Numerical Simulations of Magnetic Reconnection in an Asymmetric Current Sheet *

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Previous particle-in-cell simulations have shown that electron phase-space holes (electron holes), where the associated parallel electric field has a bipolar structure, exist near the four separatrices in anti-parallel magnetic reconnection. By performing two-dimensional (2-D) particle-in-cell (PIC) simulations, here we investigate magnetic reconnection in an asymmetric current sheet, with emphasis on the parallel electric field near the separatrices. Compared with magnetic reconnection in a symmetric current sheet, it is found that the parallel electric field with a bipolar structure only exists around the separatrices in the upper region with a lower density (upper separatrices). Such a bipolar structure of the parallel electric field is considered to be associated with electron holes resulting from the nonlinear evolution of the electron beam instability excited by the high-speed electron flow formed after their acceleration around the X line. The disappearance of the parallel electric field around the separatrices in the lower region with a higher density (lower separatrices) may be due to the transverse instability, which is unstable in a weak magnetized plasma.

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Magnetic reconnection rapidly converts magnetic energy into plasma energy,[1,2] which is used to explain many explosive phenomena in space and laboratory plasma, such as solar flares, magnetospheric substorms and tokamak disruptions.[3−7] The structure of anti-parallel collisionless reconnection in a symmetric current sheet has been thoroughly studied.[8−11] In an ion diffusion region, ions are demagnetized, while electrons are magnetized and move toward the X line along the separatrices because of the effect of the magnetic mirror. These electrons are accelerated after they reach the vicinity of the X line, and then directed away from the X line along the magnetic field lines just inside the separatrices. The resulting Hall currents are directed toward the X line along the magnetic field lines just inside the separatrices and away from the X line along the separatrices, which leads to the quadrupolar structure of the out-of-plane magnetic field.[12−14] At the same time, the Hall electric field, which points toward the center of the current sheet,[15−17] and electron phase-space holes (electron holes) with a bipolar structure of the parallel electric field, are also formed around the four separatrices.[18,19] These electron holes are considered to be generated during the nonlinear evolution of the electron beam instability, which is excited by the electron beam around the separatrices.[20,21] The structures of both the magnetic field and electric field during anti-parallel magnetic reconnection in a symmetric current sheet have a good symmetry.

However, magnetic reconnection may also occur at an asymmetric current sheet. For example, magnetic reconnection at the earth's magnetopause occurs between two topologically distinct regions with quite different properties, such as the magnetic field and plasma density.[22] Cassak and Shay[23] obtained scaling relations predicting asymmetric reconnection properties including reconnection rate, outflow speed and outflow density etc. Such a scaling theory has been verified by particle-in-cell (PIC) simulations.[24,25] Huang *et al.*[26] found that in asymmetric reconnection, intense perpendicular electrostatic structure only exists near the separatrices with lower density. In this Letter, with 2-D PIC simulations, we investigate magnetic reconnection in an asymmetric current sheet, with emphasis on electron holes with a bipolar structure of the parallel electric field near the separatrices.

We carry out 2-D PIC simulations to investigate anti-parallel collisionless magnetic reconnection in an asymmetric current sheet. In the simulation model, the electromagnetic fields are defined on the grids and updated by integrating the Maxwell equations with an explicit leapfrog algorithm, and the ions and electrons are advanced in the electromagnetic field. The initial equilibrium configuration of the asymmetric current

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in the (x,z) plane has been described by Quest and Coroniti,[27] and the initial magnetic field is given by

$$\boldsymbol{B}_0(z) = B_0[\tanh(z/\delta) + R]\boldsymbol{e}_x, \quad (1)$$

where δ is half the width of the current sheet, and $|R| < 1$.

The number density is assumed to have the form

$$n(z) = n_0[1 - \alpha_1 \tanh(z/\delta) - \alpha_2 \tanh^2(z/\delta)]. \quad (2)$$

A pressure balance $n(T_{i0} + T_{e0}) + B_{0x}^2/2\mu_0 = \text{const}$ across the current sheet should be satisfied, where T_{i0} and T_{e0} are the initial temperatures for ions and electrons, respectively. Then,

$$\alpha_2 = \frac{B_0^2/2\mu_0}{n_0(T_{i0} + T_{e0})}, \quad (3)$$

$$\alpha_1 = 2R\alpha_2. \quad (4)$$

For $R = 0$ and $\alpha_2 = 1$, one recovers the symmetric Harris current sheet.

The initial distribution function of ions and electrons is Maxwellian. The current is supported by the drift speeds of the ions and electrons, which correspond to the part $\alpha_2 n_0 \sec h^2(z/\delta)$ in the number density. The drift speeds satisfy the equation $V_{i0}/V_{e0} = -T_{i0}/T_{e0}$, where V_{i0} (V_{e0}) and T_{i0} (T_{e0}) are the initial drift speed and temperature of the ions (electrons), respectively. In our simulation, we set $T_{i0}/T_{e0} = 4$. The initial half width of the Harris current sheet is $\delta = 0.5c/\omega_{pi}$, where c/ω_{pi} is the ion inertial length defined by n_0. The mass ratio m_i/m_e is chosen to be 64. The light speed is $c = 15v_{\rm A}$, where $v_{\rm A}$ is the Alfven speed based on B_0 and n_0.

The computation is carried out in a rectangular domain in the (x, z) plane with the dimension $L_x \times L_z = (25.6c/\omega_{pi}) \times (12.8c/\omega_{pi})$. The grid number is $N_x \times N_z = 512 \times 256$. The time step is $\varOmega_i t = 0.001$, where $\varOmega_i = eB_0/m_i$ is the ion gyrofrequency. We employ more than 5×10^7 particles per species to simulate the plasma. The periodic boundary conditions are used along the x direction; at the same time, ideal conducting boundary conditions for the electromagnetic fields and reflected boundary conditions for particles are used in the z direction. In order to make the system enter the nonlinear stage quickly, the initial current sheet is modified by including an initial flux perturbation.

We run two cases in total, and their parameters are listed in Table 1. Run 1 is anti-parallel reconnection in a symmetric current sheet, and run 2 is anti-parallel reconnection in an asymmetric current sheet. In run 2, we choose $R = 1/5$, $\alpha_1 = 5/12$, and $\alpha_2 = 25/42$. The profile of the magnetic field B_{x0} and density n in the asymmetric current sheet is plotted in Fig. 1. Such a profile is commonly observed across the magnetopause boundary layer.[28] In the asymmetric current sheet, $B_{x0} = 0$ at $z = -0.1c/\omega_{pi}$.

Table 1. The summary of parameters in runs 1 and 2.

Run	R	α_1	α_2
1	0	0	1
2	1/5	5/12	25/42

Figure 2 shows the time evolution of the reconnected magnetic flux $\Delta\psi$ for runs 1 and 2. Here the magnetic flux $\Delta\psi$ is defined as the flux difference between the X and O lines, and its slope can be regarded as an indicator of the magnetic reconnection rate. Similar to previous simulations,[29] the asymmetric current sheet can lead to the decrease of the reconnection rate.

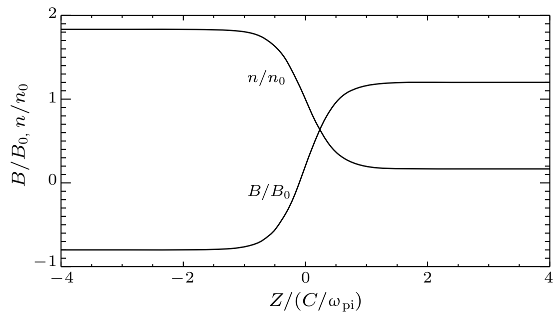

Fig. 1. The profile of the magnetic field B_{x0} and density n in the asymmetric current sheet.

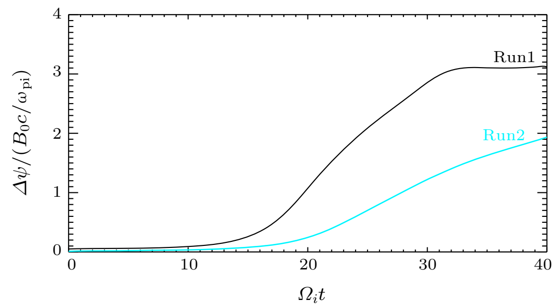

Fig. 2. The time evolution of the reconnected magnetic flux $\Delta\psi$ for runs 1 and 2. The black line represents the symmetric current sheet and the blue line represents the asymmetric current sheet.

Figure 3 plots the contours of the y component of the magnetic field B_y, the parallel electric field $E_{||} = E \cdot B/B$, and the perpendicular electric field $E_{\perp} = |E - E_{||}B/B|$ at (a) $\varOmega_i t = 30$ for run 1, and (b) $\varOmega_i t = 31.5$ for run 2. For reference, the magnetic field lines are also plotted in the figure. In run 1, in the diffusion region around the X line, a characteristic quadrupole structure of the out-of-plane magnetic field B_y is observed in the diffusion region around the X line. Such a structure is considered to be one of the key signatures of collisionless magnetic reconnection, and has been thoroughly investigated by simulations and satellite observations.[30−32] At the same time, we can find the existence of the parallel and perpendicular electric field around four separatrices. The perpendicular electric field is also considered as the key signature of the Hall effect. Around the separatrices, electrons are magnetized and move along the magnetic field lines, while ions are unmagnetized and can cross the magnetic field lines. This leads to the charge separation around the separatrices and results in the existence of the perpendicular electric field. The parallel electric field around the separatrices has a bipolar structure, which is the exhibition of electron holes. Different from run 1, the out-of-plane magnetic field in run 2 has a negative value in the left side of the X line, while it has a positive value in the right side of the X line. This pattern of out-of-plane magnetic field as the characteristic structure has also been observed in previous works.[24,29] Both the perpendicular electric field and the bipolar structure of the parallel electric field only exist around the separatrices in the upper region with lower density (upper separatrices), as demonstrated by Huang *et al.*[26]

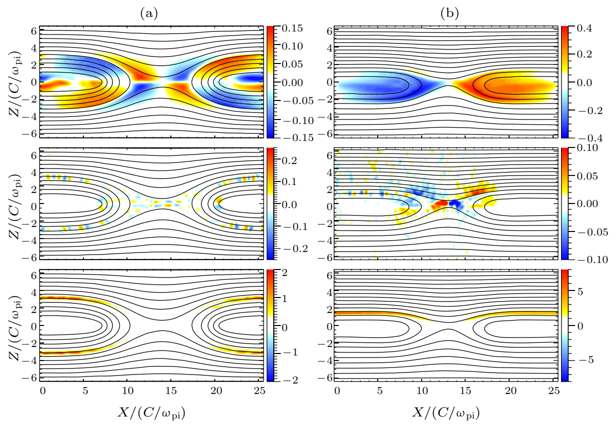

Fig. 3. From the top to the bottom, the contours of the y component of the magnetic field B_y, the parallel electric field $E_{||} = \boldsymbol{E}\cdot\boldsymbol{B}/B$, and the perpendicular electric field $E_{\perp} = |\boldsymbol{E} - E_{||}\boldsymbol{B}/B|$ at (a) $\Omega_i t = 30$ for run 1, and (b) $\Omega_i t = 31.5$ for run 2. For reference, the magnetic field lines are also plotted in the figure.

The generation of these electron holes around the separatrices is considered to the results of the nonlinear evolution of the electron beam instability. Figure 4 depicts the electron velocity along the in-plane magnetic field $V_{e||} = V_e \cdot B'/B'$ (where $B' = B_x e_x + B_z e_z$) at (a) $\Omega_i t = 30$ for run 1, and (b) $\Omega_i t = 31.5$ for run 2. For reference, the magnetic field lines are also plotted in the figure. High-speed electron flow along the magnetic field lines can be obviously identified around the separatrices. In run 1, the electrons flow away from the X line along the magnetic field lines after they are accelerated around the X line. In run 2, the electrons flow toward the X line along the magnetic field lines around the separatrices in the lower region with higher density (lower separatrices), and they flow away from the X line along the magnetic field lines around the two upper separatrices. However, in run 2, the magnetic field around the lower two separatrices is weaker, electron holes may be unstable to the transverse instability. The transverse instability in electron holes proposed by Muschietti *et al.*[33,34] is due to the dynamics of the electrons trapped in the electron holes and is a self-focusing type of instability. Perturbations in electron holes can produce transverse gradients of the electric potential. Such transverse gradients focus the trapped electrons into regions that already have a surplus of electrons, which results in larger transverse gradients and more focusing until the transverse instability finally occurs. Such a process has also been confirmed by self-consistent PIC simulations.[35−37] Therefore, we cannot observe the bipolar structure of the parallel electric field around the lower separatrices in run 2.

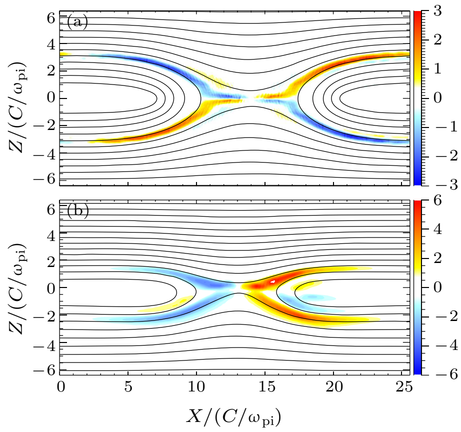

Fig. 4. The electron bulk velocity along the in-plane magnetic field $V_{e||} = \boldsymbol{V}_e\cdot\boldsymbol{B}'/B'$ ($\boldsymbol{B}' = B_x\boldsymbol{e}_x + B_z\boldsymbol{e}_z$) at (a) $\Omega_i t = 30$ for run 1, and (b) $\Omega_i t = 31.5$ for run 2. For reference, the magnetic field lines are also plotted in the figure.

In summary, by performing 2-D PIC simulations, we have investigated magnetic reconnection in an asymmetric current sheet. Compared with magnetic reconnection in a symmetric current sheet, there is no characteristic quadrupole structure of the out-of-plane magnetic field in the diffusion region. The out-of-plane magnetic field has a negative value on the left side of the X line, and a positive value on the right side of the X line. Electron holes with a bipolar structure of the parallel electric field exist in the two upper separatrices, which is considered to the nonlinear evolution of the electron beam instability excited by the high-speed electron flow after they are accelerated around the X line. We do not find the existence of the parallel electric field in the lower separatrices. The reason for this may be the excitation of the transverse instability in a weak magnetized plasma in the lower part of the asymmetric current sheet. We also find that even a small asymmetry will lead to the disappearance of electron holes in the lower separatrices, and the variation of the asymmetry will not change our conclusion.

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