas.221171311. www.pnas.org/doi/10.1073/pnas.2211713119

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