Three-dimensional electromagnetic particle code with adaptive mesh refinement technique

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Magnetic reconnection is one of the key processes playing an important role in the magnetospheric substorm and solar flares. It facilitates the fast conversion of energy stored in a compressed magnetic field into plasma kinetic and thermal energies. However, many of detailed processes around the diffusion region, where the reconnection and energy conversion take place, are poorly understood.

For example, although the onset of reconnection has been attributed to the tearing instability, it is known to saturate at low levels even in the thin current sheet with thickness of the order of the ion skin depth, before fast reconnection is triggered. Thus it is difficult for the tearing instability alone to trigger the onset of fast reconnection. Recently, it has been suggested that the lower hybrid drift instability (LHDI) intensifies the current density in the center of the current sheet, so that the growth rate of the tearing instability is enhanced in three-dimensional (3-D) systems. Previous two-dimensional (2-D) simulations in the non-tearing plane (orthogonal to the magnetic field) have also revealed that the current sheet modifications due to the LHDI lead to the evolution of a Kelvin-Helmholtz instability (KHI). However, it is still an open question how the KHI affects the tearing instability. Secondly, diffusion mechanisms to support a quasi-steady fast reconnection are not clear. Previous 2-D simulations in relatively small and closed systems have suggested that a whistler wave mediates fast reconnection, independent of the details of the diffusion mechanism near the X-line. However, recent kinetic simulations in large or open 2-D systems have shown that the reconnection rate quickly decreases after fast reconnection is temporally achieved, so that a steady state of fast reconnection is not established. This is because the diffusion region is elongated to the outflow direction, which suppresses the plasma inflow into the diffusion region. It has been suggested that wave-particle interactions along the current in the central current sheet might play an important role in enhancing the magnetic diffusion, resulting in a quasi-steady fast reconnection. These examples clearly indicate that understanding of three-dimensional processes associated with magnetic reconnection is inevitable to explain the explosive energy conversion in space and laboratory plasmas. Unfortunately, it is still very difficult to conduct a 3-D simulation in a large and fully kinetic system by using conventional kinetic codes because of limited computer resources.

So far, we have successfully developed a 2-D electromagnetic particle code using adaptive mesh refinement technique, which enables effectively high-resolution simulations by subdividing computational cells locally in space and dynamically in time. This new code has facilitated kinetic simulations on magnetic reconnection in much larger 2-D systems than the conventional kinetic codes. This time, we extended the 2-D code to a 3-D code in order to achieve a large-scale 3-D simulation in a fully kinetic system. Since, in 3-D simulations using particle-in-cell method, much more particles are required to suppress the numerical noise than in 2-D simulations, the 3-D code is massively parallelized, that is, the computational domain is divided along the sheet current and distributed on each parallel computer. We use the OpenMP to parallelize the calculations within each node, and the message passing interface (MPI) to have each process communicate between the nodes. The code was checked against the non-linear evolution of the current sheet in a relatively thin system in the current direction, in which the LHDI does not appear. We found that the evolution of the system is basically identical with that in the 2-D simulation, indicating that the 3-D code is adequately designed.

In this paper, we will show the initial results in 3-D systems and discuss the performance of the 3-D code.