# Breaking field lines during reconnection: it's anomalous viscosity not anomalous resistivity


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# Collisionless reconnection is ubiquitous

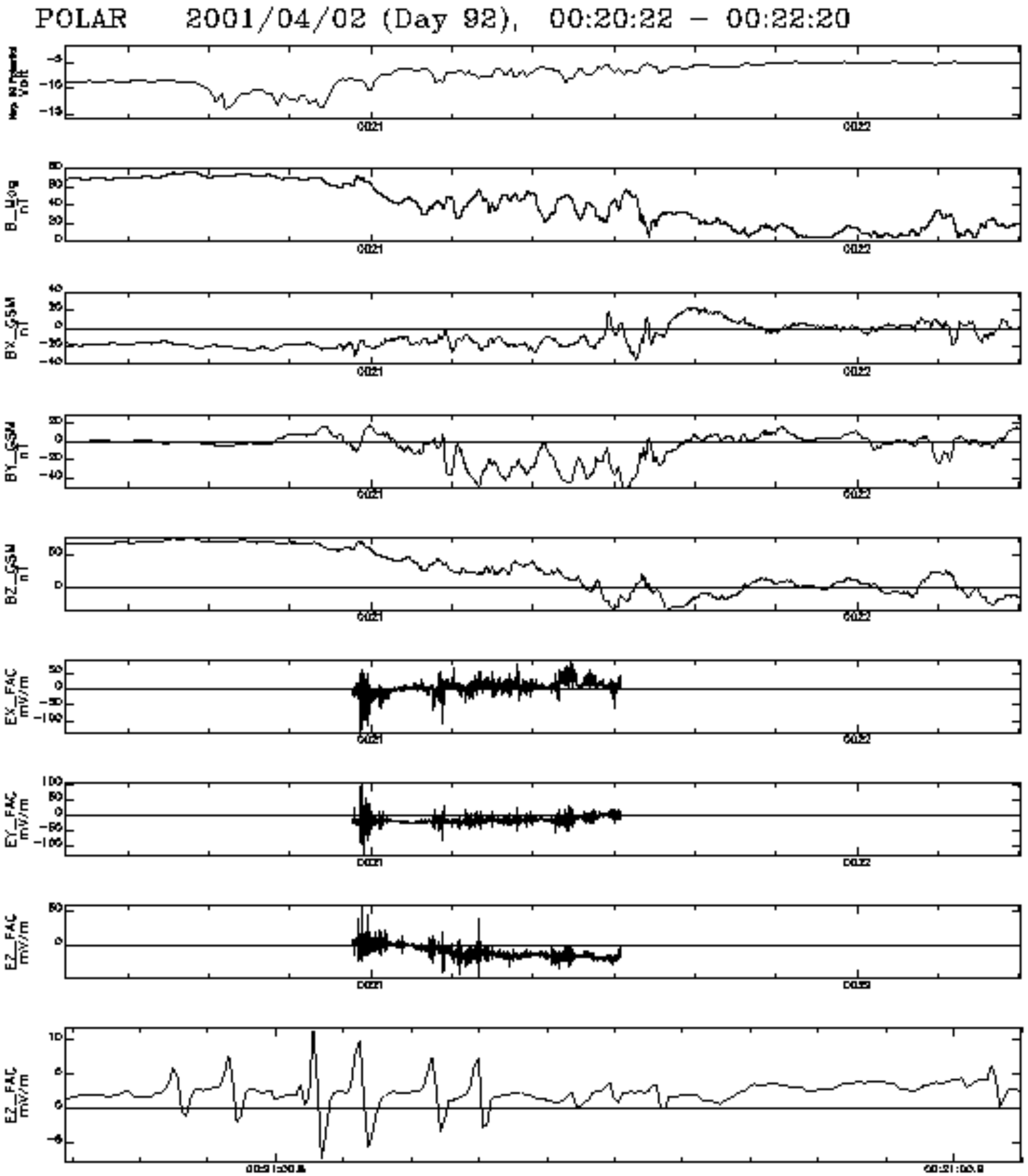
- Inductive electric fields typically exceed the Dreicer runaway field
  - classical collisions and resistivity not important
- Earth's magnetosphere
  - magnetopause
  - magnetotail
- Solar corona
  - solar flares
- Laboratory plasma
  - sawteeth

# What breaks magnetic field lines in collisionless reconnection?

- Electron momentum transport associated with thermal motion is often invoked to break magnetic field lines during reconnection
  - Described by the off-diagonal pressure tensor
- Some form of anomalous resistivity is also often invoked to break field lines
  - Strong electron-ion streaming near x-line drives turbulence and associated enhanced electron-ion drag
  - Observations reveal high frequency turbulence in the form of electron plasma waves, lower-hybrid waves, whistler waves and electron holes.
    - Their role in breaking field lines has not been established

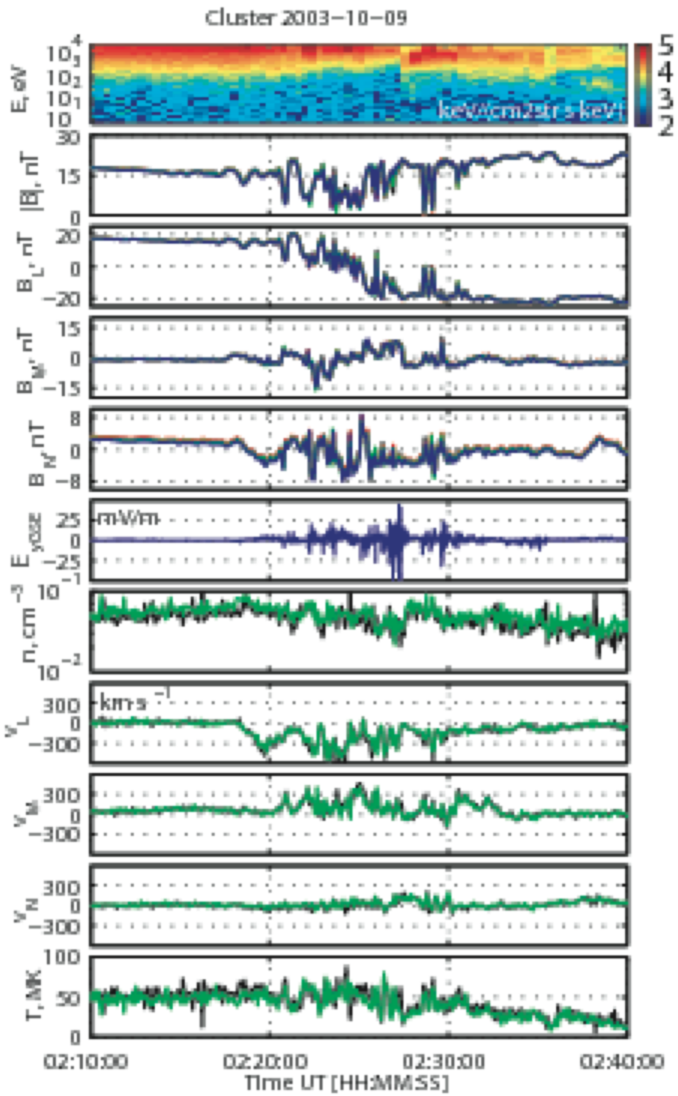
# Satellite observations of electron holes

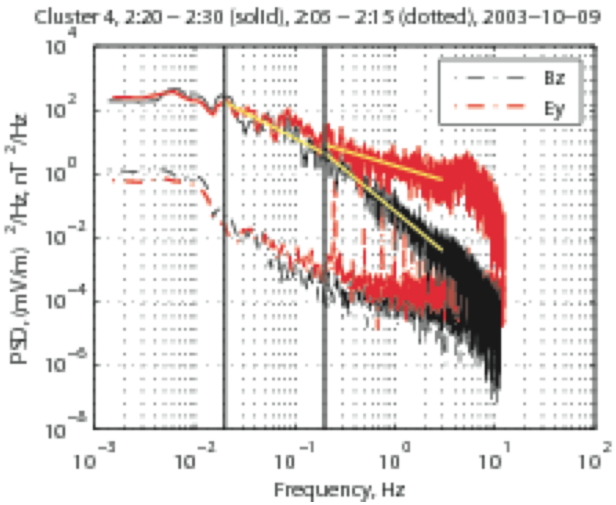
- Magnetopause observations from the Polar spacecraft (Cattell, et al., 2002)

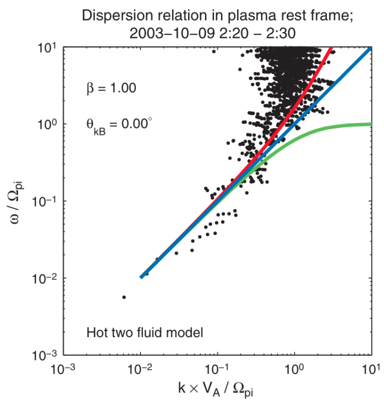


# Cluster turbulence observations

- Turbulence observations by Cluster in the ion diffusion region (Eastwood et al 2009)
  - Whistler-like spectrum
  - “the associated anomalous resistivity was not found to significantly modify the reconnection rate.”

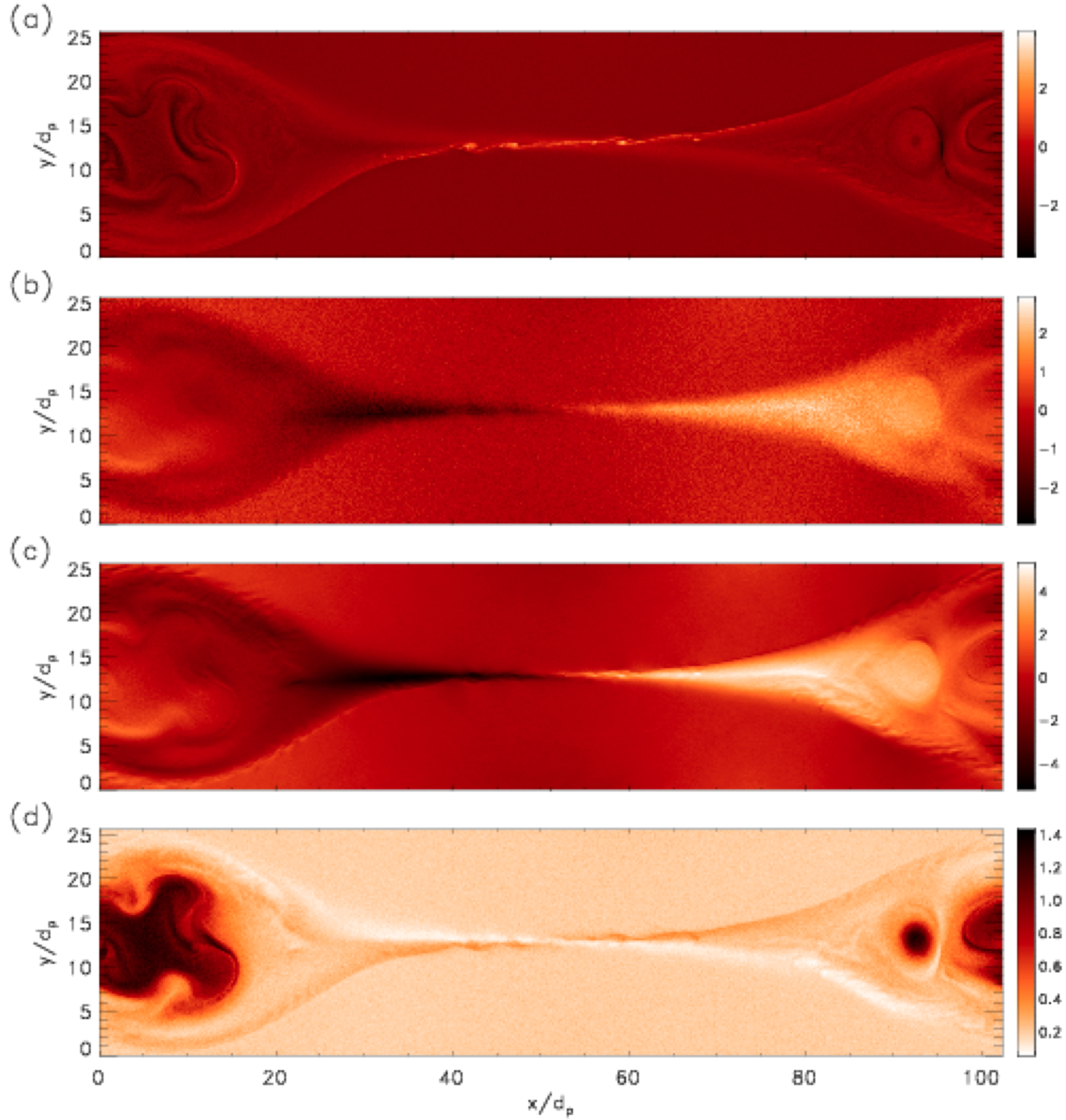


# 2-D Reconnection with guide field

- Guide field PIC simulation
  - $B_{0x}/B_{0z}$=0.5
  - Narrow tilted current layer
    - Width around $\rho_e$
    - Note structuring on electron current layer
  - Note deep density cavity



# Generalized Ohm's Law

- Electron momentum equation – z component

$$\frac{\partial p_{ez}}{\partial t} + \vec{\nabla} \bullet \vec{p}_e p_{ez} = -en_e E_z + \frac{1}{c}\left(\vec{j}_e \times \vec{B}\right)_z - \vec{\nabla} \bullet \vec{P}_{ez}$$

- Average over z direction

$$< E_z >= -\frac{1}{c}\left(< \vec{v}_e > \times < \vec{B}_\perp >\right)_z - \frac{\vec{\nabla} \bullet < \vec{P}_{ez} >}{< n_e > e} - \frac{m_e}{e}\left(\frac{\partial < v_{ez} >}{\partial t} + < \vec{v}_{e\perp} > \bullet \vec{\nabla}_\perp < v_{ez} >\right) + D_{ez} + \vec{\nabla} \bullet \vec{T}_{ez}$$

$$D_{ez} = \frac{1}{< n_e >} < \delta n_e \delta E_z >$$

$$\vec{T}_{ez} = -\frac{1}{< n_e > e} < \delta \vec{p}_{e\perp}\left(\delta v_{ez} + \frac{e}{m_e c}\delta A_z\right) >$$

Turbulent drag

Turbulent electron momentum transport

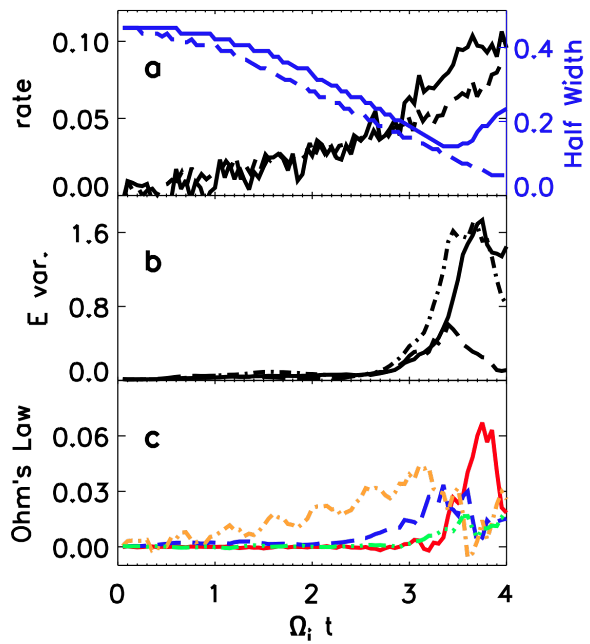
- In 2-D steady state at the x-line $$< E_z >= -\frac{\vec{\nabla} \bullet < \vec{P}_{ez} >}{< n_e > e}$$

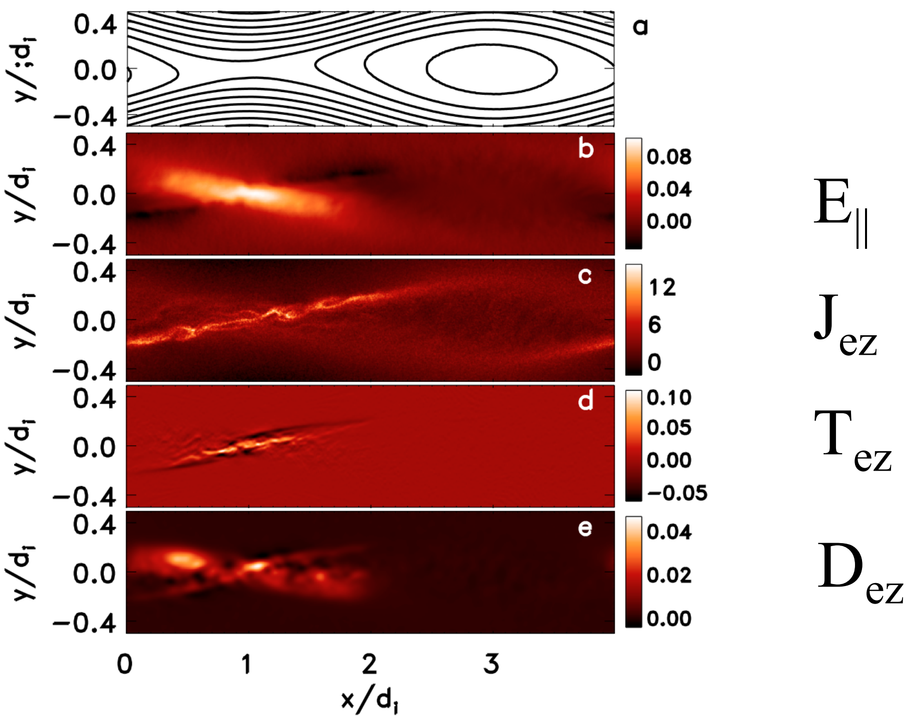
# 3-D Magnetic Reconnection

- Turbulence, anomalous resistivity and anomalous viscosity
  - self-generated gradients in pressure and current near x-line may drive turbulence
  - not present in 2-D models since requires wavenumber aligned along the direction of the out-of-plane current
- In a system with anti-parallel magnetic fields turbulence seems to play only a minor role
  - current layer near x-line is relatively stable
- Instabilities develop in the case of reconnection with a guide field in the low $\beta_e$ case
  - Islands can grow on other surfaces – not discussed
  - Strong electron streaming near x-line leads to current-driven Buneman and lower-hybrid instabilities and evolve into a nonlinear state with strong localized electric fields -- "electron-holes"
    - Modest anomalous resistivity but does not stop electron runaway – hard to resonate with all electrons
  - Electron current layer continues to narrow until an current gradient driven instability completely breaks up the current layer
    - Anomalous viscosity balances the reconnection electric field and boosts the rate of reconnection

# 3-D Magnetic Reconnection: with guide field

- Particle simulation with $L_x \times L_y \times L_z = 4d_i \times 2d_i \times 8d_i$
- $B_z = 5.0\, B_x$, $m_i/m_e = 100$, $T_e = T_i = 0.04$, $n_i = n_e = 1.0$
  - No turbulence for $T_e = T_i = 0.16$
- Development of current layer with electron parallel drift exceeding the initial thermal speed

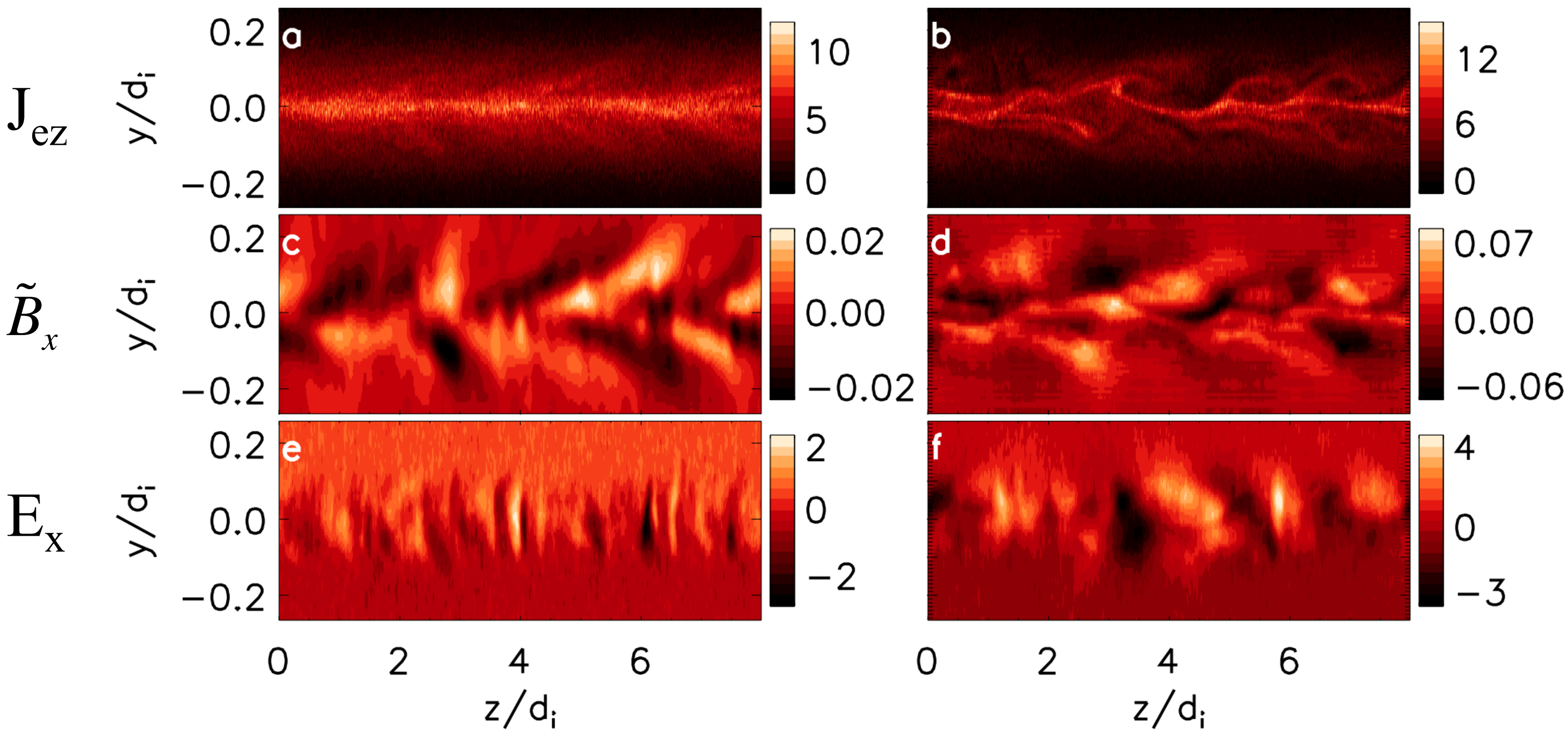


# Onset of electromagnetic instability

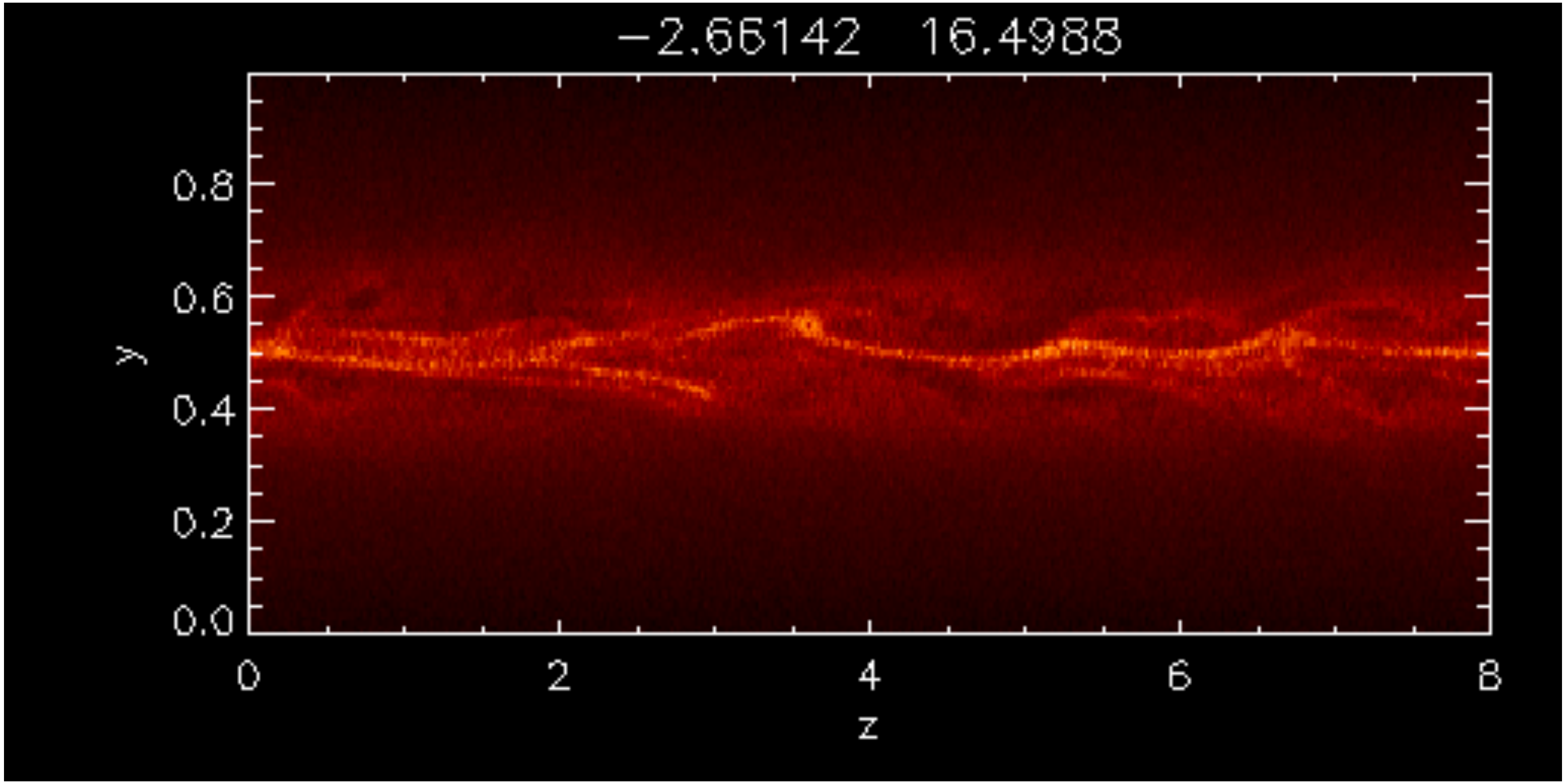
- The electromagnetic instability onsets sharply around $\Omega_i t \sim 3.25$
- Abrupt decrease in parallel wavelength and increase in magnetic perturbations

$B_z \rightarrow$



# Evolution of current layer

- $J_{ez}$ versus time in a cut along and across the current layer



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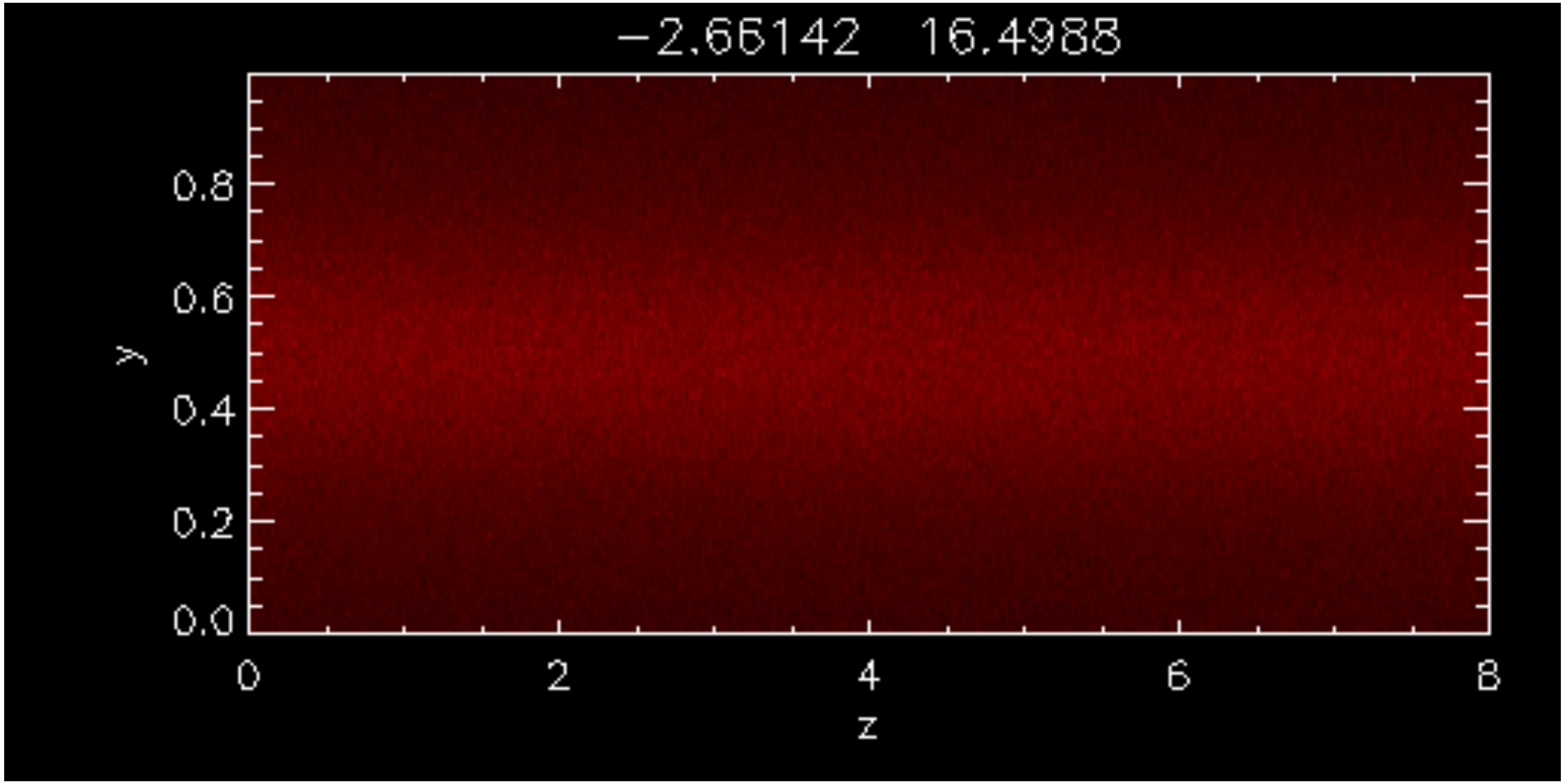
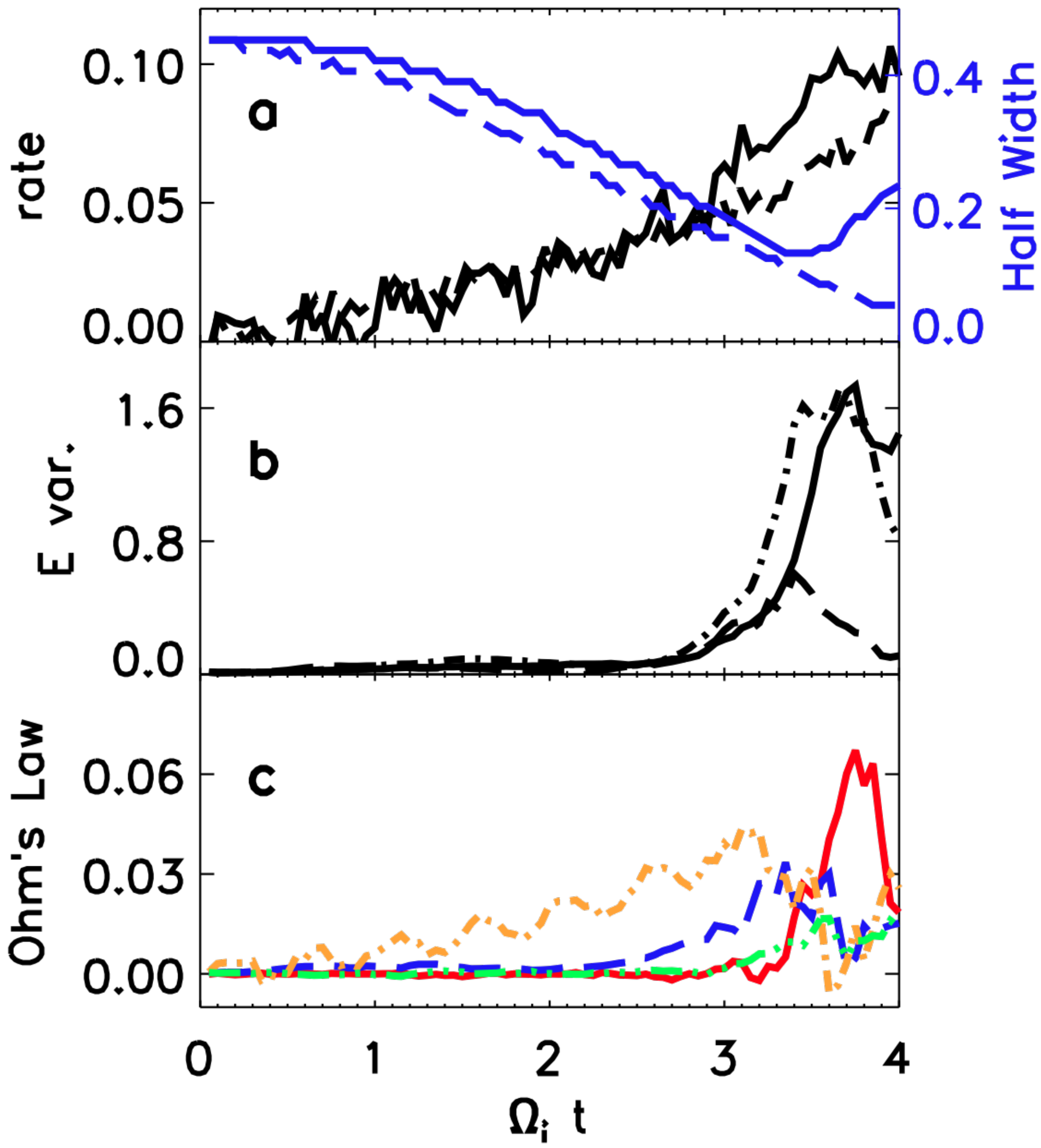


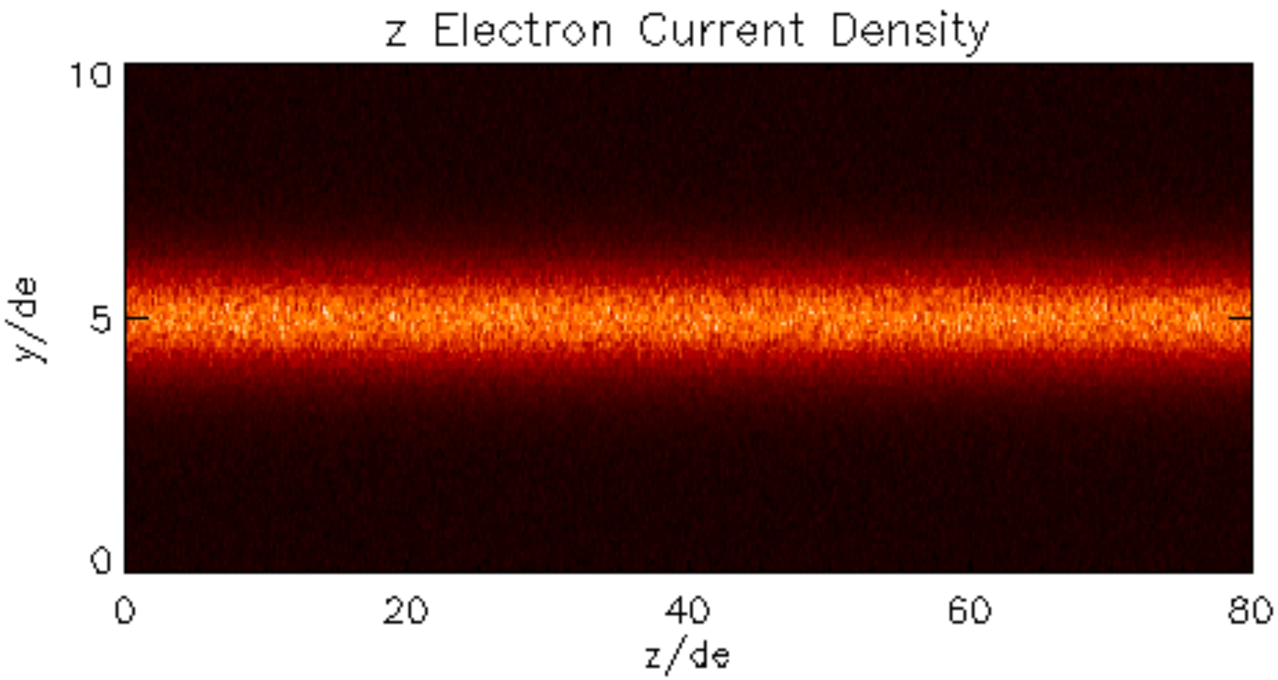
# Evolution of Ohm's law

- Dominant terms
  - Electron inertia
    - Early
  - Electron-ion drag
    - Intermediate
  - Momentum transport
    - late



# What is the instability drive?

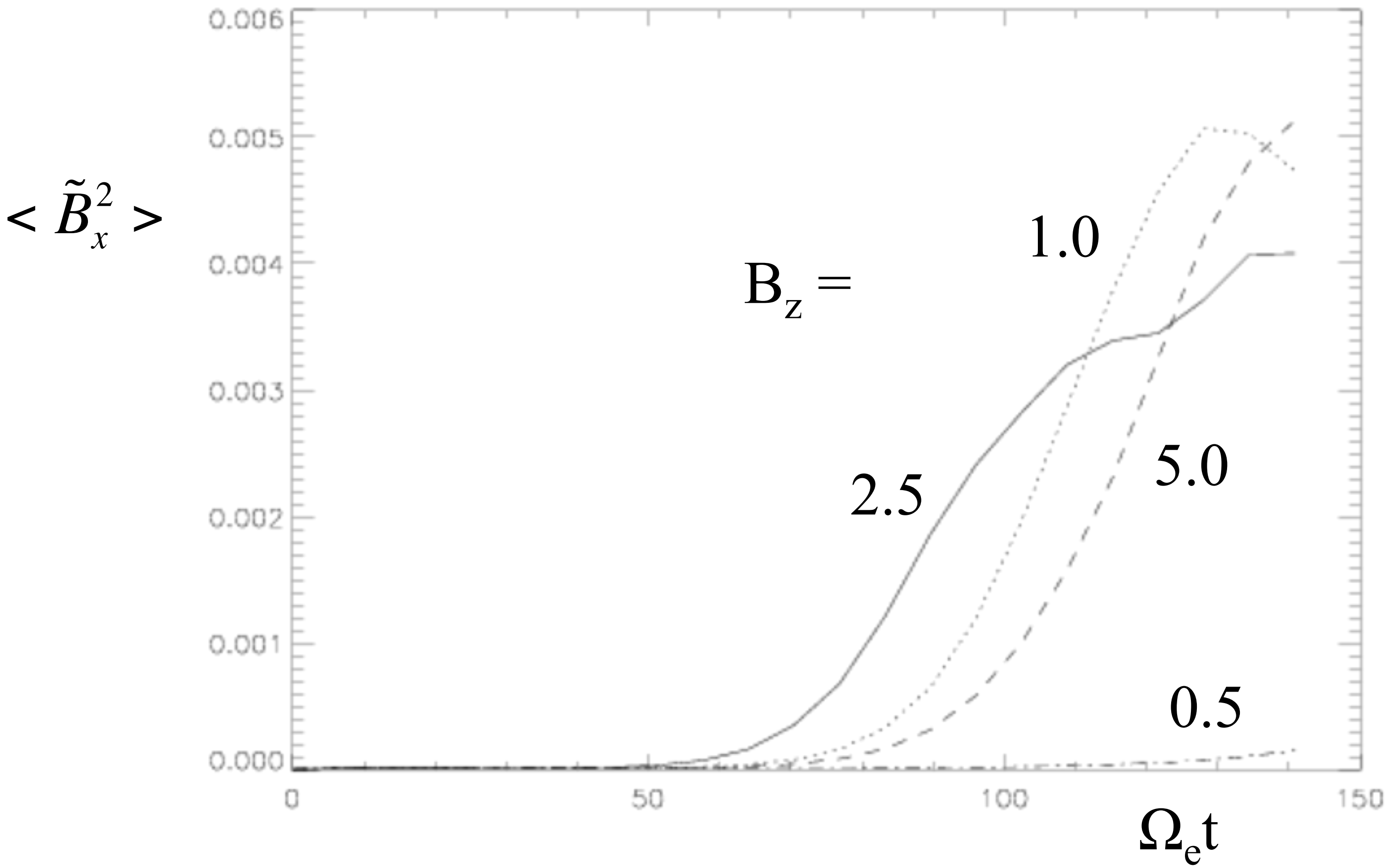
- Broadening of electron current profile suggests that it is an electron shear-flow instability
  - Role of ions? Dependence on the strength of the guide field $B_z$?
- 3-D PIC simulations of a thin electron current sheet with uniform density
  - Initial with of current layer an electron skin depth
  - Various mass-ratios $m_i/m_e$ and guide field $B_z$




$m_i = \infty$
$B_z = 2.5$

# Dependence of sheared flow instability on the guide field

- Time dependence of magnetic fluctuations
  - No instability for weak guide field
  - $k_x > k_z$



# Linearize the electron-MHD equations

- The electron-MHD equations describe the dynamics of electrons and magnetic fields at small spatial scales where ions dynamics can be neglected (Drake et al 1994; Ferraro and Rogers 2004).

$$\frac{\partial}{\partial t} P\vec{B} = \frac{1}{ne}\vec{\nabla} \times \left(\left(P\vec{B}\right) \times \vec{J}\right) \qquad P = 1 - d_e^2 \nabla^2$$

- Consider initial state with $J_{0z}(y)$ with magnetic field $\vec{B}_0 = B_{0z}\hat{z} + B_{0x}\hat{x}$ and perturbations with $\vec{k} = k_z\hat{z} + k_x\hat{x}$

# Local dispersion relation

- Consider local region with $J_{0z}$ and $dJ_{0z}/dy$

$$\bar{\gamma}\left(\bar{\gamma} - \frac{ik_z v_{ez}}{P_k}\right) = \Omega_{ez}^2 \frac{k_z d_e^2}{P_k^2}\left(-k_z k^2 d_e^2 + P_k \frac{k_x J_{ez}'}{ne\Omega_{ez}}\right) \qquad P_k = 1 + k^2 d_e^2$$

- Define $\varepsilon = (dv_{ez}/dy)/\Omega_e << 1$
- Growth rate scales like

$$\gamma = \Omega_e k d_e \sqrt{\frac{\varepsilon}{2}} \qquad k d_e < \varepsilon^{1/2} \qquad\qquad k_z < k_x$$

$$\gamma = \frac{1}{2} v_{ez}' \qquad k d_e > \varepsilon^{1/2}$$

- Stable for small $B_{0z}$

# Conclusions

- Turbulence is driven by the electron current during low-$\beta_e$ reconnection with a guide field
- Current driven instabilities such as Buneman or the lower-hybrid instability (not LHD) develop and produce anomalous resistivity and electron heating but do not stop the electrons from running away
  - Can't resonate with all electrons in the distribution
- The continued thinning of the current layer continues until an electromagnetic electron sheared-flow instability (right-hand polarized) breaks up the current layer
  - The resulting anomalous momentum transport is sufficient to balance the reconnection electric field
  - The rate of reconnection undergoes a modest jump as the shear-flow instability onsets

# Conclusions (cont.)

- 3-D simulations of a narrow electron current layer reveal that the instability remains robust for $B_{0z} >> B_{0x}$ but is stabilized for small $B_{0z}$.
  - Ions role seems not very important
- Linearization of the electron-MHD equations yields an electromagnetic instability which has characteristics matching what is seen in the simulations
- Many significant questions remain
  - What is the $\beta_e$ threshold?
  - What is the minimum guide field for the instability?
  - Non-local dispersion relation?