2D AND 3D HALL MAGNETIC RECONNECTION

J.D. Huba
Plasma Physics Division
Naval Research Laboratory
Washington, DC 20375

Modern Challenges in Nonlinear Plasma Physics
Honoring the Career of Dennis Papadopoulos
Halkidiki, Greece
June, 2009

Acknowledge: L. Rudakov

Research supported by ONR

GHOSTS OF RECONNECTION PAST

Gordon Conference 1977

WHAT IS HALL MHD

- Ohm's law (electrons frozen into magnetic field)

$$\mathbf{E} + \frac{1}{c}\mathbf{V}_e \times \mathbf{B} = 0$$

- Current definition (assumes quasineutrality)

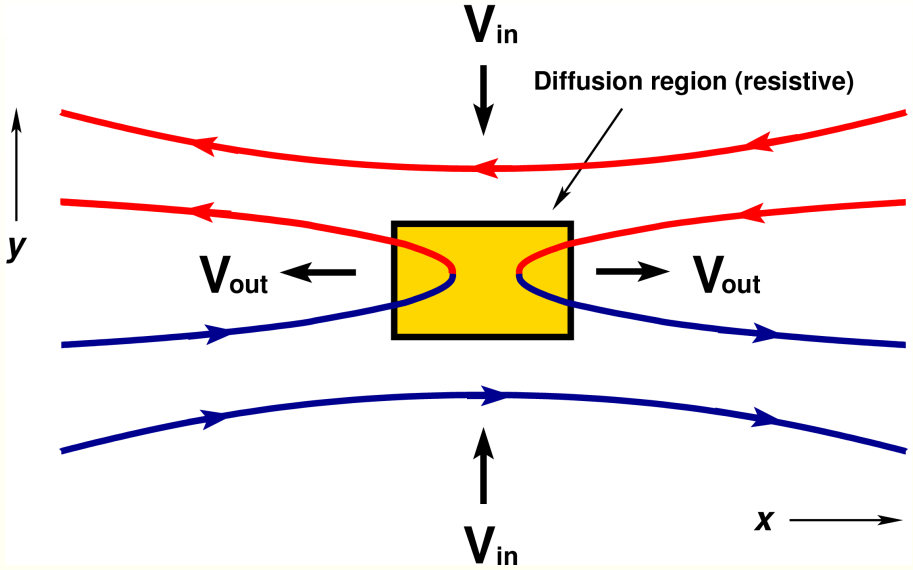
$$\mathbf{J} = ne(\mathbf{V}_i - \mathbf{V}_e) \quad \Rightarrow \quad \mathbf{V}_e = \mathbf{V}_i - \frac{1}{ne}\mathbf{J}$$

- Electric field is written as

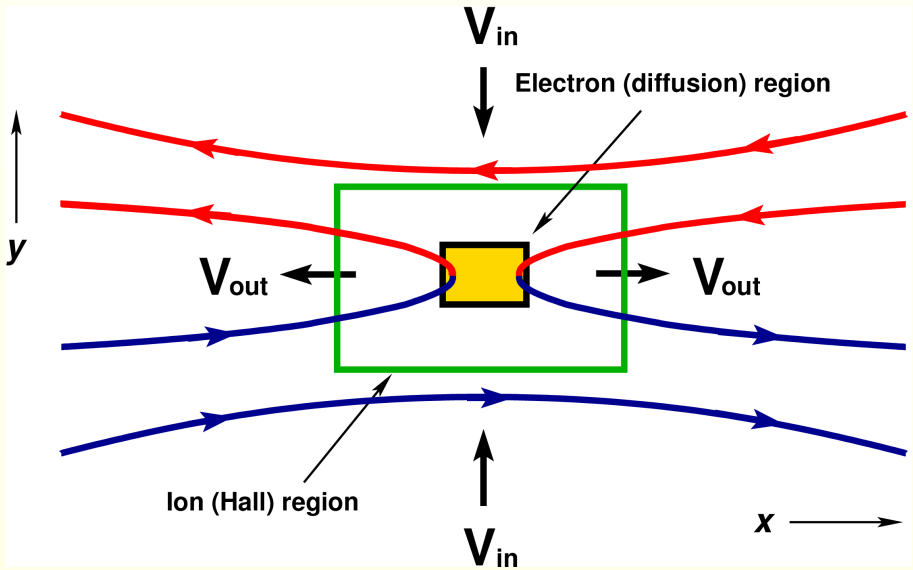
$$\mathbf{E} = -\frac{1}{c}\mathbf{V}_i \times \mathbf{B} + \overbrace{\frac{1}{nec}\mathbf{J} \times \mathbf{B}}^{Hall\ term}$$

- Physically, the Hall term decouples ion and electron motion on ion inertial length scales: $L \lesssim c/\omega_{pi}$

- Resistive (collisional) case

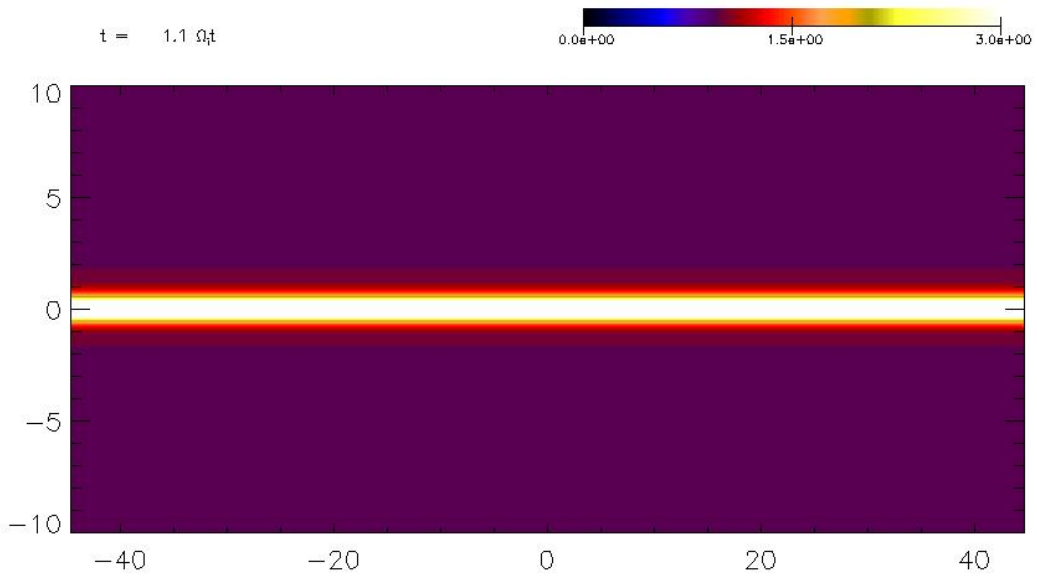


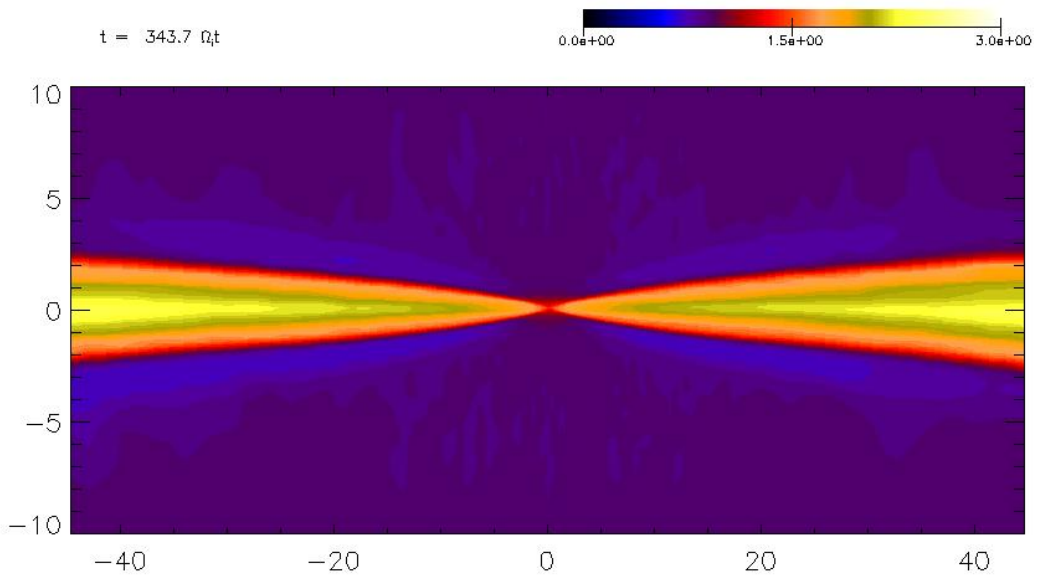
- Hall (collisionless) case



2D (STEADY STATE) HALL RECONNECTION

Density





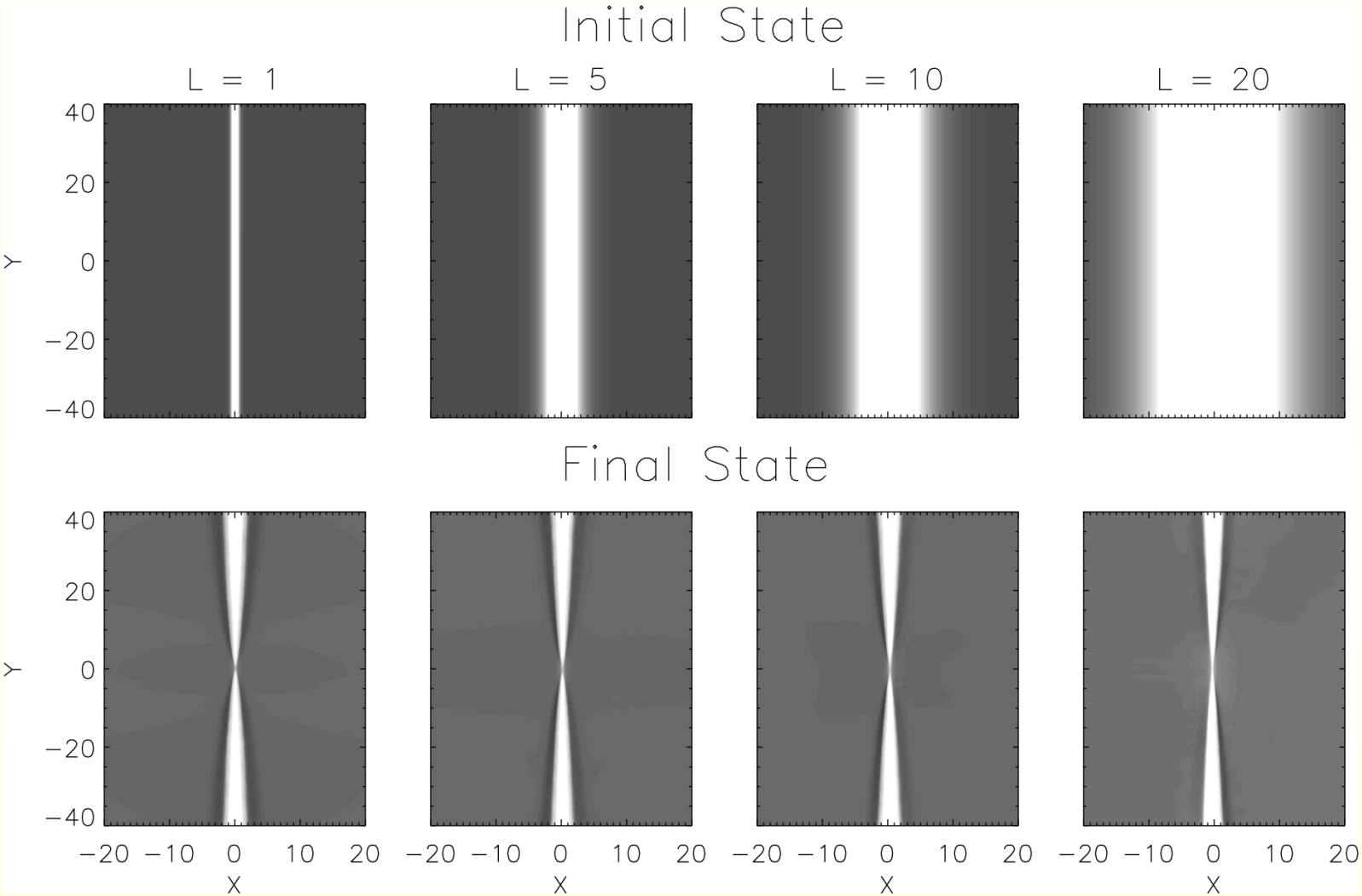
Vx

Vy

INITIAL/FINAL STATES

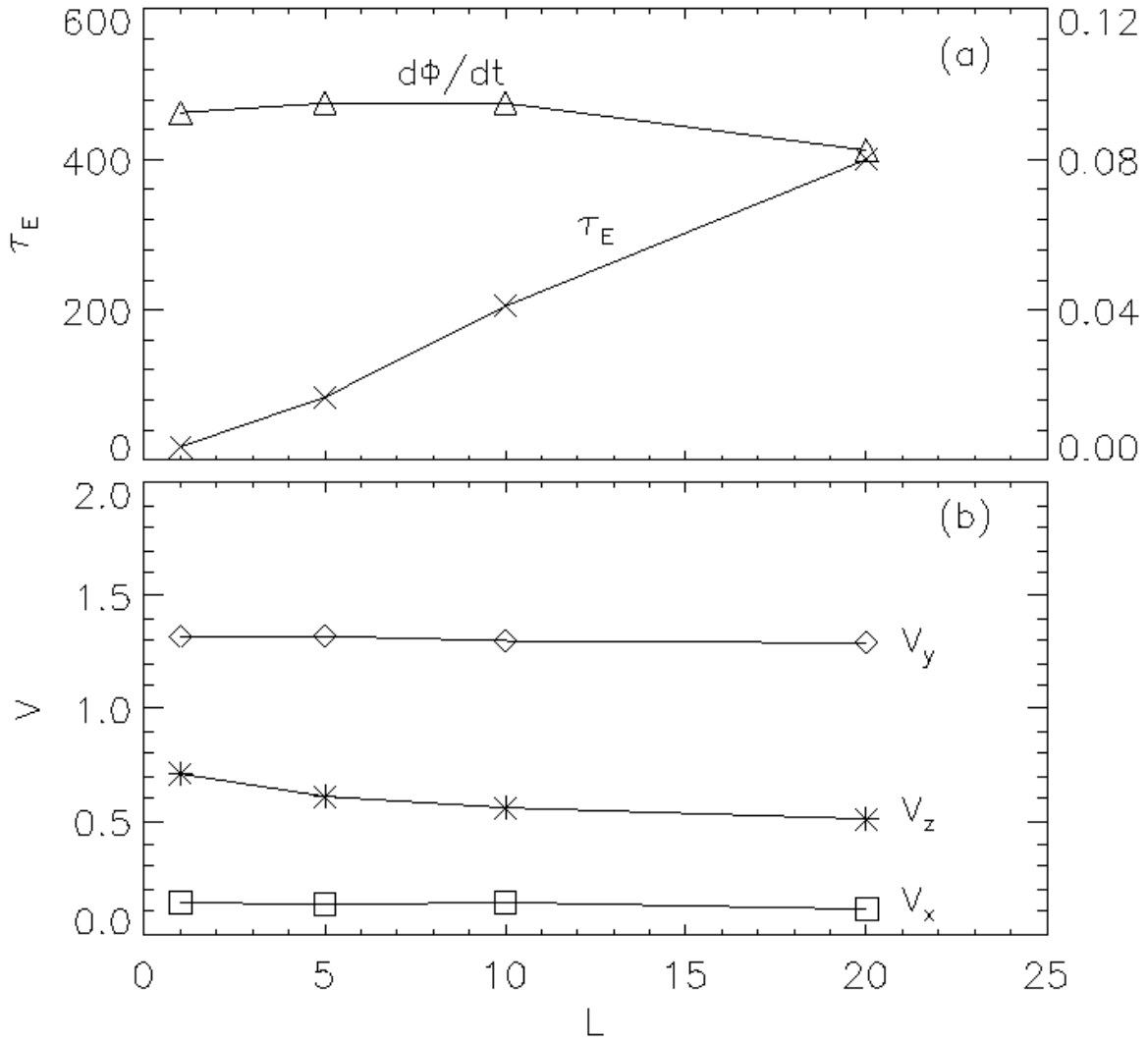
Dependence on Current Layer Width

Huba and Rudakov, *Phys. Rev. Lett. 93*, 175003, 2004.



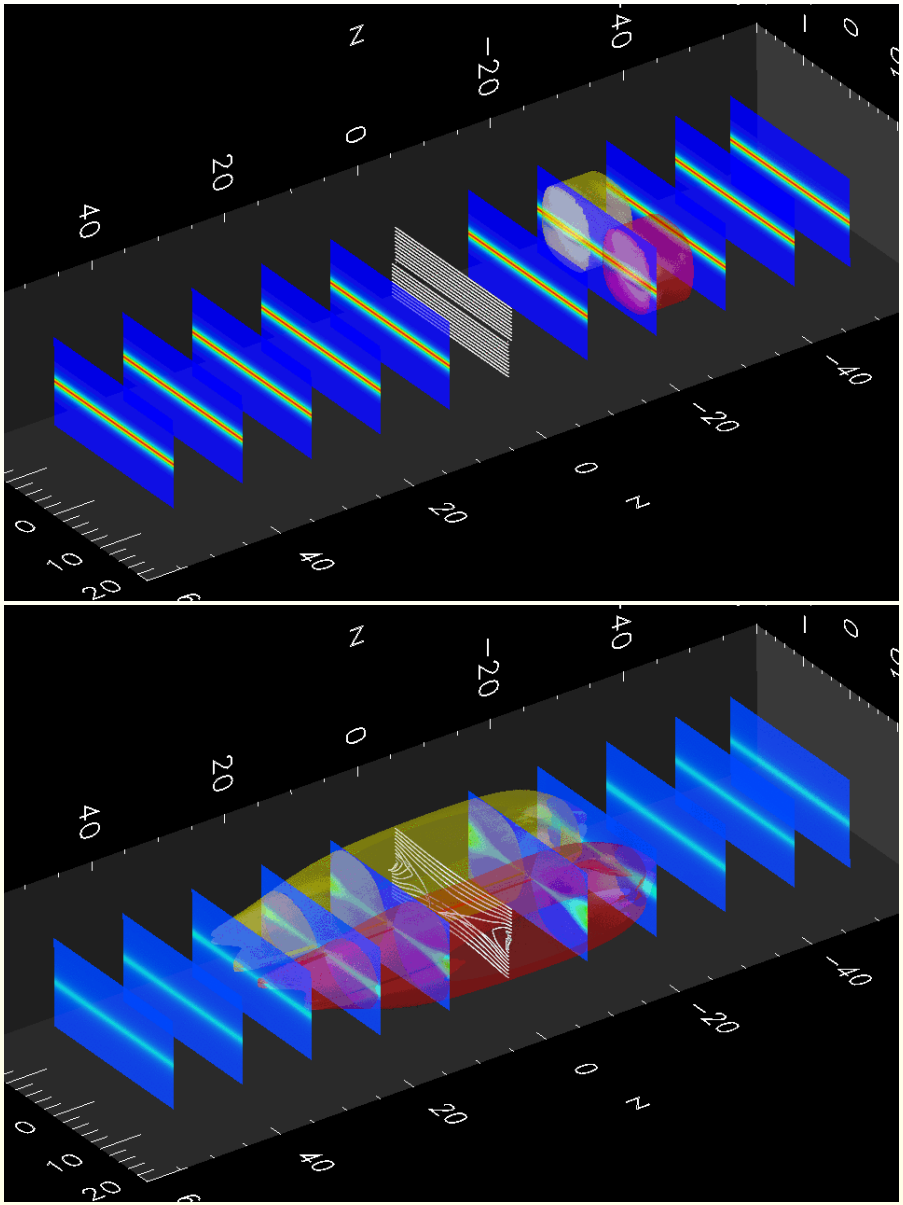
RECONNECTION RATE/ENERGIZATION TIME

Dependence on Current Layer Width



3D HALL RECONNECTION

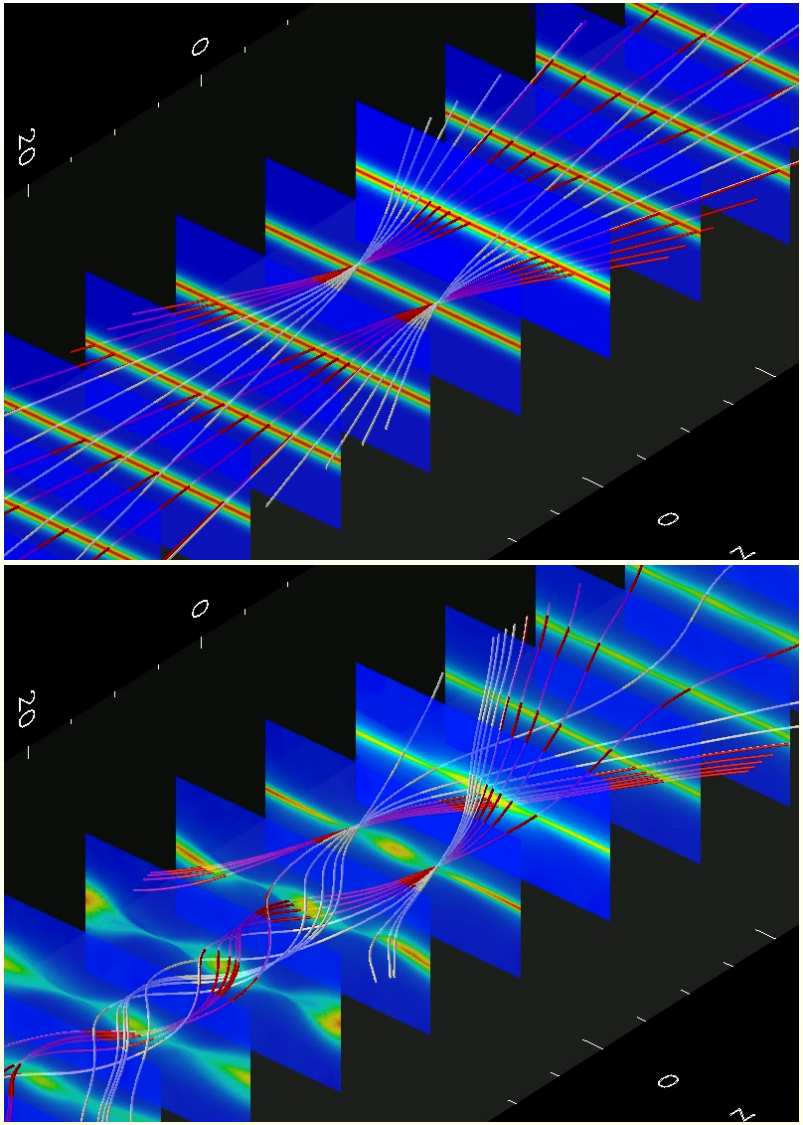
No Guide Field $B_{gf} = 0$



- Asymmetric propagation
- 'Reconnection wave'
  $\omega = k_z \frac{c}{4\pi e n} \frac{\partial B_0}{\partial y} = k_z V_B$
- Animation

3D HALL RECONNECTION

Guide Field $B_{gf} = B_0$

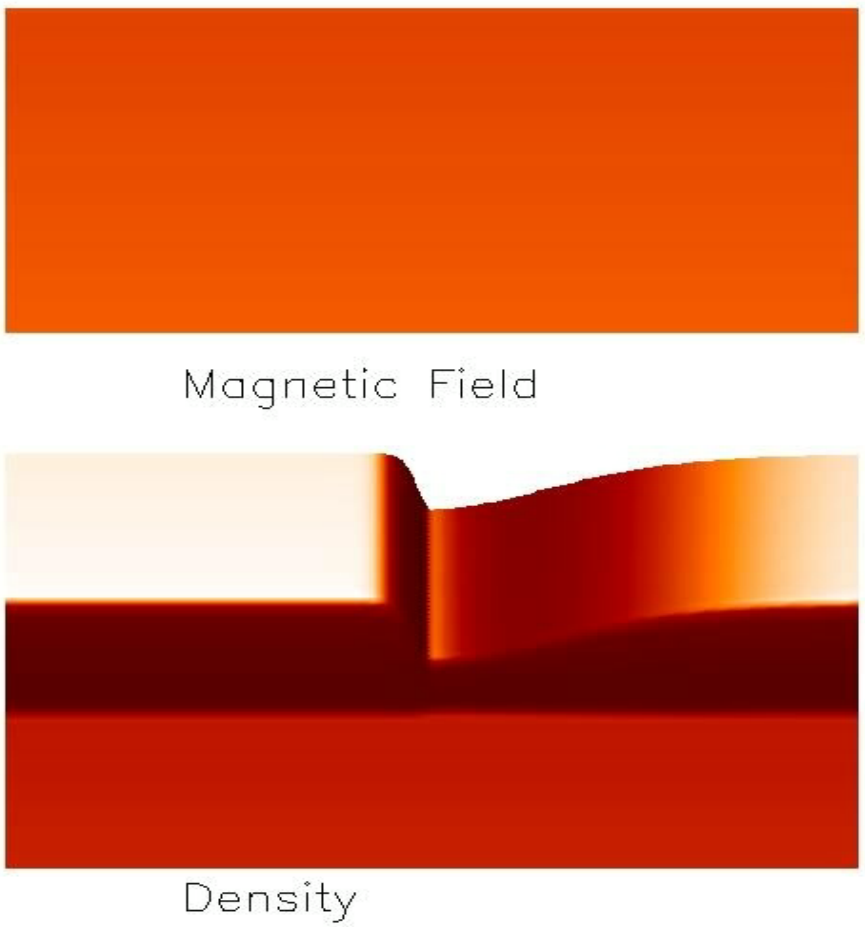


- Asymmetric propagation persists
- Animation

SUMMARY

- 2D
  - Steady state with 'open/floating' boundary conditions
  - Current layer collapses/expands to $L \sim c/\omega_{pi}$
  - Reconnection rate fast $\sim 0.1 V_A$
  - Forced reconnection (not discussed) problematic
  - Results 'at odds' with full particle simulations which show lengthening of X-line and breakup into islands
- 3D
  - Current layer collapses/expands to $L \sim c/\omega_{pi}$
  - Asymmetric behavior due to 'reconnection wave' (but frame dependent; depends on current carriers)
  - Reconnection rate fast $\sim 0.1 V_A$
  - Forced reconnection steady-state-like (preliminary)

STUPID HALL MHD TRICK

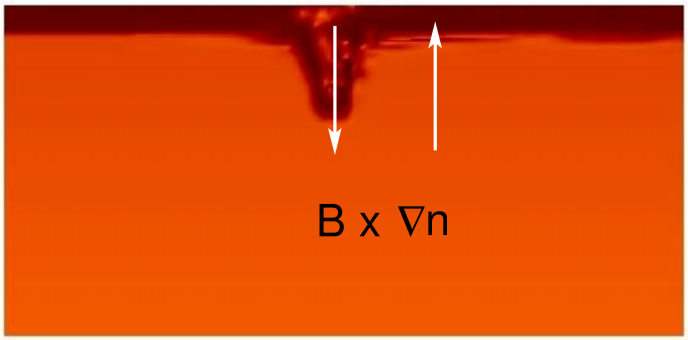


- Ideal MHD
- Hall MHD (EMHD)

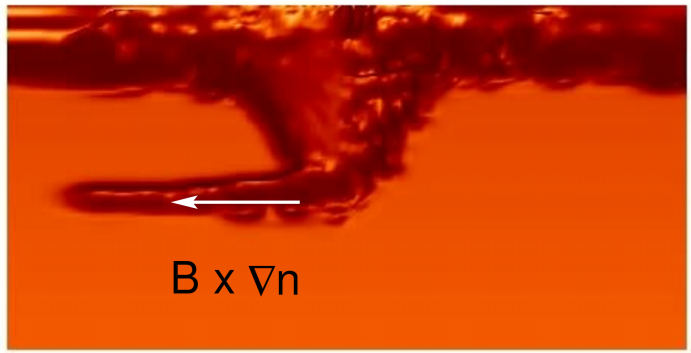
HALL MAGNETIC DRIFT WAVE (KMC)

Huba, *Phys. Fl. B*, 1991

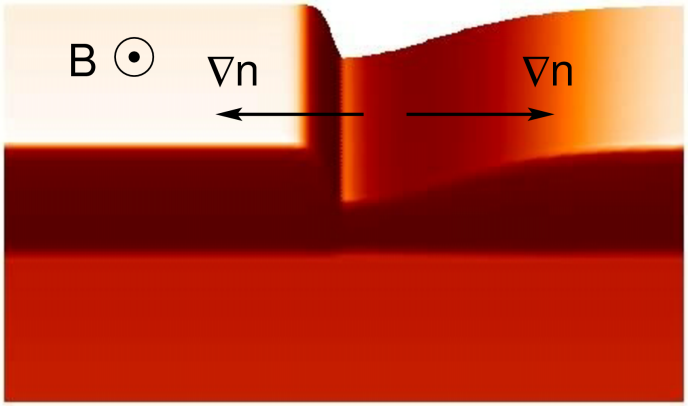
$$\omega = kV_A \left(\frac{c}{\omega_{pi}} \frac{1}{n} \frac{\partial n}{\partial x} \right)$$



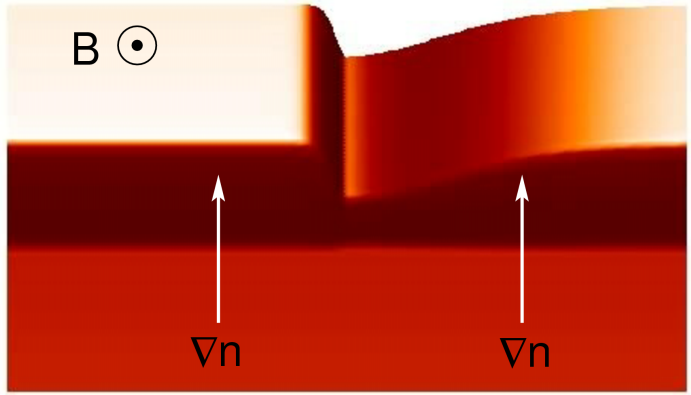
Magnetic Field



Magnetic Field



Density



Density

- Magnetic field evolution

$$\frac{\partial \mathbf{B}}{\partial t} = -c\nabla \times \mathbf{E} = \nabla \times [(\mathbf{V} + \mathbf{V}_B) \times \mathbf{B}] \quad \text{where } \mathbf{V}_B = -\mathbf{J}/ne$$

- Continuity

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{V} = 0$$

- Momentum

$$\frac{\partial \rho \mathbf{V}}{\partial t} + \nabla \cdot \left[\rho \mathbf{V}\mathbf{V} + (P + B^2/8\pi)\underline{\underline{\mathbf{I}}} - \mathbf{B}\mathbf{B}/4\pi\right] = 0$$

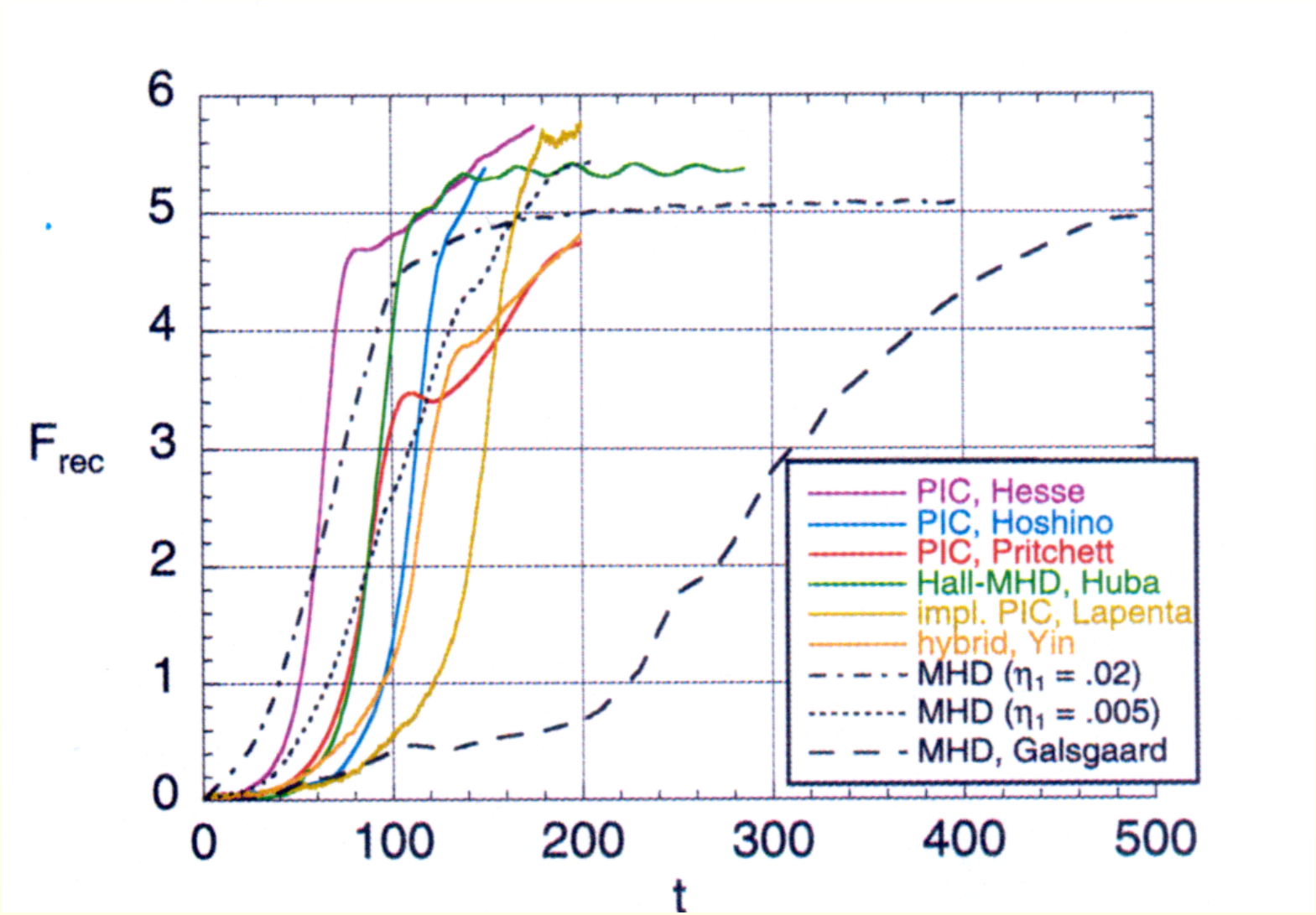
- Plasma Energy

$$\frac{\partial \epsilon}{\partial t} + \nabla \cdot [\mathbf{V}(\epsilon + \gamma P/(\gamma - 1))] = -\mathbf{J} \cdot \mathbf{E}$$

where $\epsilon = \rho V^2/2 + P/(\gamma - 1)$

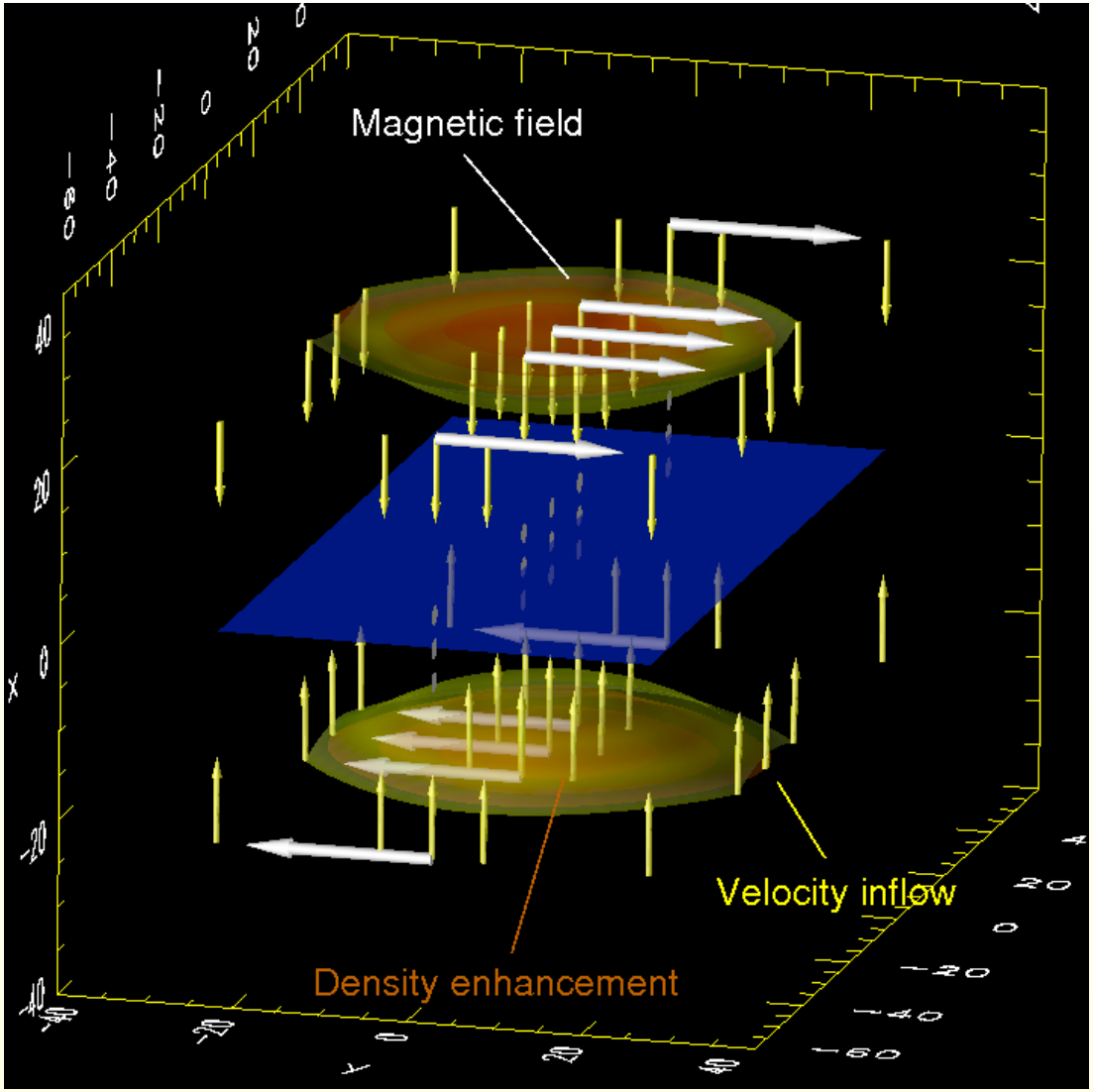
HALL MHD: FAST RECONNECTION

Newton Challenge (*Birn et al., GRL*, 2005)



3D FORCED RECONNECTION

No Guide Field $B_{gf} = 0$



3D FORCED RECONNECTION

Later in run