Dynamics and Particle Acceleration during Magnetic Reconnection

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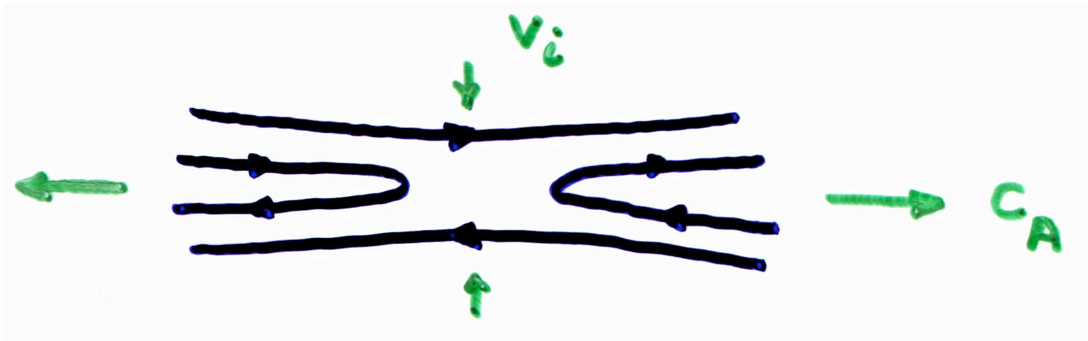
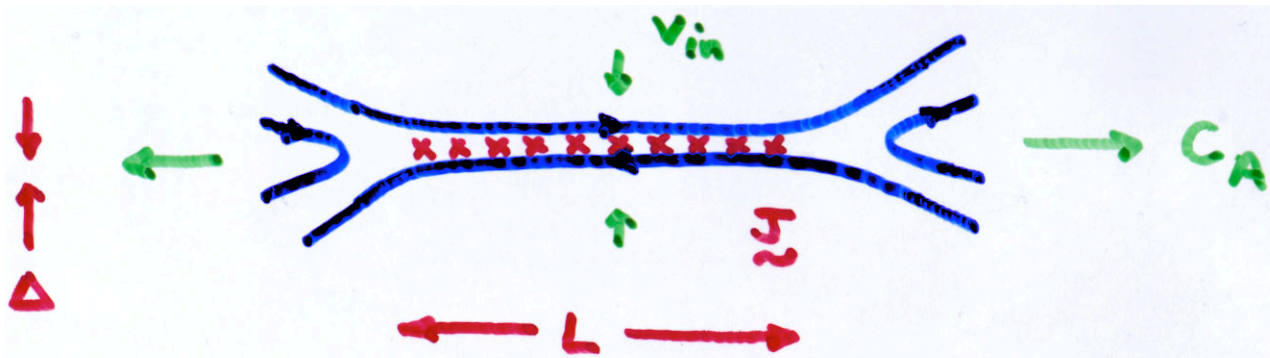
Magnetic Reconnection



- Energy release from newly reconnected magnetic field lines drives reconnection
- How newly reconnected field lines drive flow away from the x-line controls key properties of reconnection
  – Dependence on dissipation
  – Scaling of reconnection rate in large systems
- At small spatial scales Alfvenic dynamics no longer drives outflow
  – Whistler and kinetic Alfven dynamics
  – Dramatic impact on reconnection geometry

Resistive MHD Description



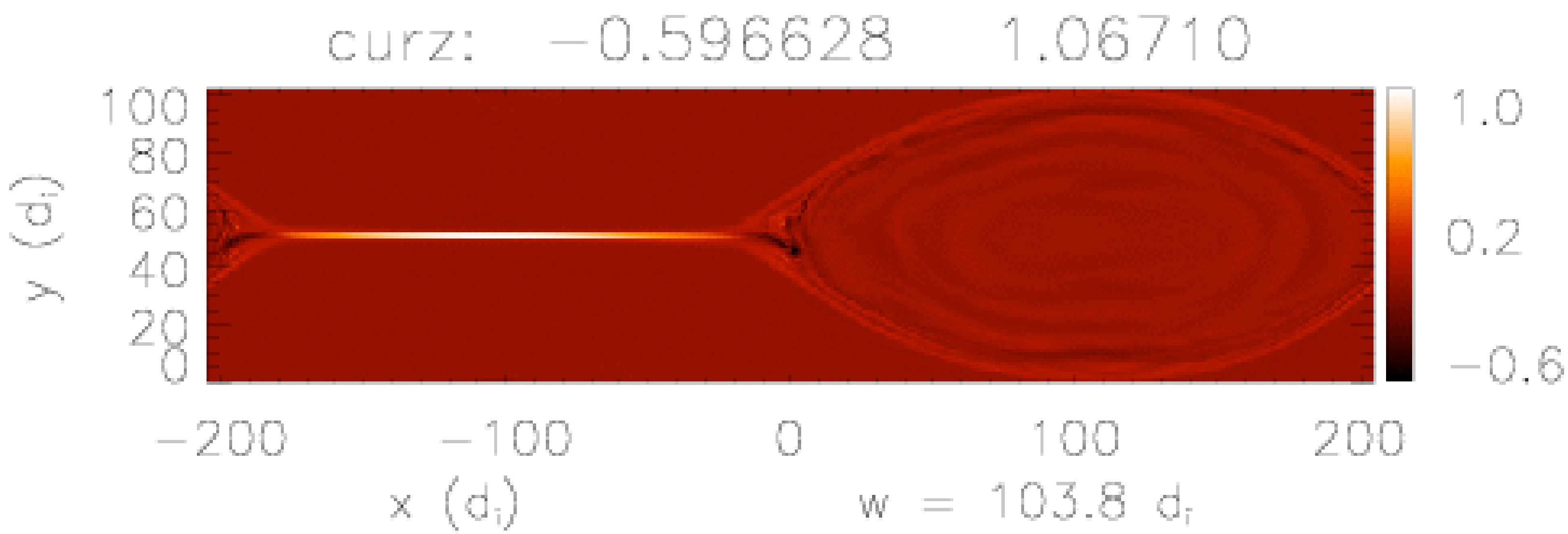
- Formation of macroscopic Sweet-Parker layer

$$V \sim (\quad /L)\, C_A \sim (\quad_A/\quad_r)^{1/2}\, C_A \ll C_A$$

•Slow reconnection
•sensitive to resistivity
•macroscopic nozzle

- Petschek-like open outflow configuration does not appear in resistive MHD models with constant resistivity (Biskamp ‘86)

Resistive MHD Solution



- Slow reconnection due to nozzle produced by Sweet-Parker current layer
  - Biskamp, 1986

Hall Reconnection

- MHD model breaks down in the dissipation region at small spatial scales where electron and ion motion decouple
- Coupling to dispersive waves at small scales produces fast magnetic reconnection
  - rate of reconnection independent of the mechanism which breaks the frozen-in condition.
  - fast reconnection even for very large systems
    - no macroscopic nozzle.
    - no dependence on inertial scales
- Key signatures of Hall reconnection have been measured by magnetospheric satellites and laboratory experiments

Generalized Ohm's Law

- Electron equation of motion

$$\frac{4}{{}^{2}_{pe}}\frac{d\vec{J}}{dt} = \vec{E} + \frac{1}{c}\vec{v}_i \quad \vec{B} \quad \frac{1}{nec}\vec{J} \quad \vec{B} + \frac{1}{ne} \quad \vec{\vec{p}}_e \quad \vec{J}$$

c/ $_{pe}$ — Electron inertia

c/ $_{pi}$ — whistler waves

$_s$ — kinetic Alfven waves

scales

•MHD valid at large scales

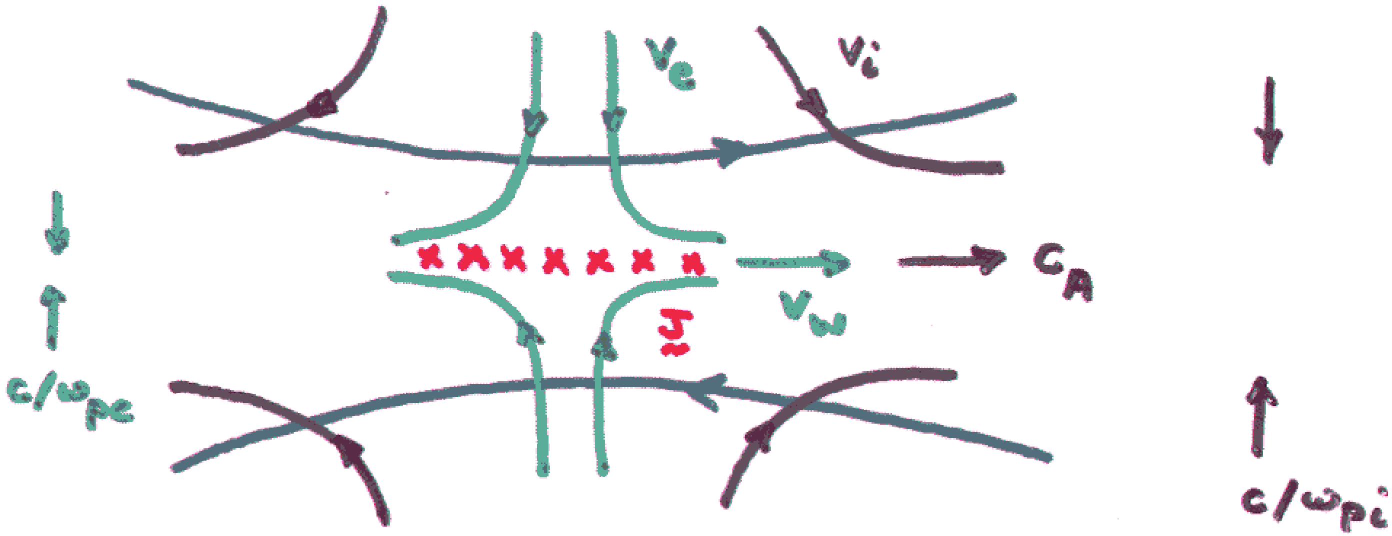
•Below c/ $_{pi}$ or $_s$ electron and ion motion decouple

•electrons frozen-in

•whistler and kinetic Alfven waves control dynamics

•Electron frozen-in condition broken below c/ $_{pe}$

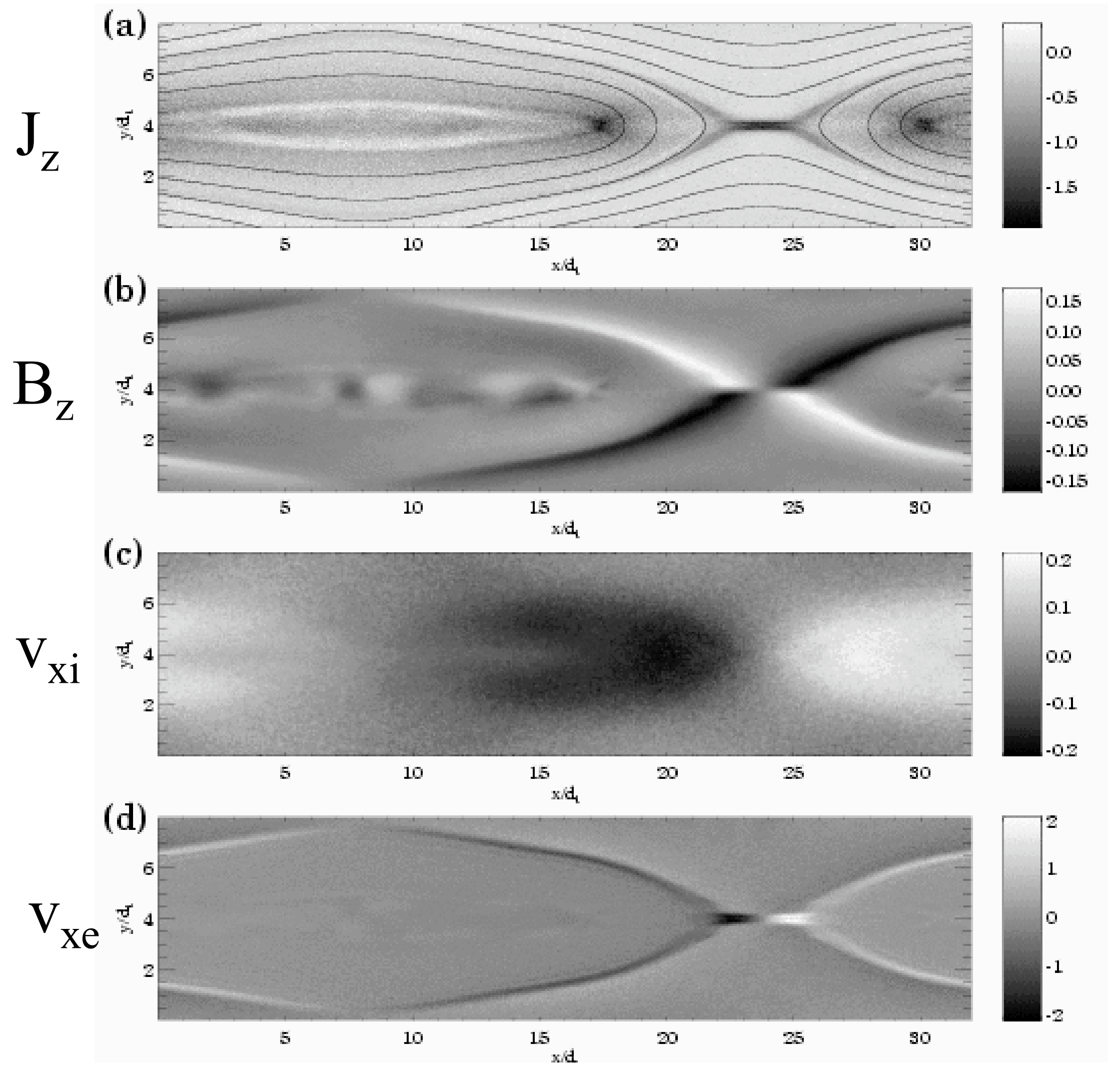
Hall Reconnection



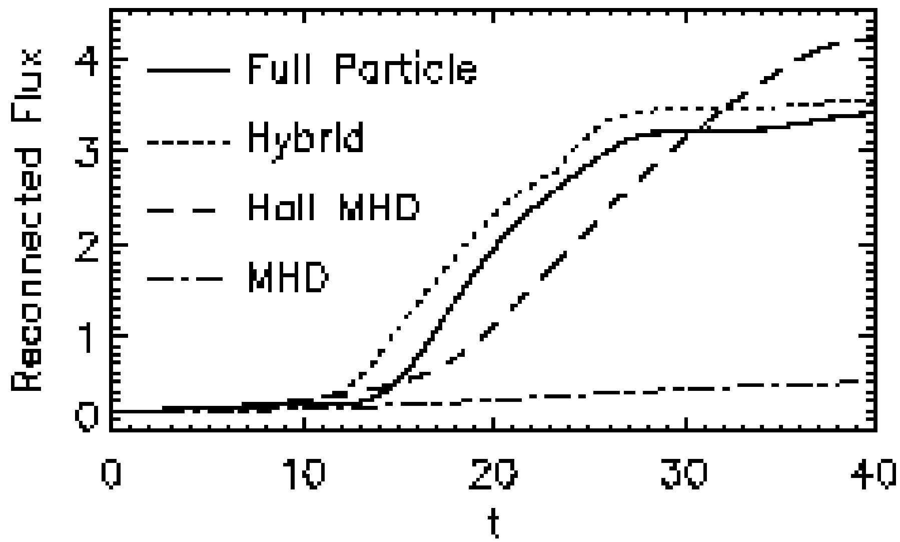
- Ion motion decouples from that of the electrons at a distance c/ω_{pi} from the x-line
  - Whistler dynamics drives outflow from x-line
- Electron velocity from x-line limited by peak speed of whistler, the electron Alfven speed, c_{Ae}.
- No large-scale Sweet-Parker current layer.

Reconnection Structure: anti-parallel case

- PIC simulation
- m_i/m_e=100



GEM Reconnection Challenge

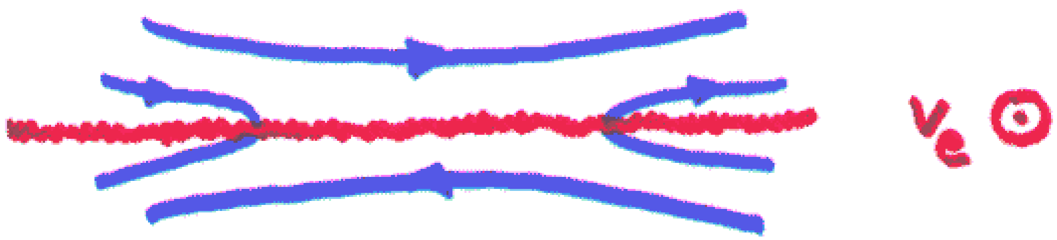


Birn, et al., 2001

- Rate of reconnection is the slope of the versus t curve
- all models which include the Hall term in Ohm's law yield essentially identical rates of reconnection
  - Rate of reconnection independent of the mechanism that breaks the frozen-in condition. Why?
- MHD reconnection is too slow by orders of magnitude

Whistler Driven Reconnection

- At spatial scales below c/ $_{pi}$ whistler waves rather than Alfven waves drive reconnection

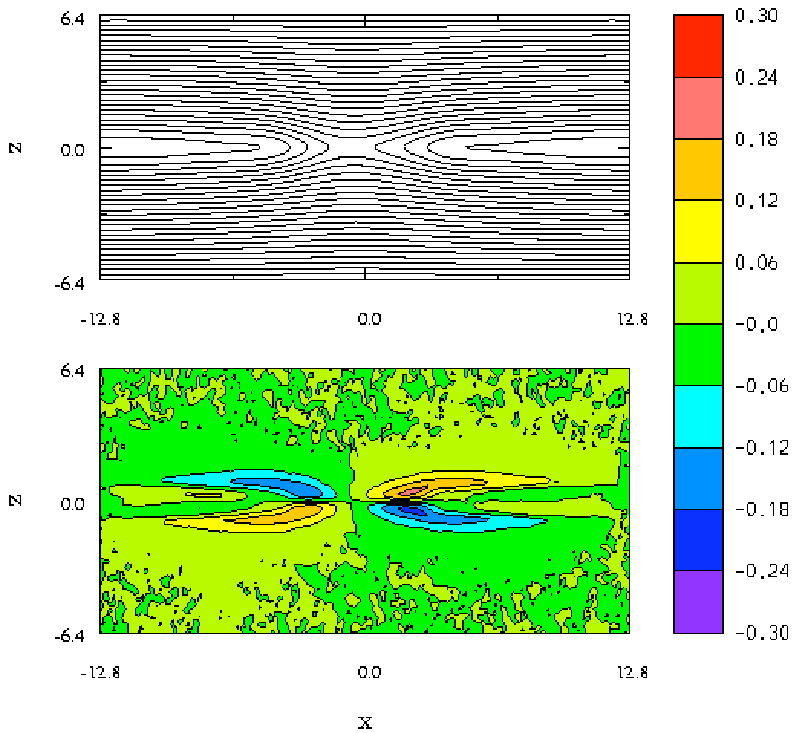


•Side view

•Whistler signature is out-of-plane magnetic field

Whistler signature

- Magnetic field from particle simulation (Pritchett, UCLA)



•Self generated out-of-plane field is whistler signature

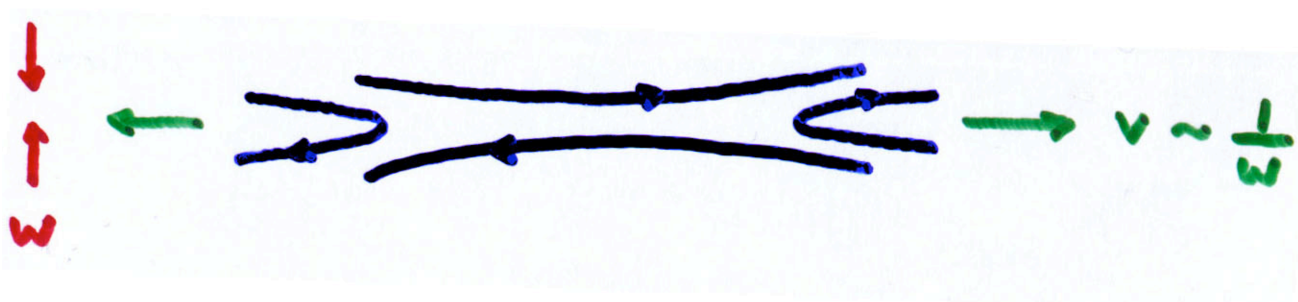
Why is wave dispersion important for the reconnection rate?

- Quadratic dispersion character

$$\sim \mathbf{k}^2$$

$$v_p \sim \mathbf{k}$$

  - smaller scales have higher velocities
  - weaker dissipation leads to higher outflow speeds

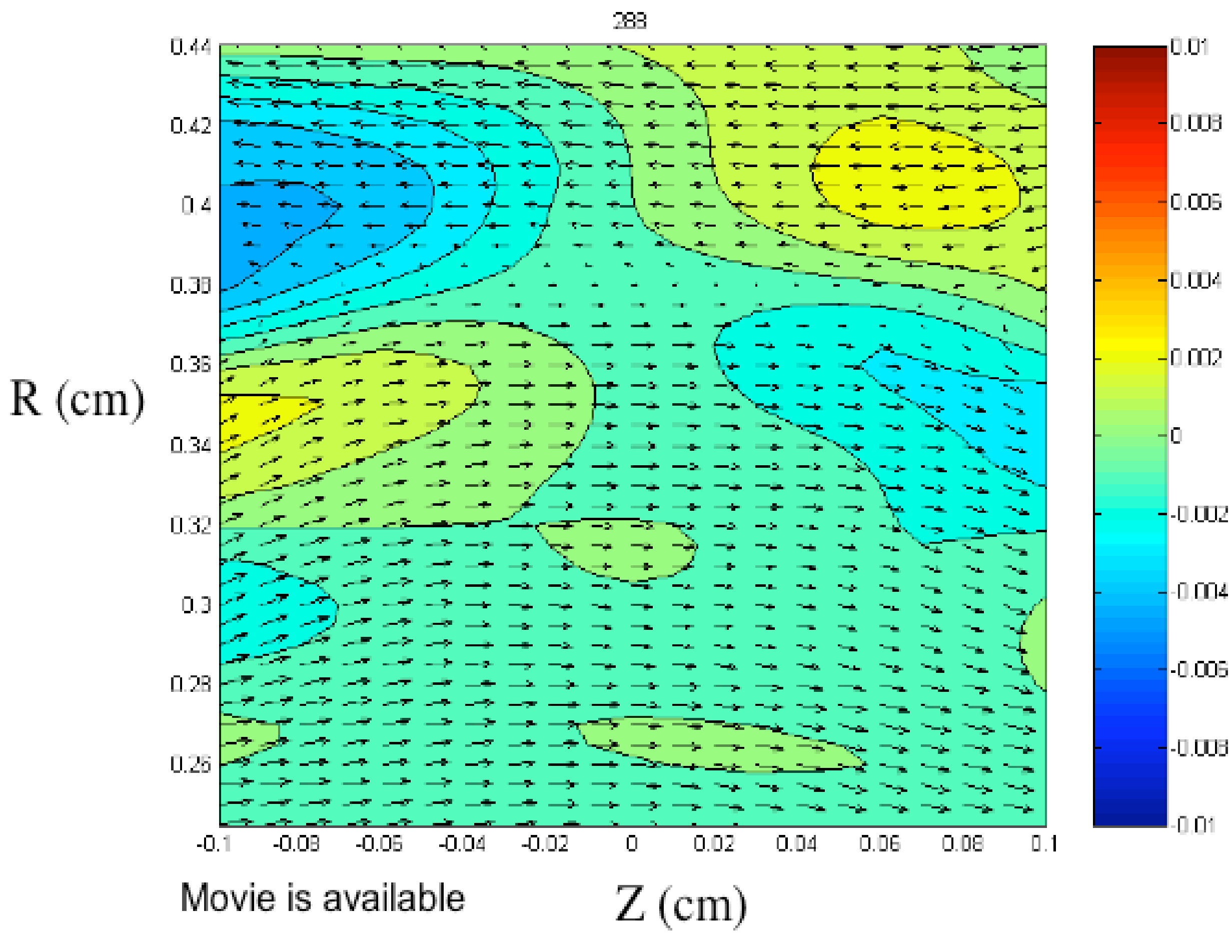


» Flux insensitive to dissipation

» Reconnection rate insensitive to dissipation

Whistler signature: MRX magnetic field data

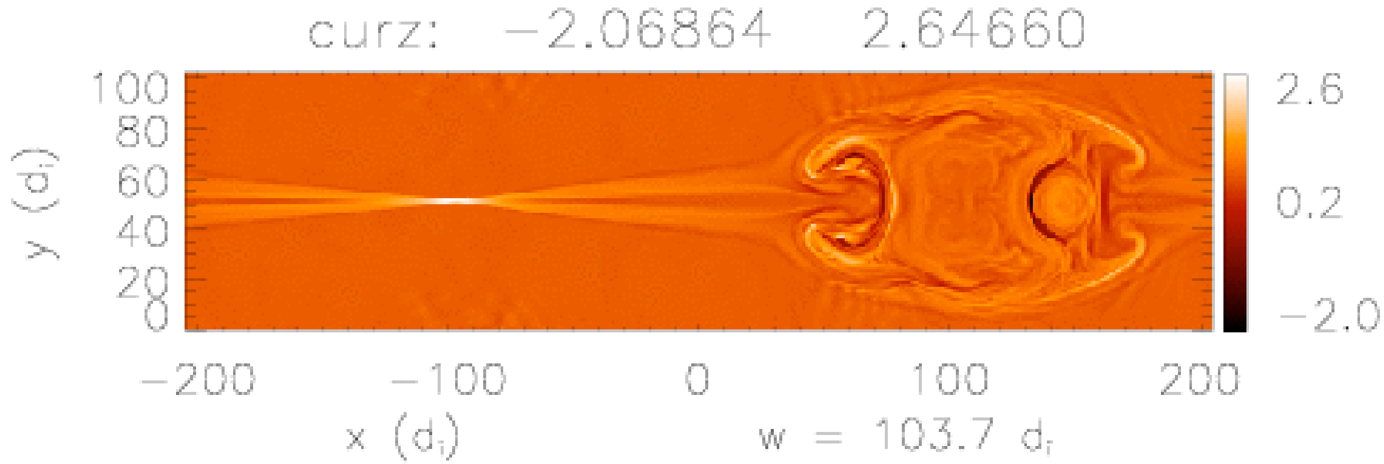
- Reconnecting field - arrows
- Self-generated out-of-plane field - colors
  - Quadrupole signature (Ren, et al., 2005)



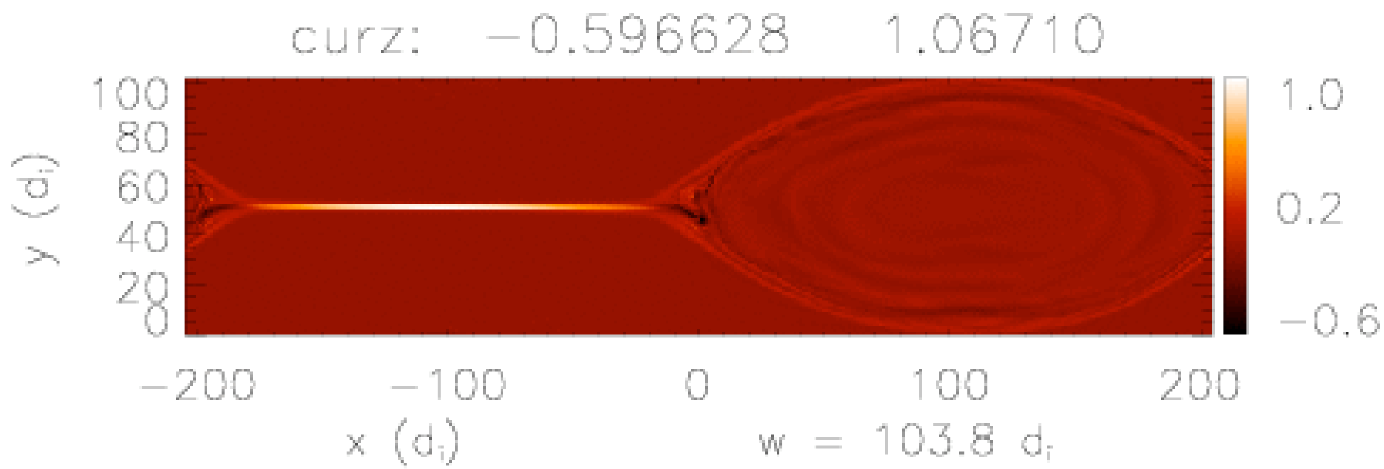
Movie is available

Reconnection in large systems (no guide field)

Hall



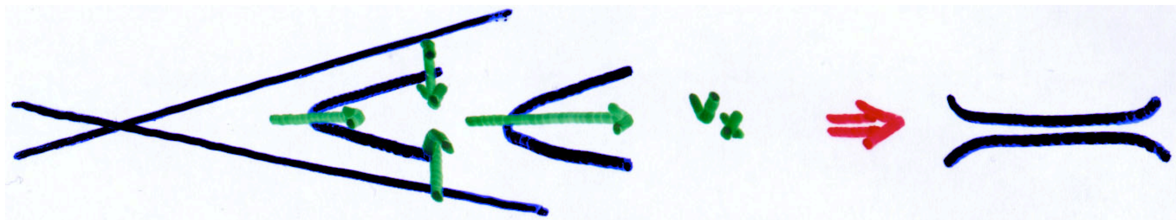
MHD



- Note Petschek-like outflow jet in Hall case
  - No Sweet-Parker current layer.

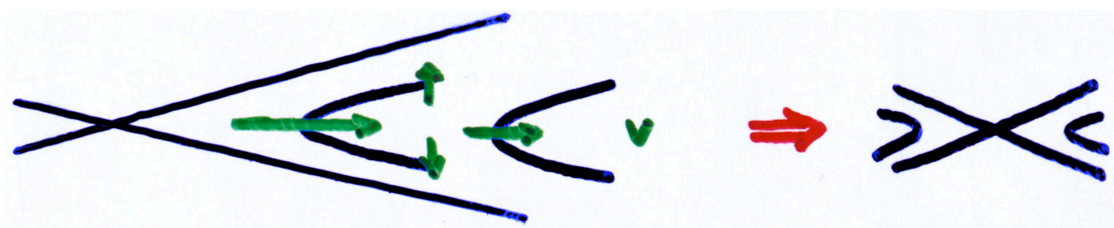
Wave dispersion and the structure of nozzle

- Controlled by the variation of the wave phase speed with distance from the x-line
  - increasing phase speed



•Closing of nozzle
•MHD case since B_n and C_A increase with distance from the x-line

- decreasing phase speed



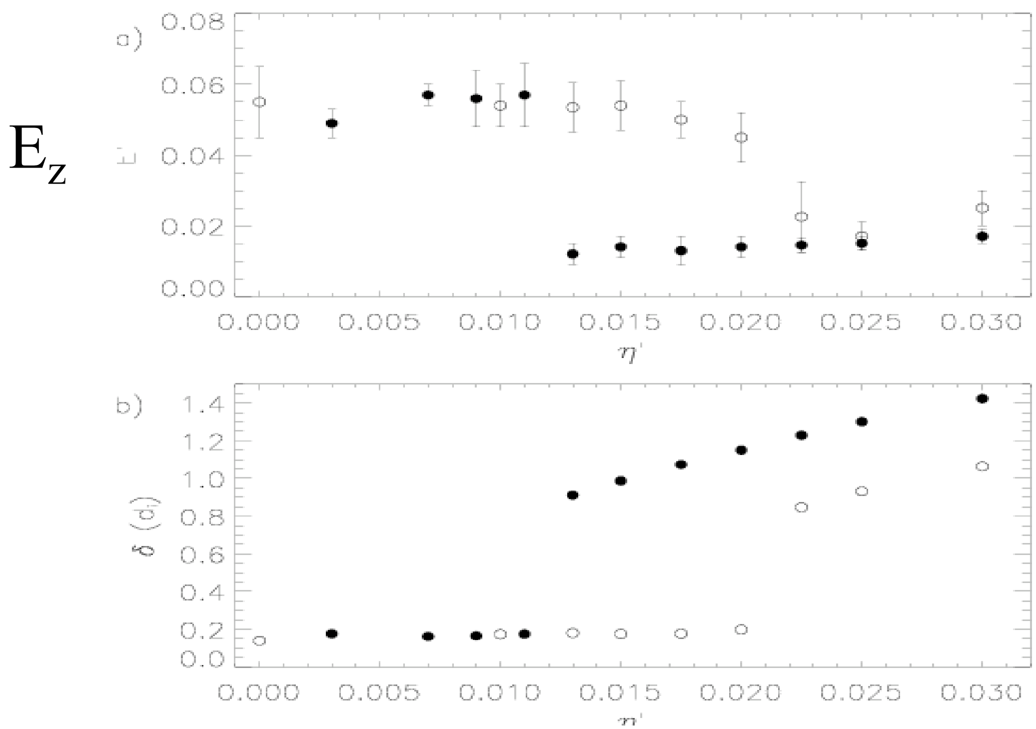
•Opening of the nozzle
•Whistler or kinetic Alfven waves $v \sim B/w$

Why does magnetic energy release occur as an explosion?

- Explaining fast reconnection in nature leads to a fundamental problem
  - How can magnetic energy in a system build up if the energy release is so fast?
- Why do magnetic fields not reconnect for long periods of time and then suddenly release large amounts of energy?
  - In the magnetotail thick current layers remain stable because of the normal magnetic field
  - What about in the solar corona and fusion experiments?

Hall versus S-P Magnetic Reconnection

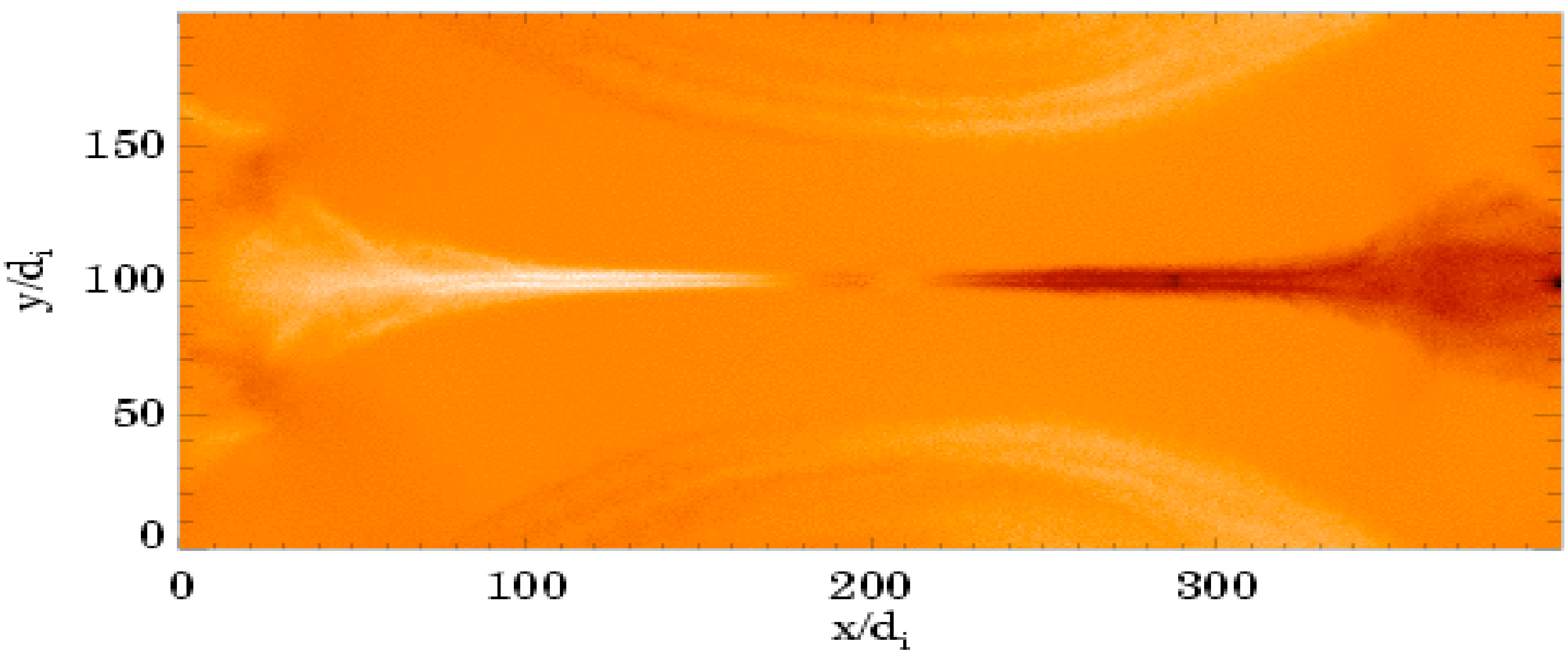
- S-P reconnection is valid if the resistive current layer width exceeds c/ $_{pi}$.
- Resistivity does not strongly influence the Hall reconnection solution   it is too fast.
  - Slow S-P reconnection and fast Hall reconnection are valid solutions for the same parameters   reconnection is bistable
  - Bistability typically extends over an enormous range of parameters
    - A range of 10^6 in resistivity for the solar corona



Cassak et al 2005

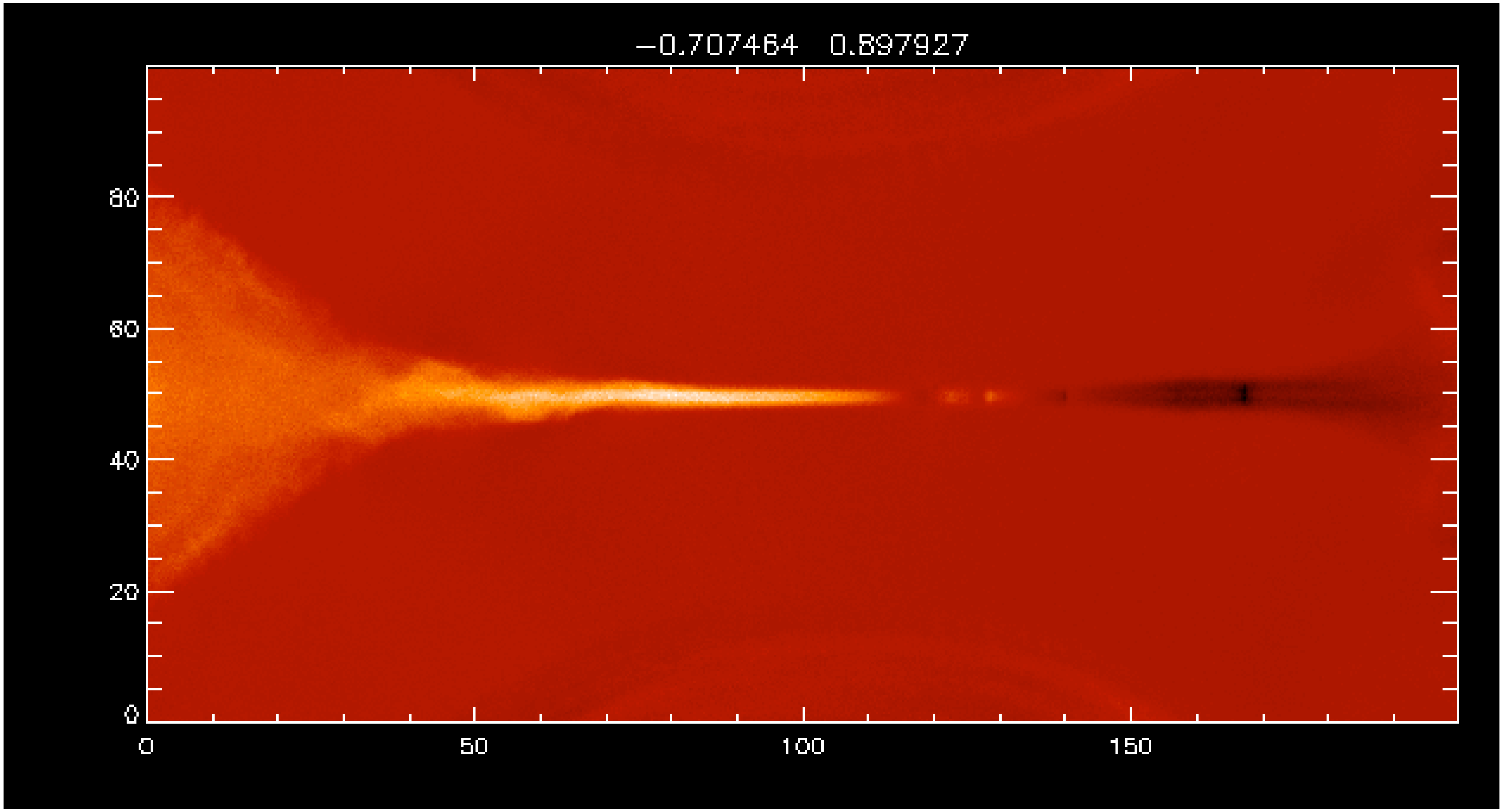
Positron-Electron Reconnection

- No decoupling of the motion of the two species
  - No dispersive whistler waves
- Displays Sweet-Parker structure but reconnection rate is high (Hesse, Bessho and Bhattacharjee).
- Scaling of reconnection rate to large systems?



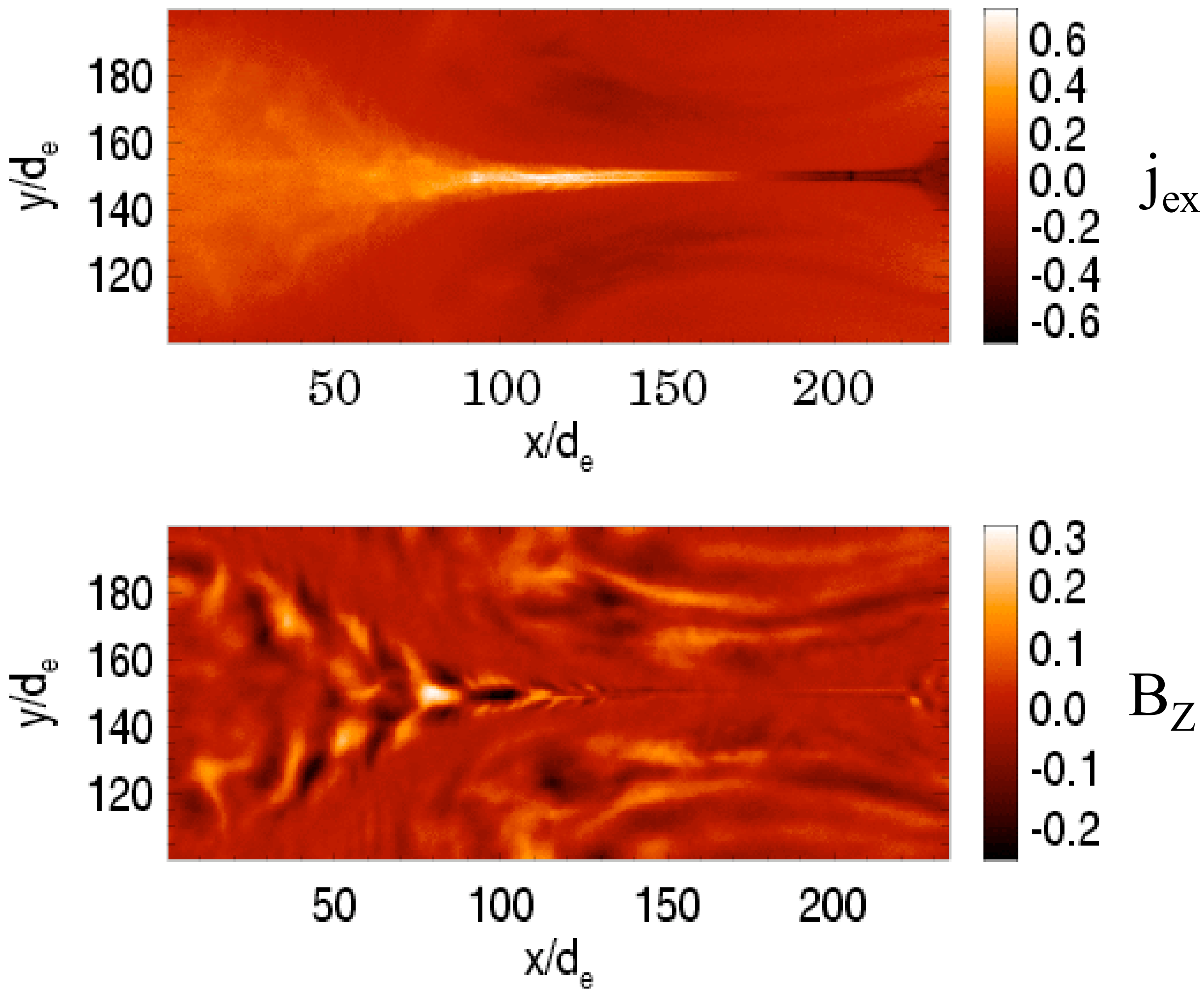
Turbulent outflow jet in electron-positron reconnection

- Outflow jet goes unstable and becomes fully turbulent
  - Broadens outflow region to Petchek-like open outflow geometry
  - Another mechanism for producing fast reconnection?



Magnetic Turbulence in Electron-Positron Reconnection

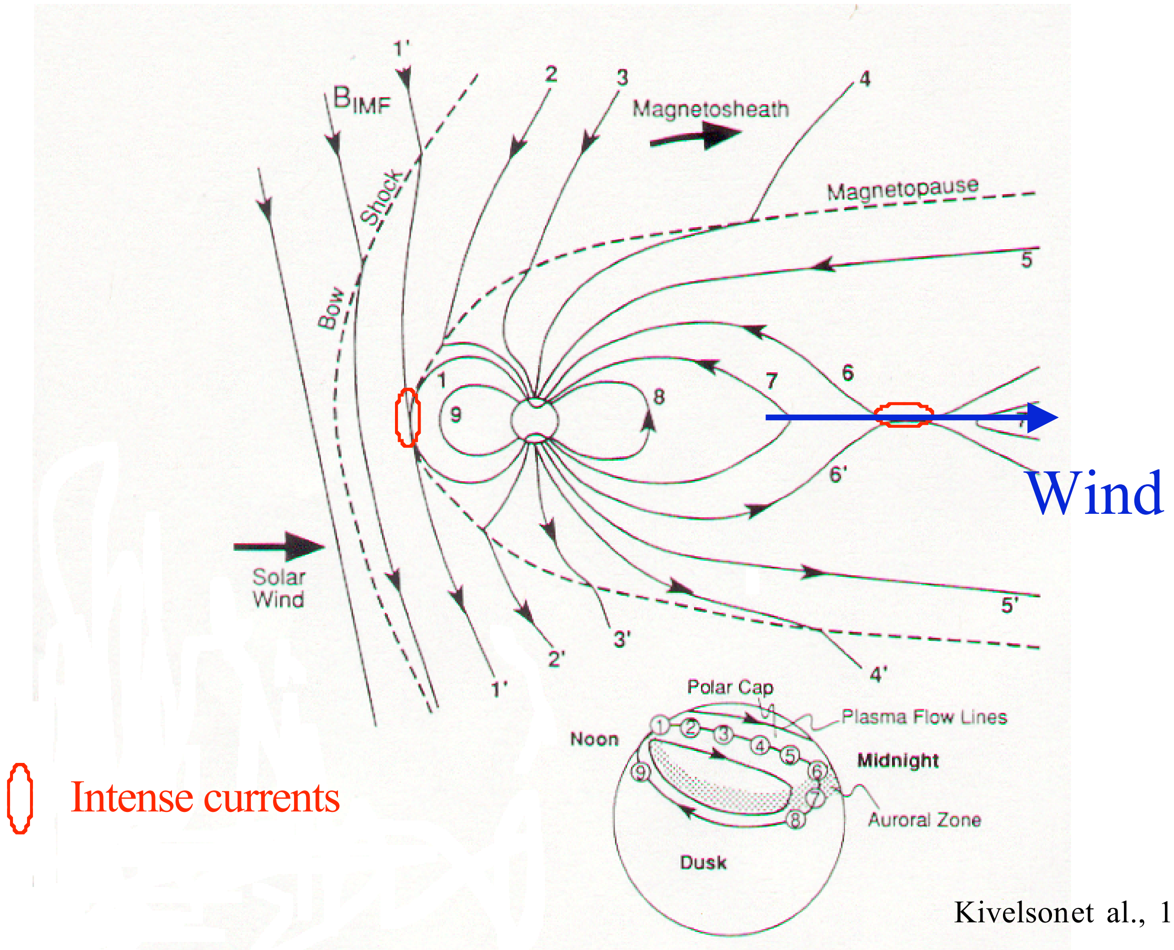
- Outflow jet develops very large anisotropic pressure with $P_{xx} >> P_{yy}, P_{zz}$
  - Firehose unstable



Energetic electron production during reconnection

- The production of energetic electrons during magnetic reconnection has been widely inferred in fusion experiments, in solar flares and in the Earth's magnetotail.
  - In solar flares up to 50% of the released magnetic energy appears in the form of energetic electrons (Lin and Hudson, 1971)
  - Energetic electrons in the Earth's magnetotail have been attributed to magnetic reconnection (Terasawa and Nishida, 1976; Baker and Stone, 1976; Meng et al, 1981).
- The mechanism for the production of energetic electrons has remained a mystery
  - Plasma flows are typically limited to the Alfven speed
    - More efficient for ion rather than electron heating
- Recent evidence that energetic electrons are produced around the x-line during reconnection (Oieroset, et al., 2002).

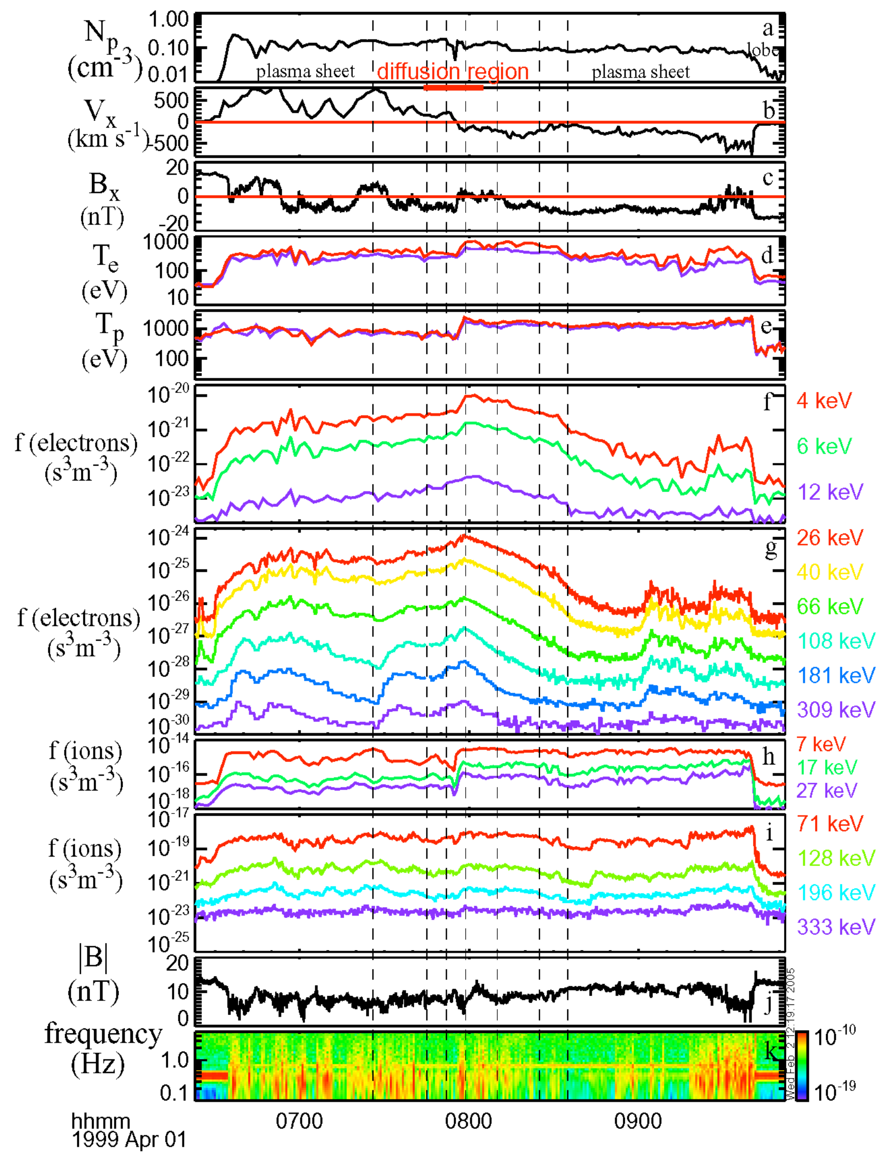
Wind spacecraft trajectory through the Earth's magnetosphere



Kivelsonet al., 1995

Wind magnetotail observations

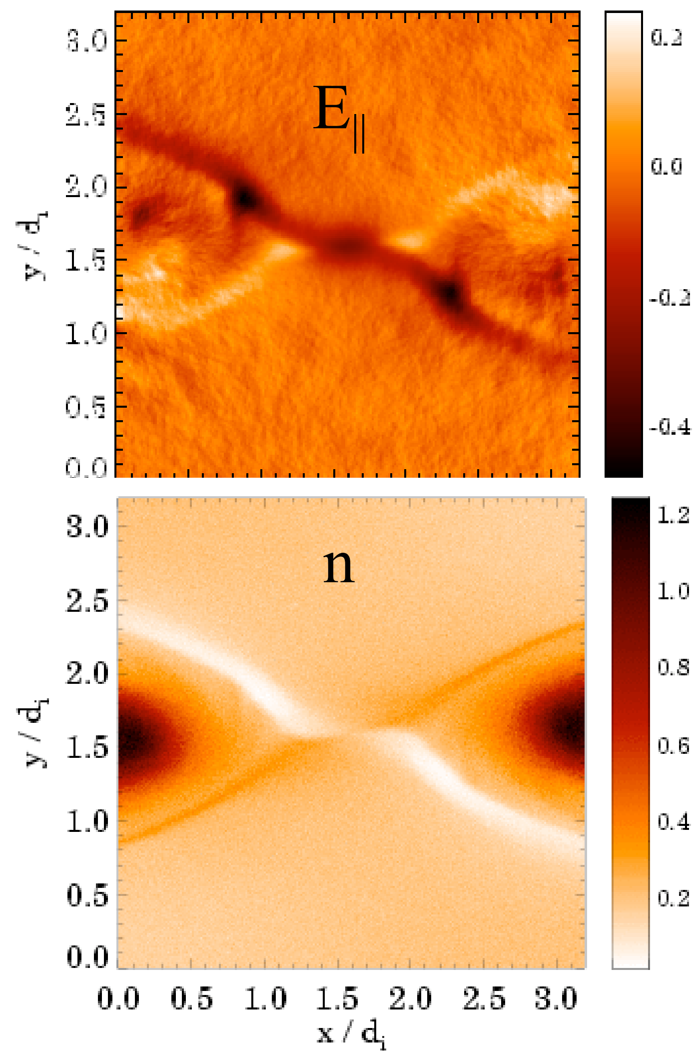
- Recent Wind spacecraft observations revealed that energetic electrons peak in the diffusion region (Oieroset, et al., 2002)
  - Energies measured up to 300kev
  - Power law distributions of energetic electrons
    - $v^2 f \sim E^{-3.8}$
  - Isotropic distributions at high energy
- Magnetic x-line can be the source of energetic electrons
  - Not just electron compression during Earthward flow
- Can the parallel electric field produce these energetic particles?



Structure of $E_{||}$ during guide-field reconnection

B_{z0}=1.0

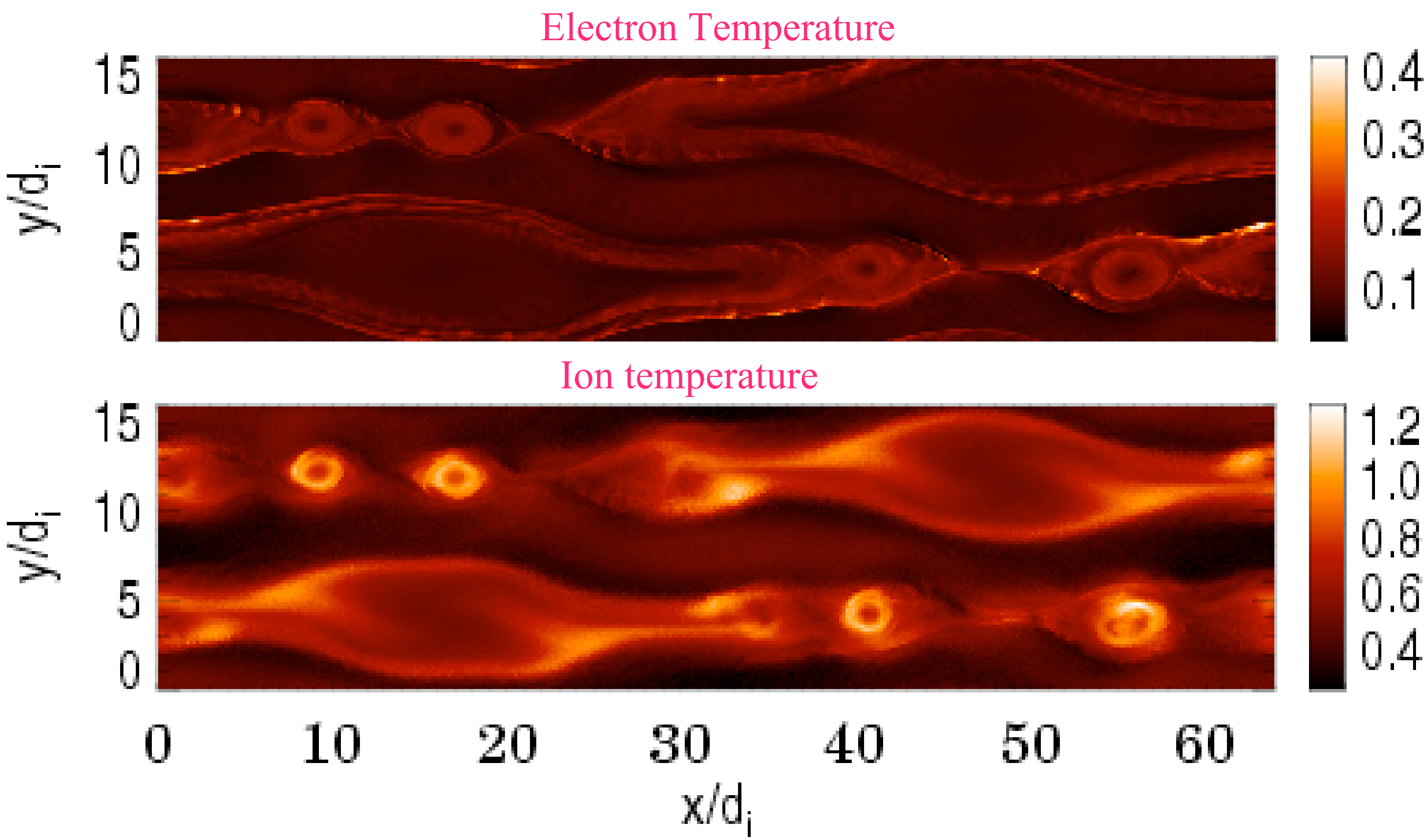
- The Wind observations have a substantial guide field.
- Guide field reconnection produces deep density cavities that map the magnetic separatrix
  - Pritchett and Coroniti, 2004
- The parallel electric field is localized within these cavities
  - Cavities are microscopic in length (Drake et al 2005)
- Electron acceleration takes place at the x-line and within these cavities



Challenges in explaining observations with parallel electric fields

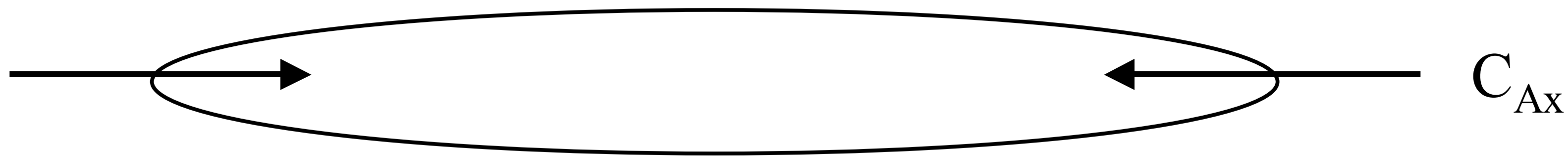
- The energetic electrons in the magnetotail
  - The energy often exceeds the potential drop across the magnetotail.
  - Distributions are isotropic above a critical energy
    - Not obviously consistent with acceleration by a parallel electric field
  - Exhibit power law distributions
    - Power laws are known to result from Fermi-like acceleration processes
  - The East-West asymmetry is only modest during active periods
- In the solar observations 50% of the energy released during magnetic reconnection can go into electrons
  - Essentially all of the electrons crossing the magnetic separatrix
    - The parallel elcctric field is too localized around the x-line
  - Why is the electron energy linked to the released magnetic energy?

Acceleration within magnetic islands



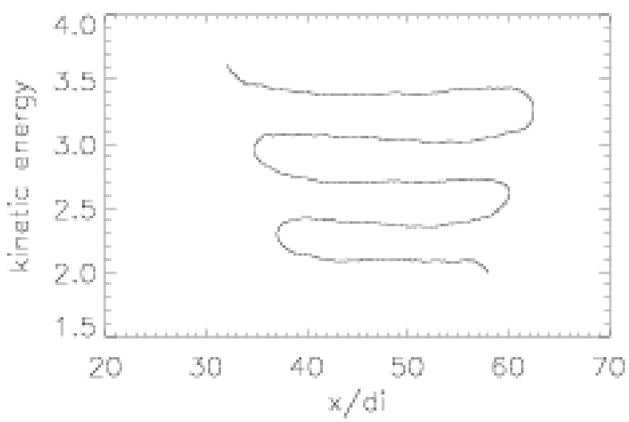
- Electron and ion heating within magnetic islands
- Does not seem to be associated with acceleration cavities

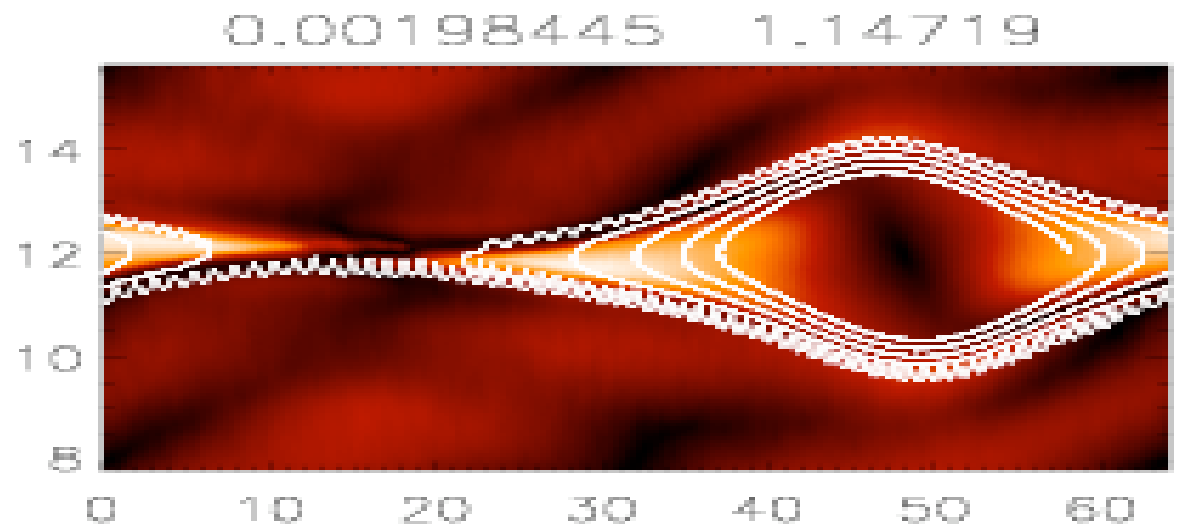
A Fermi electron acceleration mechanism inside contracting islands



- Energy is released from newly reconnected field lines through contraction of the magnetic island
- Reflection of electrons from inflowing ends of islands yields an efficient acceleration mechanism for electrons even when the parallel electric field is zero.

Electron Dynamics in magnetic islands

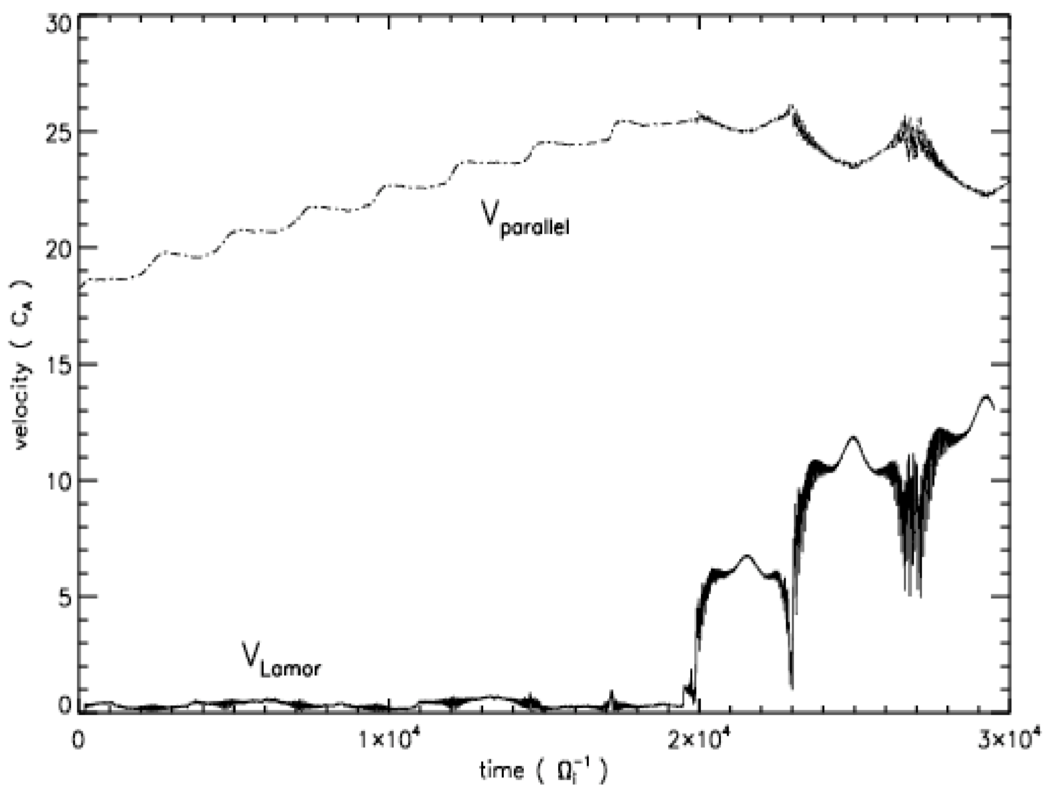




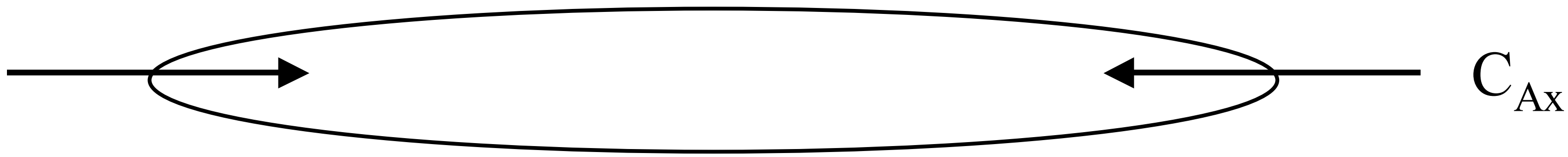
- Electrons follow field lines and drift outwards due to E B drift
  - Eventually exit the magnetic island
- Gain energy during each reflection from contracting island
  - Increase in the parallel velocity
- Electrons become demagnetized as they approach the x-line
  - Weak in-plane field and sharp directional change
  - Scattering from parallel to perpendicular velocity
    - Sudden increase in Larmor radius
    - Isotropic distribution consistent with observations?

Particle Scattering

- Increase of $v_{\parallel}$ within island
- Nearly constant v_L within island
- Scattering from $v_{\parallel}$ to v_L near the separatrix
- Isotropic particle distributions at high energy?



Energy Gain



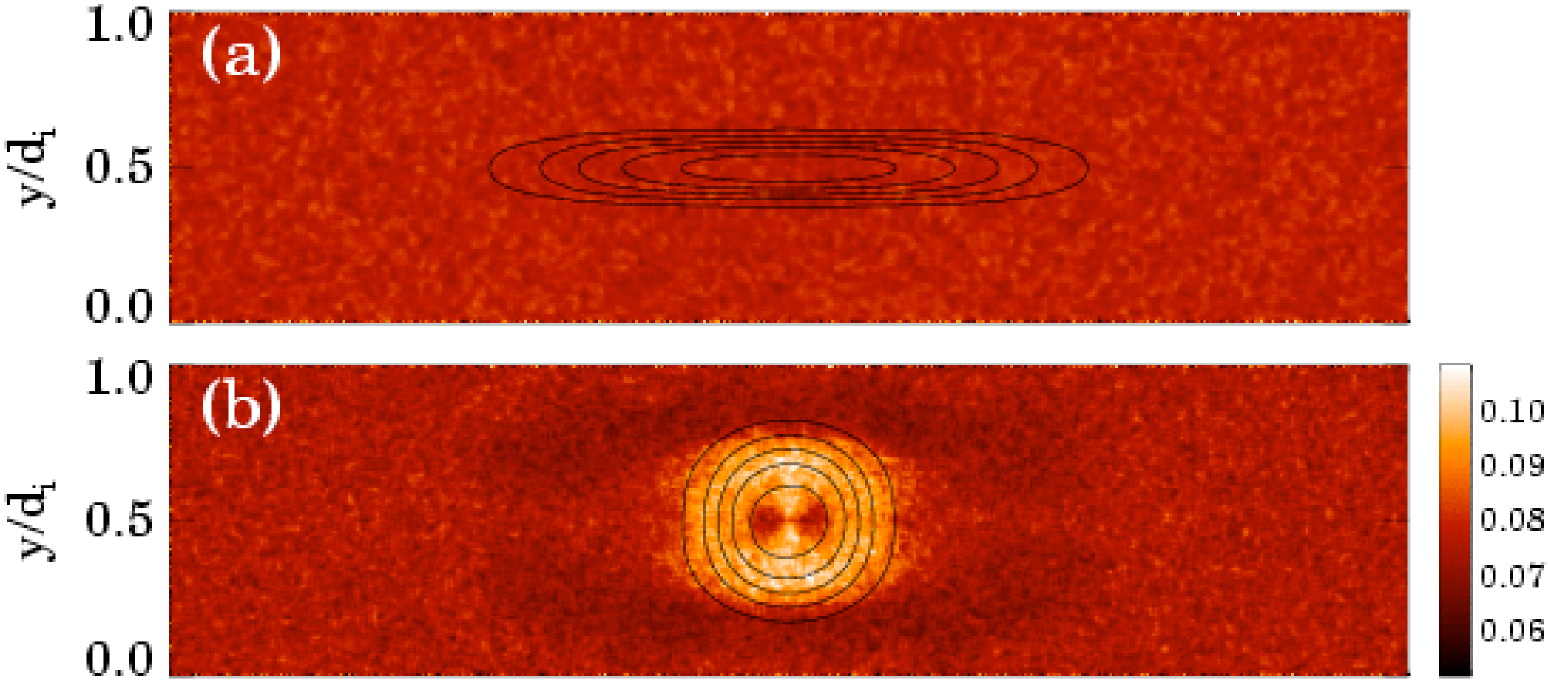
- Calculate energy gain through multiple reflections from the contracting island
  - Curvature drift during reflection has component along the inductive electric field and yields energy gain

$$\frac{d}{dt} = 2 \quad G \frac{C_{Ax}}{L_x} \qquad\qquad G(B_x, B_z) = \frac{B_x^2}{B^2}$$

  - Particles gain energy in either direction in and out of the plane
    - Can explain the lack of strong dawn-dusk asymmetry in the magnetotail

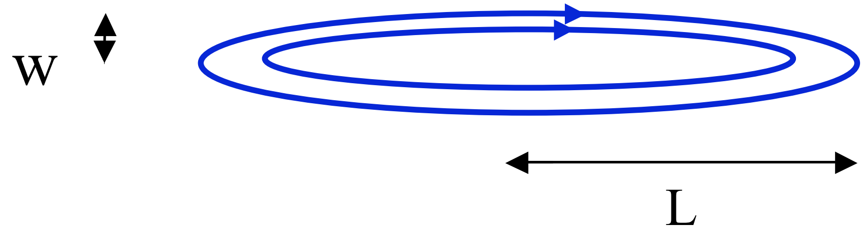
PIC Simulations of island contraction

- Separating electron heating due to the Fermi mechanism from heating due to $E_{\|}$ during reconnection is challenging
  - Study the contraction of an isolated, flattened flux bundle (m_i/m_e=1836)
  - $E_{\|}$=0



- Strong increase in $T_{\|}$ inside the bundle during contraction
  $T_{\|} \sim 3T$
- 60% of released energy goes into electrons

Linking energy gain to magnetic energy released



- Basic conservation laws
  - Magnetic flux BW = const.
  - Area WL = const.
  - Electron action VL = const.
- Magnetic energy change with L

$$W_B = \frac{B^2}{4}\frac{L}{L} < 0$$

  - Island contraction is how energy is released during reconnection
- Particle energy change with L

$$= \quad \frac{L}{L} > 0$$

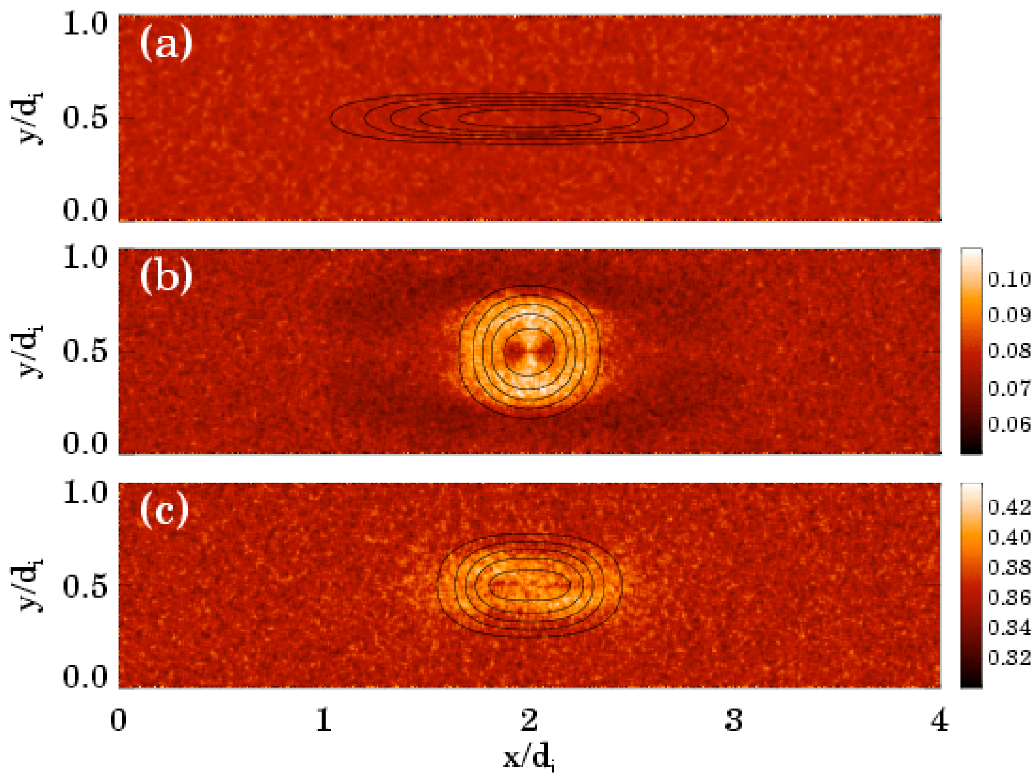
- Island contraction stops when

$$\sim \frac{B^2}{4} \qquad {}_{\parallel} \sim 1$$

- Energetic electron energy is linked to the released magnetic energy

Suppression of island contraction by energetic particle pressure

- Explore the impact of the initial on the contraction of an initially elongated island
- With low initial island becomes round at late time
- Increase in $p_{||}$ during contraction acts to inhibit island contraction when the initial is high



= 0.3

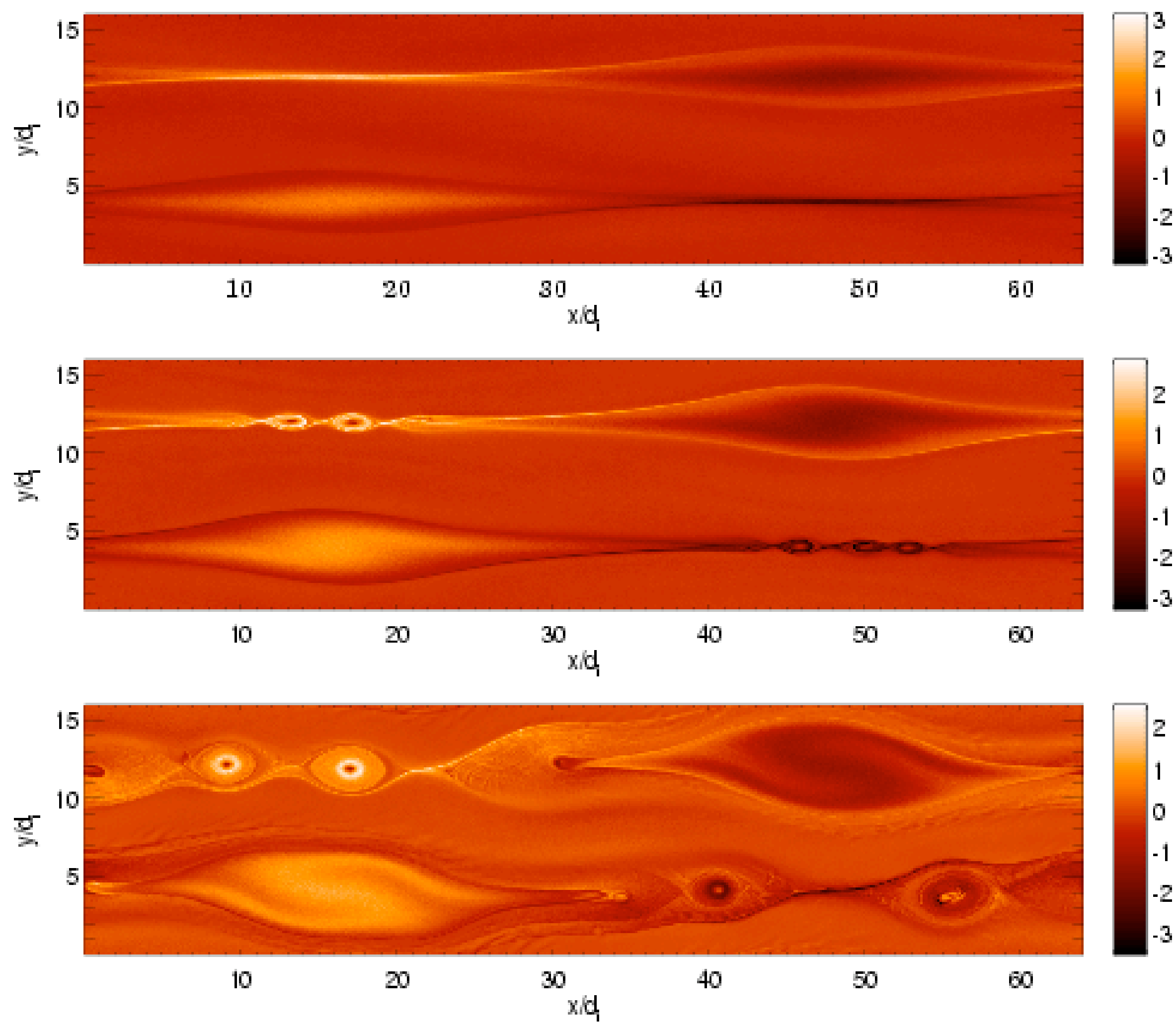
= 1.2

A multi-island acceleration model

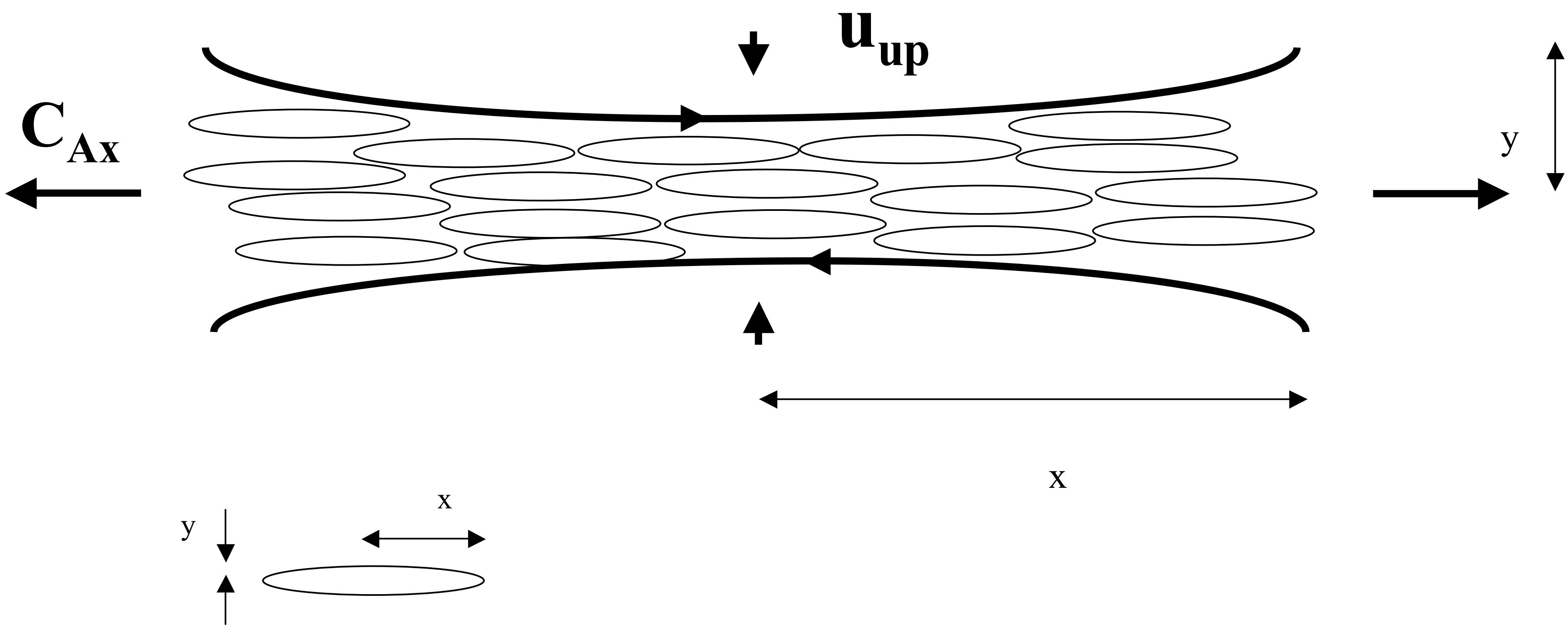
- A single open x-line does not produce the energetic electrons observed in the data
- The development of multiple magnetic islands is expected from theory and simulations of reconnection

Generation of multiple magnetic islands in reconnection with a guide field

- Narrow current layers spawn multiple magnetic islands in guide field reconnection
- In 3-D magnetic islands will be volume filling



Multi-island acceleration



- Note that the distribution of island sizes is unknown
- Islands are not expected to have kinetic scales

Kinetic equation for energetic particles

- Ensemble average over multiple islands

$$\frac{d}{dt} = \frac{2}{3} A \frac{dc_{Ax}}{dy} \qquad A = \left\langle \frac{B_{xi}^2}{B_i^2} \frac{\ \ _{yi}}{\ \ _{xi}} \right\rangle$$

- Steady state kinetic equation for electrons

$$\vec{\ } \quad \vec{u} f \quad \vec{\ } \quad \overset{\rightleftharpoons}{\ } (v) \vec{\ } f = \frac{1}{3} A \frac{dc_{Ax}}{dy} \frac{\ }{v} v f$$

  - Similar to equation for particle acceleration in a 1-D shock
  - Energy gain where have large magnetic shear instead of compression
- Can solve this equation in reconnection geometry

Electron spectra

- For large systems can take convective outflow boundary condition
  - Same as 1-D shock solutions
- Solution

$$f(v) = \frac{1}{v}\int_{0}^{v} dv' f_{up}(v') v'^{\quad 1}$$

$$= 1 + \frac{1}{\;} \qquad = \frac{_{x} < G_{i} \;\; _{yi} / \;\; _{xi} >}{3 \;\; _{y}}$$

- Spectral index
  - Depends on the ratio of the aspect ratio of the island region to the mean aspect ratio of individual islands -- not well understood
- Energy transfer to electrons is energetically important for > 0.5.
- Feedback of the energetic component on the reconnection process must be calculated

Kinetic equation with back-pressure

- Include the feedback of energetic particles on island contraction

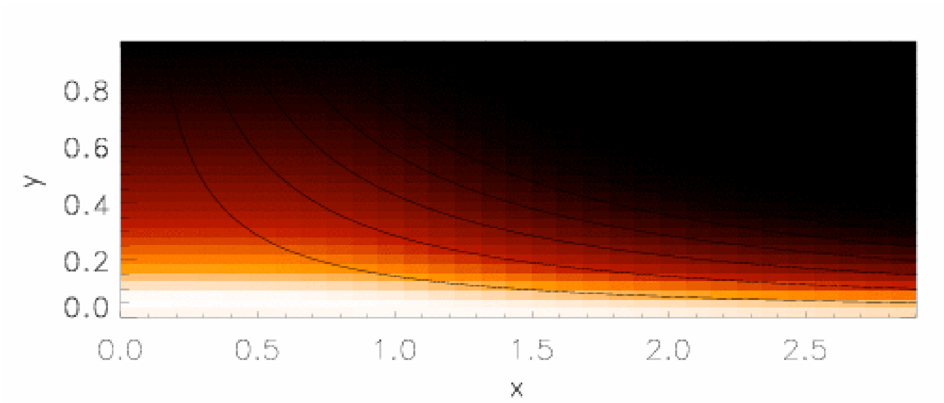
$$v = c_{Ax} \quad 1 \quad \frac{8 \quad W}{3B^2} \quad ^{1/2}$$

  - Energetic particles can stop island contraction through their large parallel pressure
- Steady state kinetic equation for electrons

$$\rightarrow \quad \vec{u}f \quad \rightarrow \quad (v) \overset{\rightarrow}{\ } f = \frac{1}{3} A \quad 1 \quad \frac{8 \quad W}{3B^2} \quad ^{1/2} \frac{dc_{Ax}}{dy} \frac{\ }{v} vf$$

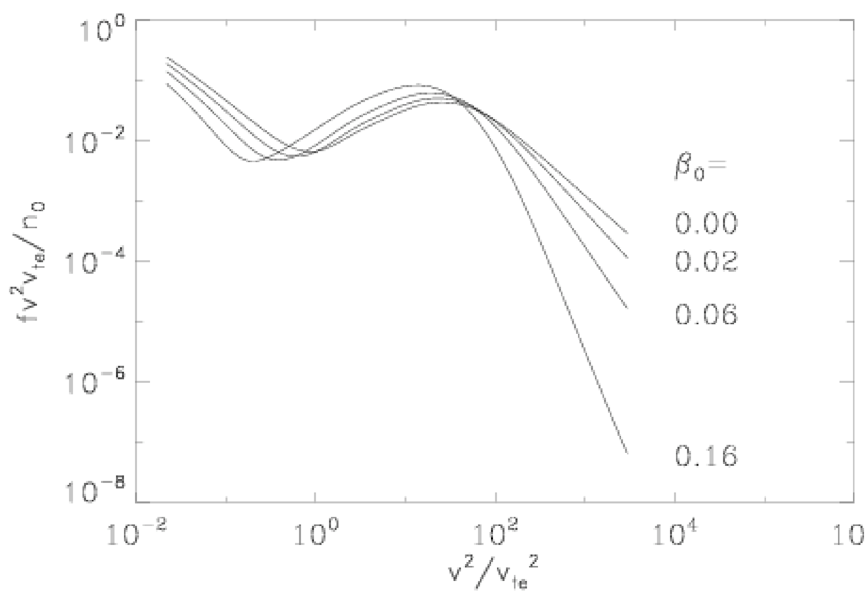
- Can solve this equation numerically in reconnection geometry
  - Saturation of energetic particle production
  - Two key dimensionless parameters:
    - Initial plasma beta: $_0$
    - Energy drive:

Energetic electron spectra



Simulation geometry

- Powerlaw spectra at high energy
- Initial plasma beta, $_0$, controls the spectral index of energetic electrons
  - For Wind magnetotail parameters where $_0 \sim 0.16$, $v^2 f \sim E^{-3.6}$
  - For the solar corona where $_0$ is small, $v^2 f \sim E^{-1.5}$
    - Universal spectrum for low $_0$
- Results are insensitive to the drive as long as is not too small
  - Back pressure always reduces the net drive so that energy transfer to electrons is comparable to the released magnetic energy



The multi-island electron acceleration model explains many of the observations

- Magnetotail
  - Energy can exceed the cross-tail potential
  - Weak East-West asymmetry across the tail
  - Velocity distributions isotropic above a critical energy
  - Powerlaw energy distributions which match the Wind observations
- Solar corona
  - Large numbers of energetic electrons
    - If island region is macroscopic
  - Electron energy gain linked to the released magnetic energy
  - Powerlaw energy distributions consistent with the observations

Conclusions

- Fast reconnection occurs as a result of the coupling to non-MHD dispersive waves at small spatial scales
  - rate independent of the mechanism which breaks the frozen-in condition
  - Open Petschek-like magnetic configuration
  - Supported by magnetospheric satellite observations
  - Can explain the explosive nature of reconnection in weakly collisional systems such as the solar corona

Conclusions

- Exploring mechanisms for electron acceleration during magnetic reconnection
  - Acceleration by parallel electric fields does not explain the observational data
  - Contracting magnetic islands heat electrons through a Fermi process
    - Energy transfer to electrons is linked to the released magnetic energy
    - Powerlaw distributions with spectral indices that are linked to the electron
      - Limiting spectral indices of 1.5 at low
  - The challenge: electron Fermi acceleration is suppressed in conventional particle simulations because of the artificial mass ratio -- thermal electrons don't have time to bounce

Representative References

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