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Anomalous resistivity due to kink modes: Three-dimensional full kinetic simulations of magnetic reconnection

Keizo Fujimoto[1]; Richard Sydora[2]

[1] STEL, Nagoya Univ.; [2] University of Alberta

The magnetic dissipation mechanism which supports a fast reconnection has been one of the longstanding issues on magnetic reconnection. The Joule heating due to classical Coulomb collisions does not provide sufficient dissipation in collisionless plasmas to explain a fast energy release associated with the magnetospheric substorm and solar flares. The alternative candidates are the anomalous resistivity due to wave-particle interactions via turbulent waves or inertial effects due to strongly accelerated particles in a thin current sheet. Especially, in the electron-scale electron diffusion region formed around the X-line, the frozen-in constraint for the electrons breaks down, so that the electron dynamics has a significant impact on the dissipation mechanism. A number of full kinetic simulations in a relatively small 2D system have demonstrated that the electron inertial effects are very important to provide sufficient dissipation for the fast reconnection. However, recent 2D simulations in large and fully kinetic systems have revealed that the electron diffusion region becomes elongated in the outflow direction and as a result the electron inertial effects are reduced. On the other hand, the anomalous resistivity due to wave-particle interactions along the cross-field current could enhance the magnetic dissipation, if the non-uniformity along the current sheet were incorporated into the system. Several instabilities have been considered, e.g., the ion-acoustic instability, lower hybrid drift instability (LHDI), and kink-type instability. However, it is still an open question which of them makes a significant impact on the magnetic dissipation at the nonlinear stage of the tearing instability.

In this study, we investigated the coupling processes between the tearing and cross-field instabilities via magnetic dissipation. Our simulations are performed in a large-scale 3D system including the fully kinetic effects of plasma. The code employs the adaptive mesh refinement (AMR), which facilitates high-resolution simulations of the current sheet. The LHDI is quickly excited at the edges of the current sheet due to the plasma density gradient. Although this instability enhances the growth rate of the tearing mode, it disappears from the vicinity of the diffusion region at the nonlinear stage of the tearing mode, because the plasma density gradient is eliminated. The subsequent mode is a kink mode, which is driven by the drifting ions. It is found that the kink mode survives even when the diffusion region is filled by the lobe plasma which has initially no drift velocity. This is because the lobe ions are accelerated due to the induction electric field and support the kink mode. Thus the tearing and kink modes can coexist in the 3D system.

The kink mode broadens the width of the net current sheet and reduces the peak current density. This indicates that this mode suppresses the magnetic dissipation originating from the electron inertial effects. Regardless of this effect, we found that the global reconnection rate was almost identical to the case without the kink mode. Actually, the magnetic dissipation in the system with the kink mode is supported by the anomalous resistivity, while the electron inertial effects as seen in the system without the kink mode are negligible. Although the 3D simulations were performed under mi/me=25, 2D simulations up to mi/me=400 in the plane orthogonal to the reconnection plane have confirmed that the anomalous resistivity due to kink modes is still persistent under higher mass ratios and provides sufficient dissipation to support the fast reconnection.

In this paper, we compare the two 3D simulations with and without the kink mode and show that the reconnection rates are almost identical, but the dissipation mechanisms are completely different between the two cases. We also discuss the mechanism of the anomalous resistivity in terms of the wave-particle interaction.