JIFT workshop (Nov.21-22, 2008,Dallas)

Relationship between Macro and Micro Physics in Collisionless Driven Reconnection

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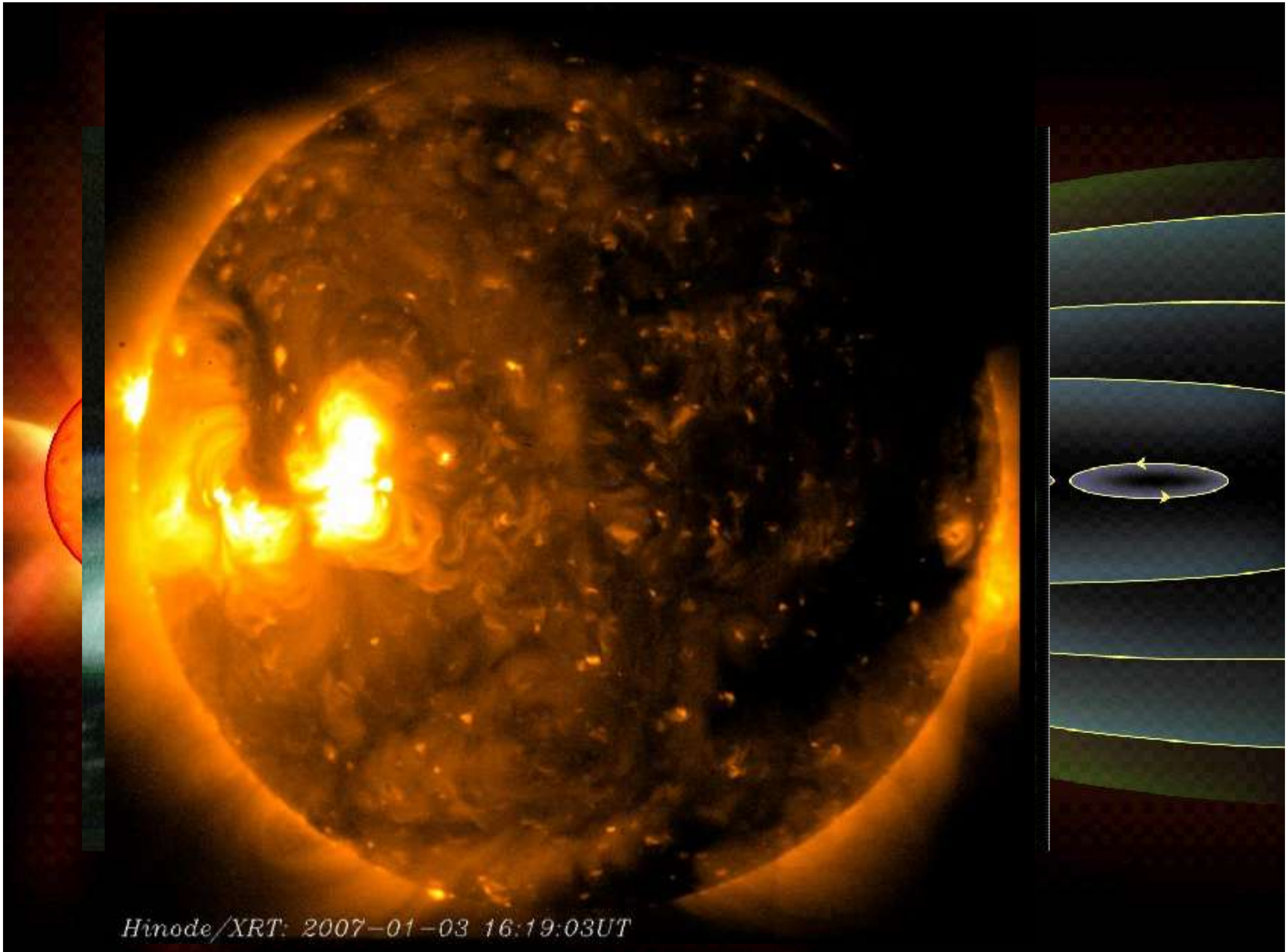
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Exploration of magnetic reconnection phenomena in nature → Multi-hierarchy simulation

Macro hierarchy

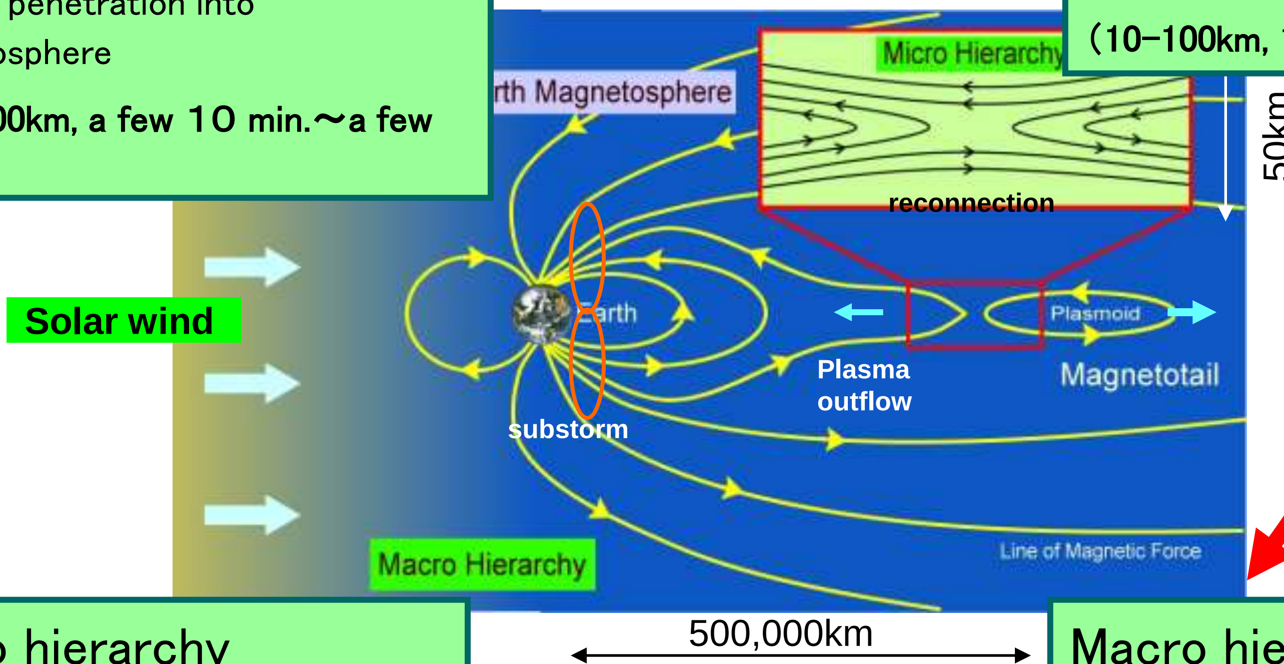
Interaction between solar wind plasmas and earth magnetosphere, plasma penetration into magnetosphere

(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)



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.)

Purpose

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.

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).**

➔ **Multi-hierarchy simulation model** to solve both microscopic physics and macroscopic physics consistently and simultaneously is needed for full understanding of magnetic reconnection. (→ S. Usami)

➔ We consider microscopic system interacting with surrounding macroscopic system.

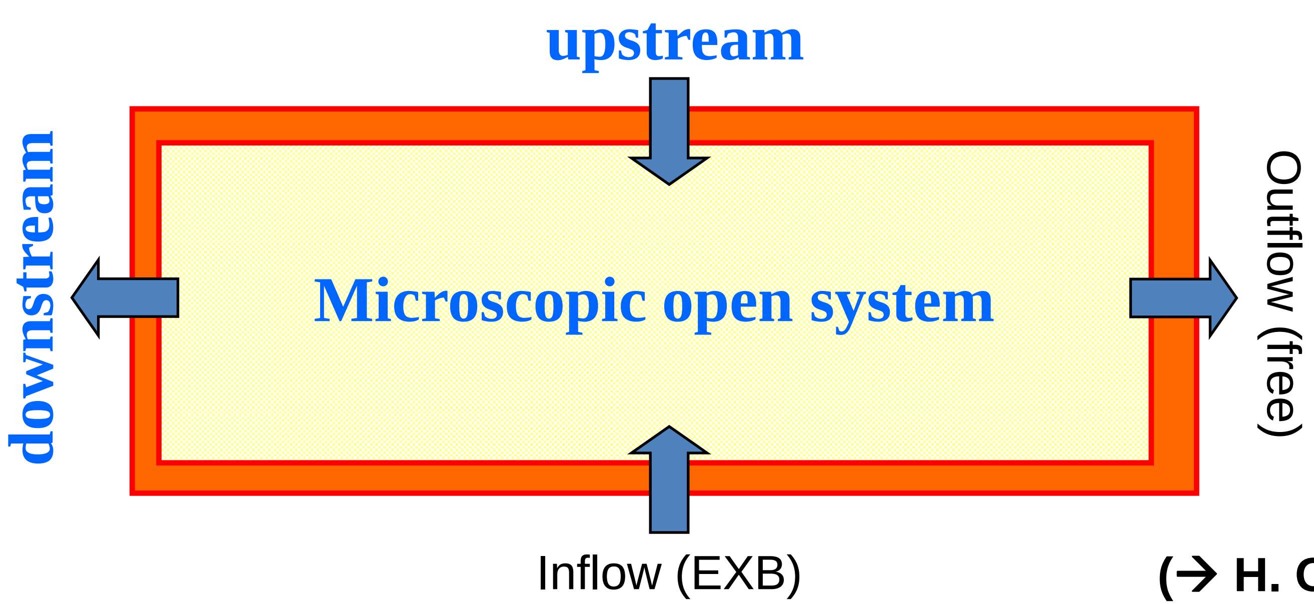
➔ How does microscopic physics of collisionless driven reconnection evolve under the influence of external driving source?

Simulation model for microscopic physics

Based on standard explicit electromagnetic **PIC** algorism, we have developed the **PASMO** code with an open boundary model.

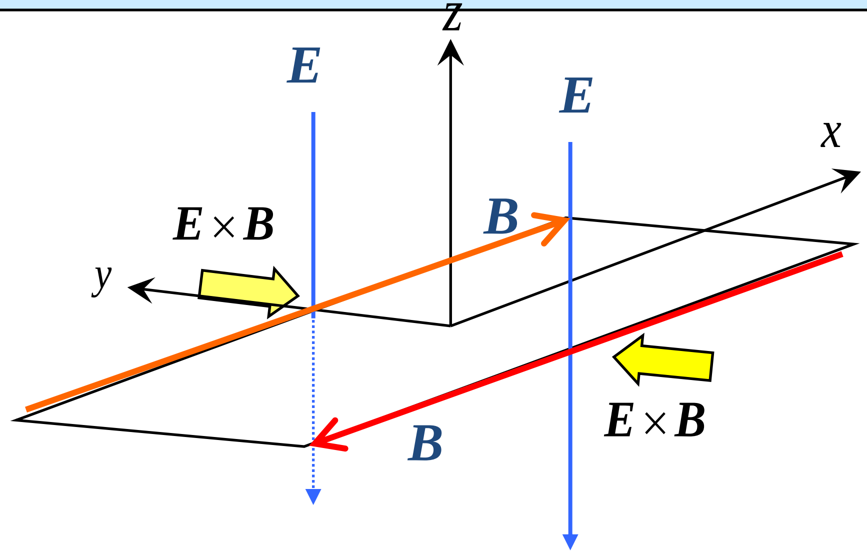
PASMO : PArticle Simulation code for Magnetic reconnection in an Open system :

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



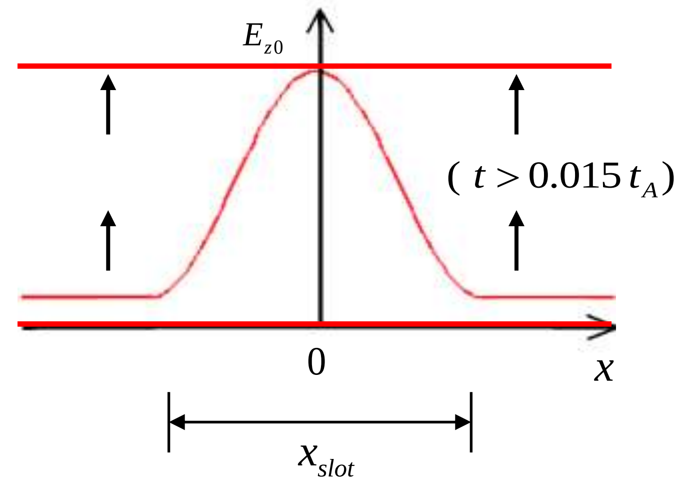
(→ H. Ohtani)

Simulation parameters, boundary conditions, and initial conditions



Initial: Harris-type equilibrium

$$B_x(y) = B_0 \tanh(y/L)$$



440,000,000 particles

256 × 129 × 128 spatial grids

$$\Delta y = \lambda_{d0} (= v_{Te0} / \omega_{pe0})$$

$$\rho_i = 0.93L, T_i / T_e = 1, m_i / m_e = 50,$$

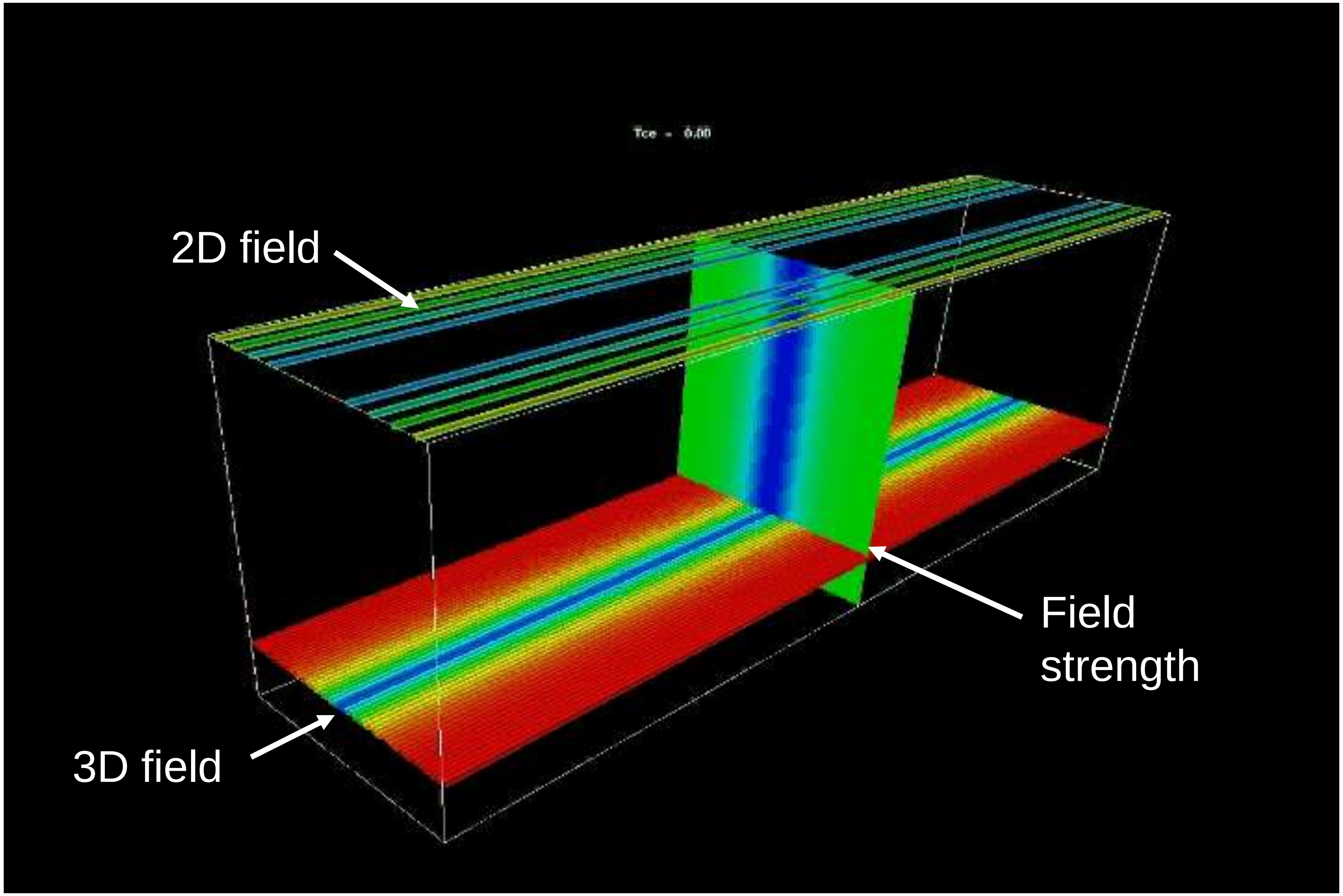
$$E_0 = -0.04 B_0, \omega_{pe} / \omega_{ce} = 2.5, x_{slot} = 10.8 \rho_i$$

normalized unit;

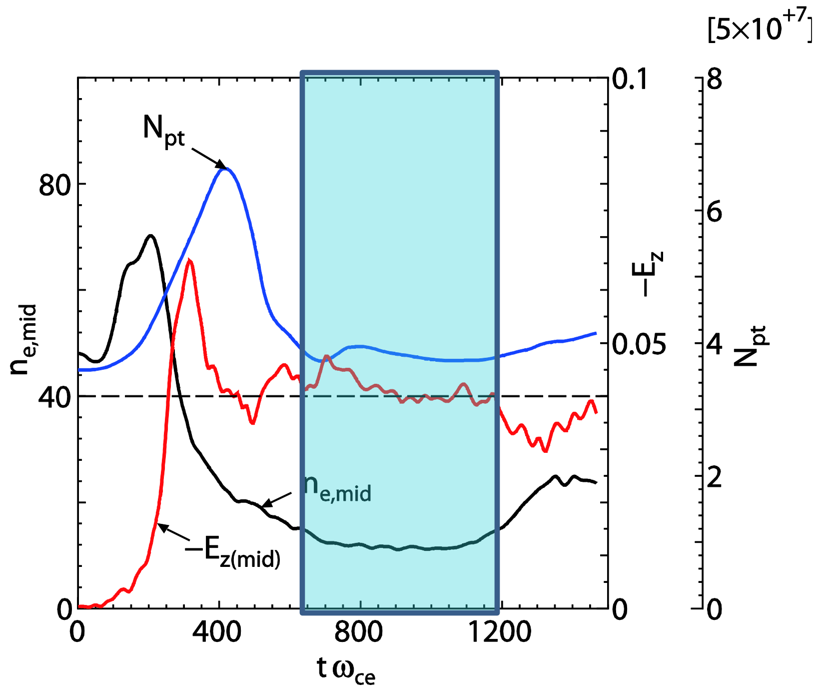
time : $1/\omega_{ce}$, velocity : light velocity c, spatial scale : c/ω_{ce}

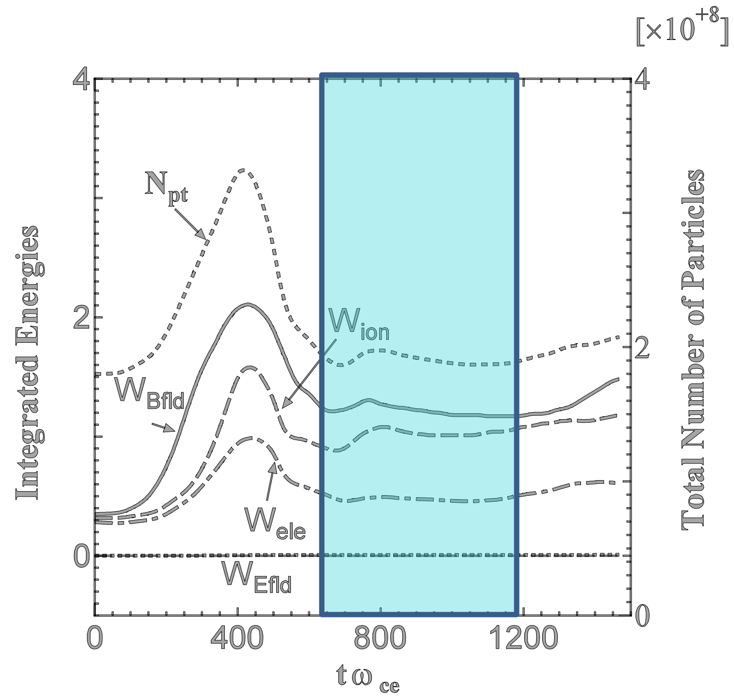
Three-dimensional particle simulation of collisionless driven reconnection

Magnetic field in 3D open system



Steady collisionless driven reconnection





Temporal evolutions of reconnection electric field (red), electron number density per cell
at the mid-point (black), and total number of particles (blue).

Temporal evolutions of magnetic field energy (solid), ion energy (dashed), electron energy (dot-dashed), electric field energy (dotted), and total number of particles (short dashed).

➔ Steady state for 1200 > ω_{ce} t >600

Triggering mechanism of magnetic reconnection
➔ violation of plasma frozen-in condition

- **Violation of frozen-in condition in a steady, collisionless plasma –**

- Electron fluid : $$\mathbf{E} + \mathbf{v}_e \times \mathbf{B}/c \approx \frac{-1}{en} \nabla \cdot \overleftrightarrow{\mathbf{P}}_e - \frac{m_e}{e} \mathbf{v}_e \cdot \nabla \mathbf{v}_e$$

- Ion fluid : $$\mathbf{E} + \mathbf{v}_i \times \mathbf{B}/c \approx \frac{1}{en} \nabla \cdot \overleftrightarrow{\mathbf{P}}_i + \frac{m_i}{e} \mathbf{v}_i \cdot \nabla \mathbf{v}_i$$

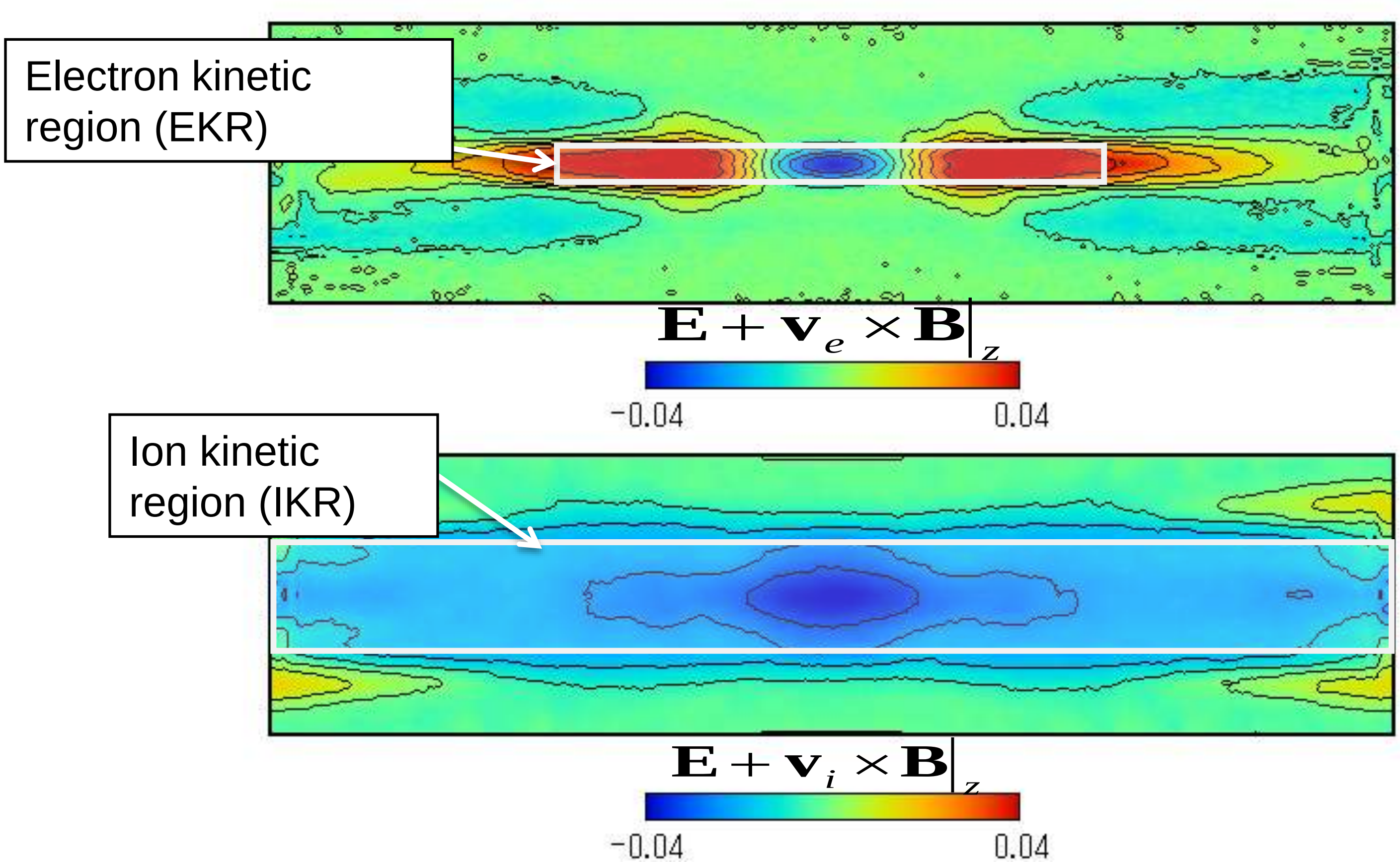
$$\overleftrightarrow{\mathbf{P}}_e, \overleftrightarrow{\mathbf{P}}_i : \text{nongyrotropic pressure tensor}$$

1. First term on RHS : finite thermal orbit effect ➔ meandering orbit amplitude
2. Second term on RHS : inertia effect ➔ collisionless skin depth
3. Anomalous resistivity due to plasma instability

$$\langle \delta\mathbf{v} \times \delta\mathbf{B} \rangle = \text{finite}$$

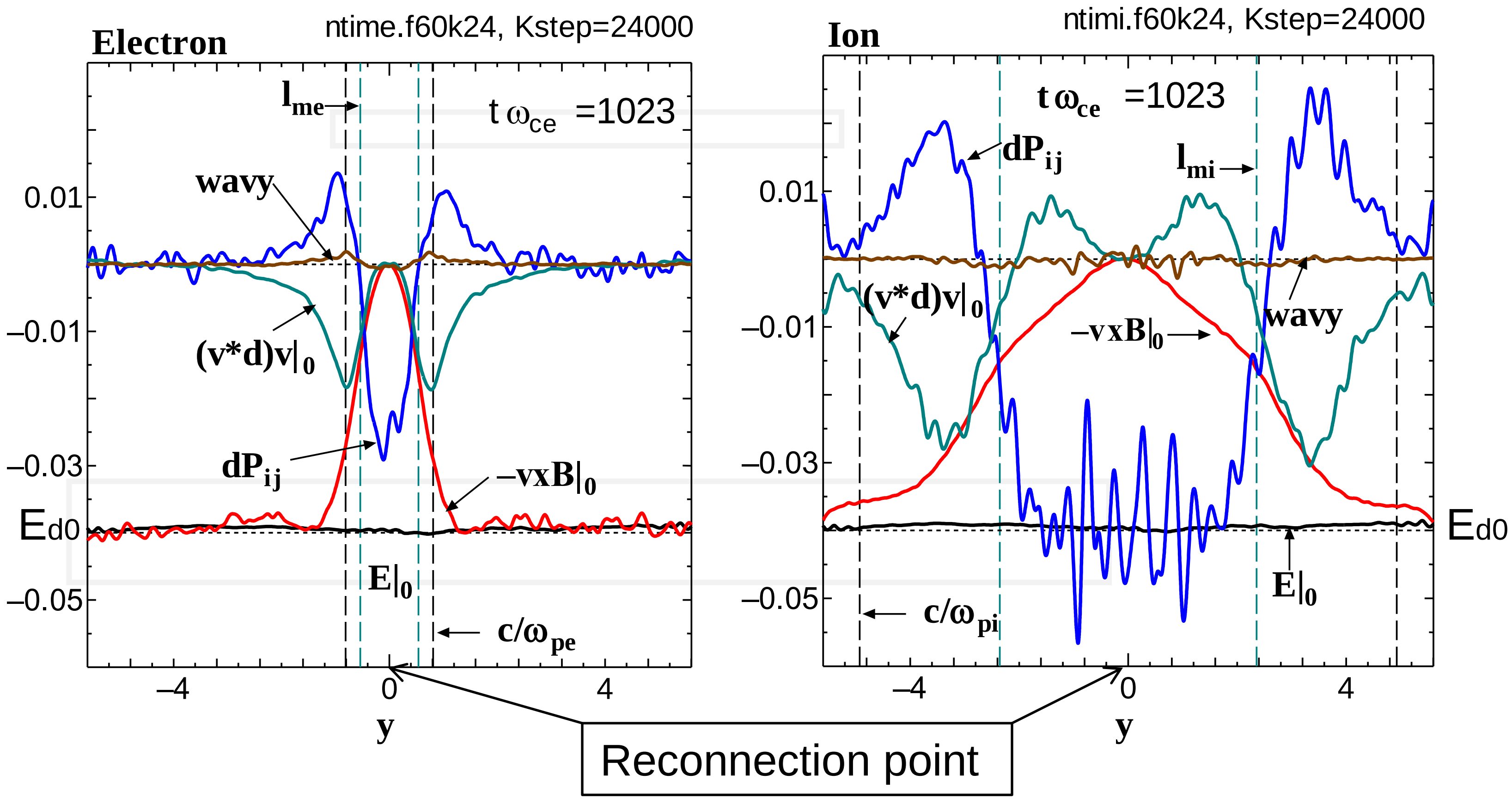
Two-scale structure of kinetic regime

[R. Horiuchi et al: Comm.Comp.Phys. (2008)]



- What microscopic mechanism breaks the frozen-in condition?

Violation of frozen-in condition in a steady state



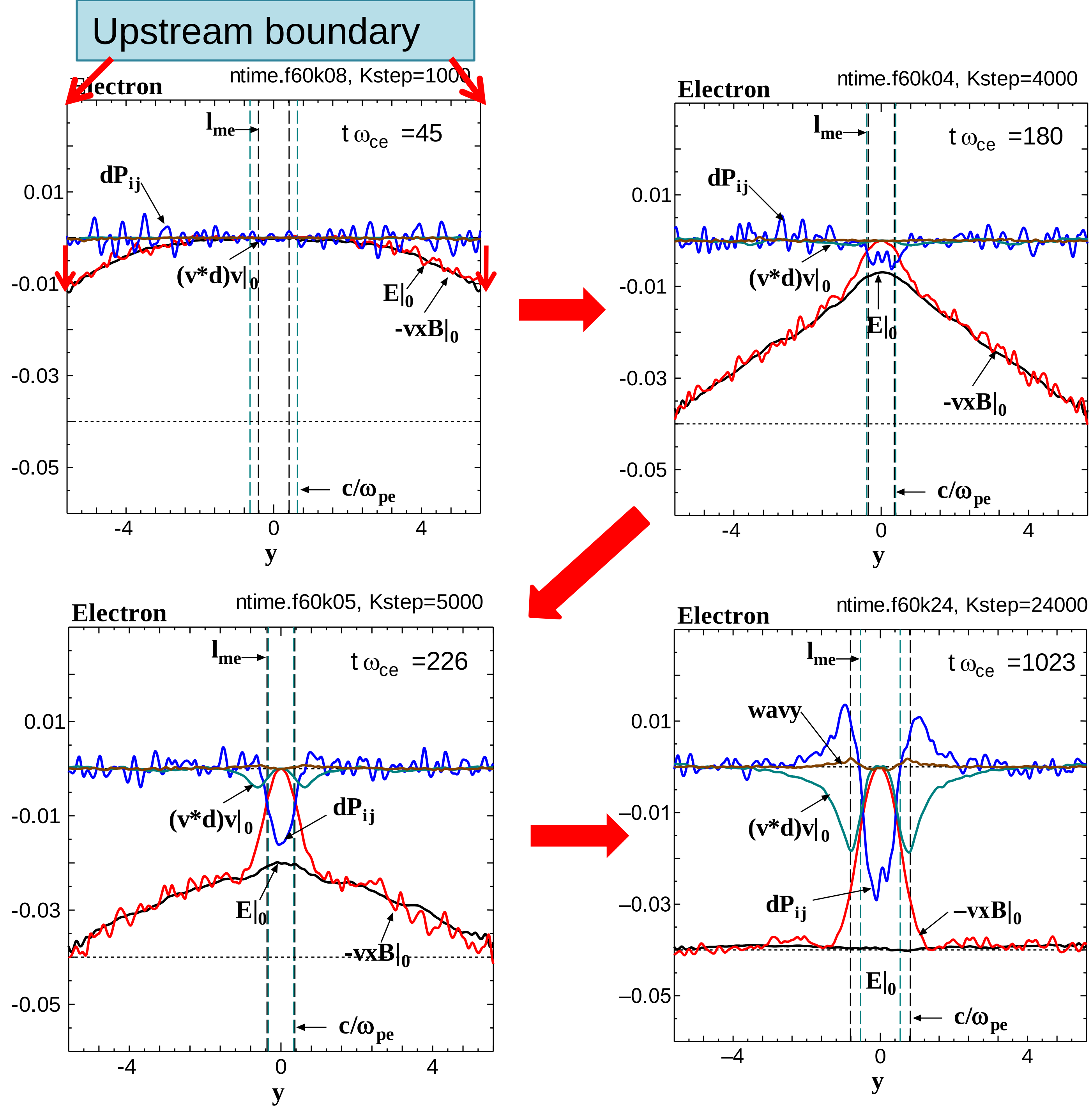
Both for electror ... ition is caused
by **pressure ter** ... rotoropic
motion called **m...** ... l sheet.

$$\mathbf{E}_{d0} \approx \mathbf{E}_{rec} \approx \frac{1}{en} \nabla \cdot \overleftrightarrow{\mathbf{P}}_i \Big|_{rec} \approx \frac{-1}{en} \nabla \cdot \overleftrightarrow{\mathbf{P}}_e \Big|_{rec}$$

Macroscopic quantity at upstream boundary balances microscopic one in reconnection region.

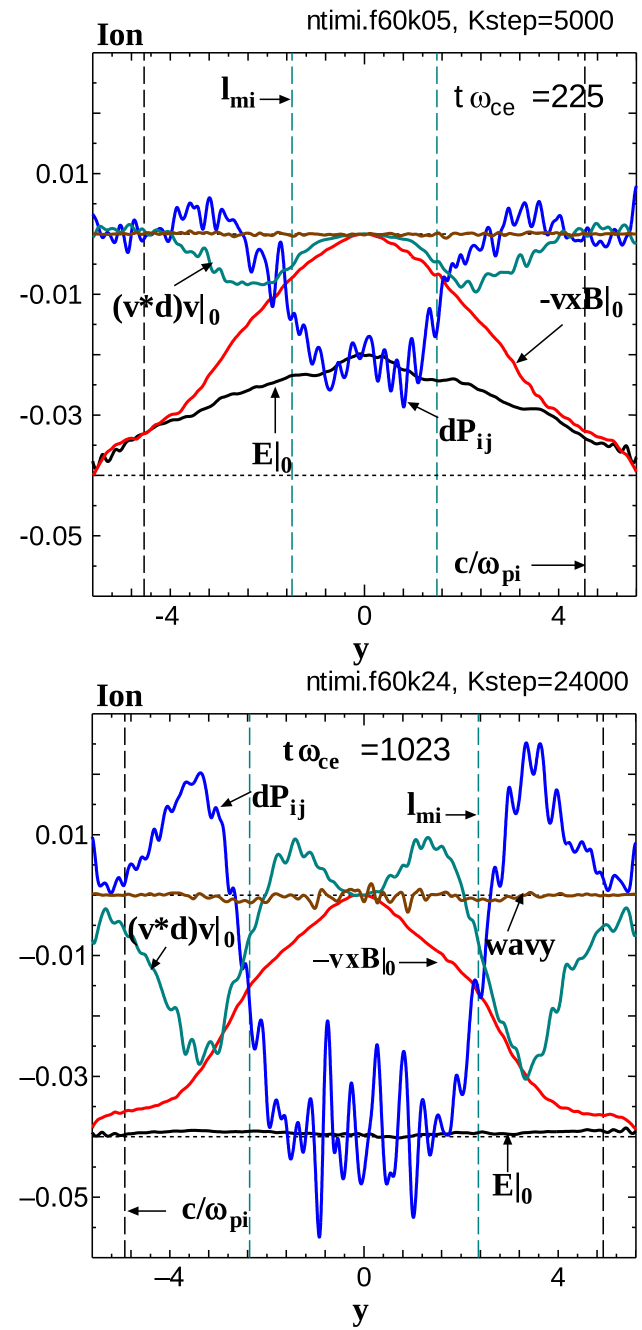
$$\mathbf{E}_d = -\mathbf{v} \times \mathbf{B} \Leftrightarrow \mathbf{E}_{rec} \approx \frac{-1}{en} \nabla \cdot \overleftrightarrow{\mathbf{P}}_e$$

- **How is macroscopic information transferred to microscopic system?**
- **How does microscopic physics relating to collisionless reconnection evolve in the system?**

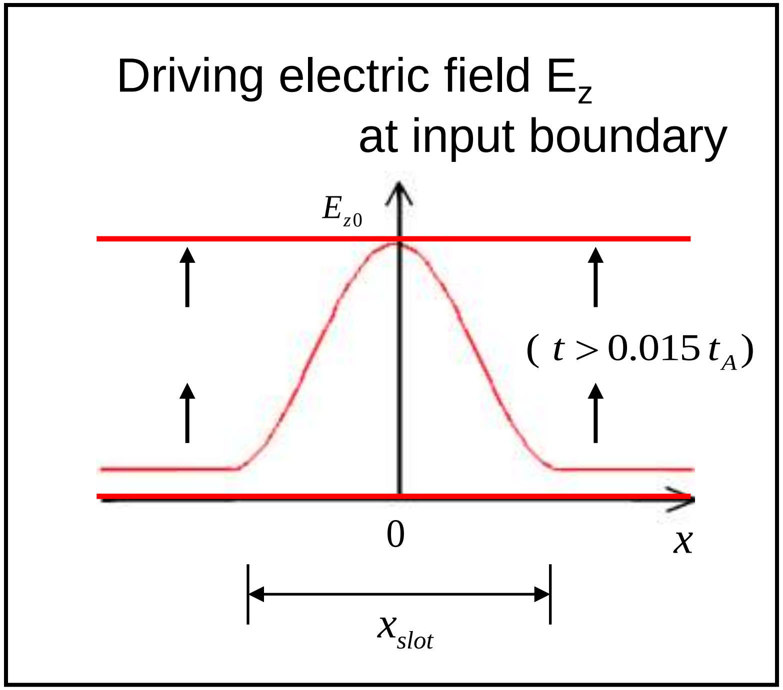

Upstream boundary
Electron
ntime.f60k08, Kstep=1000
t ωce =45
lme
dPij
(v*d)v|0
E|0
-vxB|0
c/ωpe
y
Electron
ntime.f60k04, Kstep=4000
t ωce =180
Electron
ntime.f60k05, Kstep=5000
t ωce =226
Electron
ntime.f60k24, Kstep=24000
t ωce =1023
wavy

Dynamical evolution of microscopic physics in an open system

- Driving electric field penetrates into the system with EXB drift motion.
- When plasma inflow reaches the dissipation region where frozen-in condition is broken, **non-ideal effect dominated by pressure tensor force evolves so as to sustain the penetrated electric field.**
- Thus, reconnection rate or electric field at reconnection point, which is sustained mainly by pressure tensor term, balances the flux inflow rate or driving electric field.



- **The system relaxes to a steady state while keeping balance condition between macro and micro physics.**
- **When macroscopic condition (external driving field) changes,**
  1. **How does the system behave dynamically?**
  2. **How does microscopic physics response to this change?**
  3. **In what condition does the system relax to a steady state?**



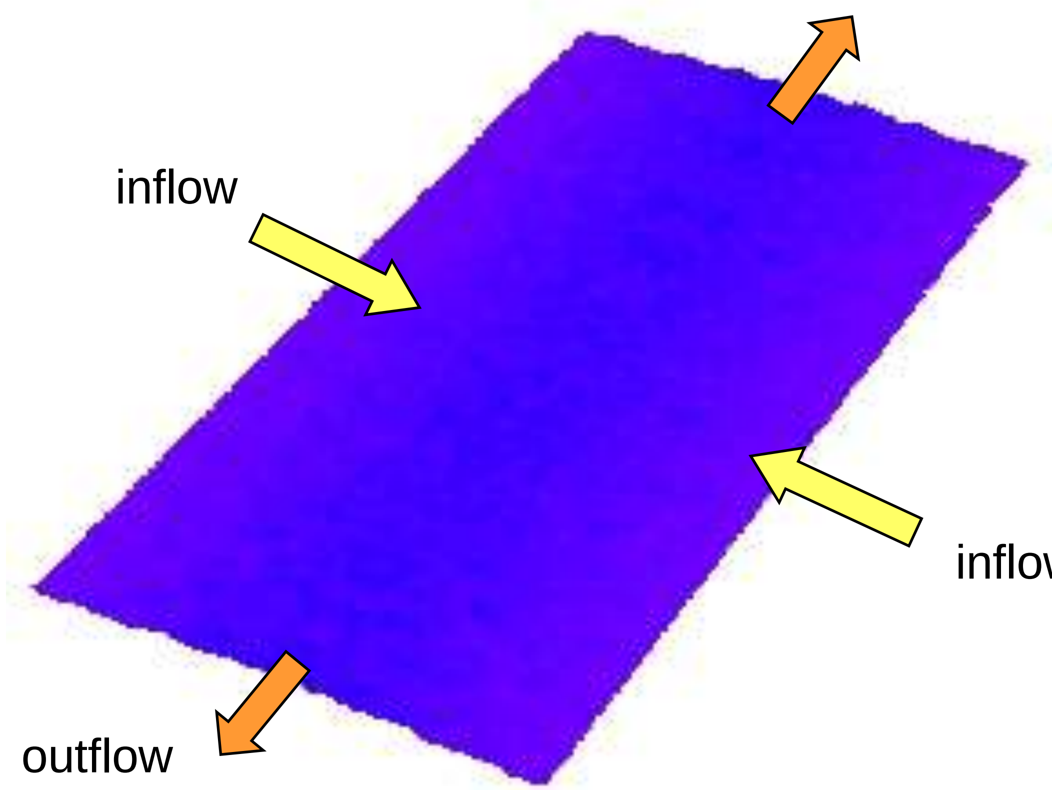
Driving electric field is controlled by two parameters, i.e., maximum flux inflow rate E_{z0} and inflow window size X_{slot}.

[W. Pei, R. Horiuchi, PoP, 2001]

Current density Jz in 2D open system

(narrow input window)

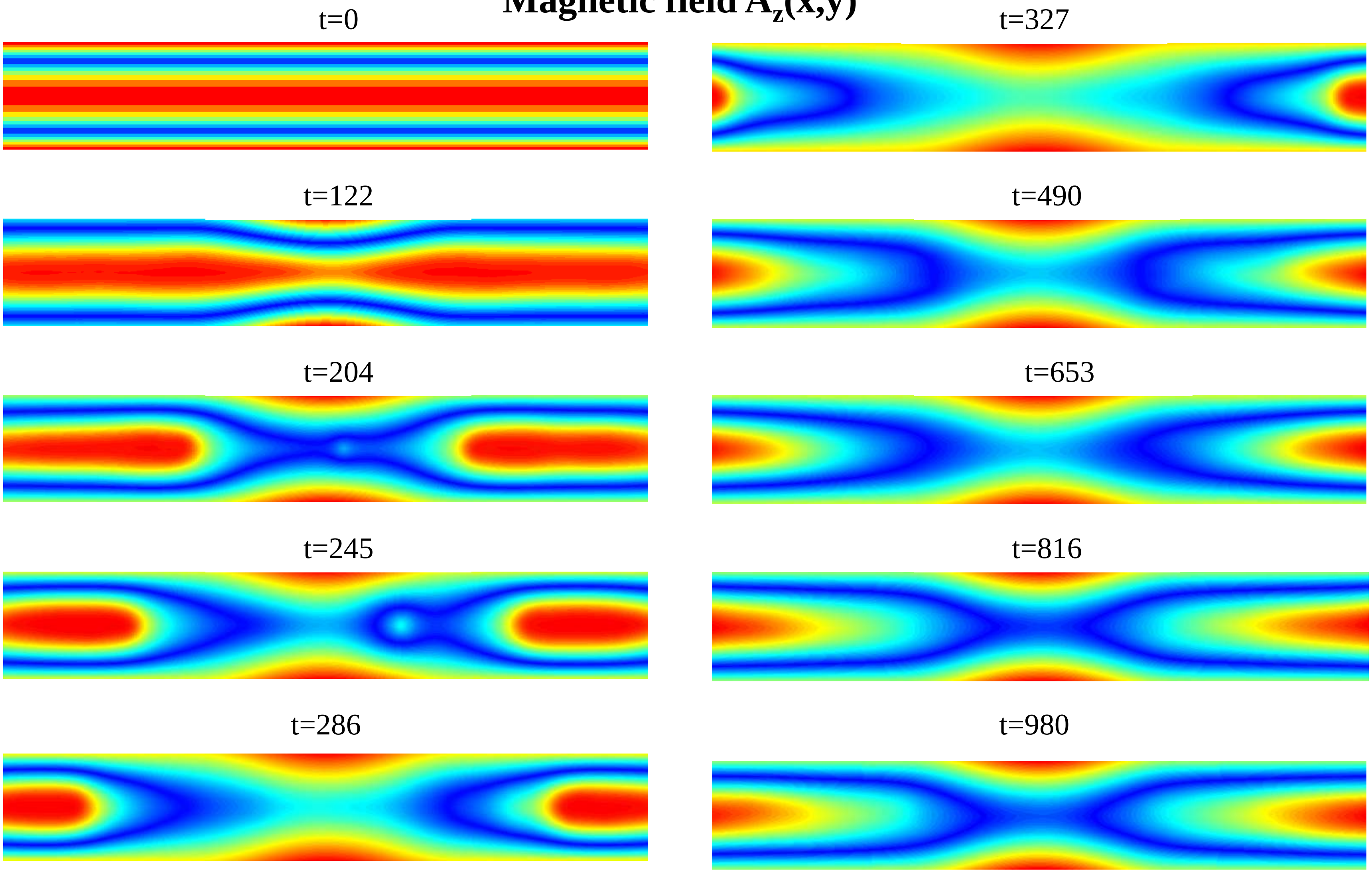
Current density Jz in 2D open system



[A.Ishizawa, R. Horiuchi, 2005]

Steady reconnection

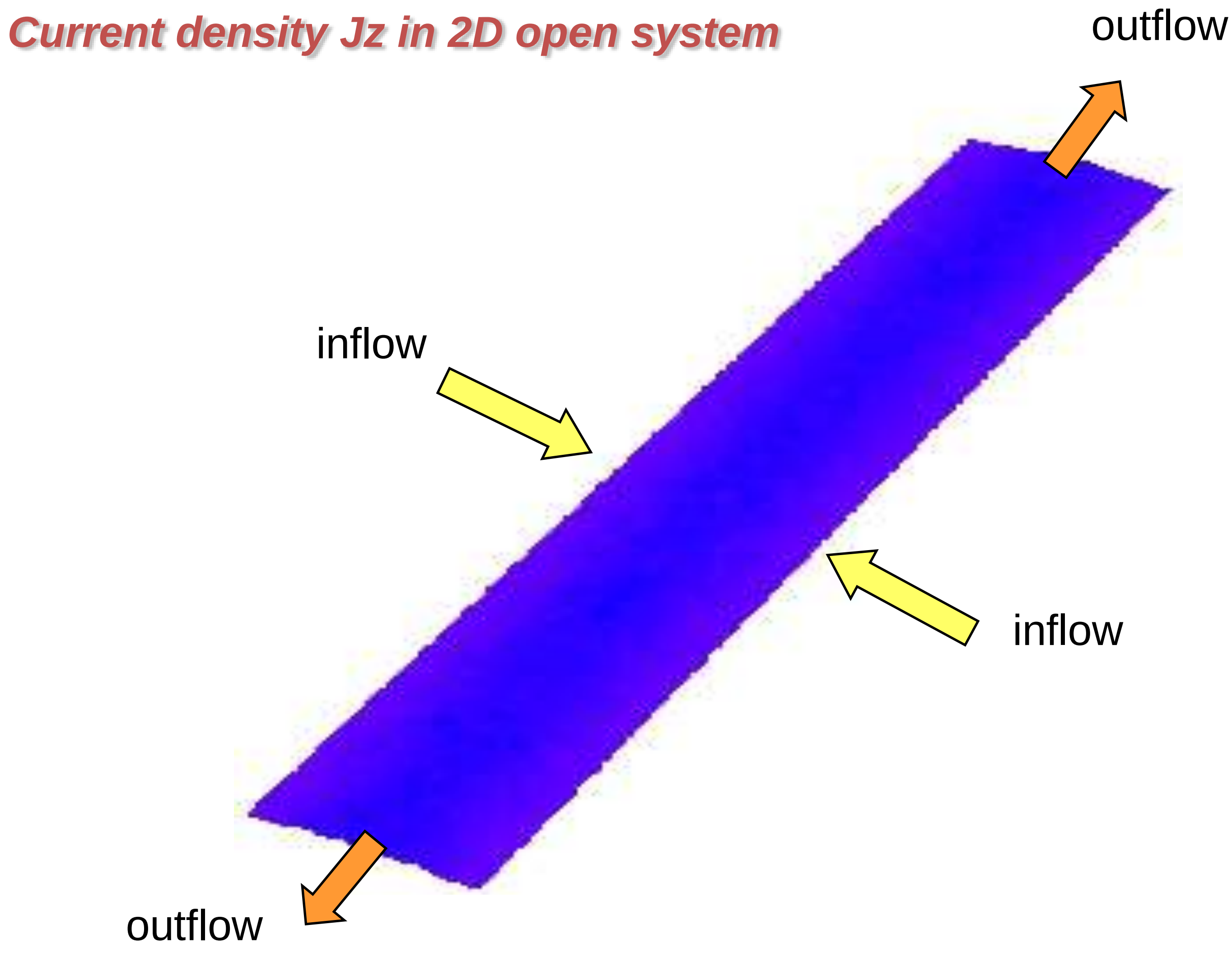
Magnetic field $A_z(x,y)$



$$x_{slot} / \rho_i = 18; E_{d0} = -0.04 B_0$$

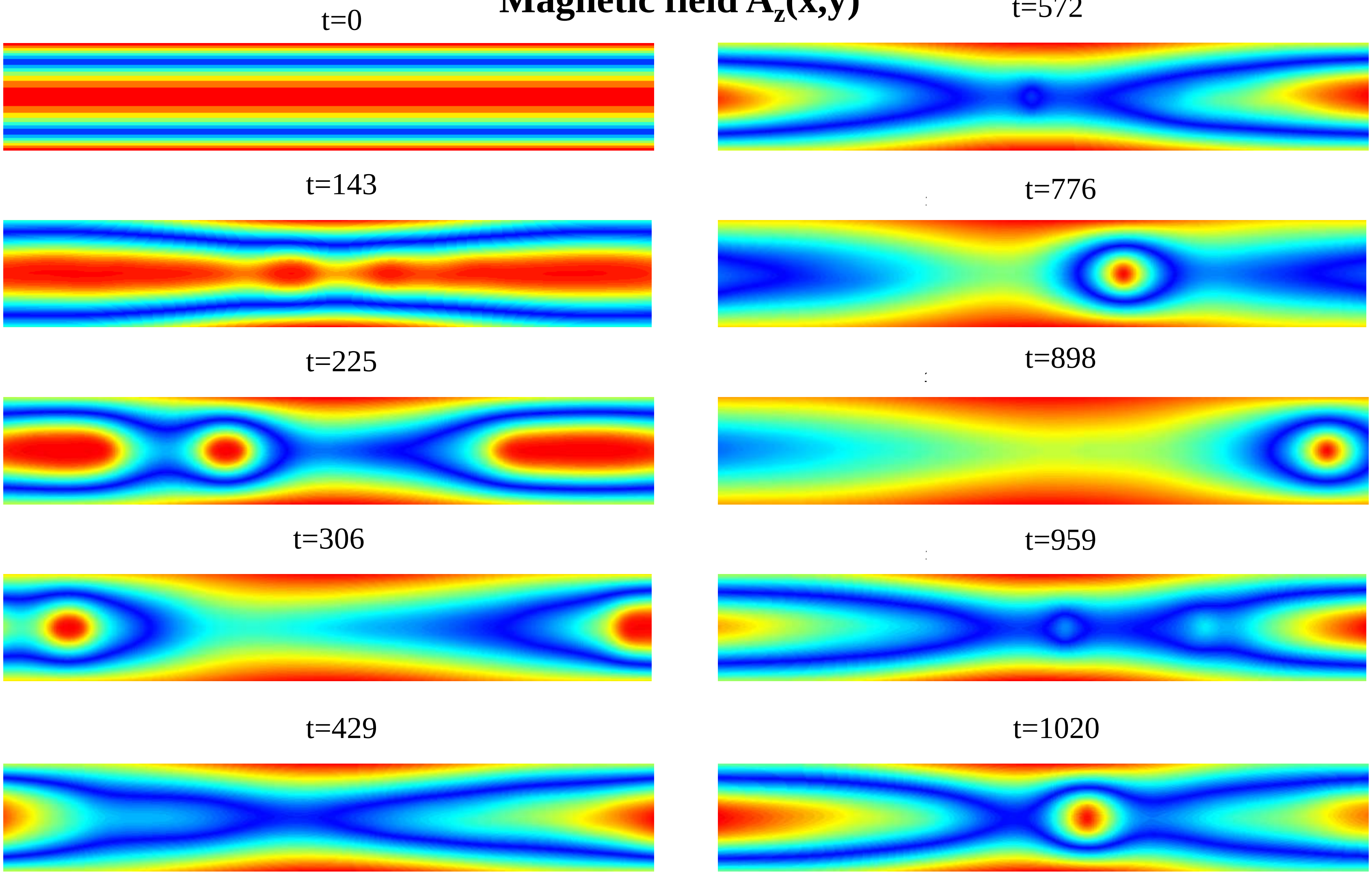
Intermittent Reconnection

(wide input window)



System never reaches a steady state for wide input window

Magnetic field $A_z(x,y)$



$$x_{slot} / \rho_i = 36; E_{d0} = -0.04 B_0$$

Reconnection evolution behavior is controlled by input window size x_{slot}

[W. Pei, R. Horiuchi, PoP2001]

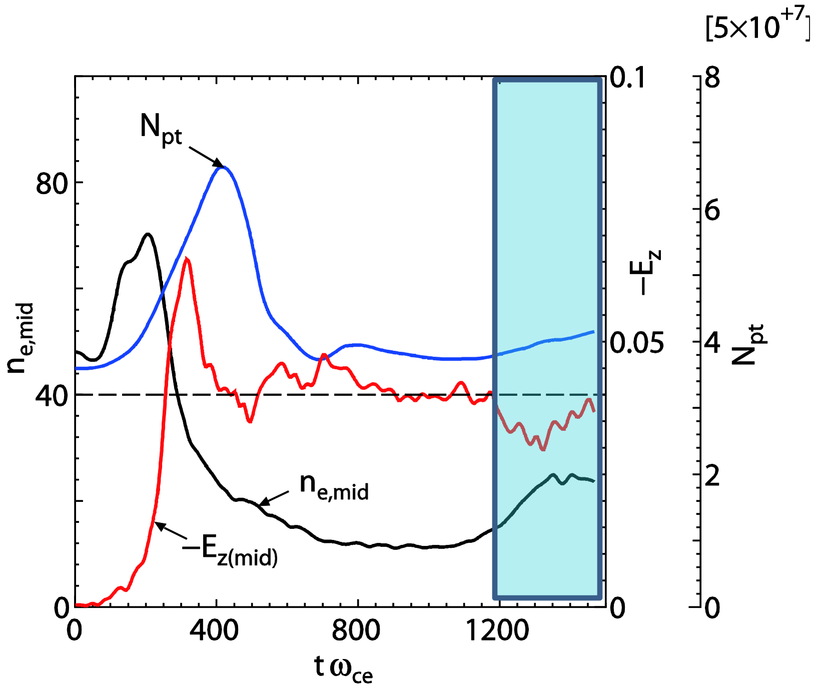
E_{d0}/B_0 \ x_{slot}/ρ_i	18	27	36
-0.04	Steady (Run 1)	Steady (Run 2)	Intermittent (Run 3)
-0.06	Steady (Run 4)	Steady (Run 5)	Intermittent (Run 6)
-0.08	Steady (Run 7)	Steady (Run 8)	Intermittent (Run 9)

(ρ_i : ion Larmor radius)

- **Two evolving ways:** steady for small x_{slot}; intermittent for big x_{slot}
- **The temporal evolution way is insensitive to E_{d0}.**

Plasma instability grows after a steady phase

(ω_{ce} t >1200)



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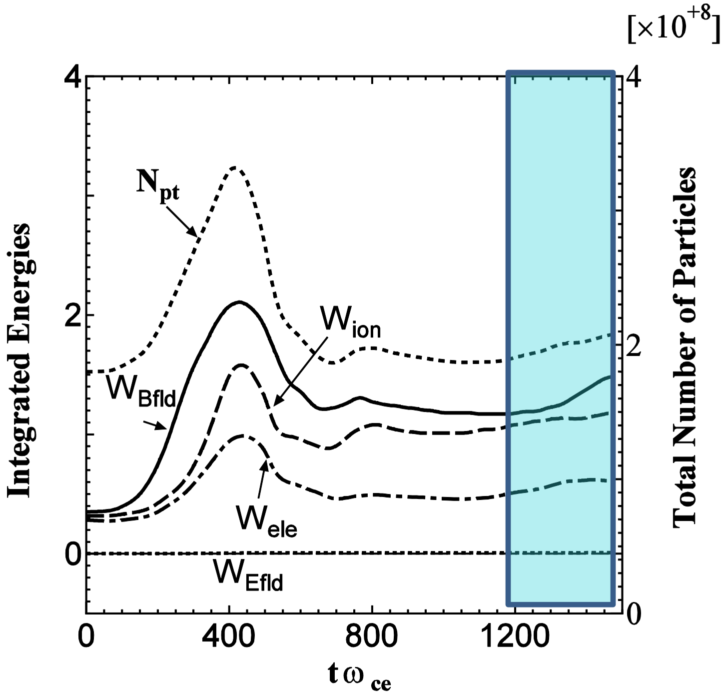

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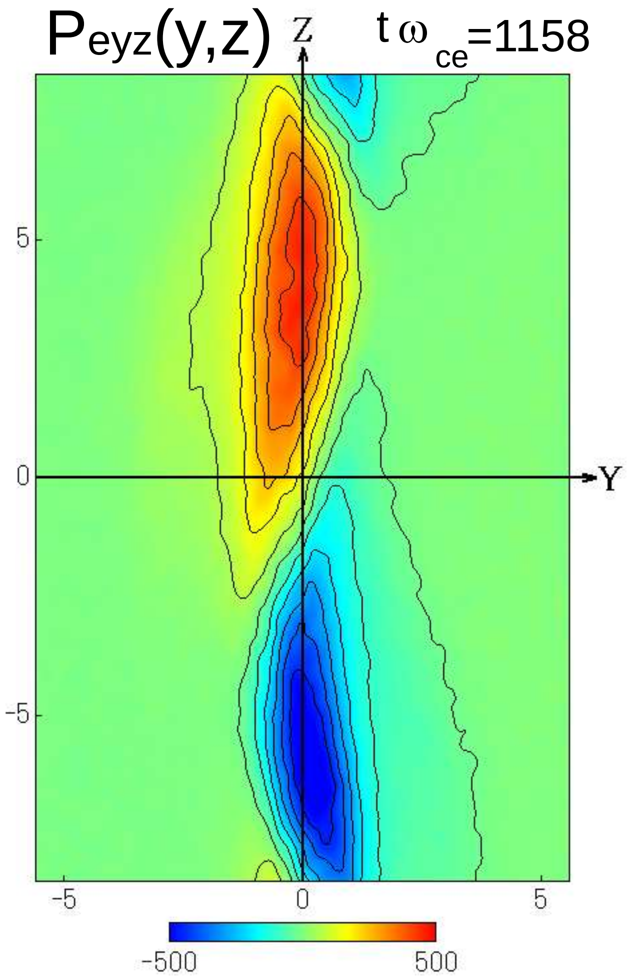
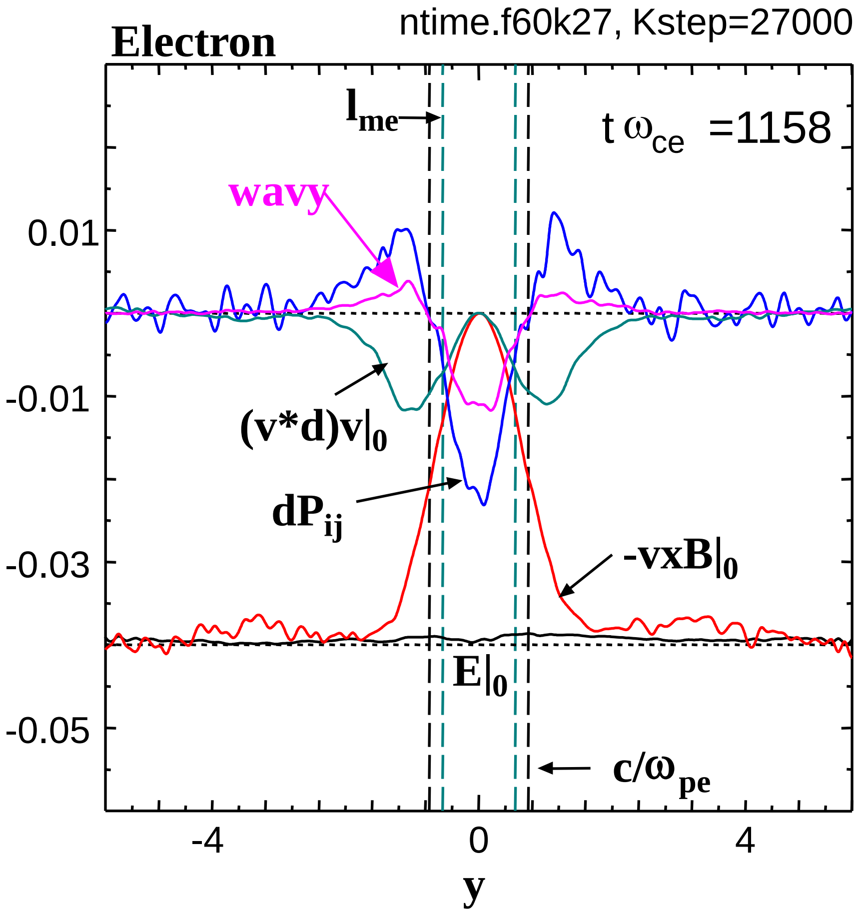
Contribution of plasma instability





As plasma instability (DKI) grows, contribution of pressure tensor term becomes small due to wavy modification. Instead, nonlinear wave coupling term becomes more significant.

Summary

- The influence of global macroscopic physics on microscopic physics of collisionless driven reconnection is studied by using an electromagnetic particle simulation code in a microscopic open system (PASMO).
- When plasma inflow supplied from the upstream boundary reaches the kinetic regime, **stochastic orbit effect represented by pressure tensor term evolves so as to make the penetration of electric field into the current sheet possible.**

➔ **Microscopic physics adjusts itself so as to balance external macroscopic physics, and the self-adjustment mechanism enables the system to relax to the steady state even in an open system.**

- When the spatial scale of plasma inflow exceeds some critical value, the dynamical behavior of collisionless reconnection becomes intermittent, suggesting that the self-adjustment mechanism does not work well.

Reference

[1] R. Horiuchi, H. Ohtani, and A. Ishizawa, *Comp. Phys. Comm.*, **164** (2004)17-22.

[2] A. Ishizawa and R. Horiuchi, *Phys. Rev. Let.*, **95** (2005) 045003.

[3] W. Pei, R. Horiuchi, T. Sato, Phys. Plasmas , Vol. 8, (2001) 3251.

[4] R. Horiuchi and H. Ohtani, *Comm. Comp. Phys, Vol. 4,*(2008) 496.

[5] R. Horiuchi, S. Usaim, H. Ohtani, and M. Den, PFR (2009), accepted