Magnetic Reconnection

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A presentation to celebrate the 50th anniversary of the Princeton Plasma Physics Laboratory

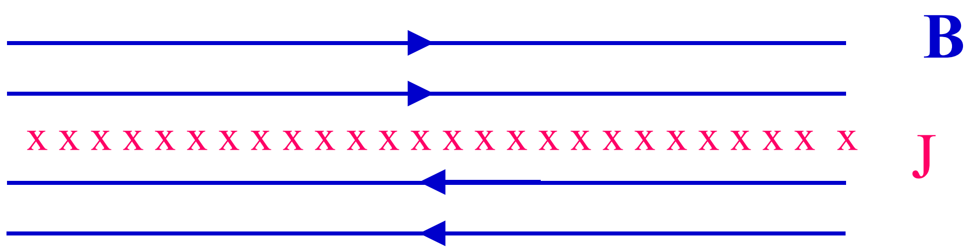
June 5, 2002

Magnetic Energy Dissipation in the Universe

- The conversion of magnetic energy to heat and high speed flows underlies many important phenomena in nature
  - solar and stellar flares
  - magnetospheric substorms
  - disruptions in laboratory fusion experiments
- More generally understanding how magnetic energy is dissipated is essential to model the generation and dissipation of magnetic field energy in astrophysical systems
  - accretion disks
  - stellar dynamos
  - supernova shocks
- Known systems are characterized by a slow buildup of magnetic energy and fast release
  - trigger?
  - mechanism for fast release?
- Production of energetic particles

Magnetic Free Energy

- A reversed magnetic field is a source of free energy

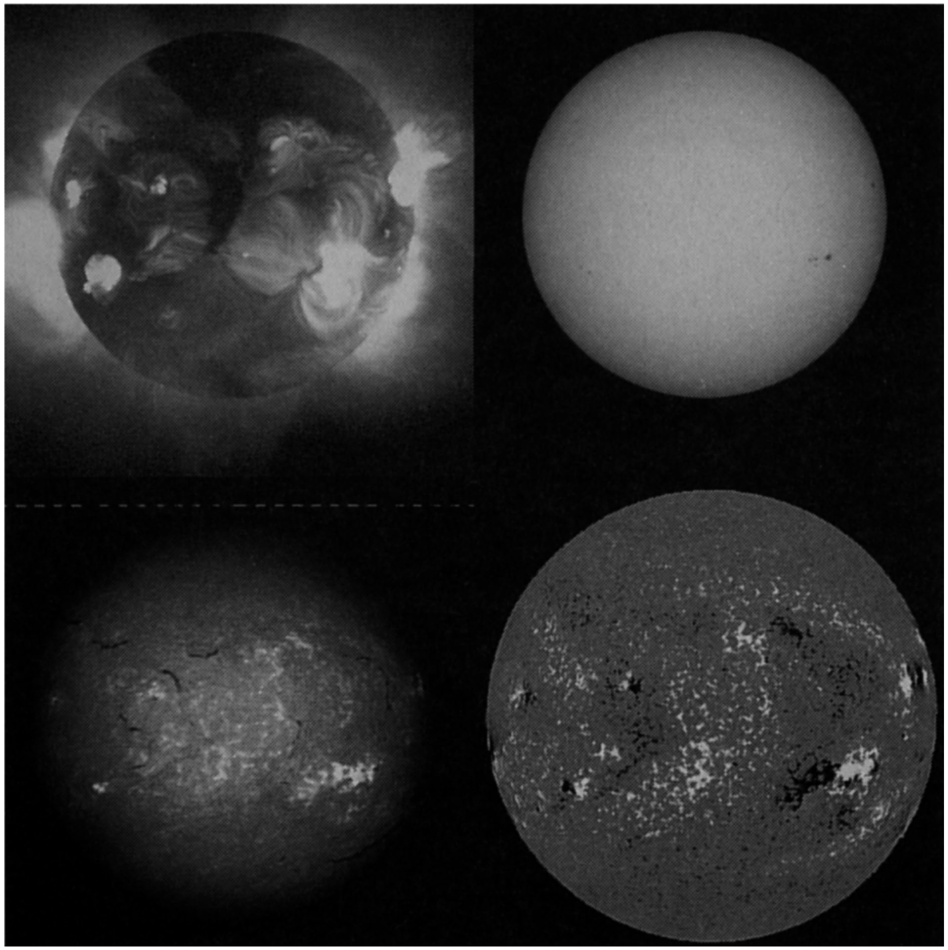


•Can imagine **B** simply self-annihilating
•What happens in a plasma?

Yohkoh Images of the Sun

- Tsuneda '96

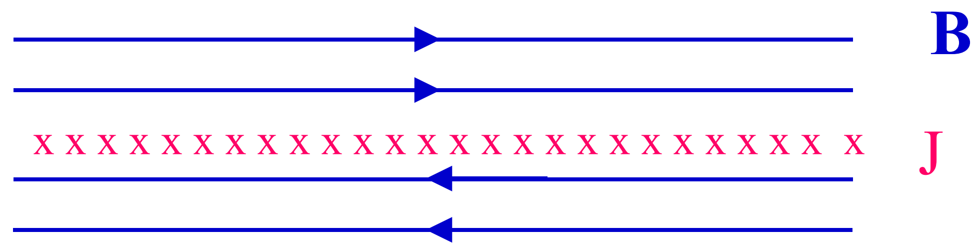
Soft x-rays

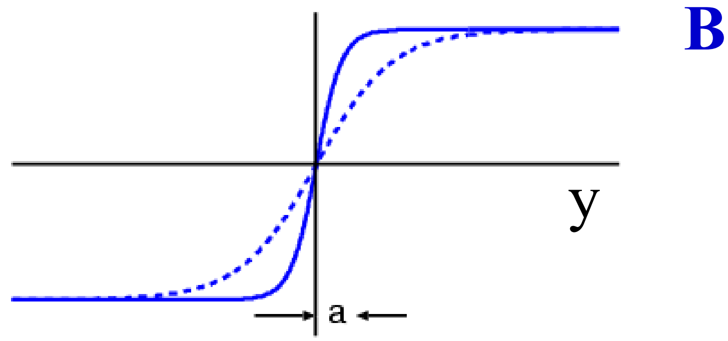


Normal B at photosphere

•Active regions occur where B is large and reverses direction

Resistive Diffusion





- Diffusion of magnetic flux

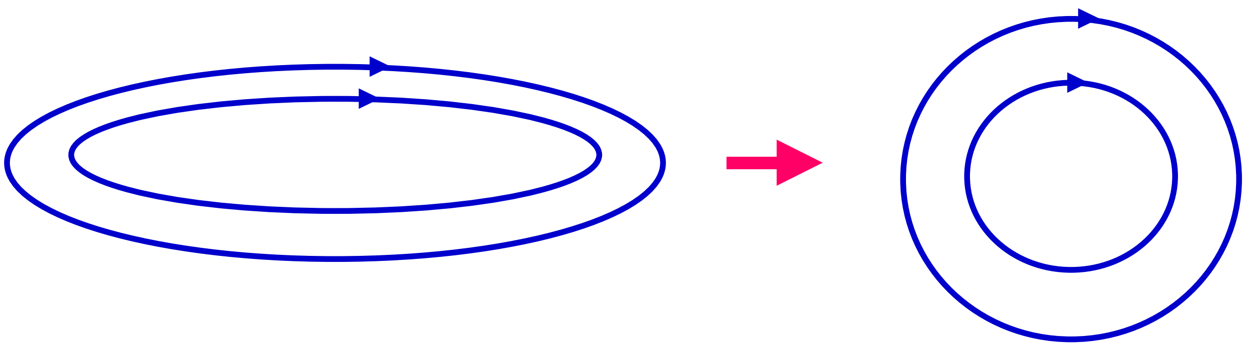
$$\frac{\partial B}{\partial t} = \frac{\eta c^2}{4\pi} \frac{\partial^2 B}{\partial y^2}$$

$$\tau_r = 4\pi a^2 / \eta c^2 = \text{resistive time}$$

Characteristic Diffusion Times

	Resistive Time	Observed Energy Release Time
Laboratory Tokamaks	1 - 10 sec	100 μsec
Solar Flares	~ 10^4 years	~ 20 min
Magnetospheric Substorms	~ ×	30 min

Energy Release from Squashed Bubble

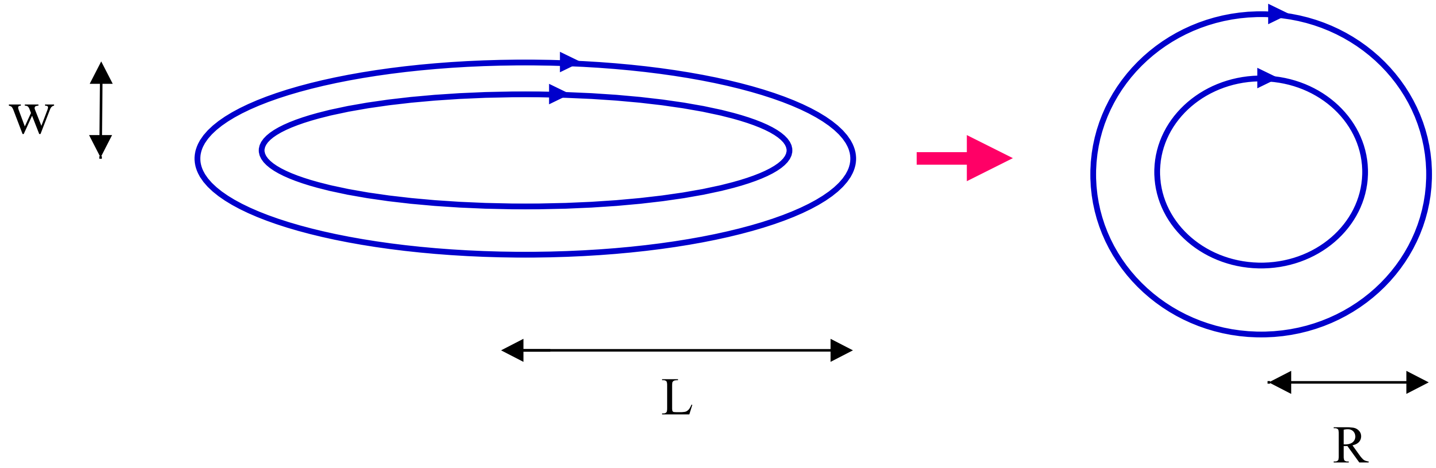


$$\vec{F} = - \quad (p + \frac{B^2}{8\partial}) + \frac{1}{4\partial}\vec{B}\langle \quad \vec{B}$$

magnetic tension

- Magnetic field lines want to become round

Energy Release (cont.)



- Evaluate initial and final magnetic energies
  - use conservation law for ideal motion
    - magnetic flux conserved
    - area for nearly incompressible motion

$$W_f \sim (w^2/L^2)\, W_i \ll W_i$$

•Most of the magnetic energy is released

Flow Generation

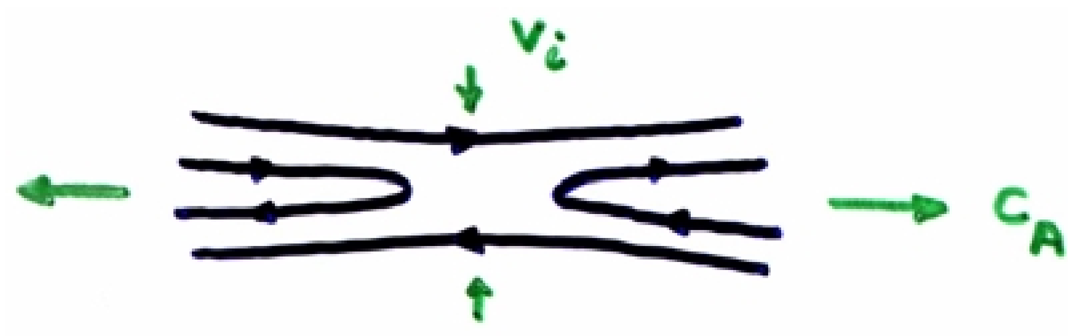
- Released magnetic energy is converted into plasma flow

$$\frac{1}{2}\rho v^2 = \frac{B^2}{8\pi}$$

$$v \cup v_A \ldots (\frac{B^2}{4\pi\rho})^{1/2} \qquad \tau_A = L / v_A$$

•Alfven time τ_A is much shorter than observed energy release time

Magnetic Reconnection



- Strong observational support for this general picture both from astrophysical and laboratory data

Sawteeth

- Internal disruption events were first observed in the soft x-ray data in the ST tokamak (von Goeler, et al., 1974)

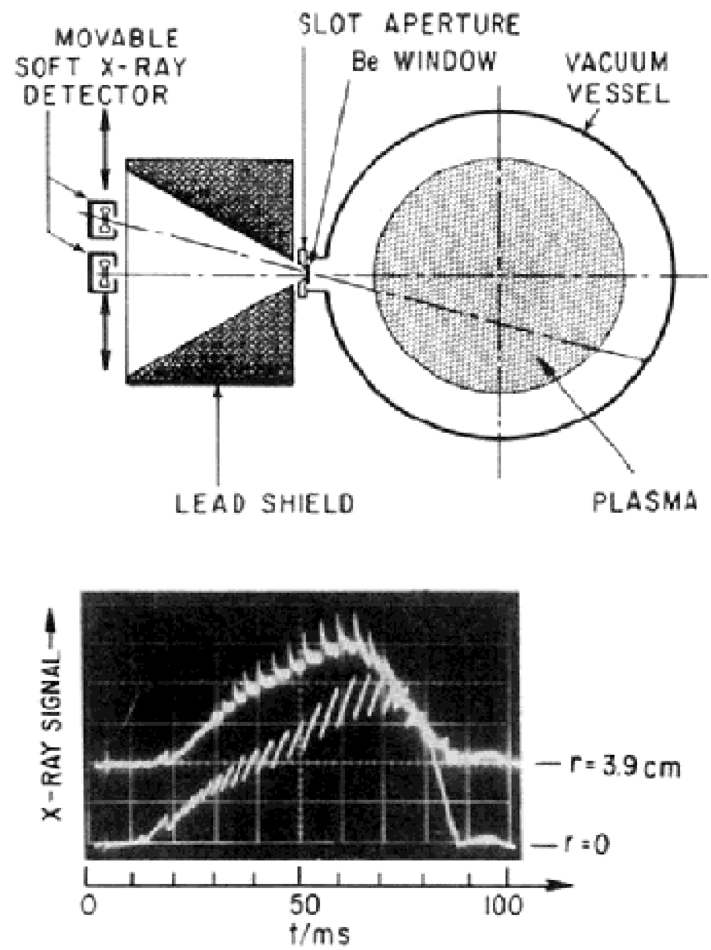
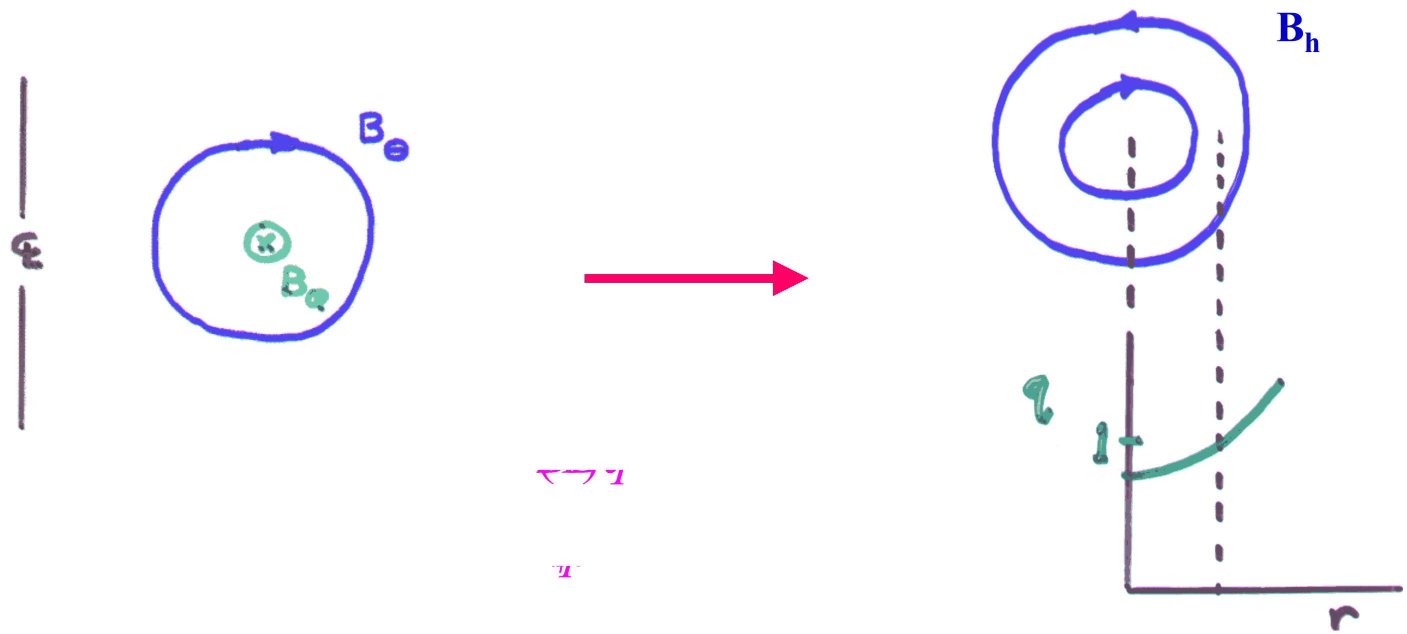


FIG. 1. Experimental arrangement of x-ray detectors. The x-ray traces exhibit internal disruptions.

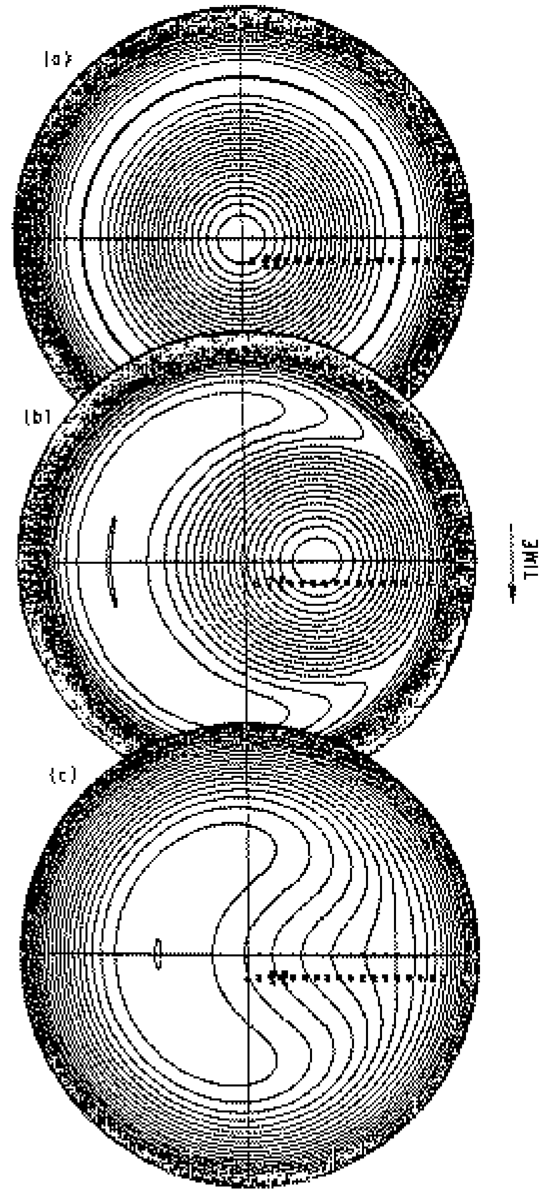
Kadomtsev Reconnection Model

- Transformation to a twisted coordinate system reveals classical reversal in the magnetic field which drives reconnection (Kadomtsev, 1975)



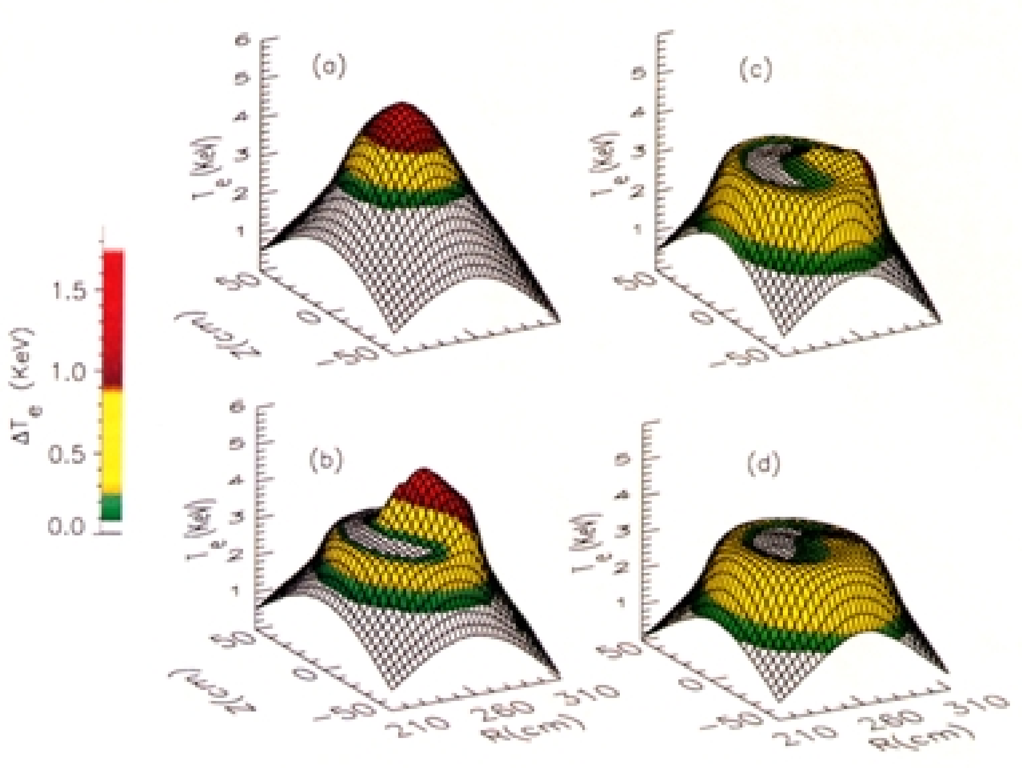
Simulation of Sawtooth Reconnection

- Based on the magnetohydrodynamic (MHD) equations (Park, et al., 1984)



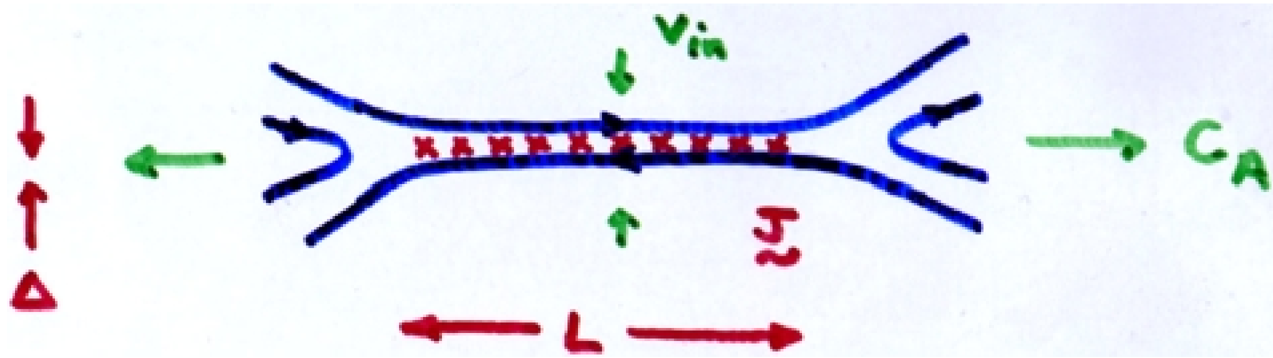
Expulsion of Core Temperature

- Measurements of the core electron temperature in the TFTR tokamak documented the loss of core energy during the "sawtooth crash" (Yamada, et al., 1994)



- Observations consistent with Kadomtsev model

Resistive MHD Description



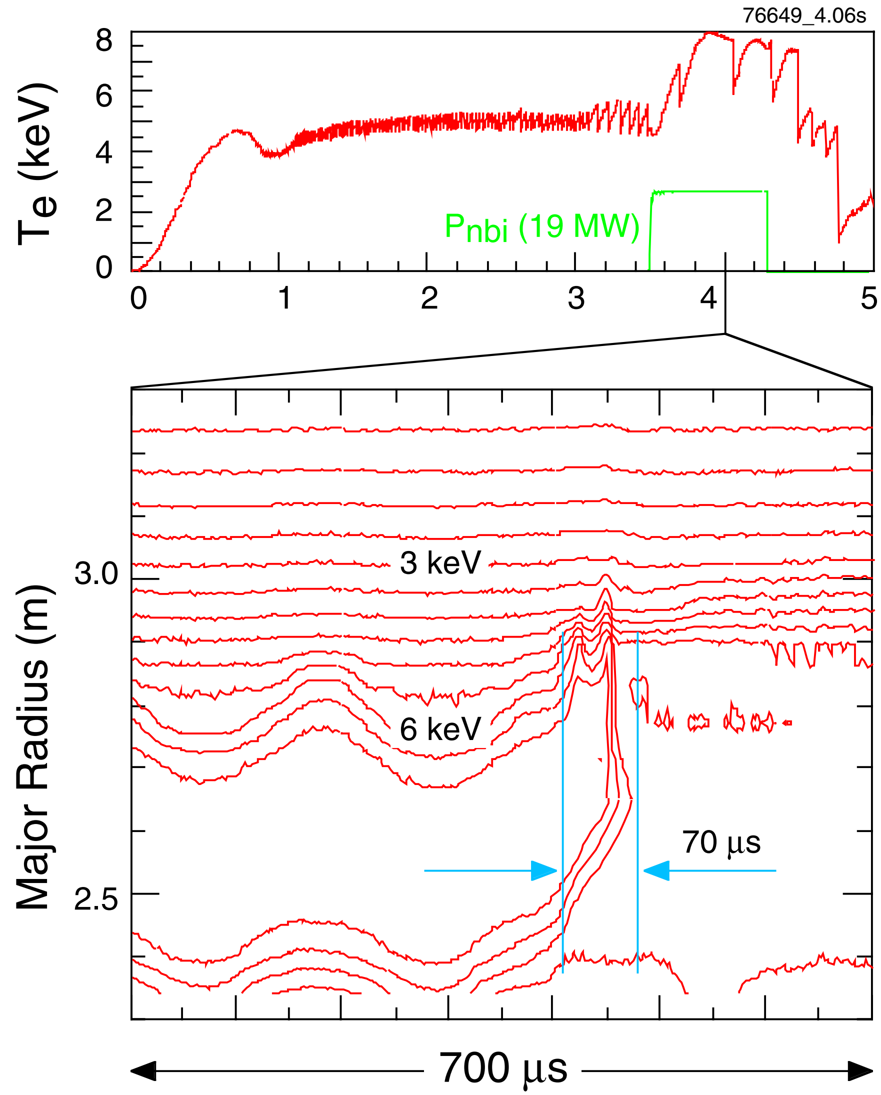
- Formation of macroscopic Sweet-Parker layer

$$V \sim (\Delta / L)\, C_A \sim (\tau_A/\tau_r)^{1/2}\, C_A \ll C_A$$

- Slow reconnection
- sensitive to resistivity
- macroscopic nozzle

Sawtooth Crash Time

- Observations of the sawtooth crash on TFTR, JET and JT-60 tokamaks let to a major surprise
  - crash time was actually shorter than in the earlier lower temperature machines
    - inconsistent with resistive MHD model



Frederickson, et al., 94

Failure of the MHD Model

- Reconnection rates too slow to explain observations
  - solar flares
  - sawtooth crash
  - magnetospheric substorms
- Some form of anomalous resistivity is often invoked to explain discrepancies
  - strong electron-ion streaming near x-line drives turbulence and associated enhanced electron-ion drag
  - no convincing theory of anomalous resistivity
- Non-MHD physics at the small spatial scales where the frozen-in condition is broken produces fast reconnection consistent with observations

Role of Dispersive Waves

- Coupling to dispersive waves at small scale is the key to understanding fast magnetic reconnection
  – rate of reconnection independent of the mechanism which breaks the frozen-in condition
  – fast reconnection even for large systems
    - no macroscopic nozzle

Generalized Ohm's Law

- Electron equation of motion

$$\frac{4\pi}{\omega_{pe}^2}\frac{d\vec{J}}{dt} = \vec{E} + \frac{1}{c}\vec{v}_i \times \vec{B} - \frac{1}{nec}\vec{J} \times \vec{B} + \frac{1}{ne} \quad p_e - \eta\vec{J}$$

c/ω_{pe}	c/ω_{pi}	ρ_s	scales
Electron inertia	whistler waves	kinetic Alfven waves	

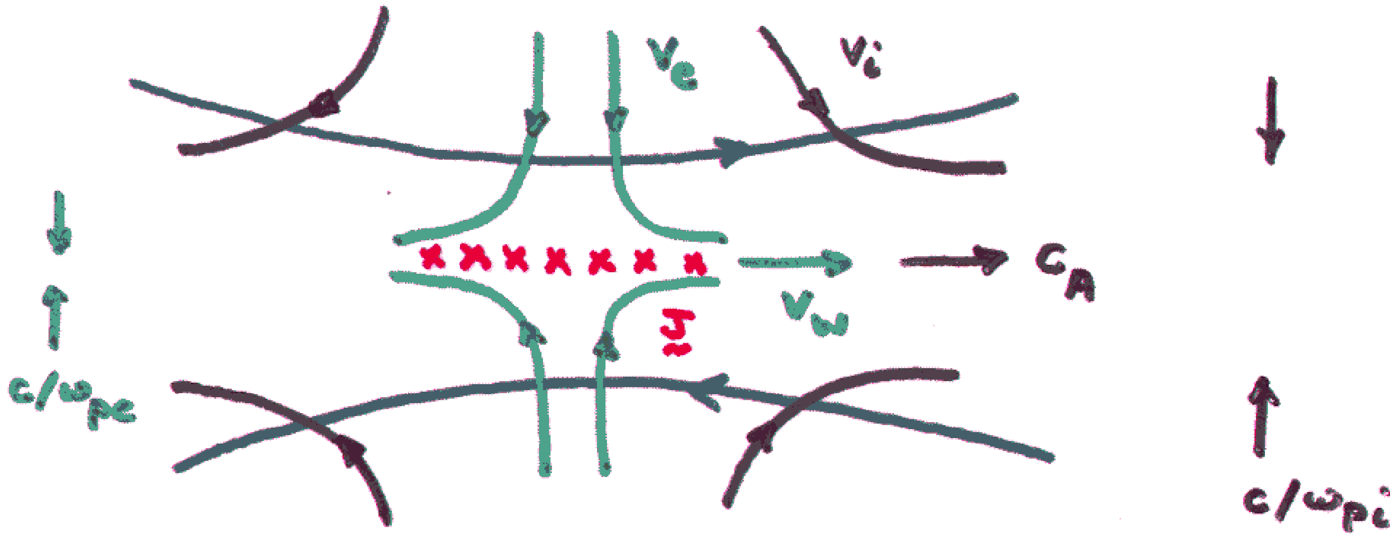
•MHD valid at large scales

•Below c/ω_{pi} electron and ion motion decouple

  •electrons frozen-in

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

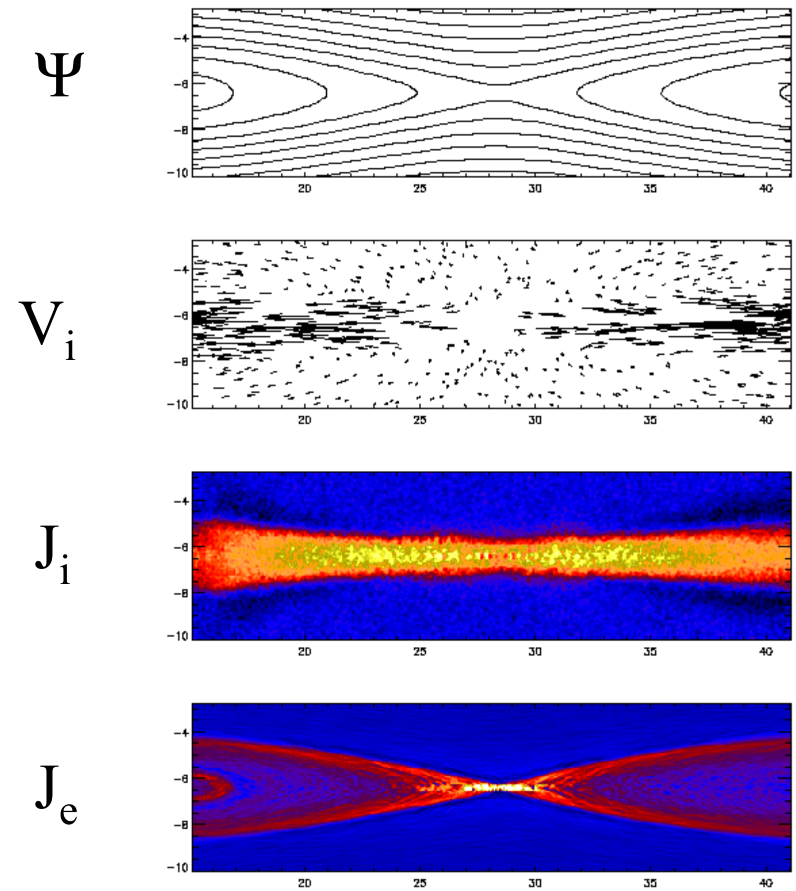
Kinetic Reconnection



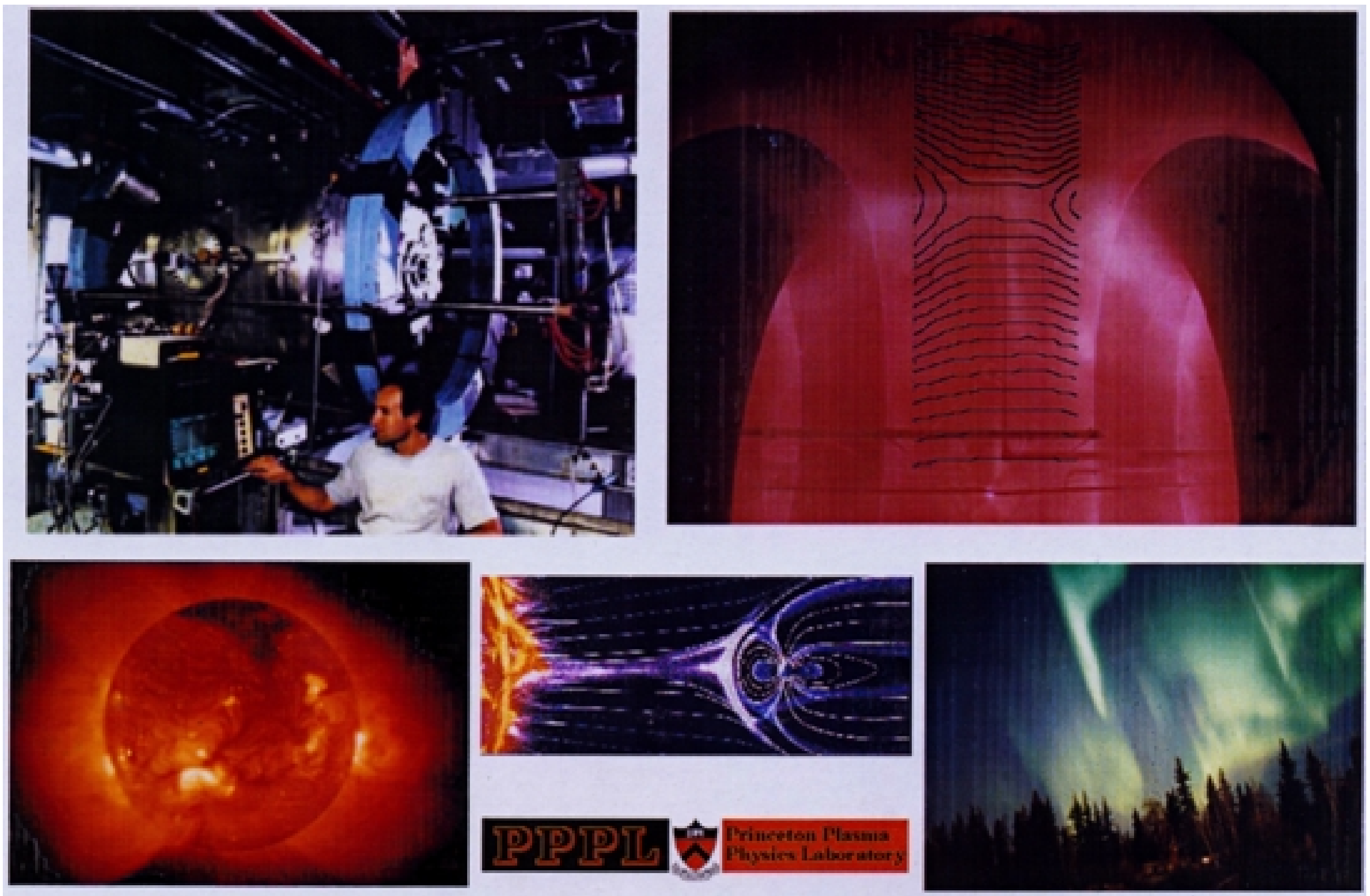
- Ion motion decouples from that of the electrons at a distance c/ω_{pi} from the x-line
  - ion outflow width c/ω_{pi}
- electron current layer and outflow width c/ω_{pe}

Multiscale Structure of Dissipation Region

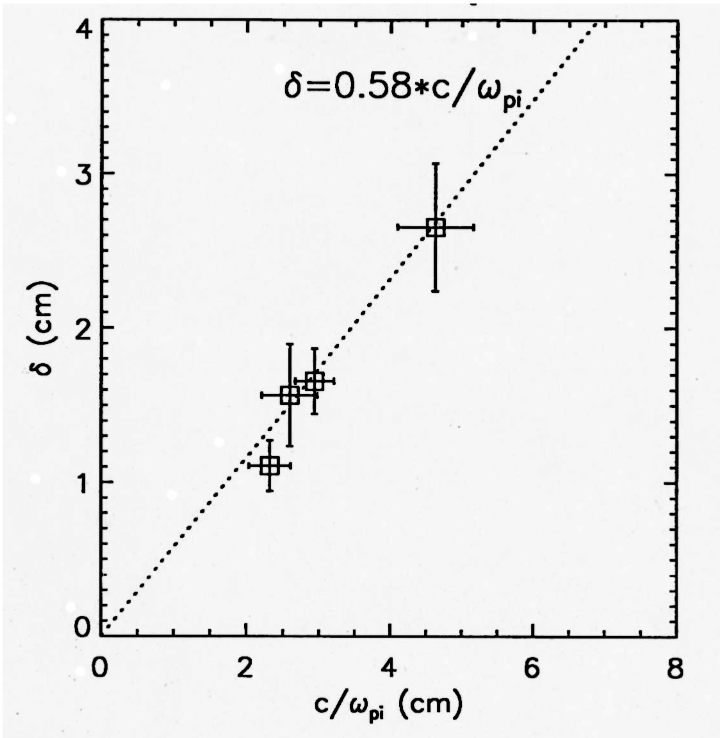
- Large scale hybrid (particle ions and fluid electrons) simulation (Shay et al., 1999)
  - Clear separation of ion and electron scales



MRX Reconnection Experiment



Scaling of width of current layer



- Width of current layer scales with c/ω_{pi}

GEM Reconnection Challenge

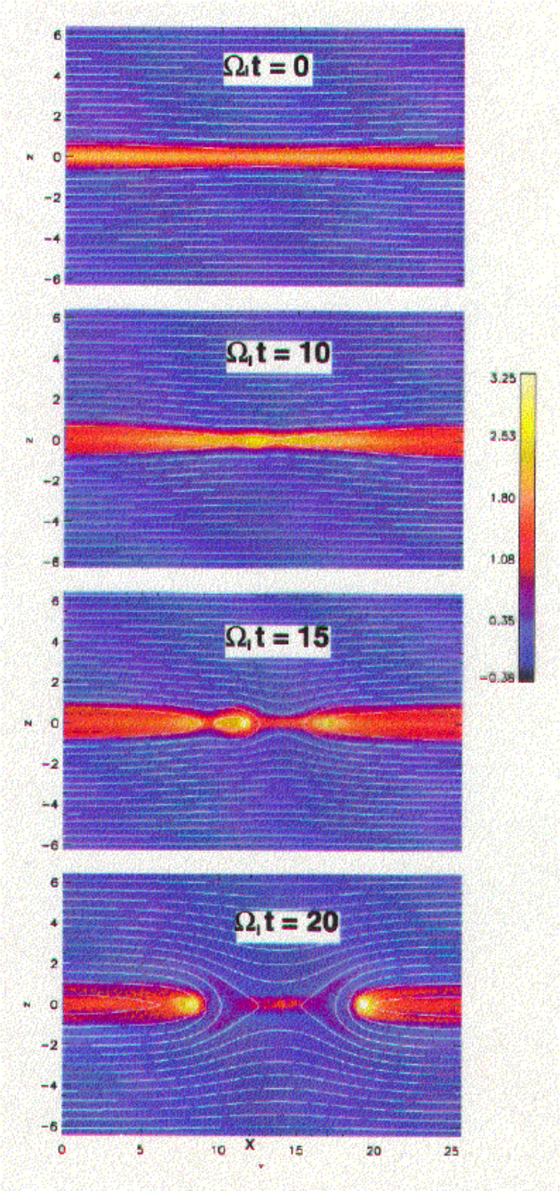
- National collaboration to explore reconnection with a variety of codes (Birn, et al., 2001)
  - MHD, two-fluid, hybrid, full-particle
- nonlinear tearing mode in a 1-D Harris current sheet

$$B_x = B_0 \tanh(z/w)$$

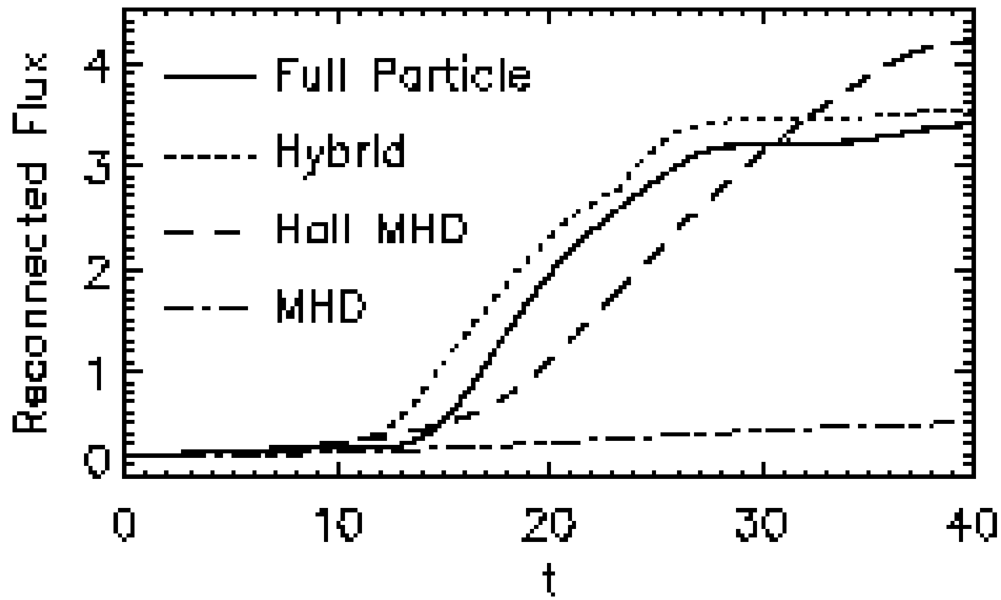
$$w = 0.5\ c/\omega_{pi}$$

GEM tearing mode evolution

- Full particle simulation (Hesse,GSFC)



Rates of Magnetic Reconnection



Birn, et al., 2001

- Rate of reconnection is the slope of the Ψ versus t curve
- all models which include the Hall term in Ohm's law yield essentially identical rates of reconnection
  - Why?
- MHD reconnection is too slow by orders of magnitude
- MHD is not adequate to model magnetic reconnection
  - this is a general conclusion

Whistler Dispersion

- Quadratic dispersion character

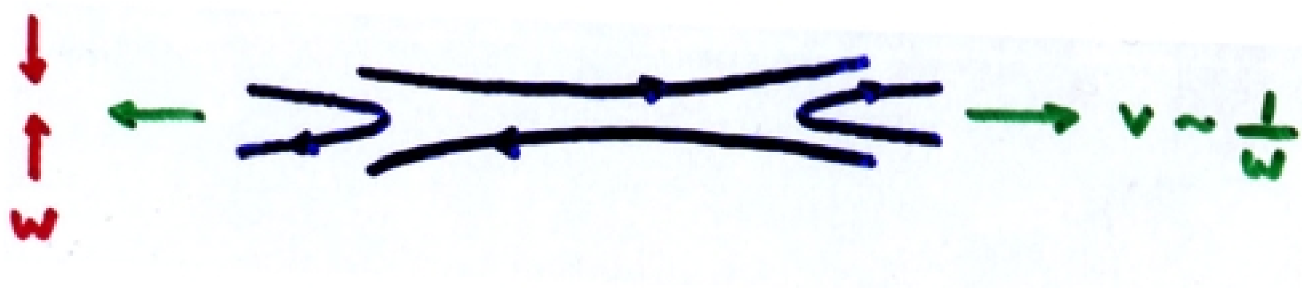
$$\omega \sim k^2$$

$$v_p \sim k$$

  - smaller scales have higher velocities
- Key to understanding kinetic reconnection
  - insensitivity of rate of reconnection to the mechanism which breaks the frozen-in condition
  - absence of macroscopic nozzle

Sensitivity of reconnection to dissipation mechanism

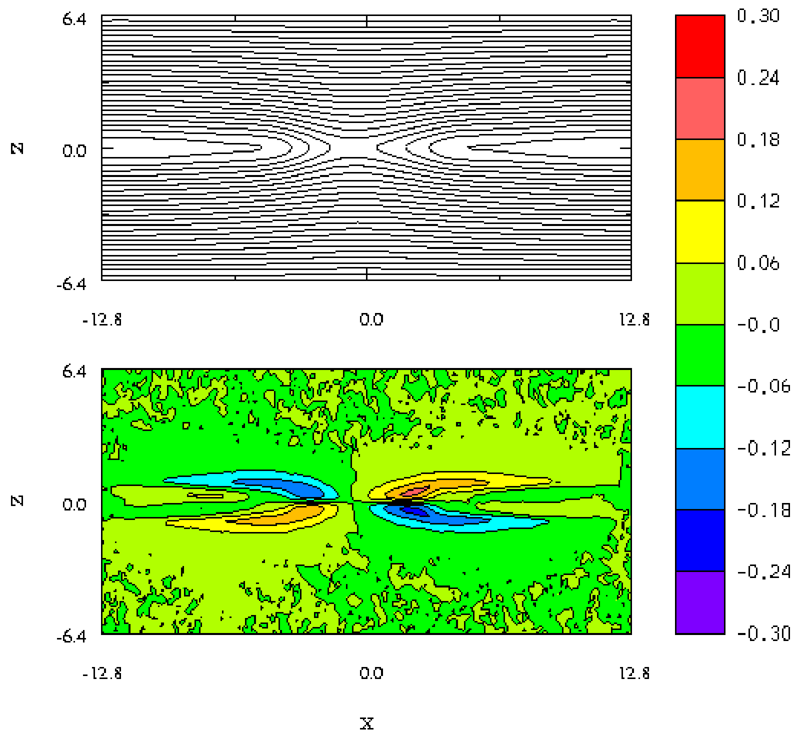
- Assume frozen-in condition broken at scale w



- plasma flux from x-line ~ vw
  - independent of scale w
  - plasma flux independent of mechanism which breaks frozen-in condition

Whistler signature

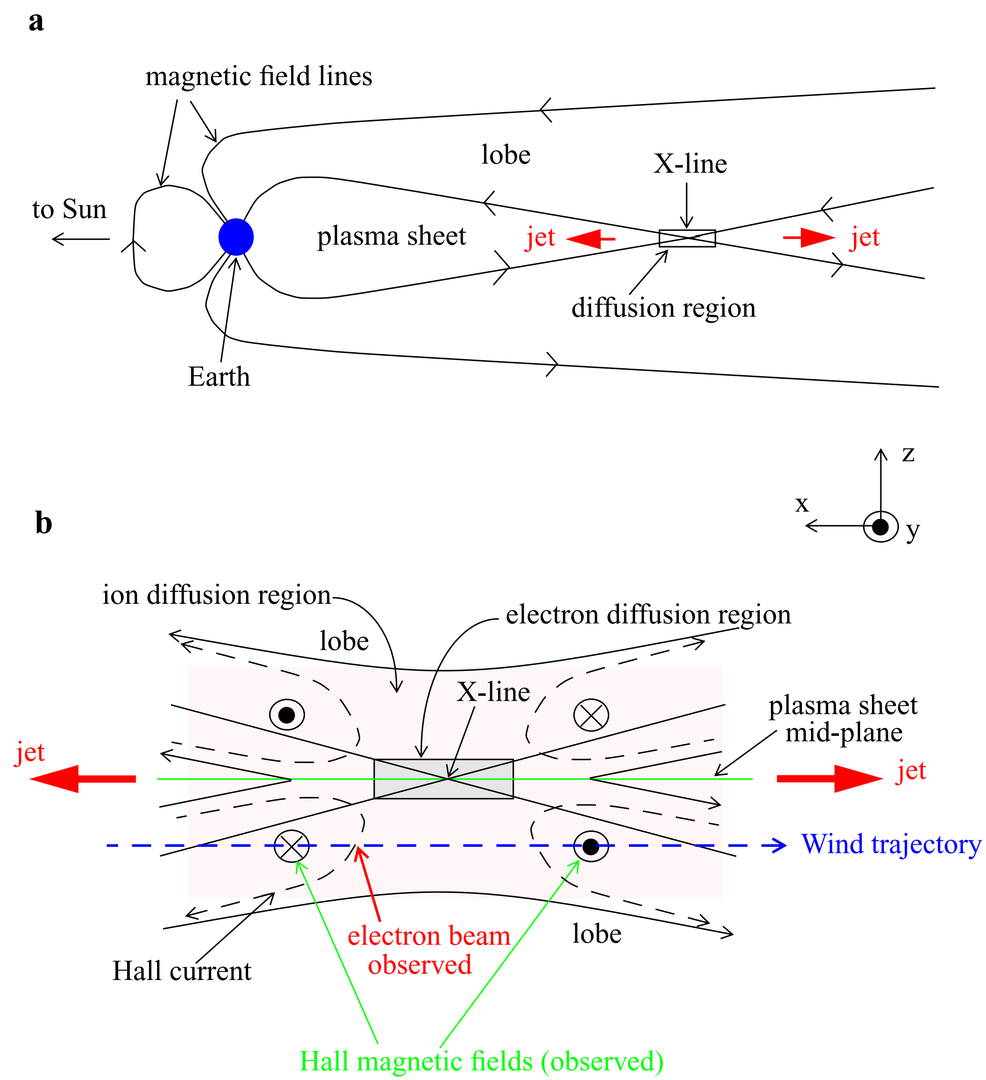
- Magnetic field from particle simulation (Pritchett, UCLA)



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

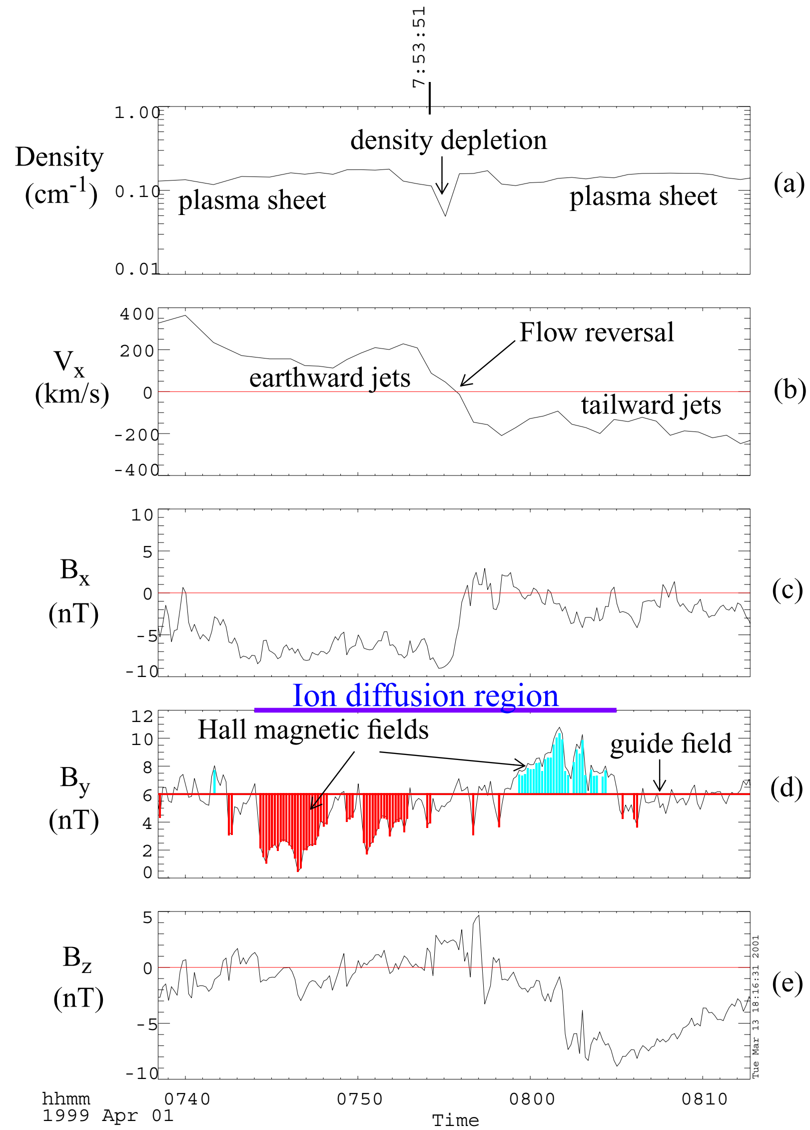
Observational Support for Whistler Wave Role in Reconnection

- Recent encounter of Wind spacecraft with reconnection site in the Earth's magnetotail (Oeierset, et al., 2001)



Magnetic Field Data from Wind

- Out-of-plane magnetic fields seen as expected from standing whistler

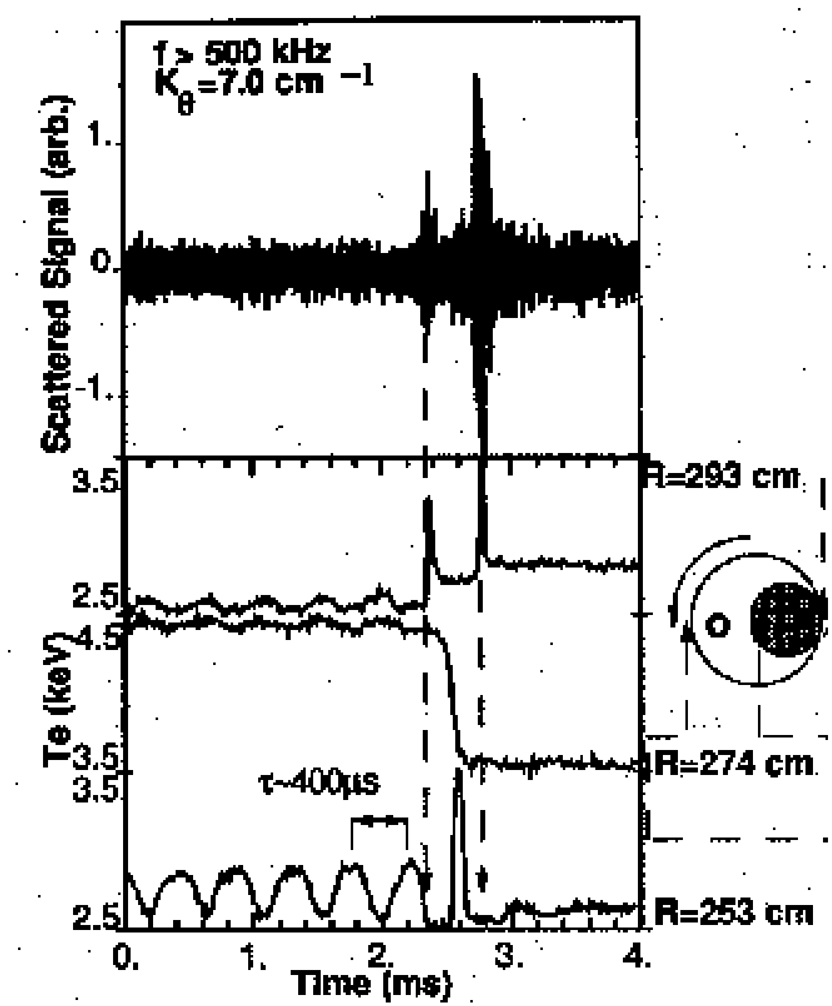


Important Unresolved Issues

- Turbulence and anomalous resistivity
  - Is the widely invoked "anomalous resistivity" a reality?
  - Strong currents driven near the x-line drive turbulence
    - observed during sawtooth crash and at the Earth's magnetopause
    - scattering of particles by intense electric fields produce an effective resistivity
- Production of energetic particles
  - Why are so many energetic electrons produced?
    - Particle scattering produces strong heating

Observations of turbulence during the sawteeth

- Turbulence measured near the x-line during the sawtooth crash
  - microwave scattering on TFTR (Nazikian, et al., 1991)
- What is the drive mechanism for the turbulence?
- Does the turbulence cause anomalous resistivity
- Requires exploration of reconnection in 3-D geometry

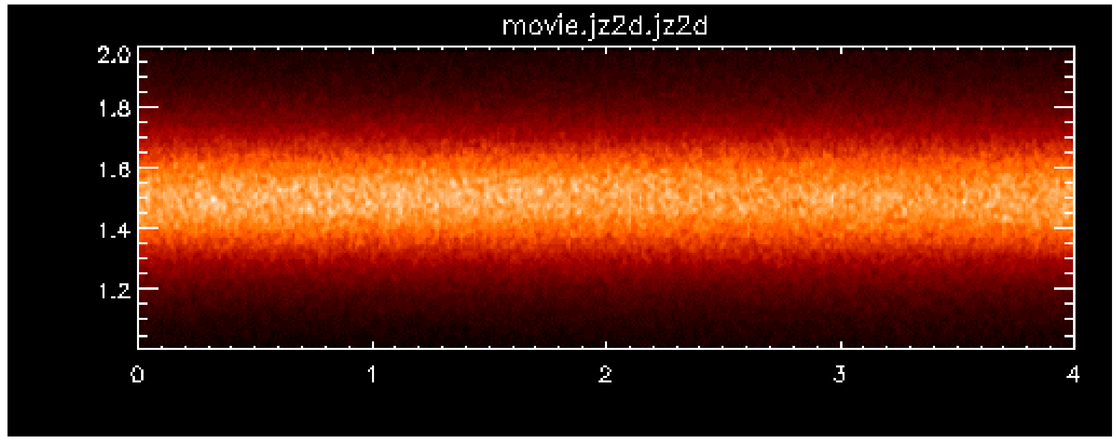


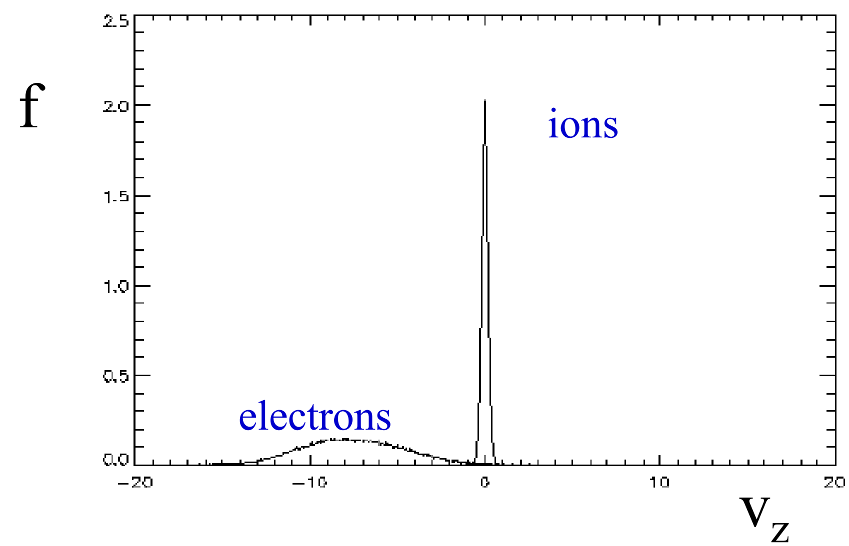
Observational Challenges (heating and energetic particle production)

- What controls electron and ion heating?
  - Ion heating observed during reconnection in the Reversed Field Pinch and more recently in the NSTX Spherical Torus.
    - Strong ion heating seen even in the 2-D reconnection models
    - Characteristic reconnection flows exceed ion thermal speeds
      - a variety of mechanisms for heating ions
  - The production of large numbers of energetic electrons are seen during solar flares and in other astrophysical systems
    - heating by waves (Miller, et al., 1999)?
    - Remains poorly understood

Turbulence and particle energization in 3-D Magnetic Reconnection

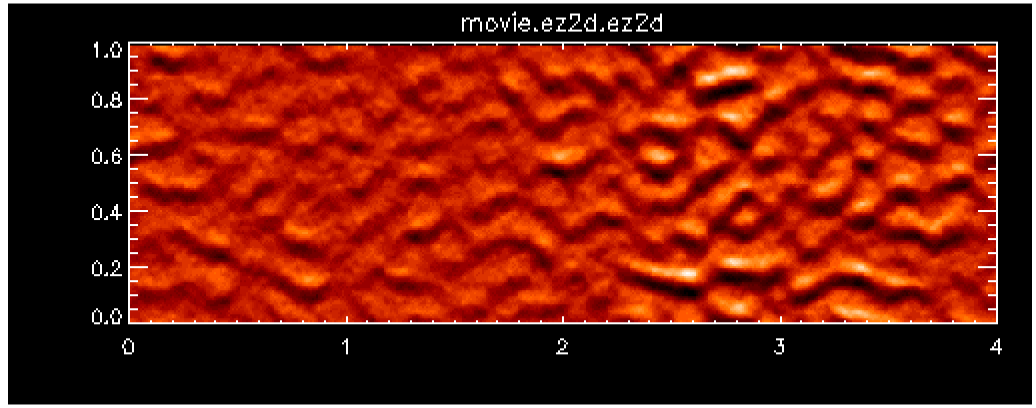
- Large electron streaming near the x-line
  - drives strong turbulence
- Full particle simulation on a 512 x 256 x 128 grid with 670 million particles
  - new computational tools enabling exploration of new physics

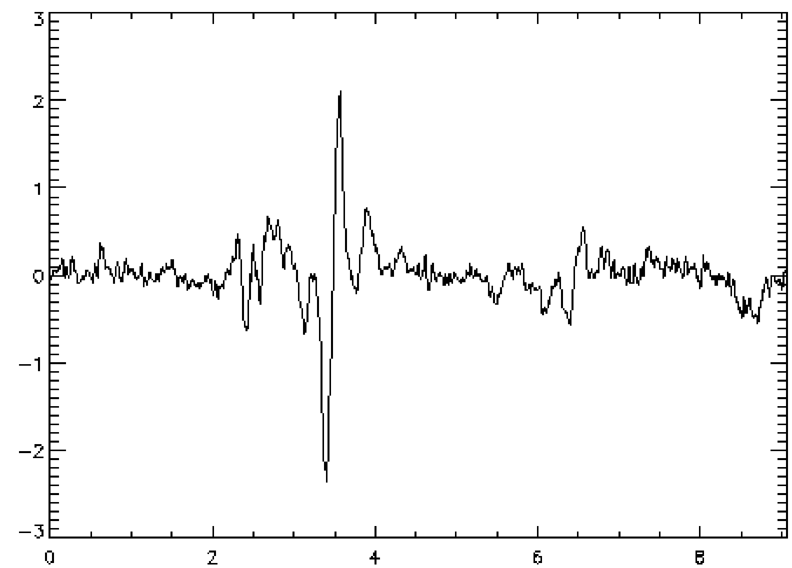




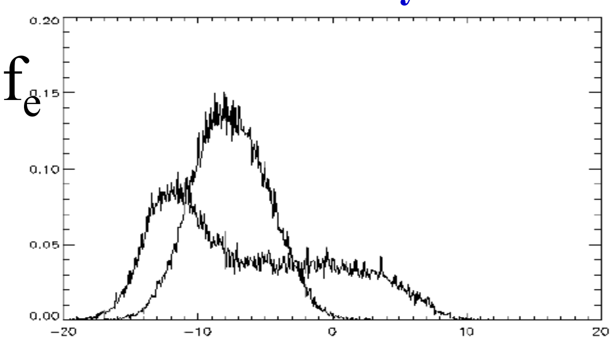
Development of electron holes and particle scattering

- Electron beams generate two-stream instability
  - nonlinear evolution into electron holes
    - localized regions of intense anti-parallel electric field
  - strong electron scattering



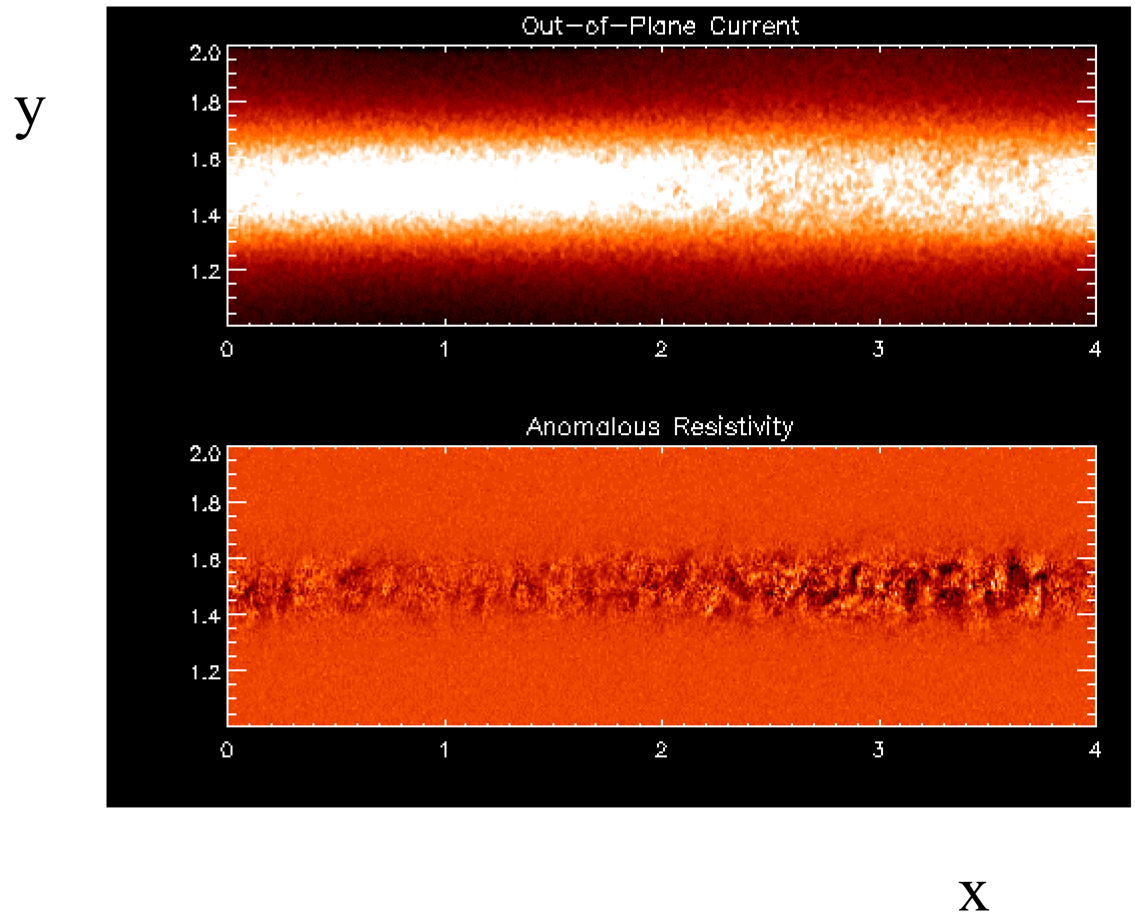


Electron velocity distribution



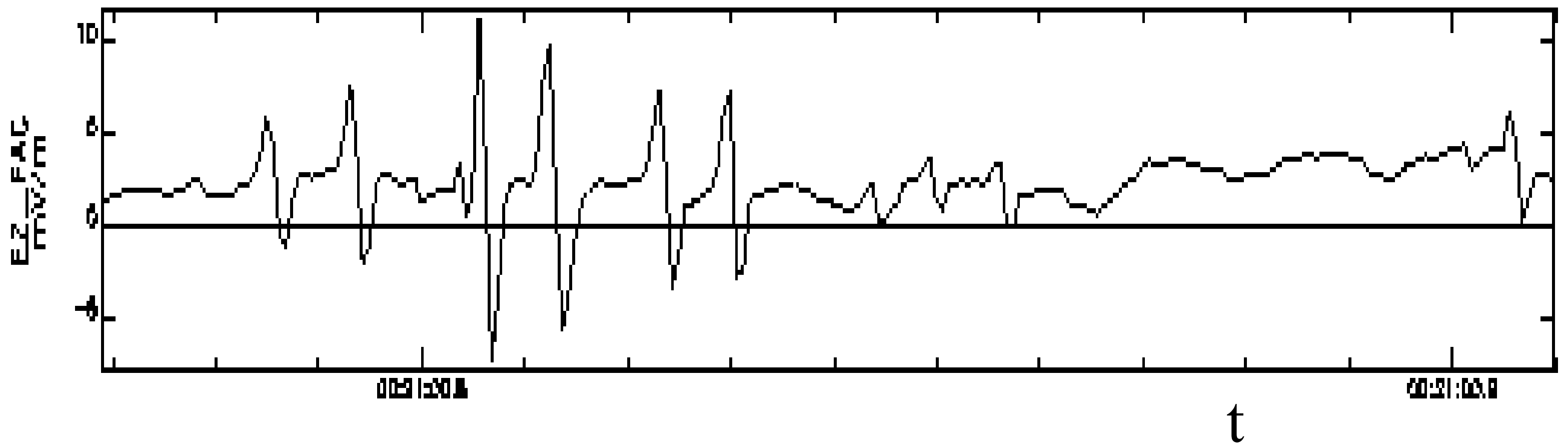
"Anomalous resistivity" due to scattering by parallel electric fields

- Enhanced resistivity has a complex spatial and temporal structure with positive and negative values
  - not expected

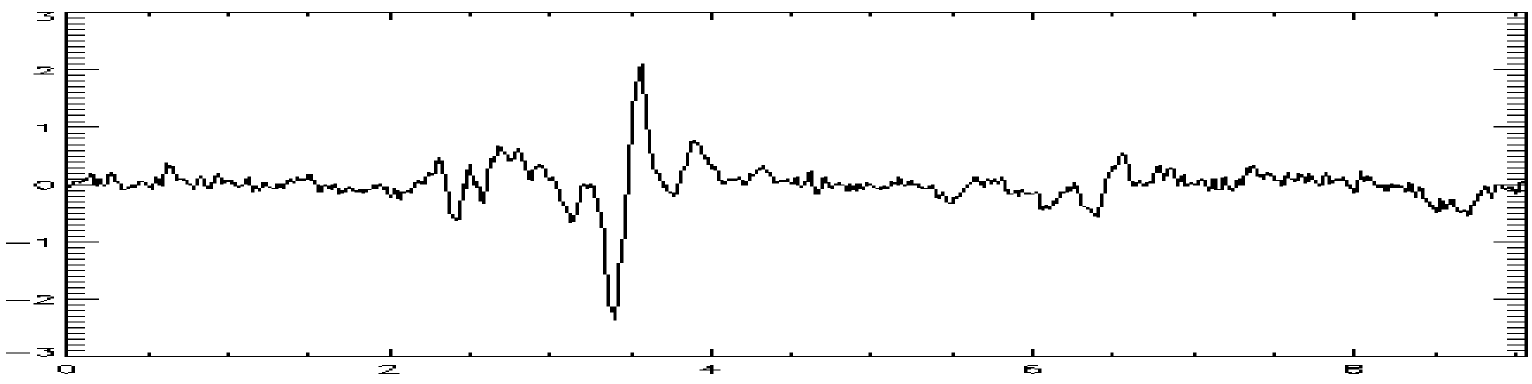


Observational evidence for electron holes

Polar satellite observations at the magnetopause (Cattell, et al., 2002)



Cut through the computational domain



Computational Challenge

- Magnetic reconnection is intrinsically a multi-space and multi-time scale problem
  - macroscales must be included to correctly describe stability in fusion as well as space/astrophysical plasma
  - coupling to dispersive waves essential to describe reconnection in real physical systems
  - sharp boundary layers which develop become turbulent
    - high frequency and short-scale lengths are a generic consequence
- The clear separation of micro-scale and macro-scale phenomena does not exist
- Essential to develop the computational tools to treat these multi-scale problems

Conclusions

- Fast reconnection depends critically on the coupling to dispersive waves at small scales
  - rate independent of the mechanism which breaks the frozen-in condition
  - inflow velocities rate independent of all kinetic scales $\sim 0.1\ C_A$
- The role of turbulence at self-generated boundary layers and the role of anomalous resistivity is not well understood.
  - New observational and computational evidence for the self-generation of electron holes and associated anomalous resistivity
    - An exciting new development facilitated by the synergistic interaction of experiment and theory
    - Mechanism for electron heating in laboratory and astrophysical systems?
    - Can energetic electrons be measured in laboratory experiments?

Conclusions (cont.)

- Trigger for the onset of reconnection remains poorly understood and may not be generic.
- Reconnection during the sawtooth crash sometimes remains incomplete in spite of the complete expulsion of the hot core plasma. Why?
  - Role of secondary instabilities?
- Strong coupling between theory/computation and laboratory and astrophysical observations essential to confront theoretical predictions and to resolve outstanding questions.
- Exploring magnetic reconnection is intrinsically a multi-space and time scale computational problem
  - development of boundary layers and secondary instabilities link macro and micro scales