26pC01

Collisionless Plasma Dynamics in Driven Magnetic Rconnection

C. Z. Cheng(1), S. Inoue(2), Y. Ono(1), R. Horiuchi(3)

(1) School of Frontier Sciences, University of Tokyo, Japan
(2) Japan Atomic Energy Agency, Japan
(3) National Institute for Fusion Science, Japan

Physics of magnetic reconnection has been studied by using various models and experiments. Based on the MHD model, there are two well-known steady-state magnetic reconnection models: the Sweet-Parker model and the Petschek model. In the Sweet-Parker model, both electrons and ions flow together from the upstream region through the magnetic reconnection diffusion layer into the downstream region and the outflow velocity speeds up to the Alfven speed by the reconnection electric field. The reconnection rate (and the inflow speed) is proportional to the square root of the plasma resistivity and is too low to account for observations. To overcome the slow reconnection rate and inflow bottleneck problems, the Petschek model proposes that both electrons and ions flow together mainly across the field line separatrix into the downstream and the plasma outflow velocity is accelerated by the $\vec{J}\times\vec{B}$ force at the slow mode shock which is located in the downstream region. Then, the magnetic reconnection rate can be enhanced to realistic value. On the other hand, based on the Hall-MHD model, the electron flow decouples from the ion flow. The electron flow velocity perpendicular to $\vec{B}$ is governed by the $c\vec{E}\times\vec{B}/B^2$ drift velocity, and the ion flow velocity is controlled by the $\vec{J}\times\vec{B}$ and pressure gradient forces. However, the charge quasi-neutrality is assumed so that there is no electrostatic electric field, the plasma pressure is assumed to be isotropic and obey the adiabatic pressure law, and there is no separate information on the electron and ion parallel flow velocities along the magnetic field. Moreover, there is no information on plasma heating and acceleration. The main additional feature of the Hall-MHD model is the generation of the quadrupole out-of-plane magnetic field because the electron outflow velocity is much larger than the ion outflow velocity in the downstream region.

However, the physical processes of magnetic reconnection based on the full kinetic model are drastically different from those based on the MHD and Hall-MHD models. In this paper we present the physical mechanisms of key plasma dynamical processes during driven magnetic reconnection of anti-parallel magnetic fields in collisionless plasmas by examining the 2-1/2 dimensional particle-in-cell (PIC) simulation results [1]. In particular, we provide explanation on the generation of the electric and magnetic fields, the electron and ion flow dynamics, and acceleration and heating of electrons and ions.

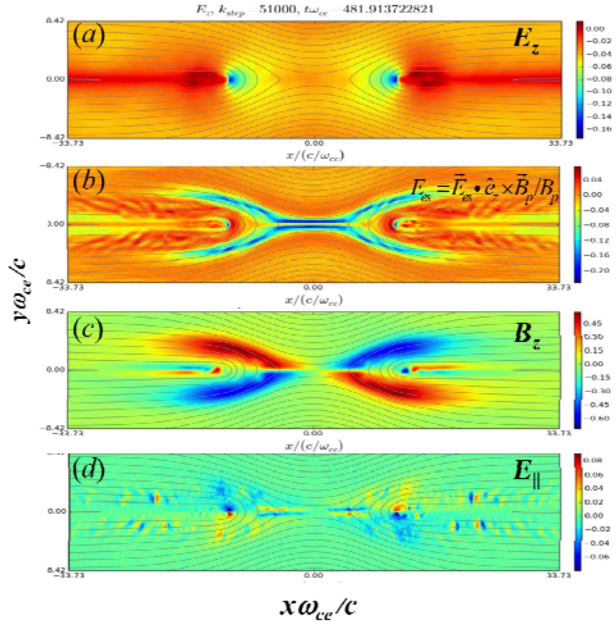

Fig. 1 Poloidal distributions of (*a*) driving inductive electric field $\vec{E}_z$, (*b*) electrostatic electric field $\vec{E}_{es}$, (*c*) quadrupole magnetic field $\vec{B}_z$, and (*d*) parallel electric field $\vec{E}_{\|}$ at $\omega_{ce}t=481.91$.

One of the key kinetic reconnection physics is the decoupling of electron and ion dynamics around the magnetic reconnection and separatrix regions. When oppositely directed magnetic fields are driven by the inductive electric field $\vec{E}_z$ (shown in Fig. 1(*a*)) toward the neutral sheet to reconnect, both the electrons and ions convect together with the magnetic field. Around the neutral sheet region, the particle motion becomes meandering because the magnetic field is weakened and reversed across the neutral sheet. Because the ion meandering width is $(T_i m_i/T_e m_e)^{1/4}$ times the electron meandering width, the electron and ion orbits are decoupled. Inside the orbit meandering region, the particle density accumulates and is roughly uniform, and thus the ion density is larger (smaller) than the electron density outside (inside) the electron orbit meandering region. The charge separation produces a pair of in-plane bipolar converging electrostatic electric field $\vec{E}_{es}$ pointing toward the neutral sheet (shown in Fig. 1(*b*)).

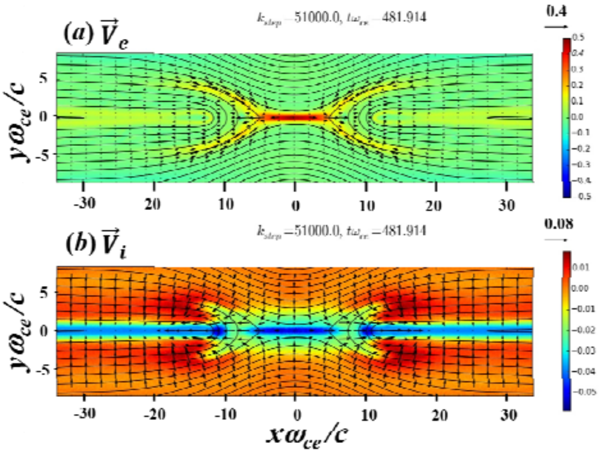

Fig. 2 Poloidal distributions of (*a*) electron flow velocity $\vec{V}_e$, and (*b*) ion flow velocity $\vec{V}_i$. Arrows indicate poloidal components and color indicate the z-components.

Electrons flow from the upstream region mainly through the magnetic field reconnection region into the downstream region as shown in Fig. 2(*a*). Although some ions flow through the reconnection current layer into the downstream, most ions flow across the field line separatrix into the downstream as shown in Fig. 2(*b*). The electron outflow velocity from the reconnection region dominates over the ion outflow velocity in the downstream exhaust region, and thus a pair of currents flow inward toward the reconnection region in the reconnection plane to generate the out-of-plane quadrupole magnetic field $\vec{B}_z$ as shown in Fig. 1(*c*). The quadrupole magnetic field concentrates mainly around the separatrix region and causes parallel electric field $\vec{E}_{\parallel} \simeq (\vec{E}_z \bullet \vec{B}_z / B^2)\vec{B}$ (mainly from the inductive $\vec{E}_z$) to accelerate particles along the magnetic field line. Because $\vec{E}_{\parallel}$ points mainly outward from the reconnection region toward the downstream direction as shown in Fig. 1(*d*), electrons are accelerated by $\vec{E}_{\parallel}$ around the separatrix region to flow along the field lines toward the reconnection region.

Around the separatrix region, electrons flow very fast mainly along the field line and ions flow mainly across the field line slowly. The decoupling of the electron and ion flow dynamics produces net positive (negative) charge on upstream (downstream) side of the separatrix and thus an electrostatic electric field $\vec{E}_{es}$ pointing toward the downstream midplane direction (shown in Fig. 1(*b*)) is produced. Note that $\vec{E}_{es}$ is mainly perpendicular to the ambient magnetic field because fast moving electrons can smear out the charge separation along the field line and thus $\vec{E}_{es}$ is also perpendicular to $\vec{E}_z$. Then, the perpendicular electric field is $\vec{E}_{\perp} = \vec{E}_{es} + (1 - B_z^2/B^2)\vec{E}_z - (E_z B_z / B^2)\vec{B}_p$ due to both $\vec{E}_{es}$ and $\vec{E}_z$.

With the physical understanding of how $\vec{E}_{es}$ and $\vec{B}_z$ and thus $\vec{E}_{\parallel}$ and $\vec{E}_{\perp}$ are produced, we can understand the electron and ion dynamics and their velocity distributions and flow structures during the driven reconnection as they move from the upstream to the downstream. In particular, we address the following key physics issues:

(1) around the reconnection neutral sheet region, how electrons and ions are accelerated/decelerated by the converging bipolar $\vec{E}_{es}$ and accelerated by the inductive $\vec{E}_z$, and how the electron and ion inflow velocities are slowed down;

(2) why the electron outflow velocity from the reconnection region reaches super-Alfvenic speed and the ion outflow velocity reaches Alfvenic speed;

(3) how electrons and ions are accelerated by $\vec{E}_{\parallel}$ around the separatrix region, and why electrons have a flat-top parallel velocity distribution in the upstream just outside the reconnection region;

(4) how ions gain energy from both $\vec{E}_{\parallel}$ and $\vec{E}_{\perp}$ as they move across the separatrix region into the downstream, and how the ion velocity distribution is thermalized in the downstream; and

(5) how electrons move across the separatrix region and from reconnection layer into the downstream and how the electron velocity distribution is thermalized in the downstream.

Finally, we present the distribution of $\vec{E}_z \bullet \vec{J}_e$, $\vec{E}_{es} \bullet \vec{J}_e$, $\vec{E}_z \bullet \vec{J}_i$ and $\vec{E}_{es} \bullet \vec{J}_i$ energy dissipation in the poloidal plane and show that electrons gain both kinetic and thermal energy from the inductive $\vec{E}_z$ in the reconnection current layer and the separatrix region, but spend energy to maintain $\vec{E}_{es}$. Ions gain energy from $\vec{E}_z$ in the reconnection current layer and the downstream regions and from $\vec{E}_{es}$ in the separatrix region. Therefore, the main energy source for driving magnetic reconnection and particle acceleration and heating is the inductive electric field $\vec{E}_z$, which accelerates both electrons and ions around the reconnection current layer and separatrix regions.

[1] C. Z. Cheng, S. Inoue, Y. Ono, R. Horiuchi, Phys. Plasmas, 22, 101205, doi: 10.1063/1.4932337 (2015).