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Large-Scale Energy Conversion of Magnetic Reconnection in Collisionless Plasma

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Magnetic reconnection is a natural energy converter from magnetic field energy into plasma kinetic energy. The magnetic dissipation driving the reconnection process takes place in a localized region formed around the x-line, while the process can extend to a large distance beyond the kinetic scales. However, the large-scale process of energy conversion has been poorly understood yet for collisionless reconnection.

So far, the large-scale dynamics of reconnection beyond the kinetic scales has been extensively investigated in the magnetohydrodynamics (MHD) framework. In the MHD reconnection model facilitating a fast reconnection, most of the energy conversion occurs at a pair of slow mode shocks extending from the diffusion region (Petschek 1964). The theoretical model based on approximations has been verified by the self-consistent MHD simulations (e.g., Ugai and Tsuda 1977). On the other hand, a number of particle-in-cell (PIC) simulations have focused on kinetic processes around the x-line. In earlier PIC simulations with relatively small system, it has been argued that the energy conversion dominates in the diffusion region and the dipolarization fronts (e.g., Sitnov et al. 2009). Therefore, the energy conversion model is distinct between in the MHD and kinetic frameworks.

The question arising here is how the kinetic process around the x-line can or cannot connect to the MHD-scale process far downstream of the x-line. In order to investigate a large-scale process of collisionless reconnection, we have carried out the PIC simulations with the adaptive mesh refinement (AMR). The AMR technique enables very efficient kinetic simulation of reconnection, subdividing the computational cells locally in space and dynamically in time (Fujimoto 2011). The present study employed a large system with $L_x \times L_z = 655\lambda_i \times 328\lambda_i$, 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 $\Delta_{LD} = 0.02\lambda_i$. Here, $\lambda_i = c/\omega_{pi}$ is the ion inertia length. Thus, the highest resolution is 32,768×16,384 and the maximum number of particles used is ~10^{10} for each species.

Figure 1 shows the instantaneous energy conversion estimated by $J.E = J_i.E+J_e.E$. It is clearly demonstrated that the ion energy gain ($J_i.E$) significantly dominates the electron energy gain ($J_e.E$) and is carried out mainly in the exhaust center rather than the exhaust boundaries. This is consistent with the ion dynamics in the exhaust far downstream of the x-line, where the ions are accelerated through the Speicer motion at the exhaust center (Fujimoto and Takamoto 2016).

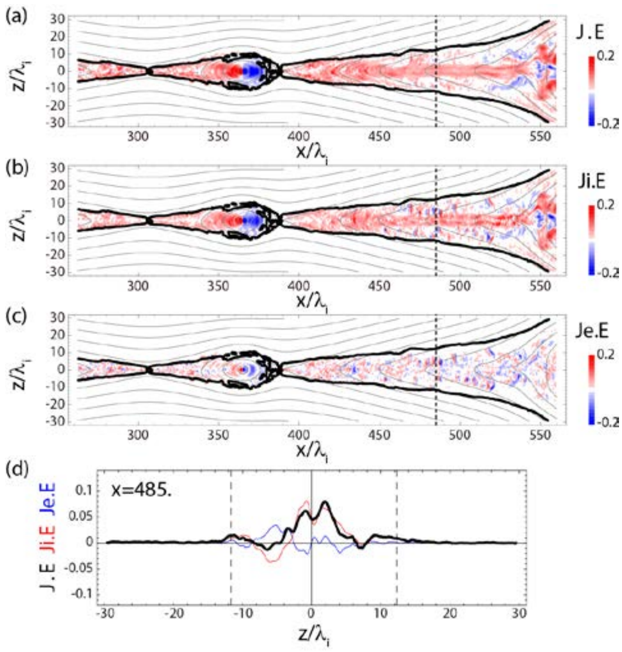

Figure 1: Snapshots of 2D AMR-PIC simulation of collisionless reconnection showing (a) J.E, (b) $J_i.E$, (c) $J_e.E$, and (d) 1D profiles along z of J.E (black curve), $J_i.E$ (red curve), and $J_e.E$ (blue curve), at $x/\lambda_i = 485$. Thick black curves in (a-c) represent the isolines of $|V_{ix}|-|V_{iz}|=0$.

The simulation results suggest that the energy conversion mechanism in collisionless reconnection is essentially different from that in the MHD reconnection model in which most energy conversion occurs at slow mode shocks formed at the exhaust boundaries. The current results also differ from previous PIC simulations in relatively small system. In large system, the diffusion region and dipolarization front region are very much localized, so that the contribution to the overall energy conversion is limited (Fujimoto 2018).

References

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