Collisional and Collisionless Magnetic Reconnection: a Review

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OUTLINE

- Introduction: What is magnetic reconnection?

PAST (classical traditions):

- Collisional reconnection: Sweet-Parker and Petschek

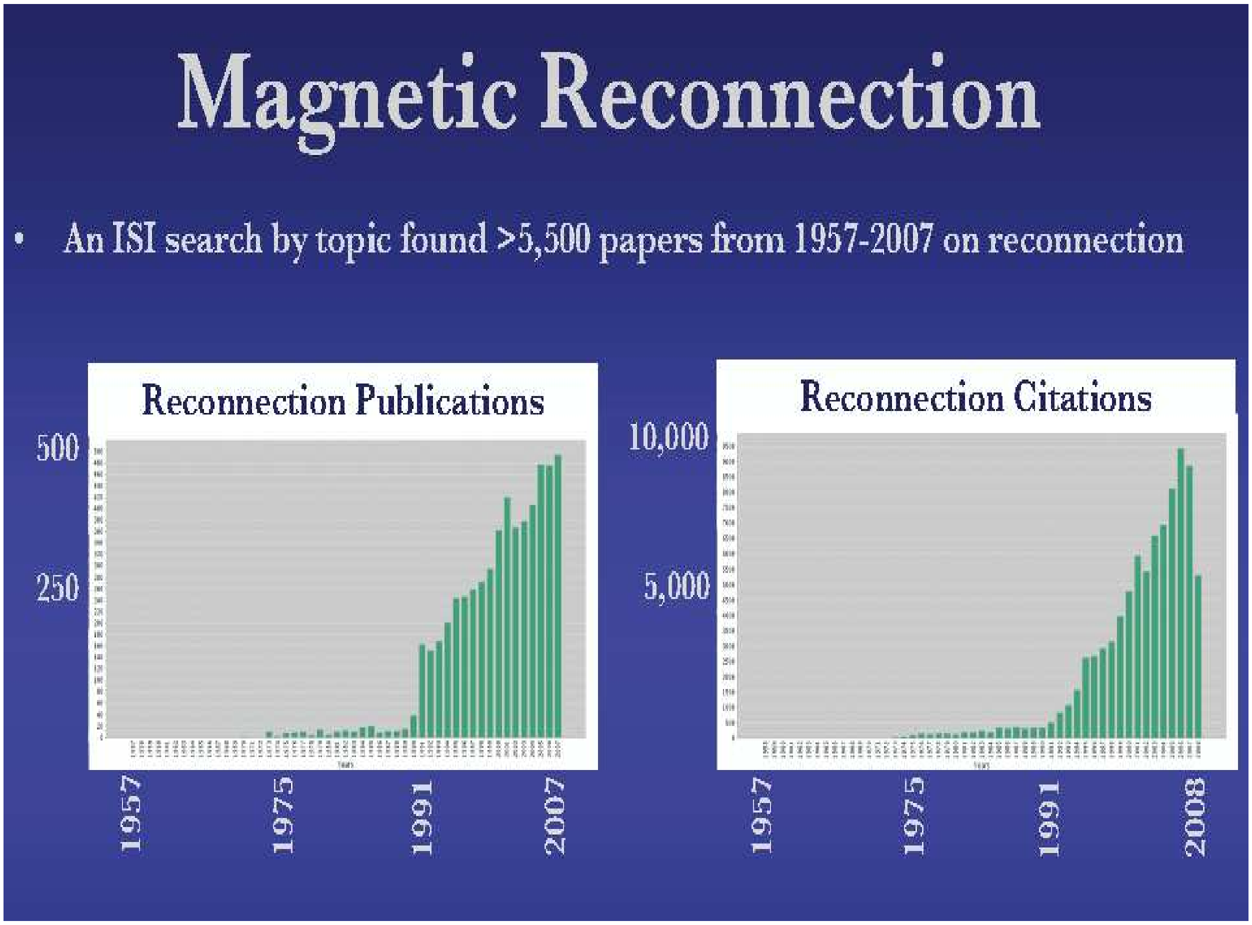
PRESENT (party line)

- Criterion for Fast Collisionless Reconnection
- Physics of Collisionless Reconnection: a Portrait
  - Quadrupole out-of-plane magnetic field, B_z
  - Bipolar in-plane electric field, E_y
    (ion heating, electron current)
  - Electron Diffusion region
    (Pressure Tensor and Electron Inertia)
  - Electron Outflow Jet

FUTURE (paradigm shift?):

- (official) Future directions of magnetic reconnection research

Magnetic Reconnection on the Rise!

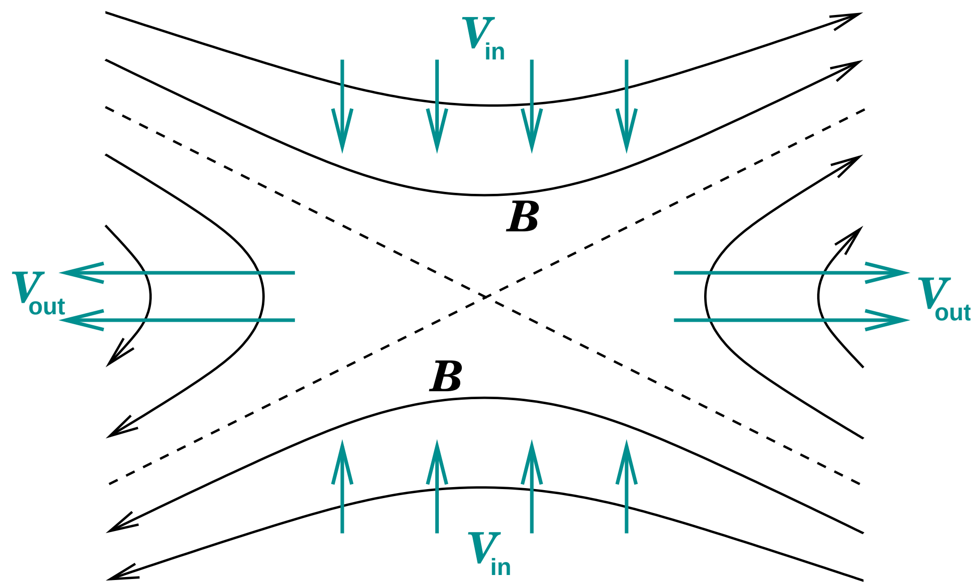


P. Cassak 2008

RECONNECTION: INTRODUCTION

Q: What is **magnetic reconnection**?

Magnetic reconnection is a rapid rearrangement of magnetic field **topology**.



- Reconnection leads to rapid, violent release of magnetically-stored energy.

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PRACTICAL QUESTIONS

- **Fast Reconnection Onset:**
  What triggers it? Why is it sometimes slow and sometimes fast ?

$$\delta_{\mathrm{SP}} < d_i \; ?$$

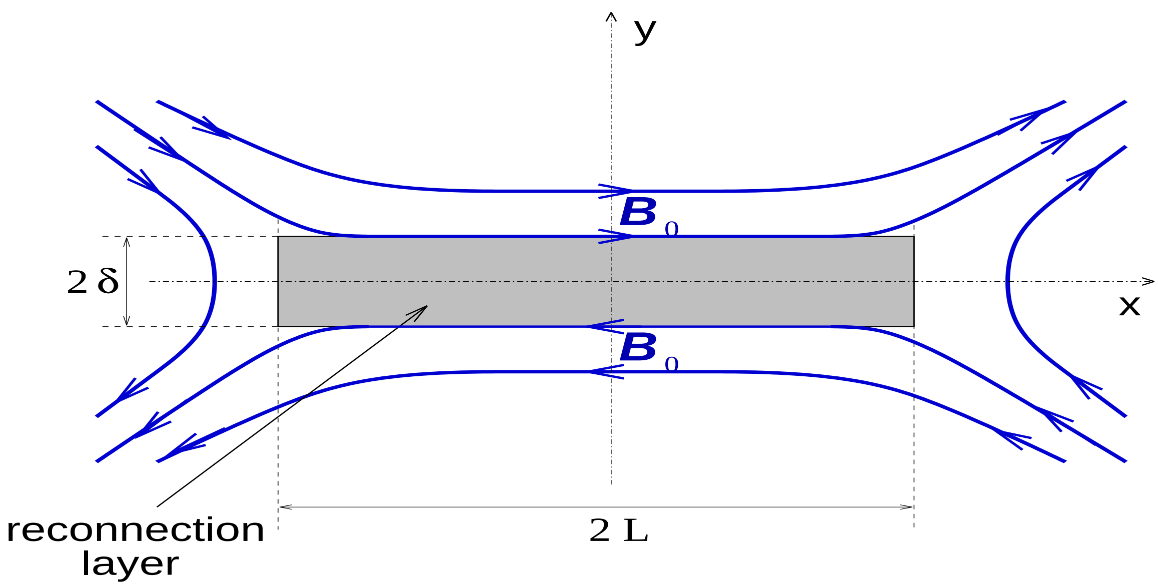
- **Reconnection rate:**
  (is the layer Sweet-Parker-like or Petschek-like? or something else?)

$$E = 0.1 \quad \text{or} \quad \frac{d_i}{L} \; ?$$

- **Energy Partitioning:**
  - internal/kinetic
  - ions/electrons
  - thermal/nonthermal

SWEET–PARKER MODEL

(Sweet 1958; Parker 1957, 1963)



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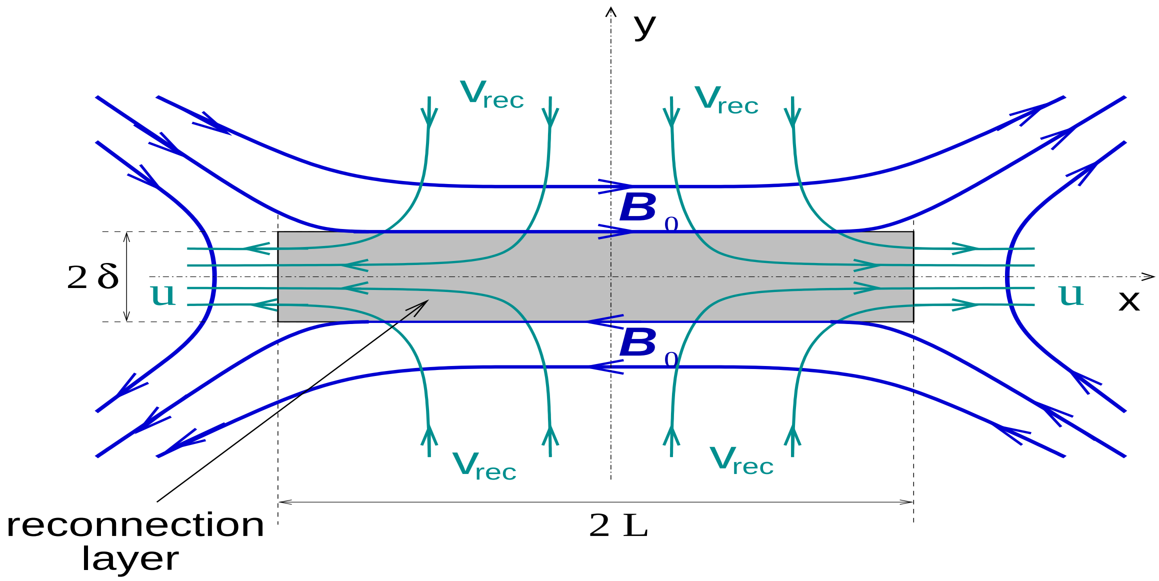
SWEET–PARKER MODEL

(Sweet 1958; Parker 1957, 1963)



- Ohm's Law: $v_{\mathsf{rec}} B_0 = E_z = \eta j_0 = \eta B_0/\delta \quad \Rightarrow \quad \eta = v_{\mathsf{rec}}\delta$
- Vertical pressure balance: $p(0,0) = p_0 + B_0^2/8\pi$
- Equation of motion: $\rho v_x \partial_x v_x = -\partial_x p \quad \Rightarrow \quad u = V_A \equiv B_0/\sqrt{4\pi\rho}$
- Mass Conservation: $v_{\mathsf{rec}} L = u\delta$
- Sweet-Parker Scaling: $S \equiv \frac{LV_A}{\eta} \gg 1$

$$\left(\frac{v_{\mathsf{rec}}}{V_A}\right)_{\mathsf{SP}} = \frac{\delta_{\mathsf{SP}}}{L} = 1/\sqrt{S}$$

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Sweet–Parker Reconnection: Too Slow for Solar Flares!

- Typical Solar Corona parameters:

$$L \sim 10^9 - 10^{10}\,\mathsf{cm} \qquad B \sim 100\,\mathsf{G}$$
$$n_e \sim 10^9 - 10^{10}\,\mathsf{cm}^{-3} \qquad T \sim 2 \cdot 10^6\,\mathsf{K}$$
$$V_A \sim 10^8\,\mathsf{cm/sec} \qquad \tau_A \sim 10 - 100\,\mathsf{sec}$$

- Lundquist number:

$$S \sim 10^{12}$$

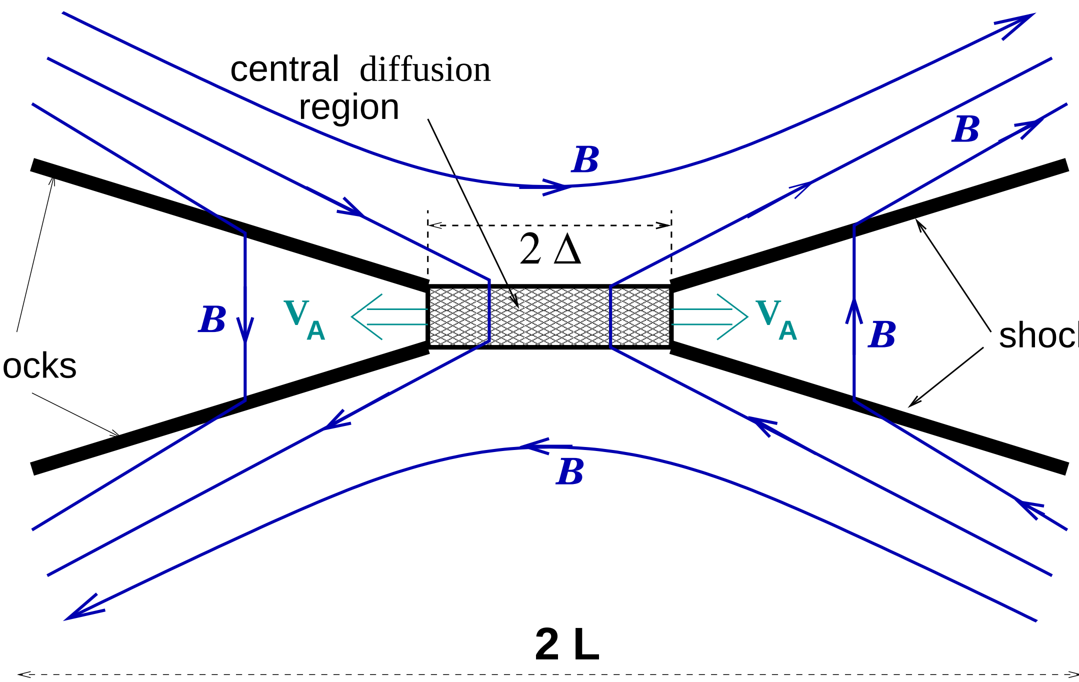
- Sweet–Parker timescale:

$$\tau_{\mathsf{rec}} \sim \tau_A \sqrt{S} \sim \mathsf{months} \gg \tau_{\mathsf{flare}} \sim 15\,\mathsf{min}$$

Thus, Sweet–Parker reconnection is too slow !

PETSCHEK's FAST RECONNECTION MODEL

(Petschek 1964):
Sweet–Parker reconnection is slow because plasma has to flow out through a narrow current channel.



A family of models with

$$S^{-1/2} < \frac{v_{\text{rec}}}{V_A} < \frac{1}{\log S}$$

- fast enough to explain solar flares!

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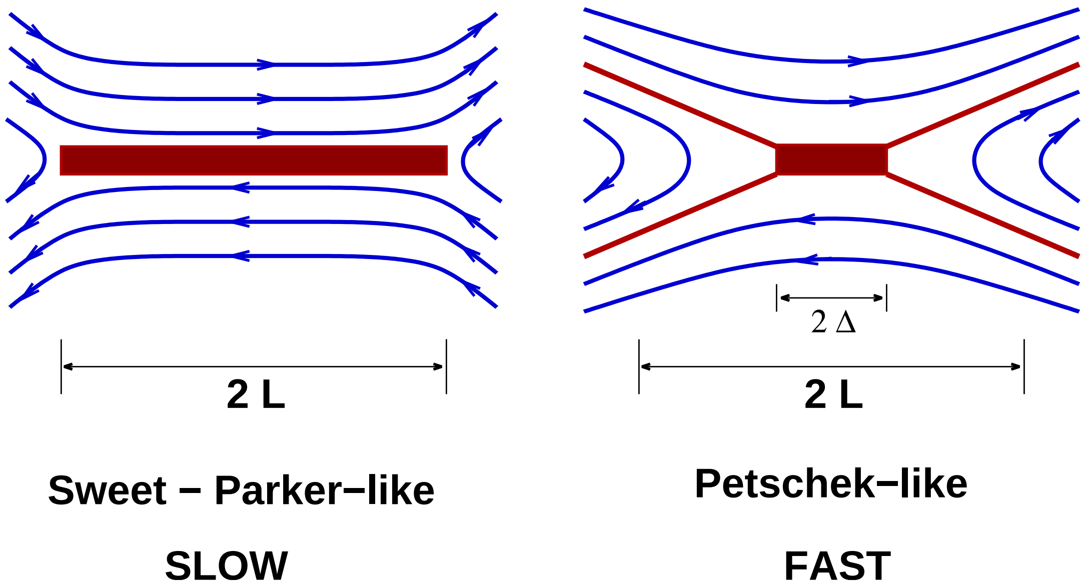
Importance of Petschek's Model



- There are physical processes (Hall effect, anomalous resistivity) that can prevent a current layer from collapsing down to the Sweet–Parker thickness: $\delta > \delta_{\rm SP} = sqrt L\eta/V_A$.
- However, $\delta > \delta_{\rm SP}$ is not enough for rapid reconnection.
- *Petschek's (1964)* geometric enhancement idea is especially important for large systems:
  $$L \gg \rho_i, d_i, \delta_{\rm SP}$$
  (e.g., solar flares: $L \sim 10^9$ cm $\gg$ $d_i \sim \delta_{\rm SP} \sim 10^2 - 10^3$ cm)

Fast Reconnection $\Leftrightarrow$ Petschek Reconnection

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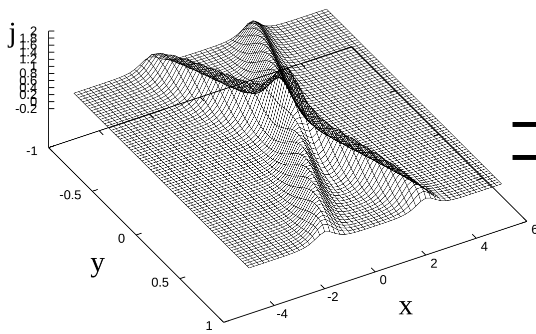
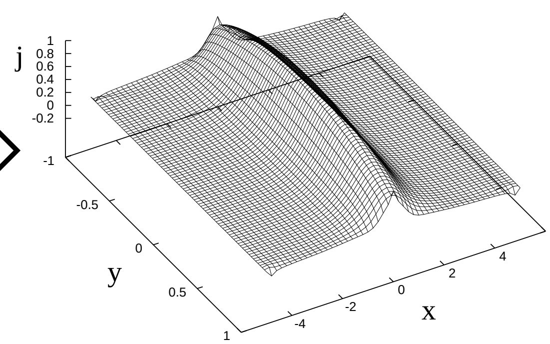
NO FAST RECONNECTION
IN COLLISIONAL PLASMAS

- Numerical Simulations *(e.g., Biskamp 1986; Ma & Bhattacharjee 1996; Uzdensky & Kulsrud 1998, 2000; Breslau & Jardin 2003; Malyshkin et al. 2005)*
- Analytical Work *(Kulsrud 2001; Malyshkin et al. 2005)*
- Laboratory Experiments (MRX) *(Ji et al. 1998)*

show: Reconnection in collisional plasmas is **SLOW**!



$\Longrightarrow$



initial Petschek

Final Sweet−−Parker

(Uzdensky & Kulsrud 2000)

Large-scale fast reconnection requires **collisionless** plasma.

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FAST RECONNECTION
means COLLISIONLESS RECONNECTION

Q: Is Fast Reconnection Possible in Collisionless Plasmas ?

YES !!!

Two candidates for fast collisionless reconnection:

- **Hall-MHD reconnection** involving two-fluid laminar configuration *(e.g., Mandt et al. 1994; Shay et al. 1998; Birn et al. 2001; Bhattacharjee et al. 2001; Breslau & Jardin 2003; Cassak et al. 2005)*
- Spatially-localized **anomalous resistivity** due to plasma micro-instabilities *(e.g., Ugai & Tsuda 1977; Sato & Hayashi 1979; Scholer 1989; Erkaev et al. 2001; Kulsrud 2001; Biskamp & Schwarz 2001; Malyshkin et al. 2005)*

Both mechanisms observed in MRX.

Fast Reconnection = Collisionless Reconnection

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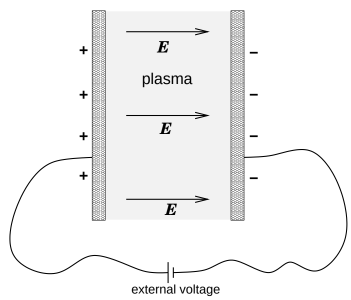
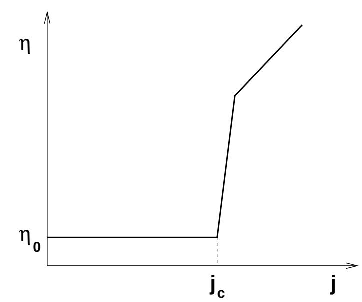
Fast Collisionless Reconnection
ANOMALOUS RESISTIVITY

- What is the physically-relevant resistivity η?





- Physical Mechanism:
  when
  $$v_d = \frac{j}{en_e} > v_c \sim v_{\rm thermal}\,,$$
  plasma instabilities are excited $\Rightarrow$ developed microturbulence. Scattering of electrons by waves enhances resistivity.

- As the layer's thickness δ decreases down to critical thickness
  $$\delta_c \equiv \frac{cB_0}{4\pi j_c}, \qquad \text{where } j_c \equiv en_e v_c,$$
  anomalous resistivity $\eta = \eta(j)$ turns on.

- Anomalous resistivity $\eta = \eta(j)$ is localized near the center.

- Simulations: strongly-localized resistivity $\Rightarrow$ Petschek-like configuration (also theory by *Kulsrud 2001; Malyshkin et al. 2005).*

- Dual role of anomalous resistivity:
  - *direct:* $\eta_{\rm anom} \gg \eta_{\rm coll}$
  - *indirect:* enables Petschek mechanism

- Resulting rate plausible for solar flares *(e.g., Uzdensky 2003).*

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FAST COLLISIONLESS RECONNECTION: HALL EFFECT

- Electron equation of motion $\Rightarrow$ Generalized Ohm's law:

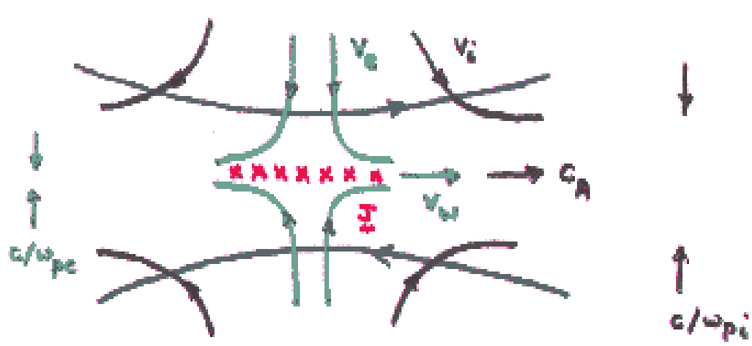
$$\mathbf{E} = -\frac{1}{c}[\mathbf{v}_e \times \mathbf{B}] + \eta\mathbf{j} = \underbrace{-\frac{1}{c}[\mathbf{v} \times \mathbf{B}] + \eta\mathbf{j}}_{resistive\ MHD} + \underbrace{\frac{\mathbf{j} \times \mathbf{B}}{n_e e c}}_{Hall\ term}$$

$[\mathbf{j} = n_e e\,(\mathbf{v_i} - \mathbf{v_e})]$

- Hall-term spatial scale:

$$d_i \equiv \frac{c}{\omega_{pi}} = c\sqrt{\frac{m_i}{4\pi n_e e^2}}\,.$$

- Two-fluid effects: on scales $< d_i$, ions are no longer tied to field lines but electrons still are $\Rightarrow$ ions and electrons move separately:



- Reconnection layer thickness $\delta \simeq d_i\ (\gg \delta_{\mathsf{SP}})$.
  But this is not sufficient since still $d_i \ll L$!

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Condition for Collisionless Reconnection:

- Collisional (resistive) reconnection scale — Sweet–Parker reconnection layer thickness:

$$\delta_{\mathrm{SP}} = \sqrt{L\eta/V_A}$$

- Collisionless reconnection scale — ion skin depth:

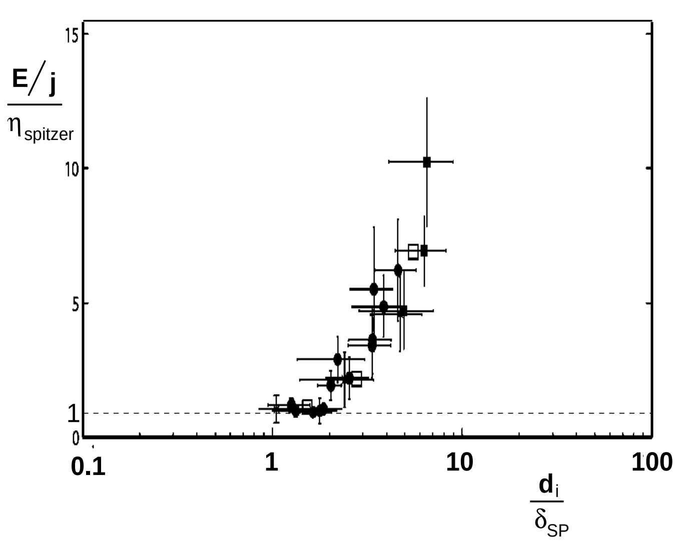
$$d_i \equiv \frac{c}{\omega_{pi}} = c\sqrt{\frac{m_i}{4\pi n_e e^2}}$$

- **Collisionless Reconnection Condition:**

$$\delta_{\mathrm{SP}} < d_i$$

(Ma & Bhattacharjee 1996; Kulsrud 2001, '05; Uzdensky 2003, '06, '07; Cassak et al. 2005, '06; Yamada et al. 2006)

- Experimental evidence (MRX) for this transition:



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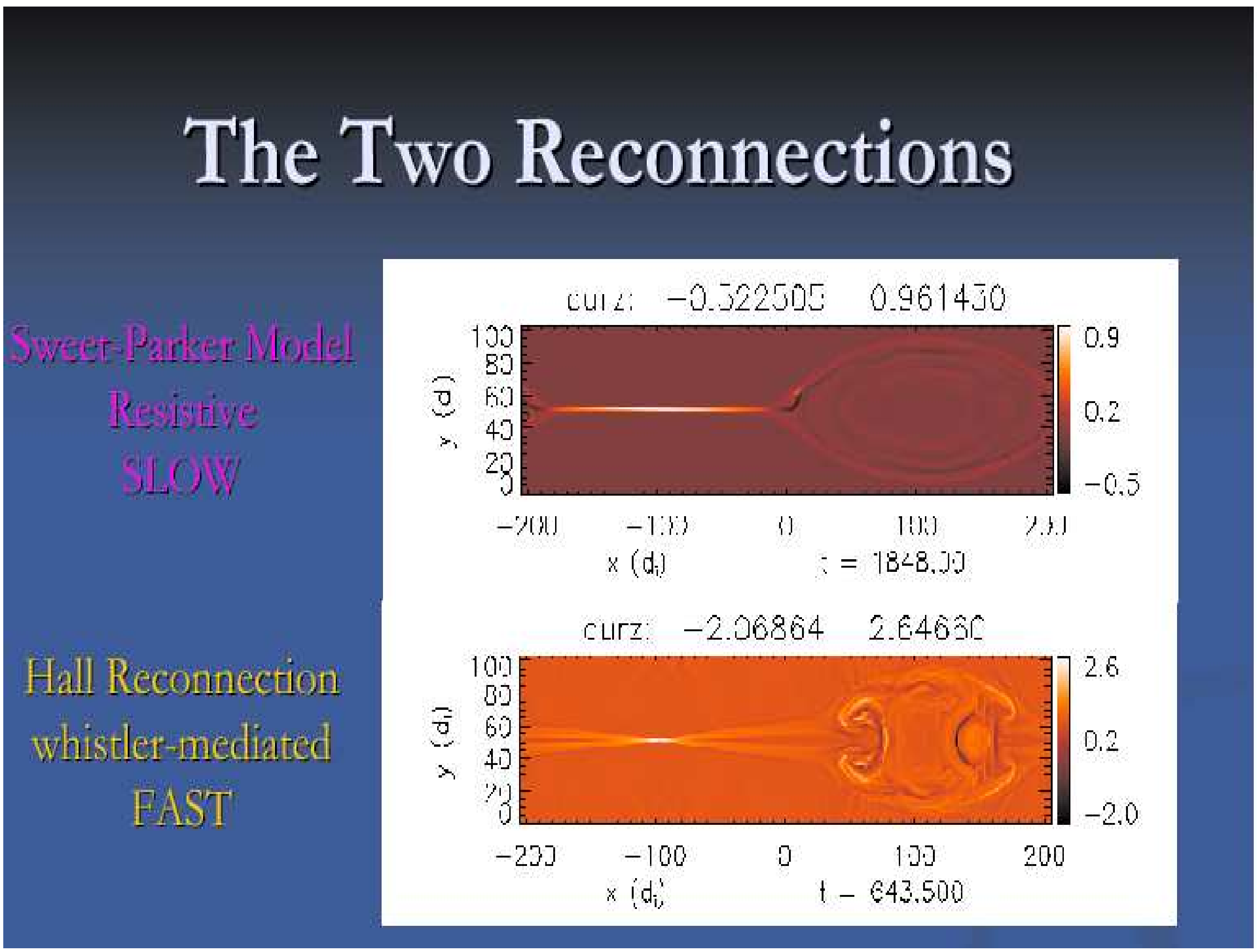
FAST COLLISIONLESS RECONNECTION: HALL EFFECT

- Numerical simulations:
  Hall effect enables Petschek-like structure
  with $v_{\rm rec} \le 0.1\, V_A$ *(e.g., Shay et al. 1998).*



Cassak et al. 2005

(Cassak, Shay, & Drake 2005)

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Condition for Collisionless Reconnection: Weak Guide Field Case

Collisionless vs. collisional: in what sense?

- Using collisional resistivity *(Yamada et al. 2006)*:

$$\frac{\delta_{\mathsf{SP}}}{d_i} \sim \left(\frac{L}{\lambda_{e,\mathsf{mfp}}}\right)^{1/2} \left[\frac{m_e}{m_i}\right]^{1/4}$$

- Then, fast reconnection requires

$$L < \lambda_{e,\mathsf{mfp}} \sqrt{m_i/m_e} \sim 40\,\lambda_{e,\mathsf{mfp}}$$

<u>Moving Forward:</u> *(Uzdensky 2006, 2007)*

- Collisional mean-free path: $\lambda_{e,\mathsf{mfp}} \simeq 7 \cdot 10^7 \mathsf{cm}\ n_{10}^{-1}\, T_7^2$
- Central Electron Temperature:

$$T_e = \frac{B_0^2/8\pi}{2k_B n_e} \simeq 1.4 \cdot 10^7\,\mathsf{K}\ B_{1.5}^2\, n_{10}^{-1}$$

Here, $B_{1.5} \equiv B_0/(30\,G)$, etc.

- Final **fast collisionless reconnection condition:**

$$L < L_c(n, B_0) \simeq 6 \cdot 10^9\,\mathsf{cm}\ n_{10}^{-3}\, B_{1.5}^4$$

– in terms of **macroscopic** quantities!

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Condition for Collisionless Reconnection: Strong Guide Field Case

- Collisional (resistive) reconnection scale — Sweet–Parker reconnection layer thickness:

$$\delta_{\mathsf{SP}} = \sqrt{L\eta/V_A}$$

- Collisionless reconnection scale in the strong guide field case, $B_z \gg B_0$, — ion-sound Larmor radius:

$$\rho_s = c_s \, \Omega_i^{-1} \sim d_i \; \beta_e^{1/2} \; \frac{B_0}{B_z}$$

- **Collisionless Reconnection Condition:**

$$\delta_{\mathsf{SP}} < \rho_s$$

- Final form:

$$L < L_c = \lambda_{e,\mathsf{mfp}} \sqrt{\frac{m_i}{m_e}} \, (\frac{B_0}{B_z})^2 \simeq 6 \cdot 10^9 \, \mathsf{cm} \, n_{10}^{-3} \, B_{1.5}^4 \, (\frac{B_0}{B_z})^2$$

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Physics of Collisionless Reconnection:

Current Status

- Significant progress in recent years:
  - numerical simulations
  - laboratory experiments
  - spacecraft observations

- Lack of **analytical theory** and basic physical understanding.

Collisionless Reconnection Layer:

A PHYSICAL PORTRAIT

(Sorry, no Guide Field!)

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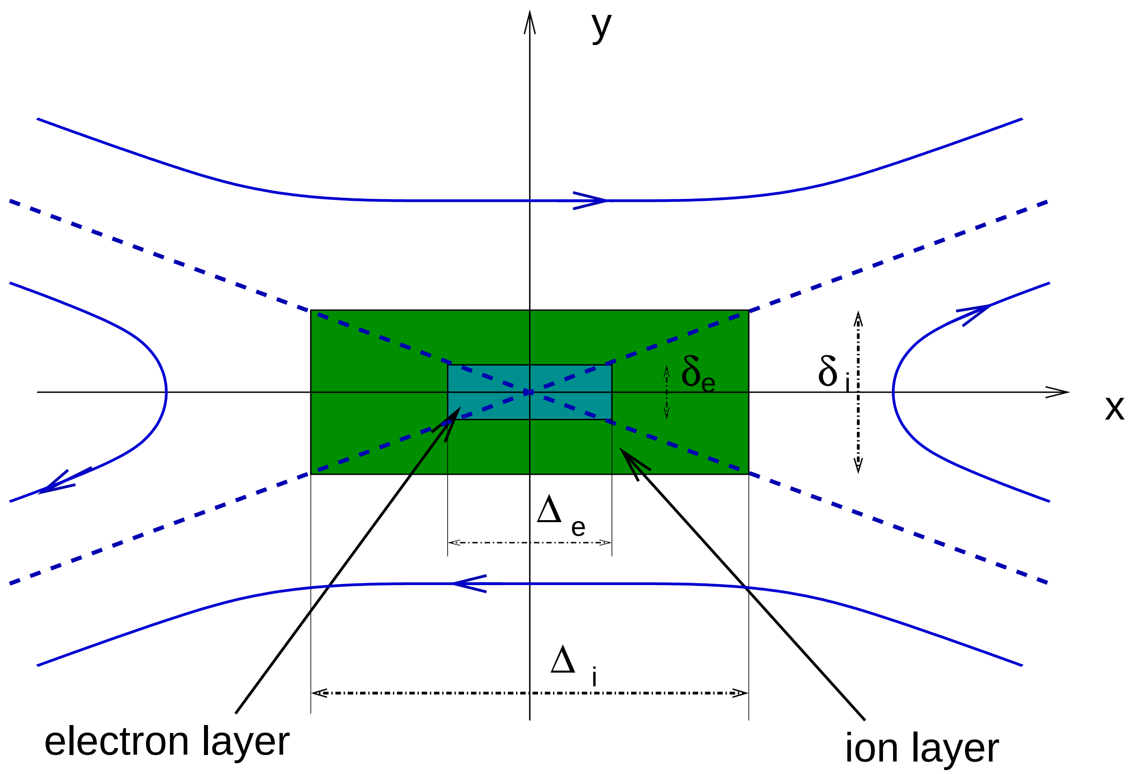
Collisionless Reconnection Layer: General Morphology



$$\delta_i \sim d_i \ll \Delta_i \simeq 10\, d_i \ll L$$

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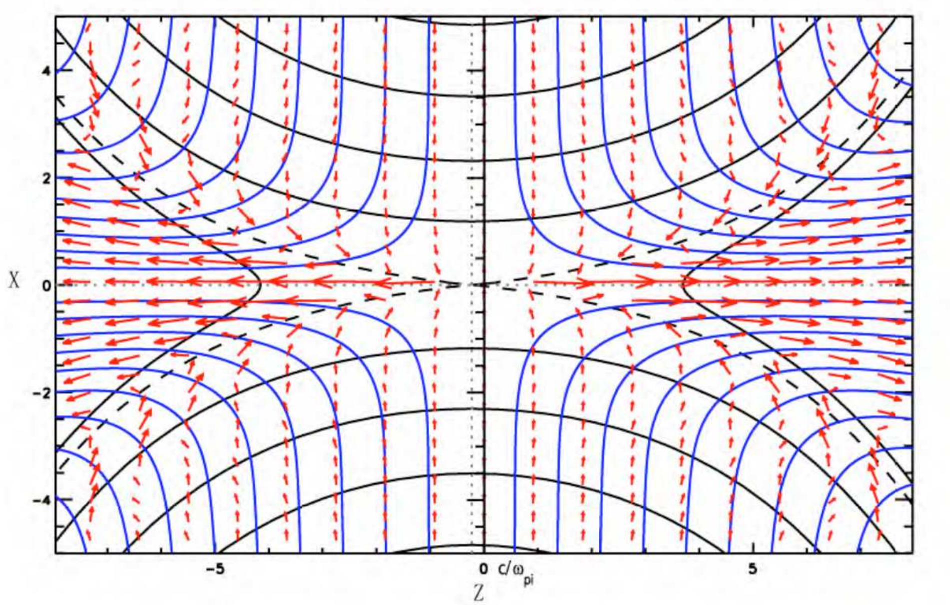
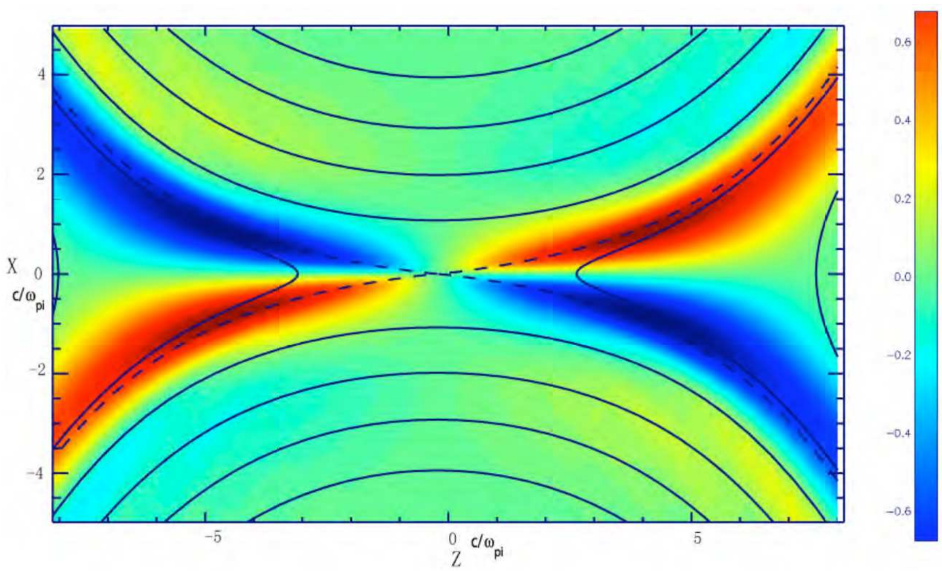
Quadrupole Magnetic Field: Numerical Simulations

Ion and electron streamlines:



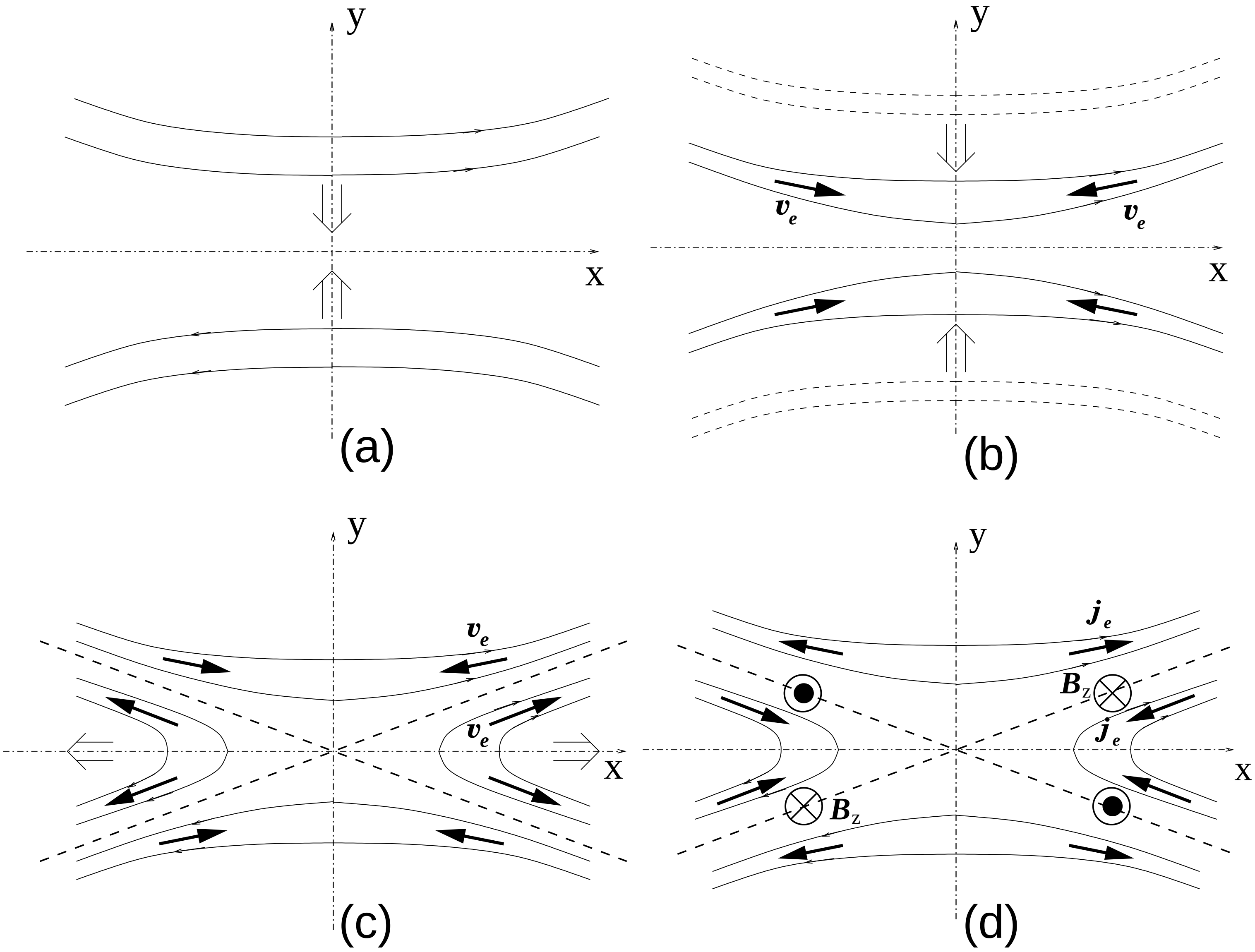
Quadrupole out-of-plane magnetic field:



(Simulations by J. Breslau & S. Jardin 2003)

Quadrupole Magnetic Field: Basic Explanation I

(Uzdensky & Kulsrud 2006)



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Ideal Incompressible Electron MHD: General Results

(Uzdensky & Kulsrud 2006)

Three Important Functions:

– volume per flux: $V(x,\Psi) = \int\limits_0^x \frac{dl_{\rm pol}}{B_{\rm pol}}\,|_\Psi$

– electron stream function: Φ_e

– out-of-plane magnetic field: B_z

General Relationships between them:

- Incompressibility + flux freezing:

$$\Phi_e(x,\Psi) = c\,|E_z|\,V(x,\Psi)\,. \tag{1}$$

- Ampere's law:

$$B_z = -\,D\,\Phi_e = -\,cD|E_z|\,V(x,\Psi)\,, \tag{2}$$

where $D \equiv 4\pi n_e e/c = B_0/(d_i V_A) = \mathrm{const.}$

Eqn. (2) $\Rightarrow$ $\mathbf{v}_{\rm pol}^{(e)} \cdot \nabla B_z \equiv 0.$

But $(d/dt)\,B_z^{(e)} = \mathbf{v}_{\rm pol}^{(e)} \cdot \nabla B_z = \mathbf{B}_{\rm pol}^{(e)} \cdot \nabla v_z^{(e)}.$

Thus, $v_z^{(e)}$ and $j_z^{(e)}$ must be constant along $\mathbf{B}_{\rm pol}$: $\nabla^2\Psi = F(\Psi)$.

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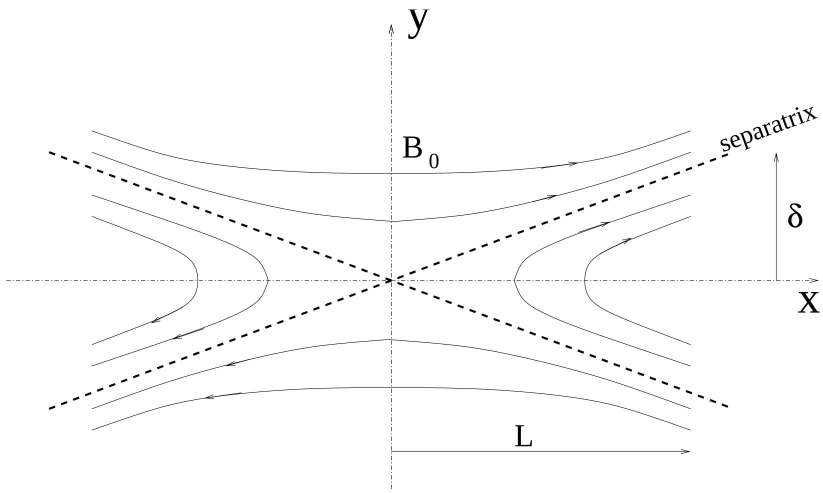
Example: Simple X-point Configuration

(Uzdensky & Kulsrud 2006)



$$\bar{x} = \frac{x}{L}$$

$$\bar{y} = \frac{y}{\delta}$$

Simple X-point configuration: $\Psi(x,y) = \frac{1}{2} B_0 \delta \, (\bar{y}^2 - \bar{x}^2)$

- Electron Velocity Field:

$$v_x^{(e)} = -\, x \, \frac{c\,|E_z|}{2\,\Psi(x,y)}$$

$$v_y^{(e)} = -\, y \, \frac{c\,|E_z|}{2\,\Psi(x,y)}$$

- Out-of-Plane Magnetic Field:

$$B_z(x,y) = -\,\frac{B_0}{2}\frac{\delta}{d_i}\frac{u}{V_A}\;\log\left|\frac{y/\delta + x/L}{y/\delta - x/L}\right|.$$

- Main Features:
  - electron streamlines are straight radial rays $\bar{y} = C\bar{x}$;
  - B_z is simply advected by the electron fluid: $v_e \cdot \nabla B_z = 0$;
  - hence, $B_z = \mathrm{const}$ along rays $\bar{y} = C\bar{x}$;
  - B_z diverges logarithmically at the separatrix $\bar{y} = \bar{x}$.

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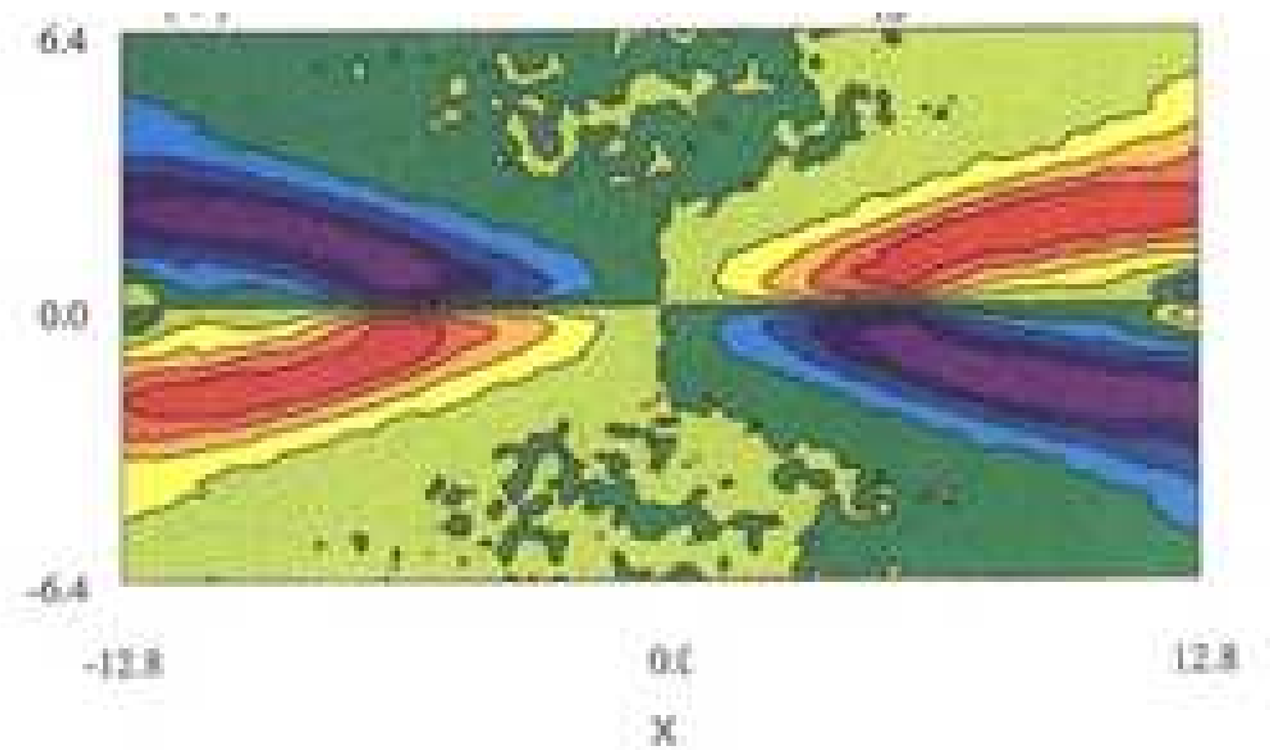
Quadrupole Field in Numerical Simulations

Quadrupole Pattern of Toroidal Magnetic Field
seen in Numerical Simulations (2-fluid and kinetic):



Pritchett et al. 2001

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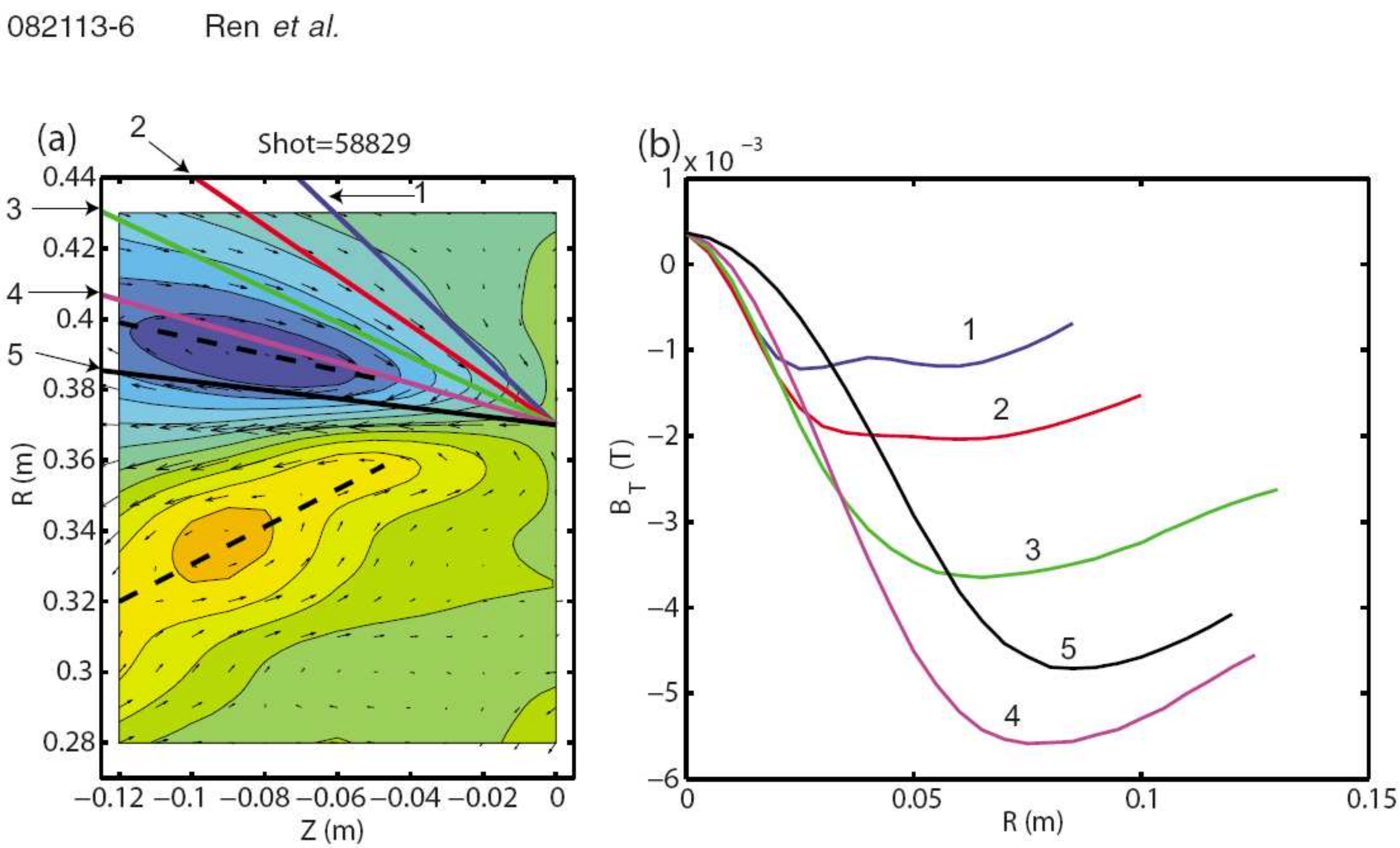
Quadrupole Field in the Laboratory (MRX)

Quadrupole Pattern of Toroidal Magnetic Field in MRX:



Ren et al. 2008

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Field-Line Shape in xz Plane

(Uzdensky & Kulsrud 2006)

Q: What is the shape $z(x,\Psi)$ of a field line in xz plane?

$$\frac{dz}{dx}|_\Psi = \frac{B_z}{B_x}$$

Integrate:

$$\Delta z(x,\Psi) \equiv z(x,\Psi) - z(0,\Psi) \ = - \ c|E_z|D \, \frac{V^2(x,\Psi)}{2} \, .$$

For a given e-fluid element with a trajectory $[X(t),\Psi(t)]$:

$$V[X(t),\Psi(t)] = \mathrm{const} \quad \Rightarrow \quad \Delta z[X(t),\Psi(t)] = \mathrm{const} \, .$$

The field line *looks* more and more stretched toroidally only because it is squeezed from the sides in the x direction, not because it is differentially stretched in the z direction!

Bipolar In-Plane Electric Field

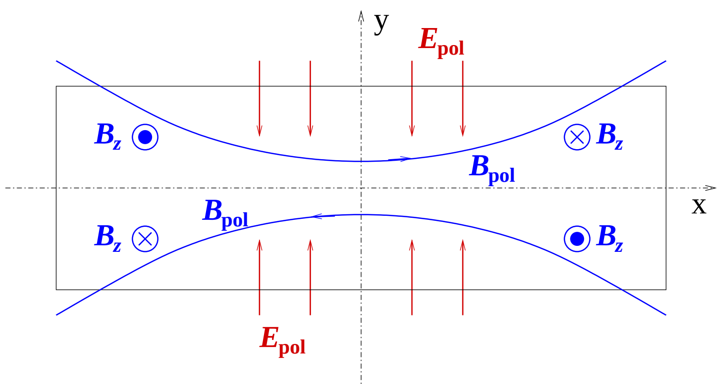
(Uzdensky & Kulsrud 2006)

Q: *Why do field lines move in the out-of-plane direction?*

The *field line velocity* v_B is just the $\mathbf{E} \times \mathbf{B}$ velocity:

$$v_{B,z} = c\,\frac{\mathbf{E}_{\mathrm{pol},\perp}}{B_{\mathrm{pol}}} \approx -\,c\,\frac{E_y}{B_x}\,.$$

Field lines move toroidally because of bipolar $\mathbf{E}_{\mathrm{pol},\perp}$!

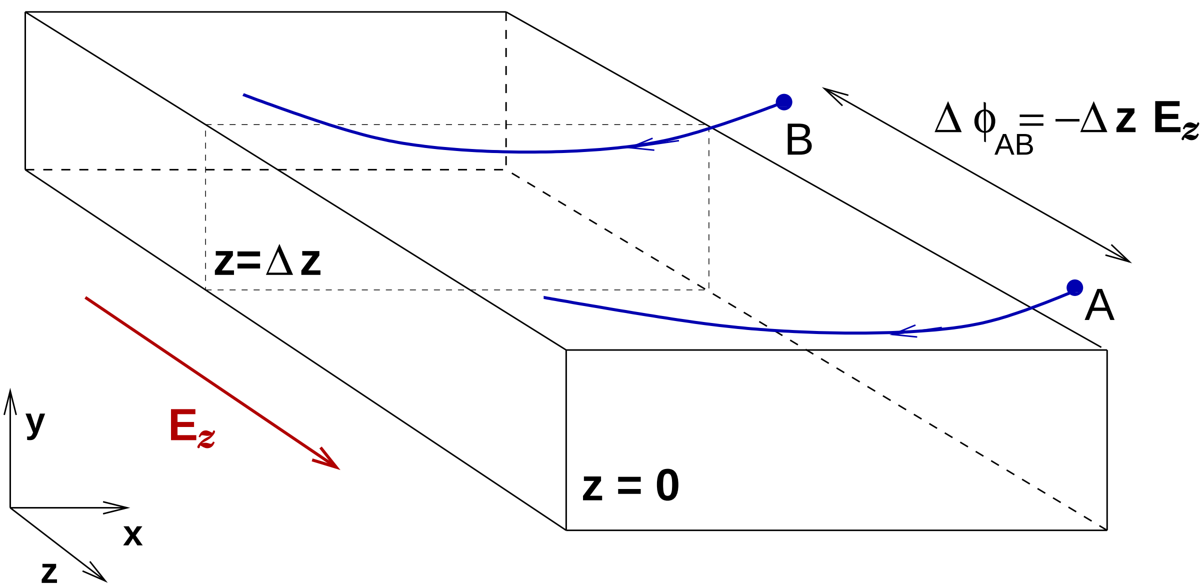


$\mathbf{E}_{\mathrm{pol},\perp}$ is an important signature of Hall reconnection.

It has been observed with spacecraft in Earth's magnetosphere *(e.g., Mozer et al. 2002; Borg et al. 2005; Wygant et al. 2005)*.

Bipolar In-Plane Electric Field: Basic Picture

(Uzdensky & Kulsrud 2006)



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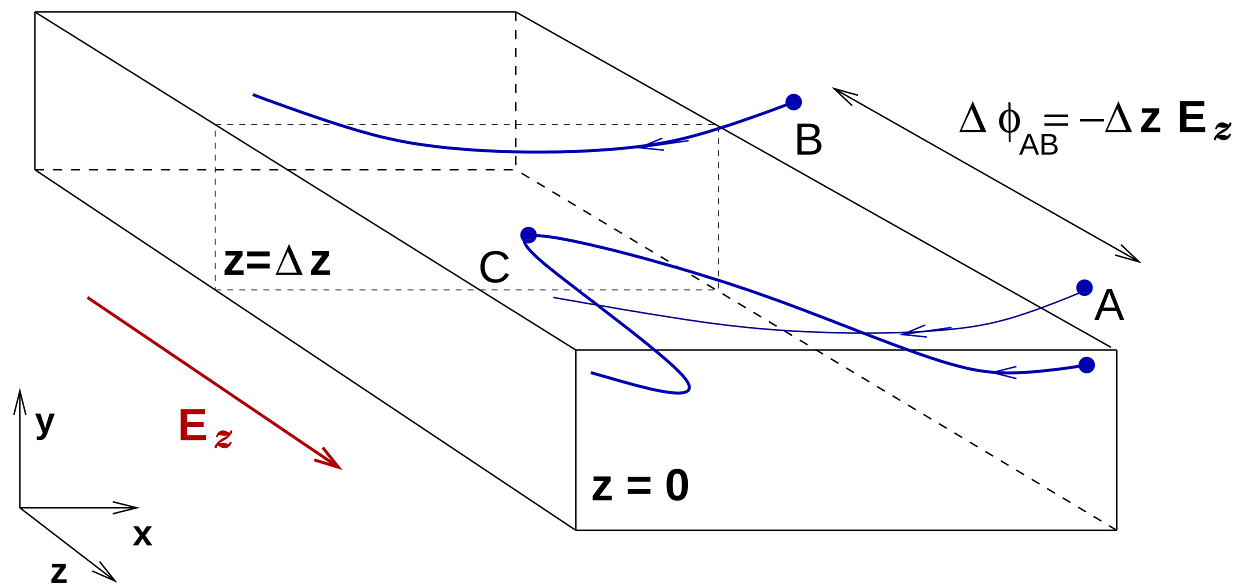
Bipolar In-Plane Electric Field: Basic Picture

(Uzdensky & Kulsrud 2006)



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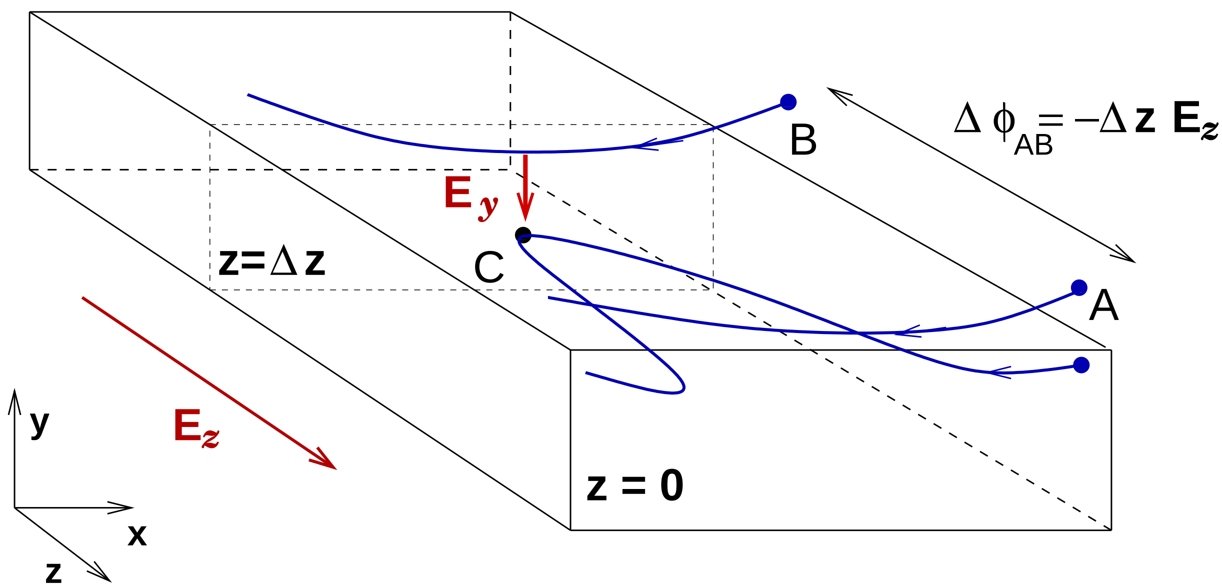
Bipolar In-Plane Electric Field: Basic Picture

(Uzdensky & Kulsrud 2006)



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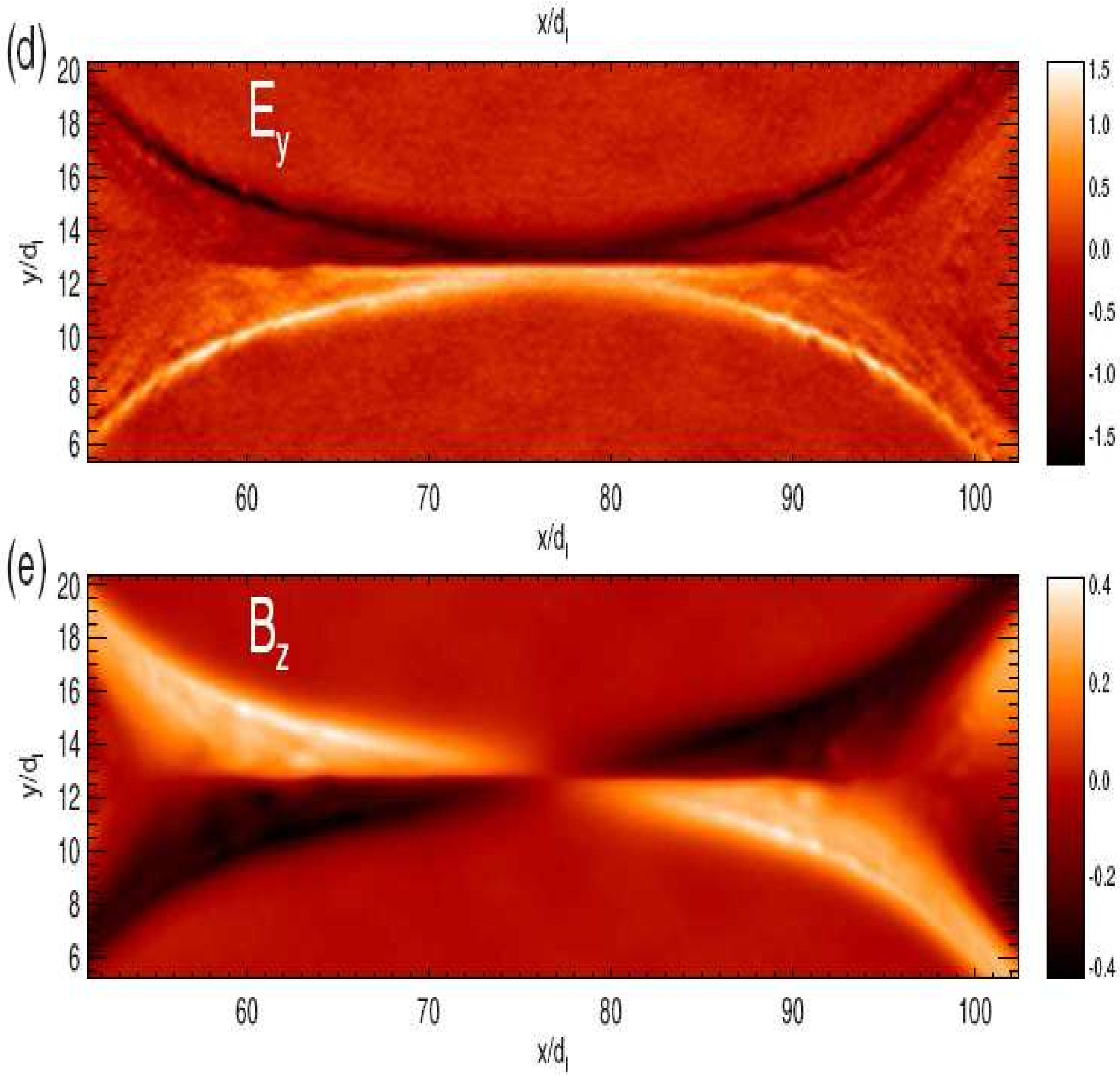
Bipolar In-Plane Electric Field: Numerical Simulations

(Drake et al. 2008)



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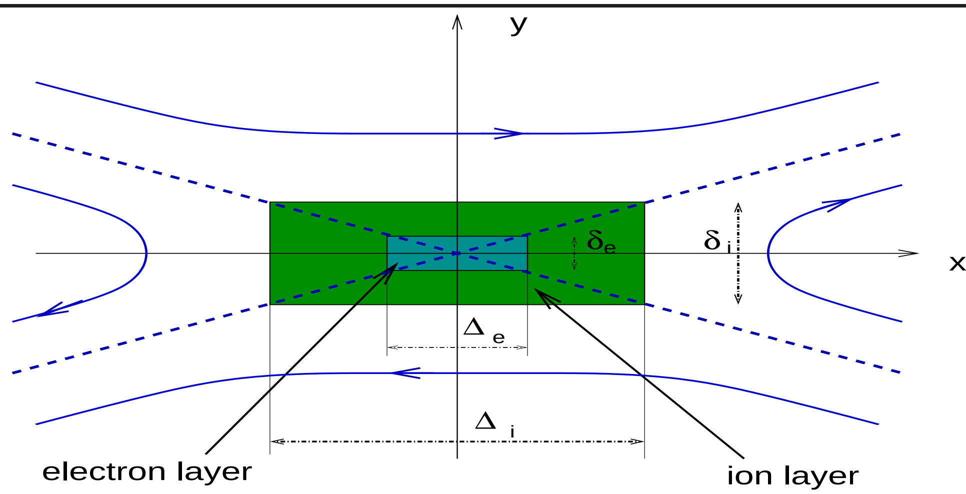
Ion and Electron Heating and the Strength of the Electron Current Layer



- Ion pressure balance:

$$\Delta P_i = ne\Delta\phi \simeq ned_i E_y \quad \Rightarrow \quad \frac{\Delta P_i}{B_0^2/8\pi} \sim \mathcal{E}_y \equiv \frac{cE_y}{B_0 V_A}\,.$$

- Electron pressure balance across EDR:

$$\Delta P_e = \frac{B_{0e}^2}{8\pi} = b_e^2\,\frac{B_0^2}{8\pi}\,.$$

[$B_{0e} = B_x(x=0, y=\delta_e)$ and $b_e \equiv B_{0e}/B_0 < 1$.]

- Total pressure balance across the layer:

$$\Delta P_i + \Delta P_e = \frac{B_0^2}{8\pi}\,, \quad \Rightarrow \quad \mathcal{E}_\mathrm{y} \simeq 1 - \mathrm{b}_\mathrm{e}^2\,.$$

- Relative electron and ion heating in terms of b_e:

$$\frac{\Delta T_e}{\Delta T_i} = \frac{b_e^2}{1-b_e^2}\,.$$

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Electron Diffusion Region

Thickness of electron diffusion region (EDR):

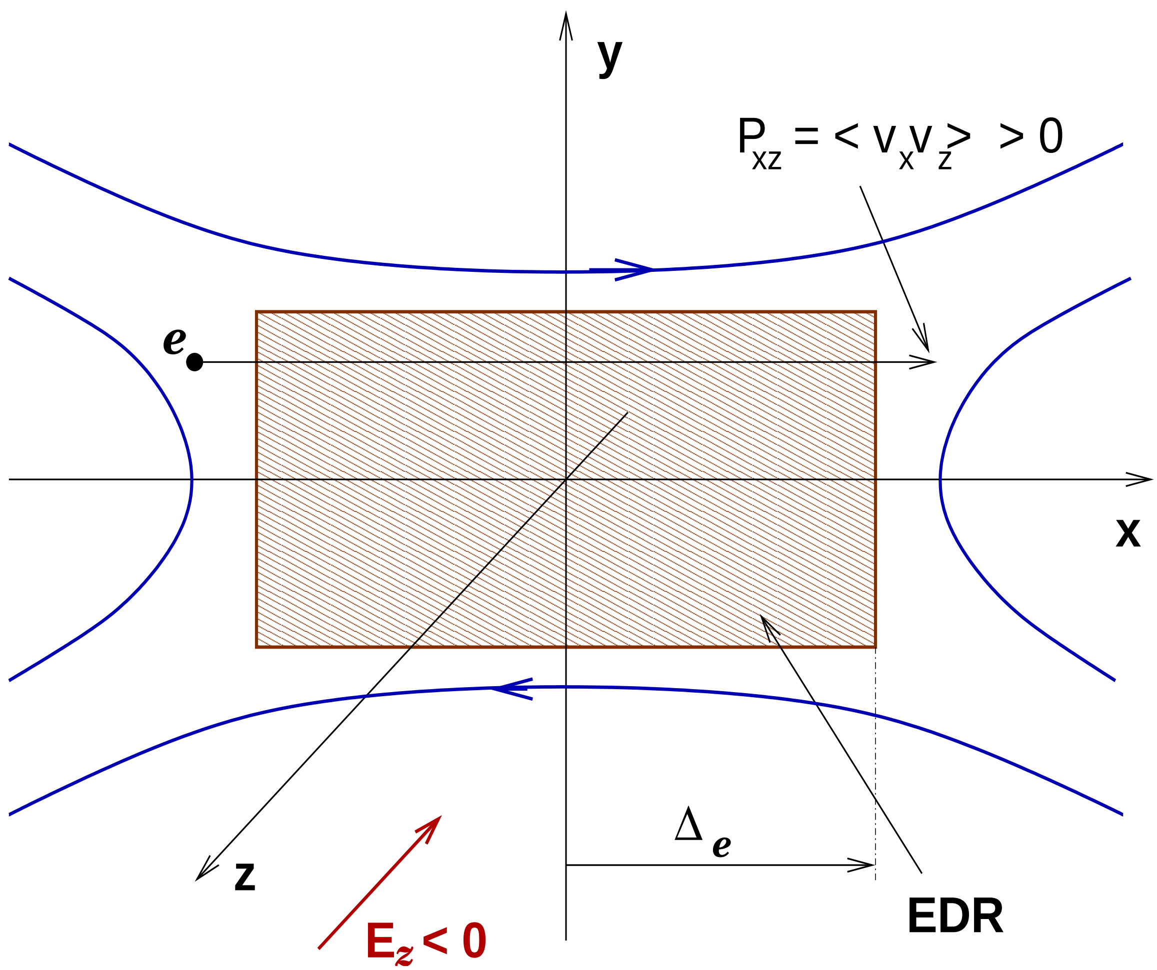
$$\delta_e \sim \rho_e[B_{0e}, T_{e0}] = \sqrt{\frac{T_e}{m_e}} \frac{m_e c}{e B_{0e}} = d_e \sqrt{\beta_{e0}/2}$$

But, if upstream electrons are cold, we expect $\beta_{e0} = 1$ from pressure balance, so

$$\delta_e \simeq d_e \quad \text{and} \quad j_{ez} \simeq e n_e V_A e$$

Electron Pressure Tensor: Physical Picture

- What breaks field lines at the center of the layer ?
  What balances the reconnection electric field, E_z ?
- In collisionless plasmas, electrons just accelerate by E_z for as long as they are inside the EDR, where they are unmagnetized.
  That is, E_z is balanced by inertia of electrons.
- Two inertial terms: inertia of the electron fluid and **non-gyrotropic pressure tensor.**



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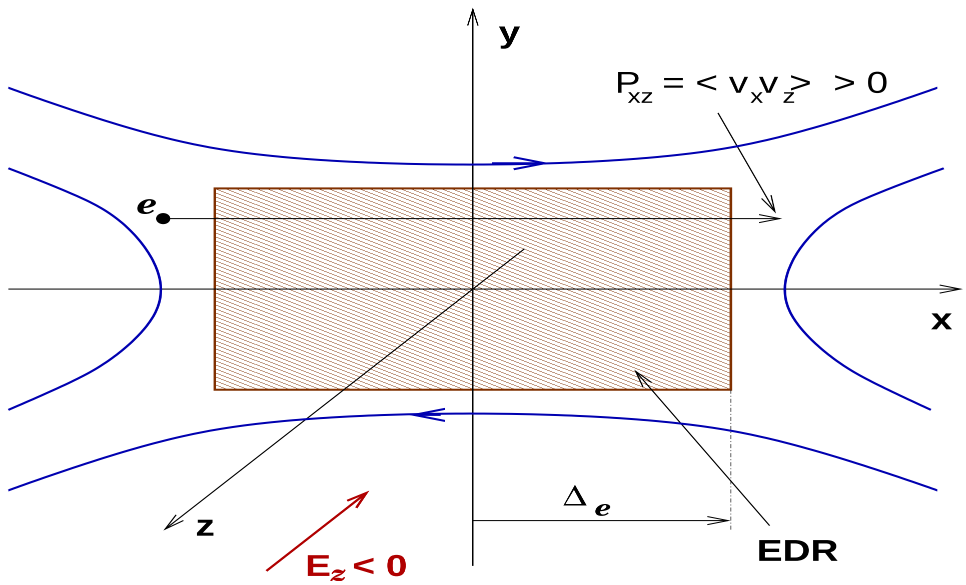
Ohm's Law with Electron Pressure Tensor



- Derive Ohm's law with pressure tensor:

$$j_{ez} = -\,en < v_{ez} > = \frac{ne^2}{m_e}\, E_z\, \tau\,.$$

- Electron fly-by time across EDR: $\tau = \Delta / v_{e,\mathrm{th}}$.
- Thus we get a relationship between Δ_e and E_z:

$$E_z = \frac{c}{\omega_{pe}^2}\, \frac{v_{e,th}}{\Delta_e}\, \frac{B_{0e}}{\delta_e} = \frac{d_e^2}{\delta_e \Delta_e}\, \frac{v_{e,\mathrm{th}}}{c}\, B_{0e} \propto 1/\Delta_e \delta_e\,,$$

or

$$\mathcal{E}_z \equiv \frac{cE_z}{B_0 V_A} = b_e\, \frac{d_e^2}{\delta_e \Delta_e}\, \frac{v_{e,\mathrm{th}}}{V_A} = b_e^2\, \frac{d_e^2}{\delta_e \Delta_e} \sqrt{\frac{\beta_e}{2}} \sqrt{\frac{m_i}{m_e}} = b_e^2\, \frac{d_i}{\Delta_e}\,.$$

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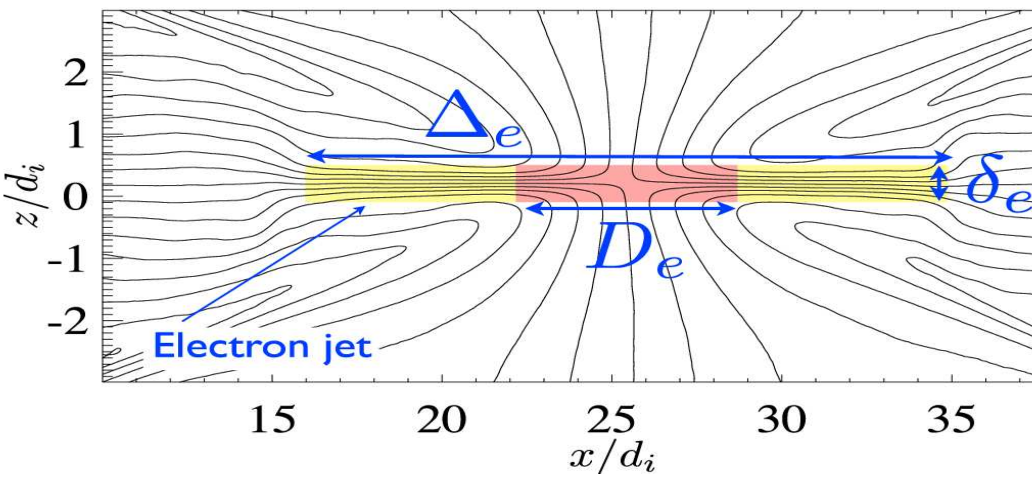
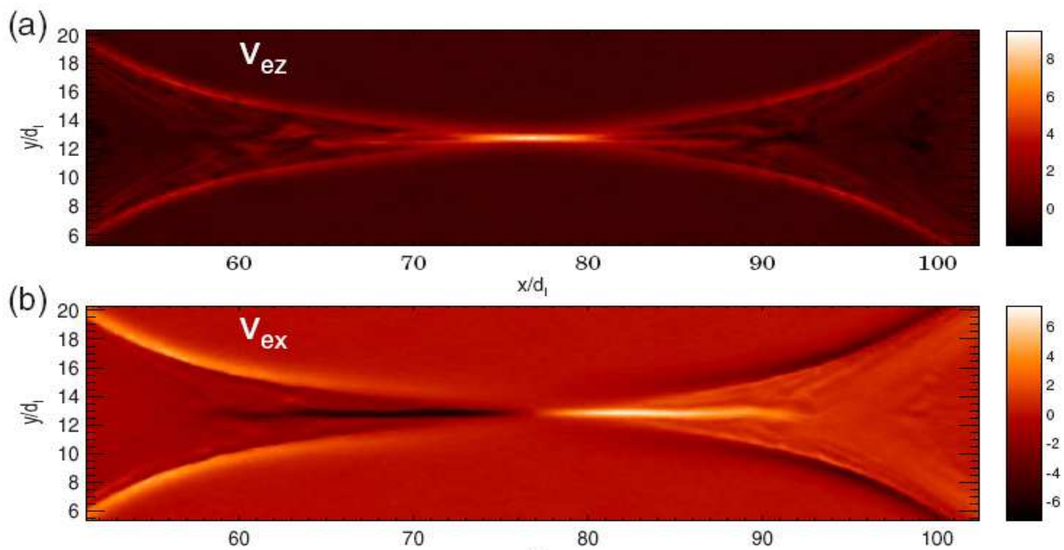
Electron Outflow Jet in PIC Simulations

- PIC simulations *(Daughton et al. 2006; Shay et al. 2007; Karimabadi et al. 2007; Drake et al. 2008)*:
  Electron Diffusion Region has two-scale structure in x-direction: short for v_{ez} and long for v_{ex} **(electron outflow jet)**!



(Karimabadi et al. 2007)

Phys. Plasmas **15**, 042306 (2008)



(Drake et al. 2008)

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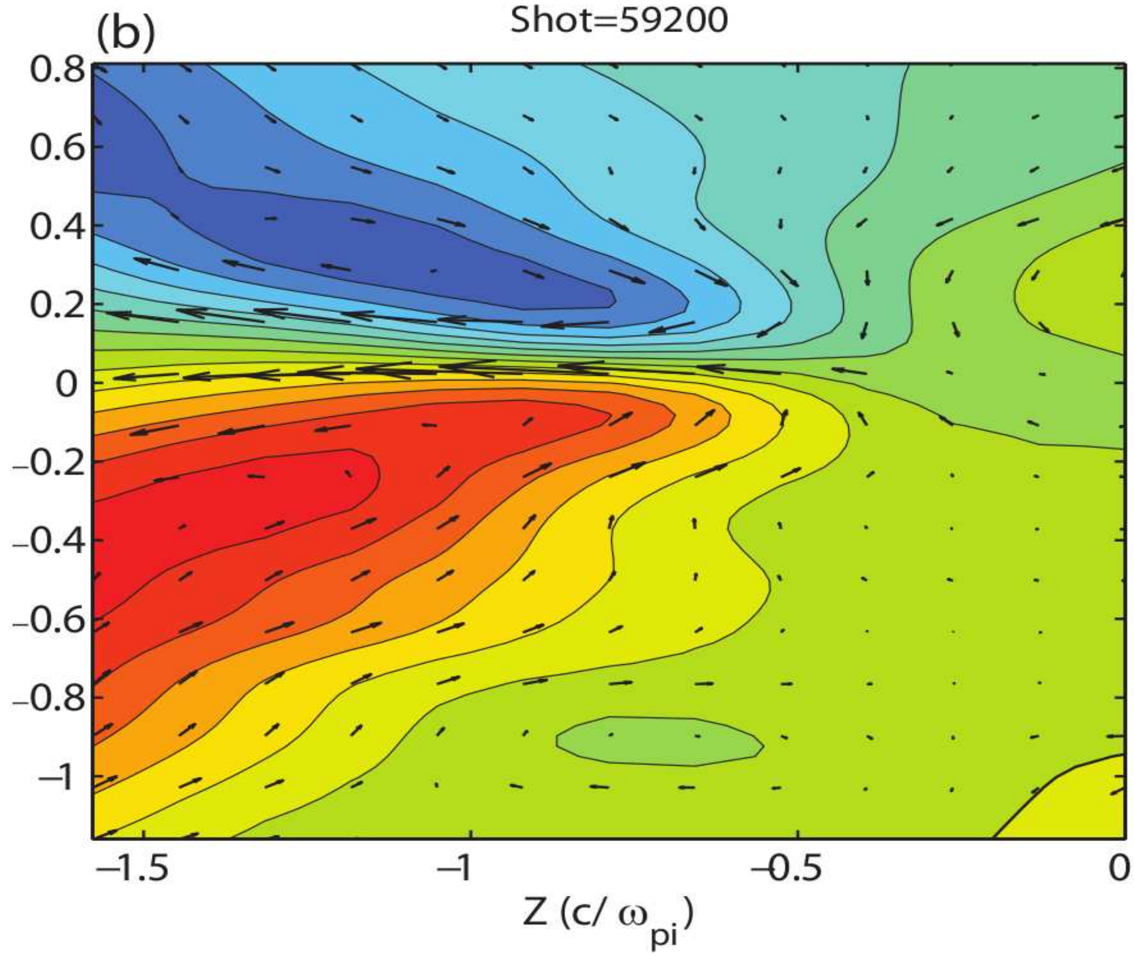
Electron Outflow Jet in Laboratory

- Electron outflow jet in MRX *(Ren et al. 2008)*



Electron Outflow Jet

Motion of electrons near the midplane ($y = 0$):

- Near x-point: electrons accelerated by E_z and then diverted out in the x-direction by the Lorentz force due to the reconnected B_y field
- Electron current turns from z-direction to x-direction hence magnetic field it produces just above the electron current layer turns from B_x to B_z.
- At $x = \Delta_e$ electrons become magnetized by the weak B_y field:

$$\Delta_e = \rho_e[B_y(x = \Delta_e)] \quad \Rightarrow \quad B_y(x = \Delta_e) \sim \frac{cE_z}{v_{Ae}} \sim B_{0e}\,\frac{\delta_e}{\Delta_e}$$

Electron Outflow Jet

- Beyond $x = \Delta_e$, electrons $\mathbf{E_z} \times \mathbf{B_y}$-drift outwards (caveat: recent PIC simulations: electrons out-running the field lines)
- electron orbits are betatron orbits in the reversing quadrupole (B_z) field, superimposed on a large-scale drifting gyro-orbits due to weaker B_y field.
- Eventually, at $x = \Delta_i$ ions become magnetized also:

$$B_y(\Delta_i) = \frac{cE_z}{V_A} \sim B_0 \mathcal{E}_z \tag{1}$$

- Electrons and ions start moving together (MHD regime), j_x becomes small, B_z just above and below the midplane drops, the electrons are no longer confined to the midplane, the electron outflow jet decays.
- Beyond that, B_z concentration departs from the midplane and just follows the separatrix.

SUMMARY

Collisionless Reconnection Layer:

A PORTRAIT

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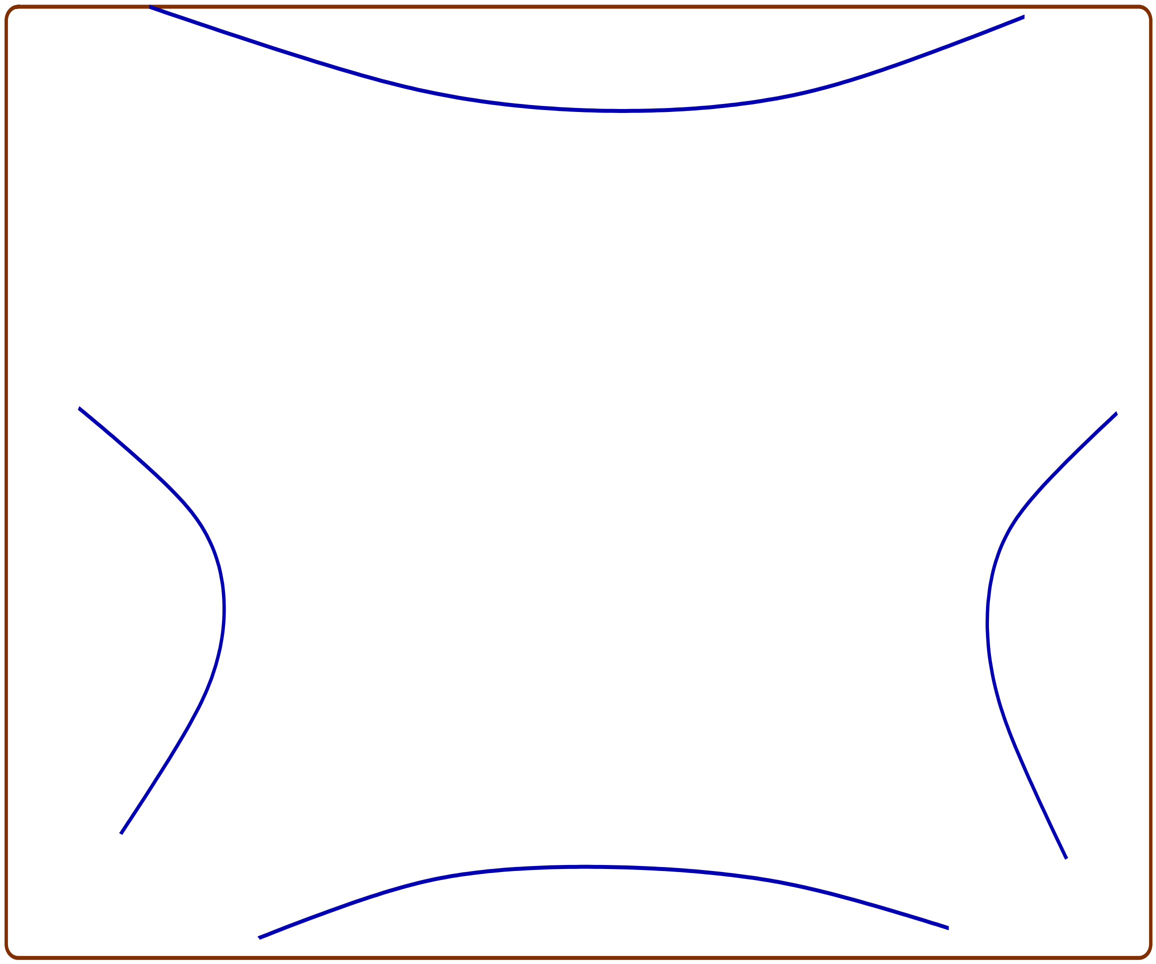
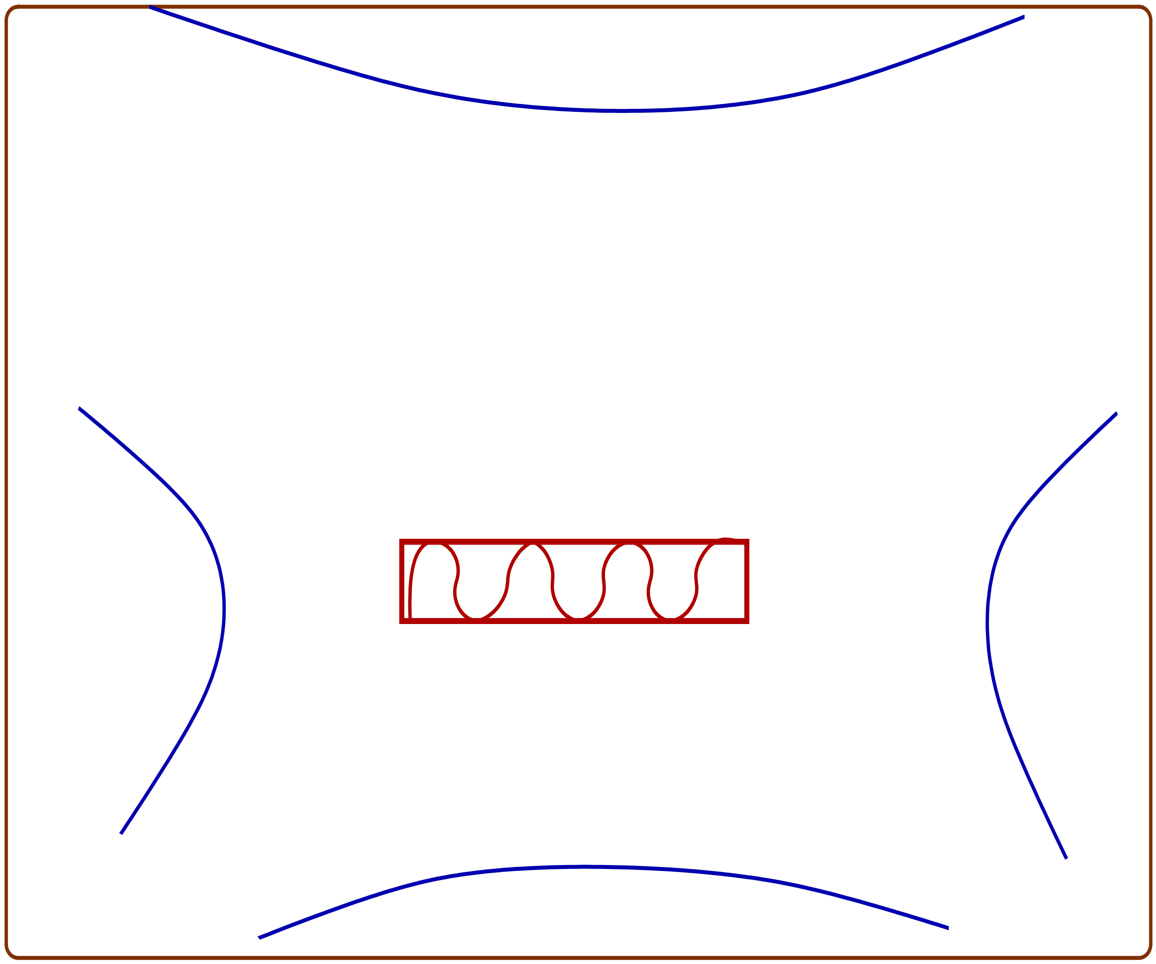
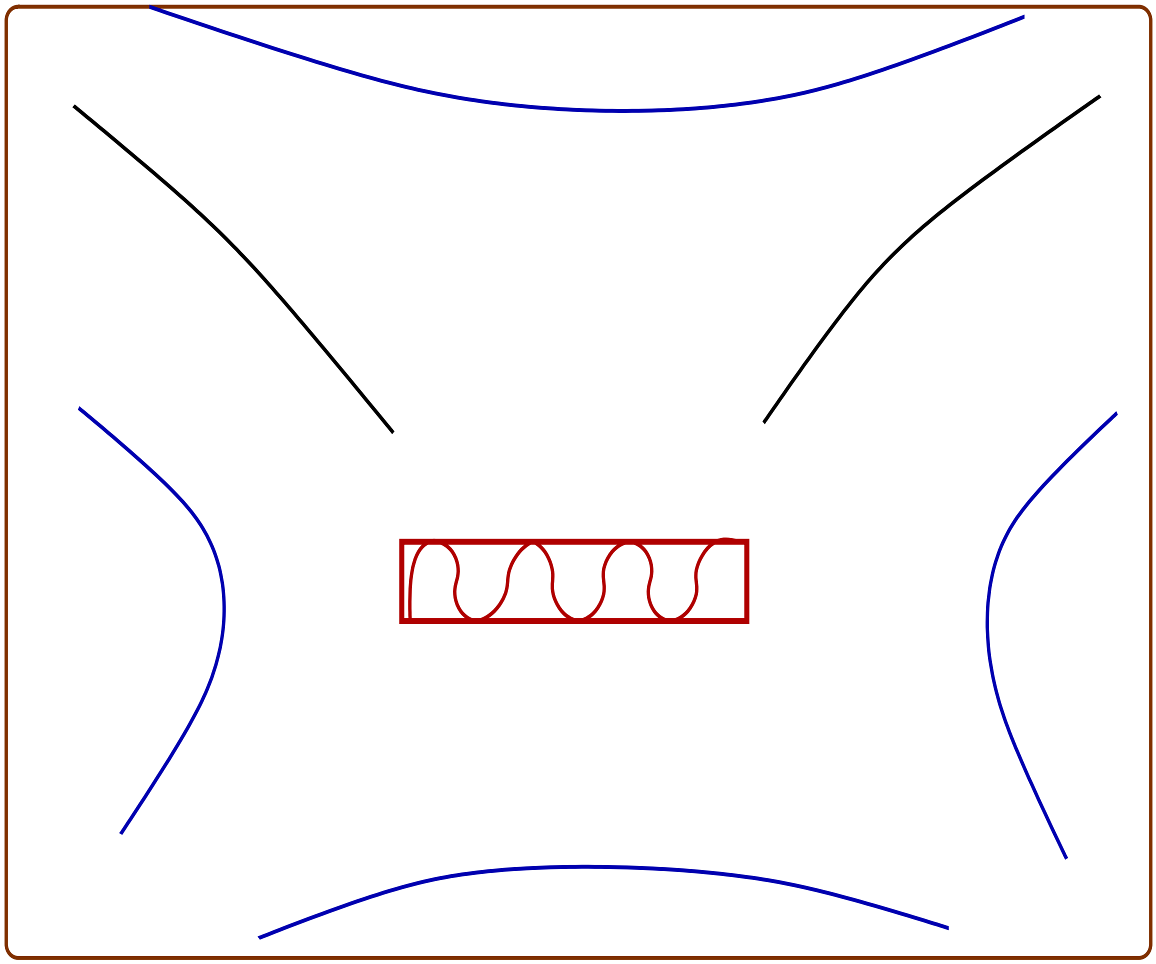


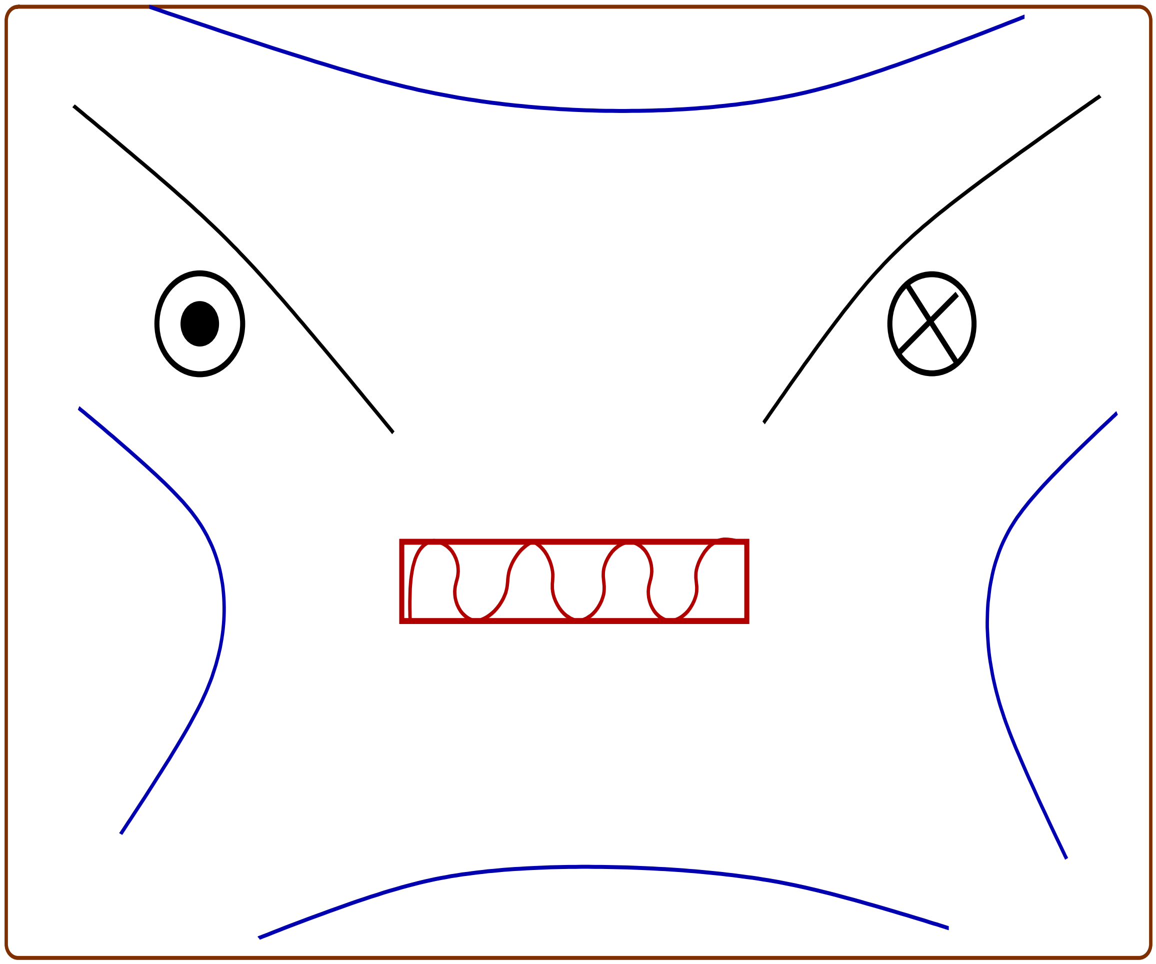
- Outer Ion Layer



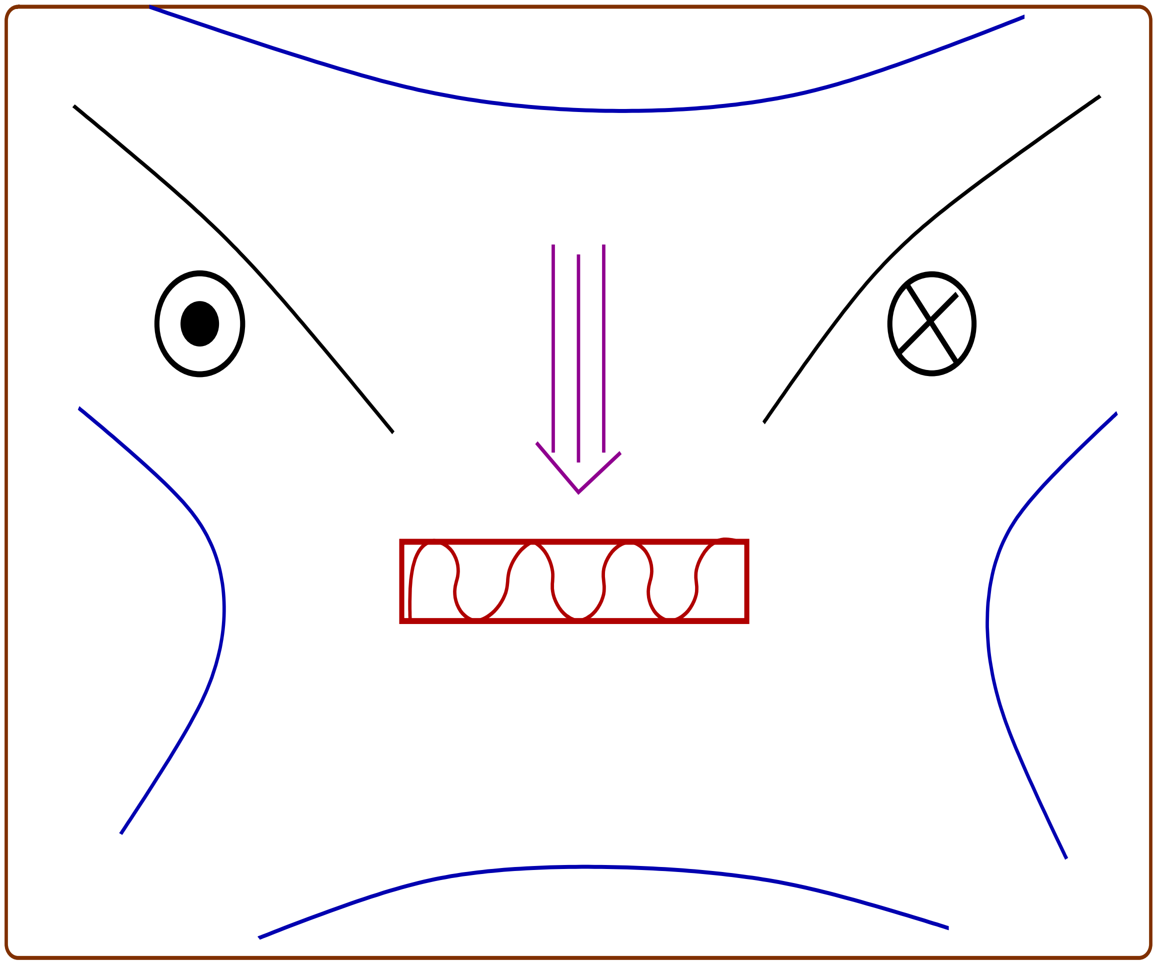
- Outer Ion Layer
- Inner Electron Layer



- Outer Ion Layer
- Inner Electron Layer
- Separatrices



- Outer Ion Layer
- Inner Electron Layer
- Separatrices
- Quadrupole Out-of-Plane Magnetic Field



- Outer Ion Layer
- Inner Electron Layer
- Separatrices
- Quadrupole Out-of-Plane Magnetic Field
- Bipolar In-Plane Electrostatic Field

Ion and Electron Layers

Parameters describing collisionless reconnection layer:

- Ion layer thickness, δ_i (normalized to d_i)
- Electron layer thickness, δ_e (normalized to d_e)
- Reconnection rate, aka out-of-plane electric field E_z:

$$\mathcal{E}_z = \frac{cE_z}{B_0 V_A} \ll 1 \tag{2}$$

- Bipolar in-plane electric field, E_y, and associated electrostatic potential drop, $\Delta\phi = E_y \delta_i \simeq E_y d_i$:

$$\mathcal{E}_y = \frac{cE_y}{B_0 V_A} \tag{3}$$

- Reconnecting magnetic field just outside EDR, B_{0e} (fraction of total current carried by electrons within EDR):

$$b_e \equiv \frac{B_{0e}}{B_0} < 1 \tag{4}$$

- Ion pressure increase across the layer, ΔP_i, normalized by $B_0^2/8\pi$:

$$\Delta\beta_i = \frac{\Delta P_i}{B_0^2/8\pi} \tag{5}$$

- Electron pressure increase across EDR, ΔP_e, normalized by $B_0^2/8\pi$:

$$\Delta\beta_e = \frac{\Delta P_e}{B_0^2/8\pi} \tag{6}$$

FUTURE DIRECTIONS

OF MAGNETIC RECONNECTION RESEARCH

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FUTURE DIRECTIONS I (officially approved recommendations)

- Time-dependent, non-stationary reconnection in very large systems susceptable to secondary tearing instability (both collisional and collisionless):
  - resistive-MHD reconnection in long current layers ($S > 10^4$) *(e.g., Bulanov et al. 1978; Loureiro et al. 2007, 2009; Lapenta 2008; Bhattacharjee et al. 2009; Samtaney et al. 2009)*
  - collisionless reconnection *(Daughton et al. 2008);*
  - what is the effect of secondary plasmoids on the time-averaged reconnection rate?
  - what is the effect of secondary plasmoids on non-thermal particle acceleration *(Drake et al. 2006)*?
  - now accessible to numerical simulations!

- Interaction between two fundamental plasma processes: **reconnection and turbulence**, e.g., externally-driven resistive-MHD turbulence *(e.g., Lazarian & Vishniac 1999; Kowal et al. 2008; Loureiro et al. 2009, in preparation)*

FUTURE DIRECTIONS II (officially approved recommendations)

Astrophysically motivated questions:

- How is the released magnetic energy partitioned between: E_{kin}, $E_{e,\text{th}}$, $E_{i,\text{th}}$, and $E_{\text{non-therm}}$?
- A new frontier in astrophysical reconnection: High-energy-density (HED), radiative environements *(Uzdensky 2008, 2009 in prep.)*:
  - radiative cooling (e.g., Compton) of the reconnection layer (black-hole coronae; magnetar flares);
  - Compton resistivity (radiation drag; black-hole coronae/jets)
  - radiation pressure (collapsars and magnetar flares)
  - pair creation (BH coronae; collapsars and magnetar flares)
- **Prospects for experimental research:**
  - Next generation (medium-scale) reconnection expt: larger ($S > 10^4$), better separation of scales; better diagnostics (incl. energetic particles)
  - HED reconnection with radiation cooling/pressure effects: laser-plasma facilities

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OPEN QUESTIONS I:
Collisional (resistive-MHD) regime

Is it really slow? How slow?

What are the effects of:

1. Actual Spitzer resistivity instead of constant uniform resistivity ?
2. Ohmic heating and realistic e-thermal conduction ?
3. Compressibility: small $\beta_{\mathrm{upstream}}$?
4. Viscosity (anisotropic) ?
5. Secondary tearing instability in very long current layers (for $S > 10^4$) ? *(e.g., Bulanov et al. 1978; Loureiro et al. 2007; Samtaney et al. 2009)*
6. MHD turbulence ? *(e.g., Lazarian & Vishniac 1999)*
7. Additional (astro-)physical effects:
   - weakly-ionized plasma (ISM, molecular clouds) *(Zweibel 1989)*;
   - radiative (e.g., Compton) cooling (black-hole coronae);
   - Compton resistivity (radiation drag; black-hole coronae and jets);
   - pair creation (black holes and magnetars)

More lab studies, especially in large-S limit !

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OPEN QUESTIONS II:
collisionless reconnection

1. Physical nature of η_{anom} ? *(e.g., Kulsrud et al. 2005; Ji et al. 2005 ?)*
2. Petschek-like structure for given functional shape of η_{anom}?
   Reconnection rate in terms of basic plasma parameters ?
   Where is η_{anom} excited: central diffusion region/separatrices ?
   (Malyshkin et al. 2005)
3. How do two-fluid effects and anomalous resistivity interact ?
4. What are the effects of B_z and $\beta_{\mathsf{upstream}}$ on triggering η_{anom} ?
   on Hall reconnection ?
5. What system parameters affect reconnection rate in two-fluid regime ?
6. Is collisionless reconnection laminar or bursty ?
   What is time-averaged reconnection rate ?
   (Bhattacharjee 2004; Daughton et al. 2006; Karimabadi et al. 2007)
7. How is the released energy partitioned between:
   E_{kin}, $E_{e,\mathsf{th}}$, $E_{i,\mathsf{th}}$, and $E_{\mathsf{non-therm}}$?

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