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Waves and Turbulence in 3D Magnetotail Magnetic Reconnection: Large-Scale Particle Simulations

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Magnetic reconnection is a process enabling fast release of the energy stored in the magnetic field, triggering magnetospheric substorms and solar flares. The magnetic dissipation is needed in the current layer to drive the reconnection process. However, the mechanisms to generate the dissipation are poorly understood in collisionless plasma where the Coulomb collisions are too weak to drive a fast reconnection. Intense wave activities have been often detected in the current layer in space and laboratory observations. The waves arising around the reconnection x-line can potentially produce the dissipation through momentum exchange between the species and/or momentum transport across the flow shear layer. Recent 3D simulations have also shown intense wave activities in the thin current layer. Nevertheless of these evidences in observations and simulations, the mechanisms of the wave generation and dissipation have been unrevealed yet.

We have carried out a large-scale 3D particle-in-cell (PIC) simulation for the anti-parallel and no guide-field configuration to investigate the magnetotail reconnection process. 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.

The simulation is initiated with a small perturbation to B_x and B_z to trigger magnetic reconnection. The laminar current layer at early stage is subject to flow shear instabilities, and becomes significantly turbulent, in particular, after plasmoid ejections from the current layer (Fujimoto & Sydora, 2012) as shown in Fig. 1a. Figure 1b shows the power spectrum density (PSD) of δE_y in the current layer. 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) (Fujimoto, 2016). Both modes give rise to electromagnetic (EM) turbulence that provides significant contribution to the dissipation at the x-line (Fig. 1c).

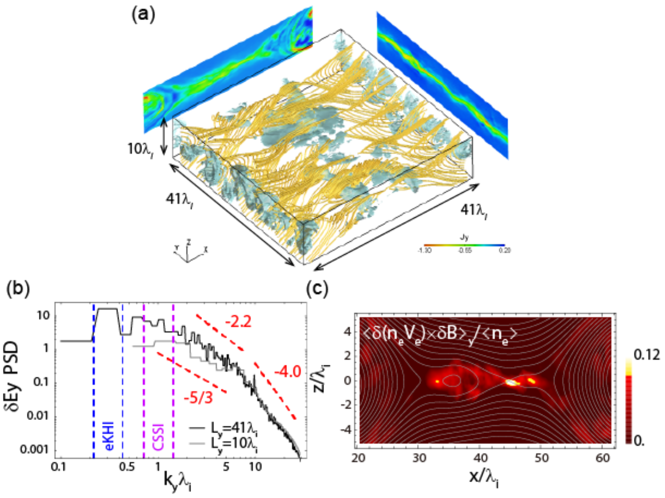

Figure 1: Simulation results showing (a) 3D view of the turbulent current layer during a fast reconnection with an iso-surface of the current density, yellow tubes indicating the magnetic field lines, and 2D profiles showing the contours of J_y, (b) PSD of δE_y at the average x-line (black curve) with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

It is found that the EM turbulence mainly works on the electrons alone, while the ions are not significantly affected. This means that the EM turbulence hardly drives the momentum exchange between the species, which fails to produce the electrical resistivity (Miyamoto, 1989). Instead, we found that the EM turbulence causes the momentum transport across the flow shear layer, leading to the viscosity around the x-line (Fujimoto & Sydora, 2021). The results suggest a fundamental modification of the current MHD models using the resistivity to drive reconnection. In fact, our preliminary MHD simulations comparing the two cases of uniform resistivity and uniform viscosity have shown that the energy conversion rate in reconnection is remarkably enhanced for the viscosity case.

References

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