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Waves and Turbulence in the Electron Diffusion Region to Drive Magnetic Reconnection

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Magnetic reconnection is an MHD process that enables fast energy release of the magnetic field energy into plasma kinetic and thermal energies. The reconnection process has a significant impact on triggering of MHD-scale phenomena in space such as solar flares and magnetospheric substorms. On the other hand, the process requires the magnetic dissipation as a driver that takes place in a kinetic scale region, so-called the diffusion region, to break the field line connectivity. Most of the plasma fluid equations have employed the electrical resistivity to generate the magnetic dissipation to drive magnetic reconnection. However, there has been no clear evidence that such a description is appropriate for the diffusion region in terms of the kinetic physics in collisoinless plasma where the Coulomb collision frequencies are negligibly small.

To unveil the mechanism of the magnetic dissipation in the reconnection diffusion region, we have performed a large-scale particle-in-cell simulation in the 3D system for the anti-parallel and no guide-field configuration. The initial setup employs a Harris-type current sheet with the magnetic field $B_x(z) = -B_0\tanh(z/\delta)$ and the number density $n(z) = n_0\mathrm{sech}^2(z/\delta)+n_b\tanh^2(z/\delta)$, where $\delta = 0.5\lambda_i$ (λ_i is the ion inertia length) and $n_b=0.044n_0$ are chosen. The simulation code employs the adaptive mesh refinement (AMR) to achieve efficient computation of multiscale processes. The system size is $L_x\times L_y\times L_z = 82\lambda_i\times 41\lambda_i\times 82\lambda_i$, which is entirely covered by base-level (coarsest) cells with $\Delta_{LB} = 0.08\lambda_i$ and can be locally subdivided up to dynamic range level with $\Delta_{LD} = 0.02\lambda_i$. The resultant highest resolution is 4096×2048×4096 and the maximum number of particles is $\sim 4\times 10^{11}$. The physical parameters are $m_i/m_e=100$, $c/V_A=27$, and $T_{0i}/T_{0e}=5$, where V_A is the Alfven velocity based on B_0 and n_0.

Magnetic reconnection is initiated with a small perturbation to the magnetic field components B_x and B_z, which produces an x-line at the center of the xz plane uniformly along the y axis. At an early phase of reconnection, the thin current layer is formed around the x-line, which is recognized as the electron diffusion region (EDR). The EDR is unstable to the flow shear instabilities resulting in significant electromagnetic (EM) turbulence as shown in Fig. 1a [1]. Figure 1b shows the power spectrum density (PSD) of δE_y in the EDR. One can see that the energy cascading is well established from macroscale to microscale as typical in plasma turbulence. We found that two kinds of the shear modes dominate at the x-line, which are identified as the current sheet shear instability (CSSI) and the electron Kelvin-Helmholtz instability (eKHI) [2].

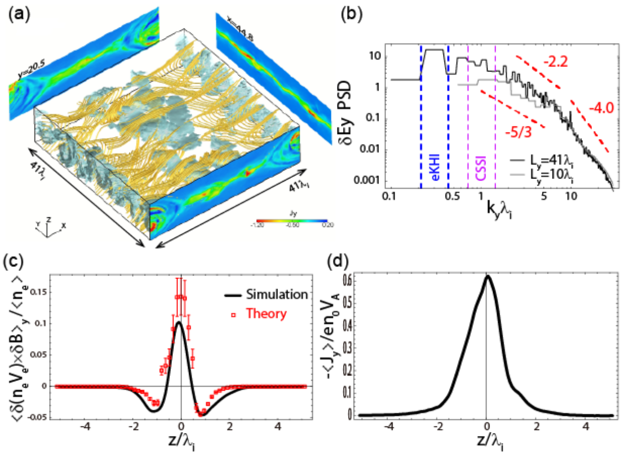

Figure 1: Simulation results showing (a) 3D view of the turbulent current layer during a fast reconnection with an iso-surface of the current density, yellow tubes indicating the magnetic field lines, and 2D profiles showing the contours of J_y, (b) PSD of δE_y at the average x-line (black curve) with a reference result from the simulation with $L_y=10\lambda_i$ (gray curve), and (c), (d) 1D profiles across the x-line of (c) EM turbulence, $\langle\delta(n_eV_e)\times\delta B\rangle/\langle n_e\rangle$ (black curve), and (d) current density, $-\langle J_y\rangle$, with theoretical estimate (red squares) in (c).

We consider the spatial distribution of the non-ideal electric field $E_{NI}=-(\langle E\rangle+\langle V_e\rangle\times\langle B\rangle)_y$ which almost balances the induction electric field due to the EM turbulence $\langle\delta(n_eV_e)\times\delta B\rangle/\langle n_e\rangle$ (Fig 1c). It is found that the E_{NI} profile has clear negative dips near the edges of the EDR, while such dips do not appear in the current density profile (Fig. 1d). This indicates that the E_{NI} profile cannot be described by the resistivity η in the form $E=\eta J$, provided η is generally positive. Instead, we found that the EM turbulence causes the momentum transport of the electrons across the flow shear layer, leading to the viscous dissipation in the EDR [3]. In fact, the induction field by the EM turbulence can be derived in the form $E=-\mu\Delta J$, which profile shown in Fig. 1c (red squares) is well consistent with the simulation result. Our result suggests a fundamental modification of the plasma fluid equations using the resistivity in the Ohm's law.

References

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