Bridging Fusion and Space and Astrophysical Plasma Physics

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Possible Strategies for the Future (continued)

Establish a group in *Basic Plasma Science*, which

- Will serve as incubator of fundamental ideas which can be tied eventually to important applications (wave physics, turbulence and self-organization, laser-plasma interactions)
- Will serve as meeting ground of fusion with beam and space physics theorists.
- Some of these ideas can intersect and leverage the work of the recently established Max Planck-Princeton Plasma Physics Center.

Opportunities in PPPL

- Space Plasma Physics Group
- Beam Dynamics and Non-neutral Plasma Group
- Magnetic Reconnection Experiment (MRX) and its Possible Successor (LRX)
- Magnetorotational Instability Experiment
- Laser-Plasma Interactions and High-Energy Density Physics: Experiment and Theory
- Low-temperature Plasma Physics
- Hall Thruster Experiment

Impulsive Reconnection: The Onset/Trigger Problem

- Dynamics exhibits an impulsiveness, that is, a sudden change in the time-derivative of the reconnection rate.
- Dynamics is characterized by the formation of near-singular current sheets which need to be resolved in computer simulations: a classic multi-scale problem coupling large scales to small.
- Magnetic reconnection is likely *not* the whole story, requiring intervention of secondary instabilities.

Examples

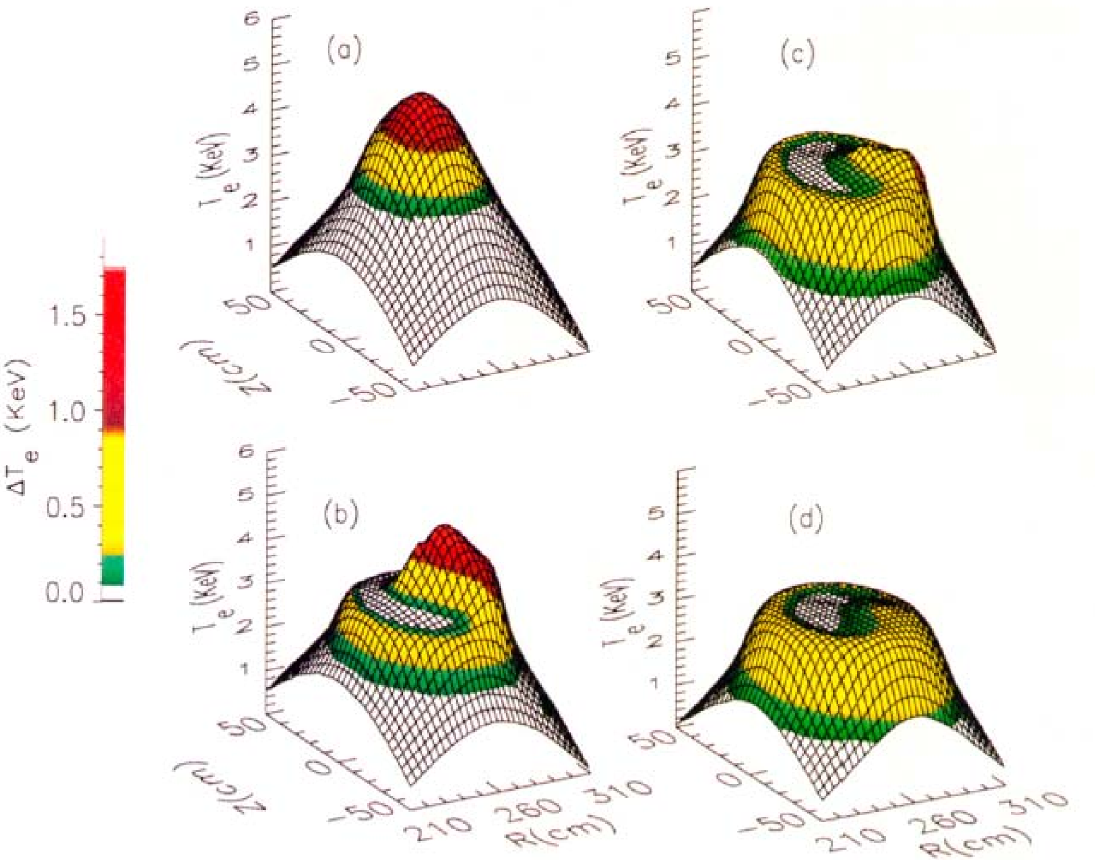
Sawtooth oscillations in tokamaks

Magnetospheric substorms

Impulsive solar/stellar flares

Sawtooth crash in tokamaks

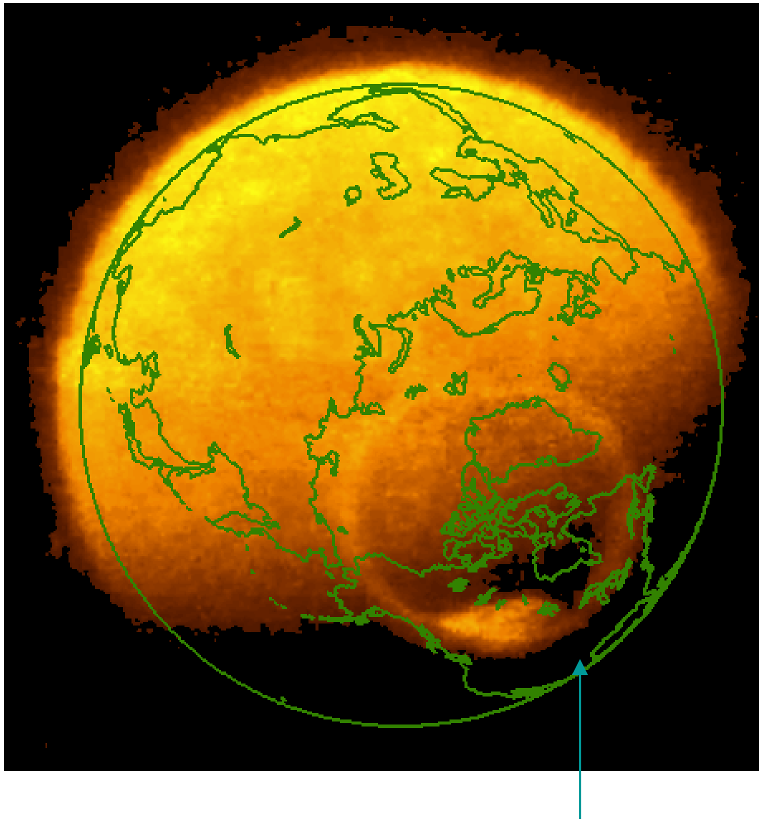
Time-evolution of electron temperature profile in TFTR by ECE emission



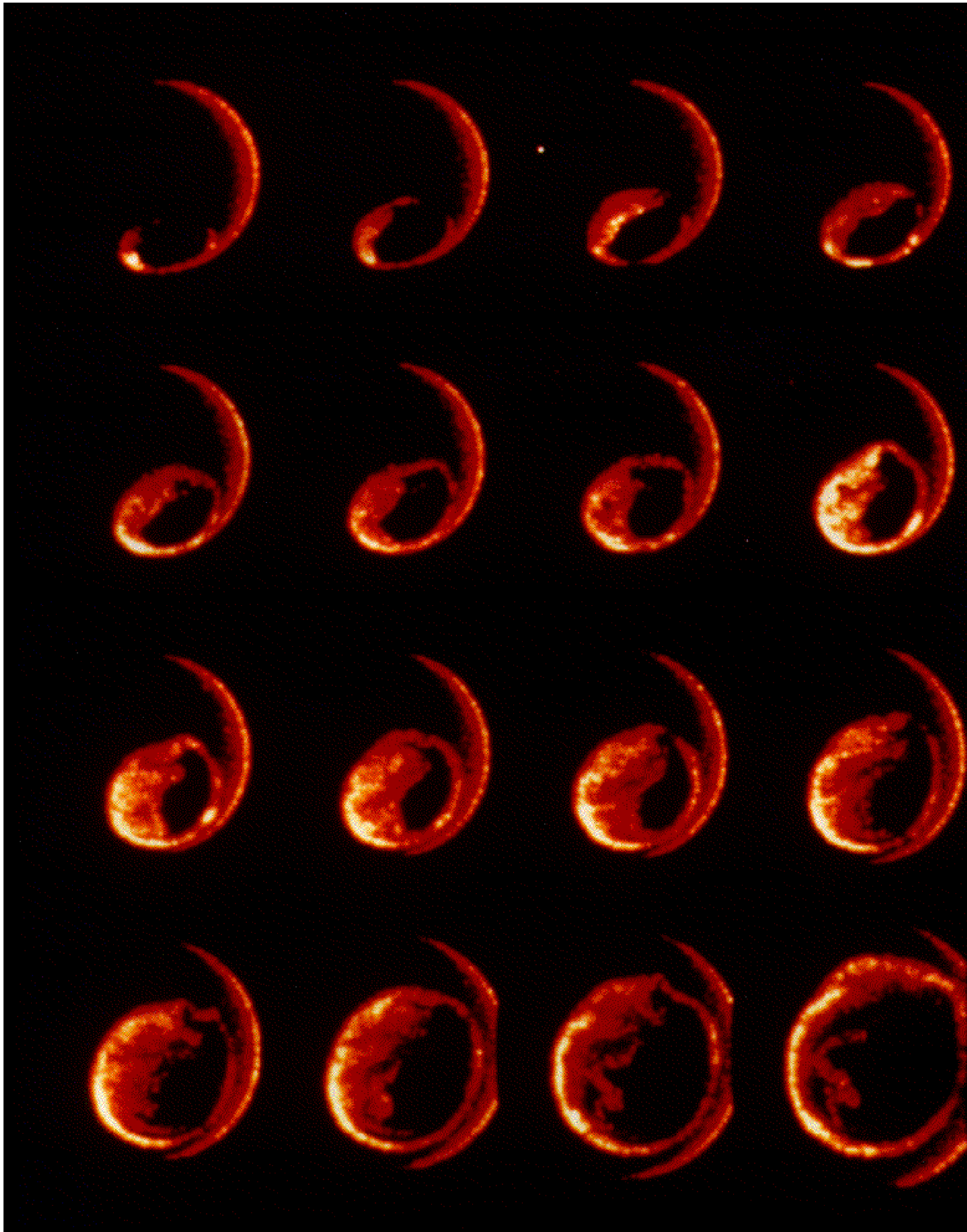
$$\Delta T_e(r, \theta, t) = T_e(r, \theta, t) - T_e^{\min}(r, \theta)$$

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

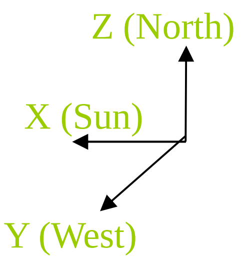
Substorm Onset:

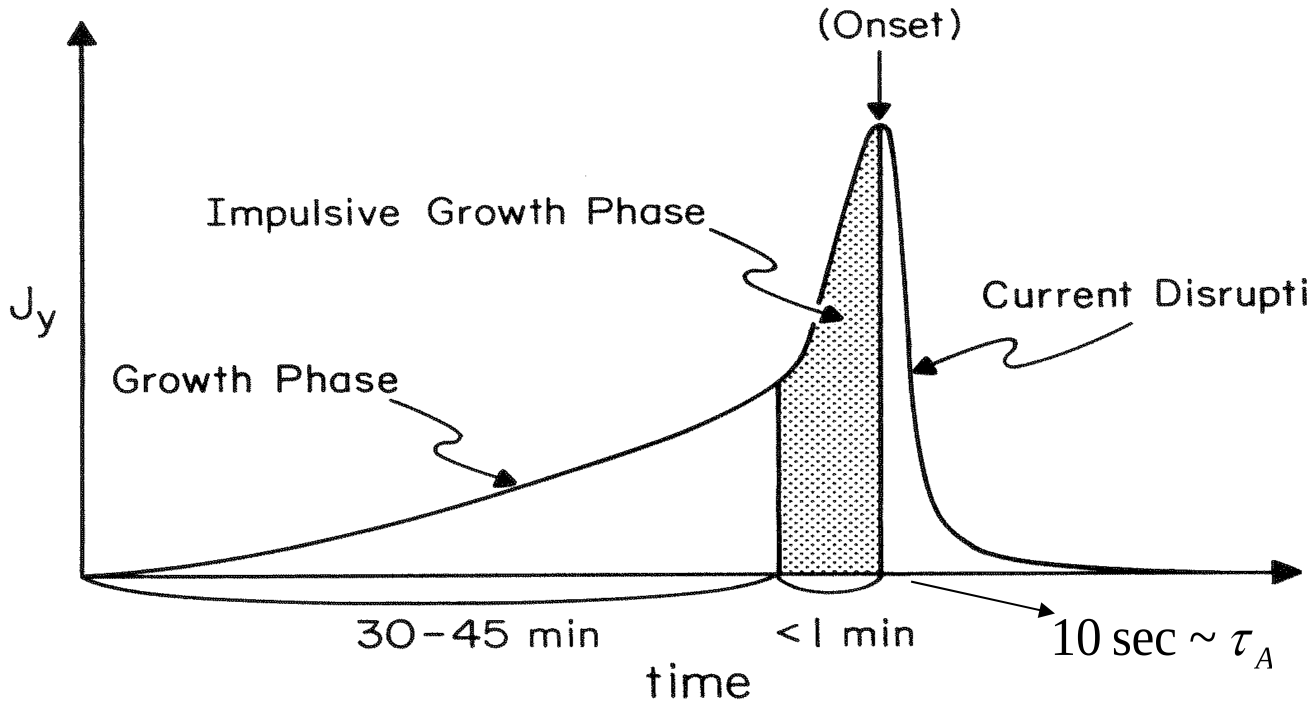


Auroral bulge



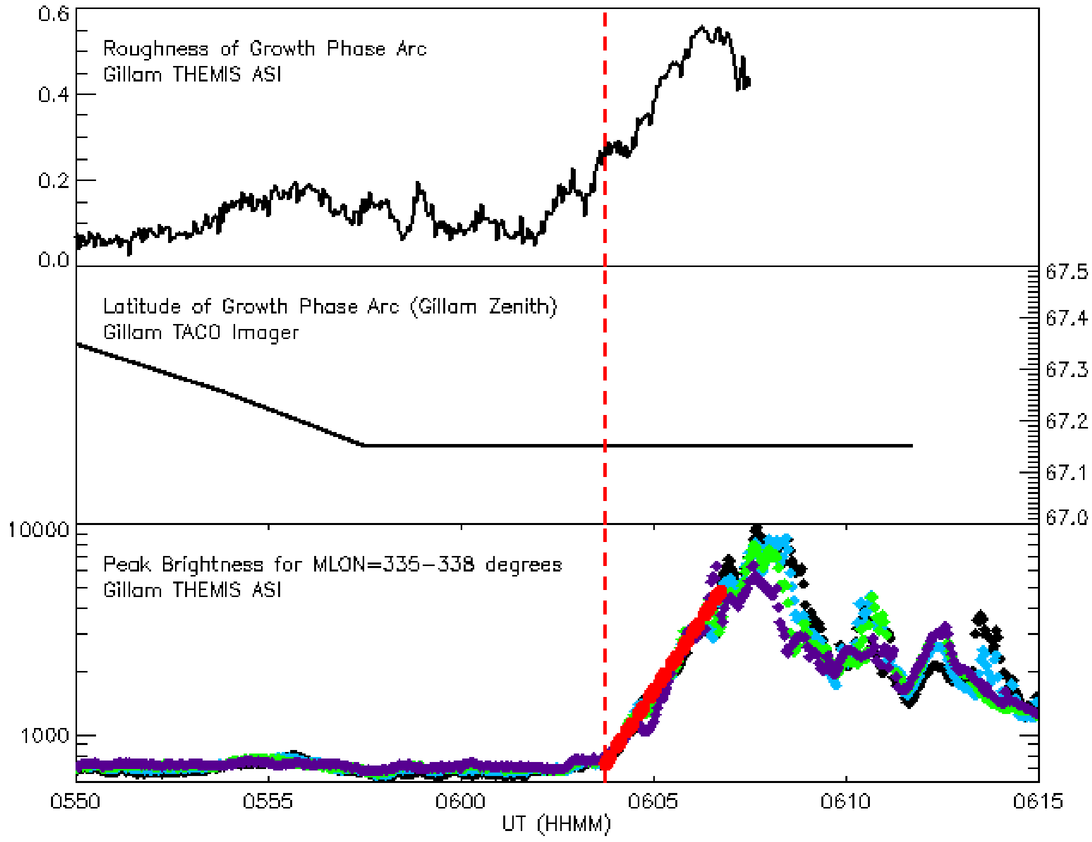
Substorm Onset: When does it occur?





(Ohtani et al., 1992)

Growth Expansion Recovery



Courtesy: E. Donovan (THEMIS)

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 $\rho_s \equiv \sqrt{\beta}c/\omega_{pi}$ if there is a guide field)

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

Generalized Ohm's law (dimensionless form)

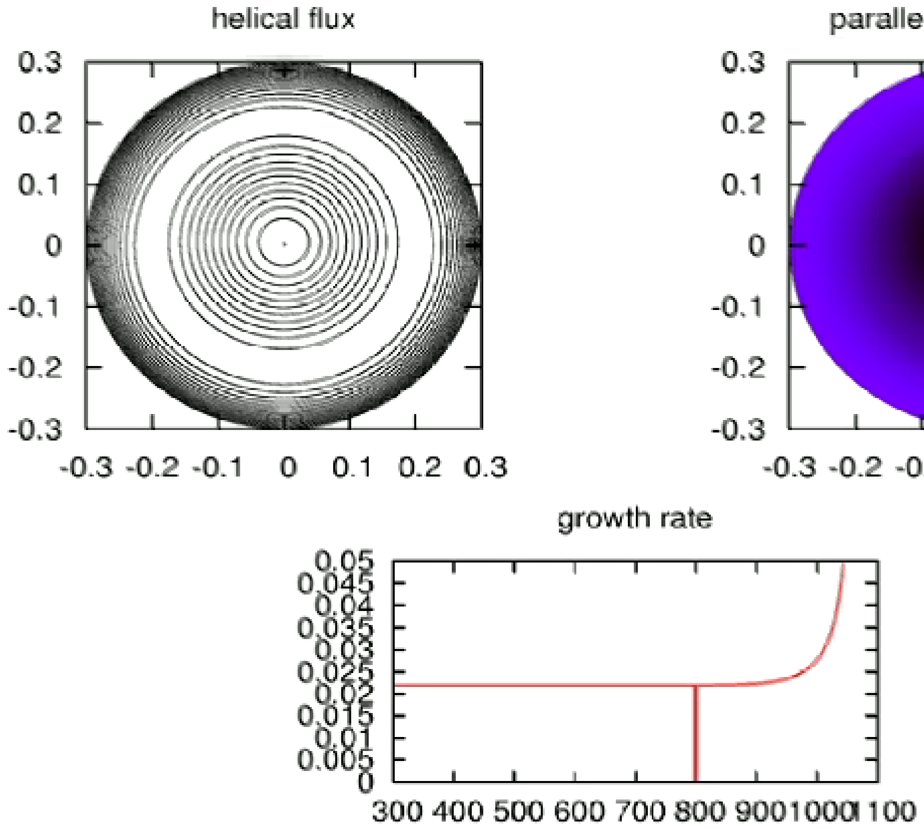
$$\mathbf{E}+\mathbf{v}\times\mathbf{B}=\frac{1}{S}\mathbf{J}+d_e^2\frac{d\mathbf{J}}{dt}+\frac{d_i}{n}\left(\mathbf{J}\times\mathbf{B}-\nabla p_e\right)$$

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

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

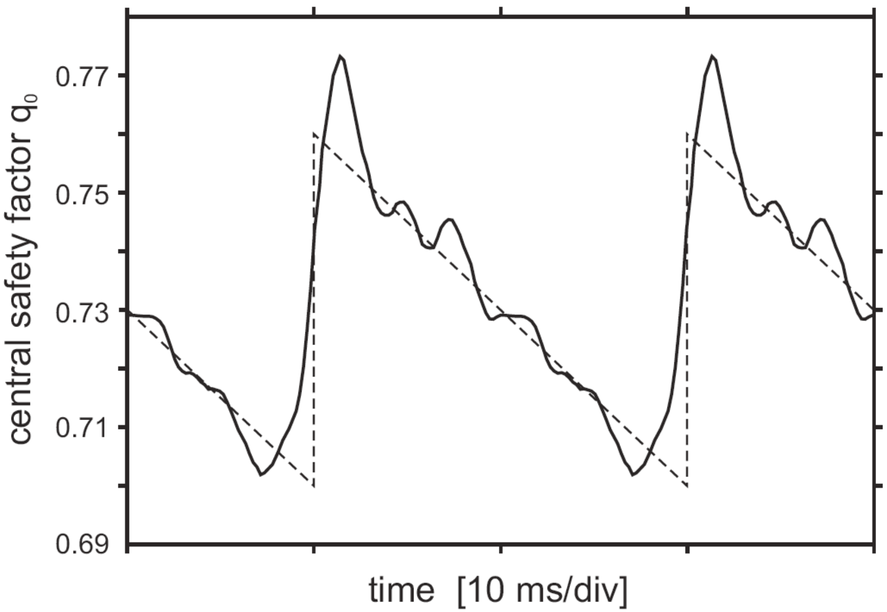
Electron beta β_e

Accelerated growth of the m=1 instability due to Hall MHD effects

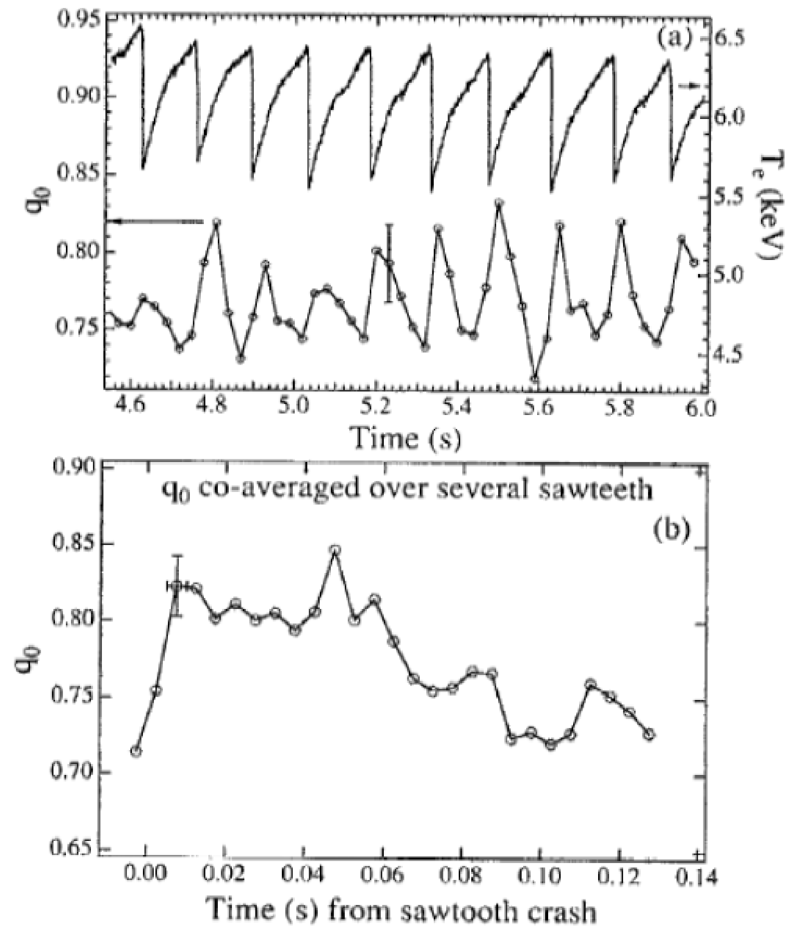


[Germaschewski and Bhattacharjee, 2009]

The $q(0)$ problem



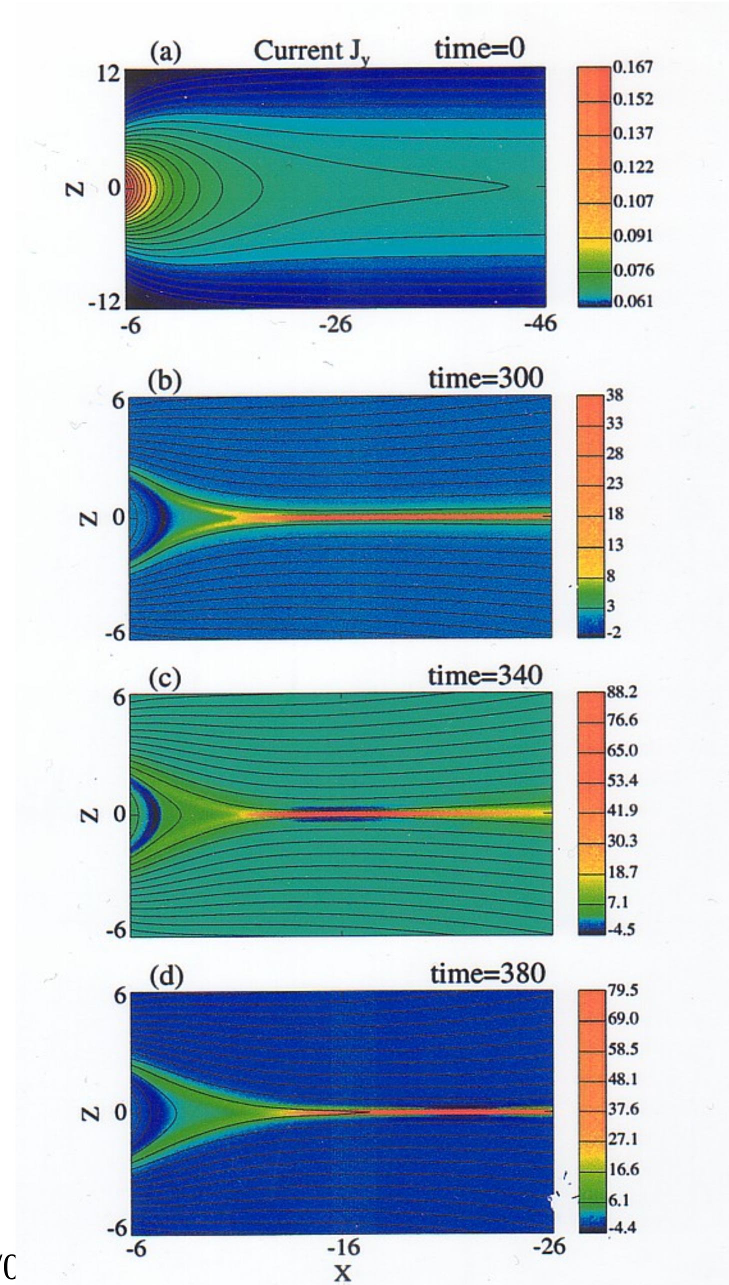
TEXTOR [Soltwisch 1987]

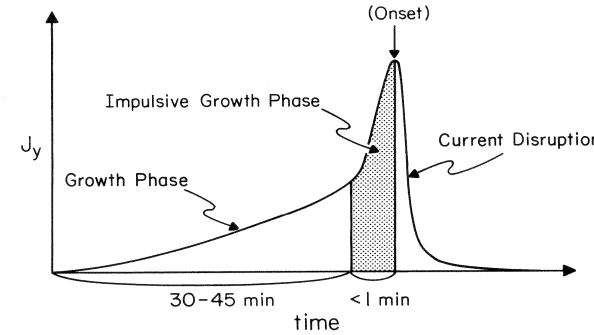


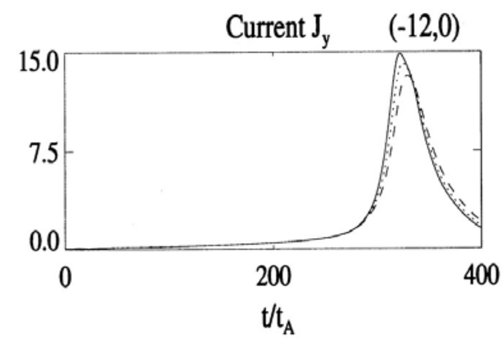
TFTR [Yamada et al. 1994]

Future directions in sawtooth research

- We have identified mechanisms within the framework of Hall MHD (through geometric adjustment in forming X-points) that account for the impulsiveness of sawtooth crashes, but we have *not* accounted for the q(0) problem.
- Current sheets produced during nonlinear evolution of the sawtooth instability are likely to be unstable to secondary ballooning modes that may thwart complete reconnection. There is some experimental evidence, especially in recent TEXTOR observations [Park et al. 2006] as well as simulations [Nishimura et al. 1999].
- Need to run sawtooth simulations including two-fluid (or Hall MHD) equations in toroidal geometry, including heat conduction [cf. Jardin et al., IAEA, 2012].
- Non-monotonic q-profiles in NSTX (with q(0)>1) can excite double-tearing modes that can exhibit analogous dynamics.



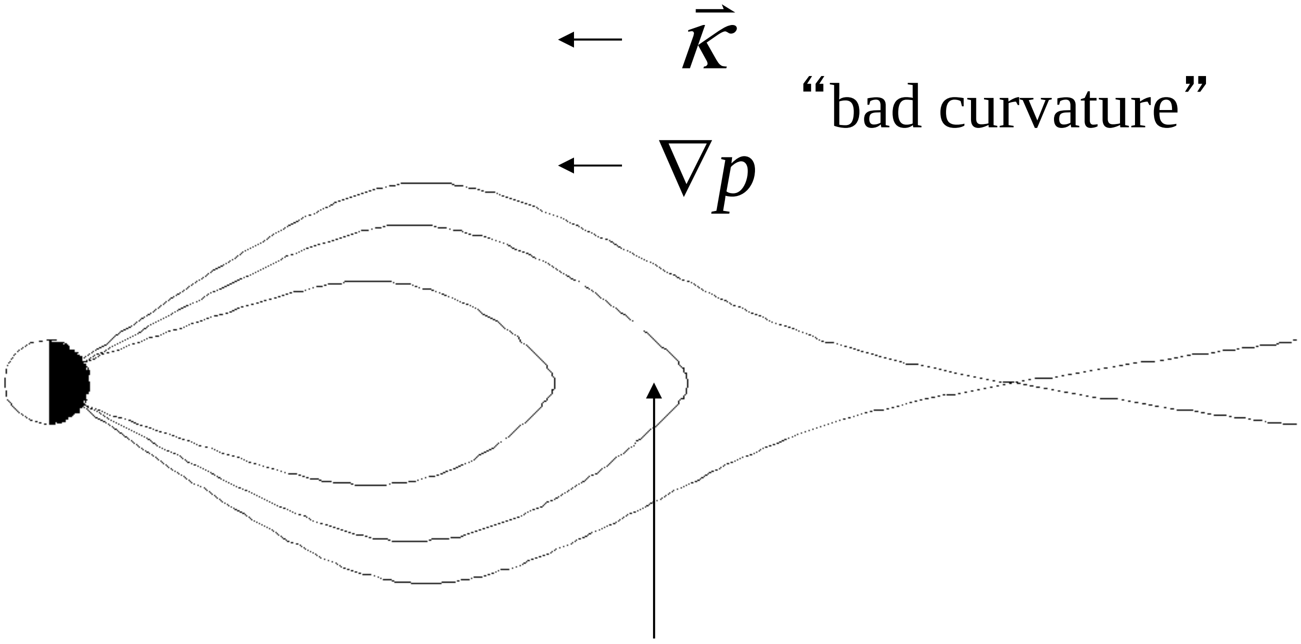




2D Hall-MHD Simulation

(Ma and Bhattacharjee, 1998)

Is Near-Earth Magnetotail Ballooning Unstable?



$$\text{Near - Tail } (7 \sim 10\ R_E)$$

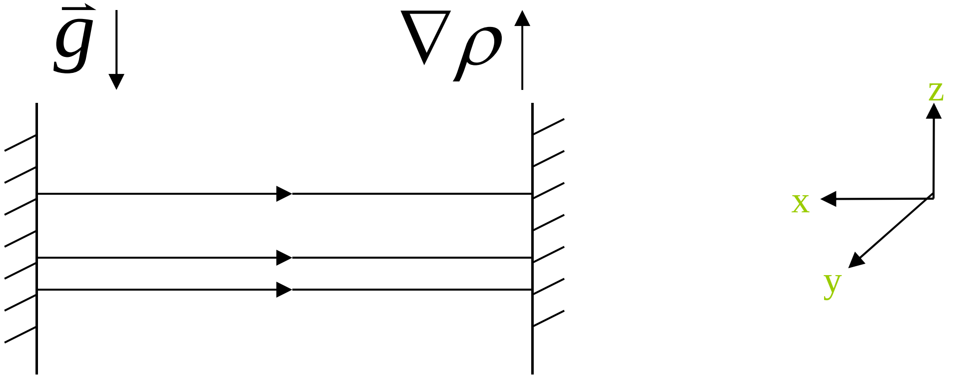
$$\beta_{eq} \sim O(1) - O(100)\ !!$$

Nonlinear Ballooning: Does that cause substorm onset?

- Full set of nonlinear fluid equations.
- Line-tying boundary condition is specified on the earth-side of computation domain, which represents the surface of ionosphere.
- Does the magnetotail "detonate" in an impulsive manner due to nonlinear ballooning (as suggested by Hurricane, Fong, Cowley, Coroniti, Kennel and Pellat, 1999)?

Nonlinear line-tied Parker instability: analogous to the line-tied ballooning instability

Equilibrium

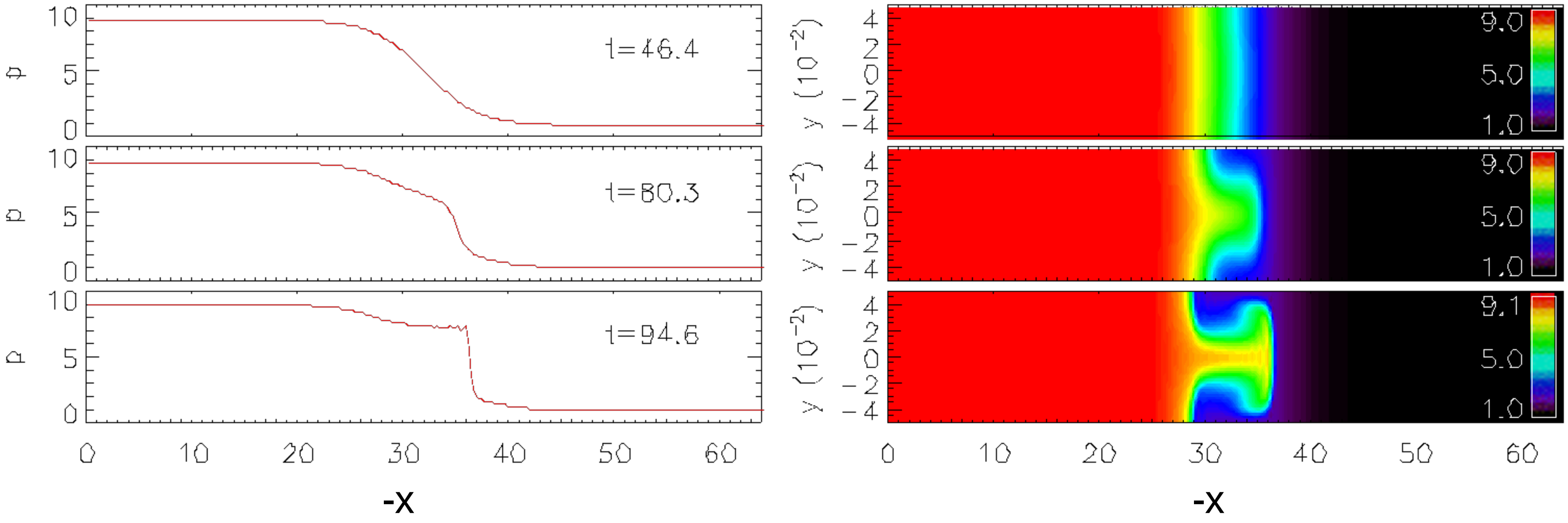


$$\rho = \rho(z), \quad p = p(z), \quad \vec{B} = B(z)\hat{x}, \quad \vec{g} = -g\hat{z}$$

$$\frac{d\rho}{dz} > 0, \quad \frac{d}{dz}\left(p + \frac{B^2}{2}\right) = -\rho g$$

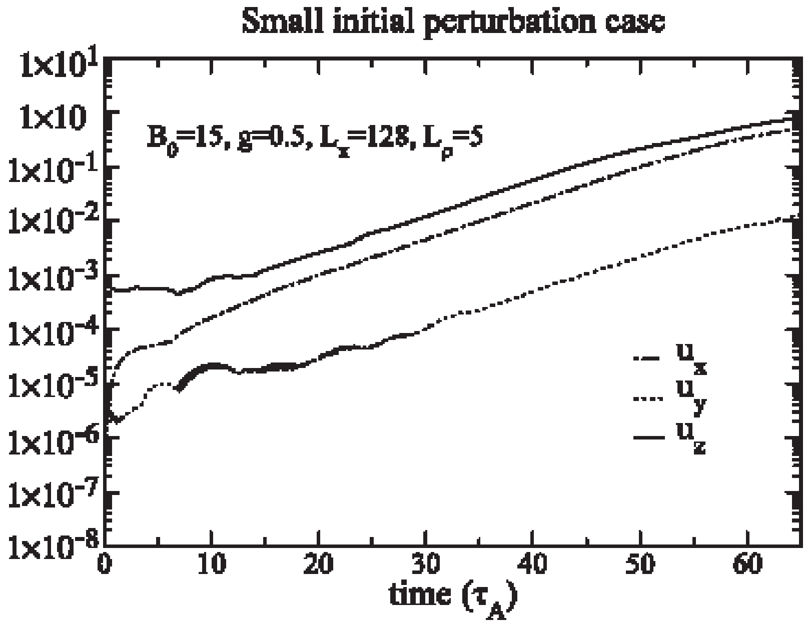
(Zweibel and Bruhwiler 1992, Matsumoto et al. 1993, Cowley et al. 1996)

Nonlinear ballooning instability: formation of fingers and generation of strong sheared flows



(P. Zhu, A. Bhattacharjee, and K. Germaschewski, PRL, 96, 0265001, 2006)

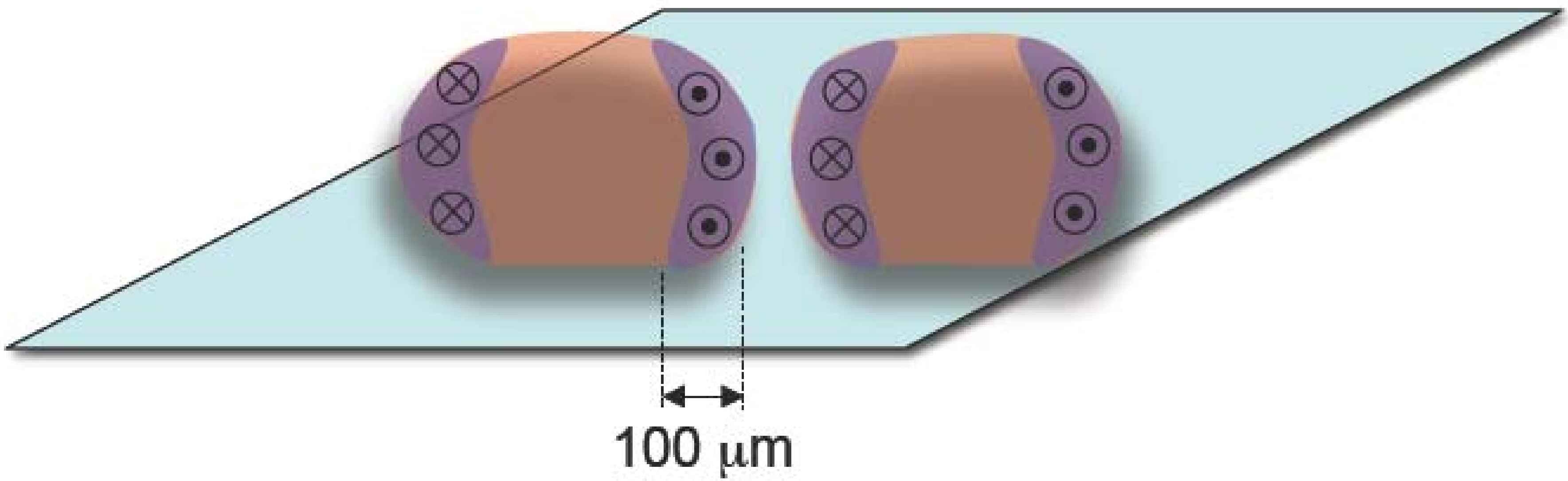
Nonlinear ballooning instability: absence of detonation and saturation



Detonation is not generic during nonlinear ballooning. There is a remarkable cancellation between nonlinear stabilizing and destabilizing contributions, with the consequence that the mode evolves nonlinearly at the linear growth rate.

Bubbles have a toroidal magnetic field

B ~ 50 T ("Megagauss")

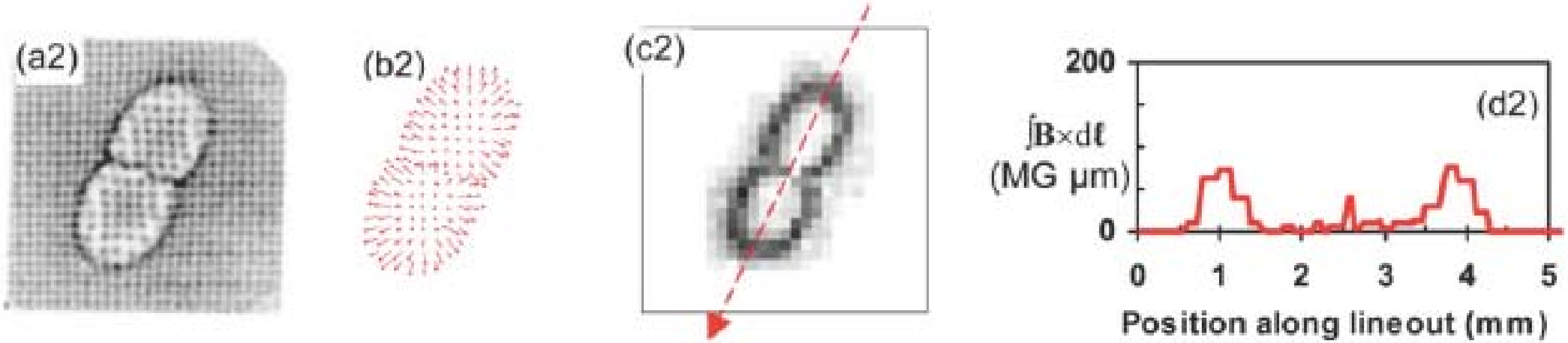


B field believed to arise through a two-fluid effect

$$\frac{\partial B}{\partial t} = \nabla \times (v \times B) - \frac{1}{ne}(\nabla n \times \nabla T)$$

Omega Laser Experiment: MIT-Rochester Collaboration

Reconnection of magnetic fields observed!



B field observed to be destroyed as "fast as possible" Inflow is supersonic (and super-Alfvenic),

Sweet-Parker rates are too low.

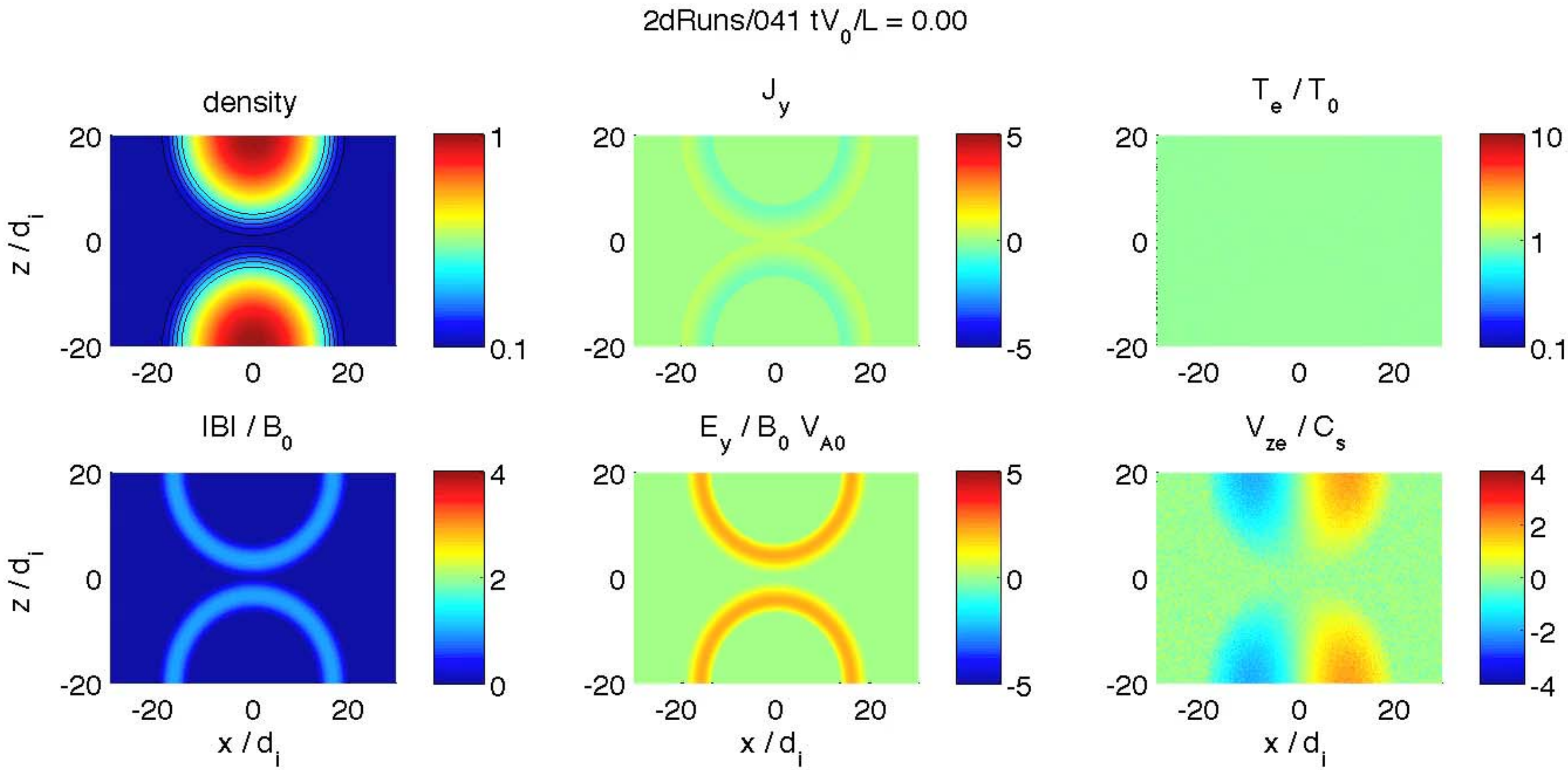
HED bubble reconnection regime

Estimates:

- $L/d_i \sim 20\text{-}100$, $L_B/d_i \sim 3\text{-}5$, $d_i > \delta_{SP}$
- $V_{in} / V_A >= 1$ (strong reconnection drive)

A problem, since fast “two-fluid” reconnection typically gives us only $V_{in} / V_A \sim 0.1\text{-}0.2$

We find this leads to highly dynamic current sheet geometry and *flux pileup*. Compression of B raises *instantaneous* V_A over *nominal* V_{A0}.


2dRuns/041 tV0/L = 0.00
density
Jy
Te / T0
|B| / B0
Ey / B0 VA0
Vze / Cs
z / di
x / di
20
0
-20
-20
0
20
1
0.1
5
0
-5
10
1
0.1
4
2
0
5
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-5
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2
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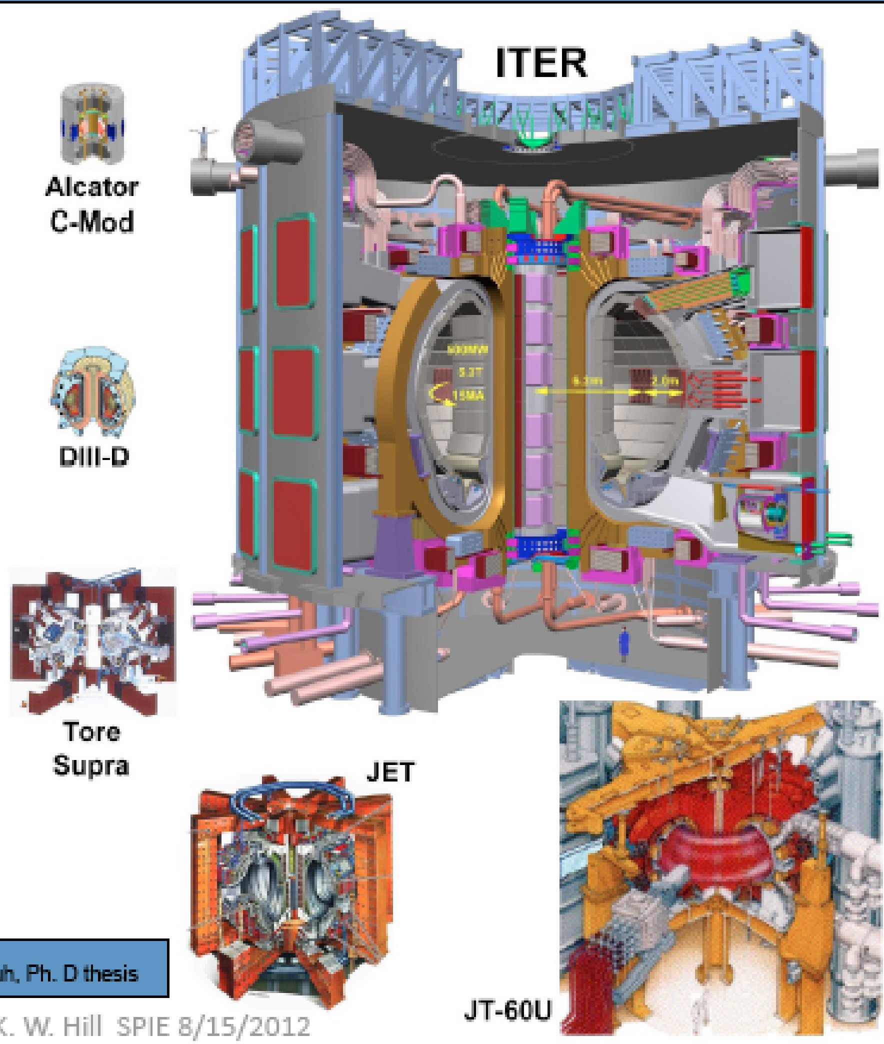
-2
-4

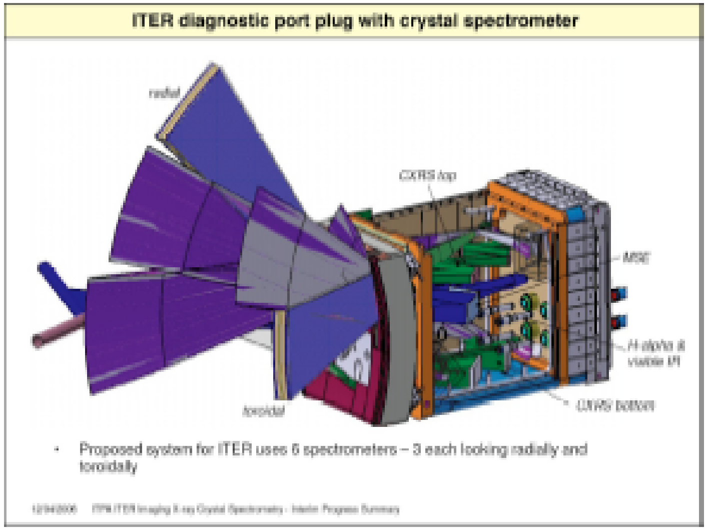
ITER's size requires passive spectroscopy for measuring core temperature and ion motion

Sizes of various magnetic fusion machines



H. Yuh, Ph. D thesis

- ITER plasma cross section is 4 m wide and 7 m high
- Charge-exchange-recombination spectroscopy is not effective in core

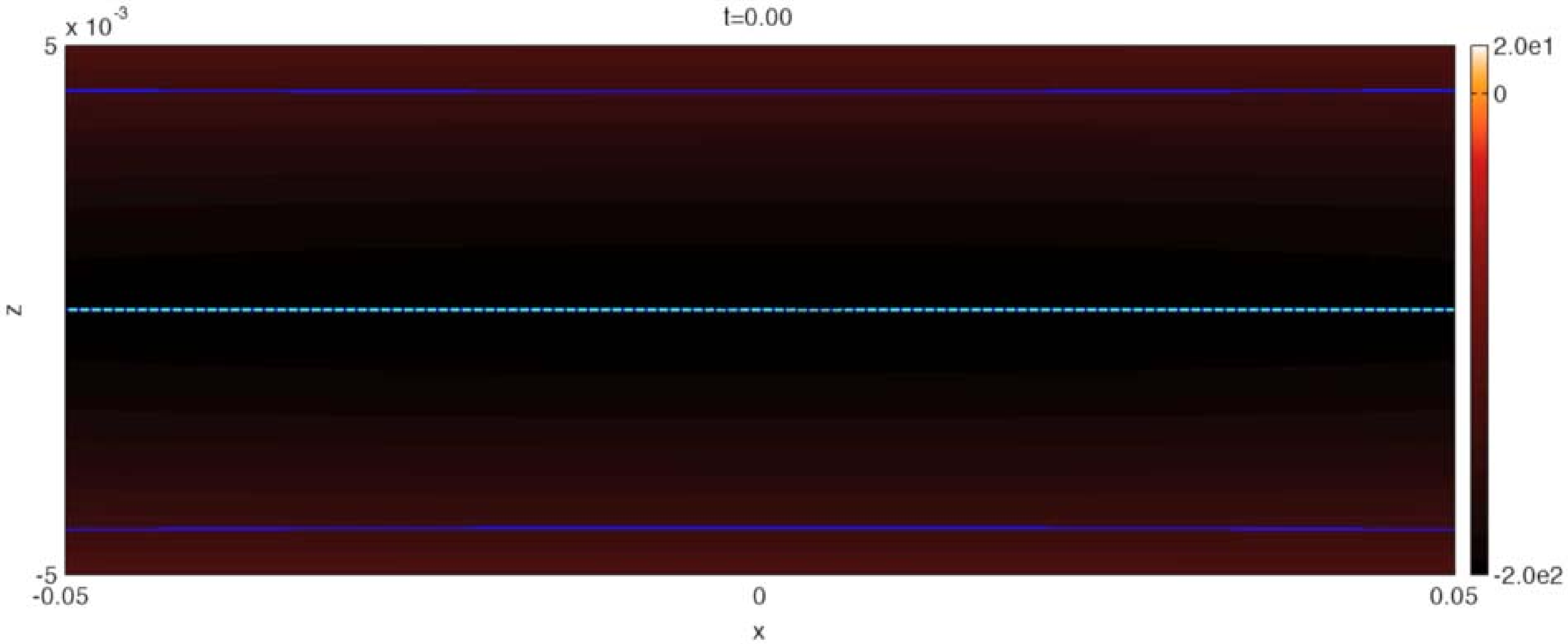


Design is being carried out at PPPL and LLNL

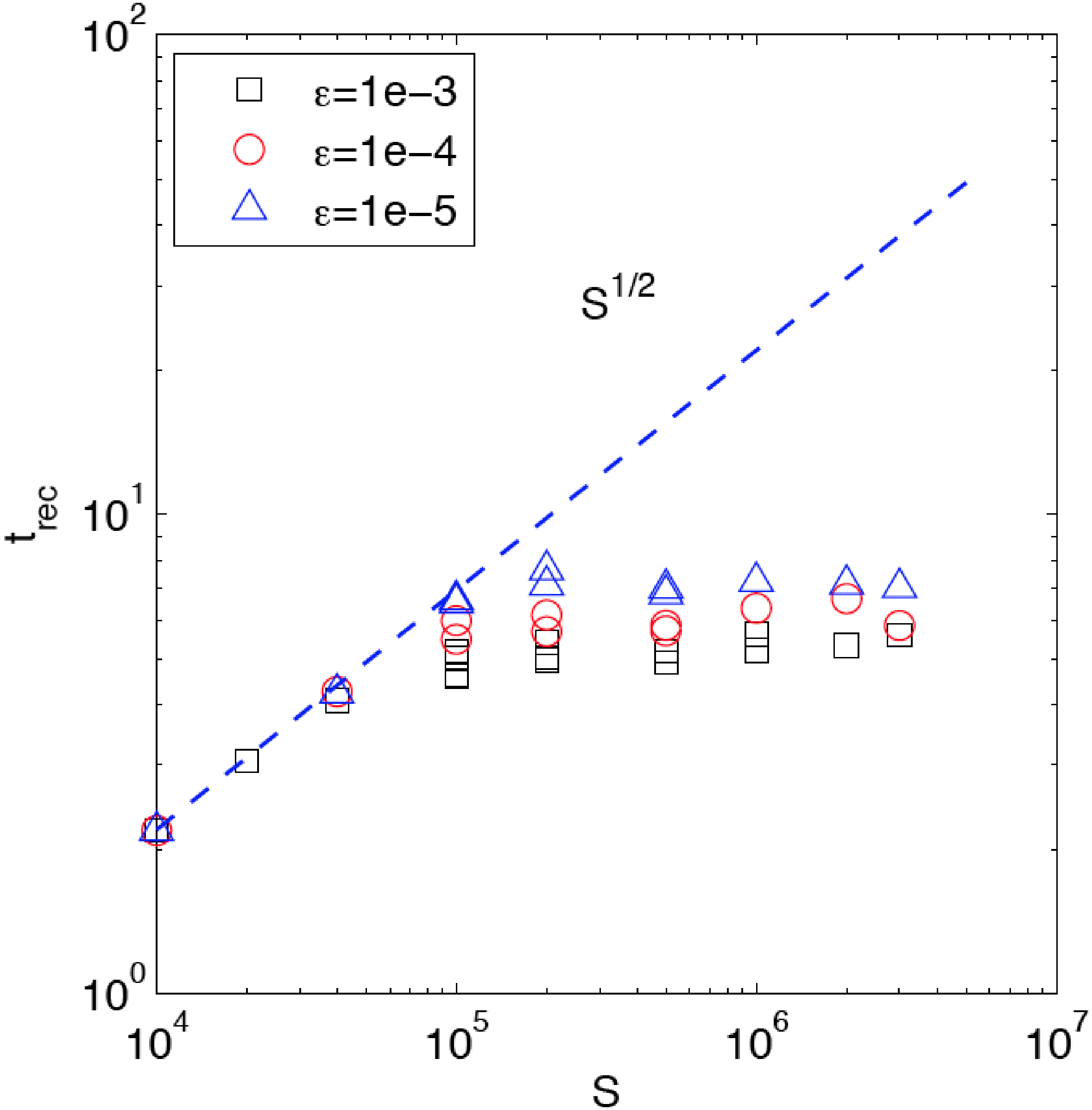
Main Points

- **Spatially resolved x-ray spectroscopy** with a spherical crystal and 2D pixelated x-ray detector is a highly successful instrument on tokamaks worldwide
- $E/\Delta E$ ~ 10,000 enables Doppler measurements of ion temperature T_i & plasma flow velocity, v
- Much new physics understanding has evolved
- We are doing the conceptual design for the ITER spectrometers
- **The technology should also be beneficial on small sources such as High Energy Density (HED) and Synchrotron Radiation (SR) experiments**
  - Should provide new HED physics (most previous work with $E/\Delta E$ ~ 1000)
  - Possibly improved throughput for SR experiments
- 2D x-ray imaging schemes using matched pairs of spherical crystals with ~ 10,000 times higher throughput than typical pinhole imagers for HED experiments should benefit both types of experiments

Plasmoid Instability of *Large-Scale* Current Sheets

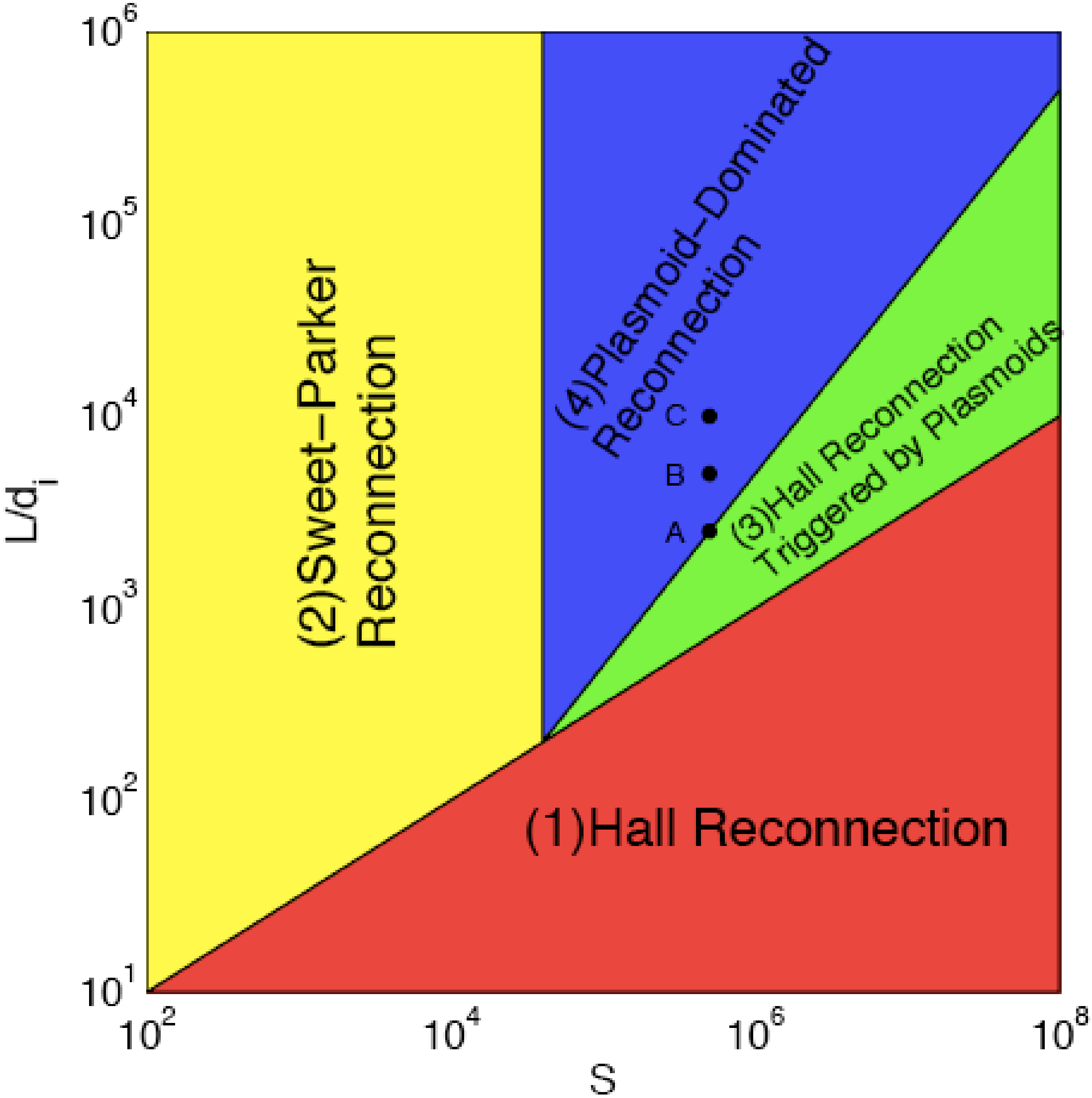


Reconnection Time of 25% of Initial Flux



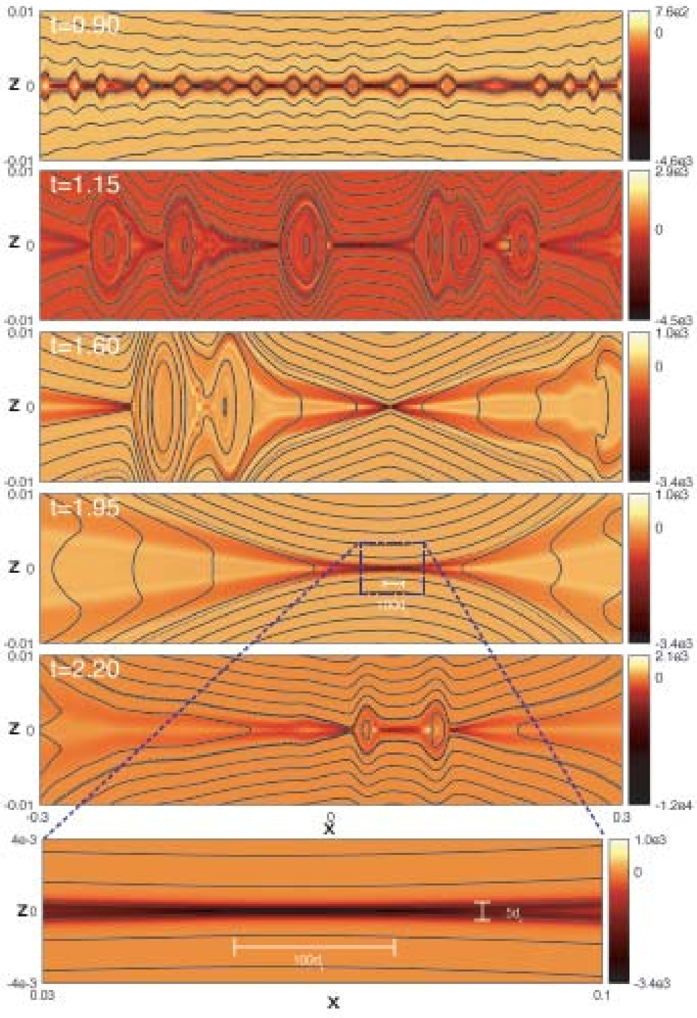
$$< \frac{1}{V_A B}\frac{d\psi}{dt} > \sim 0.01$$

$$< u_i > \sim 0.01 V_A$$

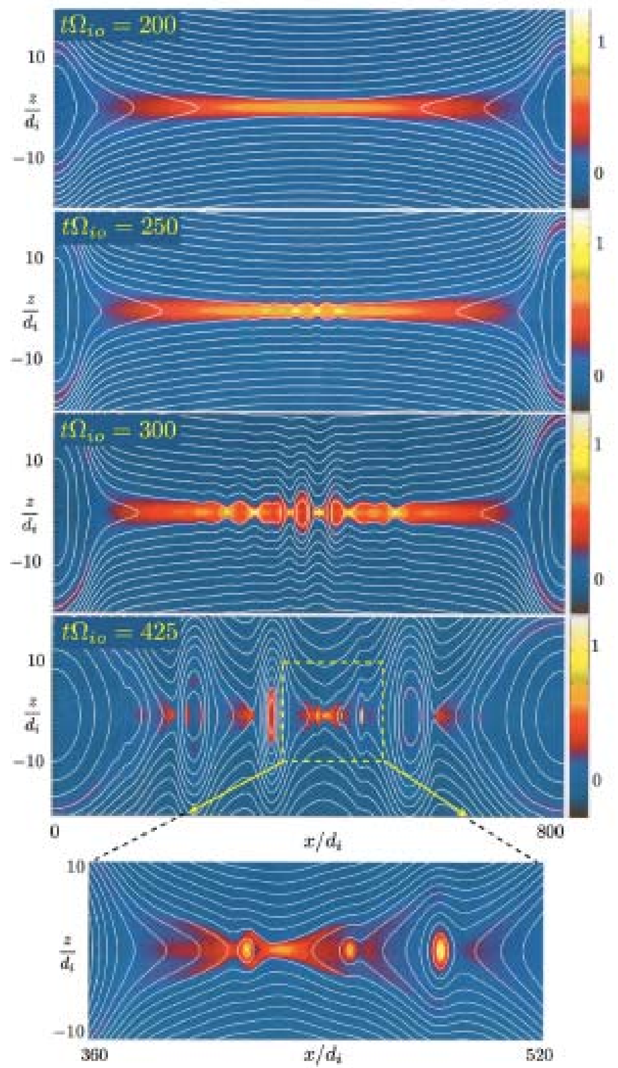


A: $S = 5 \times 10^5, d_i = 4 \times 10^{-4}$
B: $S = 5 \times 10^5, d_i = 2 \times 10^{-4}$
C: $S = 5 \times 10^5, d_i = 10^{-4}$
D: $S = 5 \times 10^5, d_i = 0$

Also see Ji and Daughton, 2012



Run B, resistive Hall



Daughton et al. (2009), PIC

Largest 2D Hall MHD simulation to date

What are the tools and challenges?

- *Simulation tools*: Extended MHD (fluid), particle-in-cell (fully kinetic electrons and ions), hybrid (fluid electrons, kinetic ions), and gyrokinetics (somewhat underexplored but very interesting, as is evident in the recent work of the PPPL Space Physics Group).

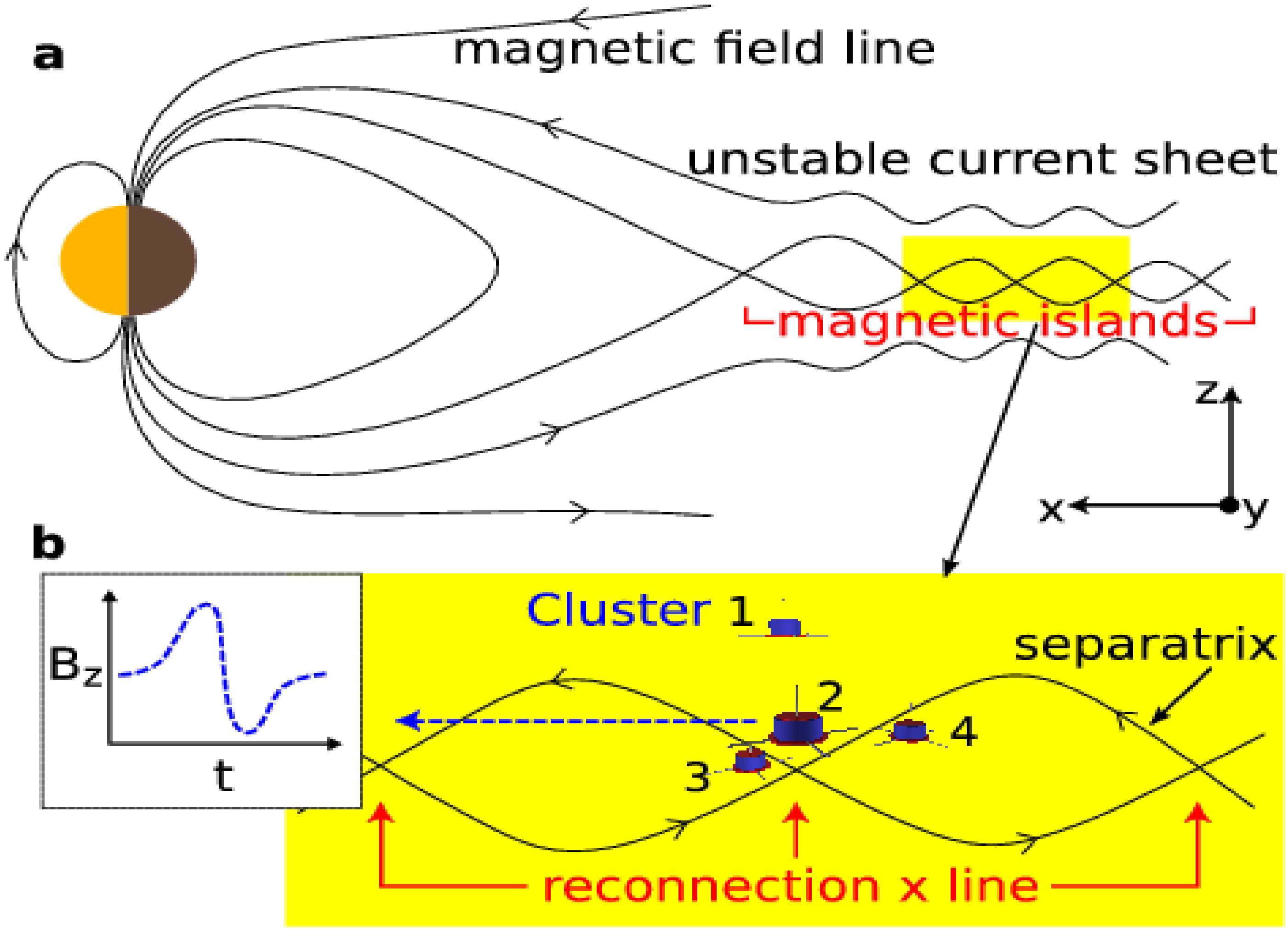
Many challenges:

- *Closure:* Are there fluid closures or representations for kinetic processes?
- *Algorithmic:* For example, development of scalable implicit time-integration methods, improved pre-conditioners, AMR.

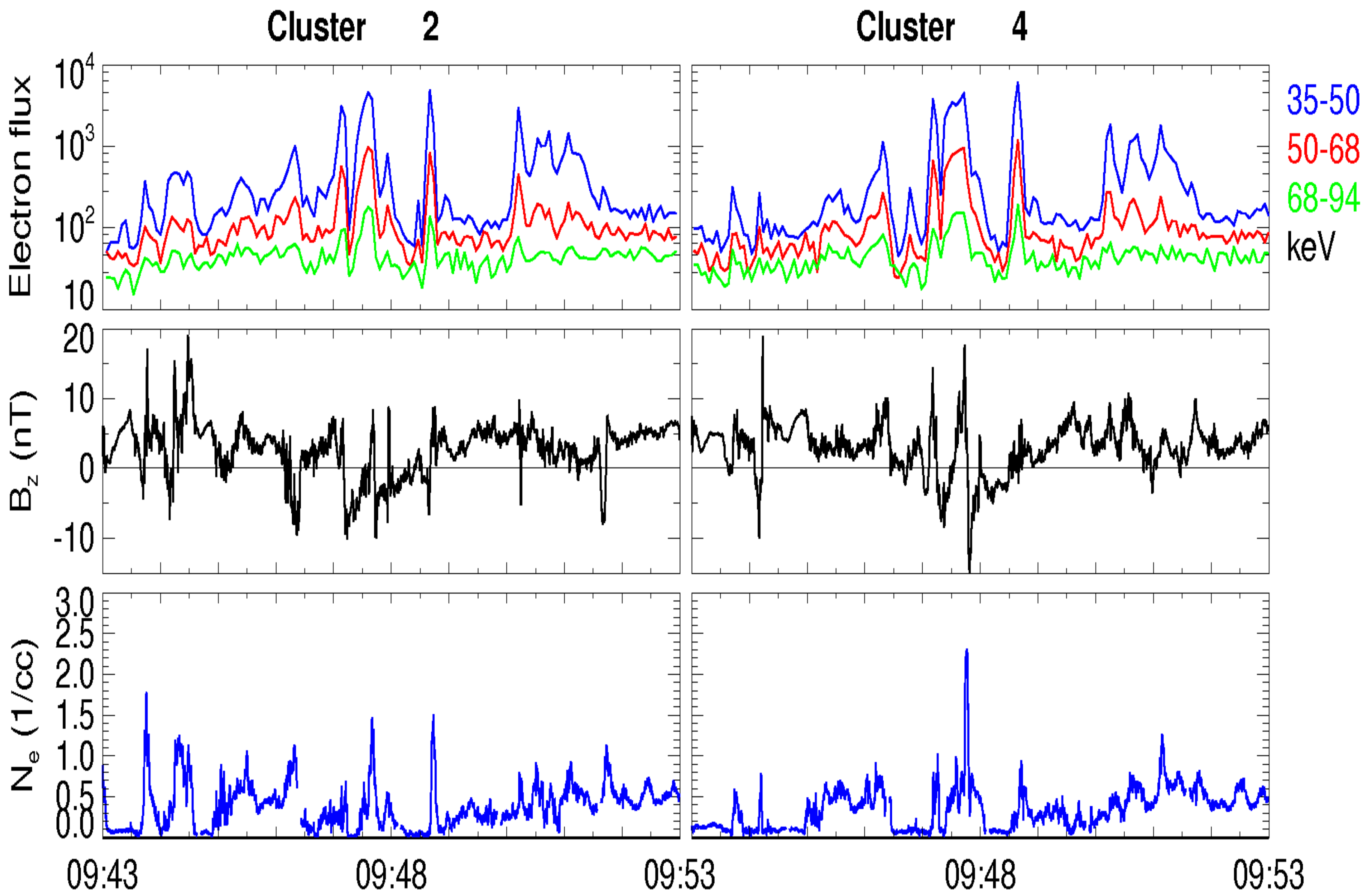
Great opportunities for collaborations between applied mathematicians, computer scientists, and physicists.

Fluxes of energetic electrons peak within magnetic islands

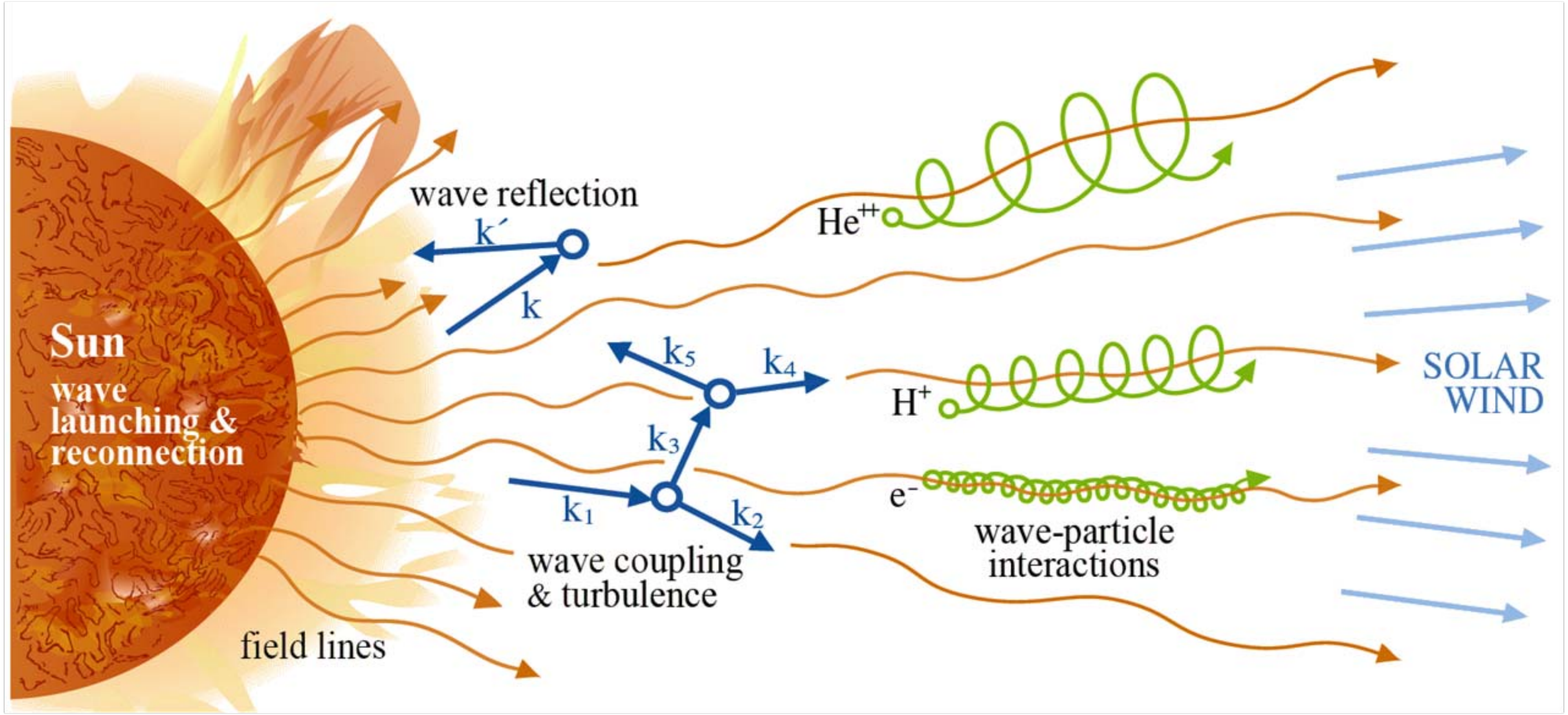
[Chen et al., Nature Phys., 2008]



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

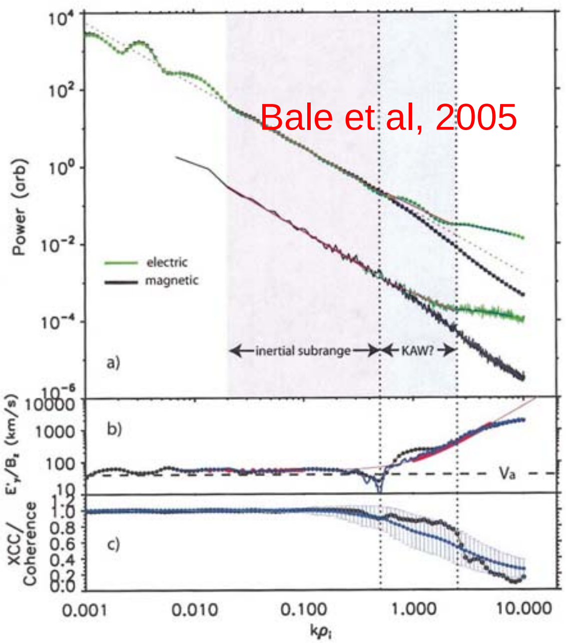


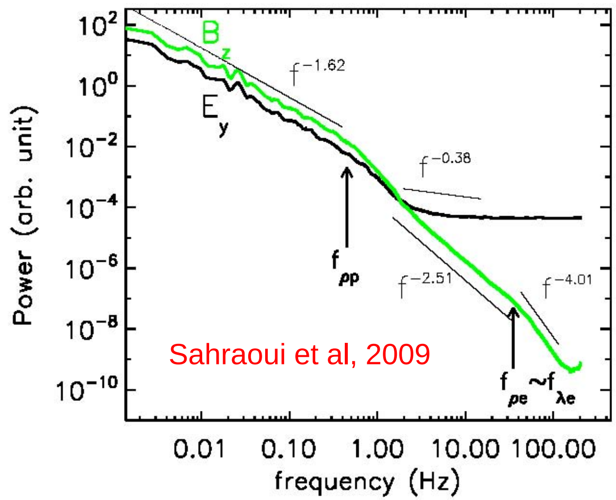
Kinetic dissipation processes in the solar corona

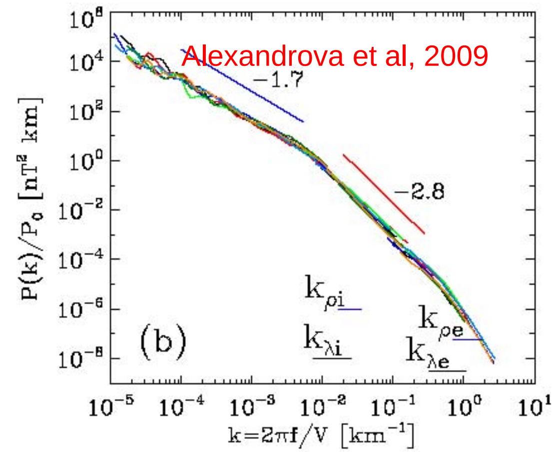


Courtesy: B. Chandran, M. Lee, and K. Donahue, UNH

Major scientific questions







- Is there dissipation at ion scales?
- In region between ion and electron scales: is there dissipation, cascade?
- What is the nature of dissipation at electron scales?
- Is the activity at MHD scales and/or kinetic scales akin to interacting waves?
- Are homogenous linear Vlasov predictions, e.g., damping rates, correct, or useful?
- Where is the entropy actually generated and how?
- Rich area for gyrokinetic simulations (both PIC and continuum)