First Demonstration of Collisionless Driven Reconnection in a Multi-Hierarchy Simulation

Shunsuke USAMI[1)], Hiroaki OHTANI[1,2)], Ritoku HORIUCHI[1,2)] and Mitsue DEN[3)]

[1)]*National Institute for Fusion Science, Toki 509-5292, Japan*

[2)]*The Graduate University for Advanced Studies (SOKENDAI), Toki 509-5292, Japan*

[3)]*National Institute of Information and Communications Technology, Koganei 184-8795, Japan*

(Received 31 August 2009 / Accepted 22 September 2009)

A multi-hierarchy simulation model for magnetic reconnection studies is developed in which macroscopic and microscopic physics are expressed consistently and simultaneously. We are the first to have successfully demonstrated collisionless driven reconnection in the framework of a multi-hierarchy model. Magnetic reconnection is found to occur in a micro-hierarchy upon plasma injection from a macro-hierarchy.

Keywords: multi-hierarchy simulation, magnetic reconnection, MHD, PIC

DOI: 10.1585/pfr.4.049

Magnetic reconnection is believed to play an important role in solar flares, geomagnetic substorms, and tokamak disruptions [1–3]. Furthermore, in recent years, magnetic reconnection has attracted considerable attention as a multi-hierarchy phenomenon. When magnetic reconnection occurs, the field topology changes on a macroscopic scale and global plasma transport takes place. On the other hand, an electric resistivity controlled by a microscopic process is necessary as a trigger. Therefore, for complete understanding of magnetic reconnection [4], in the magnetic reconnection interlocked simulation (MARIS) project, we develop a (three-dimensional) multi-hierarchy simulation model, which calculates both microscopic and macroscopic physics consistently and simultaneously.

In the multi-hierarchy structure of magnetic reconnection, the characteristic space-time scale changes with distance from the neutral sheet. Dynamics within the ion-meandering orbit scale l_{mi} is controlled by kinetic physics, while plasma behaviors outside the ion skin depth d_{i} can be expressed by a one-fluid model [5].

Based on the above features, we employ the domain decomposition method for our multi-hierarchy model [6–8]. The domains differ in algorithm. Physics in the domain where microscopic kinetic effects play crucial roles is solved by particle-in-cell (PIC) simulation method [9]. This domain is called PIC domain. On the other hand, dynamics on the periphery of the PIC domain is expressed by magnetohydrodynamics (MHD) simulation method. We shall refer to this domain as MHD domain. Between the PIC and MHD domains, an Interface domain with a finite width is inserted. The physics in the Interface domain is calculated by both the PIC and MHD algorithms. Macroscopic physical quantities in the Interface domain (for instance, magnetic field and fluid velocities) are obtained by a hand-shake scheme, $Q_{\mathrm{Interface}} = aQ_{\mathrm{MHD}} + (1 - a)Q_{\mathrm{PIC}}$, where Q_{MHD} and Q_{PIC} indicate the values of Q calculated by the MHD and PIC algorithms, respectively. The parameter a is a function of the coordinates. Individual particle velocities in the Interface domain are newly determined so as to satisfy the (shifted) Maxwellian distribution using the obtained macroscopic quantities at every time step. The PIC and MHD domains can be smoothly interlocked via the Interface domain.

In previous work, as numerical tests, we simulated the propagation of linear Alfvén waves in the multi-hierarchy model [6, 7]. The model was not configured for reconnection. For instance, the external magnetic field was not anti-parallel but was uniform (see Refs. [6, 7] for details). Smooth wave propagation was observed.

In this paper, we connect the PIC and MHD domains at the upstream boundary for simulations of collisionless driven reconnection. Figure 1 shows a schematic diagram of our multi-hierarchy model. The PIC domain covers the central region close to the neutral sheet ($|y/(c/\omega_{\mathrm{ce}})| <$ 11.875), and the MHD domains are outside the PIC domain ($15.875 < |y/(c/\omega_{\mathrm{ce}})| < 19.875$), where c is the speed of light, and ω_{ce} is the electron gyrofrequency. The Interface domain is located between the PIC and MHD domains ($11.875 < |y/(c/\omega_{\mathrm{ce}})| < 15.875$).

The initial condition is given by a one-dimensional Harris-type equilibrium as $B_x(y) = B_0 \tanh(y/L)$ for the magnetic field, where B_0 is a constant, and L is the scale height along the y axis. The system is periodic in the x and z directions and is free in the y direction. An external electric field $E_{\mathrm{zd}}(t)$ is applied at the entire outside boundary ($y/(c/\omega_{\mathrm{ce}}) = \pm 19.875$) of the MHD domain. Plasmas are injected inward in the y direction. The electric field $E_{\mathrm{zd}}(t)$

author's e-mail: usami.shunsuke@nifs.ac.jp

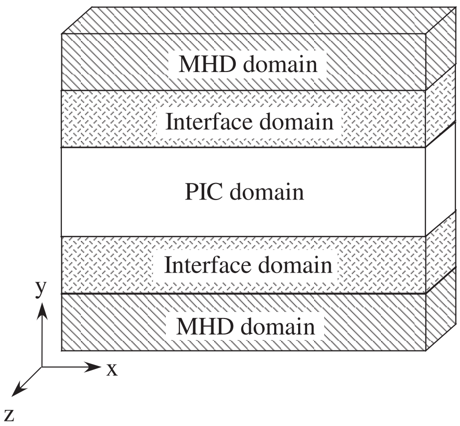

Fig. 1 Schematic diagram of the multi-hierarchy simulation box. The simulation domain is divided into PIC, Interface, and MHD domains.

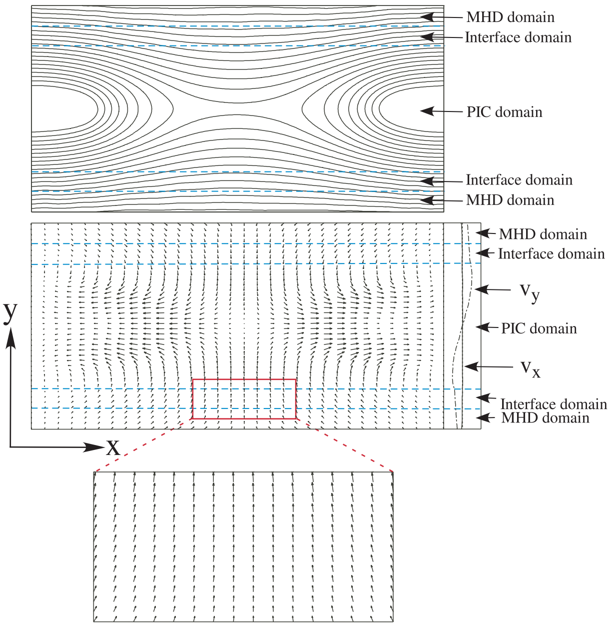

Fig. 2 Magnetic lines of force (top panel) and fluid velocity vectors (second and third panels) at $\omega_{ce}t = 1323$. The fluid velocities v_x (solid line) and v_y (dash-dot line) along the y axis passing the X point are shown in the right side of the second panel. The third small panel is an enlarged view of the red rectangular region in the second panel.

in the MHD domain is programmed to evolve from zero to a constant value E_0, which corresponds to $-0.04B_0$ with the PIC unit system.

Figure 2 displays the magnetic lines of force (top panel) and fluid velocity vectors (second and third panels) in the (x, y) plane in the whole multi-hierarchy simulation domain at $\omega_{ce}t = 1323$. (An enlarged view of the red rectangular region is also presented in the third panel.) The lines of force and the fluid velocity are smoothly connected between the MHD and PIC domains via the Interface domain. An X point exists at the center. We can see that inflows come inward from the MHD domain and drive magnetic reconnection at the center in the PIC domain. Note that magnetic reconnection does not completely reach a steady state. Unfortunately, if the simulation continues for a longer time, two outflows would collide with each other because the x direction is taken to be a periodic boundary condition.

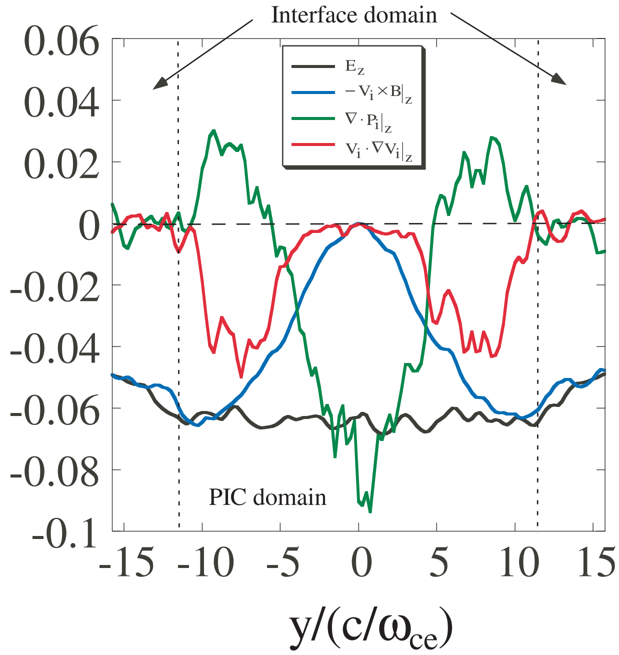

Fig. 3 Spatial profiles of various terms in the out-of-plane components of the ion momentum equation along the y axis passing the X point at $\omega_{ce}t = 1323$.

Here, we need to examine whether the collisionless driven reconnection found in our multi-hierarchy simulation model represents a true physical phenomenon. Ishizawa and Horiuchi [5] studied the violation mechanism of the frozen-in condition in magnetic reconnection with a PIC simulation. They found that ion nongyrotropic pressure causes violation of the ion frozen-in constraint by comparing terms in the momentum equation of ions,

$$\boldsymbol{E} + \boldsymbol{v}_i/c \times \boldsymbol{B} \simeq -(1/en)\nabla \cdot \boldsymbol{P}_i + (m_i/e)\boldsymbol{v}_i \cdot \nabla \boldsymbol{v}_i, \quad (1)$$

where $\boldsymbol{E}$ is the electric field, and e, n, m_i, $\boldsymbol{v}_i$, and $\boldsymbol{P}_i$ represent the charge, number density, mass, fluid velocity, and pressure tensor of ions, respectively. In Fig. 3, we show the spatial profiles of the out-of-plane components of terms in Eq. (1) along the y axis passing the X point. We can see that in the region $|y/(c/\omega_{ce})| \lesssim 5 (\simeq l_{mi})$, the pressure tensor term is dominant, and it leads to breaking the frozen-in constraint. On the other hand, the pressure tensor almost cancels out the inertia term in the region $(5 \lesssim |y/(c/\omega_{ce})| \lesssim 10 (\simeq d_i))$, and the relation $\boldsymbol{E}+\boldsymbol{v}_i/c\times\boldsymbol{B}|_z = 0$ holds approximately. These results are consistent with those obtained in Ref. [5]. Therefore, our multi-hierarchy model exhibits a true physical phenomenon.

This work was done as a first step in the multi-hierarchy simulation of magnetic reconnection. Next, we change the boundary conditions in the *x* direction from periodic to open. This enables us to continue simulations for a much longer time, until a steady state of magnetic reconnection. In the near future, we would also like to consider hierarchy connections at the reconnection downstream boundary.

This work was partially supported by the Research Cooperation Program on Hierarchy and Holism in Natural Sciences 2 at the National Institutes of Natural Sciences and the General Coordinated Research at the National Institute for Fusion Science (NIFS08KTAL015, NIFS09KNXN174).

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