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Mass Ratio Dependence of Current Layer Structure in Collisionless Driven Reconnection

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Abstract

A steady two-scale structure of current layer is demonstrated in the collisionless driven reconnection without a guide field by means of two-dimensional full-particle simulations in an open system. The current density profile along the inflow direction consists of two parts. One is a low shoulder controlled by the ion-meandering motion, which is a bouncing motion in a field reversal region. The other is a sharp peak caused mainly by the electron-meandering motion. The separation of the shoulder from the sharp peak is revealed by virtue of a large mass ratio calculation $m_i/m_e = 200$ because the ratio of the ion-meandering orbit amplitude to the electron-meandering orbit amplitude is proportional to $(m_i/m_e)^{1/4}$.

Keywords:
driven reconnection, collisionless, particle simulation, current layer

1. Introduction

The collisionless magnetic reconnection is a fundamental mechanism of the rapid release of magnetic energy in the solar corona, the high temperature tokamak discharge, the magnetospheric substorm, and reconnection experiments [1,2,3]. Recent computer simulations reveal that a small scale current layer, where the frozen-in condition of the plasma is violated, adjusts its structure so as to realize a large reconnection rate demanded by a large scaleideal magnetohydrodynamics (MHD) evolution [4-14]. The simplest physical model of the violation necessary to generate the large reconnection rate, i.e. the large reconnection electric field, is the Hall-MHD model which includes the Hall-term characterized by the ion skin depth [4-9].

A plasma is frozen in magnetic field lines in the ideal MHD, and thus reconnection does not occur. This circumstance is related to the fact that there is no typical scale length that characterizes a small scale current layer profile. When we introduce non-ideal effects leading to violation of the frozen-in constraint, the width of the current layer is determined by typical scale lengths of non-ideal effects. The plasma profile in the kinetic approach is characterized by the spatial scale lengths such as the electron skin depth due to the electron inertia effect, the ion skin depth due to the ion inertia effect, the electron Larmor radius, and the ion Larmor radius.

The current layer structure is studied using hybrid simulations and full particle simulations [4-14]. Most of these simulations present time dependent reconnections in closed systems [6-12]. In the time dependent magnetic reconnection, two structures related to the current layer are found [5,6]. One is out-of-plane electron flow characterized by the electron skin depth, the other is out-of-plane ion flow characterized by the ion skin depth [5,6].

On the other hand, steady states of the reconnection are found in the long-time scale dynamics of the driven reconnection in an open system [13,14]. In the steady reconnection, the reconnection rate is controlled only by an external driving flow due to an applied electric field because the Faraday's law requires that the out-of-plane electric field should be uniform in the steady state [11-14]. The current layer profile adjusts itself to accommodate the uniform electric field.

In the steady reconnection, it is found that the current layer width is controlled only by ion dynamics [13,14], although the current is dominated by the out-of-plane electron flow. It is claimed that the ion-meandering motion controls the current layer which adjusts itself to sustain the uniform out-of-plane component of the electric field. These studies are, however, limited by the small mass ratio of ion and electron $m_i/m_e = 25$. The significance of the ion dynamics should be clarified by examining a dependence on the mass ratio.

In this paper, we will investigate steady states of the collisionless driven reconnection in an open system for several cases with different mass ratio, namely: $m_i/m_e = 25$, 50, 100 and 200. The large mass ratio leads to a clear separation of the ion-meandering orbit amplitude from the electron-

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meandering orbit amplitude because the ratio of these amplitudes is proportional to $(m_i/m_e)^{1/4}$. We reveal a two-scale structure of the current layer, a sharp peak and low shoulders. The sharp peak is mainly controlled by the electron-meandering motion. The half-width of the current layer is determined by this sharp peak. The ion dynamics forms low shoulders of the current layer, and thereby resulting in a two-scale structure of the layer. The structure is mainly caused by the meandering motion of ions and electrons because they strongly violate the frozen-in constraint.

2. Simulation model

We consider a square open region in xy-plane, the size of which is $2y_b$ in height and $2x_b$ in width. We use a two-and-a-half-dimensional explicit electromagnetic particle simulation code developed in the previous work [11-14].

Boundary conditions are as follows. At upstream boundary, ions and electrons are frozen in magnetic field lines, and thus plasma inflow is driven by $E \times B$ drift due to an external electric field $E_{zd}(x,t)$ applied in z direction at $y = \pm y_b$. The condition for the incoming particle distribution is a shifted Maxwellian with the averaged velocity given by $E \times B$ drift. The boundary conditions for remaining field quantities are following: $E_x = 0$ and $\partial_y E_y = 0$ at $y = \pm y_b$. The external field $E_{zd}(x,t)$ evolves from zero, so as to induce a steady reconnection. To excite magnetic reconnection at the center of simulation domain, the external field is assumed to be strong within the input window size x_d around $x = 0$ at early phase, then the field profile becomes uniform E_0 after one Alfvén time $\tau_A = y_b/V_A$, where V_A is the initial average Alfvén velocity. This uniform field E_0 plays a role to maintain deformed magnetic field lines within the input window at the inflow boundary, and correspondingly the system relaxes to a steady state [13,14].

At the downstream boundary $x = \pm x_b$, the plasma can freely flow in or out. The boundary condition for particles is determined by both the charge neutrality condition and the condition of the net number flux, which is associated with the fluid velocity in the vicinity of the boundary [14]. Thus, the total number of particles varies with time in this open system. The field quantities E_x, E_y and $\partial_x E_z$ are continuous at the downstream boundary. These conditions enable magnetic islands to go through the boundary. The remaining components of the field quantities are given by solving the Maxwell equations at the boundary.

The initial condition is a one-dimensional Harris type equilibrium as $B_x\,(y) = B_0 \tanh(y/y_h)$, $P(y) = B_0^2/8\pi\, \mathrm{sech}^2(y/y_h)$, that has a neutral sheet at $y = 0$, where y_h is the scale hight. The distribution of particles is a shifted Maxwellian with a uniform temperature $T_{i0} = T_{e0}$.

We set the ratio of the plasma frequency to the electron cyclotron frequency $\omega_{pe0}/\omega_{ce0} = 3.\ 5$, the strength of the inflow velocity $E_0/B_0 = -0.\ 04$, andthe input window size $x_d = 0.\ 42\ x_b$ in our numerical simulations.

3. Current layer structure

Here we examine a spatial profile of out-of plane current density when the system is relaxed into a steady state.

We show current density profiles along the vertical line passing the X-point in Fig. 1 for m_i/m_e = 25, 50, 100, and 200. For m_i/m_e = 200 we observe clear shoulders at $y \approx \pm 35\lambda_d$ and a sharp peak that has a size nearly equal to $10\lambda_d$ in width. On the other hand, the profile consists of one wide peak for m_i/m_e = 25 because ion-scale and electron-scale are not well separated. We, therefore, conclude that the current density profile has a two-scale structure consists of a sharp peak and low shoulders for a large mass ratio.

Next, we consider the two-scale structure of the current layer more quantitatively, and then reveal that the meandering motions of ions and electrons play crucial roles in the formation of the structure. We introduce several spatial scale lengths describing the layer structure, and consider the time evolution of the spatial scale lengths, namely: the half-width of the distance of shoulders, the half-width of a sharp peak, the half-width of a current layer, the ion-meandering orbit amplitude l_{mi}, the ion skin depth $d_i = c/\omega_{ci}$, the electron-meandering orbit amplitude l_{me}, and electron skin depth $d_e = c/\omega_{ce}$. These scales are normalized by the Debye length and are evaluated from the spatial profile of plasma along the vertical line passing the X-point. The meandering orbit amplitude of species s is defined by the distance y which satisfies the condition $\rho_s(y)/y = 1$ [7,14], where $\rho_i(y)$, and $\rho_e(y)$ are the local ion Larmor radius, and the local electron Larmor radius, respectively. The half-widths of the shoulder and of the sharp peak are defined by the half-widths at 20 % and 80 % of maximum value of the current density, respectively. Figure 2 shows that the scales are relaxed into the following values: $l_{mi} \approx 35\lambda_d$, $l_{me} \approx 5\lambda_d$, $d_i \approx 80\lambda_d$, and $d_e \approx 7\lambda_d$. The width of the shoulder closes to the ion-meandering orbit amplitude, while the width of the sharp peak closes to the electron-meandering orbit amplitude in the steady state. The half-width of the current layer is dominated by the sharp peak, and correspondingly the half-width of the layer relaxes into the electron scale $\leq 10\lambda_d$. Figure 3 shows the mass ratio dependence of current layer width in a steady state. The half-width of current layer closes to the electron meandering orbit

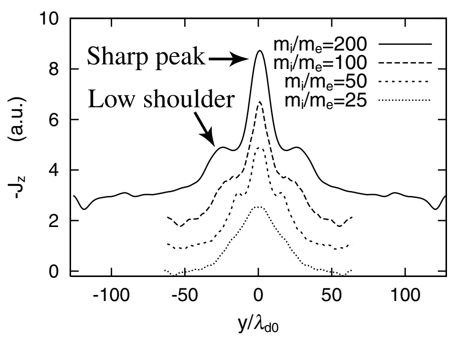

Fig. 1 The current density profile along the vertical line passing through the X-point. The profile consists of a sharp peak and shoulders for large mass ratio.

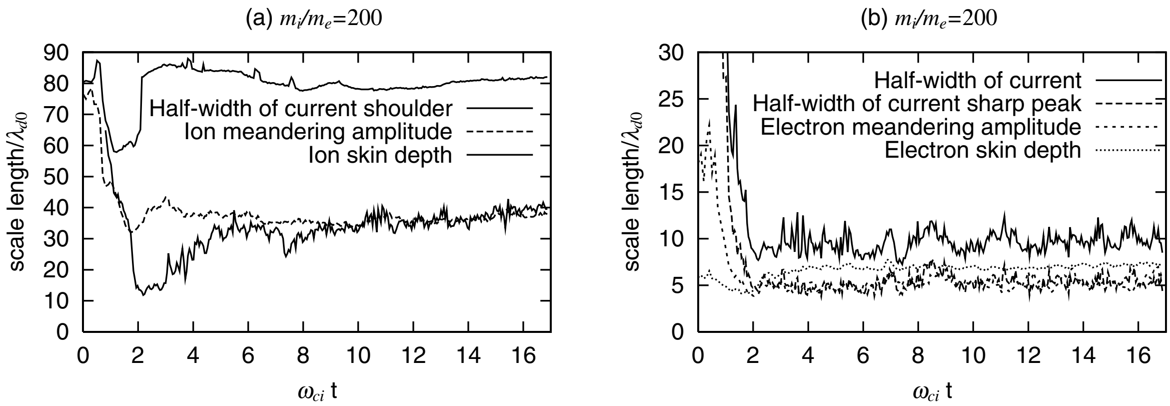

Fig. 2 The time evolutions of several scale lengths: (a) the half-width of the distance of current shoulders, the ion-meandering orbit amplitude λ_{mi}, and the ion skin depth $d_i = c/\omega_{ci}$, (b) the half-width of a sharp peak of current, the half-width of a current layer, the electron-meandering orbit amplitude λ_{me}, and electron skin depth $d_e = c/\omega_{ce}$.

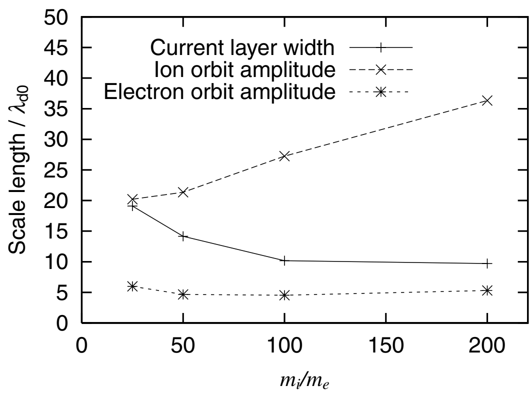

Fig. 3 The mass ratio dependence of scale lengths in the steady state. The half-width of current layer closes to the electron scale for a large mass ratio.

amplitude rather than the ion meandering orbit amplitude for the large mass ratio. The current layer width is, therefore, mainly controlled by the electron dynamics. The ion dynamics generates low shoulders which are characterized by the ion-meandering orbit amplitude $l_{mi} \approx 35\lambda_d$. Therefore, the meandering motion of ions and electrons is the dominant mechanism of the two-scale structure formation of the out-of plane current density in the steady state of the driven reconnection.

4. Summary

We have newly found a steady two-scale structure of the current layer, a sharp peak and low shoulders, in the collisionless driven reconnection. This two-scale structure is significantly different from that characterized by the ion skin depth and the electron skin depth in previous simulations of the time dependent reconnection [5,6].

The sharp peak is mainly controlled by the electron-meandering motionbecause the motion strongly violates the electron frozen-in constraint. In spite of the fact that the electron inertia also violates the frozen-in constraint at a scale below the electron skin depth, the meandering motion dominantly violates the frozen-in constraint near the *X*-point. The sharp peak structure dominates the current layer profile, and thus the half-width of current layer is controlled by the electron dynamics.

The ion-meandering motion creates shoulders of the current layer. The shoulder structure corresponds to the current layer found in Refs. [13,14]. The shoulder structure is controlled by the ion-meandering orbit amplitude because the ion frozen-in constraint is strongly broken by the meandering motion. Although the ion inertia also violates the frozen-in constraint at a scale below the ion skin depth c/ω_{pi}, the violation due to the ion inertia is weak compared to the violation caused by the ion-meandering motion. The mechanism of current layer formation and its relation to the violation by the meandering motion will be discussed in details elsewhere [15].

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