Structure formation and dynamical behavior of kinetic plasmas controlled by magnetic reconnection

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abstract

Structure formation and dynamical behavior of kinetic plasmas controlled by magnetic reconnection is investigated by means of electromagnetic particle simulations. Two-dimensional simulation in a long time scale reveals that there are two evolving regimes in the temporal behavior of current layer structure, dependently on the spatial size of plasma inflow through the upstream boundary, i.e., a steady regime and an intermittent regime. In three-dimensional case the spatial structure of current sheet is dynamically modified by plasma instabilities excited through wave-particle interaction.

1 Introduction

Self-organization phenomena have attracted many scientists in the wide academic fields to the study of the underlying universal rules [1]. Plasma is a typical example in which self-organization phenomena are often observed in spite of its complex natures [2]. Thus, many efforts have been made to understand the spontaneous formation of structures by the plasma itself and to improve plasma confinement in a fusion device by taking optimal advantage of this self-organization. There are four key factors to make the behavior of plasmas complex, i.e., 1) a hierarchy consisting of micro-scale physics through macro-scale physics, 2) non-linearity, 3) non-equilibrium, and 4) an open system. In this paper we investigate the role of these factors in the self-organization by examining the structure formation process and dynamical behavior of kinetic plasmas in an open system, where energy inflow and outflow exist through the boundary. Especially, we focus on the physics of magnetic reconnection because it is a fundamental mechanism to control the structure formation process of magnetized plasmas in the complex open system.

There are two key issues in considering magnetic reconnection. One is a local or microscopic issue. The excitation of magnetic reconnection needs a microscopic process, which leads to the generation of electric resistivity, such as wave-particle interaction, binary collisions, and so on. The other issue is a global or macroscopic issue. Magnetic reconnection results in global plasma transport and global change of field topology. The problem is how to solve both microscopic physics and macroscopic physics consistently and simultaneously. It is impossible to solve numerically the dynamical evolution of the whole system consisting from the microscopic process through macroscopic process by using only equations based on the first principle (equations of motion for particles and the Maxwell equations) due to the power limitation of presently existing computers.

Instead, we propose two approaches to attack this problem. The first approach is to use an open model, in which the information of physics in the external (surrounding) system is introduced as a boundary condition, and only a local reconnection system is solved under a given boundary condition. Thus, there is an energy flow through the boundary in this approach. The second approach is to construct the cross-hierarchy model connecting the microscopic physics and macroscopic physics. Microscopic physics is solved by kinetic model, while macroscopic physics is solved by MHD model. In this approach, both models are coupled by taking in the information from each other and their dynamical evolutions are solved simultaneously. In this paper we discuss the model and the simulation results in the first approach.

2 Open boundary model

A local reconnection system is solved by means of an explicit electromagnetic particle simulation [3]. As an initial condition we adopt a one-dimensional equilibrium with the Harris-type anti-parallel magnetic configuration as

$$\mathbf{B}(y) = (B_x(y), 0, 0), \tag{1}$$

$$B_x(y) = B_0 \tanh(y/L), \tag{2}$$

$$P(y) = B_0^2/8\pi \, \mathrm{sech}^2(y/L), \tag{3}$$

where B_0 is a constant and L is the scale height along the y-axis. There is a magnetically neutral sheet at $y = 0$ in the initial equilibrium. 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.

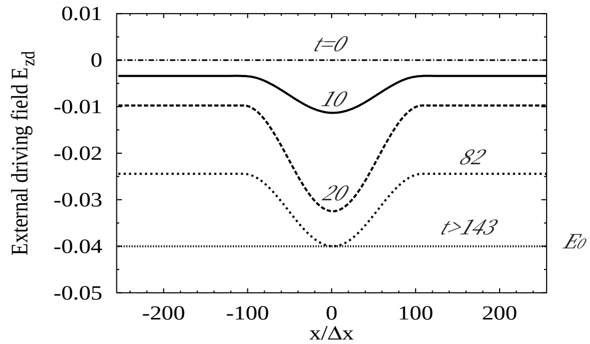

Figure 1: Spatial profiles of the driving electric field imposed at the upstream boundary at five different time periods in the case of $x_d = 0.84x_b$ and $E_0 = -0.04B_0$, where the time unit is ω_{ce}^{-1}.

In order to study the dynamical evolution of the reconnection system mutually interacting with surroundings 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 ($y = \pm y_b$) [4,5,6]. The plasma inflows are symmetrically driven from two upstream boundaries by the external electric field imposed in the z direction. Figure 1 shows the spatial profiles of the driving electric field imposed at the upstream boundary at five different time periods [5]. 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 parameters E_0 and x_d control the openness of system. 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.

Field quantities E_x, E_y and $\partial E_z/\partial x$ are assumed to be continuous at the downstream boundary ($x = \pm x_b$). The condition $\partial E_z/\partial x =$ finite allows the change in the y-component of magnetic field which is the necessary condition for a magnetic island to go freely through the boundary. The boundary condition for particles is determined so that charge neutrality is maintained and the net number flux of particles at the boundary is equal to that associated with the fluid velocity in the vicinity of the downstream boundary. That is, there exist both outgoing particles and incoming particles through the downstream boundary in this model, and their difference gives the net number flux. We know the number flux of outgoing particles by observing them directly at the boundary. Under the assumptions that the net number flux of ions is the same as that of electrons, and the incoming particles satisfy the same distribution function as that just inside the boundary, we can calculate the number fluxes of incoming ions and electrons, and get their velocities and positions. Thus, the total number of particles is a function of time in this open model.

3 Dynamical behavior of collisionlss reconnection

We examine the relationship between the dynamical behavior of kinetic plasmas and the openness of system by carrying out several simulation runs with different values of the input window size x_d and the flux input rate E_0. As a result, it is found from the two-dimensional particle simulations that there are two evolving 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 [4,5]. The steady collisionless reconnection is realized when the input window size is small, while an intermittent regime appears as the window size increases. In the followings we discuss the simulation results in two typical cases, i.e., the narrow input window case ($E_0 = -0.04B_0$, $x_d = 18\rho_i$, $m_i/m_e = 25$) and the wide input window case ($E_0 = -0.04B_0$, $x_d = 36\rho_i$, $m_i/m_e = 25$).

First, let us consider the case of the narrow input window ($x_d = 18\rho_i$) [4,5,6]. Figure 2 shows the perspective view of spatiotemporal structure of the off-plane electric field E_z in the t-y plane where the reconnection point is located at the mid y-axis. After experiencing the initial transient phase, the system relaxes into a steady state in which the off-plane electric field becomes uniform in space and constant in time, and thus must be equal to the external driving field E_0 at the upstream boundary. In other words, the reconnection rate is balanced with the flux input rate at the upstream boundary in the steady state.

When the input window size x_d increases twofold ($x_d = 36\rho_i$), the system reveals a quite different behavior from the narrow input window case ($x_d = 18\rho_i$) [4,5]. An elongated current sheet along the x-axis is created as a result of the plasma compression over a relatively long range in the wide window case. The length of the current sheet is roughly estimated as $L_{cs} \approx 10\rho_i$, which means that the current sheet becomes unstable against a collisionless tearing instability. Magnetic islands are frequently created in the central region of the current sheet through the tearing instability, as is shown in Fig. 3. Consequently, the system never reaches steady state with a single reconnection point and a constant reconnection rate in the wide input window case. Furthermore, it is also found that the growth of magnetic islands is caused by the increase of electron current density through

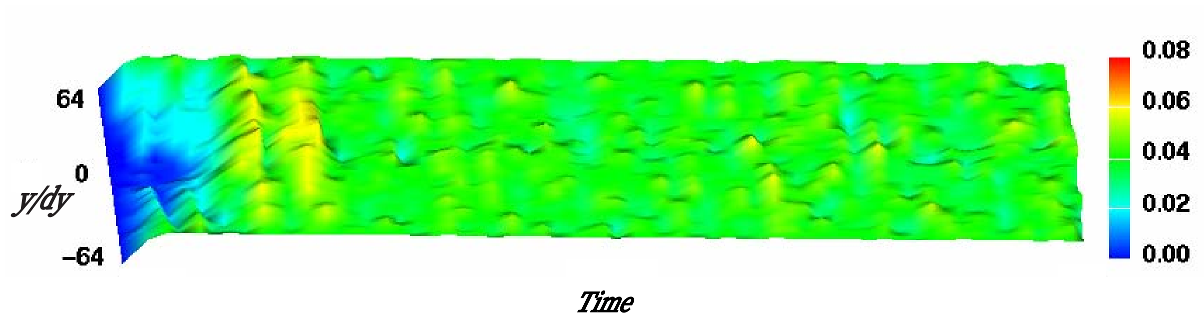

Figure 2: Spatiotemporal structure of off-plane electric field $-E_z(t,y)$ for the narrow input window

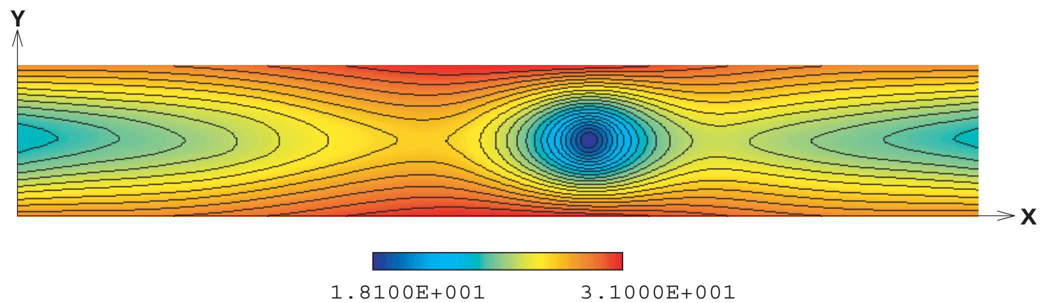

Figure 3: Contour plots of vector potential $A_z(x,y)$ at $\omega_{ce}t = 755$ for the wide input window.

the electron trapping inside magnetic islands.

4 Structure formation of kinetic plasmas

The dissipation region has a two-scale structure underlying the quite different characteristic scale lengths of electron and ion dynamics [6,7]. The ion motion decouples from the magnetic field due to the inertia effect within the region of $|y| < c/\omega_{pi}$, while the electrons remain to be frozen in the magnetic field until they enter the region of c/ω_{pe} which is slightly larger than an electron thermal scale [6]. Figure 4 shows the spatial profiles of current density for $m_i/m_e = 200$ (solid) and $m_i/m_e = 25$ (dashed) in the steady state, where $E_0 = -0.04B_0$, and $x_d = 18\rho_i$. In the case of $m_i/m_e = 25$, the current density profile has the same scale as the ion thermal scale, which is given by the average orbit amplitude of meandering ions in the vicinity of neutral sheet [7]. When the mass ratio increases to 200, a two-scale structure of the current density profile becomes visible,

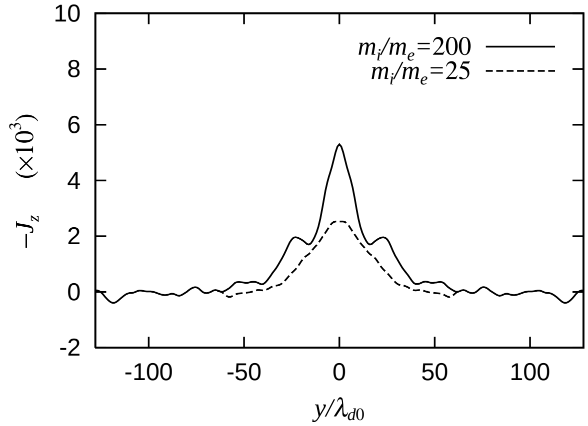

Figure 4: Spatial profile of current density in the steady state where the solid and dashed lines represent the profiles along the y-axis for $m_i/m_e = 200$ and $m_i/m_e = 25$, respectively.

i.e., a large spatial structure (a low shoulder) in the ion thermal scale and a small spatial structure (a central peak) near the center in the electron inertia scale. Figure 5 displays the time evolution of the reconnection electric field in the case of $m_i/m_e = 200$, where $E_0 = -0.04B_0$ and $x_d = 18\rho_i$. It is noteworthy in this figure that the steady state is realized regardless of mass ratio when the window size is small ($x_d = 18\rho_i$).

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) [8,9] is observed to grow in the periphery of current layer in an early period, while a drift-kink instability (DKI) [10,11] 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[4,12]. 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.

How does an external driving flow affect collisionless reconnection in three dimensions? Figure 6 illustrates the spatiotemporal structure of the $n = 8$ mode of the electric field E_z in the case of the driving field $E_0 = -0.02B_0$, where n is the fourier mode number in the z-direction, the neutral sheet is located at the mid-point of y-axis at the initial stage, $x_d/2x_b = 0.42$, and $m_i/m_e = 100$. The LHDI is excited in the pheriphery at the relatively early period. This mode has an electromagnetic feature as well as an electrostatic feature [13]. The driving electric field imposed at the upstream boundary carries the plasma towards the current sheet and compresses it. The anomalous resistivity

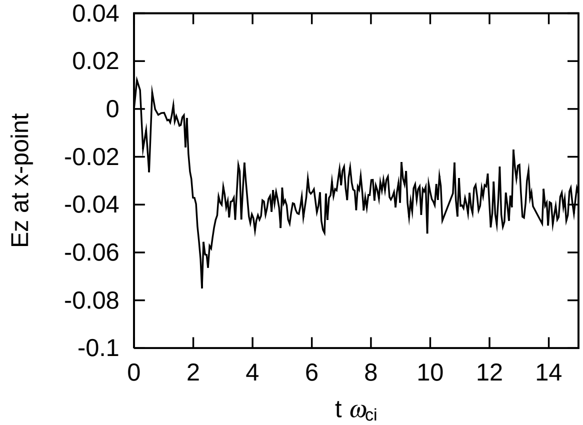

Figure 5: Temporal evolution of the reconnection electric field at the X-point for the narrow input window, where $m_i/m_e = 200$.

generated through the interaction between particles and the LHD wave leads to the penetration of the driving electric field into the current sheet. Figure 6 indicates that the LHD wave itself propagates towards the center of the current sheet together with the driving field. When the electric field reaches the neutral sheet, collisionless reconnection is triggered and the generated fast reconnection flow carries the magnetic flux towards the downstream region.

The excitation of magnetic reconnection changes the spatial structure of the current sheet. Figure 7 illustrates the perspective view of magnetic field strength $(B_x^2 + B_y^2)$ in case of $E_0 = -0.04B_0$ and $m_i/m_e = 64$, when magnetic reconnection fully develops ($\omega_{ce}t = 244$). The current sheet is splitted into five pieces, i.e., a small island at the center, two large islands in the downstream, and two pieces near the boundary. 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-like instability is triggered resulting in the destruction of the island structures. In the case of Fig. 7 the kink-like instability occurs at the small middle island first and then at two islands in the downstream region. It is found that the DKI excited in the middle island can be a cause of anomalous resistivity.

5 Summary

Structure formation and dynamical behavior of kinetic plasmas controlled by magnetic reconnection is investigated by using newly developed electromagnetic particle simulation codes [4,5,6]. Two-

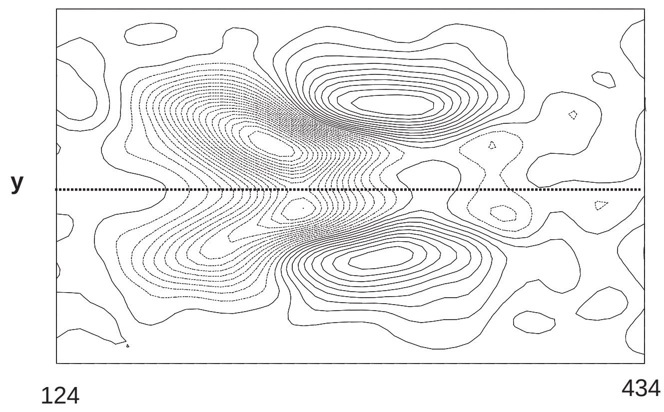

Figure 6: Spatiotemporal structure of the $n = 8$ mode of the electric field E_z in the narrow window case of $x_d/2x_b = 0.42$.

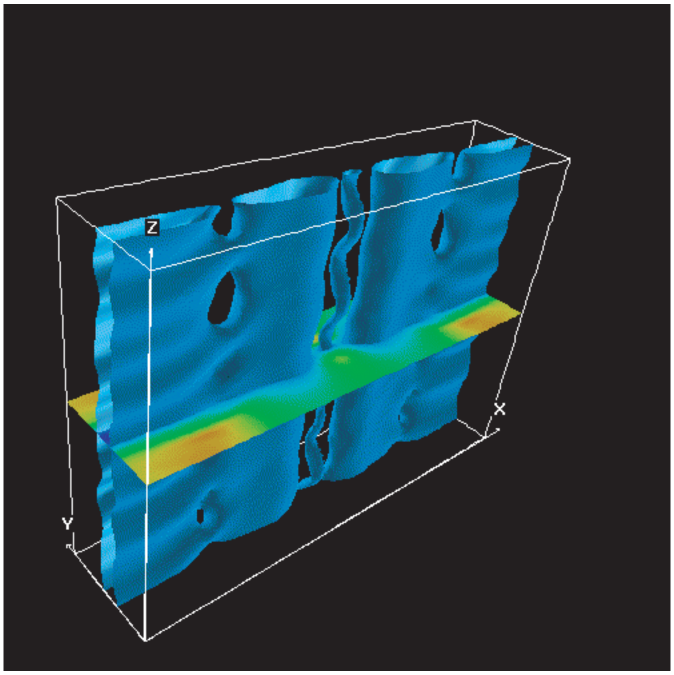

Figure 7: Perspective view of magnetic field strength $(B_x^2 + B_y^2)$ in three dimensions at $\omega_{ce}t = 244$, where $E_0 = -0.04B_0$, $m_i/m_e = 64$, and the weak field region is plotted by an isosurface in bule.

dimensional simulation in a long time scale reveals that there are two evolving regimes in the temporal behavior of current sheet structure, dependently on the spatial size of plasma inflow through the upstream boundary, i.e., a steady regime and an intermittent regime. The steady collisionless reconnection is realized in the case of small input window size, in which the reconnection rate is balanced with the flux input rate at the upstream boundary. As the window size increases, the current sheet becomes longer, which is favorable to the excitation of a collisionless electron tearing instability. In this case the system evolves toward the intermittent regime, in which magnetic islands are frequently generated in the current sheet. The current density profile has a two-scale structure underlying the quite different characteristic scale lengths of electron and ion dynamics, i.e., a large spatial structure in the ion thermal scale and a small spatial structure near the center in the electron inertia scale.

In the three-dimensional case the spatial structure of current sheet is dynamically modified by plasma instabilities excited through wave-particle interaction. In the presence of an external driving source the 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 are generated in the current sheet as a result of collisionless reconnection. The accumulation of current density inside the islands leads to the excitation of the kink-like instability leading to the destruction of the island structure.

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