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Onset of Fast Reconnection in Laboratory and Space Plasmas

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Center for Integrated Computation and Analysis of Reconnection and Turbulence (CICART)

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Outline

- What is magnetic reconnection? Why is it important?
- Brief history
- Onset of fast reconnection or the "trigger problem": applications to fusion/laboratory experiments, and to space and astrophysical plasmas.
- Hall (or extended) MHD model and the solutions it offers to the trigger problem.
- What stabilizes or quenches fast reconnection?
- Role of secondary instabilities of thin current sheets mediating reconnection in *large* systems.

What is Magnetic Reconnection?

If a plasma is perfectly conducting, that is, it obeys the ideal Ohm's law,

$$\mathbf{E} + \mathbf{v} \times \mathbf{B}/c = 0$$

B-lines are frozen in the plasma, and no reconnection occurs.

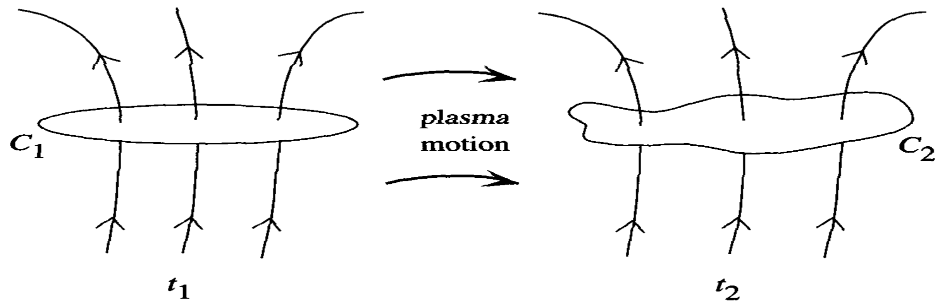


Fig. 1.6. Magnetic flux conservation: if a curve C_1 is distorted into C_2 by plasma motion, the flux through C_1 at t_1 equals the flux through C_2 at t_2.

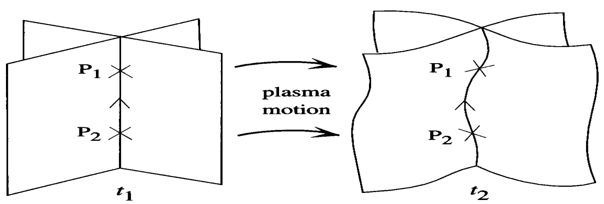


Fig. 1.7. Magnetic field-line conservation: if plasma elements P_1 and P_2 lie on a field line at time t_1, then they will lie on the same line at a later time t_2.

Magnetic Reconnection: Working Definition

Departures from ideal behavior, represented by

$$\mathbf{E} + \mathbf{v} \times \mathbf{B}/c = \mathbf{R}, \quad \nabla \times \mathbf{R} \neq \mathbf{0}$$

break ideal topological invariants, allowing field lines to break and reconnect.

In the generalized Ohm’s law for weakly collisional or collisionless plasmas, **R** contains resistivity, Hall current, electron inertia and pressure.

Example of Topological Change: Magnetic Island Formation

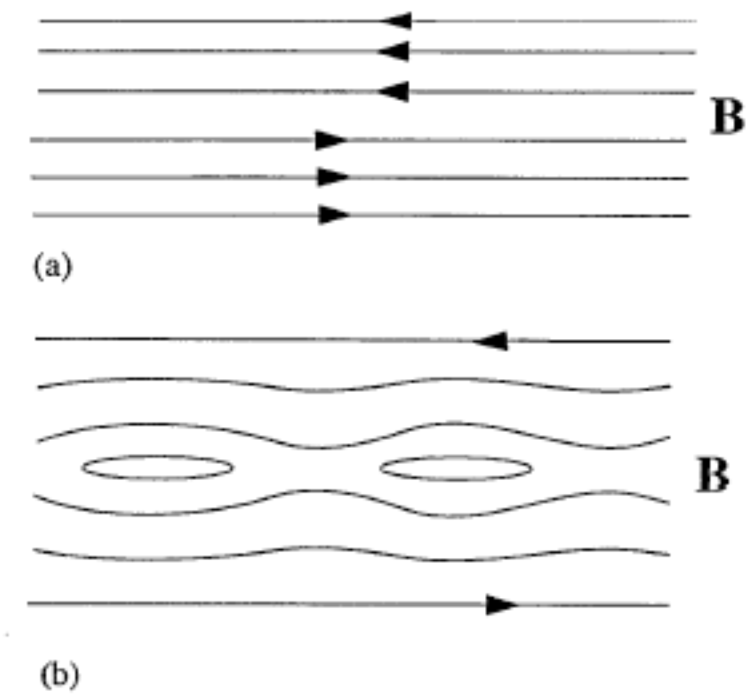


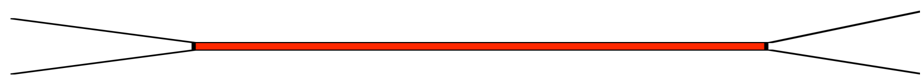
FIG. 1. (a) The topology of field lines in the Harris equilibrium $\mathbf{B}=B_0\tanh(z/a)\hat{\mathbf{x}}$. (b) The topology of field lines when the perturbation $\mathbf{b}=b\sin(kx)\hat{\mathbf{z}}$ is imposed on the Harris equilibrium.

Why is magnetic reconnection important?

- Magnetic reconnection enables a system to access states of lower energy by topological relaxation of the magnetic field. The energy thus liberated can be converted to the kinetic energy of particles and heat. Since the Universe is permeated by magnetic fields (in Nature and the laboratory), magnetic reconnection is a ubiquitous mechanism wherever such phenomena occur, including eruptive stellar/solar flares, magnetospheric storms, and disruptions in fusion plasmas.
- By allowing small-scale, tangled fields to reconnect and forming larger-scale fields, reconnection plays a critical role in the "dynamo effect"----the mechanism most widely invoked on how large-scale magnetic fields in the Universe are spontaneously generated from various types of plasma turbulence. Understanding of fast reconnection is central to the question: "Why is the Universe magnetized?"

Classical (2D) Steady-State Models of Reconnection

Sweet-Parker [Sweet 1958, Parker 1957]



Geometry of reconnection layer : Y-points [Syrovatskii 1971]

Length of the reconnection layer is of the order of the system size >> width Δ

Reconnection time scale

$$\tau_{SP} = \left(\tau_A \tau_R\right)^{1/2} = S^{1/2} \tau_A$$

Solar flares: $S \sim 10^{12}, \quad \tau_A \sim 1s$

$\Rightarrow \tau_{SP} \sim 10^6 s$ Too long to account for solar flares!

Q. Why is Sweet-Parker reconnection so slow?

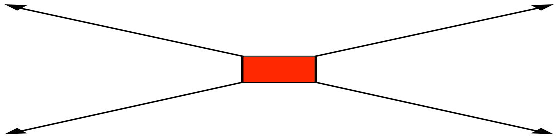
A. Geometry

Conservation relations of mass, energy, and flux

$$V_{in} L = V_{out} \delta, \quad V_{out} = V_A$$

$$V_{in} = \frac{\delta}{L} V_A, \quad \frac{\delta}{L} = S^{-1/2}$$

Petschek [1964]



Geometry of reconnection layer: X-point

Length Δ ($<< L$) is of the order of the width δ

$$\tau_{PK} = \tau_A \ln S$$

Solar flares: $\tau_{PK} \sim 10^2 s$

Computational Tests of the Petschek Model

[Sato and Hayashi 1979, Ugai 1984, Biskamp 1986, Forbes and Priest 1987, Scholer 1989, Yan, Lee and Priest 1993, Ma et al. 1995, Uzdensky and Kulsrud 2000, Breslau and Jardin 2003, Malyshkin, Linde and Kulsrud 2005]

Conclusions

• Petschek model is not realizable in high-S plasmas, unless the resistivity is locally strongly enhanced at the X-point.
• In the absence of such anomalous enhancement, the reconnection layer evolves dynamically to form Y-points and realize a Sweet-Parker regime.

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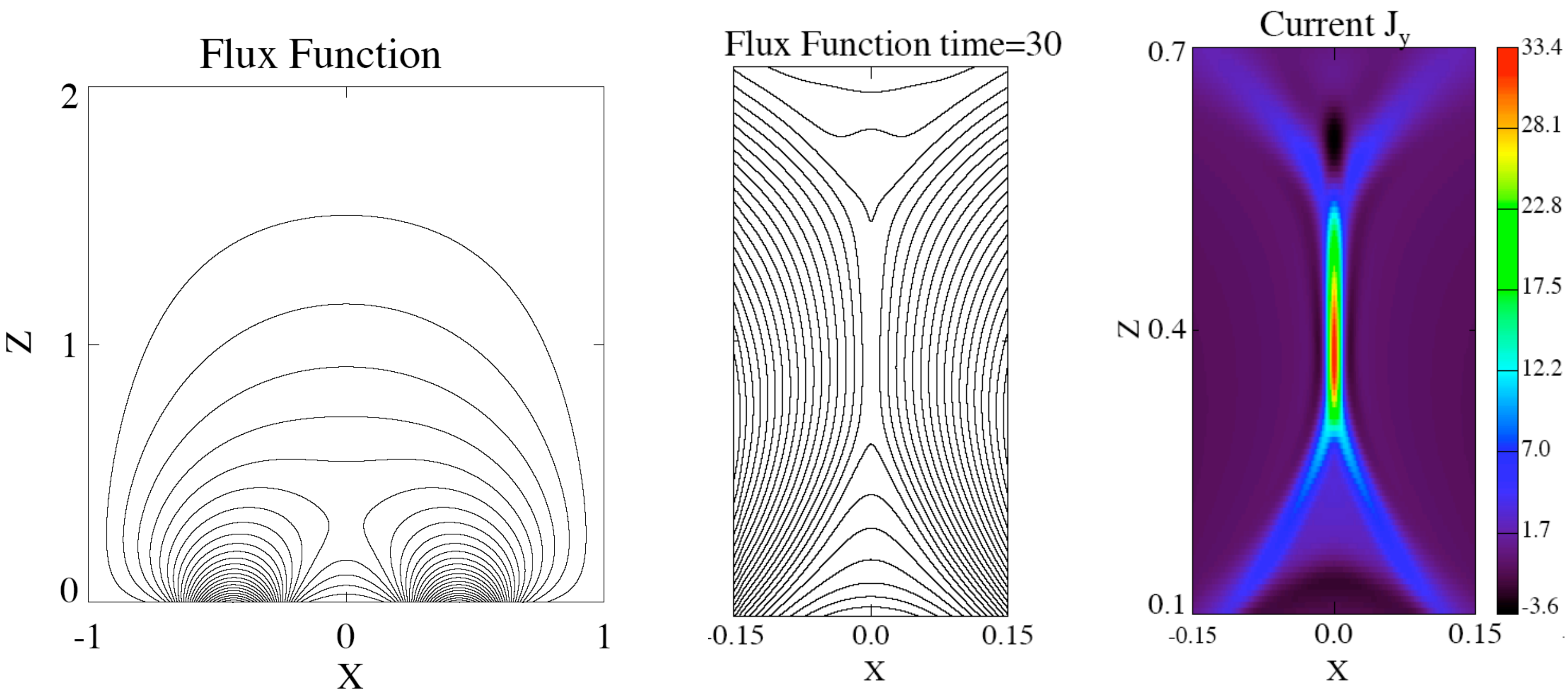
2D coronal loop : high-Lundquist number resistive MHD simulation



T = 0 T = 30

[Ma, Ng, Wang, and Bhattacharjee 1995]

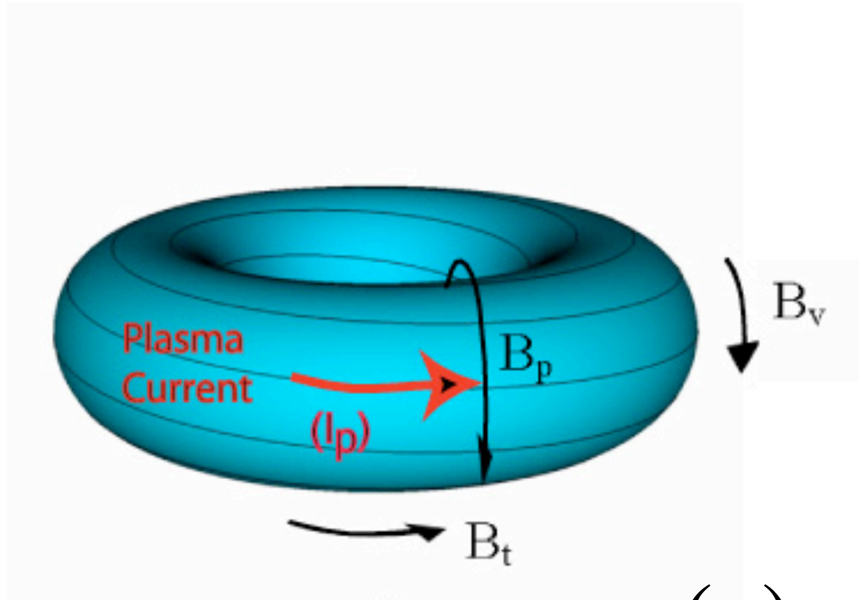
Onset of Fast Reconnection or the Trigger Problem

Dynamics exhibits an impulsiveness, that is, a sudden change in the time-derivative of the reconnection rate.

The magnetic configuration evolves slowly for a long period of time, only to undergo a sudden dynamical change over a much shorter period of time.
Dynamics is characterized by the formation of near-singular current sheets which need to be resolved in computer simulations and in experiments: a classic multi-scale problem coupling large scales to small.

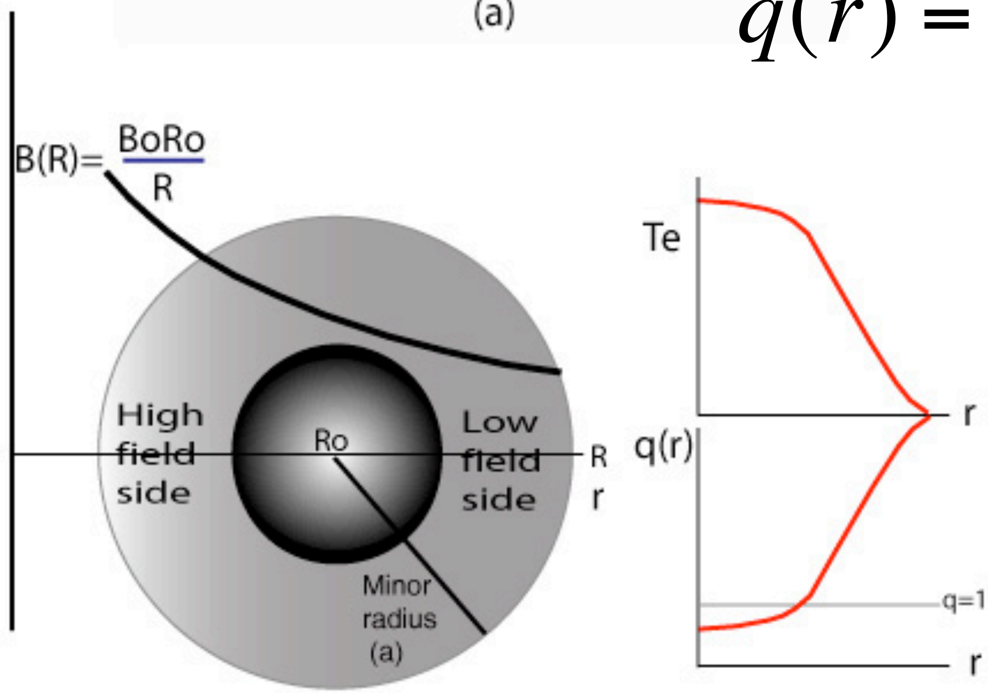
Examples

Sawtooth oscillations in tokamaks
Magnetospheric substorms
Impulsive solar flares


Plasma
Current
(Ip)
Bp
Bv
Bt

(a)

$$q(r) = rB_t / RB_p$$


B(R)= BoRo / R
High field side
Ro
Low field side
R
r
Minor radius (a)
Te
r
q(r)
q=1
r

(b)

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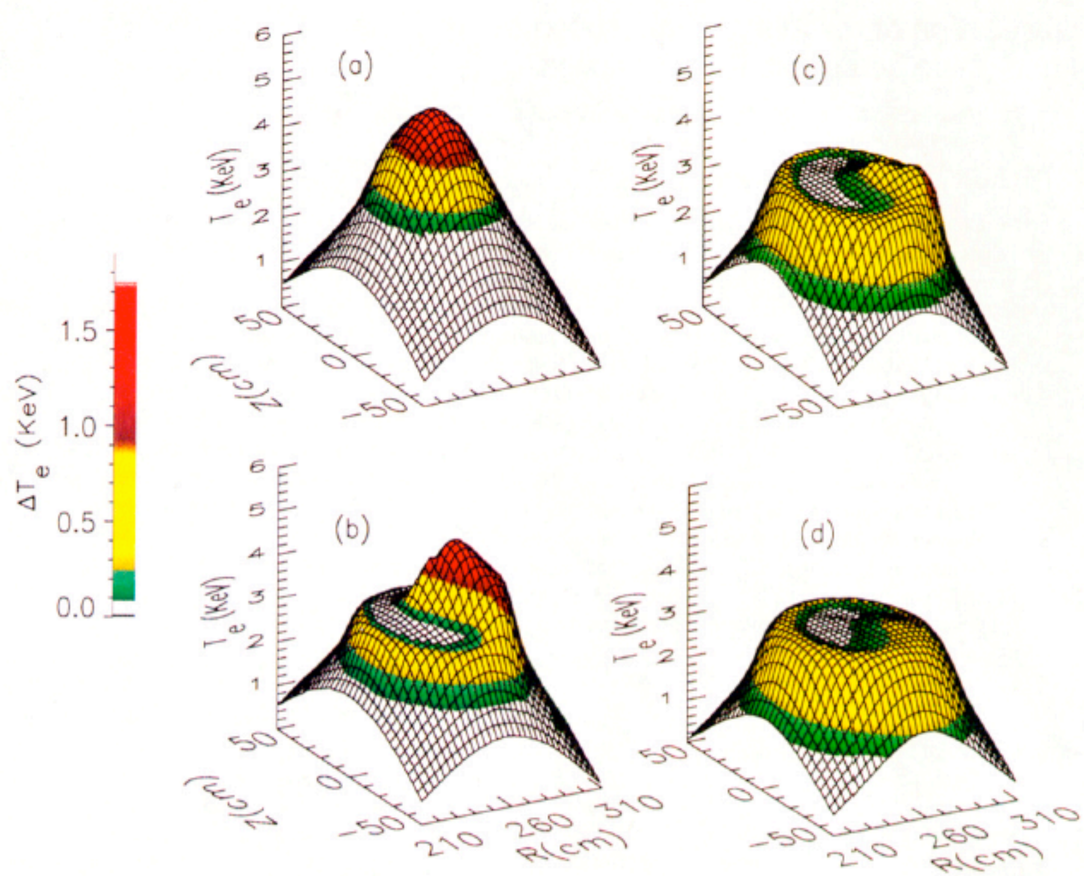
Sawtooth crash in tokamaks

Time-evolution of electron temperature profile in TFTR by ECE emission



$\Delta T_e(r, \theta, t)$
$= T_e(r, \theta, t) -$
$T_e^{\min}(r, \theta)$

[Yamada, Levinton, Pomphrey, Budny, Manickam, and Nagayama 1994]

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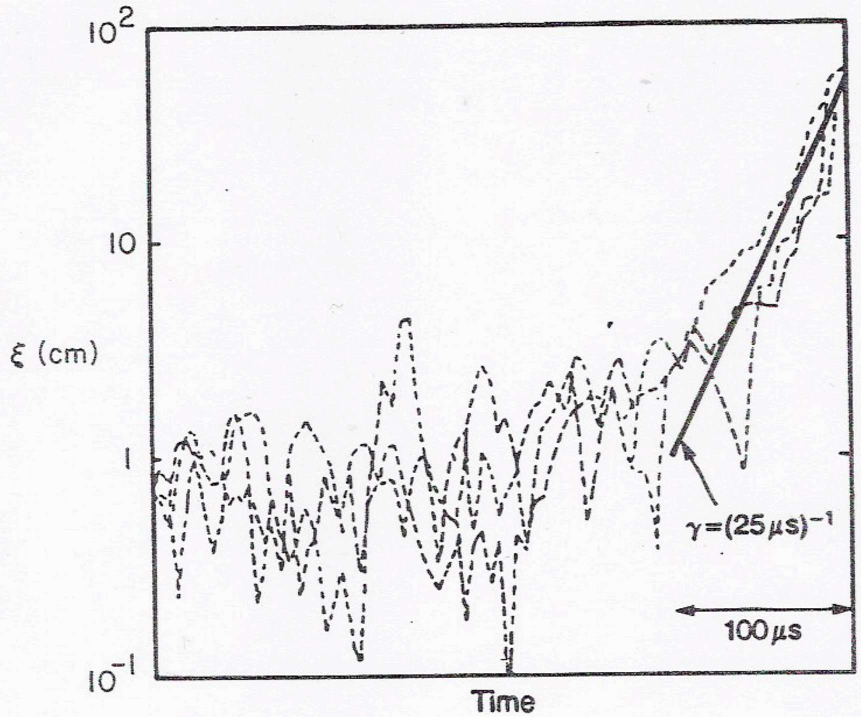
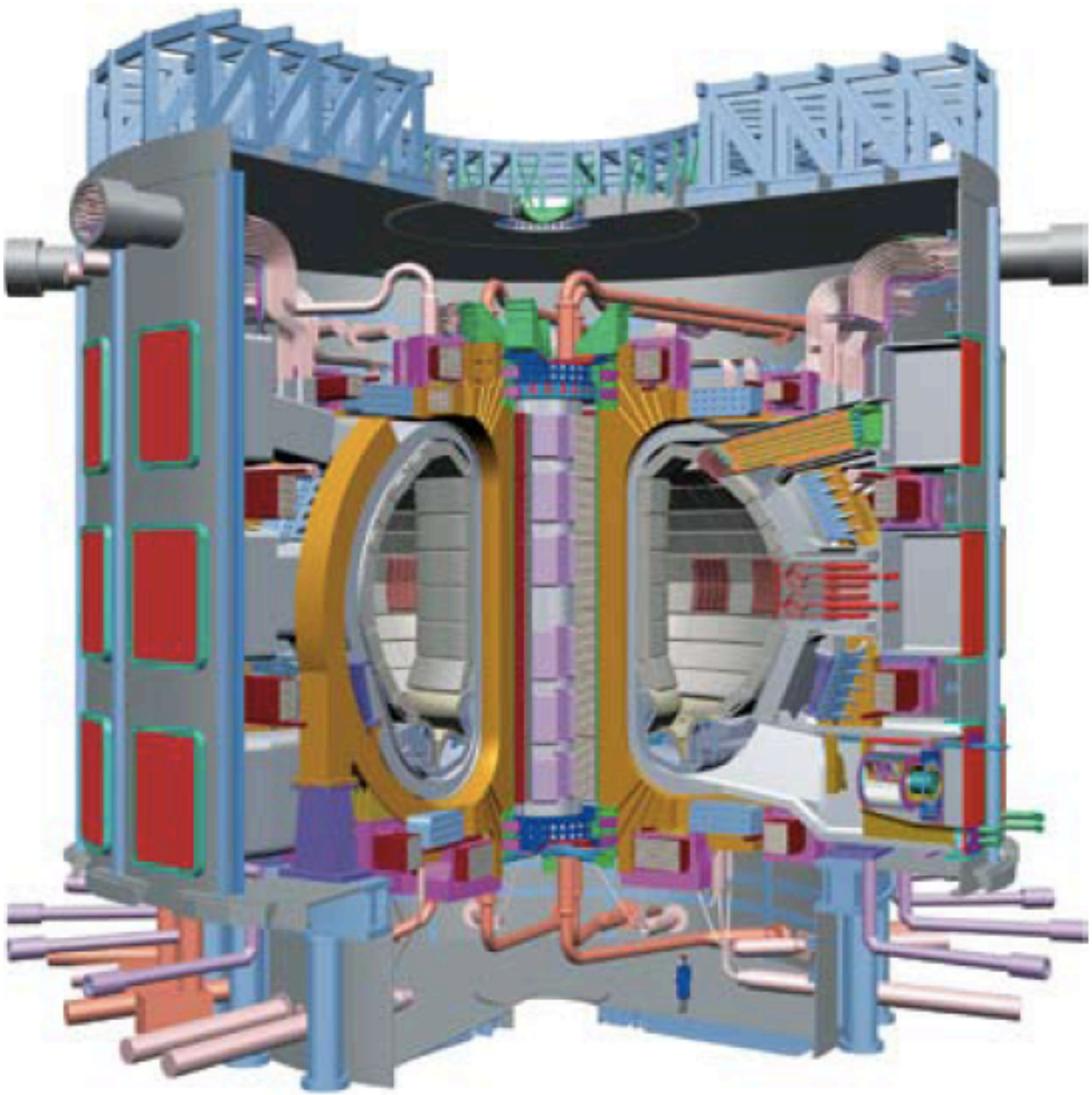
Sawtooth trigger

Soft X-ray measurements on JET



[Wesson, Edwards, and Granetz 1991]



Control of sawteeth is important for ITER because they can trigger “neo-classical” tearing instabilities that can trigger major current disruptions.

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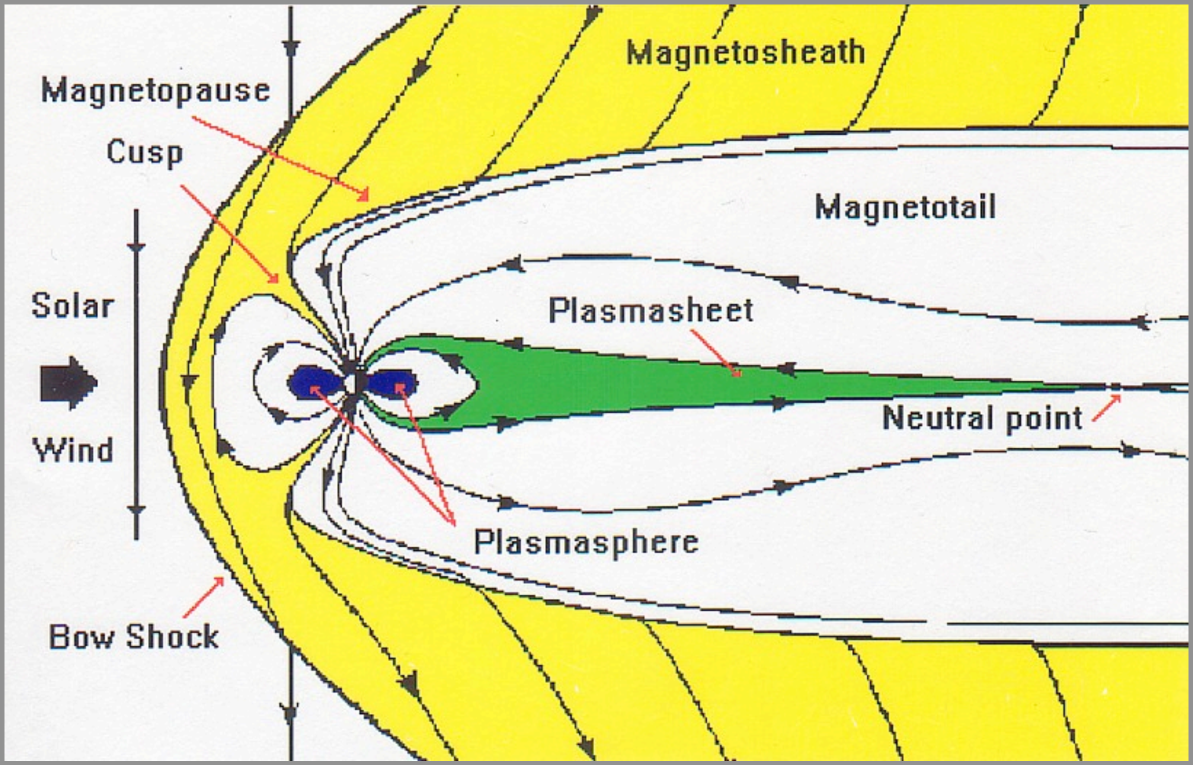
Magnetospheric Substorms



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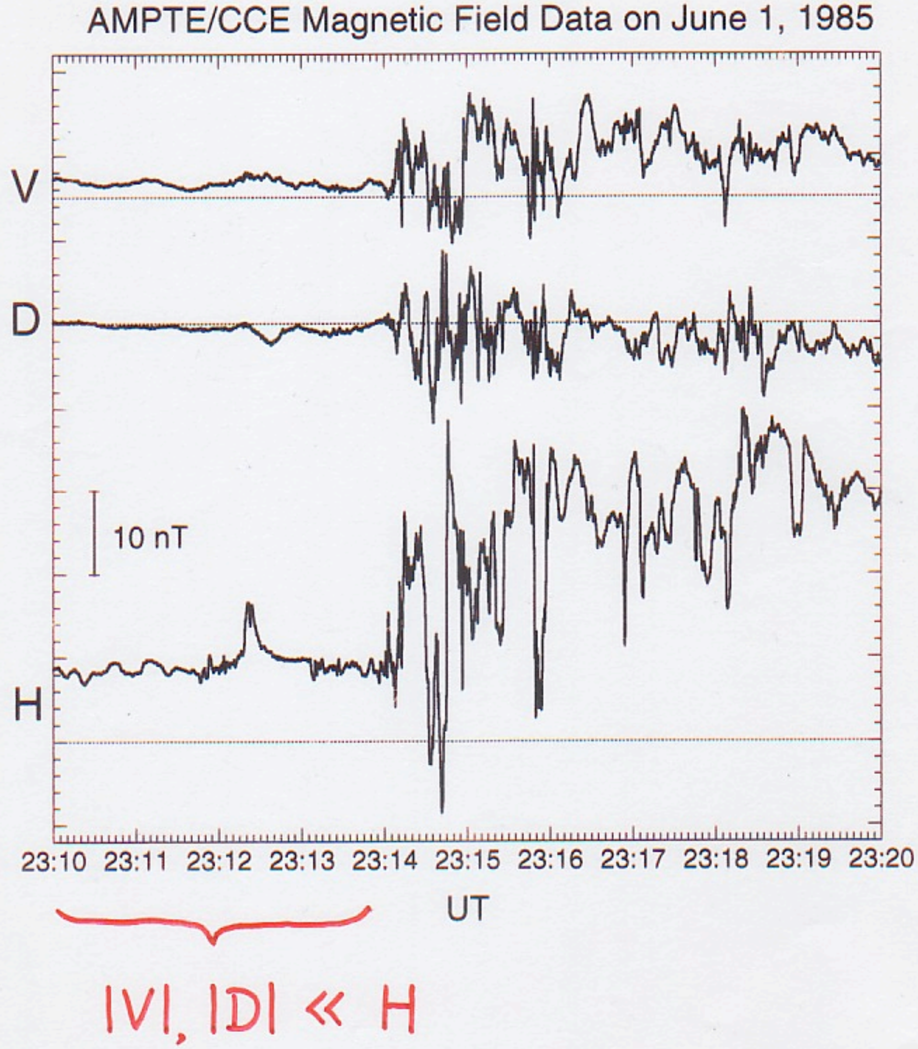
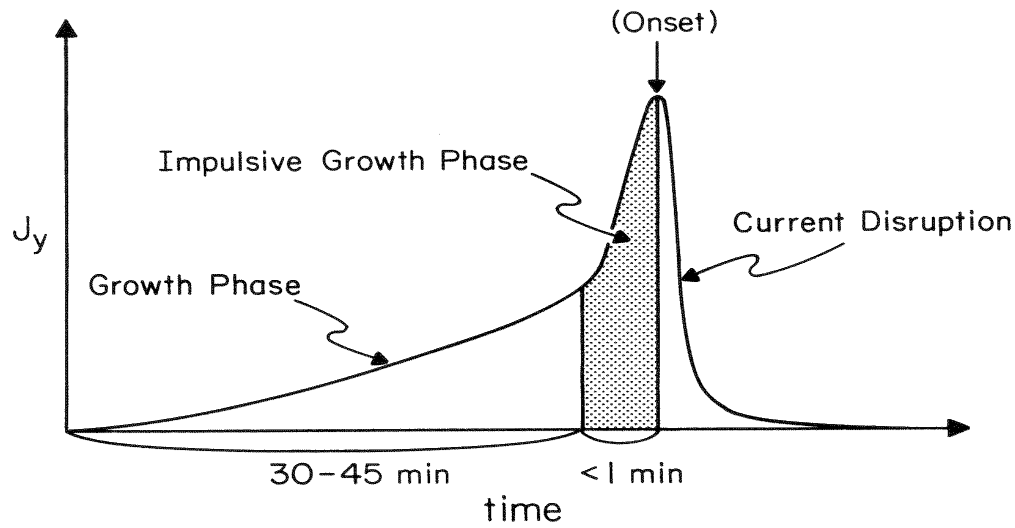
Photograph of the aurora by Dirk Obudzinski, near the Yukon River in Circle, Alaska (August 29, 2000).

R = 8.79 R_E
MLT = 0.27



See Lui et al. [1988, 1992]

Current Disruption in the Near-Earth Magnetotail



[Ohtani, Kokubun, and Russell 1992]

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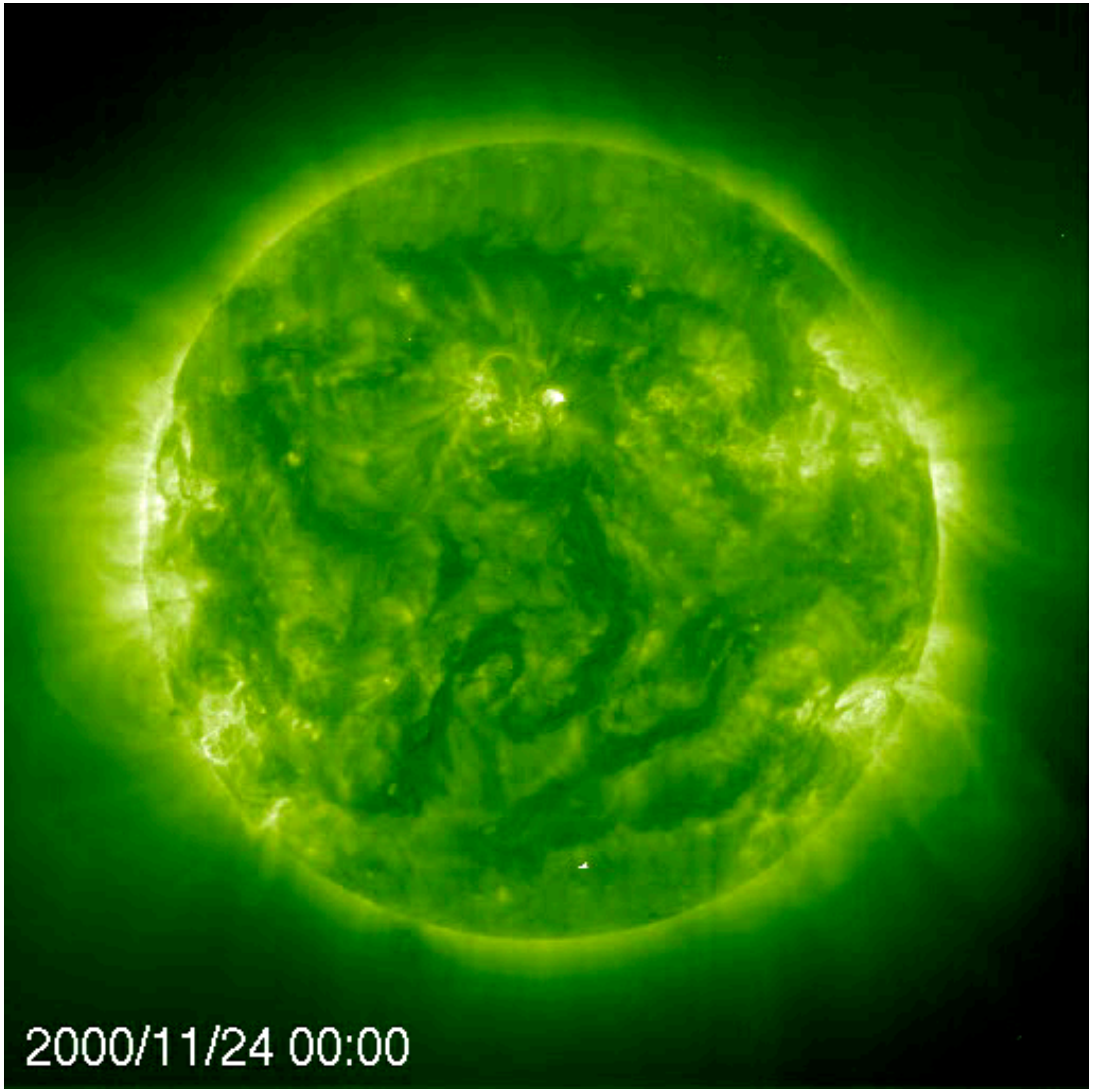
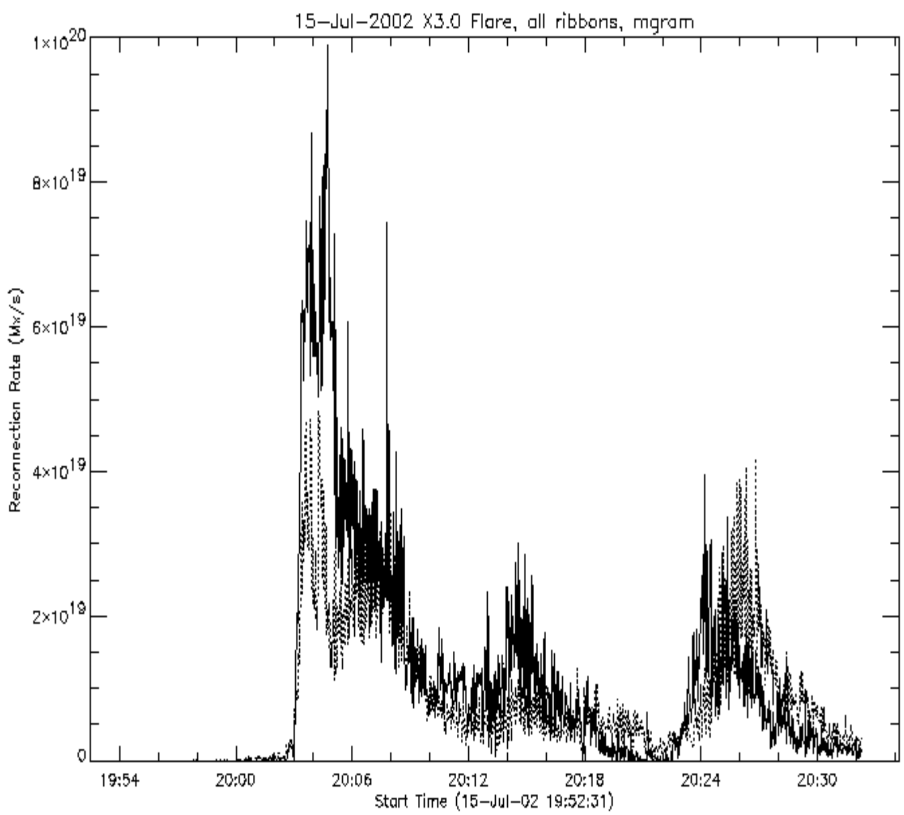
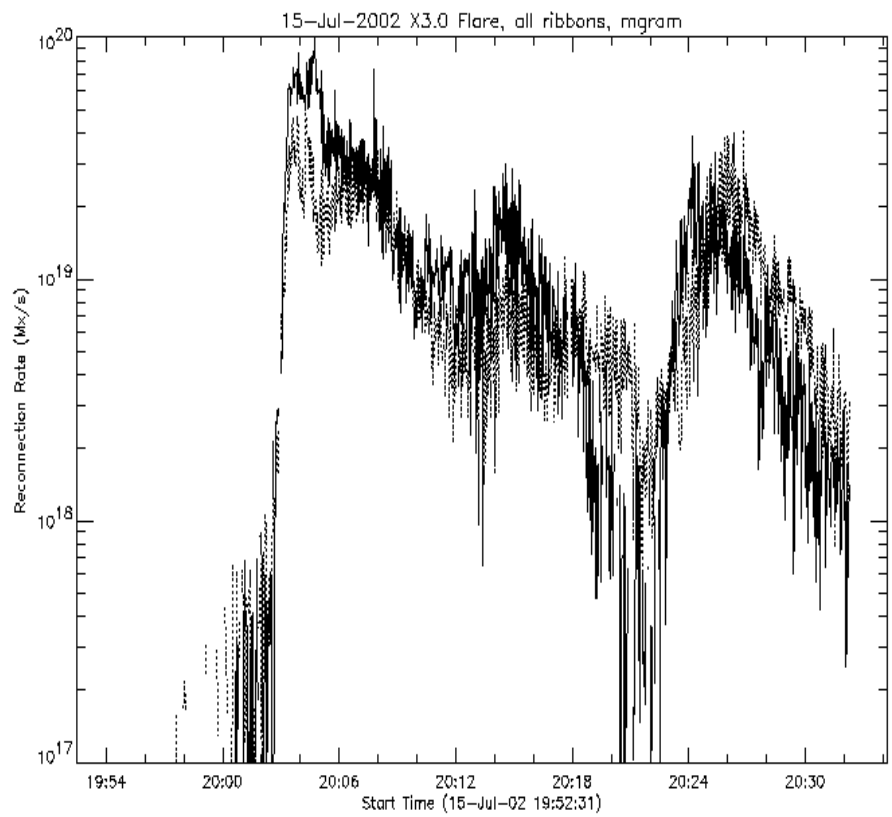


SOHO/EIT

Time Profile of Reconnection Rates for X3 Flare observed by TRACE



Linear Plot



Log Plot

[Saba, Tarbell, and Gaeng 2003]

Hall MHD (or Extended MHD) Model and the Generalized Ohm's Law

In high-S plasmas, when the width of the thin current sheet (Δ_η) satisfies

$\Delta_\eta < c/\omega_{pi}$ (or $\sqrt{\beta}c/\omega_{pi}$ if there is a guide field)

"collisionless" terms in the generalized Ohm's law cannot be ignored.

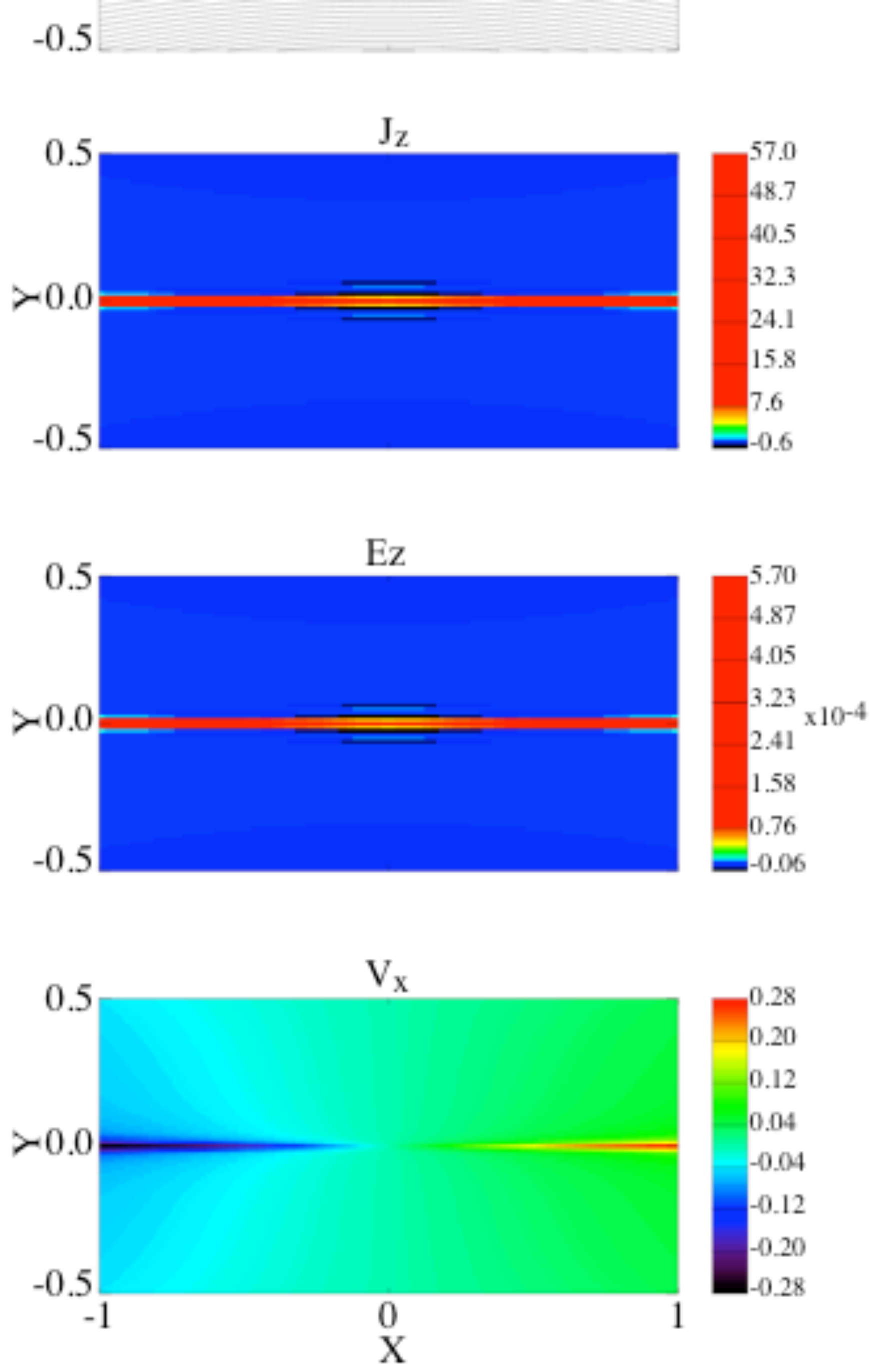
Generalized Ohm's law (dimensionless form)

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \frac{1}{S}\mathbf{J} + {d_e}^2 \frac{d\mathbf{J}}{dt} + \frac{d_i}{n}\left(\mathbf{J} \times \mathbf{B} - \nabla \bullet \overleftrightarrow{p}_e\right)$$

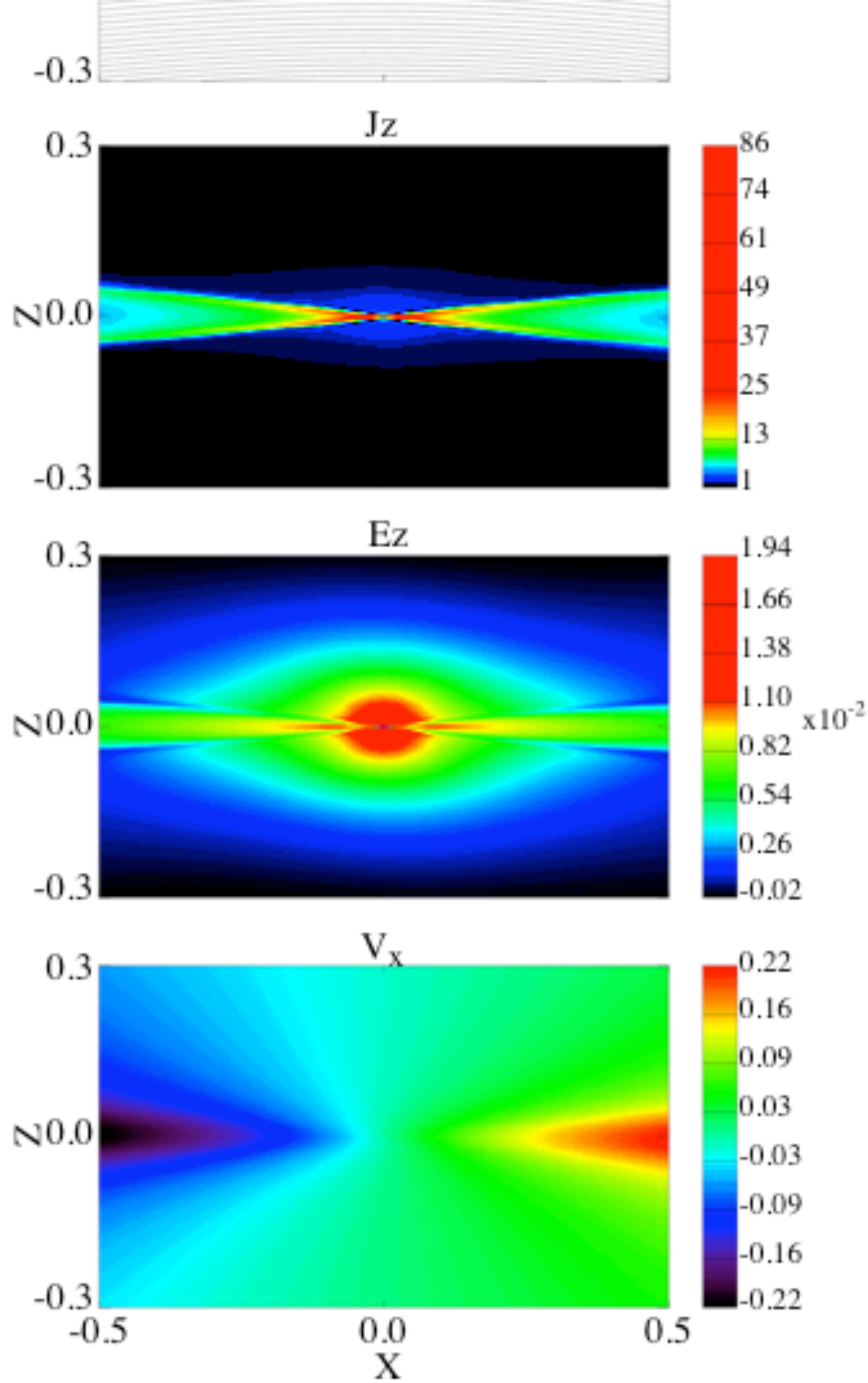
Electron skin depth $d_e \equiv L^{-1}\left(c/\omega_{pe}\right)$

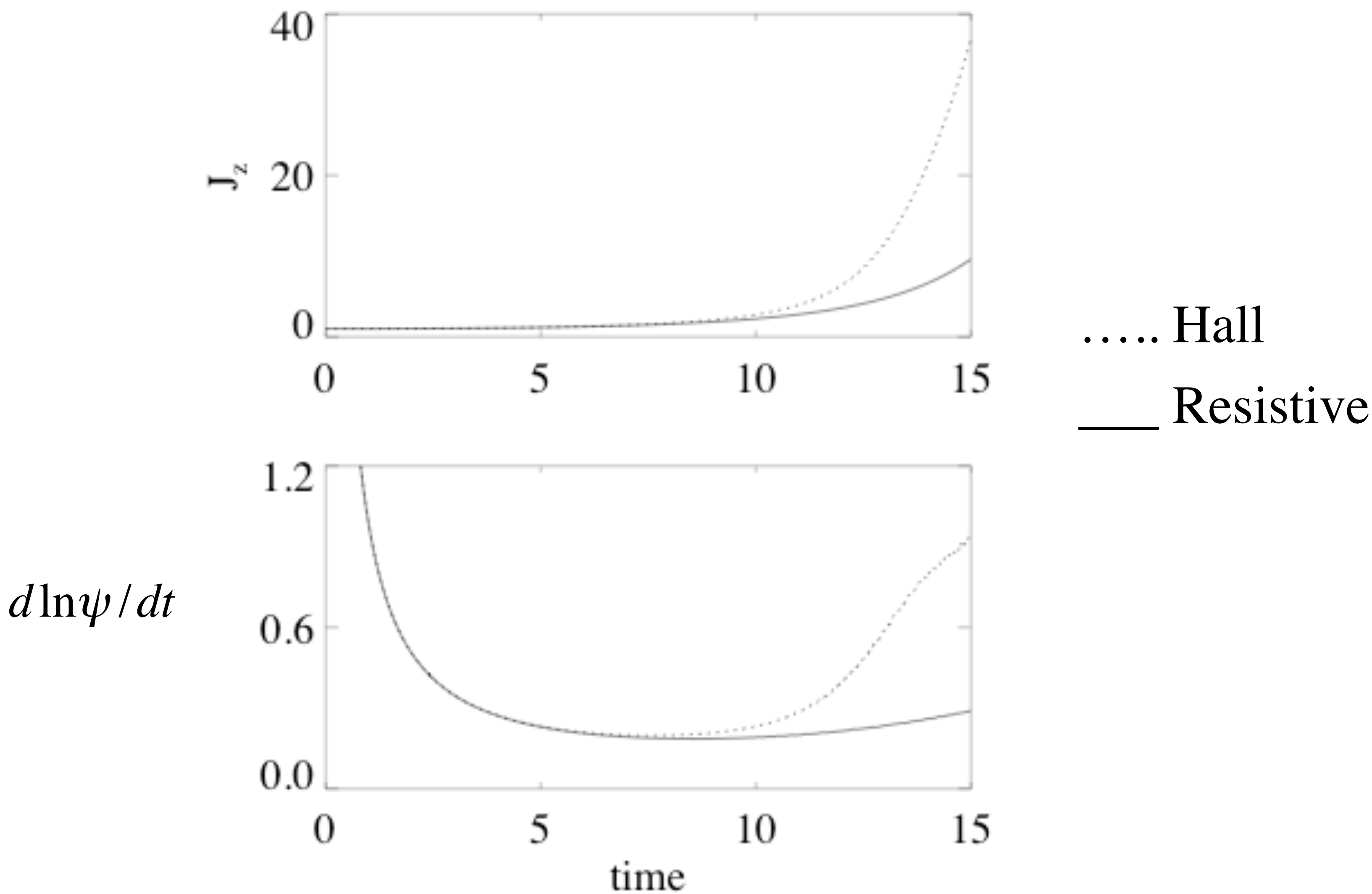
Ion skin depth $d_i \equiv L^{-1}\left(c/\omega_{pi}\right)$

Electron beta β_e



-0.5
J_z
0.5
Y 0.0
-0.5
57.0
48.7
40.5
32.3
24.1
15.8
7.6
-0.6
Ez
0.5
Y 0.0
-0.5
5.70
4.87
4.05
3.23
2.41
1.58
0.76
-0.06
x10^{-4}
V_x
0.5
Y 0.0
-0.5
0.28
0.20
0.12
0.04
-0.04
-0.12
-0.20
-0.28
-1
0
1
X


-0.3
Jz
0.3
Z0.0
-0.3
86
74
61
49
37
25
13
1
Ez
0.3
Z0.0
-0.3
1.94
1.66
1.38
1.10
0.82
0.54
0.26
-0.02
x10-2
Vx
0.3
Z0.0
-0.3
0.22
0.16
0.09
0.03
-0.03
-0.09
-0.16
-0.22
-0.5
0.0
0.5
X



40
20
0
J_z
0
5
10
15
….. Hall
___ Resistive
1.2
0.6
0.0
$d\ln\psi/dt$
0
5
10
15
time

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Transition from Collisional to Collisionless Regimes in MRX

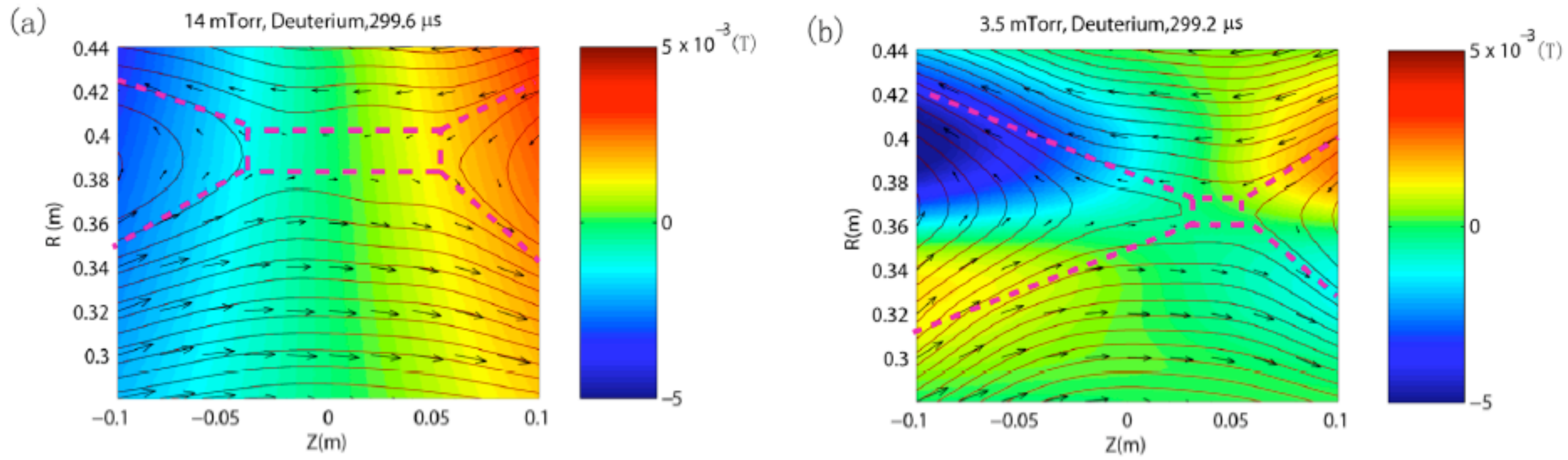

Fig.2; *Comparison of neutral sheet configuration described by measured magnetic field vectors and flux counters for high (collisional) and low density cases; (a) Collisional regime (λ_{mfp} ~1mm << δ)); (b) Nearly collisionless regime (λ_{mfp} ~1cm ~ δ). Out-of plane fields are depicted by the color codes ranged -50 G <Bt <50 G.*

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Linkage between space and laboratory plasmas

System	L (cm)	B (G)	$d_i = c/\omega_{pi}$(cm)	δ_{sp} (cm)	d_i/δ_{sp}
MRX/SSX	10	100-500	1-5	0.1-5	.2-100
MST/Tokamak	30/100	$10^3/10^4$	10	0.1	100
Magnetosphere	10^9	10^{-3}	10^7	10^4	1000
Solar flare	10^9	100	10^4	10^2	100
ISM	10^{18}	10^{-6}	10^7	10^{10}	0.001
Proto-star	$d_i/\delta_s >> 1$				

$$d_i/\delta_{sp} \sim 5(\lambda_{mfp}/L)^{1/2}$$

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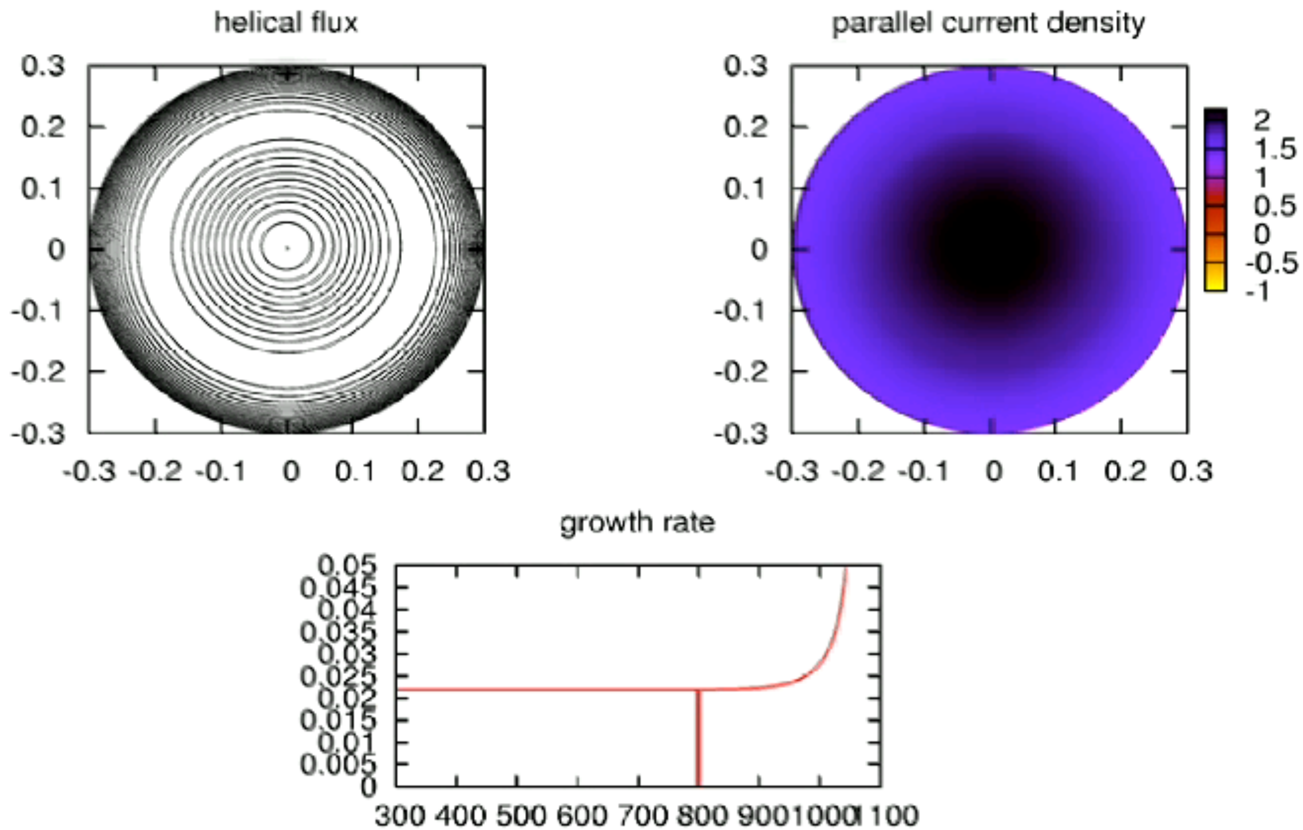
Accelerated growth of the m=1 instability due to two-fluid effects



[Germaschewski and Bhattacharjee, 2009]

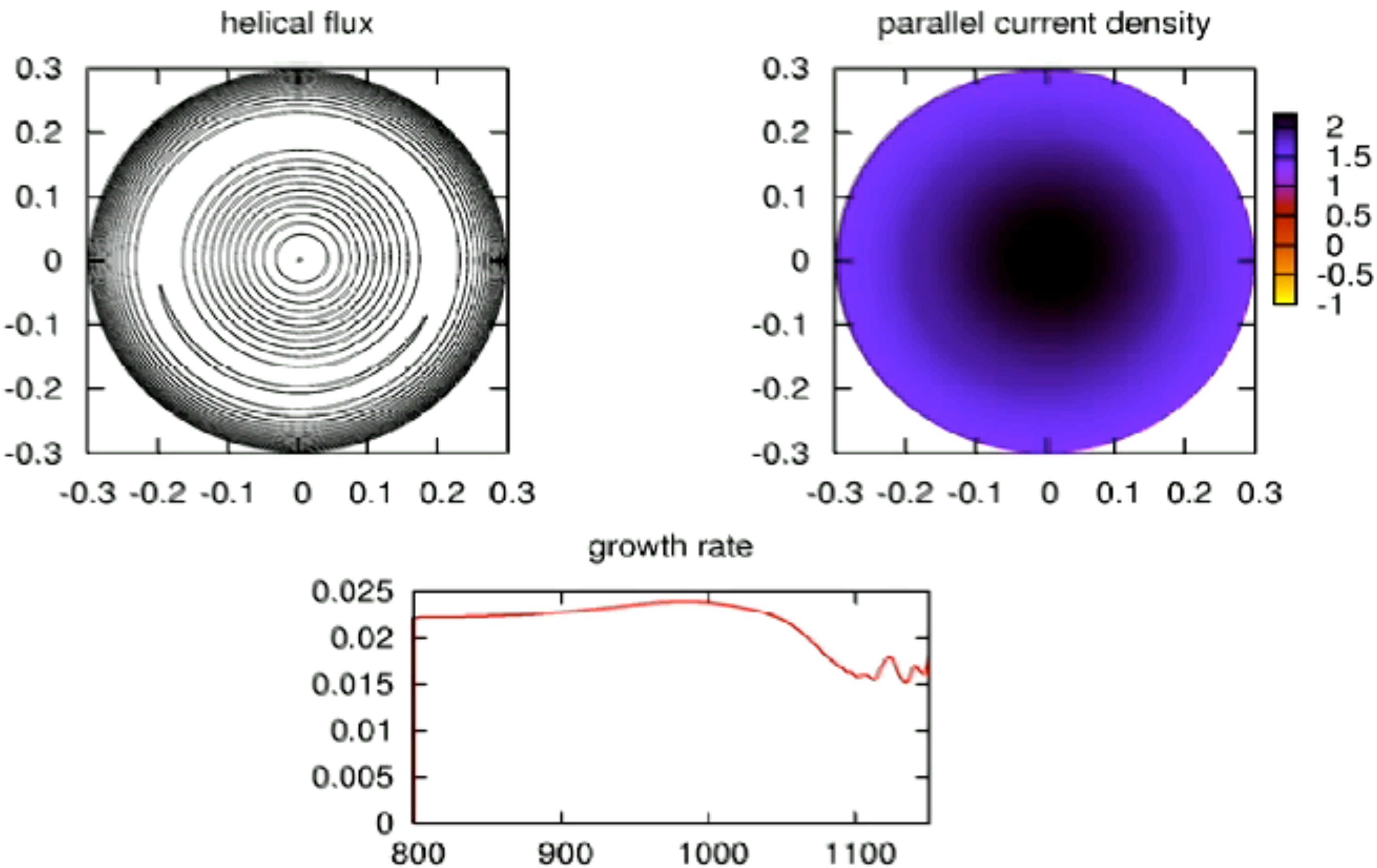
Nonlinear Diamagnetic Stabilization

Two-fluid models incorporate naturally diamagnetic fluid drifts (poloidal):

$$\omega_{*j} = -p_j'(r)/(nerB),\ j = e,i$$

The mode is linearly unstable, but stabilizes nonlinearly as the density gradient steepens at the mode-rational surface. [Rogers and Zakharov 1995]

This diamagnetic drift causes a spatial separation between the maximum of the current density and the stagnation point of the flow. This separation is caused by the effects of Hall current and electron pressure gradient, and is absent in resistive MHD.



helical flux
parallel current density
2
1.5
1
0.5
0
-0.5
-1
growth rate
0.025
0.02
0.015
0.01
0.005
0
800
900
1000
1100

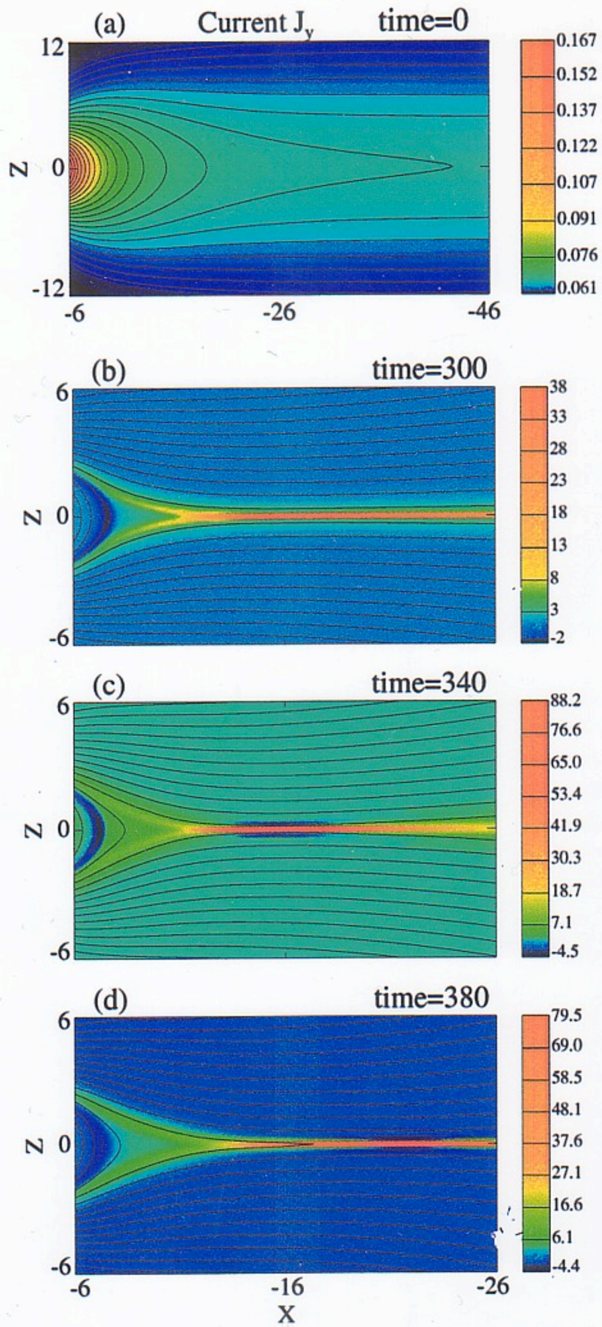
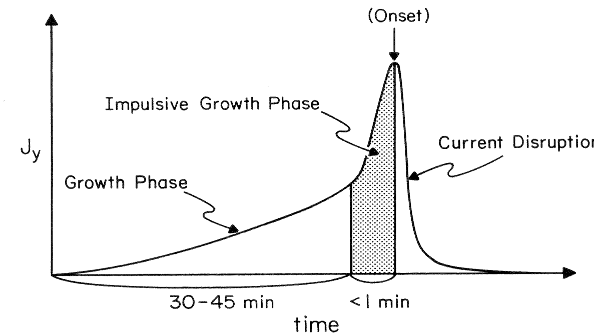
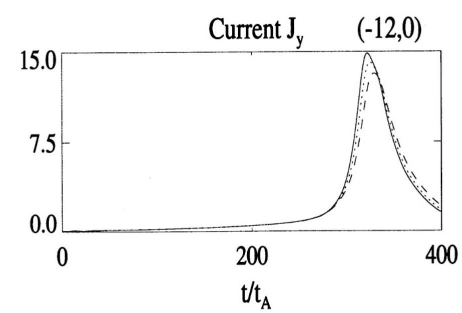


Fig. 1

Observations (Ohtani et al. 1992)



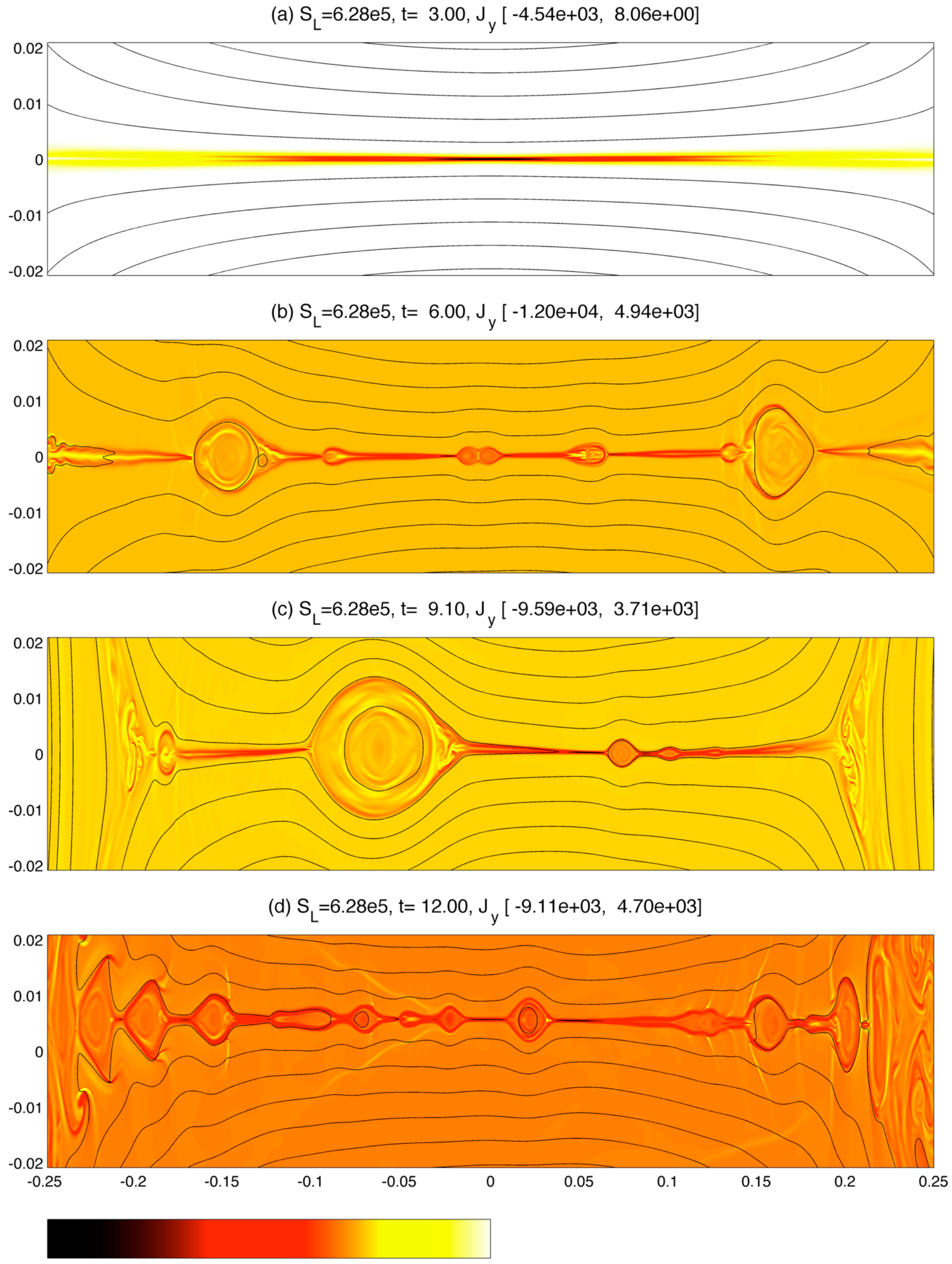
Hall MHD Simulation



[Ma and Bhattacharjee 1998]

Fast Reconnection in Large Systems

- Extended thin current sheets of high Lundquist number are unstable to a super-Alfvenic tearing instability (Loureiro et al. 2007), which we call the "plasmoid instability," because it generates a large number of plasmoids. We will show that the fastest growing plasmoid instability is contained in the classical dispersion equation for tearing modes.
- In the nonlinear regime, the reconnection rate becomes nearly independent of the Lundquist number, and is much larger than the Sweet-Parker rate.


(a) S_L=6.28e5, t= 3.00, J_y [-4.54e+03, 8.06e+00]
(b) S_L=6.28e5, t= 6.00, J_y [-1.20e+04, 4.94e+03]
(c) S_L=6.28e5, t= 9.10, J_y [-9.59e+03, 3.71e+03]
(d) S_L=6.28e5, t= 12.00, J_y [-9.11e+03, 4.70e+03]
0.02
0.01
0
-0.01
-0.02
-0.25
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2
0.25

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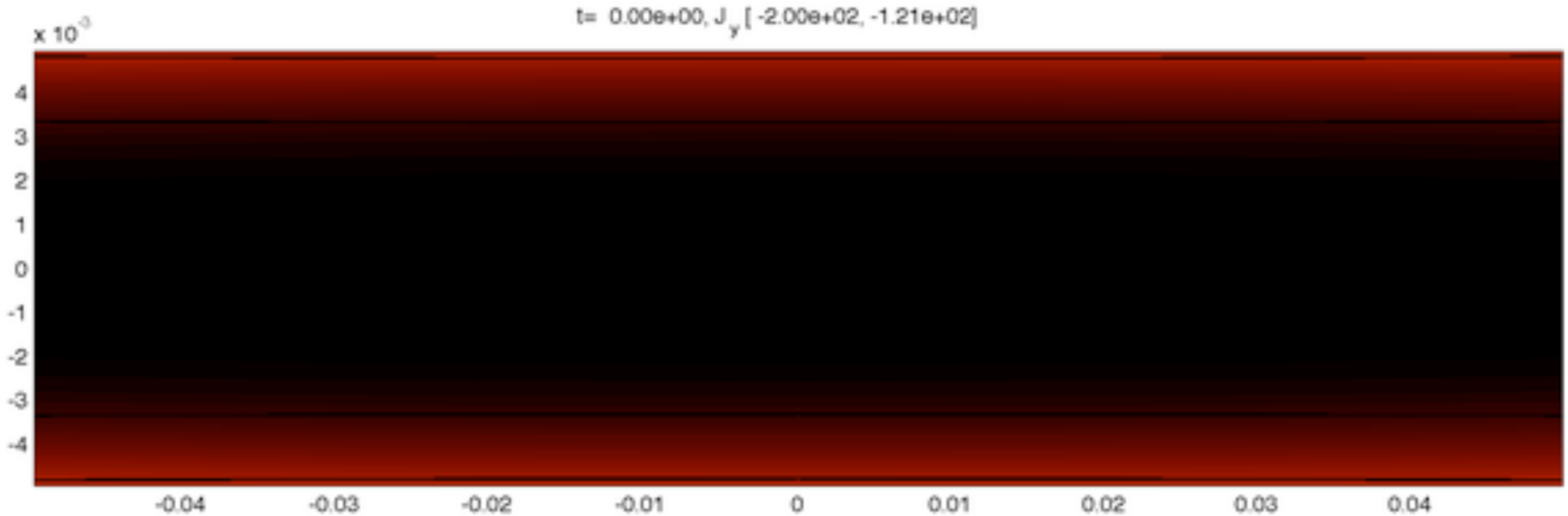

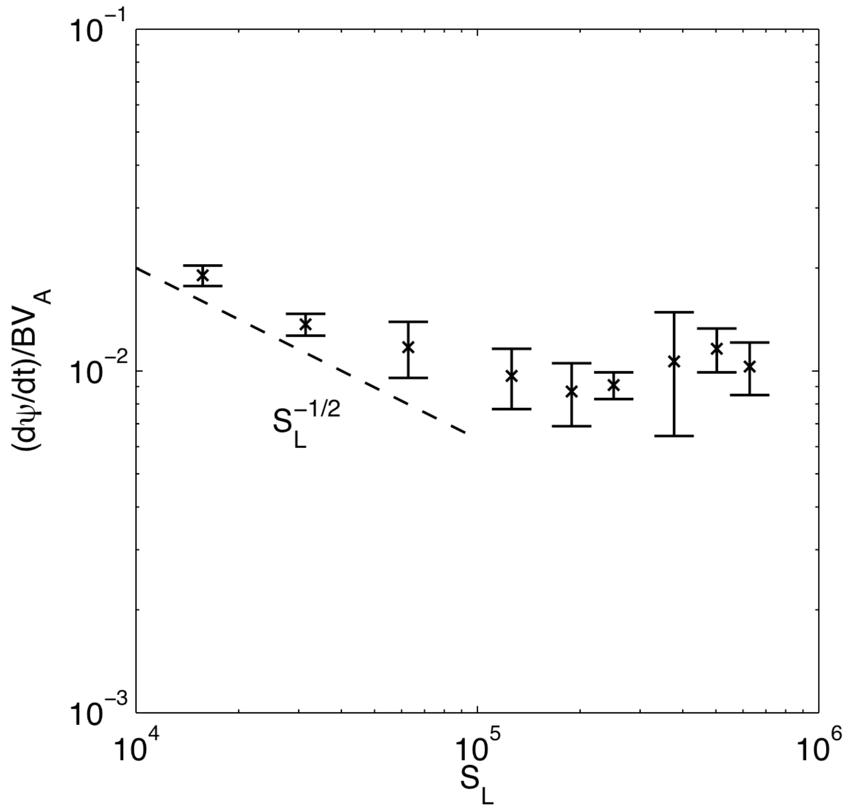

10^{-1}
10^{-2}
10^{-3}
10^{4}
10^{5}
10^{6}
$(d\psi/dt)/BV_A$
S_L
$S_L^{-1/2}$

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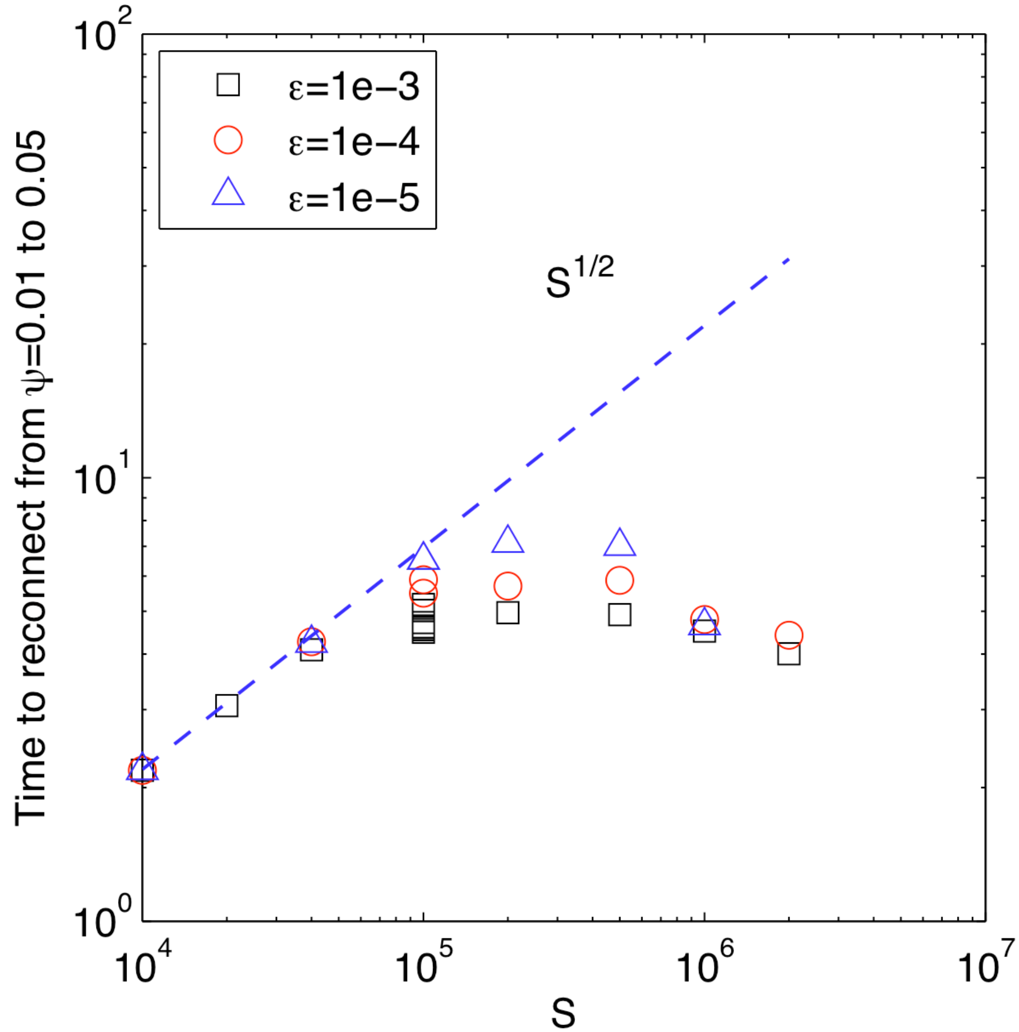

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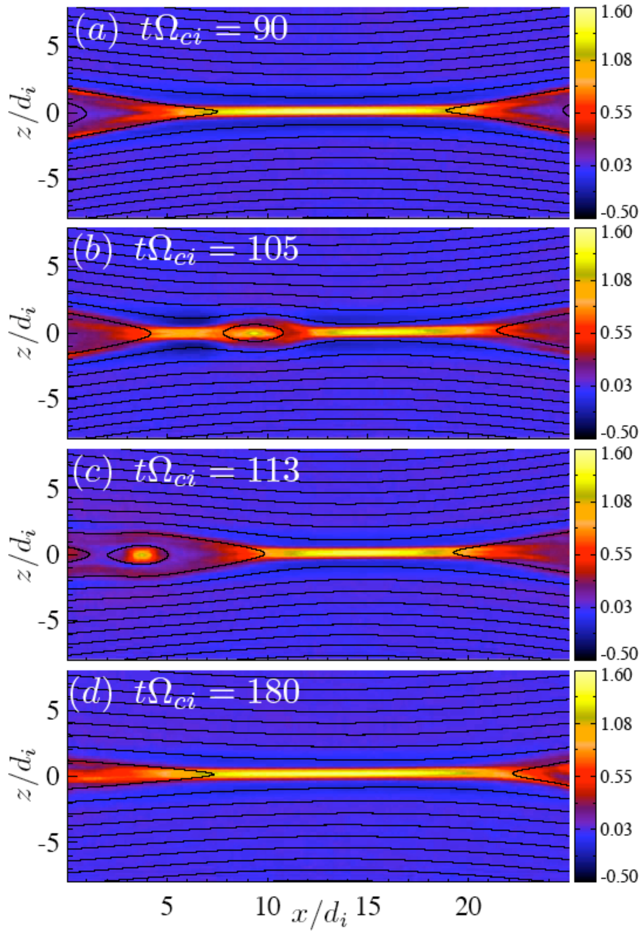
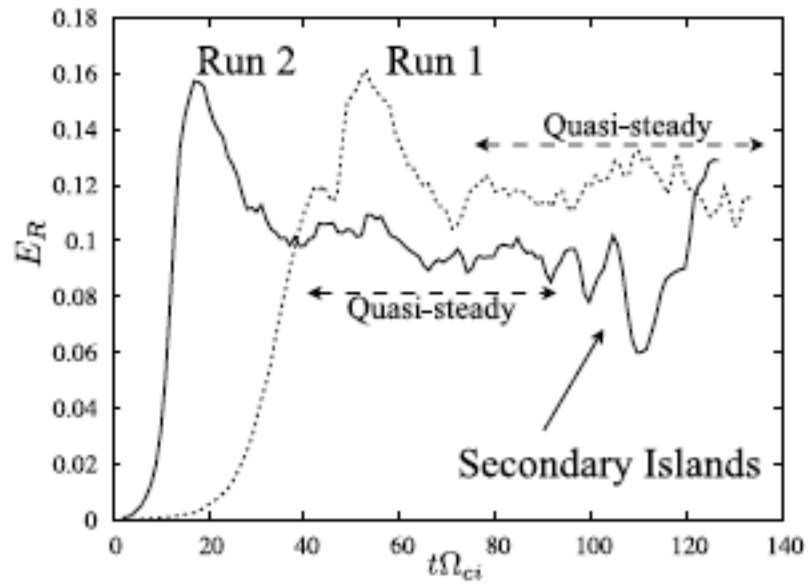
PIC simulations of reconnection in large systems

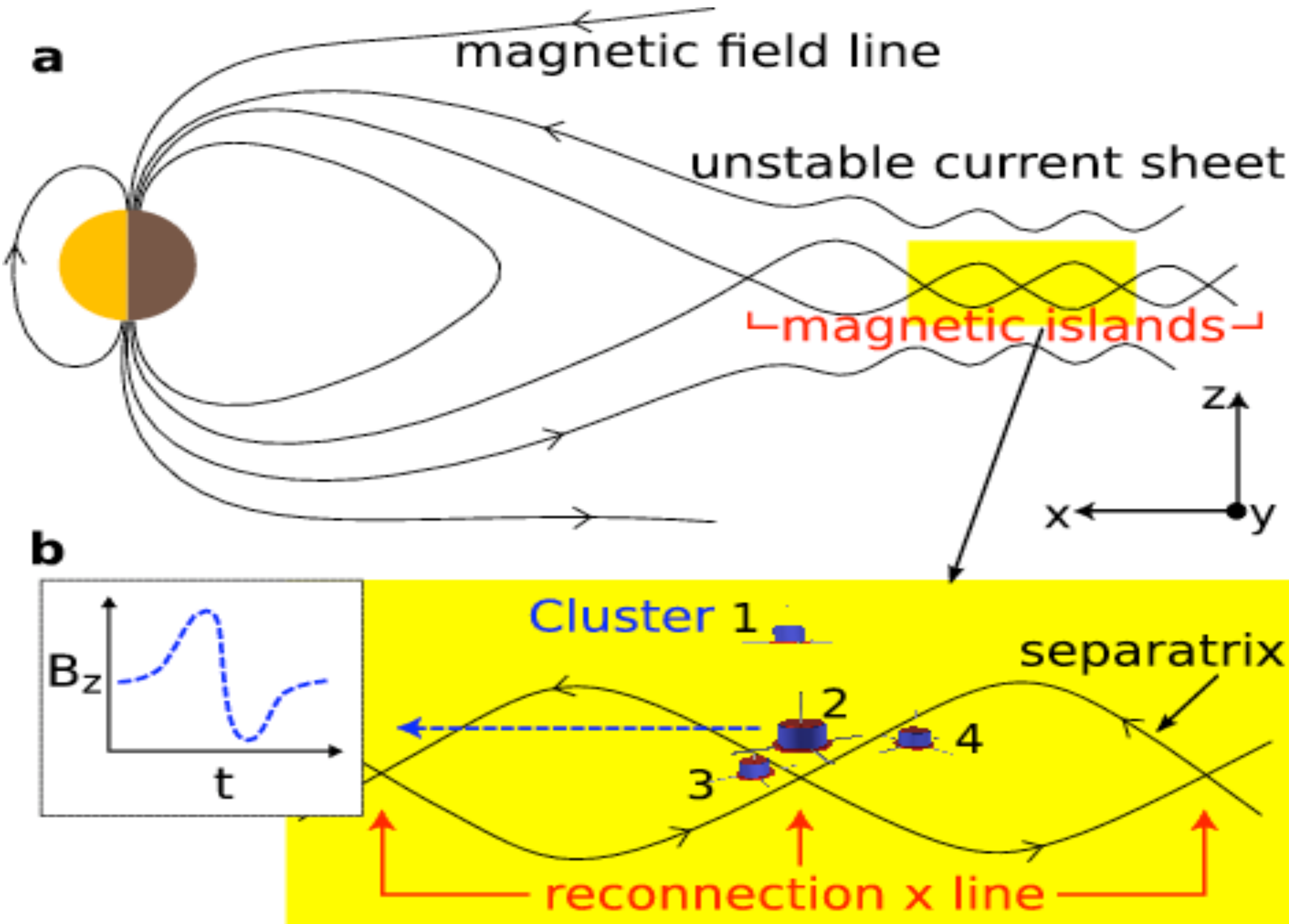




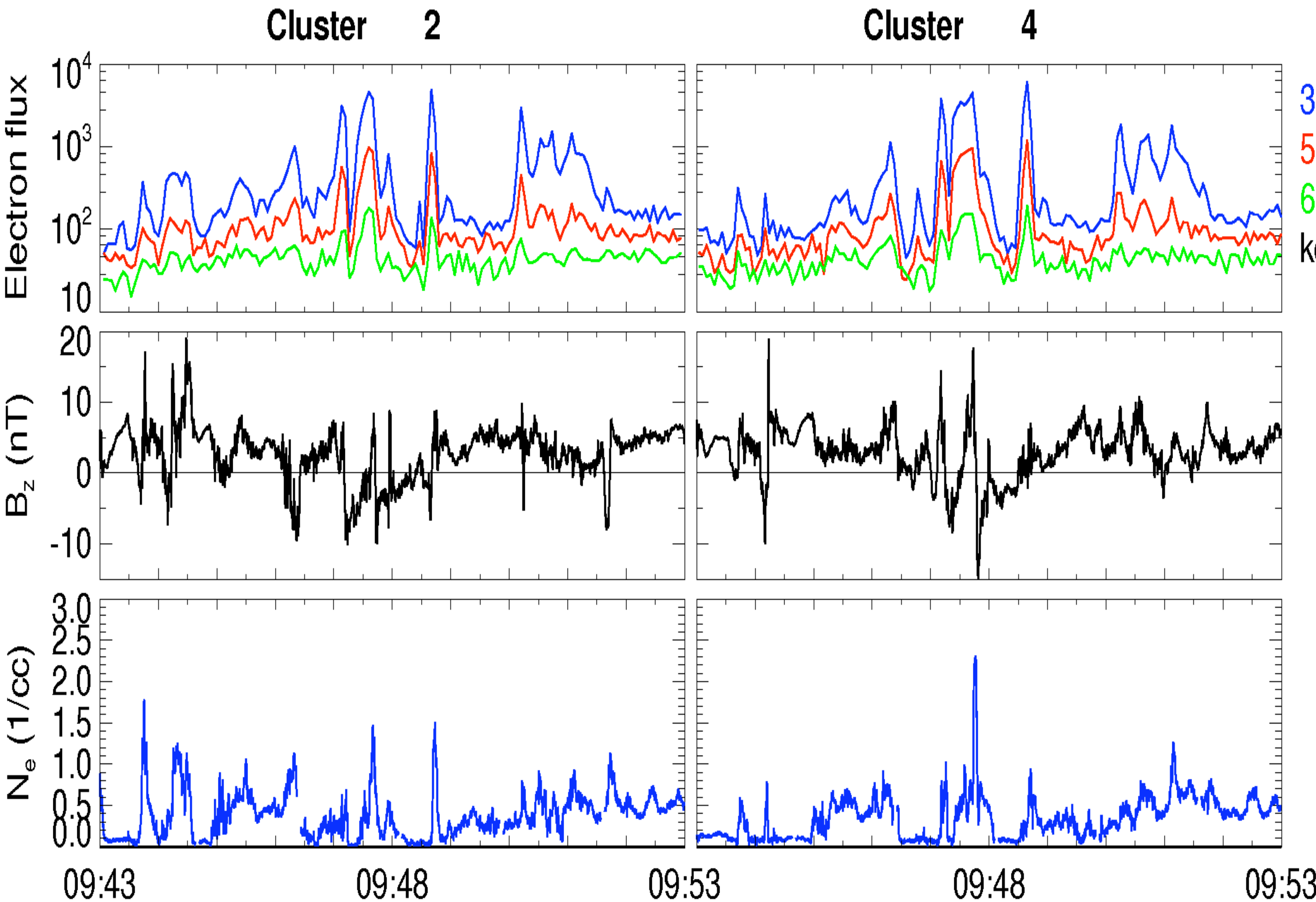
[Karimabadi, Daughton, and Scudder 2007]

Fluxes of energetic electrons peak within magnetic islands

[Chen et al., Nature Phys., 2008]



e bursts & bipolar Bz & Ne peaks
~10 islands within 10 minutes



Conclusions

Onset of fast reconnection, mediated by the dynamics of thin current sheets, in high-Lundquist-number laboratory and space plasmas. Two mechanisms:

- Hall MHD, seen in theory and laboratory experiments of moderate size, when the Sweet-Parker width falls below the ion skin depth. This onset can be nonlinear stabilized due to pressure-driven, diamagnetic drifts.
- Fast, secondary tearing instabilities of thin current sheets in large systems, substantially exceeding Sweet-Parker rates within the realm of resistive MHD (without invoking Hall MHD effects).