Three-dimensional, impulsive reconnection events in the Magnetic Reconnection Experiment (MRX)

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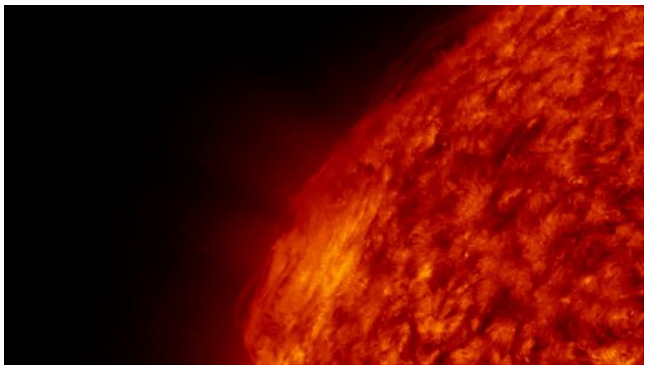
Outline

Long Standing Question: How do we explain the fast, impulsive reconnection rates observed in laboratory and natural environments?

- Introduction and Motivation: Impulsive Reconnection
- Introduction to MRX
- Experimental Investigations of Impulsive Events:
  - Ejection of "Flux Rope" Structures
  - Observed Out-of-Plane Gradients
  - Out-of-Plane Spreading of Fast Reconnection
- Proposed physical picture of 3-D two-fluid effects
- Conclusions

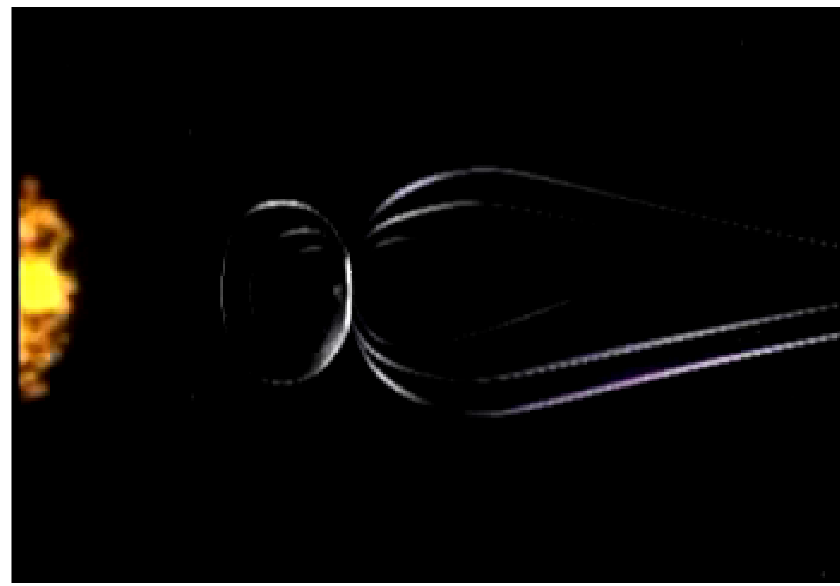
Fast, Impulsive Reconnection Observed in Lab and Space

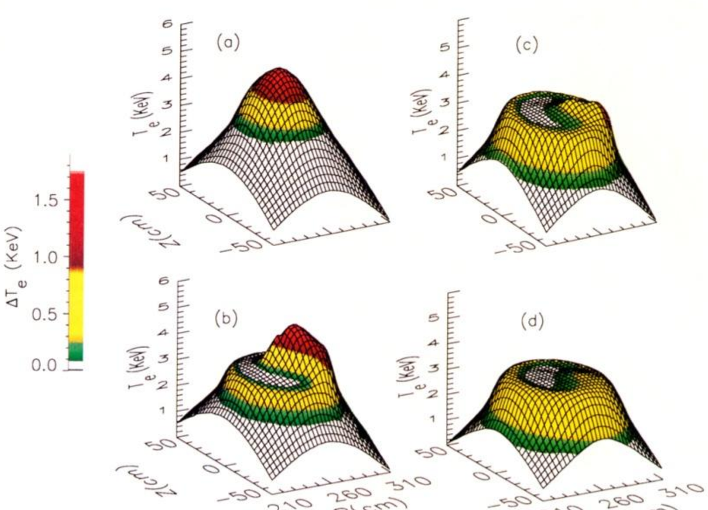
Impulsive: Slow buildup phase followed by a comparatively quick release of magnetic energy



Solar plasma (SDO Data)

Magnetosphere (NASA Animation)



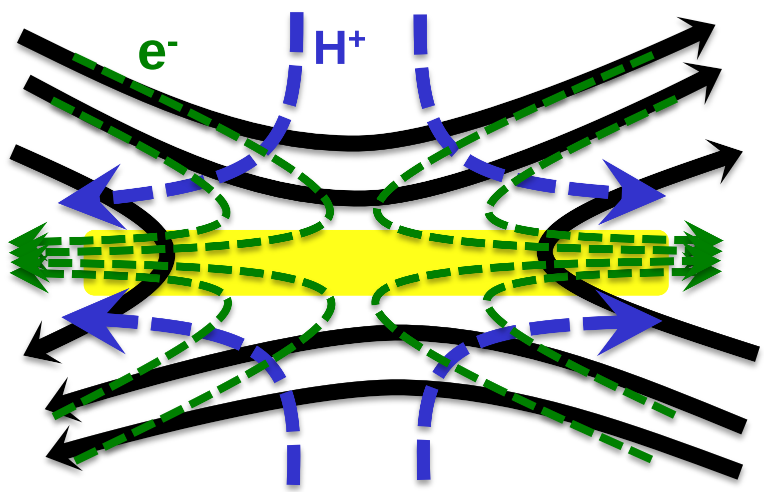


Laboratory Sawtooth Crash (Yamada, et. al., 1994)

Motivation: Is impulsive reconnection in real systems fundamentally 3-D?

Fundamentally 3-D → Variation in all three spatial dimensions necessary to explain observed behavior

2.5-D Models→ No out-of-plane variation ($\partial/\partial y$=0)



2.5-D Hall Effect (Collisonless): Fast but Steady-State

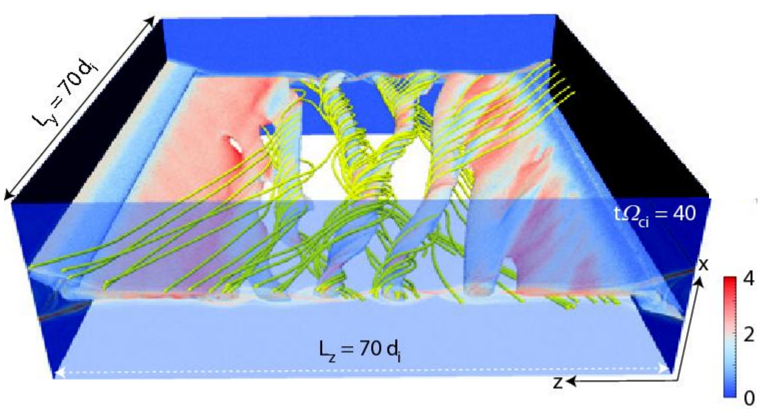
How can impulsive behavior be explained by 2.5-D models?

- Ejection of Magnetic Islands
- Transition between Collisional and Collisionless Reconnection
- Sheer Flow

How can 3-D dynamics change the reconnection process?

Complex Flux Rope Structures

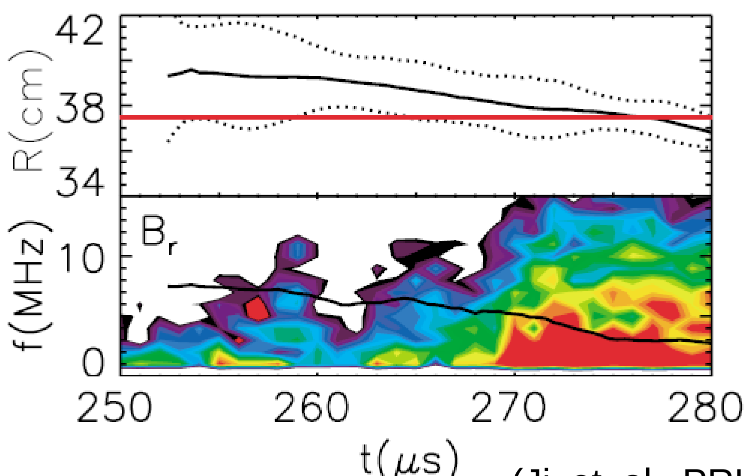
- Islands in 2.5-D are analogous to flux ropes in 3-D



(Daughton, et. al., Nature Physics, 2011)

Waves and Turbulence

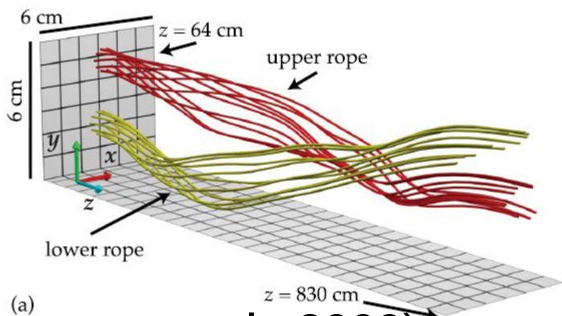
- 3-D variation allows for a large class of waves: Can these waves generate anomalous resistivity that speeds up reconnection?



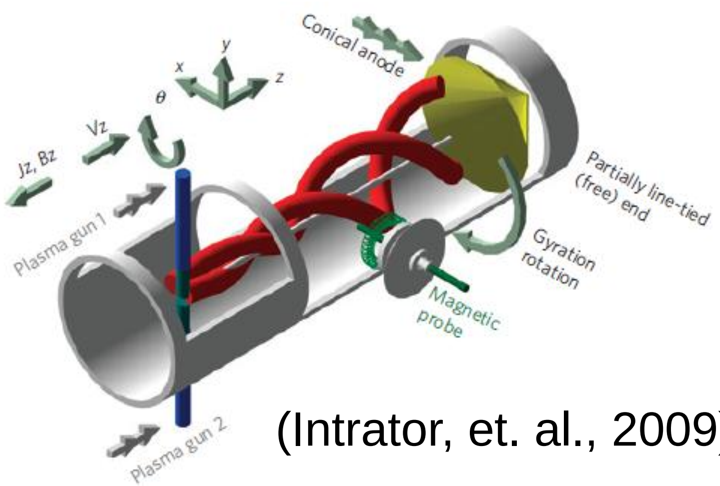
(Ji, et. al., PRL, 2004)

3-D Reconnection Previously Studied in Lab

Externally Generated 3-D Flux Ropes

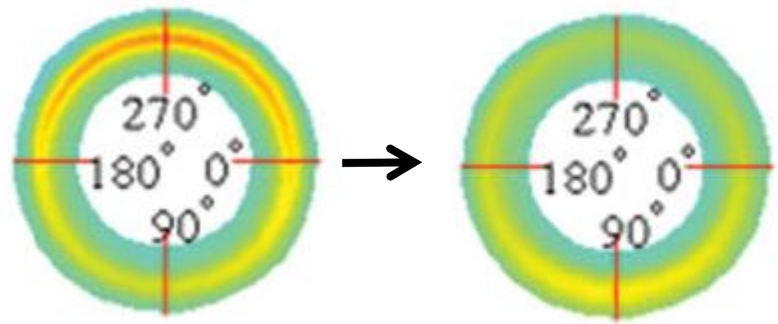


(Lawrence, et. al., 2009)



(Intrator, et. al., 2009)

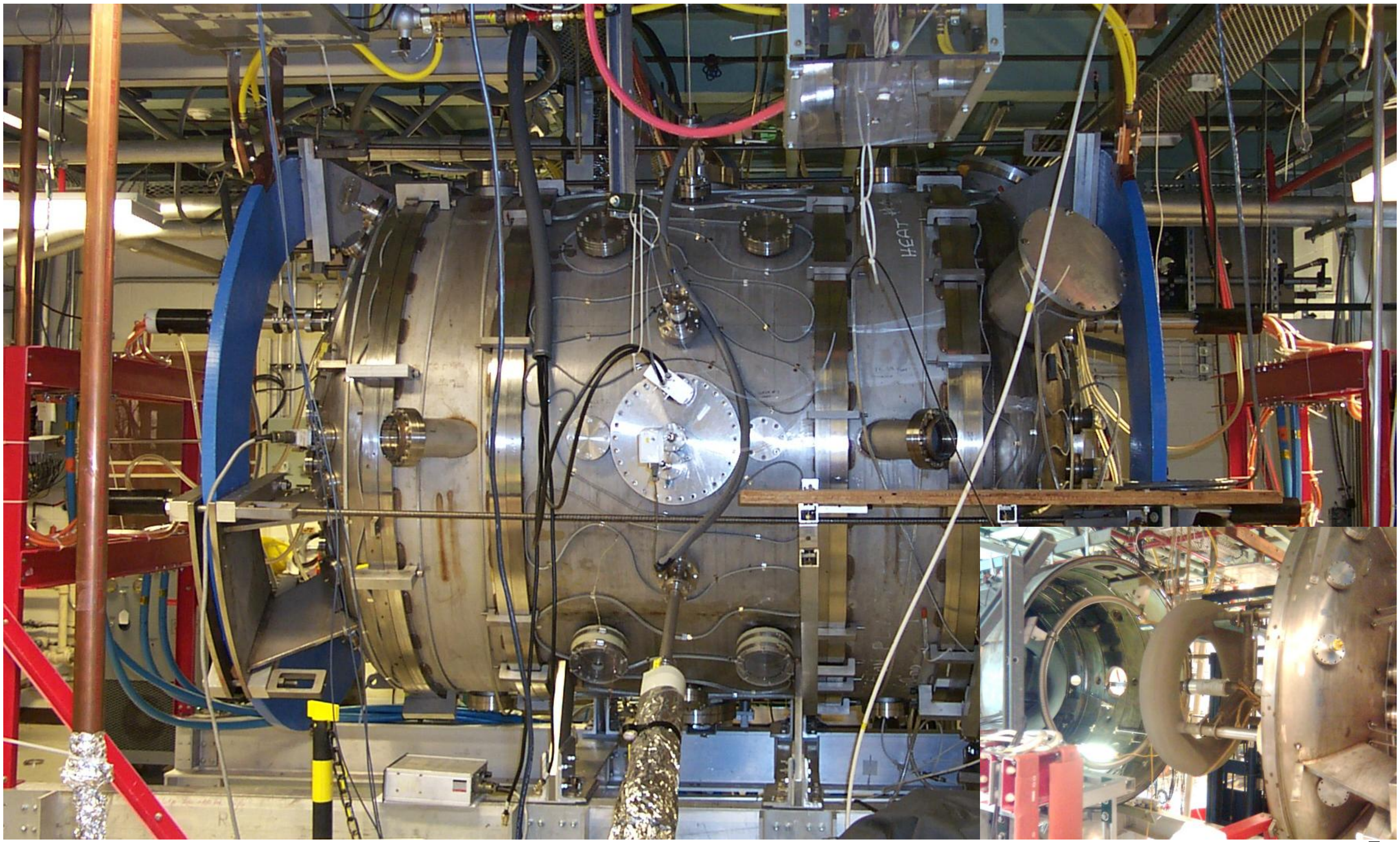
Localized Reconnection Onset due to a Global Toroidal Mode



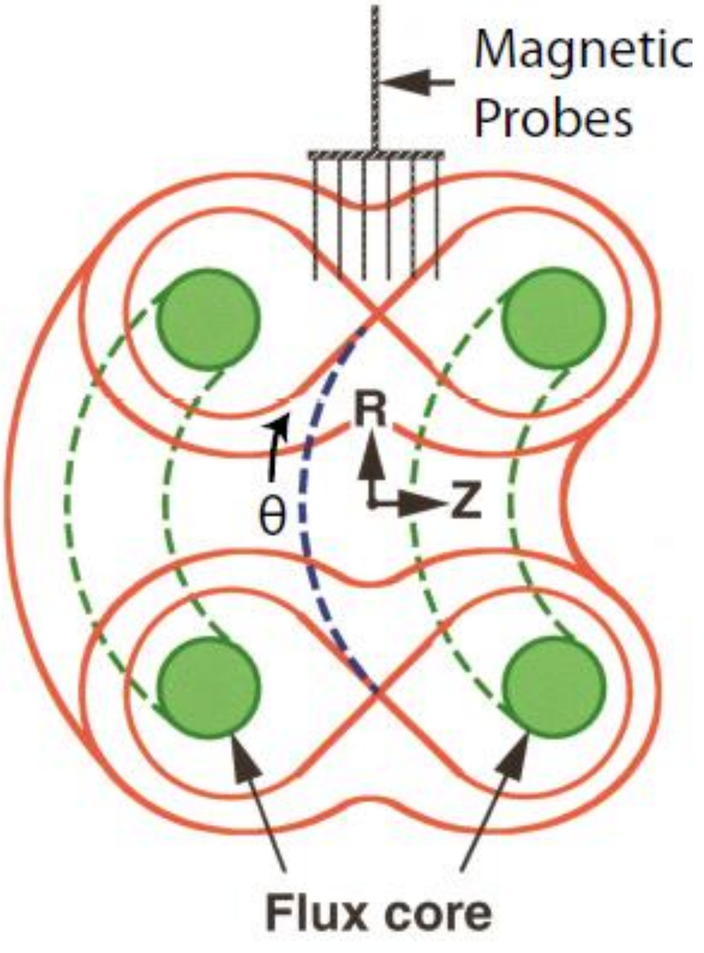
(Katz, et. al., 2010)

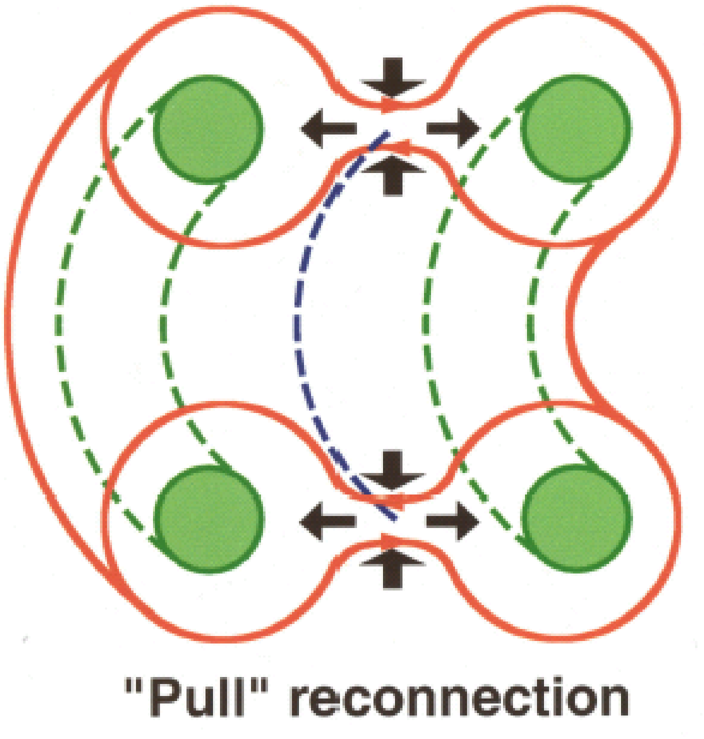
Current Work: Local 3-D Reconnection with spontaneously generated "flux ropes"

The Magnetic Reconnection Experiment (MRX)

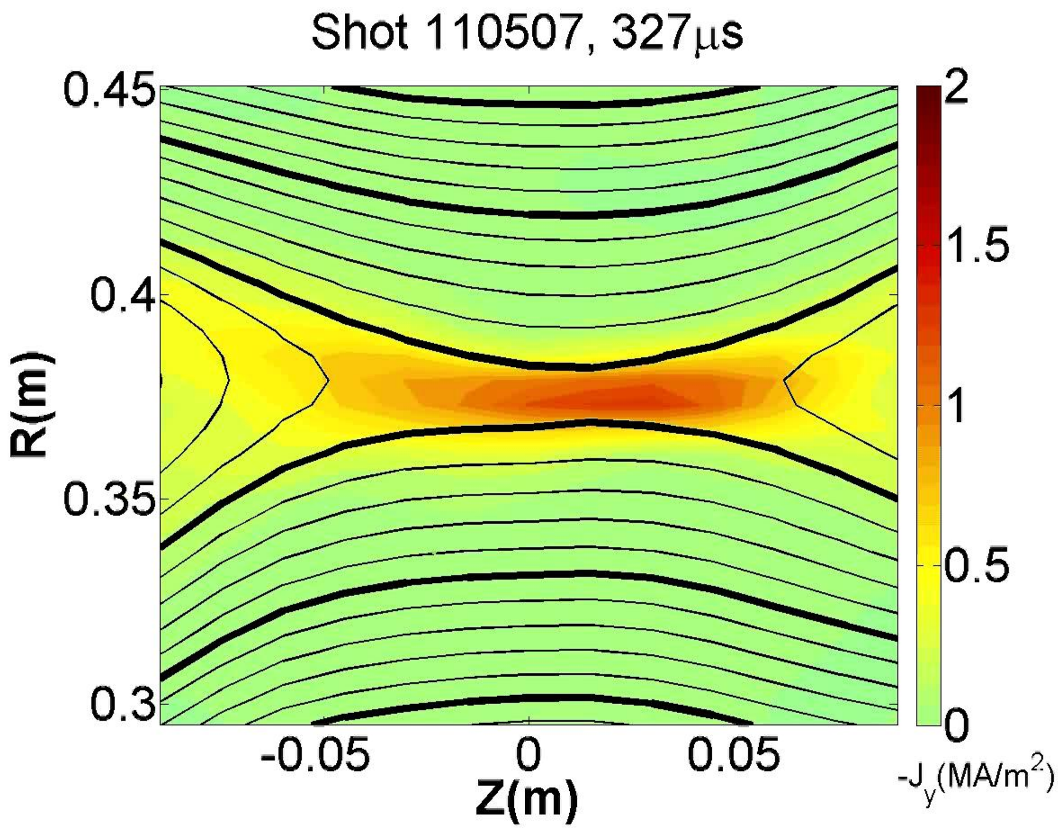


Experimental Setup in MRX





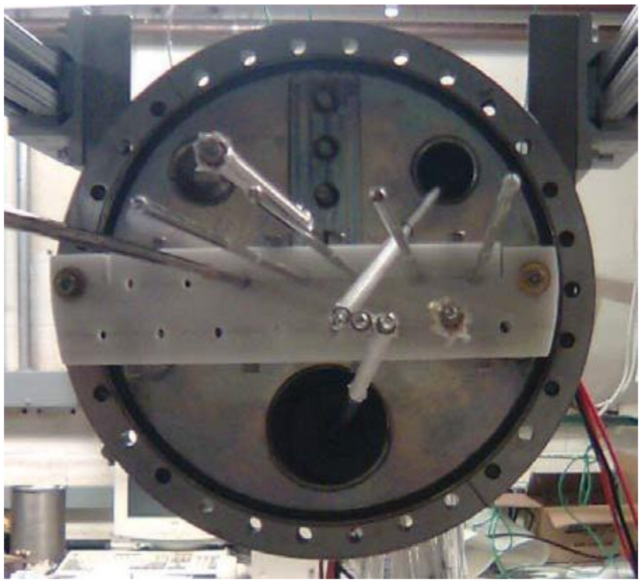
Details of reconnection layer resolved in MRX



Typical Parameters:

- Gas: H_2, D_2
- No applied guide field
- Density: 0.5-15 x $10^{13}/cm^3$
- Electron Temperature: 4-12eV
- Reconnecting Field: 150-300G
- Collisionless at the time of the impulsive behavior to be discussed

Magnetic and Electrostatic Diagnostics used to probe the details of the electron layer

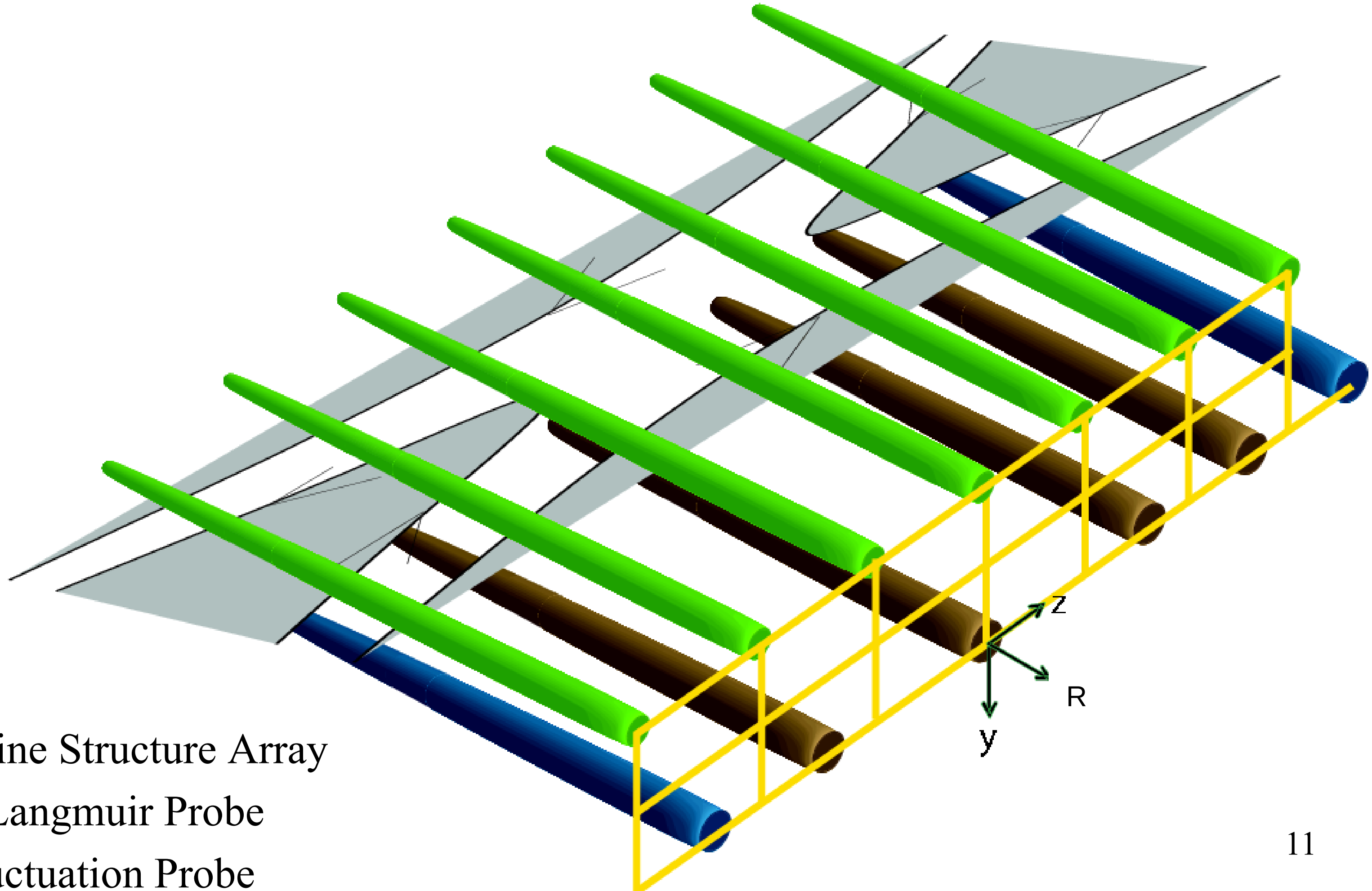


Diagnostics:
- Fine Structure Probes (Magnetic Field)
- Magnetic Fluctuation Probes
- Langmuir Probes (Density and Temperature)

Coils/Probe	50
Components	B_Z, B_y
Max Resolution	3.75mm
Coverage Area	19.25cm

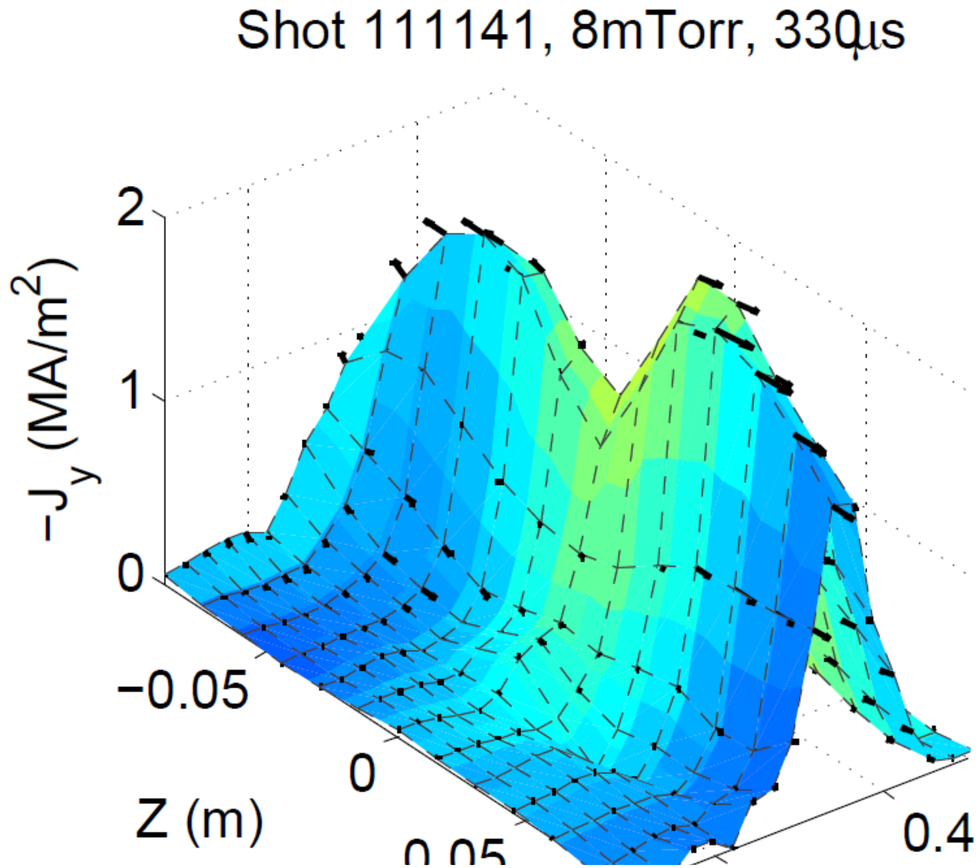
Probe Location in the Current Sheet

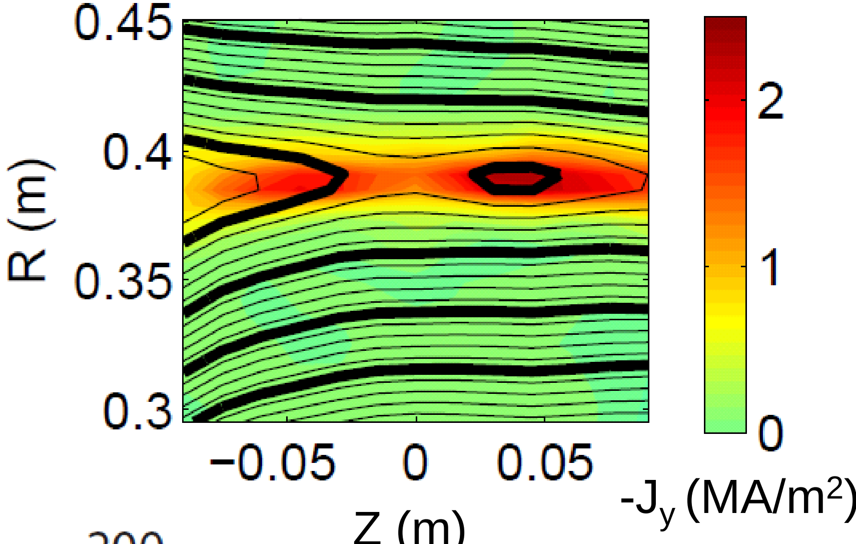
In plane measurements

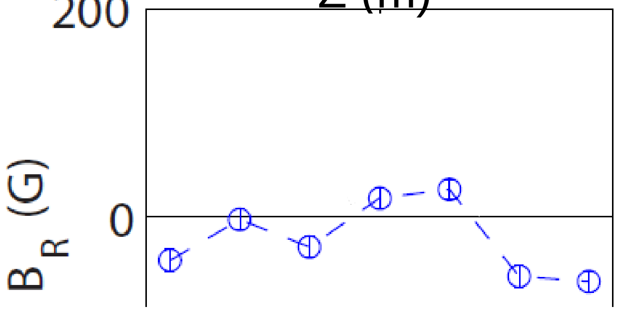


- Green = Fine Structure Array
- Brown = Langmuir Probe
- Blue = Fluctuation Probe

Current Layer with "Flux Ropes" Resolved by Magnetic Probes

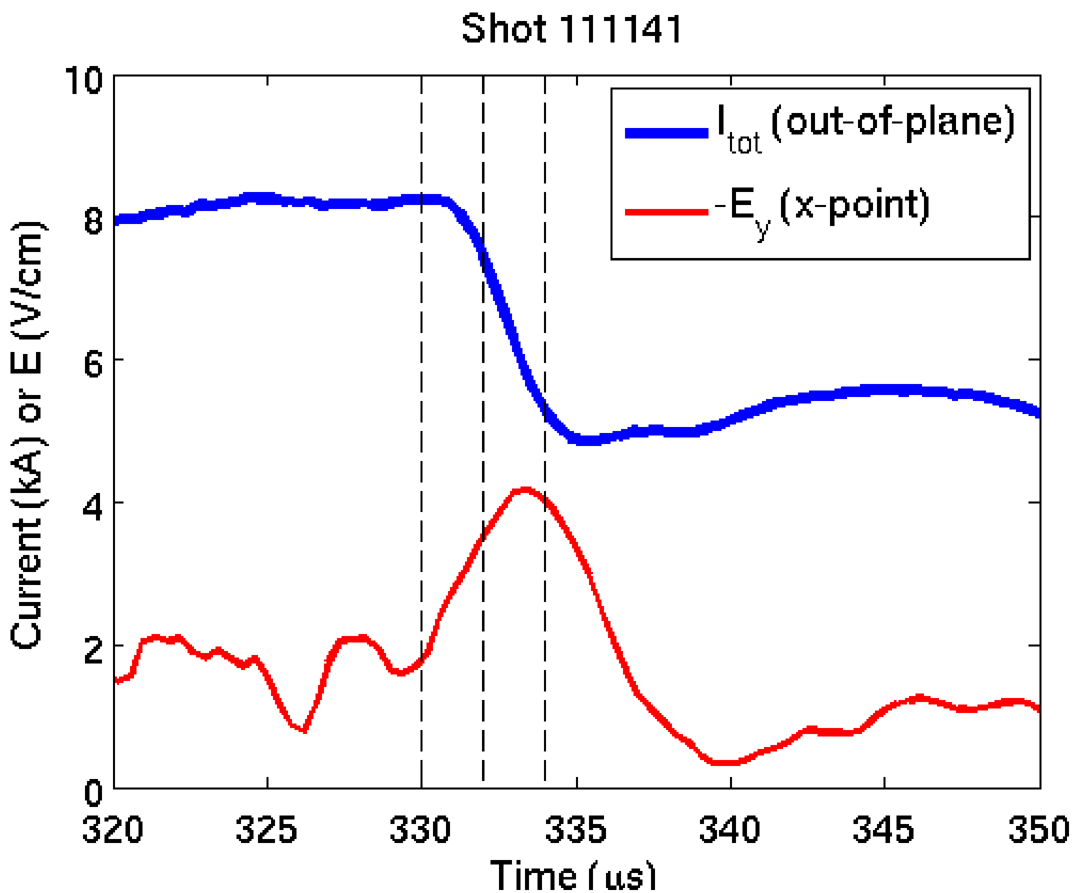






"Flux Ropes:" 3-D High Current Density Regions associated with an O point

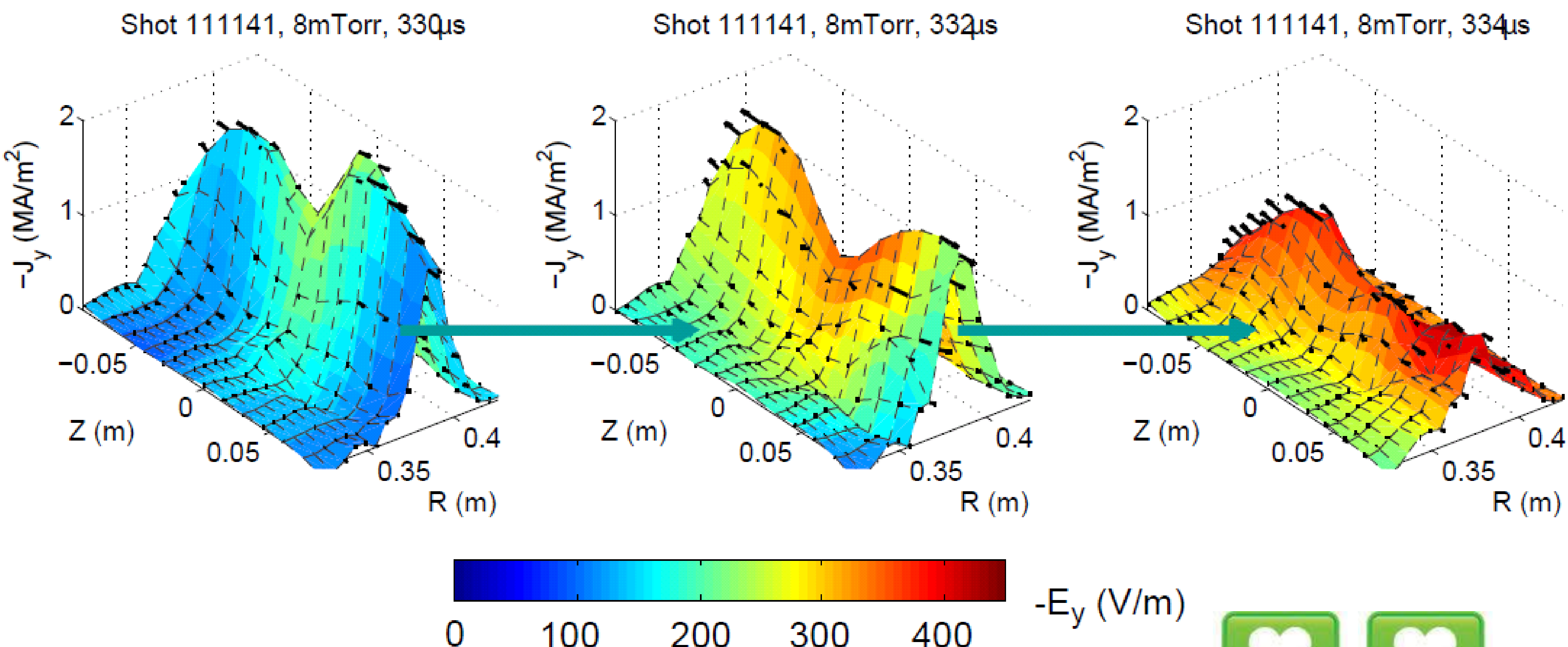
Current Layer Disrupts over a short time period



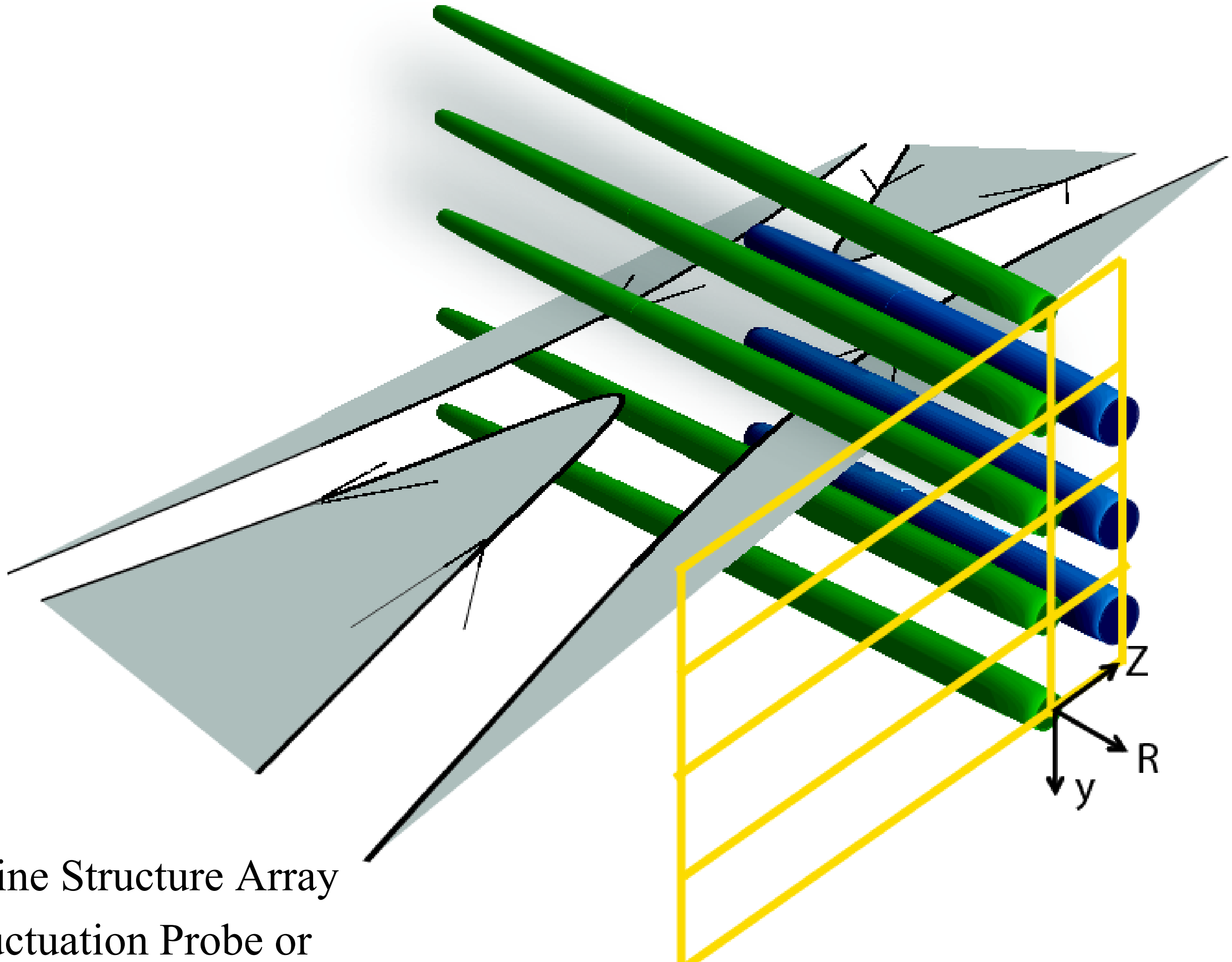
(Dorfman, et. al., Submitted to PRL)

"Disruption:" Impulsive reconnection event in which J_y drops and E_y peaks

“Flux Ropes” Ejected in Current Layer Disruption

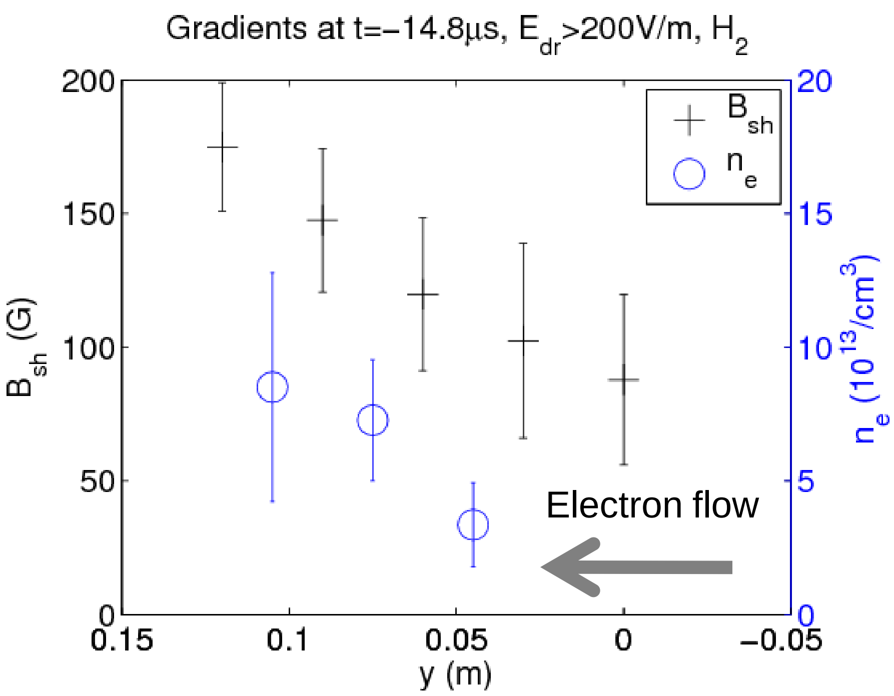


Probe setup to examine structure in the current direction

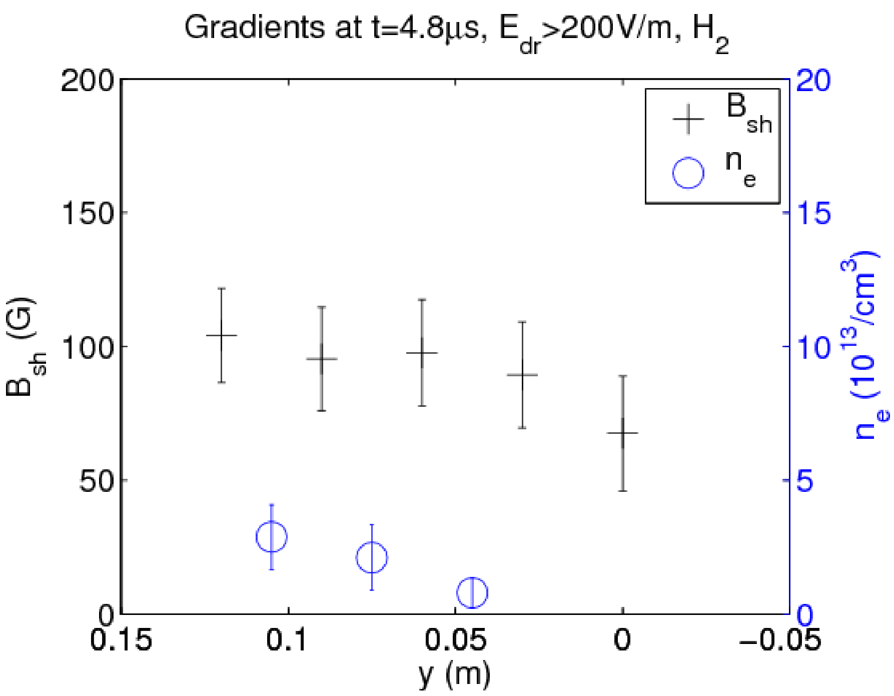


- Green = Fine Structure Array
- Blue = Fluctuation Probe or Langmuir Probe

Disruptions Occur in Discharges with Strong Out-of-Plane Gradients



Before

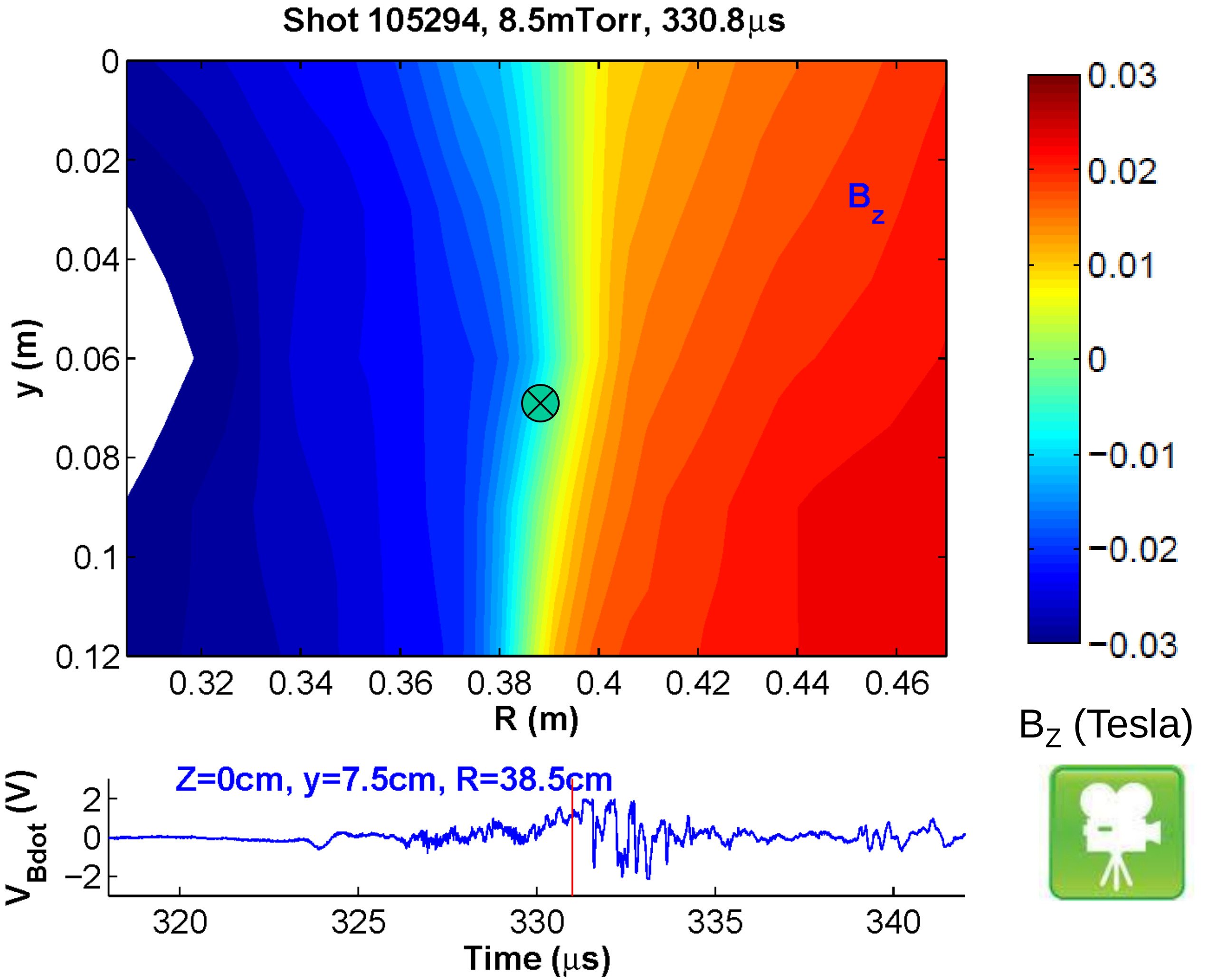


After

(Dorfman, et. al., Submitted to PRL)

Layer narrows, then suddenly disrupts in the electron flow direction!

electron flow



(Dorfman, et. al., Submitted to PRL)

During disruptions, reconnection takes place in a truly 3-D way!

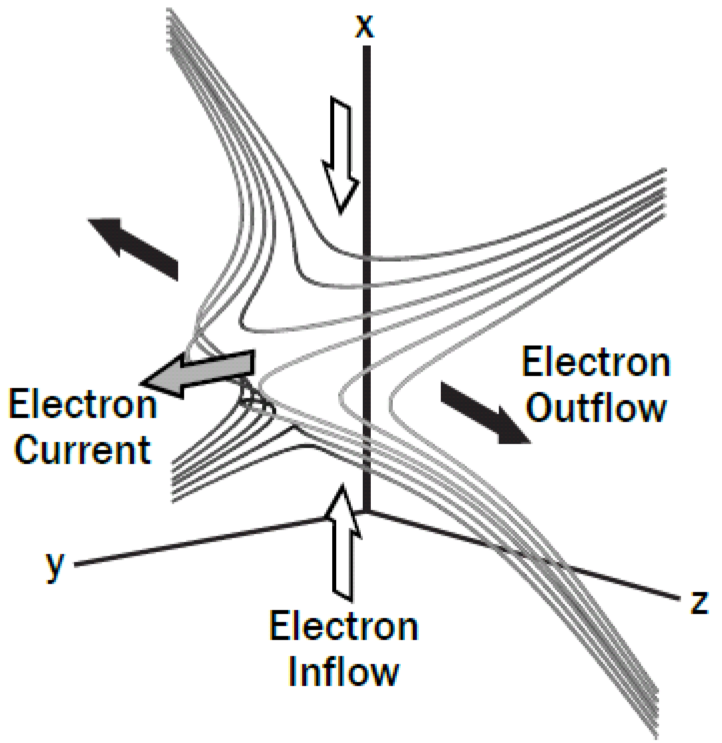
Furthermore, several observed features cannot be explained by an anomalous resistivity model.

Observed in MRX	Present in 2.5-D?	Anomalous Resistivity Model Prediction
"Flux Rope" Ejection	2.5-D island ejection	No
Out-of-Plane Gradients	No	No
Spread of Fast Reconnection in the electron flow direction	No	Yes
Magnetic Fluctuations	No	Yes

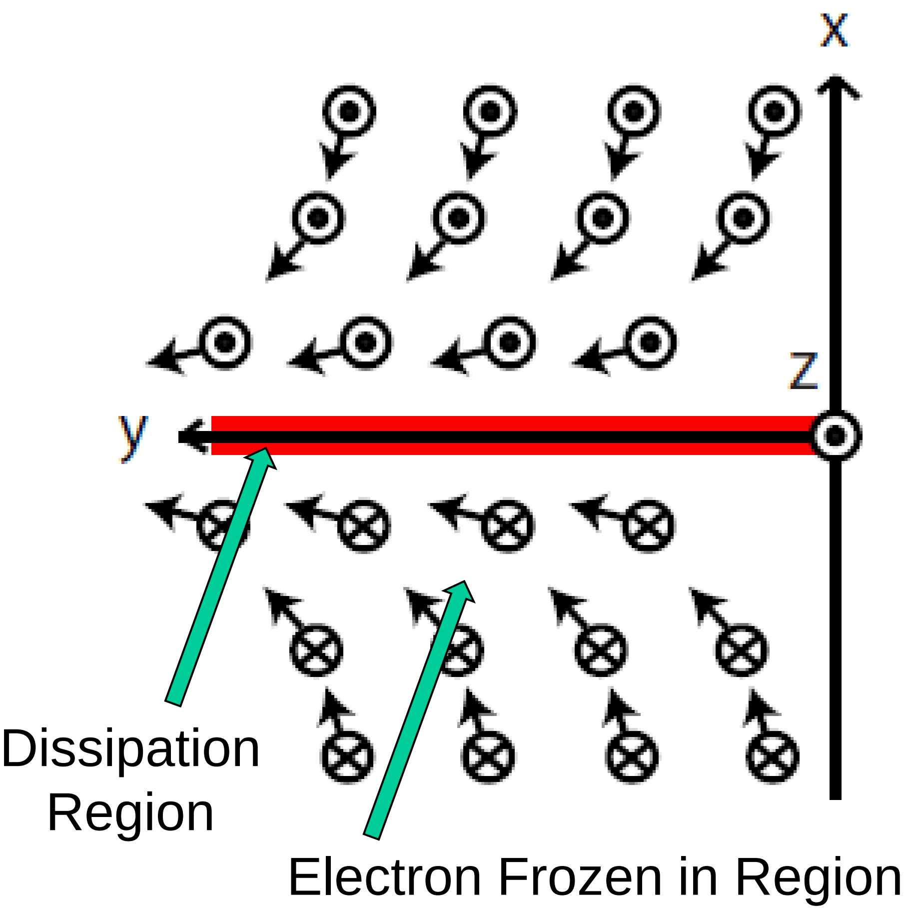
How does 3-D variation lead to disruptions?

To understand 3-D, let's first review the 2.5-D Hall Effect

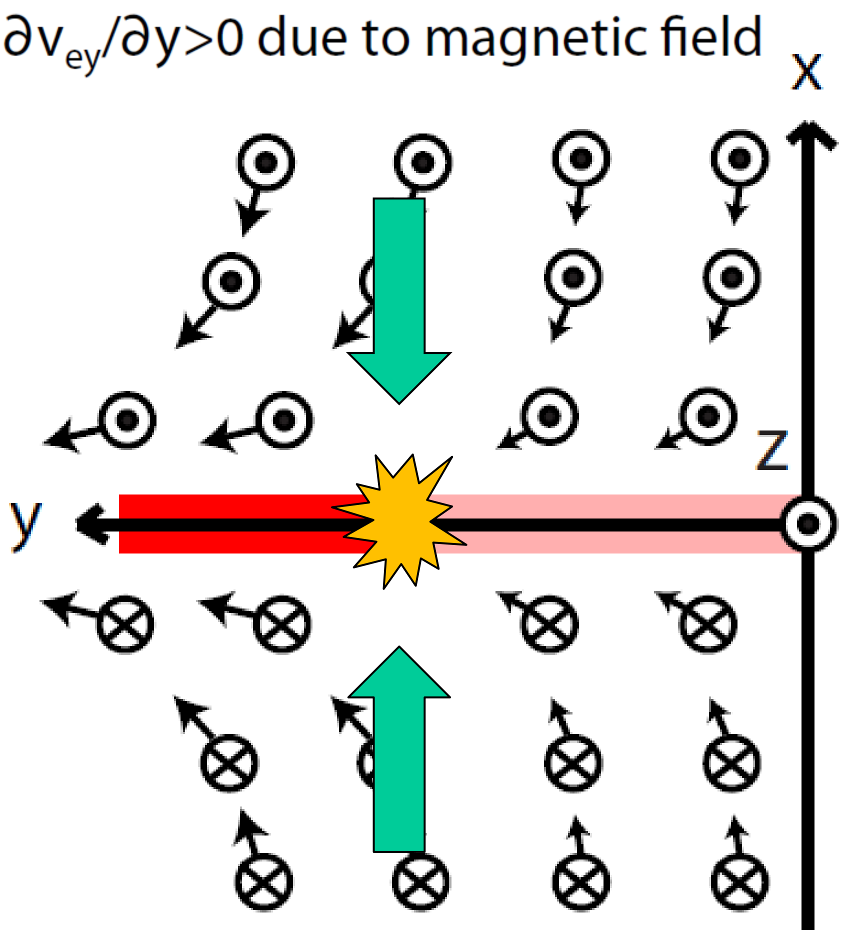
In the electron frozen in region, electrons and magnetic field move together!
Slower ions control the plasma density.



(Schematic from Yamada PoP 2011)



Proposed Physical Picture: 3-D Two-Fluid Effects



1) $\partial v_{ey}/\partial y > 0$ in inflow region along the y gradient.
2) Electron flow continuity demands increased v_{ex}.
3) Dissipation region adjusts / current layer disrupts.
4) V_{ey} gradient spreads in the +y (electron) direction.

(Related to Rudakov, et. al. 2002, Huba, et. al., 2002, Huba et. al., 2003, Lapenta et. al., 2006)

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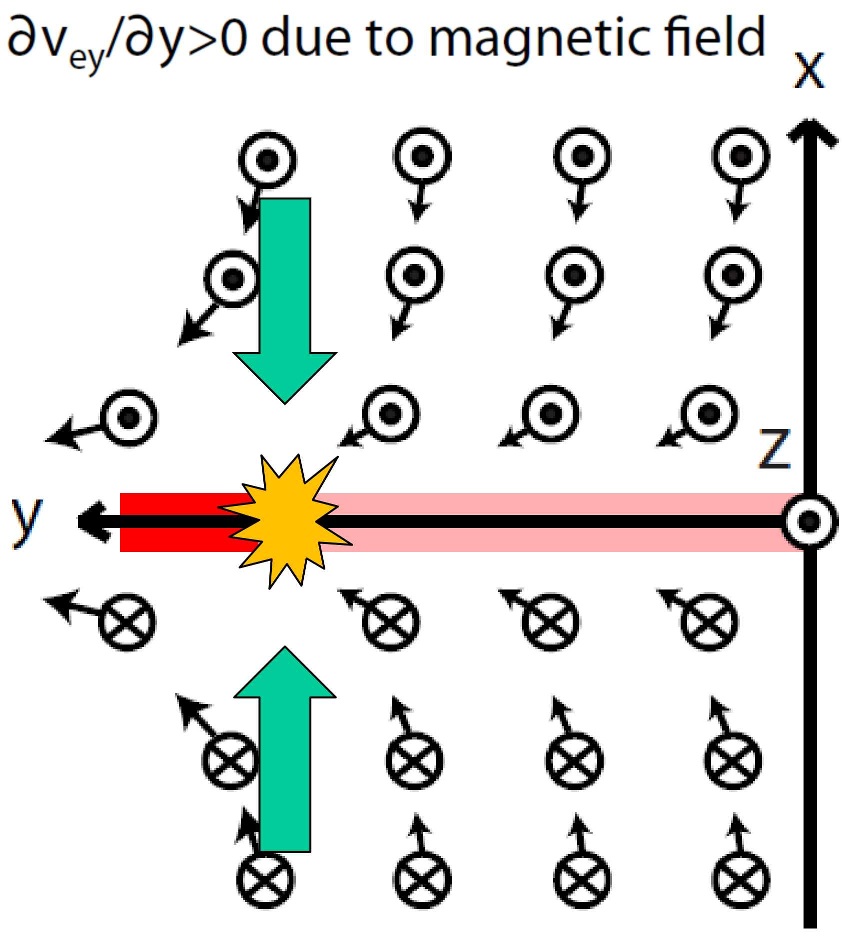

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Main Conclusions

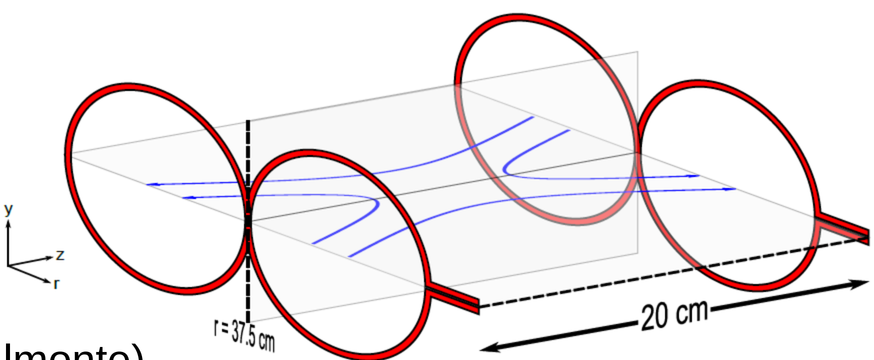
1) Observed disruptions are fundamentally three-dimensional.
2) Signatures of flux ropes identified. “Flux Ropes” play a key role in the observed disruptions.
3) Magnetic Fluctuations are not the key to impulsive reconnection.

Main Conclusions

1) Current layer disruptions are observed in MRX as a fast, impulsive, and **fundamentally three-dimensional** example of magnetic reconnection.
2) Several signatures of flux ropes are identified in the reconnecting current layer. The observed disruptions are due to the buildup and ejection of these 3-D high current density regions associated with O-points at the measurement location.
3) By contrast, magnetic fluctuations, long considered as a possible cause of anomalous resistivity, are not the key physics responsible for the observed impulsive phenomena.

Abundant Opportunities for Future Work

- 3-D Probe configuration
- Flux Ropes and small scale structure
- Origin of Out-of-plane gradients
- 3-D Simulations of Disruptions
- Generation of Disruptions via Localized Perturbations



(J. Xie and J. Almonte)