Ultrafast optical field-ionized gases: A laboratory platform to study kinetic plasma instabilities

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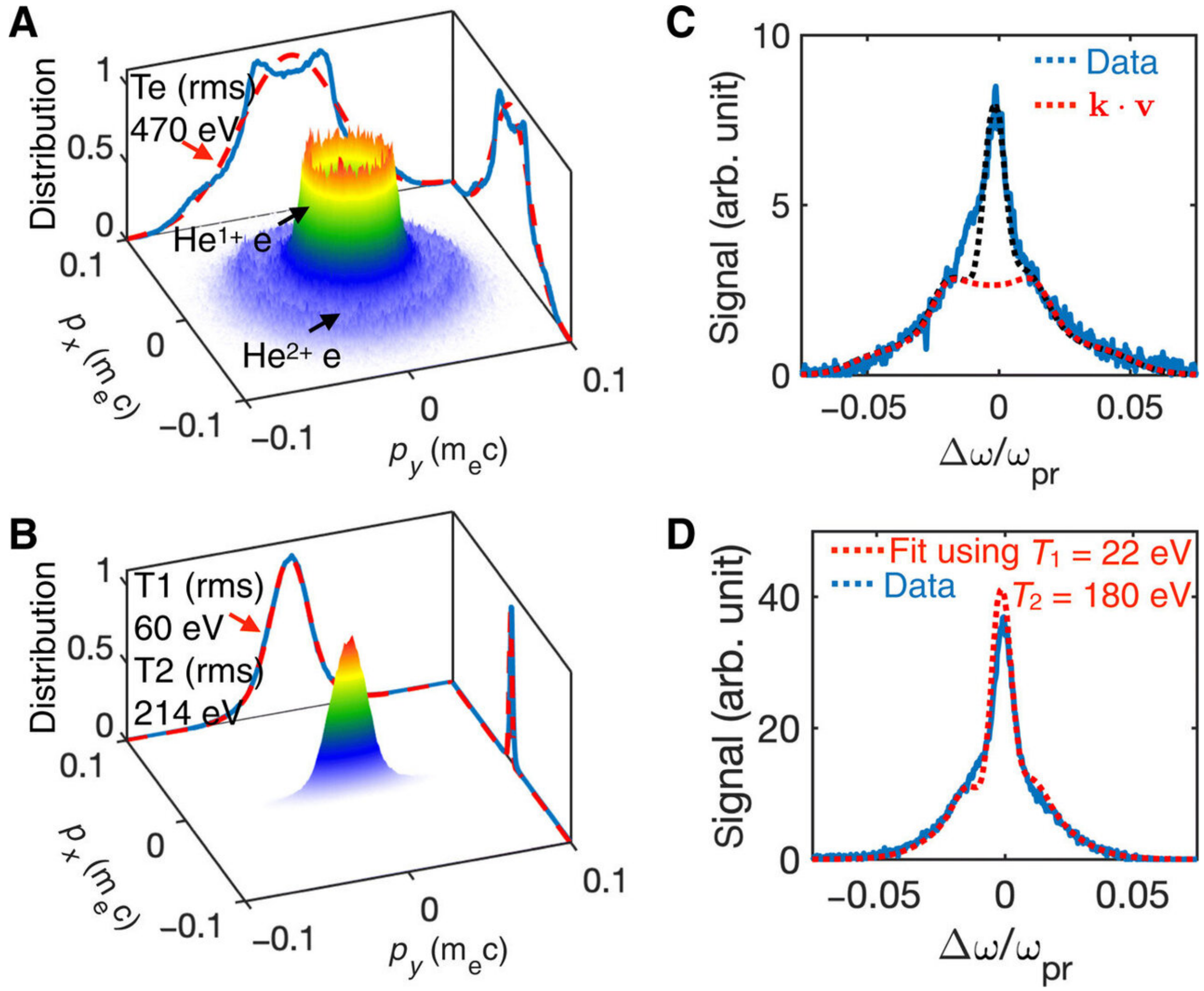
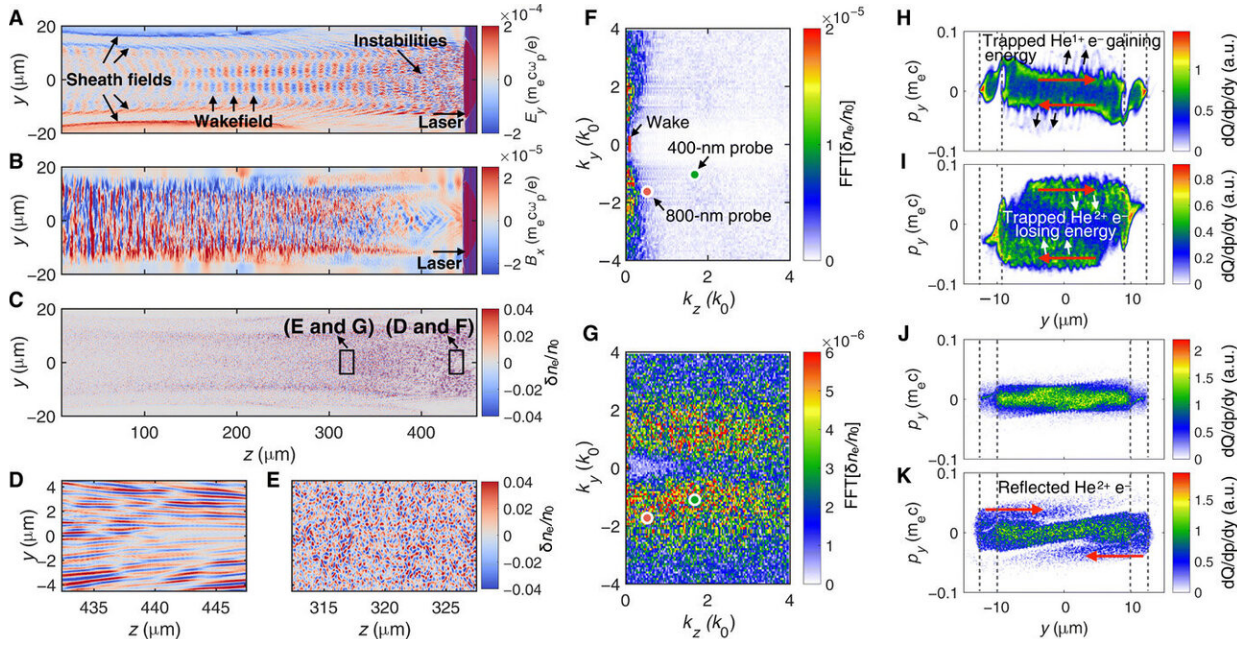


Initial electron velocity distribution (EVD) of optical field induced ionization (OFI) helium plasma. EVDs (A) for circular polarization (CP) and (B) for linear polarization (LP) laser pulse from 3D OSIRIS simulations. The solid blue lines in (A) and (B) show the projected distributions. In the CP case (A), the projected distribution deviates significantly from a Maxwellian distribution having the same root-mean-sqaure (rms) temperature of 470 eV, as shown by the red dashed line. In the LP case (B), the projected distribution can be well approximated by a two-temperature (1D Maxwellian) distribution with THe1+=60eV and THe2+=60eV = 214 eV. The blue lines in (C) and (D) show the measured TS spectrum for CP (C) and LP (D) for an initially fairly low plasma density of 6.6 × 1017 cm−3. The red dashed lines in (C) and (D) are fits to the measured spectrum. Credit: Science Advances, doi: 10.1126/sciadv.aax4545

Kinetic instabilities commonly arise from anisotropic (different properties in different directions) electron velocity distributions within ionospheric, cosmic and terrestrial plasmas. But only a handful of experiments have validated that theory so far. Ultrafast laser pulses can be used during optical field ionization of atoms to generate plasmas with known anisotropic electron velocity distributions to understand the phenomenon in practice. In a recent study, Chaojie Zhang and an interdisciplinary research team in the departments of Electrical and Computer Engineering, and Physics and Astronomy in the U.S., showed that plasma underwent two-stream filamentation following ionization—but prior to collision-based thermalization of the constituent electrons.

They observed Weibel instabilities (present in homogenous or nearly homogeneous plasma) that isotropized (similar properties in all directions) the electron distributions. The researchers measured the polarization-dependent frequency and growth rates of these kinetic instabilities using Thomson scattering (TS) of a probe laser, which agreed well with the kinetic theory and simulations. The research team demonstrated an easily deployable laboratory platform to study kinetic instabilities within plasma; the results are now published in *Science Advances*.

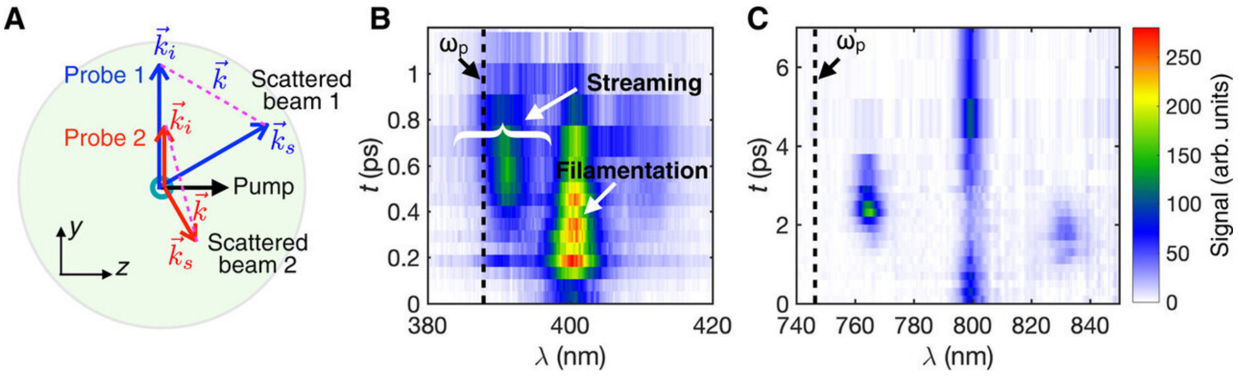
Plasmas are [susceptible to kinetic instabilities]() when the velocity distribution of its constituent plasma electrons, ions or both becomes nonthermal. Physicists can experimentally validate the theory of these instabilities if they have direct knowledge of the initial velocity distribution functions of such plasma species. With the advent of intense ultrashort-pulse, near-infrared lasers, researchers have ionized atoms and/molecules of a gas in a few laser cycles to generate anisotropic or nonthermal electron velocity distribution (EVD) functions. The process is known as [optical field-induced or tunnel ionization]() (OFI). The ability to initiate velocity distribution functions will allow researchers to quantitatively test the kinetic theory of plasmas on ultrafast time scales, prior to electron-electron (e-e) collisions and ion thermalization. However, the mechanisms and time-scale in which plasma electrons evolved from an anisotropic state to a thermal state remains an unsolved experimental problem in basic science.



2-D simulations show OFI-triggered kinetic streaming and filamentation instabilities in a helium plasma. The plasma (ne = 5 × 1018 cm−3) is ionized by a CP laser (τ = 50 fs, w0 = 8 μm, I = 1.6 × 1017 W/cm2). The Ey field, Bx field, and density fluctuations associated with the instability are shown in (A), (B), and (C), respectively. (D) and (E) are zoom in of the regions marked by the boxes in (C). The corresponding k-space of these density fluctuations is shown in (F) and (G), where the two dots mark the k of the waves being measured in experiments and where the 400-nm (800 nm) probe is used for CP (LP) pump pulses. (H and I) and (J and K) show the transverse phase space of He1+ and He2+ electrons ionized by CP and LP lasers, respectively. These results are from simulations with higher resolutions. The color bars represent the density of the electrons [in arbitrary units (a.u.)]. The simulation box is 35 μm wide in y. Because the laser only ionizes the central 20 μm of He, a 30-μm window is shown in these plots. In all cases, the electrons inside a Δz = 2-μm slab at z = 20 μm are used to show the phase space. (H) and (I) are taken 0.14 ps while (J) and (K) are taken 1.9 ps after the laser has passed the slab. The gray dashed lines mark the locations of the thin sheaths. The direction of the arrows indicates the shift of the momentum distributions. Credit: Science Advances, doi: 10.1126/sciadv.aax4545

As a result of the extremely broad range of situations that gives rise to kinetic instabilities including gamma ray flashes, electron positron plasmas, magnetic fields, proton synchrotrons, solar corona and interplanetary media. A voluminous body of theoretical work exists on the kinetic theory of plasmas. In this work, the research team first briefly described three of the most frequently studied kinetic instabilities enabled by OFI plasma for quantitative study in the lab. For example, when plasma electrons are composed of two or more co- or counter-propagating streams (beams) they can become unstable. While a great deal of theoretical work exists on kinetic instabilities in plasmas, they remain to be further verified in the lab. Research teams had previously studied these instabilities by passing relativistic electron beams through plasmas or by creating two interpenetrating plasmas.

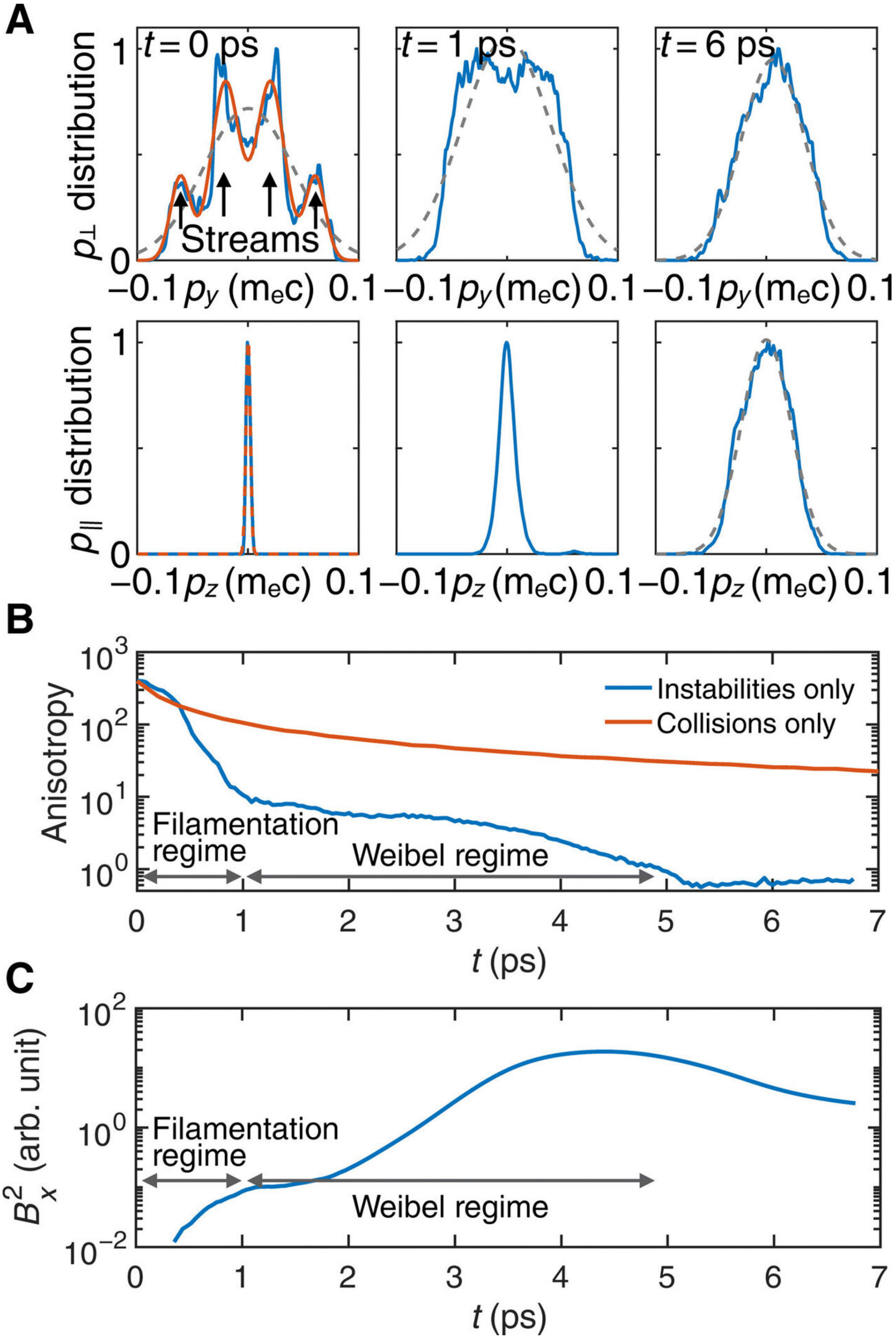
In this work, Zhang et al. showed that an ultrafast OFI (optical field induced ionization) helium plasma with a known polarization-dependent anisotropic electron velocity distribution (EVD) was susceptible to kinetic streaming, filamentation and Weibel-like filamentation instabilities. They measured the growth rates and frequencies of these instabilities using time-resolved Thomson scattering. They compared the measurements against self-consistent (exact) particle-in-cell (PIC) computer simulations and with theory thereafter, and observed good agreement.



Thomson Scattering (TS) diagram and examples of measured TS spectra. (A) k-matching diagram where a helium plasma produced by a 50-fs, 800-nm CP (LP) pump laser is diagnosed by a 400-nm, probe 1 (800-nm, probe 2) laser traversing through the plasma with a variable delay. The measured time-resolved TS spectra are shown in (B) and (C) for the CP and LP pump, respectively. Note that the time scales for the two polarizations are different. The dashed lines mark the position of the expected plasma frequency corresponding to the plasma density. The entire dataset is obtained by scanning the timing in 50- to 200-fs steps, and each step is the average of 20 individual scattering events. Time t = 0 is defined as the time when pump and probe overlap with one another (determined by locating the position of the ionization front seen in a shadowgram formed by the probe at the same location as the probe beam). Credit: Science Advances, doi: 10.1126/sciadv.aax4545

In the experiments and simulations, the team initialized anisotropic EVD (electron velocity distribution) functions by ionizing the first and the second helium (He) electron either using circularly polarized (CP) or linearly polarized (LP) Ti-Sapphire laser pulses. They monitored the ionization potential of the electron as the laser intensity required to ionize more than 90 percent of the He atoms via a tunneling mechanism developed elsewhere. During the experiments, the EVD function of the second He electron was 'hotter' than the first He electron. Zhang et al. obtained the results after the passage of linear pulses from a 3-D particle-in-cell (PIC) simulation, which they built using the OSIRIS code. The electron momentum distribution resembled a "double donut" shape for circularly polarized (CP) lasers and a two-temperature distribution in the direction of linearly polarized (LP) lasers. They confirmed the plasmas produced in this way to have EVD functions. The values measured by the research team agreed excellently with the values expected from the PIC simulation.

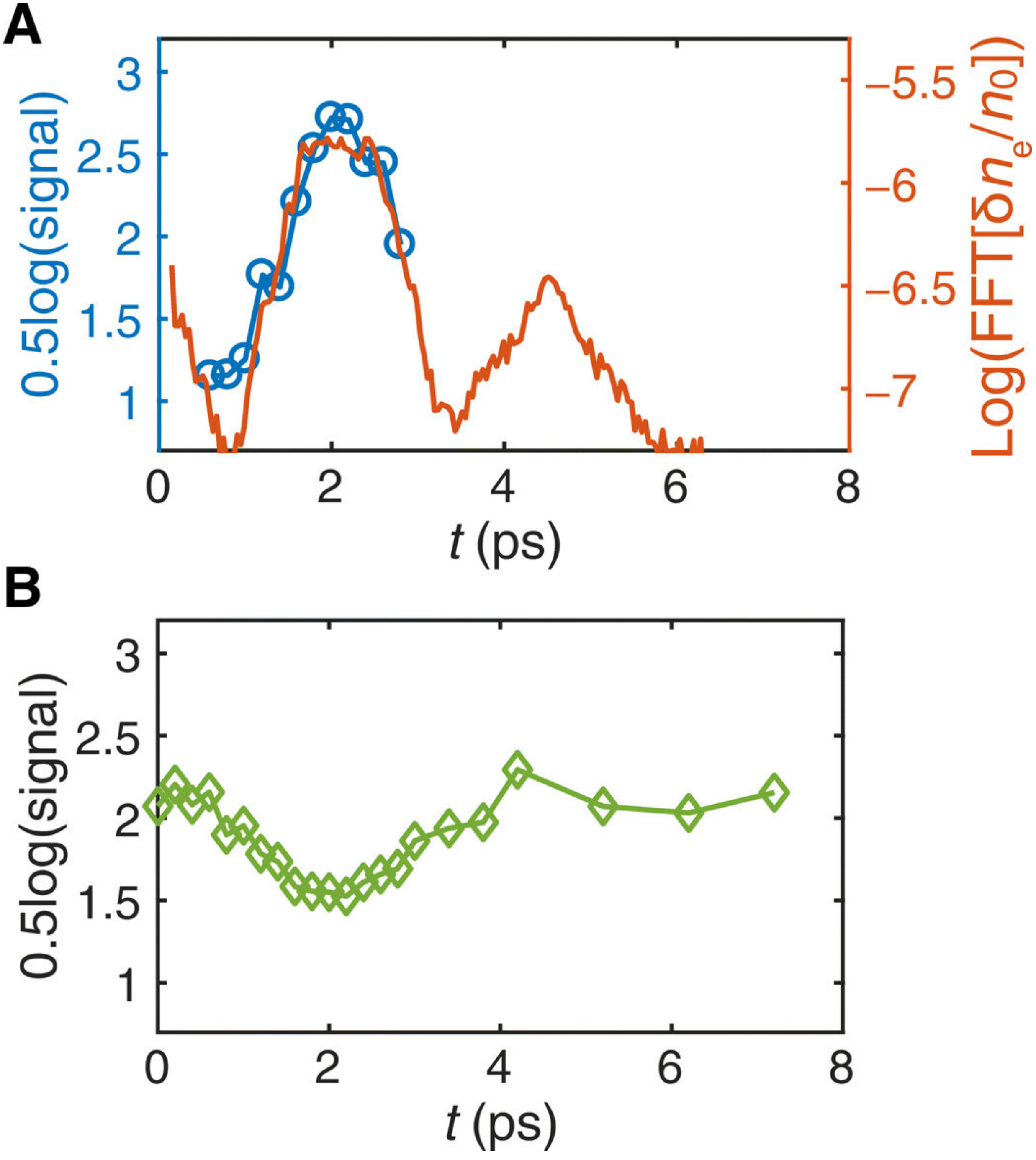
The research team then used 2-D simulations of optical field ionization (OFI)-triggered kinetic streaming and filamentation instabilities in a He plasma. Accordingly, both streaming and filamentation instability began to grow immediately after the creation of plasma. They observed the streaming instability to eventually saturate and dampen very quickly and Zhang et al. therefore similarly expected the filamentation instability to have comparable temporal behavior. At later stages, Weibel-like filamentation instability driven by a reduced but finite temperature anisotropy of the electrons began to dominate in the plasma.


A
t = 0 ps
t = 1 ps
t = 6 ps
p⊥ distribution
Streams
−0.1 py (mec) 0.1
p∥ distribution
−0.1 pz (mec) 0.1
1
0
B
Anisotropy
Instabilities only
Collisions only
Filamentation regime
Weibel regime
10^3
10^2
10^1
10^0
t (ps)
0 1 2 3 4 5 6 7
C
Bx² (arb. unit)
10^2
10^0
10^-2
Filamentation regime
Weibel regime
t (ps)
0 1 2 3 4 5 6 7

Evolution of the temperature anisotropy of the OFI plasma. The upper (lower) row in (A) shows the py (pz) distribution function of electrons at t = 0, 1, and 6 ps. The dashed gray line is a Gaussian fit to the distribution. The initial distribution can be approximated by four drifting Maxwellian beams in the transverse plane as indicated by the red line and the arrows. The red dashed line is a Gaussian fit to the pz distribution. (B) The blue line shows the anisotropy from the same simulation as in (A), which does not include collisions. The red line shows the simulation of anisotropy evolution of a preionized plasma with only Coulomb collisions included. (C) The average magnetic field energy as a function of time shows two distinct growth phases corresponding to filamentation and Weibel regimes, respectively. Credit: Science Advances, doi: 10.1126/sciadv.aax4545

To obtain further information on kinetic instability, Zhang et al. probed a wave vector. For this, they used either a 400 nm laser or an 800 nm laser with a 5nm bandwidth and 100 femtosecond (fs) pulse width and probed electrostatic components of plasma instabilities. They measured the spectra and observed two notable features. At first, the electron feature grew and saturated to dampen within a time frame much shorter than the time for electron-electron collision. Next, the spectral shift of the electron feature showed anomalous behavior from the usual Langmuir wave (electrostatic plasma oscillations). The peak frequency of the electron feature and existence of the zero-frequency feature were essential evidence for Zhang et al. to corroborate streaming and filamentous instabilities in the setup. The research team investigated further streaming, filamentation and Weibel instabilities induced by circular polarization lasers extensively within the experimental system.

The scientists also tracked the evolution of electron velocity distributions and temperature anisotropy of optical field ionization in a 2-D simulation. They consistently modeled ionization and evolution of the plasma in the simulation while excluding Coulomb collisions to isolate the effect of instabilities on temperature anisotropy. They observed kinetic instabilities in the experiments, owing to which the anisotropy of the plasma rapidly dropped.



Instabilities in a plasma ionized by an LP laser. (A) Measured (blue) and simulated (red) evolutions of the magnitude of the electron density fluctuations of the streaming instability. (B) The measured magnitude of the zero-frequency mode as a function of time, displaying an oscillatory behavior with a roughly ion acoustic period. Credit: Science Advances, doi: 10.1126/sciadv.aax4545

As the Weibel instability saturated in the simulation, the magnetic fields self-organized to a quasi-helical structure as predicted elsewhere. Using further simulations, Zhang et al. confirmed that electron collisions did not play a significant role during the first 10 picoseconds after plasma formation. During this time, kinetic instabilities dominated isotropization of the plasma, however, eventually the collisions will thermalize the plasma.

The research team also investigated the kinetic instabilities induced by linear polarization lasers, which showed contrasting results to the circularly polarized lasers. In this instance, the instability was driven by reflected electrons, which propagated through slower moving electrons. The frequency spectrum of the mode was narrower than with CP lasers. The experimental process also took longer for the streaming instability to grow and saturate. Zhang et al. observed a remarkable agreement between the measurements and simulation.

In this way, Chaojie Zhang and colleagues showed the possibility of generating "designer" EVDs using a combination of conditions including different polarizations, wavelengths, intensity profiles and ionizing media. The team controlled the drift velocity and transverse temperatures of the streams by changing the polarization ellipticity to suppress streaming or filamentation instabilities. The researchers showed that ultrafast OFI plasmas were nonthermal with a large velocity anisotropy. The plasmas underwent streaming and filamentous instabilities, followed by Weibel-like filamentation instability to isotropize the plasma. When they measured the polarization-dependent frequency and growth rate of these kinetic instabilities, the results agreed well with the kinetic theory and simulations. The research team thus developed and demonstrated an easily deployable platform to study plasma kinetic instabilities in the lab.

More information: Chaojie Zhang et al. Ultrafast optical field–ionized gases—A laboratory platform for studying kinetic plasma instabilities, *Science Advances* (2019). DOI: 10.1126/sciadv.aax4545

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