

The Emerging Physics of
Collisionless Magnetic
Reconnection

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Collisionless reconnection
is ubiquitous

- inductive electric fields exceed
the Dreicer runaway field

⇒ classical collisions
not important

- Earth's magnetosphere

⇒ magnetopause

⇒ magnetotail

- Solar corona

⇒ solar flares

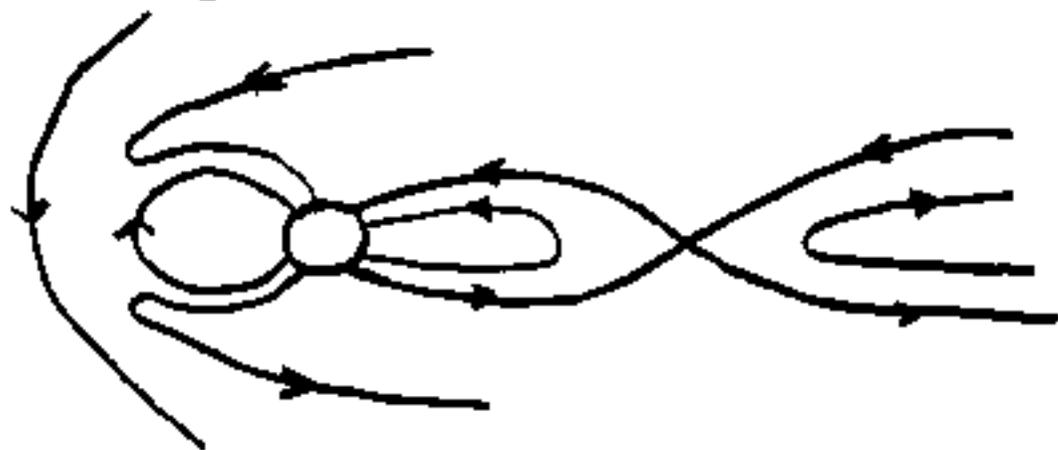
- Laboratory plasma

⇒ sawteeth

Magnetospheric Reconnection

- key role in many aspects of magnetospheric dynamics

⇒ global convection



⇒ substorms

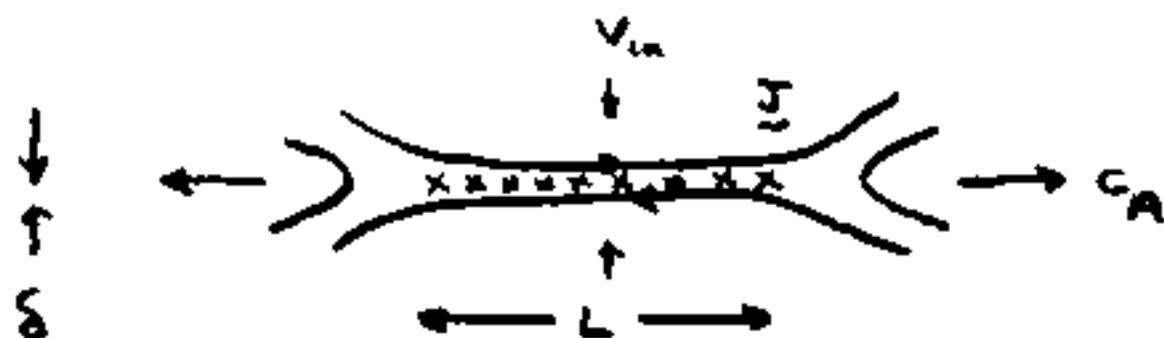
⇒ solar wind entry into the magnetosphere

⇒ flux transfer events

- understanding essential for developing scientifically credible models of these phenomena.

MHD Reconnection

- Sweet-Parker layer



$$v_i \sim \frac{\delta}{L} c_A \sim \beta^{1/2}$$

\Rightarrow slow reconnection

\Rightarrow sensitive to β

\Rightarrow slow shocks don't help

Generalized Ohm's Law

- electron eqn of motion

$$\frac{4\pi}{\omega_{pe}^2} \frac{d}{dt} \underline{J} = \underline{E} + \frac{1}{c} \underline{v}_i \times \underline{B} - \underline{J} \times \underline{B} \frac{1}{nc}$$

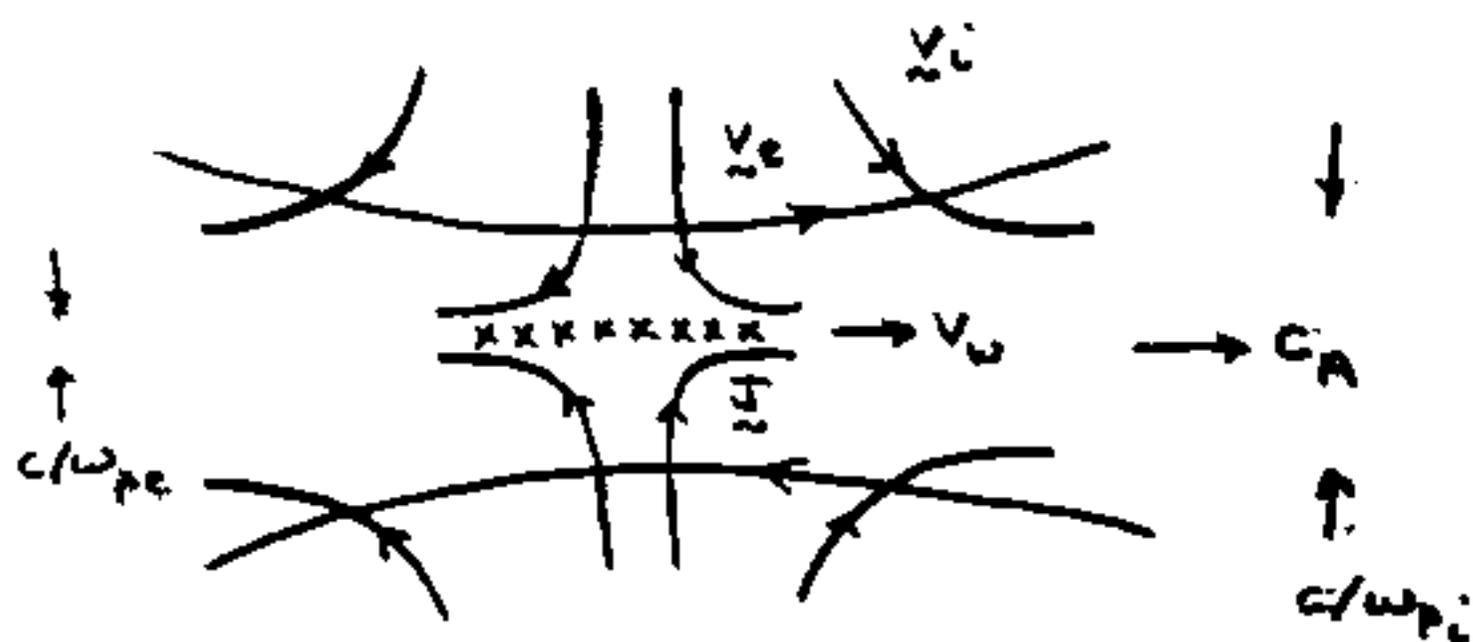
electron inertia c/ω_{pe} mhd whistler waves c/ω_{pe}

$$+ \frac{1}{ne} \nabla \cdot \underline{P}_e - \beta \underline{J} - \beta_a |\underline{J} - \underline{J}_e|^2$$

unmagnetized electrons P_e anomalous resistivity

- MHD ok at large scales
- below c/ω_{pe} : electron and ion motion decouple
 - \Rightarrow electrons frozen-in
 - \Rightarrow whistler dynamics
- electron frozen-in broken at $c/\omega_{pe}, P_e$.

Kinetic Reconnection



- ion motion decouples from that of electrons at a distance c/ω_{pi}
 \Rightarrow ion outflow width c/ω_{pi}
- electron current layer and outflow width
 $\Rightarrow \sim c/\omega_{pe}$
- reconnection rate insensitive to mechanism which breaks frozen-in condition
 \Rightarrow quadratic whistler dispersion $\omega \sim k^2$

First Reconnection Challenge

- Nonlinear tearing mode in a 2-D Harris sheet equilibrium

$$B_x = \tanh\left(\frac{z}{w}\right)$$

$$B_y = B_z = 0$$

$$n_{\max} = 1.2$$

$$n_{\min} = 0.2$$

- Parameters

$$\frac{m_e}{m_i} = \frac{1}{25}$$

$$\omega = 0.5 \frac{c}{\omega_{pi}}$$

$$\frac{T_e}{T_i} = \frac{1}{5}$$

- Boundary conditions

periodic in x : $L_x = 25.6 c/\omega_{pi}$

fixed boundary in z : $L_z = 12.8 c/\omega_p$

- normalisation

$$\Omega_i t \rightarrow \tau$$

$$\tilde{x} \omega_{pi} / c \rightarrow \tilde{x}$$

$$\tilde{v} / c_A \rightarrow \tilde{v}$$

- codes

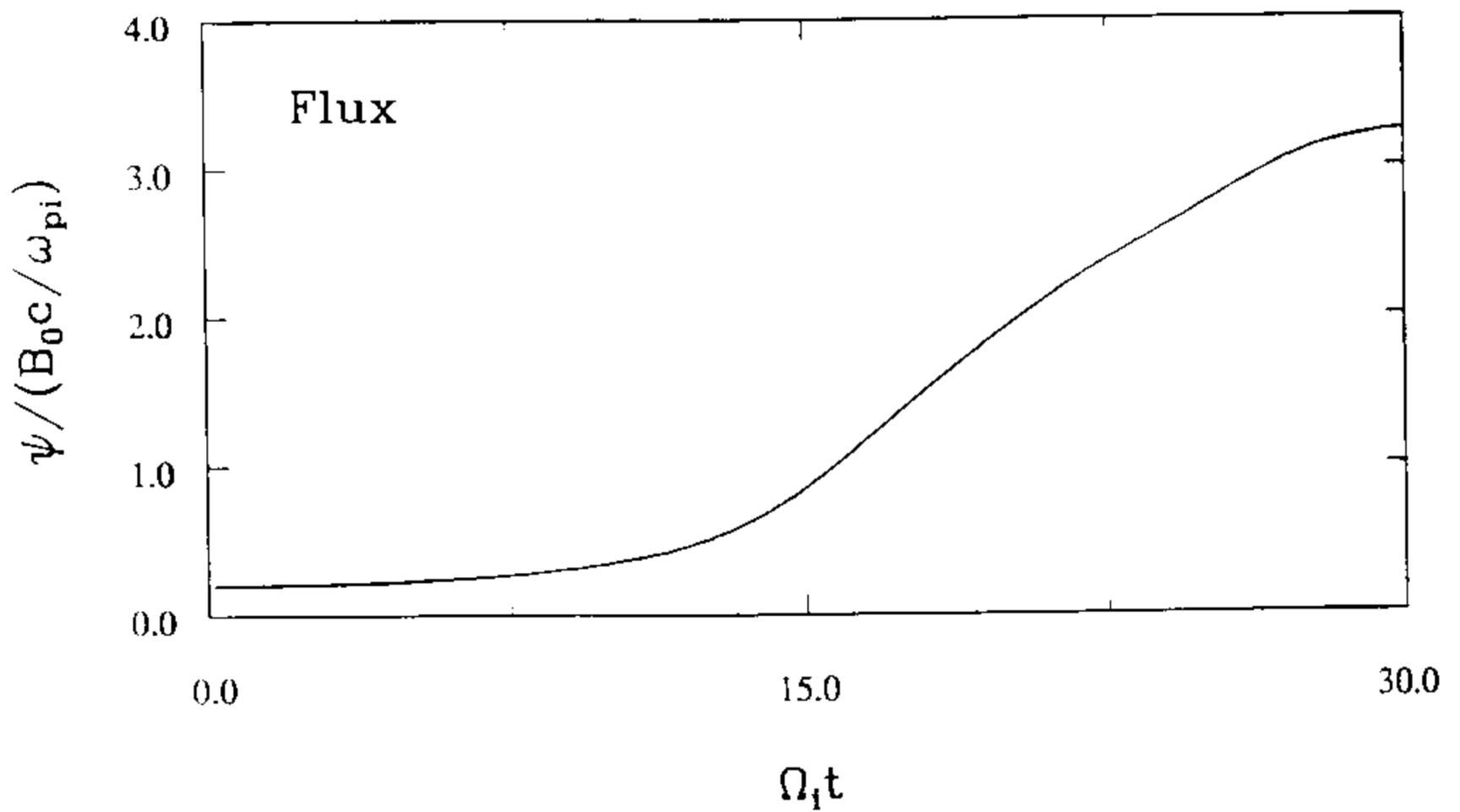
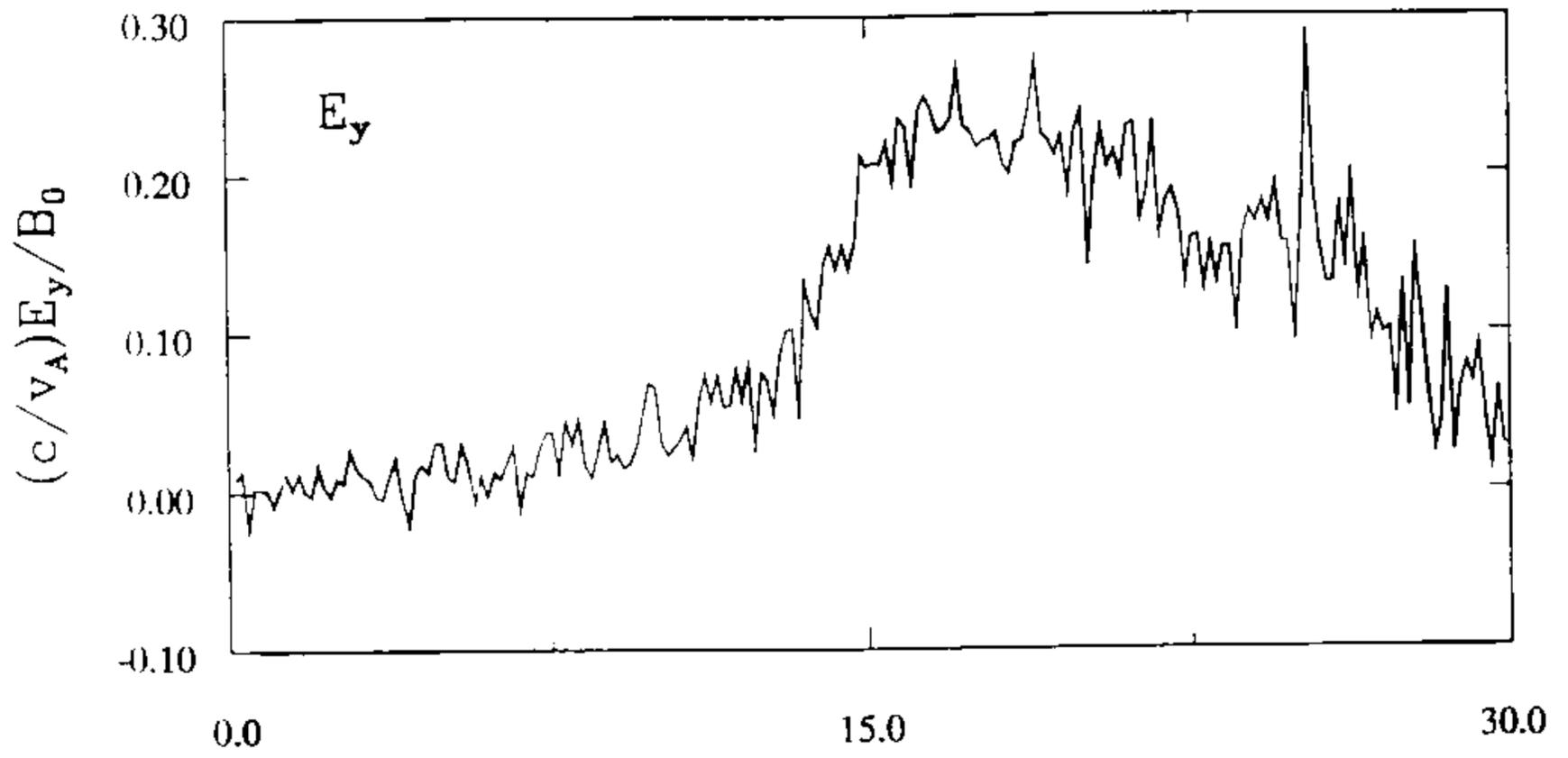
MHD

Hall MHD - resistivity, electron mass

hybrid (particle ions and fluid electrons)

full particle

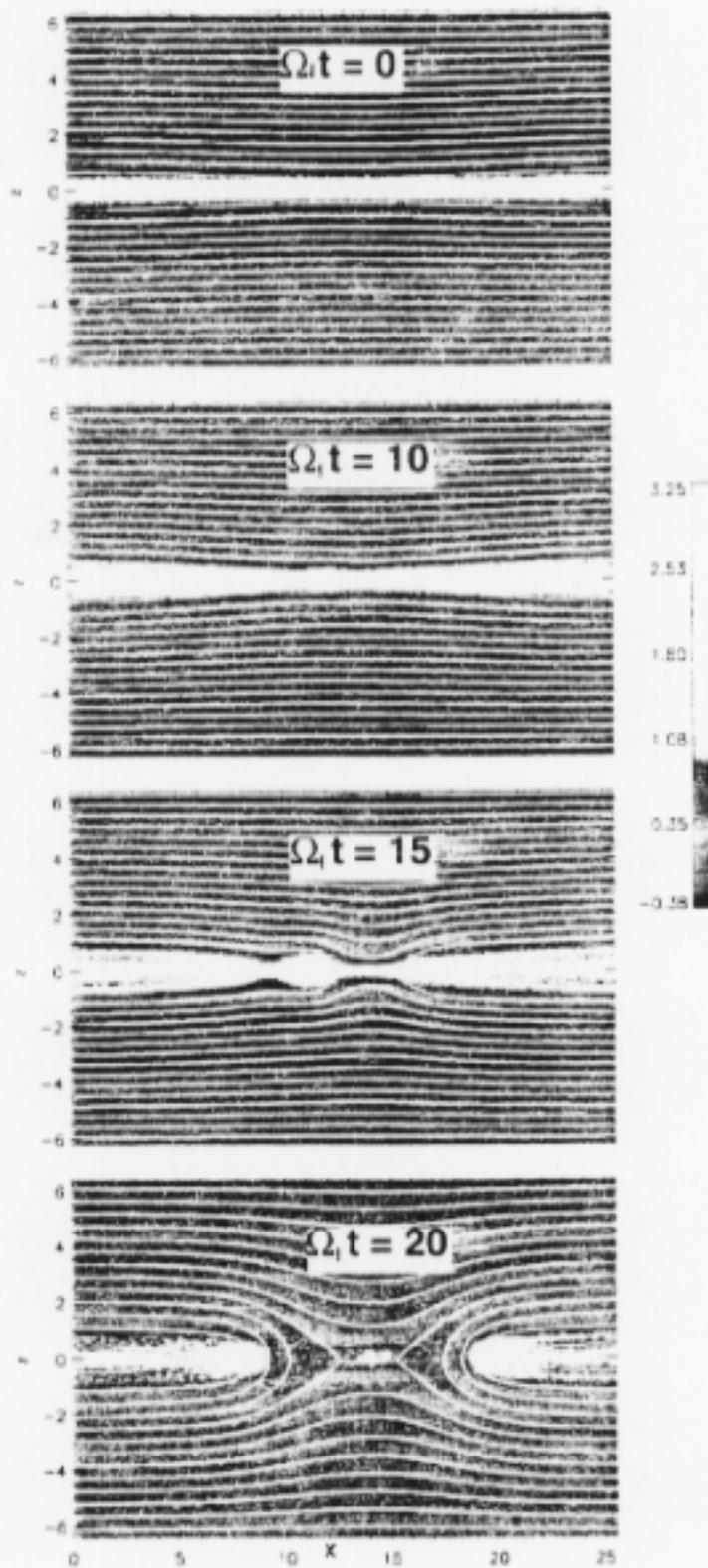
full particle model



Pritchett

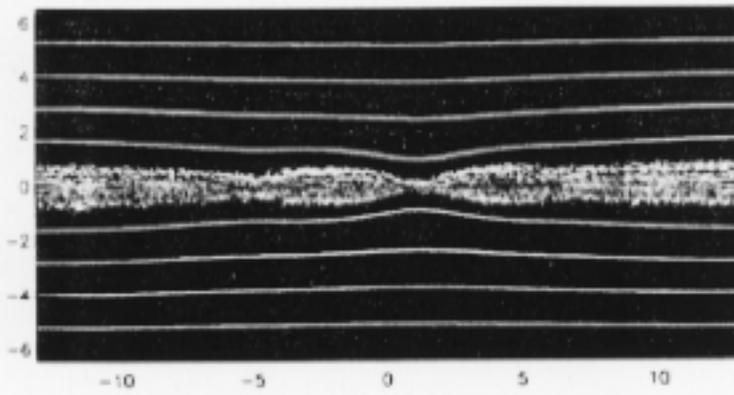
full Particle model

Magnetic Field Evolution and Cross-Tail Current Density Evolution, $m_e = 0.04$

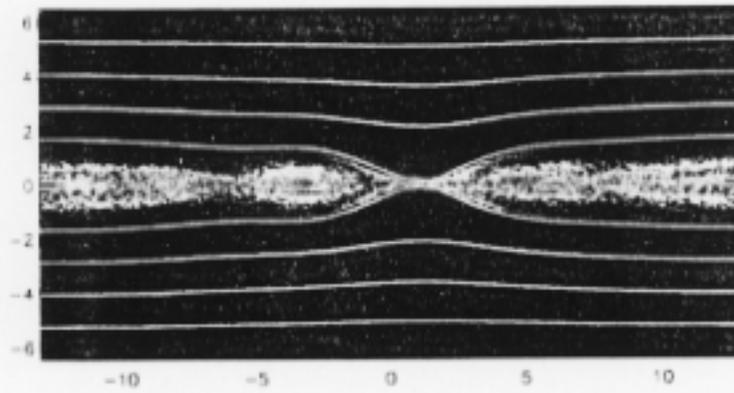


Hybrid:

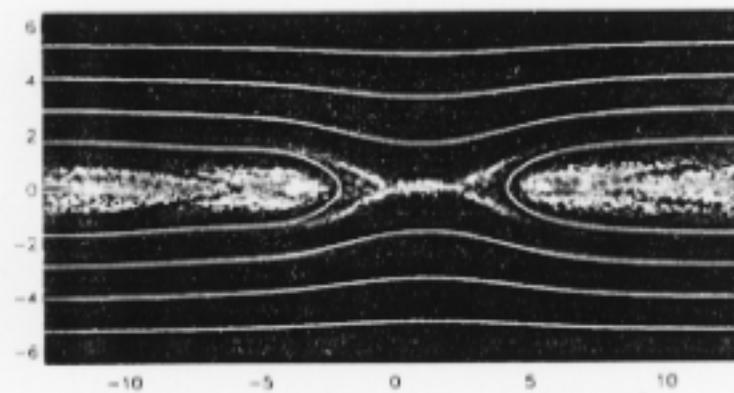
J_y, ψ



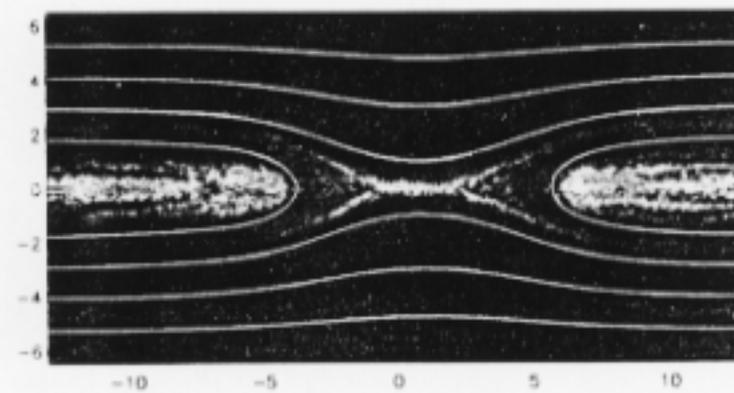
$F = 0.5$



1.0



1.5



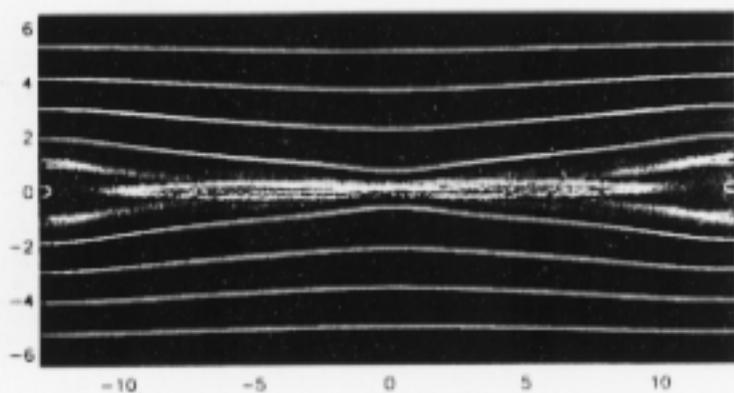
2.0



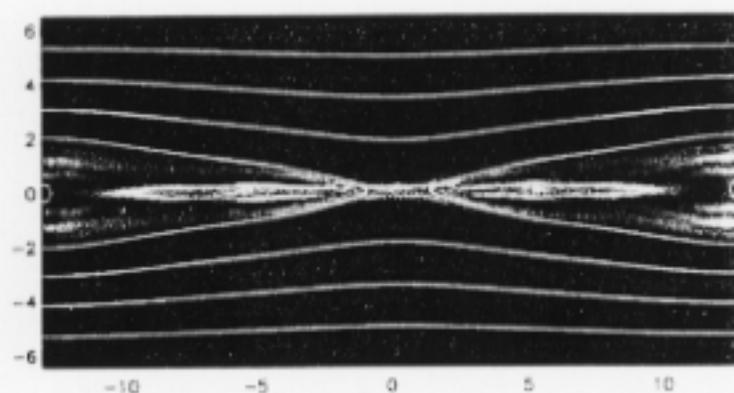
Shay / Drake

Two Fluid:

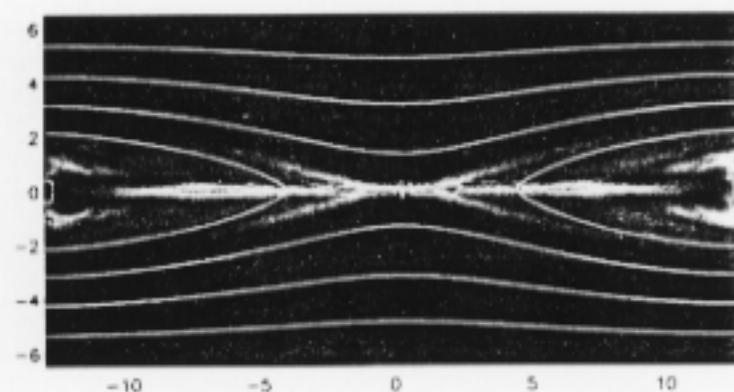
J_y, ψ



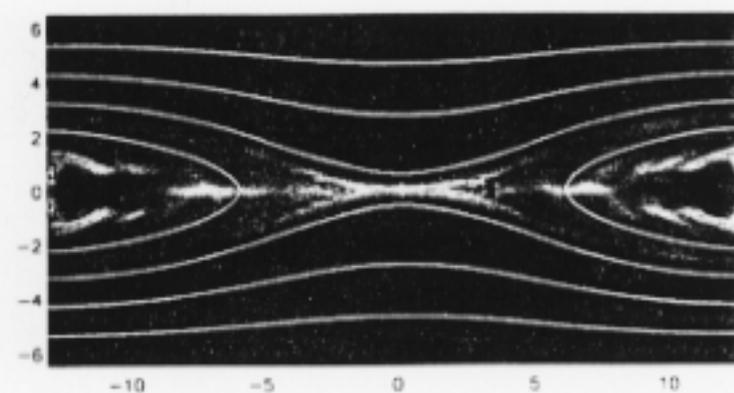
$F = 0.5$



1.0



1.5

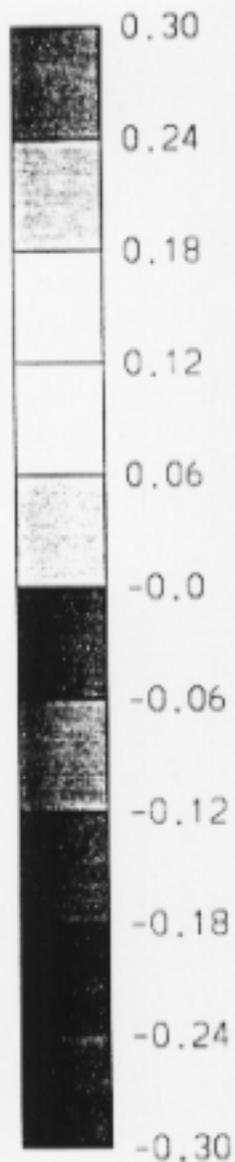
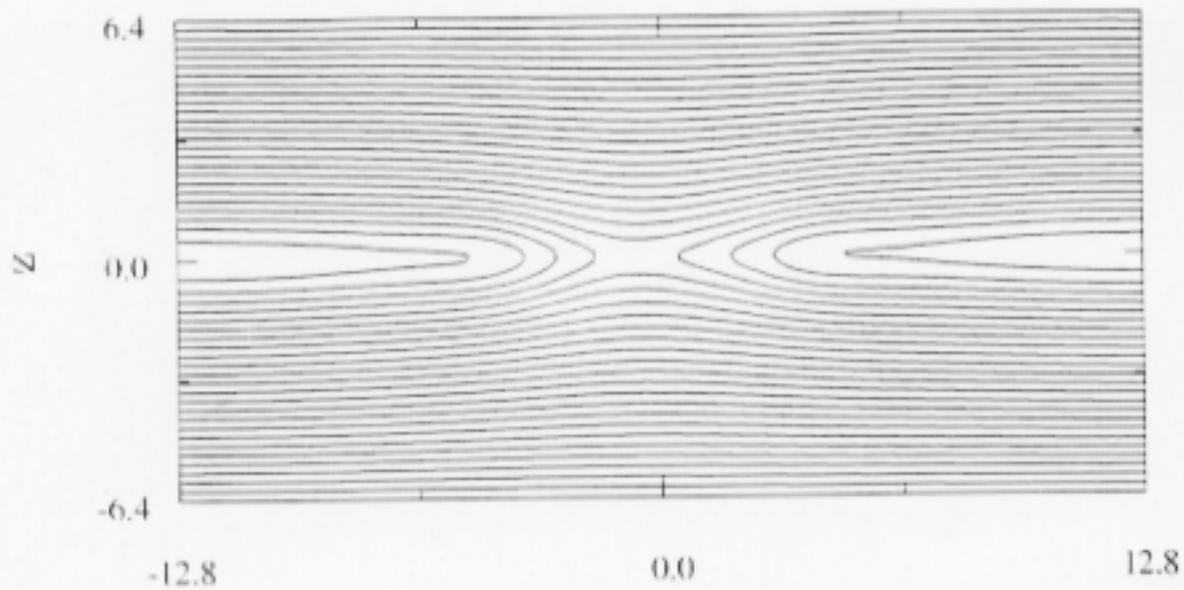


2.0

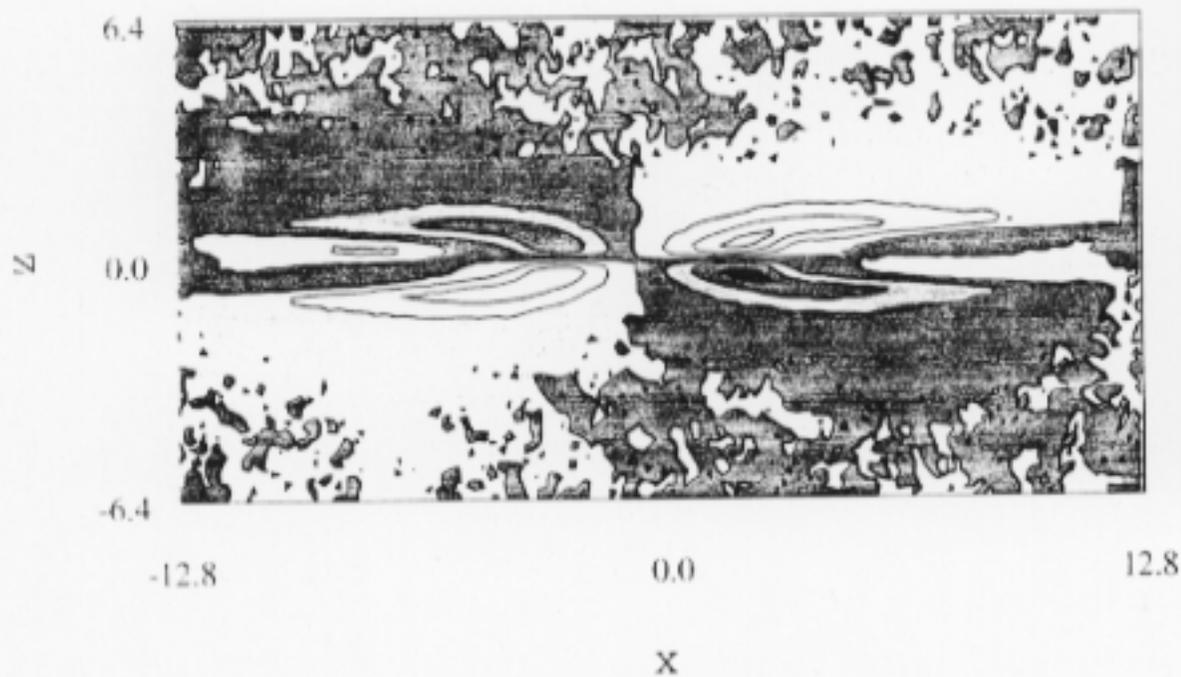


full particle model

ψ

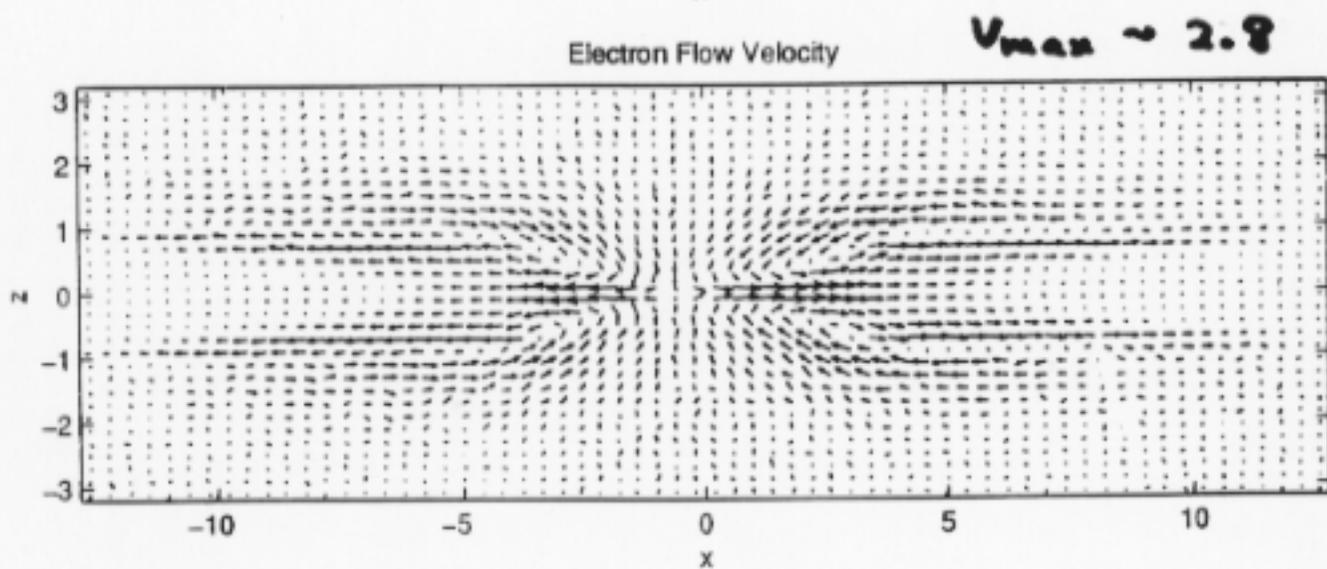
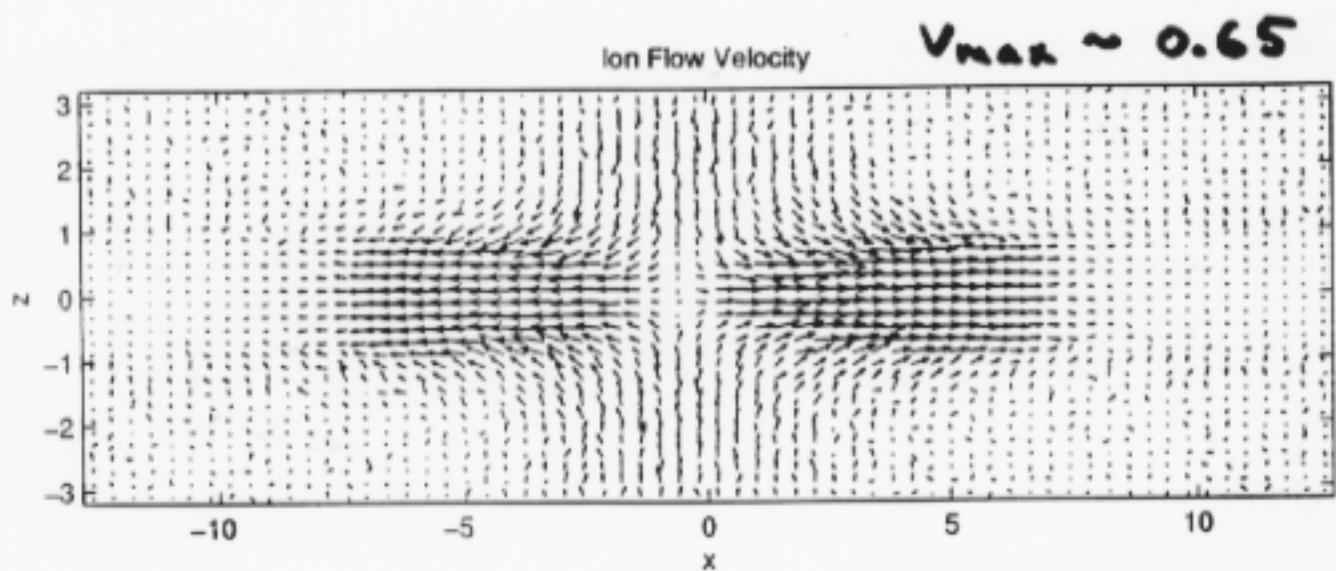


G_y



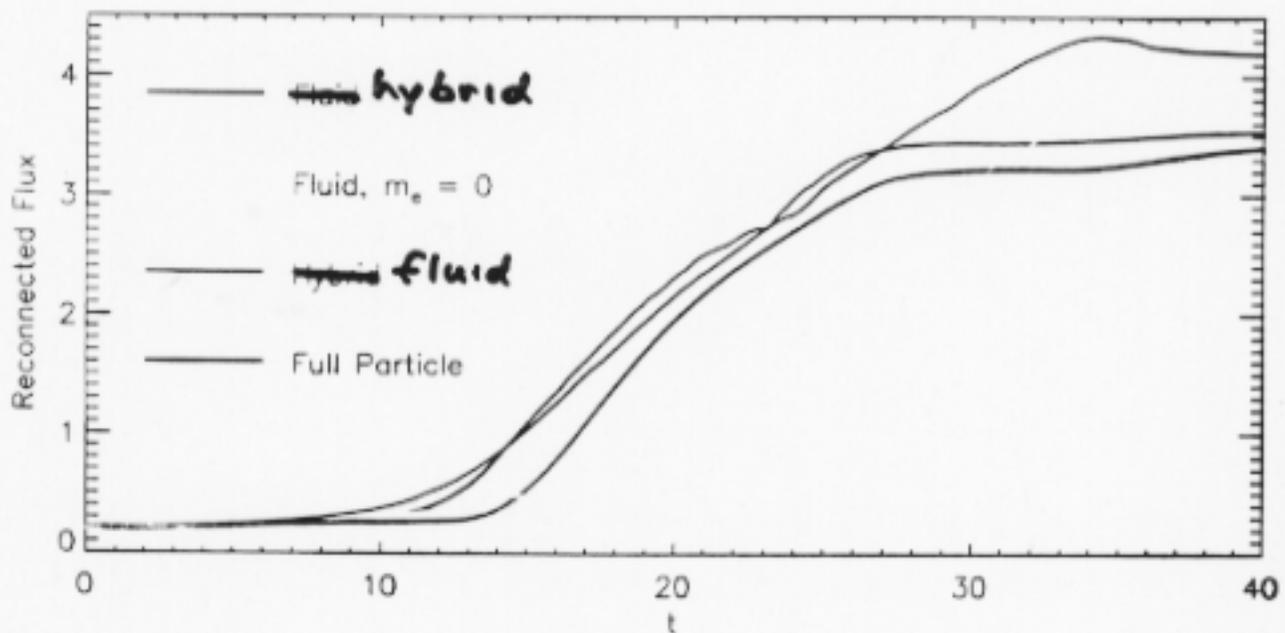
Pritchett

full particle



pritchett

Reconnected Flux



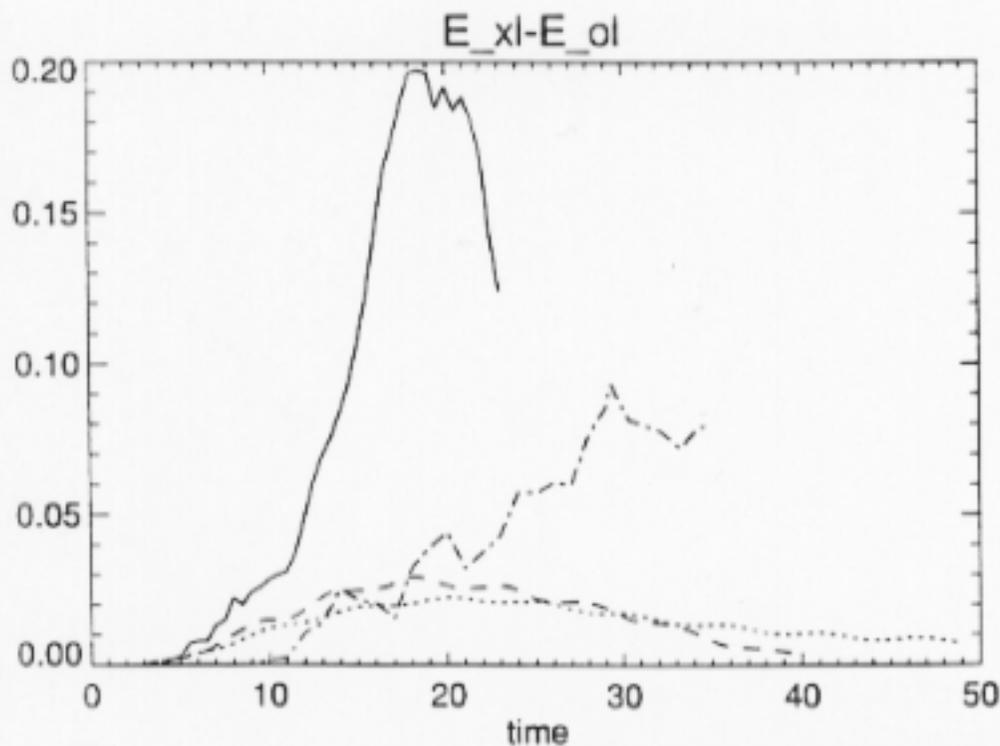
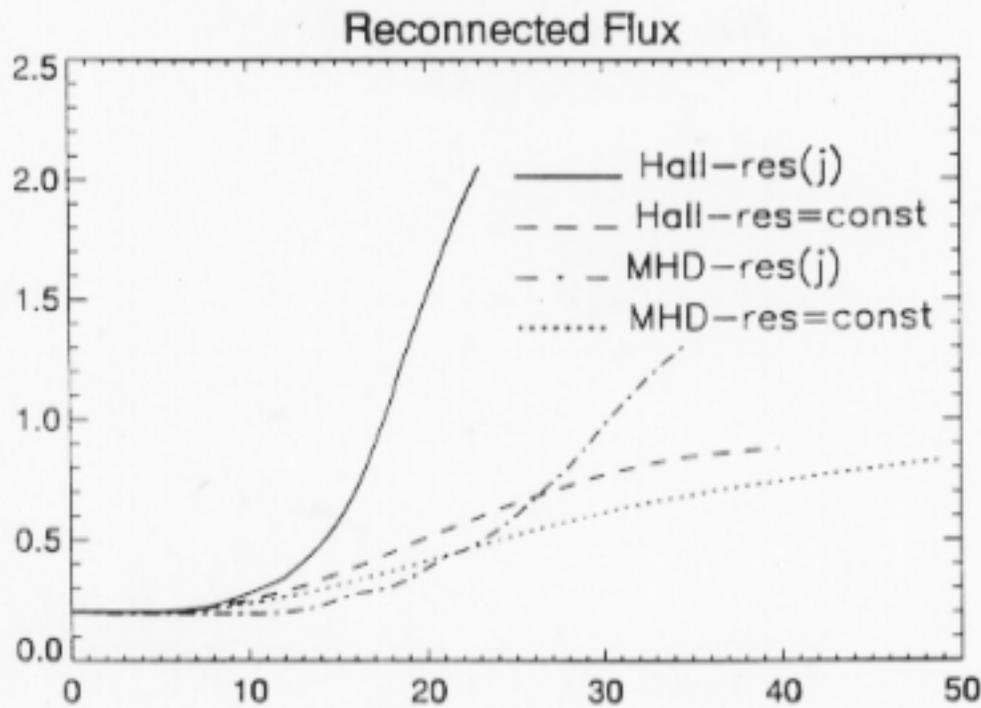
⇒ peak reconnection rate essentially identical for all models

Shay et al

MHD / Hall MHD Comparison

Hall MHD: $\eta, \eta_a (J - J_e)^2$

MHD:

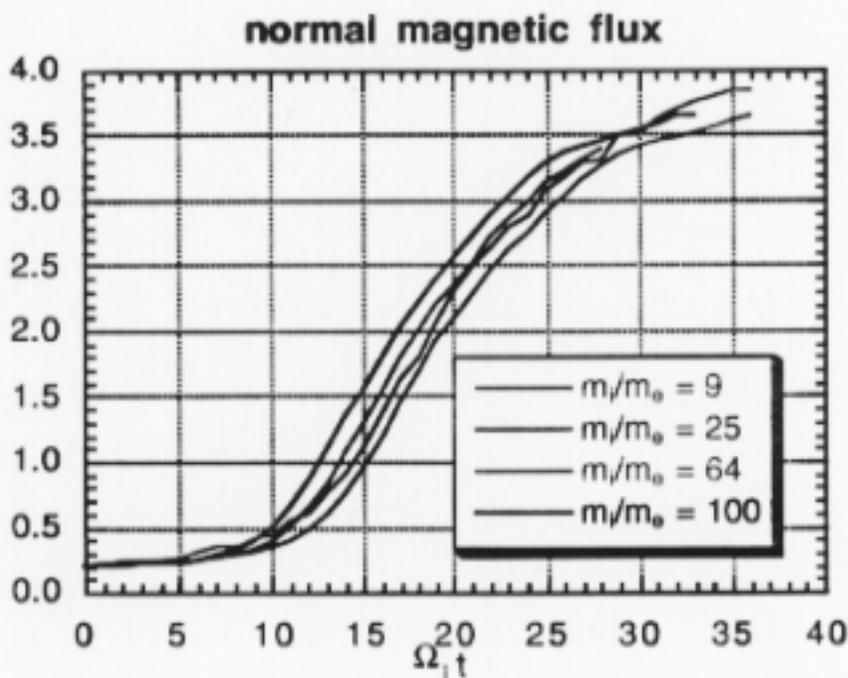


- ⇒ MHD Reconnection slow (sensitive to η)
 - ⇒ Hall MHD can be fast (need small diss.)
- OTTO

Time Evolution of Normal Magnetic Flux: Electron Mass Dependence

Investigate:

$$F = \int_X^0 B_z(x, z = 0) dx$$



-> little, if any electron mass effect

How does dissipation operate for different electron masses?

Whistlers versus Alfvén waves

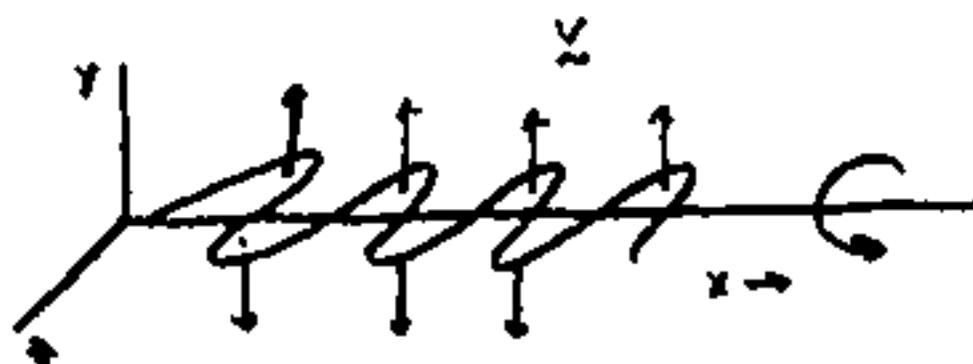
- simple standing waves

- Alfvén wave



$$v_z \sim B_z \Rightarrow \text{Alfvén velocity}$$

- whistler



$$\frac{\partial \rho}{\partial t} \sim -\nabla \times \underline{E}$$

$$E \sim \underline{J} \times \underline{B}$$

$$\underline{J} \sim \nabla \times \underline{B}$$

$$v_z \sim v_y \sim k_x B_z \sim \frac{B_z}{\delta}$$

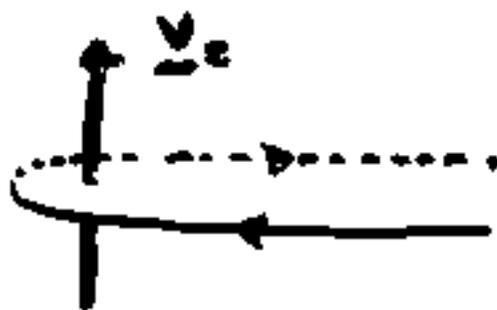
$$v_{\text{phase}} \sim k, \quad \omega \sim k^2$$

Whistler mediated reconnection (inner dissipation region)

- at spatial scales below c/ω_{pe}
whistler waves (not Alfvén waves)
drive reconnection. How?

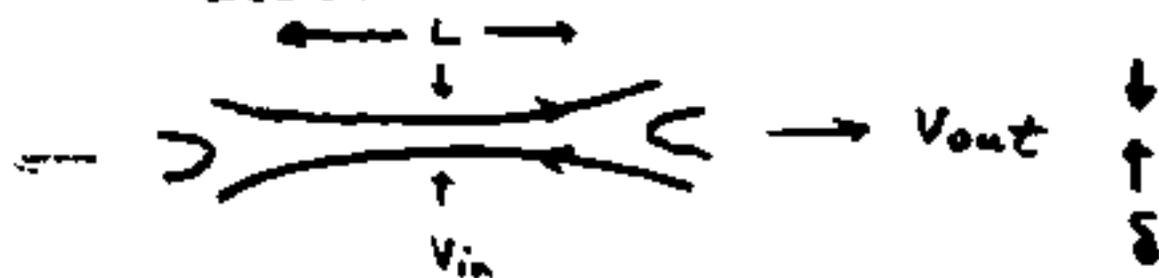


Side view



\Rightarrow whistler signature is out-of-plane
magnetic field

- Outflow velocity from whistler acceleration



$$\Rightarrow \omega \sim k^2$$

$$v_{out} \sim v_{ph} \sim k \sim \frac{1}{\delta}$$

$$v_{ph} \rightarrow \infty \text{ as } \delta \rightarrow 0$$

$$v_{in} \sim \frac{\delta}{L} v_{out} \sim \text{independent of } \delta$$

\Rightarrow reconnection rate is sensitive to mechanism which breaks frozen-in condition.

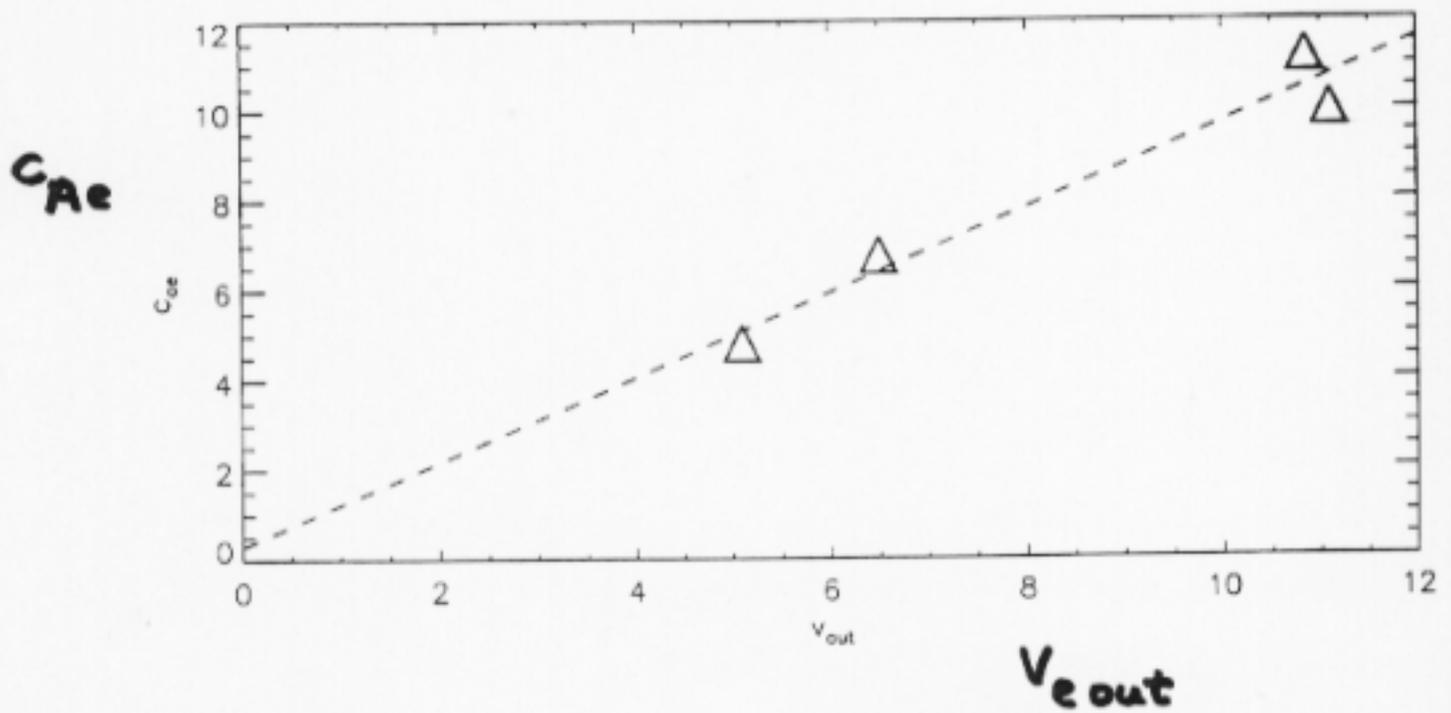
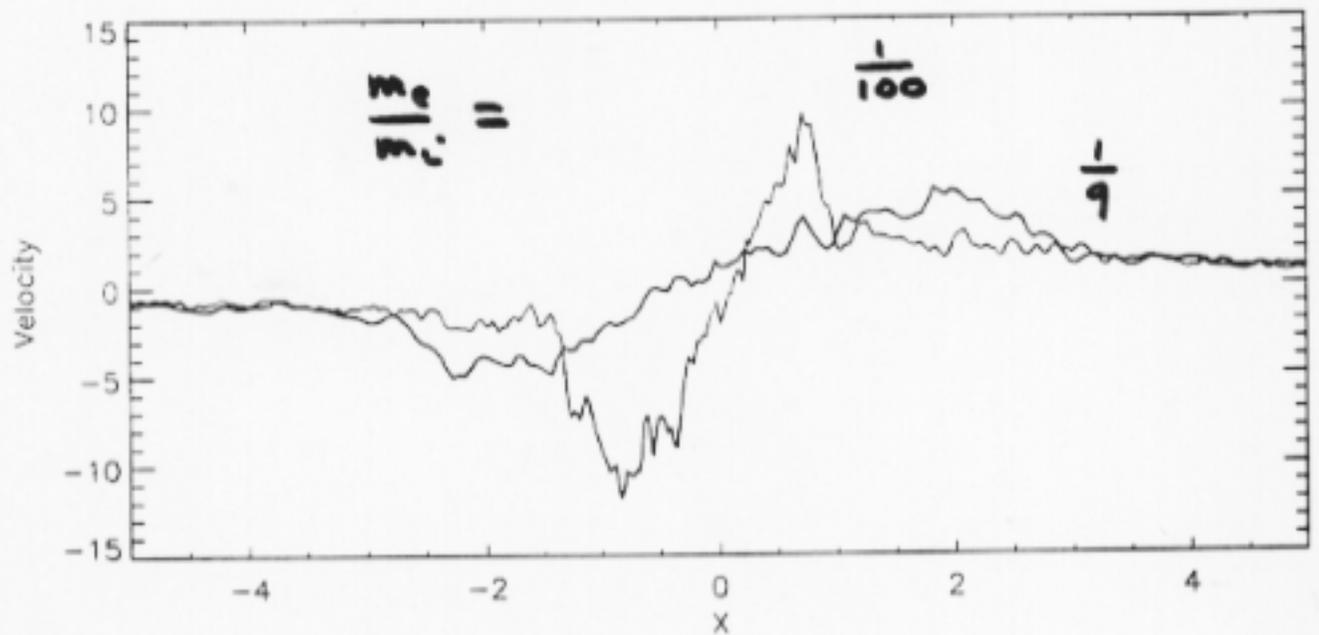
\Rightarrow electrons don't control rate

\Rightarrow unlike MHD

Electron Outflow Velocity

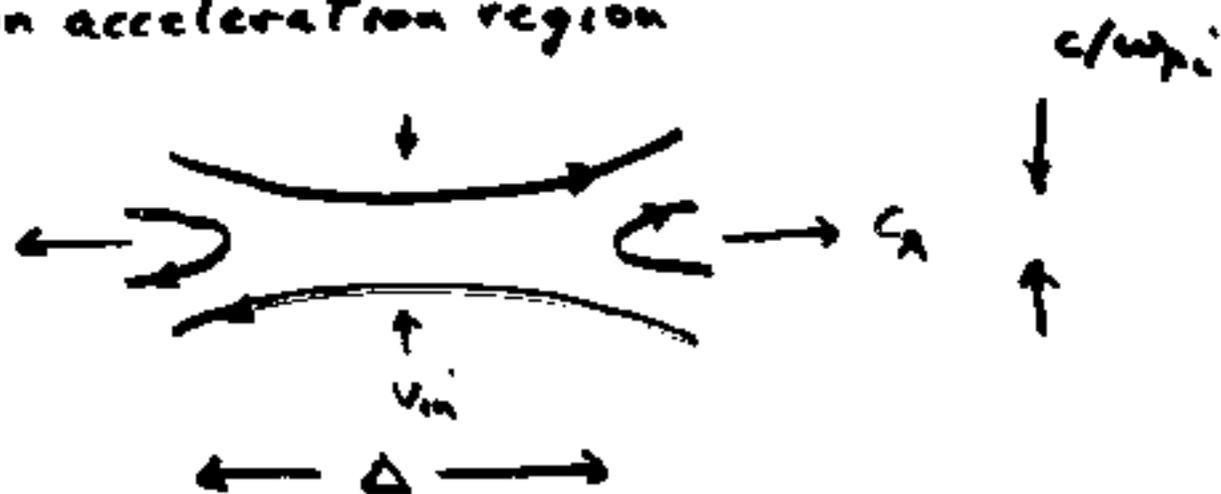
- peak whistler velocity

$$v_w \sim c_{Ae} \sim \left(\frac{B^2}{4\pi m_e n} \right)^{1/2}$$



Ion Controlled Reconnection

- ion acceleration region



$$v_{in} \sim \frac{c/\omega_{pi}}{\Delta} c_A \quad \text{what is } \Delta?$$

$$\Rightarrow \Delta \sim 10 c/\omega_{pi}$$

$$\Rightarrow \text{microscopic}$$

$$\Rightarrow v_{in} \sim 0.1 c_A$$

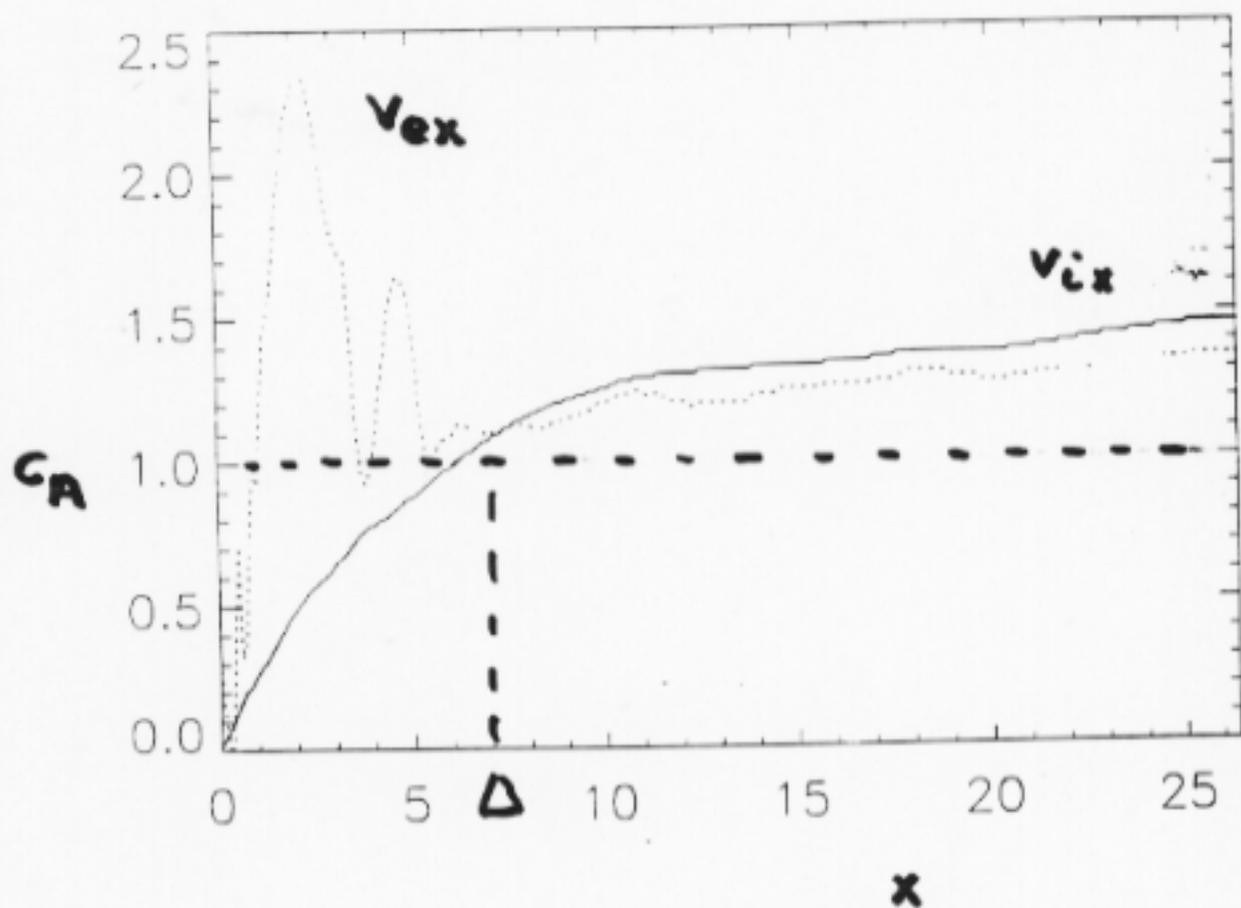
- essential physics

reconnection electric field $E_y \rightarrow E_x$

\Rightarrow whistler

$\Rightarrow E_x$ accelerates ions away from X-line

Outflow velocities

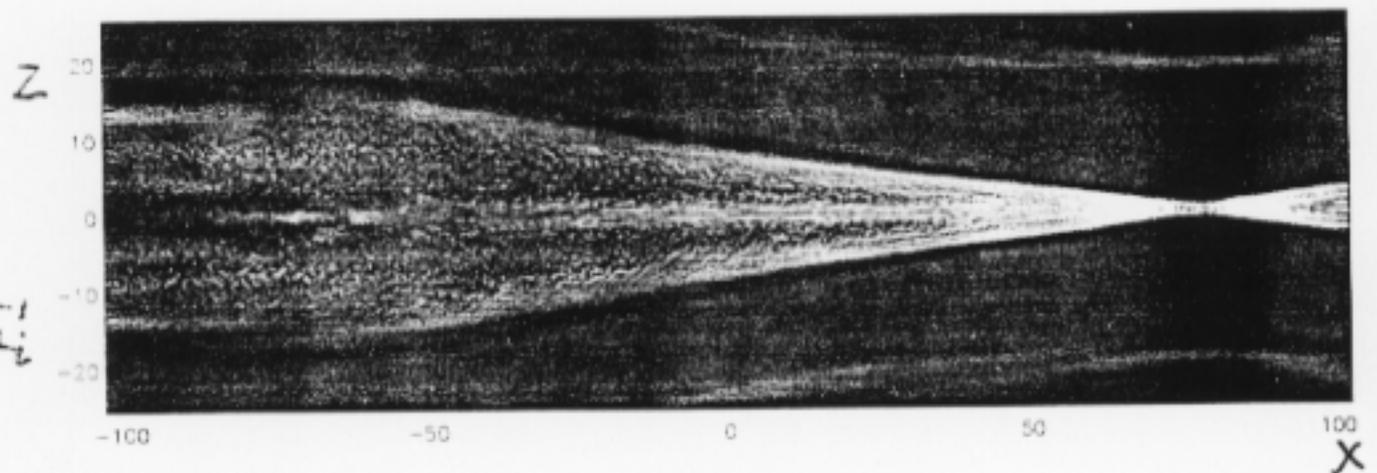
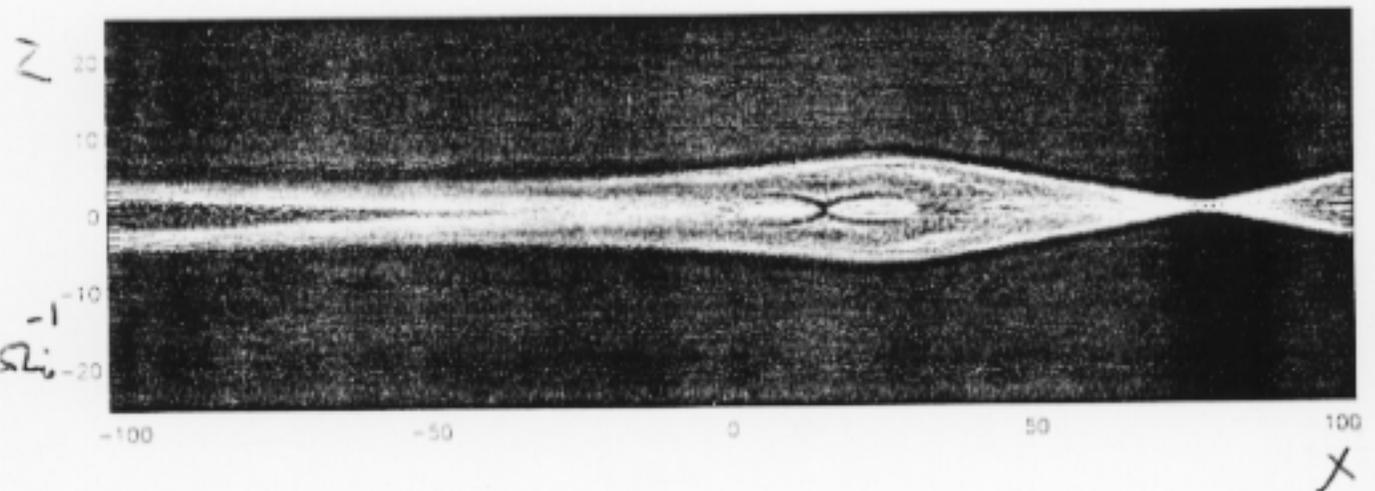


⇒ electron outflow velocity greatly exceeds c_A

⇒ ions reach c_A in a few c/ω_{pi}

Constancy of Reconnection Rate

\Rightarrow geometry forms early in time, and propagates downstream



\Rightarrow reconnection rate independent of system size

Sensitivity to dissipation

- fast reconnection in hybrid / Hall MHD codes only if dissipation is sufficiently weak

- don't use resistivity η

\Rightarrow does not prevent collapse to grid scale unless too large

\Rightarrow have whistlers at grid scale

$$\omega = k^2 \frac{c^2}{\omega_{pe}^2} \Omega_e - i \frac{3c^2}{4\pi} k^2$$

\Rightarrow no dissipation scale below which dissipation dominates

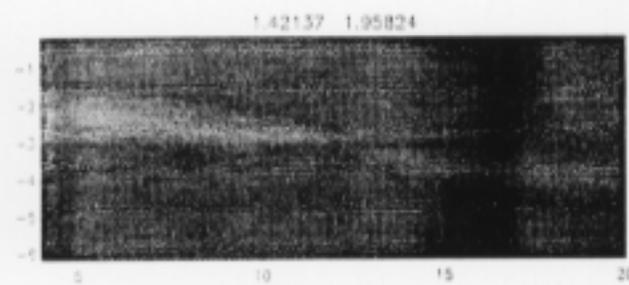
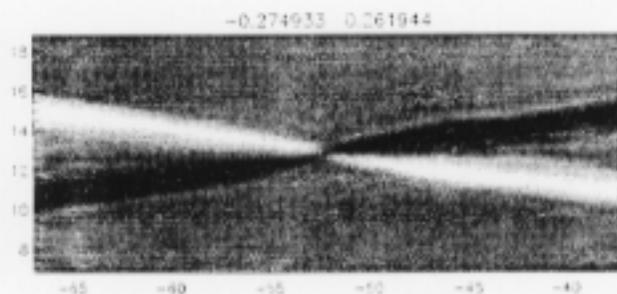
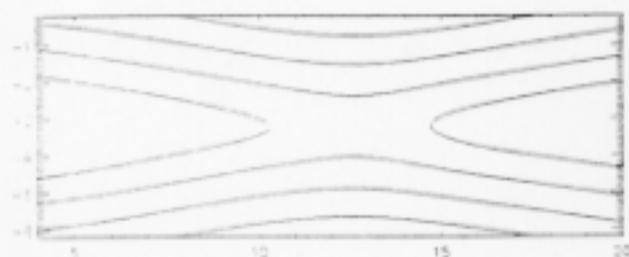
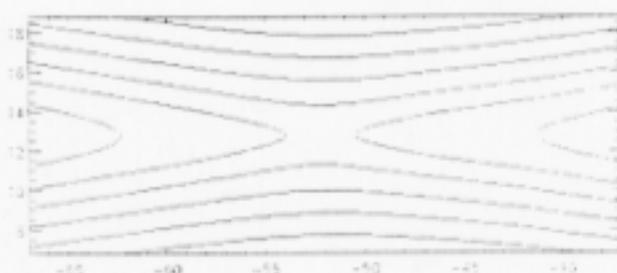
- use higher order dissipation

$$\sim \mu k^p \text{ with } p \geq 4$$

Impact of Equilibrium B_{y0}

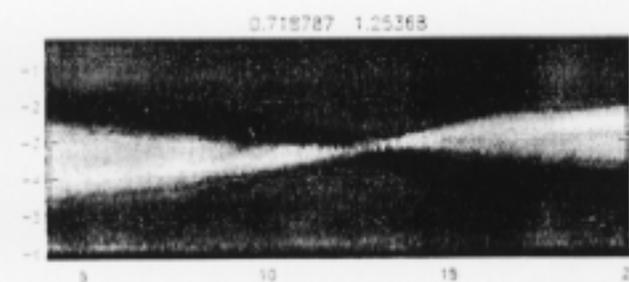
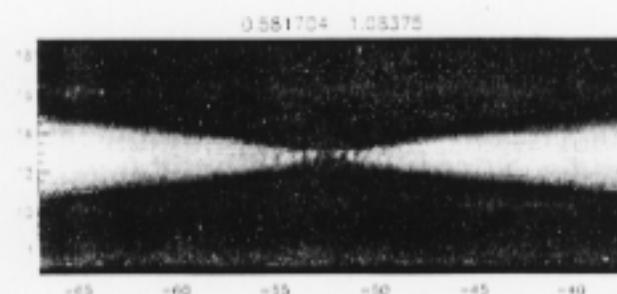
$B_{y0} = 0$

$B_{y0} = 1.5$



B_{y0} large
 \Rightarrow whistler important

B_{y0} small
 \Rightarrow whistler weak



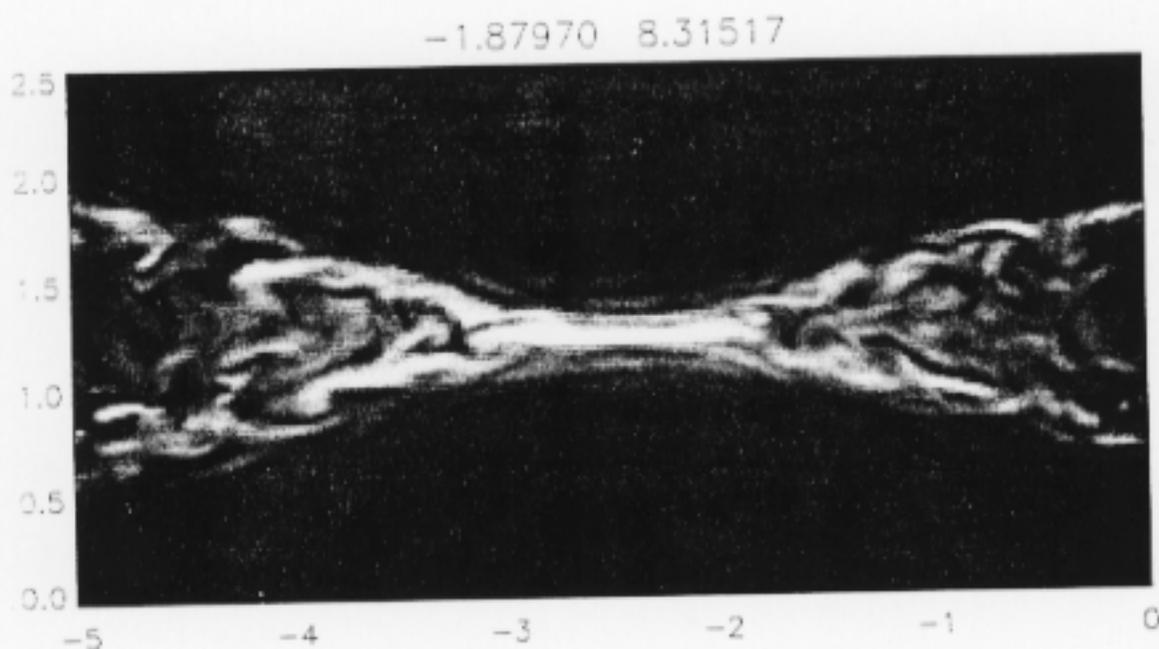
$V_{th} P_e$ small \Rightarrow no KAW

$V_{th} P_e$ large \Rightarrow KAW

Strong Turbulence in 3-D

- sharp gradients in 2-D model
break up in 3-D

J_y



B_y



Key Results

- Particle, hybrid and Hall MHD codes yield fast reconnection with nearly identical rates
 - ⇒ independent of mechanism which breaks the frozen-in condition
 - ⇒ diffusion must be weak
- The MHD model yields slow reconnection
 - ⇒ sensitive to dissipation mechanism
- Hall (whistler) physics is critical
 - ⇒ enables electrons/ions to decouple at small scales
 - ⇒ whistler rather than Alfvén waves control dynamics at small scales
 - ⇒ high whistler phase speed
 - ⇒ fast reconnection $V_{in} \sim 0.1 C_A$

- fast reconnection even for $B_{y0} \sim B_{x0}$

 - \Rightarrow kinetic Alfvén wave replaces whistler

- key issues

 - \Rightarrow structure of "slow shock" in outflow region

 - \Rightarrow turbulence in 3-D
anomalous resistivity?