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Anomalous Resistivity and Particle Kinetic Effect in Collisionless Reconnection

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Abstract

Roles of anomalous resistivity and particle kinetic effect in collisionless reconnection are investigated by means of a three-dimensional particle simulation. For no external driving source, the lower hybrid drift (LHD) instability is observed to grow in the periphery of current layer, but it cannot penetrate into a high beta region near the neutral sheet. Instead, a low requency electromagnetic(EM) instability grows to generate the electric field at the neutral sheet after the LHD instability is saturated. When an external driving flow exists, collisionless reconnection is triggered by the particle kinetic effect before the low frequency EM instability is excited.

Keywords:
anomalous resistivity, particle kinetic effect, three-dimensional particle simulation, collisionless reconnection

1. Introduction

Magnetic reconnection in a collisionless plasma, "collisionless reconnection", is an interesting and important process in considering energetically active phenomena observed in a high temperature, rarefied plasma such as the solar corona, the geomagnetic tail, laboratory plasmas, fusion plasmas, and so on. However, non-ideal effect which breaks the frozen-in condition of magnetic field is needed for the excitation of magnetic reconnection in a collisionless plasma. A number of theoretical and simulation studies have disclosed that there exist two types of triggering mechanisms which break the frozen-in condition and lead to magnetic reconnection in a collisionless plasma. One is due to the wave-particle interaction which is a cause of anomalous resistivity in the current sheet [1-3]. The other is due to the particle kinetic effect which becomes significant in a particle scale such as the collisionless skin depth and the Larmor radius [4,5].

Ozaki *et al* [3] have examined the interaction between charged particles carrying the equilibrium current and waves propagating along the equilibrium current by means of two-dimensional particle simulation and have discussed the anomalous resistivity in the current layer. The lower hybrid drift (LHD) instability [1] grows in the periphery of current layer, but it cannot penetrate into a high beta region in the vicinity of the neutral sheet. Instead, a low frequency electromagnetic (EM) instability [2] grows to generate the electric field in the vicinity of the neutral sheet.

Horiuchi and Sato [4,5] have examined the nonlinear development of collisionless reconnection in the presence of an external driving flow and clarified the role of particle kinetic effect in collisionless reconnection. Collisionless driven reconnection develops in two steps in accordance with the formation of two current layers, i.e., ion current layer in which the ion kinetic effect is dominant, and electron current layer in which the electron kinetic effect is dominant. However,

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the whole development of the system or the growth time of collisionless reconnection is controlled by the dynamics of the ion current layer but not by that of the electron current layer.

Which of two triggering mechanisms plays a leading role in the real situation? Because the above two simulations were based on the different models, we can not compare the results directly. In other words, three-dimensional treatment is needed to answer this question. We carry out the three-dimensional particle simulation in the presence of an external driving flow [6]. The simulation results will be discussed in Sec. 3 and Sec. 4.

2. Simulation Model

Let us consider three-dimensional open system which evolves dynamically due to the convergent plasma flow supplied through the boundary. The particle simulation is carried out by using three-dimensional electromagnetic codes [7]. As an initial condition we adopt a one-dimensional equilibrium with a magnetically neutral sheet at $y = 0$ as

$$\boldsymbol{B}(y) = [B_0 \tanh(y/L), 0, 0], \quad (1)$$

$$P(y) = B_0^2/8\pi \,\mathrm{sech}^2(y/L), \quad (2)$$

where B_0 is a constant and L is the scale height along the y-axis. The equilibrium current flows in the negative z-direction. The particle distribution is assumed to be a shifted Maxwellian with a spatially constant temperature. The ratio of ion to electron temperature is 2.

It is assumed that physical quantities are periodic at both the boundary of the x-axis ($x = \pm x_b$) and that of the z-axis ($z = \pm z_b$), and driving electric field exists at the boundary of the y-axis ($y = \pm y_b$) in order to supply the plasma with the $\boldsymbol{E} \times \boldsymbol{B}$ drift velocity into the simulation domain. The amplitude of driving electric field $E_{d0}(x,t)$ is described by a constant bell-shaped profile with a maximum input rate of magnetic flux E_0 at the center of the input boundary ($x = 0$, $y = \pm y_b$). The typical simulation parameters are as follows. The mass ratio $M_i/M_e = 100$, the ion Larmor radius $\rho_i = 1.12L$, the ratio of the electron drift velocity to the electron thermal velocity $v_{ze}/v_{te} = 0.16$, and $2x_b/L = 2.5$.

3. Generation of Anomalous Resistivity

In this section we discuss how two plasma instabilities, which were observed in the two-dimensional particle simulation [3], evolve in three dimensions in the absence of no external driving flow.

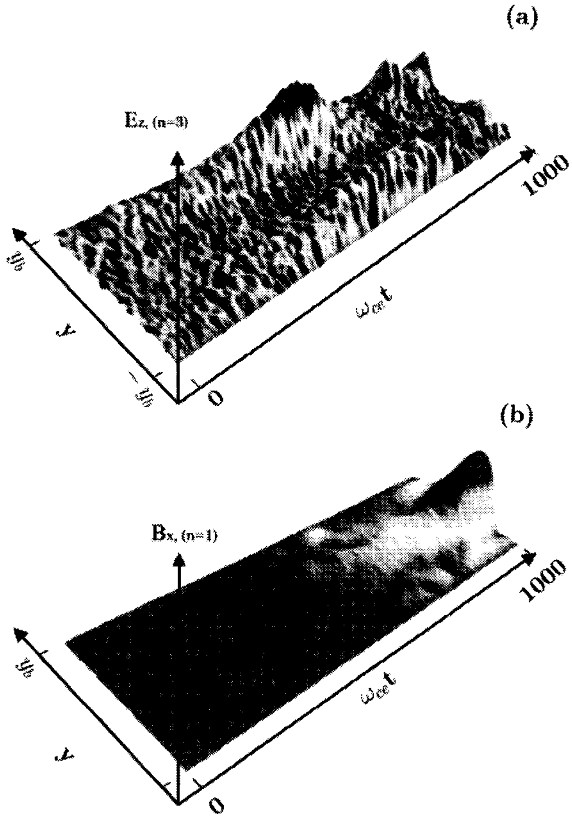

Fig. 1 The spatiotemporal structure of the Fourier amplitude $E_z^{(n=3)}$ and (b) that of $B_x^{(n-1)}$ in the (y,t) plane, respectively, where n stands for the Fourier mode along the z-axis.

Figure 1 shows (a) the spatiotemporal structure of the Fourier amplitude $E_z^{(n=3)}$ and (b) that of $B_x^{(n=1)}$ in the (y,t) plane, respectively, where n stands for the Fourier mode along the z-axis. One can see in Fig. 1-(a) that the LHD instability, $E_z^{(n=3)}$, grows in the periphery of the current layer in the intermediate temporal phase, but it can not penetrate into the central high beta region ($y \approx 0$). This result indicates that the LHD mode can not be a cause of an anomalous resistivity leading to collisionless reconnection at the neutral sheet. On the other hands, a low frequency EM mode, $B_x^{(n=1)}$, grows with a large rate in the vicinity of the neutral sheet in the late phase after the LHD mode is saturated, as is seen in Fig. 1-(b). These results are in good agreement with those obtained from the two-dimensional particle simulation in the (y,z) plane [3]. The detailed analysis [6] confirms that the low frequency EM instability is essentially two-dimensional.

An electric field is generated at the neutral sheet through the plasma instability. Temporal evolution of the DC component of the electric field E_z at the neutral

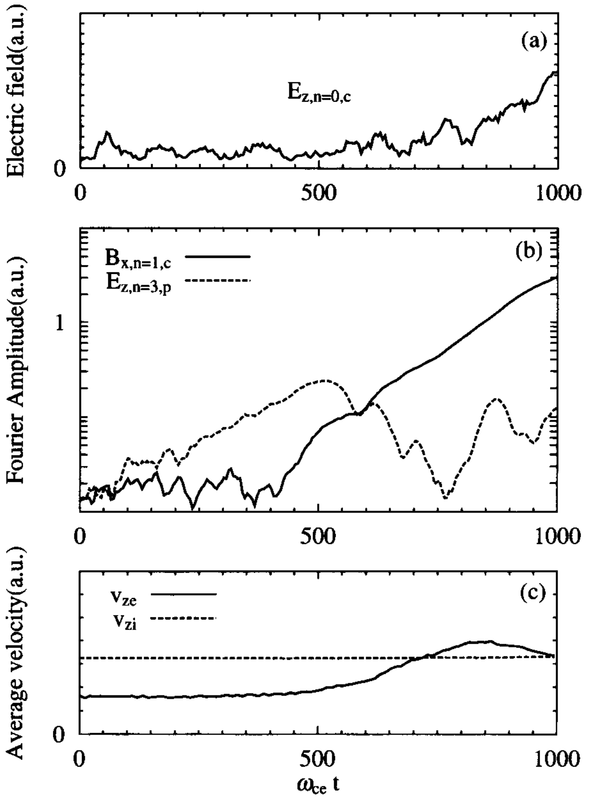

Fig. 2 Temporal evolutions of (a) the n = 0 mode of $E_z(0,0,z)$, (b) the n = 1 mode of $B_x(0,0,z)$ (solid) and the n = 3 mode of $E_z(0,y_b/2,z)$ (dashed), and (c) the average electron velocity (solid) and the average ion velocity (dashed) at the midpoint for the same case as Fig. 1.

sheet ("reconnection electric field") is shown in Fig. 2, together with those of the Fourier modes of B_x at the neutral sheet and E_z at the periphery (y = $y_b/2$), and those of the average electron velocity and the average ion velocity along the z-axis at the midpoint (x = 0, y = 0). After the LHD mode is saturated, the reconnection electric field starts to grow at the neutral sheet in accordance with the excitation of the low frequency EM mode (solid line in Fig. 2-(b)). The generated electric field accelerates the electrons in the vicinity of the neutral sheet along the equilibrium current to compensate the momentum loss through the wave-particle interaction, as is seen in Fig. 2-(c).

4. A Particle Kinetic Effect

Let us consider the case when the system evolves dynamically due to an external driving flow. The convective electric field can penetrate into the ion current layer if the current layer is compressed as thin as

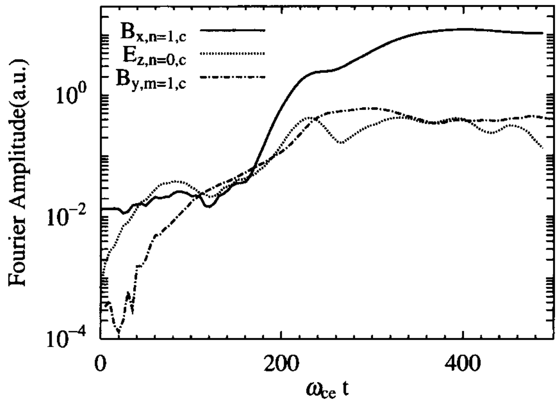

Fig. 3 Temporal evolutions of the Fourier modes for the case of E_0 = $0.02B_0$ where the solid, dashed, dotted, and dot-dashed lines represent the n = 1 mode of $B_x(0,0,z)$, the n = 0 mode of $E_z(0,0,z)$, and the m = 1 mode of $B_y(x,0,0)$, respectively. Here, m stands for the Fourier mode number along the x axis.

the ion kinetic scale by the convergent plasma flow [4,5]. The Poynting flux moves towards the neutral sheet while creating the electron current layer inside the ion current layer. As soon as the electric field reaches the neutral sheet, magnetic reconnection is triggered and the topology of magnetic field lines is changed. The temporal evolutions of the Fourier modes are shown in Fig. 3 for the case of $E_0 = 0.02B_0$. Because most of ions inside the current layer is unmagnetized in the present case, the Poynting flux supplied at the boundary reaches the neutral sheet in the electron drift time ($t_{de} = y_b B_0/cE_0 \approx 100\ \omega_{ce}^{-1}$). Thus, magnetic reconnection is triggered by the convective electric field earlier than the excitation of the low frequency EM mode (solid line). The y-component of magnetic field with the m = 1 spatial structure along the x-direction is generated as a result of magnetic reconnection (dot-dashed line). The thinning of the current layer by the convergent plasma flow results in the increase of the growth rate of the low frequency EM mode, because the growth rate strongly depends on the width of current layer [2]. Consequently, the EM mode is excited earlier and grows with a larger rate compared with that for no driving flow.

5. Summary

We have investigated the generation process of anomalous resistivity and the dynamical development of collisionless reconnection in three dimensions by means of a full particle simulation. When there is no external driving source, the LHD instability grows in the periphery of current layer in the early phase while the low frequency EM instability is excited in the vicinity of the neutral sheet after the saturation of the LHD instability. It is found that the interaction between this EM wave and charged particles carrying the equilibrium current can be a cause of an anomalous resistivity leading to collisionless reconnection in the neutral sheet. If an external driving flow exists, collisionless reconnection is triggered by the particle kinetic effect earlier than the excitation of the EM instability.

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