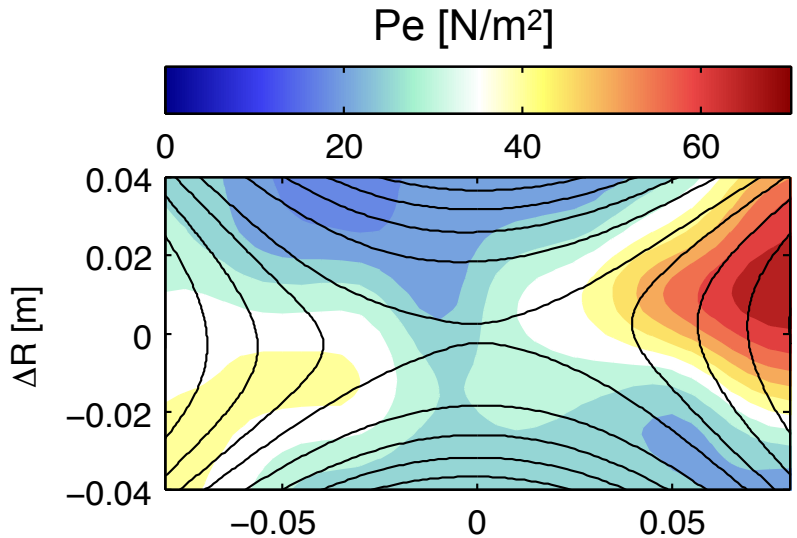
Experimental verification of the role of electron pressure in fast magnetic reconnection with a guide field



W. Fox

PPPL, with support from Max-Planck-Princeton Center for Plasma Physics

Special thanks to collaborators:

F. Sciortino - Imperial College, UK; presently at MIT

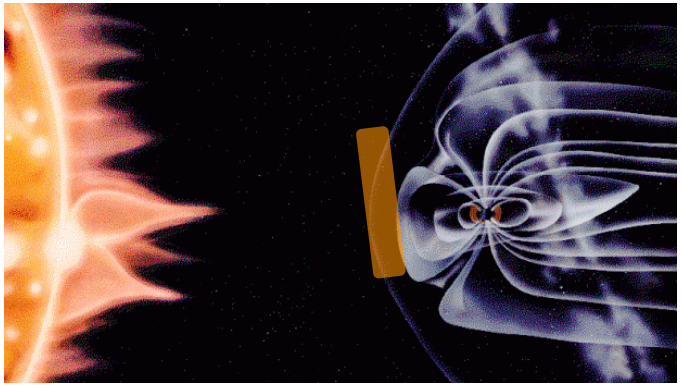
A. von Stechow - IPP Greifwald, MPPC

MRX (soon to be FLARE): **J. Yoo, J. Jara-Almonte, M.Yamada, H. Ji** - PPPL / Princeton

MMS: R. Ergun, S. Ericksson, F. Wilder; T. Phan, M. Oieroset

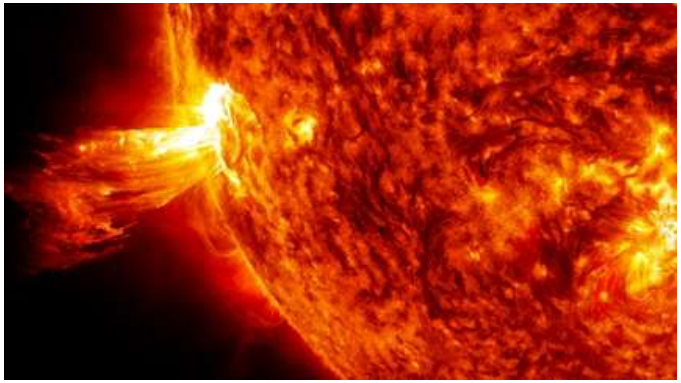
APS DPP 2017

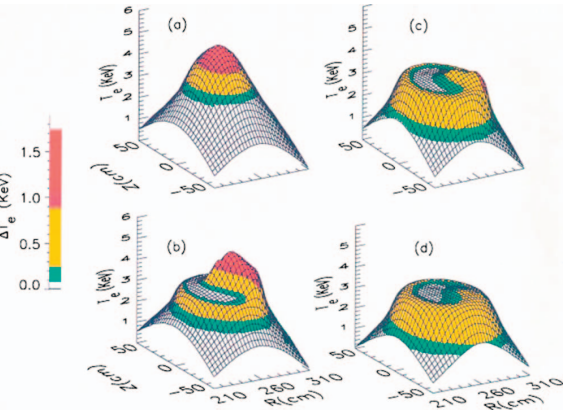
Magnetic reconnection allows rapid change in topology and explosive magnetic energy release; understanding fast *rate* of reconnection a challenge



solar-wind magnetosphere interaction:
- energy coupling, storage, rapid release
- multi-$BB technology at risk to adverse "space weather"

Solar physics:
- largest solar flare energize particles to > 1 MeV
- do "nano-flares" heat the solar corona and drive solar wind?

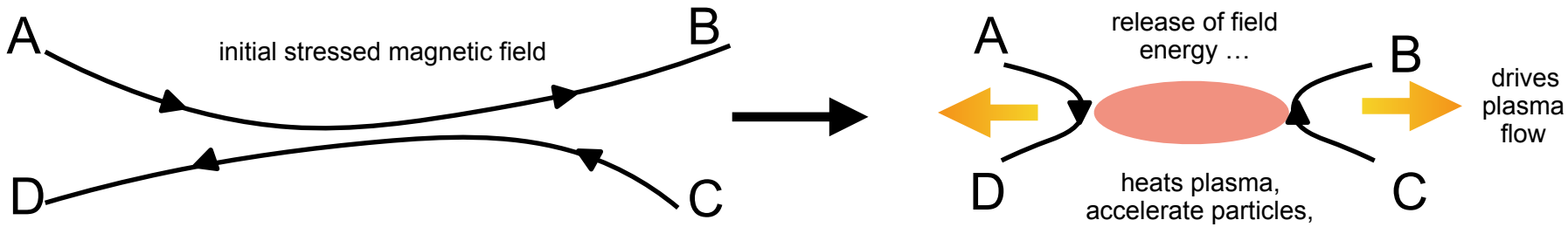




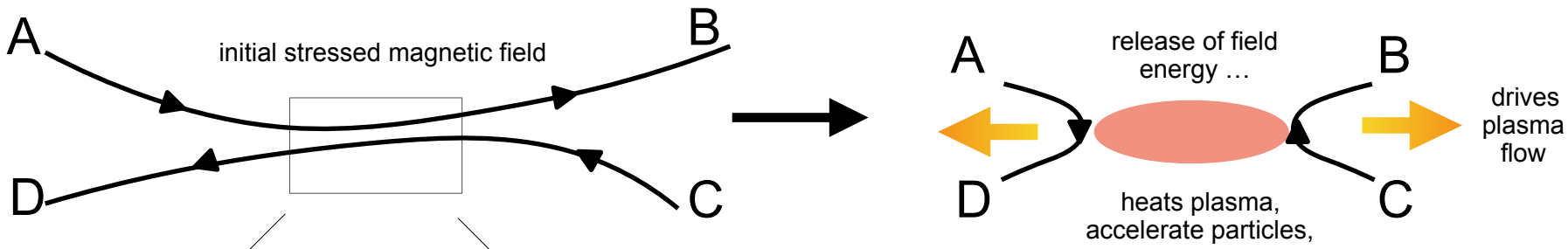
Fusion experiments: Tokamak sawtooth collapse
Rapid heat loss from core, killing performance!
[Yamada et al 1994]

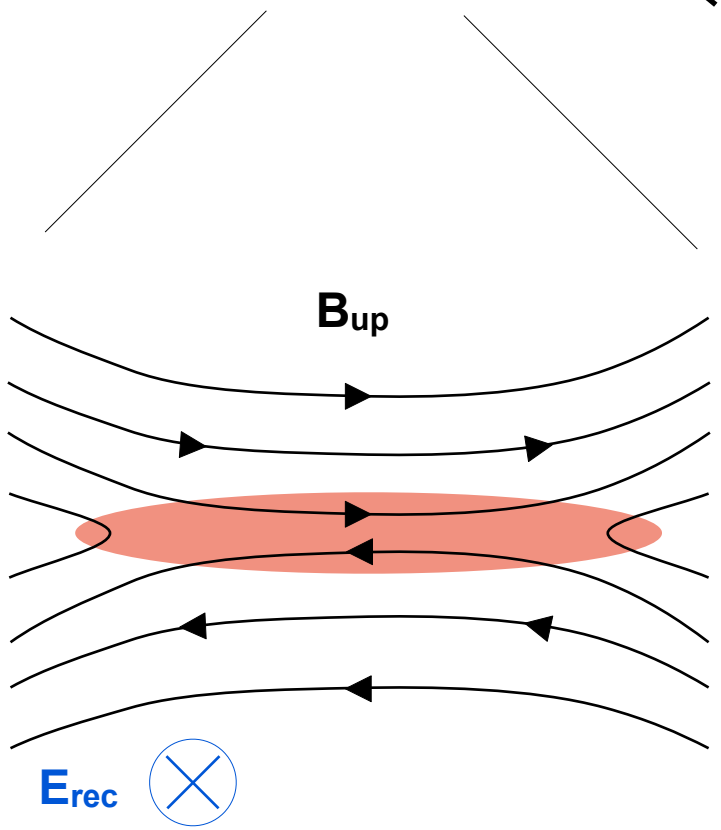
Refs: Yamada et al RMP 2010

Magnetic reconnection liberates magnetic energy.



Rapid magnetic reconnection requires large electric fields. How are they sustained?

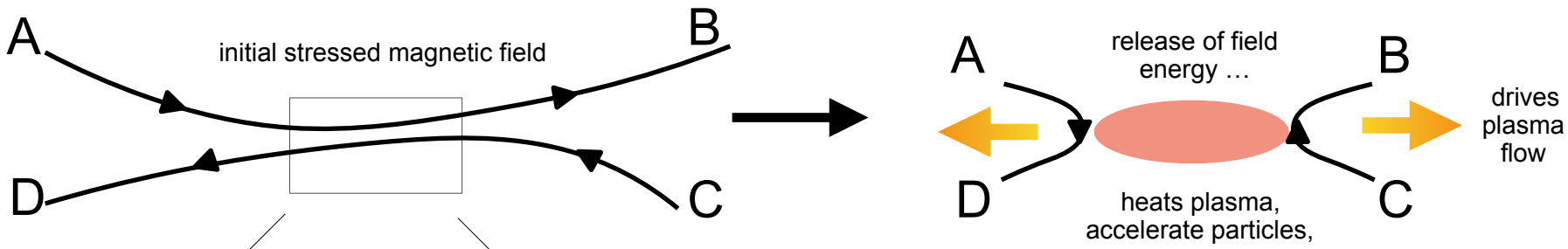


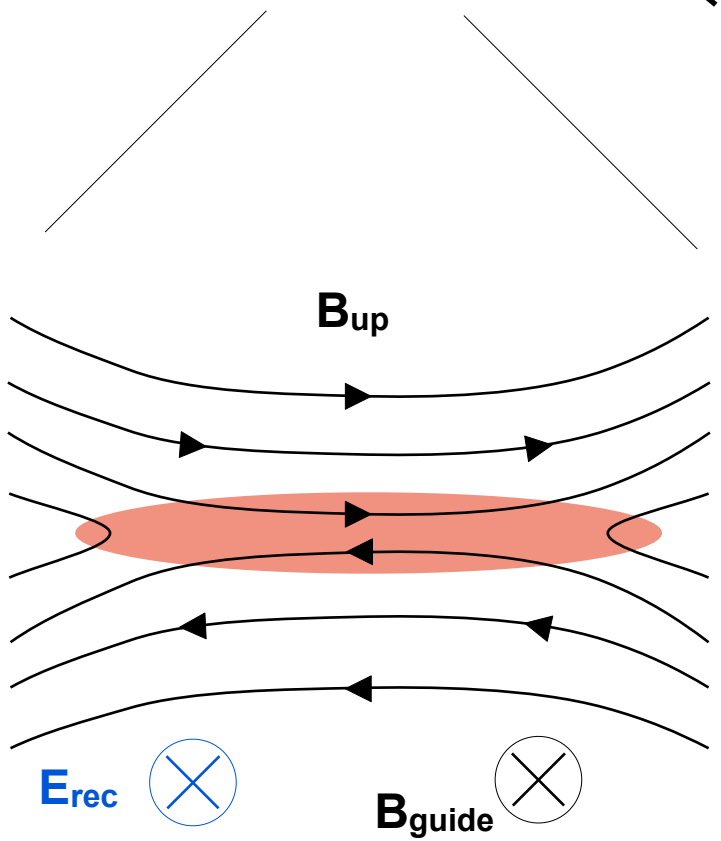


Large E_{rec} required for fast magnetic flux conversion (dB/dt)

In current sheet, $E \neq v \times B$ - dissipation is required for reconnection

Rapid magnetic reconnection requires large electric fields. How are they sustained?





Large E_{rec} required for fast magnetic flux conversion (dB/dt)

In current sheet, E ≠ v x B - dissipation is required for reconnection

When merging B fields at angle < 180 degrees, B_{guide} (|| E_{rec}) finite

Finite B_{guide} is general case, particularly important in fusion expt, solar (B_{guide} >> B_{up}).

- for B_{guide} = 0: see Ren+MRX PRL (2005)

Then, E || B in reconnection layer. How is $E_{||}$ sustained?

Outline

- How does the plasma balance the large parallel electric field ($\mathbf{E}_{||}$) during guide field reconnection?

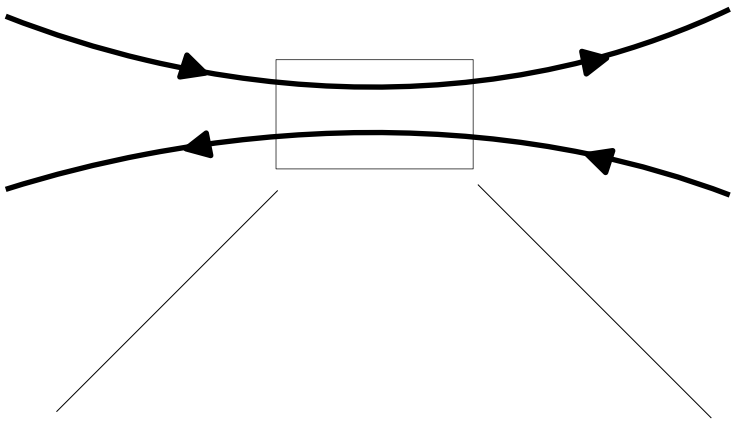
- Two-fluid theory idea: **Quadrupolar electron pressure** variations in the current sheet
  - electron pressure gradients sustain $E_{||}$ on ion-diffusion scale

- Experimental observations from MRX in guide field reconnection (B_{guide} / B_{up} ~ 1)
- Quantitative verification of **quadrupolar electron pressure variation on ion scales**
- Identification of **electron diffusion region**
- Electromagnetic waves observed, which possibly balance $E_{||}$ in EDR.

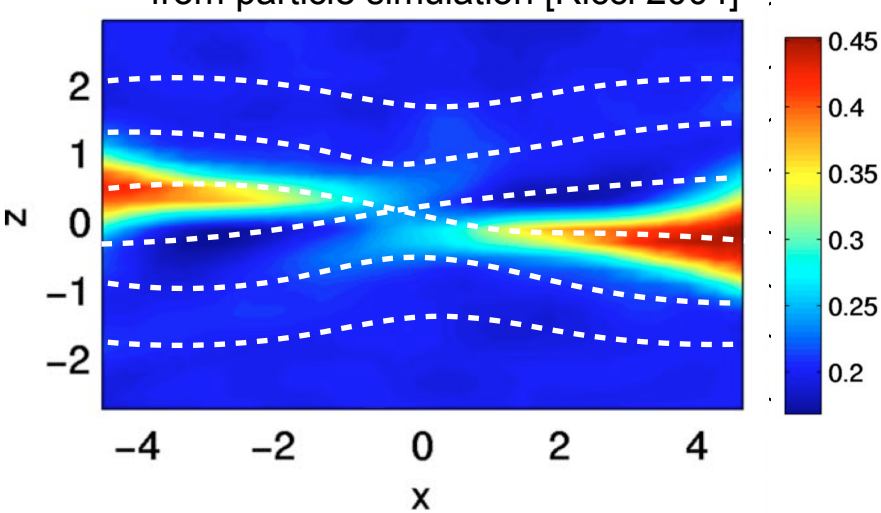
- Outlook and opportunities
  - Magnetosphere - MRX comparison
  - Extension to tokamak

[W. Fox, F. Sciortino, A. v. Stechow, + MRX group, PRL (2017)
A. v. Stechow, WF, + MRX group, submitted to PoP (2017)]

How to obtain large $E_{||}$ in reconnection layer?
Two-fluid theory predicts *electron pressure variations*



quadrupolar n_e
from particle simulation [Ricci 2004]



Generalized Ohm's law keeping electron pressure obtained fast rates :

$$E_{||} + \boxed{(1/ne)\nabla_{||}p_e} = \eta \mathbf{J}_{||} + \ldots$$

finite at two-fluid scales, when current sheet at ρ_s (= C_s/ω_{ci}) scale

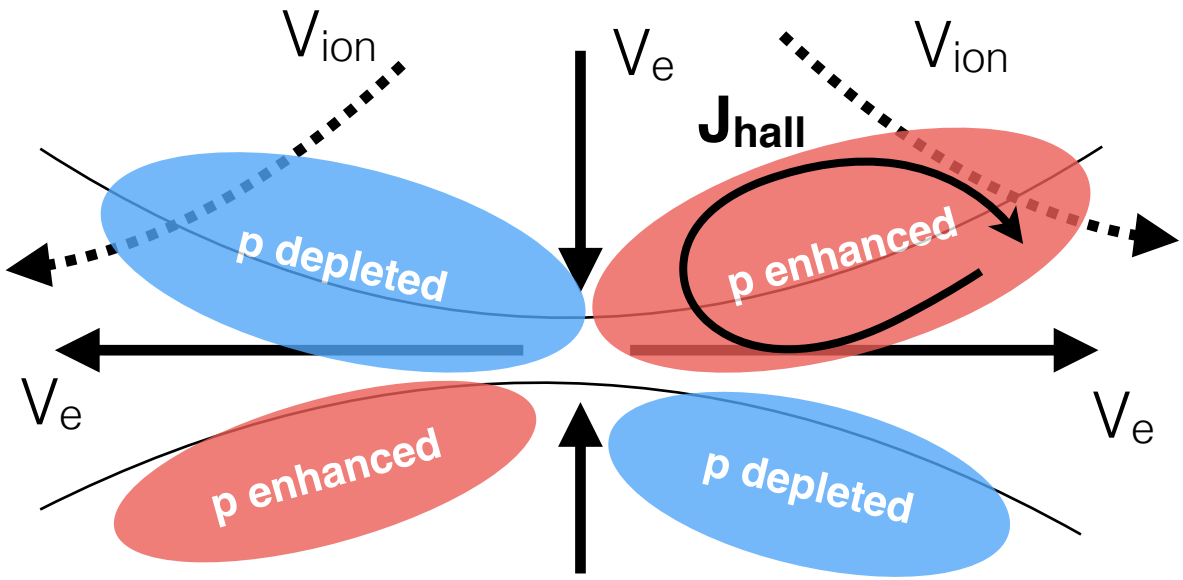
- Original theory and simulations: Aydemir (1992), Wang & Bhattacharjee (1993), Kleva, Drake, & Waelbroeck (1995).
- Extension to collisionless regime with pressure anisotropy : Egedal Nature Phys 2012; Le PRL 2013
- Recent analytic theory: Stanier PoP 2015

What happens?
- quadrupolar electron pressure variation arises in reconnection layer
- pressure variation is *in the 2-D plane of simulation*
- ***but, couples to out-of-plane reconnection electric field in parallel Ohm's law***

We want to test and verify this physics on MRX

How does the pressure perturbation arise?

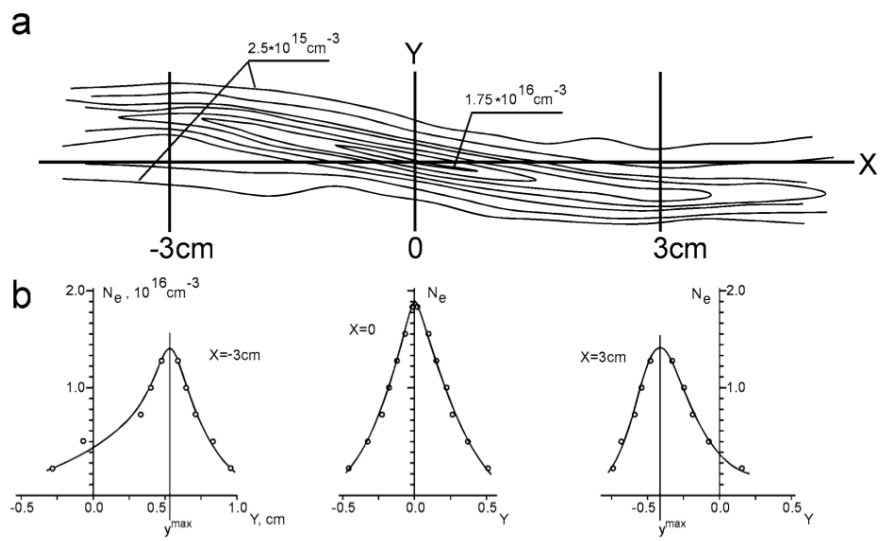
(Guide Field out of page)

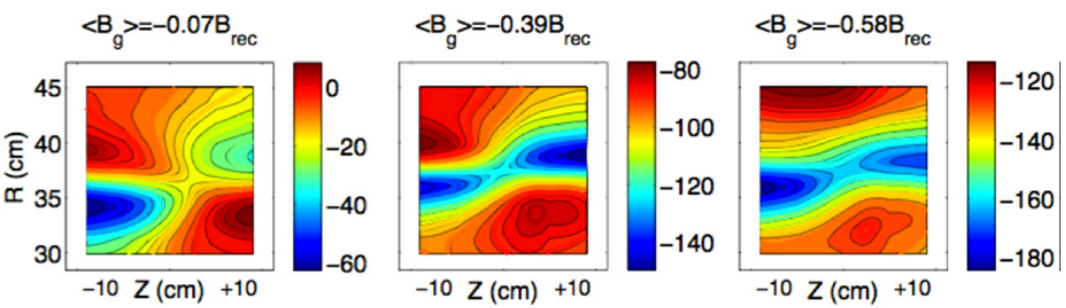


1. Two-fluid reconnection: **e- and ion take different paths through reconnection layer.**
2. They create in-plane current loops: "Hall currents"
3. Hall currents interact with Guide Field: **J x B force!**
4. Creates both p_e and B field pressure changes

- GF enhancement or depletion measured by [Tharp + MRX et al PRL 2012]
- Complements **Hall magnetic field** for anti-parallel B field reconnection [Y. Ren+MRX PRL 2006]

Previous laboratory experiments observed tilting of current sheet



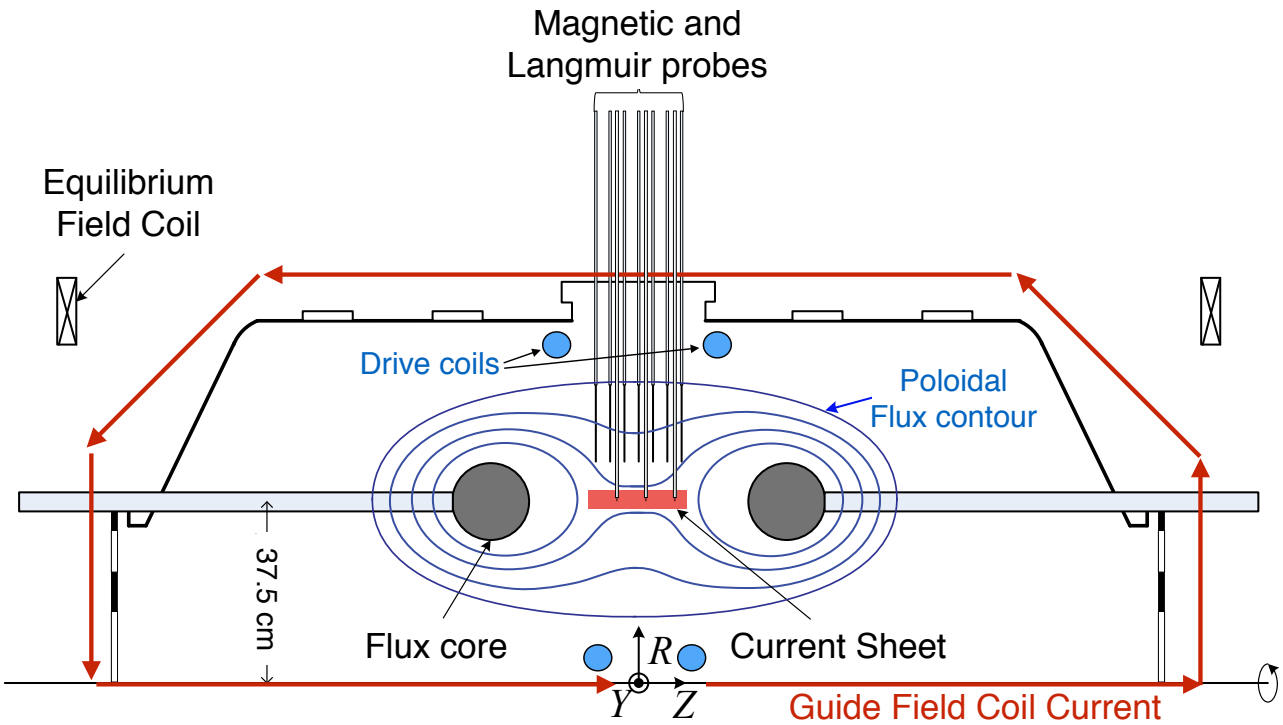


- A. Frank, et al (Phys. Lett. A 2006) - observed a tilting of density,
  - qualitatively attributed to $\mathbf{J}_{hall} \times \mathbf{B}_{guide}$ (Actual Hall currents and reconnection rate not measured)

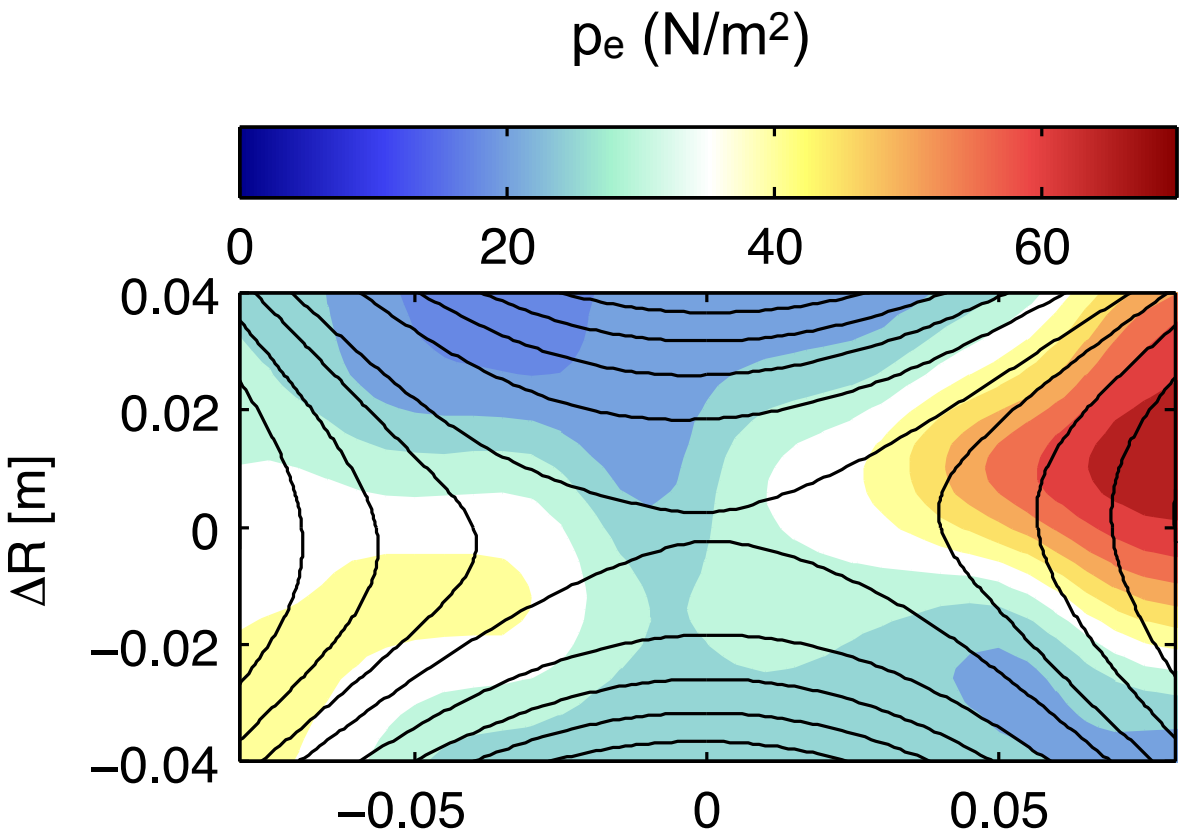
- Tharp, et al (PoP 2014) -
  - change of pure magnetic quadrupole at 0 GF to enhancement/depletion
  - current sheet tilts (in magnetics)

MRX experiments explore p_e effect in guide field reconnection

- MRX plasmas created with B_{guide} = +/- 0.7 B_{up},
- He plasmas for low collisionality and two fluid regime (**ρ_s ~ 4 cm**)
- Profiles of plasma **n_e,T_e, p_e** and **ϕ** are assembled from scanned Langmuir probes combining several 100's -1000 MRX discharges.



Large quadrupole electron pressure variation ($\delta p_e / p_e$ ~100%) directly measured in MRX

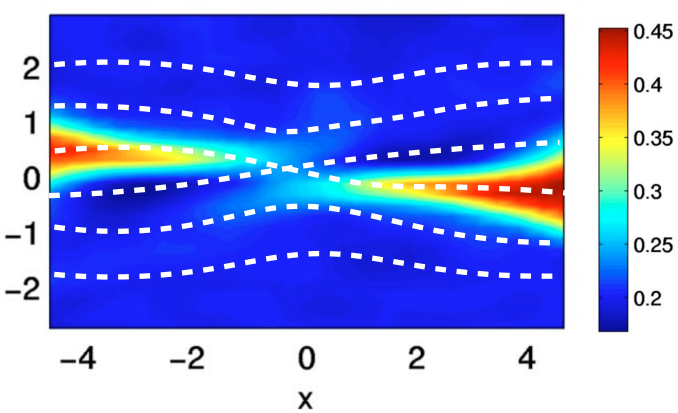


MRX directly detects how electron pressure variations arise in reconnection layer and sustain large $E_{||}$.

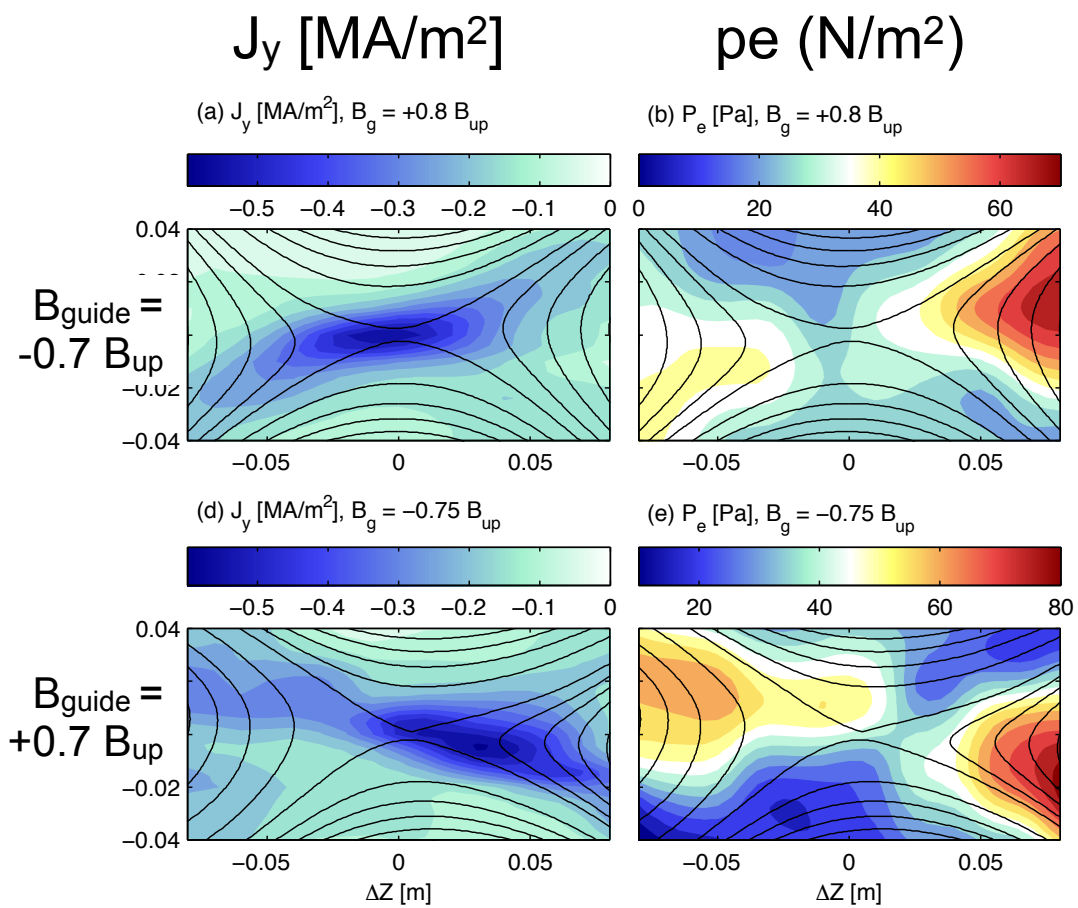
Theory prediction:
In-plane p_e gradients arise in recon layer and balance parallel electric field in Generalized Ohm's law:

$$E_{||} + (1/ne)\nabla_{||}p_e = \eta \mathbf{J}_{||} +$$

quadrupolar n_e
from particle simulation [Ricci 2004]

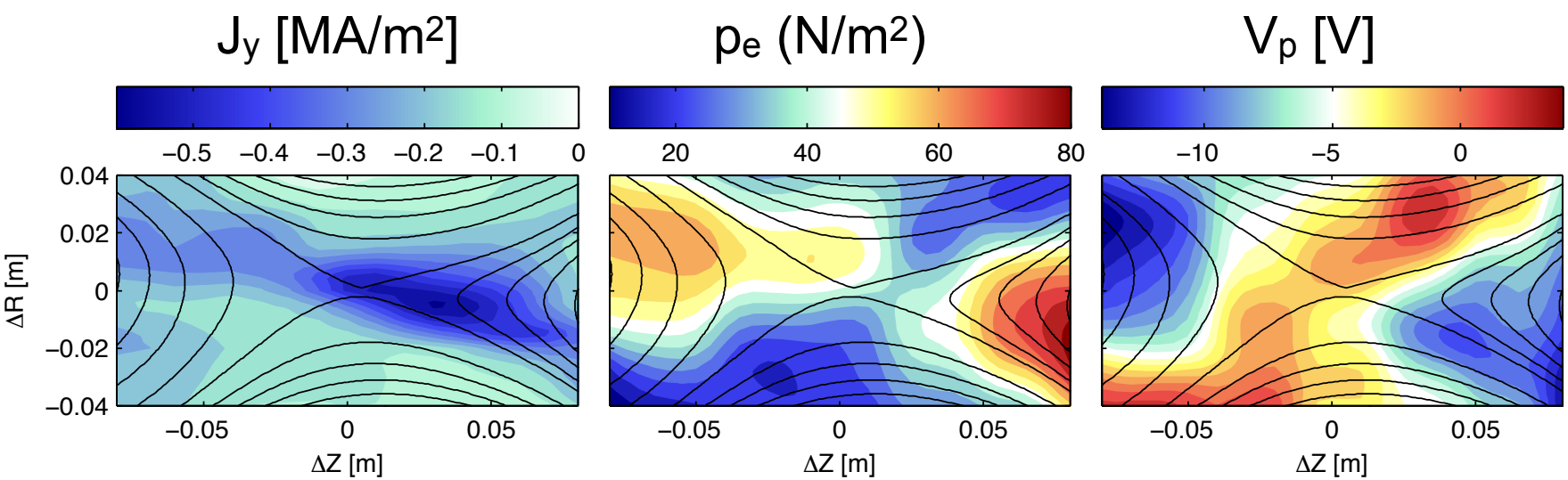


Experiment:



W.Fox, F. Sciortino, A.v.Stechow + MRX group, PRL (2017)

Quadrupolar variation of *both* electron pressure and in-plane electrostatic potential are observed.



- Quadrupole V_p associated with ExB drift of plasma in- and out- of reconnection layer [J. Egedal, et al PRL (2003)]

Both reconnection E_y and in-plane ∇V_p *together* determine $E_{||}$

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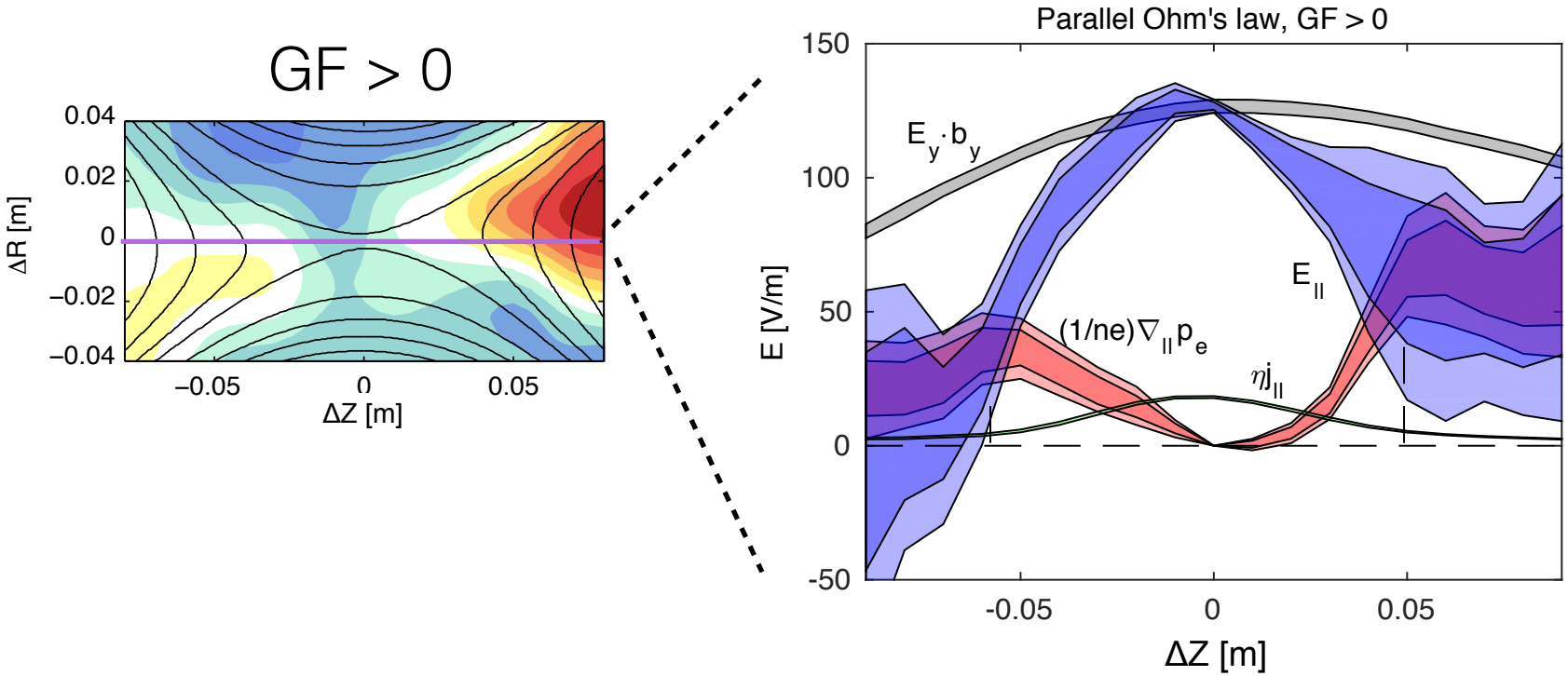
Parallel electron pressure term quantitatively balances Ohm's law in downstream, at ion scale

$$E_{||} + \nabla_{||} p/ne = \eta \mathbf{J}_{||} - \frac{1}{ne}(\nabla \cdot \Pi)_{||} + \ldots$$



Parallel electron pressure term quantitatively balances Ohm's law in downstream, at ion scale

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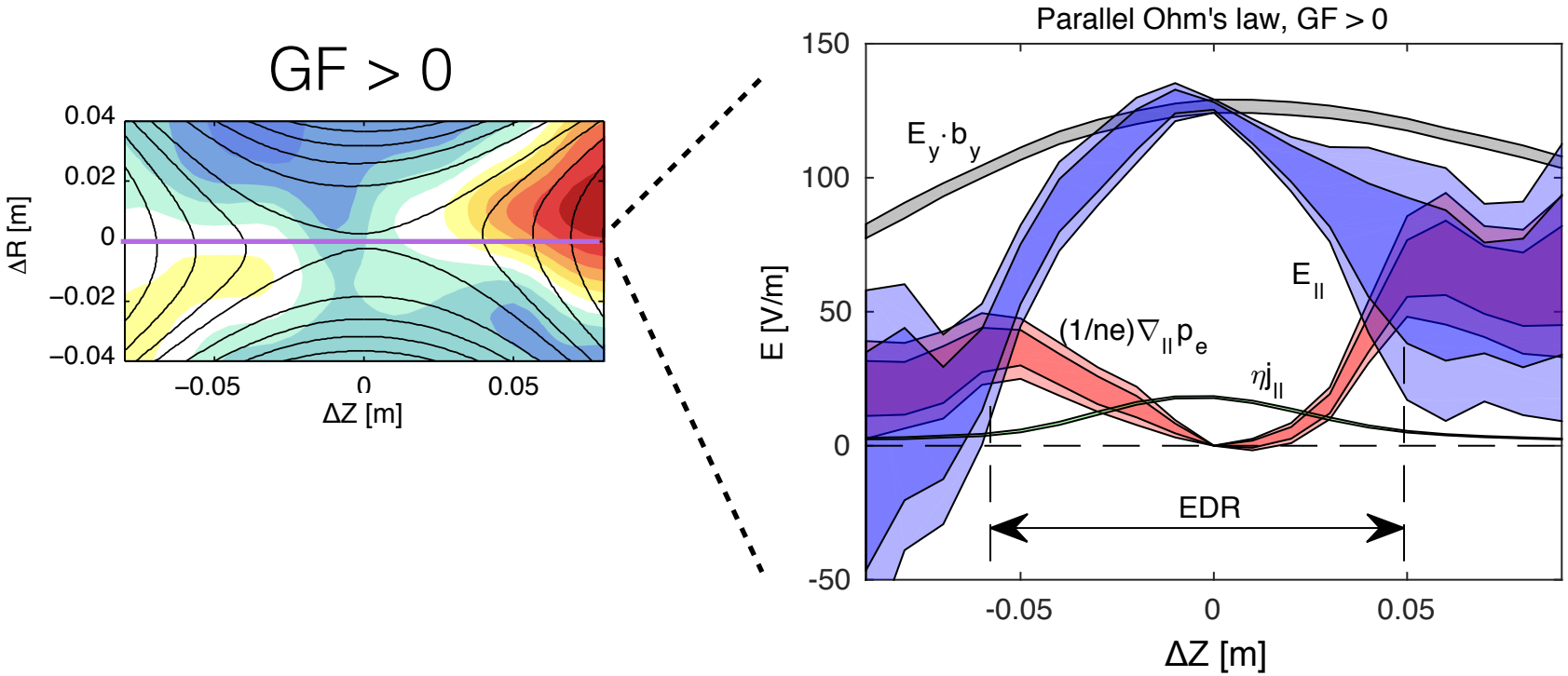

- Observe Electron diffusion region (EDR) where E|| not balanced by electron pressure effect (or resistivity)
- Future: How does size of EDR scale with guide field?

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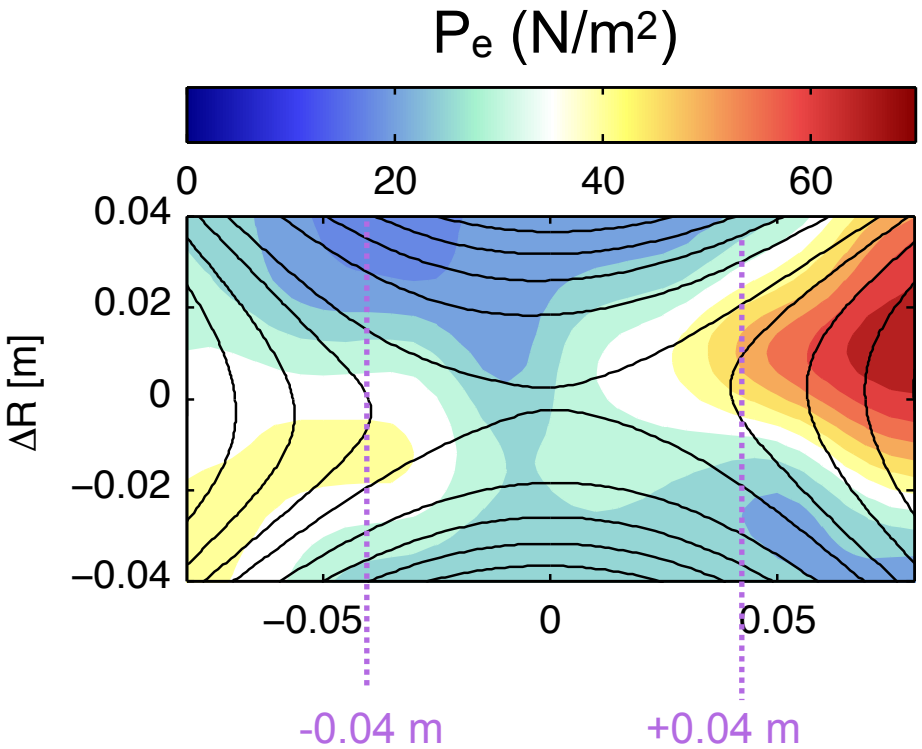
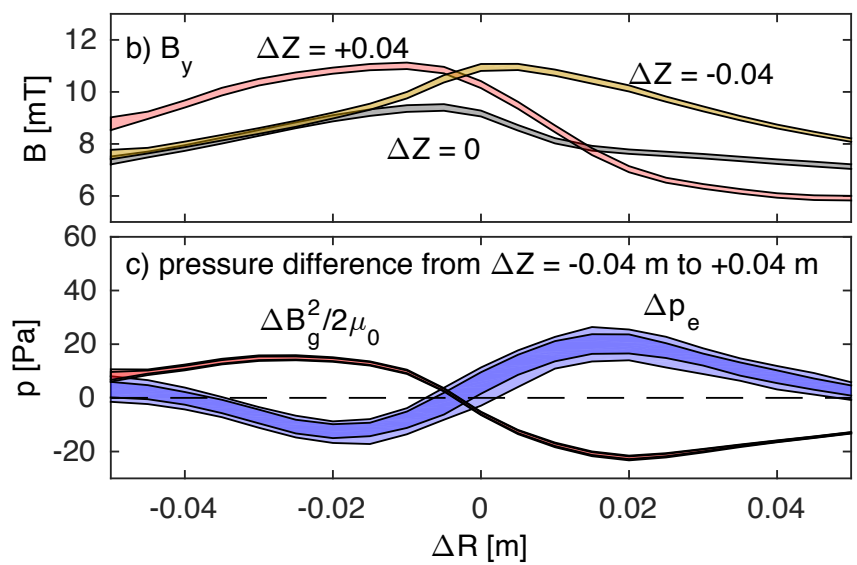
In-plane variations of electron pressure and magnetic pressure are in balance



Define variation in guide field pressure:

$$\Delta B_g^2/2\mu_0 \equiv \int_{Z_1}^{Z_2} j_r B_y dZ$$



Demonstrates connection between Hall-current perturbations to guide field [Tharp PRL 2012] and p_e variation. Electron outflows are diamagnetic!

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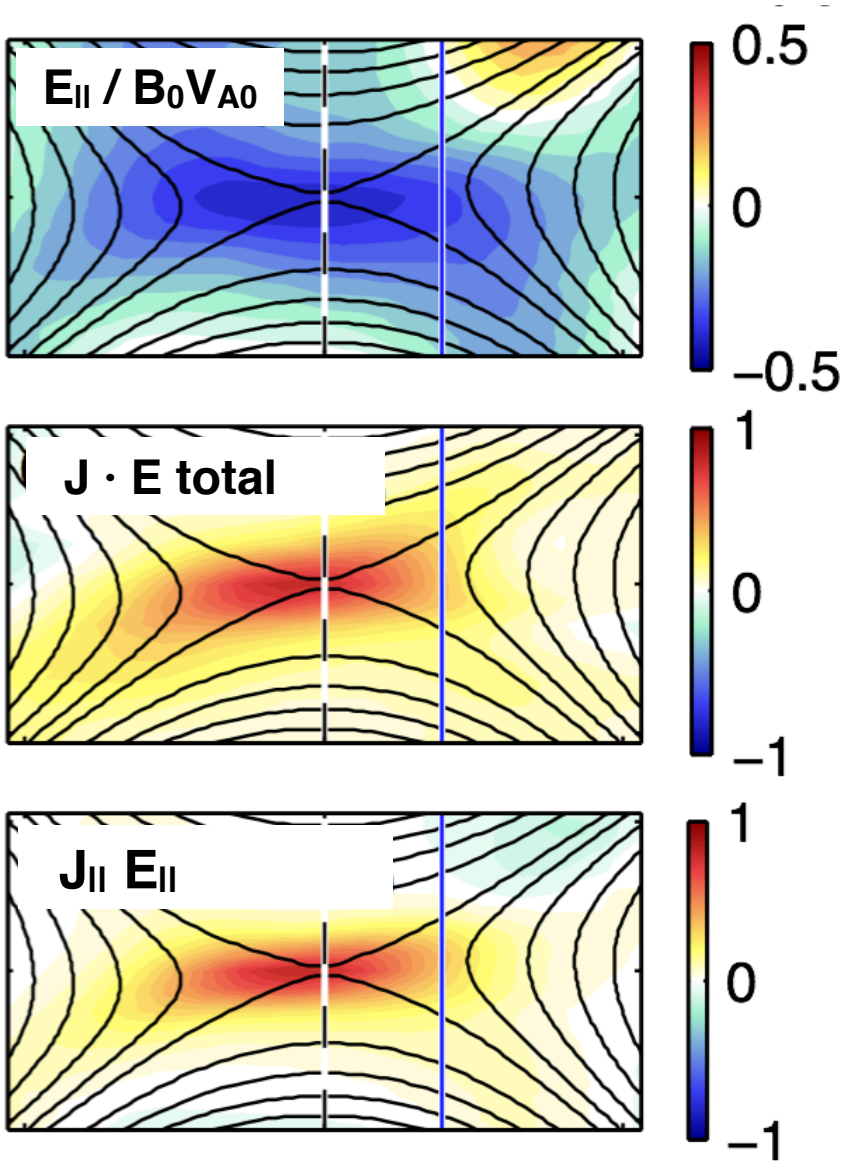
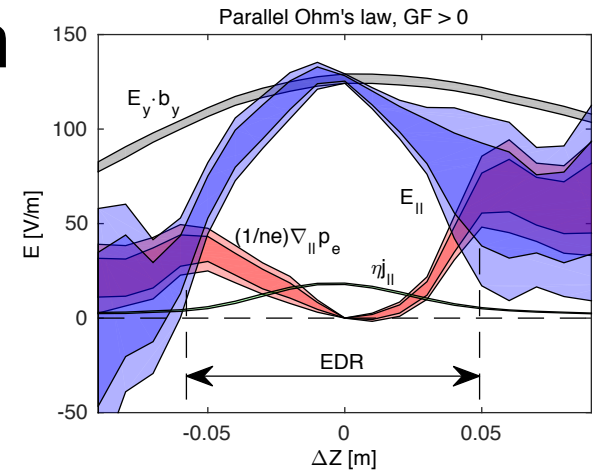
Energy conversion in GF reconnection

- $E_{||}$ localized near current sheet
- **$J \cdot E$ dominated by $J_{||}E_{||}$** at $B_g/B_{up} \sim 0.8$
- (In contrast, recall $\mathbf{J} \cdot \mathbf{E}$ dominated by $\mathbf{J}_\perp \cdot \mathbf{E}_\perp$ at GF = 0)
  - see M. Yamada, et al, PoP 2016



EDR observations motivates search for other mechanisms to balance Ohm's law



$$E_{||} + \nabla_{||} p/ne = \eta \mathbf{J}_{||} - \frac{1}{ne}(\nabla \cdot \Pi)_{||} + \ldots$$

- Spitzer resistivity (plotted green) too small by a factor of ~8.
- Pressure anisotropy (Le PRL 2013, JPP 2015) appears small. Preliminary MRX measurements < 20%. Consistent with finite collisionality. ($\nu_{ei} \sim 20\ 10^6\ s^{-1}$ >> $V_{in} / \delta_{cs} \sim 10^6\ s^{-1}$)
- Pressure tensor (Hesse 2006): estimated to be small in MRX (see also H. Ji, et al, GRL 2008):

$$en_e E_y \approx \frac{1}{2} r_L^2 \frac{\partial v_{ex}}{\partial x} \nabla^2 (n_e m_e v_y),$$

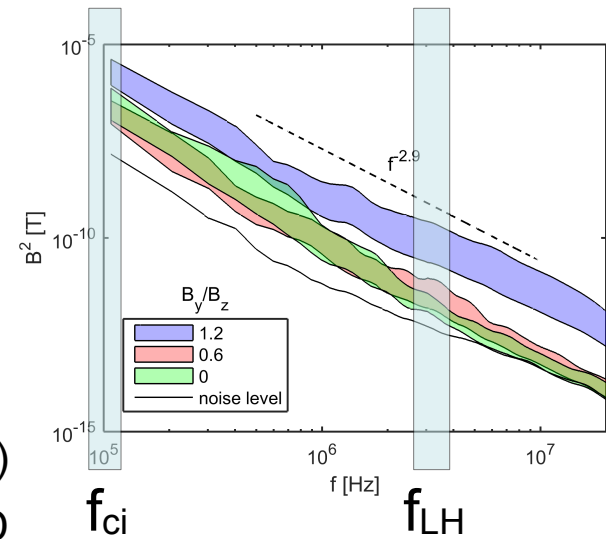
small because $r_L \sim 1$ mm << δ_{cs}

- Anomalous resistivity from wave turbulence?

Can lower-hybrid-range electromagnetic fluctuations provide EDR dissipation?

- Lower-hybrid-range fluctuations previously observed during laboratory reconnection:
  - LAPD (Gekelman, JGR 1982),
  - MRX (zero GF, Ji PRL 2004)
  - VTF (strong GF, Fox et al PRL 2008, PoP 2010),
  - Vineta (A. von Stechow, PPCF 2015)

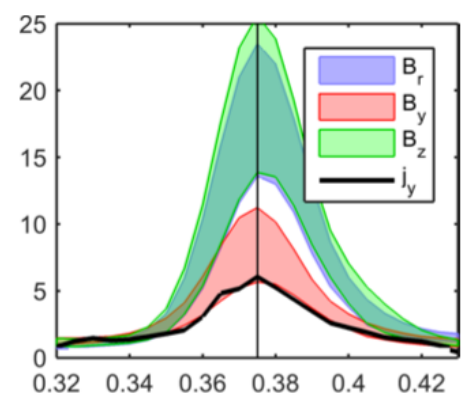
B^2 frequency spectrum



<u>New results in MRX GF Experiments</u>

- EM fluctuations observed in GF regime of MRX
  - complements previous zero GF observations (Ji PRL 2004)
- Fluctuations strongly peaked to x-line and diffusion region in 1-D profiles.
- Hodogram analysis: waves are **RH polarized**
- Fluctuations become **larger amplitude** and **less intermittent,** (more reproducible) as GF increased
  - challenges intuition of LH-instabilities (e.g. LHDI) - since electron drift becoming *more parallel* to B with GF!
- Fluctuations may apply a large resistivity, but improved estimates based on $k_{||}$ measurements are needed to confirm.

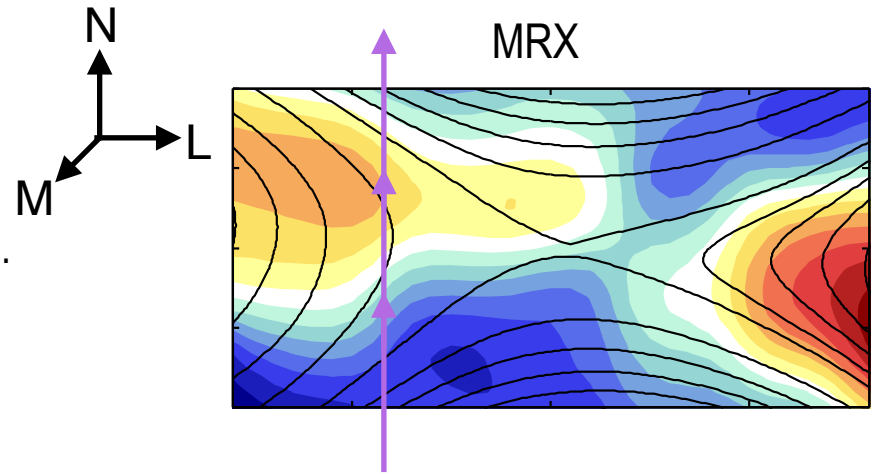
B^2 spatial profile
B_g/B_{up} = 1.2



[A. v. Stechow, WF, MRX group, submitted to PoP (2017)]

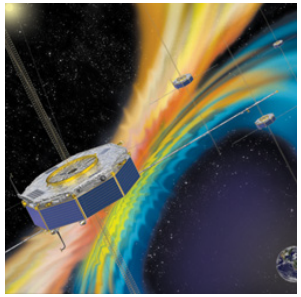
Lab experiments and spacecraft can provide important complementary data about reconnection

- **MMS:** fully kinetic data, in fully collisionless plasma. Challenge comes from 1-d nature of spacecraft.
- Has started to observe electron diffusion regions [Burch et al 2016]

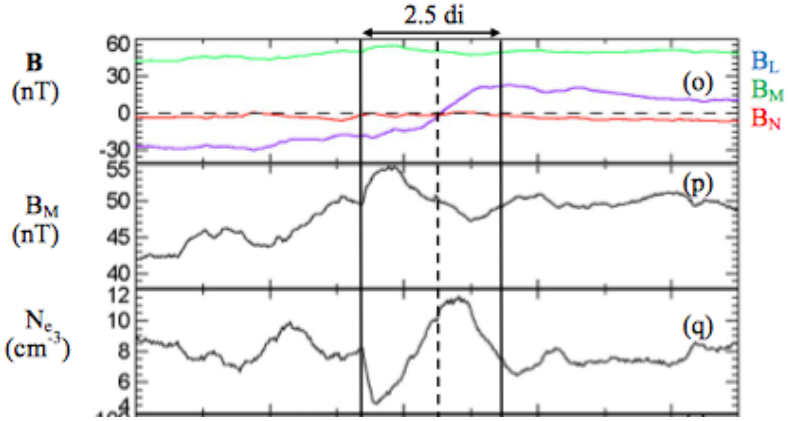


- **MRX, FLARE, TREX:** well controlled experiment, measure "everything".
- Full 2-d plane measurements, e.g. where is parallel electric field balanced?

NASA MMS mission, presently in orbit



MMS



[M. Oieroset, et al, "MMS observation of large guide field symmetric reconnection between colliding reconnection jets…." GRL (2016).]

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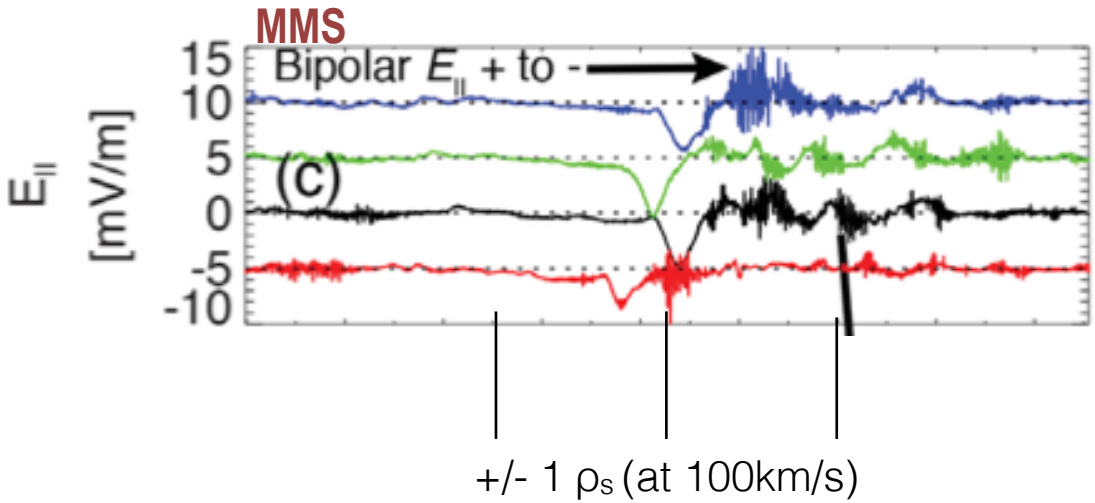
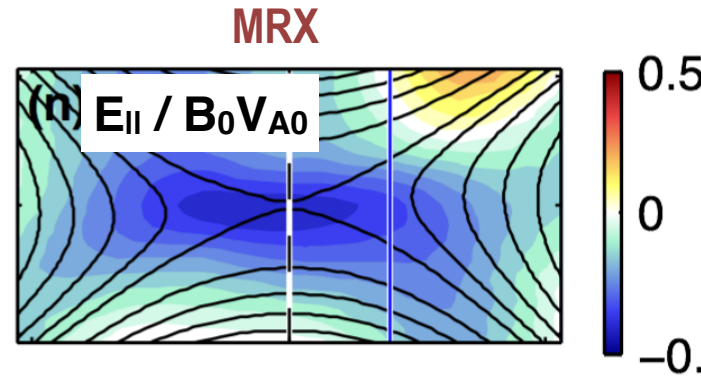
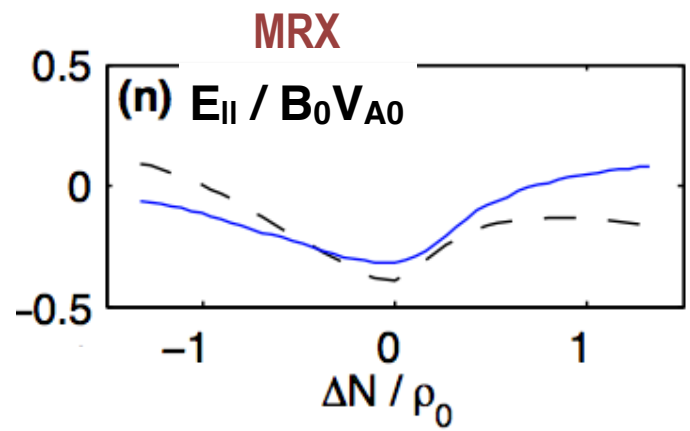
Example comparison of $E_{||}$ observations with MMS event (F. Wilder, et al PRL 2017): $E_{||}$ sharper, larger amplitude in MMS







Quantity	MMS	MRX
$E_{||} / B_0V_{A0}$	2	0.3-0.4
$w_{E||} / \rho_s$	0.3	1

– Difference in E|| may indicate transient bursty nature of reconnection events in magnetosphere; which is “averaged over” in MRX.

– MRX answers: how does reconnection occur on the average?

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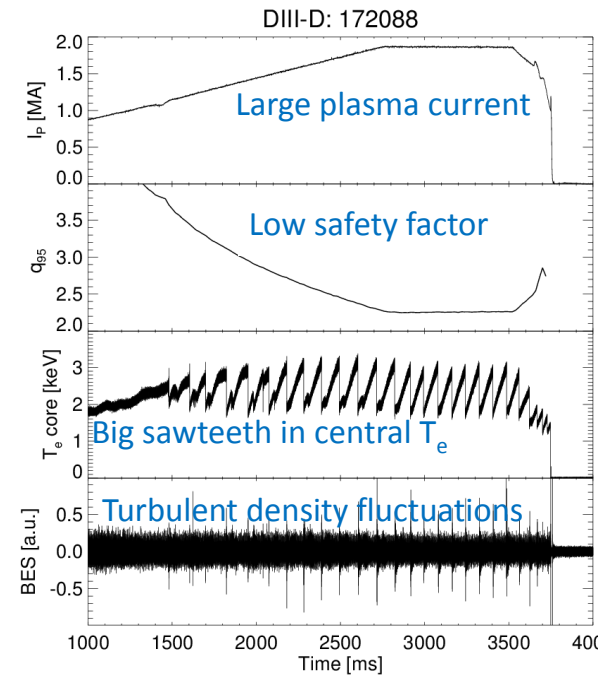
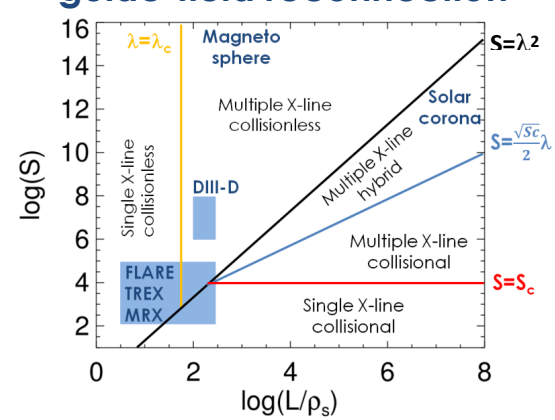
Pressure effect and other collisionless reconnection physics is being studied on a DIII-D Frontier Science Campaign, "Self-organization of unstable flux ropes"



- AIM: study **fast collisionless magnetic reconnection** in tokamaks in a parameter range of interest also for space plasmas, e.g. magnetosphere.
- Using the **great diagnostic suite** available in DIII-D to measure various quantities at multiple scales down to the ion sound gyroradius. E.g:. 2D maps of electron density and temperature.
- Large plasma current up to 2MA and very low q_{95} give <u>strong sawteeth and a q=1 radius much larger than in typical tokamak operation</u>, thus enabling measurements from diagnostics that do not normally cover the core where sawteeth typically occur.
- First experiments July 2017. A lot of work is ongoing to analyse a great dataset and to model it with nonlinear 2 fluid MHD and PIC codes.

Phase diagram for guide-field reconnection



Adapted from Ji, Daughton PoP 2011

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Slide courtesy of P. Piovesan.
Posters: Kinetic simulations: G. Lapenta (Wed AM, NP11.00169)
DIII-D Frontier Science: M. Koepke (Wed PM: PP11.112)

Summary and Outlook

- Confirmation of quadrupolar p_e variation in MRX[1].
- p_e variation balances the parallel electric field obtaining fast reconnection in two-fluid regime, at the ion diffusion region scale
- Electron diffusion region identified in GF reconnection regime.
- What balances $E_{||}$ in Electron diffusion region?
- Strong LH waves are observed in GF regime[2], but we need quantitative demonstration of their role

Future opportunities:

- **FLARE and NIF**: Zoom *out*: what about systems >> d_i or ρ_s? Plasmoid instabilities?
- **MFE/Tokamaks**: What role do two-fluid effects play?
  - Does p_e physics cause fast sawtooth crash in tokamaks?
  - Diamagnetic stabilization by p_e gradient across sheet ?
    - (theory: Rogers and Zakhavor 1995; Swisdak JGR 2003; early tokamak experiments Levinton PRL 1994; magnetosphere: Phan ApJ 2010)
- **Magnetosphere MMS**: opportunities to compare reconnection physics between lab and spacecraft

[1]W. Fox, F. Sciortino, A. v. Stechow, + MRX group PRL (2017)
[2]A. v. Stechow, WF + MRX group submitted (2017)