Magnetic Reconnection in Large and Fully Kinetic System

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Introduction of myself

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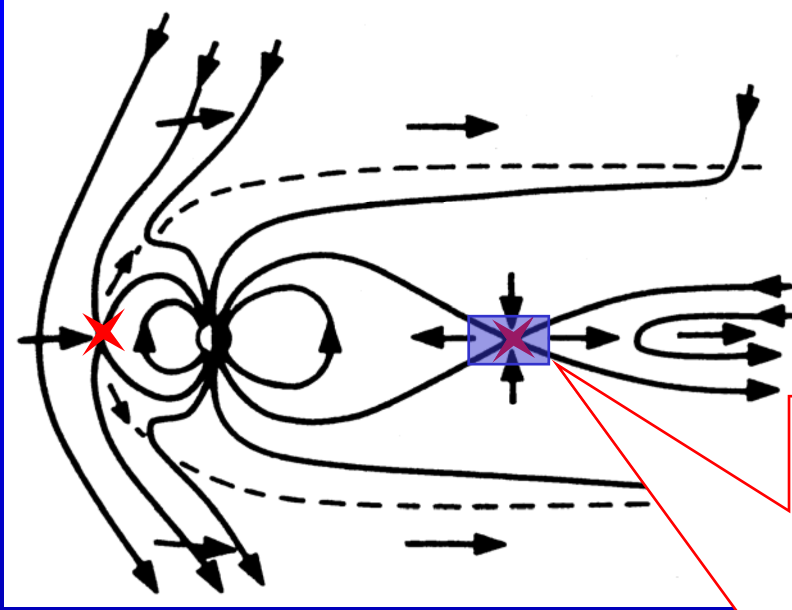
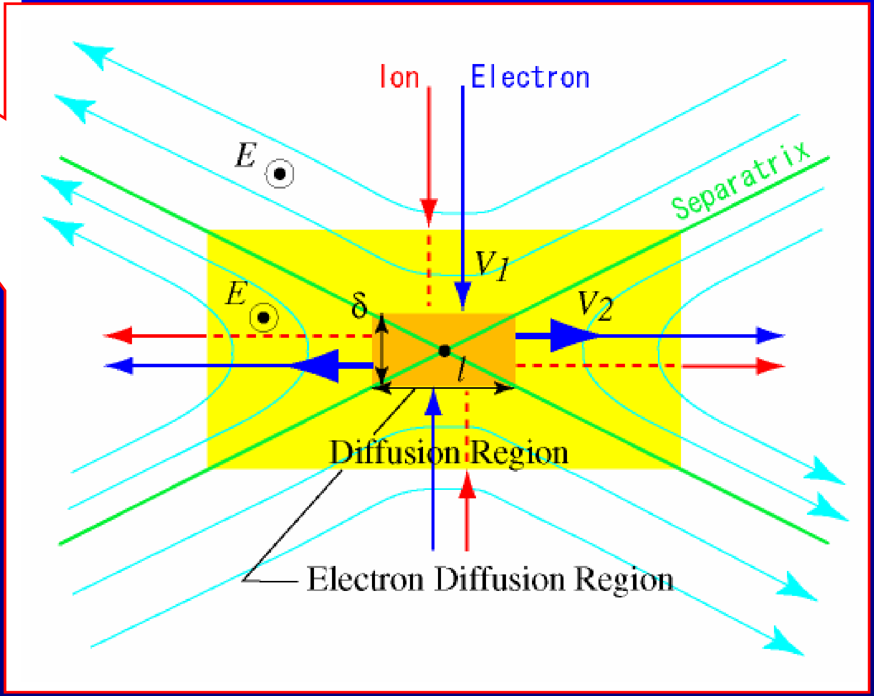
Introduction



(*Cowley*, 1985)

Non-MHD processes can affect MHD-scale dynamics.



Ion and electron-scale processes are coupling and determine the MHD-scale structure.

Introduction

- Main issues on magnetic reconnection in solar flares and magnetospheric substorm

1. What is the mechanism to quickly initiate reconnection?

   ➡ When and where can reconnection be triggered in the systems of interest?

2. What is the mechanism to support a quasi-steady fast reconnection?

   ➡ Is it possible to explain the energy release associated with solar flares and magnetospheric substorm by reconnection alone?

3. How and where can plasmas be accelerated and heated?

   ➡ What is the energy transport processes associated with reconnection?

Introduction

- What is the fast reconnection?

Fast reconnection: $E_y \sim 0.1\ V_{A0}B_0$
(V_{A0}, B_0: Alfven velocity and magnetic field in the lobes.)

- Within 10 minutes, about 15 Re of magnetic flux in lobes can be reconnected in the Earth magnetotail.

- Within 50 seconds, most of the magnetic field in the flux tube with an area 10^{18} cm^2 and a length 10^9 cm can be reconnected in the solar flares.

Introduction

- Quasi-steady models of fast reconnection

✓ MHD model: $E_y \simeq (\pi/8)[\ln(M_A^2 R_m)]^{-1}$ [*Petschek*, 1964]

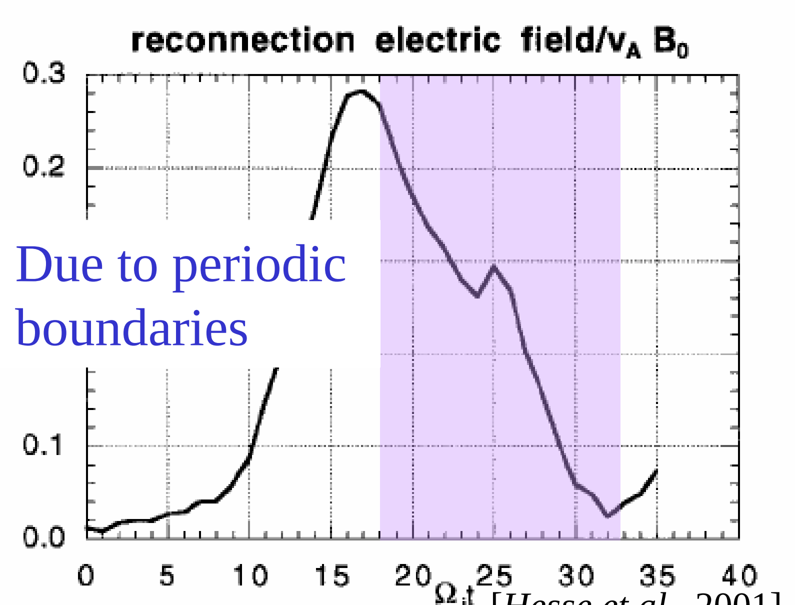
✓ Kinetic model（GEM Reconnection Challenge, 2001）:

Inside the electron diffusion region

$$E_y \simeq -\frac{1}{n_e e}(\nabla \cdot \boldsymbol{P}_e)_y - \frac{m_e}{e}(\boldsymbol{V}_e \cdot \nabla)V_{ey}$$

Outside the electron diffusion region

$$E_y \simeq \frac{1}{n_e e}(\boldsymbol{J} \times \boldsymbol{B})_y$$



Due to periodic boundaries

[*Hesse et al.*, 2001]

Inclusion of the Hall term is sufficient condition for fast reconnection. [e.g., *Birn et al.*, 2001]

However, steady-state reconnection is not achieved.

Motivation

It is necessary to perform a large-scale kinetic simulation of magnetic reconnection in order to check whether or not the Hall effects are sufficient for a steady-state fast reconnection.

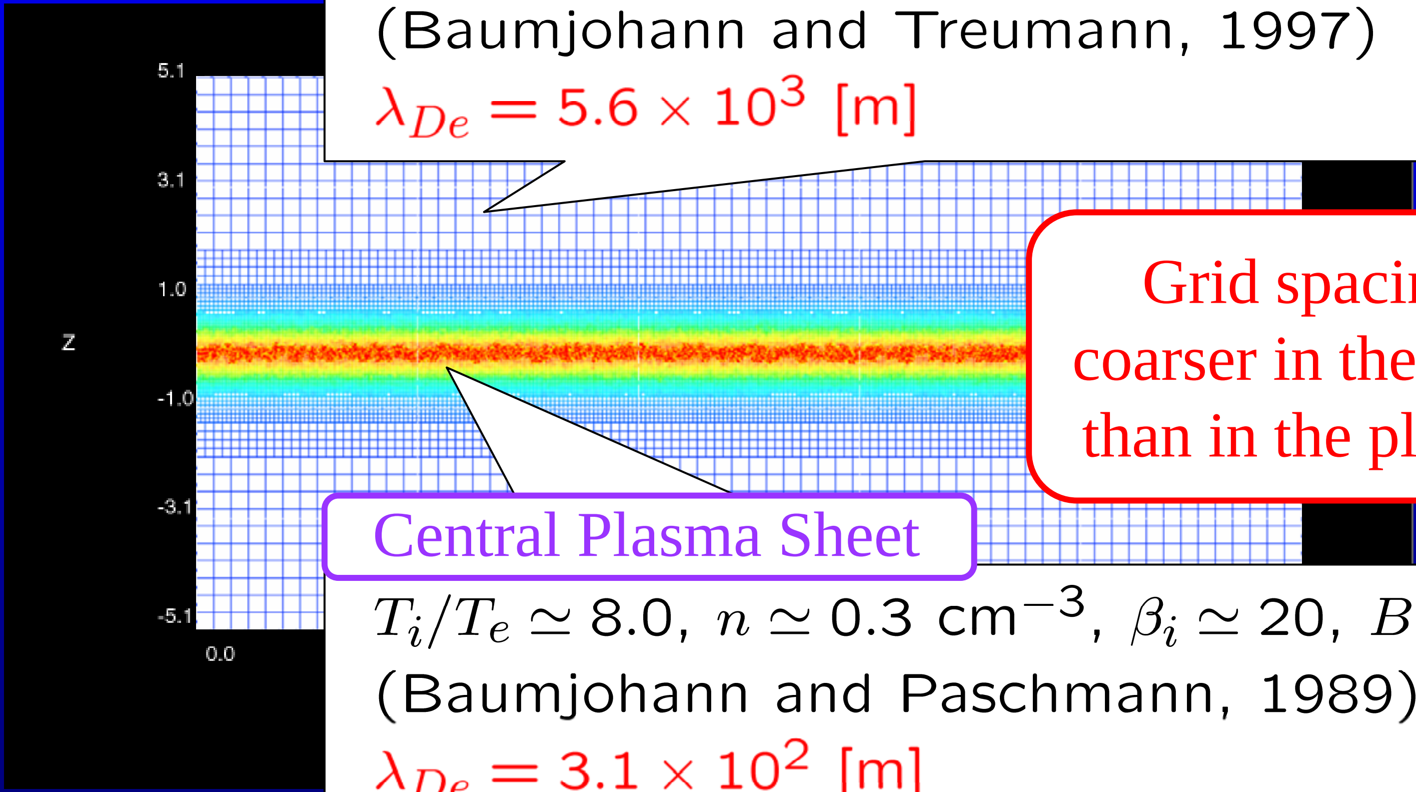
However, it is still difficult to conduct large-scale simulations using conventional particle-in-cell (PIC) codes because of limited computer resources.

In this study, I have constructed a new EM PIC code using adaptive meshes and succeeded to perform efficient kinetic simulations.

EM code with adaptive mesh refinement (AMR) technique

Restriction in full particle code: $\Delta x \lesssim 3\lambda_{De} \sim 1km$

[*Birdsall & Langdon*, 1995]



Magnetotail Lobe

$T_i/T_e \simeq 4.0$, $n \simeq 0.01$ cm^{-3}, $\beta_i \simeq 0.1$, $B = 30$ nT.
(Baumjohann and Treumann, 1997)
$\lambda_{De} = 5.6 \times 10^3$ [m]

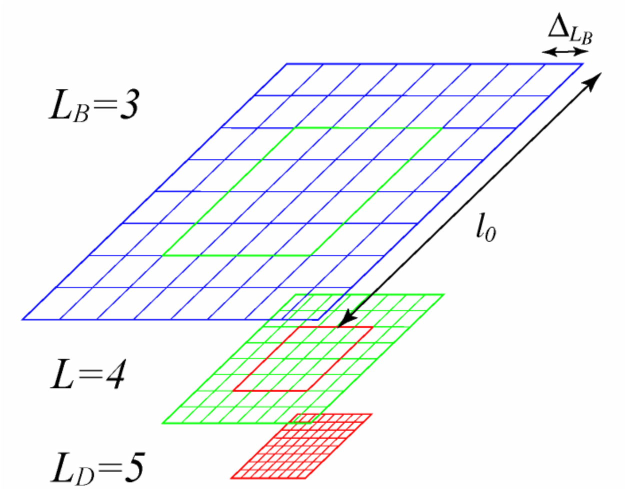
Grid spacing can be coarser in the lobe region than in the plasma sheet.

Central Plasma Sheet

$T_i/T_e \simeq 8.0$, $n \simeq 0.3$ cm^{-3}, $\beta_i \simeq 20$, $B = 5$ nT.
(Baumjohann and Paschmann, 1989)
$\lambda_{De} = 3.1 \times 10^2$ [m]

EM code with adaptive mesh refinement (AMR) technique

AMR technique



Particle splitting algorithm

$\Delta r = \Delta_L / N^{1/2}$

N: Number of particles in the cell.

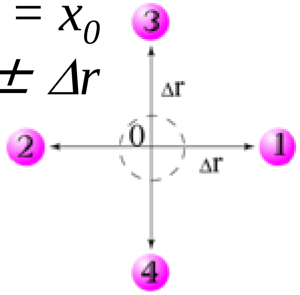
$x_{1,2} = x_0 \pm \Delta r;\ x_{3,4} = x_0$

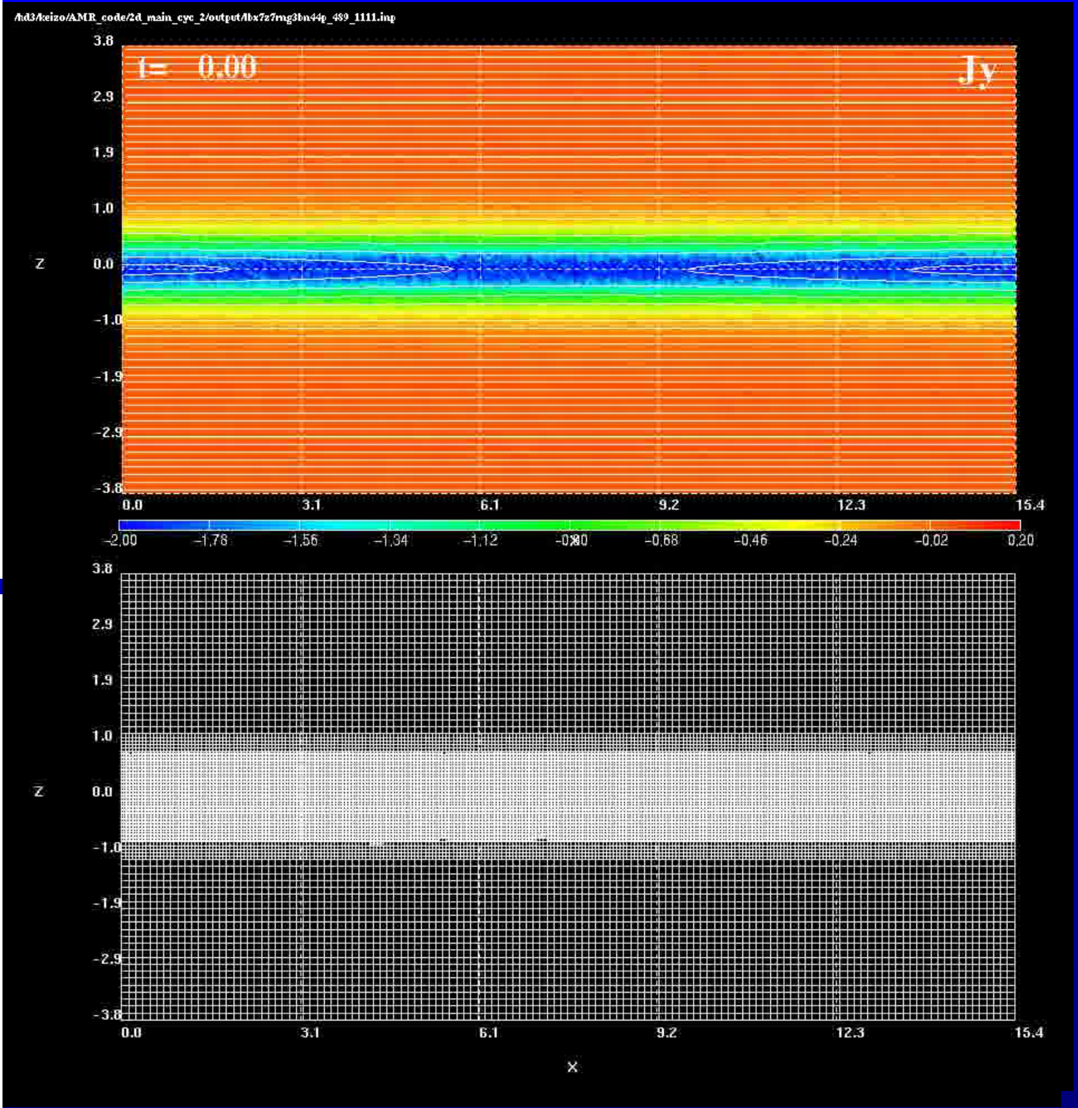
$y_{1,2} = y_0;\ y_{3,4} = y_0 \pm \Delta r$

$\mathbf{V}_{1,2,3,4} = \mathbf{V}_0;$

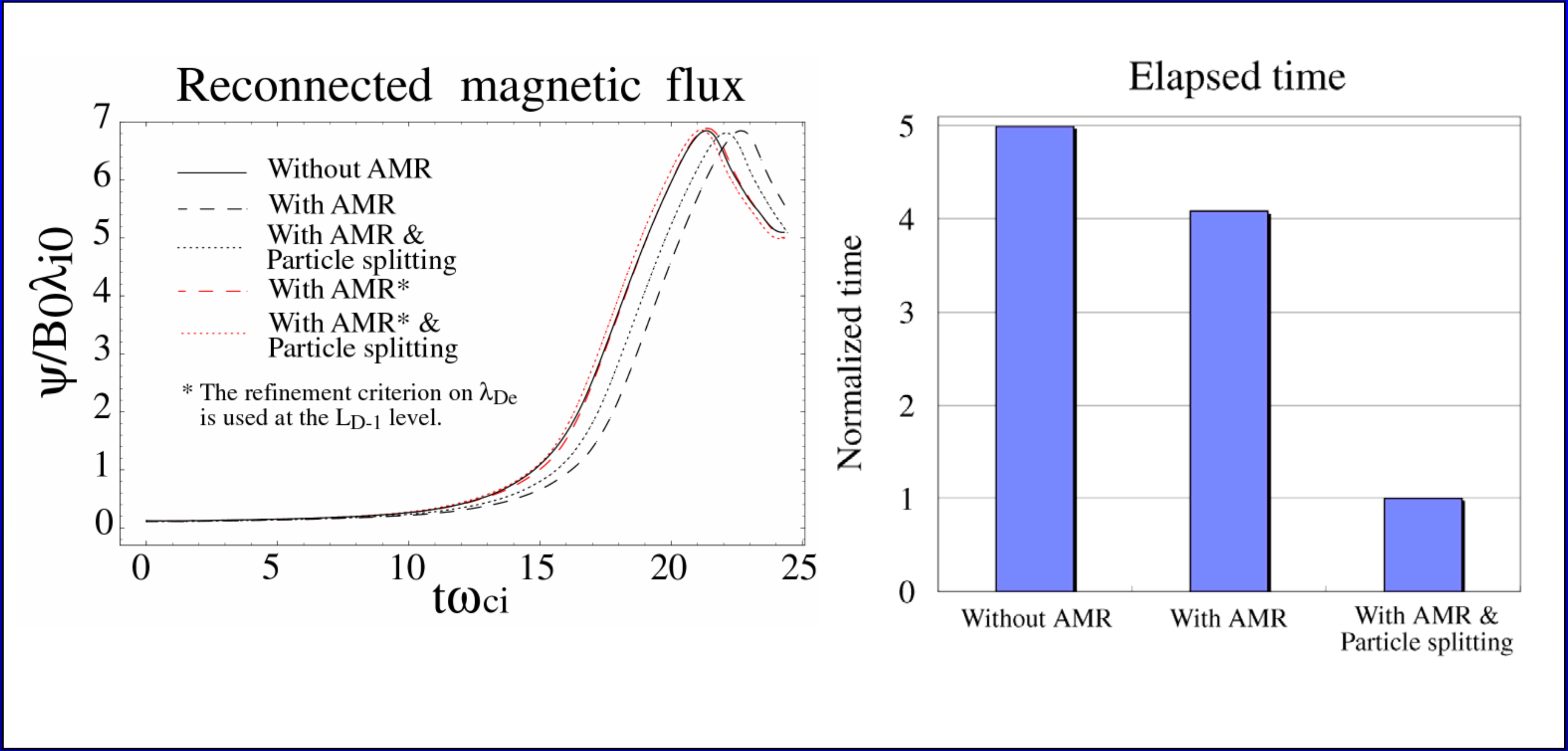
$q_{1,2,3,4} = q_0/4;$

$m_{1,2,3,4} = m_0/4$





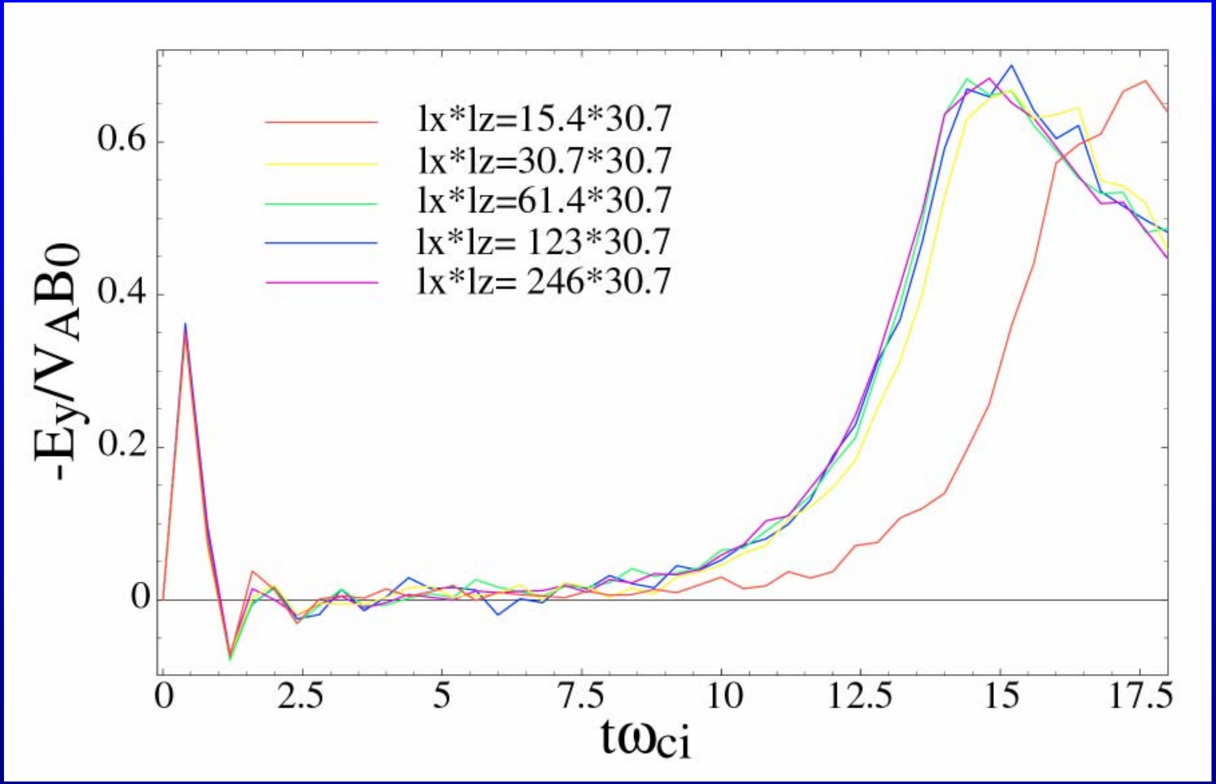
EM code with adaptive mesh refinement (AMR) technique



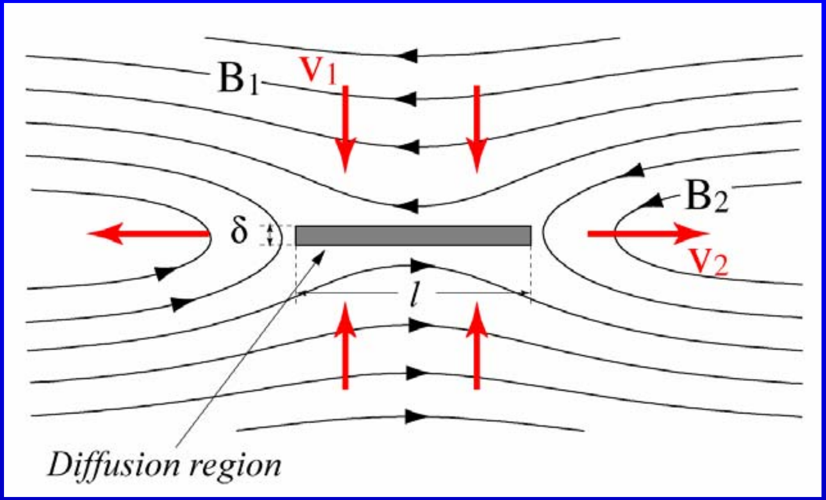
$$\psi = \int_0^{l_x} |B_z(x, z = 0)|\, dx$$

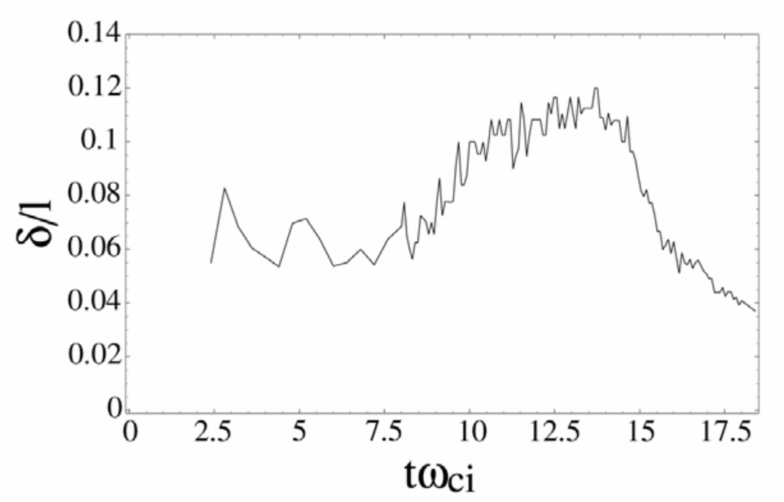
Time evolution of the reconnection rate

$$\frac{\partial \psi}{\partial t} = -E_{y,xline}$$



Why do the reconnection rate decrease?



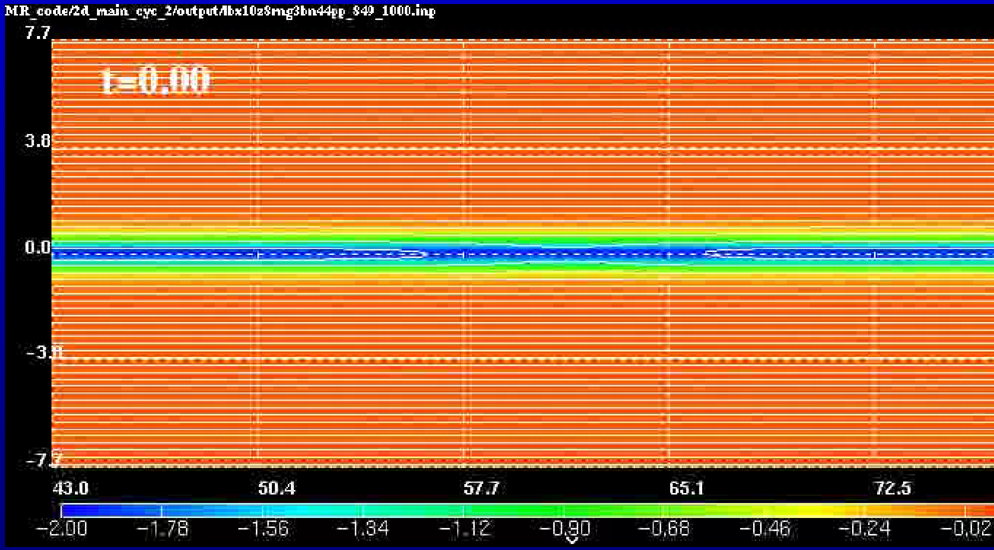


$$B_1^2/2\mu_0 \simeq n m_e V_2^2/2$$

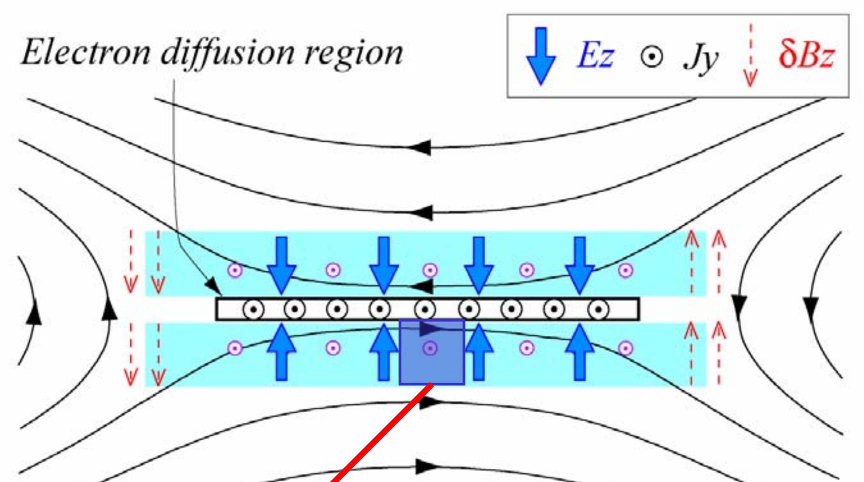
$$V_2 \simeq B_1/\sqrt{\mu_0 n m_e} = V_{Ae}$$

$$lV_1 \simeq \delta V_2, E_y = V_1 B_1$$

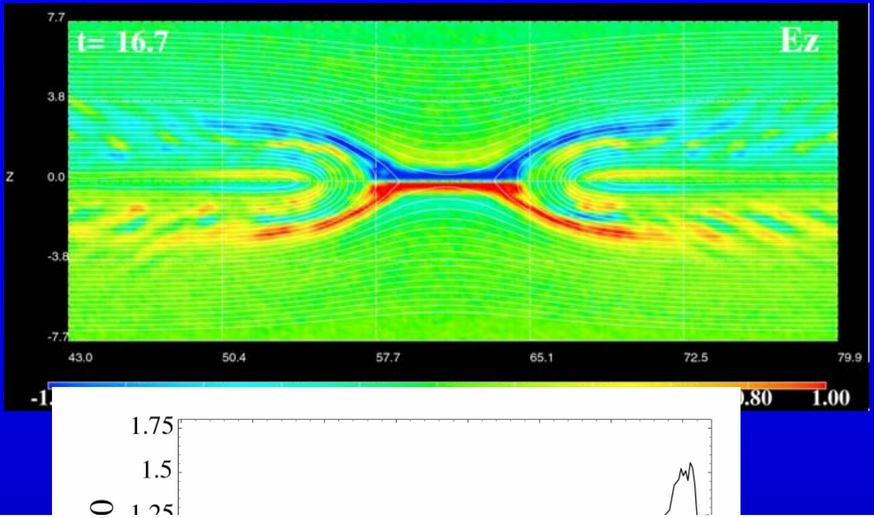
$$\boxed{E_y \sim (\sigma/l) V_A B_1}$$

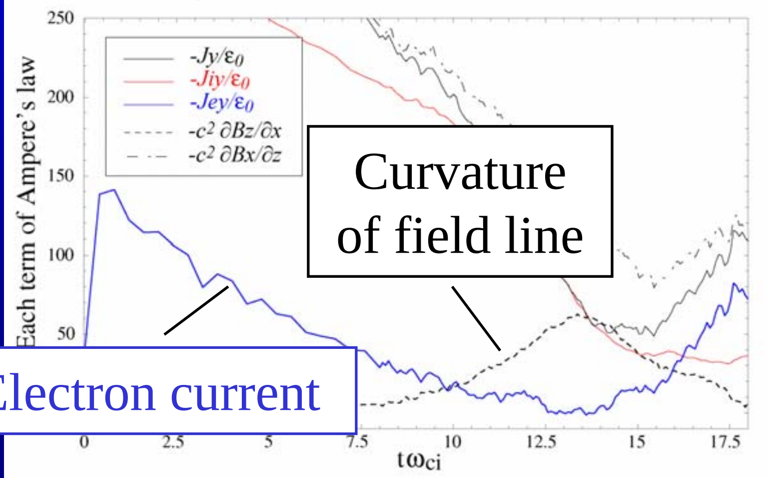


How can the electron diffusion region be elongated?



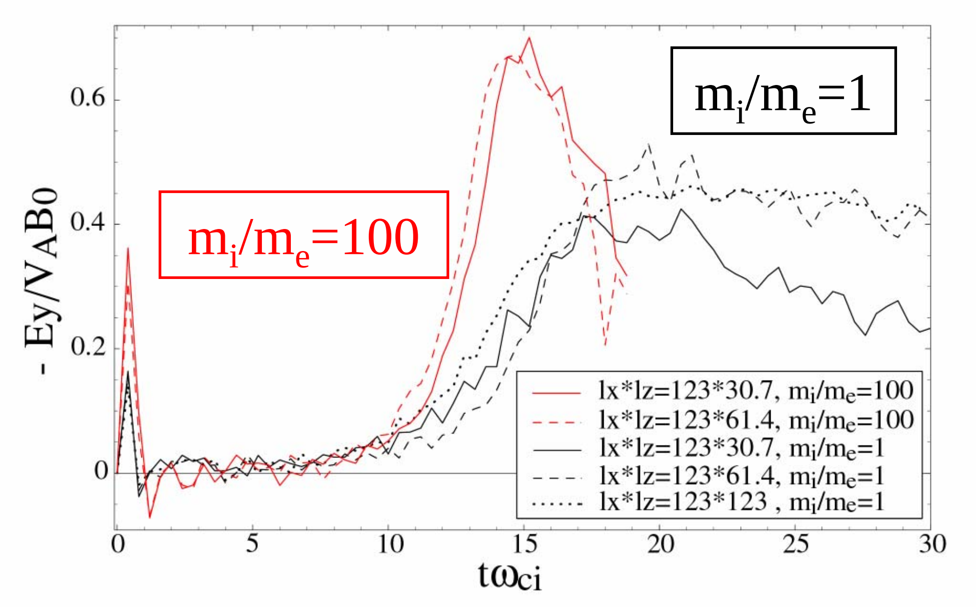
[*Fujimoto, Phys. Plasmas, 2*





Curvature of field line

Electron current



m_i/m_e=100

m_i/m_e=1

Comparison with observations

$E_{y,max} \sim 0.7 V_A B_0$ (Simulation result)

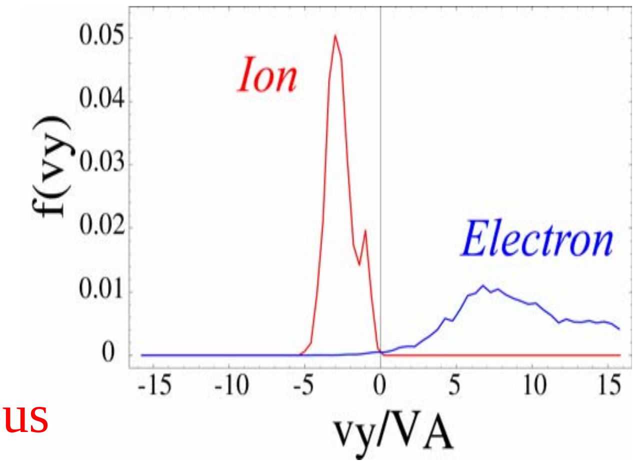
$B_0 \sim 10\,\mathrm{nT},\ n_{ps} \sim 0.5\,\mathrm{cm}^{-3} \Rightarrow E_y \sim 2.2\,\mathrm{mV/m}$

Consistent with observations. （e.g., *Asano et al.*, 2004）

Expected mechanism to enhance Ey

$V_d > v_{e,th}$ Buneman-type instability can be excited.

$$E_y = \underbrace{-\frac{1}{en_e}(\nabla\cdot\vec{P}_e)_y}_{\text{Electron pressure tensor}} \underbrace{-\frac{m_e}{e}\frac{dv_{ey}}{dt}}_{\text{Electron inertia}} + \underbrace{\eta^{an} j_y}_{\text{Anomalous resistivity}}$$



Summary and Conclusions

We have investigated the time evolution of magnetic reconnection in large and fully kinetic systems. Our kinetic code employs the AMR and particle splitting techniques.

1. Inclusion of the Hall term is NOT sufficient for quasi-steady fast reconnection.

   The polarization field, which is caused by the inertia difference between ions and electrons, elongates the electron diffusion region, so that quasi-steady reconnection is not achieved.

2. Inclusion of the Hall term is NOT necessarily required for fast reconnection.

   Even in the system without the Hall effects ($m_i/m_e = 1$), fast reconnection can occur.

Summary and Conclusions

Buneman-type instability is expected to give an anomalous resistivity, enhancing the reconnection rate. However, it is not clear how much it affects the system.

We need to extend the present 2-D code to the 3-D code and investigate the effects of the anomalous resistivity on magnetic reconnection.