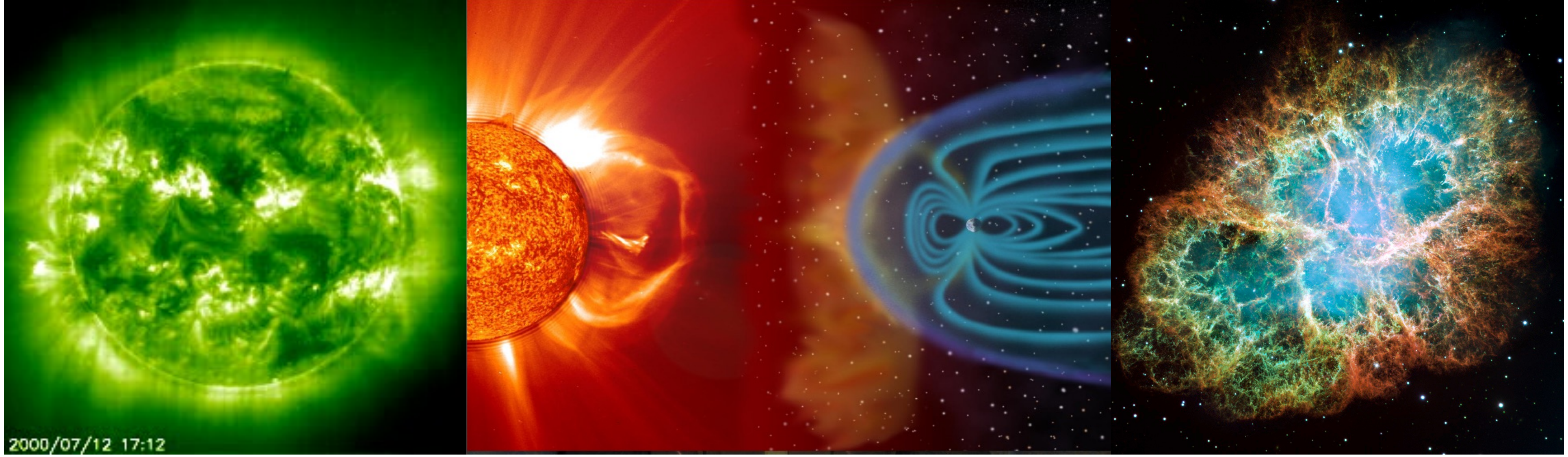


Experimental observation of Petschek's double shock structure in a two-fluid magnetic reconnection layer

by Masaaki Yamada and Jongsoo Yoo

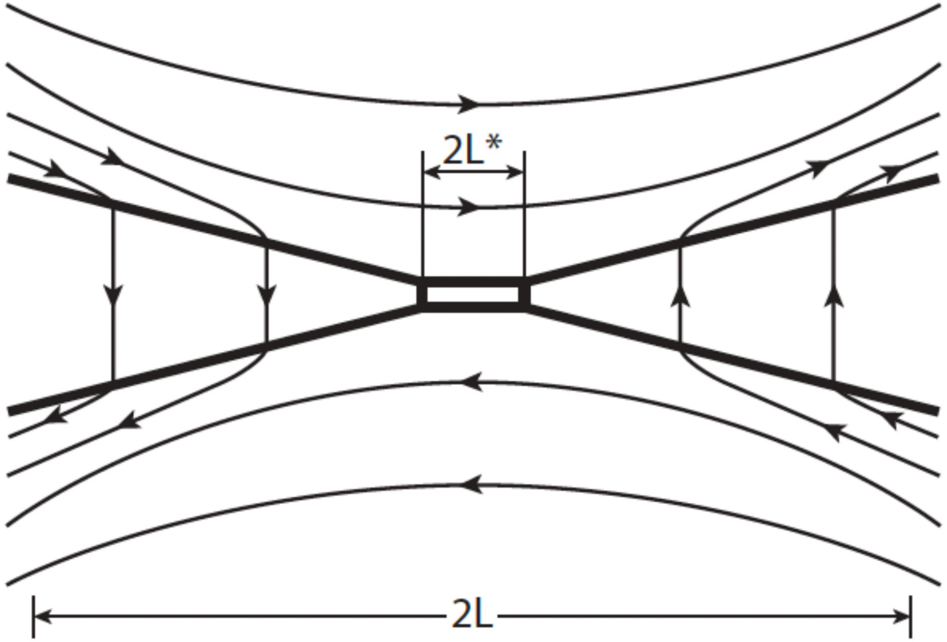
Princeton Plasma Physics Laboratory

IPELS Meeting at Garching Germany

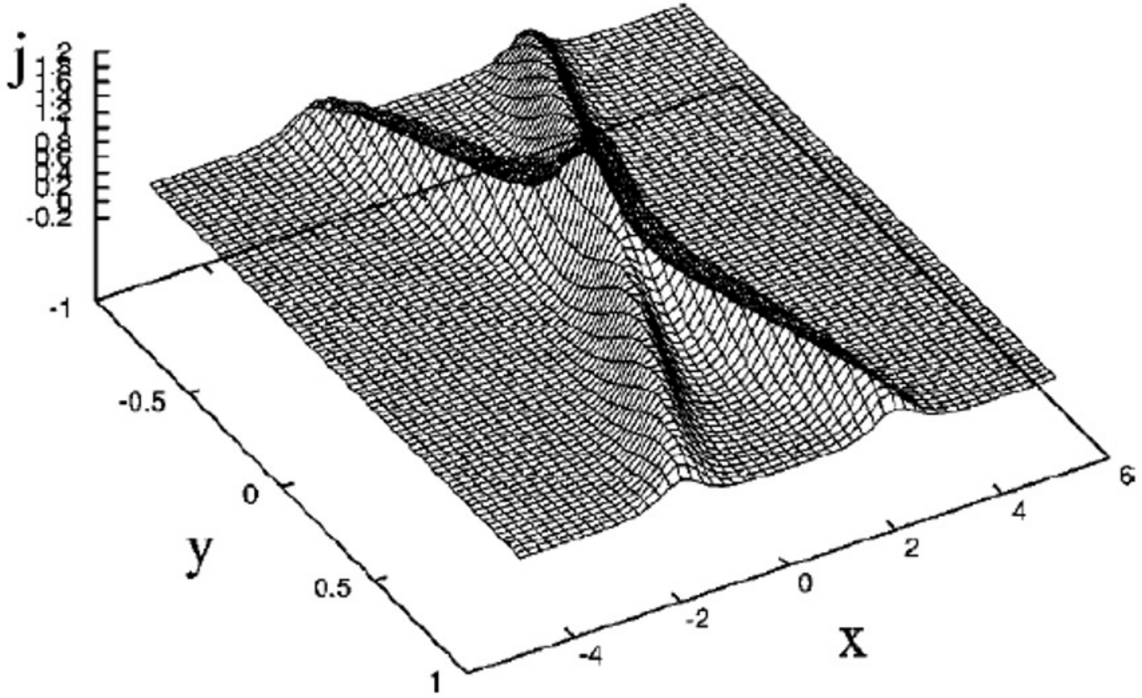
August 5, 2024

Fast reconnection model conceived by H. Petschek based on MHD in 1964 has been very popular because it agrees well observations.

But its exact mechanism has not been well understood.



Petschek Model (1963)



Sato & Hayashi (1985)

Uzdensky and Kulsrud (2000)

Outline

- Petshek Model (1964)
- Two-fluid physics of a typical magnetic reconnection layer
- The presence of sharp electron current layers at the separatrices
- **Comparison of our results with space data and simulations**
- Discussions and summary

=> A progress report for quantitative model of energy conversion and inventory

- Petschek model has been studied in the MRX

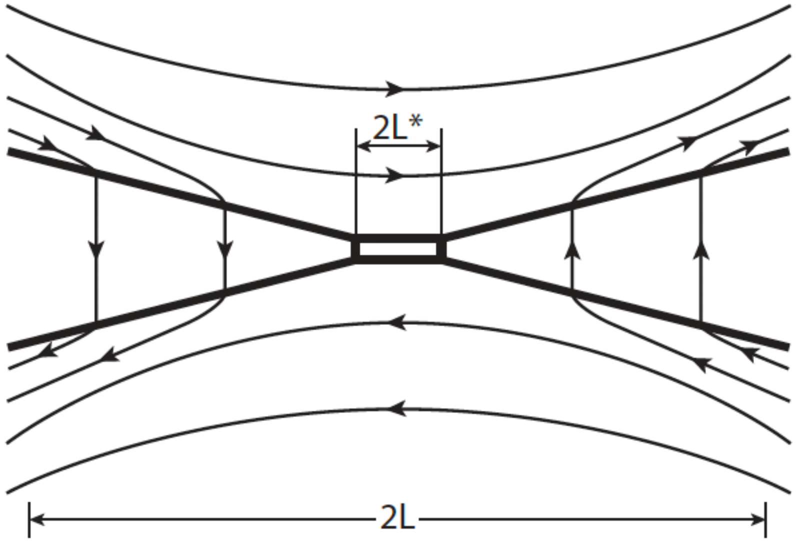
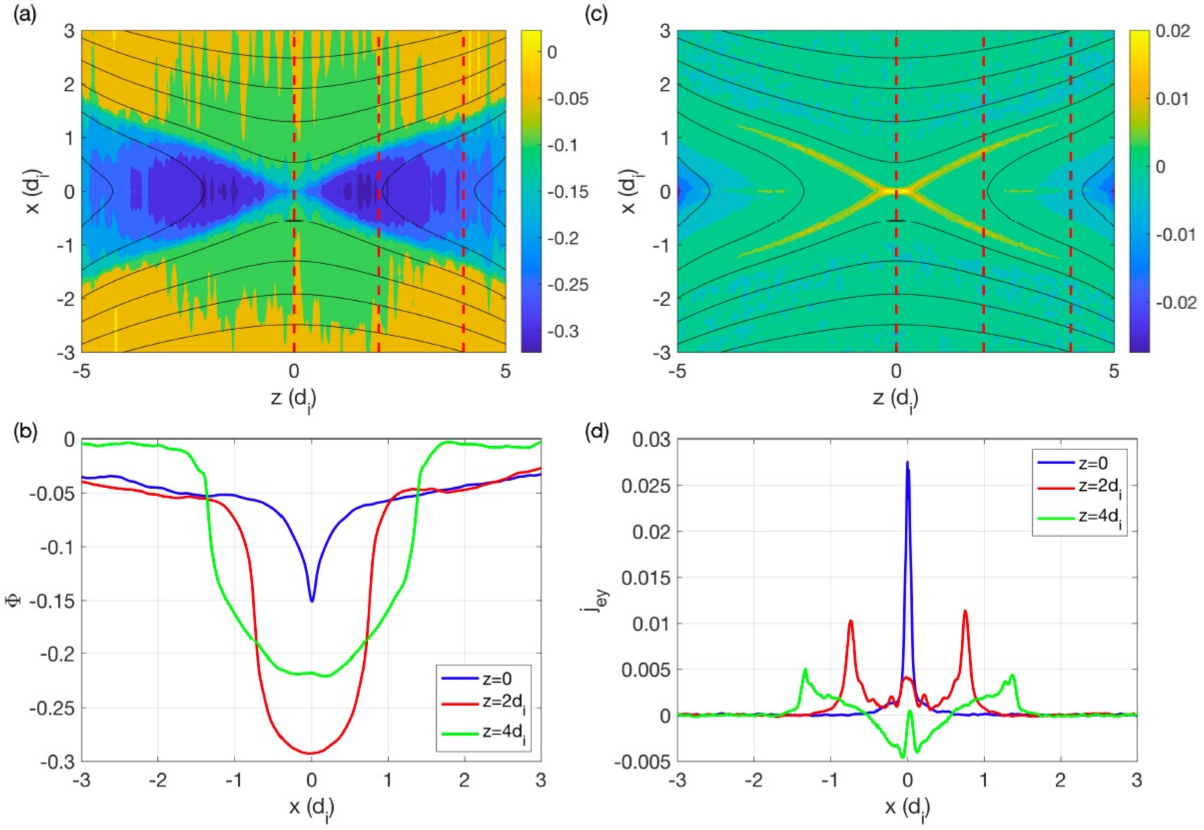
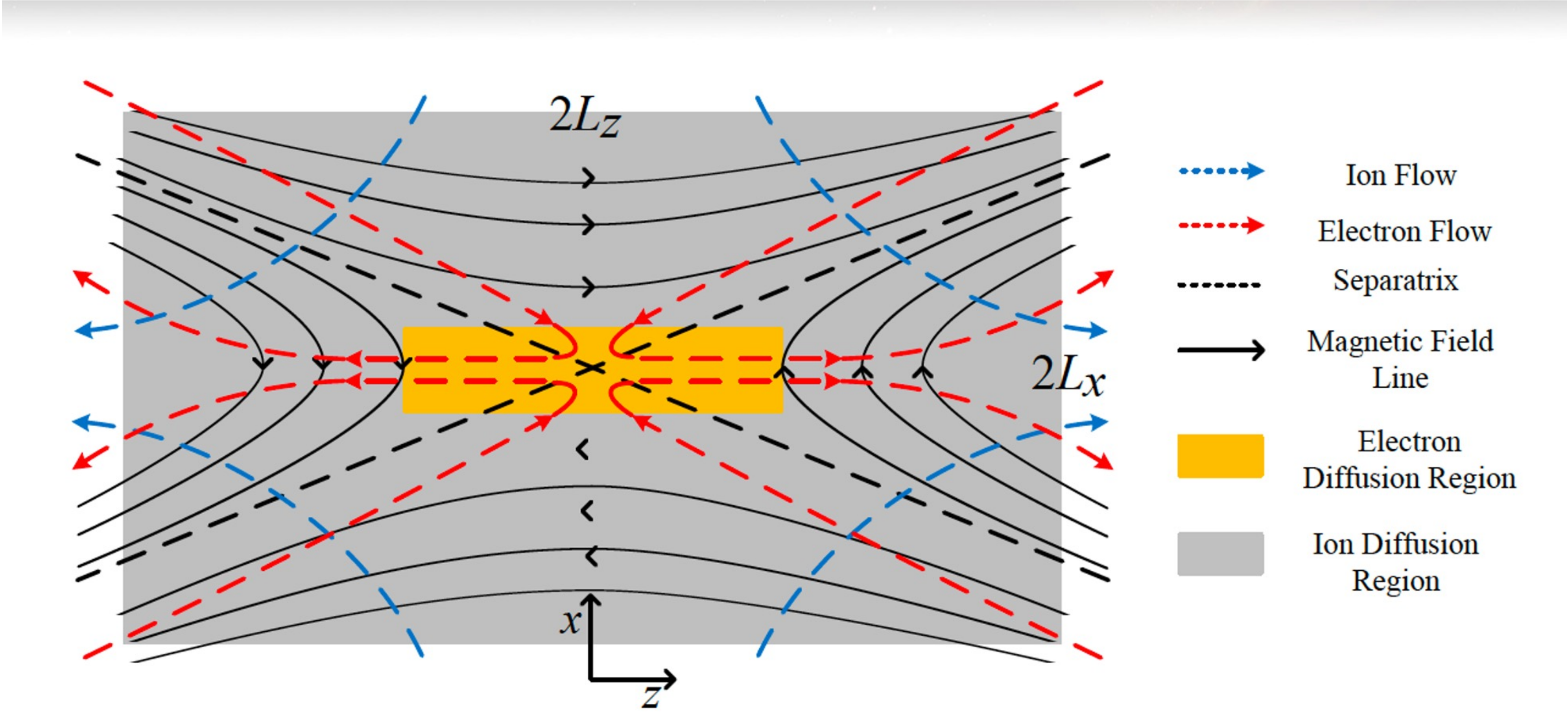


Figure 3.4. Petschek model. [From Yamada et al. (2010).]

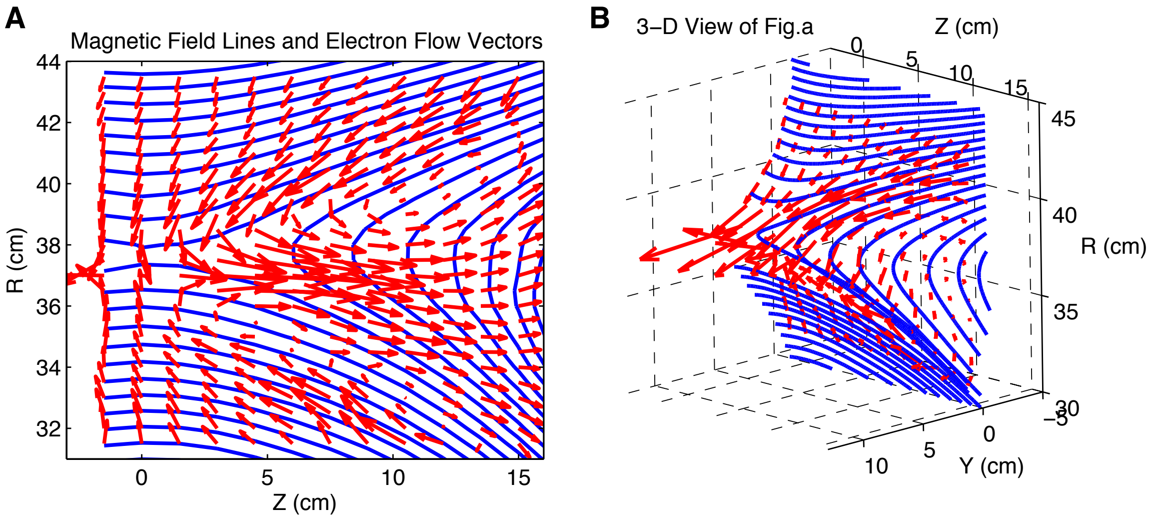
Advanced simulation for the MRX reconnection layer in the two-fluid regime (J. Yoo)



Dynamics of 2-fluid reconnection layer



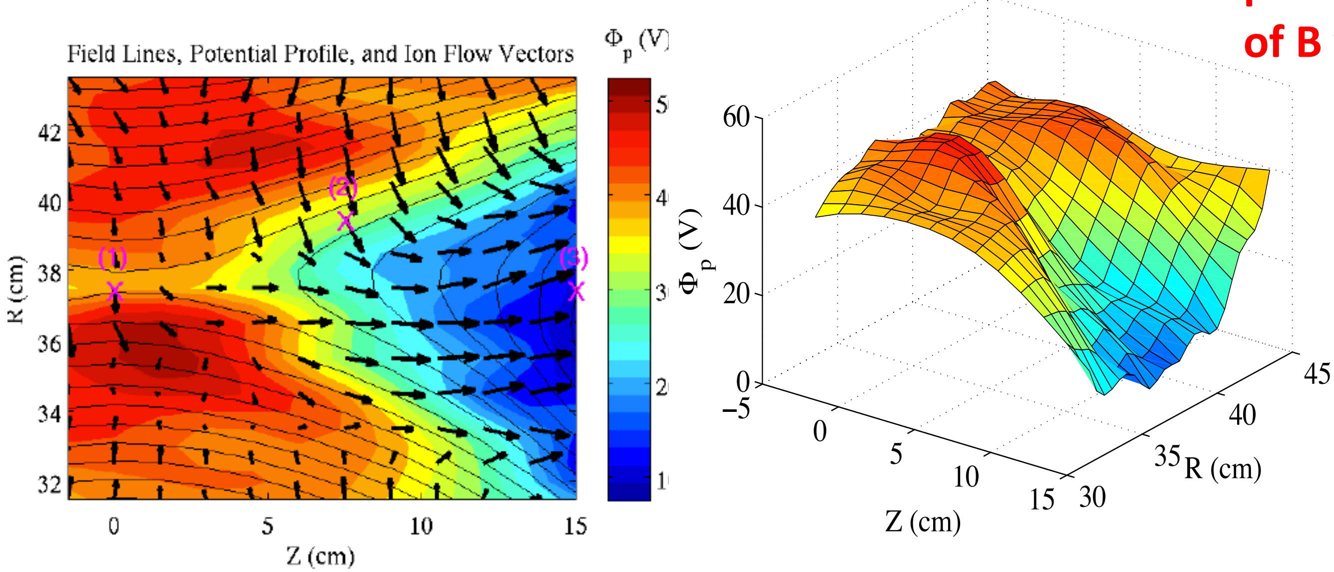
Characteristics of MRX Data: Yamada et al, Nature Comms (2014), Princeton University Press (2022)



Electron dynamics

$$\boxed{j_\perp E_\perp >> j_{//} E_{//}}$$

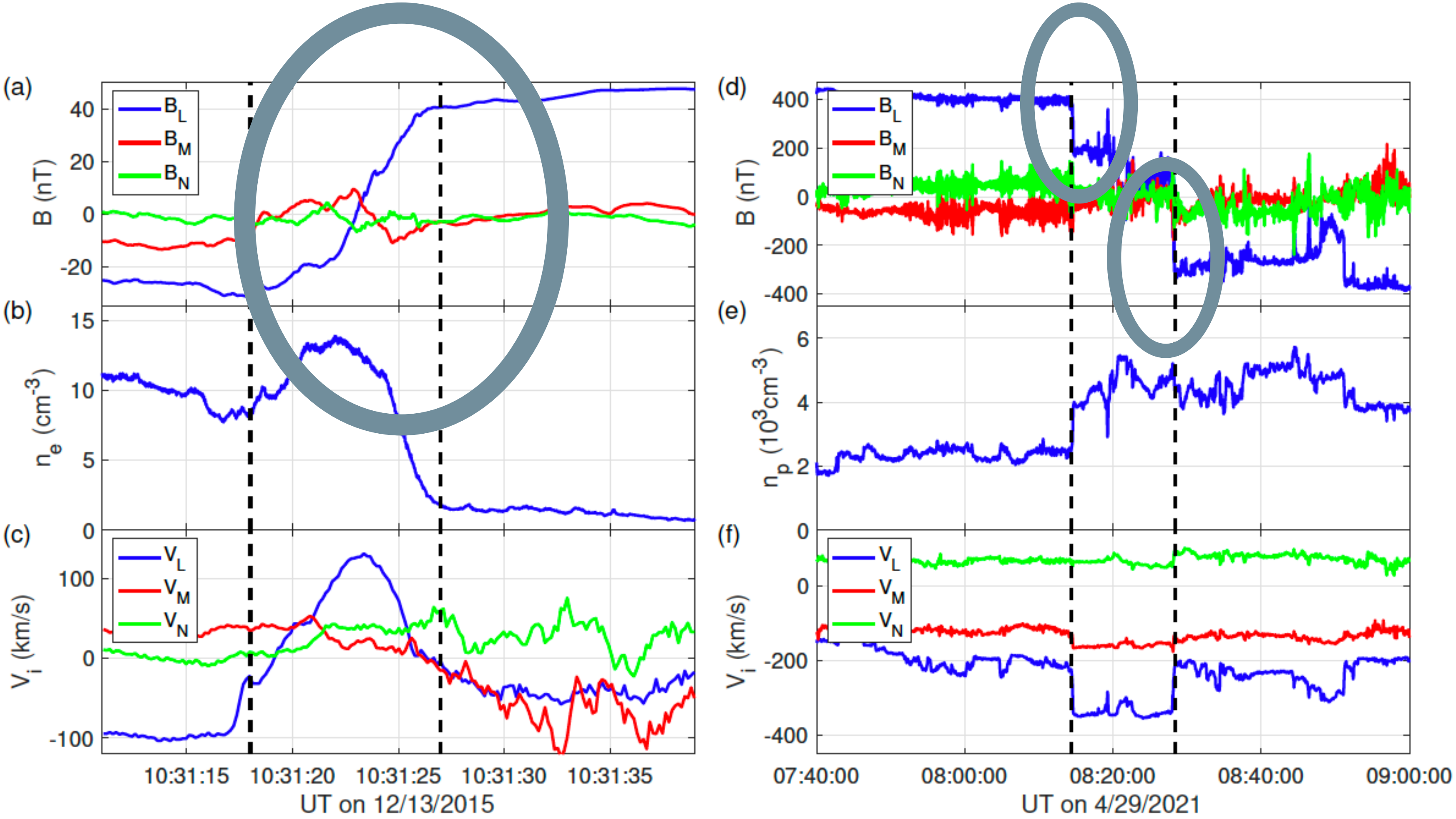
- Electron dynamics generates a strong potential well in the two-fluid reconnection layer
- **Electrons are also accelerated in out-of-plane direction, which makes sharp turns of B vectors**



Ion dynamics

Ions are directly accelerated by in-plane electrostatic fields generated by electron dynamics

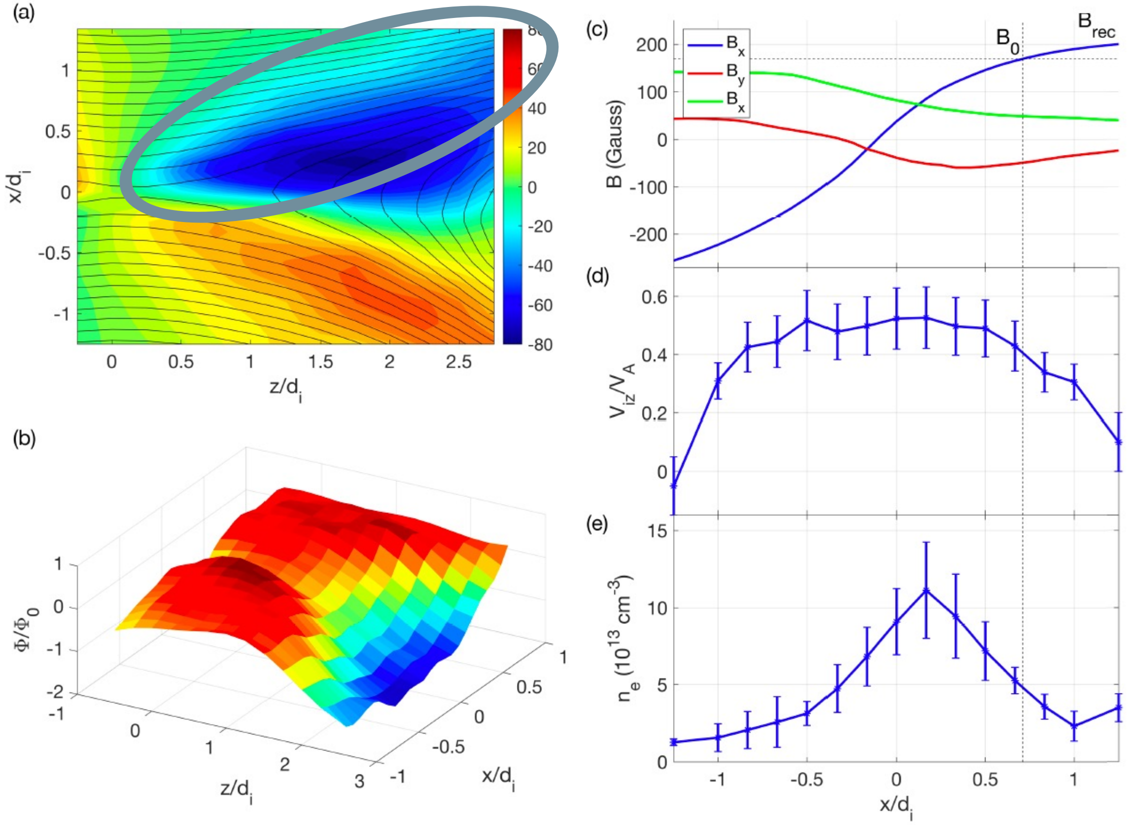
Our recent simulation agrees very well with the MMS data and Parker Probe data



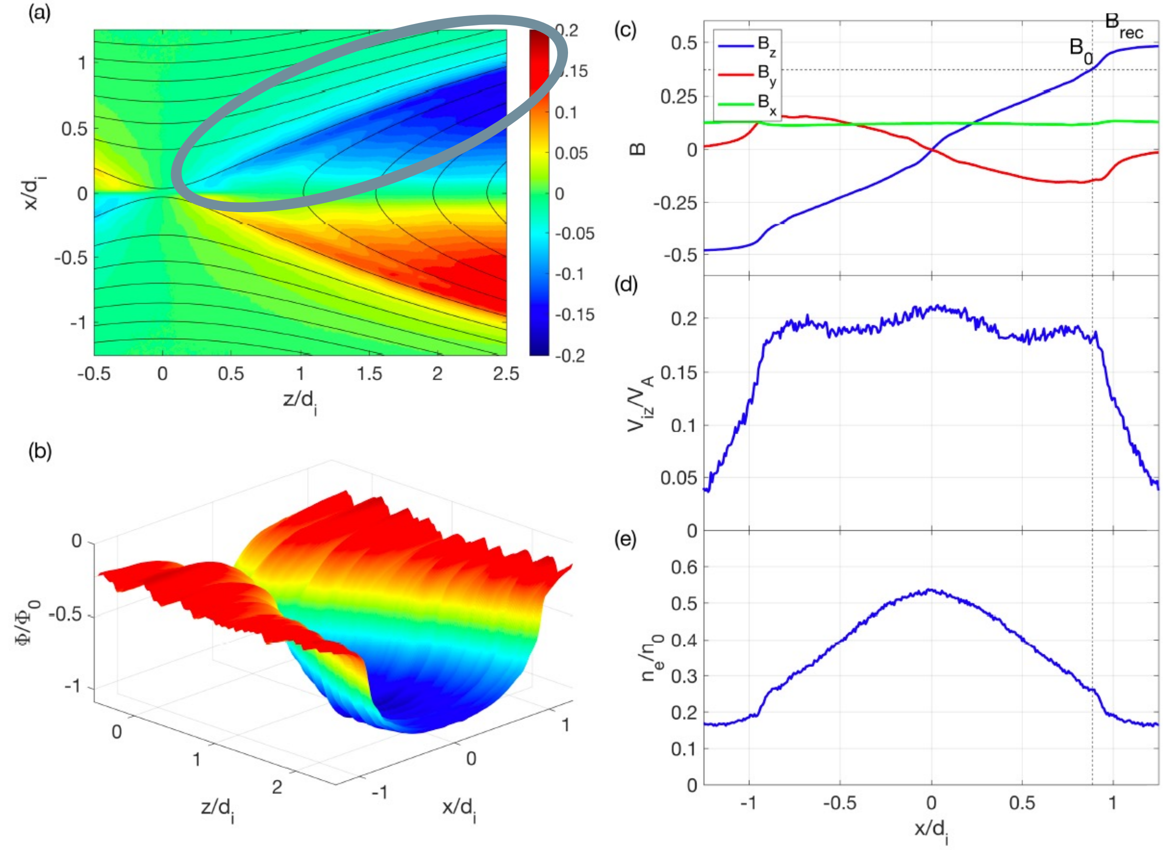
MMS data

Parker Probe data

We have focused our study at the separatrix areas

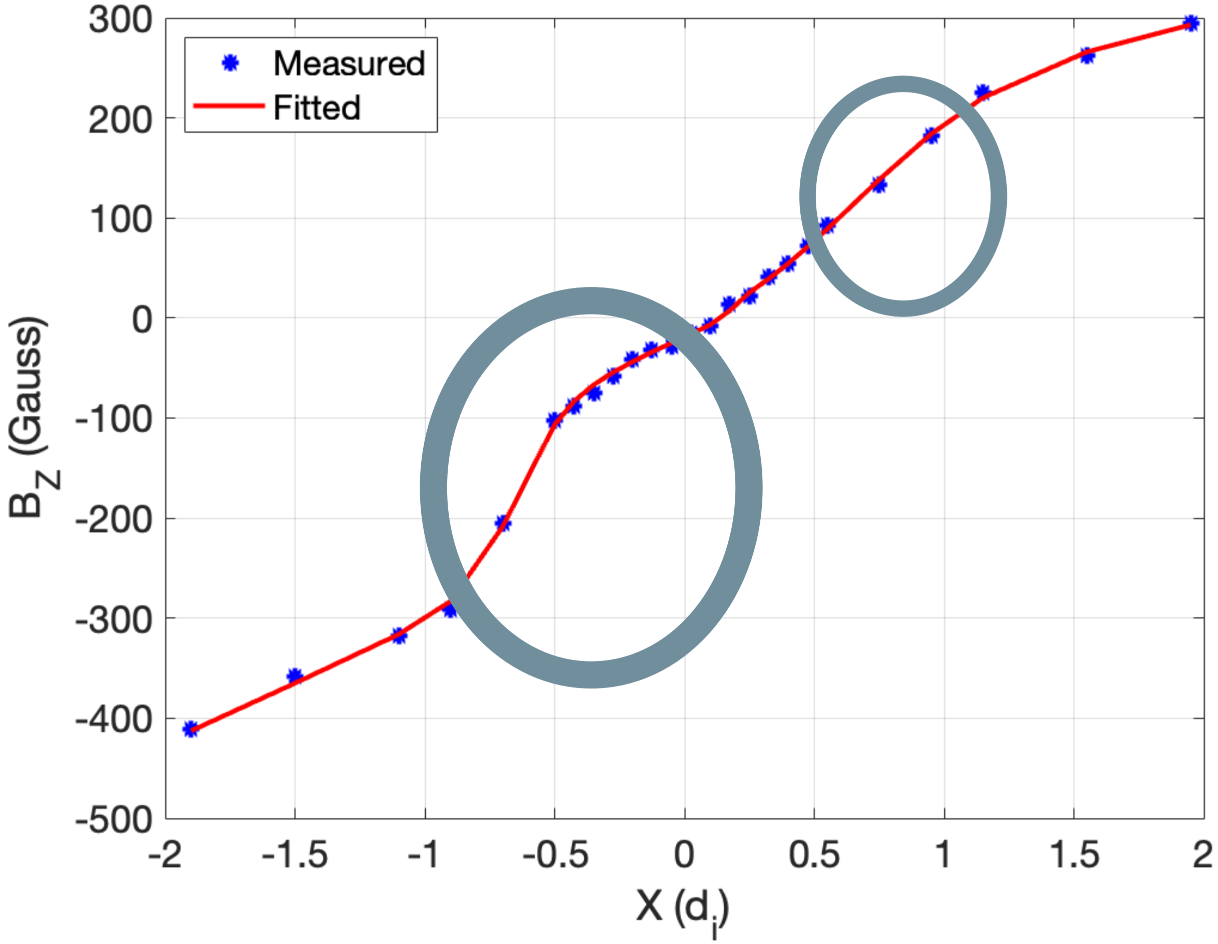


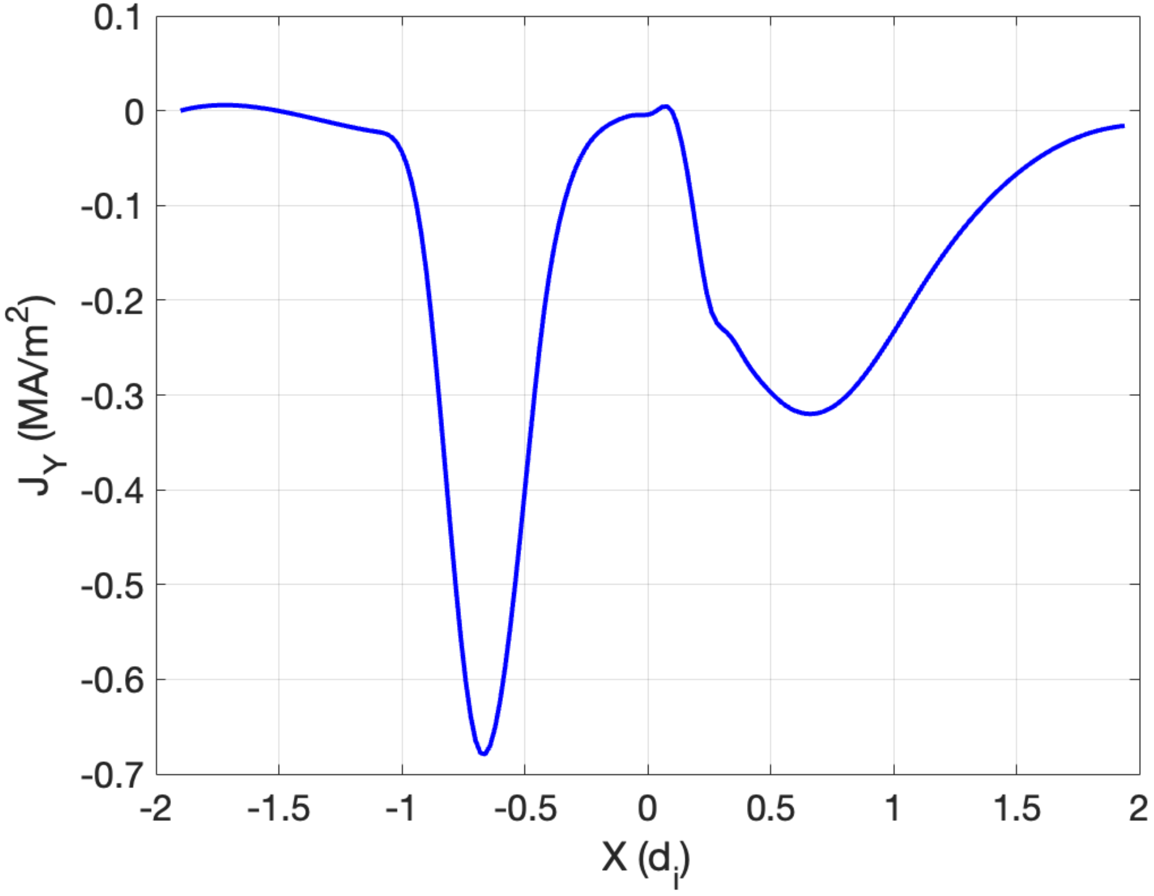
Earlier MRX data (without sufficient resolution)



Our Simulation

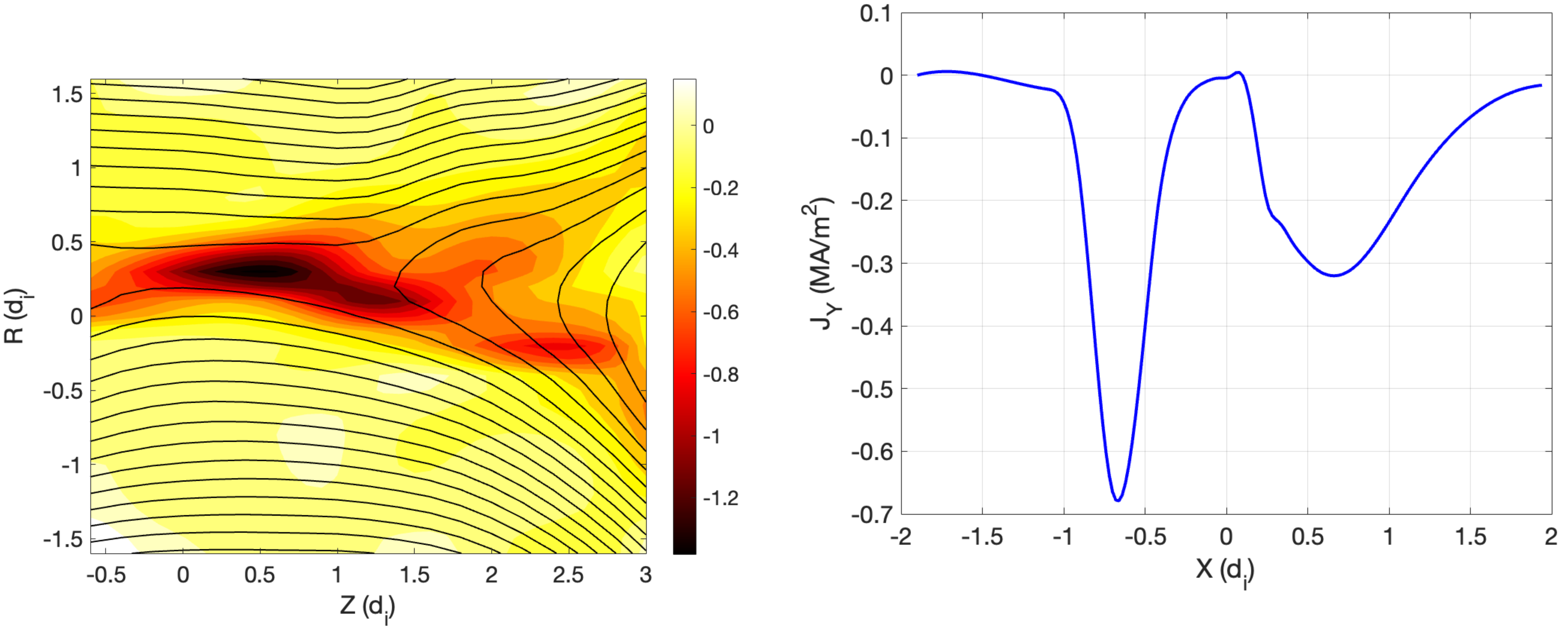
Our most recent MRX results verified a strong current sheet at the separatrix for Z > 2 di





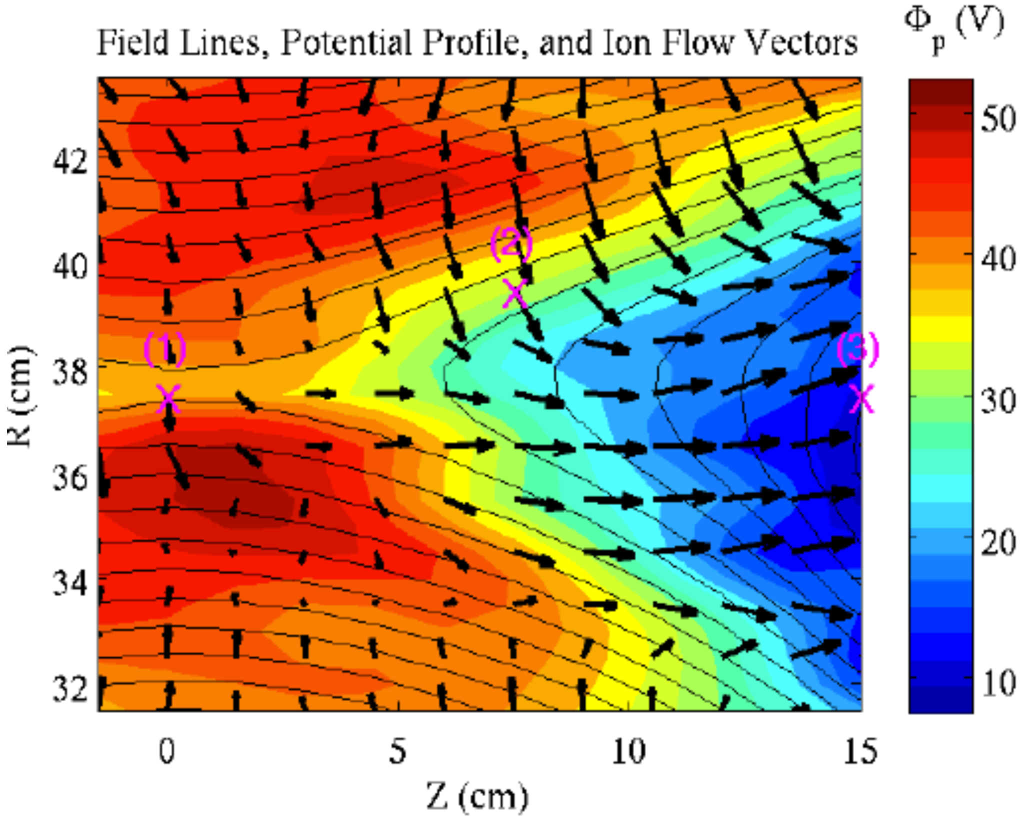
Most recent MRX data at z = 3 d_i

2-D $j_e(R, Z)$ profiles support the Petshek-like feature

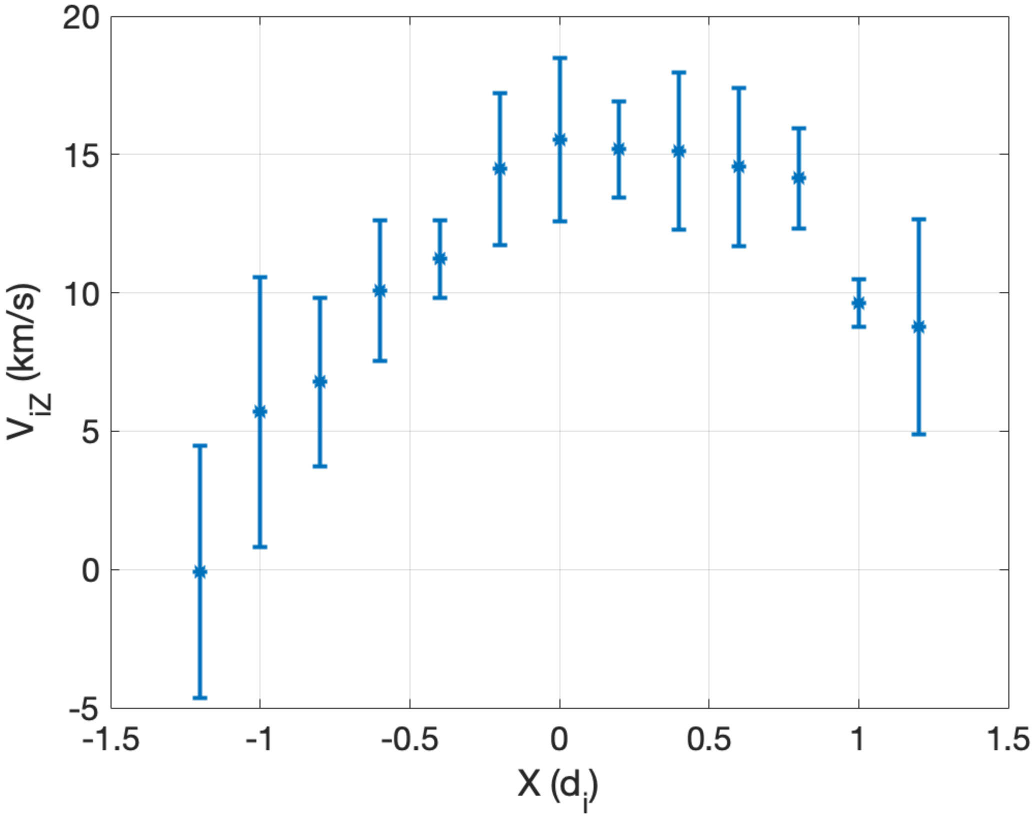


Most recent MX data

2-D V_{iZ} profiles support the Petshek-like feature

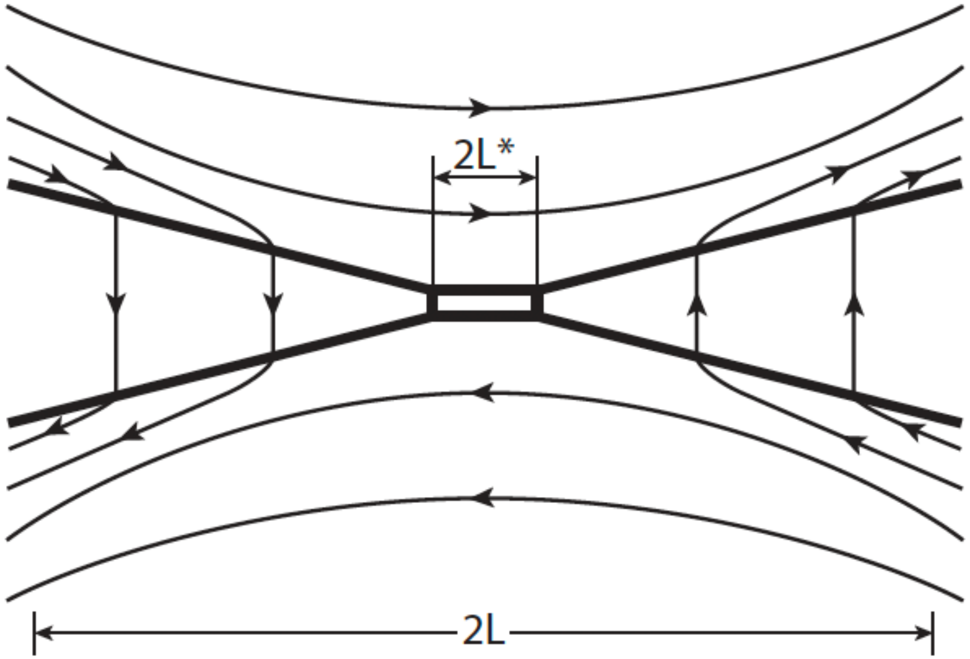


Earlier MRX data



Recent MRX data

- **Petschek concept has been revived in MRX data**



More accurate measurement will be carried out in our FLARE device for a larger system size

L > 10 di

Summary and future goals

- Petshek's double shock (1963) is observed on collisionless reconnection in MRX
- The presence of sharp electron current layers at the separatrices
- Our results are explained by two-fluid physics
- Ion acceleration and heating by re-magnetization

- **Our results agree well with space data**
- **More accurate measurements will be carried out in FLARE deice**
- **A simple model is being developed for energy conversion and partitioning**

=> Quantitative model of energy conversion and inventory

A simple analytical model has been developed based on electron force balance:

$$E_R \approx V_{ey}B_Z - \frac{1}{en_e}\frac{\partial p_e}{\partial R} \qquad (1)$$

We calculate the potential profile using Harris sheet expression (Yamada et al, PoP, 2000)

$$B_z = -B_0 \tanh\left(\frac{x}{\delta}\right)$$

$$j_y = \frac{B_0}{\mu_0 \delta}\,\mathrm{sech}^2\left(\frac{x}{\delta}\right)$$

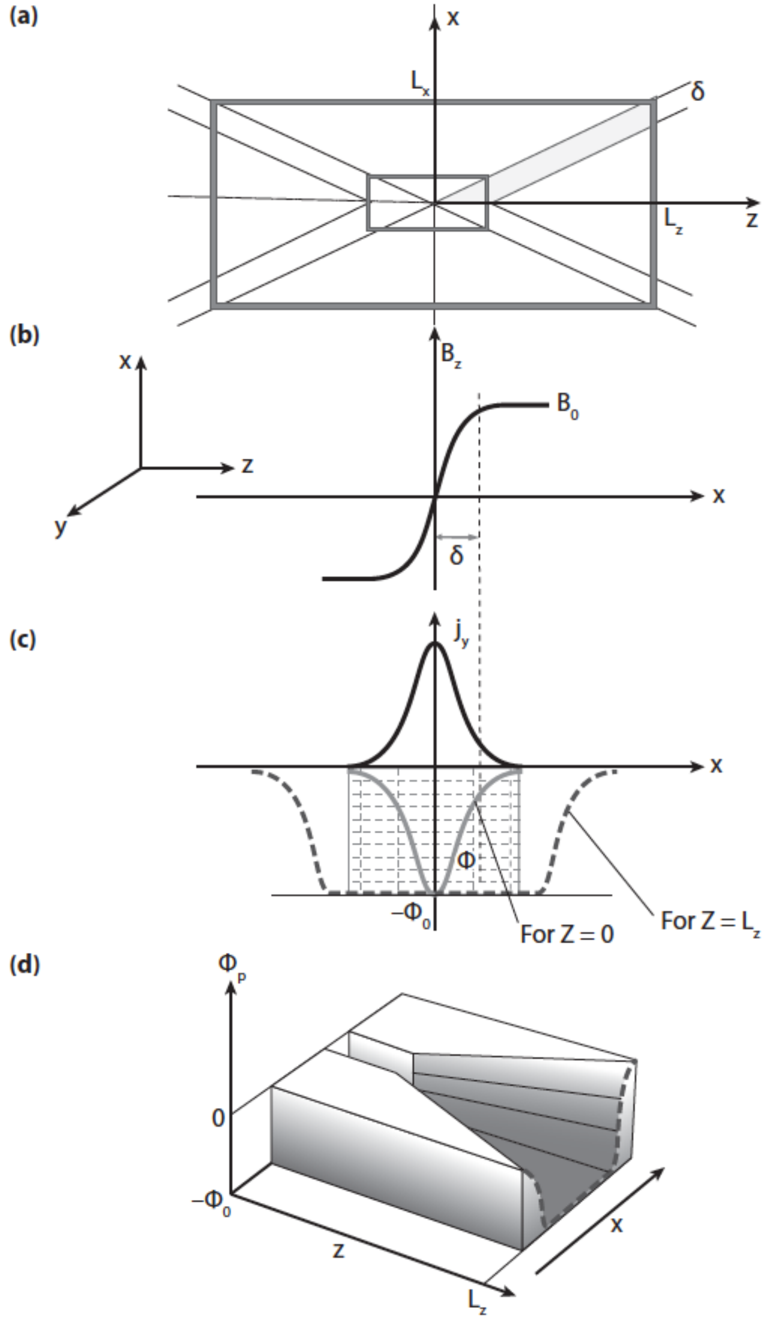
sheet thickness δ is given by

$$\delta = \frac{c}{\omega_{\mathrm{pi}}}\frac{\sqrt{2(T_e+T_i)/m_i}}{V_i - V_e} = \frac{c}{\omega_{\mathrm{pi}}}\frac{\sqrt{2}V_s}{V_{\mathrm{drift}}}$$

We obtain an analytical expression of potential (Φ) profile

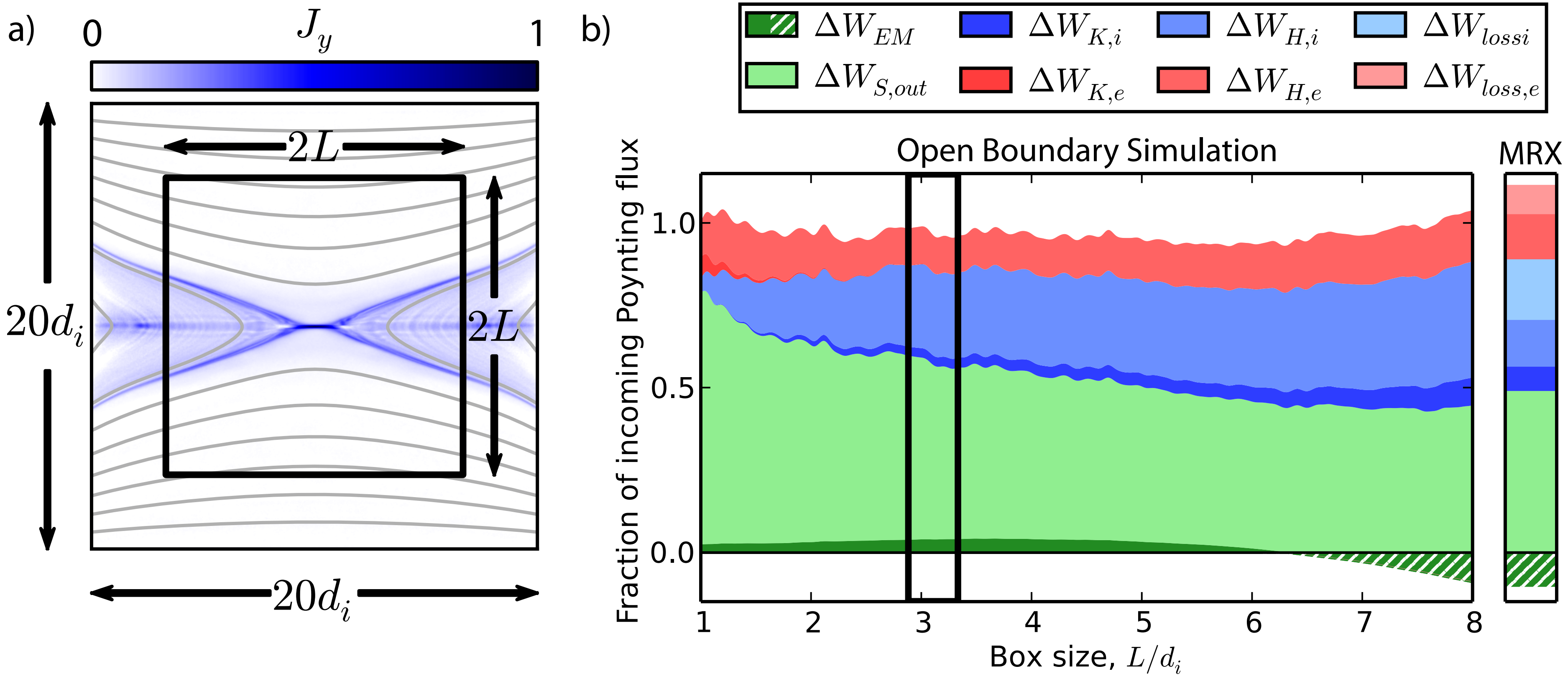
$$\Phi_p(x) = -\Phi_0 \mathrm{sech}(x) \quad \text{with} \quad \Phi_0 = \frac{B_0^2}{2\mu_0 e} - \frac{\Delta T_e}{e}$$

A half of incoming Poynting flux energy
=> Potential Energy: $e\Phi_0 = (1/2)\,(B_0^2/\mu_0)$



2D PIC simulation on energetics;

by J. Jara Almonte and W. Daughton



The energy partitioning does not strongly depend on the size of monitoring boundary

MRX data is compared with simulations and space data

	Magnetic energy Inflow	Magnetic Energy outflow rate	Energy deposition to ions	Energy deposition to electrons
MRX Data	1.00	0. 45	0.35	0.20
Numerical simulation	1.00	0. 42	0.34	0.22
Magnetotail data (Eastwood)	1.00	0.1-0.4	0.39	0.18

- Ion flux : e-flux ~ 2:1
- Enthalpy flux dominates
- Magnetic energy outflow substantial

It is notable that energy deposition to ions is generally larger than to electrons.

Since the electrons’ heat transport loss is larger than ions’,

=> T_i >> T_e

⬄ Combination of larger energy deposition and better confinement for ions