『22nd International Conference on Numerical Simulation of Plasmas (ICNSP2011)』（ September 7-9, 2011 , Long Branch, NJ, USA）

Anomalous resistivity in collisionless driven reconnection and its role in multi-hierarchy system

R. Horiuchi[1,2]

Collaborators : S. Usami[1], H. Ohtani[1,2], M. Den [3] and A. Kageyama[4]

1) National Institute for Fusion, Toki 509-5292, Japan
2) The Graduate University for Advanced Studies, Toki 509-5292, Japan
3) National Institute of Information and Communications Technology, Koganei 184-8795, Japan
4) Kobe University, Nada, Kobe 657-8501, Japan

Magnetic reconnection as multi-hierarchy phenomena in earth magnetosphere

Macro hierarchy

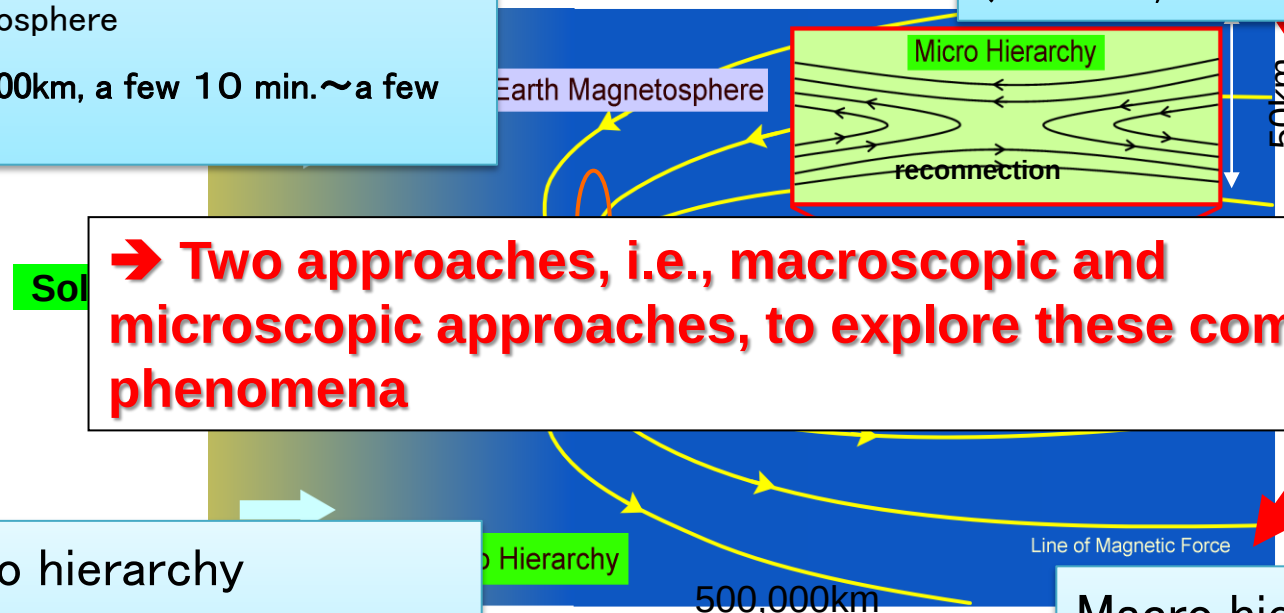
Interaction between solar wind plasmas and earth magnetosphere, plasma penetration into magnetosphere

(500,000km, a few 10 min.～a few hours)

Micro hierarchy

Fast energy conversion, generation of fast plasma outflow and plasmoid through magnetic reconnection

(10-100km, 1msec～a few sec)



➔ Two approaches, i.e., macroscopic and microscopic approaches, to explore these complex phenomena

Meso hierarchy

Magnetic substorm at earth polar regions

(10,000km,～10 min.)

Macro hierarchy

Propagation of plasmoid and fast plasma outflow in magnetosphere

(500,000km, a few 10 min.)

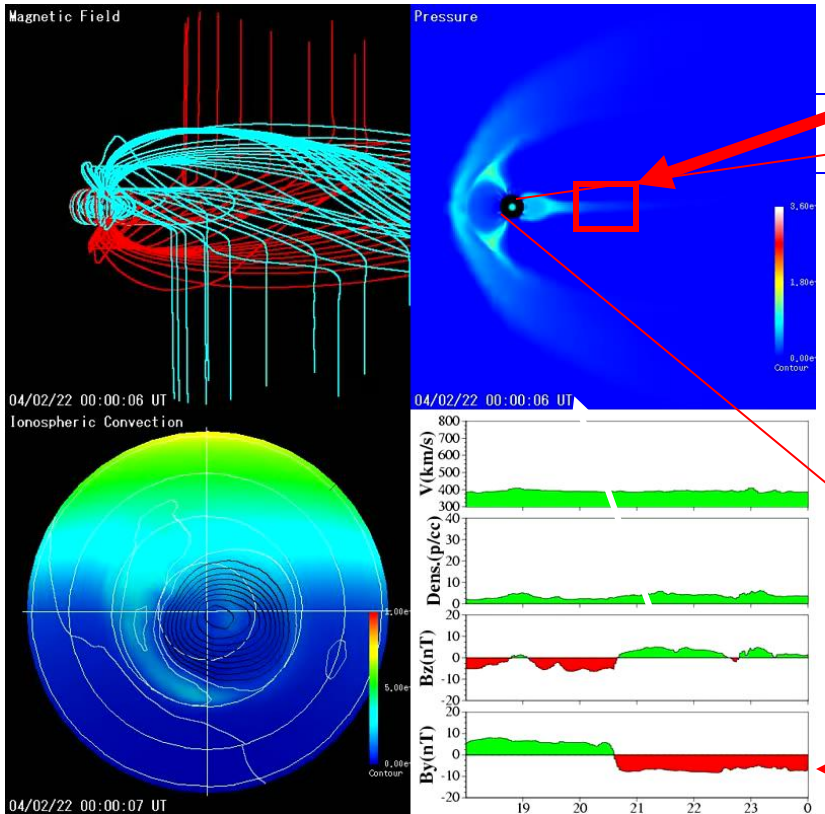
Contents

1. Two approaches to magnetic reconnection phenomena in nature
   - Macroscopic approach with anomalous resistivity which is introduced as a model of microscopic physics.
   - Microscopic approach surrounded by macroscopic hierarchy : microscopic open system is modeled
2. Multi-scale simulation for magnetic reconnection phenomena
   - Simulation model
     - Domain decomposition method
     - Multi-time step scheme
   - Applications
     - Propagation of Alfven wave
     - Plasma inflow problem
     - Collisionless driven reconnection
   - Future plan
3. Summary

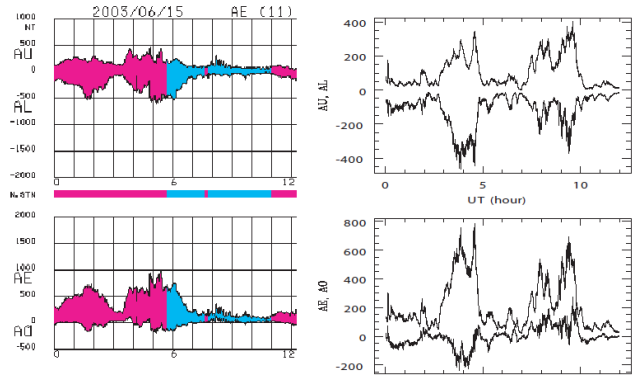
1.1 Macroscopic approach: Macroscopic MHD simulation of magnetic reconnection in earth magnetosphere

(Tanaka & Den)

1) Magnetic reconnection in magnetotail plays a crucial role in a substorm phenomenon.
2) This MHD model is developed for real time simulation of earth magnetosphere.
3) Check how MHD model can describe substorm phenomenon by assuming appropriate resistivity model. ➔ Qualitative behavior can be reproduced well.



Plasmoids are generated through magnetic reconnection



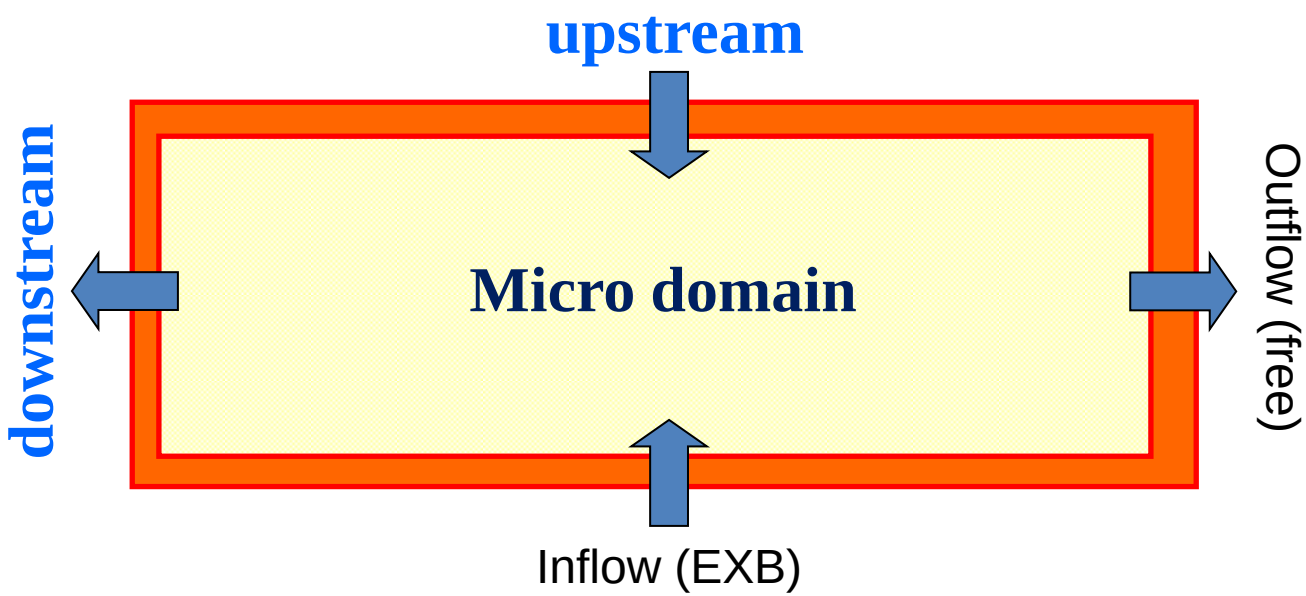
Activities of Ground Magnetic Field obtained from MHD Simulation Data

Real Time Data of Solar Wind

1.2 Microscopic approach to magnetic reconnection phenomena

PArticle Simulation code for Magnetic reconnection in an Open system (*PASMO*) :
[H. Ohtani, et al, PFR, 2009]

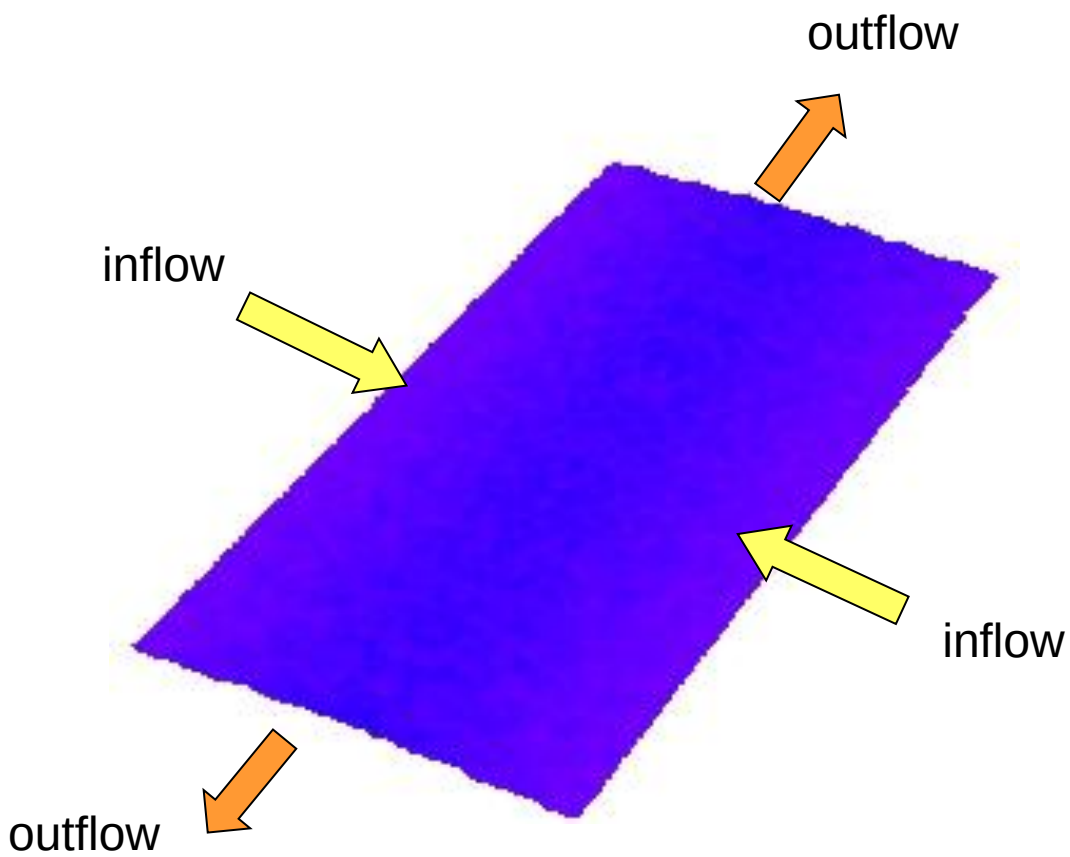
1. Code for microscopic open system, which is designed to connect with code for macroscopic system.
2. Upstream boundary: macroscopic information (T, v, B, E) → microscopic quantities
3. Downstream boundary: floating (free) condition



Steady reconnection is realized under some condition

Current density Jz in 2D open system (PASMO code, small input window size)

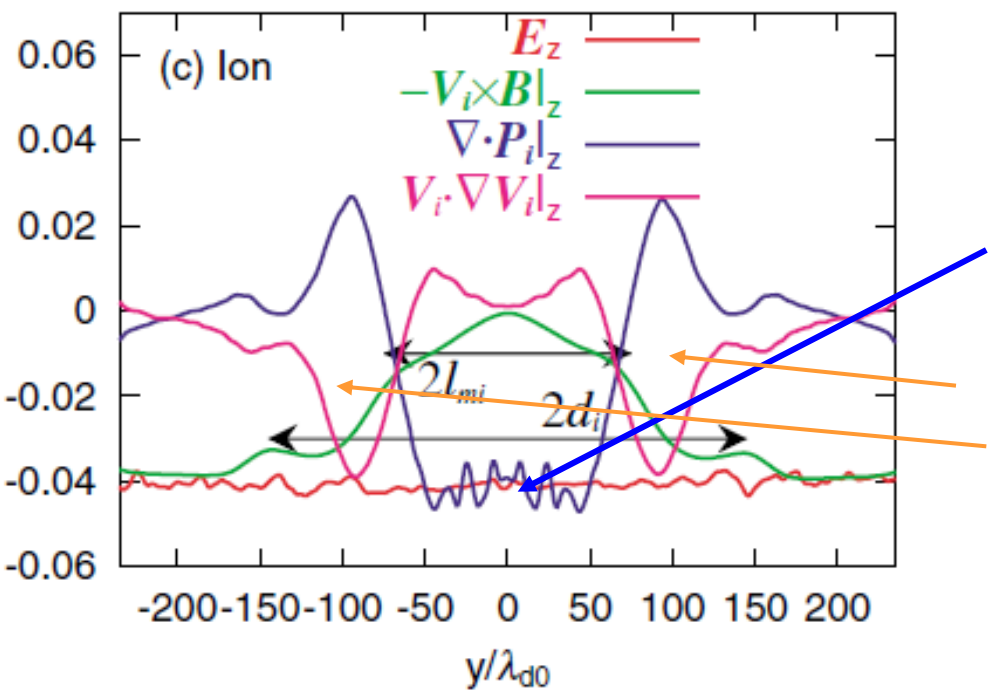
[W. Pei, et al, PRL, 2001]



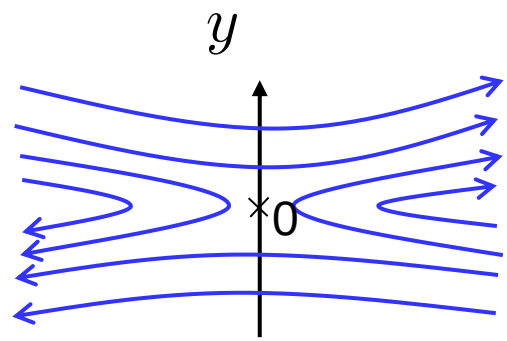
Frozen-in condition is violated due to meandering orbit effect (pressure tensor term)

[A. Ishizawa, et al, PRL 2005]

$$\boldsymbol{E} + \boldsymbol{v}_i \times \boldsymbol{B} / c \approx \frac{1}{en} \nabla \cdot \overleftrightarrow{\boldsymbol{P}}_i + \frac{m_i}{e} \boldsymbol{v}_i \cdot \nabla \boldsymbol{v}_i$$

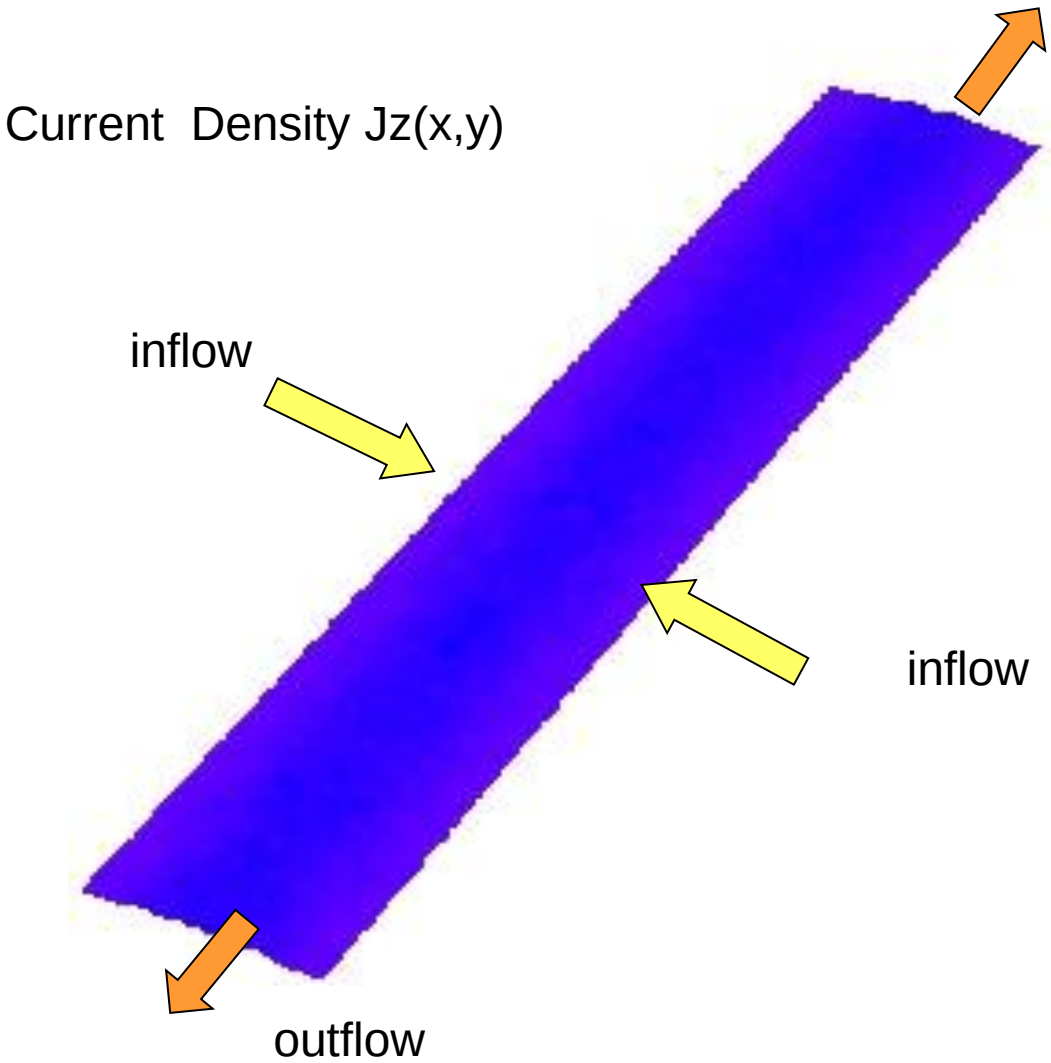


Profile of terms along the y axis passing through X point



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

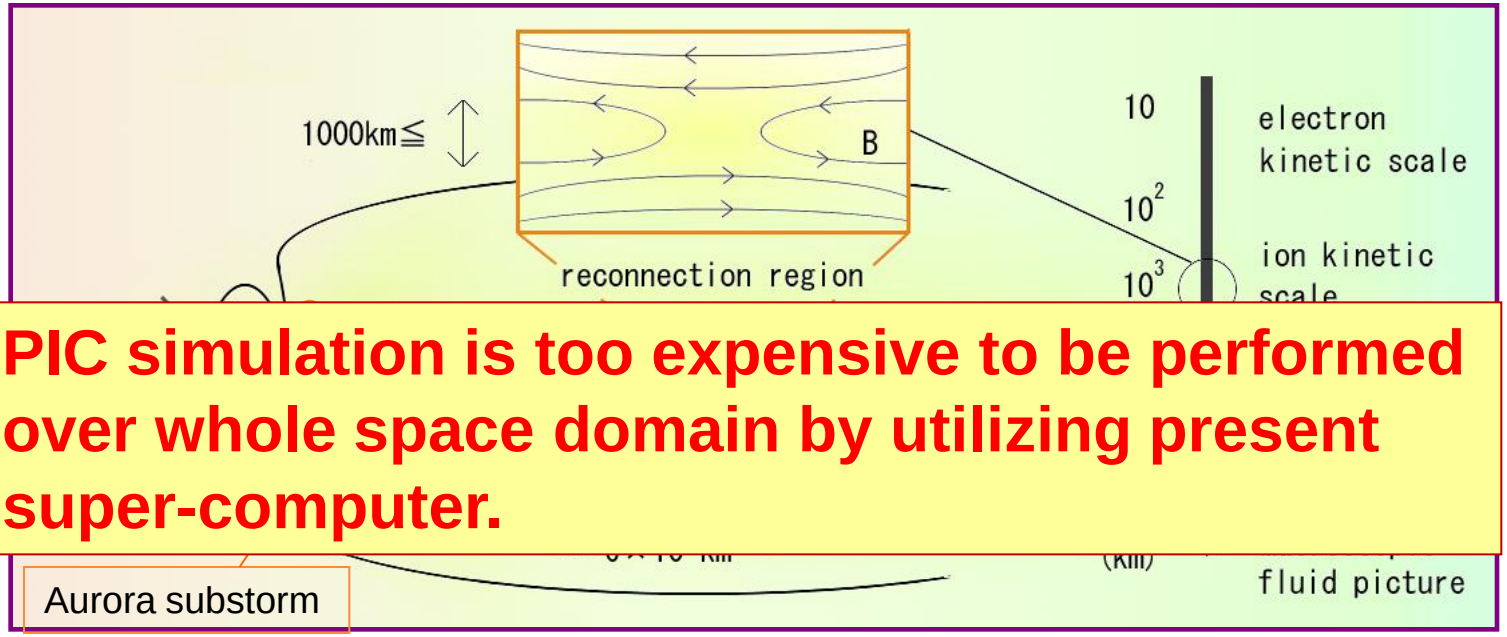
Intermittent reconnection occurs for upstream boundary condition with a wide window size



Microscopic dynamical behavior of the reconnection system is deeply coupled with macroscopic physics, which is described as upstream boundary conditions in this model.

Is it possible to simulate magnetic reconnection in earth magnetosphere using PIC model ?

Magnetic substorm in earth magnetosphere



PIC simulation is too expensive to be performed over whole space domain by utilizing present super-computer.

A.T.Y.Lui Tutorial on Geomagnetic Storm and Substorm ,IEEE trans on Plasma Physics ,**28**,1854(2002)

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

$$N_{pt} = 10^5 \times 10^5 \times 10^5 \times 30 = 3 \cdot 10^{16}$$

$$\Rightarrow \text{CPU memory} = 4 \cdot 10^{18} = 4 \cdot 10^3 \,\text{PetaByte}$$

2. Multi-scale simulation for magnetic reconnection phenomena

1. Microscopic physics

Excitation of magnetic reconnection needs a microscopic process, which leads to the generation of electric resistivity, such as wave-particle interaction, a binary collision, etc.

➔ Kinetic model

2. Macroscopic physics

Magnetic reconnection results in global plasma transport and global change of field topology. Dynamical behavior of the reconnection system is strongly coupled with an external system (macroscopic world).

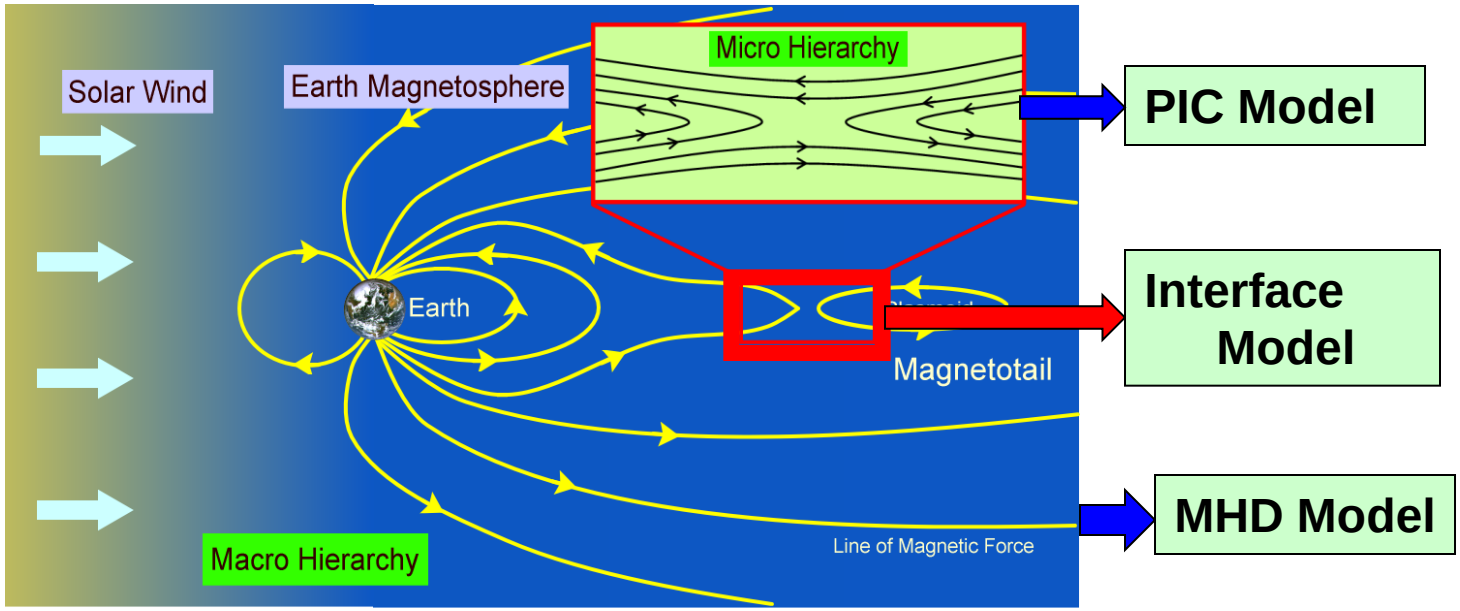
➔ MHD model

3. Multi-scale simulation model to solve both microscopic physics and macroscopic physics consistently and simultaneously is needed for full understanding of magnetic reconnection.

MARIS (MAgnetic Reconnection Interlocked Simulation) project

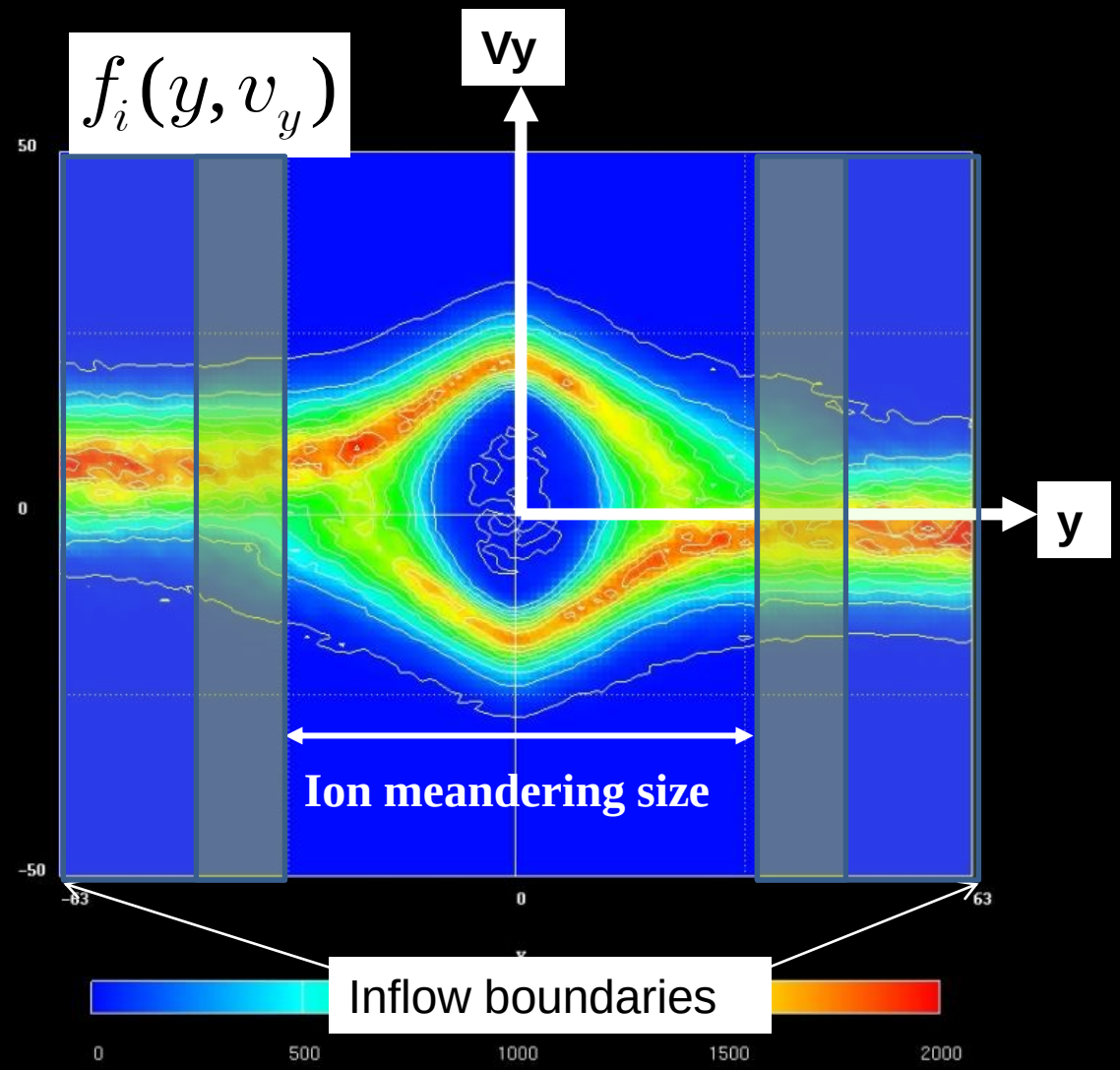
Multi-hierarchy simulation model to interlock three different simulation models based on domain decomposition method

1. **MHD model to describe global dynamics of reconnection phenomena,**
2. **PIC model to describe the microscopic processes in the vicinity of reconnection point, and**
3. **interface model to describe the interaction between micro and macro hierarchies.**



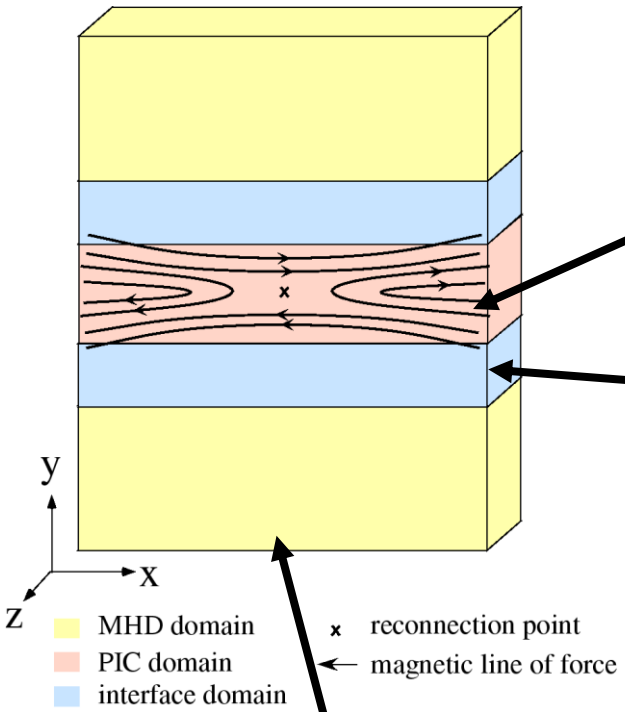
Ion distribution function along inflow direction (y—axis) from PIC simulation data [R. Horiuchi, et al, CiCP 2008]

1. Distribution is largely modified due to meandering effect inside meandering orbit size. ➔ **PIC model**
2. Distribution remains shifted-Maxwellian at outside of meandering orbit size. ➔ **MHD model**
3. **Interface domain** is inserted into PIC-side region of MHD domain for numerical stability.



Simulation domains for multi-scale model

[S. Usami, et al, CiCP 2008.]



PIC domain

$$\boldsymbol{B}, \boldsymbol{E},$$

$$\boldsymbol{v}_j, \boldsymbol{x}_j \text{ (particles)}$$

Interface domain

Macroscopic quantity ($\boldsymbol{E}$, $\boldsymbol{B}$, $\boldsymbol{u}$, P, ρ) in the interface domain Q is given by a **hand-shake scheme**;

$$Q_{\text{interface}} = aQ_{\text{MHD}} + (1-a)Q_{\text{PIC}}$$

New data for MHD

$$\boldsymbol{B}, P, \rho,$$

$$\boldsymbol{u}(\text{fluid})$$

New data for PIC

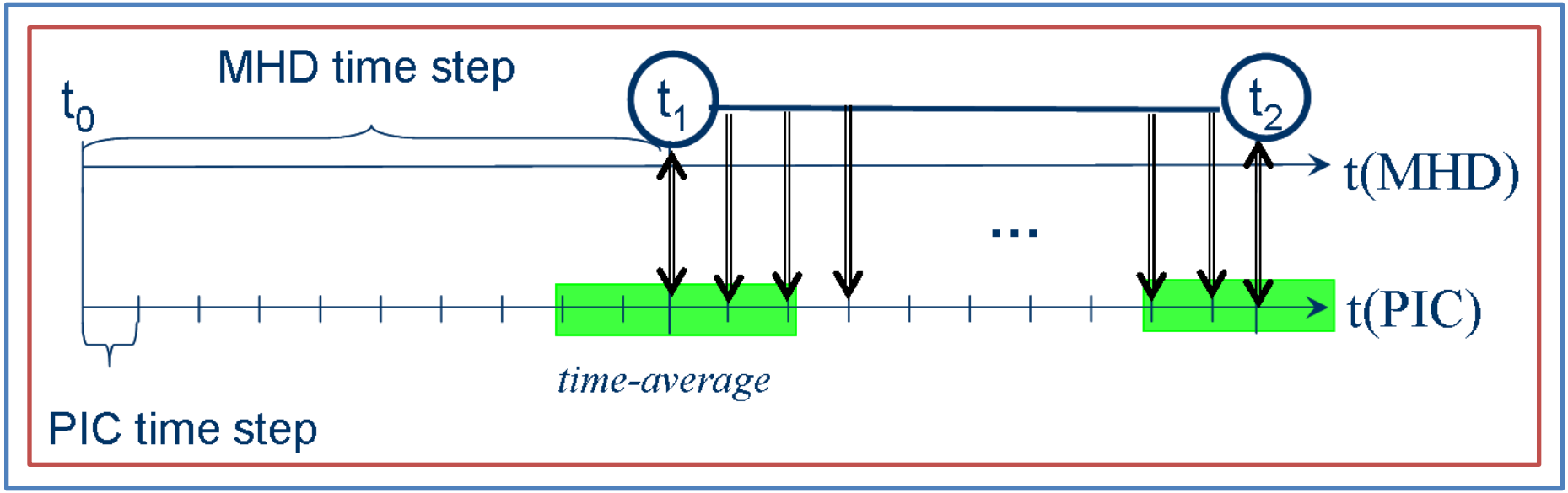
$$\boldsymbol{B}, \boldsymbol{E},$$

$$\boldsymbol{v}_j, \boldsymbol{x}_j$$

MHD domain

$$\boldsymbol{B}, P, \rho, \boldsymbol{u}(\text{fluid})$$

2.1.B Multi-time step scheme for advancing time



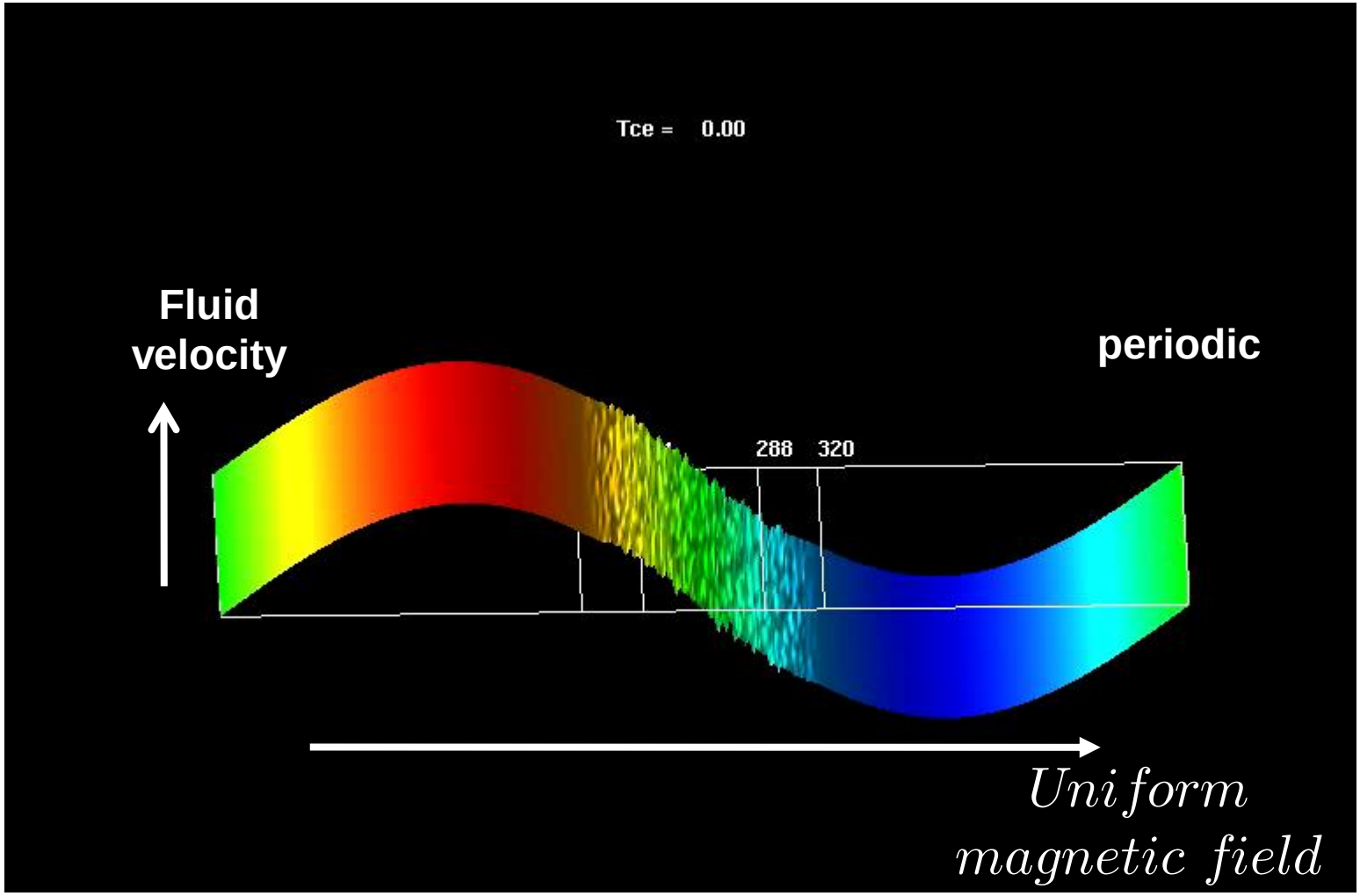
Large time step is for MHD, and small one is for PIC. From t_1 to t_2, PIC receives interpolated data at t_1 and at t_2 from MHD. On the other hand, PIC data averaged over several steps around t_1 is sent to MHD at t_1.

Multi-scale model has been developed step by step by examining numerical applicability

1. **Propagation of 1D Alfven wave**
2. **Plasma inflow from upstream boundary towards reconnection region ➔ upstream interlocking model**
3. **Excitation of collisionless reconnection ➔ first demonstration**
4. High velocity outflow from reconnection region ➔ downstream interlocking model

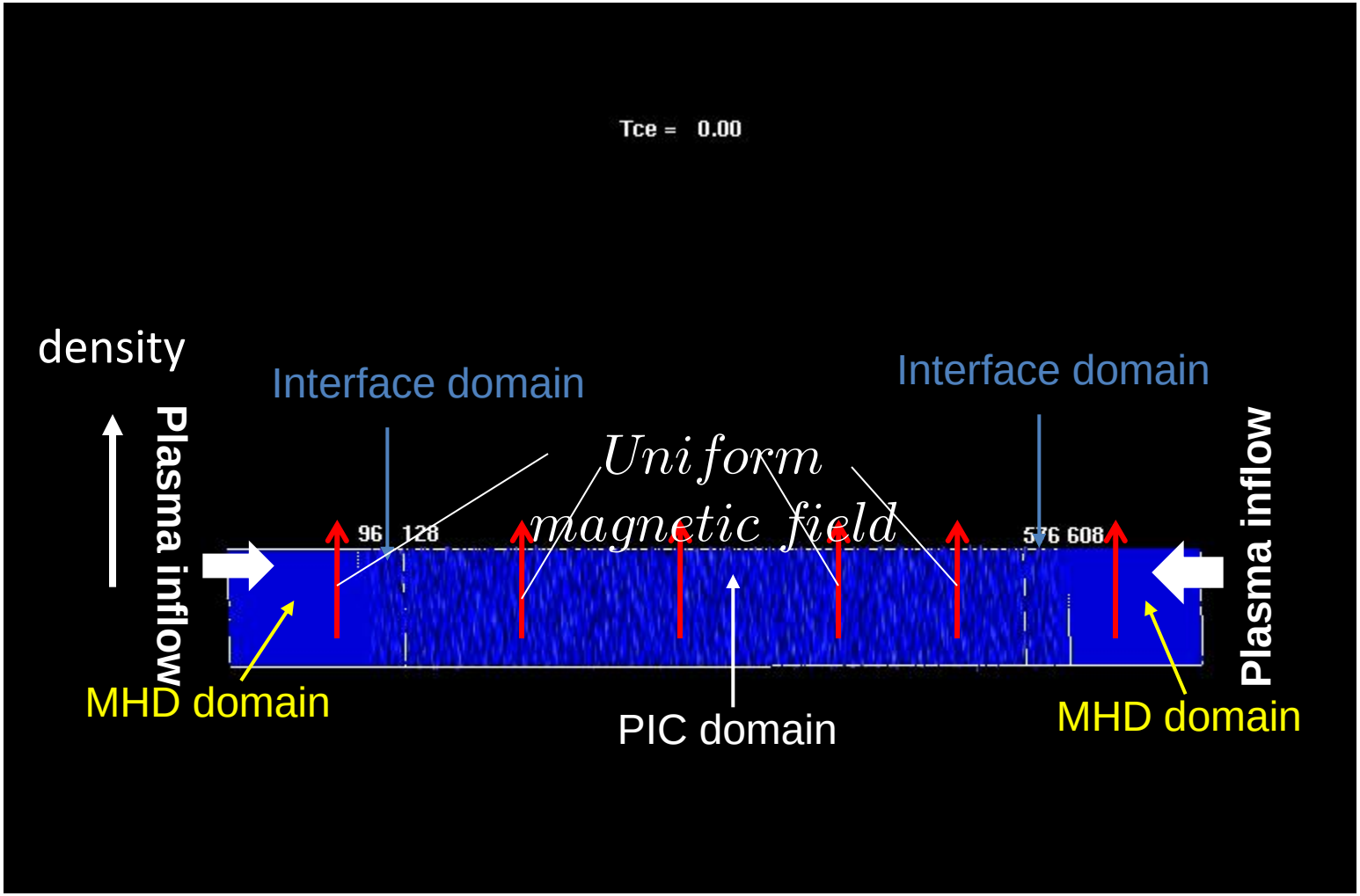
Multi-Scale Simulation of 1D Alfven wave

[Horiuchi et al, PFR 2010]



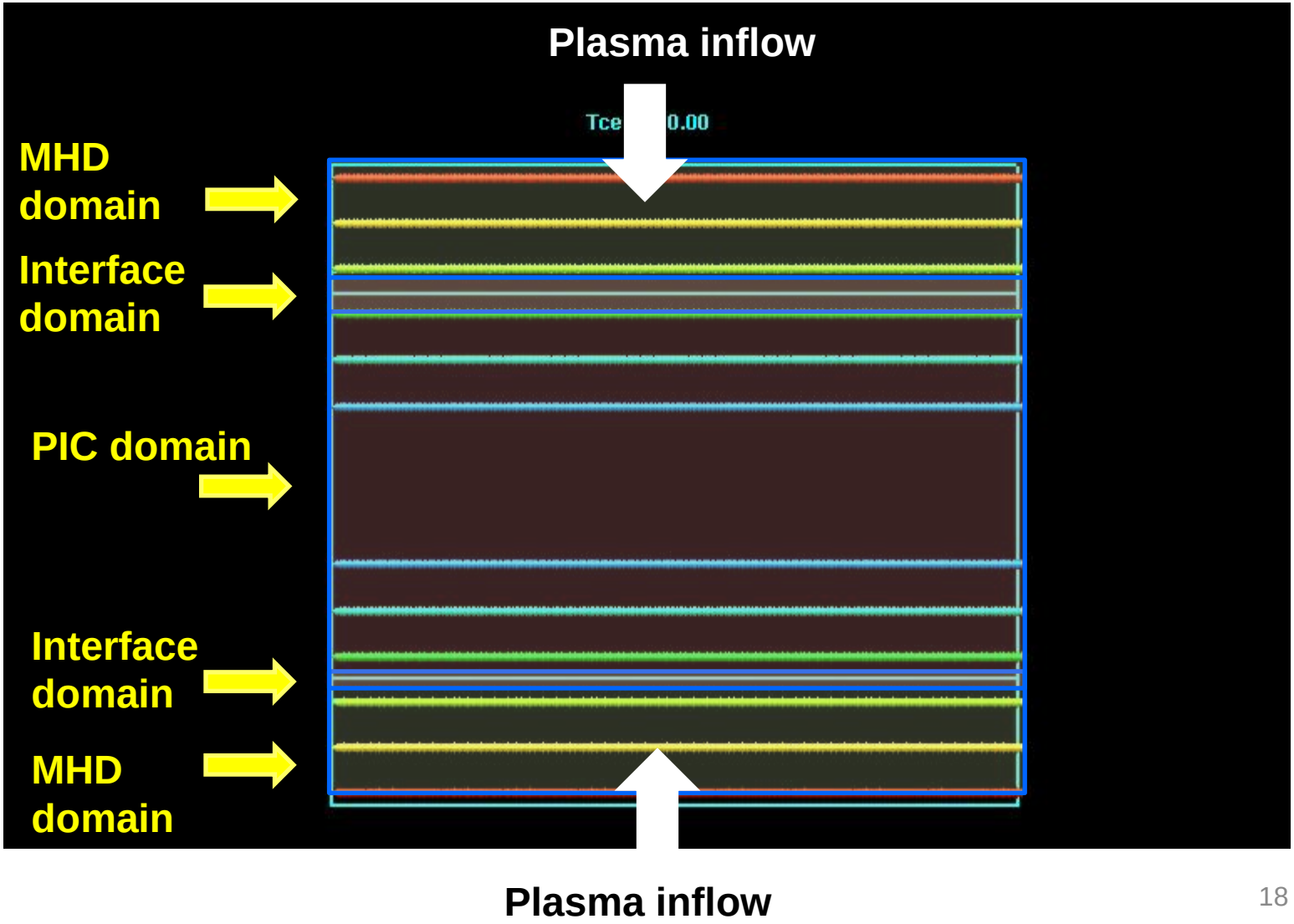
Multi-Scale Simulation of Plasma inflow

[Usami et al, CiCP 2011]



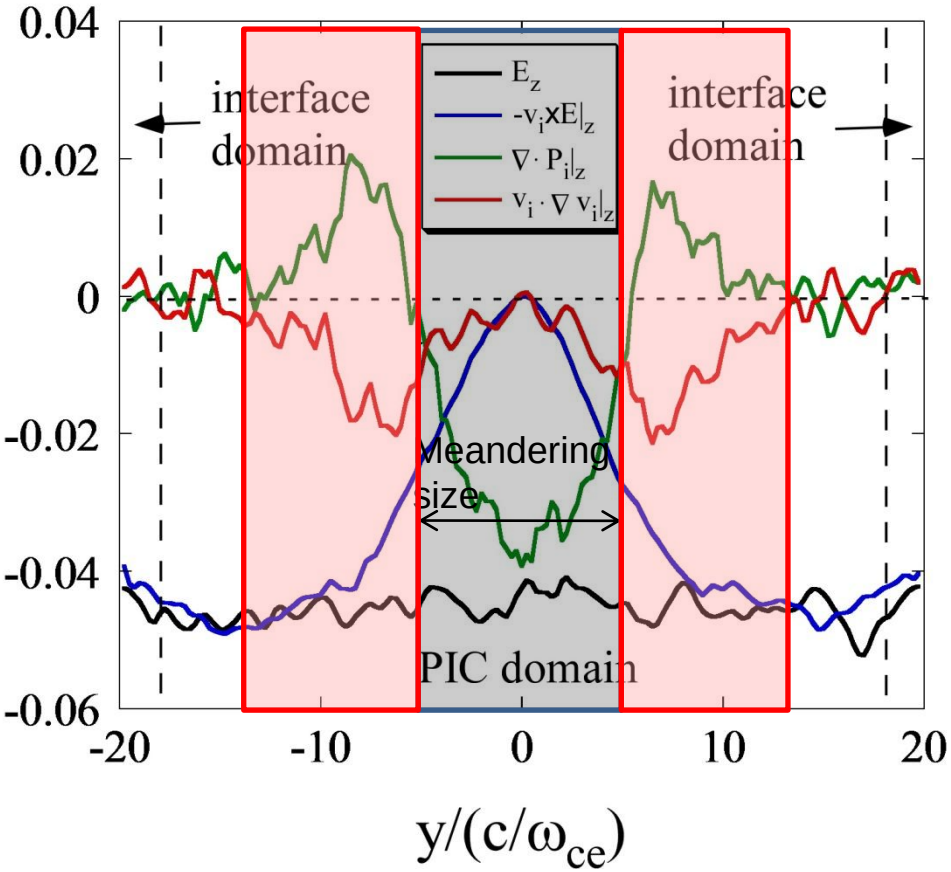
Multi-Scale Simulation of Collisionless Driven Reconnection

[Usami et al, PFR 2009]

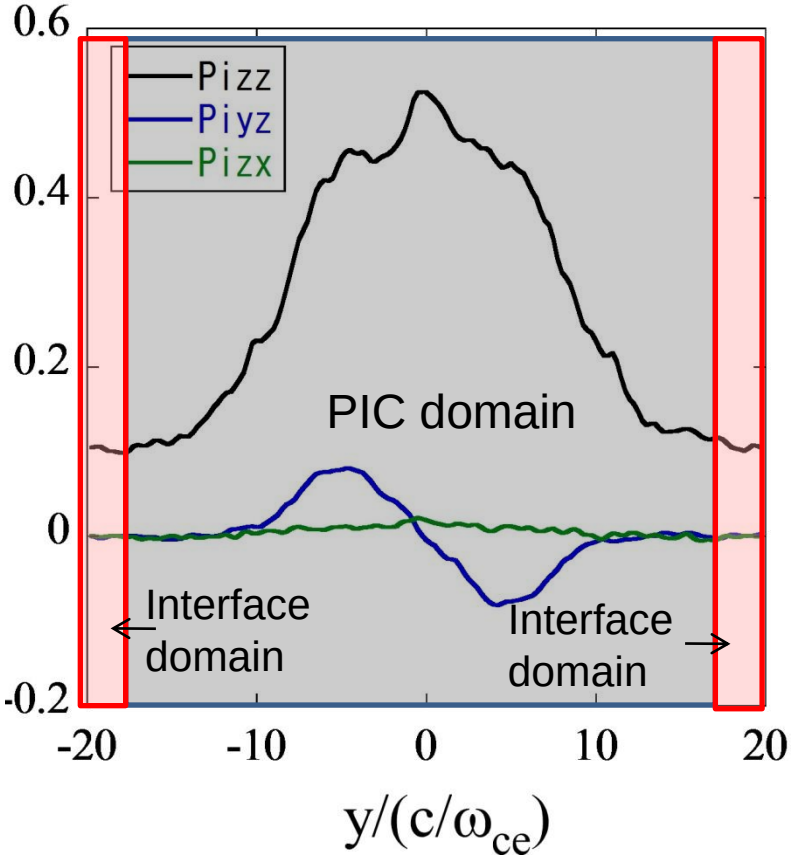


Check of numerical applicability of multi-scale model

Ion force balance



Pressure Tensor components



From the comparison with full PIC simulation data it is confirmed that reconnection process is described correctly.

Case of Non-uniform mesh

- All results shown until now have uniform mesh through MHD, PIC, and interface domains.
- Several days ago, we have just succeeded in performing multi-hierarchy model with non-uniform mesh.

Micro Hierarchy

3. Future Plan

Our final goal is to apply our multi-hierarchy model to various magnetic phenomena in nature by utilizing present supercomputers.

3.1 Two big problems in future directions

(1) Is Multi-hierarchy model effective to explore magnetic reconnection phenomena in Nature?

➔ How much CPU memory or CPU time is reduced to by utilizing multi-hierarchy model?

(2) Is it possible to develop an interlocking model along downstream direction? 🡸 This is because particle distribution may be modified largely from Maxwllian due to fast plasma outburst as a result of magnetic reconnection.

Summary

1. We have disclosed **two approaches** of collisionless reconnection, i.e., (1) macroscopic approach (2)microscopic approach
2. We have recently developed **multi-scale simulation model** for magnetic reconnection in an open system, which can describe macroscopic physics and microscopic physics self-consistently and simultaneously.
   - ① Three models are interconnected based on **domain decomposition method**, i.e., MHD model to describe global dynamics of reconnection phenomena, PIC model (PASMO) to describe the microscopic processes in the vicinity of reconnection point, and interface model with a finite width to describe the interaction between micro and macro hierarchies. [1]
   - ② In order to check **numerical applicability** of multi-scale simulation model, we have applied it to the propagation of linear Alfven wave and plasma inflow from the upstream boundary to PIC region. And we have confirmed that it works well. [1-3]
   - ③ Next, we **applied our multi-scale simulation model to collisionless driven reconnection**. It is confirmed from the comparison with PASMO simulation data that collisionless driven reconnection is described physically correctly. [4,5]

Reference

[1] S. Usami, H. Ohtani, R. Horiuchi, and M. Den, *Comm. Comput. Phys,Vol.4,* (2008) 537.
[2] R. Horiuchi, S. Usami, H. Ohtani, and M. Den, *J. Plasma Fusion Res. Series* vol. 8 (2009) 184.
[3] S. Usami, H. Ohtani, R. Horiuchi, and M. Den, *Comm. Comput. Phys.* in press.
[4] S. Usami, H. Ohtani, R. Horiuchi, and M. Den, *Plasma Fusion Res. Vol. 4* (2009) 049.
[5] R. Horiuchi, S. Usami, H. Ohtani, and T. Moritaka, *Plasma Fusion Res. Vol. 5* , (2010) S2006.