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Plasma instabilities and anomalous resistivity in the current sheet

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Abstract. The role of microscopic plasma instabilities in the current sheet in the violation of the ideal magnetohydrodynamic (MHD) condition is investigated by means of a $2\frac{1}{2}$-dimensional explicit particle simulation code. Two instabilities, lower hybrid drift instabilities (LHDIs) and drift kink instabilities (DKIs) are found to evolve in the current sheet. In the LHDI growing phase, nonlinear coupling of the fluctuations of the electric field and particle density generates the outward flow and deforms the current sheet profile. The DC electric field leading to the magnetic flux reduction and the damping of equilibrium current are observed in the DKI growing phase. The force balance between the averaged electric force term and the additional wavy component associated with the fluctuations of magnetic field and current density holds at the neutral sheet. This suggests that the DKI can contribute to creating anomalous resistivity and triggering the collisionless magnetic reconnection.

1. Introduction

Magnetic reconnection leads to a topological change of magnetic field and fast energy conversion from a magnetic field to particles and is widely believed to be a fundamental process of the active and global phenomena observed in the Solar corona, the geomagnetic tail and fusion plasma. On the other hand, the results of laboratory experiments and satellite observations at the magnetosphere suggest that the ion-scale structure in the reconnection region plays a critical role in magnetic reconnection [1]. Instead of binary collisions, microscopic non-ideal effects can violate the frozen-in condition of a magnetic field and cause collisionless magnetic reconnection in these systems.

A variety of microscopic plasma instabilities which can excite in the current sheet have so far been studied by linear analyses and simulations [2–5]. It is important to clarify how these instabilities cause the non-ideal effect and collisionless magnetic reconnection. In this paper we study current-driven microscopic plasma instabilities in the ion gyro-scale current sheet and clarify the role of these instabilities in the violation of the ideal condition and the triggering mechanism of collisionless magnetic reconnection.

2. Simulation model

The simulation is carried out by using a $2\frac{1}{2}$-dimensional explicit electromagnetic particle simulation code. We adopt the Harris-type equilibrium with the neutral

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sheet (NS) and the antiparallel magnetic field configuration. A periodic boundary condition is imposed in the equilibrium current direction (x direction) and a fixed boundary condition is imposed in the magnetic gradient direction (y direction), where the xy-plane is the simulation domain. The important simulation parameters are as follows: mass ratio $m_\mathrm{i}/m_\mathrm{e} = 25$, temperature ratio $T_\mathrm{i}/T_\mathrm{e} = 2.0$ and initial curent sheet scale (L) to ion Larmor radius in the external region (ρ_i), $L/\rho_\mathrm{i} = 1.12$.

Force balance in a fluid description is examined using the particle simulation results. The force balance equation averaged over the x-variation is

$$\langle n_j \mathbf{E} \rangle + \langle n_j \mathbf{v}_j \times \mathbf{B} \rangle = \left\langle \frac{m_j}{q_j} n_j \frac{\partial}{\partial t} \mathbf{u}_j + \frac{m_j}{q_j} n_j (\mathbf{u}_j \cdot \nabla) \mathbf{u}_j \right\rangle + \frac{1}{q_j} \langle \nabla \cdot \mathbf{P}_j \rangle \qquad (2.1)$$

where subscript j denotes particle species, $\langle X \rangle$ and $\tilde{X}$ represent averaged component and wavy component, respectively. From periodic condition, the perturbation itself averages zero, but the wavy coupling terms such as $\langle \tilde{n}\tilde{\mathbf{E}} \rangle$ and $\langle \tilde{n}\tilde{\mathbf{v}} \times \tilde{\mathbf{B}} \rangle$ can contribute additional macroscopic Lorentz force terms. In this equation, the frozen-in condition which prohibits magnetic reconnection is expressed as the condition $\langle \mathbf{E} \rangle + \langle \mathbf{v}_j \rangle \times \langle \mathbf{B} \rangle = 0$ and thus the onset of magnetic reconnection requires the other terms (wavy coupling terms and the right-hand side of (2.1)) are finite. In the simulation domain, the development of magnetic reconnection is expressed as the reduction of antiparallel magnetic flux. From the fixed boundary condition, the variation of the total magnetic flux Φ in the half domain can be related to the electric force term at NS by $(d/dt)\Phi = -\langle E_x \rangle L_x$ (L_x is the domain length along x direction).

3. Simulation results

3.1. The role of lower hybrid drift instability

In the early phase of the simulation ($t\omega_\mathrm{ci} \sim 0.0$–$5.0$), the electric and magnetic field perturbations which have short wavelength $k\rho_\mathrm{e} \sim 1.5$ are observed to grow at the periphery of the current sheet. The dispersion relation is in good agreement with the linear analysis of lower hybrid drift instability (LHDI) [6]. LHDI is also found in the high beta region at the vicinity of the NS [2], but the propagation of LHDI does not penetrate into the NS because of the electron thermal effect [3]. Figure 1(a) shows the force balance at this phase. The nonlinear coupling of the perturbations of the electric field and particle density ($\tilde{n}\tilde{\mathbf{E}}$) balances the magnetic force term ($\langle n\mathbf{v} \rangle \times \langle \mathbf{B} \rangle$) with average outward flow of particle $\langle n\mathbf{v} \rangle$ in the periphery of the current sheet.

This coupling term suggests the nonlinear interaction between particles and the oscillations of LHDI in the current sheet [7]. The heating of electrons and ions found at the periphery is related by the resonance with this oscillation. The force balance of this coupling term suggests the interaction also contributes average outward flow. This correlation between the perturbation of electric field and accelerated particles by the field results in the net outward electron $\mathbf{E} \times \mathbf{B}$ drift to the equilibrium current direction on average. The average outward transport can modify not only the density profile but also the diamagnetic current density profile so that the current density is concentrated into the central region.

Although the lower hybrid drift wave does not penetrate into the NS, the outward transport can affect the vicinity of the NS by the modification of the orbits of the meandering particles moving between the periphery and the NS. The modification

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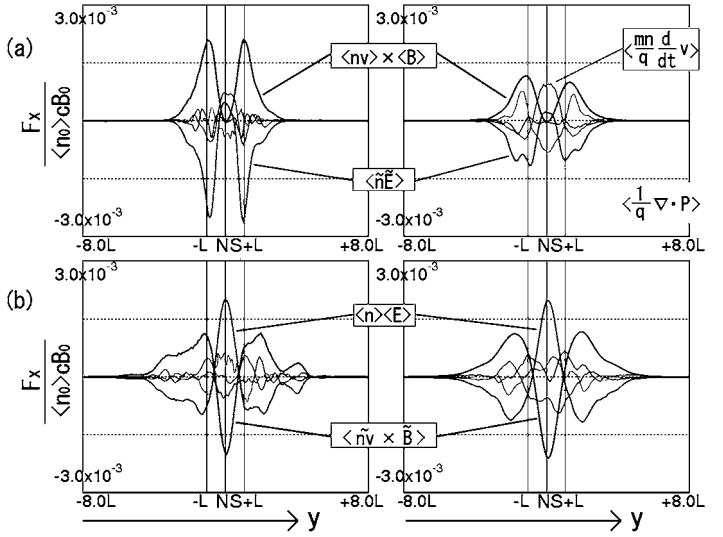


Figure 1. The spatial profiles of force balance in the x-direction for electrons (left) and ions (right): (a) at the LHDI phase $t\omega_{ci} = 5.46$ and (b) at the DKI phase $t\omega_{ci} = 13.9$.

of velocity distribution from the initial isotropic Maxwell distribution leads to the particle acceleration by the pressure tensor term and temperature anisotropy around the NS. However, the DC electric field $\langle \mathbf{E} \rangle$ in the NS or magnetic flux reduction is not observed in this phase. This suggests that these process cannot trigger magnetic reconnection directly.

3.2. The role of drift kink instability

After the saturation of LHDI, the growth of the longer scale magnetic wave ($k_x L \sim 1.0$) is observed to grow dominantly at the NS ($t\omega_{ci} \geqslant 10.0$). The fundamental property of this wave has agreement with the result of linear analysis of the drift kink instability (DKI) [4]. The average DC electric field $\langle \mathbf{E} \rangle$ appears at the NS in this phase. The reduction of total magnetic flux consistent with the DC electric field is also found.

Figure 1(b) shows the force balance at this phase. At the periphery, average magnetic force term and wavy electric term are balanced similar to the force balance at the LHDI phase. At NS, the fluctuations of magnetic field and current density form the finite wavy component $\langle \tilde{n}\mathbf{v} \times \tilde{\mathbf{B}} \rangle$ in the Lorentz force term, and this term balances the average electric force term $\langle n \rangle \langle \mathbf{E} \rangle$. The perturbations of the magnetic field and current density which have wave number $k_x L \sim 1.0$ dominantly contribute to this wavy component.

Figure 2 show the time dependence of force balance at the NS, current density, DC electric field, and variation of total magnetic flux. As the DKI grows, the wave coupling term grows while balancing the electric force term, and the magnetic flux becomes reduced. Although the current density is concentrated at the LHDI phase, rapid dissipation of current density takes place at the DKI growing phase. The effective collision frequency estimated from the damping rate of electron current density is $\nu_e \sim 0.011\omega_{ce}$. Anomalous resistivity is evaluated to be about $\eta \sim 0.005\omega_{ce}^{-1}$ which is of the same order as the effective resistivity estimated from the DC electric field.

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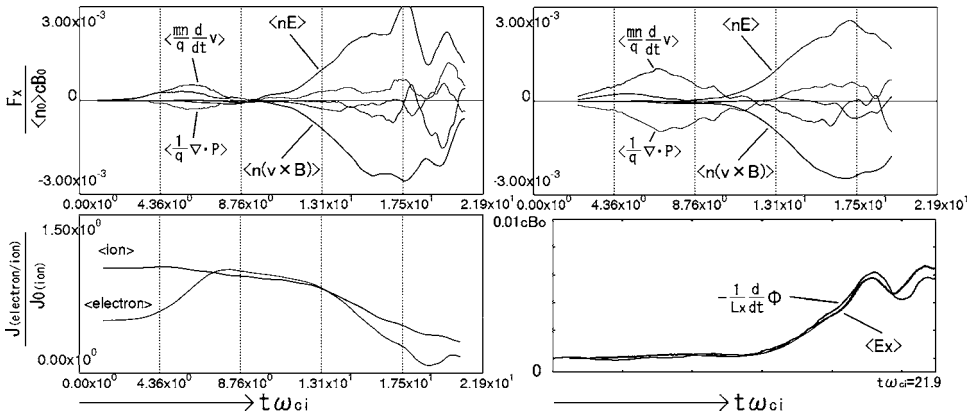


Figure 2. Time dependence of force balance at the neutral sheet for electrons (top left) and ions (top right) and time dependence of current density (bottom left) and DC electric field (bottom right) ($0.0 < t\omega_{ci} < 21.9$).

It is concluded that the nonlinear coupling between the fluctuation of magnetic field and microscopic plasma flow created by the DKI generates the anomalous resistivity and triggers the magnetic reconnection.

4. Conclusions

In order to clarify the role of microscopic plasma instabilities in collisionless reconnection, non-ideal terms in the force balance equation have been examined by means of explicit particle simulation. While the magnetic flux is re-distributed in the phase of LHDI, a reduction of total magnetic flux is observed in the DKI phase. This result is in good agreement with the three-dimensional simulation about collisionless reconnection [8]. The nonlinear wavy coupling term $\langle \tilde{n}\tilde{\mathbf{v}} \times \tilde{\mathbf{B}} \rangle$ generates the DC electric field at the NS leading to the flux reduction. It is concluded that the nonlinear development of DKI plays an important role in creating anomalous resistivity and triggering collisionless magnetic reconnection.

References

[1] Sergeev, V. A. et al. 1995 *In situ* observations of magnetotail reconnection prior to the onset of a small substorm. *J.Geophys. Res.* **100**, 19 121–19 133.

[2] Mal'kov, M. A. et al. 1981 Current driven instability of large beta drift waves in the magnetosphere. *Sov. J. Plasma Phys.* **7**, 405–406.

[3] Huba, J. D. et al. 1978 Lower-hybrid-drift instability in field reserved plasmas. *Phys. Plasmas.* **23**, 552–561.

[4] Daughton, W. 1999 The unstable eigenmodes of a neutral sheet. *Phys. Plasmas.* **6**, 1329–43.

[5] Ozaki, M. et al. 1996 Electromagnetic instability and anomalous resistivity in a magnetic neutral sheet. *Phys. Plasmas.* **3**, 2265–2274.

[6] Davidson, R. C. et al. 1977 Effects of finite plasma beta on lower-hybrid-drift in stability. *Phys. Fluid* **20**, 301–310.

[7] Sotnikov, V. I. et al. 1980 The nonlinear theory of the current instability of short wavelength drift oscillations. *Sov. Phys.–JETP.* **51**, 295–310.

[8] Horiuchi, R. and Sato, T. 1999 Three-dimensional particle simulation of plasma instabilities and collisionless reconnection in a current sheet. *Phys. Plasmas.* **6**, 4565–4574.

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