Multi-Scale Kinetic Simulation of Collisionless Magnetic Reconnection

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Ref. *Fujimoto & Takamoto, Physics of Plasmas* ***23****, 012903 (2016)*

Outline

- Motivation of the current study
- Strategy of multi-scale simulation
- Simulation results --- Multiscale dynamics of reconnection
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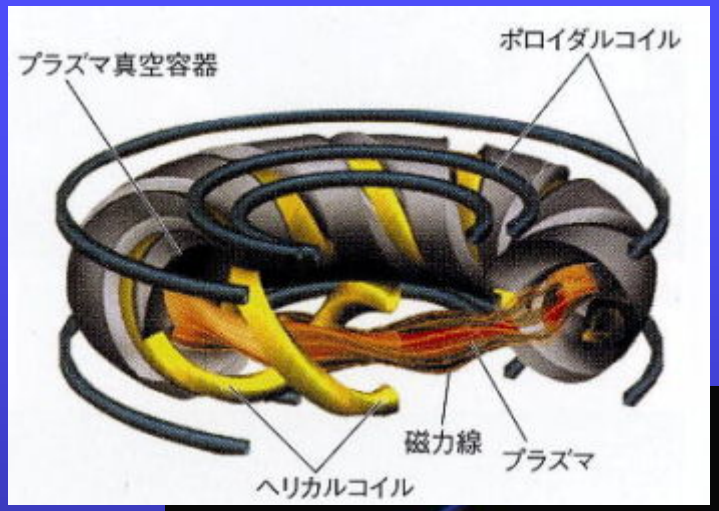
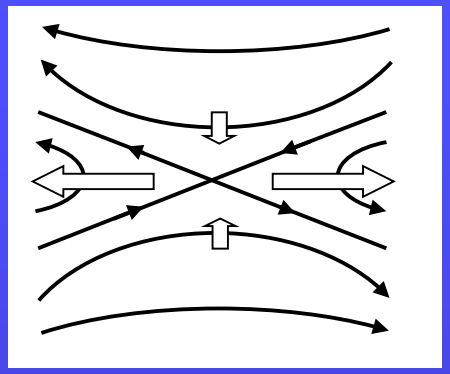
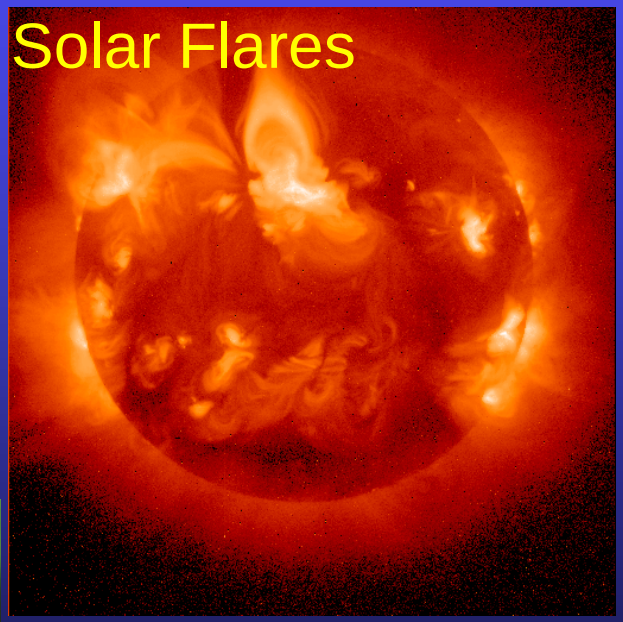
Magnetic Reconnection



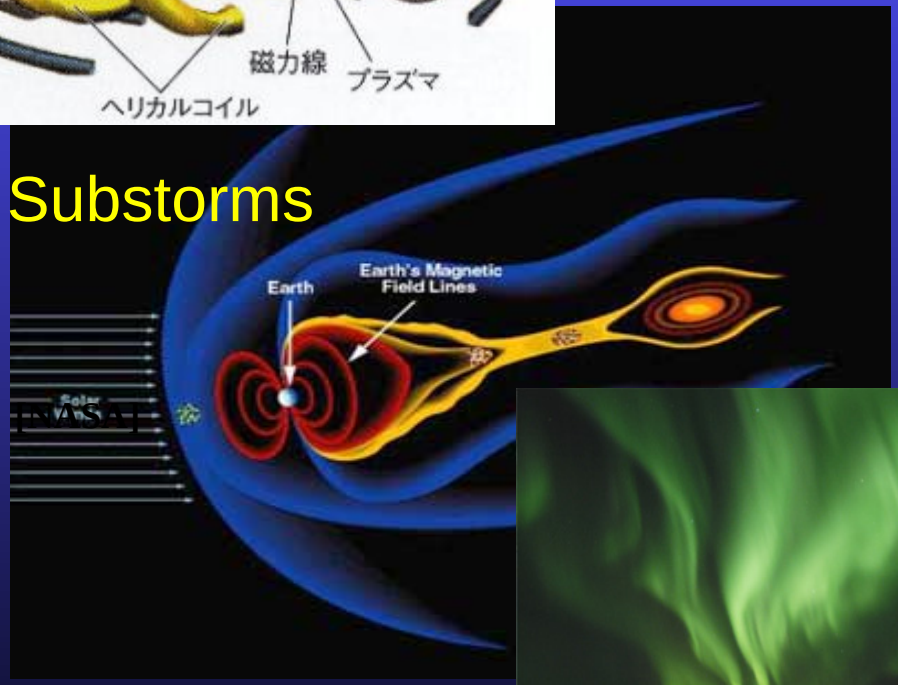
Fusion Device

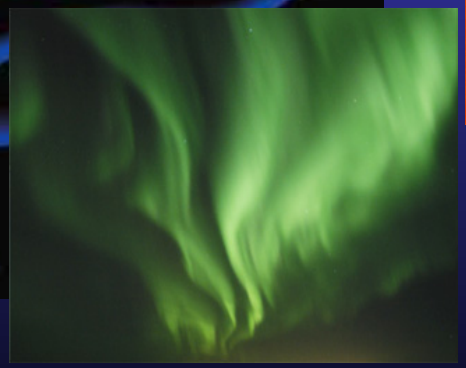


Solar Flares



Auroral Substorms

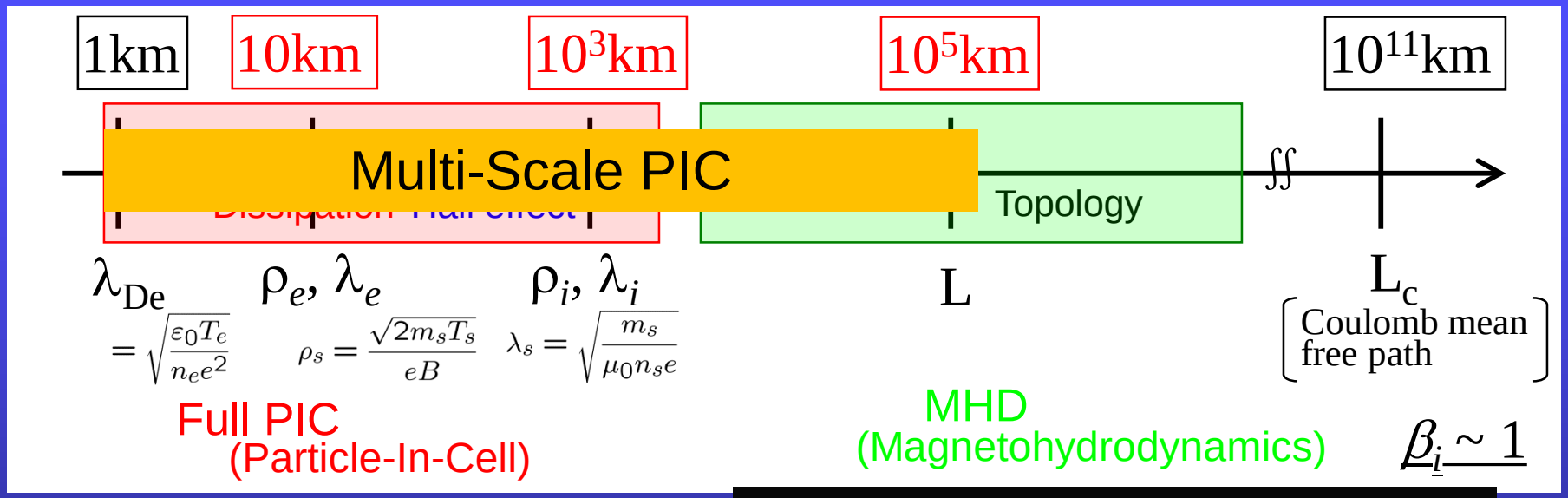


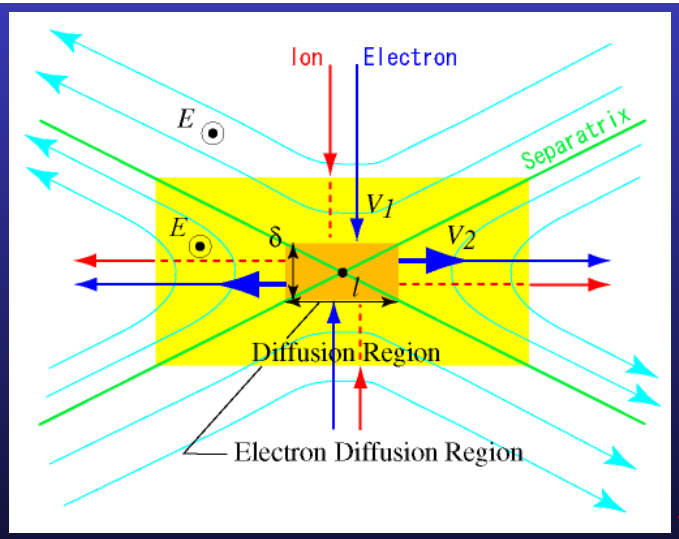


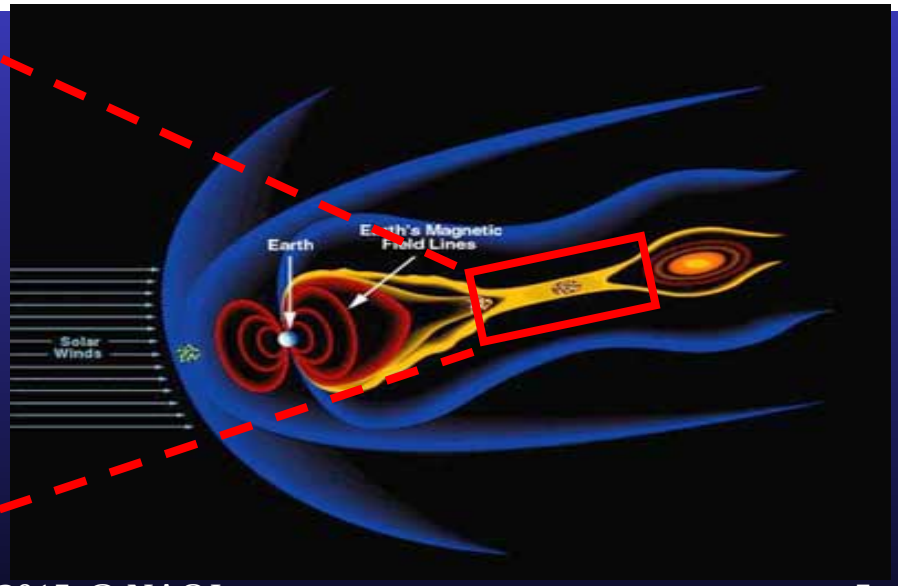
$\omega >> \omega_{collision}$

Collisionless plasma

Multi-Scale Nature of Reconnection

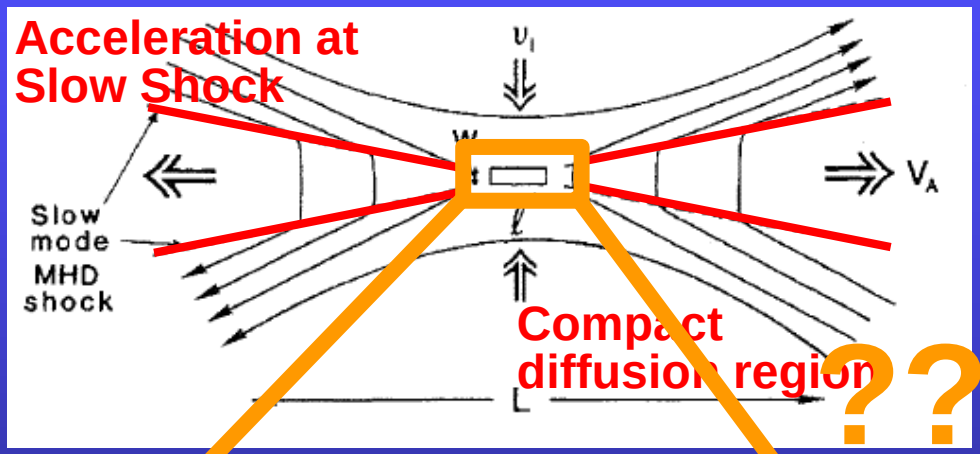






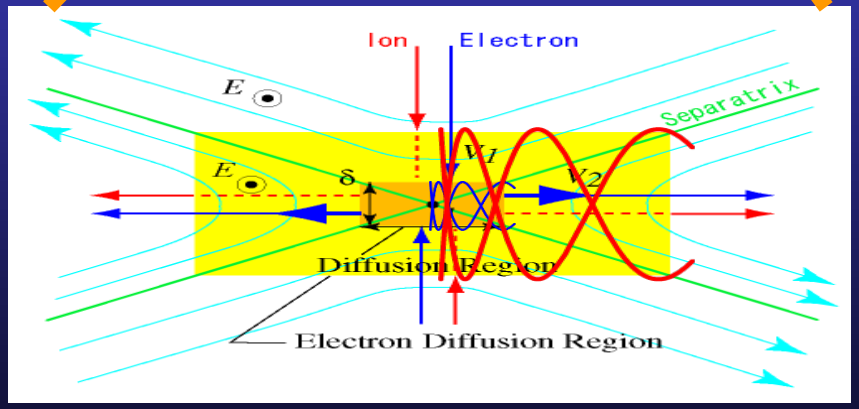
MHD vs. Kinetic Reconnection

MHD Reconnection (Petschek Model [Petschek, 1964])



- Fast reconnection
- Compact diffusion region
- Acceleration at slow shock
- Reproduced in MHD simulation [Ugai & Tsuda, 1977; …etc]
- Slow shocks were observed. [Feldman et al., 1984; …etc]

Kinetic Reconnection



- Fast reconnection
- Ion/electron Speiser accel.
- Hall electric current
- Reproduced in PIC simulation [Birn et al., 2001; …etc]
- Hall field was observed. [Nagai et al., 2001; …etc]

Purpose of This Study

Understanding of the MHD-scale dynamics of collisionless reconnection, by means of large-scale PIC simulation.

- Can the Petschek reconnection be achieved?
- How does the kinetic process connect to the MHD processes?

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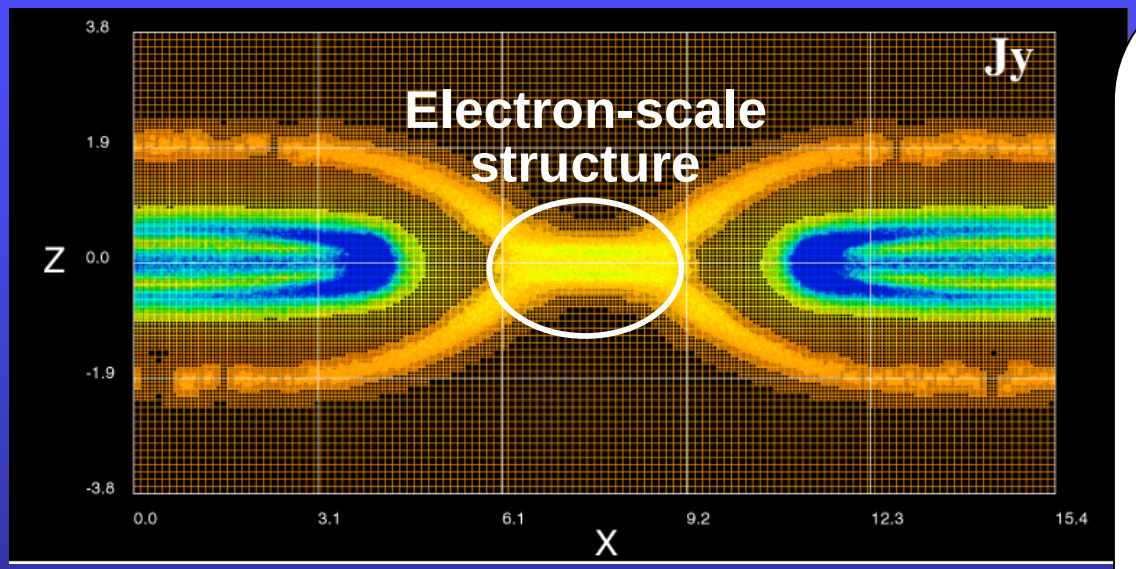
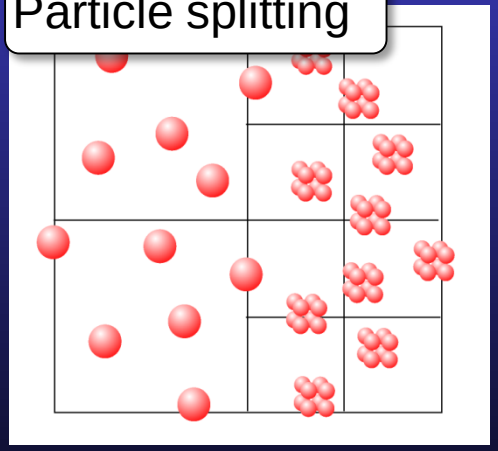
AMR-PIC Model [Fujimoto, JCP, 2011]

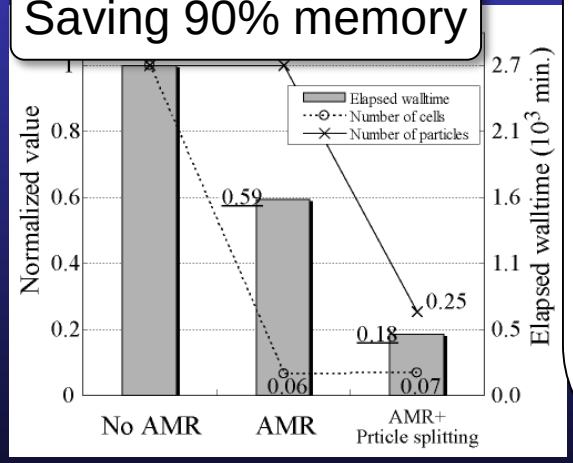
(Adaptive Mesh Refinement – Particle-in-Cell)



Particle splitting



Saving 90% memory



Particles

$$\frac{d\vec{v}_s}{dt} = \frac{q_s}{m_s}\left(\vec{E} + \vec{v}_s \times \vec{B}\right)$$

$$\frac{d\vec{x}_s}{dt} = \vec{v}_s$$

Electric and magnetic fields

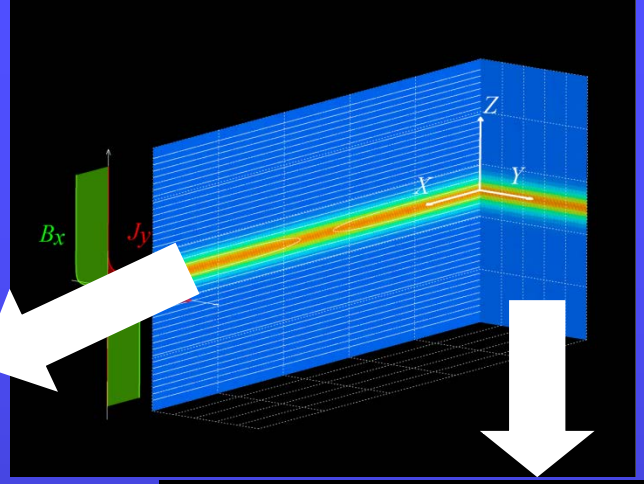
$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}$$

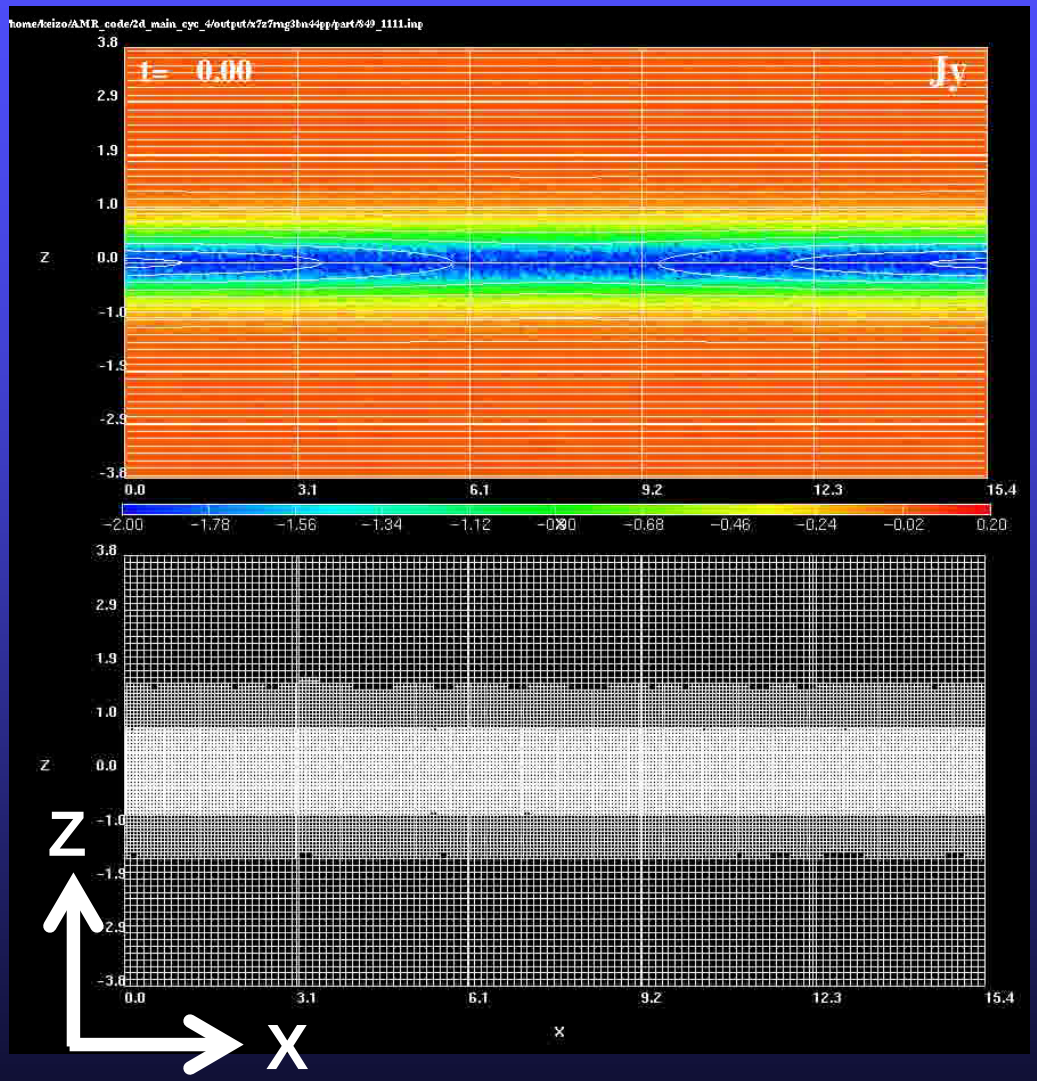
$$\frac{\partial \vec{E}}{\partial t} = c^2 \nabla \times \vec{E} - \frac{1}{\varepsilon_0}\vec{J}$$

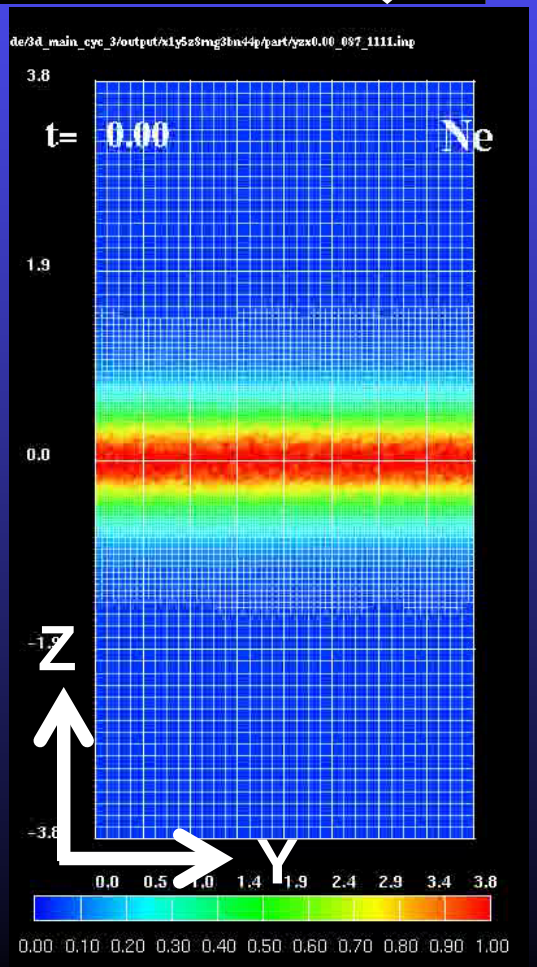
Current density

$$\vec{J} = \sum_s q_s \int \vec{v} f_s(\vec{v}) d^3 v$$

AMR-PIC Simulations

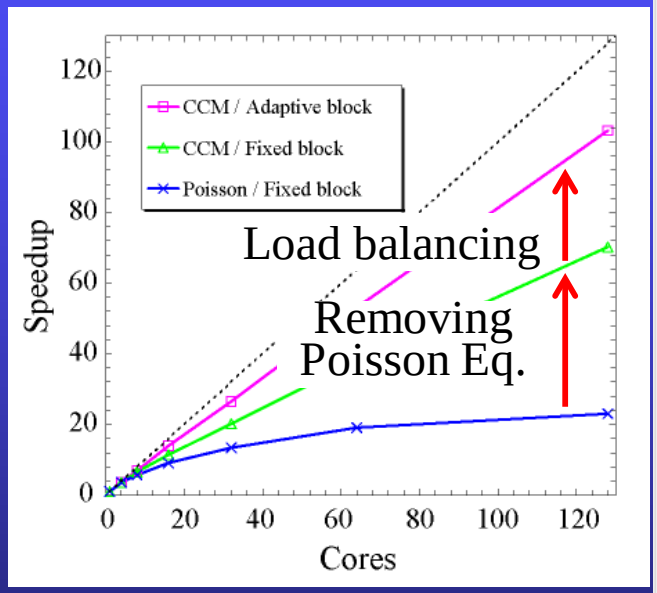


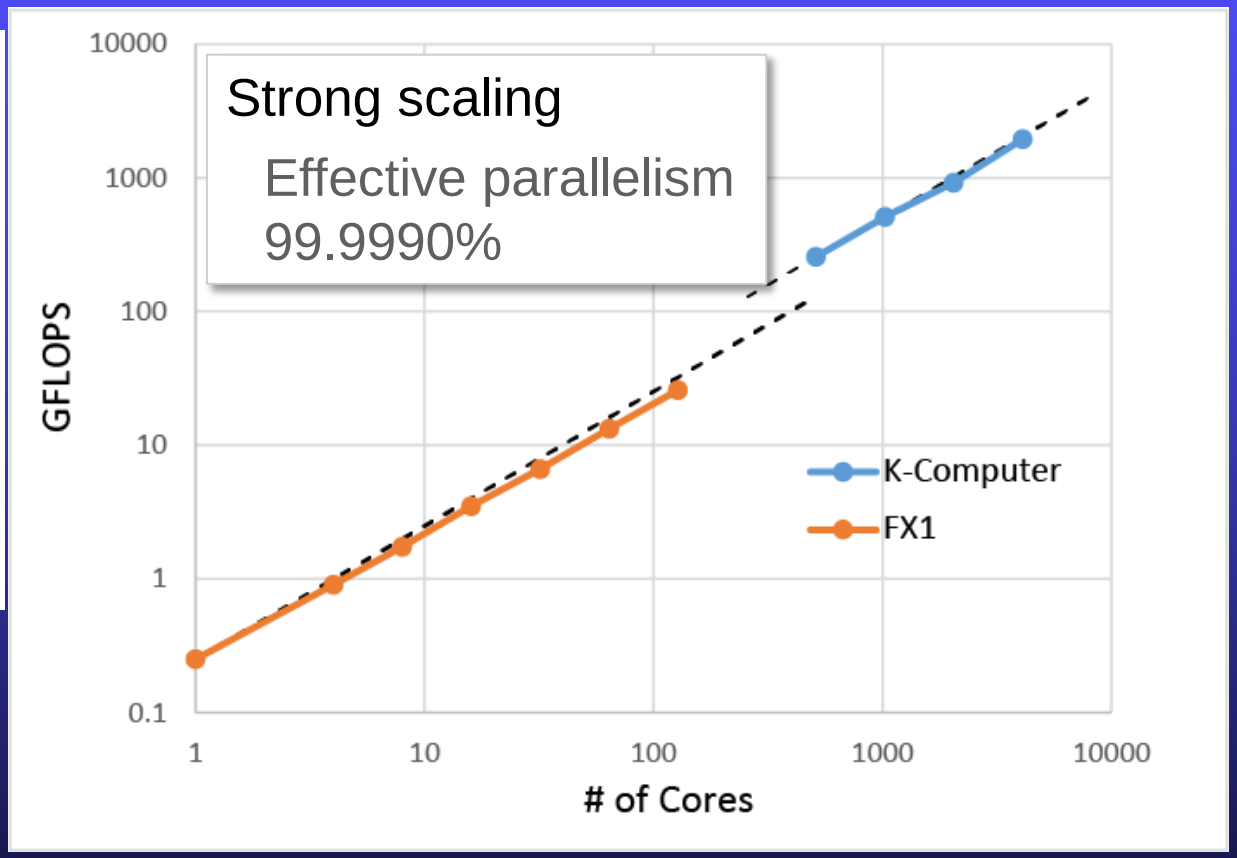




Performance of AMR-PIC Simulation

Massively parallelized for a reconnection problem.





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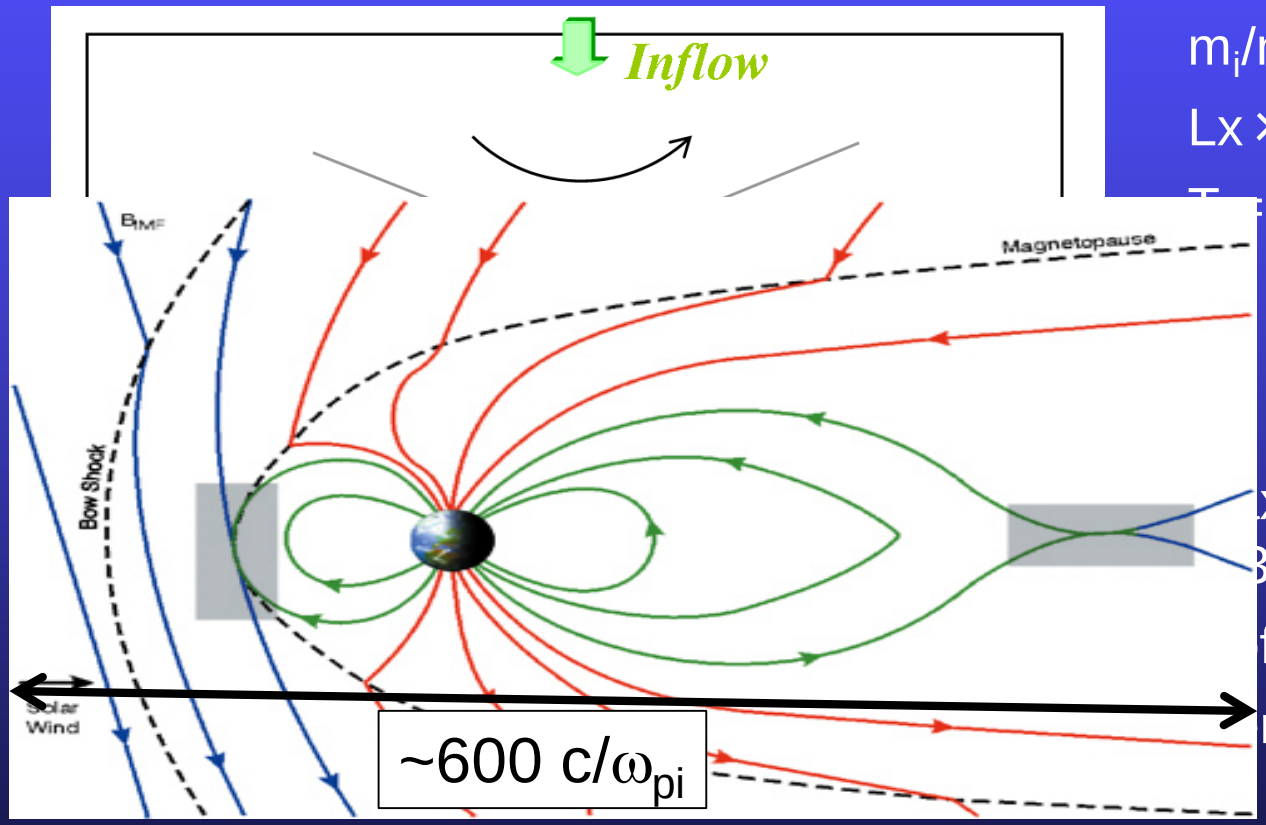
Simulation Setup

With an open boundary condition [Fujimoto, GRL, 2014]



$m_i/m_e = 100$

$Lx \times Lz = 660\lambda_i \times 330\lambda_i$

$T_{end} = 140\ \omega_{ci}^{-1}$

$B_x = B_0 \tanh[z/L]$

$L = \lambda_i$

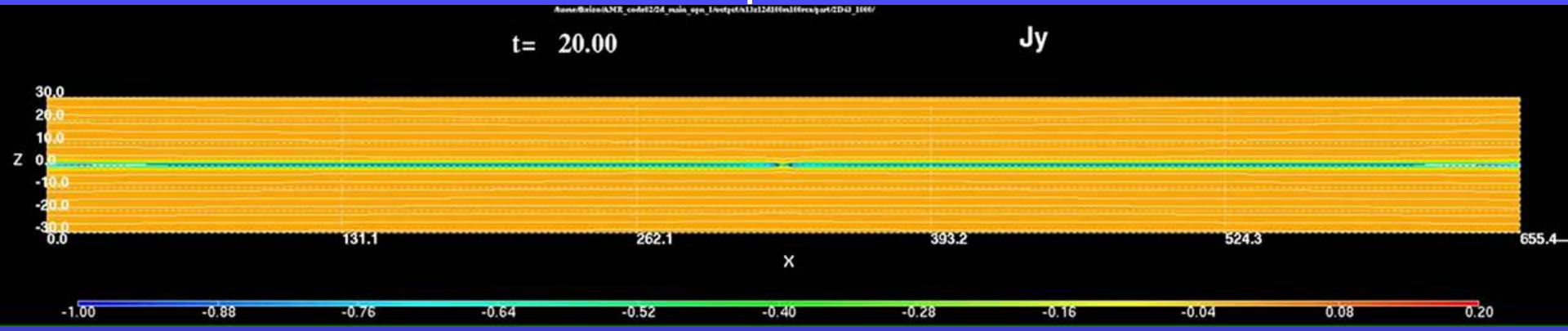
Maximum resolution: 32,768 × 16,384

# of particles: ~ 2×10^{10}

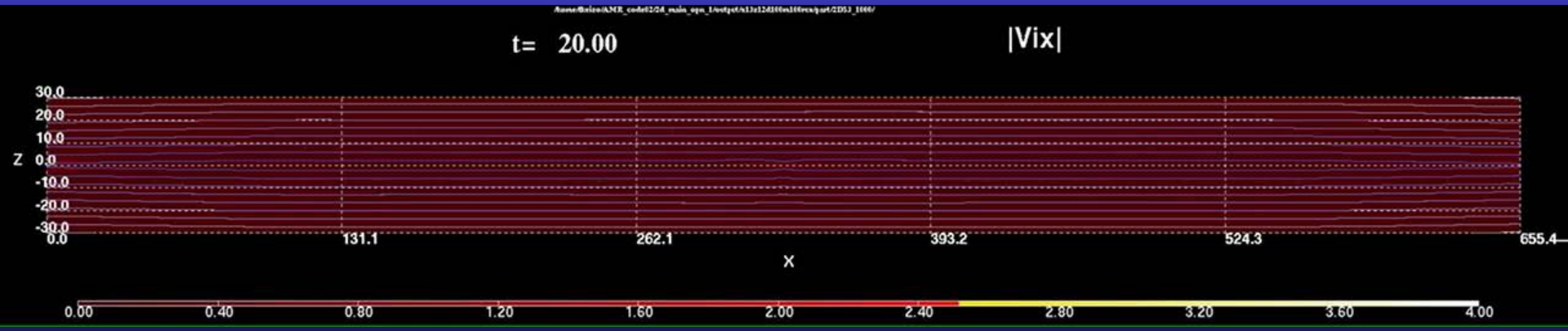
Memory needed: ~ 2 TB

Time Evolution of Current Sheet

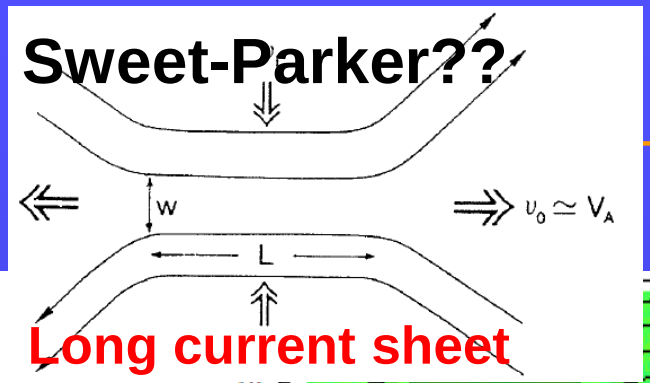
Out-of-plane J

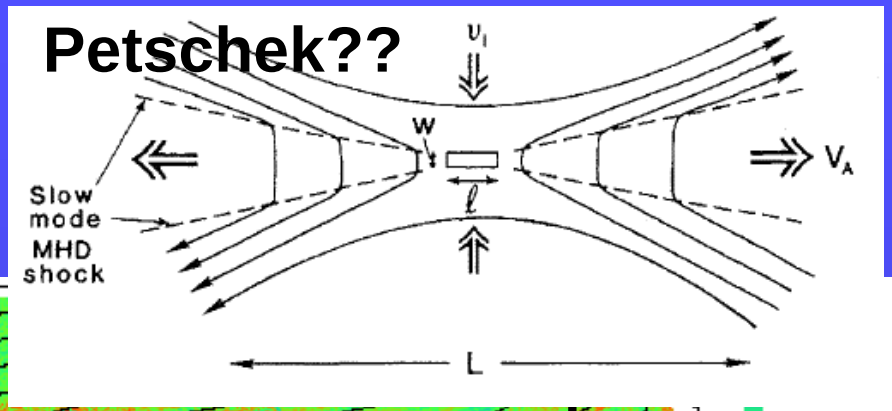


Ion outflow speed

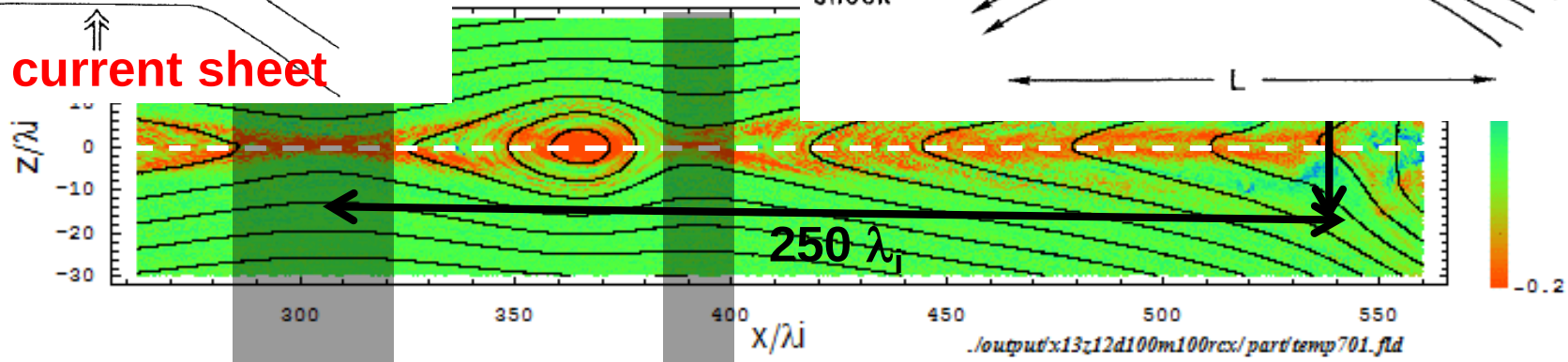


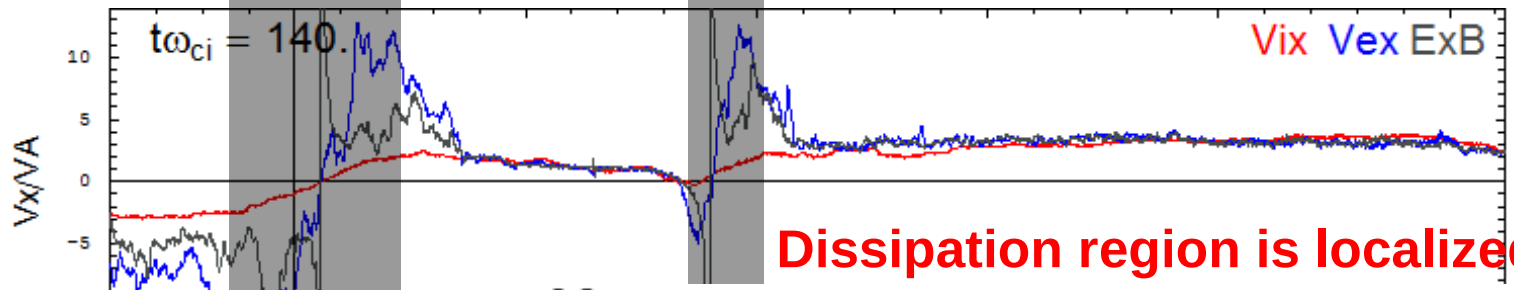
660 λ_i



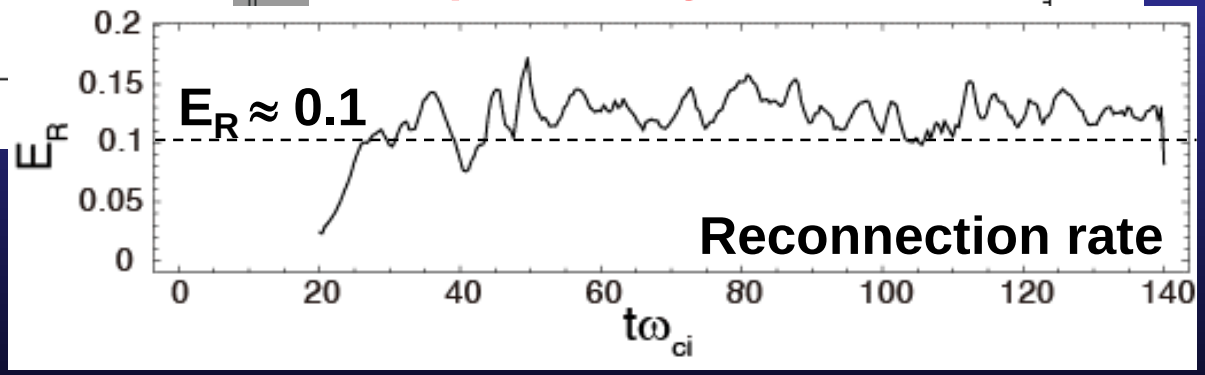


J

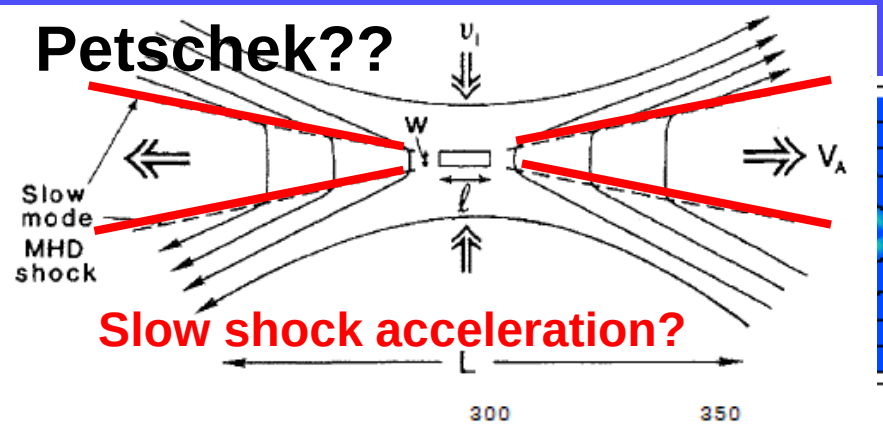


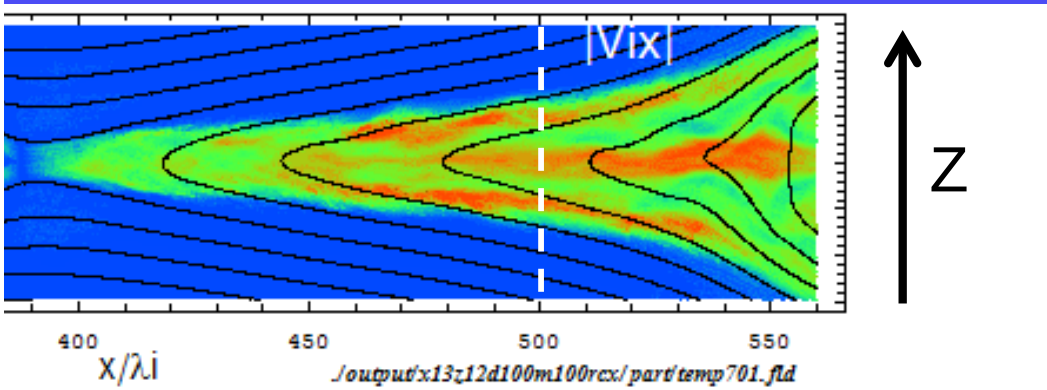


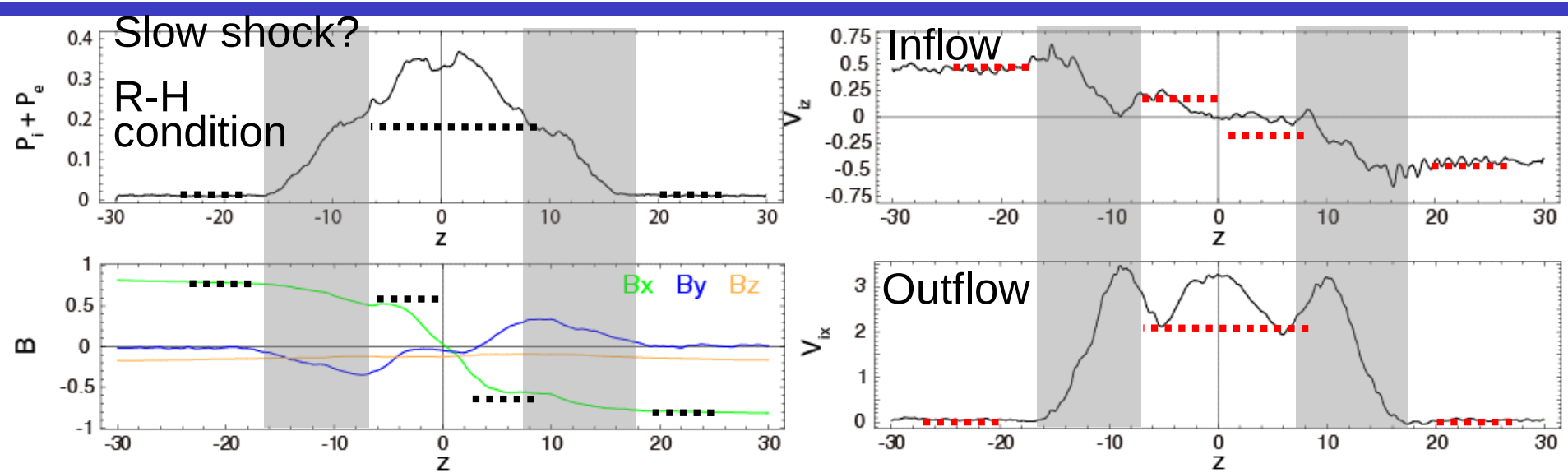
Dissipation region is localized.



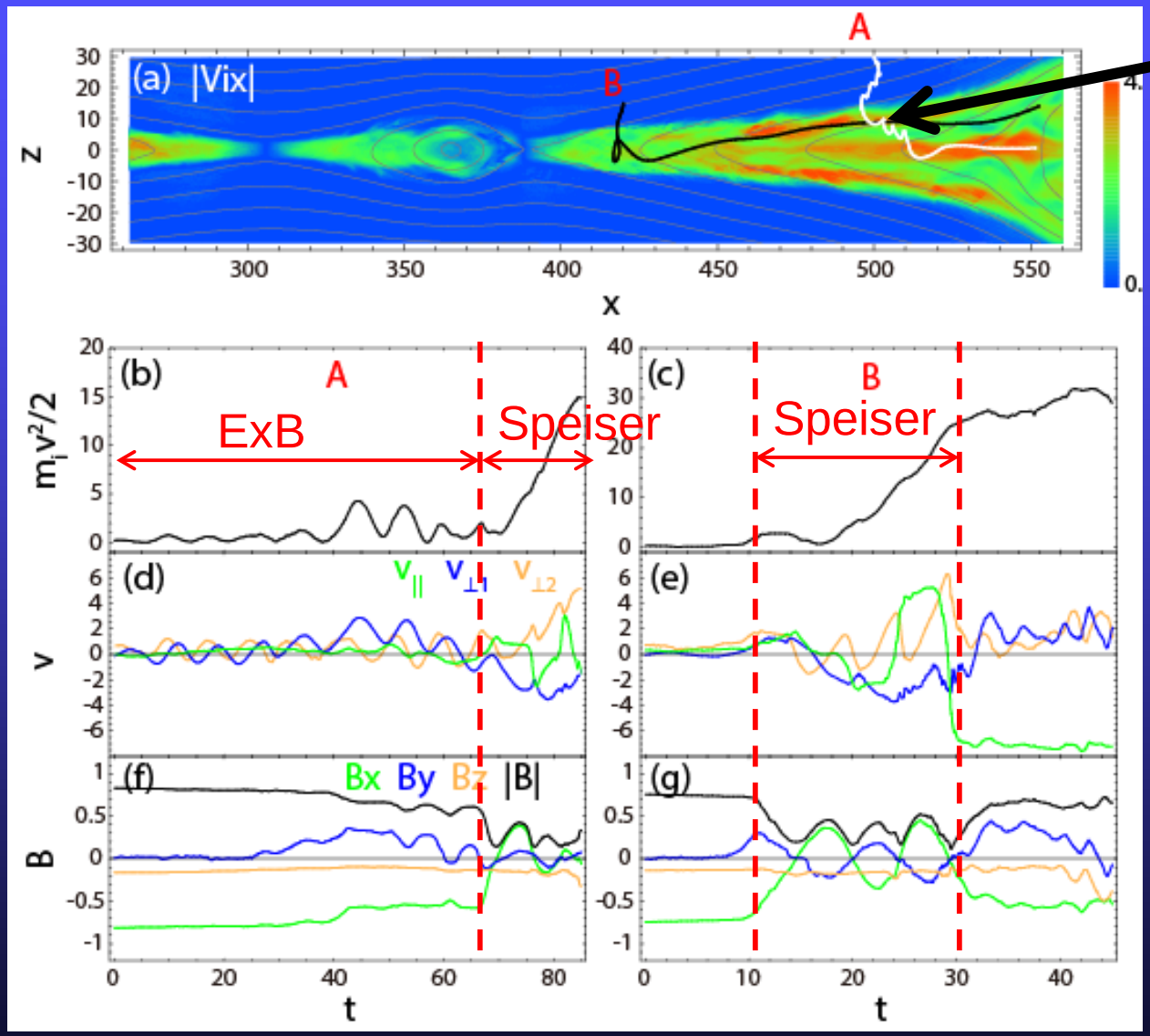
Slow Mode Shocks?

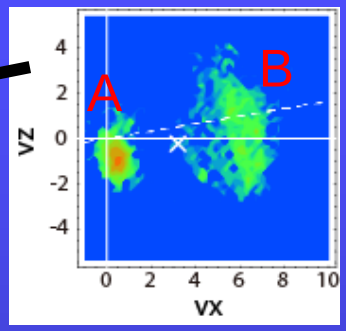






Ion Acceleration





Trajectory A:

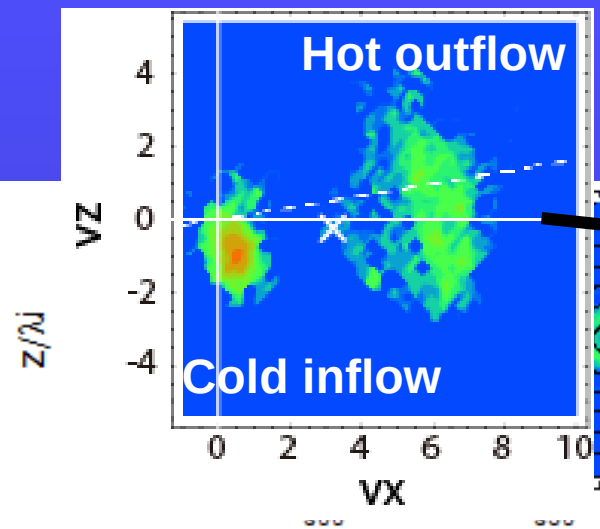
1. ExB drift without acceleration
2. Speiser acceleration in the current sheet

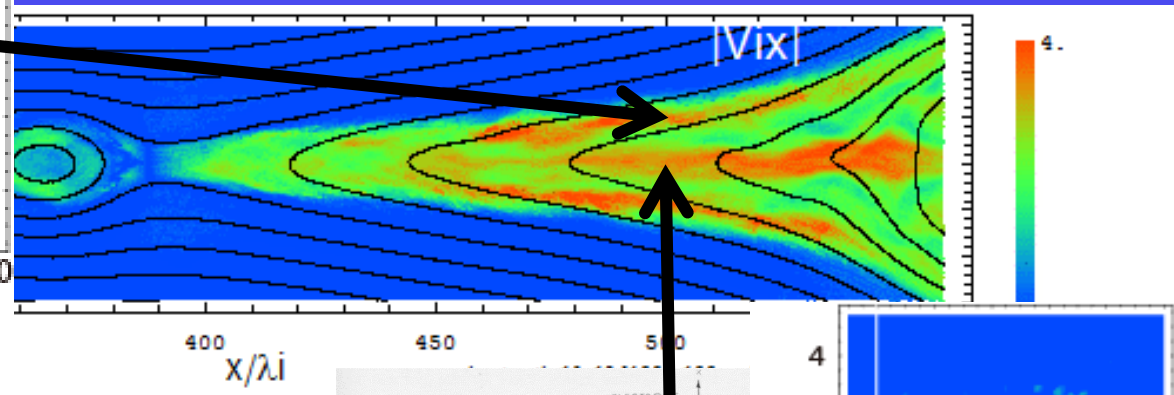
Trajectory B:

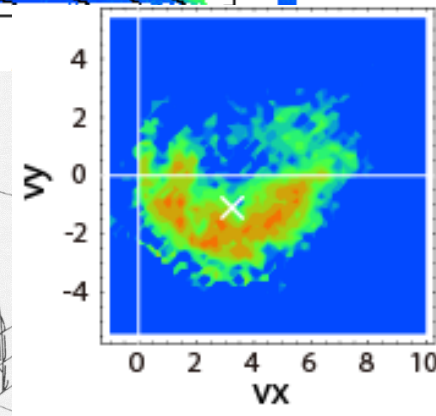
1. Speiser acceleration in the current sheet
2. Drifting along field line without acceleration

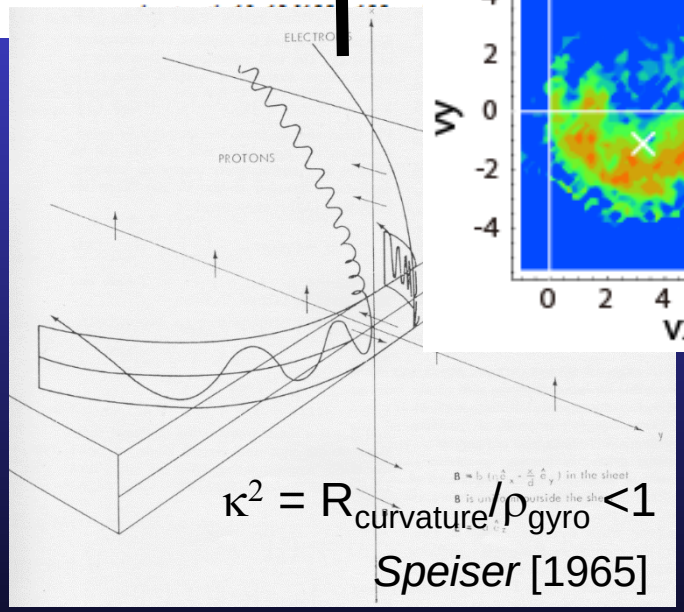
Ion Acceleration

Consistent with hybrid simulations (*Lottermoser et al*, 1998) and PIC simulations (*Hoshino et al*, 1998) around the x-line.









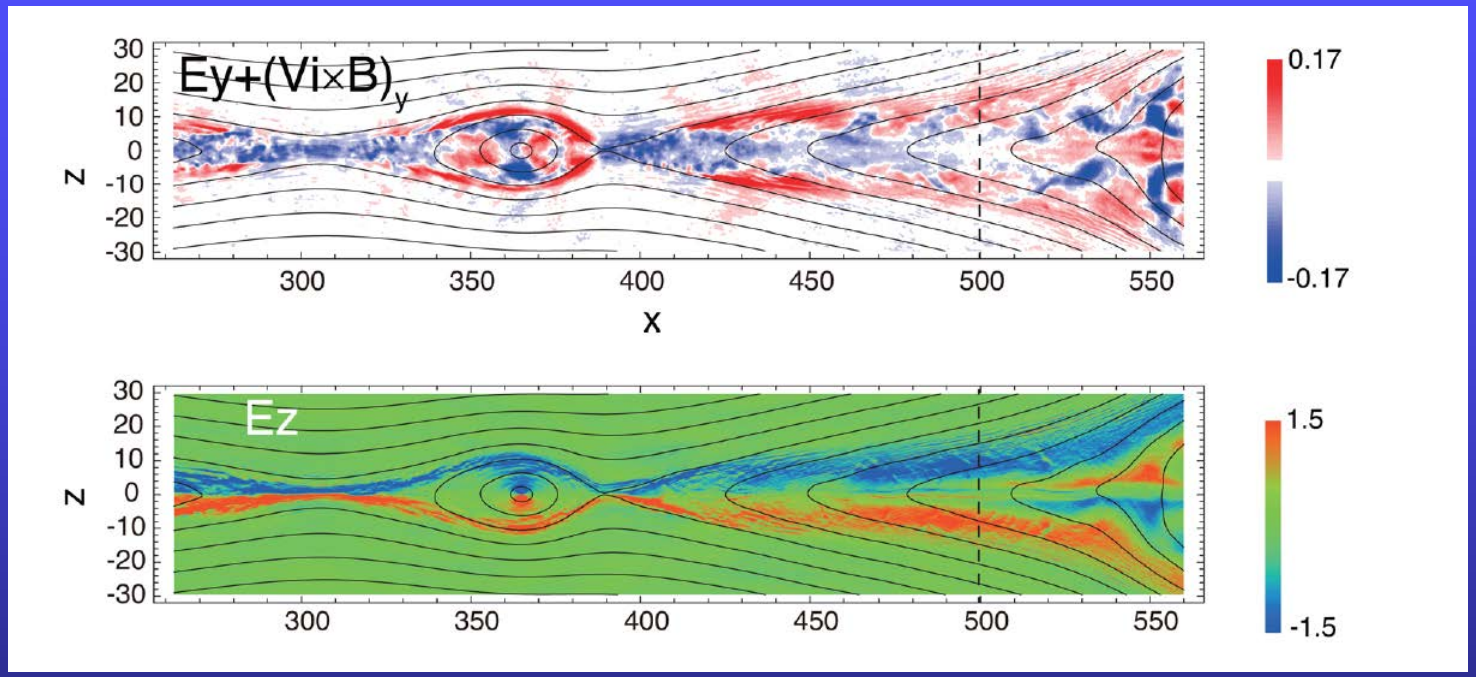
$\kappa^2 = R_{curvature}/\rho_{gyro} < 1$

Speiser [1965]

- No ion acceleration at slow shock-like structure.
- Speiser-type acceleration in the current sheet.

⇒ Acceleration mechanism different from the Petschek's.

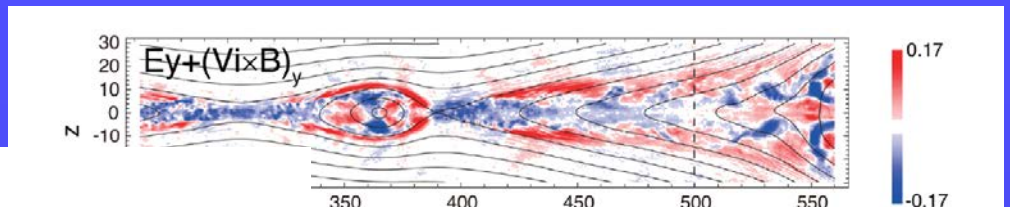
Ideal MHD Condition



Ideal MHD condition breaks down over broad area in the outflow exhaust.

→ Hall term is dominant in the generalized Ohm's law.

Hall Current



Equations of motion

$$\frac{d\vec{v}}{dt} = \frac{\omega_c}{B}\left(\underline{\vec{E}} + \underline{\vec{v}\times\vec{B}}\right)$$

Electric force Lorentz force

$$\frac{d^2 v_z}{dt^2} = -\omega_c^2\left(v_z + \underline{\frac{E_y}{B_x}}\right) + \frac{\omega_c}{B_x}\underline{\frac{dE_z}{dt}}$$

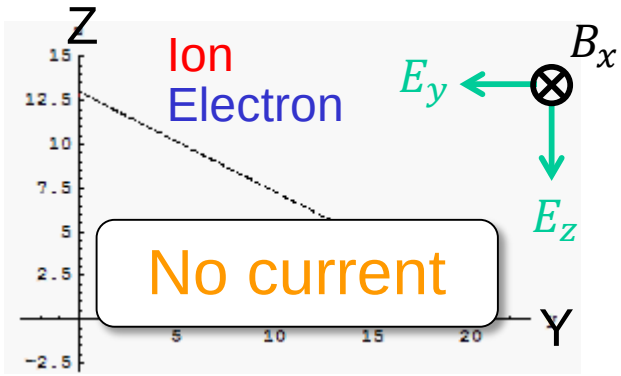
ExB drift velocity Time evolution of Ez along particle trajectory $\approx v_z \frac{\partial E_z}{\partial z}$

$$\frac{d^2 v_z}{dt^2} \approx -\Omega_c^2 (v_z - V_d)$$

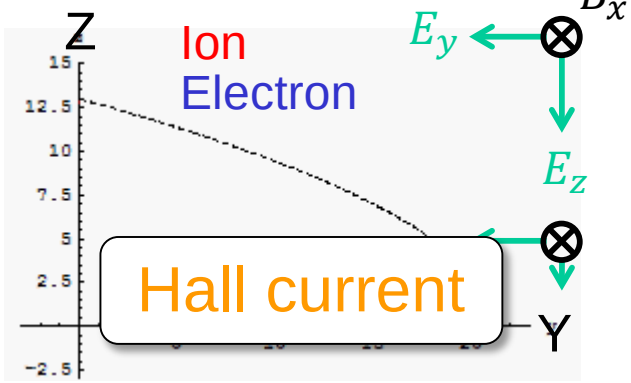
$$V_d = -\frac{1}{1 - \frac{1}{\omega_c}\frac{E_z'}{B_x}}\frac{E_y}{B_x} \qquad E_z' = \frac{\partial E_z}{\partial z}$$

Modified ExB drift velocity

Uniform Ez



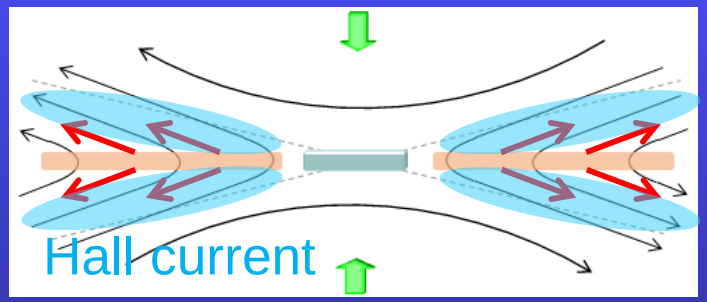
Non-uniform Ez



Summary

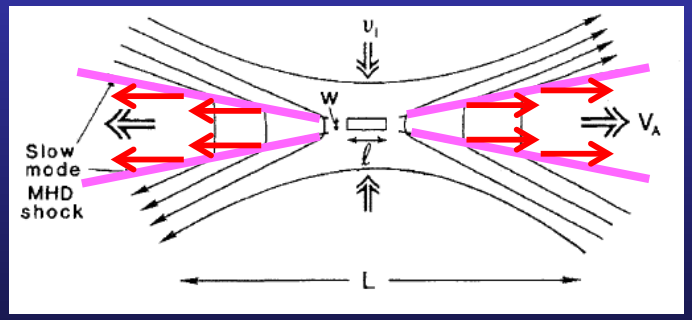
Collisionless reconnection differs from MHD reconnection
even in the region far downstream of the x-line.

Collisionless Reconnection



- No slow shock. Speiser–type acceleration of ions in the extended current layer
- Hall electric current in broad area in the outflow exhaust.

MHD Reconnection (Petschek model)



- Plasma acceleration at slow shock
- Localized current layer around the x-line

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