Dynamical Evolution of Thin Current Sheets in a Three-Dimensional Open System

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Abstract

Dynamical behavior of thin current sheets under the influence of collisionless reconnection in an open system is investigated by using newly developed electromagnetic (EM) particle simulation codes. In a three-dimensional open system collisionless driven reconnection evolves dynamically under the influence of an external driving flow and three different types of plasma instabilities excited in a thin current sheet. Driving electric field imposed at the boundary penetrates into the current sheet in accordance with the propagation of the lower hybrid drift wave excited in the periphery. When the electric field reaches the neutral sheet, collisionless reconnection is triggered. The current sheet is split as a result of collisionless reconnection, and thus small islands appear in the downstream. The accumulation of current density inside the islands excites the kink instability leading to the destruction of the island structure. A low frequency EM instability is triggered in the current sheet after the island structure disappears in the system.

Keywords:

collisionless reconnection, open system, thin current layer, plasma instabilities, particle kinetic effects

1.Introduction

Collisionless magnetic reconnection plays a crucial role in a number of interesting phenomena with fast magnetic energy release, plasma acceleration and heating both in space plasmas [1] and in laboratory plasmas [2]. Magnetic reconnection dynamically evolves in an open system in which both plasma inflow and outflow exist through the boundary. Steady reconnection is realized only when the flux input rate into the system is balanced with the reconnection rate. However, this balance condition is not always assured because magnetic reconnection is controlled by two different processes with different time scales, i.e., an external global process and an internal microscopic process.

In order to study the dynamical evolution of collisionless reconnection in the presence of an external driving source we have developed a new open boundary model, in which a free condition is used at the downstream boundary ($x = \pm x_b$) and an input condition is used at the upstream boundary ($y = \pm y_b$) [3,4,5]. The plasma inflows are symmetrically driven from two upstream boundaries by the external electric field imposed in the z direction. The amplitude of driving field $E_{zd}(x,t)$ is initialized to zero at t=0, and increases with time while keeping a bell-shaped profile near the center and a flat profile in the periphery for an initial short time. After then a constant profile is kept with maximum flux input rate E_0. The spatial size of initial bell-shaped profile x_d is named input window size, because the inflow velocity is locally enhanced within this region. The distribution function of incoming particles at the input boundary is assumed to be a shifted Maxwellian with a constant temperature and the average velocity equal to the $\mathbf{E} \times \mathbf{B}$ drift velocity.

As an initial condition we adopt a one-dimensional equilibrium with the Harris-type anti-parallel magnetic configuration, in which physical quantities depends only on the y coordinate and the magnetic field is parallel to the x axis. The initial particle distribution is assumed to be a shifted Maxwellian with spatially constant temperature and average particle velocity, which is equal to the diamagnetic drift velocity.

2. Dynamical evolution of the current sheet

2.1 Two types of dynamic evolution

We have examined the relationship between the dynamical behavior of kinetic plasmas and the driving field by carrying out several two-dimensional particle simulations with different values of the input window size x_d and the flux input rate E_0 [4,5]. As a result, it is found that there are two dynamic regimes in the temporal behavior of collisionless reconnection, which is strongly dependent on the value of x_d, but insensitive to the value of E_0. The steady collisionless reconnection is realized when the input window size is small, while an intermittent regime appears as the window size increases.

2.2 Plasma instabilities in non-driven case

In three-dimensional case the spatial structure of current sheet is dynamically modified by plasma instabilities excited through wave-particle interaction. In the absence of an external driving source the lower hybrid drift instability (LHDI) [6,7] is observed to grow in the periphery of current layer in an early period, while a drift-kink instability (DKI) [8,9] is triggered at the neutral sheet as a second instability after the current sheet is modified through nonlinear evolution of the LHDI and its width becomes less than ion Larmor radius[3,10]. In this way, the LHDI is not a direct cause of an anomalous resistivity at the neutral sheet, but collisionless reconnection is triggered by the DKI in the non-driven case.

2.3 Effect of an external driving flow in three dimensions

How does an external driving flow affect collisionless reconnection in three dimensions? Figure 1 shows the temporal evolution of the integrated energies in the case of the driving field $E_0 = -0.04B_0$ and the mass ratio $m_i/m_e = 100$, where the solid, dotted, dashed, and dot-dashed lines stand for the magnetic field, electric field, ion, and electron energies, respectively. There are three typical phases in the evolution of the energirs, i.e., (1) the initial ramp-up phase, (2) the intermediate phase in which the energies drop suddenly, and (3) the late quasi-steady phase. We can see three different plasma instabilities in these temporal phases.

Figure 2 illustrates the spatiotemporal structure of the $n = 7$ mode of the electric field E_z in the (t,y) plane, where n is the Fourier mode number in the z-direction and the neutral sheet is located at the mid-point of y-axis (vertical axis). The LHDI is excited in the periphery at the relatively early period in the same way as in the non-driven case. This mode has an electromagnetic feature as well as an electrostatic feature [11]. The driving electric field imposed at the upstream boundary carries the plasma towards the current sheet and compresses it. The anomalous resistivity generated through the interaction between particles and the LHD wave leads to the penetration of the driving electric field into the current sheet. Figure 3 shows the temporal evolution of two Fourier modes of the electric field E_z at the midpoint. Figures 2 and 3 indicate that the LHD wave ($n = 7$ mode) itself propagates towards the center of the current sheet together with the driving field ($n = 0$ mode) and triggers collisionless reconnection at the neutral sheet.

Magnetic reconnection generates the fast divergent flow which carries the magnetic flux towards the downstream region, thus leading to the change in the spatial structure of the current sheet. Figure 4 illustrates the perspective view of magnetic field strength $B_x^2 + B_y^2$ at $\omega_{ce}t = 456$ in three-dimensional space, where the weak field region is plotted by an isosurface. The weak field region is split into three pieces as a result of magnetic reconnection, i.e., the central region around a magnetic "x"-point, and two islands in the downstream which include a magnetic "o"-point. The reconnected magnetic flux accumulates inside the magnetic islands and increases the current density there. When the current density exceeds some critical value, a kink instability is triggered resulting in the destruction of the island structures, as is shown in Fig. 4.

When the magnetic islands move out though the boundary, the extra energy is suddenly expelled from the system together with the magnetic islands (see Fig. 1). After this event, the system relaxes into a quasi-steady state. However, it is also found that a low-frequency EM instability is excited near the central region in this late phase. Spatiotemporal structure of the $n = 1$ mode of the magnetic field B_x is plotted in Fig. 5. This EM mode is excited in the late phase and has a frequency comparable to the ion cyclotron frequency which is much lower than the lower hybrid frequency. The detailed examination leads to the conclusion that this mode is nothing but the drift kink instability and is a possible candidate for anomalous resistivity in the neutral sheet.

3. Summary

Dynamical behavior of thin current sheets controlled by collisionless reconnection has been examined by means of three-dimensional EM particle simulation in an open system which is subject to an external driving source. Collisionless driven reconnection evolves dynamically under the influence of three different types of plasma instabilities excited in a thin current sheet. Driving electric field imposed at the boundary penetrates into the current sheet in accordance with the propagation of the lower hybrid drift wave excited in the periphery. When the electric field reaches the neutral sheet, collisionless reconnection is triggered. Small islands, which are generated in the downstream as a result of collisionless reconnection, suffer from the kink instability leading to the destruction of the island structure. A low frequency EM instability is also triggered in the current sheet in the late phase when there is no island structure in the system.

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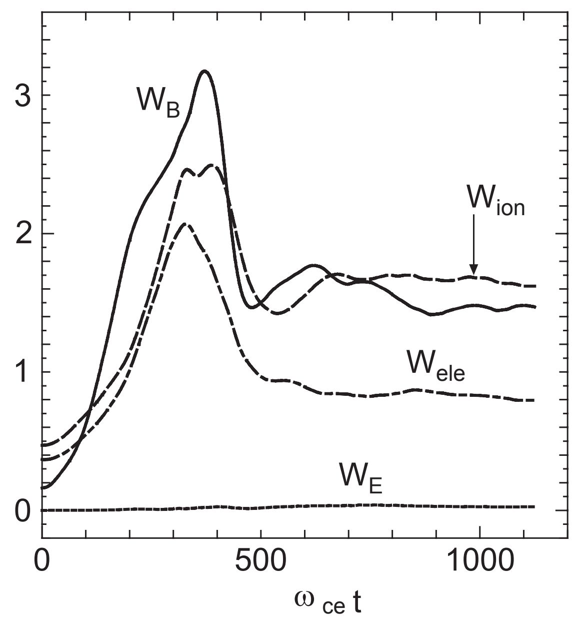

Figure 1: Temporal evolution of volume-integral values of magnetic field, electric field, ion, and electron energies.

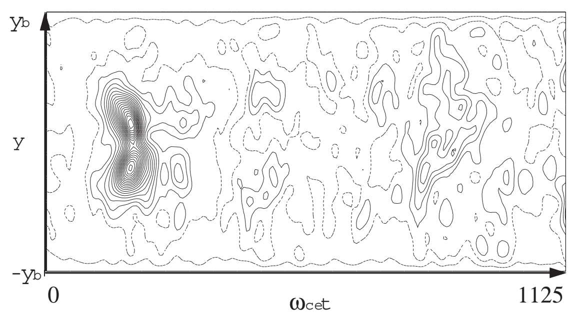

Figure 2: Spatiotemporal structure of the $n = 7$ mode of the electric field E_z in the (t,y) plane.

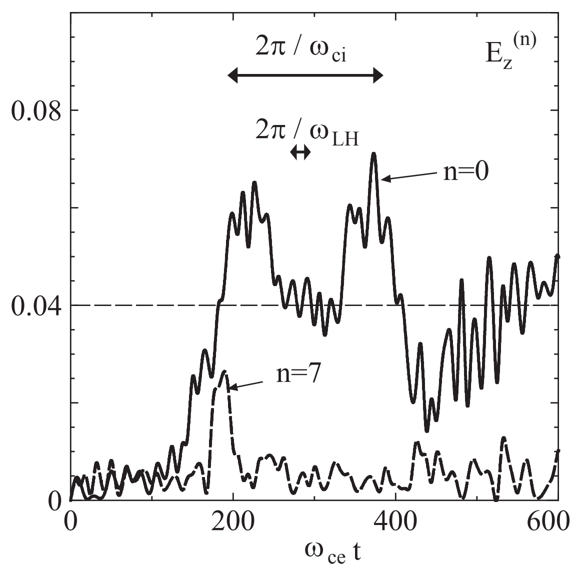

Figure 3: Temporal evolution of two Fourier modes the electric field E_z at the midpoint, where the solid and dashed lines correspond to the $n = 0$ and $n = 7$ modes, respectively.

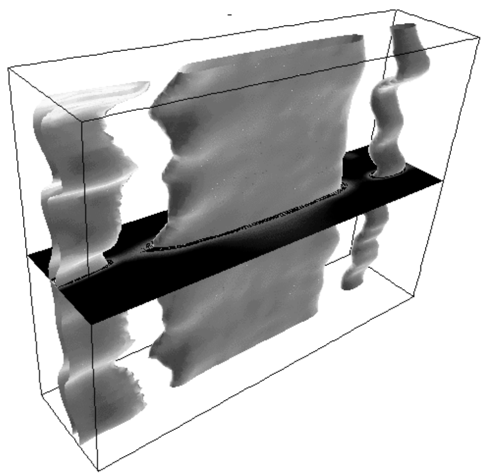

Figure 4: Perspective view of the magnetic field $B_x^2 + B_y^2$ at $\omega_{ce}t = 456$, where the weak field region is plotted by an isosurface.

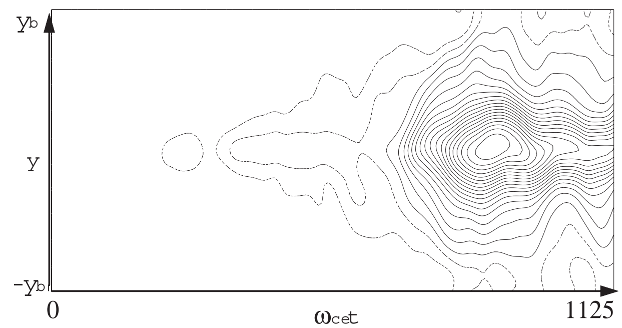

Figure 5: Spatiotemporal structure of the $(n = 1)$ mode of the magnetic field B_x in the (t,y) plane.