Dissipation Mechanism in 3D Magnetic Reconnection

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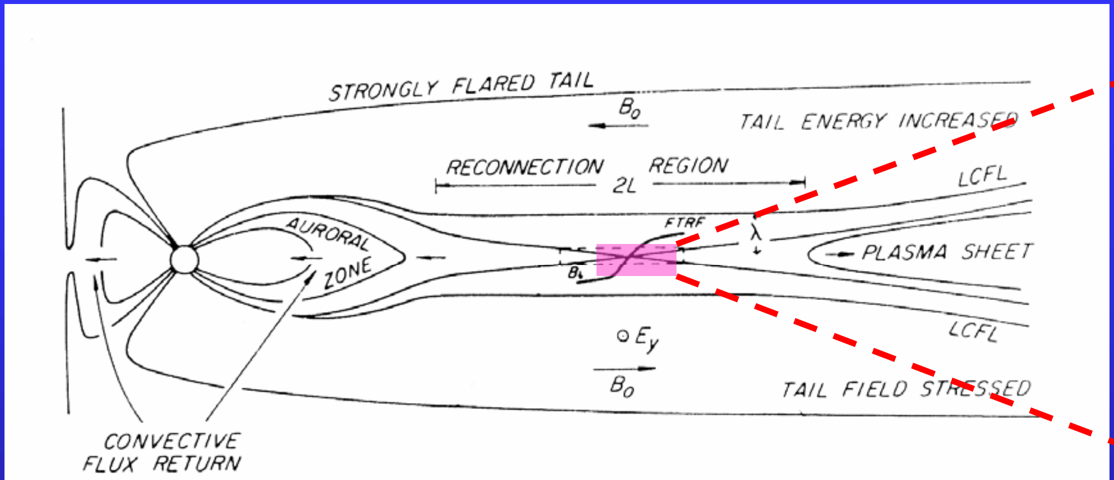
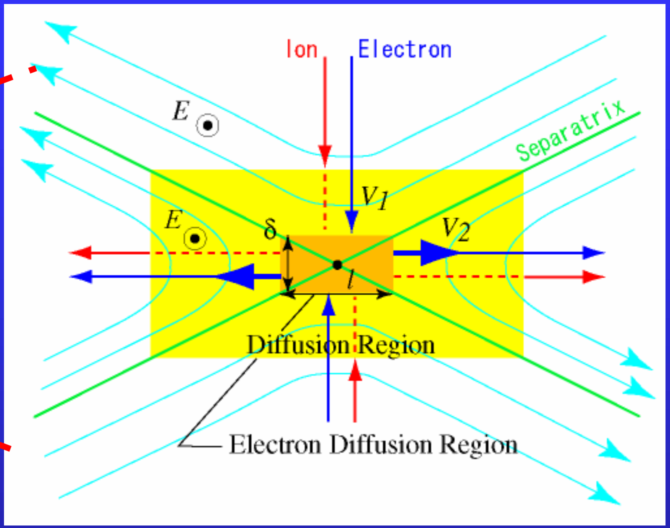
Reconnection (in the Earth Magnetosphere)



Coroniti [1985]



10 km

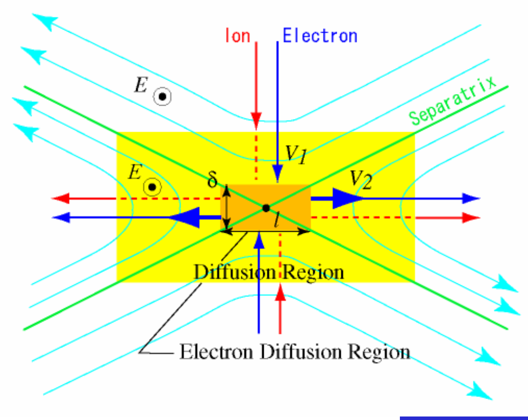
10^5 km

10^3 km

- Can induce global-scale convection causing change in the field line topology,
- Is intrinsically multi-scale process.

Why is the dissipation mechanism important?

Our goal is to understand macroscopic dynamics in a variety of systems.



Diffusion equation: $\frac{\partial \vec{B}}{\partial t} = \frac{\eta}{\mu_0} \nabla^2 \vec{B}$

η: Electric resistivity → Macroscopic parameter originating from microscopic (kinetic) processes.

In the MHD framework…

The reconnection rate depends on the resistivity model.

(Biskamp,1986; Ugai, 1995)

Global responses in substorm and flares are sensitive to the parameterization of the resistivity.

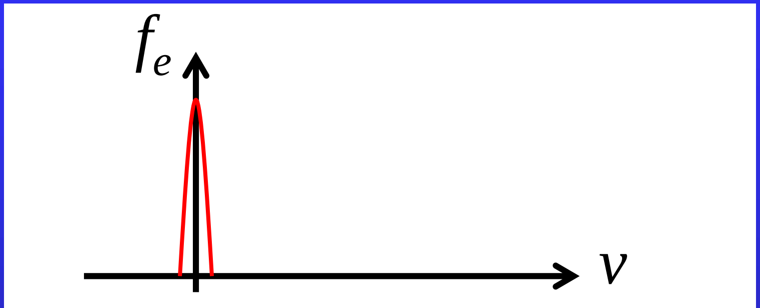
(Raeder et al.,2001; Kuznetsova et al., 2007)

How is the resistivity generated?

The motion of charged particles supporting the current density must be disturbed by "collision".

Collision with other particles

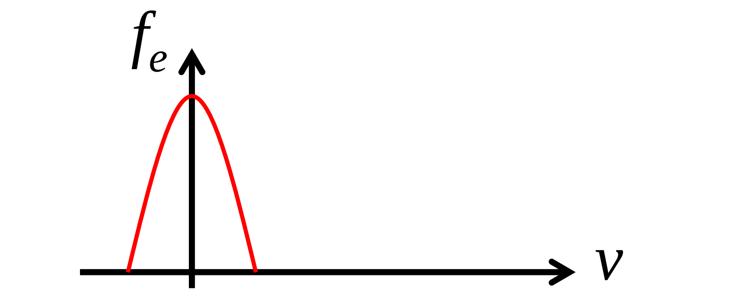
$$\eta = \frac{m_e \nu_c}{n_e e^2}, \qquad \nu_c = \frac{1}{\tau_c}$$



➢ ***How does the "collision" occur in collisionless plasmas?***
= How does the momentum transport occur?

Inertia resistivity

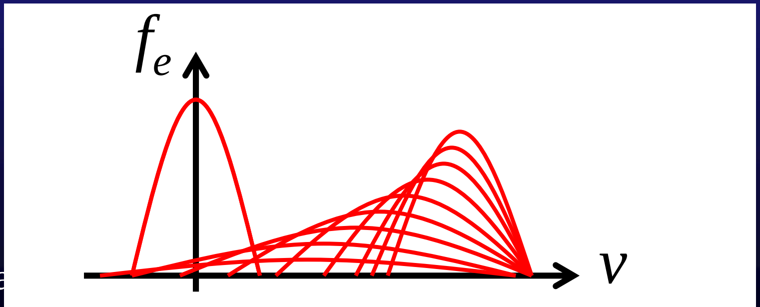
$$\eta = \frac{m_e \nu_T}{n_e e^2}, \qquad \nu_T = \frac{1}{\tau_T} \sim \frac{V}{L}$$



Anomalous resistivity
(Wave-particle interaction)

$$\eta = \frac{m_e \nu_w}{n_e e^2}, \qquad \nu_w \approx \frac{R_e^{an}}{n_e m_e V_e}$$

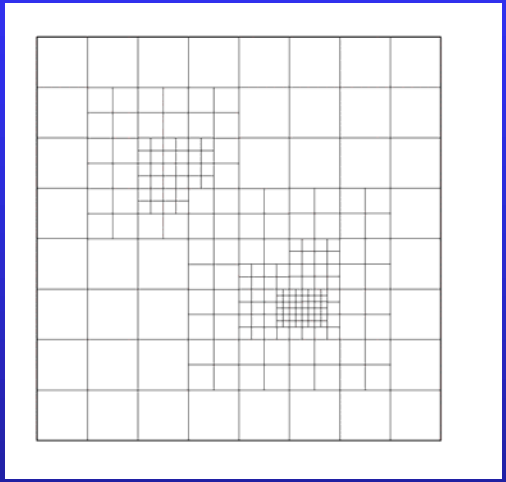
$$R_e^{an} = -e\left(\left\langle \delta n_e \delta \vec{E} \right\rangle + \left\langle \delta (n_e \vec{V}_e) \times \delta \vec{B} \right\rangle\right)$$

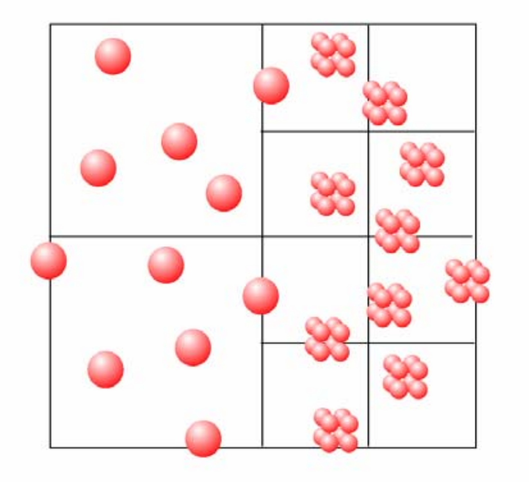


Simulation Model

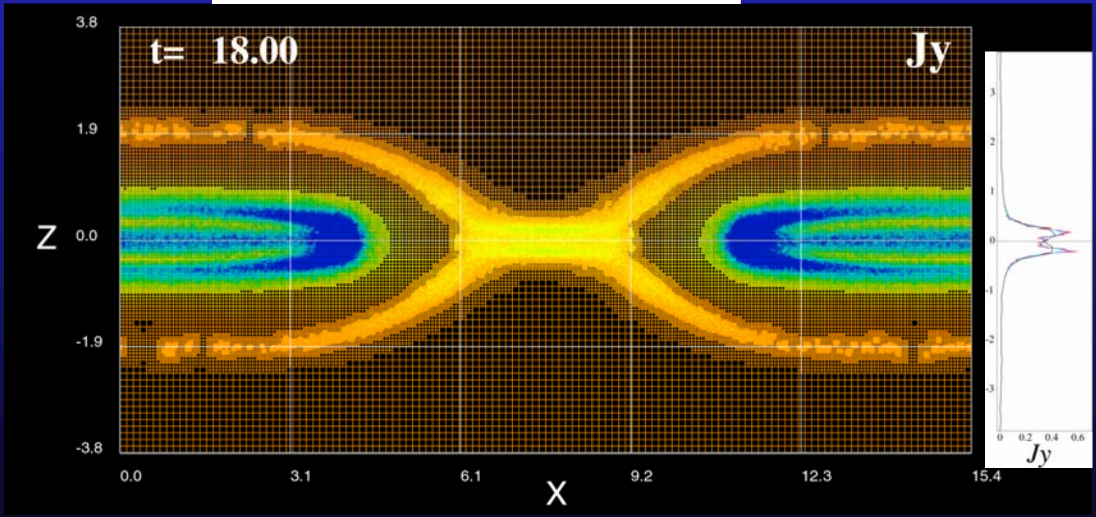
PIC + Adaptive Mesh Refinement (AMR)

[Fujimoto & Machida, JCP, 2006; Fujimoto & Sydora, CPC, 2008]

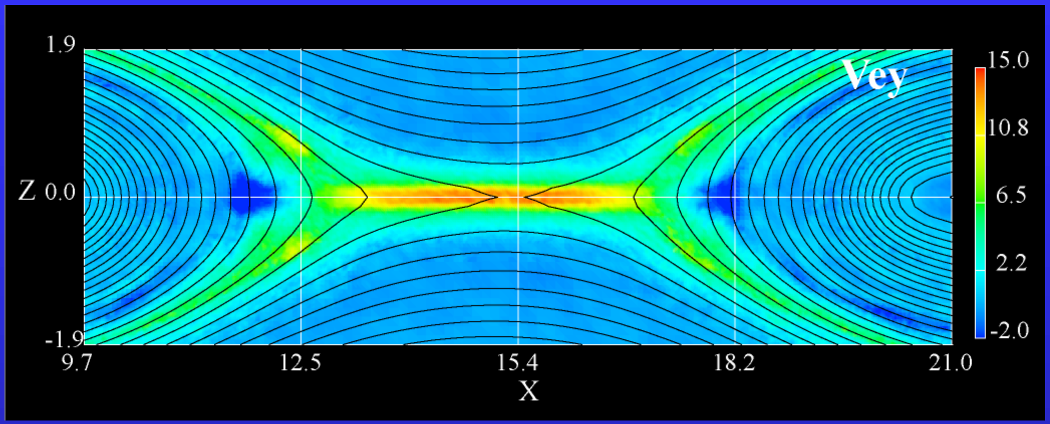


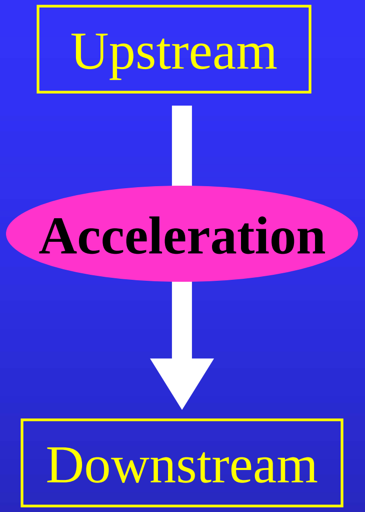


Refinement cells are selectively allocated around the X-line and separatrices.



2D Reconnection

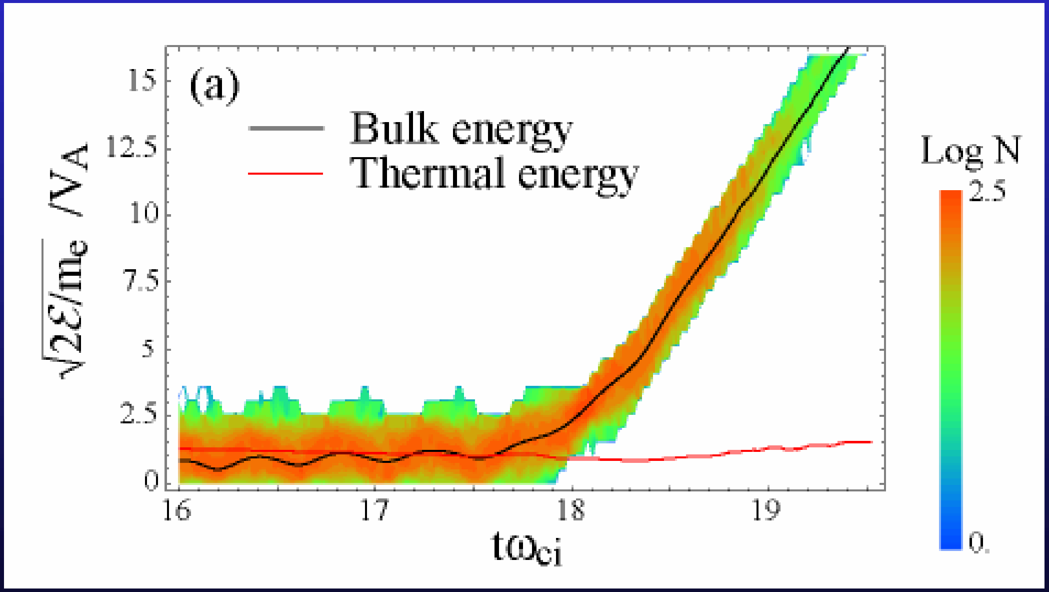




Electrons are…

- Coherently accelerated in the diffusion region,
- Not thermalized.

➡ Inertia resistivity



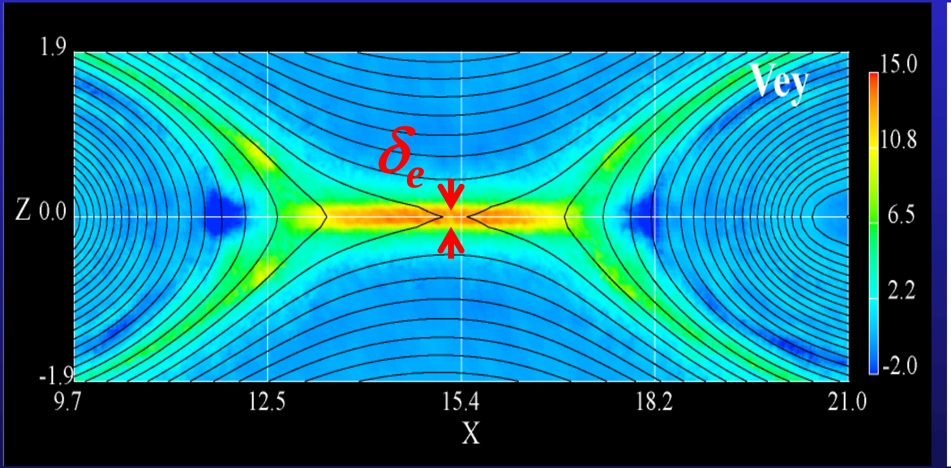
Electron Inertia Resistivity

[Speiser, 1970; Tanaka, 1995; Fujimoto & Sydora, 2009]

$$\eta_{in} = \frac{m_e \nu}{n_e e^2}, \quad \nu = \frac{1}{\tau_{tr}}$$

$$E_R = \eta_{in} j \approx \frac{m_e}{e} \frac{V_{ey}}{\tau_{tr}}$$

The electrons must be accelerated quickly up to electron Alfven velocity.



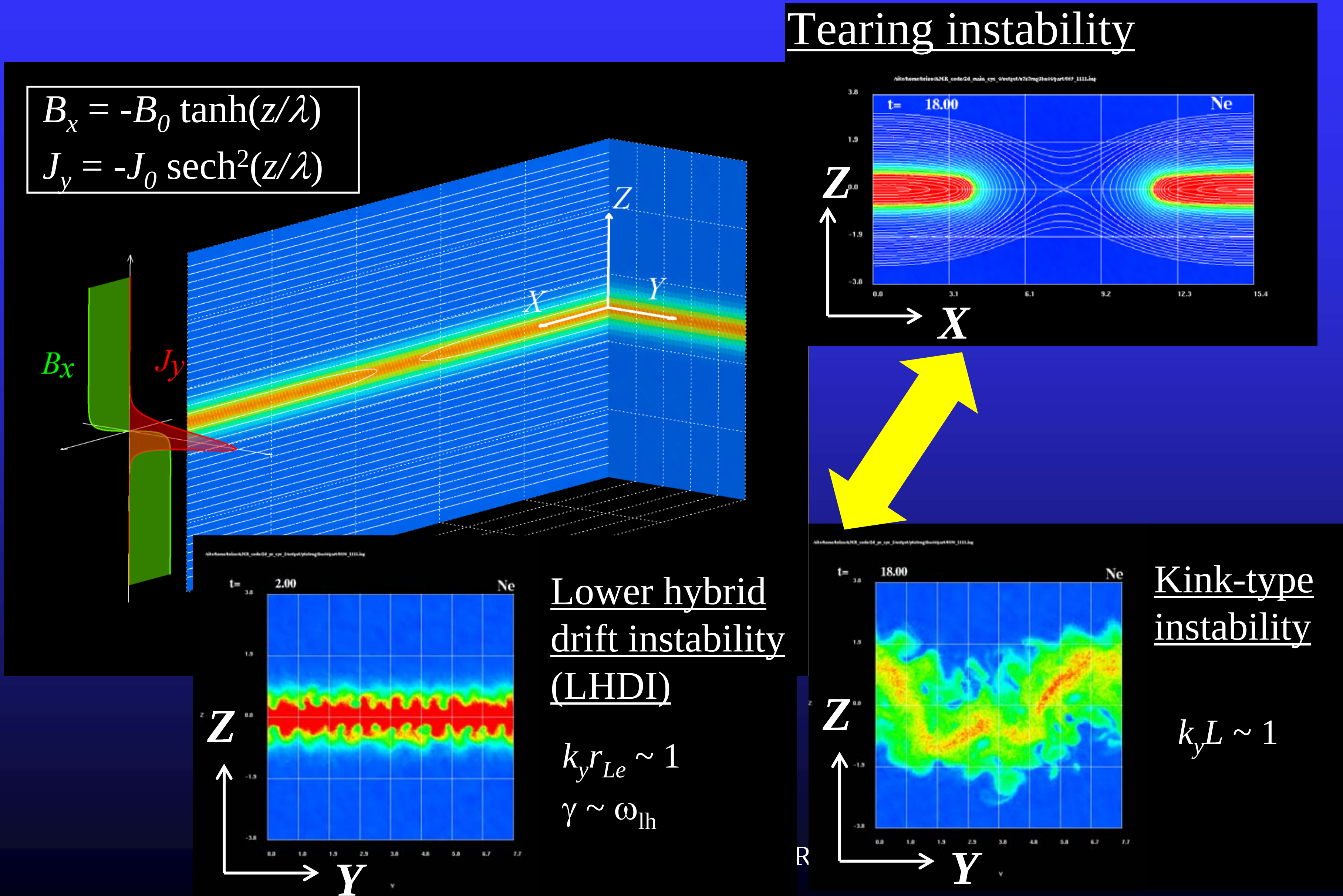
$$\delta_e \approx \lambda_e \,(= c/\omega_{pe})$$

Magnetotail : ~ 10km (⇔10^5km)

Solar Flare : ~ 10^{-5}km (⇔10^4km)

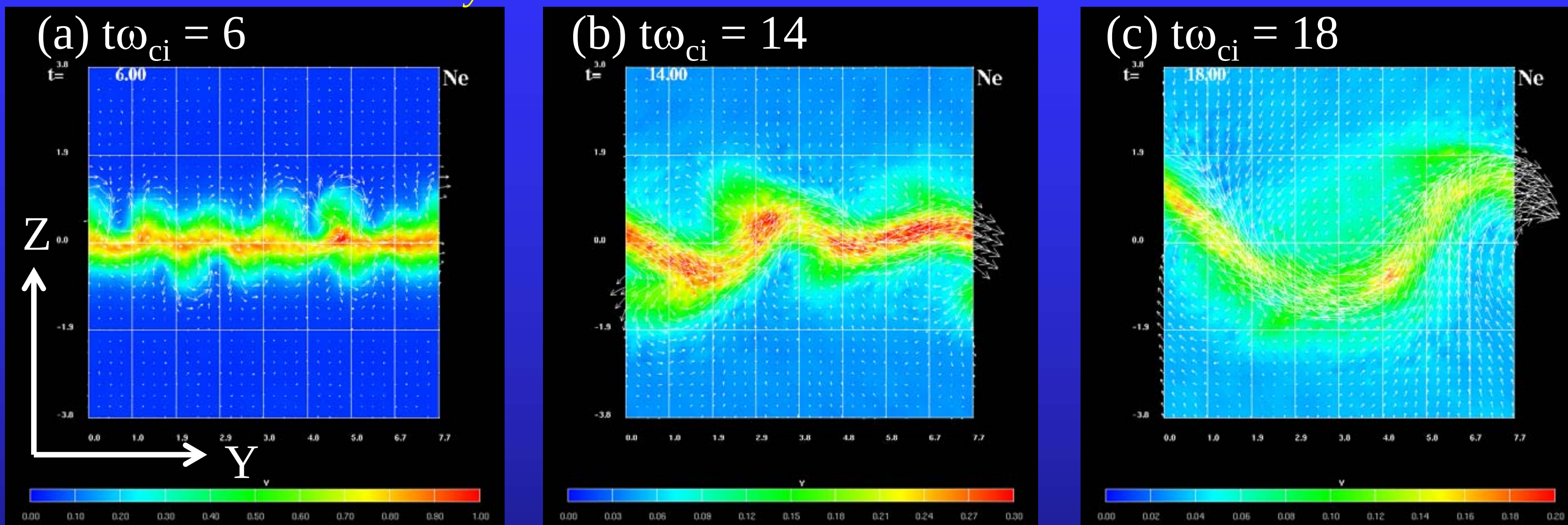
→ Is such a thin current sheet really stable in 3D system?

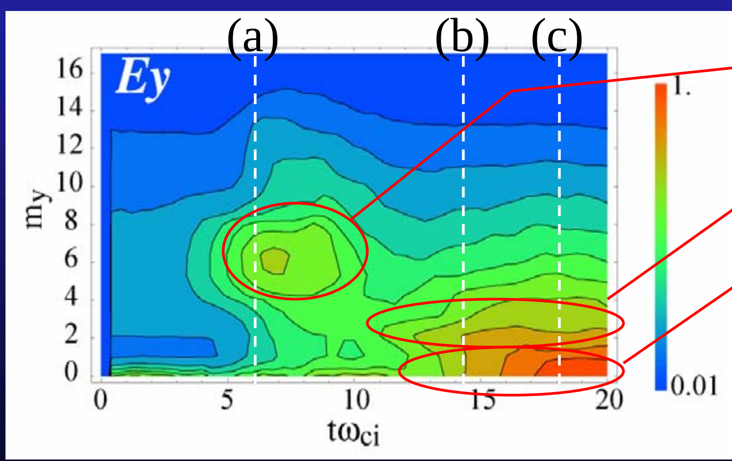
Unstable Modes Expected in the Current Sheet



Time Evolution of the Current Sheet in the YZ Plane

$m_i/m_e = 25,\ \ L_x \times L_y \times L_z = 31 \times 7.7 \times 31$





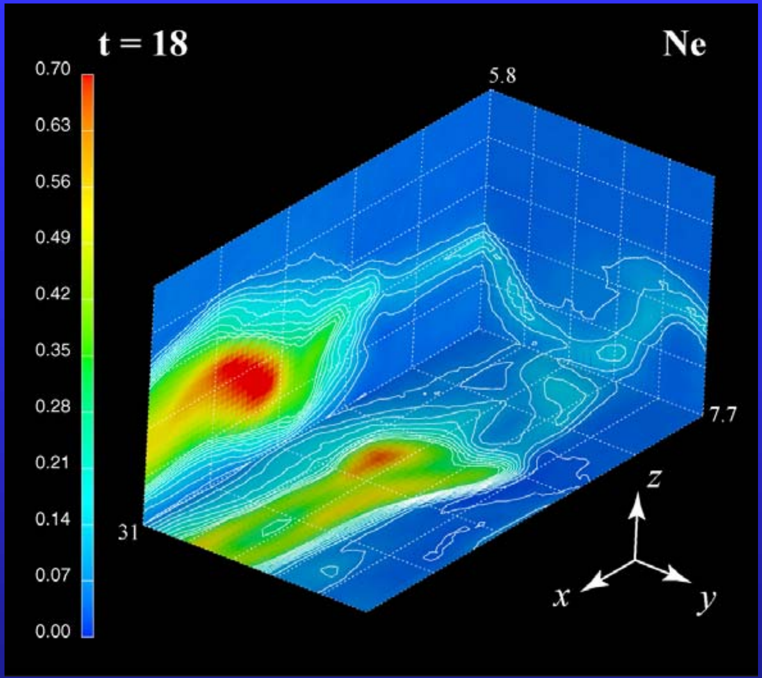
Lower hybrid drift instability (LHDI)

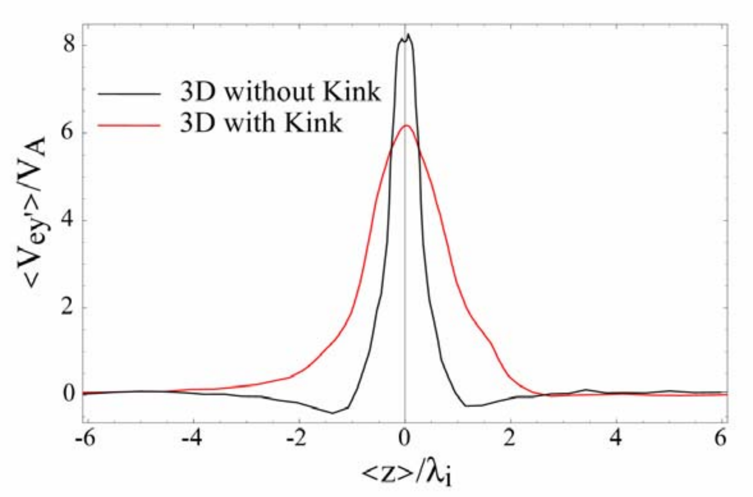
Kink-type instability

Induction field due to tearing instability

Kink instability coexists with the tearing mode.

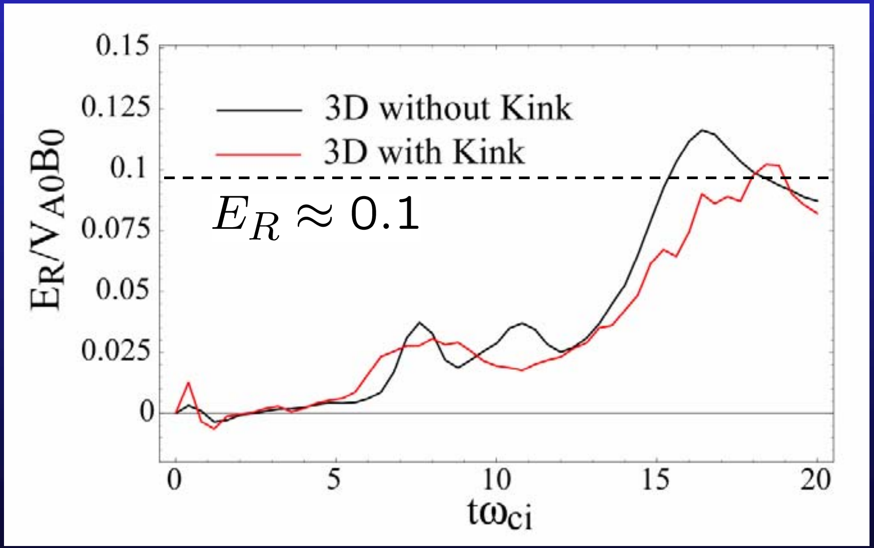
Reconnection Rate & Current Sheet Width





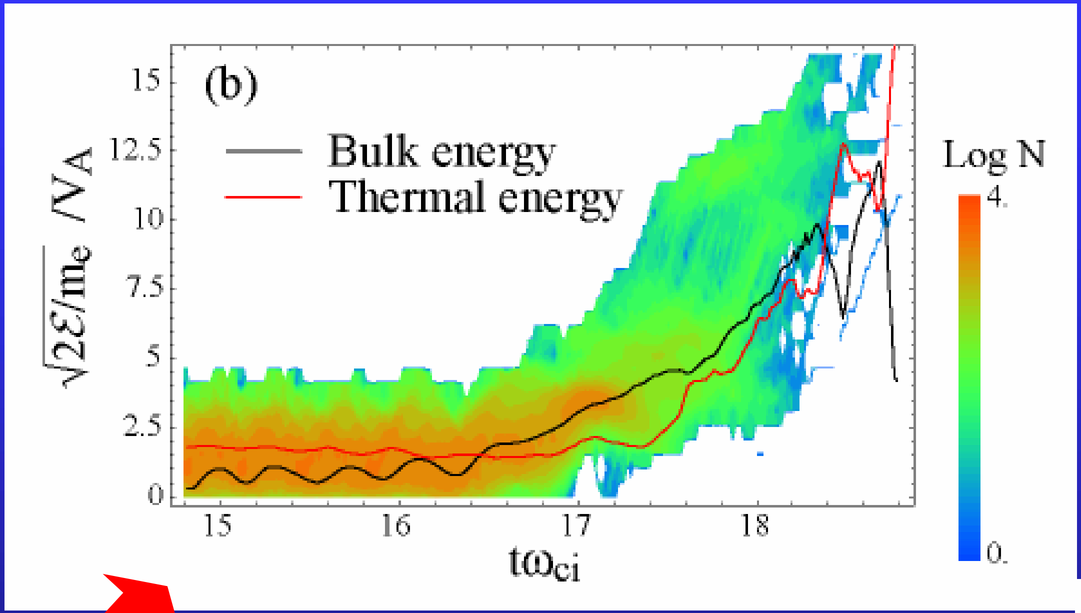
If the inertia resistivity alone supported the dissipation, the E_R would be significantly reduced.

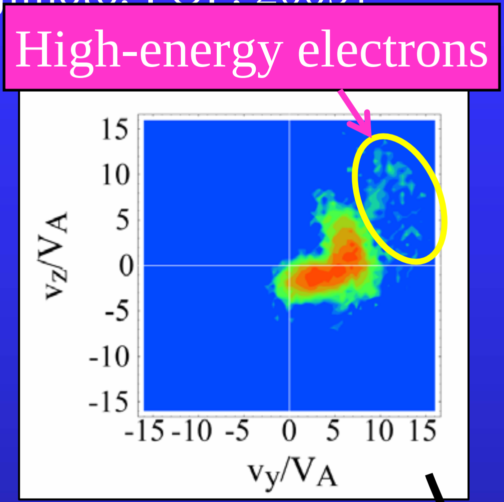
$$\frac{E_{R,kink}}{E_{R,nokink}} \propto \left(\frac{V_{e,kink}}{V_{e,nokink}}\right)^2 \approx 0.56$$

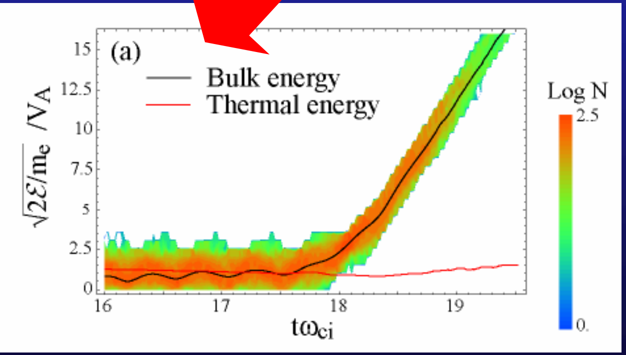


Dissipation Mechanism in 3D Reconnection

[Fujimoto, POP, 2009]

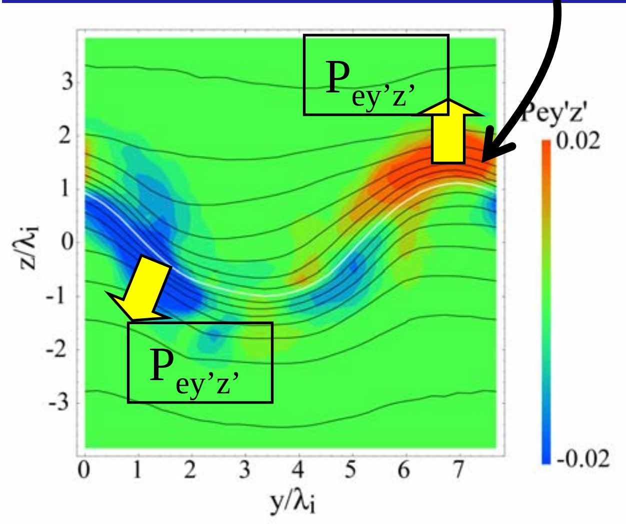






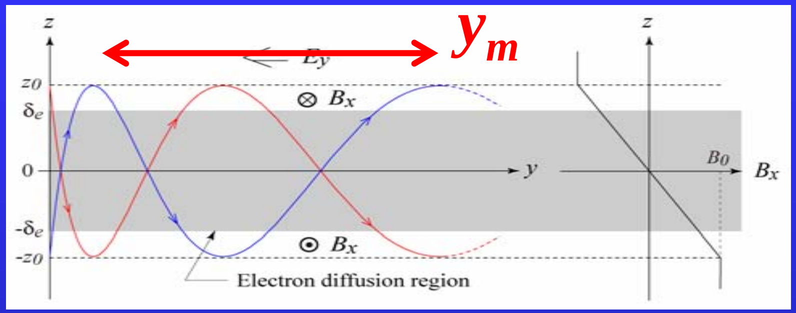
(2D reconnection case)

The electrons are intensely thermalized as well as accelerated in bulk.



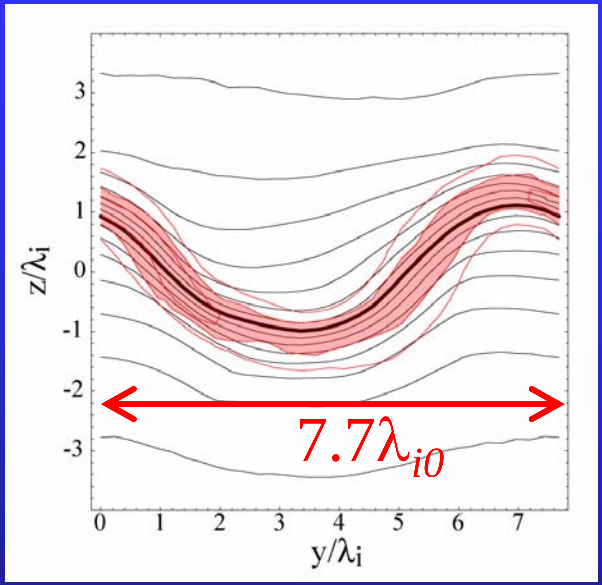
Meandering Scale & Wavelength

- Electron meandering scale



$$\omega \approx \frac{2}{3}\frac{V_{ey'}}{c}\omega_{pe} \quad [\textit{Speiser}, 1965]$$

$$y_m \approx V_{ey'}\frac{2\pi}{\omega} = 3\pi\lambda_e \approx 9\lambda_{i0}$$

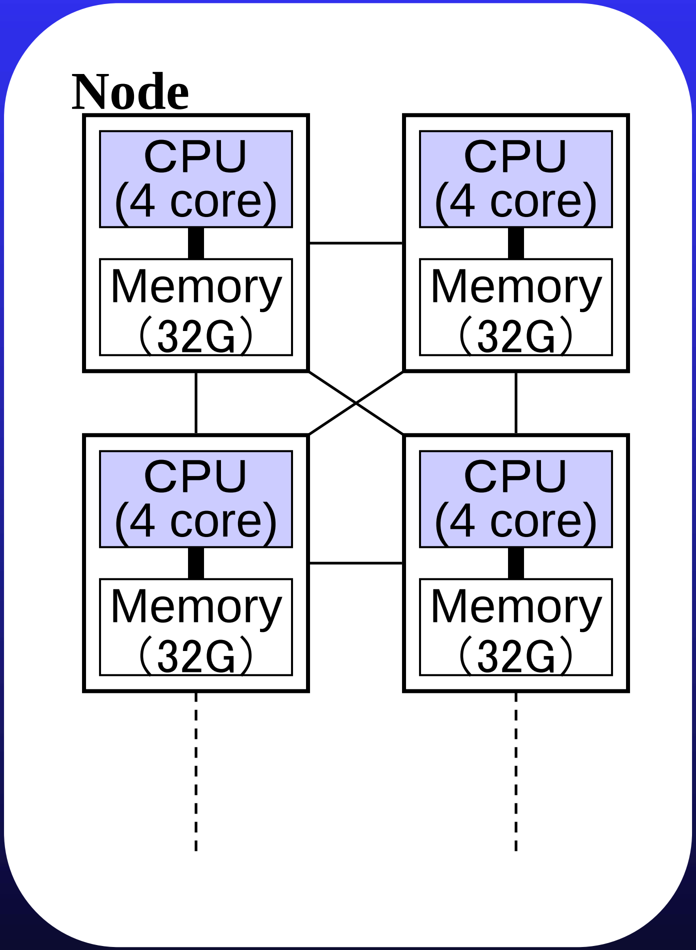


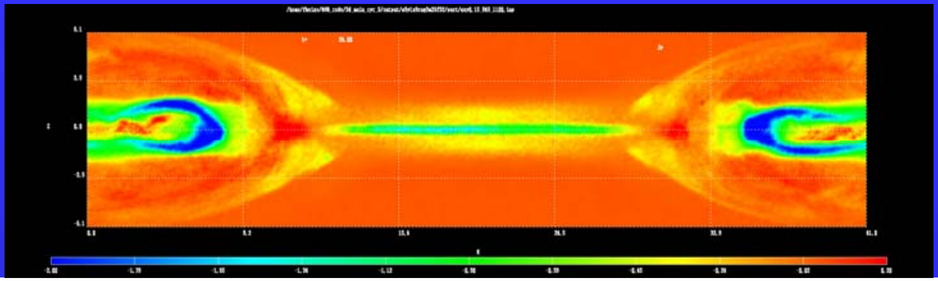
Meandering scale ~ Wavelength of the kink mode

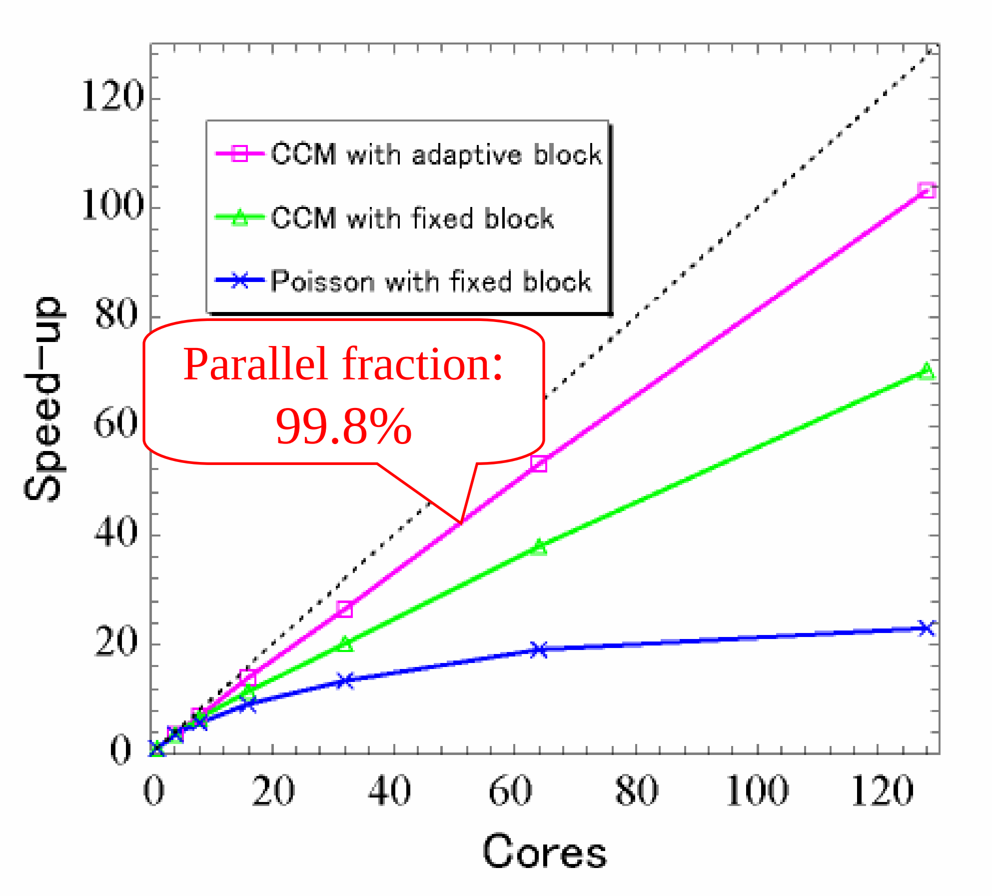
Does the wave-particle interaction still occur in higher mass ratio cases?

Massively parallel AMR-PIC code

Fujitsu FX1



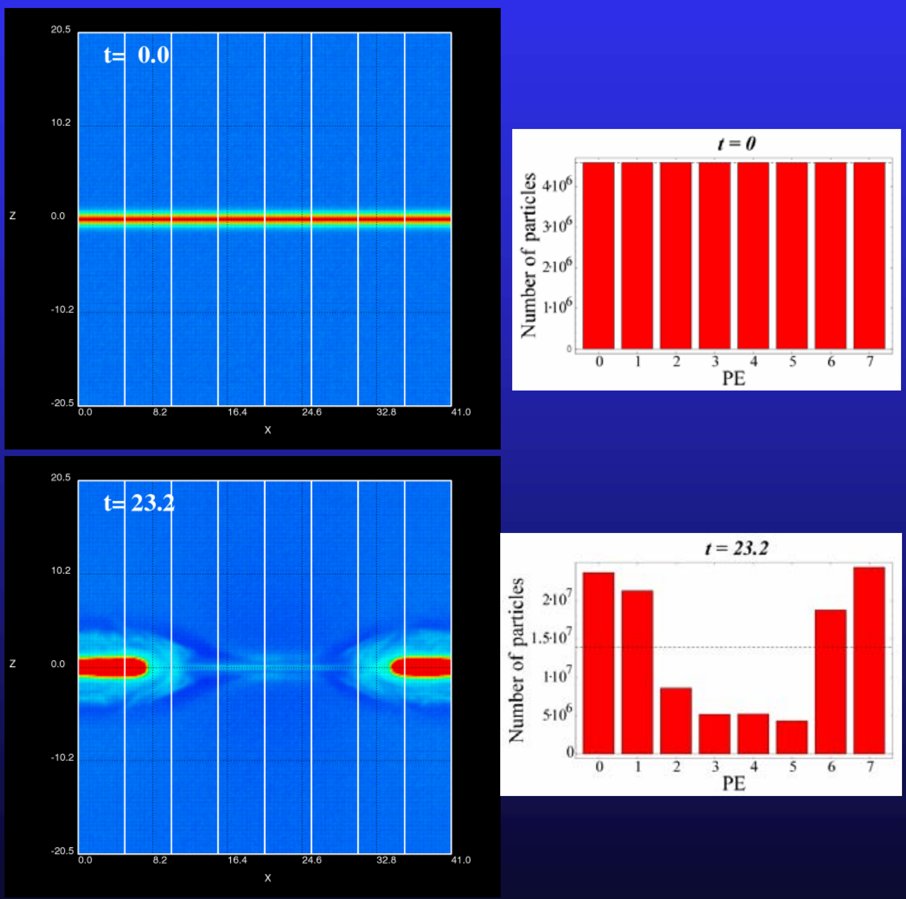




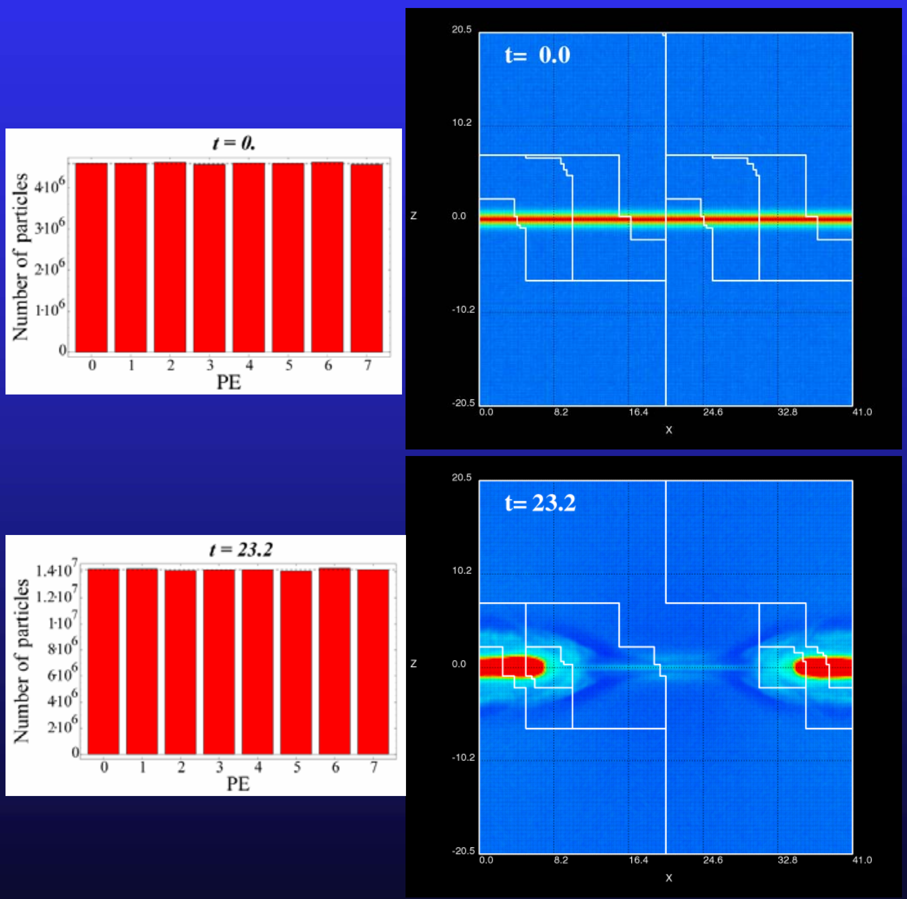
Load Balancing Technique

Example of 8-node parallelization

Fixed block

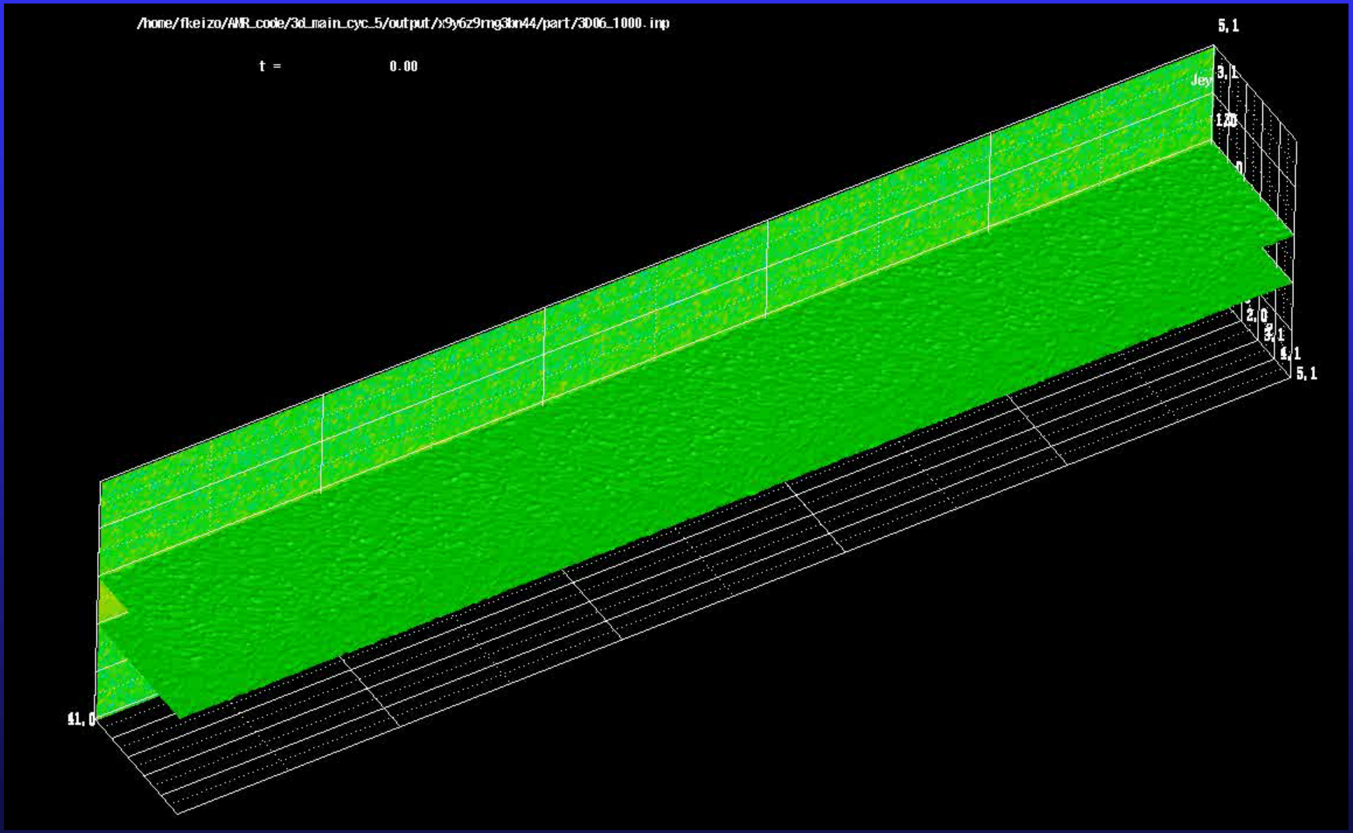


Adaptive block

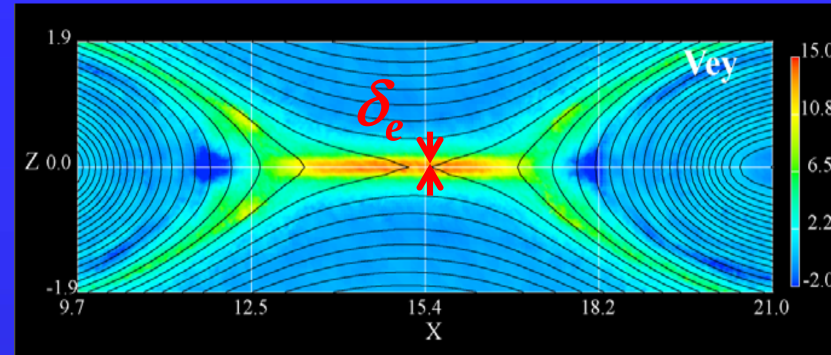


Large-scale 3D simulation: First result

$$m_i/m_e = 100, \qquad L_x \times L_y \times L_z = 41\lambda_i \times 5.1\lambda_i \times 41\lambda_i$$

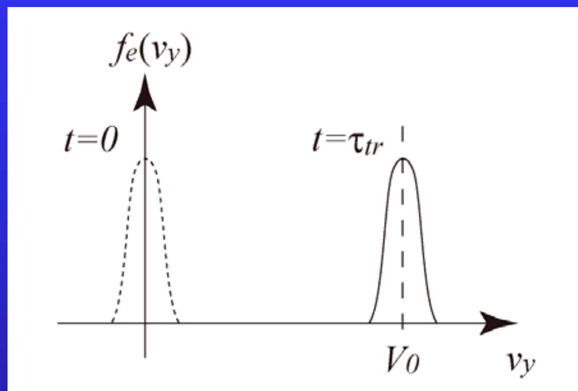


Current Sheet Width (δ_e)



2D case

(Inertia resistivity)

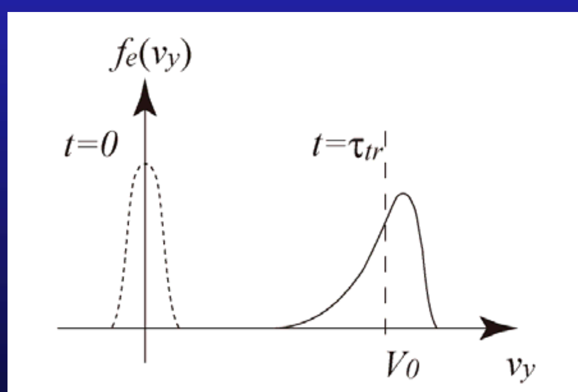


$$\frac{e|E_y|}{m_e}\tau_{tr} = V_0 \qquad \tau_{tr} \sim \frac{\delta_e}{V_{in}}$$

$$\Rightarrow \quad \delta_e \sim c/\omega_{pe}$$

3D case

(Inertia + anomalous resistivity)

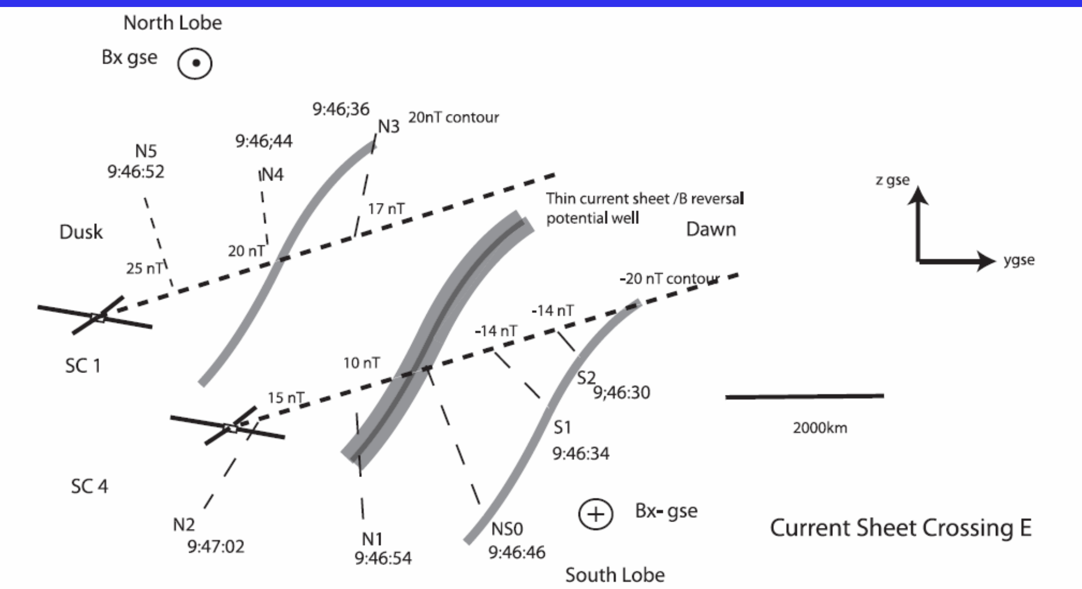


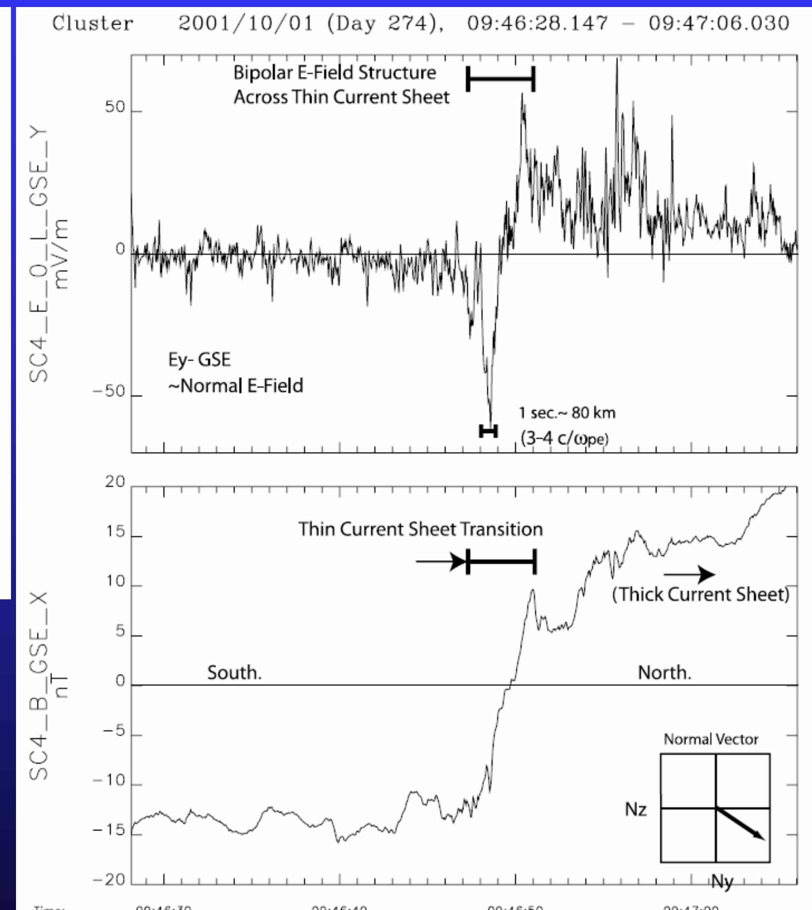
$$\frac{e|E_y|}{m_e}\tau_{tr} > V_0 \qquad \tau_{tr} \sim \frac{\delta_e}{V_{in}}$$

$$\Rightarrow \quad \delta_e > c/\omega_{pe}$$

In the Earth Magnetotail

Cluster observation of normal electric field in the kinked current sheet [Wygant et al., 2005]





Spiky normal electric field

- Duration = 1 sec ~ 80 km
- $3 – 4\ c/\omega_{pe} > c/\omega_{pe}$

Summary and Conclusions

The present study has investigated the dissipation mechanism in 3D magnetic reconnection in comparison with 2D reconnection, using a large-scale PIC simulations.

- Reconnection rate

  E_R ~ 0.1 both the cases of 2D and 3D reconnections

- Dissipation mechanism

  2D reconnection → Inertia resistivity

  3D reconnection → Inertia resistivity + Anomalous resistivity (Electron heating due to wave-particle interaction)

  → Current sheet width larger than c/ω_{pe}

Both the 3D simulation and observation studies indicate the existence of some wave-particle interaction at the X-line.