Electron Stochastic and Shock Acceleration in Laboratory-Produced Turbulent Plasmas

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Turbulent plasma plays a critical role in the acceleration of cosmic rays. By utilizing high-power laser-driven plasma collisions, we experimentally generated turbulent magnetic fields, demonstrating the capability to produce kinetic turbulence at high flow velocities and MHD turbulence with Biermann magnetic field at lower velocities through perforated target designs.

We present experimental results demonstrating kinetic turbulence with a typical spectrum $k^{-2.9}$ driven by Weibel instability, accompanied by energetic electron following a power-law distribution. Simulations reveal thermal electrons are stochastically accelerated by interactions with magnetic island-like structures in the turbulent region. This study highlights a critical transition period during supernova explosion, where kinetic turbulence originating from Weibel instability emerge prior to collisionless shock formation. Our results suggest that electrons undergo stochastic acceleration during this transition phase.

In the well-established model of diffusive shock acceleration, relativistic particles gain energy through repeated crossings of the shock front, interacting with turbulent plasma on both sides. Using laser ablation of two opposing perforated targets, we generated magnetized turbulent plasma upstream of the shock, where the upstream turbulence plays a critical role in particle acceleration. The generation of shock is confirmed by both X-ray and proton radiography. The upstream turbulent magnetic field perturbs and distorts the shock front, leading to the formation of complex, non-stationary structures within the shock over time. Clear experimental evidence of shock acceleration is observed, exhibiting a power-law distribution with spectral index of -3 in the range of 250~350 keV. This is consistent with the injection threshold of DSA as defined by the cyclotron resonance condition in the low-frequency limit $k_* r_g \sim 1$ under the diffusion approximation, opening the way for controlled laboratory studies of electron diffusive shock acceleration.

Our experiments have successfully demonstrated electron stochastic acceleration in Weibel turbulent plasmas mediated by magnetic island interactions. [1,2] In a separate but complementary study[3,4], we established a magnetized turbulence platform upstream and observed significant disruption of the shock front. Proton radiography revealed pronounced shock front distortion caused by turbulence, accompanied by clear evidence of electron acceleration. These results emphasize the role of turbulent magnetic fields in electron acceleration efficiency, advancing laboratory insights into DSA mechanisms. This work is supported by the National Key R&D Program of China (grant Nos. 2022YFA1603200, B.Q. and 2022YFA1603204, G.Y.L.)

References

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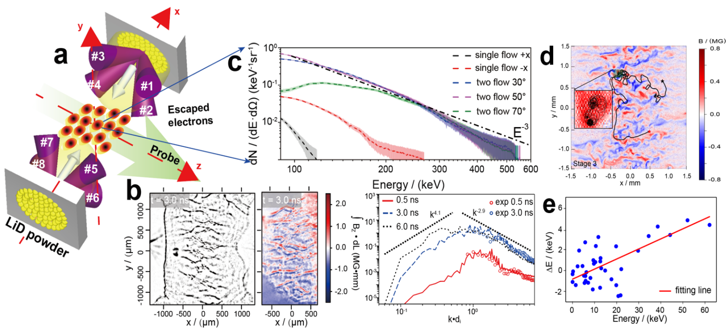

Figure 1. Experimental study of electron stochastic acceleration. (a) Experimental setup. (b) Kinetic turbulence plasma induced by nonlinear Weibel instability. (c) Typical energy spectra of thermal and nonthermal electrons. (d) Simulated trajectories of accelerated electrons. (e) Energy gain of electrons in each reflection.

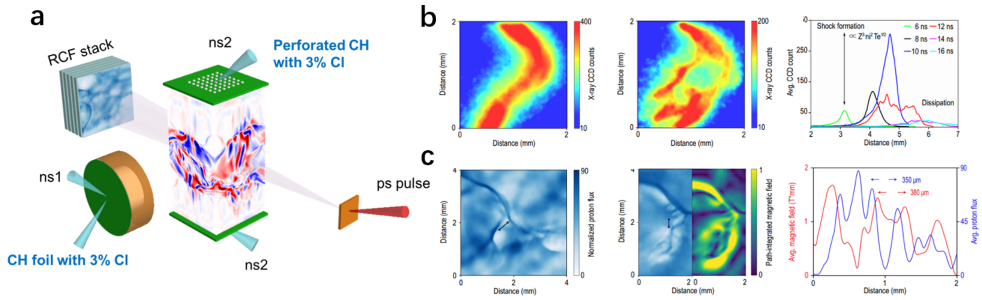

Figure 2. Experimental study of electron shock acceleration. (a) Experimental setup. (b) X-ray radiation emitted from the shock front, captured by gated camera. (c) Shock front distortion by upstream turbulent fields, forming complex non-stationary structures, revealed by proton radiography.