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Power-Law Generation of Accelerated Particles in 3D Reconnection

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Magnetic reconnection is one of the primary mechanisms for accelerating nonthermal particles in various space, solar, and astrophysical plasmas. One remarkable example is solar flares, where observations have suggested that a large amount of energetic electrons and ions are produced during magnetic reconnection. While there is strong observational evidence suggesting that power-law energy distributions are a ubiquitous consequence of magnetic reconnection in solar flare conditions, this feature has not been reproduced in self-consistent kinetic simulations in the non-relativistic reconnection regime.

Here we present results from 3D PIC simulations of low-beta magnetic reconnection[1]. We find that the global spectrum integrated over the entire domain has power-law tails with a spectral index p ~ 4 in the 3D simulation, which persist throughout the nonlinear reconnection phase until saturation., as shown in Fig. 1. In contrast, the spectrum in the 2D simulation rapidly evolves and quickly becomes soft.

We show that 3D effects such as self-generated turbulence and chaotic field lines enable the transport of high-energy electrons across the reconnection layer and allow them to access several main acceleration regions. Fig. 2 (a) shows that the reconnection current layer is fragmented, indicated that turbulence is generated. The magnetic field lines quickly diverge from each other as they pass through the fragmented current layer, which indicates that the magnetic field lines become chaotic. Particles following the chaotic field lines will be quickly transported to a broad region and they can be scattered by the self-generated turbulence. Fig. 2 (b) and (c) show one electron trajectory. Because of the efficient transport, this electron can access multiple acceleration regions and gets continuously accelerated.

Since particles with different energies can access the same acceleration regions. The resulting particle acceleration rate is nearly a constant as shown in Fig. 3 (a). The major acceleration is due to particle curvature drift motions along the motional electric field (Fig. 3 (b)), similar as earlier 2D simulations[2,3]. To explain the power-law index, we identify the major acceleration region where the acceleration associated with particle curvature drift is strong, and calculate the electron acceleration rate and escape rate. The resulted power-law index that uses Fermi acceleration formula fluctuates around 4, consistent with the simulation result. This shows that the electron power-law energy spectrum is a dynamical balance between acceleration and escape, as in the classical Fermi-type acceleration processes. These results could be important for explaining the formation of power-law energy spectra in non-relativistic plasmas, e.g., solar flares.

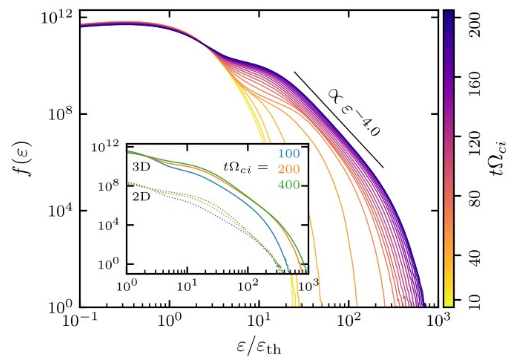

Fig. 1 Time evolution of the global electron energy spectrum in the 3D simulation; the embedded plot compares this with the 2D simulation at three time frames.

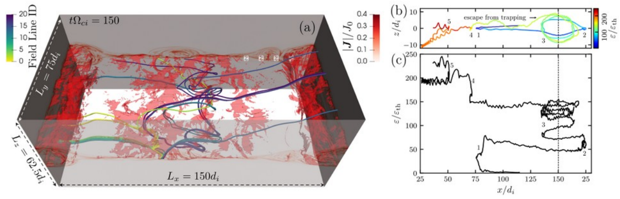

Fig.2 Turbulent reconnection layer and associated particle transport. (a) Fragmented current sheet overplotted with chaotic field lines. (b) One electron trajectory color-coded by its kinetic energy. (c) x-position of the electron versus its kinetic energy.

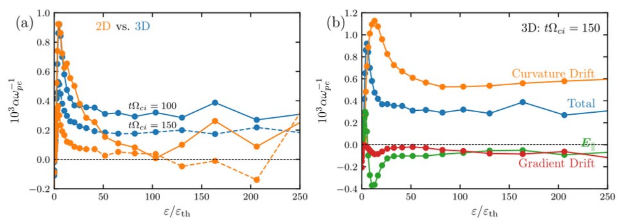

Fig. 3 (a) The acceleration rates in 2D and 3D simulations. (b) The acceleration rates due to different mechanisms in the 3D simulation.

References:
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