Kinetic Properties of the Reconnection Electron Diffusion Region, Explored Through Theory and Experiment

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In collaboration with the WiPPL team,

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Outline

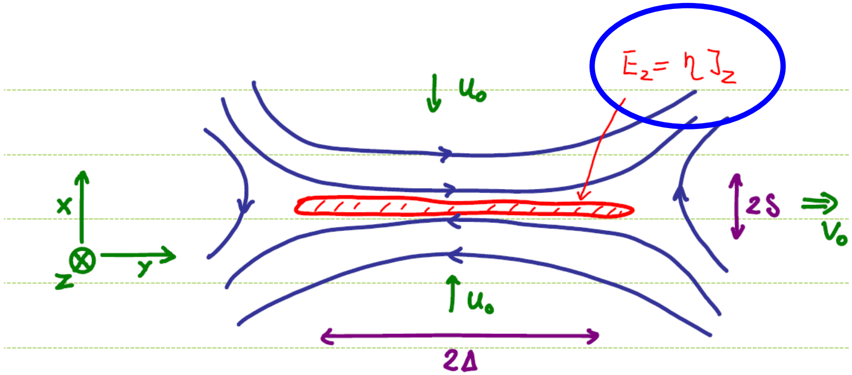
- The IDR and EDR are sensitive to collisions
- In the collisionless/kinetic regime electron trapping causes new terms in the Ohm's law to dominate

$$p_{e||} \gg p_{e\perp}$$

$$\mathbf{E} + \mathbf{u}_e \times \mathbf{B} = \eta \mathbf{J} + \frac{1}{ne}\nabla \cdot \mathbf{p}_e + \frac{m_e}{e}\mathbf{u}_e \cdot \nabla \mathbf{u}_e$$

- This will be shown in theory, PIC simulations, spacecraft observations and laboratory data
- Conclusions

Sweet-Parker Reconnection



Mass : $\Rightarrow$ $u_0 \Delta = V_0 \delta$ (A)

Ideal upstream $E_z = u_0 B_0$

Resistive layer : $E_z = \eta J_z \overset{\text{Ampere}}{=} \eta \dfrac{B_0}{\mu_0 \delta}$

$$\frac{\partial}{\partial t} \simeq 0 \Rightarrow u_0 = \frac{\eta}{\delta \mu_0} \quad \text{(B)}$$

Pressure balance along x $\quad \dfrac{\partial}{\partial x}\left(p + \dfrac{B^2}{2\mu_0}\right) = 0$

$$\Rightarrow P_0 + \frac{B^2}{2\mu_0} = P_{max}$$

along y $\quad \dfrac{\partial}{\partial y}\left(\frac{1}{2}\rho v_y^2\right) = -\dfrac{\partial p}{\partial y}$

$$\Rightarrow \frac{1}{2}\rho v_0^2 = P_{max} - P_0$$

$$V_0 = \frac{B_0}{\sqrt{\mu_0 \rho}} = V_A \quad \text{(C)}$$

(A), (B) and (C), 3 eqs. in 5 unknowns u_0, V_0, δ, Δ and η

$$\left(\frac{\delta}{\Delta}\right)^2 = \frac{(\eta/\mu_0)}{\Delta V_A} \equiv S_0^{-1}$$

S = Lundquist # = τ_η / τ_A

$$\Rightarrow \left(\frac{\Delta}{\delta}\right) = S_0^{1/2} \gg 1$$

in space plasma

$$\frac{u_0}{V_0} = \frac{u_0}{V_A} = S_0^{-1/2} \ll 1$$

$\Rightarrow$ Sweet Parker reconnection ($S_0^{1/2}$) is much faster than resistive diffusion (S_0).

However, Sweet-Parker reconnection is still too slow to explain space observations.

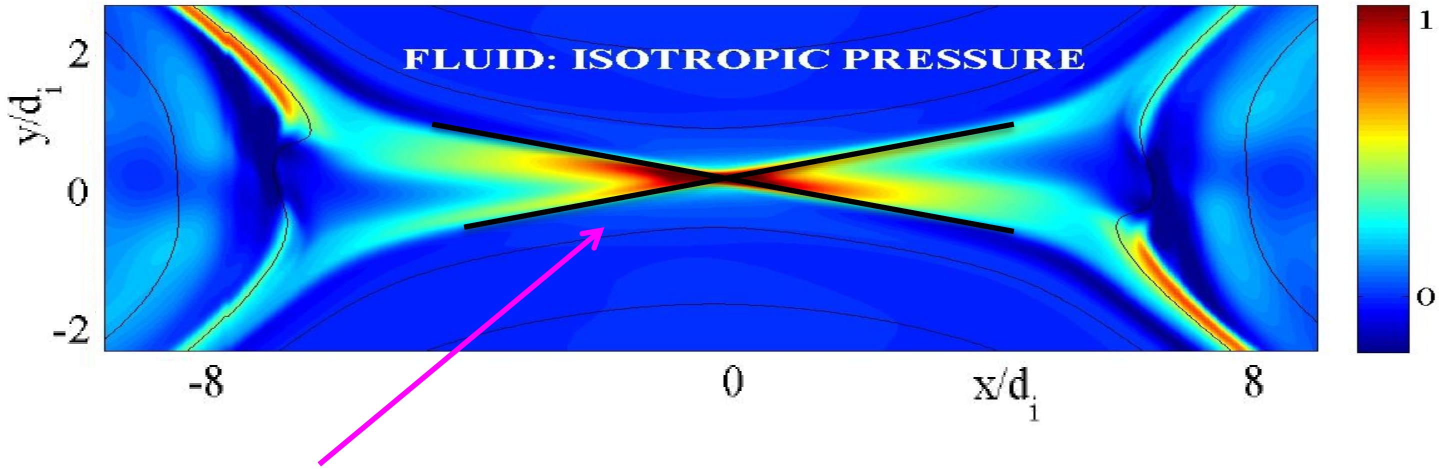
Two-Fluid Simulation

GEM challenge (Hall reconnection)

$\mathbf{E} + \mathbf{v}\times\mathbf{B} = (\mathbf{j}\times\mathbf{B})/ne$ [Birn,… Drake, et al. (2001)]

Out of plane current

Isotropic pressure



Aspect ratio: 1 / 10

➔ $v_{in} \sim v_A / 10$

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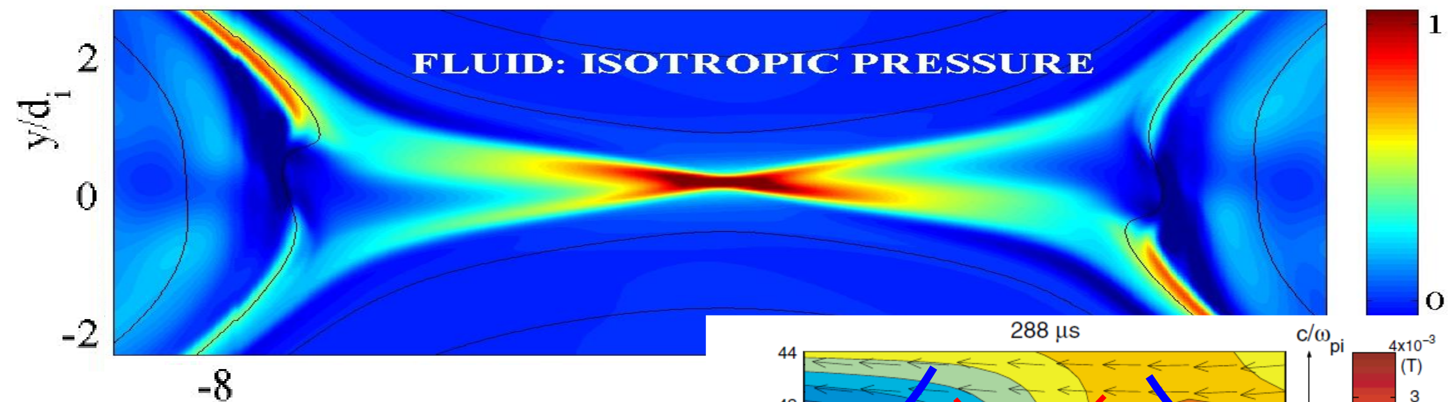
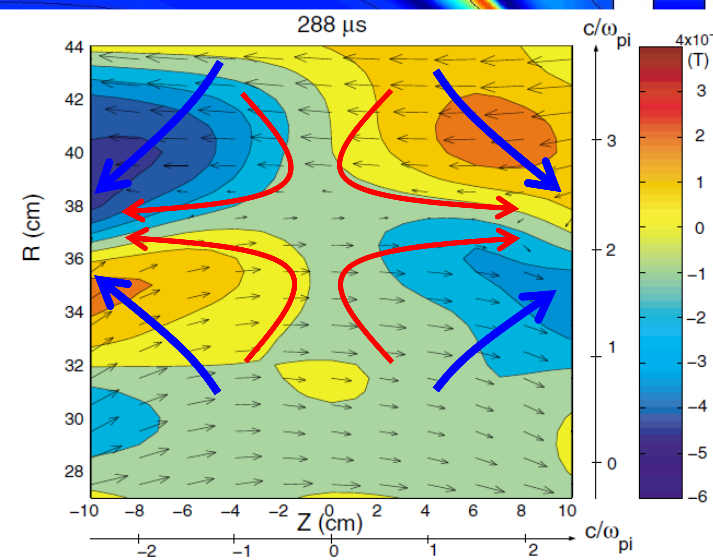


The Hall term is associated with quadrupolar out of plane fields, as observed in the Magnetic Reconnection Experiment (MRX) [Ren, PRL, 2005]



Most important within IDF: $\mathbf{E} + \mathbf{u}_e \times \mathbf{B} = \eta \mathbf{J}$

The Phase Diagram of Reconneciton

Phase diagram of magnetic reconnection. [Daughton, Roytershteyn & Ji, Daughton 2021]

Kinetic regime defined in [Le+, JPP, 2015]

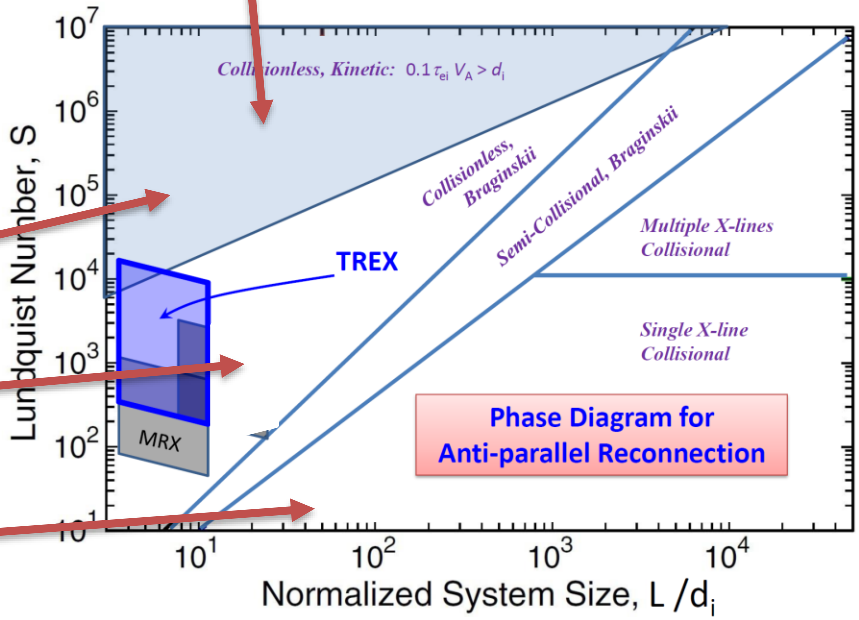
Most important terms within the IDF:

$$p_{e\|} \gg p_{e\perp}$$

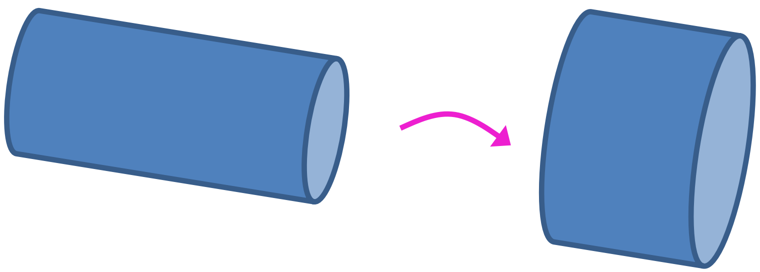
Kinetic: $\mathbf{E} + \mathbf{u}_e \times \mathbf{B} = \eta \mathbf{J} + \frac{1}{ne}\nabla \cdot \mathbf{p}_e + \frac{m_e}{e}\mathbf{u}_e \cdot \nabla \mathbf{u}_e$

Hall: $\mathbf{E} + \mathbf{u}_e \times \mathbf{B} = \eta \mathbf{J}$

Resistive: $\mathbf{E} + \mathbf{u}_e \times \mathbf{B} = \eta \mathbf{J}$



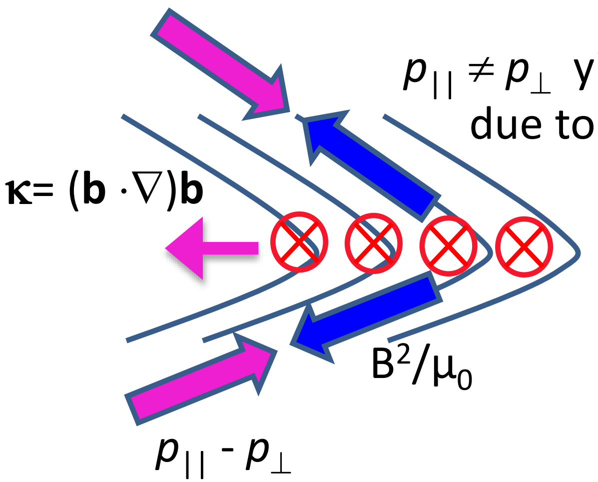
A Few Basic Plasma Physics Results



If magnetized and zero heat-fluxes, [CGL, 1956]

$$p_{\|} \propto \frac{n^3}{B^2}, \quad p_{\perp} \propto nB$$

If large heat-fluxes: $p_{||} \sim p_{\perp} = nT$ (Boltzmann)



$p_{||} \neq p_{\perp}$ yields current beyond MHD due to curvature drift:

$$\mathbf{J}_{\perp\,\mathrm{extra}} = [(p_{\|} - p_{\perp})/B]\mathbf{b} \times \kappa.$$

When $p_{||} - p_{\perp} = B^2/\mu_0$, then $\boldsymbol{J}_{\perp\mathrm{extra}}$ provides all the current needed to bend the field.

$p_{||} - p_{\perp} = B^2/\mu_0$ is the marginal firehose condition.

1D current sheets are in force balance at $p_{||} - p_{\perp} = B^2/\mu_0$, [SWH Cowley, 1979]

A Harris-like Solution for a 1D Current Layer

On a Plasma Sheath Separating Regions of Oppositely Directed Magnetic Field.

E. G. Harris (*)

Euratom C.N.E.N. - Frascati

(ricevuto il 4 Settembre 1961)

$$f_i = \left(\frac{M}{2\pi\theta}\right)^{\frac{3}{2}} N \exp\left[-\frac{M}{2\theta}\left[\alpha_1^2 + (\alpha_2 - V_i)^2 + \alpha_3^2\right]\right],$$

$$f_e = \left(\frac{m}{2\pi\theta}\right)^{\frac{3}{2}} N \exp\left[-\frac{m}{2\theta}\left[\alpha_1^2 + (\alpha_2 - V_e)^2 + \alpha_3^2\right]\right],$$

where V_i and V_e are the mean velocities of ions and electrons respectively.

$$B = \sqrt{16\pi N\theta}\ \mathrm{tgh}\left(\frac{Vx}{cL_D}\right).$$

$$n_i = n_e = N \exp\left[\left(\frac{eV}{\theta c}A_y\right)\right]$$

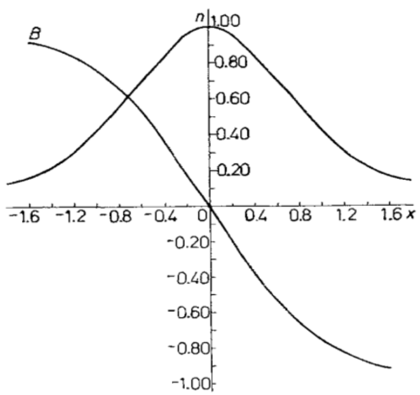
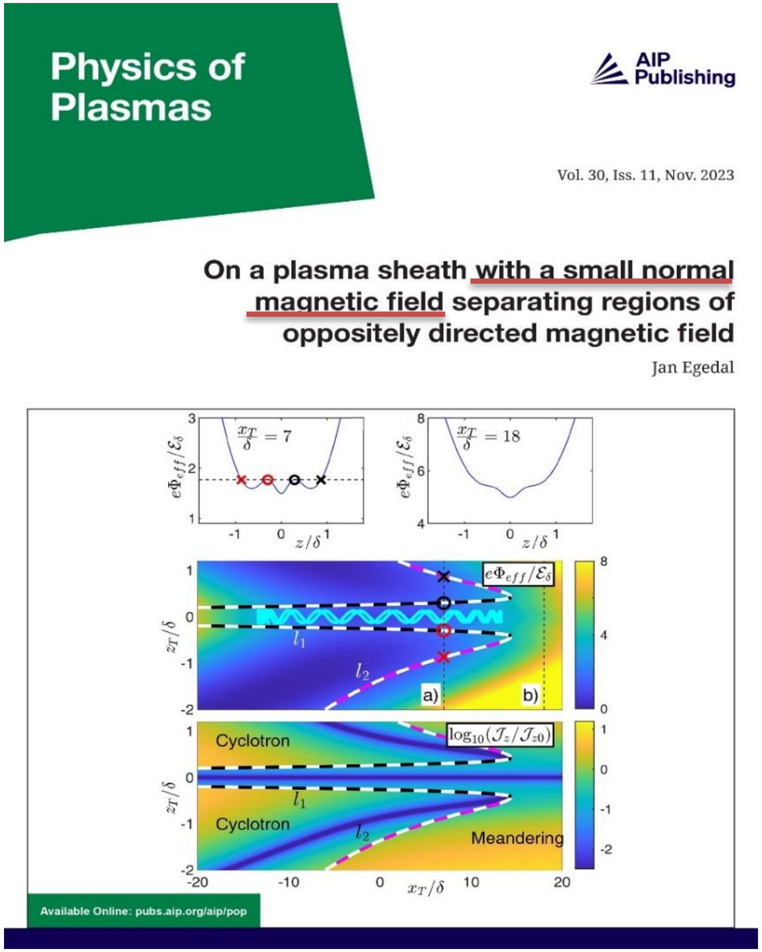


Fig. 1. — The variation of B and n across the sheath.



$\mathcal{J}_z \propto \oint v_z dz$ [Speiser 1970; Sonnerup 1971; Buchner 1989]

Similar approach used for ions in magnetotail [Zelenyi+ 2004, 2011]

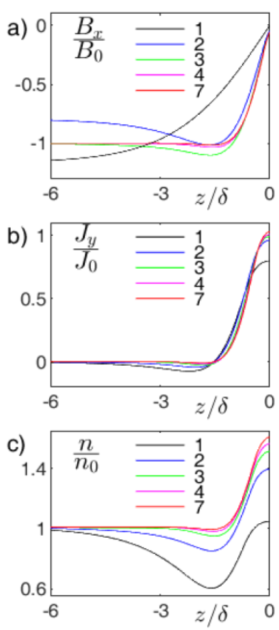
A Harris-like Solution for a 1D Current Layer

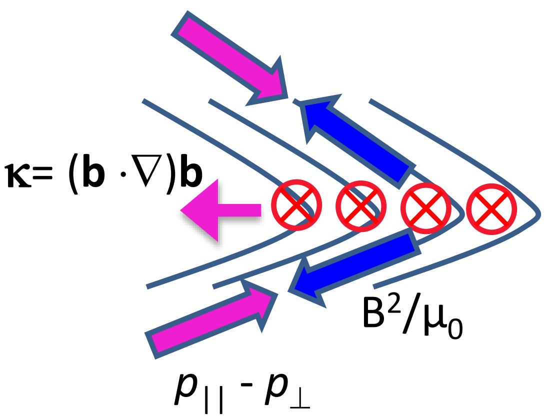
➔ Boltzmann Ions and Electron Distributions:

$$n_i(z) = n_0 \exp\left(-\frac{e\Phi(z)}{T_i}\right) \quad .$$

$$f_e(z, \mathbf{v}) = f_{e\infty}(U, \mathcal{J}_z), \quad \text{where } U = \mathcal{E} - e\Phi$$

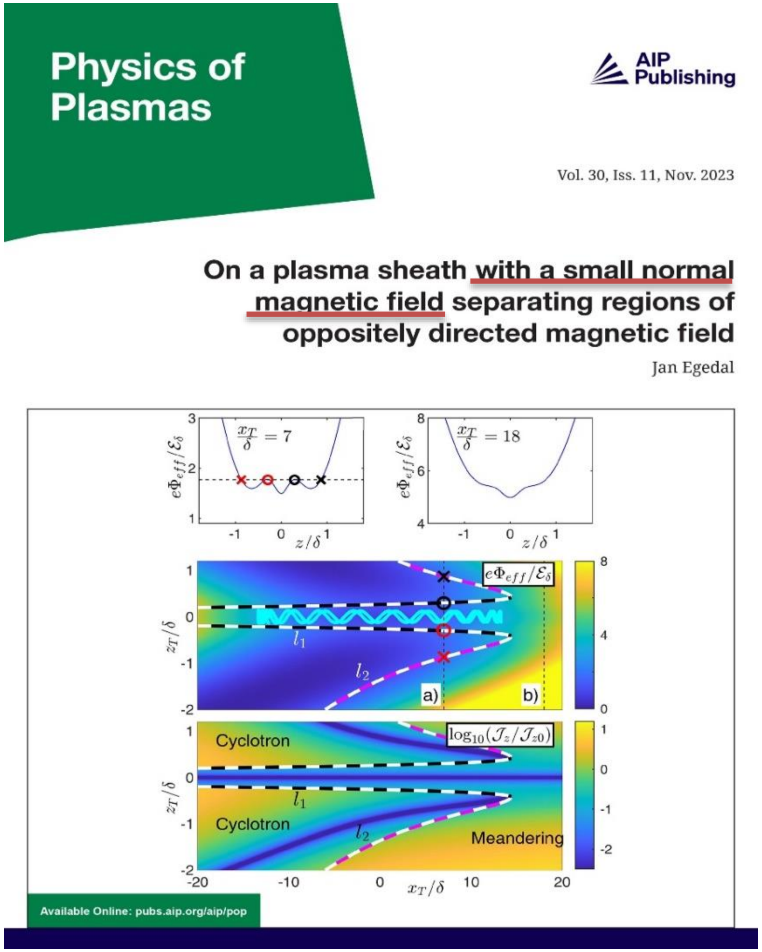
Self consistent solution through iterations in Matlab:





Firehose condition

$$B_0 = \sqrt{\mu_0 n_0 (T_{e\|0} - T_{e\perp 0})}$$



$\mathcal{J}_z \propto \oint v_z dz$ [Speiser 1970; Sonnerup 1971; Buchner 1989]

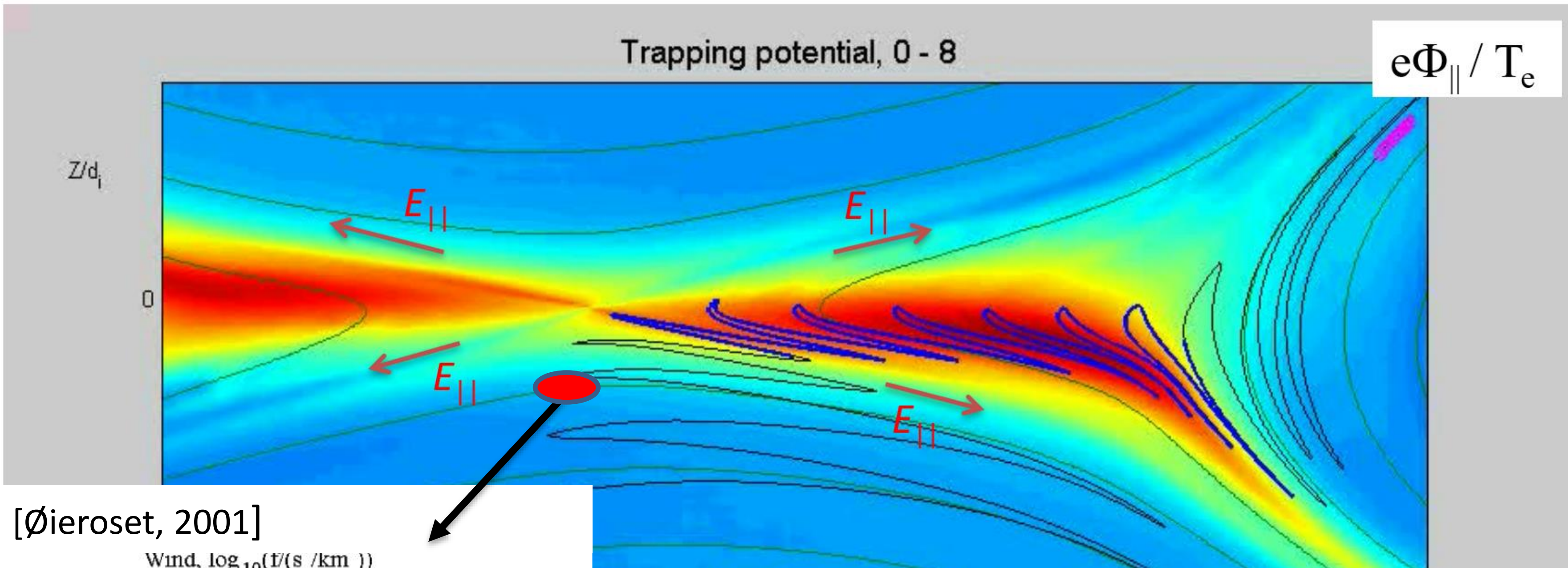
Similar approach used for ions in magnetotail [Zelenyi+ 2004, 2011]

Electrons Trapped by $\Phi_{||}$, $B_g = 0.4$

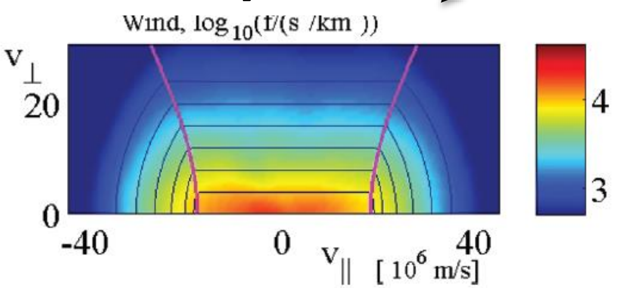
When / where trapping dominates
- ➔ Zero Heat Flux:
- ➔ CGL-scaling laws

$$p_{||} \propto \frac{n^3}{B^2}\,, \qquad p_\perp \propto nB$$

$$\Phi_{||}(\mathbf{x}) = \int_{\mathbf{x}}^{\infty} \mathbf{E} \cdot d\mathbf{l}$$



[Øieroset, 2001]



Drift kinetic model with m_i/m_e ➔ ∞

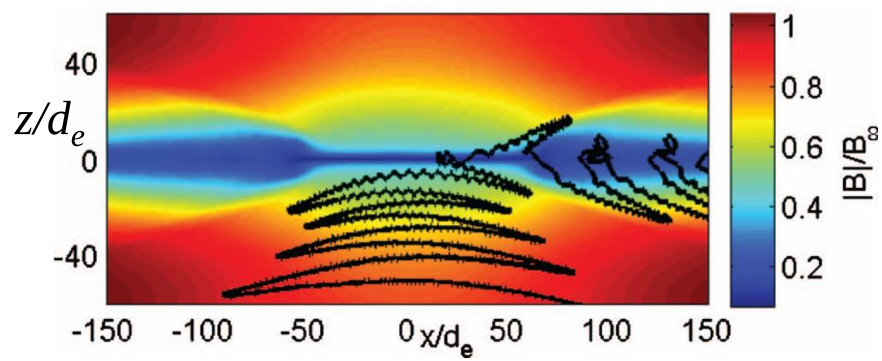
$$\bar{f}_0(\mathcal{E}_{||}, \mathcal{E}_\perp) = \begin{cases} \bar{f}_\infty(\mu B_\infty), & \text{trapped} \\ \bar{f}_\infty(\mathcal{E} - e\Phi_{||}), & \text{passing.} \end{cases}$$

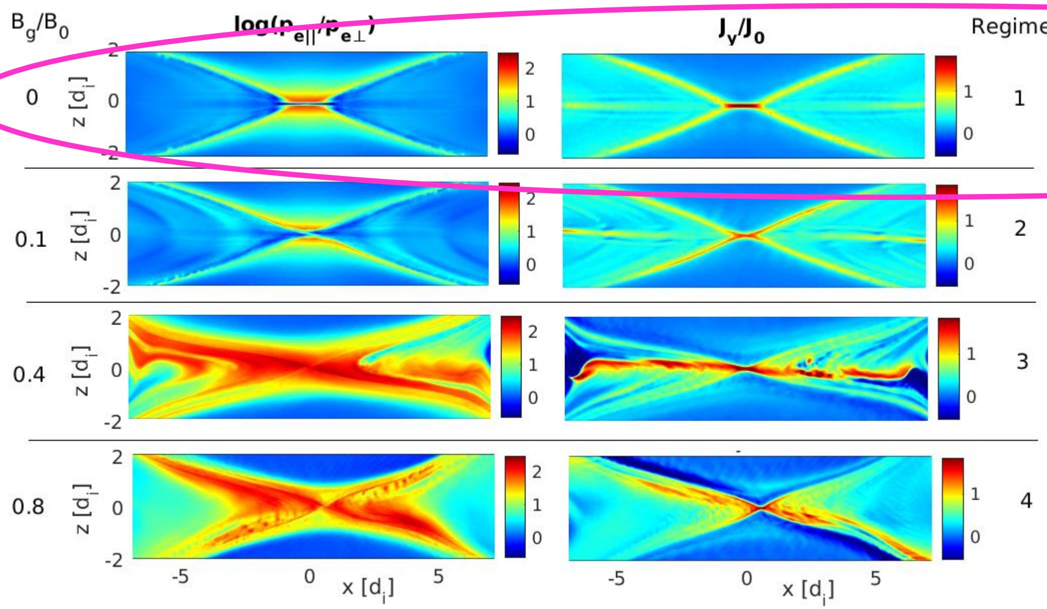
[Egedal, et al., 2005, 2007, 2013]

4 Regimes of Symmetric Reconnection

Trapped electron dynamics yields $P_{e\|} > P_{e\perp}$

B_g/B_{rec} controls 4 regimes of the EDR



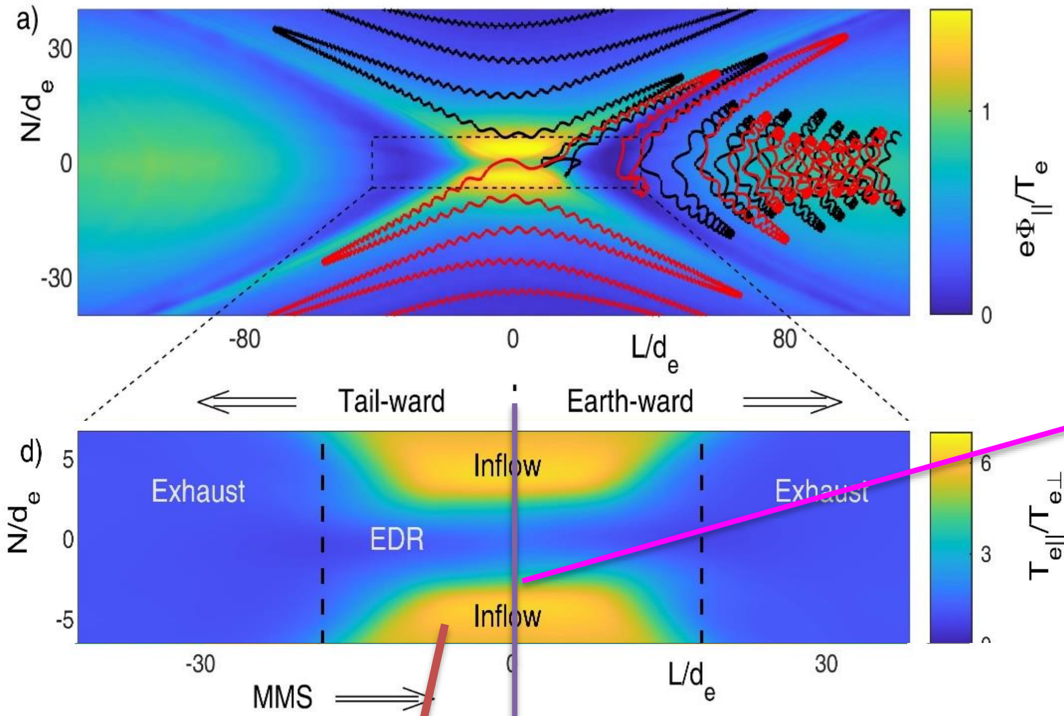


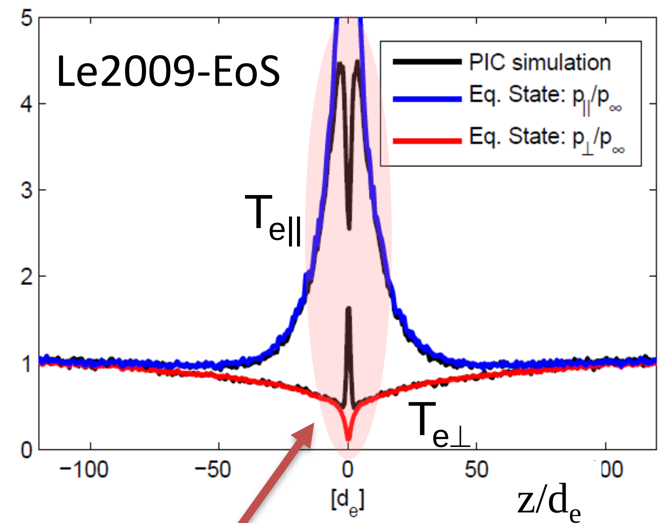
Regime		
1	Meandering Electrons $P_{e\|} \sim P_{e\perp}$ in exhaust	[Torbert+, Science, 2018]
2	No meandering Electrons $P_{e\|} \sim P_{e\perp}$ in exhaust	[Zhou+, ApJ, 2019]
3	No meandering Electrons $P_{e\|} > P_{e\perp}$ in exhaust, Jets	[Wilder+, PRL, 2017] [TREX]
4	No meandering Electrons $P_{e\|} > P_{e\perp}$ in exhaust, no Jets	[Oieroset+, GRL, 2016]

[Le+, 2013, PRL]

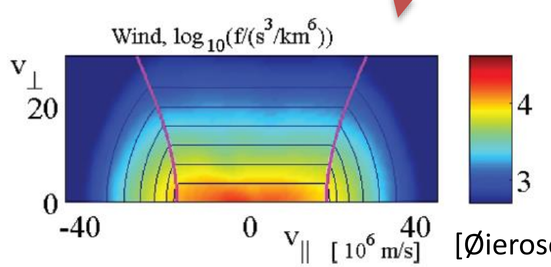
Inflow of Anti-Parallel Reconnection

The electrons are only magnetized in the inflow regions:





Le2009 EoS fantastic in inflows, but break in the EDR



[Øieroset, PRL, 2001]

Drift kinetic model with m_i/m_e ➔ ∞

$$\bar{f}_0(\mathcal{E}_{||},\mathcal{E}_\perp) = \begin{cases} \bar{f}_\infty(\mu B_\infty), & \text{trapped} \\ \bar{f}_\infty(\mathcal{E} - e\Phi_{||}), & \text{passing.} \end{cases}$$

[Egedal, et al., 2005, 2007, 2013]

Le2009-EoS, (CGL-like)

$$p_{||} \propto \frac{n^3}{B^2}, \quad p_\perp \propto nB$$

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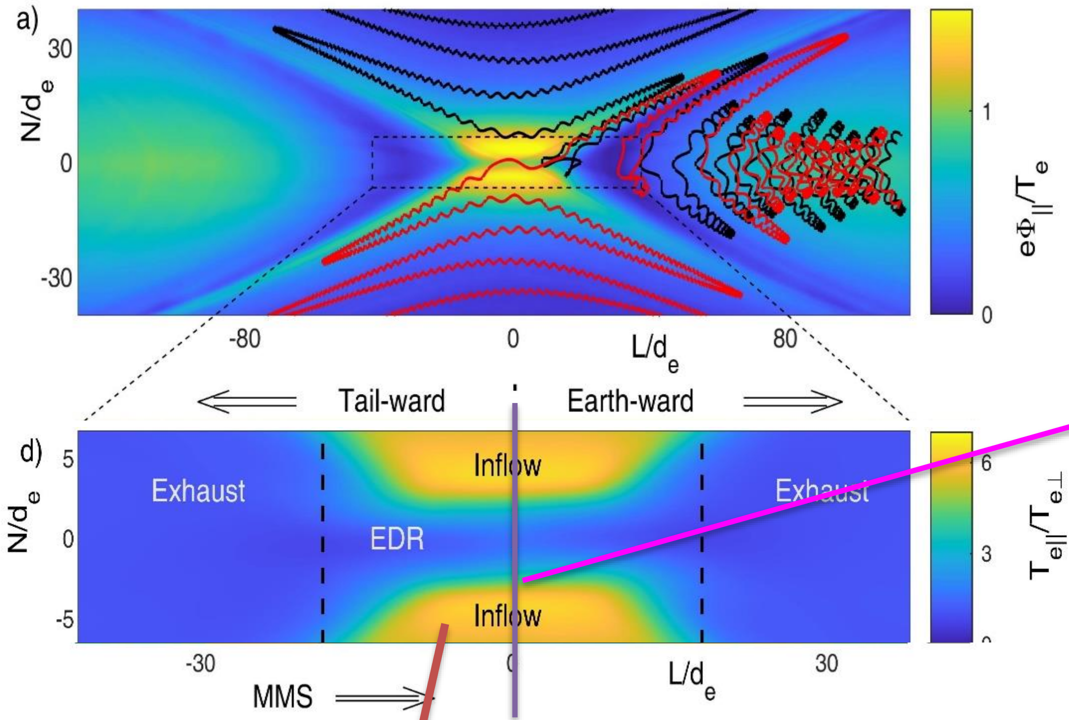

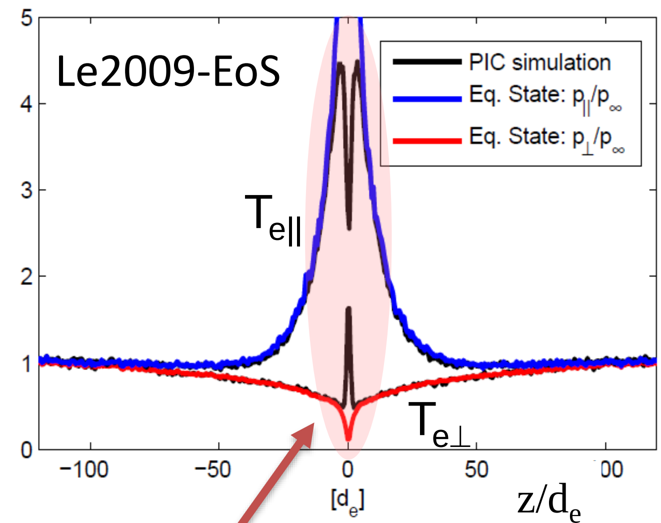

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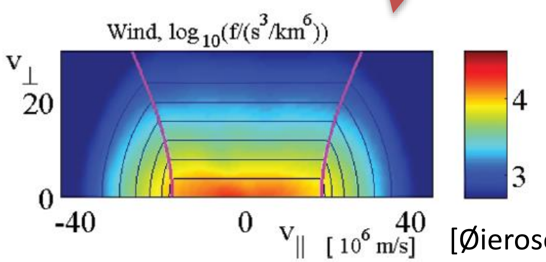


[Øieroset, PRL, 2001]

Drift kinetic model with $m_i/m_e \rightarrow \infty$

$$\bar{f}_0(\mathcal{E}_{||}, \mathcal{E}_\perp) = \begin{cases} \bar{f}_\infty(\mu B_\infty), & \text{trapped} \\ \bar{f}_\infty(\mathcal{E} - e\Phi_{||}), & \text{passing.} \end{cases}$$

[Egedal, et al., 2005, 2007, 2013]

Replace with: $\mathcal{J}_z \propto \oint v_z dz$

Le2009-EoS, (CGL-like)

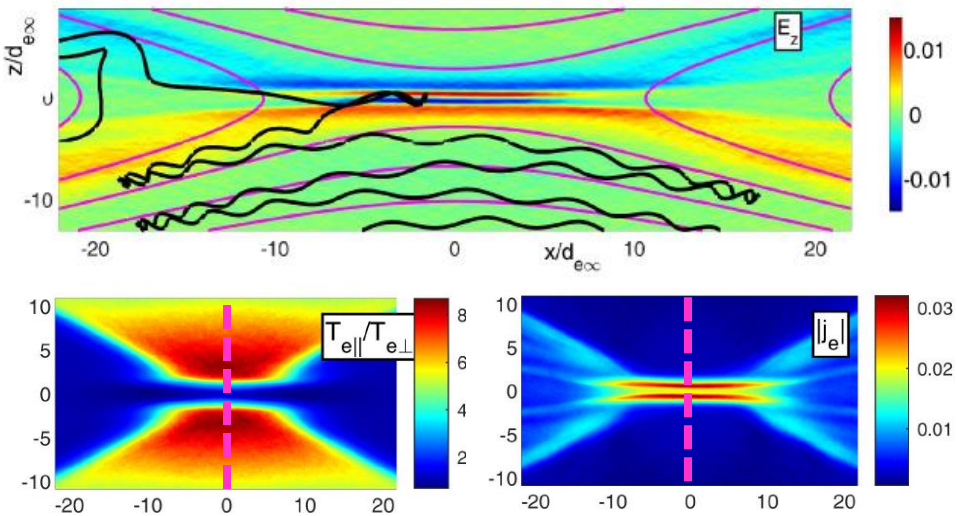
$$p_{||} \propto \frac{n^3}{B^2}, \quad p_\perp \propto nB$$

[Speiser 1970; Sonnerup 1971; Buchner 1989]

Application to Anti-Parallel Magnetic Reconnection

EDR includes a 1D current layer, driven by $T_{e\|} \gg T_{e\perp}$

[Le+ 2009, Egedal+ 2013]



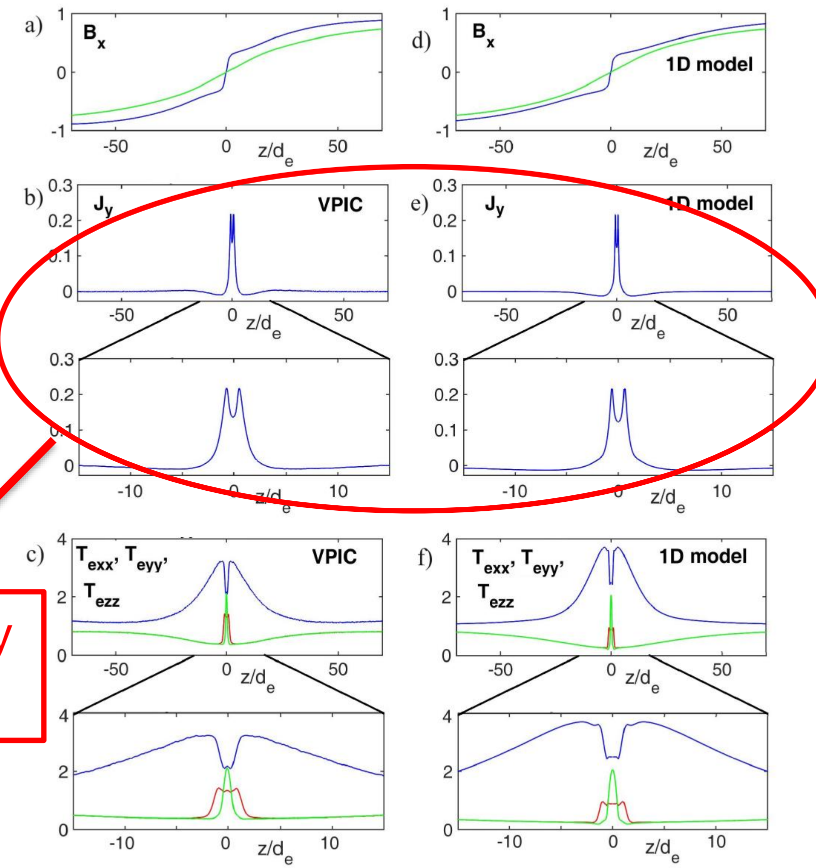
Update previous inflow model:

$$f(z, \mathbf{v}) = \begin{cases} \bar{f}_\infty(\mathcal{J}_z B_\infty) & , \text{ trapped} \\ \bar{f}_\infty(\mathcal{E} - e\Phi(z)) & , \text{ passing} \end{cases}$$

Now applies to Inflow <u>and EDR</u>

Solution in agreement with VPIC

[Egedal, GRL, 2024]



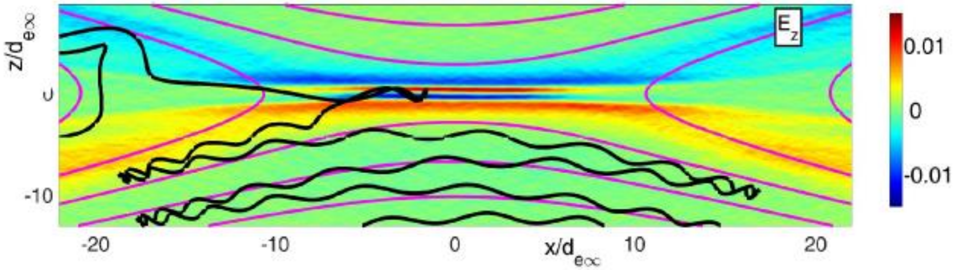
J_{ey} driven by $T_{e\|} \gg T_{e\perp}$

Only inputs: B from ions, ion density, and $f_{e\infty}(v)$.

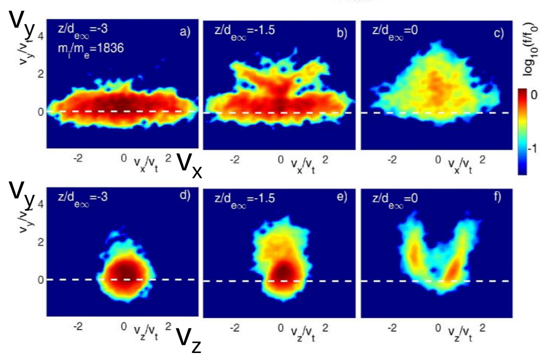
Note: E_{rec} not important to 1D model

Application to Anti-Parallel Magnetic Reconnection

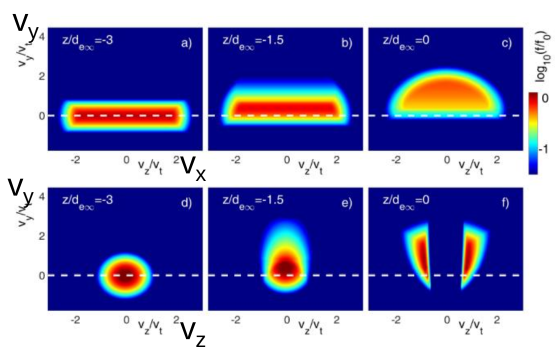
EDR includes a 1D current layer, driven by $T_{e\|} >> T_{e\perp}$
[Le+ 2009, Egedal+ 2013]



VPIC f_e :

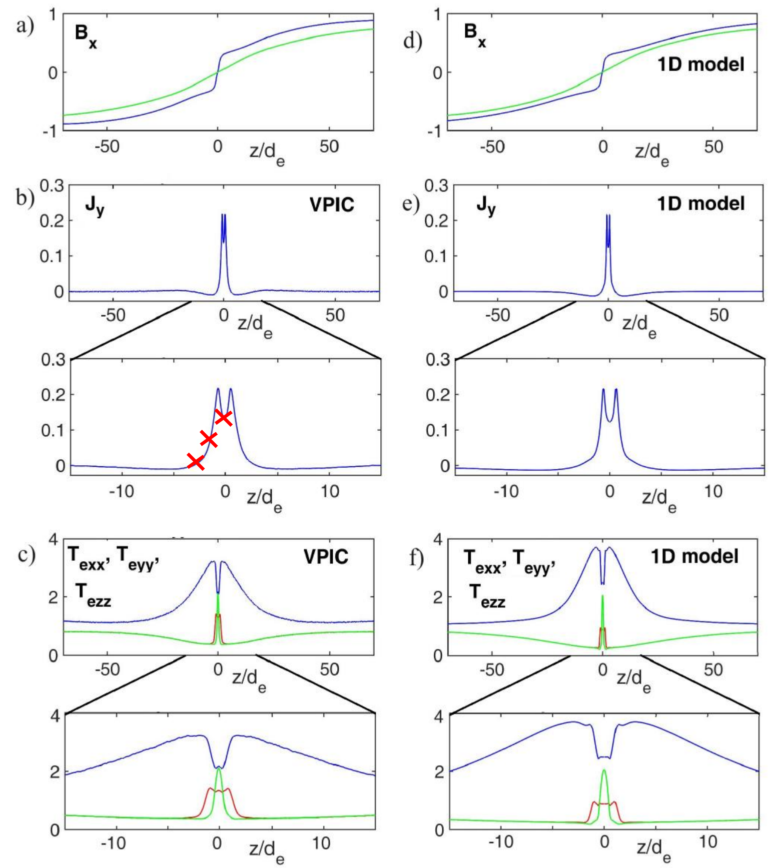


Model f_e :



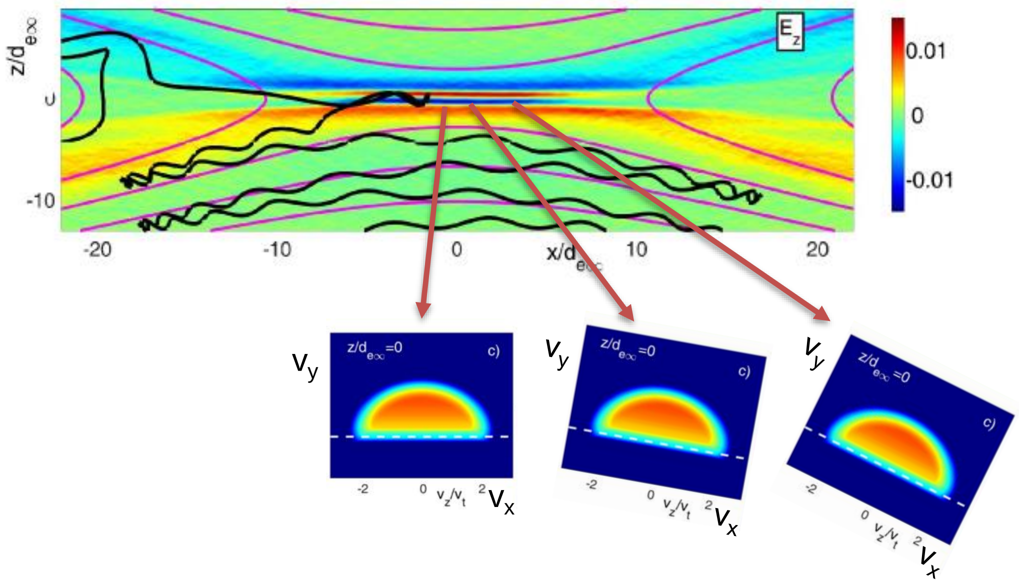
Off-diagonal stress?

Solution in agreement with VPIC
[Egedal, GRL, 2024]



Only inputs: B from ions, ion density, and $f_{e\infty}(v)$.
Note: E_{rec} not important to 1D model

How E_{rec} is balance by thermal forces



EDR distributions rotate like a solid body at the rate x/l_u

$$p_{exy} = \frac{x}{l_u} \left(p_{eyy} - p_{exx}\right)|_{\text{X-line}}$$

$$-\frac{1}{en}\frac{\partial p_{exy}}{\partial x} = -\frac{1}{enl_u}\left(p_{eyy} - p_{exx}\right)\Big|_{X-line}$$

$$-\frac{1}{en}\frac{\partial p_{eyz}}{\partial z} = \frac{1}{enl_u}\left(p_{eyy} - p_{exx}\right)\Big|_{X-line}$$

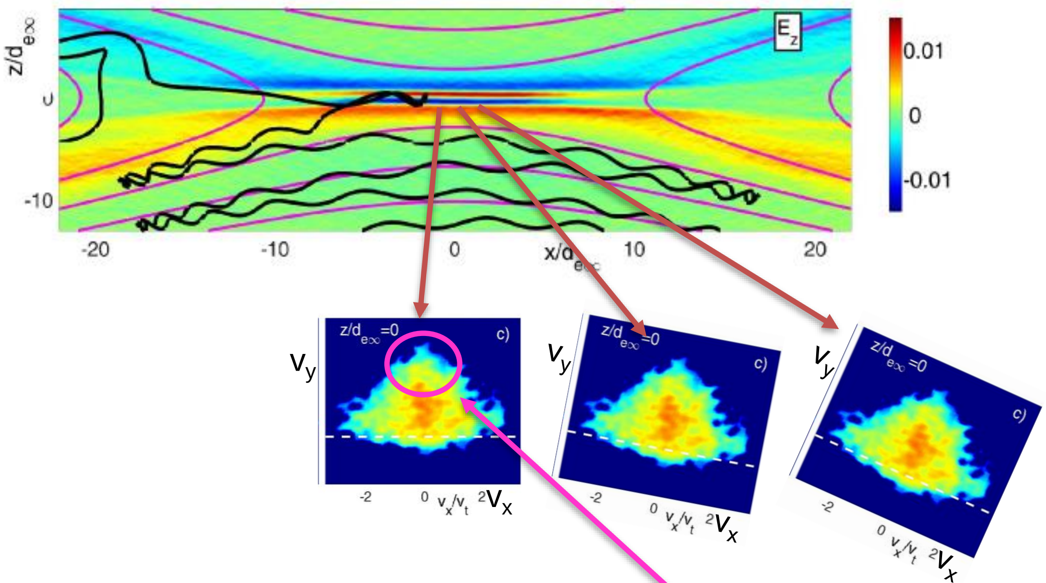
At X-line:

$$E_{\text{rec}} = -\frac{1}{en}\left(\frac{\partial p_{exy}}{\partial x} + \frac{\partial p_{eyz}}{\partial z}\right) = 0$$

For 1D model with E_{rec}=0, terms must cancel

Off-diagonal stress?

How E_{rec} is balance by thermal forces



EDR distributions rotate like a solid body at the rate x/l_u

$$p_{exy} = \frac{x}{l_u}\,(p_{eyy} - p_{exx})|_{\text{X-line}}$$

$+\Delta p_{eyy}$

$$-\frac{1}{en}\frac{\partial p_{exy}}{\partial x} = -\frac{1}{enl_u}(p_{eyy} - p_{exx})\Big|_{X-line}$$

$$-\frac{1}{en}\frac{\partial p_{eyz}}{\partial z} = \frac{1}{enl_u}(p_{eyy} - p_{exx})\Big|_{X-line}$$

E_{rec} enhances p_{eyy} , by Δp_{eyy}

At X-line:

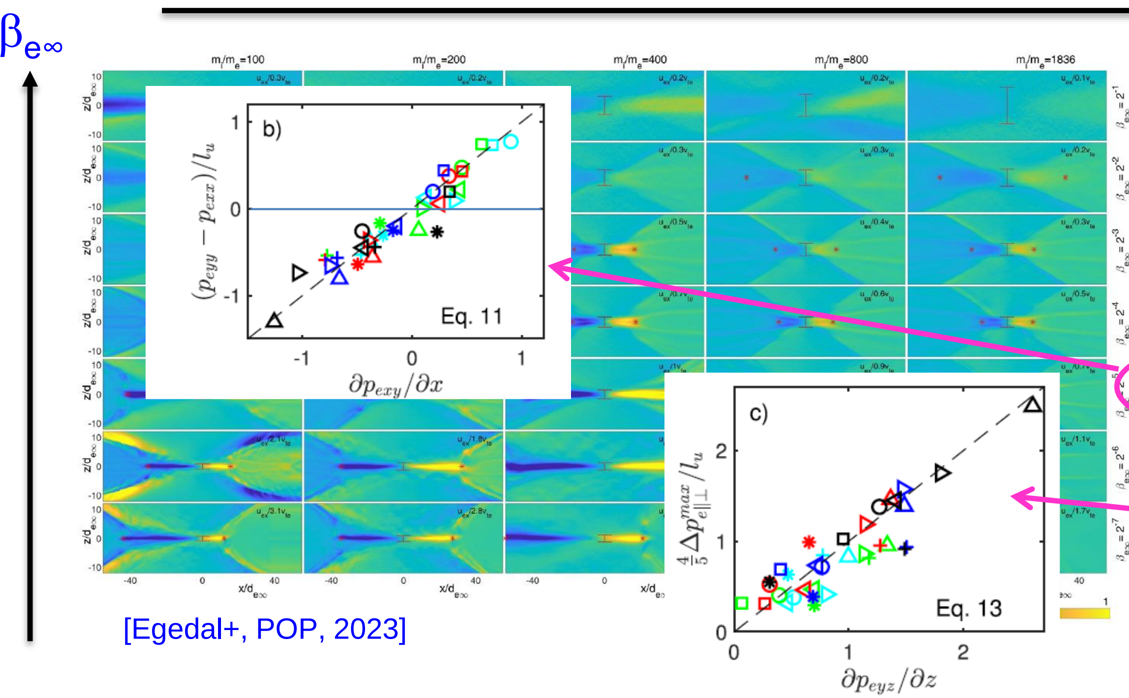
$$E_{\text{rec}} = -\frac{1}{en}\left(\frac{\partial p_{exy}}{\partial x} + \frac{\partial p_{eyz}}{\partial z}\right) = \Delta p_{eyy}/\,(enl_u)$$

For 1D model with E_{rec}=0, terms must cancel

E_{rec} balanced by $\Delta p_{eyy}/\,(enl_u)$

Off-diagonal stress?

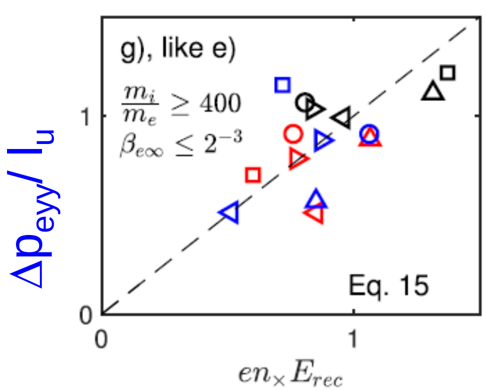
Confirmed by matrix of kinetic simulations



[Egedal+, POP, 2023]

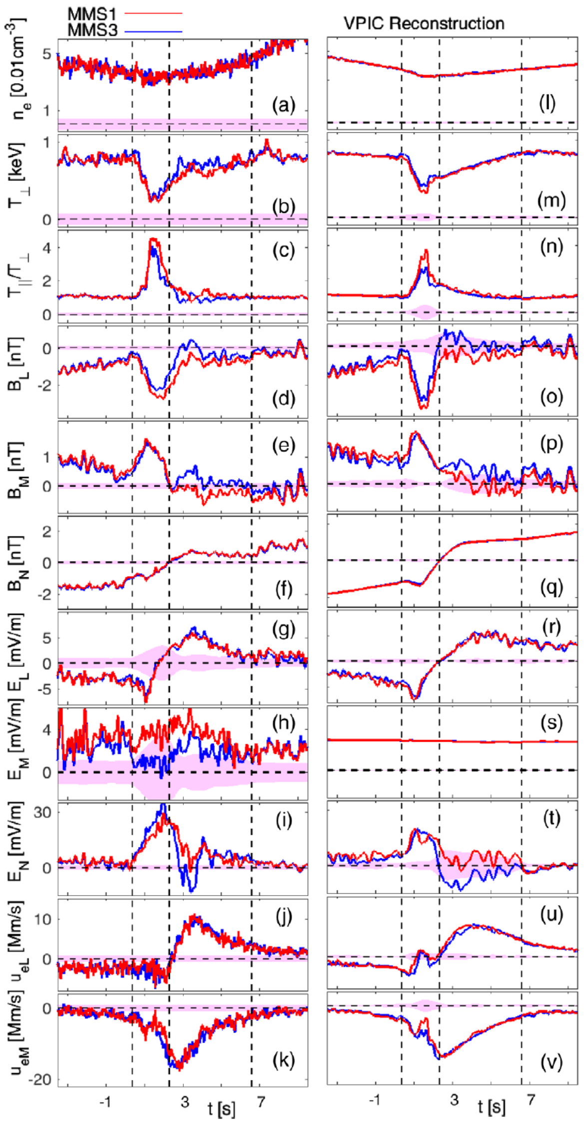
$$-\frac{1}{en}\frac{\partial p_{exy}}{\partial x} = -\frac{1}{enl_u}(p_{eyy} - p_{exx})\Big|_{X-line}$$

$$-\frac{1}{en}\frac{\partial p_{eyz}}{\partial z} = \frac{1}{enl_u}(p_{eyy} - p_{exx})\Big|_{X-line}$$

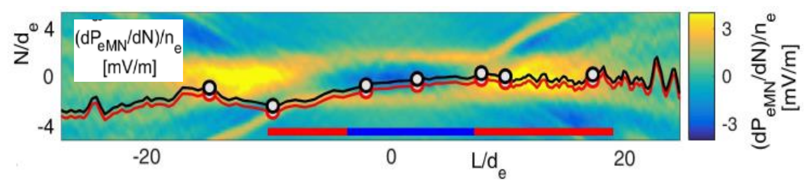


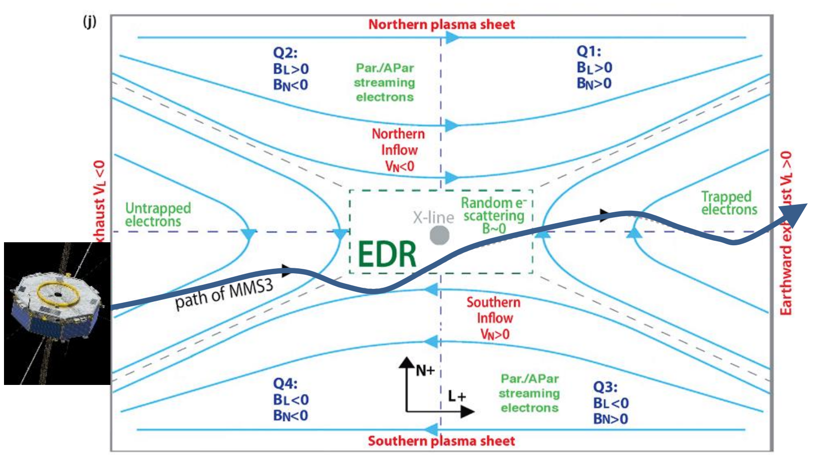
E_{rec} balanced by $\Delta p_{eyy}/ (enl_u)$

Torbert's tail event, MMS 11 July 2017



$$-\frac{1}{en}\frac{\partial p_{exy}}{\partial x} = -\frac{1}{enl_u}(p_{eyy} - p_{exx})\bigg|_{X-line}$$





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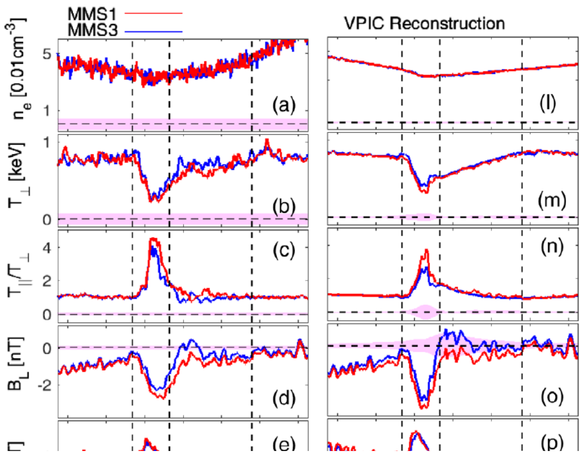
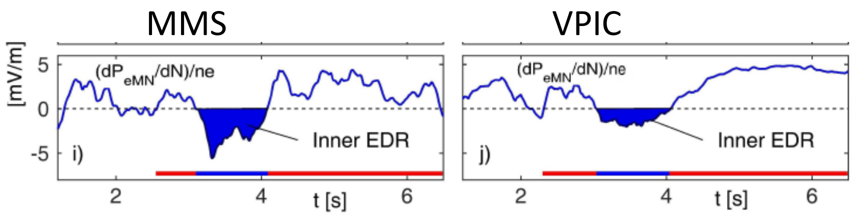
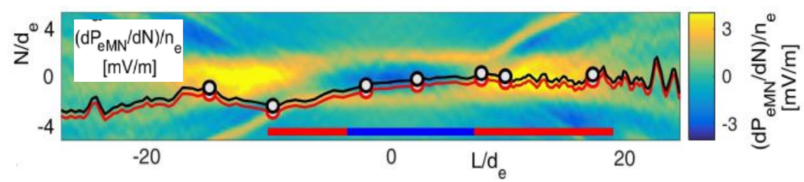


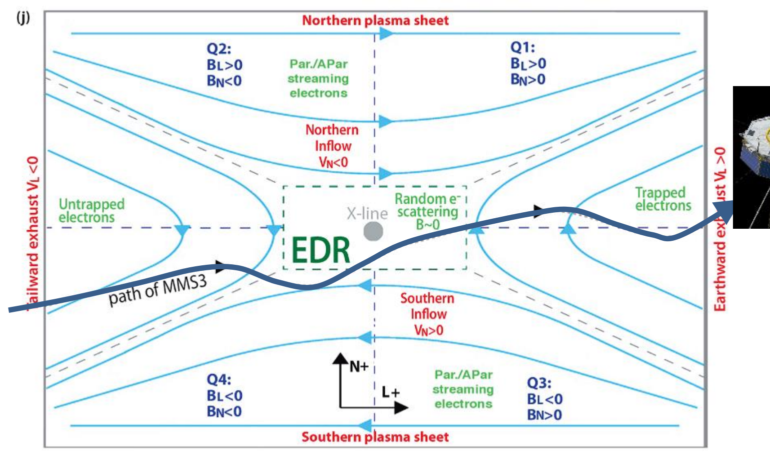
$$-\frac{1}{en}\frac{\partial p_{exy}}{\partial x} = -\frac{1}{enl_u}(p_{eyy} - p_{exx})\Big|_{X-line}$$





$$E_M + (\partial P_{eLM}/\partial L)/ne = \ 4 \pm 1 \text{ mV/m}$$

$$(\partial P_{eMN}/\partial N)/ne \simeq \ -3.6 \pm 0.8 \text{ mV/m}$$



MMS confirms:

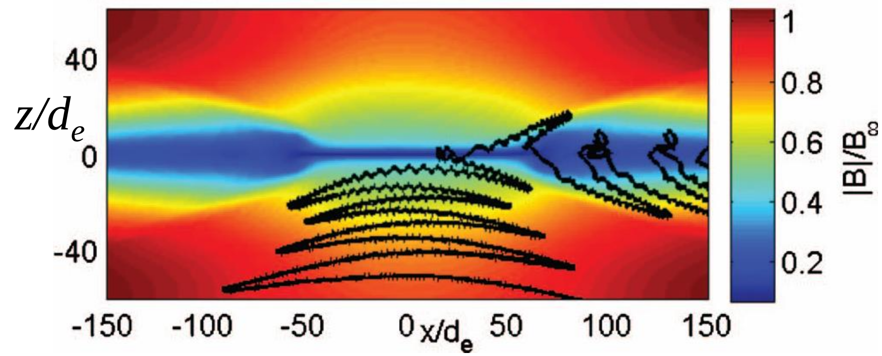
$$E_{\rm rec} = -\frac{1}{en}\left(\frac{\partial P_{eLM}}{\partial L} + \frac{\partial P_{eMN}}{\partial N}\right)$$

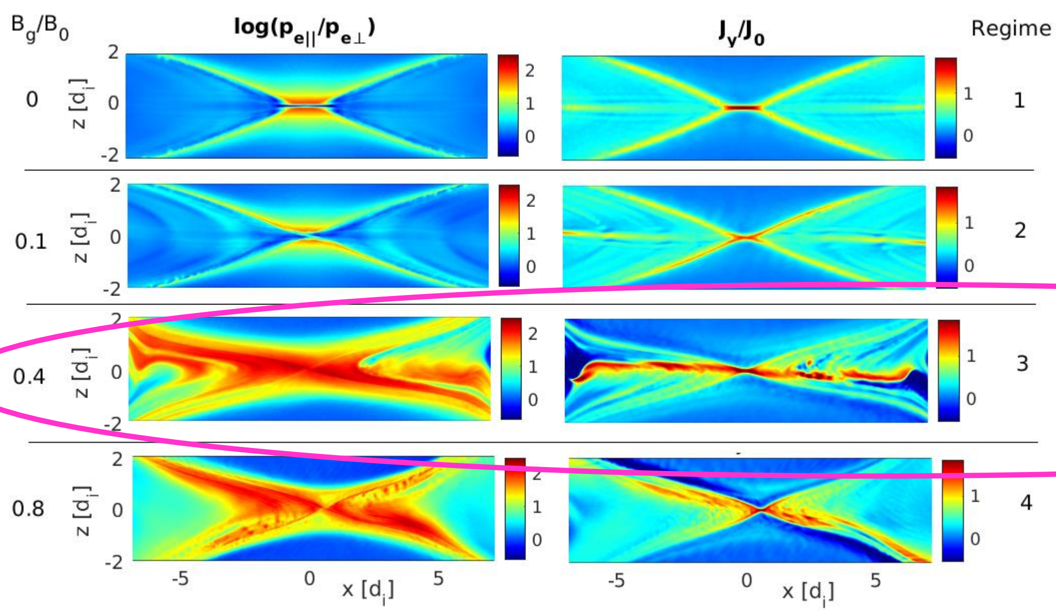
[Egedal+, PRL, 2016]

4 Regimes of Symmetric Reconnection

Trapped electron dynamics yields $P_{e\parallel} > P_{e\perp}$

B_g/B_{rec} controls 4 regimes of the EDR





Meandering Electrons [Torbert+, Science, 2018]
$P_{e\parallel} \sim P_{e\perp}$ in exhaust

No meandering Electrons [Zhou+, ApJ, 2019]
$P_{e\parallel} \sim P_{e\perp}$ in exhaust

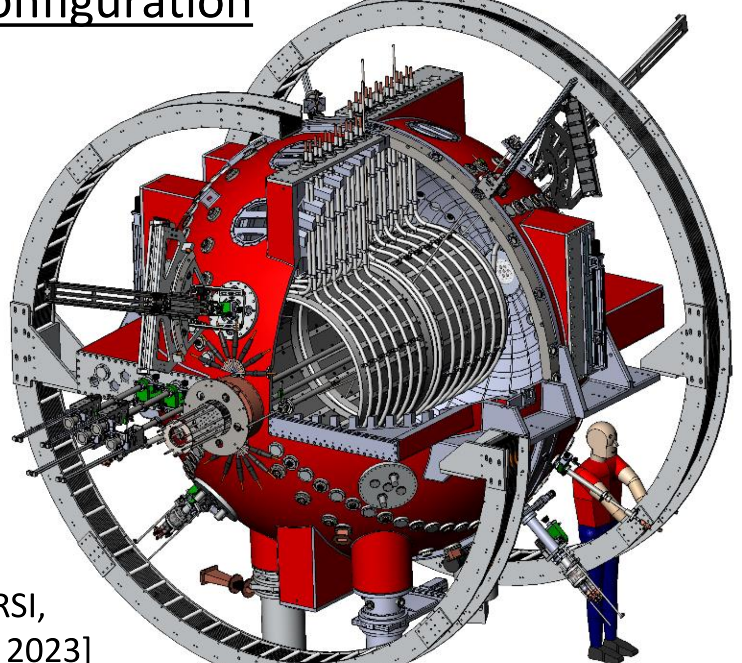
No meandering Electrons [Wilder+, PRL, 2017]
$P_{e\parallel} > P_{e\perp}$ in exhaust, Jets [TREX]

No meandering Electrons [Oieroset+, GRL, 2016]
$P_{e\parallel} > P_{e\perp}$ in exhaust, no Jets

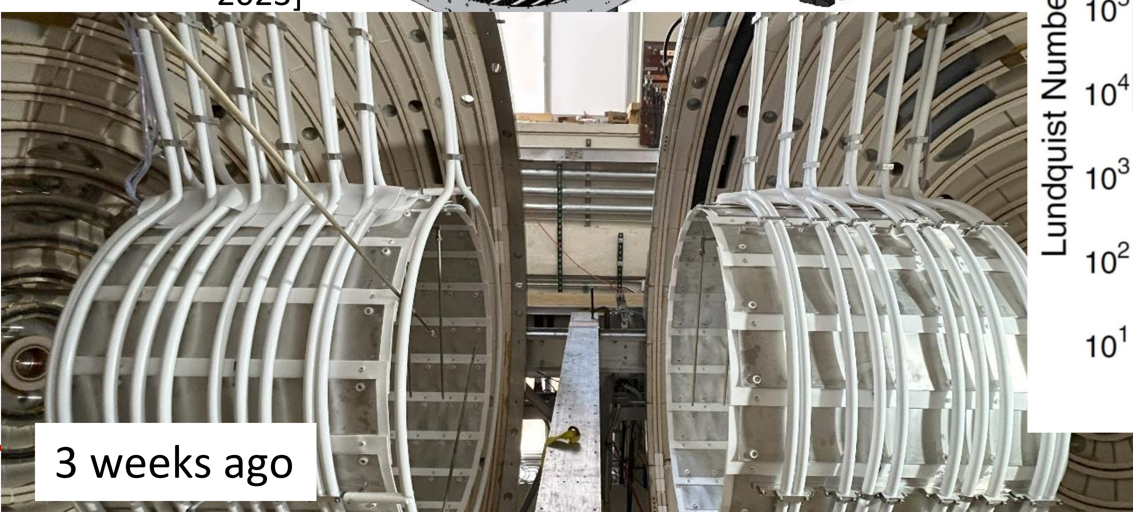
[Le+, 2013, PRL]

Kinetic Regime at Reach in TREX

<u>TREX Configuration</u>

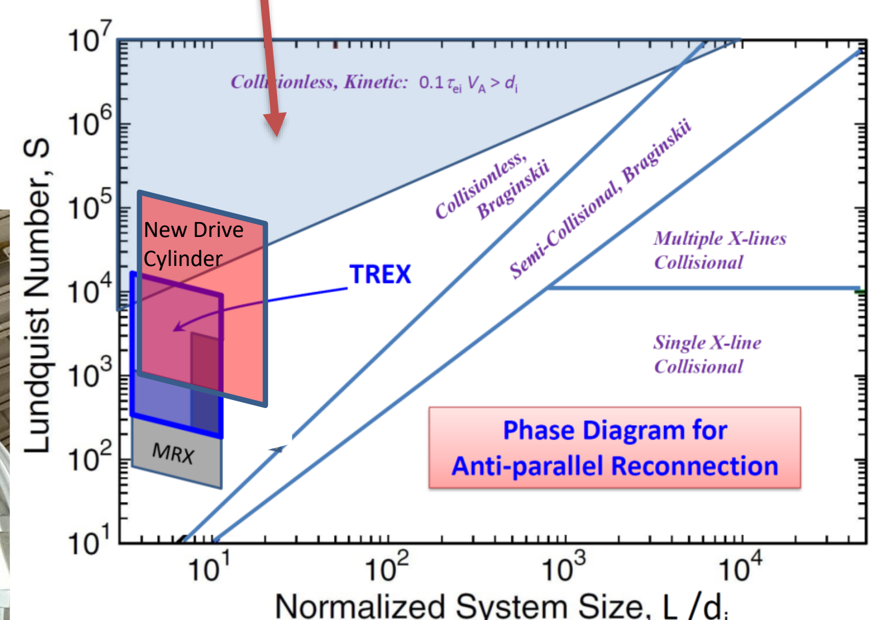


[Gradney+, RSI, 2023]



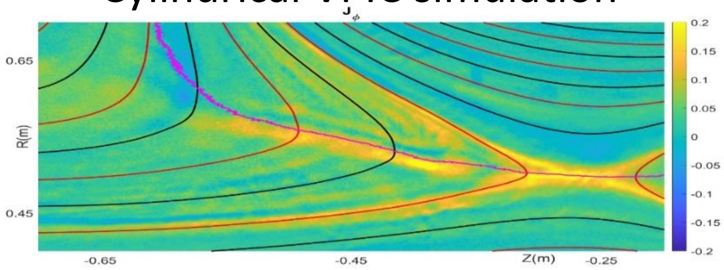
Phase diagram of magnetic reconnection. [Daughton,Roytershteyn & Ji , Daughton 2021]

Kinetic regime defined in [Le+, JPP, 2015]

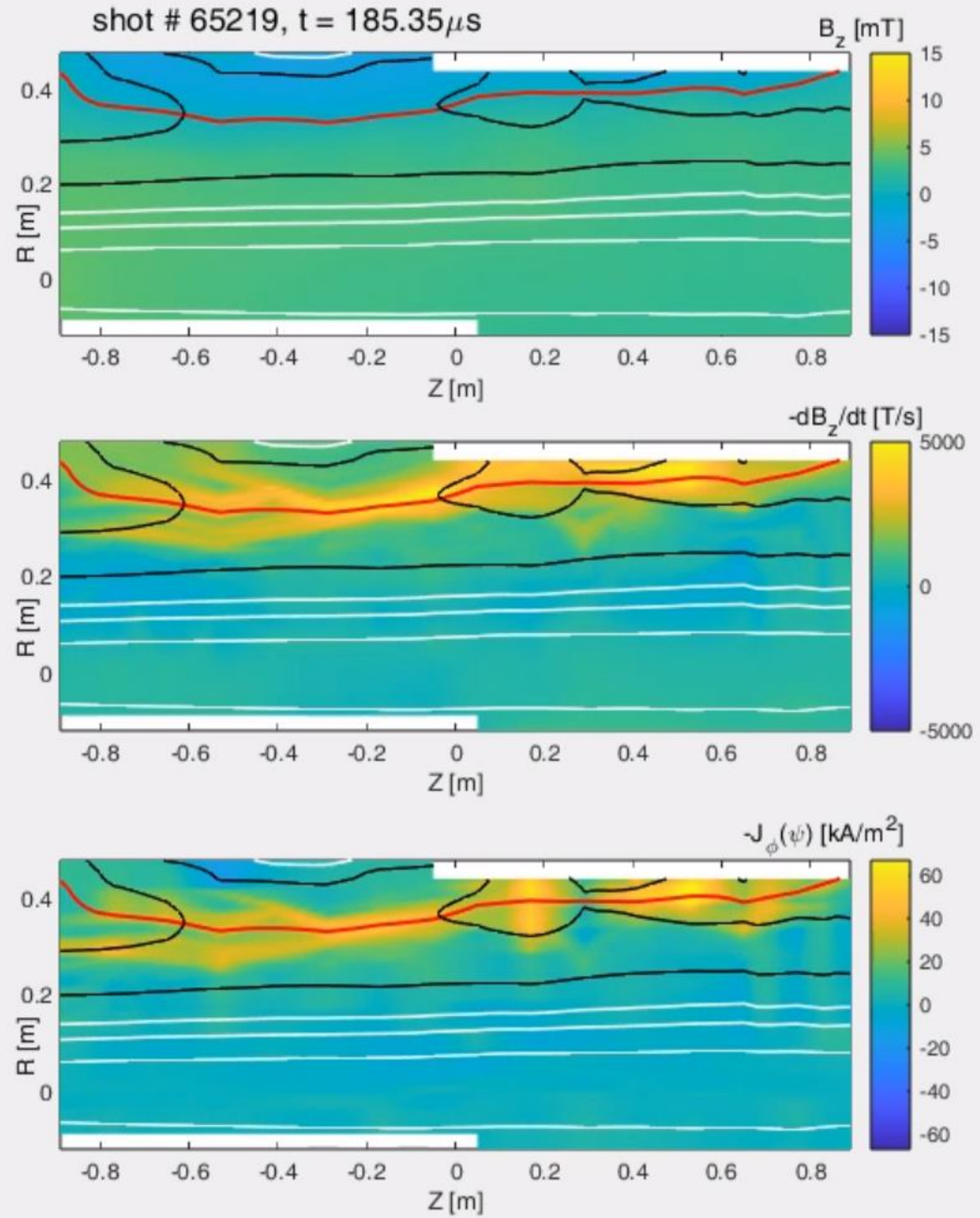


Kinetic Regime at

Cylindrical VPIC simulation



For more on TREX, see
Paul Gradney's poster



Conclusions

- In the collisionless regime trapping shots down electron heat-fluxes. Convection of flux-tubes into the region of low B yields strong electron anisotropy, $p_{e\|} \gg p_{e\perp}$, within the IDR
- Currents driven by $p_{e\|} \gg p_{e\perp}$ dominates the structures of the IDR and EDR
- An adiabatic model using $\mathcal{J}_z \propto \oint v_z dz$ accounts for the anisotropic heating and electrons currents across the inflow and EDR of anti-parallel reconnection
- TREX can now access the kinetic regime
- WiPPL is a user-facility, and we are open for your business!