Two-scale structure of the current layer controlled by meandering motion during steady-state collisionless driven reconnection

A. Ishizawa, a) R. Horiuchi, and H. Ohtani
National Institute for Fusion Science, Toki 509-5292, Japan

(Received 28 October 2003; accepted 8 April 2004; published online 10 June 2004)

A steady two-scale structure of current layer is demonstrated in the collisionless driven reconnections 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 shoulder structure is clearly separated from the sharp peak for the case 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 \( (m_i/m_e)^{1/4} \). Although the ion frozen-in constraint is broken within a distance of the ion skin depth \( c/\omega_{pi} \), the violation due to the ion inertia is weak compared to the strong violation caused by the ion-meandering motion. The violation of the electron frozen-in constraint caused by the electron-meandering motion is stronger than the violation due to the electron inertia, and thus the electron-meandering motion produces the reconnection electric field in the central region where the current has the sharp peak structure. © 2004 American Institute of Physics. [DOI: 10.1063/1.1758718]

I. 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.1–5 Recent computer simulations reveal that a small scale current layer, i.e., the dissipation region, where the frozen-in condition of the plasma is violated, adjusts its structure so as to realize a large reconnection rate necessary for a global scale evolution controlled by ideal magnetohydrodynamics (MHD).6–22 The simplest physical model to break the frozen-in condition and generate the reconnection electric field is to introduce the Hall-term characterized by the ion skin depth into the ideal magnetohydrodynamic (MHD) equations.6–15

A plasma is frozen into magnetic field lines in the ideal MHD, and thus magnetic reconnection does not occur. In other words, there is no typical scale length in an ideal MHD that characterizes a small scale current layer profile in association with a dissipation mechanism. When we introduce nonideal effects leading to violation of the frozen-in constraint, the width of the current layer is determined by the typical scale lengths of nonideal effects. The spatial profile of a kinetic plasma is characterized by the 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 has previously been studied using hybrid simulations and full particle simulations.6–21 Most of these simulations have treated the time-dependent reconnections in closed systems such as the coalescence of flux bundles7 and the transit evolution of the perturbed Harris sheet.8–12,16–18 On the other hand, a steady-state reconnection is found to realize in the long-time scale evolution of driven reconnection in an open system when a spatial scale of an external driving flow, an input window size, is small.19–21 The intermittent behavior appears when the widow size is large.21 In the steady reconnection, the reconnection rate is controlled only by an external driving electric field imposed at the boundary because the Faraday’s law requires that the out-of-plane electric field should be uniform during the steady state.17–22 Namely, microscopic scale physics adjusts the spatial plasma profile to realize the uniform electric field.

The analyses of time-dependent reconnection have revealed that the dissipation region has a two-scale structure.7,8,12,17,18 However, they reported two different mechanisms in the formation of the current layer structure. Some studies indicated that the out-of-plane electron flow is characterized by the electron skin depth, while the out-of-plane ion flow is characterized by the ion skin depth.7,8,12 On the other hand, others indicated that the scale length of the electron current layer is controlled by the electron-meandering motion, that is bouncing of electrons in a field reversal region, rather than electron inertia.10,13,17,18 The dissipation due to this particle motion is expressed by the non-gyrotrropic electron pressure tensor terms in the two-fluid equations.10,11,13

In the steady reconnection,19,21 it is found that the current layer width is controlled only by ion dynamics, although the current is dominated by the electron flow. It is claimed that the ion-meandering motion controls the plasma profile, which adjusts itself to sustain the uniform out-of-plane com-
ponent of the electric field. These studies are, however, limited to 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 collisionless driven reconnection in an open system for two different mass ratios, namely: $m_i/m_e = 25$ and 200. In particular, the relation between the current layer structure and the mechanism of collisionless driven reconnection in a steady state is examined in detail. The large mass ratio leads to the clear separation of the ion-meandering orbit amplitude from the electron-meandering orbit amplitude because the ratio of these amplitudes is proportional to $(m_i/m_e)^{1/4}$. We have succeeded in demonstrating the two-scale structure of the current density profile consisting of a sharp peak and a low shoulder in case of $m_i/m_e = 200$. The sharp peak is mainly controlled by the electron-magnetization motion. The half-width of the current layer is determined by this sharp peak. The ion dynamics forms a low shoulder 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 break the frozen-in constraint.

The paper is organized as follows. We describe our simulation model for driven reconnection in an open system in Sec. II. Then, we show in Sec. III that the reconnection is relaxed into a steady state. In Sec. IV we demonstrate that the two-scale structure of the current layer is clearly formed for a large mass ratio. Roles of ion-meandering motion in the formation of this structure are also discussed. The details of the frozen-in constraint violation are examined in Sec. V. Finally, we summarize obtained results in Sec. VI.

II. 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.$^{17\text{--}21}$

Boundary conditions are as follows. At upstream boundary, ions and electrons are frozen into 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 $\partial_x E_y = 0$ at $y = \pm y_b$. The external field $E_{zd}(x,t)$ is programmed to evolve from zero to a constant value during an early phase, $0 < t < \tau_A$, where $\tau_A = y_b/V_A$ is Alfvén transit time and $V_A$ is an initial average Alfvén velocity. 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 $x = 0$ during the early phase and then take a uniform profile with a constant value $E_0$. 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.$^{19\text{--}21}$ To examine the structure of current sheet in a steady state, rather than an intermittent state, we adopt a narrow input window size in this work.

<table>
<thead>
<tr>
<th>Run</th>
<th>$m_i/m_e$</th>
<th>$E_0/B_0$</th>
<th>$x_d/x_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>200</td>
<td>−0.04</td>
<td>0.42</td>
</tr>
<tr>
<td>B</td>
<td>200</td>
<td>−0.04</td>
<td>0.8</td>
</tr>
<tr>
<td>C</td>
<td>200</td>
<td>−0.06</td>
<td>0.42</td>
</tr>
<tr>
<td>D</td>
<td>25</td>
<td>−0.04</td>
<td>0.42</td>
</tr>
</tbody>
</table>

Table I. Simulation parameters.

At the downstream boundary $x = \pm x_b$, the plasma can freely flow in or out. The boundary condition for the 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.$^{20,21}$ 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 given by a one-dimensional Harris type equilibrium as

$$B_z(y) = B_0 \tanh(y/y_b), \quad P(y) = B_0^2/8\pi \operatorname{sech}^2(y/y_b), \quad (1)$$

where a neutral sheet is located at $y = 0$ and $y_b$ is the scale height. The distribution of particles is a shifted Maxwellian with a uniform temperature $T_{i0} = T_{e0}$ and a uniform average velocity equal to the diamagnetic drift velocity.

We set the time step $\omega_{pe0} \Delta t = 0.02$, the ratio of the plasma frequency to the electron cyclotron frequency $\omega_{pe0}/\omega_{ce0} = 3.5$. We perform four simulation runs with different values of the mass ratio $m_i/m_e$, the driving electric field $E_0/B_0$, and the input widow size $x_d/x_b$, which are listed in Table I. The following discussion on the features of steady reconnection is based on the numerical results for Run A, i.e., $m_i/m_e = 200$, $E_0/B_0 = -0.04$, and $x_d = 0.42 x_b$, except in Fig. 4. For the case of the mass ratio $m_i/m_e = 200$, we use a $512 \times 256$ point grid, 12.8 million particles, and the aspect ratio of simulation box $x_b/y_b = 2$. For the case of the mass ratio $m_i/m_e = 25$, we use a $512 \times 128$ point grid, 6.4 million particles, and the aspect ratio of simulation box $x_b/y_b = 6$, which are the same as those in Refs. 19–21.

III. RELAXATION INTO STEADY STATE

We analyze the long time behavior of collisionless driven reconnection for the mass ratio $m_i/m_e = 200$, and show that the system relaxes into a steady state after the initial transient phase.

Figure 1(a) shows the temporal evolution of the spatial profile of electric field $E_x$ along the vertical line passing the X point. The reconnection electric field is defined by the out-of-plane component of the electric field at the X point, i.e., the value at $y = 0$ in Fig. 1(a). The absolute value of the reconnection electric field reaches a maximum at $\omega_{ce} t \approx 2.5$, and the system relaxes into a steady state after $\omega_{ce} t \approx 8$. The reconnection electric field is approximately equal to the strength of the external driving electric field $E_0/B_0 = -0.04$ in the steady state. This is because the Faraday's
law demands that the out-of-plane component of the electric field must be uniform in space during the steady state. The reconnection rate is, therefore, mainly controlled by the external driving field.

Next, let us pay attention to the current density profile during the initial transient phase. Figure 1 shows the temporal evolution of the current density profile along the vertical line passing the X point, (a) out-of-plane electric field $E_z/B_0$ and (b) out-of-plane current density $J_z$.

![Figure 1](image1.png)

**FIG. 1.** (Color) The time evolution of spatial profiles along the vertical line passing the X point. (a) out-of-plane electric field $E_z/B_0$ and (b) out-of-plane current density $J_z$.  

IV. CURRENT LAYER STRUCTURE IN STEADY STATE

A. Two-scale structure

Let us examine spatial profiles of the out-of-plane current density when the system is relaxed into the steady state. Figure 3 shows the perspective view of the current density profile in the $xy$ plane in the steady state, where the spatial profile is averaged over the time from $\omega_{ci} t = 12.2$ to 13.0. The profile has two-scale structure, i.e., a sharp peak near the X point and low shoulders in the periphery. To clarify the physical meaning of the two-scale structure we plot a current density profile along the vertical line passing the X point in Fig. 4 for $m_i/m_e = 200$ (Run A) and for $m_i/m_e = 25$ (Run D). In case of $m_i/m_e = 200$ we observe clear shoulders at $y = \pm 35 \lambda_{d0}$ and a sharp peak with a size nearly equal to $10 \lambda_{d0}$ in width. On the other hand, the profile consists of one wide peak for $m_i/m_e = 25$. The dependence of current density profile on the simulation parameters, the driving electric field, and input window width is shown in Fig. 4(b). The shoulder width and sharp peak width do not depend on the driving field and input window width in our simulation parameter range. Thus, it is concluded that the current density profile has the two-scale structure and consists of the sharp peak and the low shoulders for the large mass ratio.

Next, we examine the two-scale structure of the current density profile more quantitatively and clarify the role of the...
ion and electron dynamics in the formation of the two-scale structure. We introduce physical values describing the layer structure and analyze the time evolution of 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 \( r_s(y)/y = 1 \), 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-width at 20% and 80% of maximum value of the current density, respectively. Figure 5 shows that the scales are relaxed in the steady state into the following values: \( l_{mi} = 35\lambda_{d0} \), \( l_{me} = 5\lambda_{d0} \), \( d_i = 80\lambda_{d0} \), and \( d_e = 7\lambda_{d0} \). In the steady state, 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 during the steady state. This result means that the existence of the sharp peak is closely related to the electron-meandering motion, while the low shoulder is created through the ion-meandering motion. Thus, it is concluded that the meandering motion of ions and electrons is the key process in the two-scale structure formation of the current density profile in the steady state of collisionless driven reconnection.

B. Formation mechanism of current layer structure

Although the current density is dominated by the electron current (see Fig. 6), the ion-scale shoulders appear in the current density profile. Let us consider the formation process

FIG. 4. The current density profile along the vertical line passing the \( X \) point in the steady state (a) for \( m_i/m_e = 200 \) (Run A) and \( m_i/m_e = 25 \) (Run D), (b) for \( m_i/m_e = 200 \) with the sets of driving electric field and input widow widths, \( E_z = -0.04 \) and \( x_d/x_b = 0.42 \) (Run A), \( E_z = -0.04 \) and \( x_d/x_b = 0.8 \) (Run B), and \( E_z = -0.06 \) and \( x_d/x_b = 0.42 \) (Run C).

FIG. 5. (Color) The time evolutions of several scale lengths: the half-width of the distance of current shoulders, the half-width of a sharp peak of current, 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 \( d_e = c/\omega_{ce} \). The half-width of the low shoulder closes to the ion-meandering orbit amplitude, while the half-width of the sharp peak closes to the electron-meandering orbit amplitude in the steady state. The half-width of current layer closes to the electron scale.

FIG. 6. The profile of out-of-plane component of current density, ion current density, and electron current density along the vertical line passing the \( X \) point in the steady state.
of the electron current shoulders based on the fact that the electron current is the product of the electron flow velocity and the electron number density.

First, we examine the profile of various velocities. Figure 7 plots the spatial profiles of the out-of-plane electron flow velocity \( V_{ez} \), the ion flow velocity \( V_{iz} \), and the \( E \times B \) drift velocity due to the inflow-direction component of the electrostatic field \(-E_y/B_z\) along the vertical line passing the X point in steady state, where the velocities are normalized by the initial electron thermal velocity \( V_{te0} \). The decoupling of electron motion from ion motion generates the electrostatic field \(-E_y/B_z\) along the vertical line passing the X point in steady state, where the velocities are normalized by the initial electron thermal velocity \( V_{te0} \). The decoupling of electron motion from ion motion generates the electrostatic field \(-E_y/B_z\) along the vertical line passing the X point. Thus, the electron flow is generated by the \( E \times B \) drift due to the electrostatic field. Notice that the electron velocity profile has tails, which spread over the ion scale and contribute to the current shoulder formation.

The appearance of the shoulder is deeply related to the plasma density profile. Figure 8 shows the electron density profile, which is similar to the ion density profile because of the quasi-neutrality. The profile exhibits two peaks at the side of the X point. The density profile with two peaks is created in association with the ion-meandering motion and the peak positions corresponds to the average turning points of the ion-meandering motion. Hence, their distance is controlled by the ion-meandering orbit amplitude.\(^{19}\) In this way, the ion-scale shoulder structure is formed in the current density profile.

![Figure 7](image_url)  
**FIG. 7.** The profile of out-of-plane velocity of electron flow, ion flow, and \( E \times B \) drift along the vertical line passing the X point in the steady state.

![Figure 8](image_url)  
**FIG. 8.** The spatial profile of electron density along the vertical line passing through the X point in the steady state.

### V. Violation of Frozen-In Constraint by Meandering Motion

The ions and electrons are frozen into the magnetic field until the ideal MHD approximation breaks down and they decouple from the magnetic field. Non-ideal effects in kinetic plasmas violates the frozen-in constraint and lead to the generation of the reconnection electric field at the neutral sheet. Let us investigate the violation mechanism in detail.

Figure 9(a) shows the amount of the violation of the ion frozen-in constraint \([E + v_e \times B]\) in the steady state. The ions are frozen into the magnetic field in most of the upstream region (dark blue region). When the ions approach the X point, their meandering motion strongly breaks down the frozen-in constraint at the scale below the ion-meandering orbit amplitude. In this region electrons are still frozen in the field. Figure 9(b) shows that the amount of violation of the electron frozen-in constraint \([E + v_e \times B]\) is small in the region where the ion frozen-in constraint is broken. Thus electrons are still frozen into magnetic field and are decoupled from ions in this region. The decoupling of electrons from ions forms a quadrupole structure of out-of-plane magnetic field in the region as shown in Fig. 9(c). The electrons are frozen into the magnetic field until they come into the electron dissipation region near the X point where they exhibit the meandering motion. Since the ion-meandering and electron-meandering motions strongly violate the frozen-in constraint, these motions determine the out-of-plane electron flow profile and dominantly control the current profile.

In order to clarify the violation mechanism of the electron frozen-in constraint in relation to the sharp peak formation, let us examine the non-ideal terms in the electron momentum equation in the two-fluid model

\[
E = -\frac{1}{c}v_e \times B - \frac{1}{en_e} \nabla p_e - \frac{1}{en_e} \nabla p_e - \frac{m_e}{e} v_e \cdot \nabla v_e \tag{2}
\]

based on the particle simulation data. Figure 10 shows the spatial profile of the terms in Eq. (2) where the profile of each out-of-plane component along the vertical line passing the X point is plotted. Note that the out-of-plane component of the pressure term \(-\nabla p_e / en_e\) vanishes in two-dimensional systems. The electrons are frozen into the field except near the X point and their in-plane fluid velocity is the same as in-plane \(E \times B\) drift of electrons, i.e., \(E = -v_e \times B/c\). The non-gyrotropic pressure tensor term \(-\nabla p_e / en_e\) and electron inertia term \(-m_e v_e \cdot \nabla v_e / e\) break the electron frozen-in constraint near the X point. The electron inertia term vanishes at the X point, while the electron pressure tensor term has a sharp peak and it vanishes with the electric field there. Thus, the reconnection electric field is generated by the pressure tensor originating from the electron-meandering motion in the vicinity of the X point as suggested in Refs. 10 and 13. Although the electron inertia also violates the electron frozen-in constraint and the electron skin depth closes to the width of sharp peak, the effect of the electron-meandering motion is strong compared to the electron inertia effect. Therefore, the electron-meandering motion strongly violates the frozen-in constraint near the X point and mainly sustains the sharp peak structure of electron current density.
VI. SUMMARY

In order to clarify the roles of ion dynamics and electron dynamics on steady collisionless reconnection, we have carried out full-particle simulations of collisionless driven reconnection in an open system for a large mass ratio. Especially, we have examined the relationship between the violation mechanism of the frozen-in constraint of plasmas and the current layer structure in detail. We summarize our results as follows.

It is confirmed that the system relaxes into a steady state even in case of a large mass ratio \((m_i/m_e = 200)\) when the window size of driving field is small. The reconnection rate is balanced with flux input rate at the boundary in the steady state. This means that microscopic scale physics adjusts itself to macroscopic scale physics in order to realize the steady collisionless reconnection.\(^{17-21}\)

A steady two-scale structure consisting of a sharp peak and low shoulders is formed in the current density profile in the steady reconnection. The sharp peak is mainly controlled by the electron-meandering motion, while the ion-meandering motion creates shoulders of the current layer. The formation of shoulder structure is deeply related to the facts that the local peaks of number density profile are formed at the average turning point of ion-meandering motion,\(^{19,21}\) and that the out-of-plane electron \(E \times B\) drift is created by in-plane electrostatic field which is generated as a result of strong decoupling of ion motion from electron motion. Thus, this structure is significantly different from the one controlled by the ion skin depth and the electron skin depth in the previous simulations of time-dependent reconnection.\(^{7,8}\)

We have not observed any current density structure in the ion-skin-depth scale. This is because the violation of ion frozen-in constraint due to the ion inertia is weak compared with the one due to the ion-meandering motion. The electron frozen-in constraint is violated when electrons enter into the electron diffusion region within the electron skin depth. However, the violation of electron frozen-in constraint due to the electron inertia becomes negligibly small near the reconnection point. Instead, the electron pressure tensor term is balanced with the reconnection electric field at the \(X\) point as suggested by Refs. 10, 13, and 18. Thus, the electron-

\[ -E_z = -\nabla \cdot P_{elz} - \frac{1}{en_e} \mathbf{v}_e \cdot \mathbf{v}_e - \frac{1}{en_e} \mathbf{v}_e \cdot \mathbf{B} \]

FIG. 9. (Color) The perspective view of spatial profiles: (a) the amount of breaking ion frozen-in constraint \( |\mathbf{E} + v_i \mathbf{B}| \), (b) the amount of breaking electron frozen-in constraint \( |\mathbf{E} + v_e \mathbf{B}| \), (c) the out-of-plane magnetic field \( B_z \) on the \( xy \) plane in the steady state.

\[ V_x \nabla B_{yz} \]

FIG. 10. (Color) The spatial profile of each term in the out-of-plane component of the electron momentum equation \( \mathbf{E} = -\nabla \cdot P_{elz} - \frac{1}{en_e} \mathbf{v}_e \cdot \mathbf{v}_e - \frac{1}{en_e} \mathbf{v}_e \cdot \mathbf{B} \) along the vertical line passing the \( X \) point in the steady state. The reconnection electric field is generated by the pressure tensor term, \(-E_z = \frac{1}{en_e} \nabla \cdot P_{elz}\), at the \( X \) point \( y = 0 \).
meandering motion, which contributes to the electron pressure tensor, is a dominant cause of steady collisionless reconnection at the neutral sheet in two-dimensional open system. We have discussed the spatial structure during the steady-state collisionless driven reconnection in this paper. Finally, we give a comment on the difference between the steady state and the initial transition phase. Figure 11 plots the spatial profiles of ion current density (solid) and electron current density (dotted) in the initial transient phase ($\omega_{ci}t = 2.5$). The half-width of the out-of-plane ion current is the ion skin depth $c/\omega_{pi} = 80\lambda_{d0}$, while the out-of-plane electron current has one sharp peak without ion-scale shoulders. The two-scale structure found in previous work is similar to the structure of electron current and that of ion current during the initial transient phase for the driven reconnection. Thus, it is concluded that the structure in the transient phase is entirely different from that in the steady state.

**ACKNOWLEDGMENTS**

The authors would like to thank Professor M. Okamoto at the National Institute for Fusion Science (NIFS) for his encouragement. All calculations carried out by the NIFS MISSION System (Grand Man-Machine Interactive System for Simulation).

This work was partially supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology in Japan (No. 13640414).

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