Studies on Magnetic Reconnection with Multi-Hierarchy Simulations Based on Real-Space Decomposition

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Overview

1. Introduction
2. Development of the multi-hierarchy model
3. Influence of macroscopic physics on dynamical behaviors of magnetic reconnection
4. Summary and future work
1. Introduction
Multi-hierarchy and multi-physics in fusion plasmas

- A fusion plasma consists of multiple hierarchies and multiple physics.
- Studies on each hierarch/physics are advancing remarkably, while interaction between hierarchies or physics is poorly understood.
Contributing to studies on fusion plasmas

**Fusion plasmas**

- **Multi-Hierarchy model**
- **Modeling of transport/diffusion**

**Method:**
Decomposition of real-space in a simulation domain (Hierarchy-interlocking between MHD and PIC)

**Macro**
- Equilibrium and stability
- Neo classical transport
- Peripheral plasma transport
- Turbulent transport
- Wave-particle interaction
- Sheath formation
- Plasma-wall interaction

**Micro**
- Equilibrium and stability
- Neo classical transport
- Peripheral plasma transport
- Turbulent transport
- Wave-particle interaction
- Sheath formation
- Plasma-wall interaction
Magnetic reconnection

- We have developed a multi-hierarchy simulation model.
  - **Macro**: MHD code
  - **Micro**: particle (PIC) code

- With the multi-hierarchy model, we aim to clarify the complete picture of magnetic reconnection as a multi-hierarchy phenomenon.
  - It is believed that sawtooth oscillation in tokamak is deeply involved with magnetic reconnection.
  - Furthermore, magnetic reconnection plays a important role in solar flares and geomagnetic substorms etc.
2. Development of the multi-hierarchy model

Where and how should macro and micro be interlocked?
Our group has found the hierarchical structure of magnetic reconnection in the upstream direction. It depends on the distance from the neutral sheet.

- Kinetic
- Intermediate
- MHD (one-fluid)

Violation of MHD is so-called confined within the ion inertia length.
Domain decomposition method

- We connect PIC and MHD in the **upstream direction**, since MHD condition holds at the upstream ($y > d_i$).
- Three domains
  - PIC domain
  - MHD domain
  - Interface domain (technical overlapped region)
- Physics in the interface domain is solved by both PIC and MHD algorithms.
Physics in the interface domain (1)

- Macroscopic quantities in the interface domain $Q_{\text{interface}}$ ($E, B, u, P, \rho$) are given by a hand-shake scheme:

$$Q_{\text{interface}} = FQ_{\text{MHD}} + (1 - F)Q_{\text{PIC}}$$

$$F = F(x, y, z)$$

near MHD $F \to 1$

near PIC $F \to 0$
The PIC basic equations also are solved in the interface domain. Thus, information of individual particles are needed.

- Big gap in degree of freedom
  - MHD: 8
  - PIC: nearly infinity

In order to bridge this gap, shifted Maxwellian velocity distribution is assumed.

Particle positions and velocities are removed and freshly loaded so as to satisfy $P_{\text{interface}}$, $\rho_{\text{interface}}$, $u_{\text{interface}}$, which are obtained by the hand-shake scheme.
Large time steps are for MHD, and small ones are for PIC. From $t_1$ to $t_2$, PIC receives interpolated data at $t_1$ and at $t_2$ from MHD. On the other hand, PIC data averaged over several steps around $t_1$ is sent to MHD at $t_1$. 
Magnetic Reconnection

Color: Reconnecting field

Height: Reconnected field
3. Influence of macroscopic physics on dynamical behaviors of reconnection

The first results with our multi-hierarchy model is reported
We perform multi-hierarchy simulations of magnetic reconnection under various inflow conditions in order to observe how reconnection physics depends on macroscopic dynamics.

<table>
<thead>
<tr>
<th></th>
<th>128.0 x 114.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Box size ((c/\omega_{ce}))</td>
<td></td>
</tr>
<tr>
<td>Number of grids</td>
<td>512 x 303</td>
</tr>
<tr>
<td>Number of grids (non-uniform grids in MHD)</td>
<td></td>
</tr>
<tr>
<td>Number of particles</td>
<td>2.86 x 10^6 (initial)</td>
</tr>
<tr>
<td>(\omega_{pe}/\omega_{ce})</td>
<td>1.5</td>
</tr>
</tbody>
</table>

 Domain decomposition
- PIC domain: \(|y/(c/\omega_{ce})|<17.875\)
- Interface domain: \(17.875<|y/(c/\omega_{ce})|<19.875\)
- MHD domain: \(19.875<|y/(c/\omega_{ce})|<57.375\)
Various spatial patterns of inflows

- The driving electric field $E_z$ is imposed at the upstream boundary of the MHD domain.
- $E_z$ begins to grow first around the center of the upstream boundary.
- The inflow region expands with the velocity $v_w$.
- $E_z$ develops until it reaches $E_z = -0.04B_0$ on the entire upstream boundary.
Expanding speed $v_w=0.6 \, v_{A0}$

This reconnection phenomenon clearly has a single X-point almost at the center in the PIC domain, and this position is at rest. The system is likely to transit to the steady state.
Expanding speed $v_w = 4.0 \nu_{A0}$

Intermittent magnetic reconnection with multiple X-points takes place. A magnetic island is formed, grows up, and moves in the downstream ($x$) direction.
<table>
<thead>
<tr>
<th>$v_w$</th>
<th>result</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.25 v_{A0}$</td>
<td>Single X-point</td>
</tr>
<tr>
<td>$0.35 v_{A0}$</td>
<td>Multiple X-point</td>
</tr>
<tr>
<td>$0.50 v_{A0}$</td>
<td>Single X-point</td>
</tr>
<tr>
<td>$0.60 v_{A0}$</td>
<td>Single X-point</td>
</tr>
<tr>
<td>$2.0 v_{A0}$</td>
<td>Multiple X-point</td>
</tr>
<tr>
<td>$3.0 v_{A0}$</td>
<td>Multiple X-point</td>
</tr>
<tr>
<td>$4.0 v_{A0}$</td>
<td>Multiple X-point</td>
</tr>
<tr>
<td>$5.0 v_{A0}$</td>
<td>Multiple X-point</td>
</tr>
</tbody>
</table>

- When the width of an MHD inflow increases slowly $v_w \leq v_{A0}$, we can see the tendency that magnetic reconnection with a single X-point is driven and the system seems to relax to the steady state.

- In the cases of $v_w \geq 2.0 v_{A0}$ a magnetic island is produced, i.e. intermittent reconnection with multiple X-points takes place.
The expanding speed of an MHD inflow controls the aspect ratio of the current sheet.

When the width of an MHD inflow increases slowly, the current sheet pushed is short. The region where reconnection points could emerge is limited to a small central region.

\[ \text{Single X-point} \]

In cases in which an MHD inflow expands fast, the current sheet pushed, i.e., the region where reconnection points could emerge becomes long.

\[ \text{Multiple X-points} \]
Comparing to the phase diagram

- Small $v_w$ of MHD inflows effectively corresponds to small $\lambda$, and large $v_w$ corresponds to large $\lambda$.
- Our result is consistent with the phase diagram of magnetic reconnection from a qualitative viewpoint at least.

$\lambda = L / d_i$

$L$: current sheet length

$d_i$: ion inertia length

$S$: Lundquist number

H. Ji and W. Daughton
Phys. Plasmas 18 (2011)111207
4. Summary and future work
Summary 1

- We have reported the first results on analysis of collisionless driven reconnection with a multi-hierarchy simulation model.

- In the multi-hierarchy model, real-space is divided into 3 parts:
  - **PIC** domain to solve microscopic physics
  - **MHD** domain to deal with macroscopic dynamics
  - **Interface domain** to commute the two domains

- We have successfully performed multi-hierarchy simulations of collisionless driven reconnection.
By using the multi-hierarchy model, we have investigated the influence of macroscopic dynamics on microscopic physics of magnetic reconnection.

- In cases of $v_w \leq v_{A0}$, magnetic reconnection with a single X-point is driven and the system is likely to relax to the steady state.
- In cases $v_w \geq 2.0v_{A0}$, reconnection dynamics are intermittent and multiple X-points appear.
Future work

- We will investigate the influence of MHD inflows on reconnection physics by using larger-scale simulations, in which the current sheet is longer.

- In some cases of MHD inflows, magnetic reconnection with more than two X-points will be driven.

- For applying to sawtooth oscillation, physics of magnetic reconnection in the presence of a guide magnetic field need to be investigated, since a strong guide (toroidal) field exists in fusion devices such as tokamak.

- Extended MHD-PIC interlocking
Thank you for your attention.