Review of Reconnection Experiments

Troy Carter
Dept. of Physics and Astronomy, UCLA

UCLA

Summary/Outline

- (Yet another) Introduction to Magnetic Reconnection
  - Sweet-Parker versus “fast” reconnection
- Discussion of dedicated experiments on reconnection (a little MRX-centric…)
- Experiments exploring what makes reconnection fast:
  - Turbulence and anomalous resistivity?
  - Fast reconnection via two-fluid effects
  - Plasmoid instability

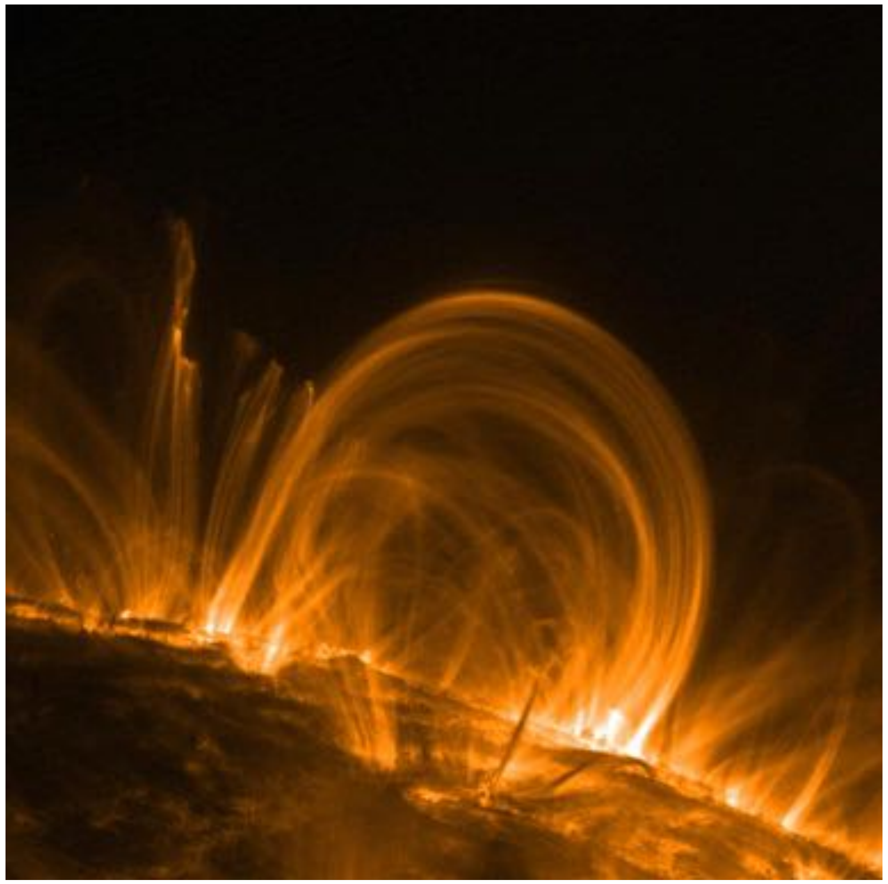
Why is magnetic reconnection important?

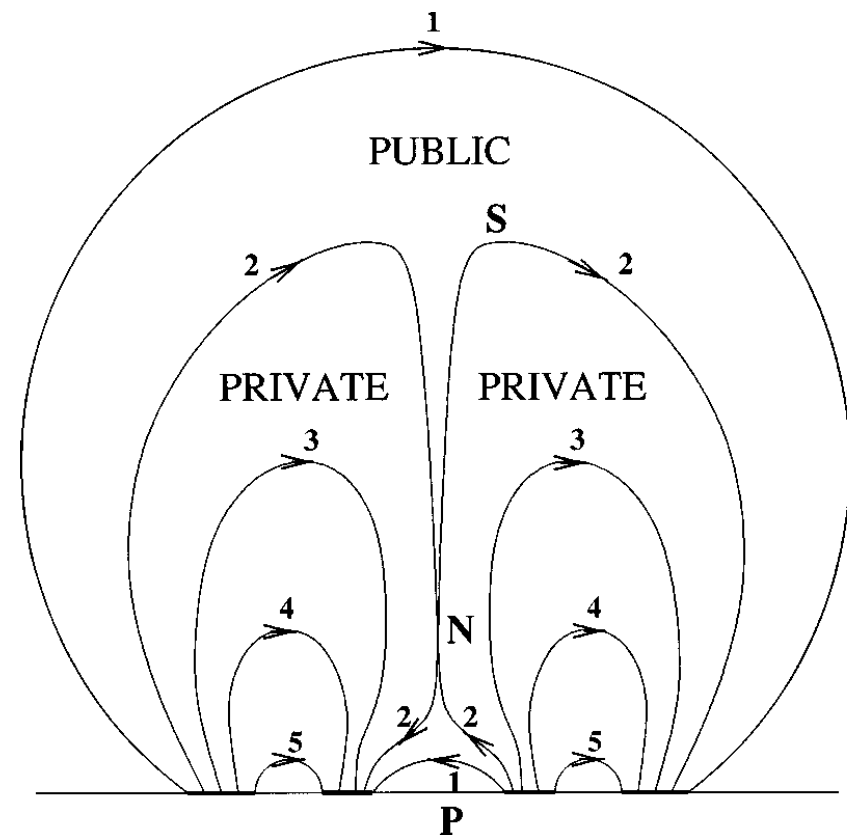
First, a working definition:

> Process by which rapid ($\tau \ll \tau_R$) changes in magnetic topology and rapid release of magnetic energy can occur in a highly conducting plasma. Reconnection causes changes on local (heating, particle acceleration) and global (topology, transport) scales.

- ▷ Solar Corona: Flares, Heating, CME's
- ▷ Magnetosphere: Solar wind interaction with the earth's dipole field
- ▷ Other Astrophysical Plasmas: Accretion disks, star formation
- ▷ Dynamo: Reconnection could be a rate-limiting step
- ▷ Fusion Devices: IRE's, Sawtooth crash, Helicity injection

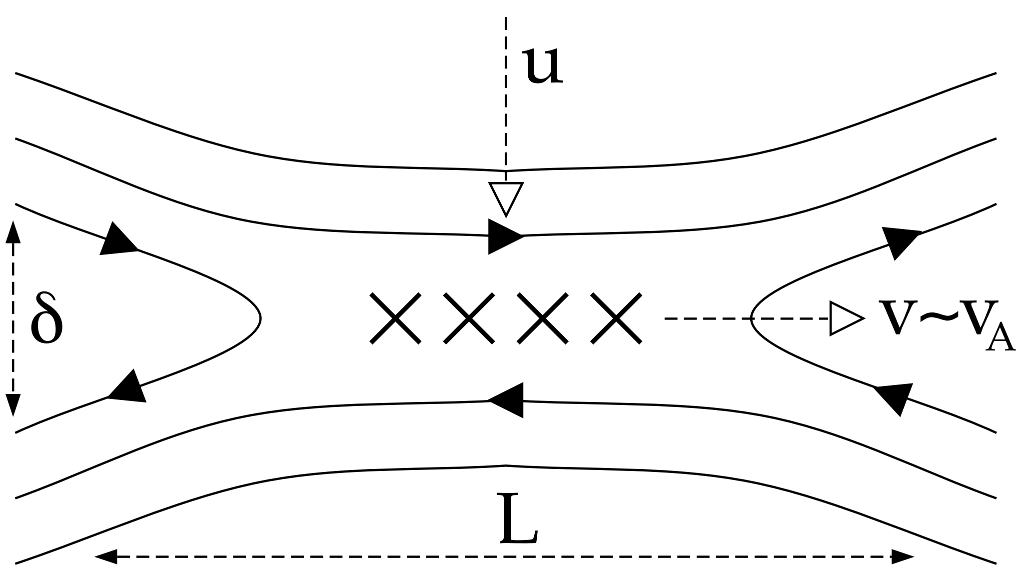
Example: Reconnection in the solar corona





- ▷ Sweet's picture: formation of current sheets & reconnection between magnetic loops in the corona
- ▷ Reconnection models must explain solar flare timescales: ten's of minutes to hours ($\ll \tau_r$)

Sweet-Parker theory: Resistive MHD reconnection



$$\frac{\partial \mathbf{B}}{\partial t} = 0 = \underbrace{\nabla \times (\mathbf{v} \times \mathbf{B})}_{\tau_A} + \underbrace{\frac{\eta c^2}{4\pi}\nabla^2 \mathbf{B}}_{\tau_R}$$

Along with force balance and mass conservation:

$$\frac{u}{v_A} = \sqrt{\frac{1}{S}} \;\; ; \;\; S = \frac{\tau_R}{\tau_A} \;\; ; \;\; \tau = \sqrt{\tau_R \tau_A}$$

- ▷ Significantly faster than resistive diffusion, but still too slow to explain observations
- ▷ Bottleneck: δ must be very small due to η; this limits mass outflow, which in turn limits inflow, u (reconnection rate)
- ▷ What additional physics must be added to this model to match observations?

What could make reconnection faster than Sweet-Parker?

Generalized Ohm's Law (electron momentum equation):

$$\underbrace{\mathbf{E} + \frac{\mathbf{v}\times\mathbf{B}}{c} = \eta\mathbf{j}}_{\text{resistive MHD}} + \underbrace{\eta^{*}\mathbf{j}}_{\text{turbulence}} + \underbrace{\frac{\mathbf{j}\times\mathbf{B}}{nec}}_{\text{Hall, } c/\omega_{\mathrm{p,i}}} + \underbrace{\frac{\nabla\cdot\mathbf{P}}{ne}}_{\rho_{\mathrm{s}}} + \underbrace{\frac{m_{\mathrm{e}}}{e^2}\mathbf{v}_{\mathrm{e}}\cdot\nabla\frac{\mathbf{j}}{n}}_{c/\omega_{\mathrm{p,e}}}$$

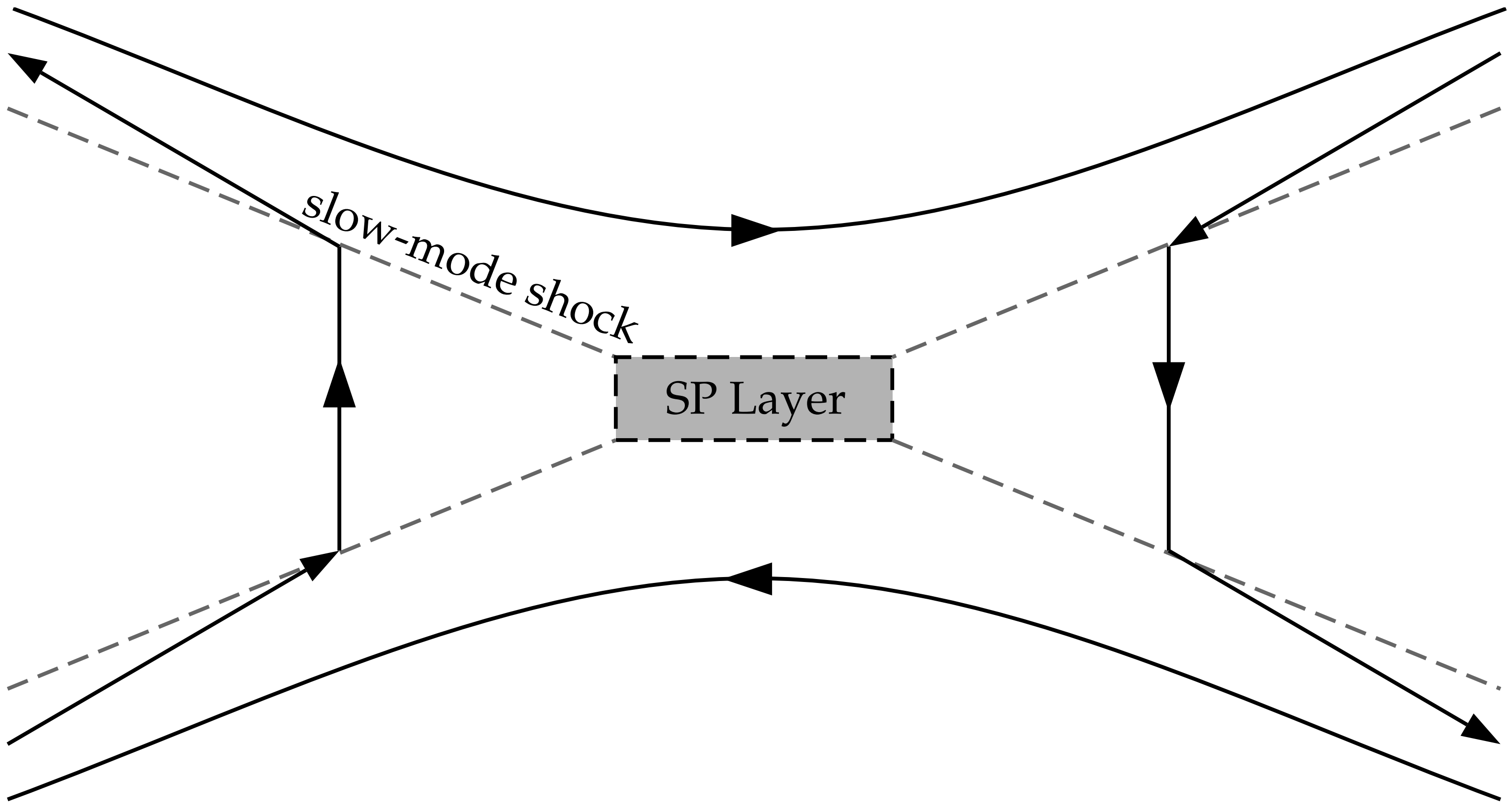
Turbulent anomalous resistivity
[Syrovatskii, Heyvaerts, ...]

- Modify Sweet-Parker using increased η, δ widened, reconnection rate enhanced
- Can get Petschek-like reconnection with $\eta = \eta(j)$
- Turbulence is essential, but what instability?

Hall dominated reconnection
[Biskamp, Drake, Birn, ...]

- Reconnected field lines relax via whistler wave; favorably changes CS geometry (Petschek-like geometry)
- Reconnection rate independent of dissipation mechanism
- 3D: Turbulence may slow down reconnection [Rogers]

Petschek Reconnection



- ▷ Mass flow and dissipation are decoupled
- ▷ Won't work under resistive MHD – not self-consistent (B_y regeneration [Biskamp, Kulsrud])
- ▷ Will work if $\eta = \eta(j)$ under resistive MHD
- ▷ Same effect is accomplished when the Hall term is introduced, but the shocks are replaced by standing whistler waves.
- ▷ So anomalous resistivity or the Hall term might lead to fast reconnection, but which mechanism is dominant?

First laboratory experiments to observe reconnection: fusion experiments

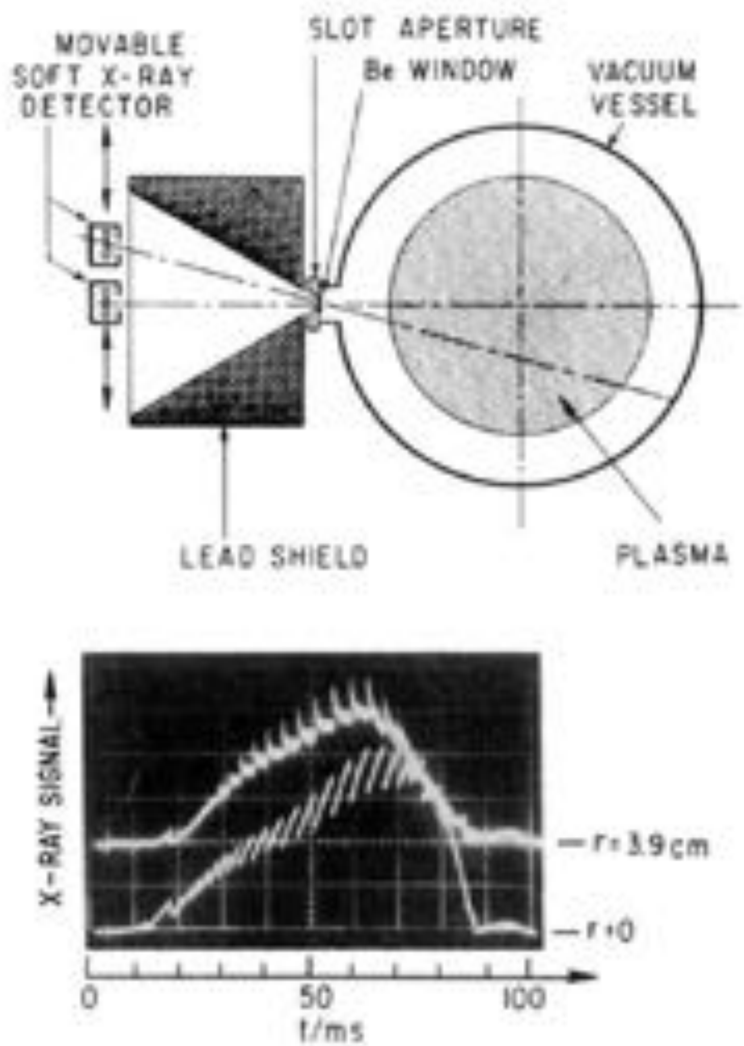
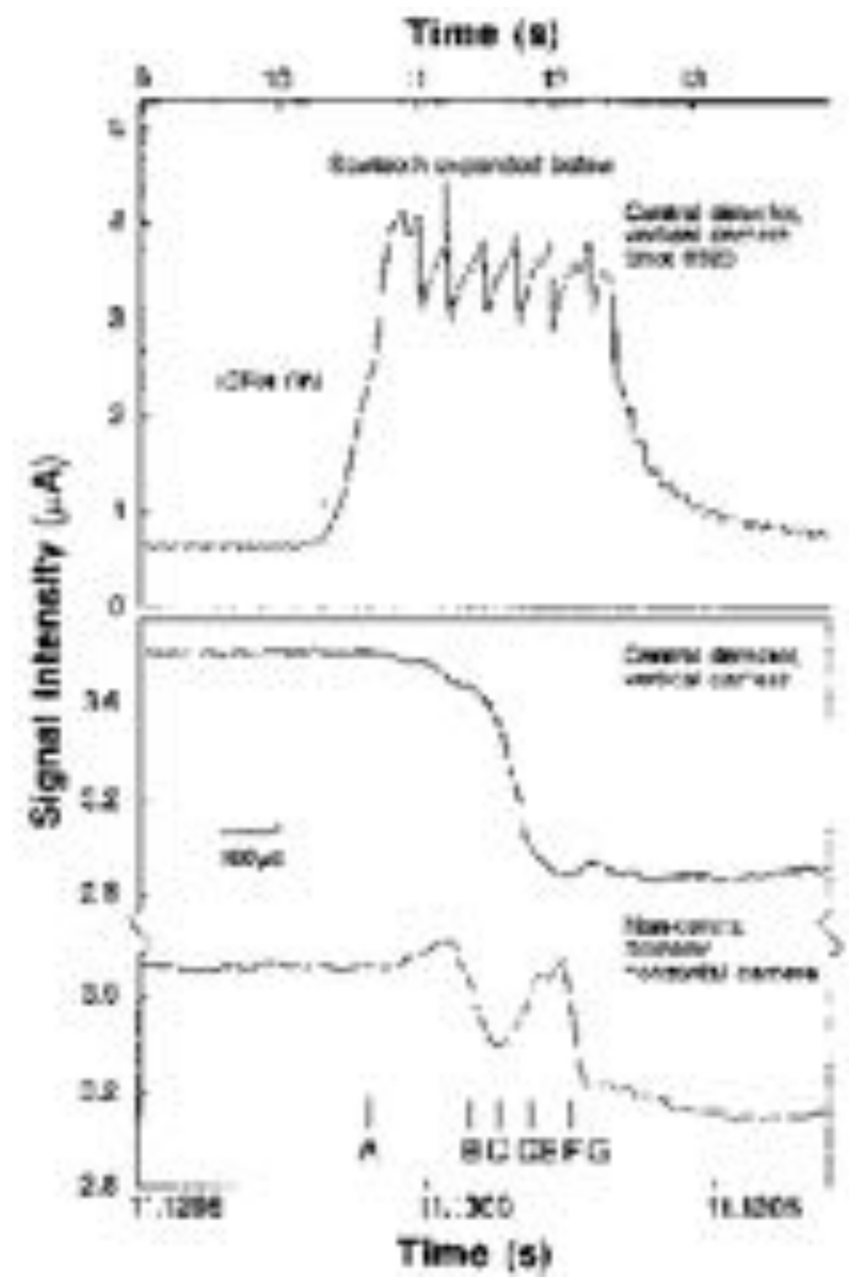
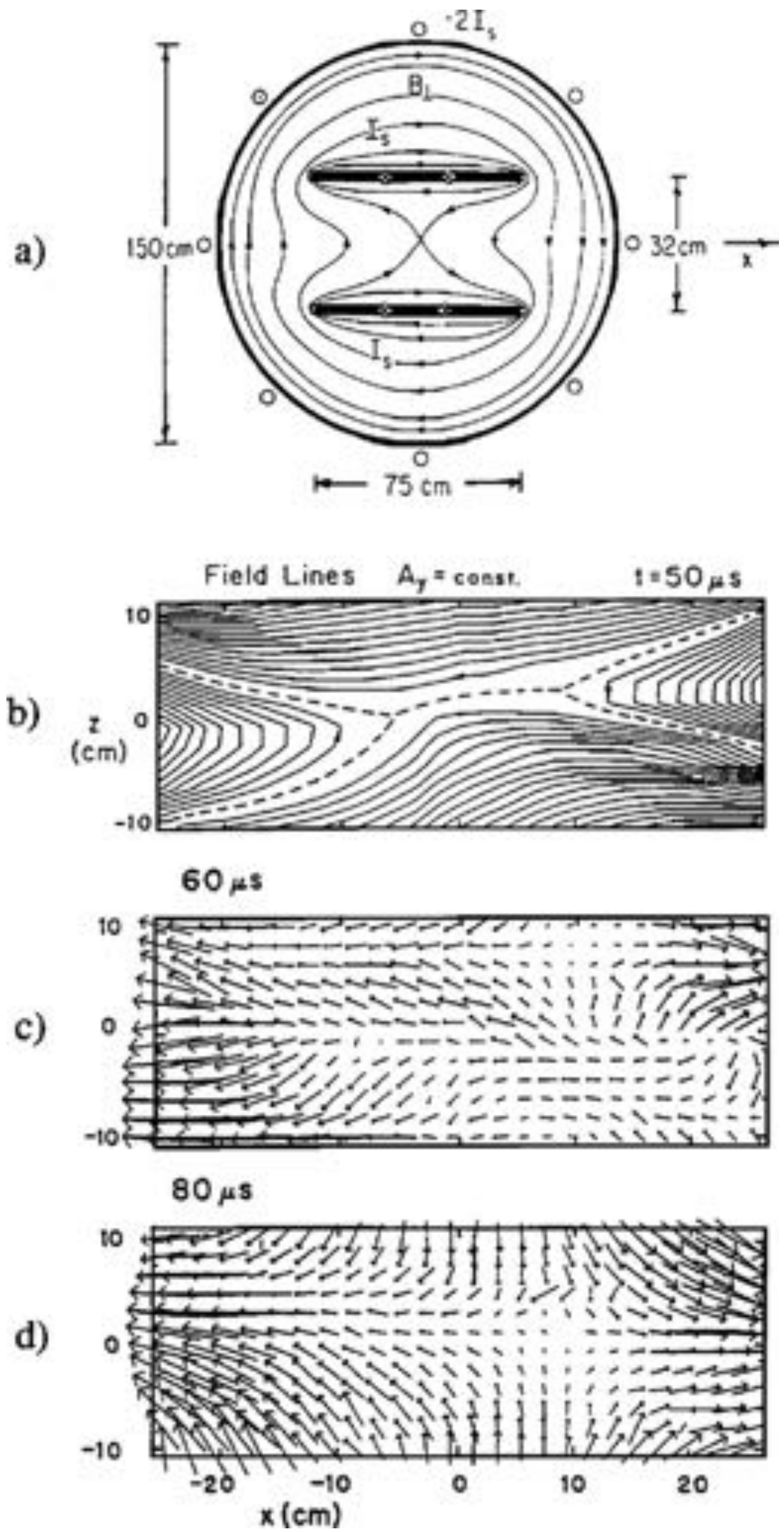


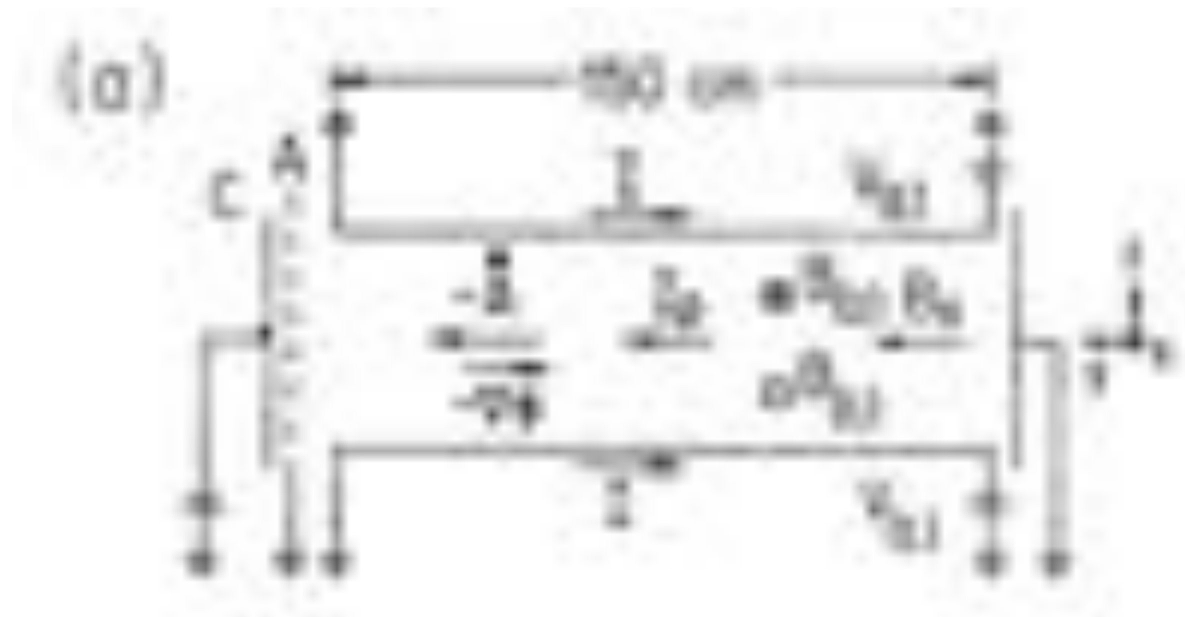
FIG. 1. Experimental arrangement of x-ray detectors. The x-ray traces exhibit internal disruptions.



- e.g. Sawteeth: on ST tokamak (Von Goeler, et al, PRL 33, 1201 (1974))
- Time-resolved measurements of structure on JET (Edwards, et al, PRL 57, 210 (1986)): Period ~100ms, crash < 100μs

UCLA Reconnection Experiments (80’s)

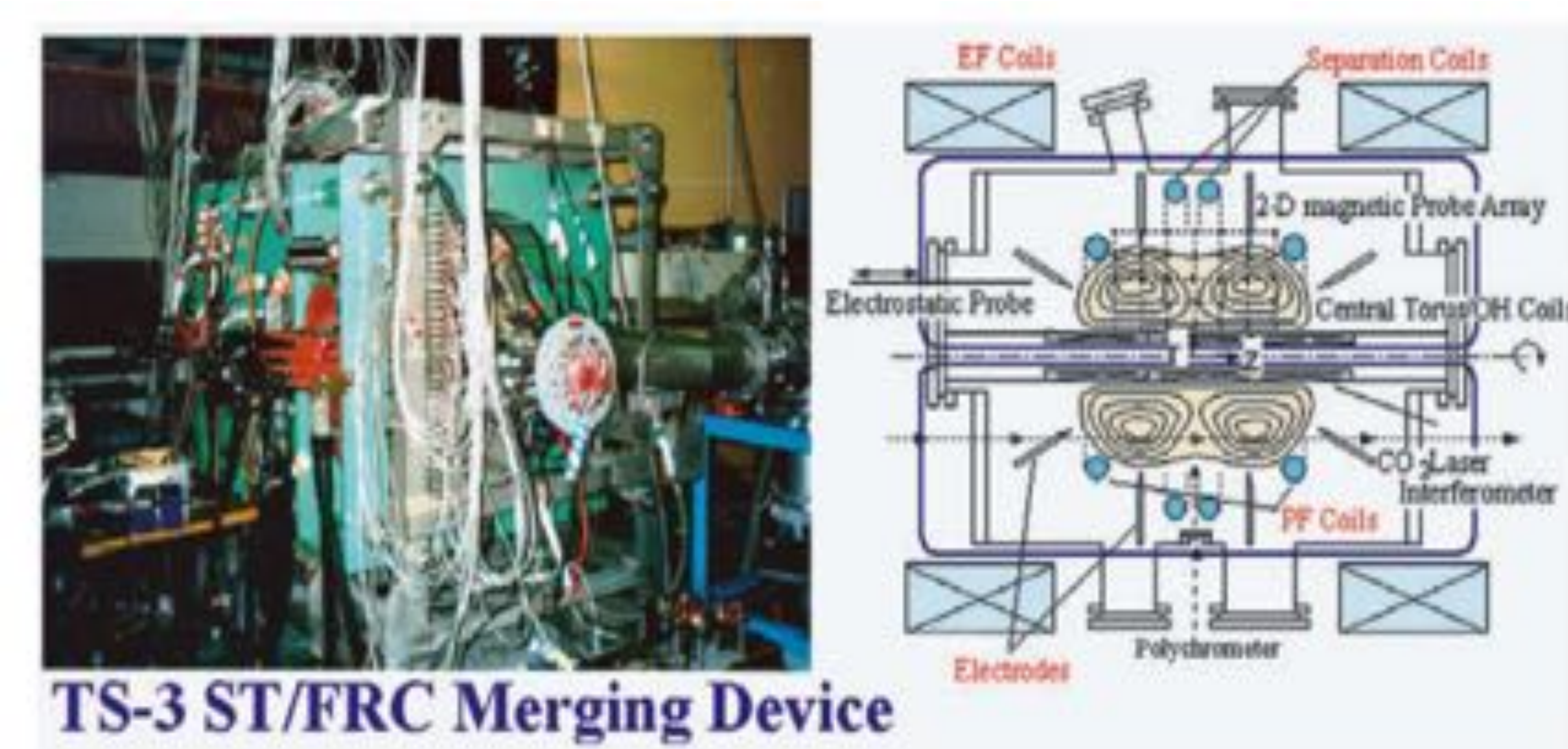




- Documented current sheet formation, Alfvénic outflow
- Reconnection rate ~0.3V_A; but very low S and essentially unmagnetized ions (in retrospect, they were studying the electron layer?)
- Saw anomalous scattering/resistivity due to current driven instabilities (ion acoustic, Langmuir)

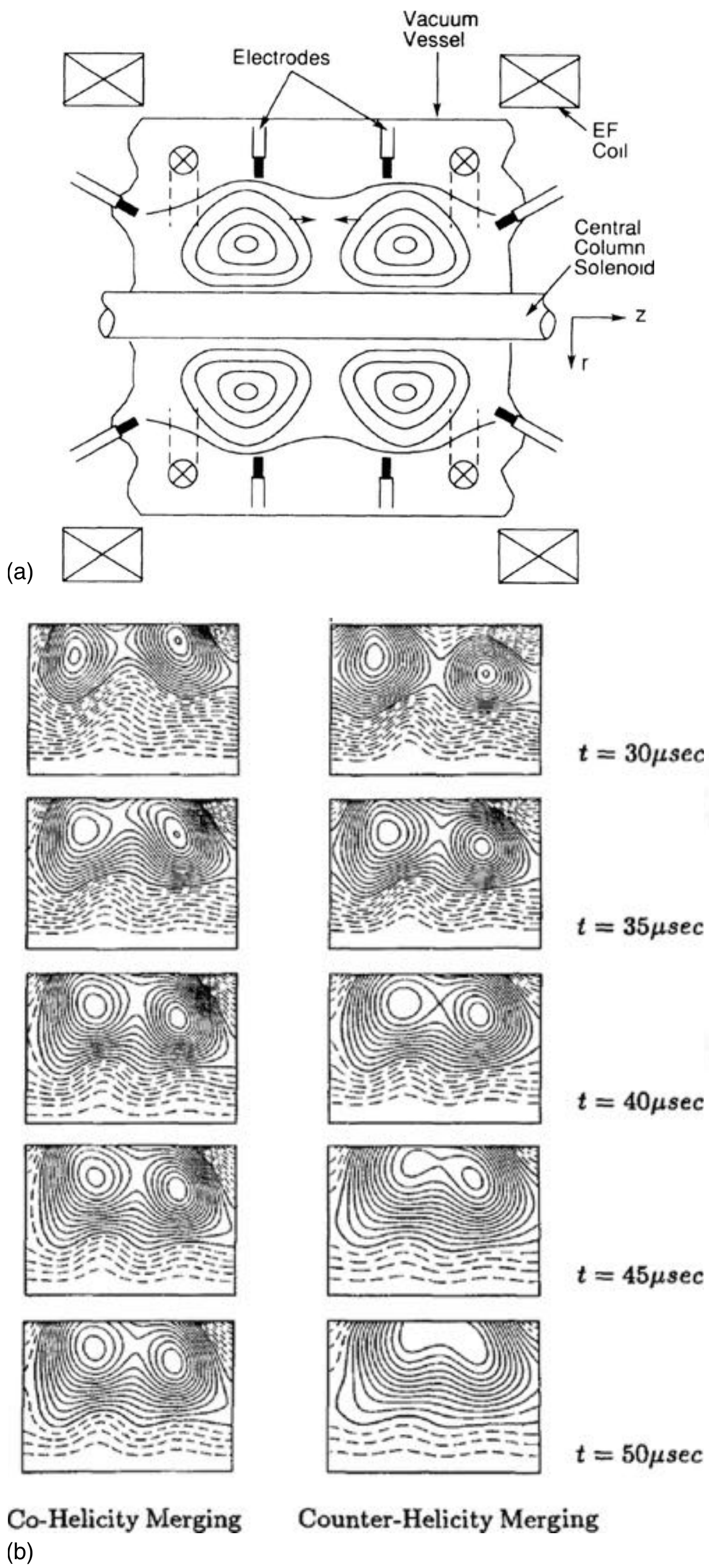
Stenzel & Gekelman, PRL 42, 1055 (1979)
Geleman, Stenzel & Wild JGR 87, 101 (1982)

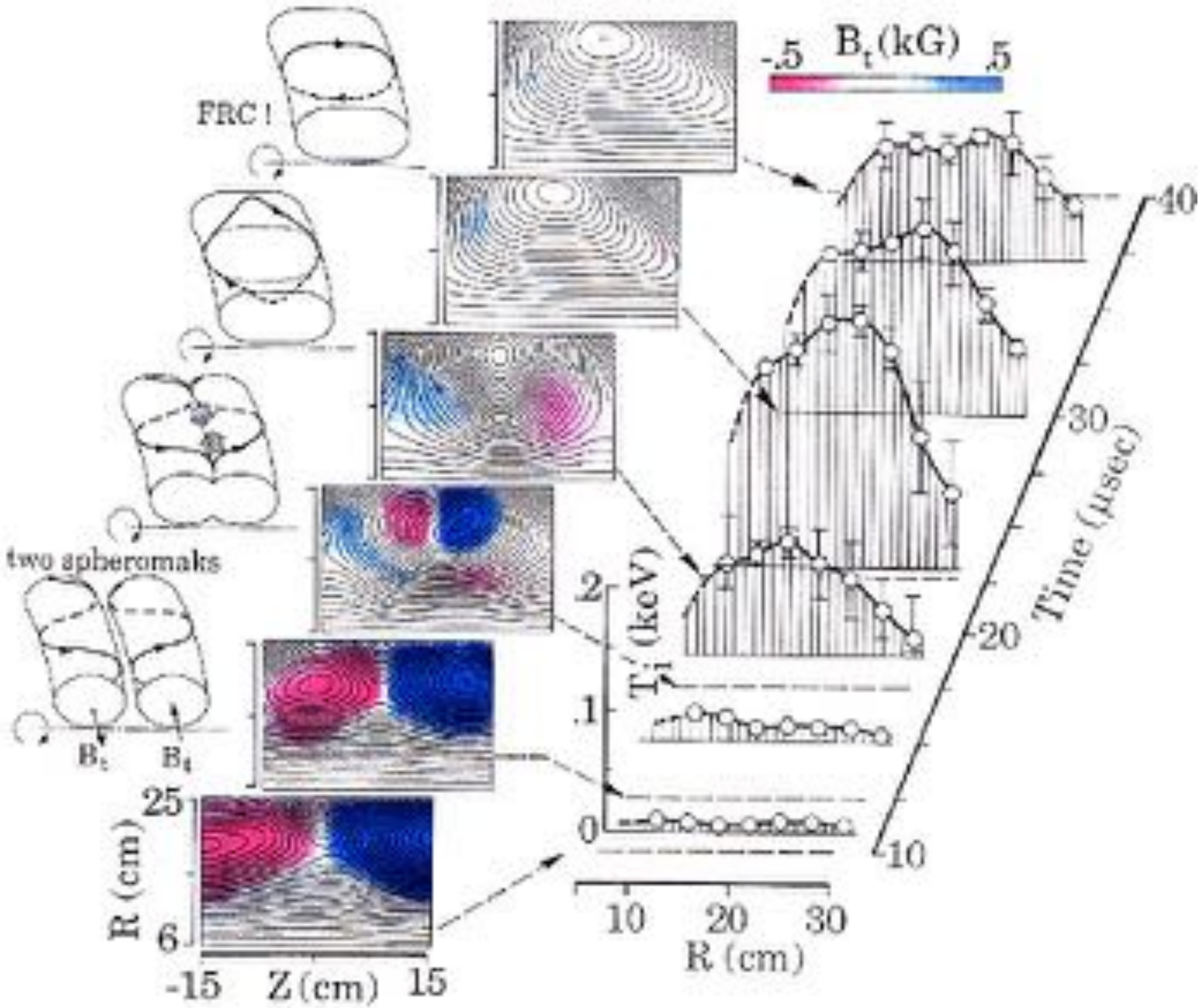
Spheromak Merging Experiments (early 90's)



- Form two compact toroids (spheromaks) and merge them, causing reconnection of both poloidal and toroidal components of B

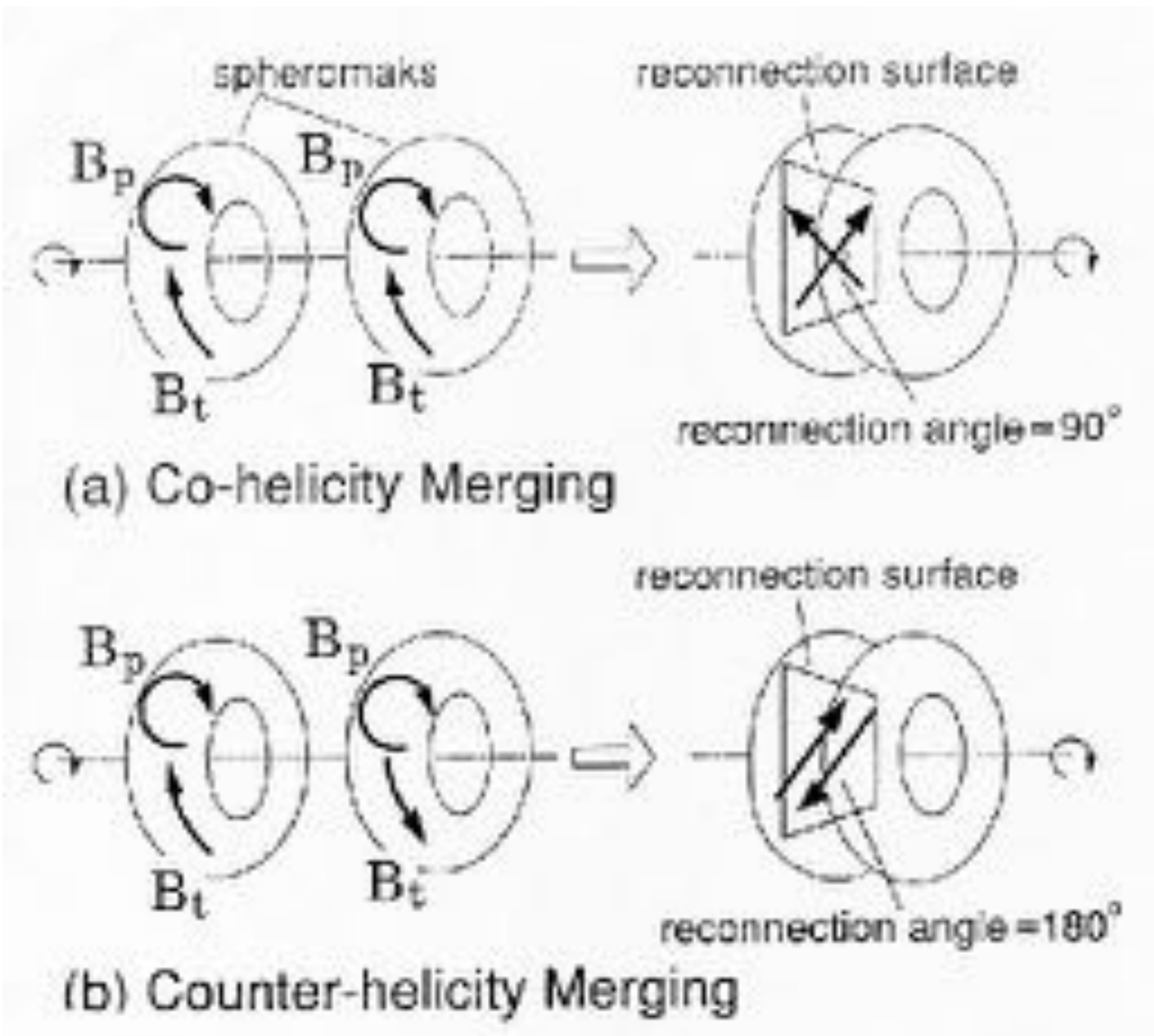
Ion heating observed during merging experiments

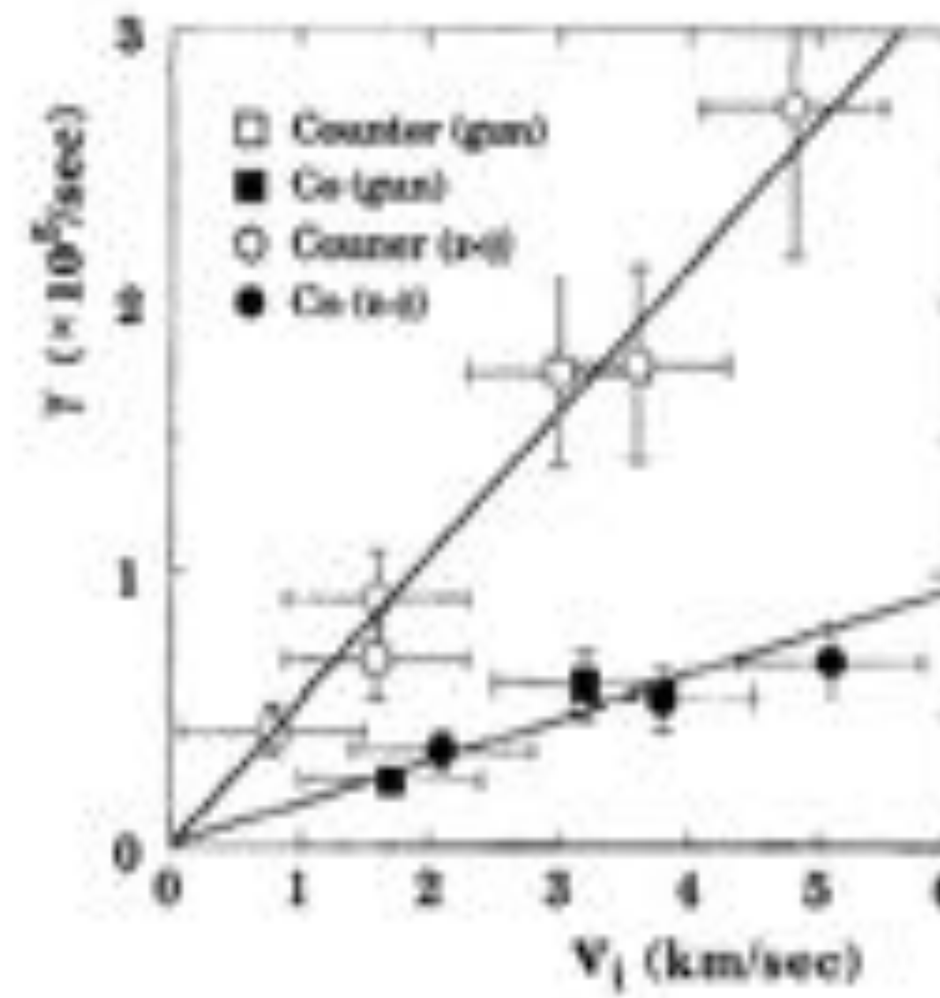




Ono et al, PRL,v76, 3328 (1996)

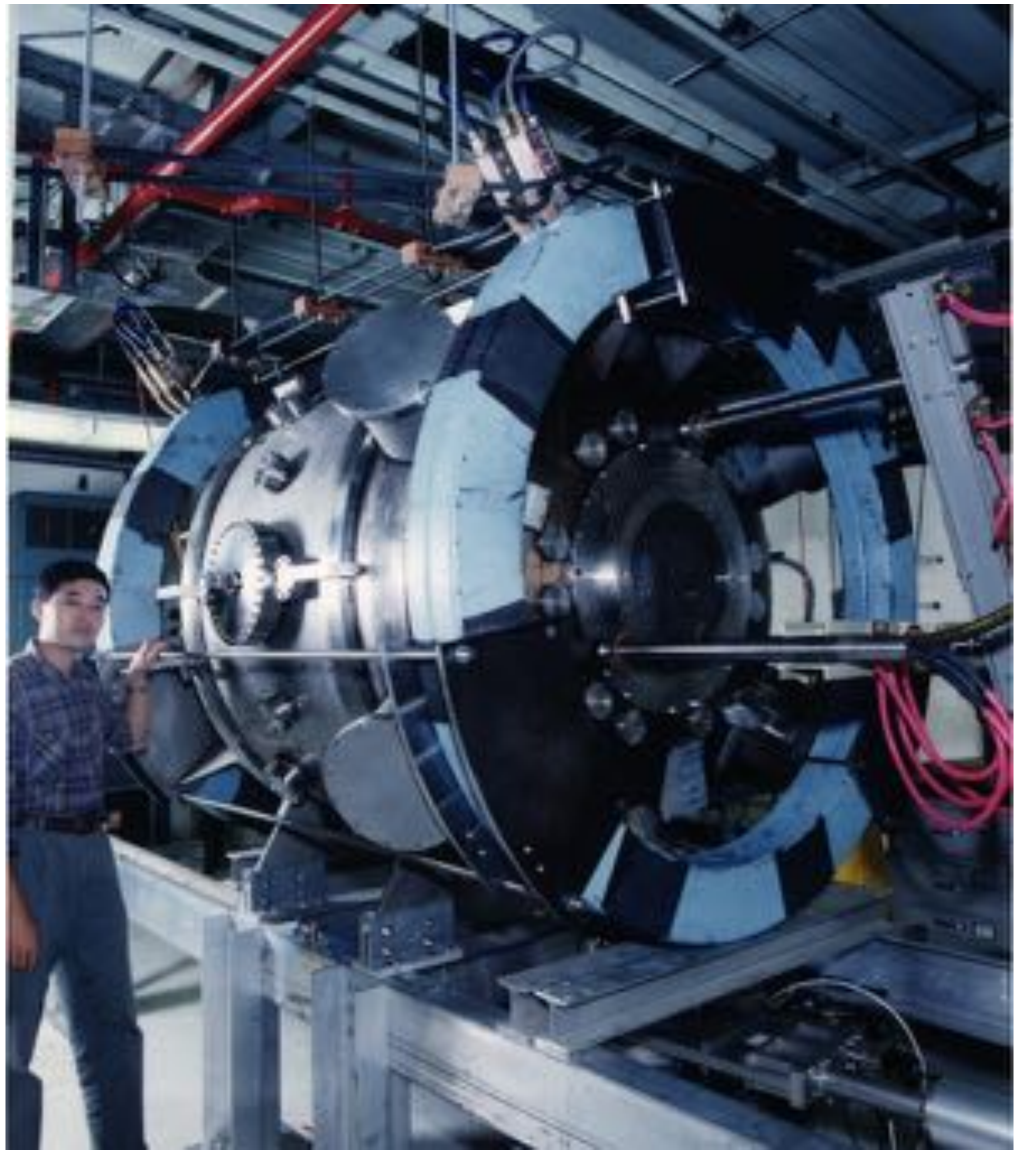
Slower Reconnection with Guide Field than Without

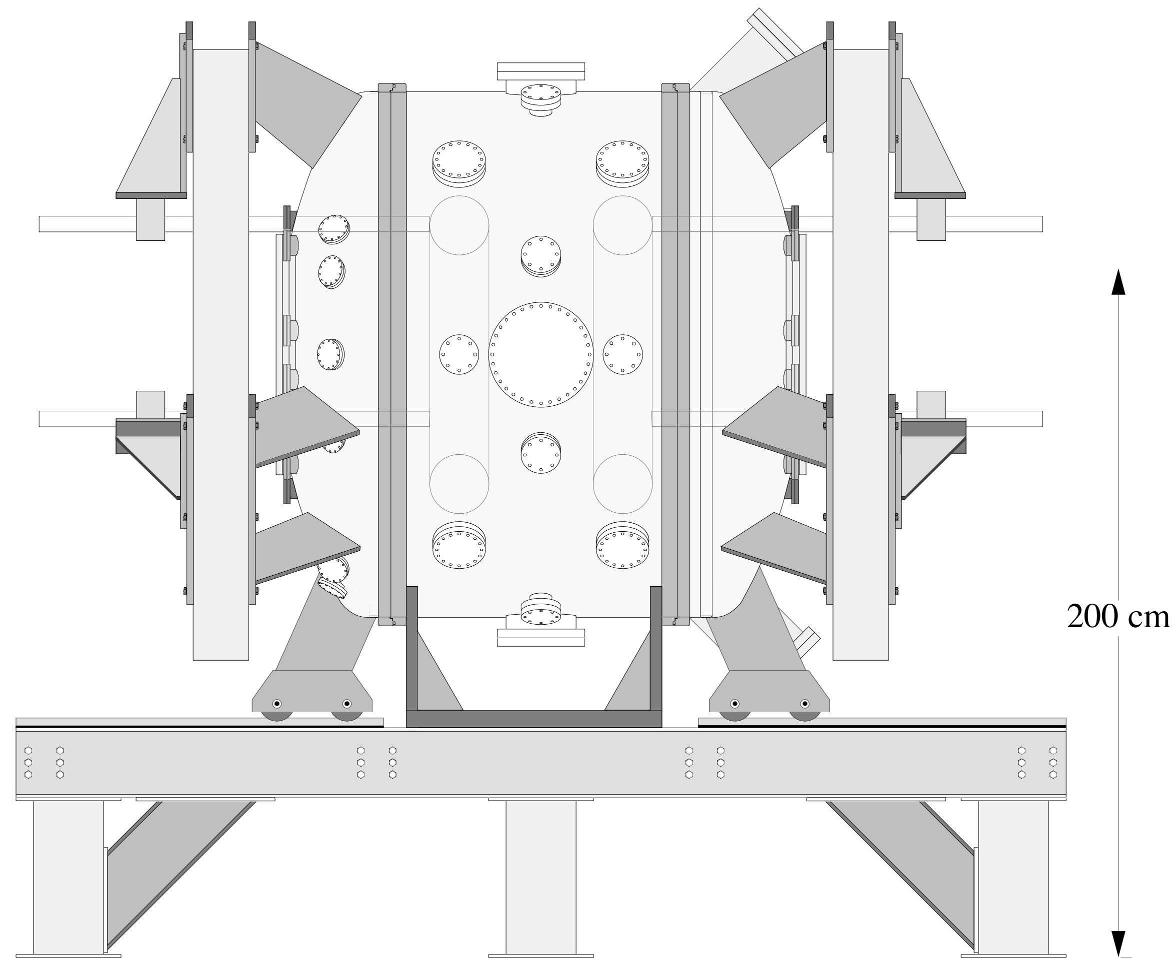




M. Yamada et al., PRL, v65, 721 (1990)

Magnetic Reconnection Experiment





Plasma parameters:

$n_e \approx 0.2\text{–}1.2 \times 10^{14}\ \text{cm}^{-3}$

$T_e \sim T_i \approx 5\text{–}30\ \text{eV}$

$B \approx 200\text{–}500\ \text{G}$

$S \approx 200\text{–}1000$

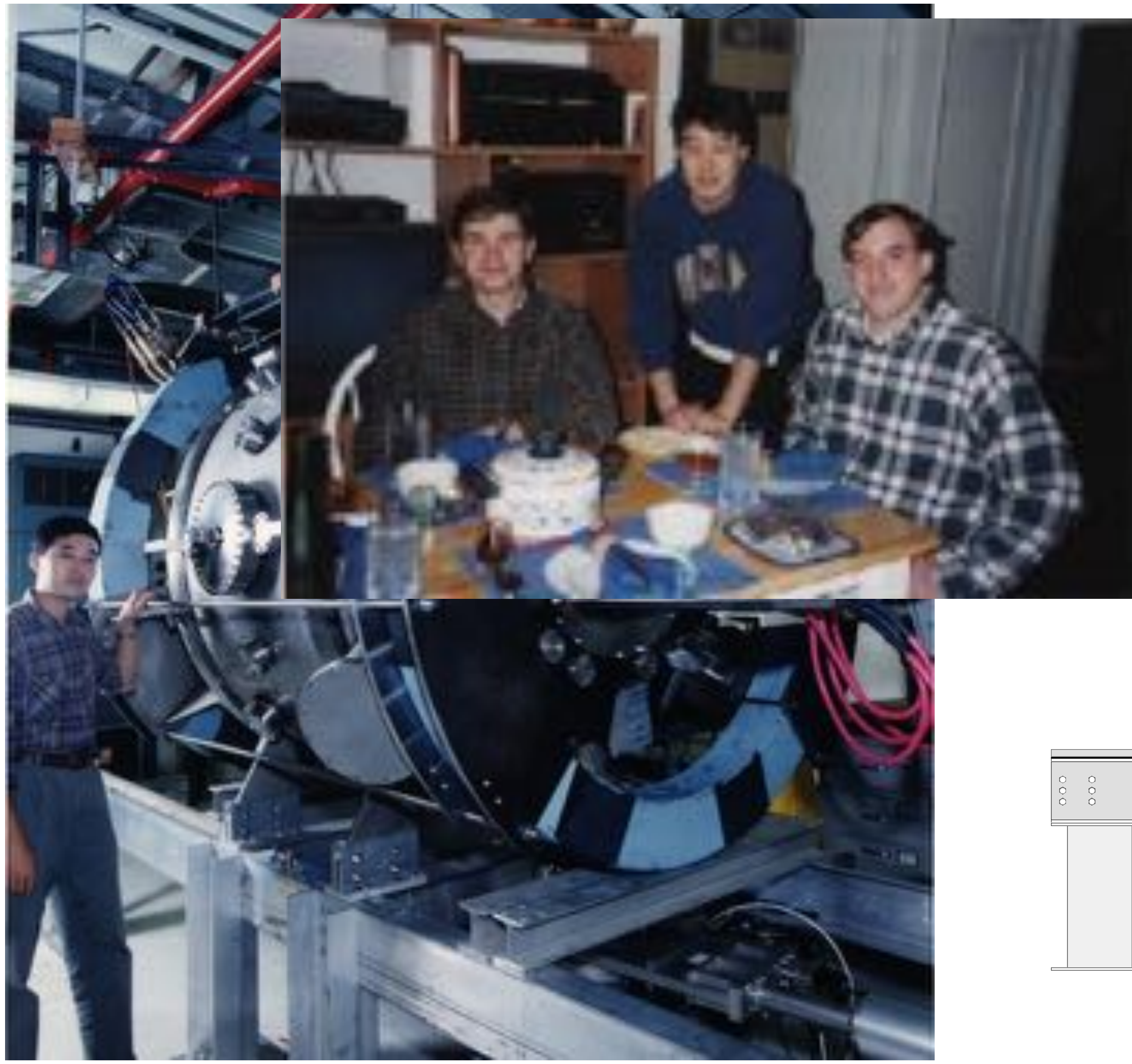
$L \sim 10\ \text{cm}$

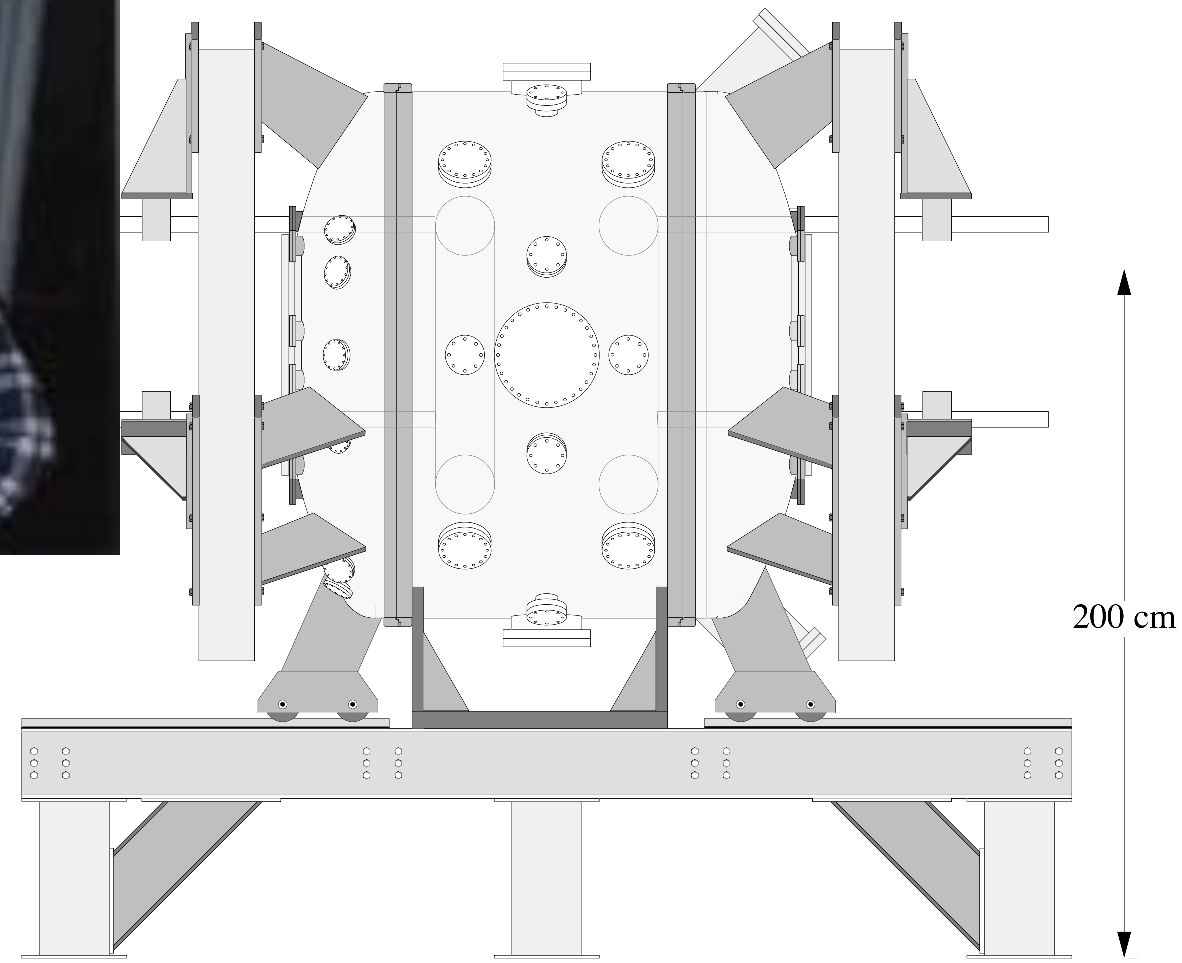
$\delta \sim \rho_i \sim c/\omega_{p,i} \sim 2\ \text{cm}$

$\lambda_{mfp,e}/\delta \sim 0.3\text{–}10$

- Goal was to produce controlled reconnection in MHD plasma (ρ_i << L, S>>1)

Magnetic Reconnection Experiment





Plasma parameters:

$n_e \approx 0.2\text{–}1.2 \times 10^{14}\ \text{cm}^{-3}$

$T_e \sim T_i \approx 5\text{–}30\ \text{eV}$

$B \approx 200\text{–}500\ \text{G}$

$S \approx 200\text{–}1000$

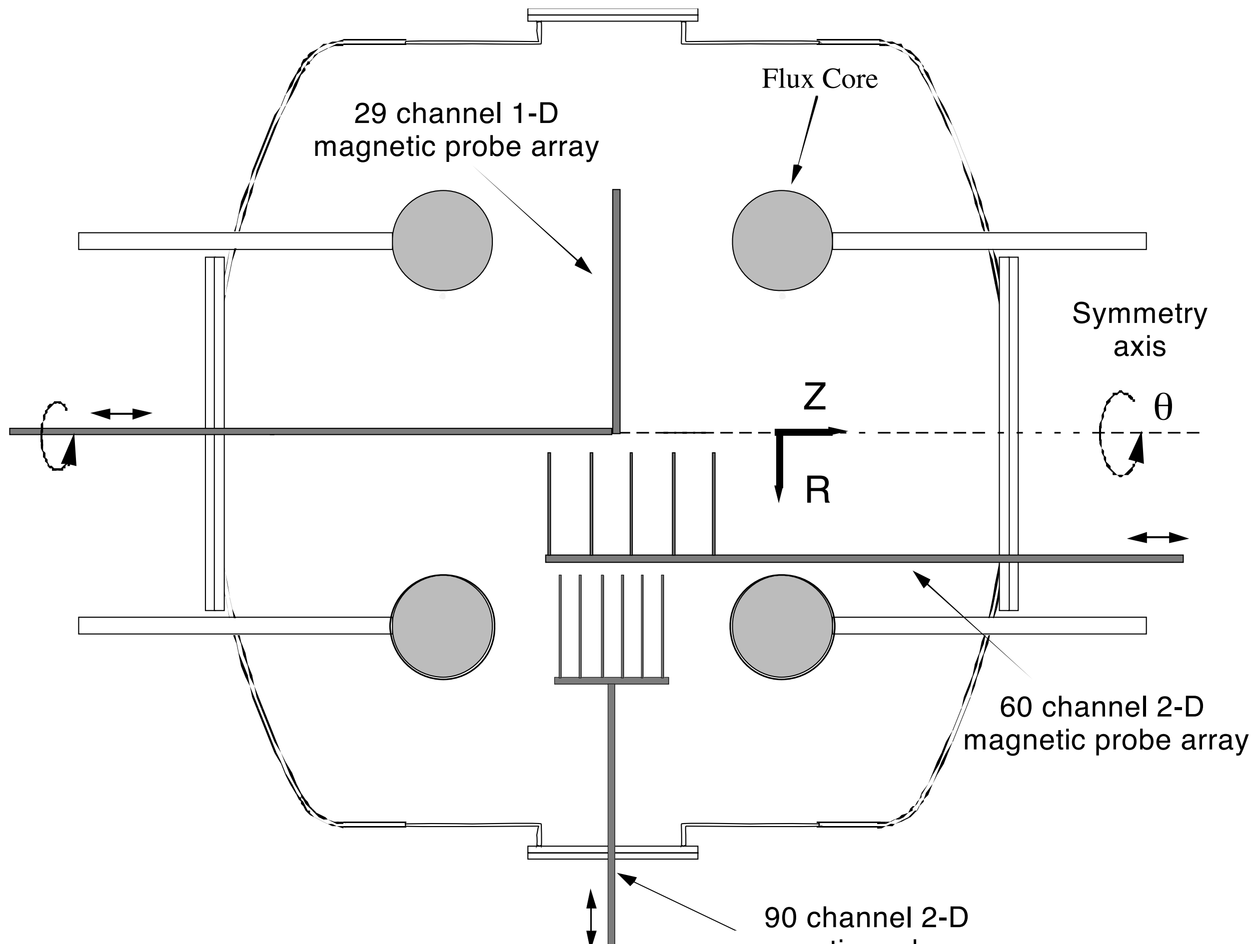
$L \sim 10\ \text{cm}$

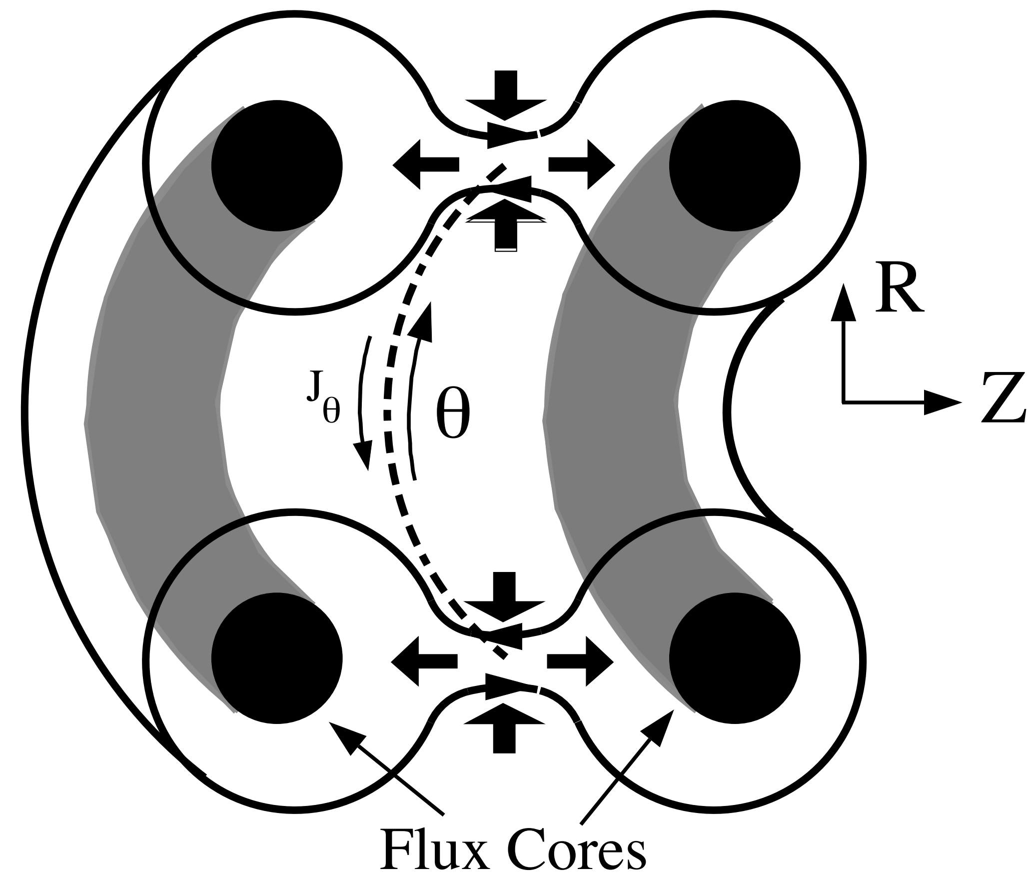
$\delta \sim \rho_i \sim c/\omega_{p,i} \sim 2\ \text{cm}$

$\lambda_{mfp,e}/\delta \sim 0.3\text{–}10$

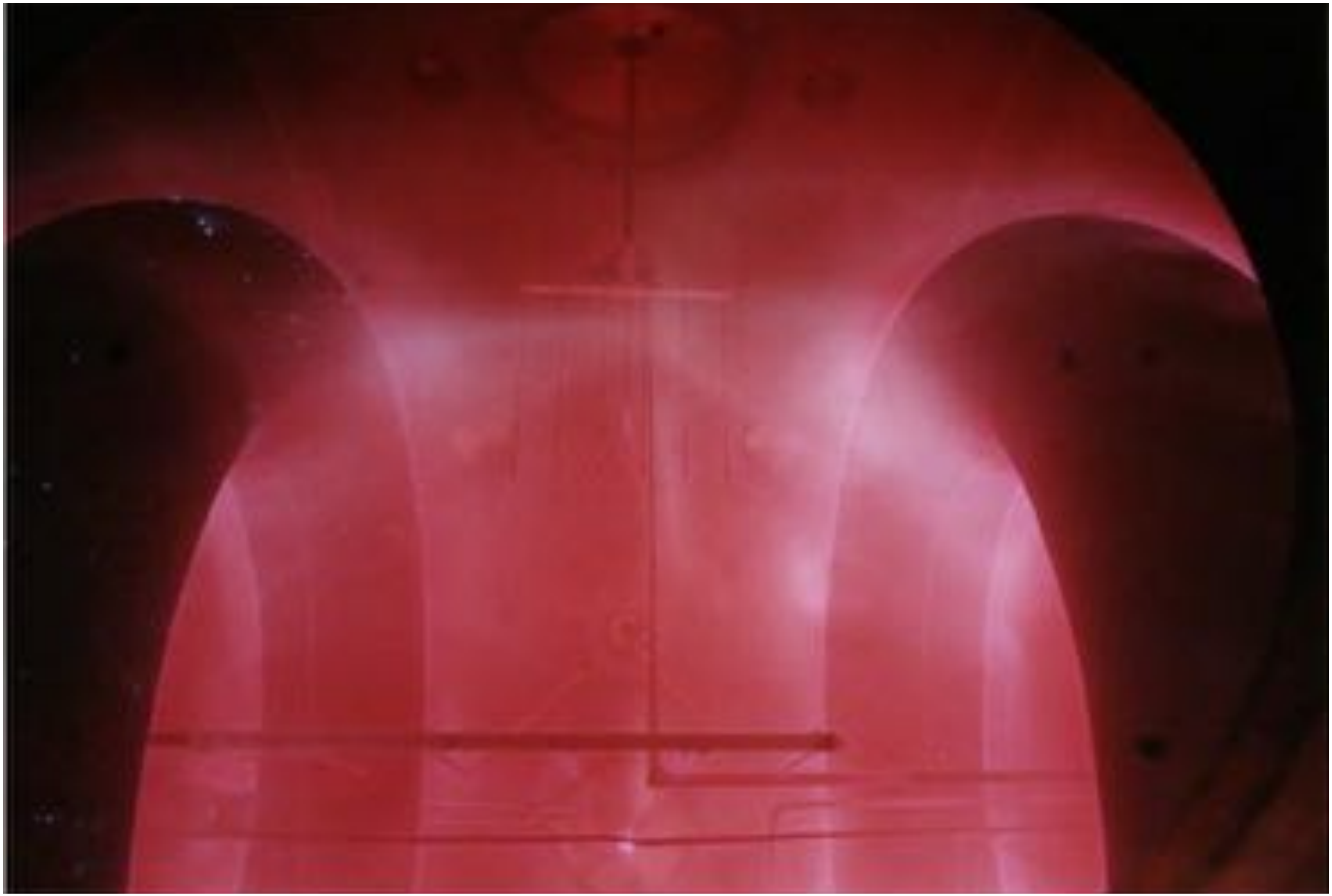
- Goal was to produce controlled reconnection in MHD plasma ($\rho_i << L$, $S>>1$)

"Flux cores" to generate plasma and drive reconnection

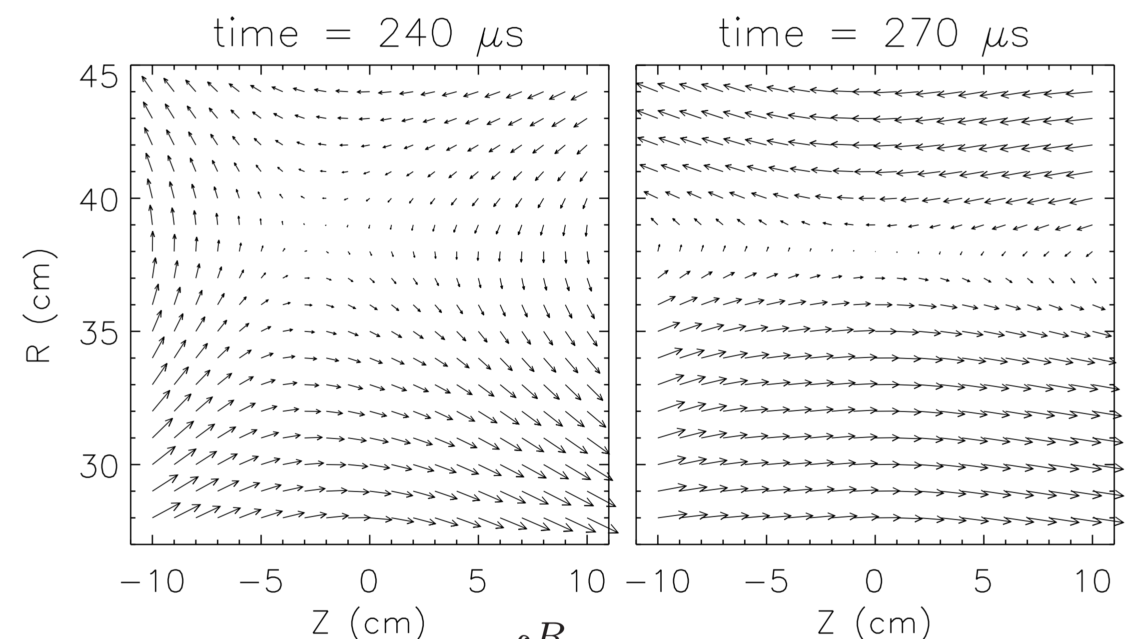




- Used "flux core" technology from spheromak formation (toroidal solenoid + poloidal field coil) to generate plasma and drive reconnection
- Fixed arrays of probes to measure magnetic structure

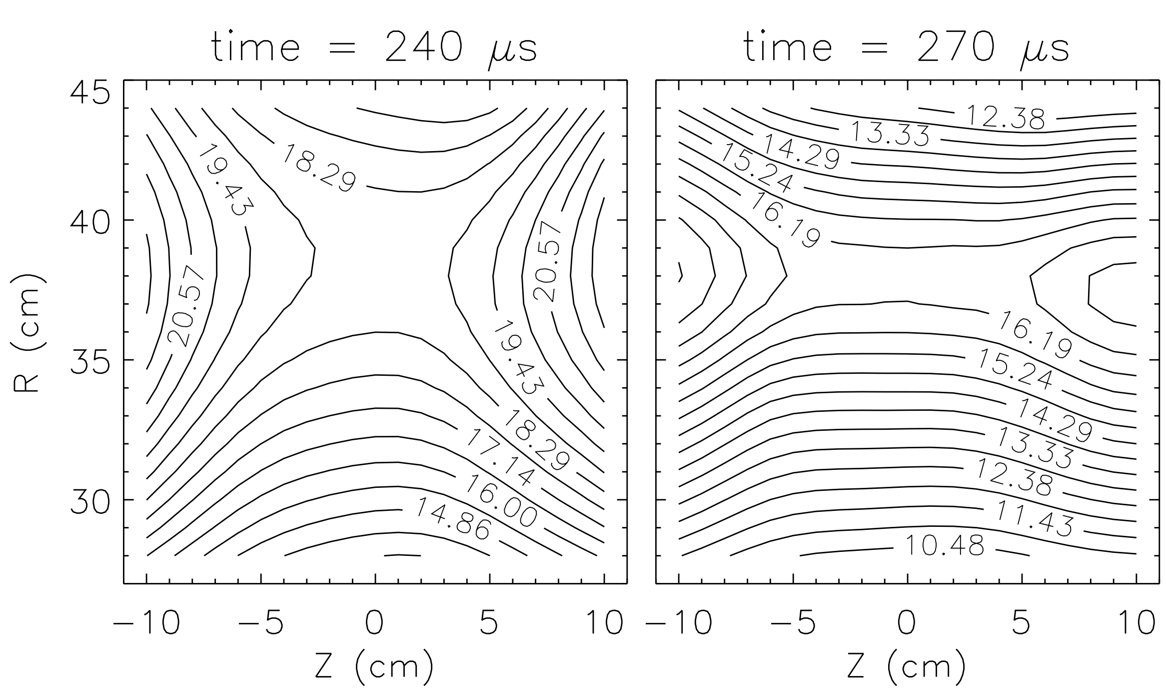


Determination of magnetic flux and reconnection rate in MRX

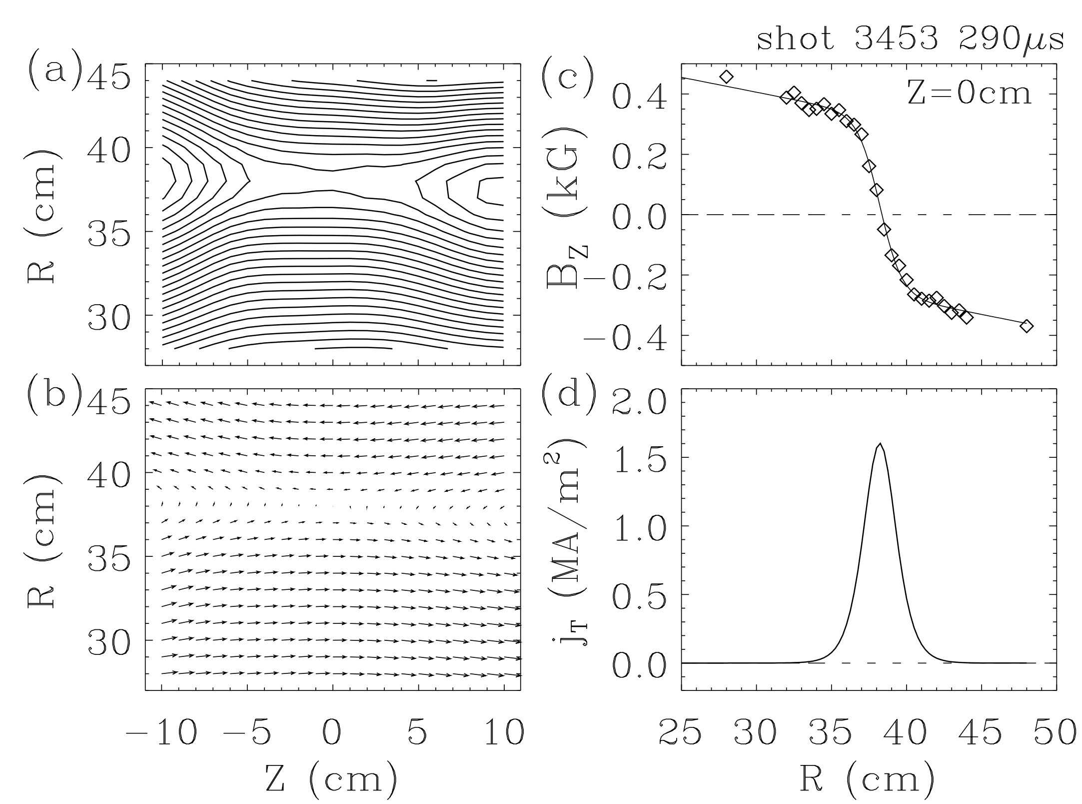


$$\psi = \int_0^R 2\pi R' B_z(R')\mathrm{d}R'$$

$$E_\theta = -\frac{1}{2\pi R}\frac{\partial\psi}{\partial t} \quad ; \quad V_\mathrm{R} = -(\frac{\partial\psi}{\partial t})(\frac{\partial\psi}{\partial R})^{-1}$$



- Assume axisymmetry (cross your fingers….)
- Can compute poloidal flux function, reconnection rate, current from measured magnetic fields



MRX

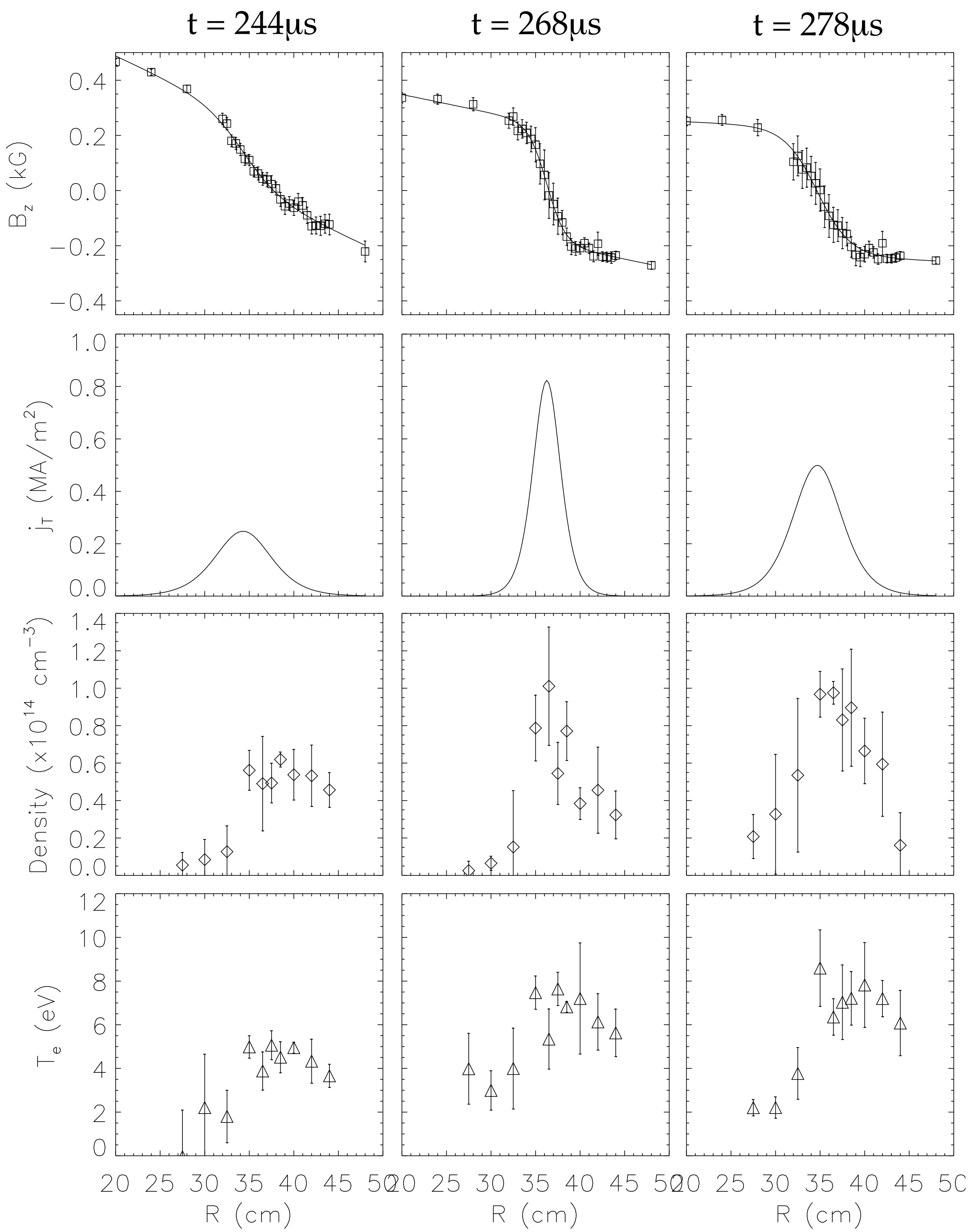
Magnetic
Reconnection
Experiment

Poloidal Flux Evolution

Null-helicity Reconnection

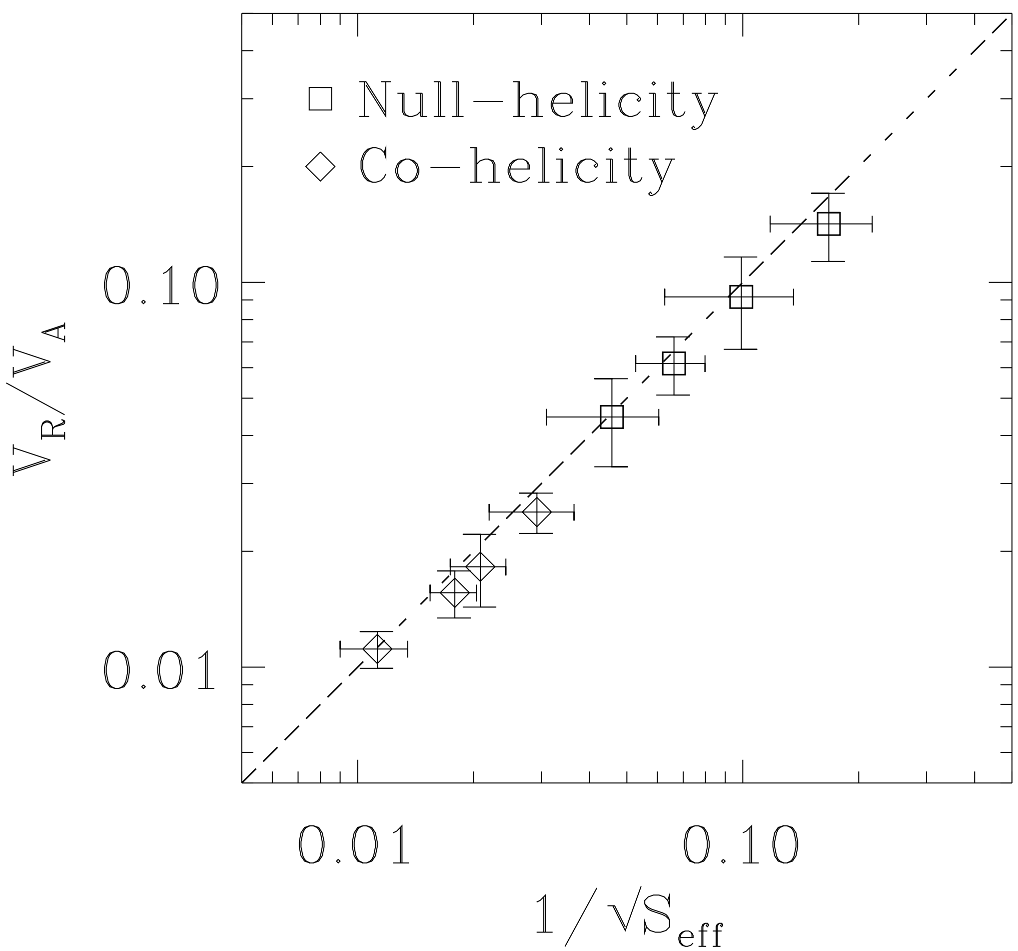
Princeton Plasma Physics Laboratory, Princeton University

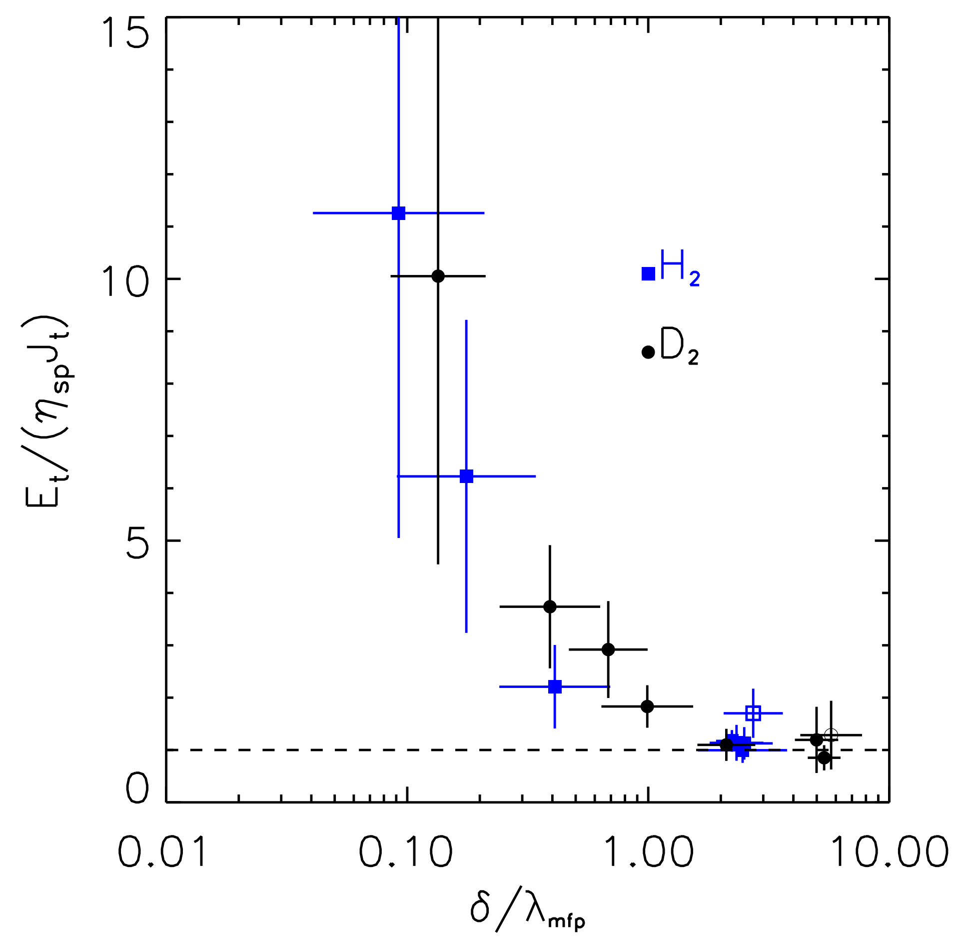
Profiles of magnetic field, density, and temperature



- ▷ Triple Langmuir probe for T_e, n_e
- ▷ $n_e \sim 1 - 20 \times 10^{13}$ cm^{-3}, peaked at the current sheet
- ▷ $T_e \lesssim 20$eV
- ▷ Radial asymmetries in B and n_e

Reconnection rate and Ohm's law in MRX

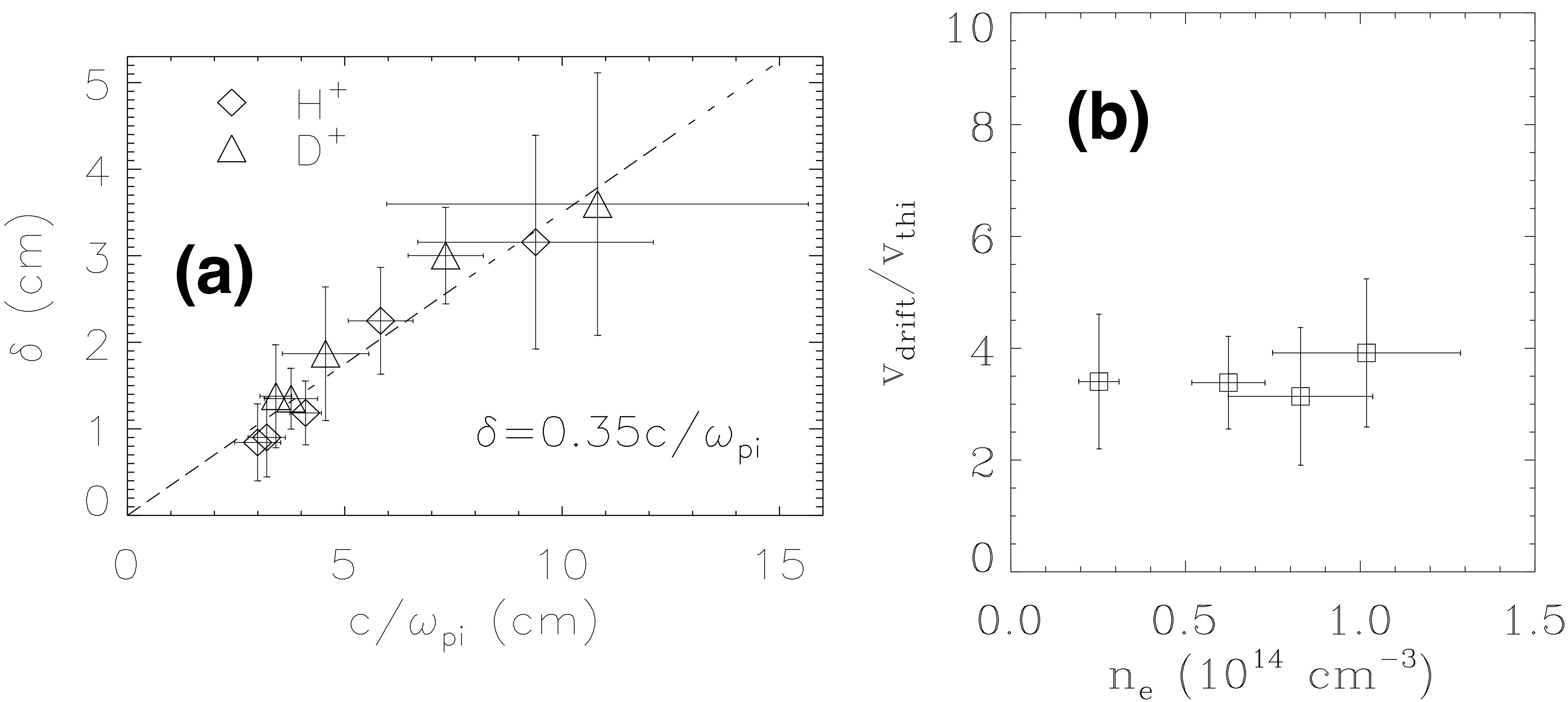




Ji et al., Phys. Rev. Lett. 80, 3256 (1998)

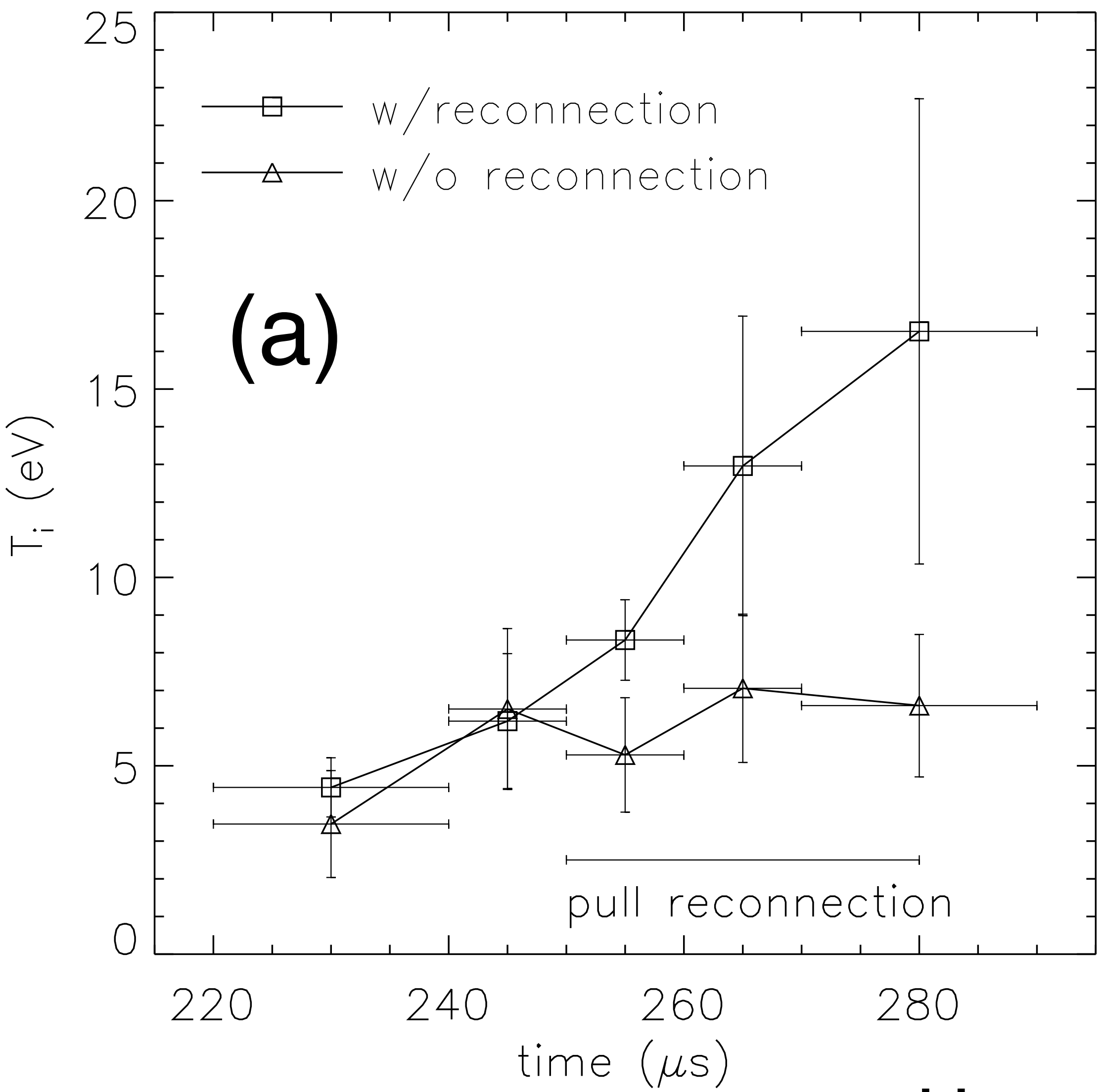
- ▷ MRX data well described by *generalized* Sweet-Parker model, including measured η^* [Ji]
- ▷ $E_\theta/(\eta_{sp} j_\theta) = \eta^*/\eta$ is found to be large at low collisionality (δ/λ_{mfp} small) [Ji, Trintchouk]
- ▷ Does a turbulent resistivity explain the discrepancy at low collisionality?

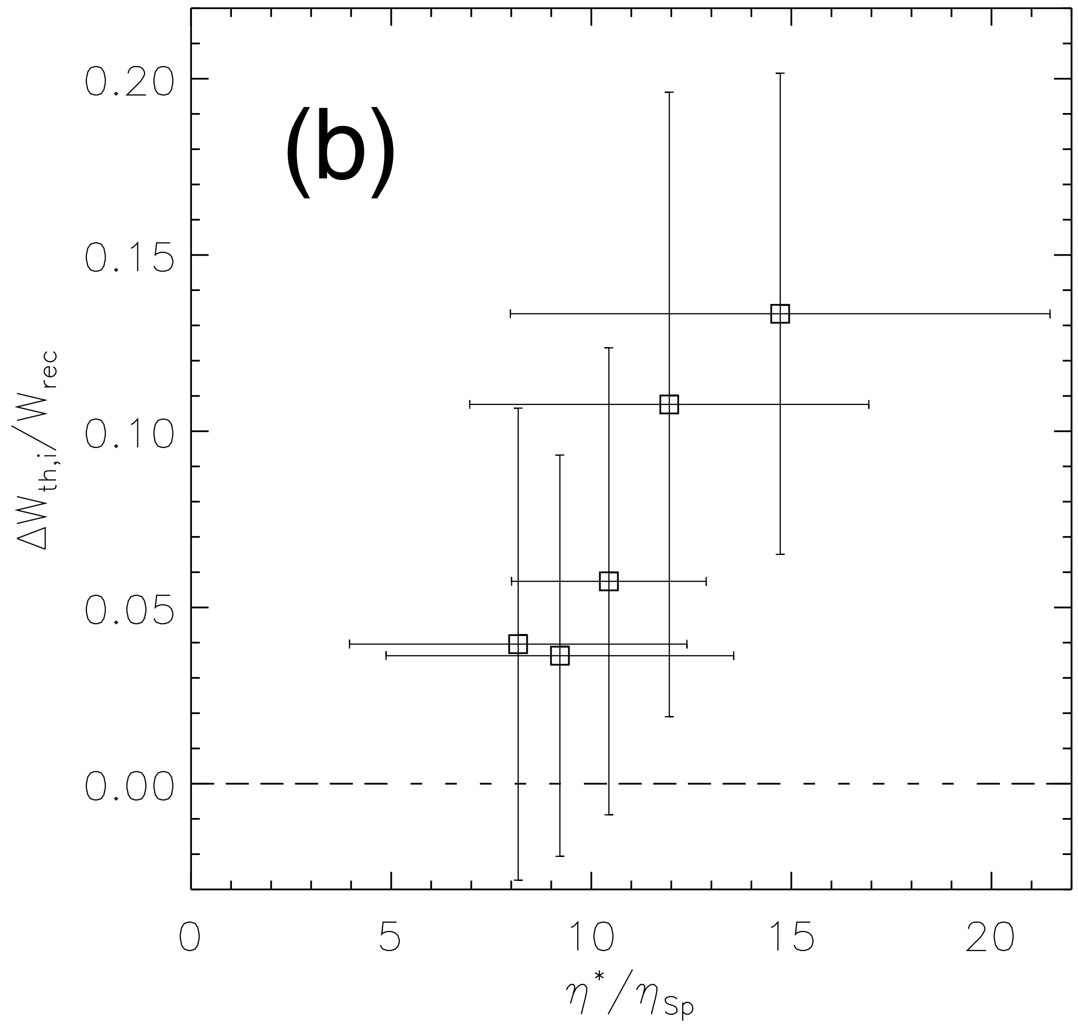
MRX current sheets are $c/\omega_{p,i}$ or ρ_i thick



- ▷ Measured neutral sheet width scales as $c/\omega_{p,i}$ or ρ_i
- ▷ Diamagnetic cross-field currents $\rightarrow$ constant cross-field drift velocity
- ▷ Marginal state of a current-driven instability or the Hall term in action?

Ion heating in MRX current sheets: Is turbulence to blame?





Hsu, et al., Phys. Rev. Lett. 84, 3859 (2000)

- ▷ Ions are heated non-classically. [Hsu]
- ▷ $T_i \gtrsim T_e$
- ▷ Collisionality data suggests some tie to mechanism behind fast reconnection in MRX

What instability might provide η in MRX current sheets?

- ▷ Decades of theoretical studies of CS instabilities (e.g., Buneman [Heyvaerts], ECDI [Haerendel], IA turbulence [Coroniti], ...)
  - ▷ Several “ruled out” based on requirements: $T_i/T_e \gtrsim 1$, $V/v_{th,i} \sim 1$
  - ▷ Some (e.g., Buneman) unlikely to provide resistive effect ($\omega > \omega_{p,i}$)
- ▷ Lower-hybrid drift instability (LHDI) [Krall, Davidson, Gladd, Huba, Drake, *et. al.*]
  - ▷ Strongly growing in ρ_i scale density gradients, even (especially) for $T_i/T_e \gg 1$
  - ▷ However, linearly stabilized by high β, which might exclude it from the center of the current sheet
  - ▷ Observational evidence for LHDI in magnetotail [Huba, Shinohara]
  - ▷ Simulations show LHDI during reconnection, but disagree on role of the LHDI [Horiuchi, Shinohara, Rogers]
  - ▷ Considered by some to be the “best bet” for anomalous resistivity during reconnection [Shinohara, *et. al.*]

Review of the lower-hybrid drift instability

- Instability is driven by density gradient and cross-field drift, negative energy drift-wave in ion frame ($n'/n \sim 1/\rho_\mathrm{i}$, $\omega^* \sim \omega_\mathrm{LH}$), driven by ion Landau damping ($\omega/k \sim v_\mathrm{th,i}$)
- $\omega \sim \omega_\mathrm{LH}, k\rho_\mathrm{e} \sim 1, \gamma \sim \omega_\mathrm{LH}$
- $k_\perp \gg k_\|$, propagates in electron diamagnetic direction (ion reference frame)
- Linear, local, electrostatic model (following Krall, Huba, Davidson):

$$0 = 1 - \frac{\omega_\mathrm{p,i}^2}{2k^2 v_\mathrm{th,i}^2} Z'\left(\frac{\omega - \mathbf{k}\cdot\mathbf{V}}{k v_\mathrm{th,i}}\right) + \frac{\omega_\mathrm{p,e}^2}{k^2 v_\mathrm{th,e}^2}[1+\psi]$$

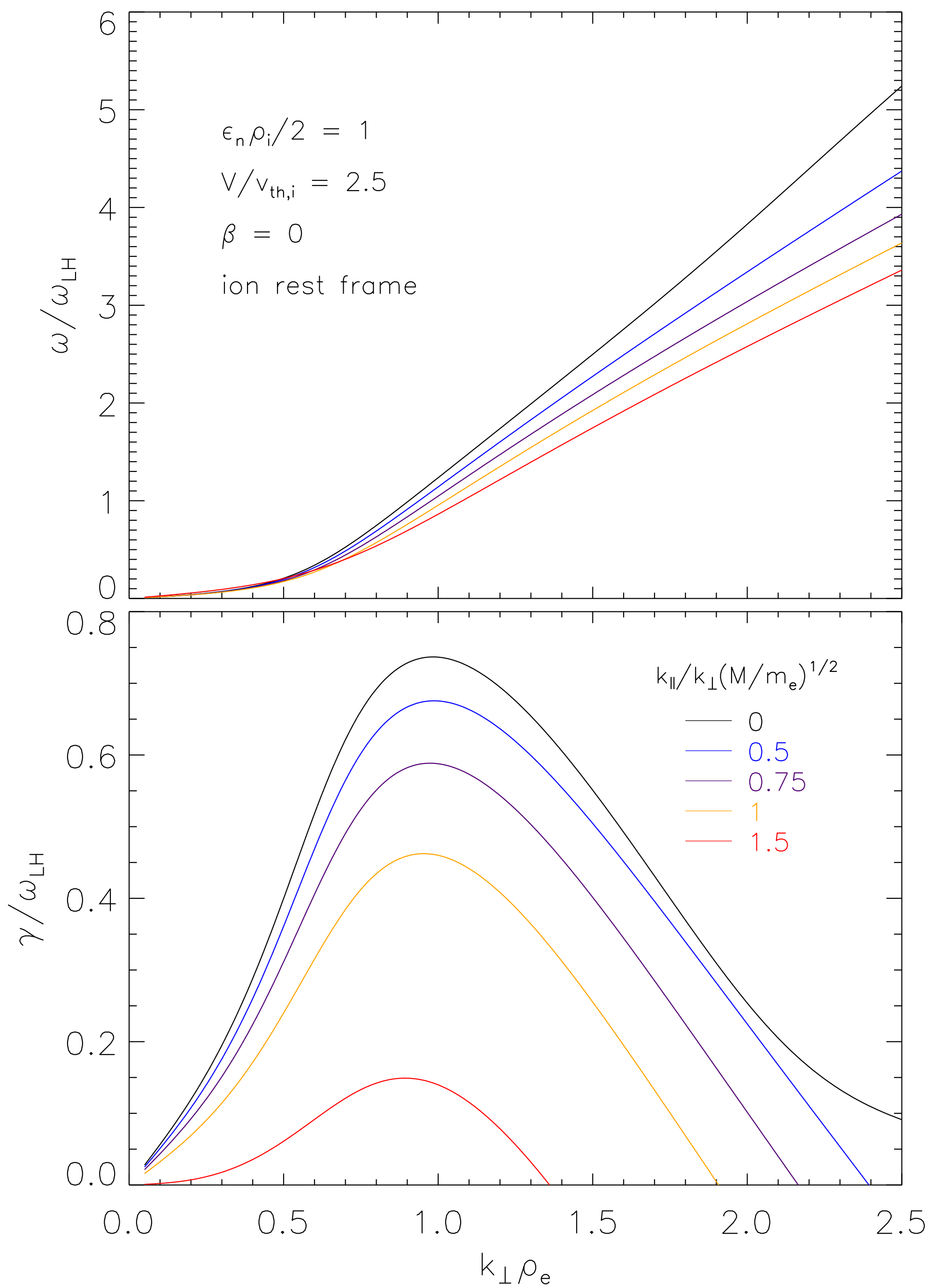
$$\psi = 2\frac{\omega}{k_\| v_\mathrm{th,e}}\left(1 - \frac{k_y V_\mathrm{D,e}}{\omega}\right)\int_0^\infty dx\, x \exp(-x^2) J_0^2(k_\perp \rho_\mathrm{e} x) Z\left(\frac{\omega - k_y \bar{V}_{\nabla B} x^2}{k_\| v_\mathrm{th,e}}\right)$$

- $V_\mathrm{D,e}$ is the electron diamagnetic drift, $\bar{V}_{\nabla B}$ is the average electron ∇B drift ($\propto \beta V_\mathrm{D,e}$), V is the cross-field ion flow, and $x = v_\perp / v_\mathrm{th,e}$
- In MRX: $V/v_\mathrm{th,i} \sim 2-4$; $\epsilon_\mathrm{n}\rho_\mathrm{i}/2 \sim 1$ ($\epsilon_\mathrm{n} = d\ln(n)/dx$); $\beta \sim 1$

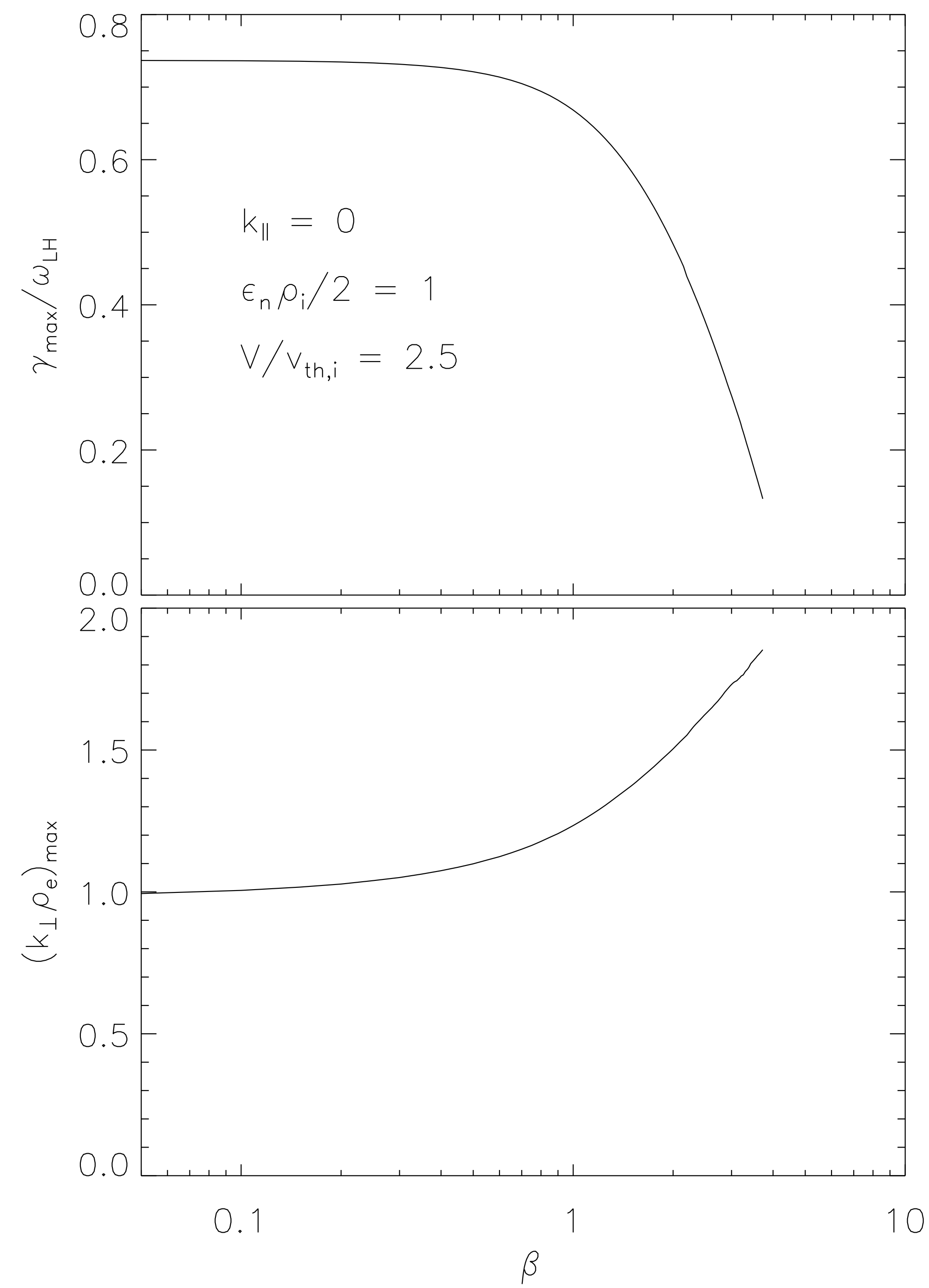
Linear characteristics of LHDI using MRX parameters

- ▷ Electrostatic, local model with finite β ∇B-drift corrections to electron orbits [Krall, Huba, Davidson]

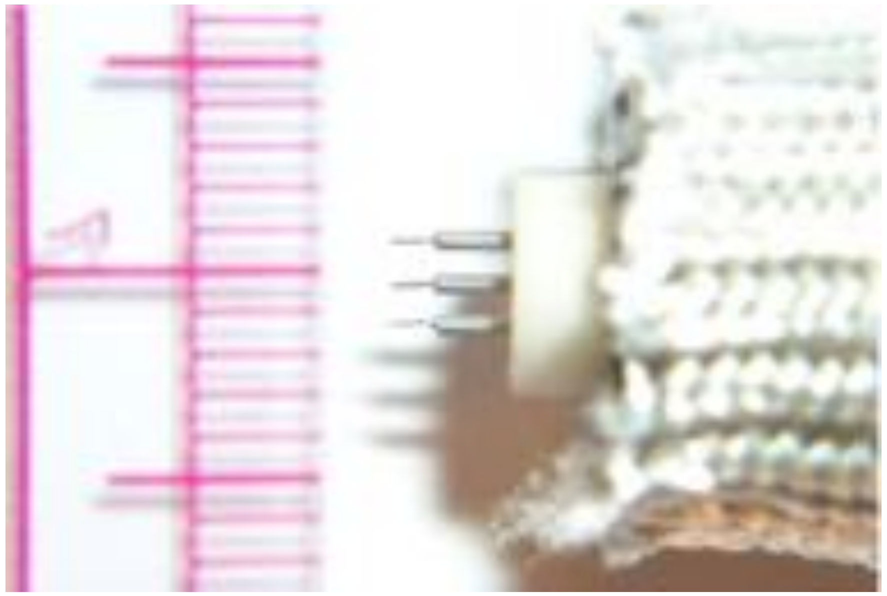
$\omega \sim \omega_{\rm LH}$, $\gamma \sim \omega_{\rm LH}$ for $k_\perp \rho_e \sim 1$

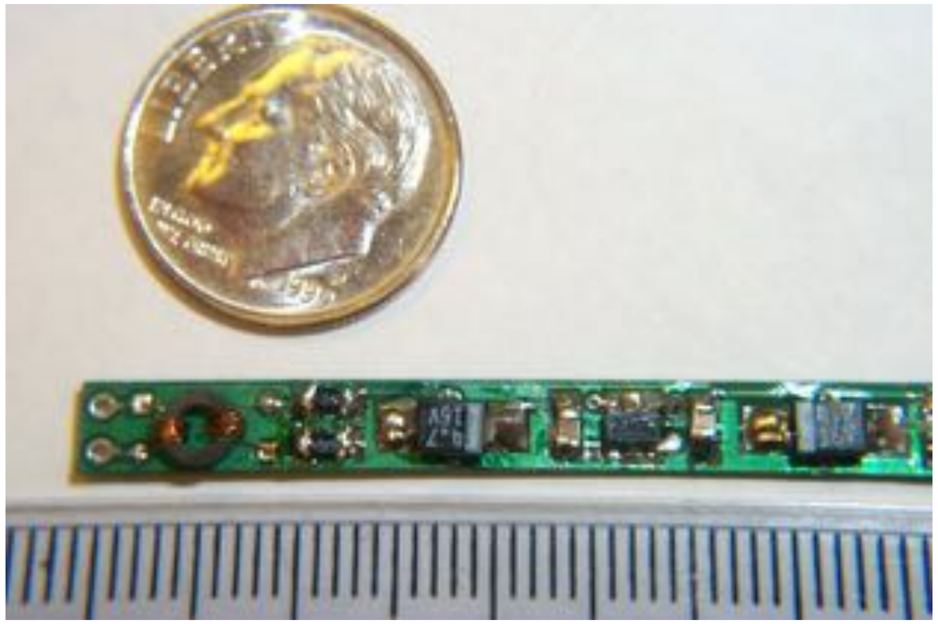


β linearly stabilizes LHDI



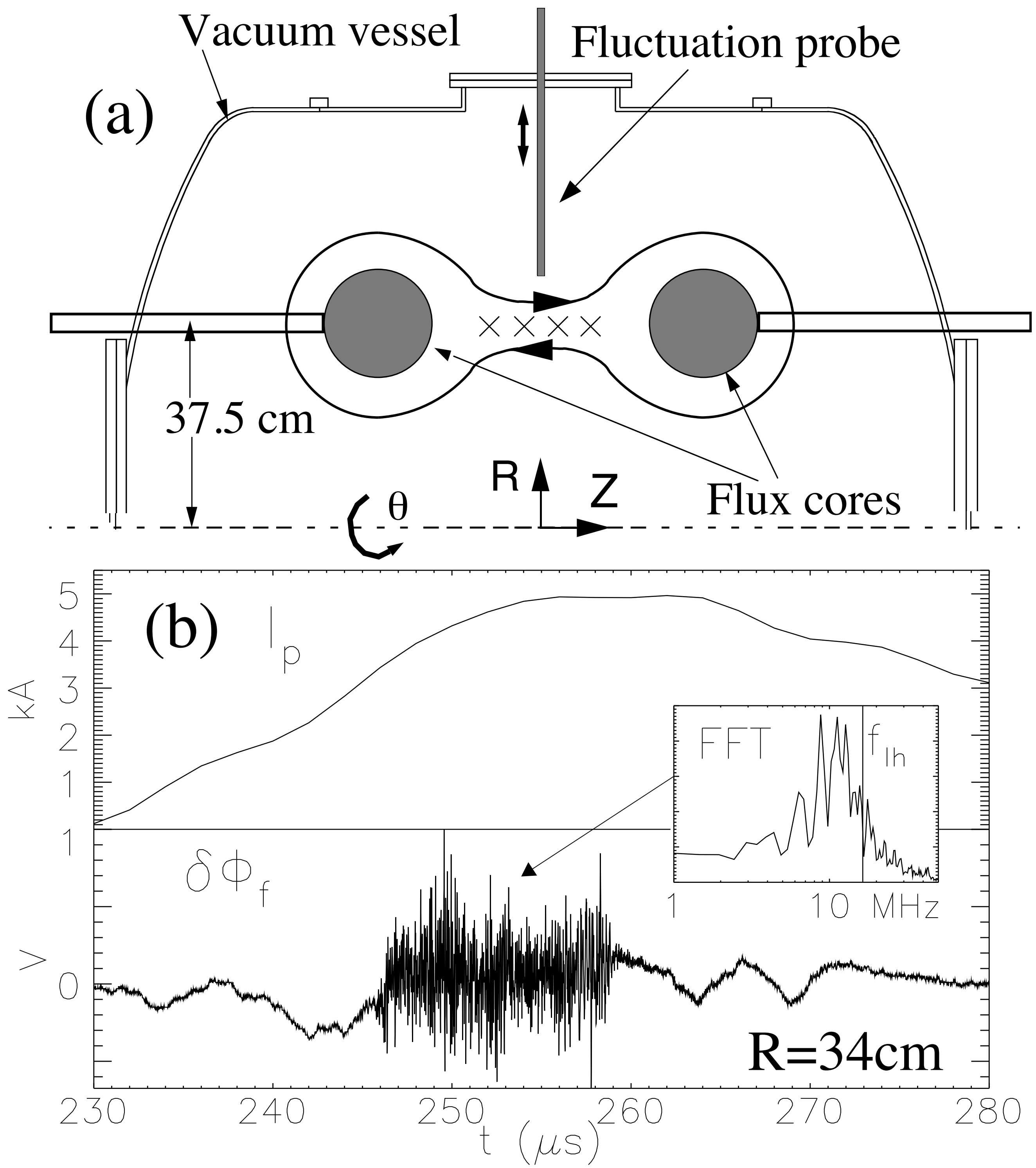
Probe-based fluctuation measurements in MRX





- ▷ Differential floating Langmuir probes, magnetic pick-up loops
- ▷ Wideband ($f \lesssim 125$ MHz) amps built into probe tips ($f_{\mathrm{LH}} \sim 5 - 15$ MHz)
  - ▹ Improved noise immunity
  - ▹ Impedance matching
  - ▹ 50Ω line driver
- ▷ Low-loss cabling: semi-rigid UT85LL in probe shafts, RG8 to digitizers
- ▷ Fast oscilloscopes: 500MS/s-1GS/s (Tek 510A, 754C)

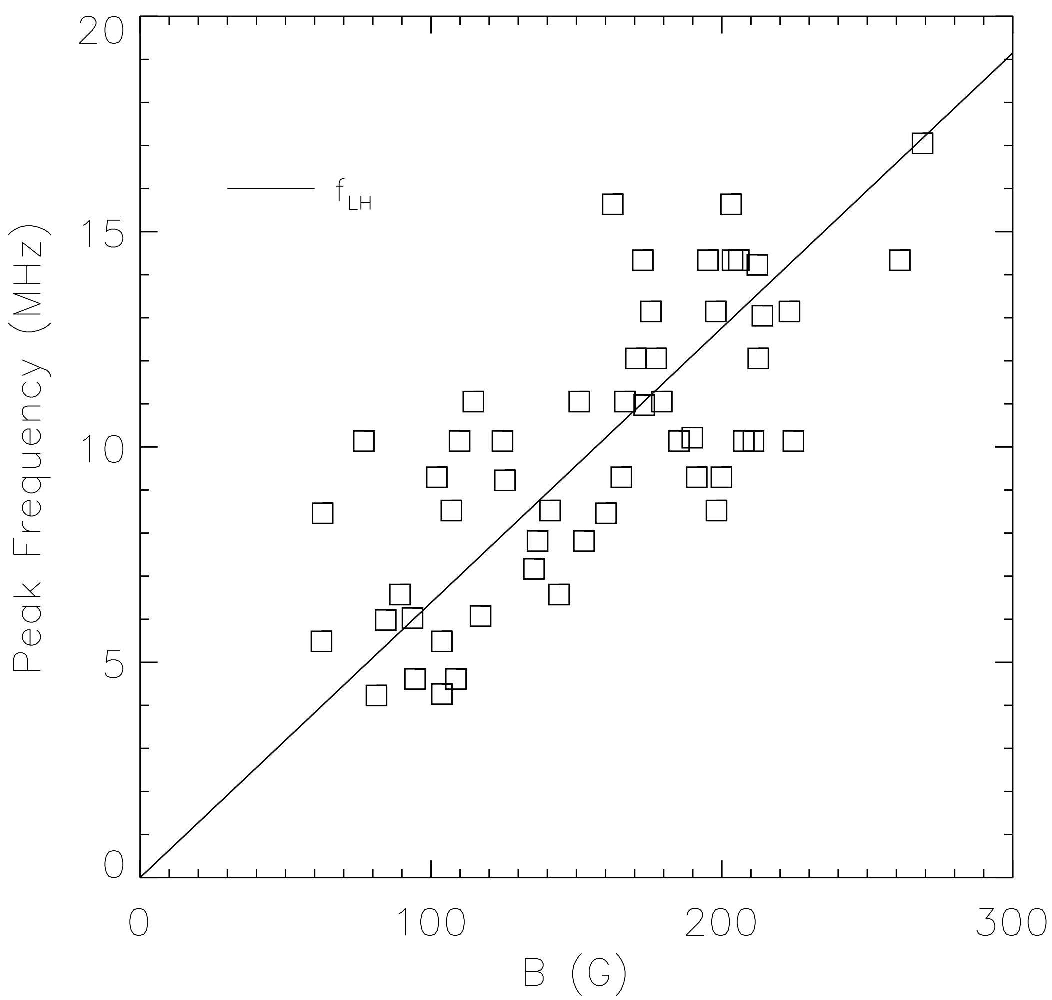
Lower hybrid frequency range fluctuations are observed in MRX Discharges

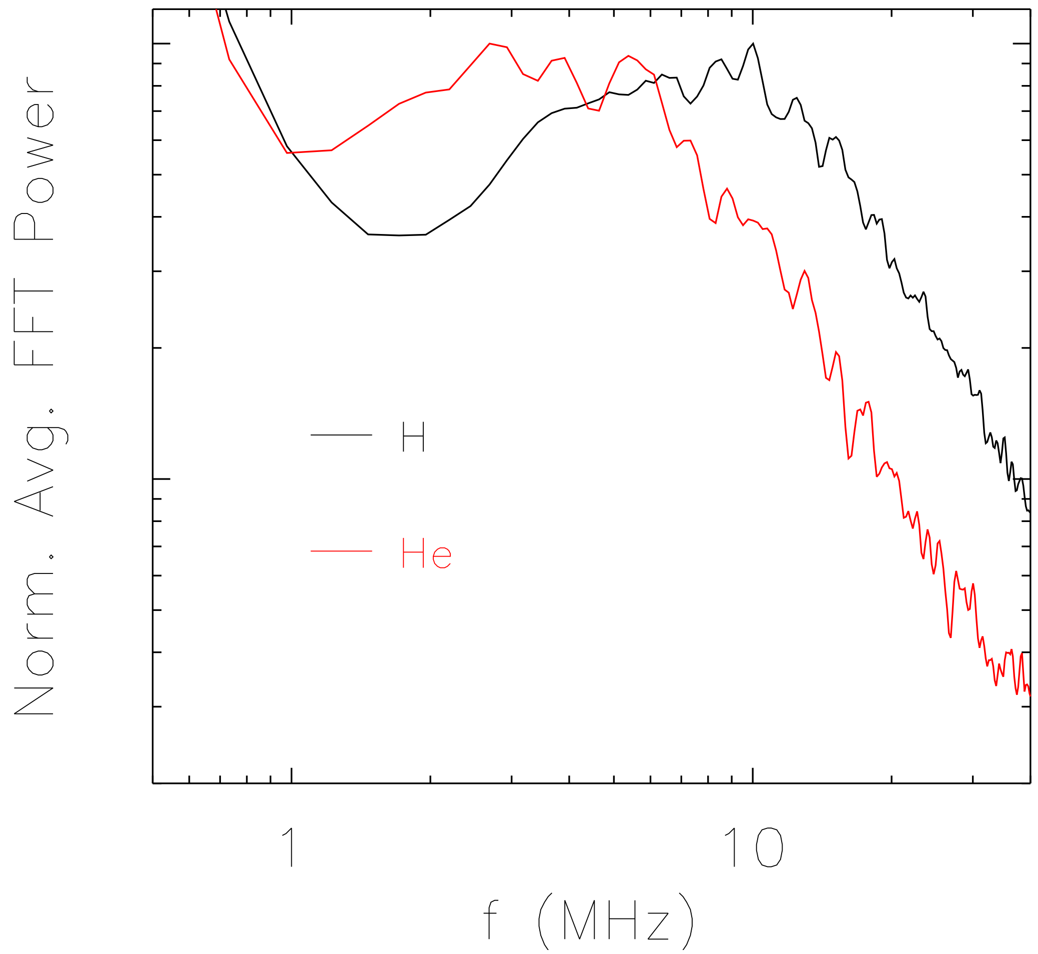


- ▷ Fluctuations begin with current sheet formation
- ▷ Spectrum near f_{LH}
- ▷ $\dfrac{e\delta\phi_{\mathrm{f}}}{T_{\mathrm{e}}} \lesssim 10\%$
- ▷ Similar magnetic fluctuations are also observed, $\delta B/B \sim 2-5\%$

Carter et al., Phys. Rev. Lett. 88, 015001(2001)
Carter et al., Phys. Plasmas 9, 3272 (2002)

Scaling of frequency spectra with M and B is consistent with the lower hybrid frequency

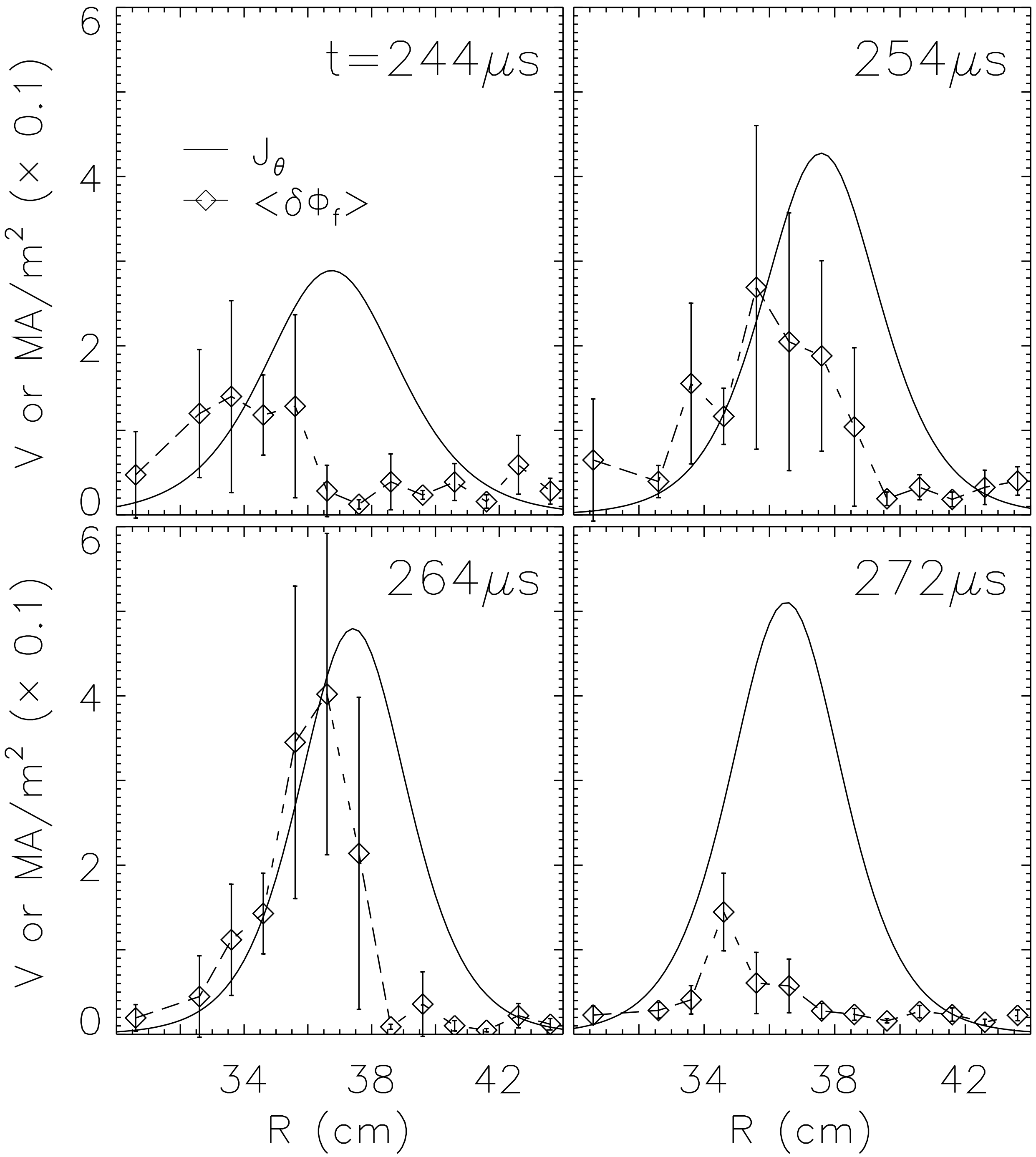




▷ Scan of peak reconnecting magnetic field (bank voltage) in hydrogen and helium

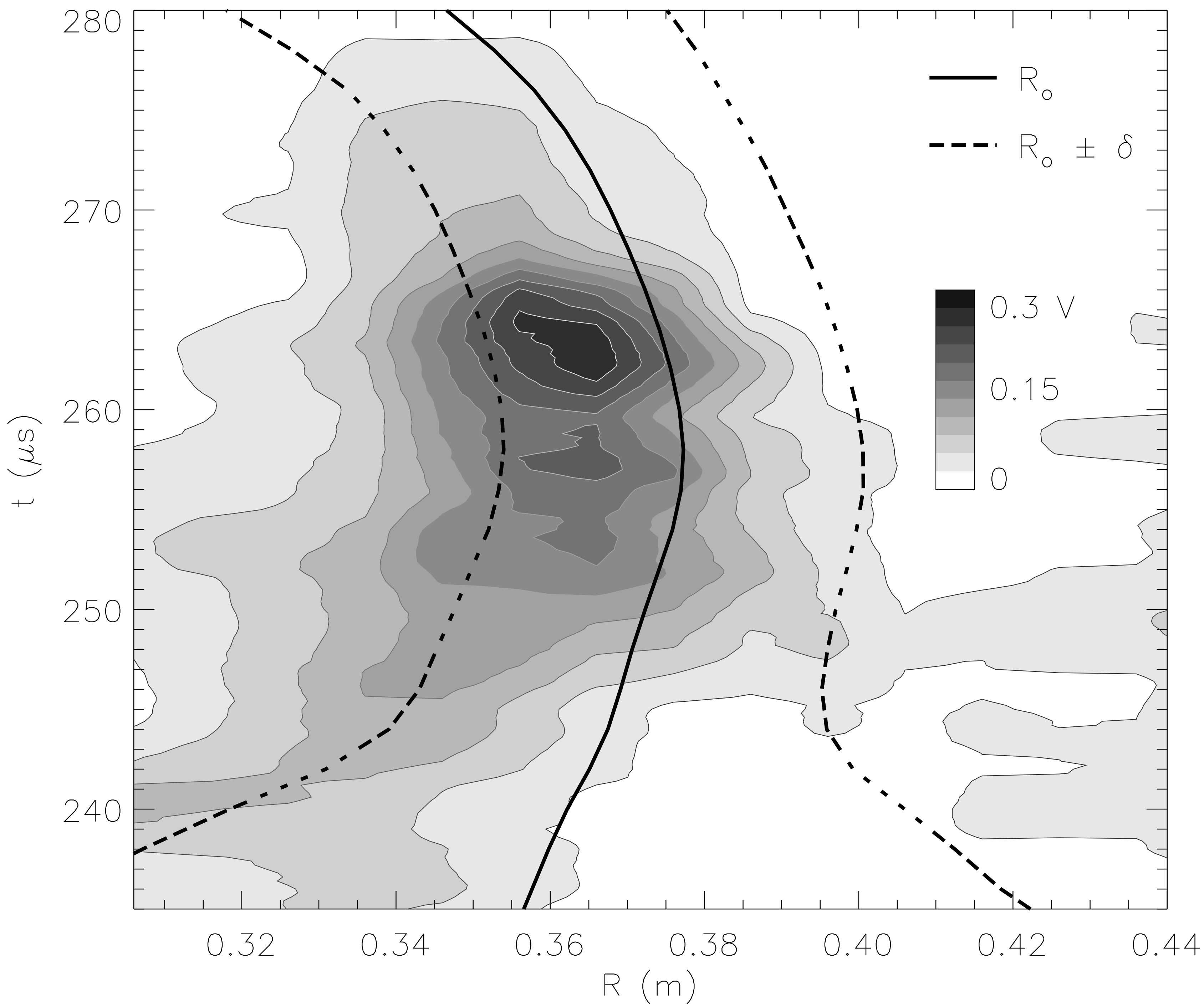
▷ Scaling of peak frequency and width of spectrum consistent with LHDI

Fluctuation amplitude is peaked at the edge of the MRX current sheet

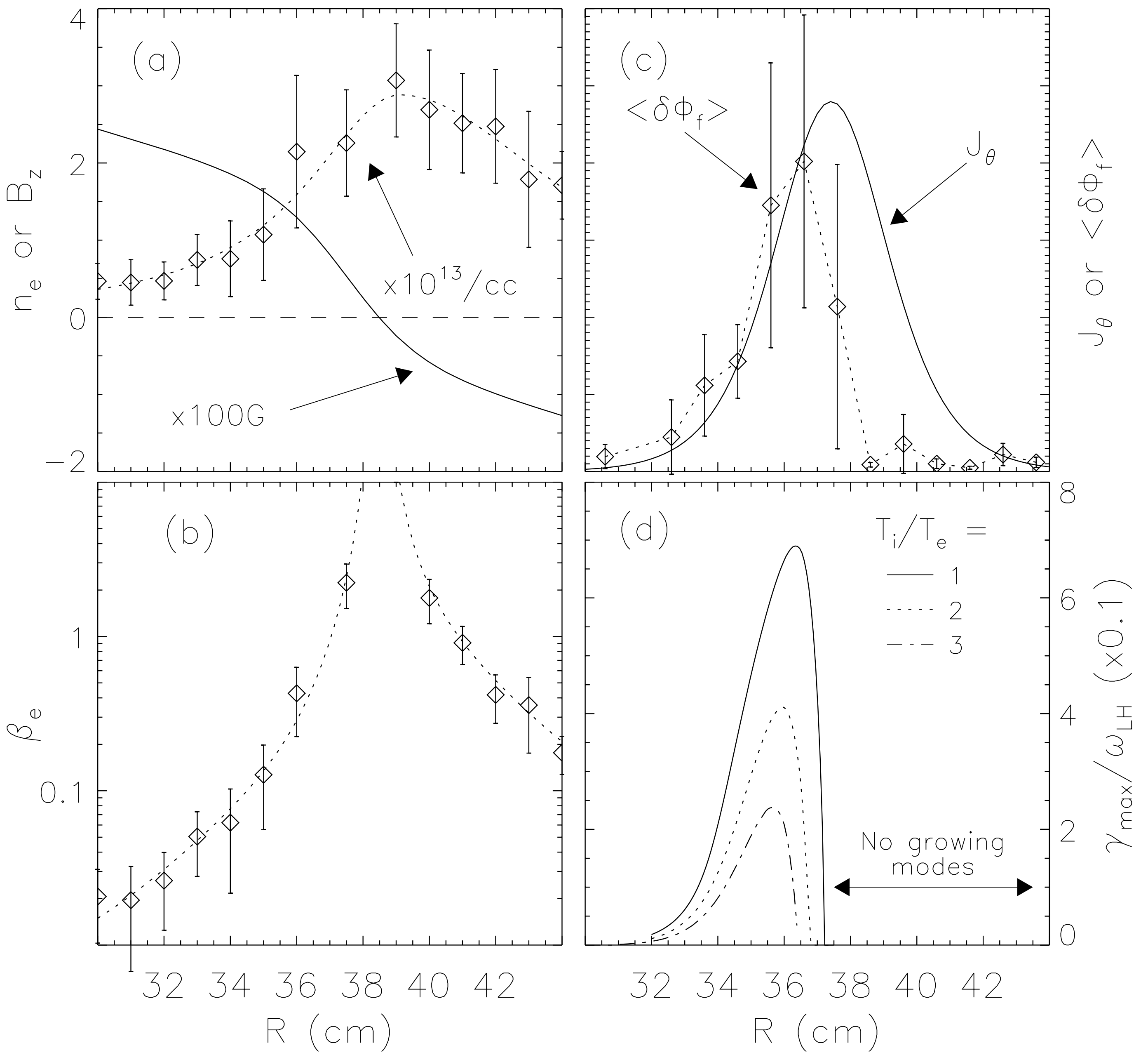


- ▷ Strongest on the inner edge of the CS and early in time
- ▷ Rapid decay of fluctuation amplitude during reconnection observed

Fluctuation amplitude is peaked at the edge of the MRX current sheet

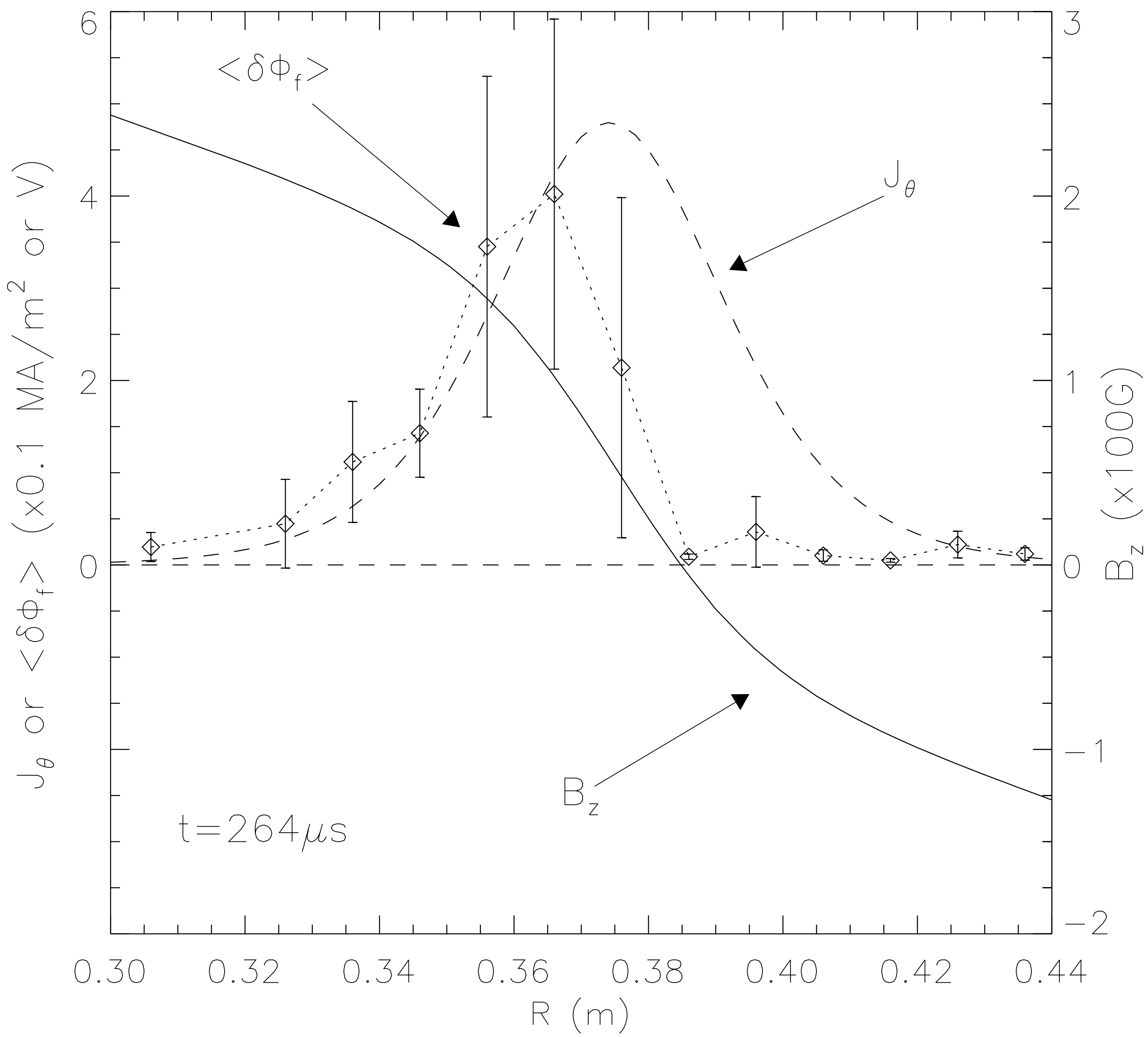


Radial amplitude profile is consistent with linear theory of LHDI



- ▷ Measured profiles used to compute roots of the LHDI dispersion relation at each radial location
- ▷ Asymmetries in ∇n, β, and drift velocity lead to asymmetric growth profile
- ▷ Decrease in growth rate with increasing $T_{\mathrm{i}}/T_{\mathrm{e}}$ could explain time behavior

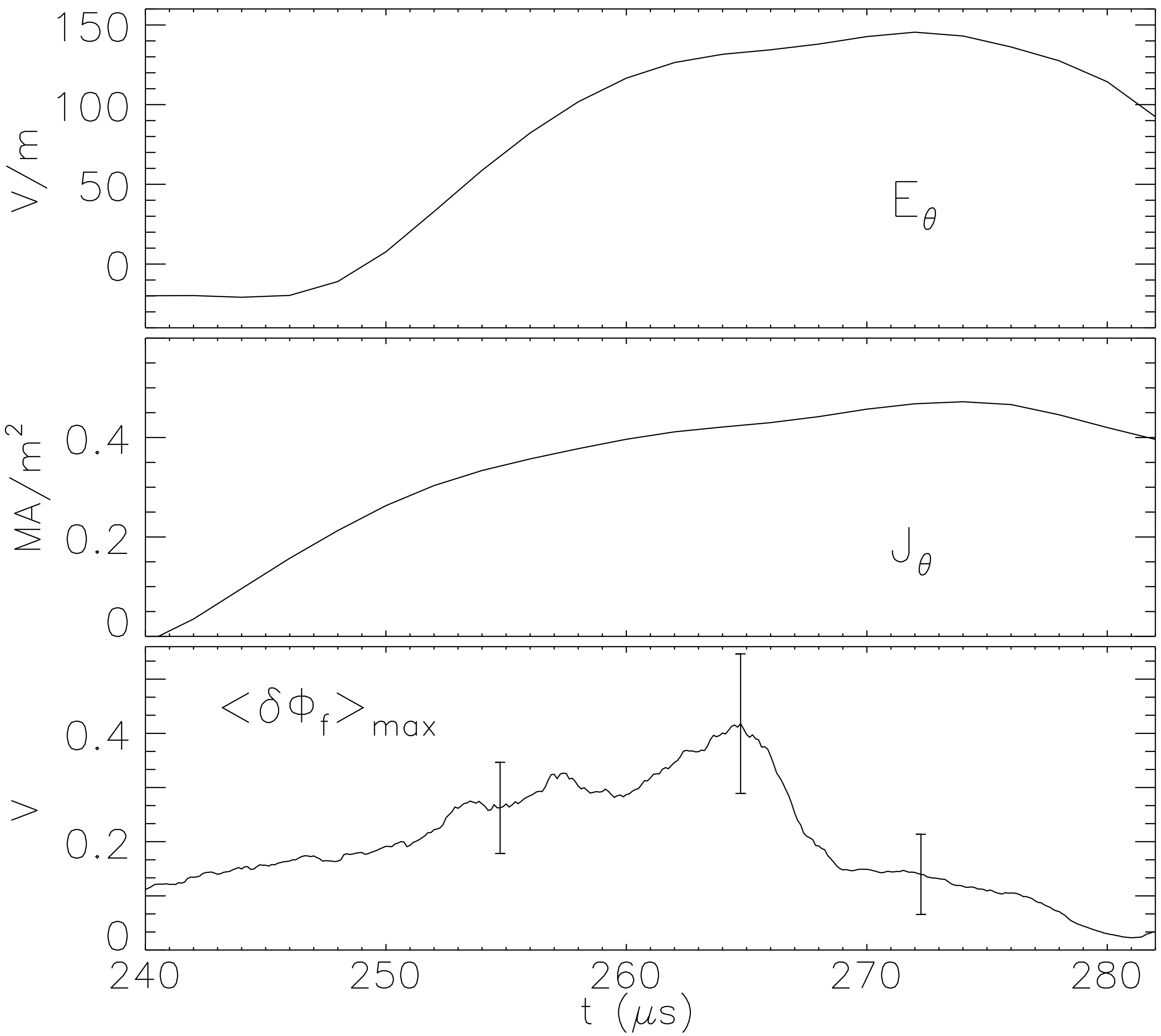
Role of the LHDI?: Measured amplitude is small at magnetic null



- ▷ Current peak is offset from null due to toroidal effects
- ▷ Consistent with expectations of linear finite-β stabilization

▷ LHDI is unlikely to directly provide a resistivity at the null through effective scattering.

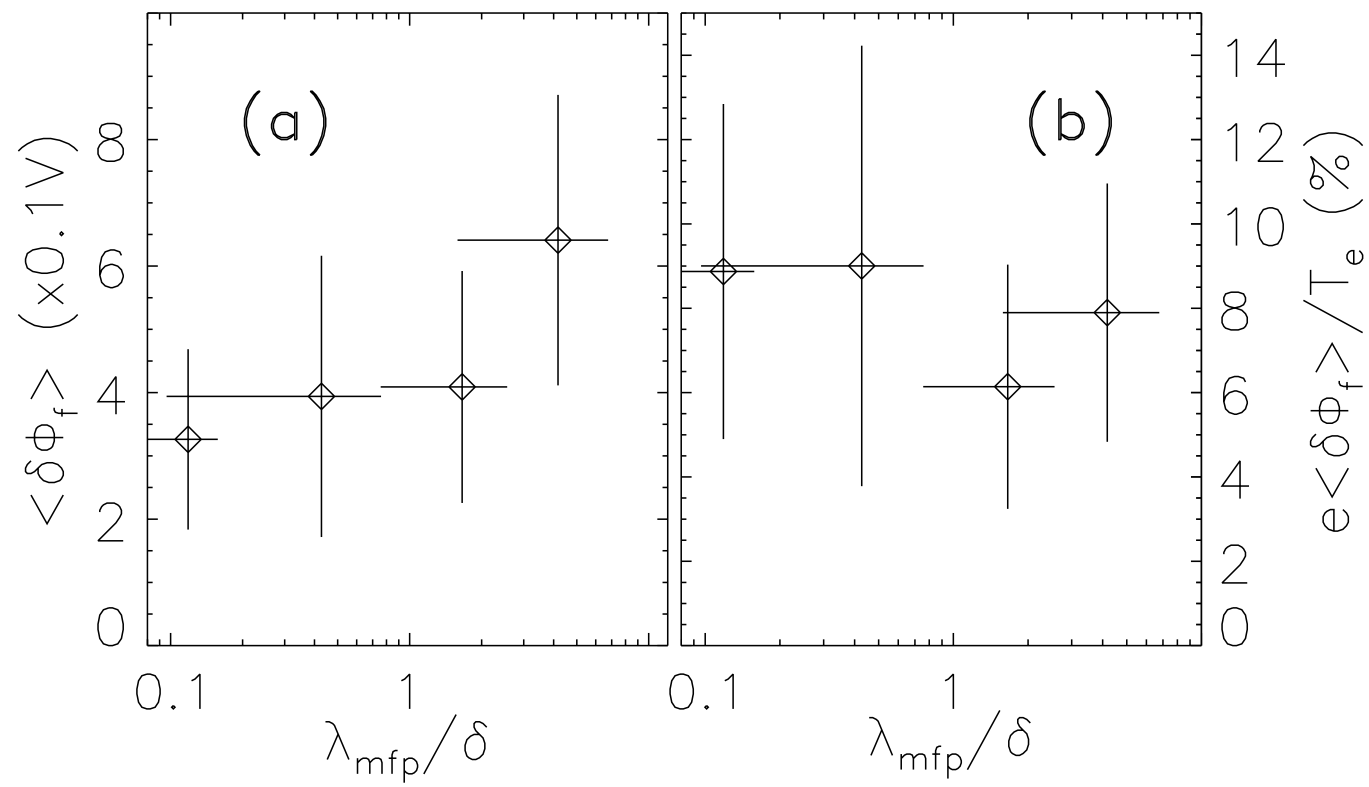
Time behavior of LHDI amplitude is inconsistent with reconnection rate



- ▷ Peak LHDI amplitude drops rapidly early in the reconnection process
- ▷ Reconnection rate (E_θ) and current density seem insensitive to the drop (and may even *increase*)

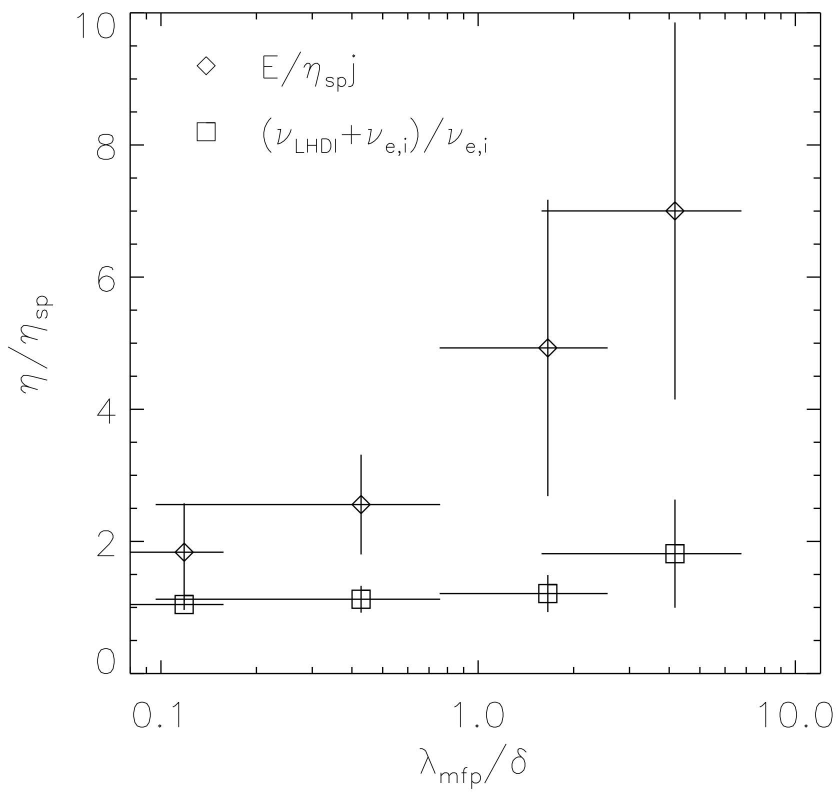
- ▷ Suggests that LHDI is not essential in determining the reconnection rate in MRX.

Significant LHDI amplitude persists in highly-collisional current sheets



- ▷ Peak amplitude in both space and time, versus collisionality
- ▷ Amplitude increases at lower collisionality, but normalized peak amplitude does not change
- ▷ Implies fairly constant effective collisionality due to LHDI as the Coulomb collisionality is widely varied

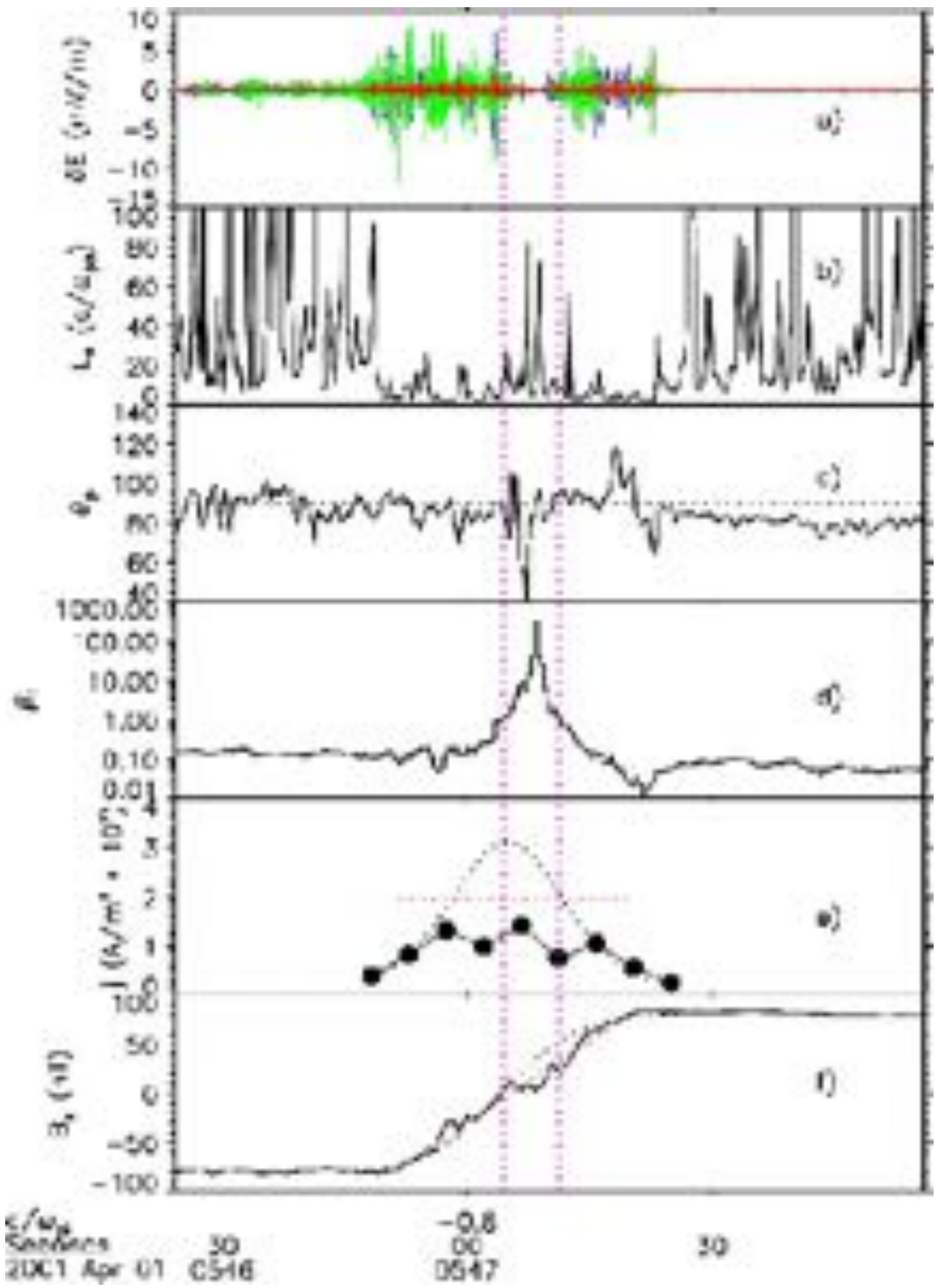
Computed quasilinear resistivity due to the LHDI



$$\nu_{\rm LHDI} = \frac{\langle \delta n \delta E \rangle}{nmV} = {\rm Im}\left[k_\perp \frac{4\omega_{\rm p,i}^2}{k_\perp^2 v_{\rm th,i}^2} \zeta_{\rm i} Z(\zeta_{\rm i}) \right]_{k_\perp^{\rm max}} \frac{T_{\rm i}}{m_{\rm e} V} \frac{\mathcal{E}}{n T_{\rm i}} \qquad \text{[Davidson]}$$

- ▷ LHDI effective collision rate computed at peak amplitude, in both space and time (generous?)
- ▷ $\nu_{\rm LHDI} \approx \omega_{\rm LH} \lesssim \nu_{\rm e,i}$ – even when using the peak amplitude for the lowest Coulomb collisionality data point

Lower hybrid drift also observed in magnetopause reconnection

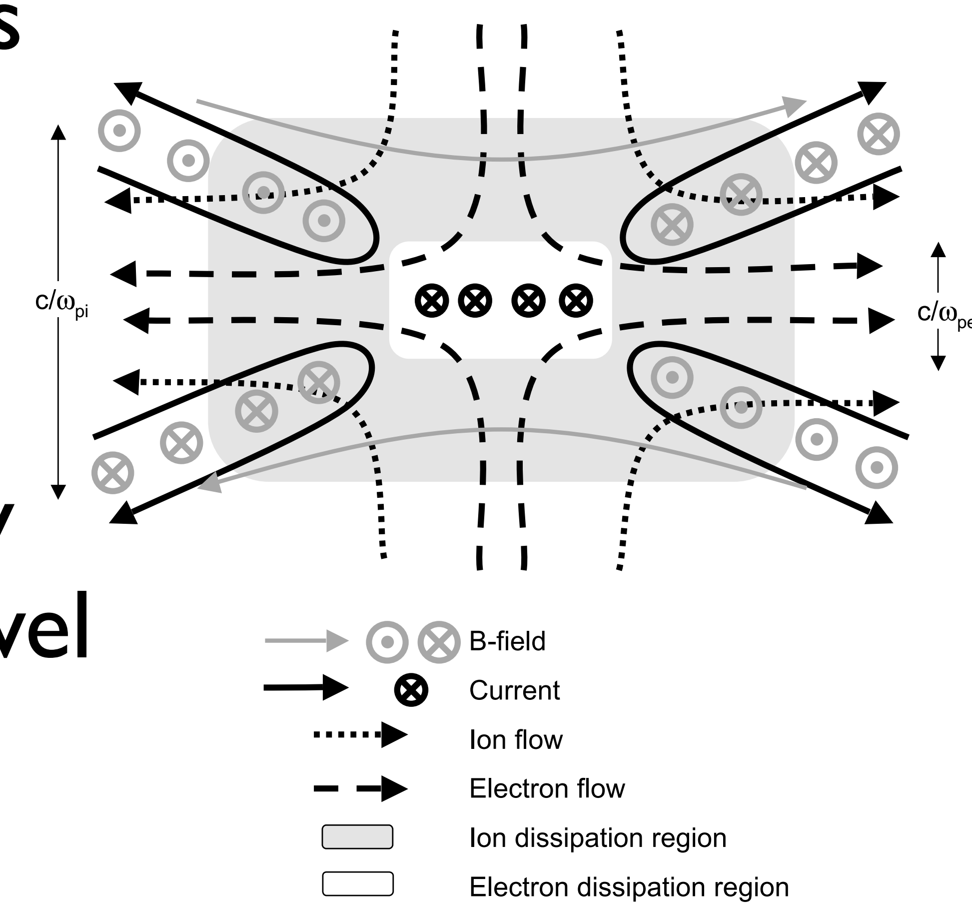


- POLAR satellite measurements in the magnetopause current sheet
- Consistent with laboratory observations: LHD turbulence on edges of current sheet, not where resistivity is needed

Bale, et al., GRL, 29, 33 (2002)

If not anomalous resistivity, then what?

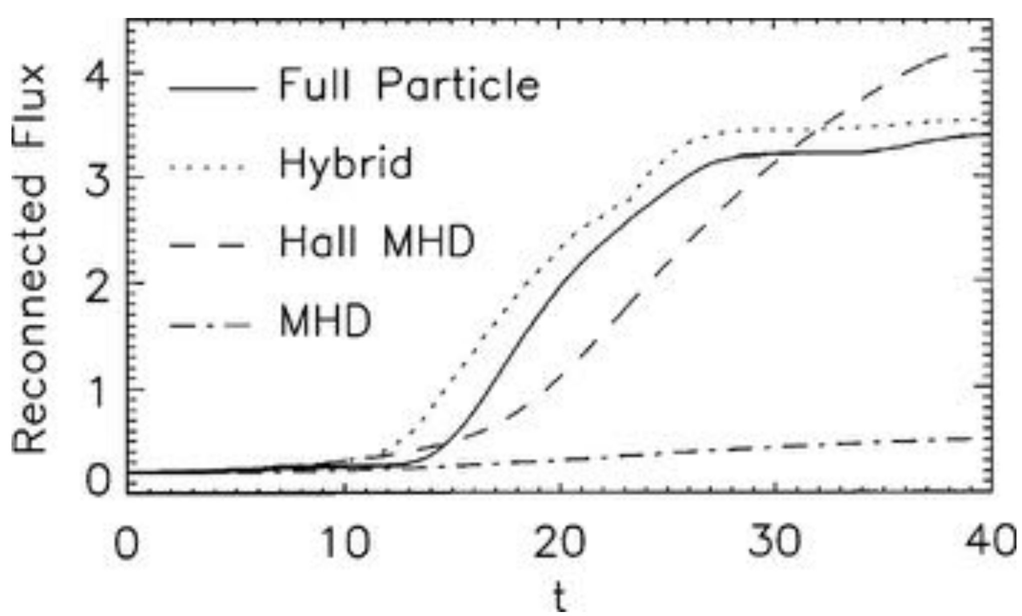
- As current sheet approaches c/ω_{pi} or ρ_i scale, two-fluid and kinetic physics becomes important
- Decoupling of electron and ion motion: two-scale current sheet predicted: ions turn the corner early (ion scale sheet) while electrons travel in to smaller electron dissipation region
  - Decouples mass flow from dissipation (solves Sweet-Parker bottleneck)



[Biskamp, Drake, Pritchett, …]

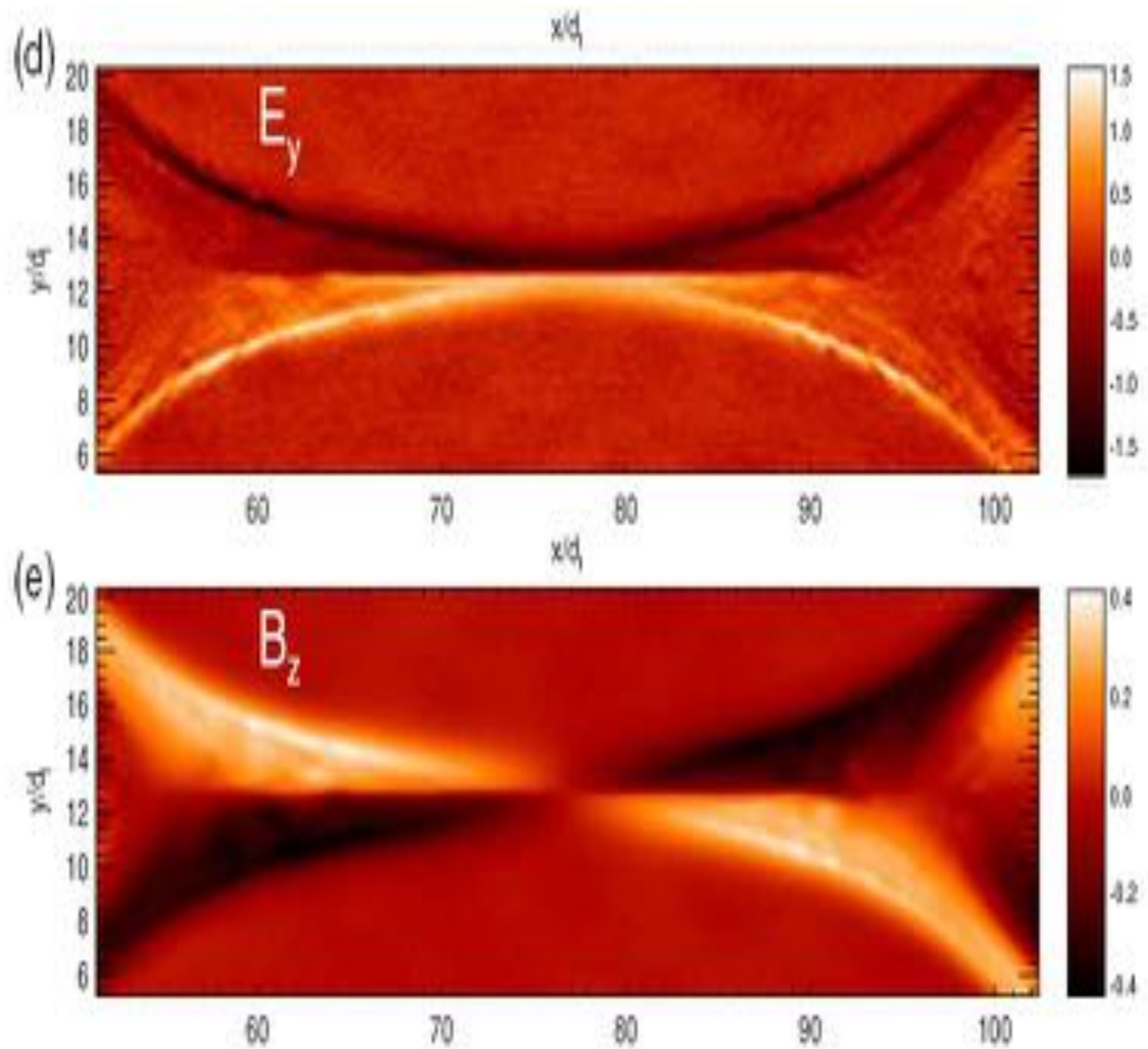
Two-fluid/Hall reconnection: reconnection rate independent of dissipation mechanism

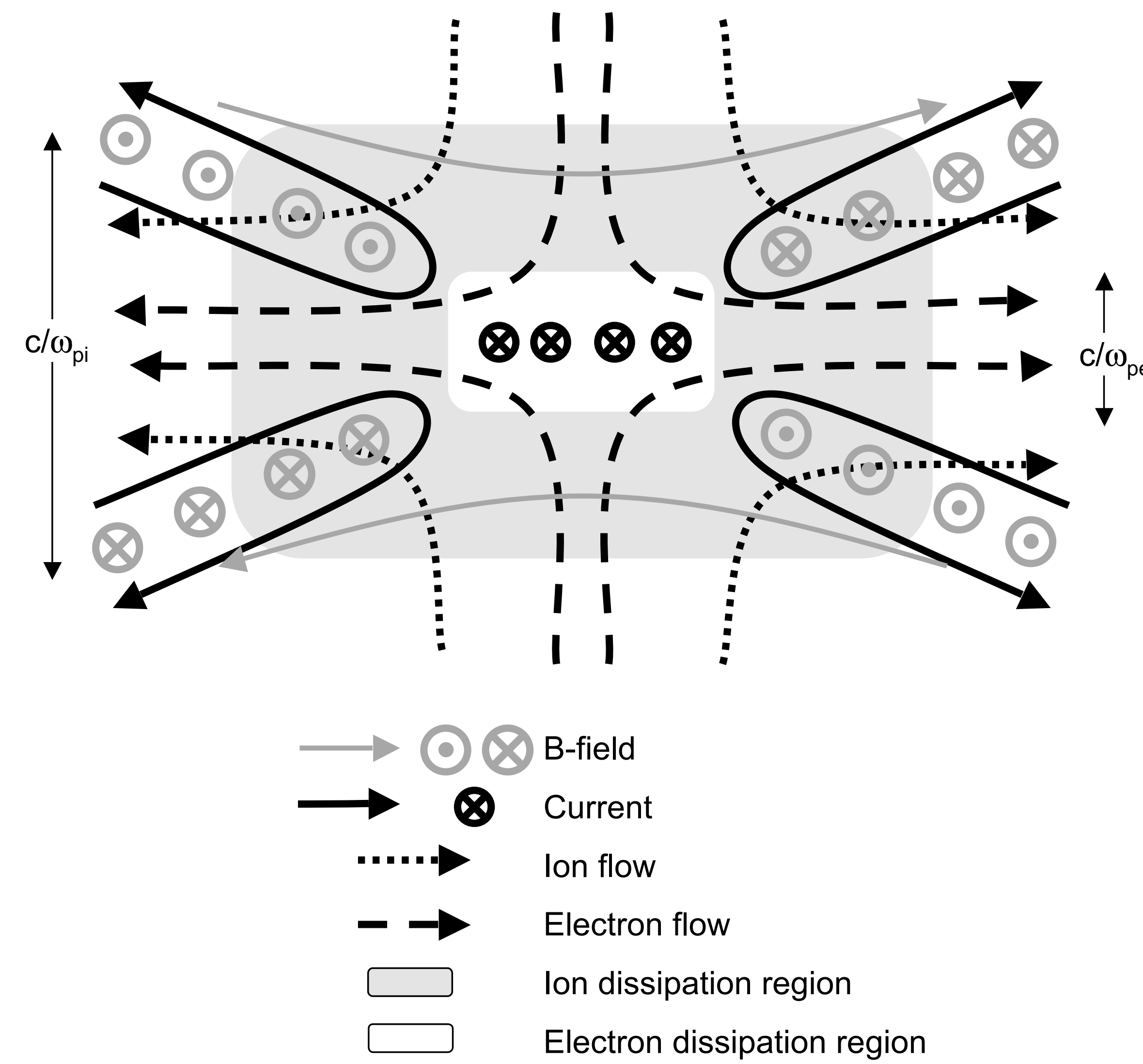
- Dissipation mechanism sets scale of inner (electron scale) current sheet, mass flow controlled by ion scale sheet
  - Reconnection rate independent of size of electron sheet (mechanism of dissipation)
  - GEM challenge result: several different simulation codes found same reconnection rate with varying dissipation mechanisms; requirement was inclusion of two-fluid physics (Hall term)



Birn, et al., JGR, 106, 3715 (2001)

Signature of two-fluid/Hall reconnection: quadrupole out-of-plane magnetic field pattern

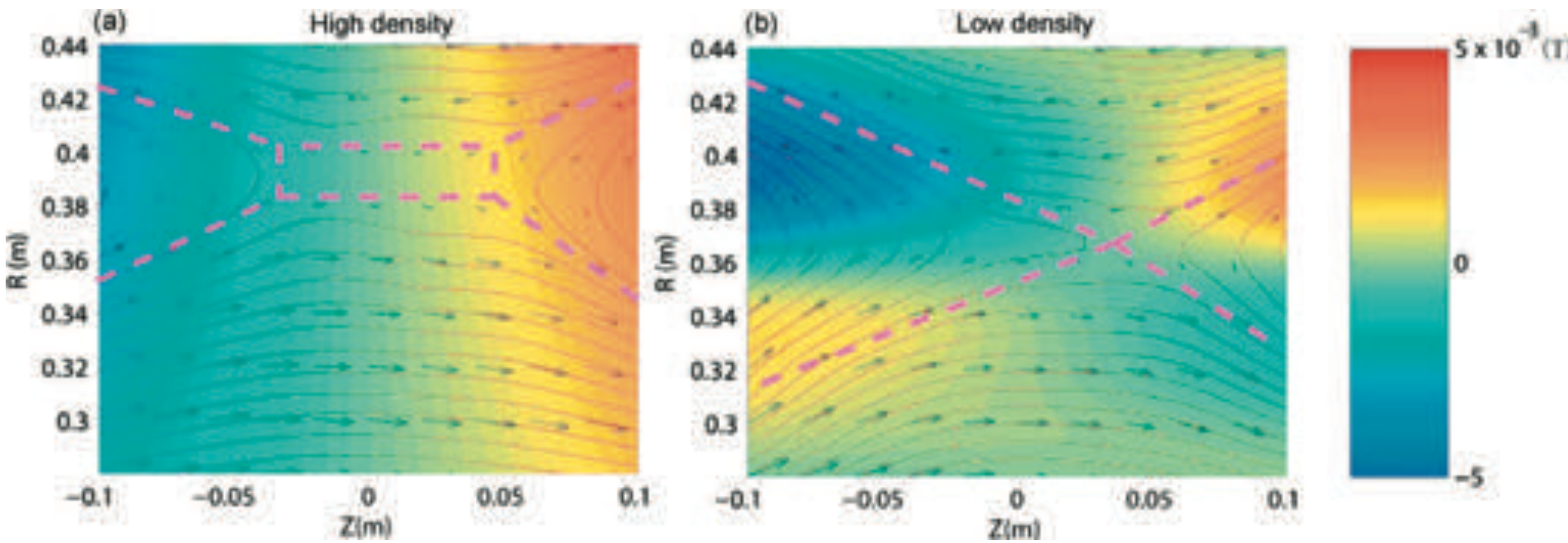




[Drake 2008]

- Hall currents bend reconnected field line out of plane; can think of the structure as standing whistler wave (no guide field — with, have kinetic Alfvén wave)

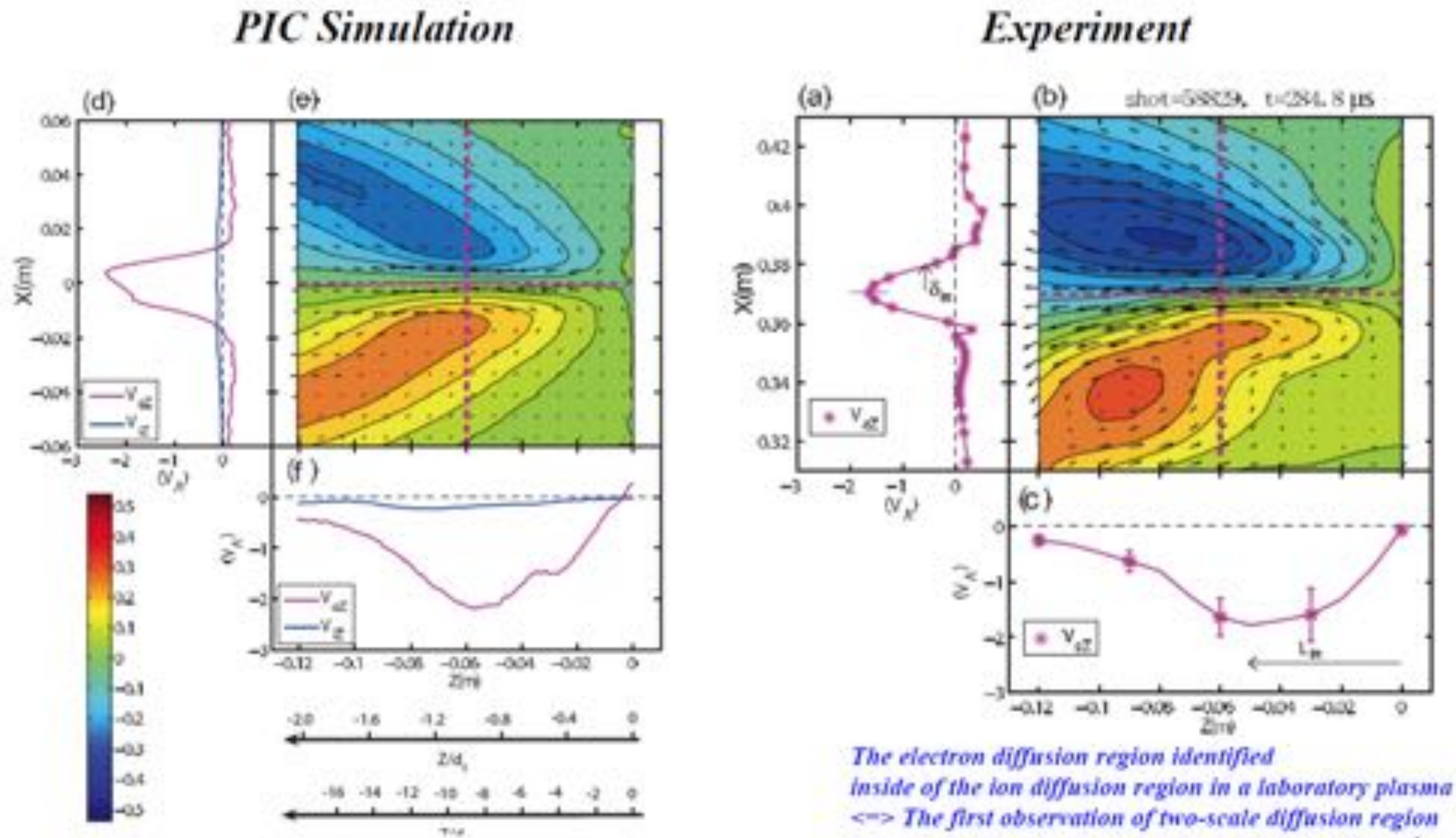
Experiments observe quadrupole signature of Hall-mediated reconnection



- MRX: lower density, lower collisionality plasmas exhibit X-point geometry and clear quadrupole out-of-plane field

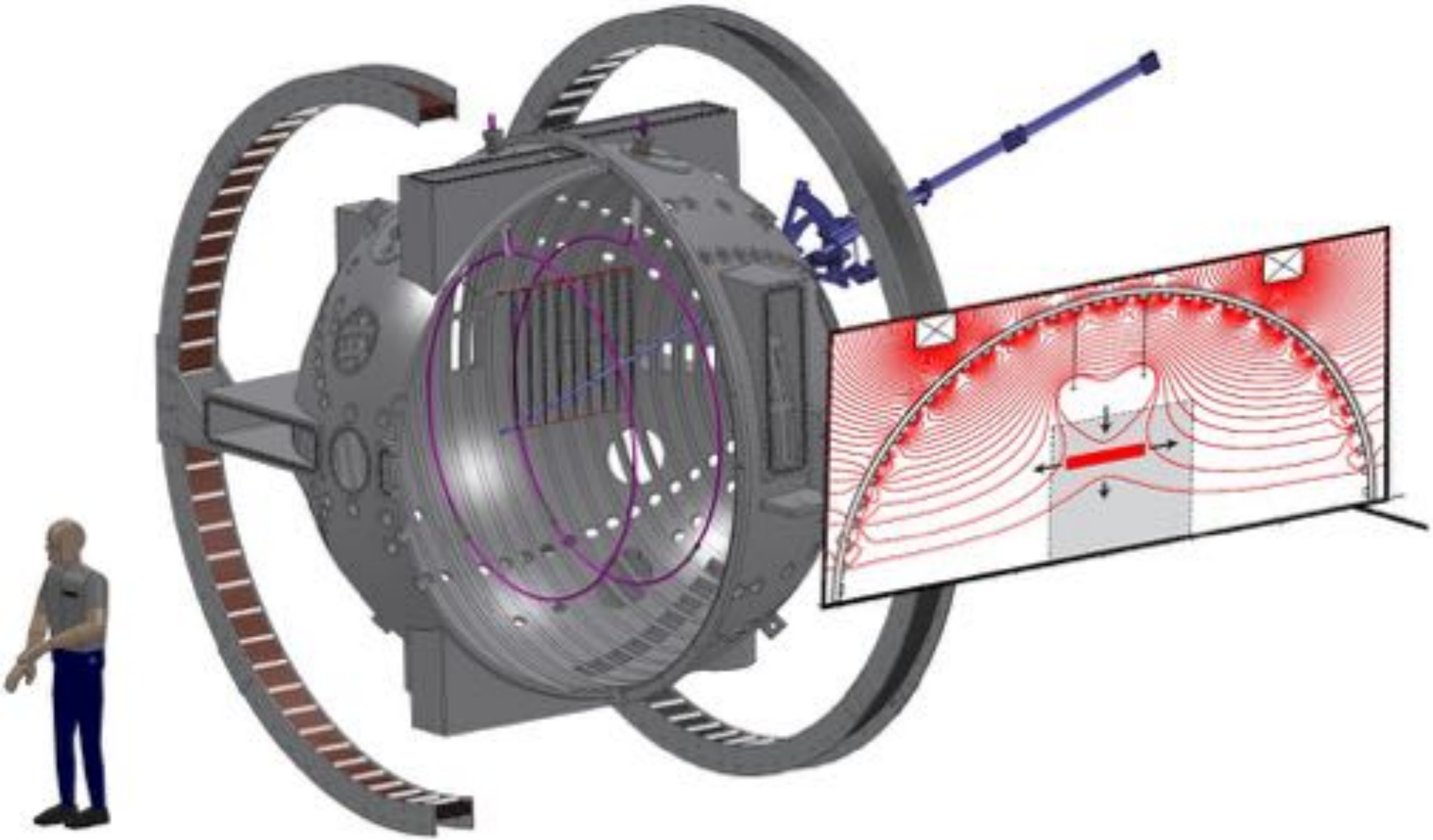
Ren, et al. PRL (2005)

Quadrupole field & Electron current layer identified



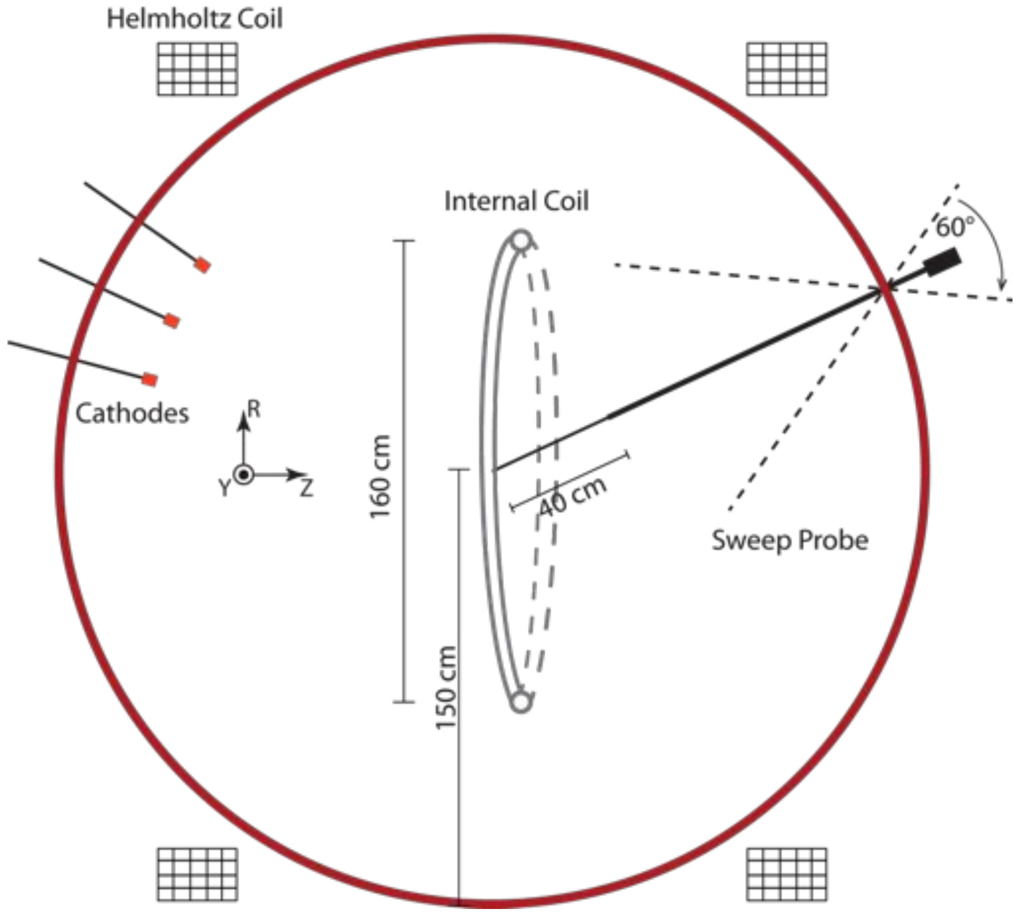
The electron diffusion region identified inside of the ion diffusion region in a laboratory plasma
<=> The first observation of two-scale diffusion region
[Ren et al, PRL 08, Ji et al GRL, 08, Dorfman et al '10]

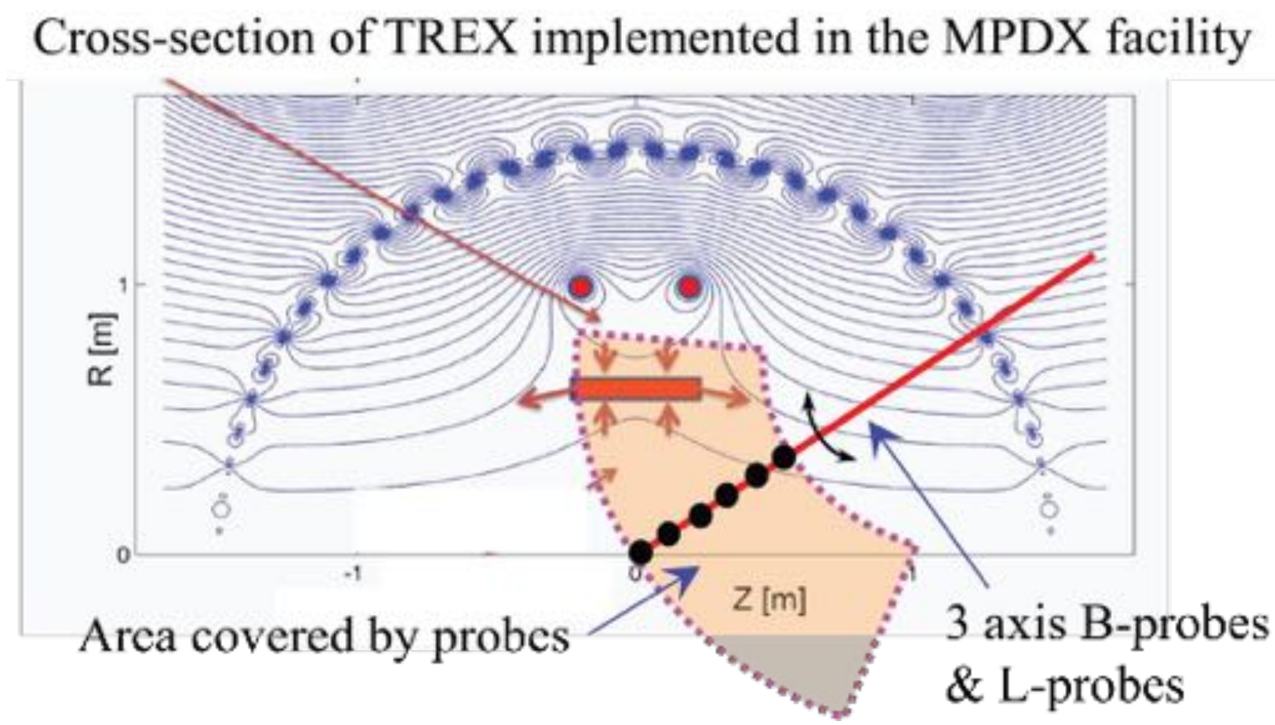
Terrestrial Reconnection EXperiment (TREX)

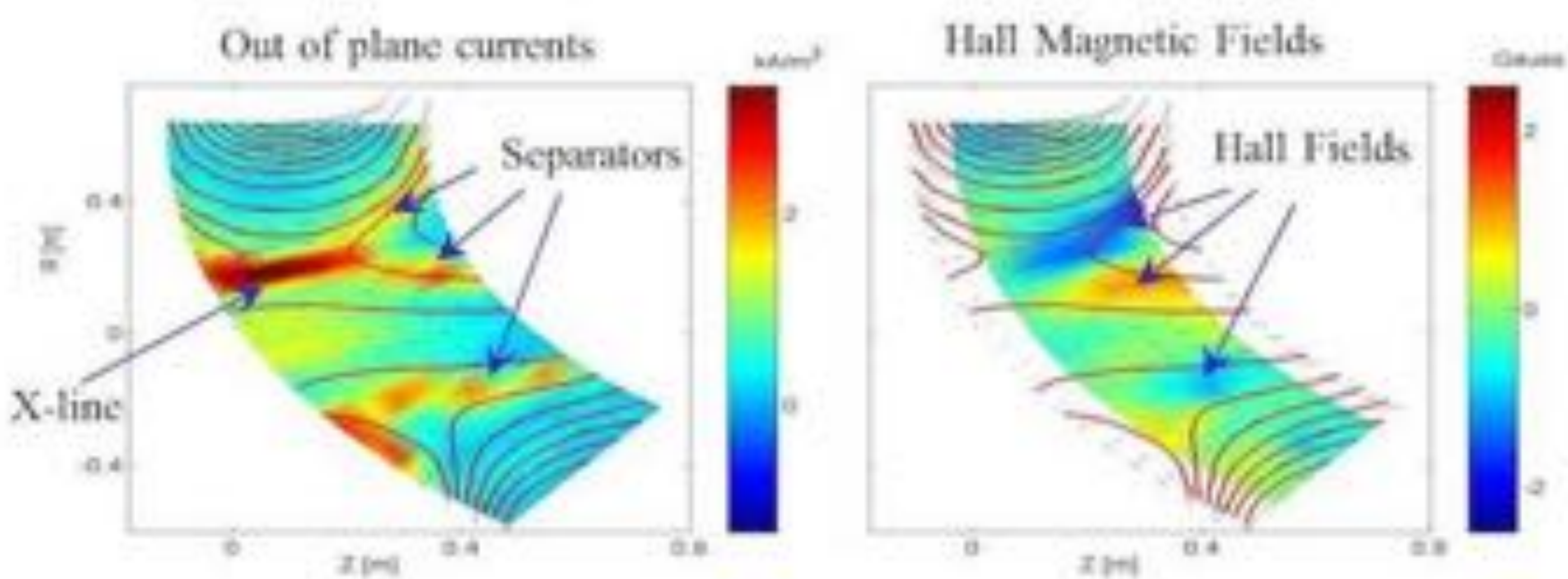


- Part of WIPAL facility (MPDX) — driven reconnection by adding internal coils + external Helmholtz

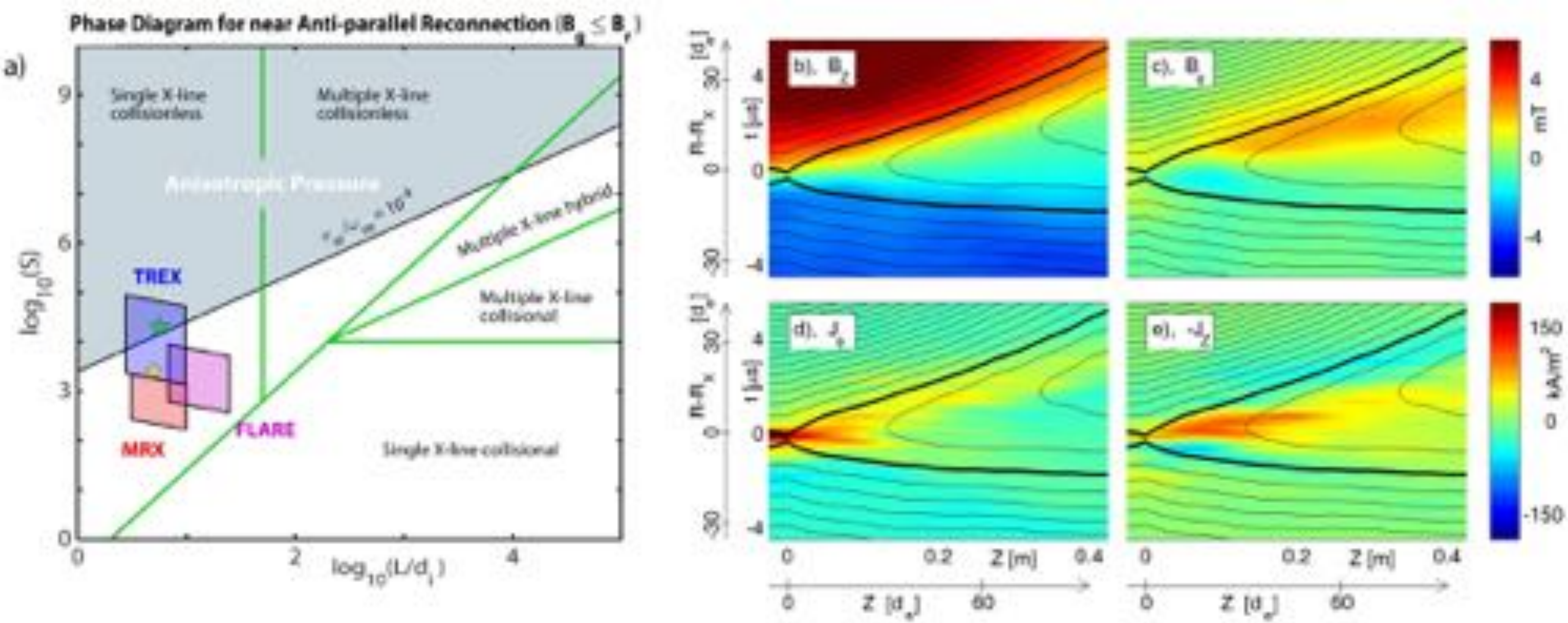
Reconnection in TREX: Quadrupole signature of fast reconnection identified





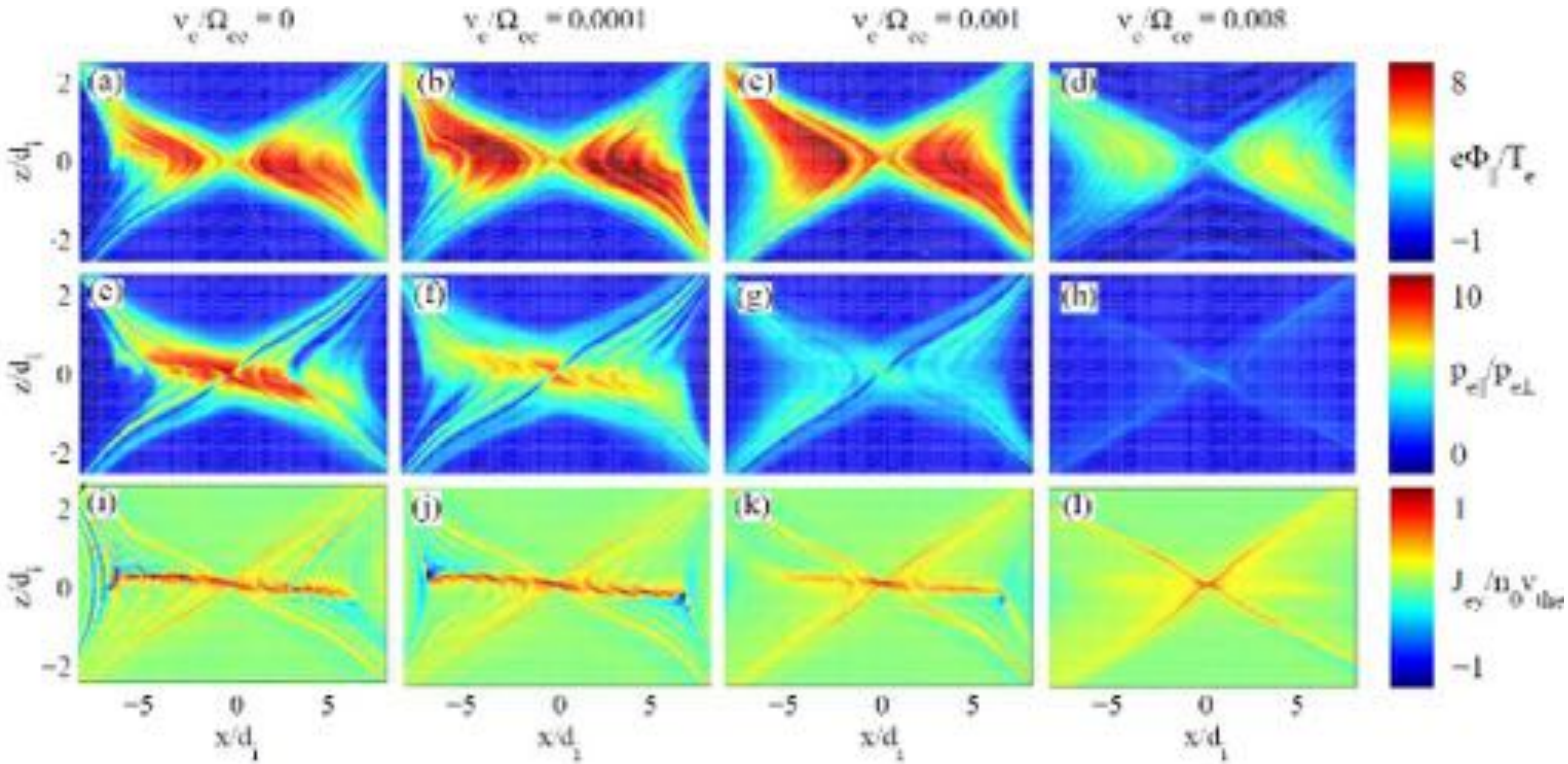


Electron pressure anisotropy & electron scale jet in TREX



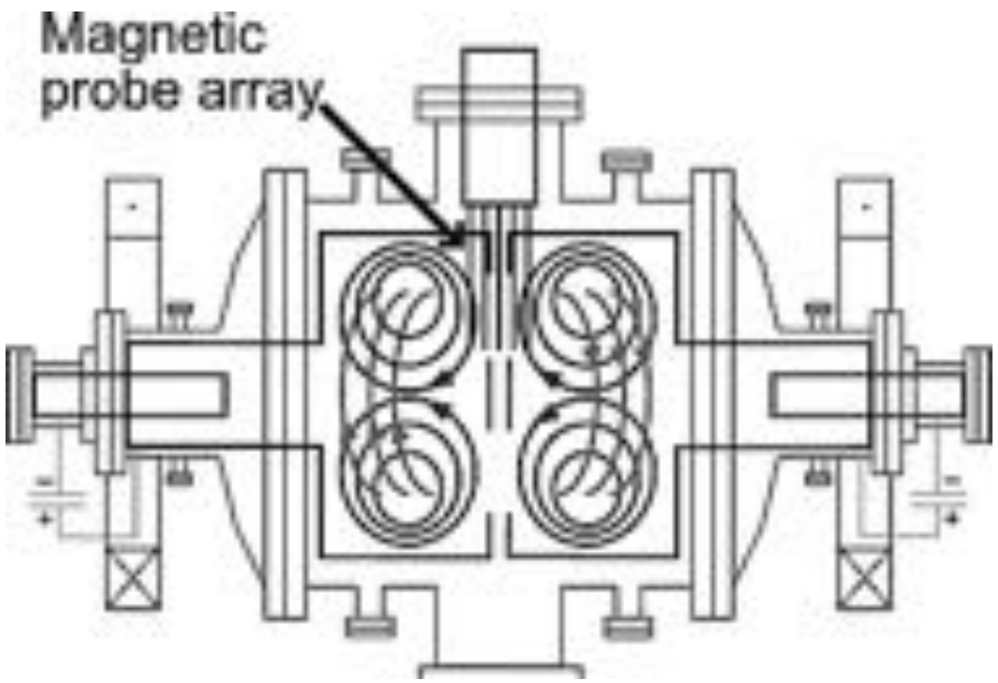
- TREX can access lower collisionality than other experiments; reaching into the regime where electron pressure anisotropy can develop
- See electron "jets" develop in this regime, as predicted by PIC simulation

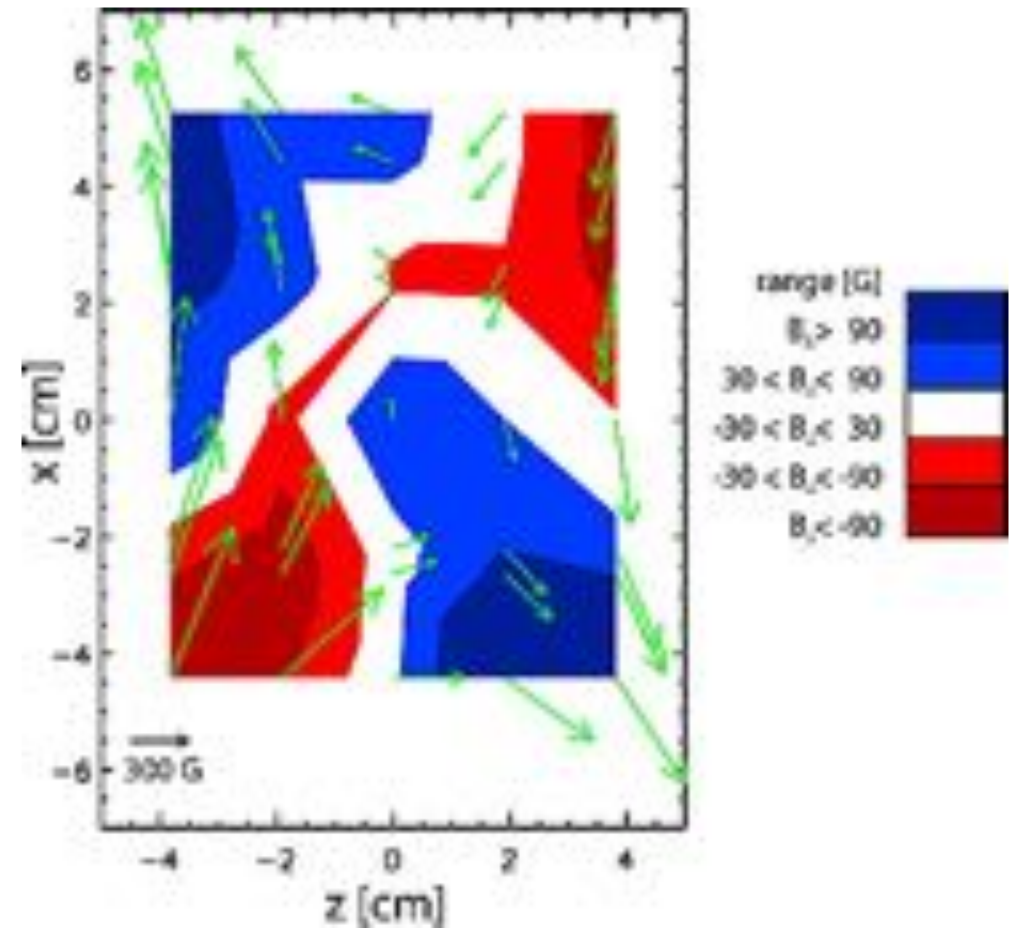
Electron pressure anisotropy & electron scale jet in TREX



- TREX can access lower collisionality than other experiments; reaching into the regime where electron pressure anisotropy can develop
- See electron “jets” develop in this regime, as predicted by PIC simulation

Quadrupole field pattern in the Swarthmore Spheromak Experiment (SSX)



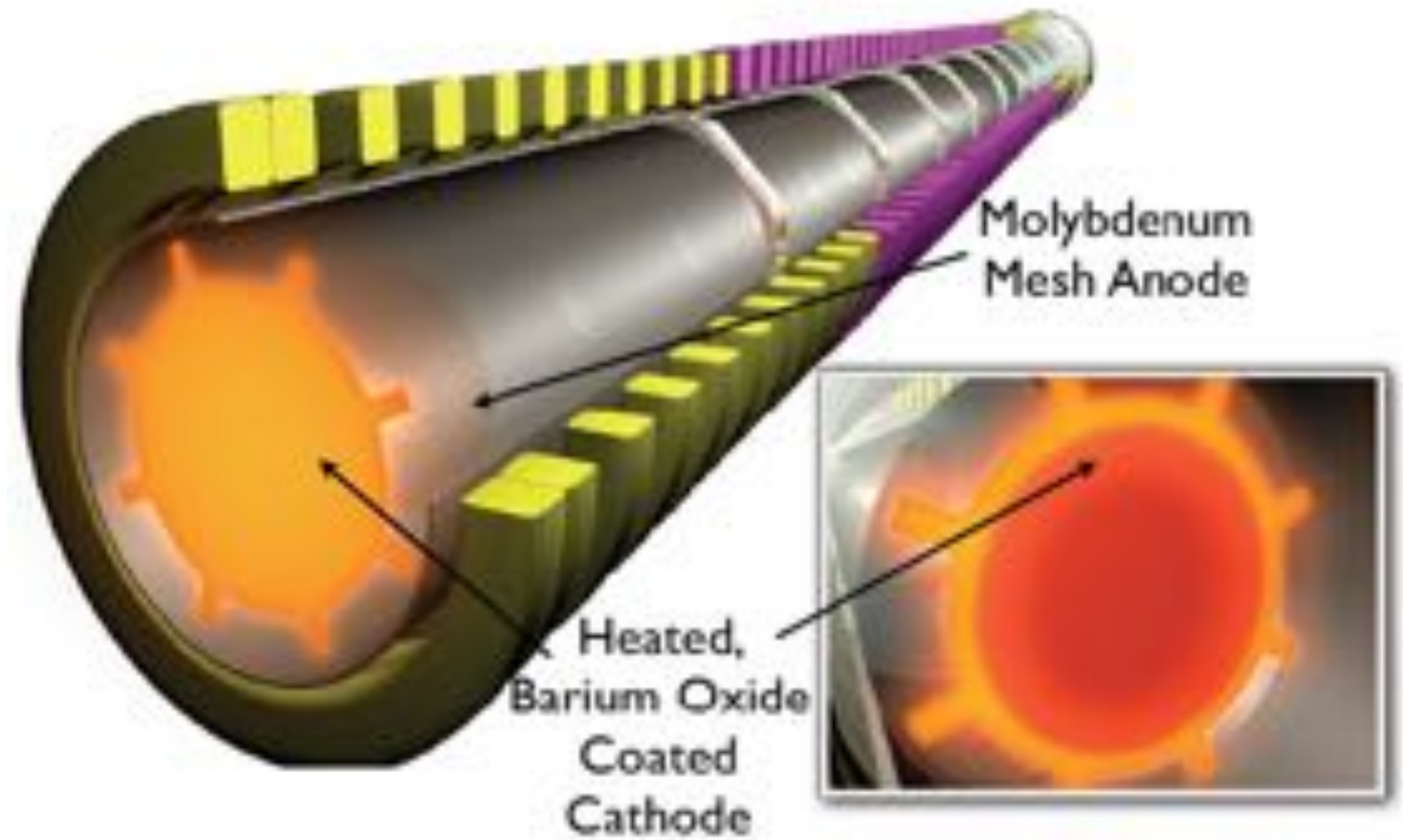


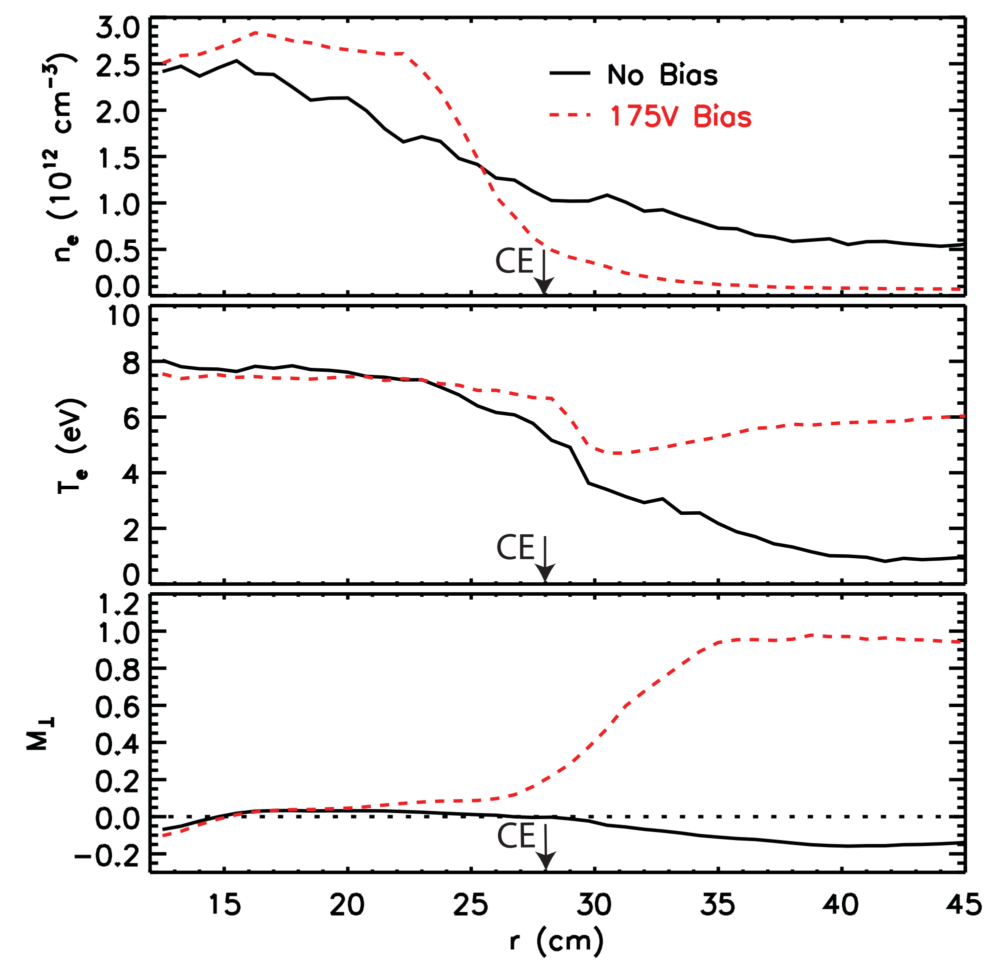
- Spheromak merging/interaction experiment (nice measurements of ion energization)
- Observes quadrupole pattern in current sheet formed between two colliding spheromaks

The LArge Plasma Device (LAPD)

- Solenoidal magnetic field, cathode discharge plasma (BaO and LaB_6)
- BaO Cathode: n ~ 10^{12} cm^{-3}, T_e ~ 5-10 eV, $T_i \lesssim$ 1 eV
- LaB_6 Cathode: n ~ 5×10^{13} cm^{-3}, T_e ~ 10-15 eV, T_i ~ 6-10 eV
- B up to 2.5kG (with control of axial field profile)
- BaO: Large plasma size, 17m long, D~60cm (1kG: ~300 ρ_i, ~100 ρ_s)
- High repetition rate: 1 Hz

LAPD BaO Plasma source



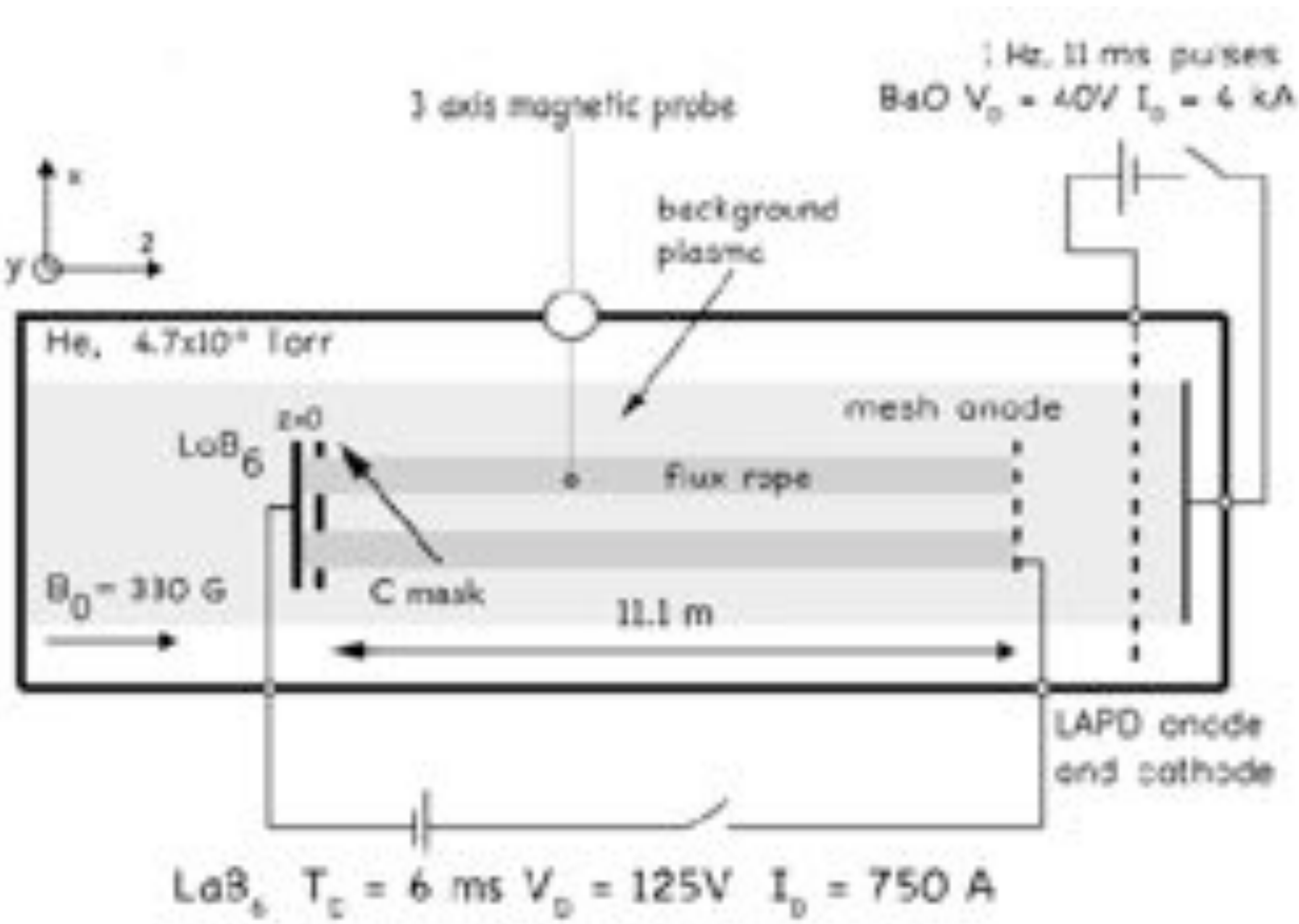


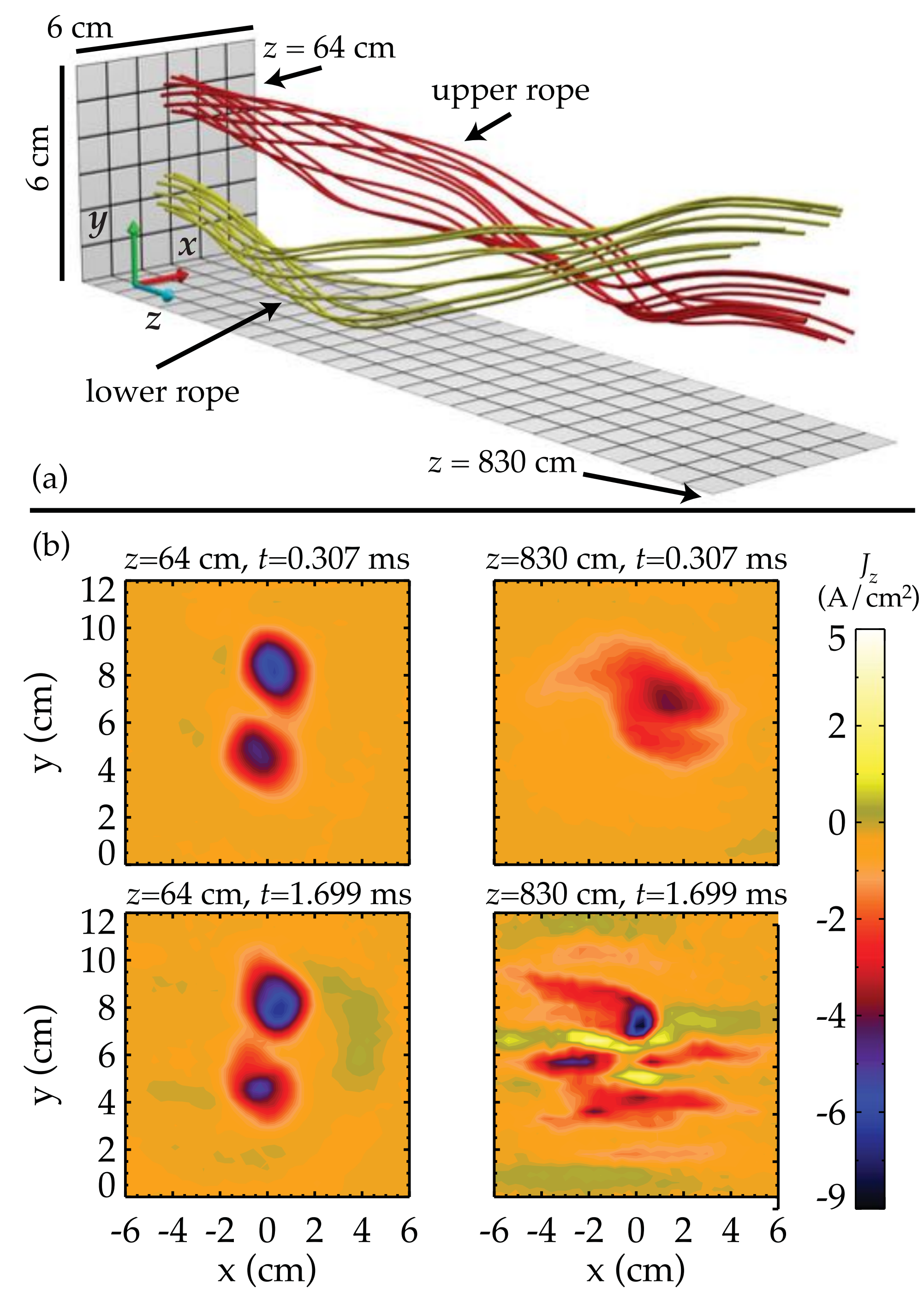
- Produces plasmas with 10-20 ms duration at 1 Hz rep rate
- $n \sim 10^{12}$ cm^{-3}, $T_e \sim$ 5-10 eV, $T_i \lesssim$ 1 eV
- Large quiescent core plasma (~60 cm diameter) for study of plasma waves, injection of ion/electron beams, etc.

Example LAPD Users and Research Areas

- Basic Physics of Plasma Waves: e.g. linear properties of inertial and kinetic Alfvén waves (Gekelman, Morales, Vincena, Kletzing, Skiff, Howes); Alfvén waves in multi-ion plasmas (Vincena, Maggs, Morales); Stationary IAWs (Koepke, Knudsen…)
- Physics of fast ion interaction with Alfvén waves and turbulence (Heidbrink, Tripathi, Carter, Breizman, …)
- Energetic electron interaction with waves (Bortnik, Thorne, Papadopolous, Van Compernolle, Gekelman…)
- Reconnection/flux ropes/current sheets (Gekelman, Daughton)
- Collisionless shocks (Niemann, Gekelman, …)
- Nonlinear Alfvén wave processes, MHD turbulence (Carter, Howes, Skiff, Kletzing, Dorfman, Boldyrev…)
- Drift-wave turbulence and transport, interaction with shear flow (Carter, Schaffner, Maggs, Morales, Van Compernolle, Horton…)
- Physics of fast waves/ion-cyclotron resonance heating (Perkins, Hosea, Martin, Caughmann, Van Compernolle, Carter, Gekelman, …)

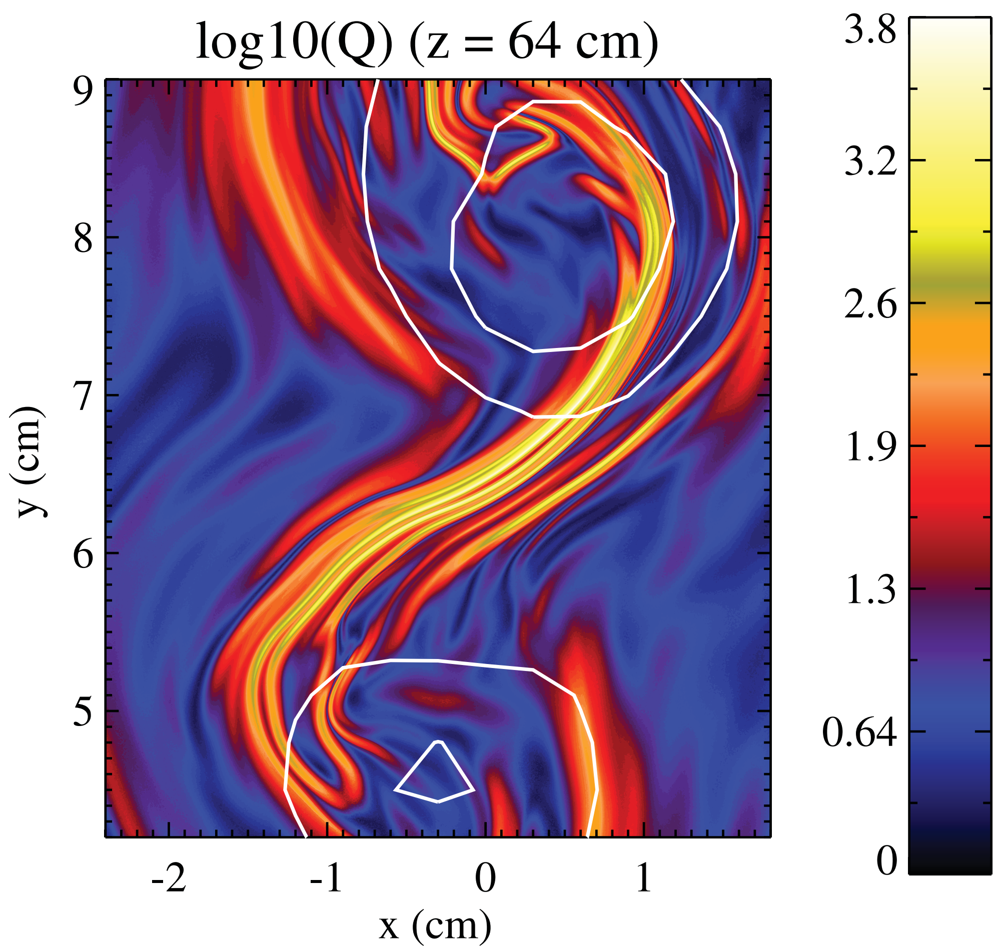
Three-dimensional reconnection: interaction of flux ropes

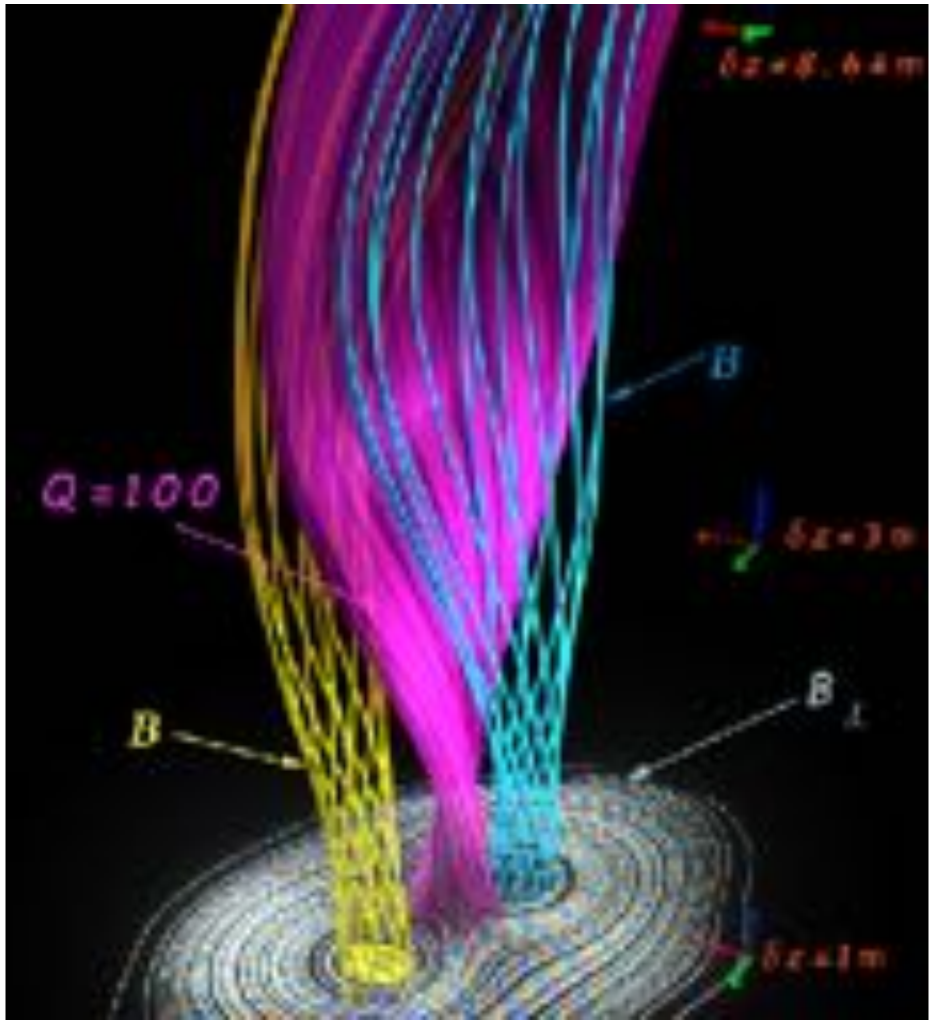




- Use additional cathodes to drive field-aligned currents (flux ropes)
- Flux ropes are kink-unstable, interact and merge (downstream from line-tied condition at cathode)

Three-dimensional reconnection in flux ropes

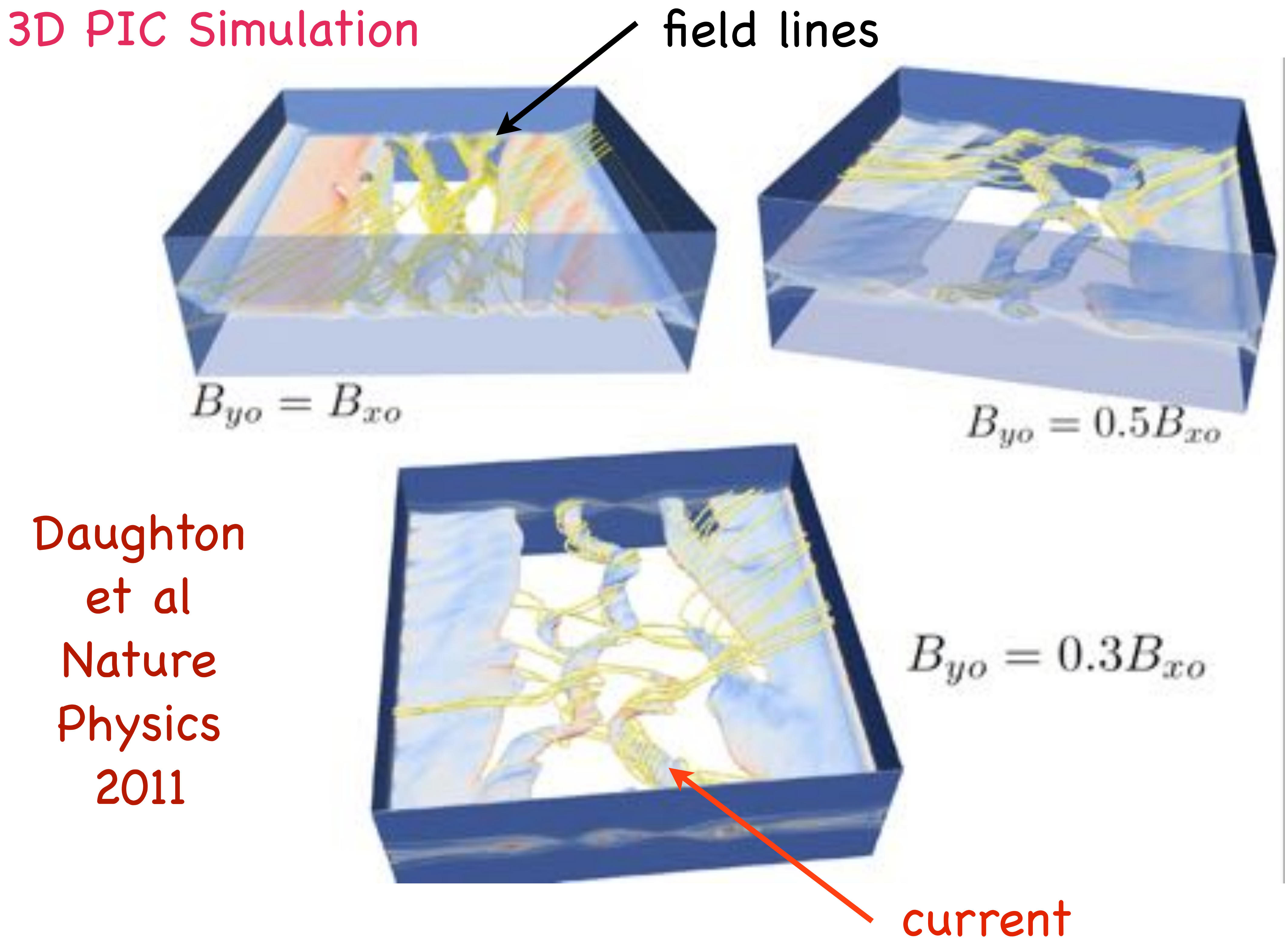




- Squashing-factor (Q) computed from 3D dataset, Quasi-separatrix layer (QSL) identified between ropes
- First time presence of QSL quantitatively linked to the reconnection rate

Lawrence, et al., PRL 103, 105002 (2009)
Gekelman, et al., PRL 116, 235101 (2016)

Flux rope interaction relevant to merging of Plasmoids?



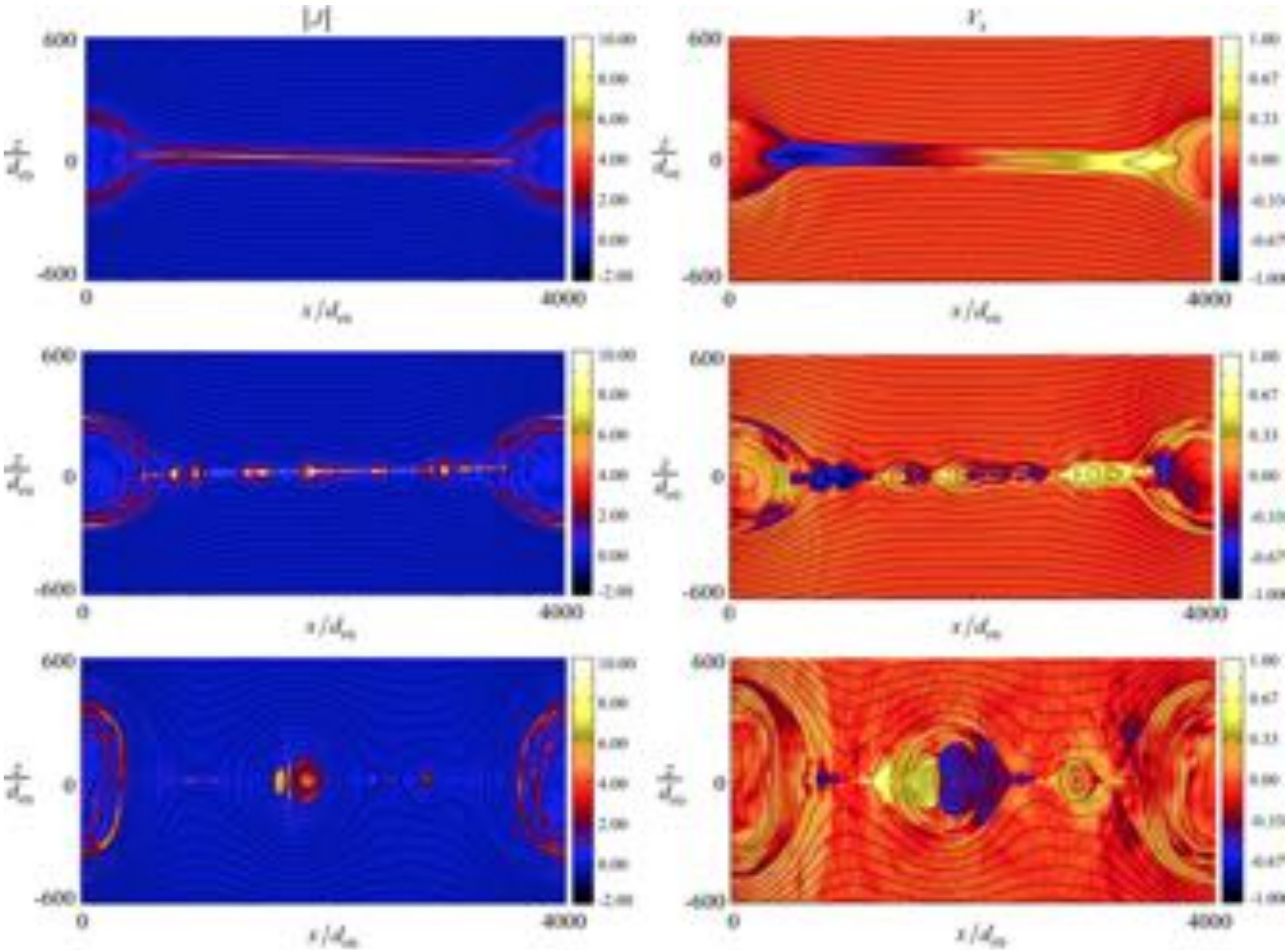
Daughton et al Nature Physics 2011

Plasmoid Instability: Route to fast reconnection in large systems

- Early 2000's: Two-fluid/Hall/Kinetic reconnection was thought to be the solution for fast reconnection in many settings
  - Consistent with observations in space and in the laboratory
- However, some systems, especially in astrophysical settings, system size was just too large to imagine current sheets on the ~d_i scale (e.g. solar corona)
- Nuno & friends to the rescue: revisited tearing mode theory to show that for sufficiently high S (and sufficiently large scale), current sheets undergo tearing/plasmoid instability

Loureiro et al., PoP 14, 100703 (2007)
Uzdensky, et al., PRL 105, 235002 (2010)
etc.

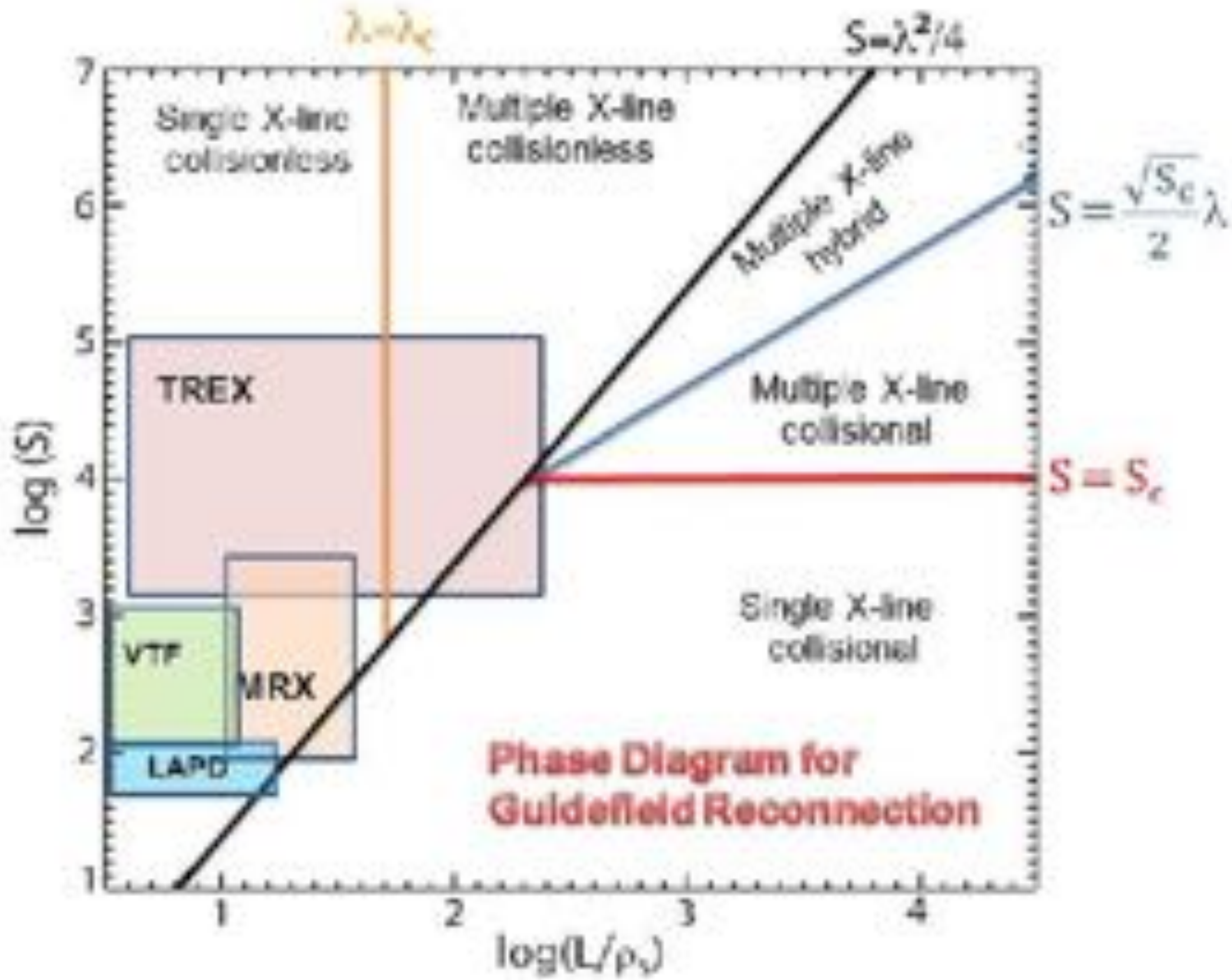
Plasmoid Instability: Route to fast reconnection in large systems



Plasmoid Instability: Route to fast reconnection in large systems

- Early 2000's: Two-fluid/Hall/Kinetic reconnection was thought to be the solution for fast reconnection in many settings
  - Consistent with observations in space and in the laboratory
- However, some systems, especially in astrophysical settings, system size was just too large to imagine current sheets on the ~d_i scale (e.g. solar corona)
- Nuno & friends to the rescue: revisited tearing mode theory to show that for sufficiently high S (and sufficiently large scale), current sheets undergo tearing/plasmoid instability
- Growth of plasmoids generates multiple reconnection sites and smaller length scales — e.g. MHD current sheet can break up into plasmoids that can create current sheets (possibly on kinetic scales)
  - Reconnection rate becomes independent of S (even in MHD)

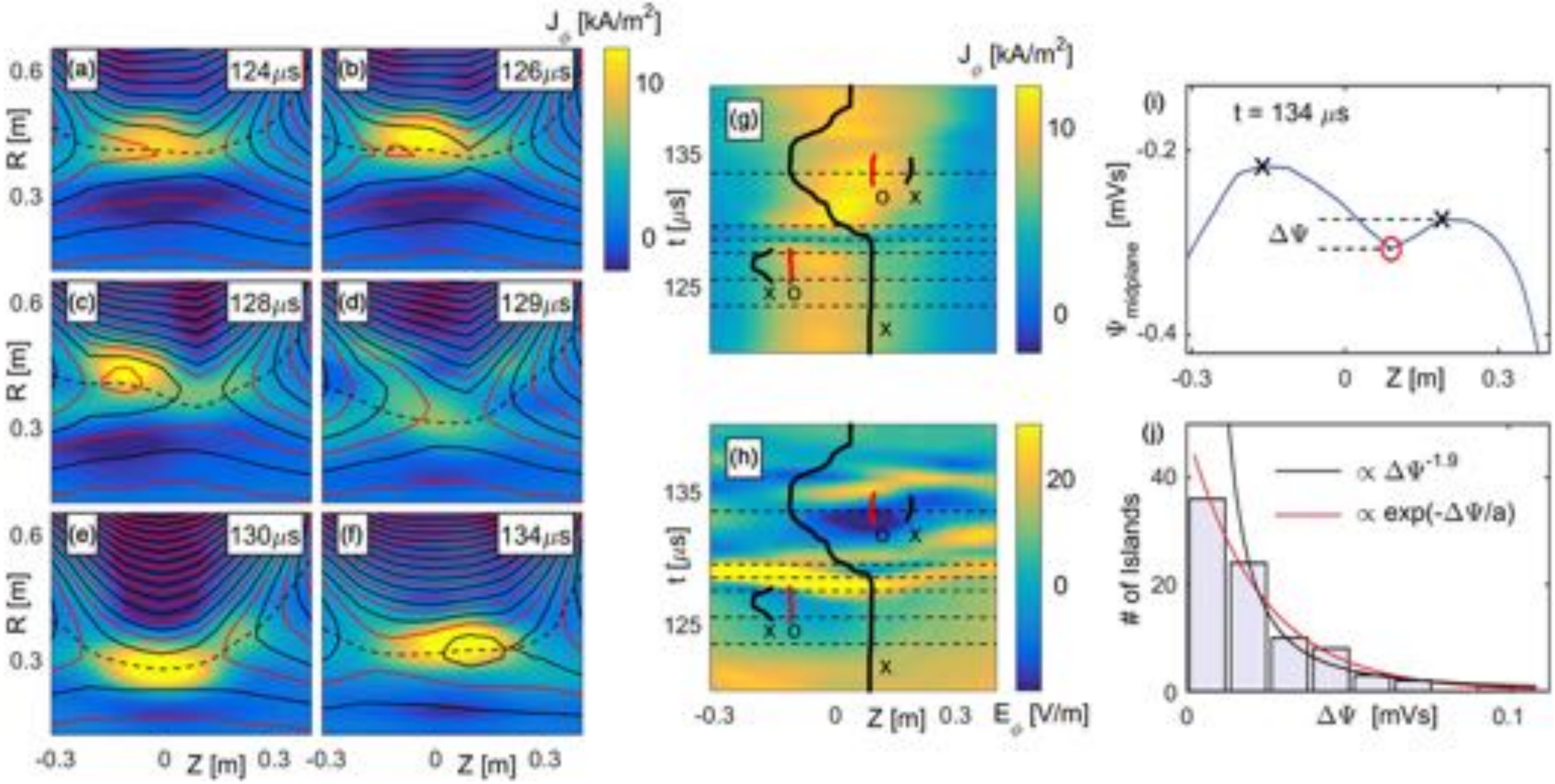
MHD/Reduced MHD: Plasmoid regime requires large size/large S



Egedal (TREX website)
Ji, et al. Physics of Plasmas **18**, 111207 (2011)

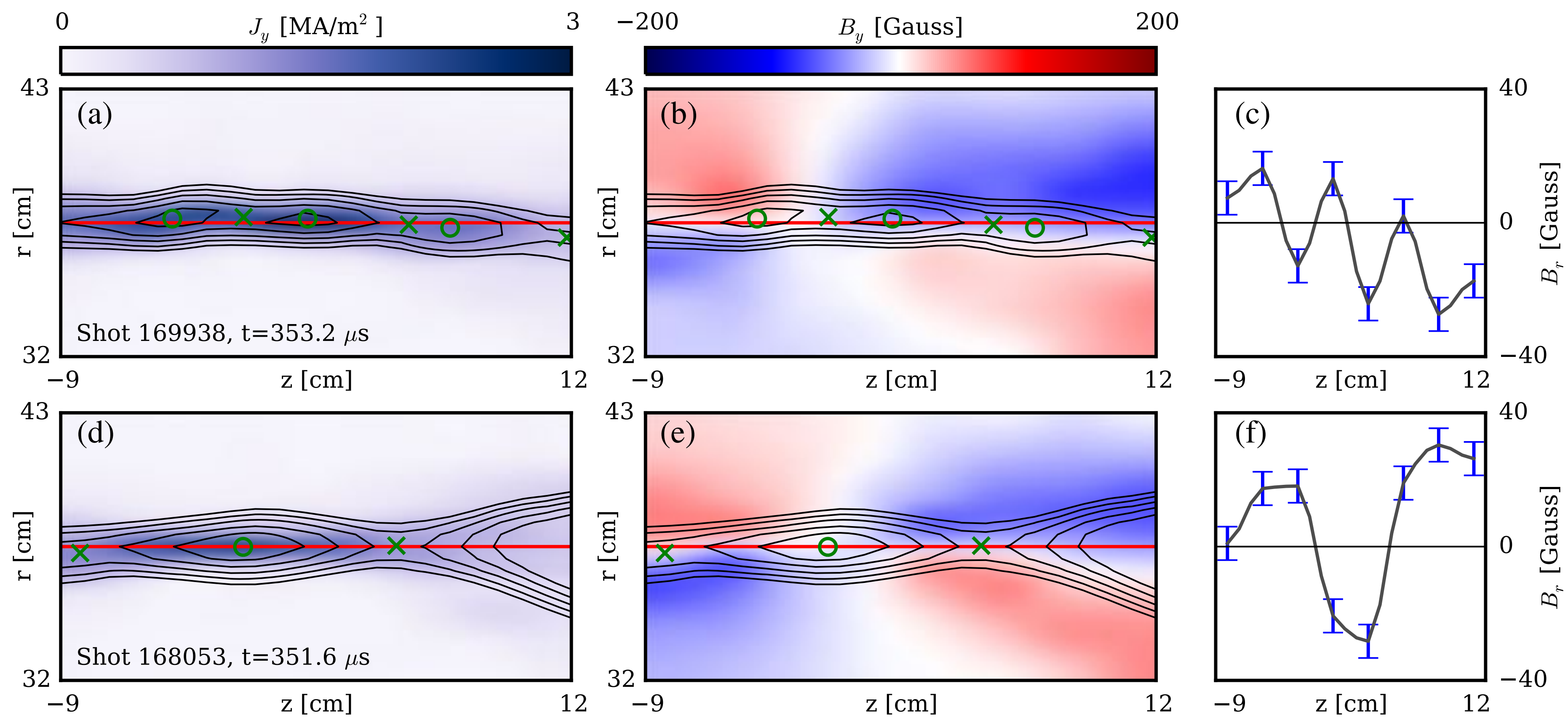
- MHD threshold: $S \sim 10^4$
- Reconnection "phase diagram": argues for large-scale new reconnection experiment (high S, large size)
- However, breaking news (this meeting): Lower threshold in S for experimental conditions (semi-collisional, departures from ideal MHD; using Viriato code)

Evidence for plasmoid generation in TREX



Olson, et al., PRL 116, 255001 (2016)

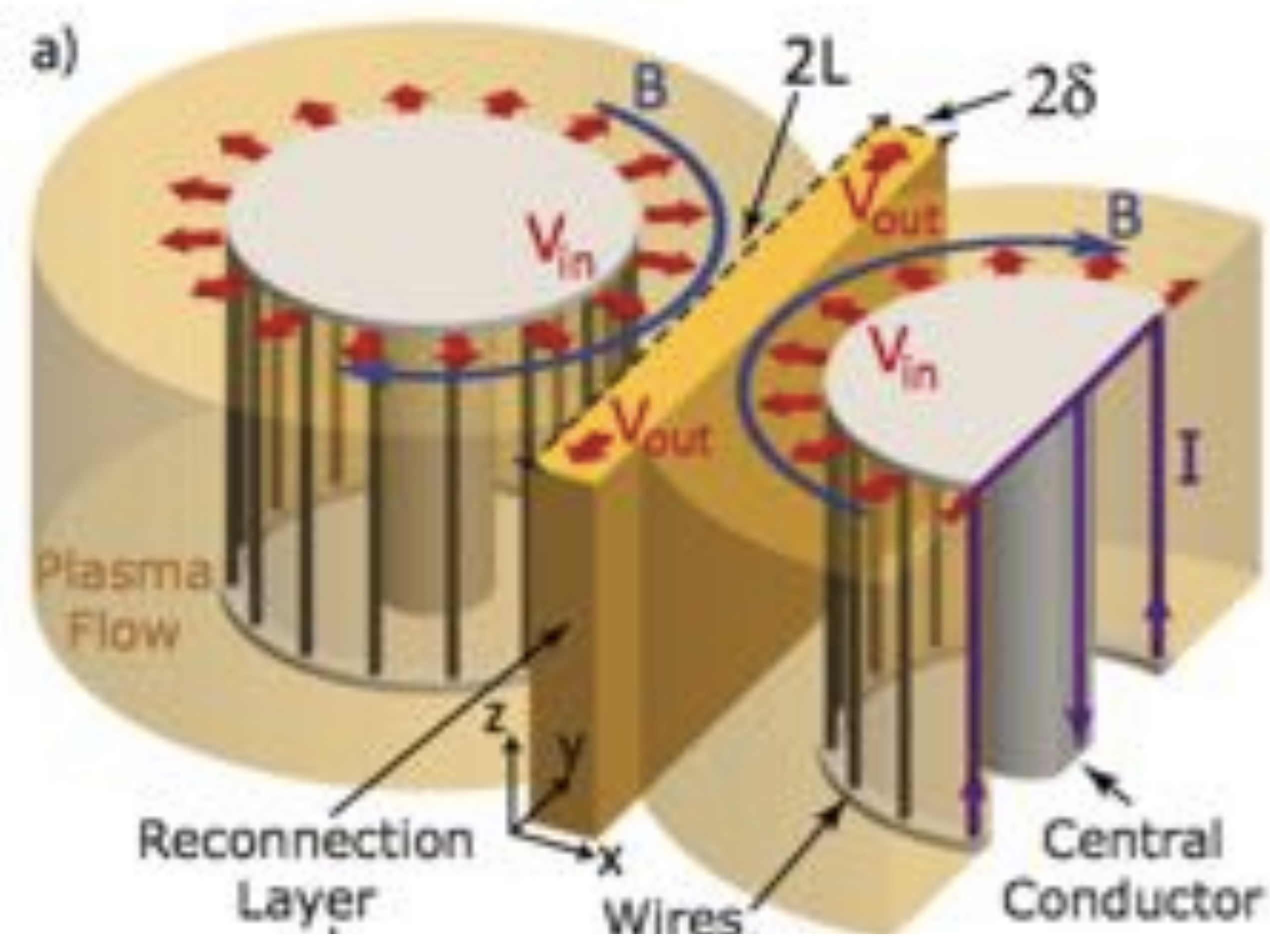
Electron-scale plasmoids in MRX



- In Ar plasmas, surprisingly at very low S (~20), structuring of the current sheet observed, consistent with tearing/plasmoid instability

Jara-Almonte, et al., Phys. Rev. Lett. 117, 095001 (2016)

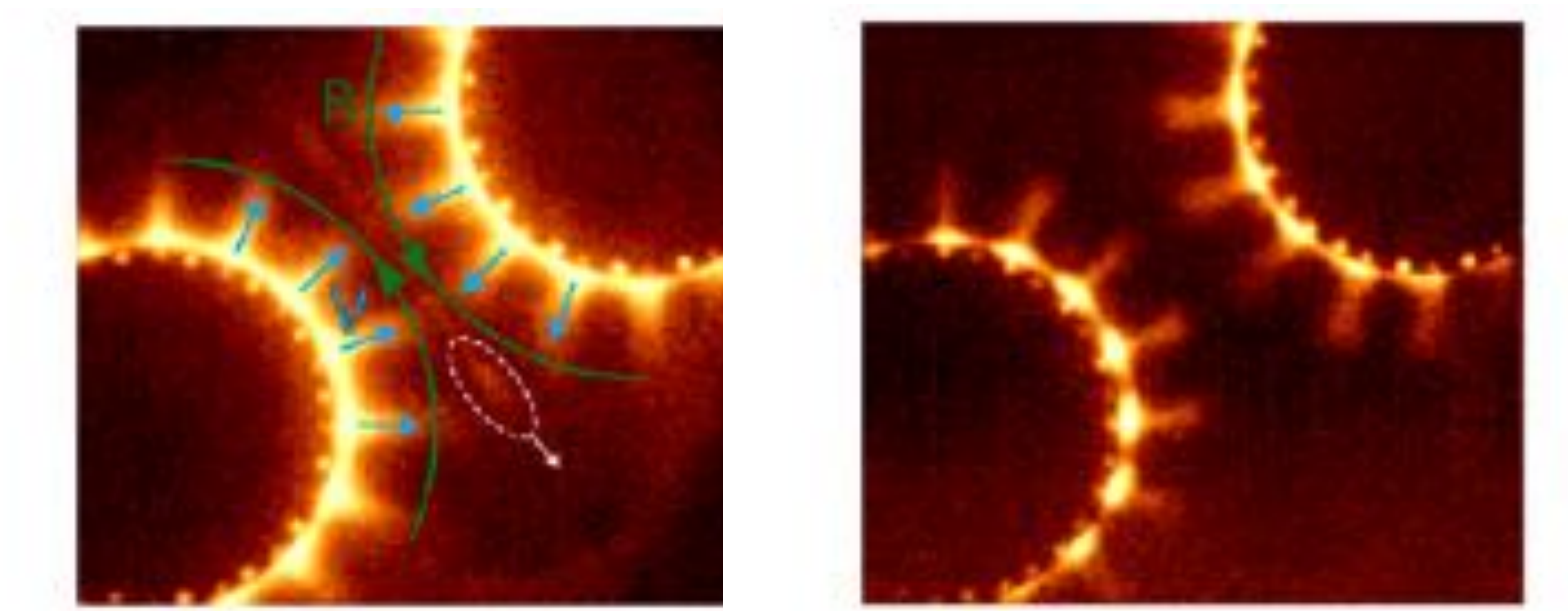
Reconnection in HED plasmas (Z-pinch)



Hare, Lebedev, Suttle, Loureiro et al., Phys. Rev. Lett. 118, 085001 (2017)

- Two wire-array Z-pinches fired off side-by-side, creating current sheet in between

Plasmoid generation in Z-pinch experiments



Hare, Lebedev, Suttle, Loureiro et al., Phys. Rev. Lett. 118, 085001 (2017)

Future directions

- New and upgraded reconnection experiments coming online: TREX, FLARE (MRX Upgrade), etc
- Targeted at accessing collisionless reconnection with large system size. Goals:
  - Demonstrate and characterize Plasmoid instability, investigate impact on reconnection rate
  - Collisionless processes in current sheets: role of pressure anisotropy
  - Can we see particle acceleration (and characterize it) in the lab?