Anomalous Resistivity due to Kink Modes: Three-Dimensional Full Kinetic Simulations of Magnetic Reconnection
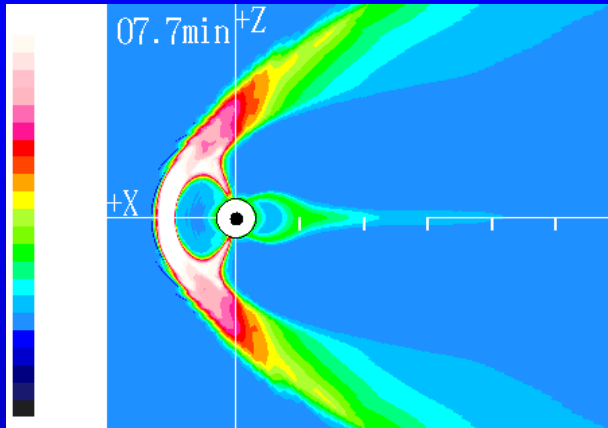
Keizo Fujimoto[1,2] and Richard D. Sydora[3]

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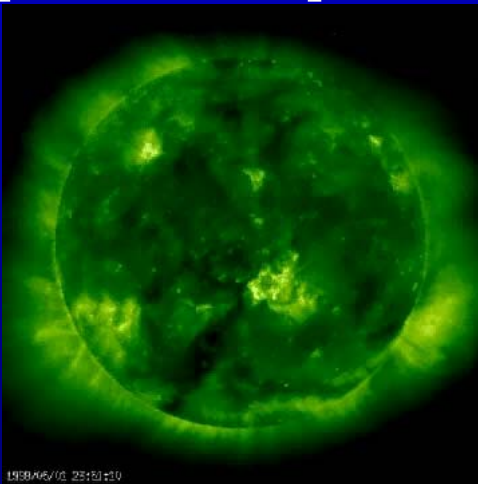3. Department of Physics, University of Alberta

Magnetic Reconnection in Space

[Magnetospheric substorms]

(*http://www2.nict.go.jp/dk/c232/*)

[Solar flares]

(*http://vestige.lmsal.com/TRACE/*)

In order to explain the explosive energy conversion by magnetic reconnection, a fast reconnection with the reconnection rate (normalized by the upstream values)

$$E_{rec} \sim 0.1 \ V_{A0}B_0$$

has to persist for the time scale of the phenomena in space plasmas
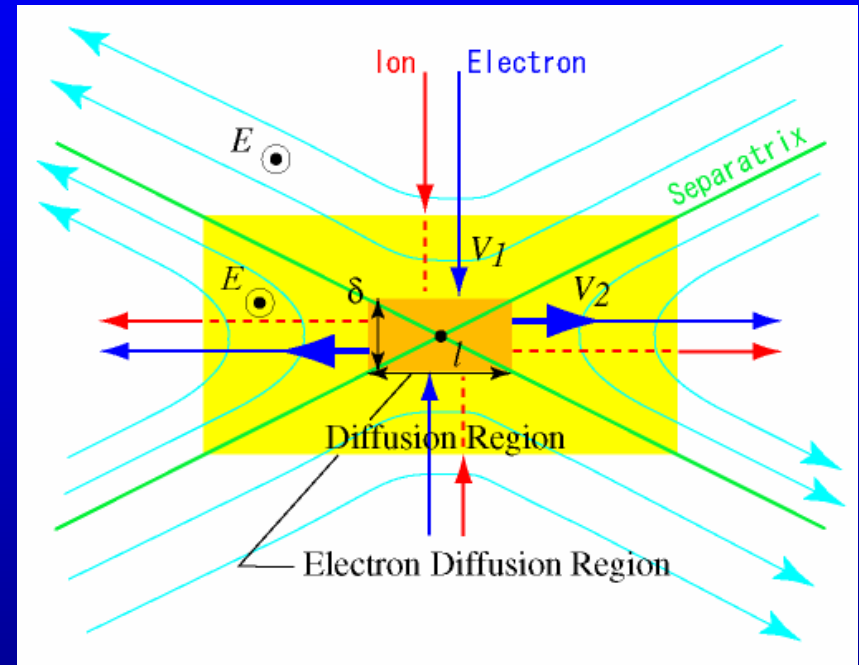
a few minutes 〜 a few hours.

<u>Diffusion Region</u>

Magnetic dissipation takes place in the diffusion region where the MHD constraints break down. Magnetic field satisfies the diffusion equation

$$\frac{\partial \boldsymbol{B}}{\partial t} = \frac{\eta}{\mu_0} \nabla^2 \boldsymbol{B}$$

η : Electric resistivity

It is still an open question how the resistivity is produced in collisionless plasmas.

Magnetic Dissipation in 2D System

It has been suggested that magnetic dissipation in 2D system is provided by the electron inertia resistivity due to the meandering/Speiser motion of the electrons.

$$E_{rec} = \eta^{in}j = \frac{1}{n_e e}(\nabla \cdot \boldsymbol{P}_e) + \frac{m_e}{e}\frac{dV_e}{dt}$$

Speiser [1965]

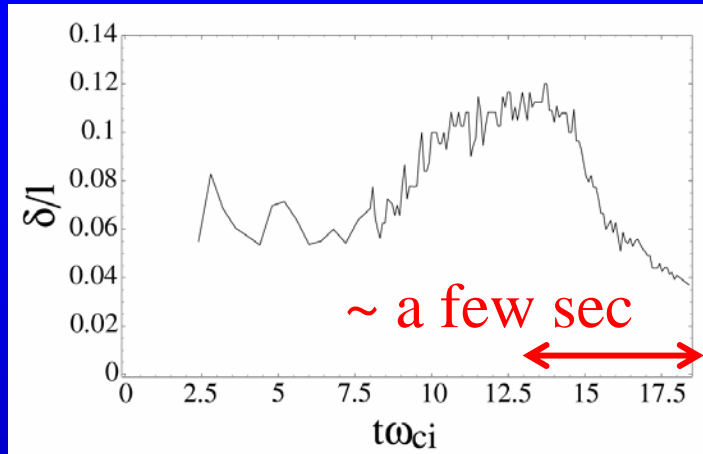In order for the inertia resistivity to be effective, the electron diffusion region has to be compact,

$$\frac{E_{rec}}{V_{A0}B_0} \simeq \frac{\sigma}{l} \sim 0.1 \qquad \left[\begin{array}{l} \sigma \sim \lambda e \\ l < \lambda i \end{array}\right]$$

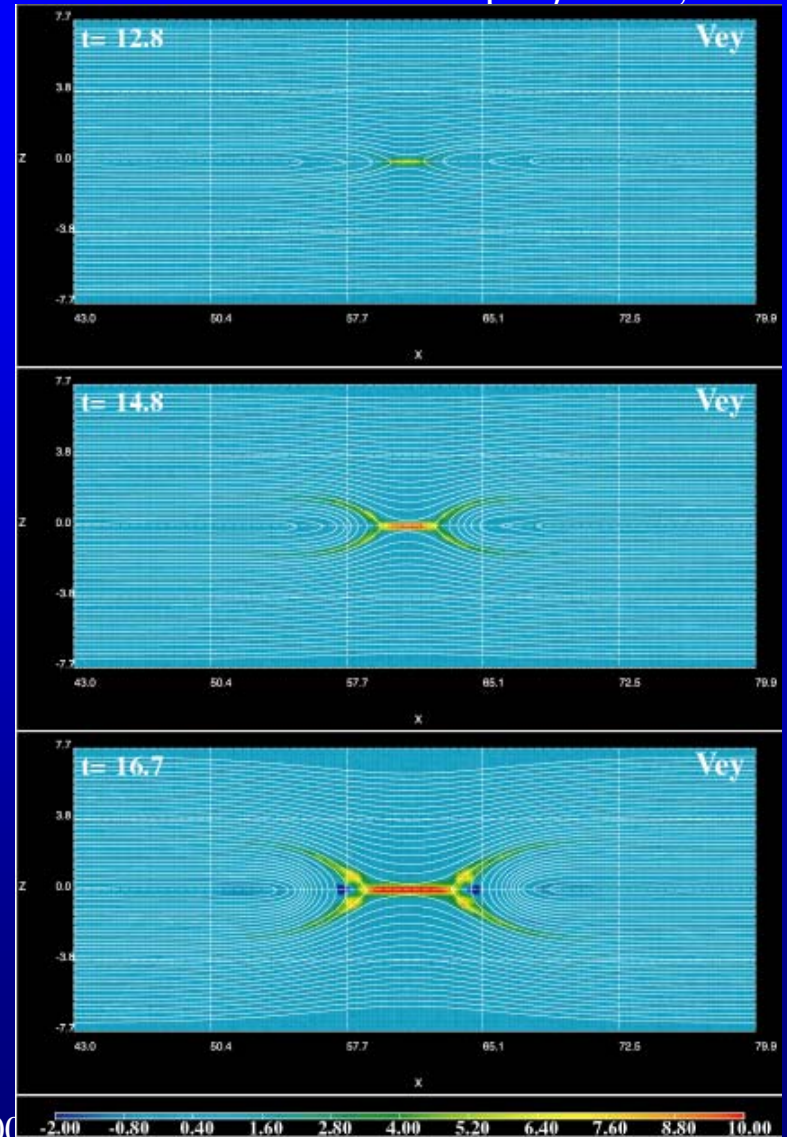which is believed to be guaranteed by the Hall effects [*Birn et al.,* 2001].
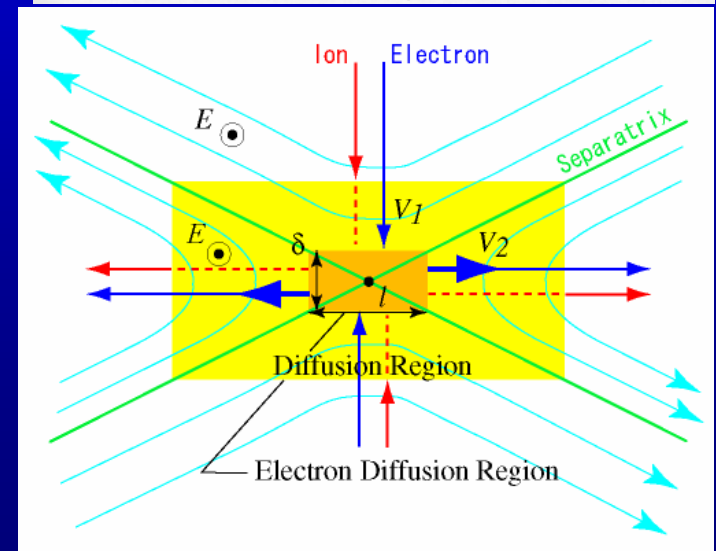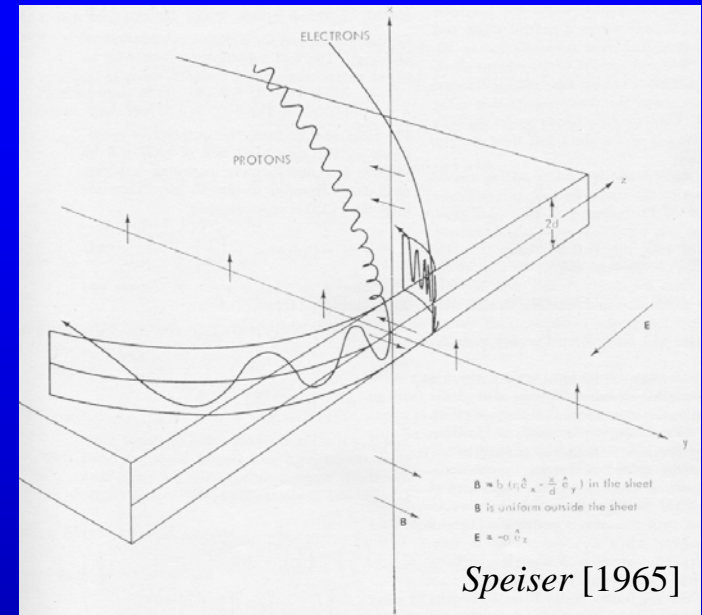
Large-Scale Particle-In-Cell Simulations in 2D System

~ a few sec

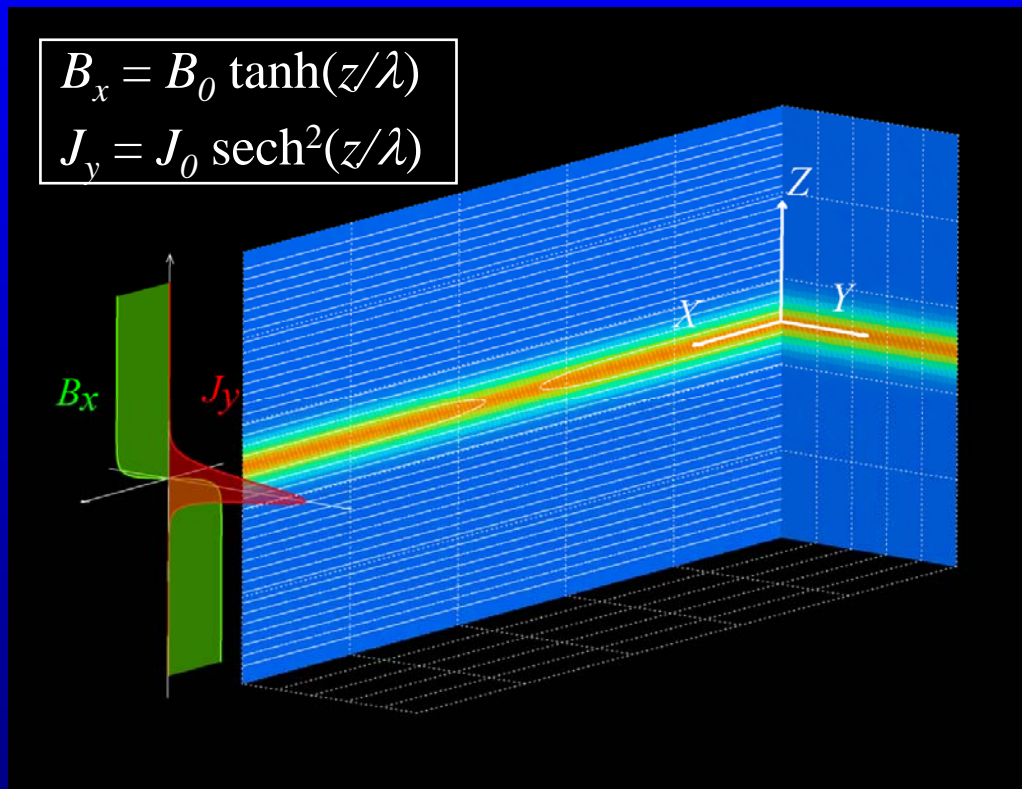$$\frac{E_{rec}}{V_{A0}B_0} \simeq \frac{\sigma}{l} << 0.1$$

It has been suggested that the elongated diffusion region is unstable in the current density direction, and anomalous resistivity could enhance the magnetic dissipation.

Large-Scale Particle-In-Cell Simulations in 3D System

Simulation code: 3D-EM-PIC + AMR (Adaptive Mesh Refinement)

[*Fujimoto and Sydora*, 2008]

$$B_x = B_0 \tanh(z/\lambda)$$
$$J_y = J_0 \operatorname{sech}^2(z/\lambda)$$

$L_x \times L_y \times L_z$
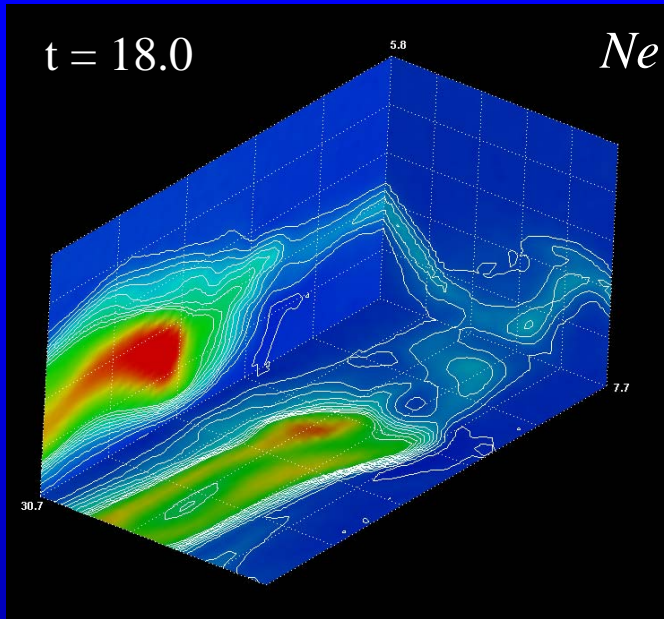$\quad = 31\,\lambda_i \times 7.7\,\lambda_i \times 31\,\lambda_i$

Maximum resolution :

$N_x \times N_y \times N_z = 1024 \times 256 \times 1024$

$m_i/m_e = 25$

The number of particles :

$$< 1.5 \times 10^9$$
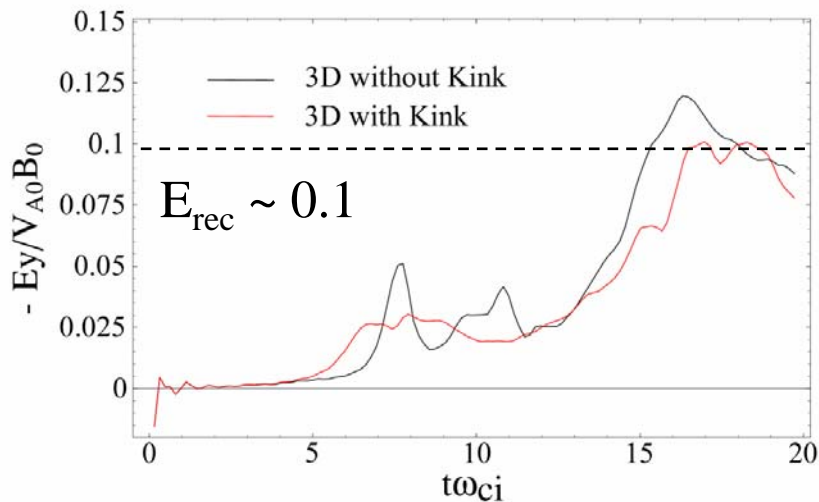
# Structure of Current Sheet, and Reconnection Rate

$t = 18.0$ *Ne*

In 3D system a kink mode is driven by the ions drifting in the cross-field direction. The kink mode deforms the current sheet structure drastically.

Nevertheless, the time profile of the reconnection electric field is almost identical to the run without the kink mode, and the fast reconnection is achieved.
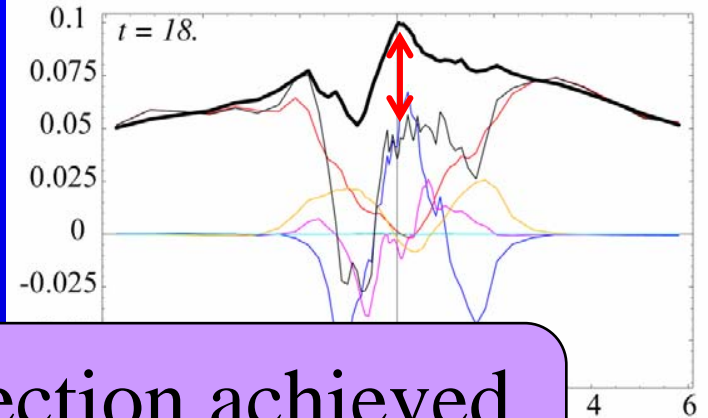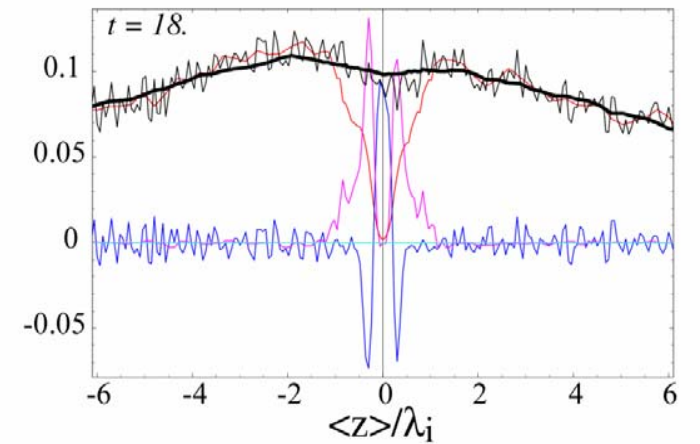
$$E_{rec} \sim 0.1 \ V_{A0}B_0$$

$E_{rec} \sim 0.1$

Generalized Ohm's Law
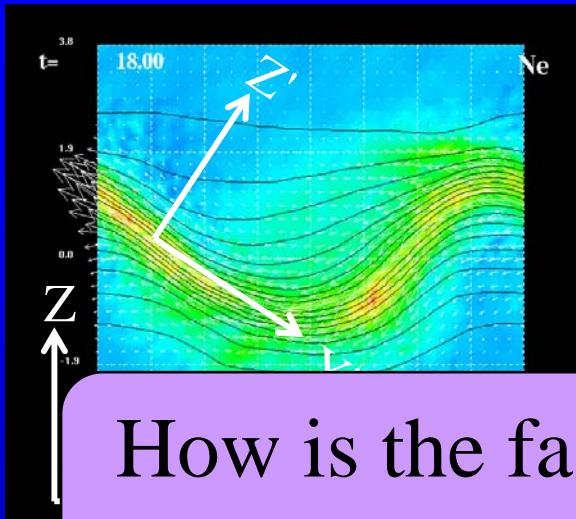
(a) With kink mode

How is the fast reconnection achieved in the system with kink mode ?

$$= \frac{1}{\langle n_e \rangle} \left(\langle n_e \vec{V}_e \rangle \times \langle \vec{B} \rangle \right)_{y'}$$

$$+ \frac{1}{e \langle n_e \rangle} \langle (\nabla' \cdot \vec{P}_e)_{y'} \rangle$$

$$+ \frac{m_e}{e \langle n_e \rangle} \left\langle \frac{dV_{ey'}}{dt} \right\rangle$$

$$+ \frac{1}{\langle n_e \rangle} \langle \delta n_e \delta E_{y'} \rangle$$

Electron inertial effects
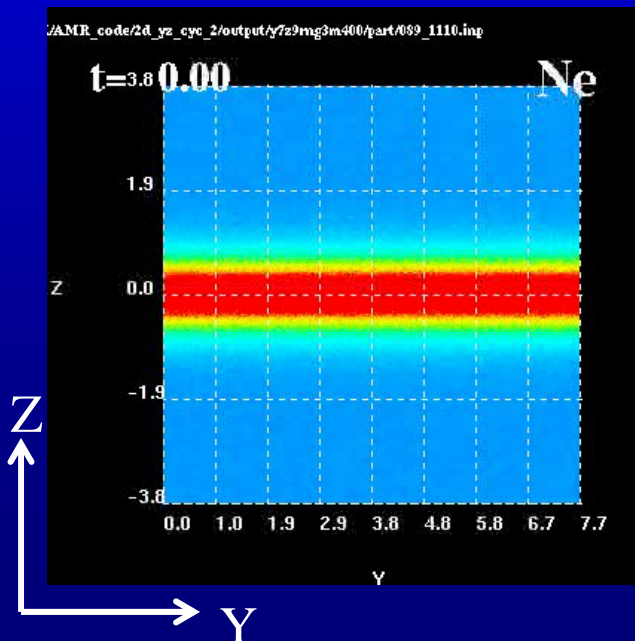
2D Simulations in the YZ Plane
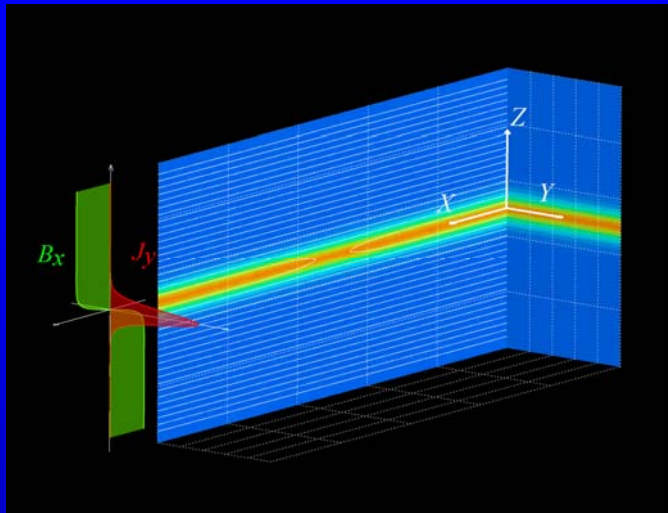
In order to clarify the dissipation mechanism associated with the kink mode, we perform 2D simulations in the system where the inertia effects are excluded.
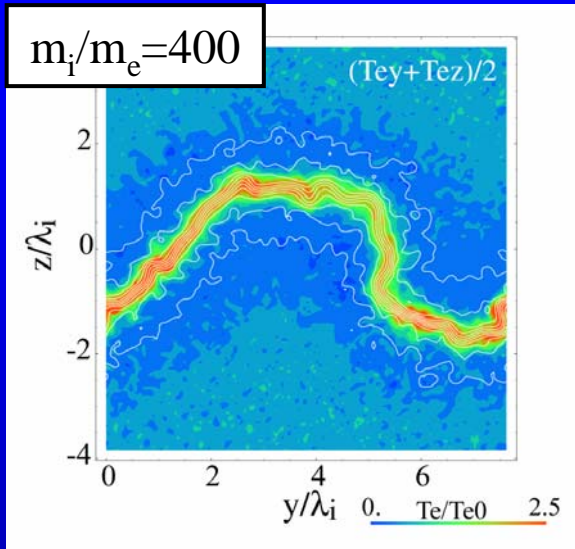
It is confirmed that the kink mode provides magnetic dissipation with an amplitude independent of the mass ratio.

[*Ozaki et al.*, 1996; *Horiuchi and Sato*, 1999; *Shinohara et al.*, 2001]

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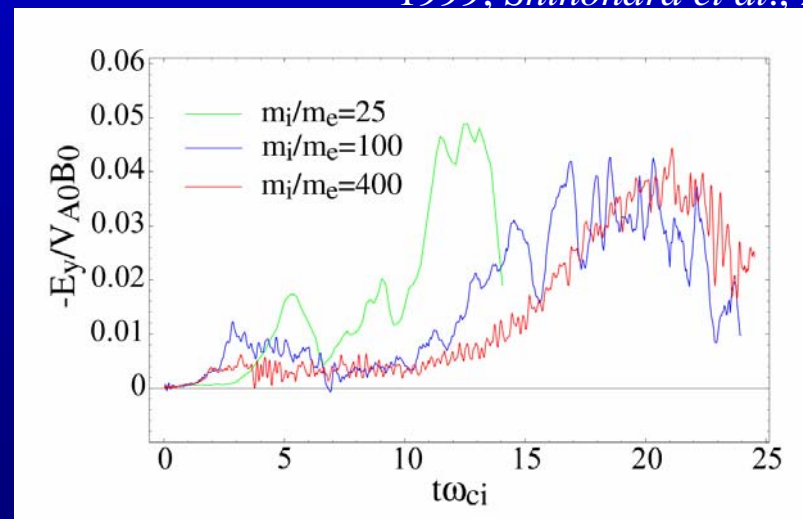
Magnetic Dissipation Associated with the Kink Mode

[Electron Temperature]

$m_i/m_e=400$

It is found that the electrons are strongly heated in the thin current sheet. This is caused due to a stochastic scattering at the corner of the "small bumps".
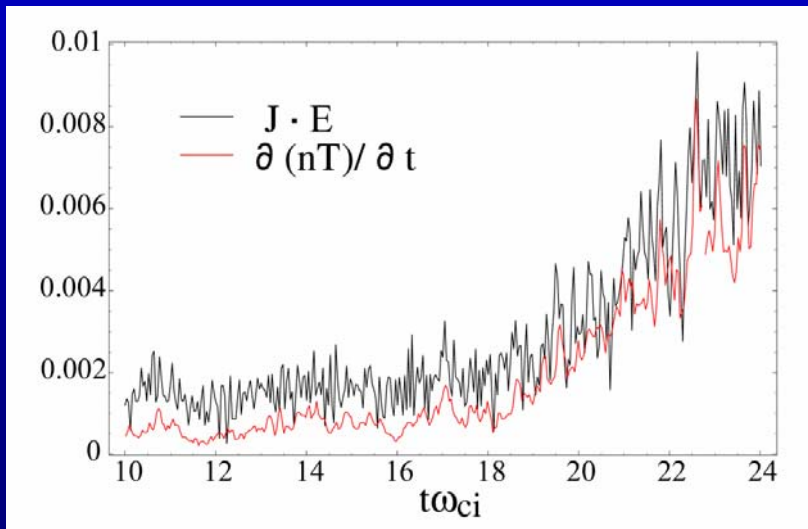
Under a steady state, the energy gain should be balanced with the energy loss.

$$\vec{j} \cdot \vec{E} \sim \frac{1}{2}n_e m_e V_{ec}^2 \nu_e + \frac{1}{2}n_i m_i V_{ic}^2 \nu_i$$

If the effective collision converts the bulk energy to the thermal energy,

$$\vec{j} \cdot \vec{E} \sim \frac{\partial(nT)}{\partial t}$$

should be satisfied.

Magnetic Dissipation in 3D System

$$\left\langle -E_{y'}\right\rangle_{xline} = \eta^{eff}\left\langle j_{y'}\right\rangle_{xline}$$

$$= \frac{1}{\left\langle n_e\right\rangle}\left(\left\langle n_e\vec{V_e}\right\rangle \times \left\langle \vec{B}\right\rangle\right)_{y'}$$

$$+ \frac{1}{e\left\langle n_e\right\rangle}\left\langle (\nabla'\cdot\vec{P_e})_{y'}\right\rangle$$

$$+ \frac{m_e}{e\left\langle n_e\right\rangle}\left\langle \frac{dV_{ey'}}{dt}\right\rangle$$

$$+ \frac{1}{\left\langle n_e\right\rangle}\left\langle \delta n_e\delta E_{y'}\right\rangle$$

$$+ \eta^{an}\left\langle j_{y'}\right\rangle$$

Electron inertial effects

Due to anomalous resistivity

Anomalous resistivity

$$\eta^{an} = \left\langle -E_{y'}^{(2D)}\right\rangle / \left\langle j_{y'}^{(2D)}\right\rangle$$

Inertia resistivity + Anomalous resistivity

It is found that the anomalous resistivity enhances the reconnection electric field, and makes a significant contribution for realizing the fast reconnection, compensating the reduction in the inertia resistivity.
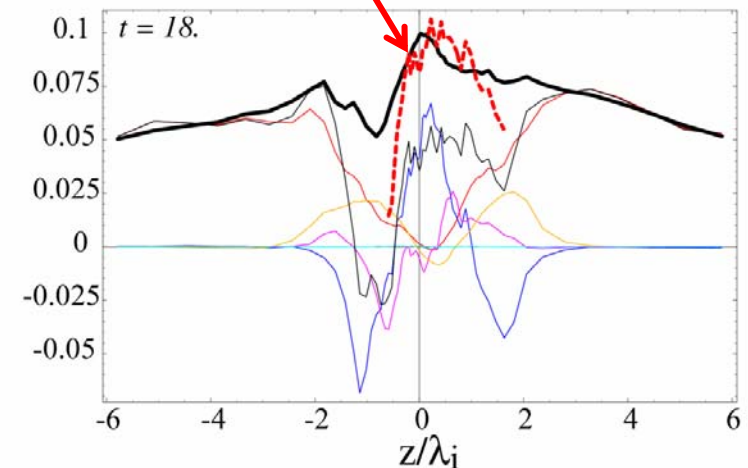
Summary and Conclusions

We have performed a 3D PIC simulation in a large system in order to investigate how the kink modes affect magnetic reconnection.

We found that the kink mode broadens the width of the current sheet and decreases the inertia resistivity. Instead, the anomalous resistivity associated with the kink mode compensates the depletion so as to keep the high reconnection rate.

The present result suggests that the electron dynamics in the elecron diffusion region is automatically adjusted so as to produce sufficient dissipation for the fast magnetic reconnection.