Multi-hierarchy simulation of magnetic reconnection
- first step of domain dynamic conversion -

National Institute for Fusion Science
S. Usami, H. Ohtani, R. Horiuchi

National Institute of Information and Communications Technology
M. Den
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1. Motivation

Why do we develop multi-hierarchy model?
Collisionless magnetic reconnection is one of the fundamental processes in which energy is converted from magnetic field to particles.

It plays an essential role in the rapid energy release in laboratory fusion device and astrophysical plasmas, etc.

Furthermore, of particular interest is an aspect of the coupling phenomenon between *multiple spatial and temporal scales*. *(multi-hierarchy phenomenon).*

**Macro:** Field topology changes on a macroscopic scale and global plasma transport takes place.

**Micro:** Electrical resistivity controlled by a microscopic process is necessary as a trigger.
Scale gap between macro and micro

- **LHD**
  - **Macro:** $\sim 1 \text{ m}$
  - **Micro:** $\sim 10^{-5} \text{ m}$

- **Earth magnetosphere**
  - **Macro:** $\sim 10^{6} \text{ km}$
  - **Micro:** $\sim 10 \text{ km}$

- **Solar flare**
  - **Macro:** $\sim 10^{4} \text{ km}$
  - **Micro:** $\sim 10^{-1} \text{ m}$
Is it possible to simulate magnetic reconnection in Earth magnetosphere using PIC model?


If PIC model with space grids comparable to electron size is applied to this problem, we need

\[ N_{pt} = 10^5 \times 10^5 \times 10^5 \times 30 = 3 \times 10^{16} \]

\[ \Rightarrow \text{CPU memory} = 4 \times 10^{18} = 4 \times 10^3 \text{ PetaByte} \]
The full understanding of magnetic reconnection process as a multi-hierarchy phenomenon is a big victory of human intelligence... I believe.

We develop multi-hierarchy simulation model to solve both microscopic and macroscopic physics consistently and simultaneously.

- **Micro**: particle (PIC) code
- **Macro**: MHD code

MARIS = MAgnetic Reconnection Interlocked Simulation
2. PIC simulation of magnetic reconnection
Steady reconnection (Pei et al.)

Physics of reconnection depends on the boundary conditions. Steady or Intermittted: Pei et al, PRL(2001)

Steady

Current density $J_z$ in 2D open system
Intermittent reconnection (Pei et al.)

Current density $J_z$ in 2D open system
Violation mechanism of frozen-in (Ishizawa et al.)

\[ E + \mathbf{v}_i \times \mathbf{B} / c \approx \frac{1}{en} \nabla \cdot \mathbf{P}_i + \frac{m_i}{e} \mathbf{v}_i \cdot \nabla \mathbf{v}_i \]

- The pressure tensor term is dominant.
- The pressure tensor term almost cancels out the inertia term.
- \( y > d_i \): MHD condition holds.

Profile of terms along the \( y \) axis passing through X point
3. Multi-hierarchy algorithm

How are MHD and PIC interlocked?
Our group has found the hierarchical structure of magnetic reconnection in the upstream direction.

- It depends on the distance from the reconnection point.
  - Kinetic
  - Intermediate
  - MHD (one-fluid)
Domain decomposition method

Larmor radius $\rho_L \propto \frac{1}{B(y)}$

$\rho \ll y$ (system spatial scale)

$\rho \gg y$ (cut of CPU and memory)

$\approx \text{Global Dynamics}$

$\approx \text{Where and how is micro-region connected to macro-region?}$

\begin{itemize}
\item Fine spatial and temporal resolutions
\item Behavior of each particles
\end{itemize}

\begin{itemize}
\item Coarse spatial and temporal resolutions
\item Global Dynamics
\end{itemize}
Domain decomposition method

Larmor radius $\rho_L \propto \frac{1}{B(y)}$

Where and how is micro-region connected to macro-region?

- **Microscopic region**
  - Fine spatial and temporal resolutions
  - Behavior of each particle

- **Macroscopic region**
  - Coarse spatial and temporal resolutions
  - Global Dynamics

(Cut of CPU and memory)
We connect PIC and MHD in the **upstream direction**, since MHD condition holds at the upstream \(y > d_i\).

- Three domains
  - PIC domain (micro)
  - MHD domain (macro)
  - interface domain

- Physics in the interface domain is solved by both PIC and MHD algorithms.
Macroscopic quantities

- Macroscopic quantity \((E, B, u, P, \rho)\) in the interface domain \(Q\) is given by a hand-shake scheme;

\[
Q_{\text{interface}} = F_Q Q_{\text{MHD}} + (1 - F) Q_{\text{PIC}}
\]

- \(Q_{\text{PIC}}\): Calculated only by PIC algorithm
- \(Q_{\text{MHD}}\): Calculated only by MHD algorithm
- \(F\) is an interconnection function.

\[
F = F(x, y, z)
\]

near MHD \(F \to 1\)

near PIC \(F \to 0\)
Microscopic quantities

- In order to solve physics in the interface domain by PIC algorithm, microscopic quantities such as individual particle positions and velocities are needed.
  - The degree of freedom in MHD: 8
  - The degree of freedom in PIC: nearly infinity

It is assumed that (shifted) Maxwellian distribution is satisfied in the interface domain (of course MHD domain, too)
4. Multi-hierarchy simulation of magnetic reconnection
Magnetic Reconnection (field line)
Magnetic Reconnection (field line)
Multi-hierarchy vs. PIC

\[ \mathbf{E} + \mathbf{v}_i \times \mathbf{B} / c \approx \frac{1}{en} \nabla \cdot \mathbf{\bar{P}}_i + \frac{m_i}{e} \mathbf{v}_i \cdot \nabla \mathbf{v}_i \]

Multi-hierarchy simulation

Pure PIC simulation

(c) Ion

- \( \mathbf{E}_z \)
- \( -\mathbf{v}_i \times \mathbf{B} |_{y=z} \)
- \( \nabla \cdot \mathbf{P}_i |_{y=z} \)
- \( \mathbf{v}_i \cdot \nabla \mathbf{v}_i |_{y=z} \)

\( 2l_{mi} \)

\( 2d_i \)
5. On going

Domain Dynamic Conversion
In nature, generally reconnection point moves with time dynamically. Therefore, region which has to be expressed by kinetic algorithm also would move.

We are developing method that automatically detects kinetic region (PIC domain) and converts calculation algorithm.
Initially, whole domain is MHD domain.

System detects reconnection point or its candidate.

Region containing this place is automatically converted from MHD to PIC domains.

If the position of reconnection point varies, system moves PIC domain.
Initially, whole domain is taken to be the MHD domain. When the conversion time passes, a part of MHD domain is converted to the PIC domain.
When should the conversion time be?

- We investigated the width of current layer and ion Larmor radius/skin depth with pure MHD simulation.

- Due to plasmas injected inward, the width of current layer is decreasing. When ion Larmor radius/skin depth is larger than width of current layer, kinetic effects play important role.

- Then we select $\omega_{ce}t = 3150$ as the conversion time.
  - $\omega_{ce}t < 3150$: MHD simulation
  - $\omega_{ce}t > 3150$: multi-hierarchy simulation
Simulation parameter

Simulation parameters

<table>
<thead>
<tr>
<th>Box size $/(c/\omega_{ce})$</th>
<th>$64.0 \times 159.75 \times 1.0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of grids</td>
<td>$256 \times 639 \times 4$</td>
</tr>
<tr>
<td>Number of particles</td>
<td>$2,000,000$ (initial)</td>
</tr>
<tr>
<td>$\omega_{pe}/\omega_{ce}$</td>
<td>$1.5$</td>
</tr>
</tbody>
</table>

Domain decomposition

- PIC domain: $|y/(c/\omega_{ce})|<15.875$
- Interface domain:
  $15.875<|y/(c/\omega_{ce})|<19.875$
- MHD domain: $19.875<|y/(c/\omega_{ce})|<79.875$
How much doe it save?

Comparing with PIC simulation for all the time and space, PIC load is 10%.

90% saving ...?
6. Summary and future work
We develop **multi-hierarchy simulation model** for complete understanding of magnetic reconnection.

Microscopic physics is described by the **PIC** algorithm, while macroscopic physics is expressed by the **MHD** algorithm.

We connect PIC and MHD in the upstream direction and successfully demonstrate collisionless driven reconnection.

Furthermore, we have succeeded in the first demonstration of based on both the **domain dynamic conversion method** and the domain decomposition method.
Future Work

- Improvement of domain dynamic conversion: method that automatically detects kinetic (PIC) domain.
- For above method, too, hierarchy-Interlock in the downstream direction.
- Investigation of reconnection process in detail with our multi-hierarchy simulation.