The Cross-field Current Instability for Substorm Expansion Onset: A Journey Started with Dennis Papadopoulos

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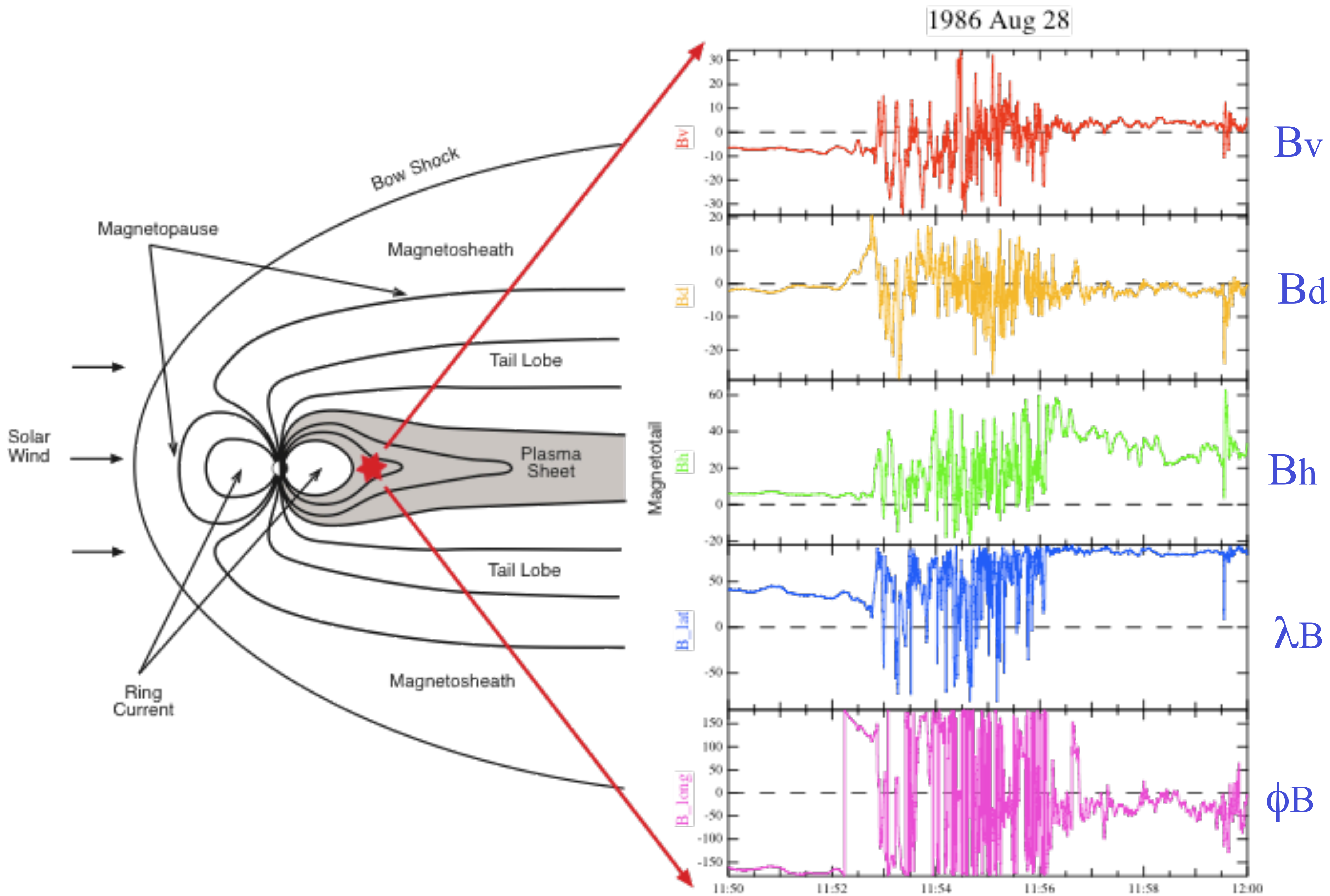
Outline

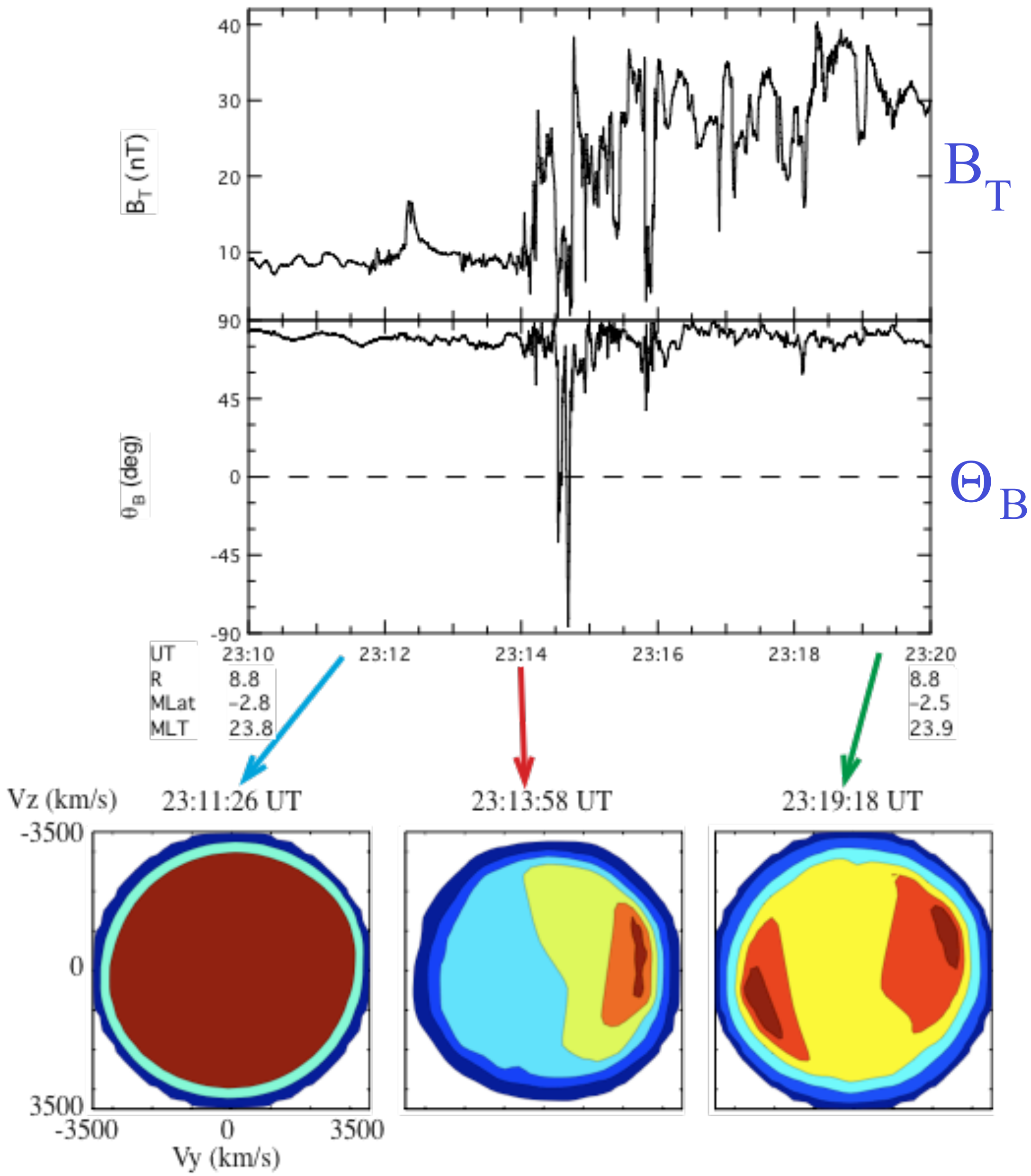
- **Observations of near-Earth substorm phenomena**
- **Kinetic instabilities - theoretical expectations**
- **1D PIC Simulation Results:**

  Ion Weibel and Modified Two Stream
- **2D PIC Simulation Results: Drift kink/sausage**
- **Implications**

Current Disruption and Dipolarization



Current Disruption - ions

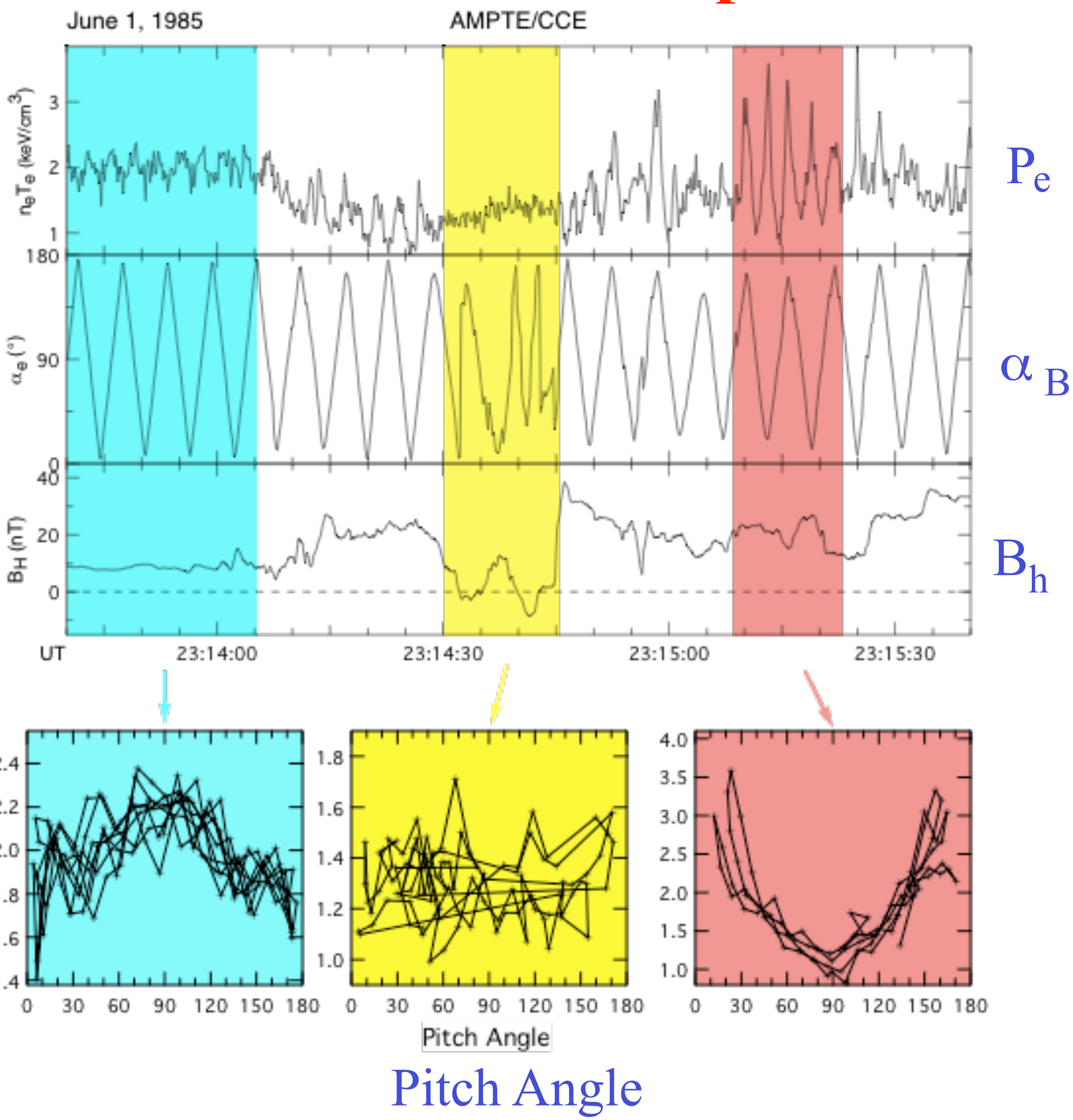


Ion Velocity Distribution

- **The CD activity was observed very near the neutral sheet as indicated by the θ_B component being nearly 90° in the whole interval.**
- **A strong duskward flow of ions occurred before CD activity - strong cross-tail current.**
- **The ions were heated perpendicular to the magnetic field at the end of CD.**

Lui et al. [1988]

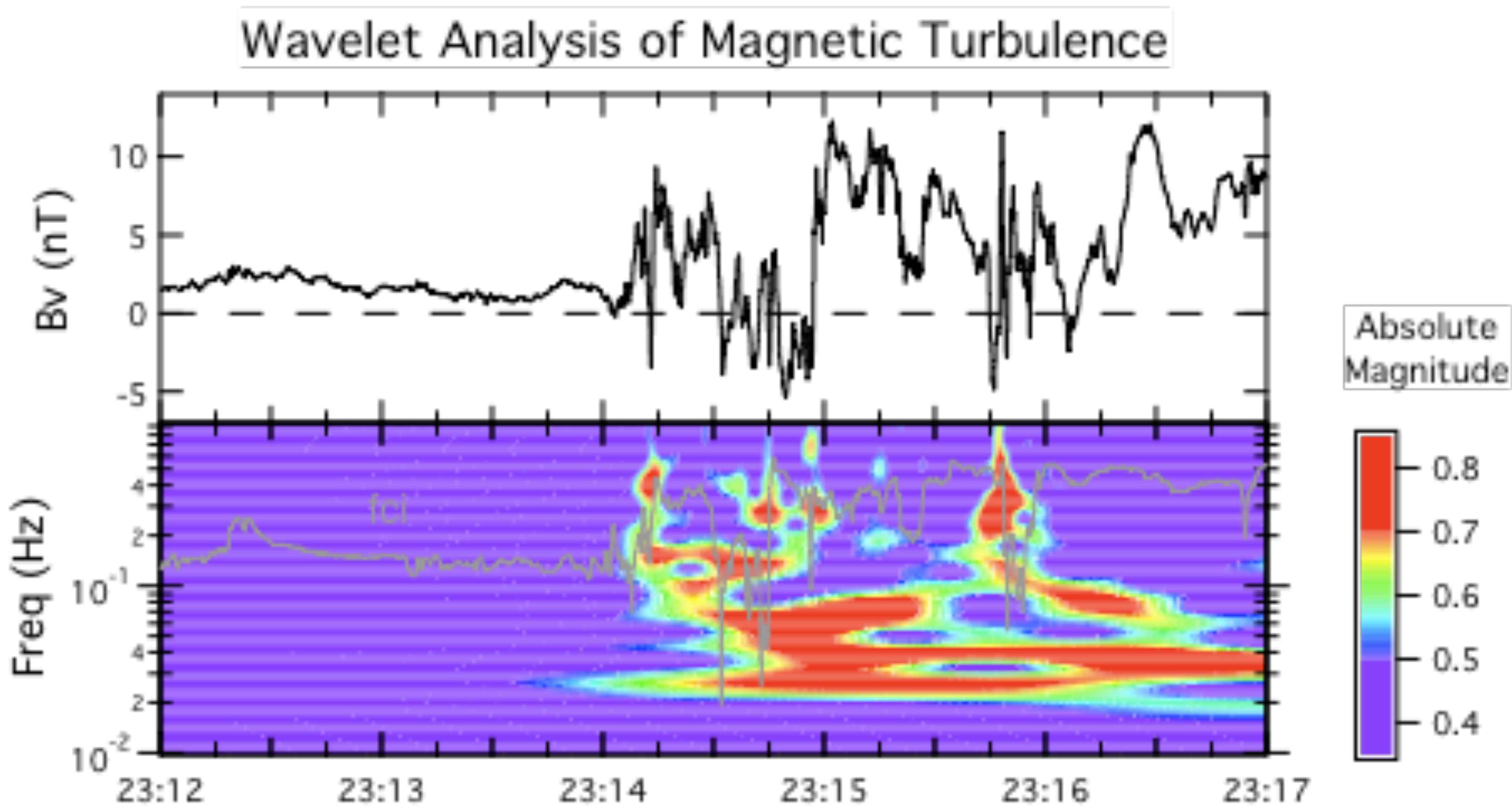
Current Disruption - electrons



- **Electrons show trapped pitch angle distribution (peak flux at 90º) before current disruption.**
- **Electrons have isotropic pitch angle distribution for a short period during the early stage of current disruption.**
- **Electrons are accelerated parallel to the magnetic field during the late stage of current disruption.**

Wavelet Analysis

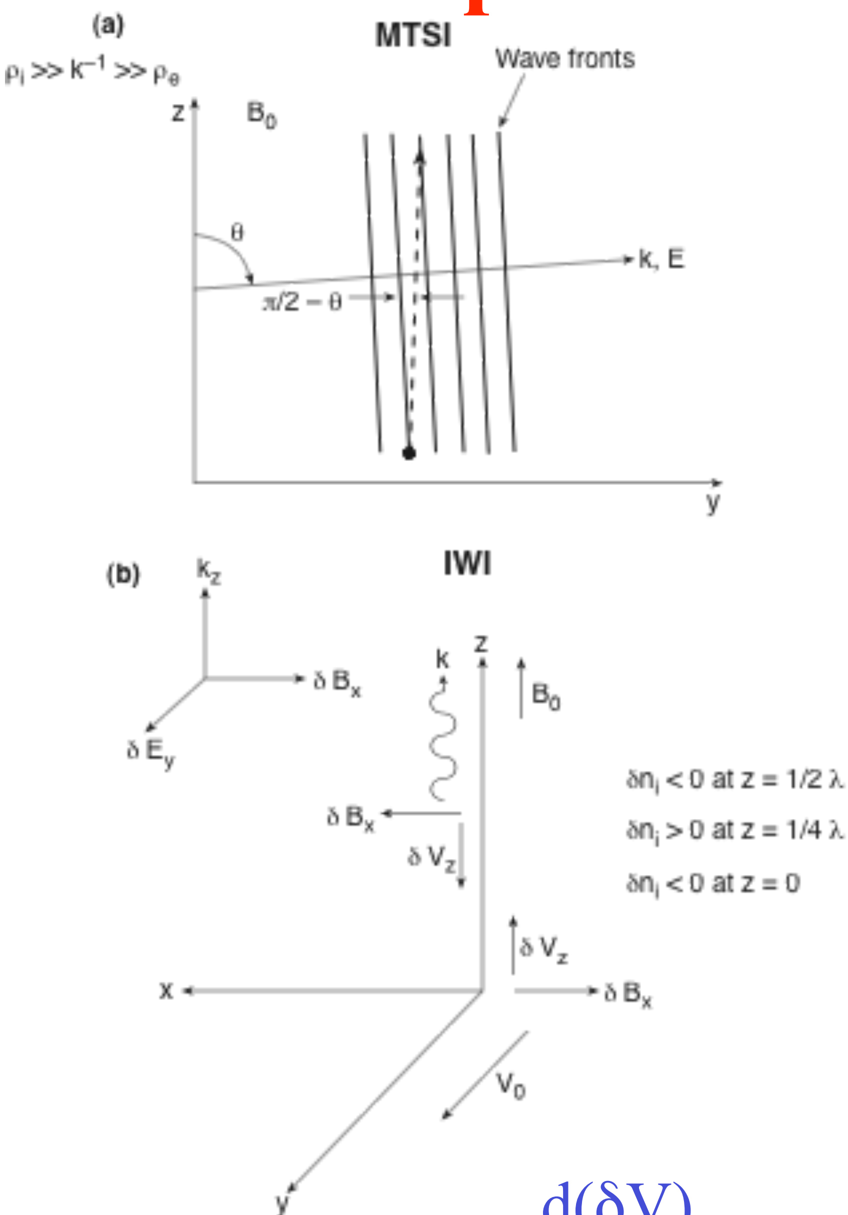
- Wavelet analysis shows multiple frequency components, inverse cascade, and intermittency in current disruption.



Time

Lui and Najmi [1997]

A Simplified Physical Picture of CCI

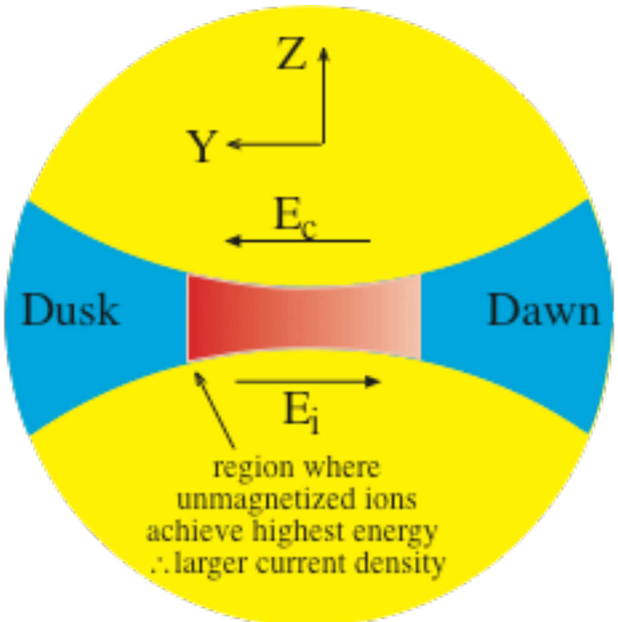


Lui, Mankofsky, Chang, Papadopoulos, Wu, JGR, 1990.

Lui, Chang, Mankofsky, Wong, and Winske, JGR, 1991.

$$m_i \frac{d(\delta V)}{dt} = q(\delta E + V_o \times \delta B + \delta V \times B_o)$$

Substorm Features From CCI Mechanism

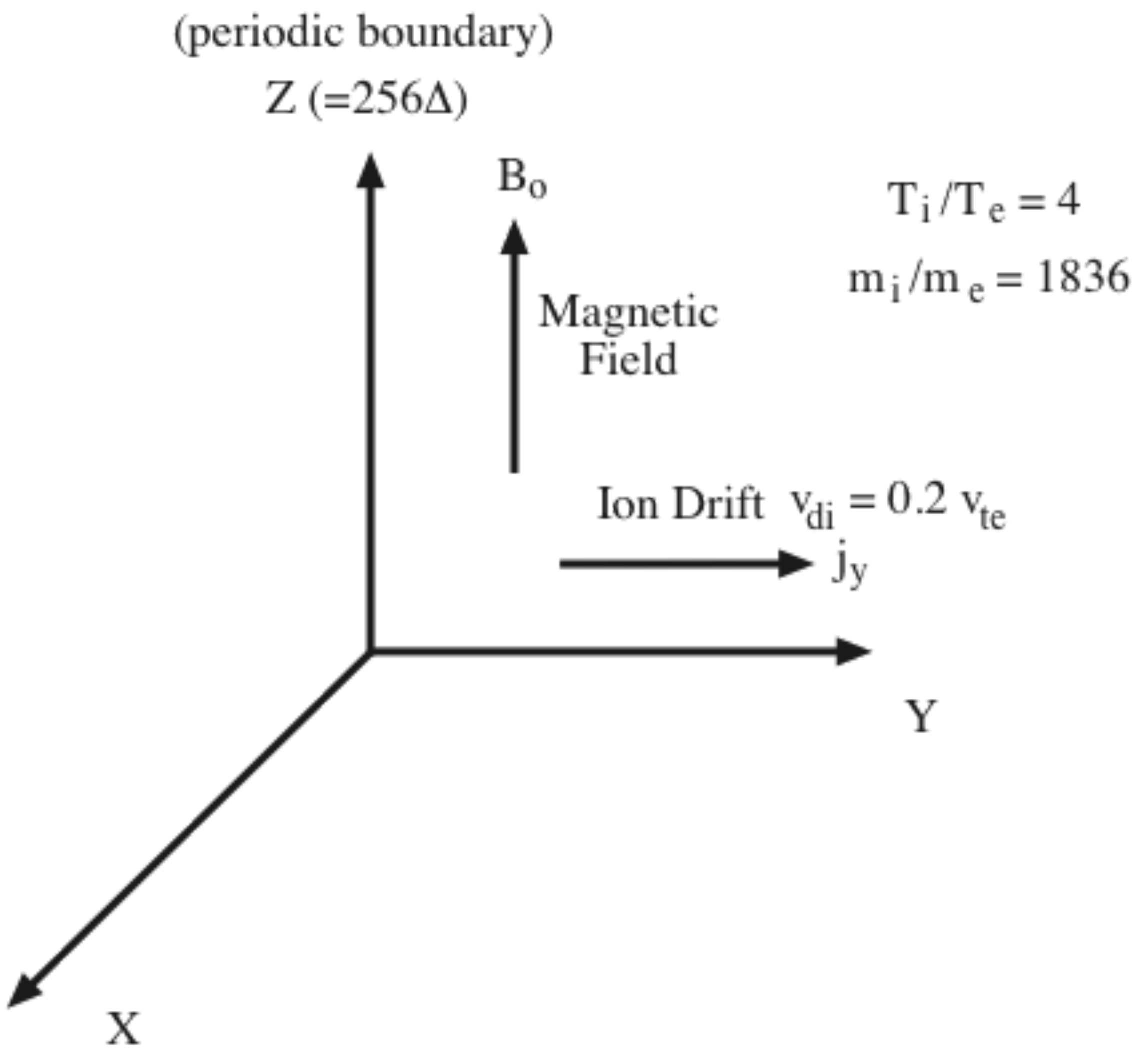


E_c = Cross-tail electric field due to solar wind magnetosphere dynamo
E_i = induced electric field from increase in tail lobe magnetic flux

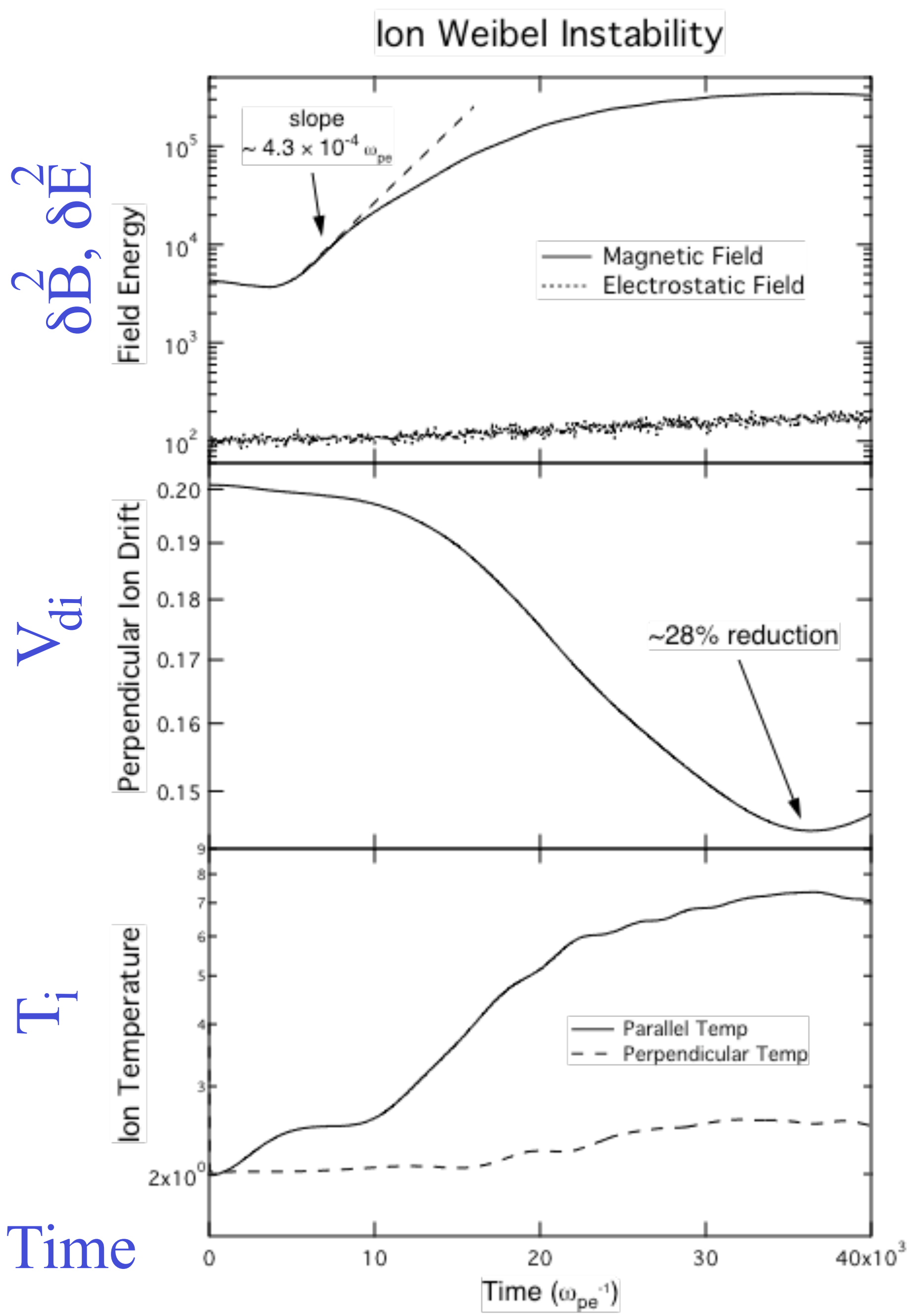
- **CCI can explain naturally why substorm onset location is preferentially skewed towards the pre-midnight local times.**
- **Its onset is tied to an existing auroral arc (Samson et al., 1991).**
- **Even though CCI is an internal mechanism, it can explain naturally why northward turning of IMF after a period of southward IMF can trigger a substorm:**

  Ei during substorm growth phase (southward IMF) can substantially reduce Ec and a northward turning of IMF reduces cancelling of Ec by Ei, allowing ions to pick up more energy and thus producing a larger current density to start CCI.

Simulation Setup: 1D Ion Weibel Instability

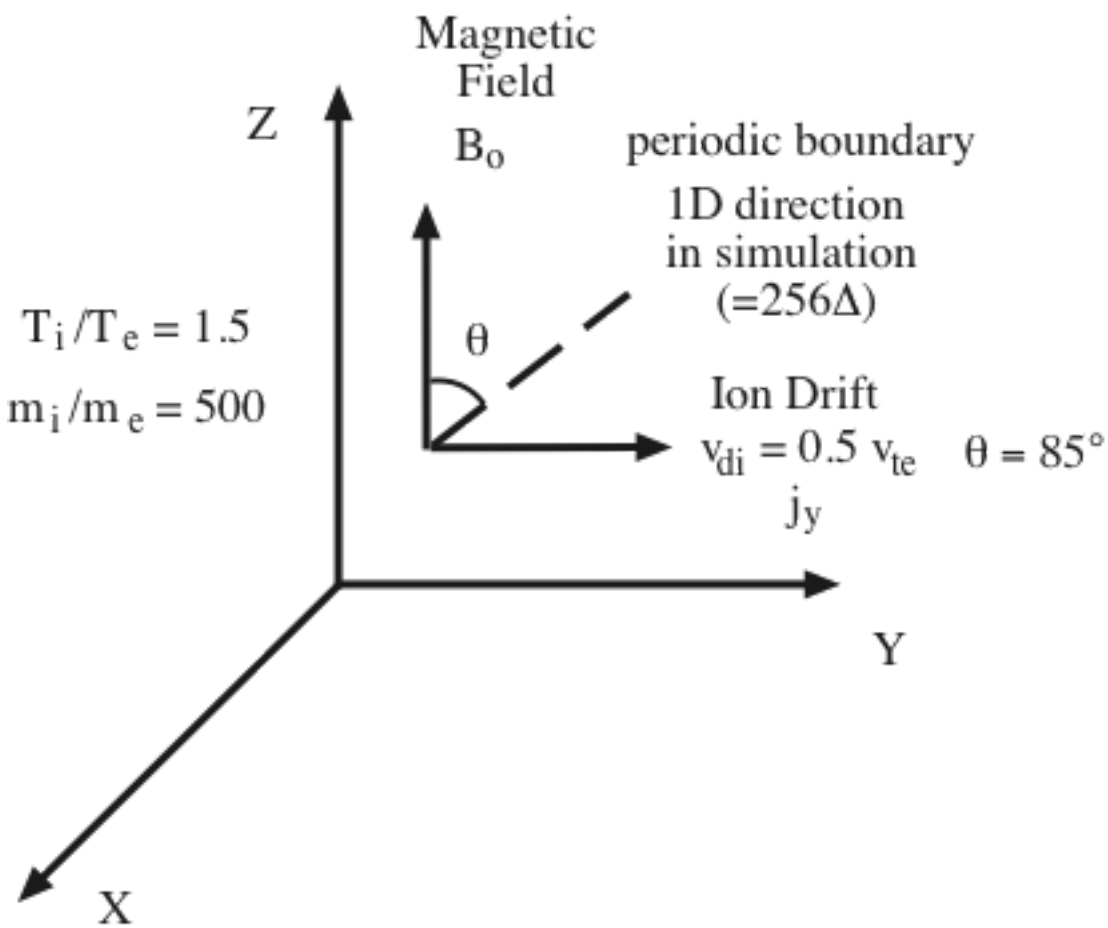


Simulation Results



- IWI is a purely growing electromagnetic mode with a theoretical growth rate for this set up to be $\gamma \sim (v_{di}/c)\ \omega_{pi} \sim 2.2 \times 10^{-4}\ \omega_{pe}$. For energy, the growth rate is $2\ \gamma \sim 4.4 \times 10^{-4}\ \omega_{pe}$.
- The simulated growth rate ($2\ \gamma \sim 4.3 \times 10^{-4}\ \omega_{pe}$) compares well with the theoretical expectation.
- Current density reduces by ~28% in this case with ions heated mainly in the parallel direction.
- These features are in good agreement with the nonlinear evolution of IWI from the theoretical quasi-linear calculation given in Lui, Yoon, and Chang (1993) although different values of parameters are used in the theoretical calculations.

Simulation Setup:
1D Modified Two Stream Instability



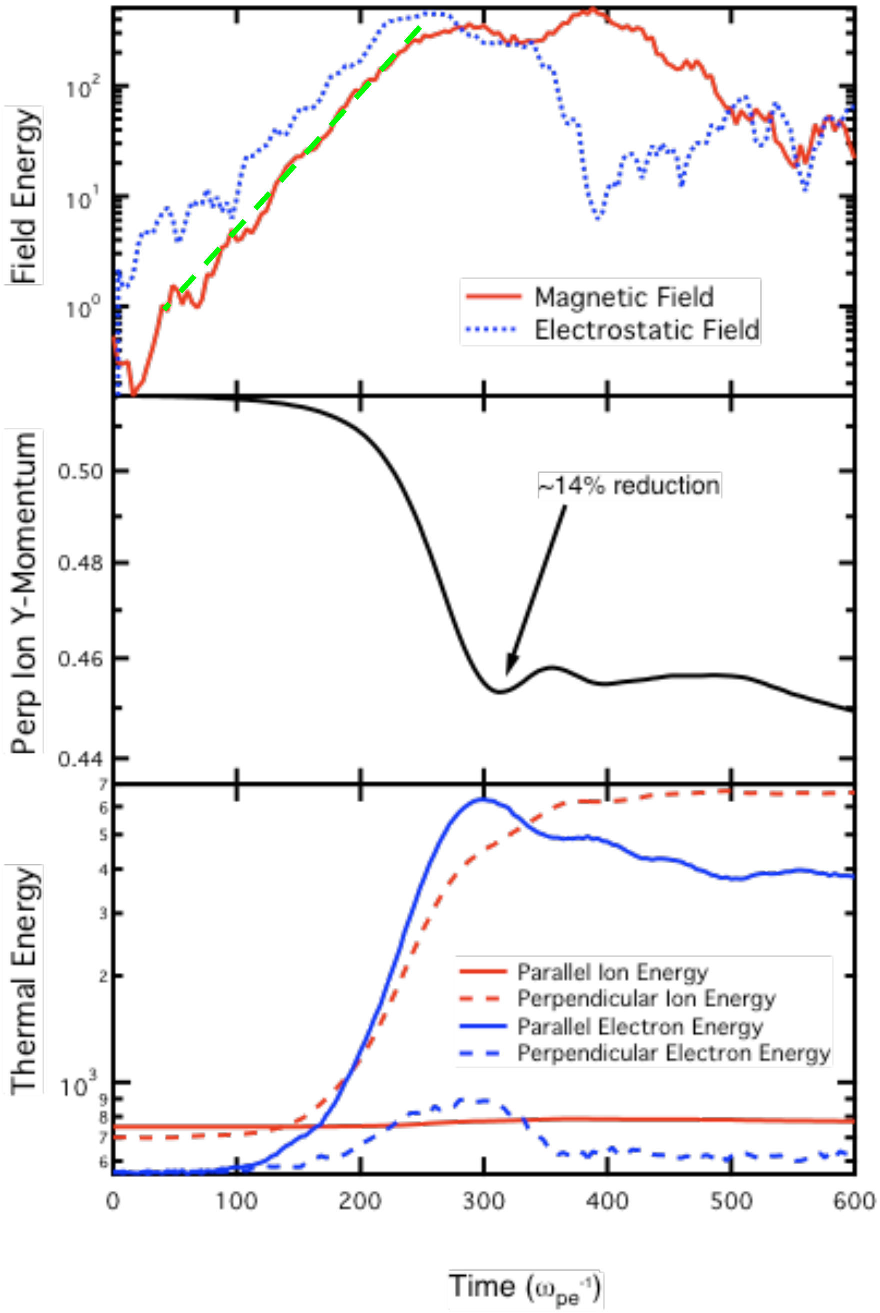
Simulation Results

δE^2 δB^2

V_{di}

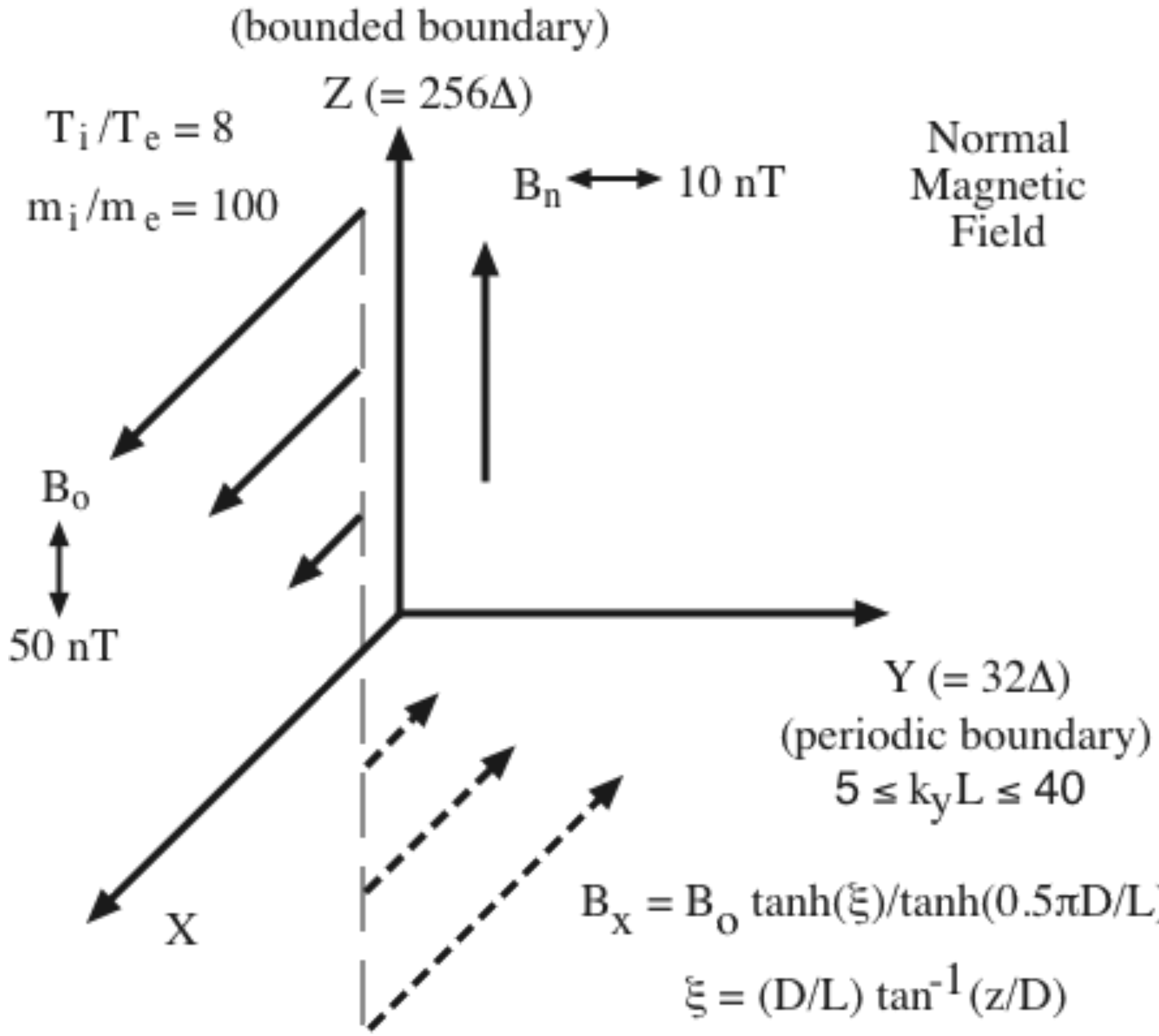
K_e K_i

Time



- **MTSI is a mixed mode with both electromagnetic and electrostatic components (McBride et al., 1972 - only e.s.).**
- **Ions are heated perpendicular to the magnetic field and electrons are heated parallel to the magnetic field.**
- **Theoretical growth rate for this set up to be $\gamma \sim 2.3 \times 10^{-2}\ \omega_{pe}$. For energy, the growth rate is $2\gamma \sim 4.6 \times 10^{-2}\ \omega_{pe}$.**
- **The simulated growth rate ($2\gamma \sim 3.9 \times 10^{-2}\ \omega_{pe}$) compares well with the theoretical expectation.**
- **Current density reduces by ~14% in this case with ions heated mainly in the perpendicular direction and electrons mainly in the parallel direction.**

Simulation Setup: 2D Thin Current Sheet



$B_x = B_o \tanh(\xi)/\tanh(0.5\pi D/L)$

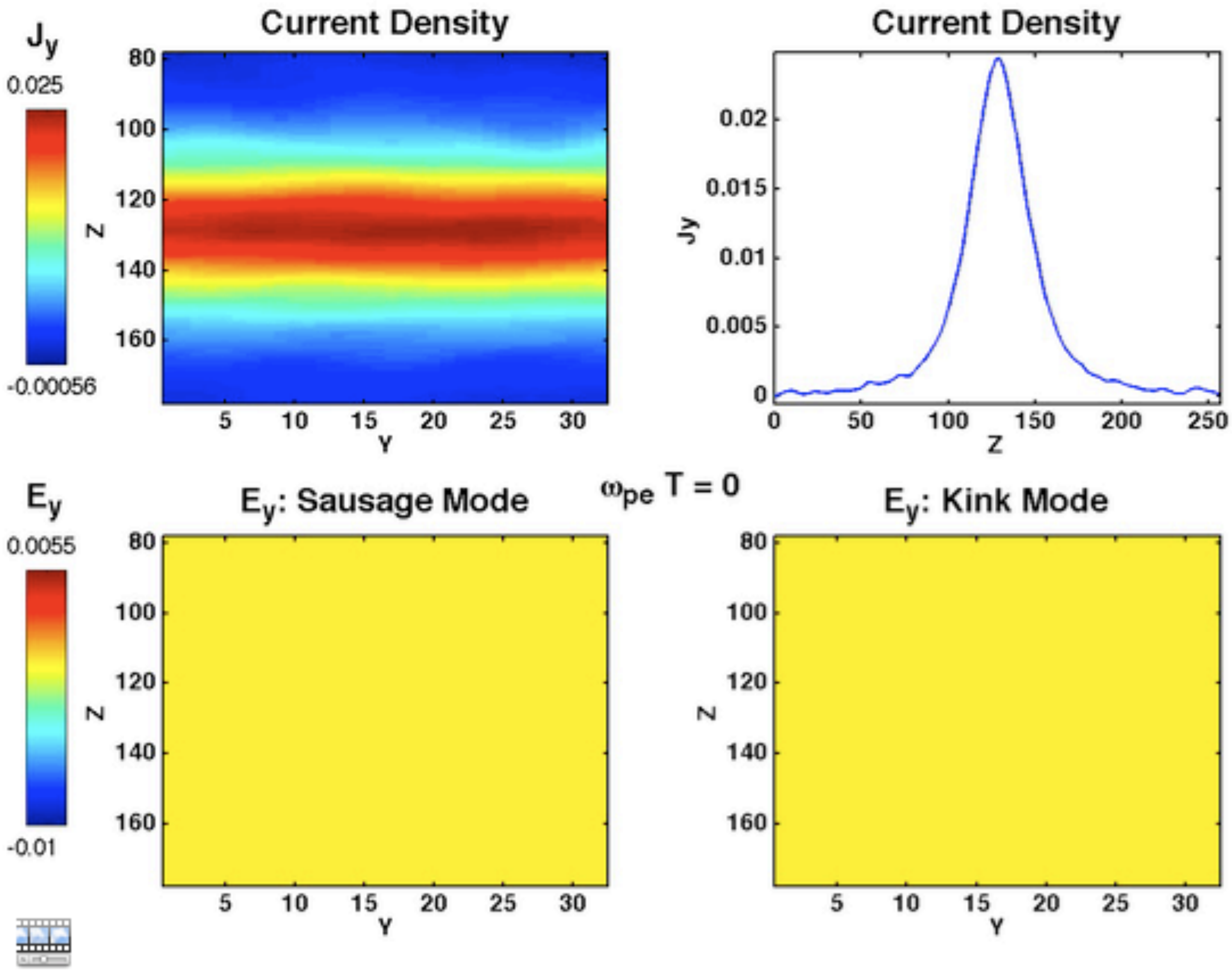
$\xi = (D/L) \tan^{-1}(z/D)$

$B_z = B_n$

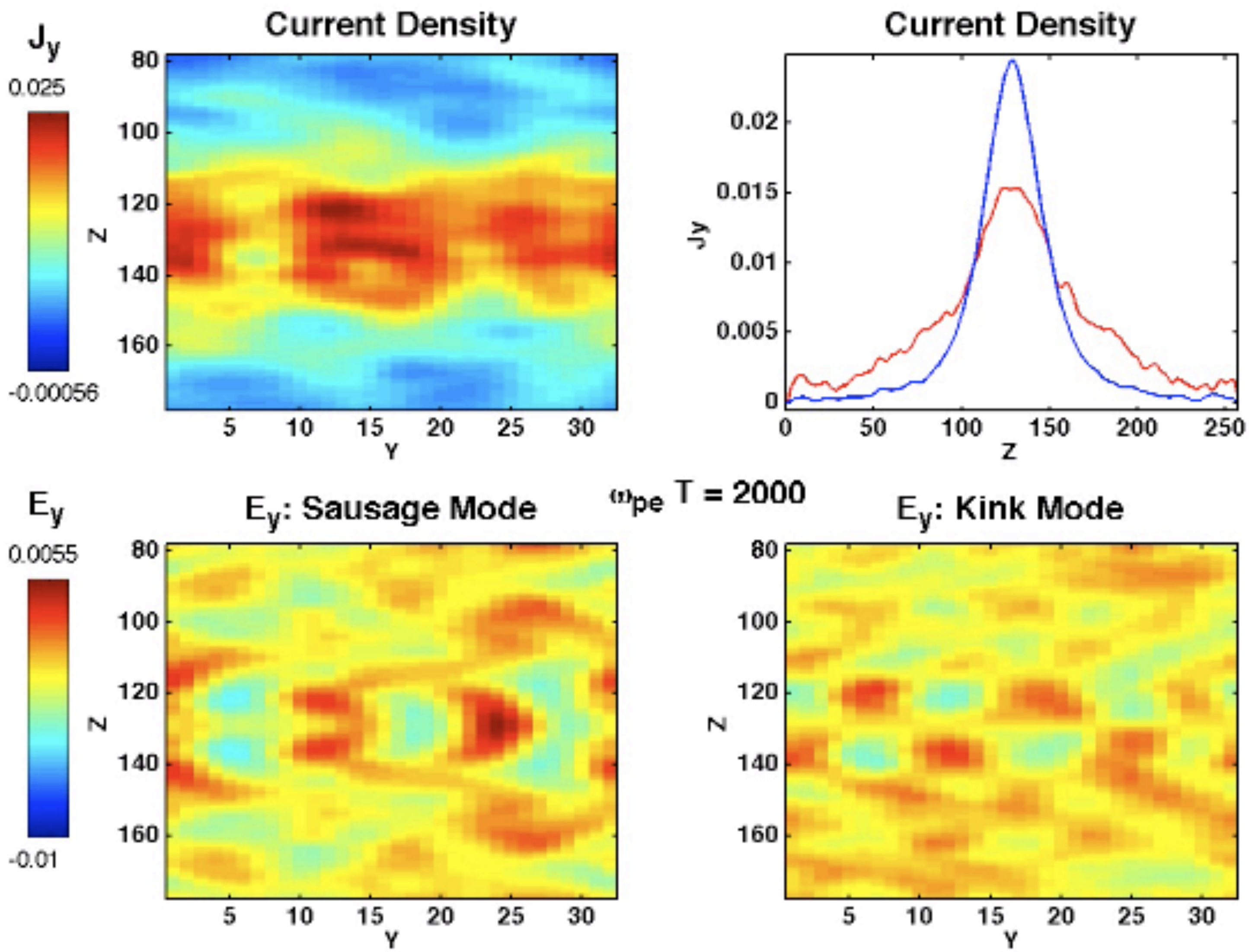
$L \approx 1.3\, \rho_i$

PIC Simulations of Thin Current Sheets

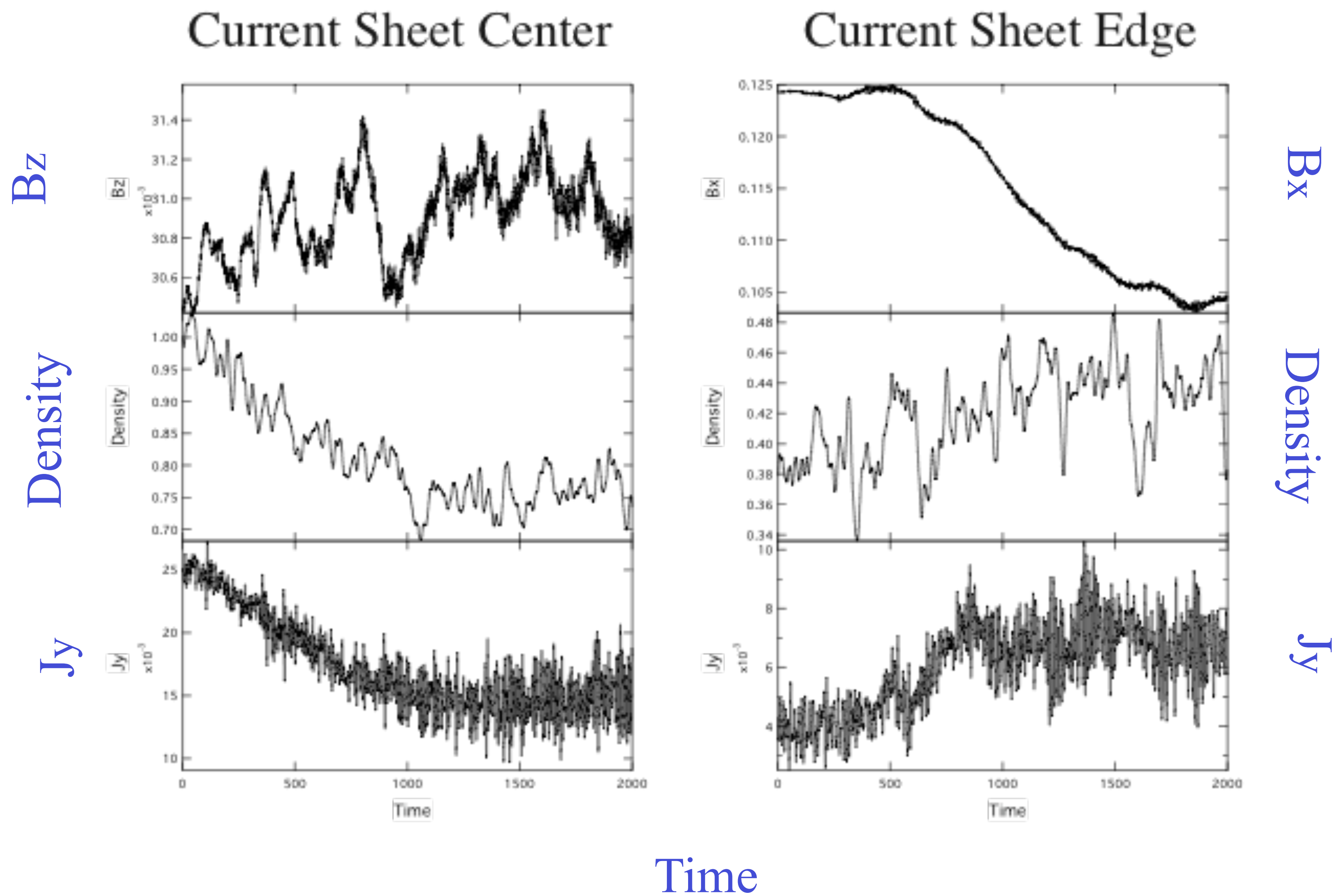
- Many PIC simulations of a thin current sheet have been performed. For example, the pioneering work by Zhu and Winglee [1996] leads to a large number of studies (simulation and theory) on drift kink/ sausage instability [Pritchett et al., 1996; Lapenta and Brackbill, 1997; Yoon et al., 1998; Daughton, 1999; Horiuchi and Sato, 1999; Shinohara et al., 2001]. Most of these studies deal with a current sheet (Harris current sheet) without a B_n component and/ or without a velocity peak in the current sheet center.
- This simulation differs from others by investigating a current sheet with a strong B_n component and a Lorentz velocity profile which resembles near-Earth current sheet just prior to current disruption onsets.



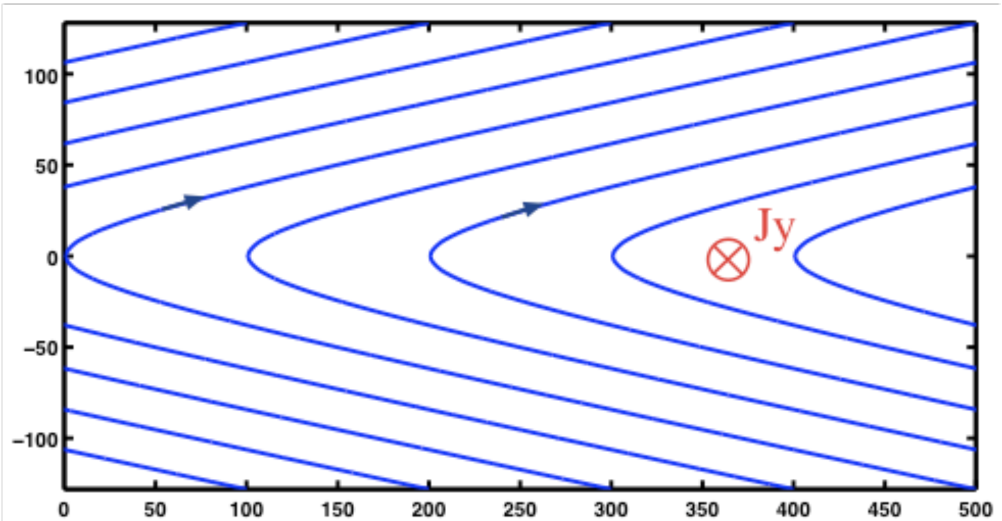
Current Density
Current Density
J_y
0.025
-0.00056
80
100
120
140
160
Z
5
10
15
20
25
30
Y
0.02
0.015
0.01
0.005
0
Jy
0
50
100
150
200
250
Z
ω_{pe} T = 0
E_y: Sausage Mode
E_y: Kink Mode
E_y
0.0055
-0.01

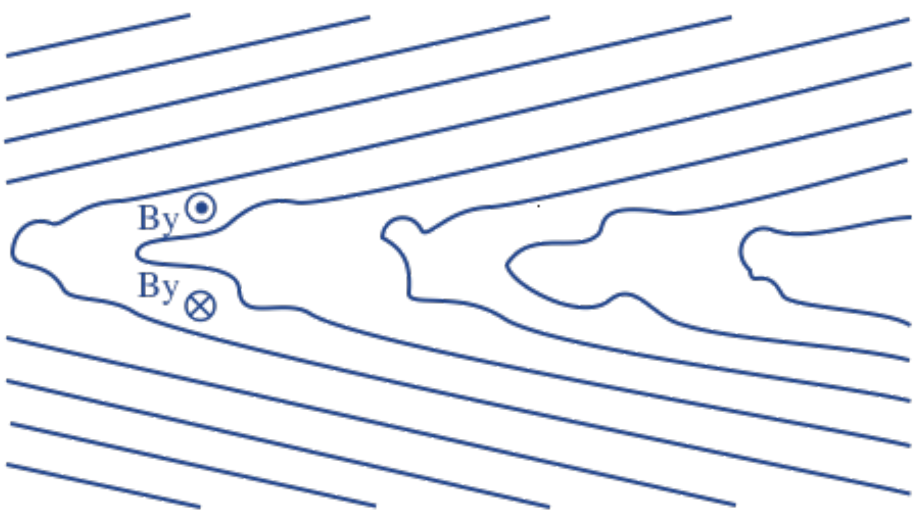

Current Density
Current Density
J_y
0.025
-0.00056
Z
Y
Jy
Z
ω_{pe} T = 2000
E_y
0.0055
-0.01
E_y: Sausage Mode
E_y: Kink Mode
80
100
120
140
160
5
10
15
20
25
30
0
50
100
150
200
250
0.005
0.01
0.015
0.02

Local Plasma Parameter Fluctuations



Schematic of Current Sheet Development





- The waves excited by CCI are oblique whistlers (Lui et al., 1991) and at the nonlinear stage, the electrons are pulled in the direction of ion bulk motion for current reduction. Therefore the out-of-the-plane magnetic field component (B_y) from CCI development has the same sense as that of the earthward part of a magnetic reconnection region. This B_y pattern is therefore not unique to neither this plasma instability process nor magnetic reconnection.

Summary-1

- **PIC simulations (1D and 2D) of the cross-field current instability have been performed. These simulations are different from almost all previous current sheet simulations because of the presence of a strong Bz component normal to the current sheet and a substantial velocity shear.**
- **The numerical experiments are first designed to examine the Ion Weibel and Modified Two Stream Instabilities in a 1D geometry:**

  the linear phase of these instabilities compares well with earlier linear analysis [Lui, Mankofsky, Chang, Papadopoulos, and Wu, 1990];

  the nonlinear evolution of these instabilities compares well with earlier quasi-linear calculations [Lui, Yoon, and Chang, 1993; Yoon and Lui, 1993].

Summary-2

- **For the 2D simulation, we adopt the current sheet configuration with a velocity shear at the current sheet center and a strong ($B_z = B_o/5$) magnetic field normal to the current sheet as documented in Lui et al. [1995] and Yoon and Lui [1996]:**

  reduction in the current density at the current sheet center, broadening of the current sheet, current sheet flapping (from the drift kink/sausage modes), B_y development, current filamentation, and particle acceleration are seen in the nonlinear stage of the development. These developments are quite encouraging in comparison with observations of current disruption in the near-Earth magnetotail.
- **Further evaluation of these instabilities as the substorm onset process requires a 3D simulation.**

I deeply appreciate Dennis Papadopoulos for enhancing tremendously my career by teaching me about kinetic plasma physics and plasma simulation