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Electric field structure inside the secondary island in the reconnection diffusion region

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Secondary islands have recently been intensively studied because of their essential role in dissipating energy during reconnection. Secondary islands generally form by tearing instability in a stretched current sheet, with or without guide field. In this article, we study the electric field structure inside a secondary island in the diffusion region using large-scale two-and-half dimensional particle-in-cell (PIC) simulation. Intense in-plane electric fields, which point toward the center of the island, form inside the secondary island. The magnitudes of the in-plane electric fields $E_x$ and $E_y$ inside the island are much larger than those outside the island in the surrounding diffusion region. The maximum magnitudes of the fields are about three times the $B_0 V_A$, where $B_0$ is the asymptotic magnetic field strength and $V_A$ is the Alfvén speed based on $B_0$ and the initial current sheet density. Our results could explain the intense electric field ($\sim 100 \text{ mV/m}$) inside the secondary island observed in the Earth’s magnetosphere. The electric field $E_y$ inside the secondary island is primarily balanced by the Hall term ($\mathbf{j} \times \mathbf{B}$)/$n_e$, while $E_x$ is balanced by a combination of ($\mathbf{j} \times \mathbf{B}$)/$n_e$, $-(\mathbf{v}_e \times \mathbf{B})$, and the divergence of electron pressure tensor, with ($\mathbf{j} \times \mathbf{B}$)/$n_e$ term being dominant. This large Hall electric field is due to the large out-of-plane current density $j_z$ inside the island, which consists mainly of accelerated electrons forming a strong bulk flow in the $–y$ direction. The electric field $E_y$ shows a bipolar structure across the island, with negative $E_y$ corresponding to negative $B_y$ and positive $E_y$ corresponding to positive $B_y$. It is balanced by ($\mathbf{j} \times \mathbf{B}$)/$n_e$ and the convective electric field. There are significant parallel electric fields, forming a quadrupolar structure inside the island, with maximum amplitude of about $0.3B_0 V_A$. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.3700194]

I. INTRODUCTION

Magnetic reconnection is a universal energy transfer phenomenon in space and laboratory plasmas. It enables the reconfiguration of magnetic field lines, during which the magnetic field energy converts into plasma kinetic and thermal energies in an explosive way. The diffusion region is generally believed as the core region where the dissipation process occurs.1 The diffusion region consists of two scale structures, i.e., the ion and the electron diffusion regions, formed by a decoupling of ion and electron motions. Electron diffusion, which is on the order of the electron inertial length, is embedded in the ion diffusion region, which is on the order of the ion inertial length. Previous studies showed that the fast reconnection rate is controlled only by ion dynamics. The mechanism of breaking field lines in the electron diffusion region plays a negligible role in determining the reconnection rate.2,3

Recent kinetic simulations show that secondary islands can be formed in the diffusion region with a guide field.4 The secondary island is characterized by its strong core field and enhanced plasma and current densities. It forms because the aspect ratio of the current sheet is large enough for the tearing mode to be unstable. The growth of the tearing mode leads to the formation of secondary islands, whereas without guide field, the current sheet is too short for the tearing instability to grow. Large-scale simulations show that the length of the electron diffusion region is no longer constrained at the electron scale and can be extended to tens of ion inertial lengths in the outflow direction.5,6 However, the reconnection rate remains fast because the elongation of the electron diffusion region does not act as a bottleneck for fast reconnection.6 Even without guide field the elongated thin current sheet is unstable to the tearing instability that forms secondary islands.5,7

Such secondary islands have been observed in/near the diffusion region of the Earth’s magnetosphere.8–11 In particular, Eastwood et al.8 reported strong electric fields inside a secondary island. The amplitude of the electric fields is two or three times larger than the normalized electric field determined by the lobe magnetic field strength ($B_0$) and the Alfvén speed ($V_A$) based on the lobe field strength and plasma sheet density. This electric field is larger than the typical Hall electric field in the diffusion region.

Secondary islands are closely related to electron acceleration during reconnection. Drake et al.12 put forward a scenario that electrons gain kinetic energy by reflecting from the ends of contracting islands that form as reconnection proceeds. The repetitive interactions between electrons with many islands allow large numbers of electrons to be efficiently energized. In addition, it is found that electrons can
be trapped inside the islands by surfing and then energized by the reconnection electric field prevalent in the reconnection diffusion region.\(^{13}\) Although there are observations of direct correlation between islands and electron acceleration,\(^{9,10,14}\) none of the above theoretical models are verified by observations. The role that magnetic islands play in electron energization during reconnection remains an open question.

In this article, we use two-and-half dimensional electromagnetic particle-in-cell (PIC) code to study the electric field structure inside a secondary island in the reconnection diffusion region. We find intense electric fields inside the island, with magnitudes consistent with satellite observations. Furthermore, we evaluate the different terms in the generalized Ohm’s law in order to understand the nature of the intense electric fields.

II. SIMULATION MODEL

Our two-and-half dimensional fully electromagnetic relativistic PIC code treats ions and electrons as individual particles using a fully kinetic model. We solve the full set of Maxwell equations to advance electromagnetic fields with time, and the Newton-Lorentz equations to advance particles. The Poisson equation is satisfied by exactly solving the charge conservation equation.\(^{15}\) Periodic boundary conditions are employed in the x and z directions for both particles and fields. In the y direction, we set \(\partial\Psi/\partial y = 0\). This code successfully models the separatrix dynamics during reconnection.\(^{16}\)

The initial magnetic field is given by two Harris current sheets,

\[
B_z = B_0 \text{tanh} \left( \frac{(z - L_z/4)}{L_0} \right) - B_0 \text{tanh} \left( \frac{(z - 3L_z/4)}{L_0} \right) - B_0,
\]

where \(B_0\) is the asymptotic magnetic field, \(L_z\) is the length in z direction, and \(L_0\) is the initial half-width of the current sheet, which is set to 1.0, where \(d_i = c/\alpha_{pi}\) is the initial ion inertial length in the central current sheet. The two current sheets model is chosen because it reproduces the large values of the tearing mode stability parameter \(\Lambda\) that characterizes the long wavelength limit of reconnection in a single current slab and does not exhibit artificial saturation due to conducting boundaries.\(^{17}\) Other parameters used for this simulation include: \(\omega_{ci} \Delta t = 0.00075\), \(\omega_{pe}/\omega_{ce} = 2\), \(c/V_A = 20\), and \(n_0/n_i = 0.2\), where \(\omega_{ci}\) is the ion cyclotron frequency, \(\omega_{ce}\) is the electron cyclotron frequency, \(\omega_{pe}\) is the electron plasma frequency, \(c\) is the speed of light, \(V_A\) is the Alfvén speed based on the asymptotic magnetic field and plasma density in the central current sheet \(n_0\), and \(n_i\) is the background plasma density. The resulting magnetic field is normalized by \(B_0\), the plasma density is normalized by \(n_0\), the electric field is normalized by \(B_0V_A\), and the velocity is normalized by \(V_A\). No initial guide field is imposed on the system. An initial flux perturbation is introduced in order to make the system enter the nonlinear stage quickly.

We use an artificial mass ratio \(m_i/m_e = 100\) due to computational limitations. To eliminate the boundary effect as much as possible, we use a large simulation box having a physical size of 100c/\(\alpha_{pi}\) in the x direction and 50c/\(\alpha_{pi}\) in the z direction, which is equivalent to 4000 \times 2000 grids. To reduce numerical noise, we set the initial number of electron-ion pairs at 600 million, resulting in an average number density of 75 per cell. The initial number density in the current sheet exceeds 300 per cell.

III. SIMULATION RESULTS

For convenience and symmetry reasons, we show only the results of the lower current sheet. In addition, we shifted the z coordinate by \(-12.5c/\alpha_{pi}\) in order to set the z coordinate of the neutral sheet to \(z = 0\), and the x coordinate by \(+25c/\alpha_{pi}\) in order to place the X-line in the center of the simulation region. Figure 1 shows the reconnected flux and the reconnection rate as a function of time. The reconnected flux is calculated from \(\Psi = \max(A_y) - \min(A_y)\) along \(z = 0\), where \(A_y\) is the y component of vector potential. The reconnection rate is defined as \(E_x = <\partial\Psi/\partial t>\), where \(<\cdot\>\) is the time average over \(\pm 0.2\omega_{ci}\) to reduce high frequency noise. We see that the reconnected flux keeps growing until the end of the simulation at about \(t_{\omega_{ci}} = 100\). The maximum reconnection rate reaches about 0.22 at \(t_{\omega_{ci}} = 63\) and then decreases to the saturation value at about 0.16; it increases again at \(t_{\omega_{ci}} = 80\) and then decreases to 0.16. The fast reconnection rate of 0.16 is consistent with recent large-scale kinetic simulation results.\(^{17}\) The decrease in the reconnection rate between \(t_{\omega_{ci}} = 63\) and \(t_{\omega_{ci}} = 80\) is due to the stretching of electron diffusion region. The sudden increase in the reconnection rate at about \(t_{\omega_{ci}} = 80\) is associated with the formation of a secondary island in the central diffusion region, as shown below.

To illustrate how the reconnection proceeds, we show the evolution of the out-of-plane current density \(j_y\) and the in-plane magnetic field lines at different times. In Fig. 2, the magnetic field points in the \(+x\) direction above the current sheet and in the \(-x\) direction below it. At \(t_{\omega_{ci}} = 45\), when the reconnected flux is low (see Fig. 1), a relatively thicker current sheet with half width of \(\sim 1.0c/\alpha_{pi}\) thins at two locations (\(x \approx 44c/\alpha_{pi}\) and \(x \approx 54c/\alpha_{pi}\)) to half width of...
X-lines. Moreover, the island moves with a speed of 0.2VA
respectively. The stretched current sheet is broken, so the
maximum of the Hall magnetic field By outside the island is
about 0.25B0, which is much larger than the Hall magnetic
field is the polarization electric field in the Hall region.\textsuperscript{18}
Away from the diffusion region, where the fluxes accumulate (manifested by |Bz| enhancement), there are electric field enhancements, with negative Ex on the right and negative Ex on the left.

To understand the nature of the intense electric field inside the island, we determine the values of different terms in the generalized Ohm’s law. The generalized Ohm’s law is shown in the following equation:

\[
\vec{E} = -\nabla \times \vec{B} + \frac{j}{n_e} \times \vec{B} \frac{\nabla}{n_e} \cdot \vec{P}_e \frac{m_e}{e} \frac{d\vec{v}_e}{dt} + \eta \vec{j}.
\]  

Right-hand side terms include the convective term, the Hall term, the divergence of electron pressure tensor, the inertial term, and the resistivity term, respectively. In our simulation, we evaluate the former four terms. The electron pressure tensor P_e is evaluated in particle simulation using the formula given in Ref. 19.

From Fig. 3(c), we can see that Ex is primarily balanced by the Hall term, i.e., (j \times B)/ne, inside the secondary island, whereas the divergence of electron pressure tensor contributes to less than 15% of the total electric field. Other terms in the generalized Ohm’s law are negligible. Expanding the Hall term we get \(j \times B = \frac{1}{n_e} \frac{d}{dt} \int \nabla E \cdot dv e\). Inside the island, j=Bz is large because of the strong out-of-plane current in the central island (Fig. 2(c)). The outward electron pressure gradient force is due to the electron density enhancement inside the island, where electrons are trapped by the closed geometry of the magnetic field lines.

\[\begin{align*}
&\text{FIG. 2. Out-of-plane current density } j_y \text{ (color coding), superposed on the in-} \\
&\text{plane magnetic field lines (black line), in the } x-z \text{ plane at three different} \\
&\text{times (a) } t_{\omega ci}=45, \text{ (b) } t_{\omega ci}=76, \text{ and (c) } t_{\omega ci}=92. \text{ (d) out-of-plane magnetic} \\
&\text{field } B_y \text{ (color coding), superposed on the in-plane magnetic field lines} \\
&\text{(black line) in the } x-z \text{ plane at } t_{\omega ci}=92. \text{ The } j_y \text{ value is normalized by } n_0 V_A. \text{The } j_y \text{ and } B_y \text{ values are averaged in a } +2c_0^2 \text{ window in order to} \\
&\text{reduce high frequency noise.}
\end{align*}\]

\[\begin{align*}
&\text{FIG. 3. (a) Electric field } E_x \text{ in the } x-z \text{ plane at time } t_{\omega ci}=92. \text{ (b) Magnetic} \\
&\text{field } B_z \text{ along the line given by } z=0 \text{ (red dashed line in panel (a)). (c) Electric} \\
&\text{field } E_y \text{ (black) and the different terms in the generalized Ohm’s law} \\
&\text{along the line given by } z=0. \text{ Colors representing each term are listed beside} \\
&\text{the panel (c).}
\end{align*}\]
Figure 4 displays the normal component $E_z$. Similar to $E_x$, the strongest $E_z$ is localized inside the island. The polarity of $E_z$ is the same as the Hall electric field in the diffusion region, which points toward the mid-plane. Figure 4(b) compares $E_z$ inside the island with that in the diffusion region, but lying outside the island. Across the thin current sheet in the vicinity of left X-line, $E_z$ forms a bipolar structure with a magnitude of about $0.8B_0V_A$, which is close to the typical Hall electric field in the normal direction observed in the diffusion region. However, $E_z$ inside the island reaches up to $3.0B_0V_A$. Very close to the neutral sheet ($|z| < 0.6c/\alpha_{Te}$), $E_z$ is primarily given by the Hall term. Away from the neutral sheet ($0.6c/\alpha_{Te} < |z| < 2.8c/\alpha_{Te}$), $E_z$ is primarily balanced by a combination of the Hall term, $\nabla \cdot \mathbf{P}_e/\epsilon_e$ term, and the convective term. The Hall term is in the opposite direction from the other two terms, with a magnitude about 3 times the sum of the other two terms. Further away, $E_z$ is given by the Hall term again. The $(j \times \mathbf{B})_z = j_xB_y - j_yB_x$ and $B_y$ are small along the line cross the center of the island, so the Hall term is dominated by $j_yB_x$.

The above analysis indicates that a strong $j_y$ is the main factor generating the intense electric fields $E_x$ and $E_z$ inside the island. Figure 5(a) shows that the strong $j_y$ current inside the island is mainly produced by electrons instead of ions. This intense electron current forms because electrons are accelerated in the $-y$ direction inside the island. Figure 5(b) shows that electrons can be accelerated to a bulk velocity of $8V_A$, which is $80\%$ of the electron Alfvén speed. The mechanism by which the electrons are accelerated inside the island is not the main concern of this paper. Detailed discussions about electron acceleration in secondary islands are found in Refs. 12 and 13. Ion flow shows a strange tri-polar structure that lies vertically across the island. At the center of island, ions flow in the $-y$ direction, which is opposite to the net current direction.

The out-of-plane electric field $E_y$ inside the island at $t\omega_e = 92$ is shown in Fig. 6. Unlike $E_x$ and $E_z$, the strongest $E_y$ is concentrated in the flux pileup region downstream of the X-line, where the electric field is mostly the convective electric field carried by fast plasma flow. One feature is that $E_y$ reverses sign across the island. It is negative corresponding to the negative $B_z$ and positive corresponding to the positive $B_z$. The magnitude of negative $E_y$ is less than that of positive $E_y$. Furthermore, $E_y$ inside the island is primarily balanced by the combination of the convective and Hall terms. Because $B_x = 0$ at $z = 0$, the convective term is due mostly to $v_xB_z$ and the Hall term is due mostly to $-j_xB_z$. On the right half of the island, where $B_z < 0$, $v_x$ is positive and $j_x$ is negative (not shown) and the resulting $E_y$ is negative. On the left half of the island, where $B_z > 0$, positive $E_y$ is balanced by a combination of the convective and Hall terms. The convective term is always positive, while the Hall term

FIG. 4. (a) Electric field $E_z$ in the x-z plane at time $t\omega_e = 92$. (b) Electric field $E_y$ along two vertical lines given by $x = 46$ and $x = 55$. (c) Electric field $E_y$ and the different terms in the generalized Ohm’s law along the line given by $x = 55$. 
changes from negative to positive going from right to left because $j_x$ reverses sign. We note that at the two X-lines, $E_y$ is primarily balanced by the divergence of electron pressure tensor, which is consistent with previous studies.1,7,17

IV. DISCUSSION AND CONCLUSION

As we mentioned in Sec. I, intense electric fields, $E_x$ and $E_z$ ($\sim$100 mV/m), have been observed in a secondary island.8 Given that the lobe magnetic field strength $|B|$ is $\sim$25 nT and the plasma sheet plasma density $n_0$ is $\sim$0.1/cm$^3$ in that case, the electric field inside the island is $E \sim 2.5B_0V_A$. Below, we compare the spacecraft observation through the secondary island with our simulation. The secondary island width observed by the spacecraft is 10–20$c$/c, which is consistent with the observed range. The spacecraft traveled through the island slightly below the current sheet (Fig. 11 in Ref. 8), where $|B_t| \sim 5$ nT $\sim 0.2B_0$, which is about 0.2$c$/c below the neutral sheet in the simulation. Figure 7 shows the three components of electric field and the magnetic fields $B_x$ and $B_y$ along the line at $z = -0.2c$/c, which mimics the spacecraft trajectory through the island as described by Eastwood et al.8 The virtual spacecraft moves from right to left, i.e., toward the $-x$ direction. From right to left, $B_z$ shows a bipolar structure that changes from negative to positive polarity, consistent with the spacecraft observation. Inside the island, $B_x$ does not show any enhancement, which contrasts with the observed island having a strong core field $B_x$. The core field $B_x$ in the observed island might be due to the compression of the small guide field, which is not included in the simulation. Furthermore, our simulation neglects the third direction variation, which is considered to be important for the generation of core field inside plasmoid.21 Near the reversal point where $B_x \sim 0$, $E_z$ shows a strong peak with a magnitude of $2.5B_0V_A$. The $E_y$ field has a bipolar structure across the island, but its magnitude is less than that observed. The spacecraft observation shows that $E_x$ has a quadrupolar structure inside the island, with maximum amplitude of about 100 mV/m $\sim 2.5B_0V_A$. Although our simulation reproduces similar magnitude for $E_x$, the polarity change is not consistent with the observation.

The in-plane electric fields pointing toward the center of island form a potential well. This is similar to the electric field structure reported in Oka et al., but with a much larger

FIG. 5. (a) Out-of-plane ion (black) and electron (red) flow, and net current density (black dashed) along the line given by $x = 55$. (b) Electron bulk velocity $v_{ye}$ along the line given by $x = 55$.

FIG. 6. Similar to Figure 3 except for $E_y$.
magnitude. The stronger electric field inevitably increases the threshold velocity of trapped electrons as suggested by Oka et al.\textsuperscript{13} The trapping condition is given by

$$ |v_j| > \frac{E_x}{E_z}. $$

(3)

Based on this, we determined the trapping velocity was about $5V_A$ in our simulation. Nevertheless, the island surfing mechanism likely still works in the island, since the pre-acceleration of electrons at X-line could energize electrons to above the threshold trapping velocity.\textsuperscript{18} We indeed found energetic electrons inside the island in our simulation, with an average energy up to 0.35$m_e$c\textsuperscript{2} (not shown). It should be noted that the strong in-plane electric fields probably do not contribute directly to electron acceleration inside the island. As shown by Oka et al.,\textsuperscript{13} electrons are accelerated mostly in the $-\gamma$ direction by $E_{\gamma}$.

The parallel electric field $E_{\|} = E \cdot b$ is shown in Fig. 8. Strong parallel electric fields are evident by the dark red or blue colors. The strong parallel electric fields are mainly inside the island and at the two X-lines bounding the island. The parallel electric fields form two thin sheets, with opposite signs slightly above and below the neutral sheet around the X-lines. The sheets extend about $8c/\rho_{pi}$ in the $x$ direction. Such a parallel electric field structure was also found in a recent kinetic simulation using realistic hydrogen to electron mass ratio.\textsuperscript{22} At the island, parallel electric fields are concentrated around the island center, forming a quadrupolar structure. Their magnitude decreases as the distance from the center decreases. The largest amplitude of $E_{\|}$ is about 0.3$B_0V_A$. This suggests that great care should be exercised before estimating the third component of electric field by assuming $E \cdot B = 0$ in secondary islands. The parallel electric field inside the secondary island is due to the strong cancellation between the in-plane electric fields $E_{b_x}$ and $E_{b_y}$.

The contribution from $E_{b_x}$ is significantly small compared with the other two terms, as shown in Fig. 8(b). Here, $b_x$, $b_y$, and $b_z$ are the three components of the unit vectors of the magnetic fields.

In conclusion, we modeled the electric field structure inside the secondary island in the diffusion region by using large-scale two-and-half dimensional PIC simulation. The magnitudes of the in-plane electric fields $E_x$ and $E_z$ inside the island are larger than those outside the island in the diffusion region. Their maximum magnitude is about 3 times $B_0V_A$. The $E_x$ field inside the secondary island is primarily balanced by the Hall term $(j \times B)/ne$, while $E_z$ is balanced by a combination of the $(j \times B)/ne, -(\nu \times B)$, and $\nabla \cdot (P_z/ne)$ terms, with the $(j \times B)/ne$ term dominating. The large Hall electric field is due to the large out-of-plane current density $j_z$ inside the island, which is mainly produced by accelerated electrons forming a strong bulk flow in the $-\gamma$ direction. The $E_x$ field shows a bipolar structure across the island, with negative $E_x$ corresponding to negative $B_z$ and positive $E_x$ corresponding to positive $B_z$. It is given by $(j \times B)/ne$ and the convective electric field. There are significant parallel electric fields, forming a quadrupolar structure inside the island, with maximum amplitude of about 0.3$B_0V_A$. Our simulation results could explain the intense electric fields inside the secondary island observed in the Earth’s magnetosphere. They are also helpful in understanding the role of secondary islands in the reconnection process.

**ACKNOWLEDGMENTS**

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\begin{table}
\centering
\begin{tabular}{|c|c|}
\hline
$E_{\|}$ & $E_{b_x}$, $E_{b_y}$, $E_{b_z}$, and $E_{\gamma}$ (magenta) along the line given by $z = -0.2$. \\
\hline
\end{tabular}
\caption{Parallel electric field $E_{\|}$ (color coding), superposed on the in-plane magnetic field lines (black line), in the $x-z$ plane at $t_{0.8} = 92$. The $E_{\|}$ values are averaged in a $\pm 0.2\alpha_{ci}$ window in order to reduce high frequency noise.}
\end{table}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure8}
\caption{(a) Parallel electric field $E_{\|}$ (color coding), superposed on the in-plane magnetic field lines (black line), in the $x-z$ plane at $t_{0.8} = 92$. The $E_{\|}$ values are averaged in a $\pm 0.2\alpha_{ci}$ window in order to reduce high frequency noise. (b) $E_{b_x}$ (black), $E_{b_y}$ (red), $E_{b_z}$ (blue), and $E_{\gamma}$ (magenta) along the line given by $z = -0.2$.}
\end{figure}

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