

Dissipation mechanism in 3D collisionless magnetic reconnection

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Abstract. Dissipation processes responsible for fast magnetic reconnection in collisionless plasma are investigated using 3D electromagnetic particle-in-cell simulations. The present study compares two simulation runs; one with small system size in the current density direction, and the other with larger system size. In the case with small system size, the reconnection processes are almost the same as those in 2D reconnection, while in the other case the drift kink mode evolves along the current density and deforms the current sheet structure drastically. Although fast reconnection is achieved in both the cases, it is found that the dissipation mechanism is very different between them. In the case without kink mode, the electrons transit the electron diffusion region without thermalization, so that the magnetic dissipation is supported by the inertia resistivity alone. On the other hand, in the kinked current sheet, the electrons are not only accelerated in bulk, but they are also partly scattered and thermalized by the kink mode, which results in the anomalous resistivity in addition to the inertia resistivity. It is discussed that in 3D reconnection the thickness of the electron current sheet becomes larger than the local electron inertia length.

1. Introduction

Magnetic reconnection is a common process in space and laboratory plasmas, releasing the energy stored in a compressed magnetic field into plasma kinetic energy. The process can change the global field line topology and cause strong acceleration of plasma particles, so that it is considered to play a key role in explosive phenomena such as geo-magnetospheric substorms and solar flares. However, these phenomena commonly occur in collisionless plasmas where the Coulomb collision frequency is so small that the magnetic dissipation is hardly generated in the classical sense. In fact, in the resistive magnetohydrodynamic (MHD) framework based on the Spitzer conductivity, the rate of reconnection is unrealistically small to explain the explosive energy release in space [1, 2]. In order to enhance the reconnection rate, the usual fluid simulations that cannot treat explicitly the dissipation processes employ ad-hoc anomalous resistivity or/and numerical resistivity [3, 4, 5]. However, it has been suggested that the rate of reconnection depends on the resistivity model [3, 4] and, in the global simulations, the global response of substorms and flares is sensitive to the parameterization of the resistivity [5, 6]. These results of the fluid simulations indicate that the dissipation processes, which take place in very small region called the diffusion region formed around the magnetic X-line, can have an impact on the large-scale dynamics of reconnection and the relevant phenomena. In this context, the present study focuses on the dissipation mechanism in collisionless reconnection, using the



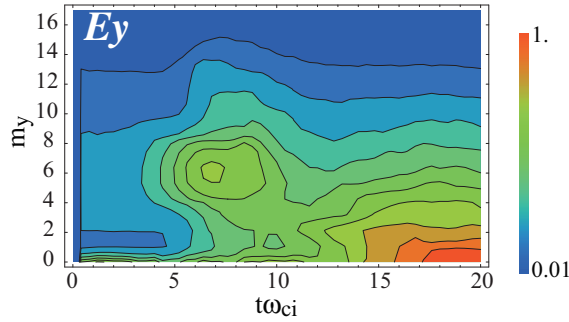


Figure 1. Time history of the wave mode amplitude for Run2 propagating in the y direction in the yz plane through the X-line.

particle-in-cell (PIC) simulations. It is found that the process in 3D reconnection is significantly different from that in 2D reconnection. In 2D case, the dissipation is totally supported by the electron momentum transport away from the X-line due to the Speiser-type motion, while in 3D case a kink mode excited along the current density causes the electron thermalization which gives rise to the electric resistivity.

2. Simulation model

The simulations are performed using an electromagnetic PIC code with the adaptive mesh refinement (AMR) and particle splitting-coalescence method [7]. The AMR technique subdivides and removes computational cells in accordance with refinement criteria so as to efficiently enhance the local spatial resolution dynamically in time. The particle splitting-coalescence method is implemented in order to control the number of particles per cell in the refinement regions. The present study examines two 3D simulations with different system size in the current density direction. The system boundaries are periodic in the x and y directions, and conducting wall in the z direction. The simulations are carried out using a Harris-type current sheet with the magnetic field $B_x(z) = -B_0 \tanh(z/L)$ and the number density $n(z) = n_{ps} \text{sech}^2(z/L) + n_b \tanh^2(z/L)$, where L is the half width of the current sheet. We choose $L = 0.5\lambda_i$ and $n_b = 0.044n_{ps}$ with λ_i the ion inertia length. The system sizes are $l_x \times l_y \times l_z = 31\lambda_i \times 1.9\lambda_i \times 31\lambda_i$ (Run1) and $31\lambda_i \times 7.7\lambda_i \times 31\lambda_i$ (Run2). The mass ratio, velocity of light, and temperature ratio are $m_i/m_e = 25$, $c/V_A = 10$, and $T_i/T_e = 5.0$, respectively. The grid spacing is set as $\Delta_{l_B} = 0.24\lambda_i$ for the base level cells and $\Delta_{l_D} = 0.03\lambda_i$ for the dynamic range level cells.

3. Simulation results

Magnetic reconnection is initiated with a small perturbation to the magnetic field, which produces the X-line in the current density direction at the center of the xz plane in the simulation domain. In both Run1 and Run2, the first growing mode has relatively short wavelength with the mode number $m_y \approx 6$ for Run2 and propagates in the direction almost perpendicular to the initial magnetic field (see figure 1). This mode is the lower hybrid drift instability (LHDI). The LHDI is driven by the diamagnetic current that is supported by the density gradient, and grows quickly around the edge of the current sheet (figure 2a). The LHDI activity modifies the current sheet structure so as to compress the current sheet, which facilitates the onset of fast reconnection. However, once the fast reconnection has been triggered, the LHDI activity is drastically suppressed around the diffusion region, because the density gradient almost

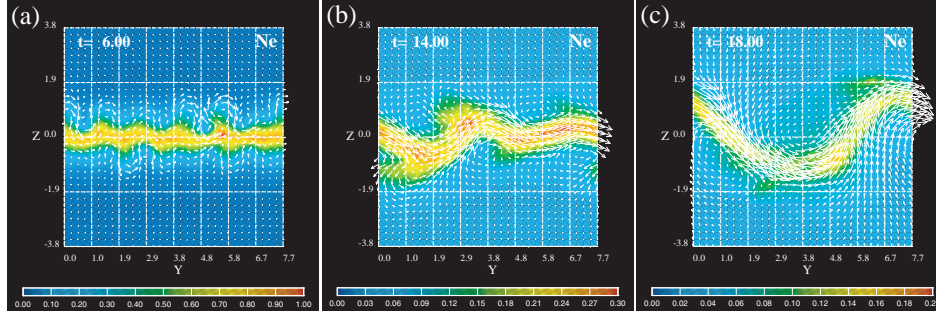


Figure 2. Electron number density for Run2 in the yz plane through the X-line at (a) $t\omega_{ci} = 6.0$, (b) $t\omega_{ci} = 14.0$, and (c) $t\omega_{ci} = 18.0$. Arrows show the electron flow vector in the plane.

disappears from the vicinity of the X-line. In Run1, because of the small system size in the y direction, the current sheet behavior is quite similar to that in 2D simulation after the onset of the fast reconnection. On the other hand, in Run2, the drift kink mode with $m_y \approx 2$ evolves along the current density (see figures 1 and 2b). This mode eventually coalesces into a large wavelength mode with $m_y = 1$ (figure 2c) as the tearing mode grows and the ion inertia scale expands in the current sheet. As shown in figure 1, the kink mode survives under reconnection (with the dc electric field), so that the magnetic dissipation proceeds in the kinked current sheet.

The reconnection electric field averaged over the X-line reaches around $E_R \approx 0.1V_{A0}B_0$ in the both the runs, where $V_{A0} = B_0/\sqrt{\mu_0 n_b m_i}$ is the Alfvén velocity in the lobe region. Nevertheless, it is found that the dissipation mechanism in the electron diffusion region is significantly different between the two cases. Figure 3 shows the evolution of the energy density in the v_y - v_z space of the electrons which were sampled in the upstream region of the electron diffusion region. In Run1 (figure 3a), once the electrons enter the electron diffusion region at $t\omega_{ci} \approx 18.0$, they are quickly accelerated in bulk due to the reconnection electric field. However, the thermal energy (dashed curve) is hardly enhanced during the acceleration. This indicates that in 2D reconnection the electrons are coherently accelerated in the electron diffusion region and the momentum gained by the reconnection electric field is transported away from the region due to the Speiser-type motion. Thus, the magnetic dissipation in Run1 is provided by the inertia resistivity alone [8, 9, 10]. On the other hand, in Run2, most electrons enter the diffusion region at $t\omega_{ci} \approx 16.6$,

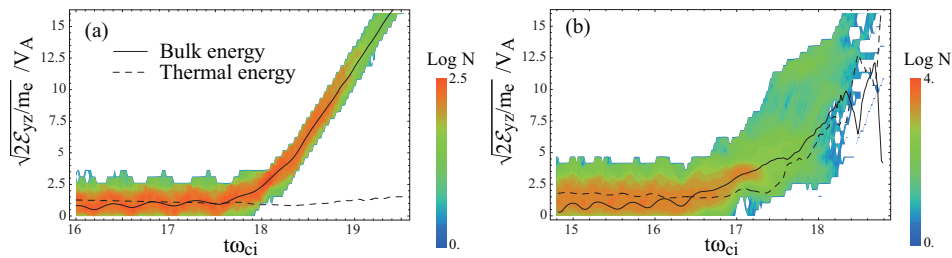


Figure 3. Time evolution of the energy density in the v_y - v_z space for the electrons which were sampled in the upstream region of the electron diffusion region. (a) is for Run1, and (b) for Run2. Solid curve represents the bulk energy of the electrons, while dashed curve denotes thermal energy.

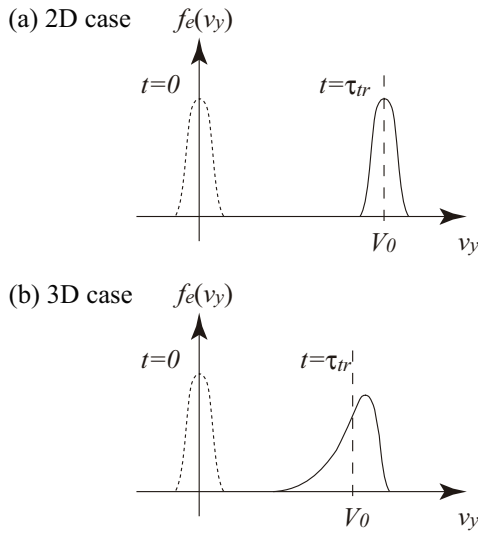


Figure 4. Schematic diagram describing the change in the electron distribution function in the electron diffusion region from $t = 0$ (when the electrons enter the electron diffusion region) till $t = \tau_{tr}$ (where τ_{tr} is the averaged transit time) for (a) 2D case and (b) 3D case.

and about 70% of them are ejected before $t\omega_{ci} \approx 17.4$ without significant thermalization, giving rise to the inertia resistivity (see figure 3b). However, a fraction of the electrons stay longer and are accelerated more around the X-line. Figure 3b shows that these electrons are not only accelerated in bulk, but they are also strongly thermalized after $t\omega_{ci} \approx 17.4$. The thermalization occurs efficiently when the high-energy particles turn the curve in the kinked current sheet. Therefore, we can conclude that the high-energy electrons are thermalized as a result of particle scattering due to the kink mode. Since the electron thermalization results in the reduction of the averaged momentum along the X-line, it causes the electric resistivity which may be called the anomalous resistivity.

4. Discussion and conclusions

The present study has investigated the dissipation mechanism in collisionless magnetic reconnection using the 3D electromagnetic PIC simulations. We have examined two simulation runs with different system size in the current density direction. In the run with larger system size, the drift kink mode evolves along the current density and reconnection proceeds in the kinked current sheet. On the other hand, in the run with smaller system size, the kink mode is not allowed to grow, so that the current sheet behavior is quite similar to the 2D case. In both the cases, a fast reconnection with $E_R \approx 0.1V_{A0}B_0$ is achieved. However, it is found that the dissipation mechanism is quite different between the two cases. In the case without the kink mode, that is, the 2D reconnection case, the electrons transit the electron diffusion region without thermalization, so that the magnetic dissipation is supported by the inertia resistivity alone. On the other hand, in the case with the kink mode, the electrons are not only accelerated in bulk, but they are also partly scattered and thermalized by the kink mode. Since the electron thermalization results in the reduction of the averaged momentum, that is, the current density, it causes the electric resistivity in addition to the inertia resistivity.

The electron behavior in the electron diffusion region is described schematically in figure 4a for the 2D case and in figure 4b for the 3D case. In the 2D case, since the electron momentum gained by the reconnection field becomes the bulk momentum totally, the bulk velocity along the X-line is provided by $V_0 = -(eE_y/m_e)\tau_{tr}$, where τ_{tr} is the averaged transit time through the electron diffusion region and is estimated as $\tau_{tr} \approx -\delta_e/V_{in}$ with δ_e the half width of the electron current sheet and V_{in} the electron inflow velocity. If we use $V_0 \approx -(1/\mu_0 en)(B_{in}/\delta_e)$ from the

Ampère's law with B_{in} the magnetic field at the inflow region and $E_y \approx -V_{in}B_{in}$, we can obtain $\delta_e \approx \lambda_e$, where λ_e is the electron inertia length. However, in the 3D case, the electrons which are accelerated by the reconnection field are partly scattered in the kinked current sheet. In this case, the bulk velocity (in absolute value) must be less than that in the 2D case under the same reconnection rate, that is, $V_0 < (e|E_y|/m_e)\tau_{tr}$, which leads to $\delta_e > \lambda_e$. Thus, in 3D reconnection where the electron scattering occurs in the electron diffusion region, the current sheet thickness should be larger than the local electron inertia length.

Acknowledgments

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