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Electron Acceleration in Collisionless Magnetic Reconnection *

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A $2\frac{1}{2}$-dimensional electromagnetic particle-in-cell (PIC) simulation code is used to investigate the electron acceleration in collisionless magnetic reconnection. The results show that the electrons are accelerated in the diffusion region near the X point, and the acceleration process can be roughly divided into two procedures: firstly the electrons are accelerated in the z direction due to the electric field in the negative z direction. Then the electrons gyrate surrounding the magnetic field with the action of the Lorentz force, through this procedure the electrons reach higher velocity in the x direction and then flow out of the diffusion region. After being accelerated away from the diffusion region, part of electrons is trapped near the O point, and the other part of electrons flows into plasma sheet boundary layer along the magnetic field.

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Magnetic reconnection is a fundamental plasma transport process which plays an important role in Earth's magnetosphere, solar corona, and laboratory plasma,[1,2] it can rapidly convert magnetic energy into kinetic and thermal energy of electrons and ions. However, much of the previous work has focused on understanding how fast magnetic field energy dissipates, and the energy conversion from the magnetic field into the particle energy has been debated.[3,4] The Hall effect plays an important role in the magnetic reconnection at the scale lengths c/ω_{pi} (c and ω_{pi} are the light speed in vacuum and the ion plasma frequency respectively). At scale lengths between c/ω_{pi} and c/ω_{pe} (ω_{pe} is the electron plasma frequency), ions are not frozen to the magnetic field and the motion of electrons and ions decouple.[2] At the scale lengths smaller than c/ω_{pe}, even electrons are not frozen to the magnetic field. However, less attention is paid to the electron dynamics at this scale length. Recent studies show that the electron acceleration and heating are important signatures of magnetic reconnection, and many physical phenomena have been thought to be related to the energetic electrons accelerated in the magnetic reconnection, such as bursts of energetic electrons in the magnetotail and x-ray observations in solar flares.[5,6] Considerable efforts have been devoted to understanding the electron dynamics in the magnetic reconnection using analytical arguments,[7,8] test particles theory,[9] and the inductive electric field near the x-type neutral line is considered to play an important role in the collisionless acceleration of electrons. Recently, electron dynamics in the magnetic reconnection are investigated with self-consistent particle simulations. However in their research the plasma $\beta \sim 1$ are used, the electrons are also accelerated owing to the ∇B drift and the curvature drift in the stronger magnetic field region after they are accelerated near the x-shaped line.[10] In this Letter, with a $2\frac{1}{2}$-dimensional electromagnetic PIC simulation code we study electron acceleration in collisionless magnetic reconnection by following two typical electron trajectories in the current sheet. In the simulation, we choose the plasma $\beta \ll 1$.

In the particle simulations, the electromagnetic fields are defined in grids, and they are updated by the Maxwell equations while the ions and electrons are taken as discrete particles and advanced in the electromagnetic fields according to their equations of motion.[11] In our particle simulation code, the electromagnetic fields are calculated with a full explicit algorithm, and the relativistic effect is included in the motion of the particles.

We choose the Harris neutral sheet equilibrium as the initial configuration in the simulations, where the magnetic field can be expressed as $\boldsymbol{B} = B_{0x}(y)\boldsymbol{x}$, and

$$B_{0x}(y) = B_0 \tanh((y - y_0)/w), \tag{1}$$

where B_0 is the asymptotic magnetic field, and w is the half-width of current sheet, y_0 is the center of current sheet. The proton and electron densities read

$$n(y) = n_c \mathrm{sech}^2((y - y_0)/w) + n_0, \tag{2}$$

where n_c and n_0 represent the current sheet and background densities, which correspond to Harris and background particles, respectively. The Harris particles drift in the z direction, and the drift speeds of the electrons and protons satisfy $V_{e0}/V_{i0} = -T_{e0}/T_{i0}$ with T_{i0} and T_{e0} being the uniform temperatures of

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** To whom correspondence should be addressed. Email: qmlu@ustc.edu.cn the protons and electrons. Both the background electrons and protons have no drift speed, and their temperatures are the same as their corresponding Harris particles.

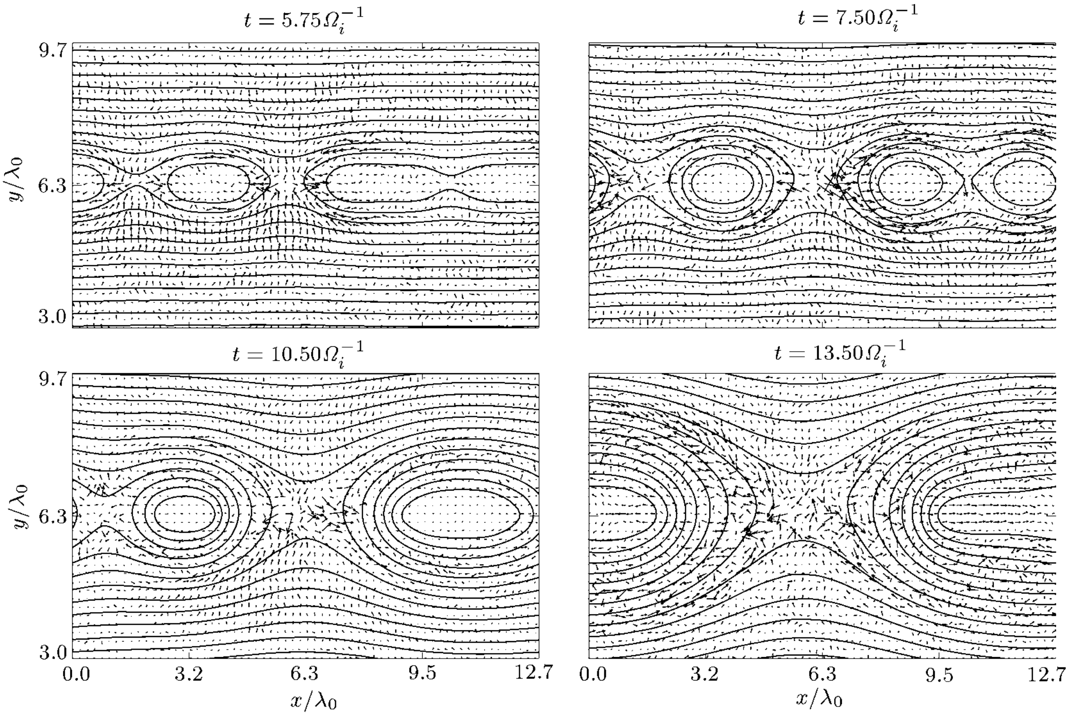

Fig. 1. The in-plane electron flows and magnetic field lines at different time, where the solid lines and arrows represent the magnetic field lines and electron flow velocities, respectively.

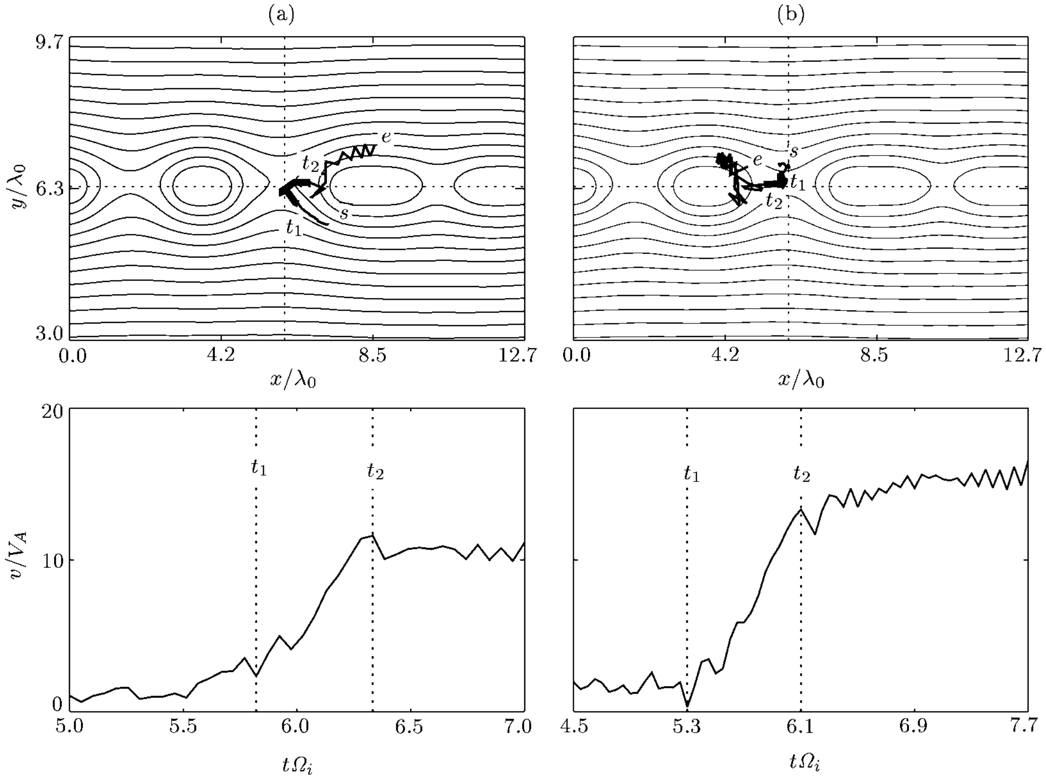

Fig. 2. The typical electron trajectories and the evolutions of their velocities $v = \sqrt{v_x^2 + v_y^2 + v_z^2}/V_A$ with time, the magnetic field lines at time t_2 are also shown in the upper panel. The left panel is for the first electron, and the right panel is for the second electron. Here s and e denote the start and end positions of the electron. The time between t_1 and t_2 denotes the period when the electron is in the diffusion region.

The half-width of the current sheet is $w = 0.5c/\omega_{pi}$, and its centre is located at $y_0 = 6.4\lambda_0$, where $\lambda_0 = c/\omega_{pi}$ is the ion inertial length defined on the background density n_0. The peak Harris density $n_c = 10n_0$, and the ratio of proton to electron temperature is $T_{i0}/T_{e0} = 6$. The mass ratio is $m_i/m_e = 64$, and the plasma β is 0.1. We employ $N_x \times N_y = 128 \times 128$ grids, and the cell size is $\Delta x = \Delta y = 0.1c/\omega_{pi}$. The time step is taken to be $\Omega_i t = 0.001$, where Ω_i is the proton cyclotron frequency based on B_0. The speed of light is chosen to be $c/V_A = 25$, where V_A is the Alfvén speed based on B_0 and n_0. Periodic boundary conditions for particles and fields are used in the x direction. Simple wave reflection boundary conditions for electromagnetic fields are employed in the y direction, and particles are specularly reflected after they reach the boundary.

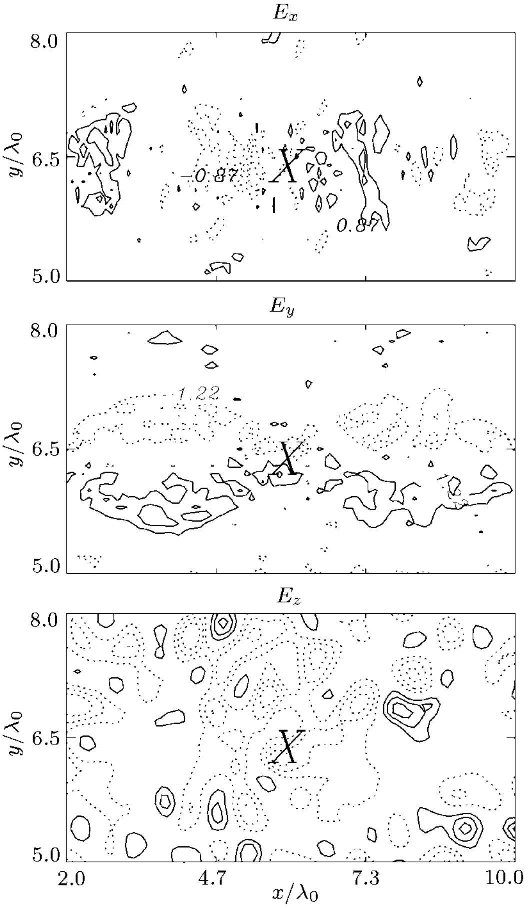

Fig. 3. From top to bottom: electric field E_x, E_y and E_z at $t = 6.1\Omega_i^{-1}$. The solid line represents the positive value while the dashed line denotes the negative value; the letter X is the neutral point.

Figure 1 shows the in-plane electron flows and magnetic field lines at different time. It can be found that the electrons are accelerated in the diffusion region near the X point, and in this region the electrons are not frozen in the magnetic fields. Then the electrons are expelled away from the X point and flow into the plasma sheet boundary layer. At larger values of $|y - y_0|$, there is a return electron flow back toward the diffusion region. In order to see clearly how the electrons are accelerated in the diffusion region, we follow two electron trajectories which cross the diffusion region, they represent two kinds of typical electron trajectories. These two typical electron trajectories are shown in Fig. 2, and the time evolutions of their velocities are also shown. They represent two types of electron trajectories that cross the diffusion region, both of them are accelerated in the diffusion region. Parts of electrons are trapped by the closed magnetic field near the O point, and these electrons oscillate in this region because they are mirrored by the close magnetic fields in plasma sheet boundary layer. Others enter the plasma sheet boundary layer after they are accelerated in the diffusion region. The exerted electric force and Lorentz force are almost balanced for these electrons, so the electrons can flow out the diffusion region along the magnetic field with almost constant velocity.

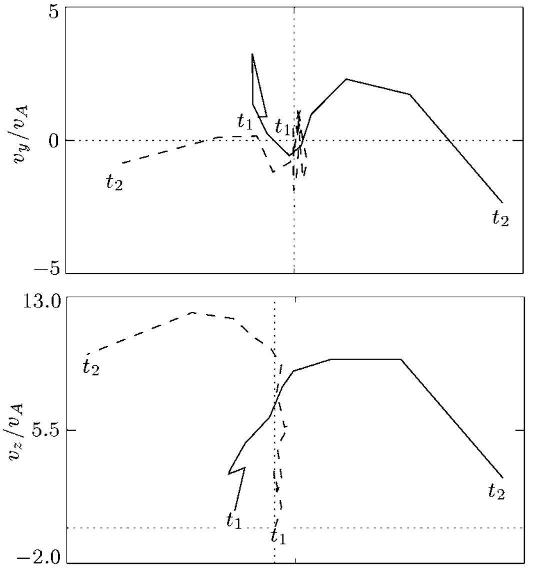

Fig. 4. The trajectories of the selected electrons between t_1 and t_2 when the electrons are in the diffusion region. The solid and dashed lines denote the two different electrons.

Figure 3 shows the spatial distributions of E_x, E_y and E_z at time $t = 6.1\Omega_i^{-1}$. Generally the electric fields can be determined by the Hall current, $E_x \sim -J_zB_y$, $E_y \sim J_zB_x$ and $E_z \sim -J_yB_x$.[3] This can explain the good symmetry of E_x and E_y in our simulations. The electric field E_z has negative value near the X point which can accelerate the electrons in the z direction. However E_x and E_y at the diffusion region are very small, and E_x decelerates electrons when electrons flow out of the diffusion region along the x direction. How the electrons obtain the velocities in the x–y plane, as shown in Fig. 4, in which we also illustrate the phase diagram of these two typical electrons in the $v_x - v_y$ and $v_x - v_z$ planes during their staying in the diffusion region. The acceleration process of the electrons can be roughly divided into two procedures. In the first procedure, the electron obtains the velocity in the z direction due to the electric field in the negative z direction near the X point. As soon as the electron leaves the diffusion region, it gyrates around the magnetic field with the action of the Lorentz force. By this procedure the electrons reach large velocities in the x direction and then flow out of the diffusion region. In our simulation, we do not find that the ∇B and curvature drift play an important role in the acceleration process of electrons which has been demonstrated by Hoshino *et al.*[10] The reason is that in our simulation, κ is much larger than 1 (κ is the square root of the ratio of the curvature radius of the magnetic field to the electron Larmor radius).

In summary, we have employed a $2\frac{1}{2}$-dimensional electromagnetic PIC simulation code to study the electron acceleration in collisionless magnetic reconnection. It is suggested that the electrons are accelerated in diffusion regions near the X point. The electrons are firstly accelerated in z direction by induced electric fields near the X point, then the velocity in the z direction is transferred into the x direction by gyration surrounding the magnetic field through the action of the Lorentz force. After expelled from the diffusion region, two typical electron trajectories can be followed: some of the electrons are trapped in the region near the O point with oscillated motion, the others flow into the plasma sheet boundary layer along the magnetic fields.

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