23F03

Multi-Hierarchy Simulation Model for Magnetic Reconnection IV
磁気リコネクション研究のための多階層シミュレーションモデルの開発 IV

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For magnetic reconnection studies, a multi-hierarchy simulation model which deals with both macroscopic and microscopic physics self-consistently and simultaneously has been developed. In this paper, our multi-hierarchy model is improved based on the dynamical domain conversion method, in which initially MHD simulation runs, and a part of simulation domain is converted to the PIC domain when some conditions are satisfied. We have successfully demonstrated collisionless driven reconnection with the improved model.

1. Introduction

Collisionless magnetic reconnection is one of the fundamental processes in which magnetic field energy is converted to kinetic energy. It plays an essential role in the rapid energy release in laboratory fusion device and astrophysical plasmas. Furthermore, magnetic reconnection attracts considerable attention as a typical multi-scale phenomenon. When magnetic reconnection takes place, the global change in field topology and large plasma transport occur, while electrical resistivity controlled by microscopic process is necessary in the vicinity of reconnection points. In order to understand its multi-hierarchy structure completely, we develop a multi-hierarchy simulation model, which deals with both microscopic and macroscopic physics consistently and simultaneously.

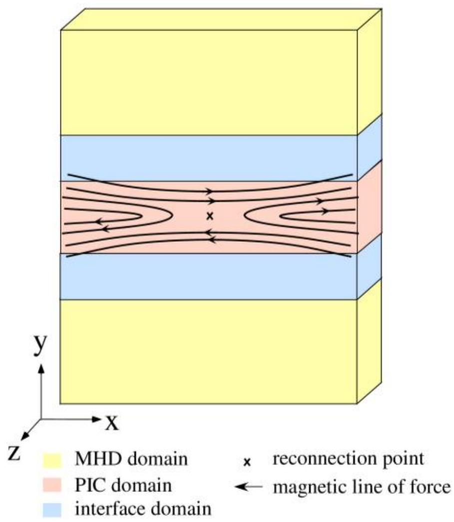

Fig.1. Schematic diagram of multi-hierarchy model for magnetic reconnection simulation

2. Multi-Hierarchy Simulation Method

The multi-scale structure of magnetic reconnection has a special feature that the characteristic space-time scales change with distance from the neutral sheet [1, 2]. Dynamics in the ion meandering orbit scale near the neutral sheet is controlled by kinetic physics, while plasma behaviors far away from the neutral sheet (outside the ion skin depth) relax to one-fluid.

Based on the above feature, the domain decomposition method [3-6] is employed for our multi-hierarchy model, in which the domains differ in algorithm. Figure 1 shows the schematic diagram of the multi-hierarchy simulation box. The simulation domain is divided into three domains. The macroscopic domain covers the region where microscopic kinetic effects play crucial roles. Since physics in the microscopic domain is solved by particle-in-cell (PIC) algorithm, we refer to this domain as “PIC domain”. On the other hand, macroscopic domain treats the periphery of the PIC domain, and dynamics in this domain is expressed by magnetohydrodynamics (MHD) algorithm. Then we call this domain “MHD domain”. Between the PIC and MHD domains, a technical interface domain with a finite width is put.

Physics in the interface domain is calculated by the PIC and MHD algorithms (Therefore note that MHD condition should be fully satisfied in the interface domain). Macroscopic physical quantities in the interface domain $Q_{\mathrm{interface}}$ (magnetic field, fluid velocities, pressure, *etc*) are obtained by a hand-shake scheme, $Q_{\mathrm{interface}} = FQ_{\mathrm{MHD}} + (1-F)\, Q_{\mathrm{PIC}}$, where Q_{MHD} and Q_{PIC} indicate the values of Q calculated by the MHD and PIC algorithms, respectively. The interconnection function F is a function of the coordinates.

On the other hand, in order to solve the physics in the interface domain with the PIC algorithm, microscopic quantities such individual particle positions and velocities are needed. 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 PIC time step.

In 2009, we have performed the simulation of collisionless driven reconnection with the multi-hierarchy model, namely plasma inflows come from the MHD domain and drive magnetic reconnection in the PIC domain [7, 8]. It was confirmed that reconnection process found in the multi-hierarchy model is true physics.

3. Improvement of Model: Dynamical Domain Conversion

In nature, however reconnection points move with time dynamically and then region which need to be expressed by kinetic algorithm also move. Therefore we have been developing improved model which automatically detects kinetic region and converts calculation domain (in other word, changes a calculation algorithm from MHD to PIC algorithms) as simulation is running. As the first step of the dynamical domain conversion method, we perform the following simulation. Initially, whole domain is taken to be the MHD domain. When the certain time passes, a part of MHD domain is converted to the PIC domain, namely the MHD simulation is switched to the multi-hierarchy simulation described in Sec. 2.

Let us show a simulation result with the above model. Figure 2 display magnetic field lines. An external electric field is applied at the top and bottom boundary of the MHD domain, and then plasmas are injected inward. In this simulation, we take $\omega_{ce}t$=3150 as the conversion time from the MHD simulation to the multi-hierarchy simulation, since the MHD simulation demonstrated that the width of current layer decreased to be nearly equal to an ion Larmor radius at $\omega_{ce}t$~3150. At the conversion time, physical quantities are correctly sent from MHD to multi-hierarchy simulations. Magnetic field line is smoothly and continuously

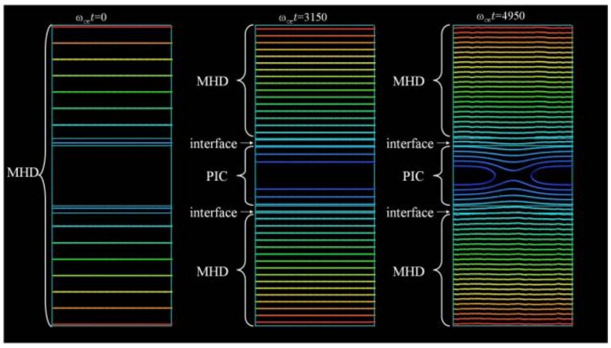

Fig.2. Magnetic field line. At $\omega_{ce}t$=3150, MHD simulation is switched to the multi-hierarchy simulation shown in Fig. 1.

connected not only at $\omega_{ce}t$=3150 but also until $\omega_{ce}t$=4950. We can see that at $\omega_{ce}t$=4950, an X point exists at the center of the PIC domain. Magnetic reconnection is found to be driven in the framework the improved multi-hierarchy model based on the dynamical domain conversion method.

4. Summary

We have developed multi-hierarchy simulation model for complete understanding of magnetic reconnection as a multi-scale phenomenon. In our model, microscopic physics is described by the PIC algorithm, while macroscopic physics is expressed by the MHD algorithm.

We improve our model and perform simulation that initially whole domain is the MHD domain, and a part of domain is converted to the PIC domain when the width of current layer decreased to be nearly equal to an ion Larmor radius. We observe that magnetic reconnection occur in the improved multi-hierarchy model.

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