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多階層物理に支配されたエネルギー開放系での磁気リコネクション
Magnetic Reconnection Controlled by Multi-Hierarchy Physics in an Open System

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Magnetic reconnection is a typical nonlinear complex phenomenon controlled by multi-hierarchy physics from microscopic physics relating to electron and ion dynamics through macroscopic one such as plasma transport in a global scale. We have developed two different types of simulation models in order to investigate multi-hierarchy physics of collisionless reconnection in an open system where an external driving plasma flow and a strong guide field exist. One is an electromagnetic PIC simulation model for a microscopic open system (“PASMO”) which enables us to simulate long time-scale behavior of collisionless reconnection [1-4]. The other is an MHD-PIC interlocked model (“MARIS”) in which a simulation region is split into PIC, MHD, and interface domains, and the micro- and macrophysics in each domain is solved with PIC and MHD models while exchanging their information through the interface domain [4,5].

Long time-scale behaviors of collisionless reconnection have been disclosed by a series of simulation studies using the PASMO codes. The frozen-in condition is broken due to microscopic kinetic effects and collisionless reconnection is triggered when current sheet is compressed as thin as ion kinetic scales under the influence of external driving flow. A reconnection system evolves into a quasi-steady state after an initial transient phase if the driving flow satisfies some condition [2,3]. In a quasi-steady state there exist two microscopic mechanisms which break the frozen-in condition and sustain magnetic reconnection in a collisionless plasma, i.e. microscopic kinetic effects of particles with finite mass and finite orbit amplitude [2-4], and anomalous resistivity associated with plasma instabilities [1,4,6].

For a no guide field case a microscopic kinetic effect originating from stochastic motion of charged particles near a reconnection point, called meandering motion, becomes dominant inside the orbit amplitude in a quasi-steady state. The reconnection electric field is sustained by pressure tensor term at this stage. Two kinds of plasma instabilities are observed to grow gradually inside an ion-scale current sheet at the quasi-steady state [1,4,6]. The lower hybrid drift instability (LHDI) grows in the periphery of the current sheet, but, this mode does not penetrate into the central high-β region of the current sheet because it undergoes strong damping there. Thus, it cannot be a direct cause of anomalous resistivity at the neutral sheet. Later, a drift kink instability (DKI) is triggered at the neutral sheet as a result of nonlinear deformation of the current sheet by LHDI. The reconnection electric field grows at the neutral sheet in accordance with the excitation of DKI. The detailed analysis [4,6] reveals that DKI consists of two modes with different wavenumbers. The short kink mode depends on the electron dynamics and its growth rate decreases as the ion-to-electron mass ratio approaches a realistic one. On the other hand, the longer mode is dominantly controlled by the ion dynamics, and its growth rate is kept constant independent of the mass ratio. Thus, the anomalous resistivity generated by the longer king mode or its reconnection rate is large enough to explain the observed value even for a realistic mass ratio case.

For a strong guide field case off-plane magnetic field evolves dynamically into a complex form, which is controlled by initial uniform guide field B_{z0}, quadrupole field created by the Hall current, and the compression by the external driving flow, as shown in Fig.1. The electron current layer grows in a long and narrow region with strong magnetic shear and its shape become asymmetric against the vertical axis passing through a reconnection point in contrast to that for a no guide field case, as shown in Fig. 2. Most of charged particles become magnetized due to the strong guide field. In order to clarify the relationship between stochastic particle motion in a vicinity of a reconnection point and current layer structure we carried out test particle simulations under fixed electromagnetic field, which was chosen at some simulation periods. Figure 3 demonstrates the spatial profiles of current density and number density along the vertical axis passing through a reconnection point for the same case as Fig. 1. The width of central peak profile of the current density is given by the electron orbit amplitude l_{me}, and its half-width is nearly equal to the electron skin depth d_{eskn}. On the other hand, the typical spatial scale of number density profile is given by the ion orbit amplitude l_{mi}. Strong guide field affects energy conversion processes from magnetic energy to particle energy in the reconnection process. Figure 4 shows the energy spectra of electrons for four different guide fields. The growth of a non-thermal component is suppressed at the lower level for the stronger guide field. This result corresponds to the fact that electron kinetic region shrinks as the guide field increases.

Because a microscopic kinetic system such as discussed above is always imbedded in a global microscopic system and its location varies in both time and space, it is very important to locate a kinetic regime in a dynamically evolving macroscopic system and clarify the role of kinetic effect in the global reconnection phenomena through the interaction between macro- and microphysics. In order to investigate full picture of magnetic reconnection phenomena in nature, we have developed a multi-hierarchy model, “MARIS”, in which MHD and PIC models are interconnected through the interface region. The model is applied to a few numerical test programs and collisionless driven reconnection in a simple geometry and is confirmed to work well [4,5]. We are now applying the model to a fusion plasma with a strong guide field.

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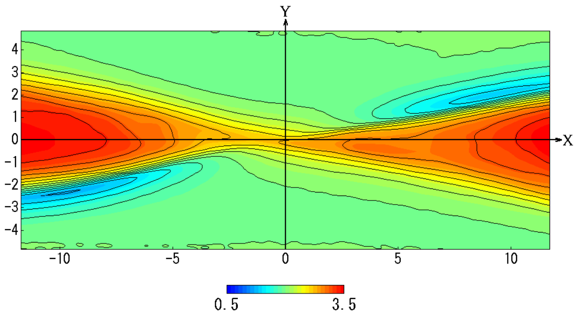

Fig. 1 Spatial profile of off-plane magnetic field at $\omega_{pe}t=5528$ for a strong guide field of $B_{z0}=2B_0$, where B_0 is an initial distant value of in-plane magnetic field.

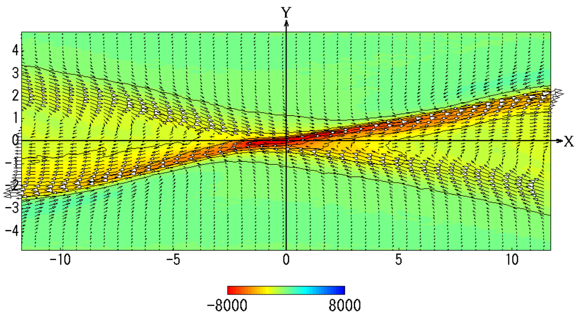

Fig. 2 Color contours of the off-plane component of electron current density and vector plots of electron flow velocity in (x,y) plane for the same case as Fig. 1.

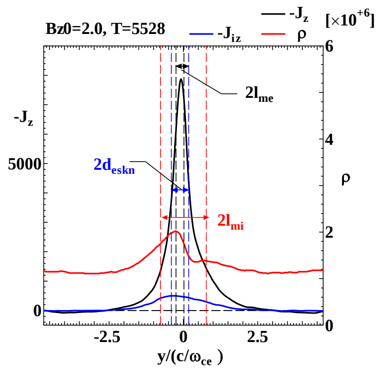

Fig. 3 Spatial profile of current density and number density along the vertical axis for the same case as Fig. 1.

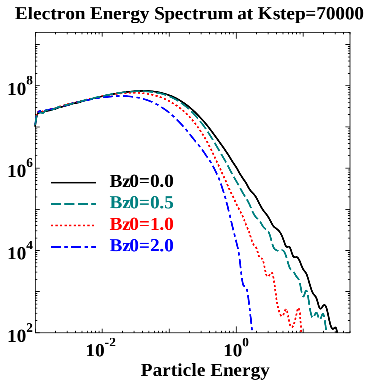

Fig. 4 Energy spectra of electrons for four different guide fields.