Transport at the Magnetospheric Boundary: Magnetic Reconnection and Kelvin-Helmholtz Modes

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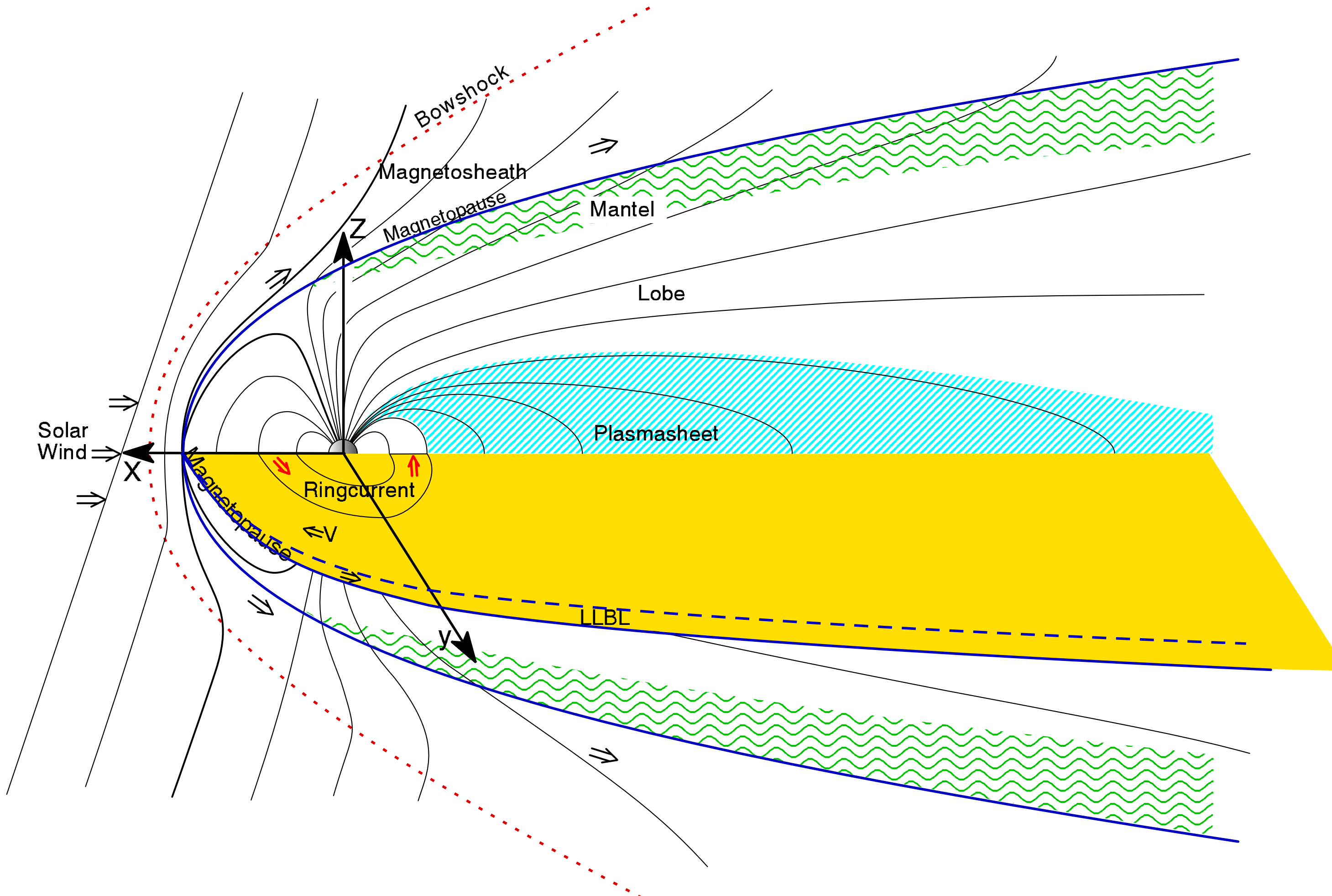
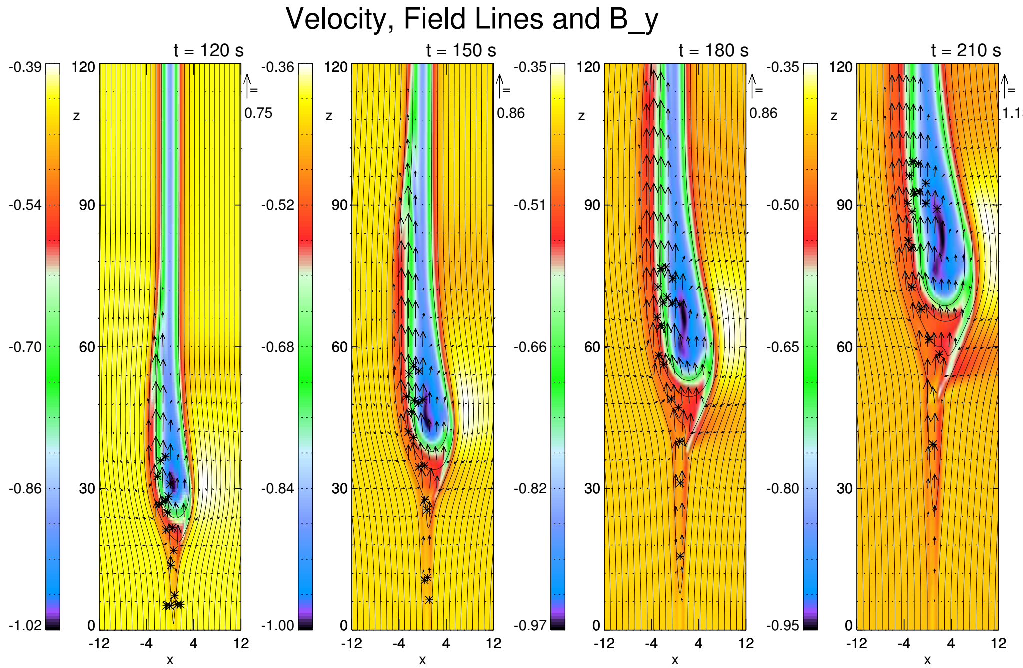
Contents:

Acknowledgements: K. Nykyri, Q. Chen, F. Hall, J. Buechner, D. Fairfield

Magnetospheric Boundaries:



Dayside Reconnection for Southward Interplanetary Magnetic Field (IMF)



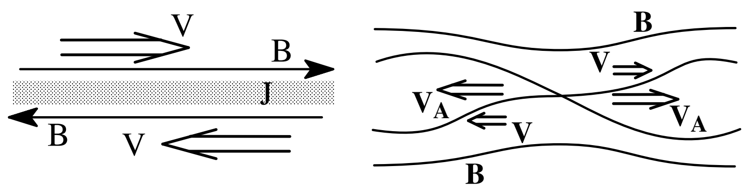
Solar Wind - Magnetosphere Interaction

Diffusion

- **Thin boundaries** r_{ci}, c/ω_{pi}

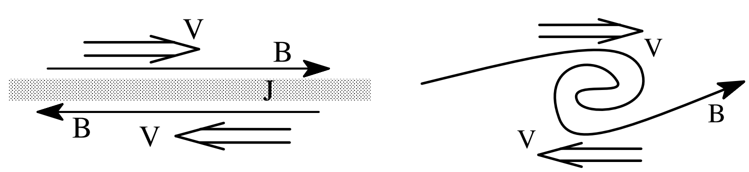
Magnetic Reconnection:

- **Transport of plasma, momentum, energy, and magnetic flux**
- **Requires large anti-parallel magnetic field components** $\Delta V_A > \Delta V$



Kelvin-Helmholtz mode:

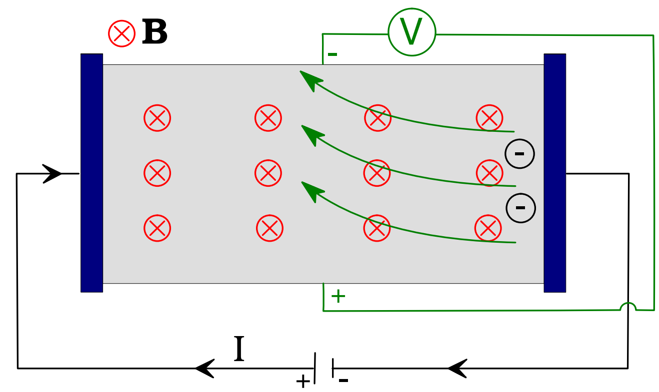
- **Ideal instability => Transport of momentum and energy (viscous coupling)**
- **Requires** $\Delta v > V_{A,typ}$ **along the k vector of the instability**



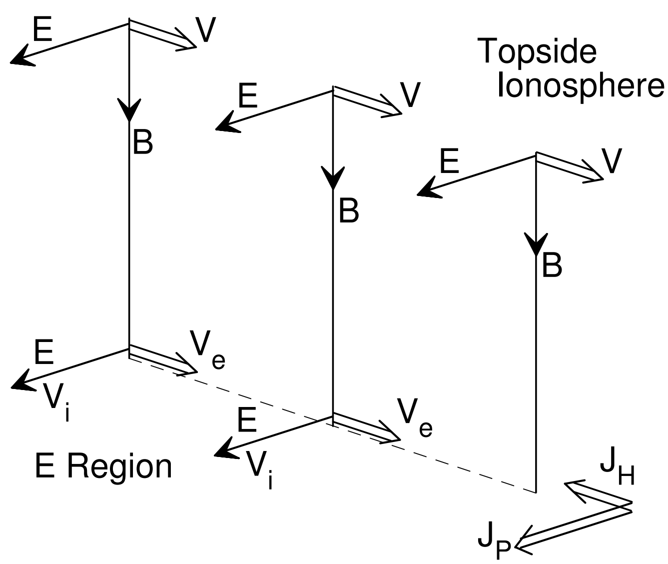
Combination of tearing/reconnection with KH (Vortex induced reconnection) in 2D??

- **Requires** $\Delta v > V_{A,typ}$ **for KH and** $\Delta v < \Delta V_A$ **for reconnection**
- **For strongly northward IMF:** Δ**B is small along the flanks of the magnetosphere**

Hall Effect (Edwin Hall, 1879)



Hall Currents in the Ionosphere



Generalized Ohm's Law

$$\mathbf{E}+\mathbf{u}\times\mathbf{B}=\frac{m_e}{e^2 n}\left[\frac{\partial\mathbf{j}}{\partial t}+\nabla\cdot(\mathbf{uj}+\mathbf{ju})\right]-\frac{1}{en}\nabla p_e+\frac{1}{en}\mathbf{j}\times\mathbf{B}+\eta\mathbf{j}$$

with $\eta = m_e\nu_c/ne^2$**.**

Normalized form (L_0, B_0, n_0, u_0, ...)

$$\mathbf{E}+\mathbf{u}\times\mathbf{B}=\frac{c^2}{\omega_{pe}^2 L_0^2}\left[\frac{\partial\mathbf{j}}{\partial t}+\nabla\cdot(\mathbf{uj}+\mathbf{ju})\right]-\frac{c}{\omega_{pi}L_0}\nabla p_e+\frac{c}{\omega_{pi}L_0}\mathbf{j}\times\mathbf{B}+\eta\mathbf{j}$$

Electron and ion inertia scale:

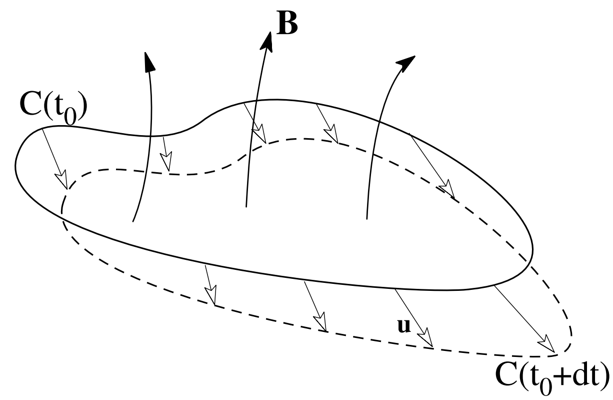
$$\begin{aligned}\lambda_e=\frac{c}{\omega_{pe}} &= \left[\frac{\epsilon_0 m_e c^2}{n_e e^2}\right]^{1/2}\approx 5km\,(MSP),\ 1\,to\,15\,cm\,(SUN)\\ \lambda_i=\frac{c}{\omega_{pi}} &= \left[\frac{m_i}{m_e}\right]^{1/2}\frac{c}{\omega_{pe}}\approx 200km\,(MSP),\ 3\,to\,100\,m\,(SUN)\end{aligned}$$

Magnetic diffusion time scale: $\tau_{diff}=L_0^2/\left(\lambda_i^2\nu_c\right)$

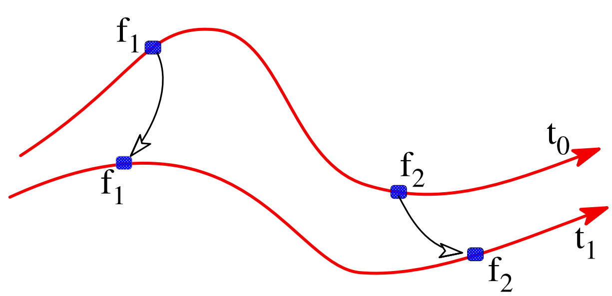
Frozen-in Condition

$$\mathbf{E} + \mathbf{u} \times \mathbf{B} = 0$$

(a) Magnetic flux through any cross section C(t) moving with velocity u remains constant



(b) Two fluid elements which are on the same field line remain connected by this field line for all times.



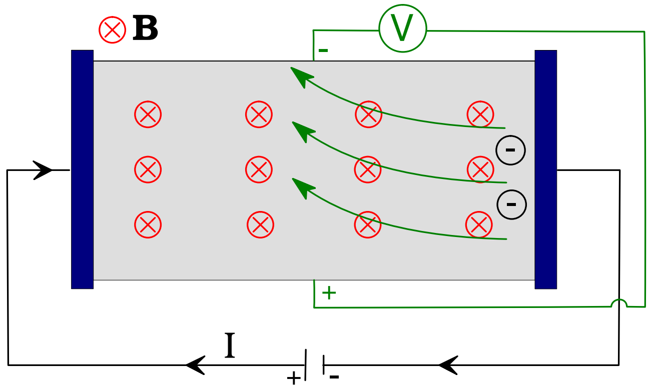
Including the Hall term:

$$\mathbf{E} + \mathbf{u} \times \mathbf{B} = \frac{1}{en}\mathbf{j} \times \mathbf{B}$$

$\mathbf{u}_e = \mathbf{u} - \frac{1}{en}\mathbf{j}$ =>

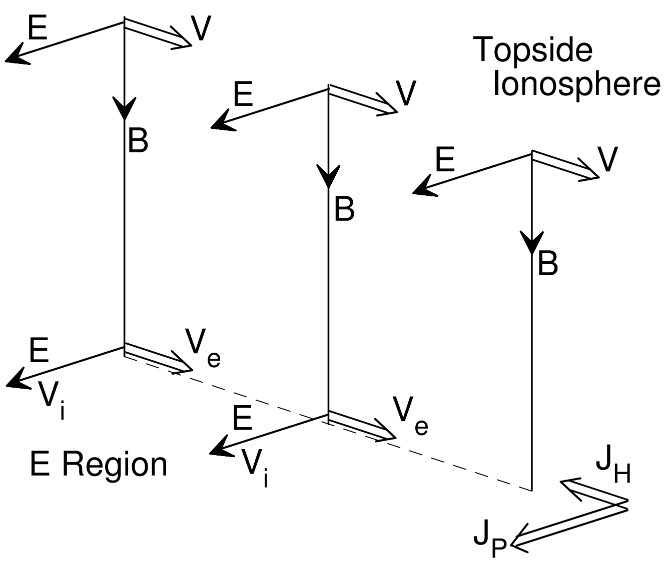
$$\mathbf{E} + \mathbf{u}_e \times \mathbf{B} = 0$$

Hall Effect



$$\mathbf{E} + \mathbf{u}_e \times \mathbf{B} = \eta \mathbf{j}$$

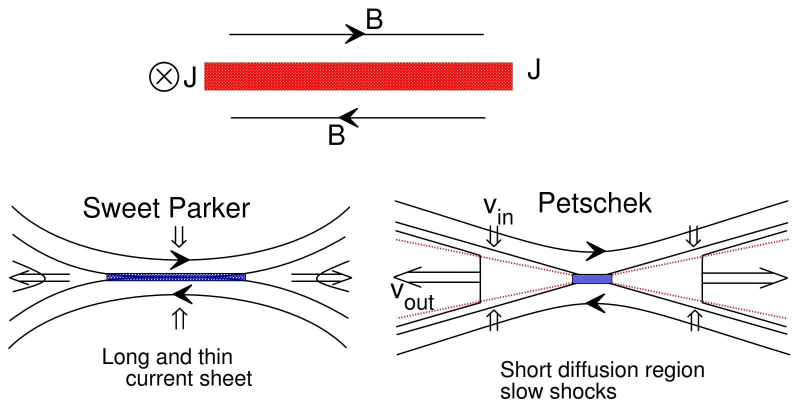
Hall Currents in the Ionosphere



$$\omega_{gi} < \nu_{ic} \quad and \quad \omega_{ge} > \nu_{ec}$$

Magnetic Reconnection

$$\mathbf{E} + \mathbf{u} \times \mathbf{B} = \eta \mathbf{j}$$



Reconnection rate: Rate with which magnetic flux is transported from the inflow to the outflow region

$$R \approx \frac{v_{in}}{v_{out}} \approx \frac{d}{l}$$

- **Sweet and Parker:**

$$R_{SP} = R_m^{-1/2} = \left[L \sigma v_{A0} \mu_0 \right]^{-1/2} = slow!!!!$$

- **Petschek:**

$$R_{SP} = \frac{\pi}{8 \ln R_m} \approx 0.1 = fast!!!!$$

Hall Physics

Inclusion of Hall term

$$\mathbf{E} + \mathbf{u} \times \mathbf{B} = \frac{1}{en}\mathbf{j} \times \mathbf{B}$$

=> Electron whistler wave

$$\omega_w = k^2 c^2 \omega_{ge} \omega_{pe}^{-2}$$

- **Phase and group velocities $\sim k$. => Numerical limitation**

Courant Condition for explicit simulation methods:

$$\Delta t \leq \frac{v_{max}}{\Delta x}$$

but including Whistler dynamics:

$$\Delta t \leq const \frac{v_{Alfven}}{(\Delta x)^2}$$

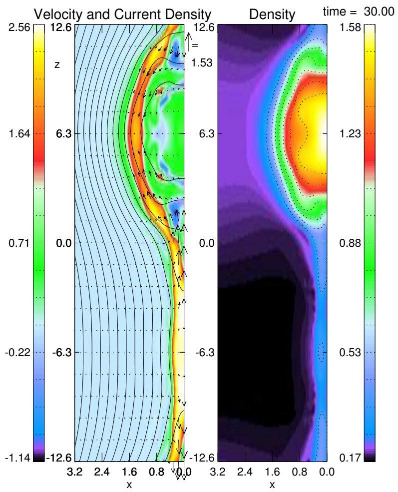
Numerical effort in two dimensions $\sim \frac{1}{(\Delta x)^4}$

GEM Reconnection Challenge

- **Identical (*simple*) initial and boundary conditions**
- **Two dimensions**
- **Comparison of different plasma approximations**
  - **Full particle electromagnetic simulation**
  - **Hybrid (ions kinetic and electrons fluid) simulation**
  - **Two-fluid simulation**
  - **Hall MHD simulation**
  - **MHD simulation**

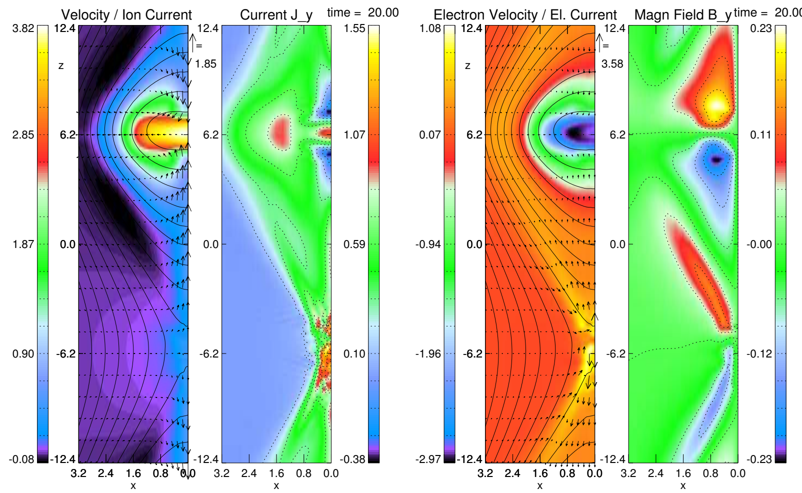
Results: Hall MHD

Unit distance = Ion inertia scale (c/ω_{pi})



MHD

Hall MHD



- **Electron current concentrated in the diffusion region**
- **Electron & ion dynamics decouple on scale < c/ω_{pi}**
- **'Quadrupolar' B_y signature**
- **Fast reconnection**

Results: Hybrid model (ions kinetic + electrons fluid)

Shay et al. (2001)

SHAY ET AL.: COLLISIONLESS MAGNETIC RECONNECTION 3763

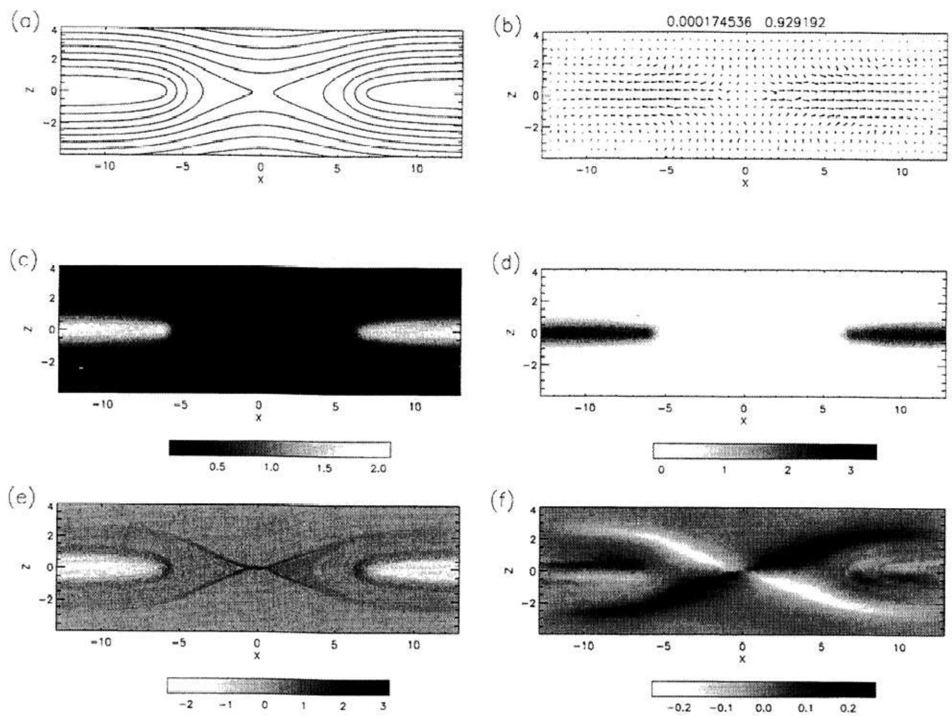


Figure 2. Results from a hybrid run with $m_e/m_i = 1/100$: (a) Magnetic field lines, (b) ion in-plane flows, (c) density, (d) ion out-of-plane current, (e) electron out-of-plane current, and (f) out-of-plane magnetic field.

Results: Full particle (electromagnetic) model

Pritchett (2001)

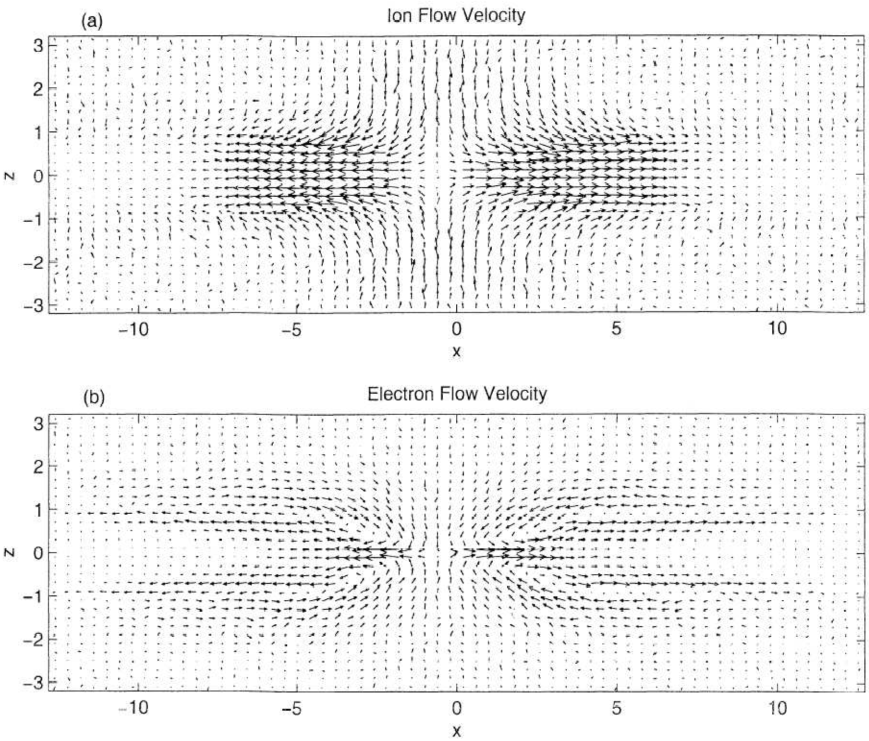
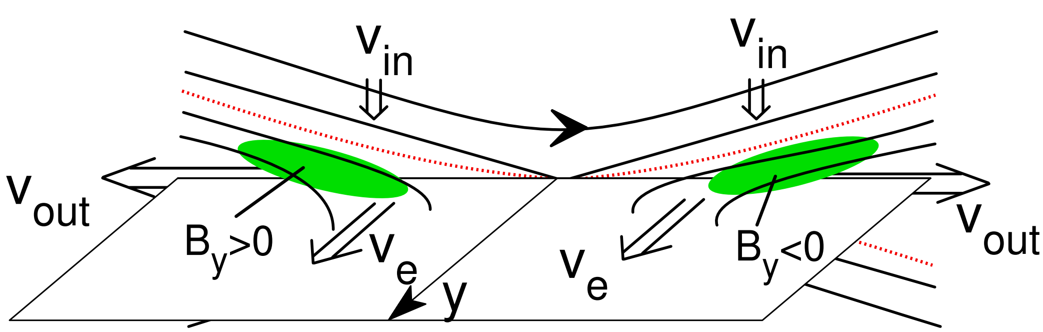


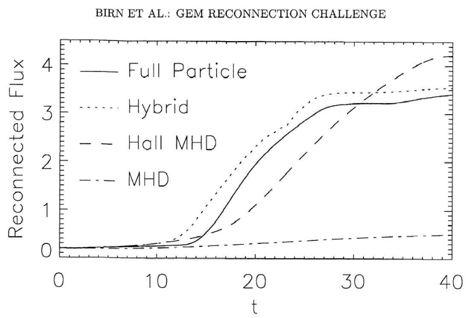
Figure 3. The in-plane (x,z) (a) ion and (b) electron flow velocities at the same time as in Plate 1.

Reconnection with Hall Physics

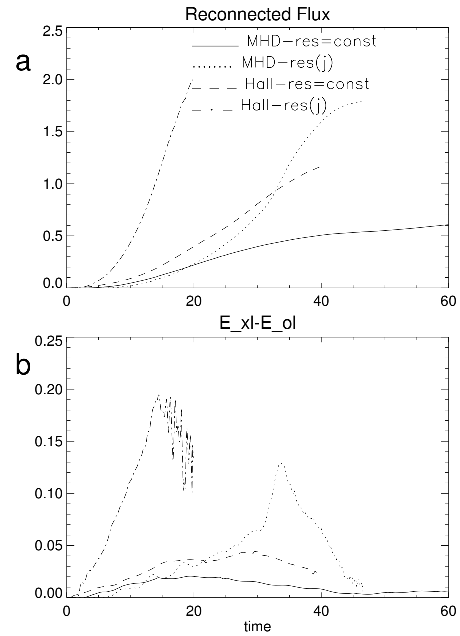


- **Simple Initial geometry with magnetic field in the x, z plane ($B_y(t=0)=0$)**
- **Reconnection generates B_z**
- **Current in diffusion region = electron current => $\mathbf{v_e}$ in the y direction**
  => motion of magnetic foot points in symmetry plane along y (frozen-in condition)
  => generation of B_y with correct polarity

Reconnection rates:



Birn et al. (2001)



- **Fast reconnection with R=0.2**
- **Reconnection rates very similar for different plasma approximations**
- **Exception: simple MHD**
- **All models with fast reconnection include Hall physics**

Fast Reconnection by including Hall physics?

- **Bulk velocity for current carriers in a current sheet with $L_0 = c/\omega_{pi}$:**

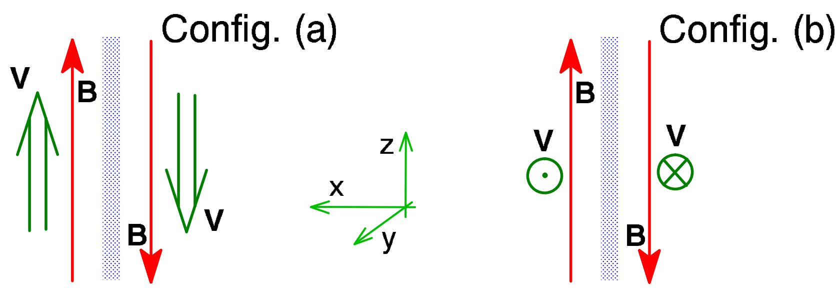
$$v_e = \frac{B_0 \omega_{pi}}{en\mu_0 c} = v_A$$

- **Length of current sheet =** $O\left(c/\omega_{pi}\right)$
- **Width limited because of the generation of** B_y

=> limits aspect ration of the diffusion region d/l **=> fast reconnection**

Reconnection determined by Hall physics with a unique reconnection rate?

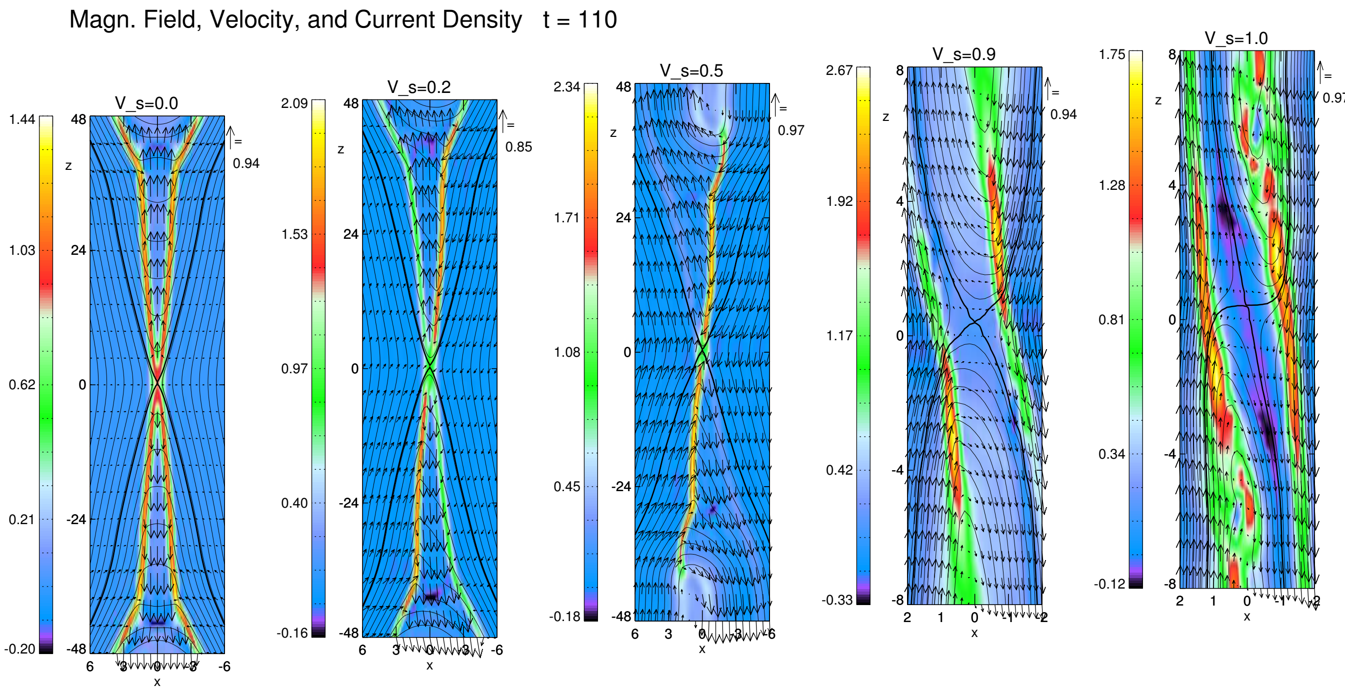
Simple configurations with plasma flow:



- **Configuration (a): Plasma flow aligned with the magnetic field**
- **Configuration (b): Plasma flow in the invariant direction**

Configuration (a): Flow shear along antiparallel magnetic field

MHD Case:



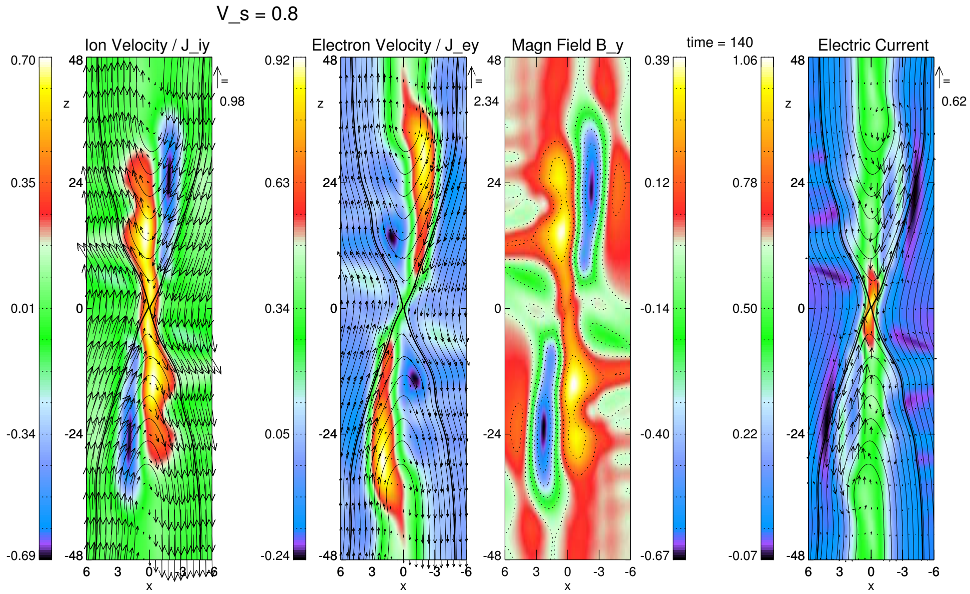
Main results:

- **Asymmetric current layers**
- **Reconnection is switched off for** $v_{shear} = v_A$

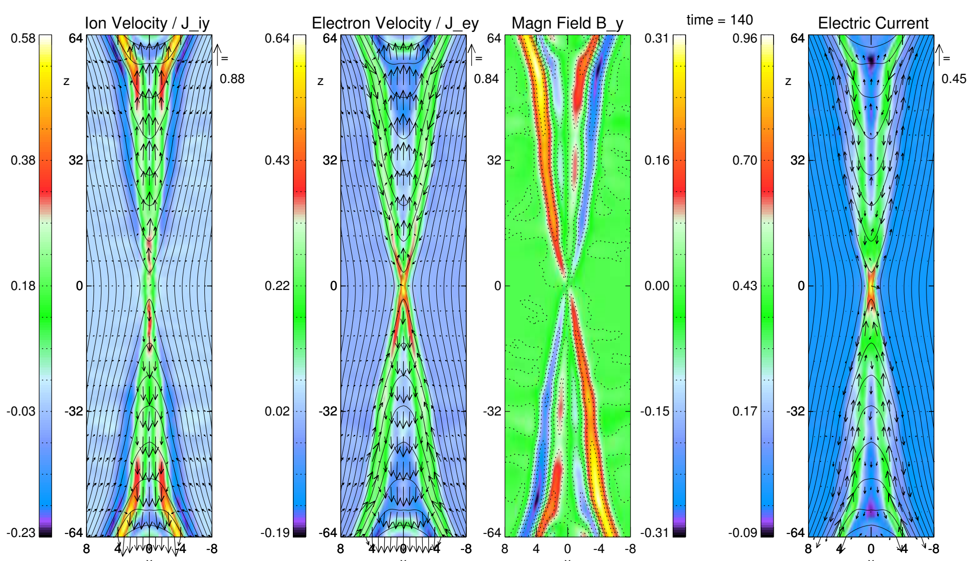
Mechanisms:

- **Acceleration into outflow region is caused j**$\times B$ **force**
  => larger acceleration required for side with shear flow opposite to outflow
  => larger current density required on this side
- **Shear flow faster than Alfven speed does not permit information to travel upstream from x line**
  => reconnection is switched off

Hall MHD for $v_{sh} = 0.8$:



$v_{sh} = 0$:

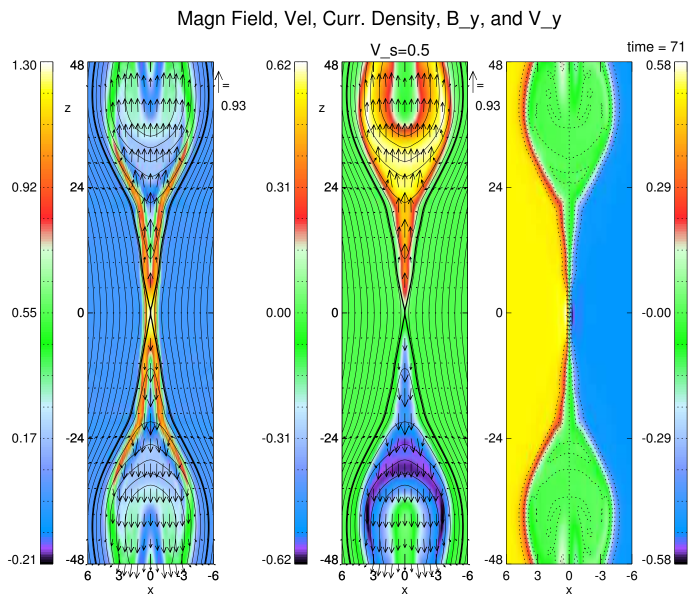


Many similarities between MHD cases and the cases with Hall term included!

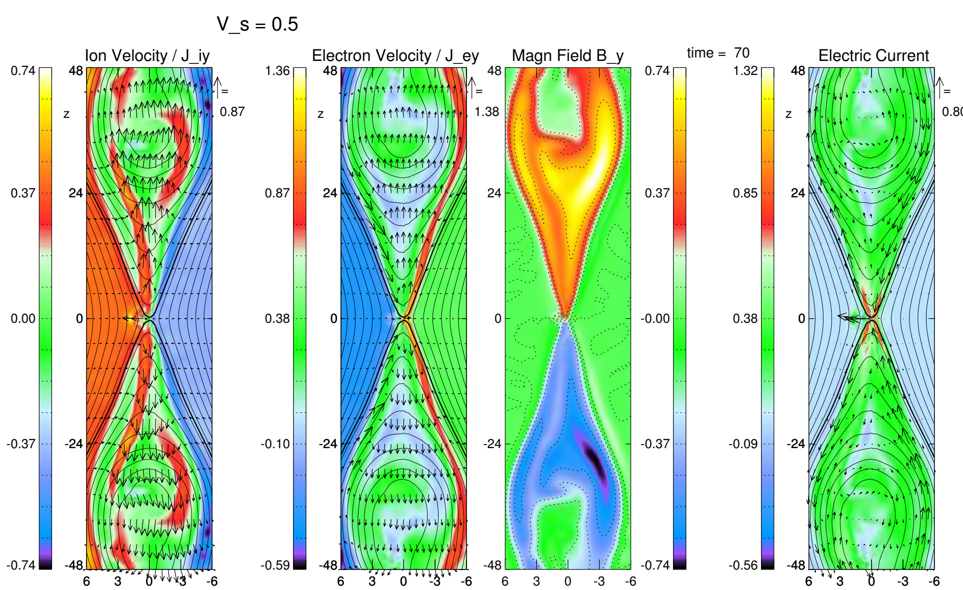
- **Same asymmetry: Main current layer shifted toward the side with flow antiparallel to the respective outflow region.**
- **Same stabilization mechanism and limits ($v_{sh} \simeq v_A$)**

Configuration (b): Flow shear along the current direction

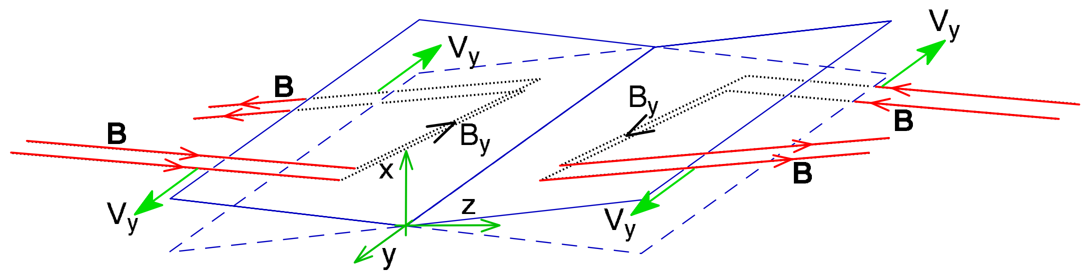
MHD Case:



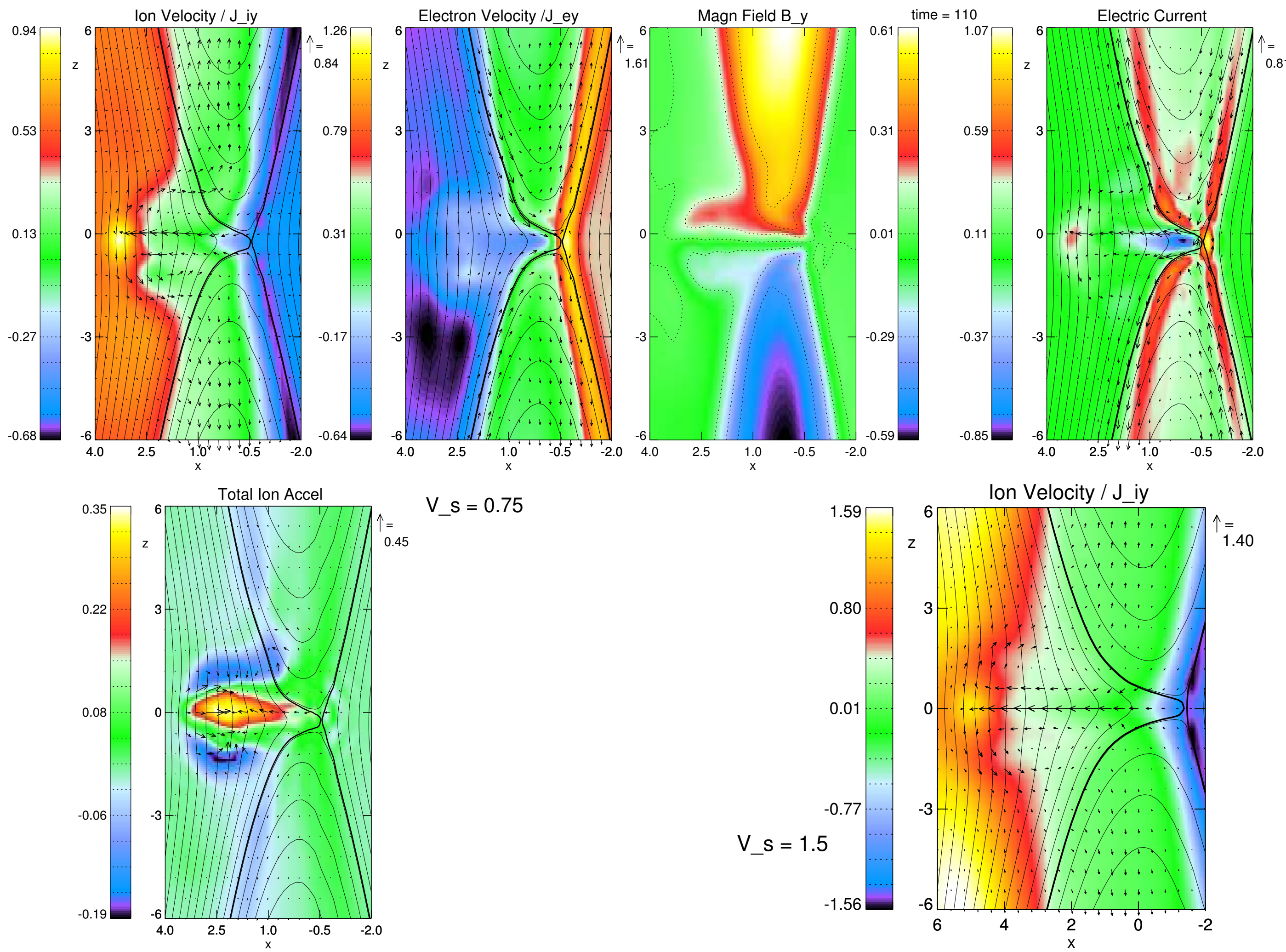
Hall Case:



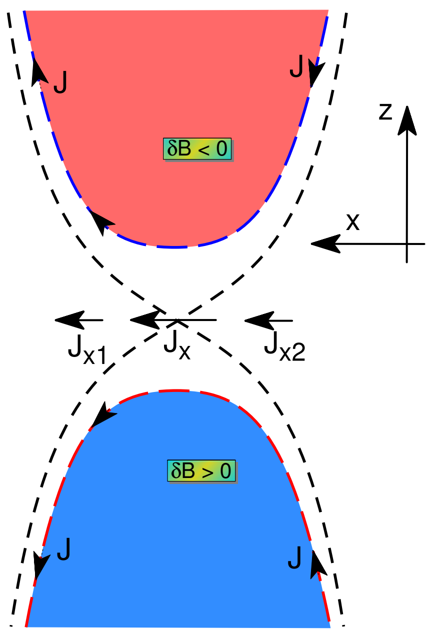
Physical mechanism for the generation of B_y:



“Ion fountain” reconnection

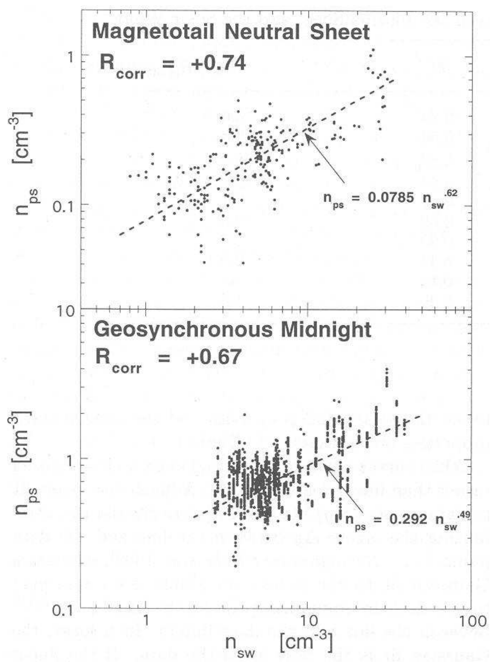


Physical mechanism for the unusual ion flow:

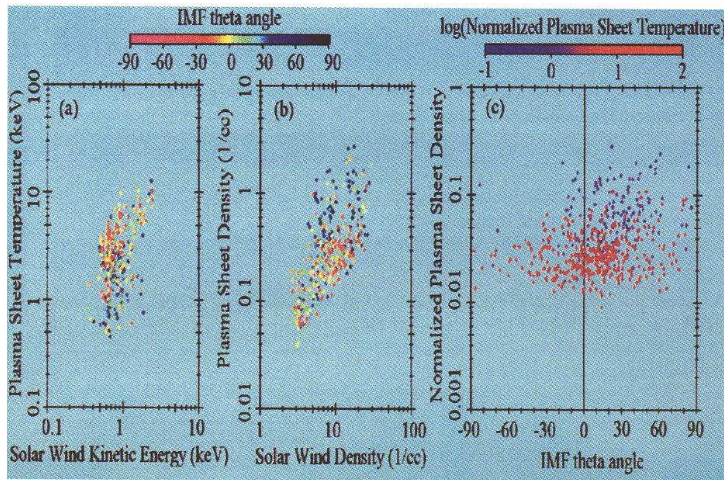


- **Opposite polarities of $B_y$require current in the x direction:** $j_x \simeq \frac{\delta B_y \omega_{pi}}{\mu_0 c}$ **with a drift velocity of** $v_{xd} = v_A \frac{\delta B_y}{B_0}$
- **Reconnection rate:** ϵ_r **=> electron inflow velocity of** $v_{ex} = \epsilon_r v_A$
- **Electron inflow not sufficient to carry the required current for** $v_{ex} < v_{xd}$ **or** $\epsilon_r < O(1)\,\frac{\delta B_y}{B_0}$ **=> ion jet needed to carry current to support the bipolar** B_y

Plasma Entry into the Magnetotail (for Northward IMF)



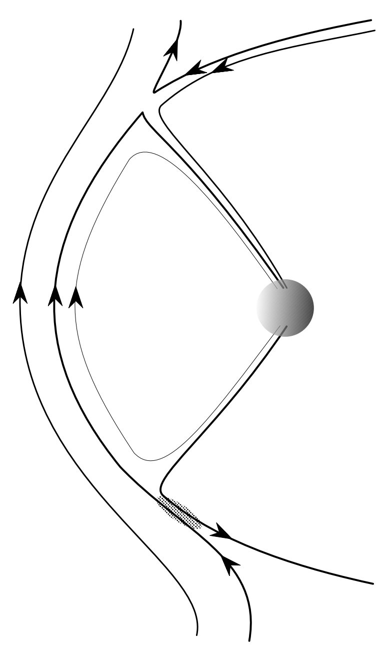
Borovsky et al. (1998): Neutral sheet density versus solar wind density.



Fujimoto et al. (1998): Neutral sheet temperature and density versus solar wind conditions.

Properties:

- **Correlation between plasma sheet density and SW density**
- **Cold dense plasma sheet for northward IMF**
- **Penetration times:**
  - **Midtail: 1 hour**
  - **Near Earth region: several hours**
- **High density and low temperature filaments on closed field lines (slow convection)**
- **Energetic (magnetospheric) and cold ion (magnetosheath) populations**
- **Possible Mechanisms for entry:**
  - **Re-reconnection at high latitudes (Song and Russell, 1992)**
  - **Diffusion**

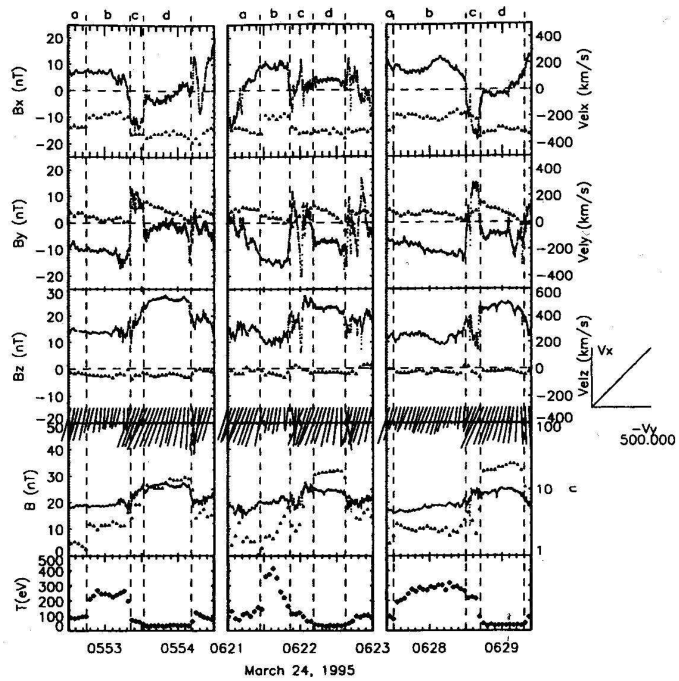


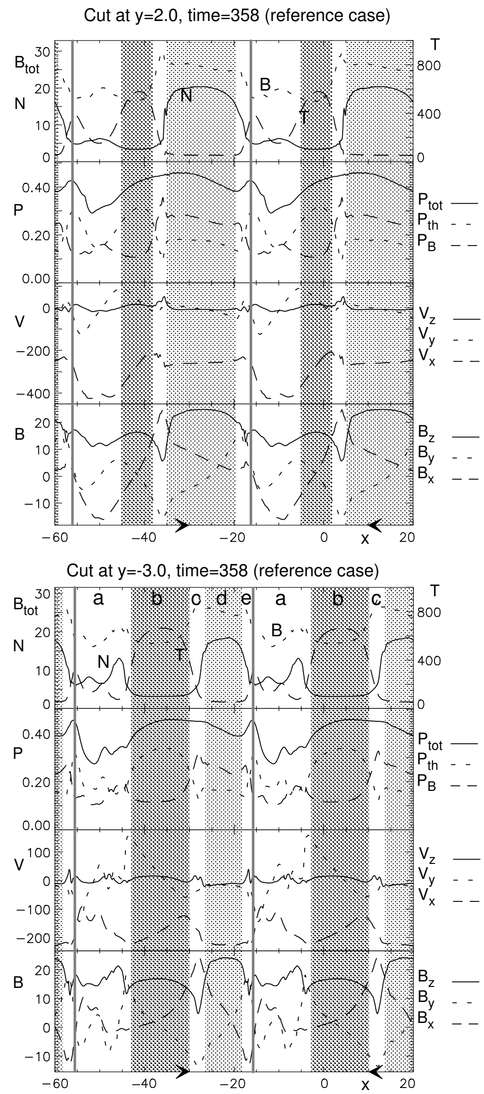
Kelvin-Helmholtz Mode at the Magnetospheric Boundary

Many Observations of quasi-periodic boundary oscillations

(Schopke et al., 1981; Ogilvie and Fitzenreiter, 1989; Chen and Kivelson, 1993, ..)

Fairfield et al. (2000)

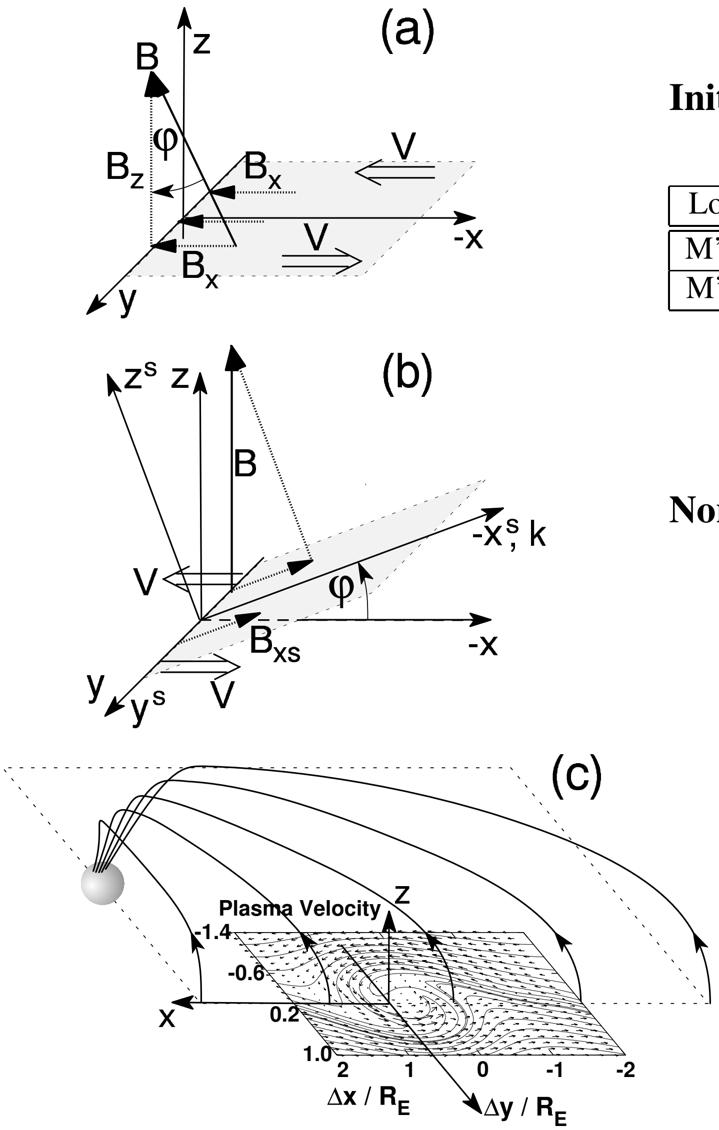




Otto and Fairfield (2000)

Initial Geometry:

No magnetic field deformation if $\mathrm{B} \perp \mathbf{k_{KH}}$!!



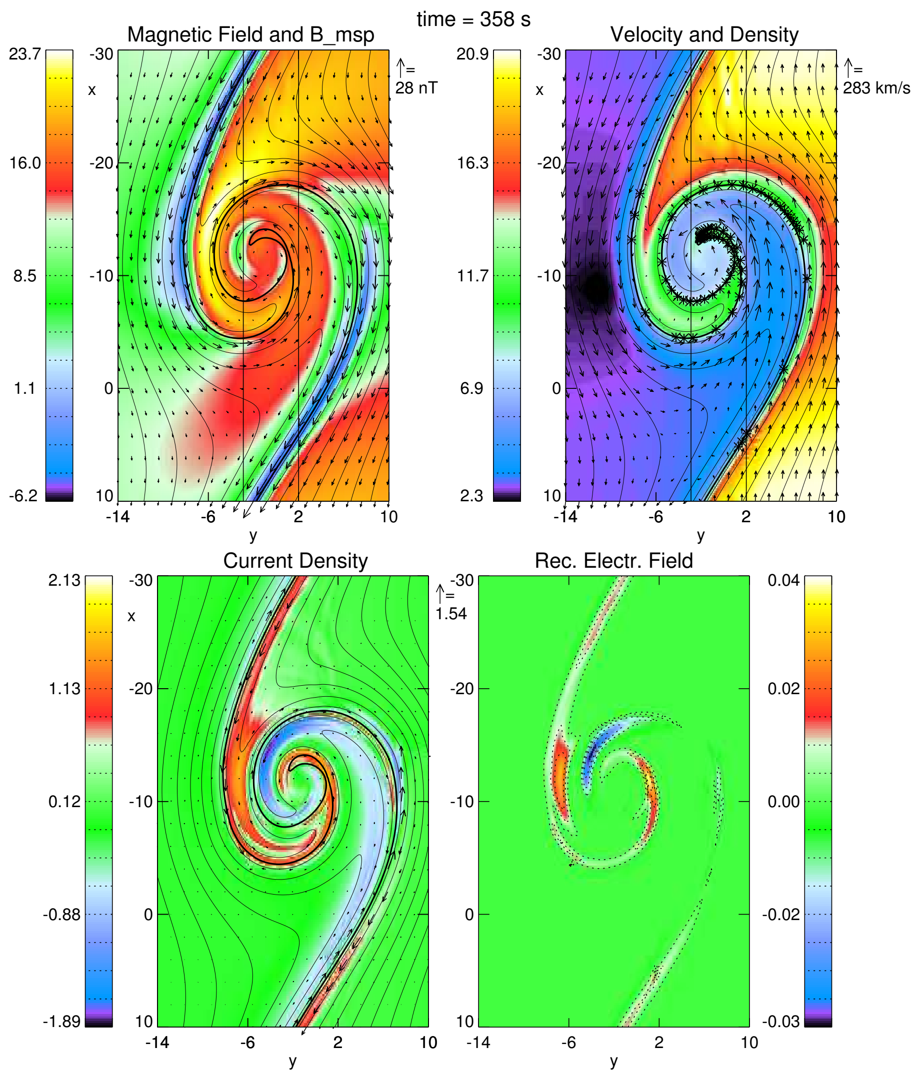
Initial Parameters:

Location	B, nT	V, km s^{-1}	n, cm^{-3}	β
M'sphere	16	0	2.8	2.8
M'sheath	24	315	19.2	0.7

Normalization:

	Units
Magnetic field B_0	16 nT
Number density n_0	11 cm^{-3}
Current density j_0	22 nA m^{-3}
Length scale L_0	600 km
Velocity v_A	105 km s^-1
Time τ_A	5.7 s

Structure of the KH Vortex



Signatures:

Region (a):

- **Core of the KH vortex**
- **Strong fluctuations in all plasma and field parameters**
- **high density spikes**

Region (b):

- **Magnetospheric plasma trailing the core of the vortex**
- **Magnetospheric temperatures and densities**
- **Small fluctuations Steady decrease in** v_y

Region (c):

- **Outbound transition into sheath-like material**
- **Decrease in temperature and increase in density**
- **Minimum in** B_z
- **Spikes in** B_x **and** B_y **with opposite polarity**

Region (d):

- **Magnetosheath-like interval**
- **Steady plasma and field properties**

Region (e):

- **Inbound transition into vortex**
- **Minimum in** B_z
- **Spikes in** B_x **and** B_y

Stability

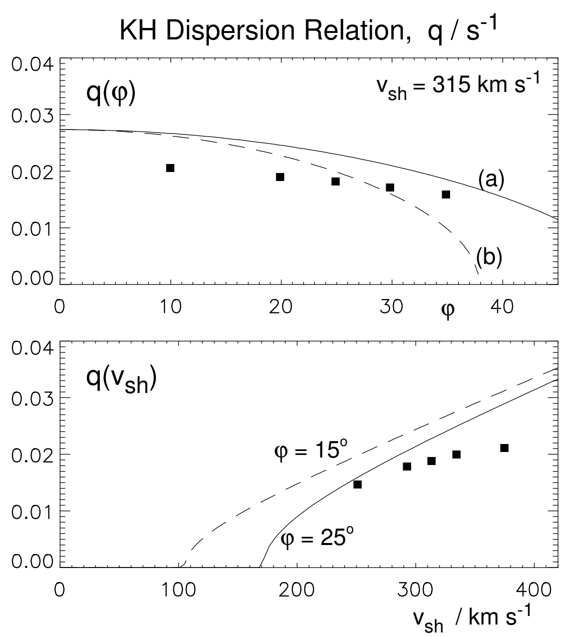
Growth rate:

$$q = \left[\alpha_1\alpha_2\left[(\mathbf{V}_1 - \mathbf{V}_2)\cdot\mathbf{k}\right]^2 - \alpha_1(\mathbf{V_{A1}}\cdot\mathbf{k})^2 - \alpha_2(\mathbf{V_{A2}}\cdot\mathbf{k})^2\right]^{1/2}$$

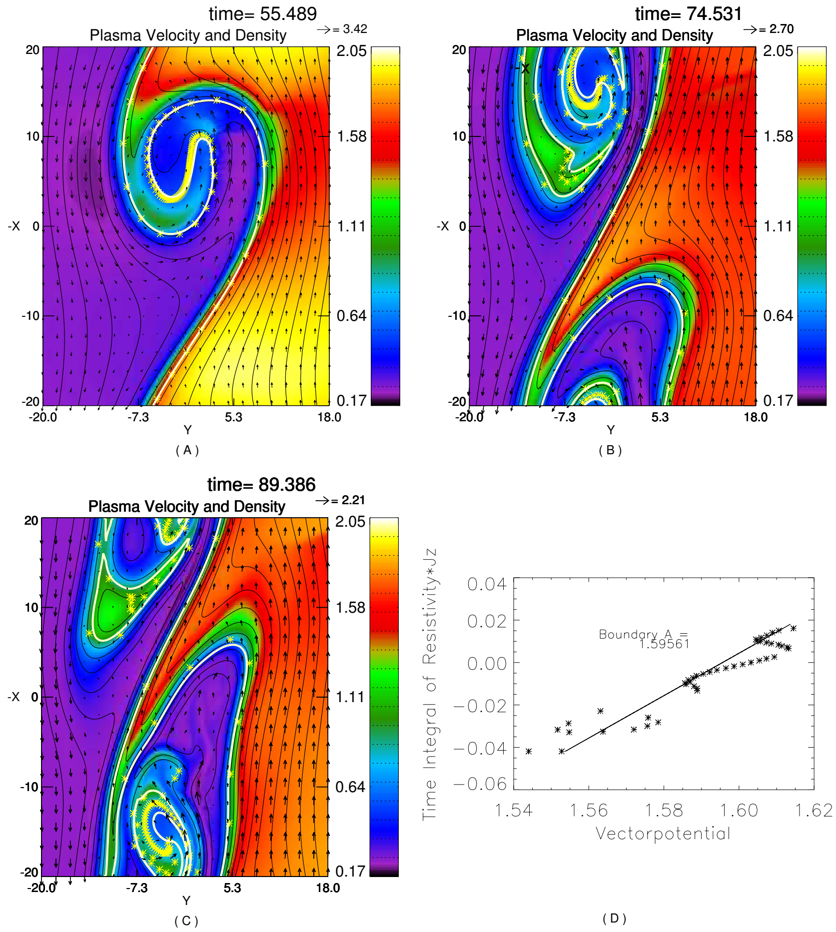
with $\alpha_i = n_i/(n_1 + n_2)$

Onset condition:

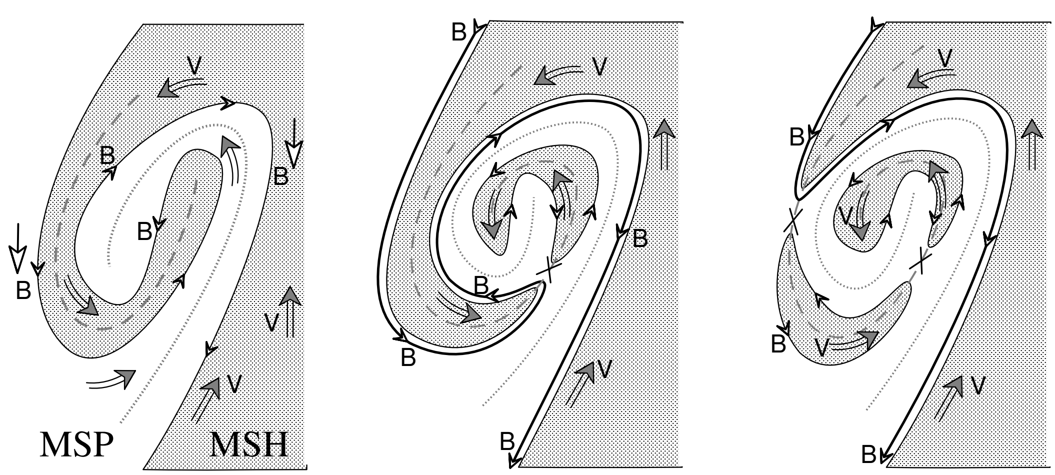
$$\left[(\mathbf{V}_1 - \mathbf{V}_2)\cdot\mathbf{k}\right]^2 > \frac{n_1 + n_2}{4\pi m_0 n_1 n_2}\left[(\mathbf{B}_1\cdot\mathbf{k})^2 - (\mathbf{B}_2\cdot\mathbf{k})^2\right]$$



Magnetic Reconnection in KH Vortices



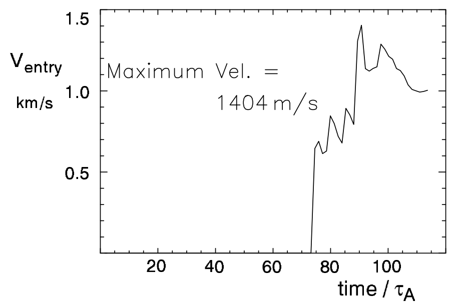
Nykyri and Otto (2001)

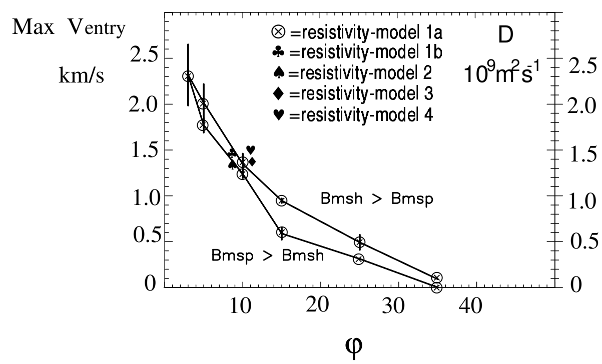


Plasma Transport

Evolution of the magnetic boundary:

$$\frac{dA_z}{dt}\Big|_{Fluidelement} = \frac{\partial A_z}{\partial t} + v \cdot \nabla A_z = -\eta J_z|_{Fluidelement}$$





Simulation cases:

Case	ϕ	B_{msp}	B_{msh}
1	3	16	24
2	3	24	16
3	5	16	24
4	5	24	16
5	10	16	24
6	10	24	16
7	15	16	24
8	15	24	16
9	25	16	24
10	25	24	16
11	35	16	24
12	35	24	16

$$v_{entry} = \frac{\Delta M}{\Delta t}\frac{1}{\rho_{msh} L_x}$$

Summary of Properties:

- **Mass transport from magnetosheath to magnetosphere**
- **Entry velocities of 0.5 to 2 km/s**

=> 45min to 3 hours to fill the plasma sheet (1 cm^{-3})

- **Limits:**
  - **Stabilization of the KH (nonlinear) by large magnetic shear** $|\phi| < 25°$
  - $\phi \to 0$ **no identification of magnetic boundary**

KH is an ideal mode:

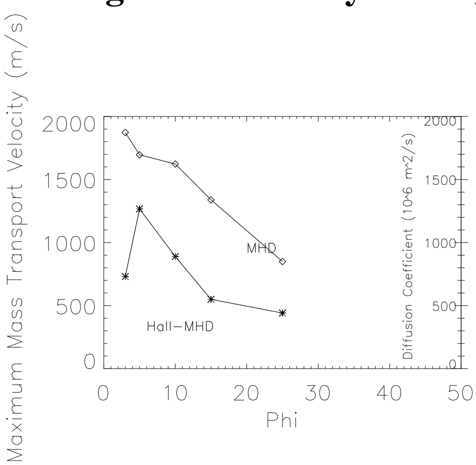
$\Delta t \sim L_{KH}$ **(for** $L_{KH} \gg L_{grad}$**)**

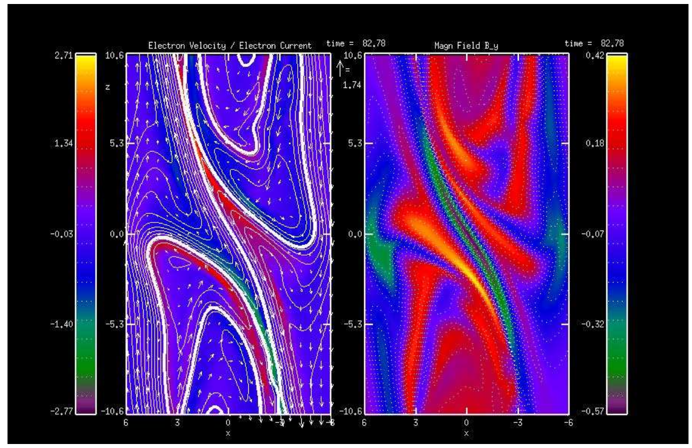
$\Delta M \sim L_{KH}^2$ **=>** v_{entry} **independent of wavelength to lowest order!**

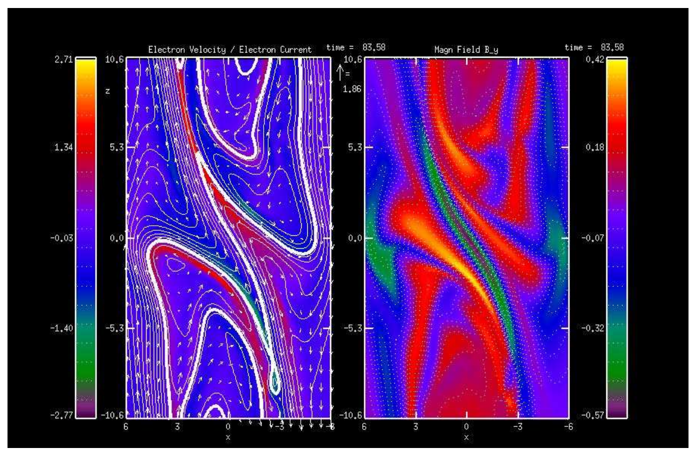
KH Mode and Hall Dynamics

Initial configuration:

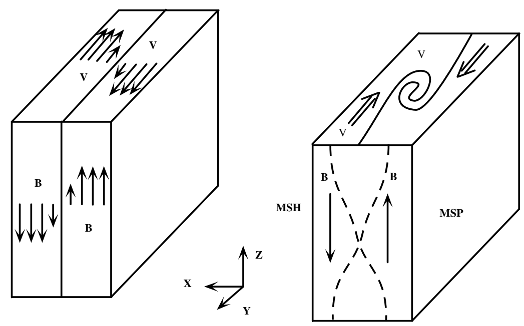
- **Density Asymmetry**
- **Magnetic Field Asymmetry**



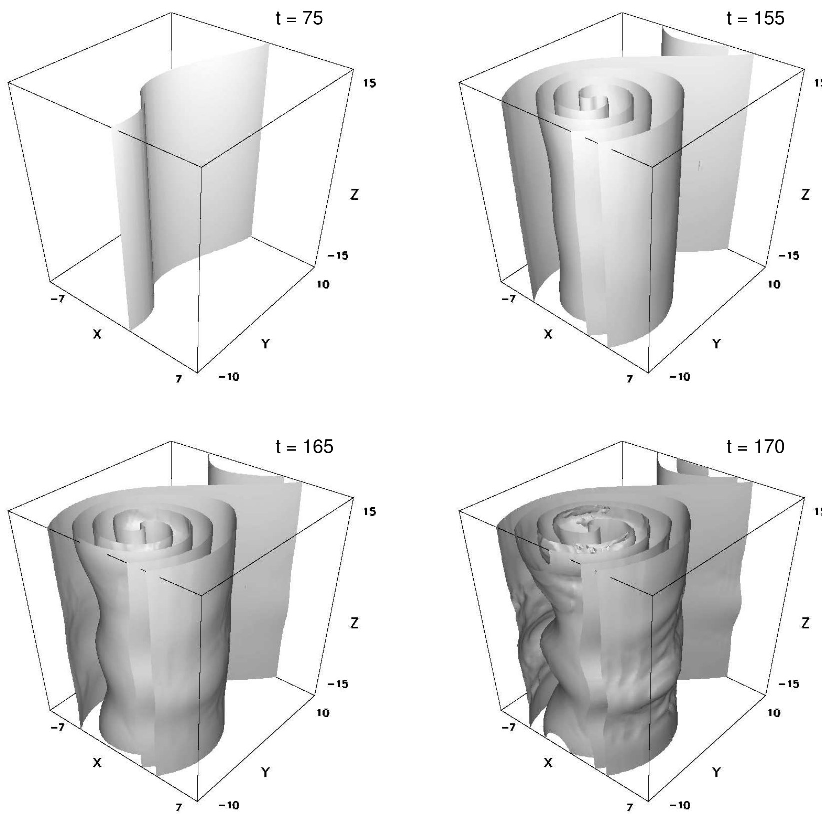


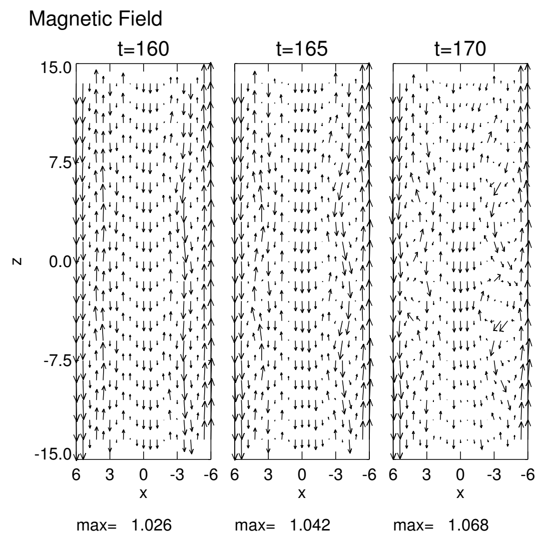


Example of three-dimensional KH and reconnection



Evolution of the B=0 surface:





Summary and Conclusions

Importance of Hall physics for magnetic reconnection

- **Enhanced reconnection rate**
- **Influence on reconnection geometry but**
- **Geometrical properties (boundary conditions, shear flow, asymmetries) equally important**
- **Hall ion fountain reconnection**

Kelvin-Helmholtz mode (ideal instability):

- **Amplification and distortion of the magnetic field in KH Vortices**
- **Plasma entry through**
  - **Diffusion over thin boundaries (Fujimoto and Terasawa, 1994,1995)**
  - **Reconnection in KH vortices**
- **Plasma transport sufficient to explain the formation of a cold dense plasma sheet for northward IMF**
- **Preference for strongly northward IMF ($\pm 50°$) and/or small $V_{A,MSP}$**
- **Mass transport not strongly dependent on Hall physics**