Collisionless Magnetic Reconnection

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OUTLINE

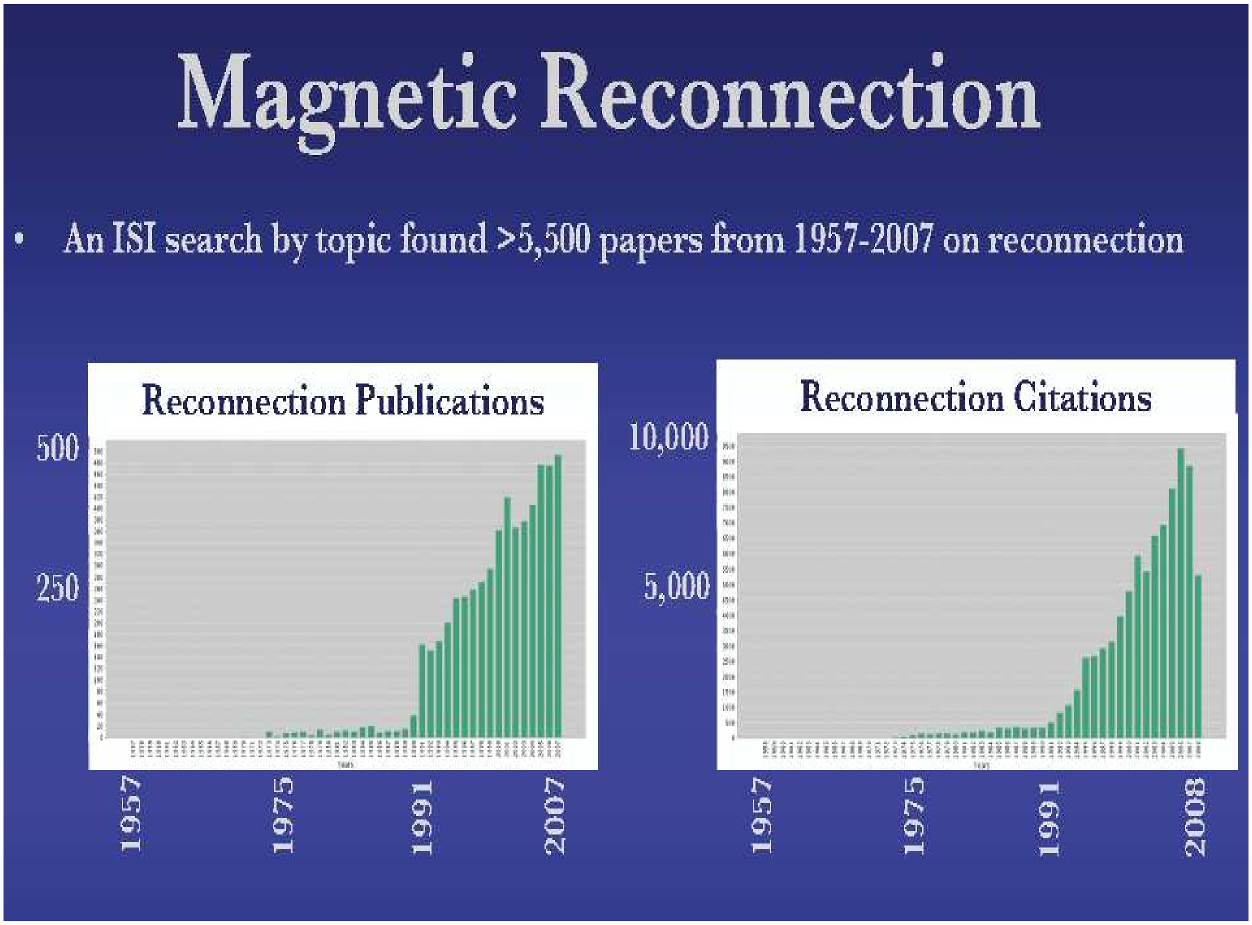
- **Introduction**

- **Why we care about collisionless reconnection?**

- **Collisionless Reconnection Layer:**
  a Physical Portret
  - 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

- **Summary**

Magnetic Reconnection on the Rise!



P. Cassak 2008

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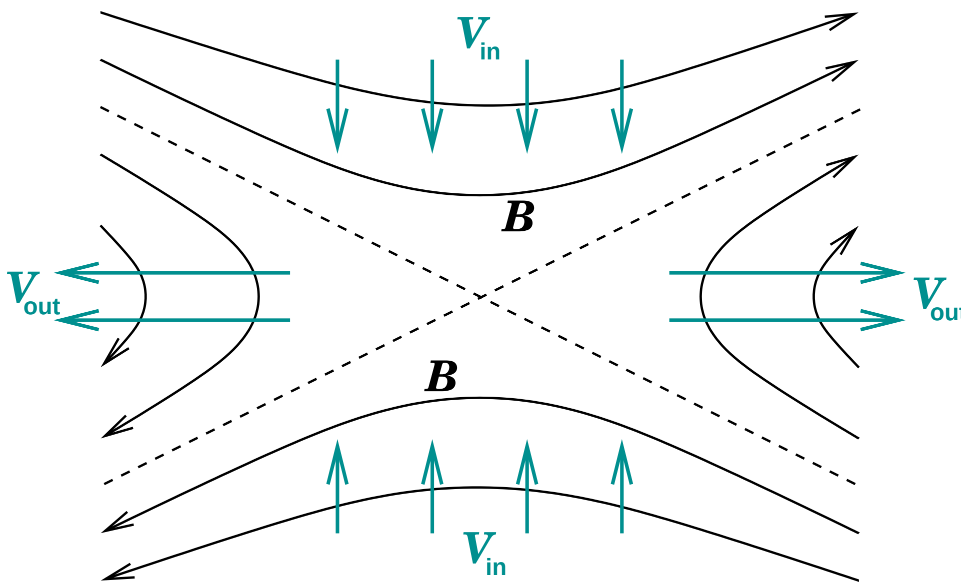
RECONNECTION: INTRODUCTION

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 ?

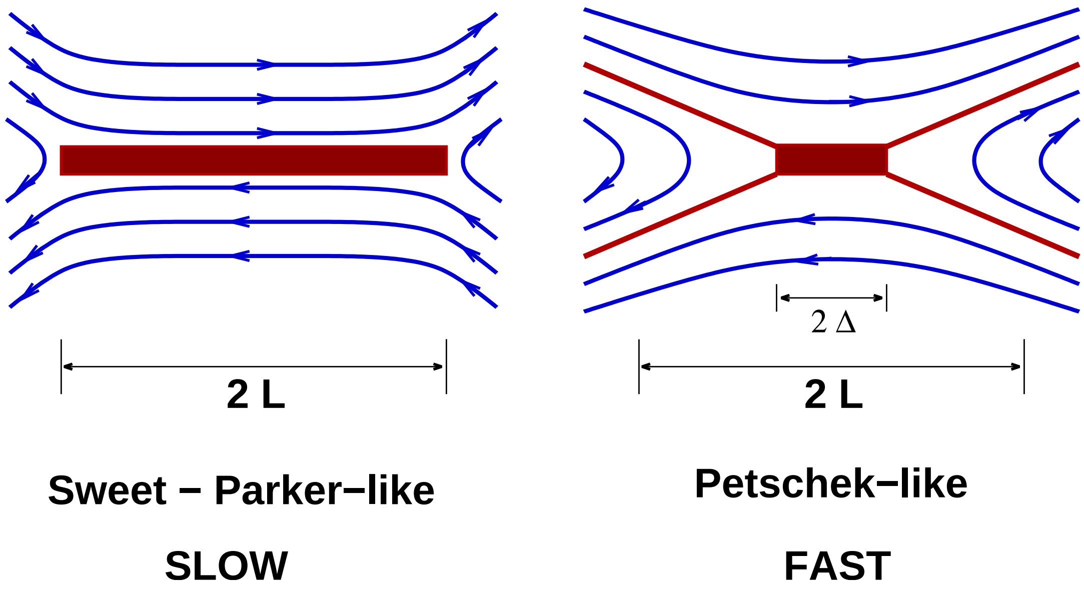
$$\delta_{\mathrm{SP}} < d_i \ ?$$

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

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

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

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: $\delta > \delta_{\mathrm{SP}} = sqrt L\eta/V_A$.

- However, $\delta > \delta_{\mathrm{SP}}$ is not enough for rapid reconnection.

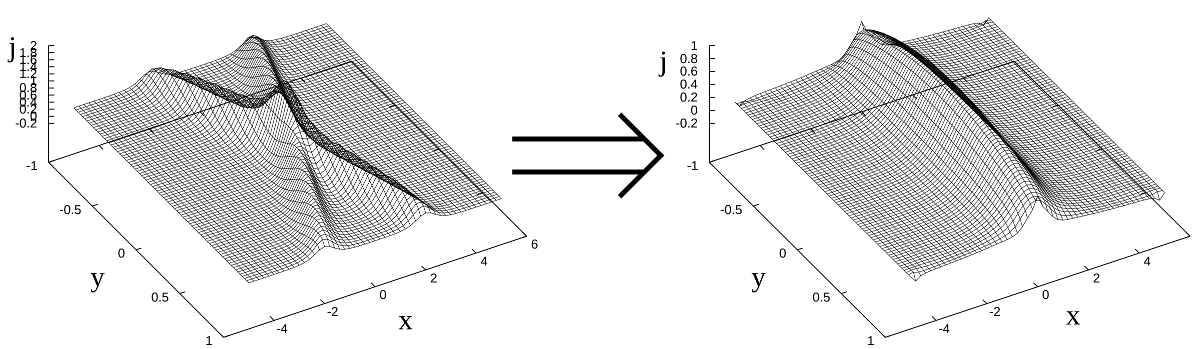
- *Petschek's (1964)* geometric enhancement idea is especially important for large systems:
$$L \gg \rho_i, d_i, \delta_{\mathrm{SP}}$$
(e.g., solar flares: $L \sim 10^9$ cm $\gg$ $d_i \sim \delta_{\mathrm{SP}} \sim 10^2 - 10^3$ cm)

Fast Reconnection $\Leftrightarrow$ Petschek Reconnection

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**!



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

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:

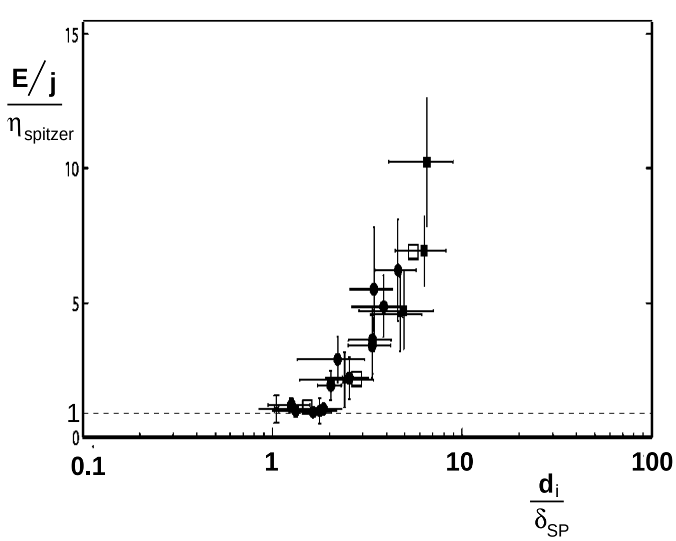
$$d_i \equiv \frac{c}{\omega_{pi}} = c\sqrt{\frac{m_i}{4\pi n_e e^2}}$$

- **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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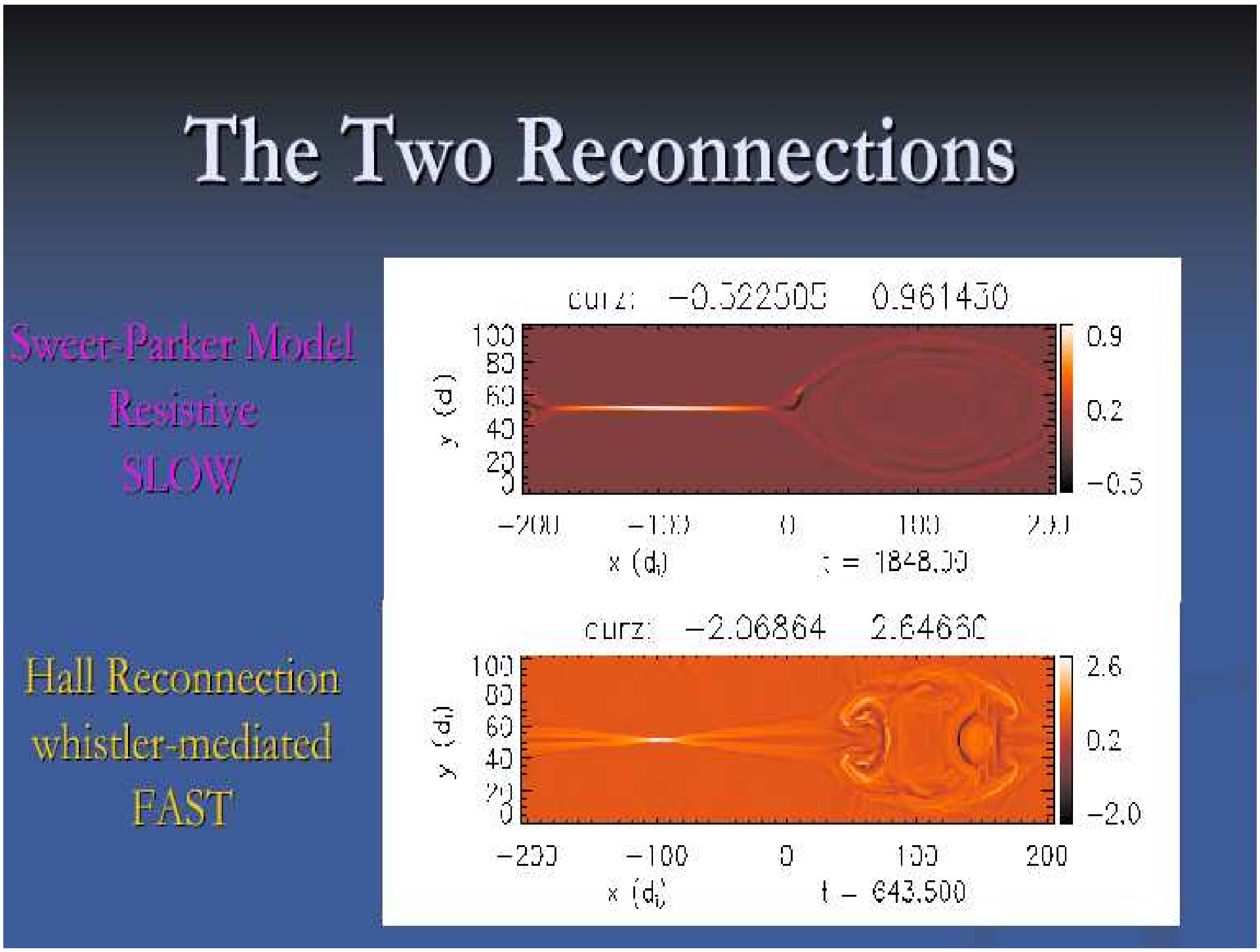
FAST COLLISIONLESS RECONNECTION: HALL EFFECT

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



Cassak et al. 2005

(Cassak, Shay, & Drake 2005)

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

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

Moving Forward: *(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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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 PORTRET

(Sorry, no Guide Field!)

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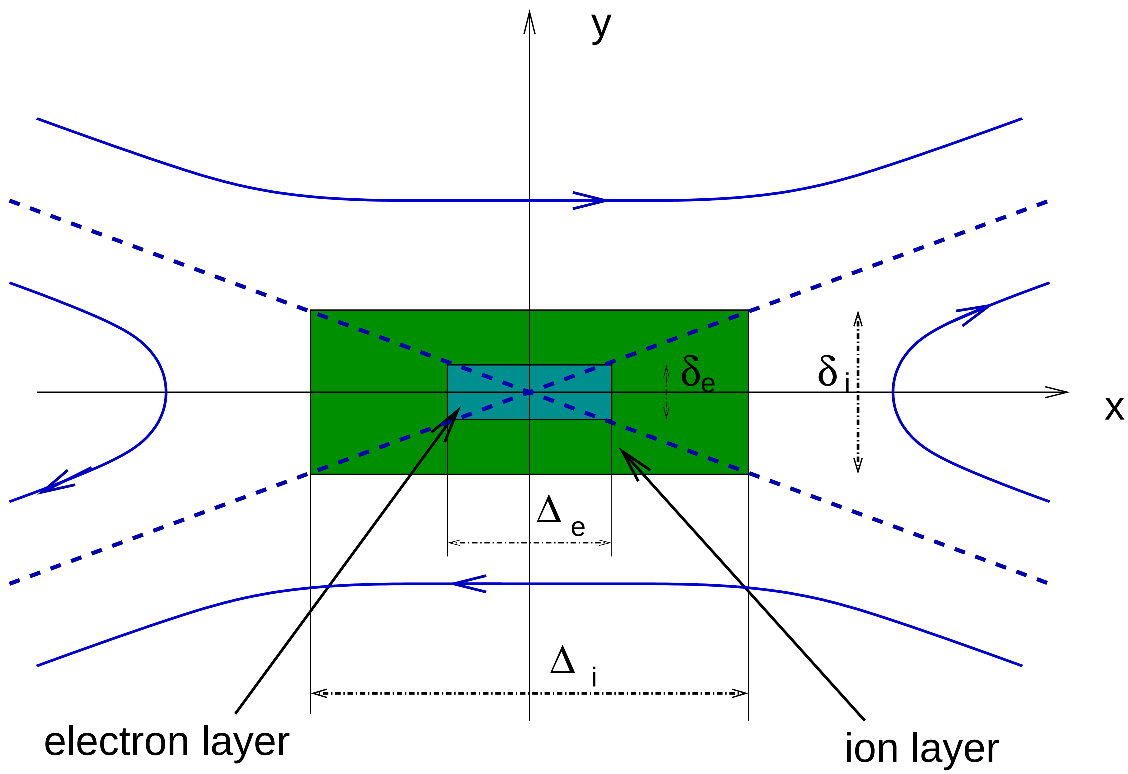
Collisionless Reconnection Layer: General Morphology



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

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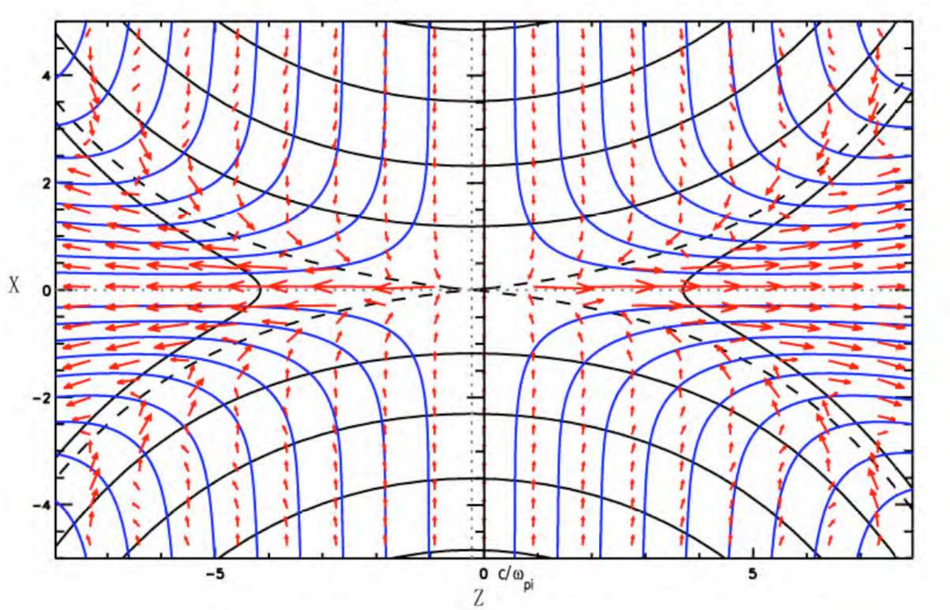
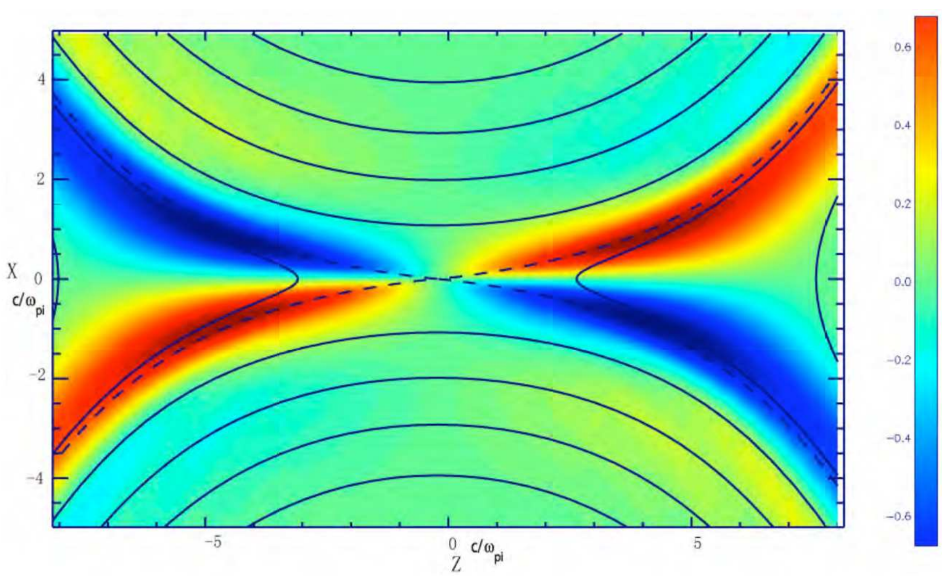
Quadrupole Magnetic Field: Numerical Simulations

Ion and electron streamlines:



Quadrupole out-of-plane magnetic field:



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

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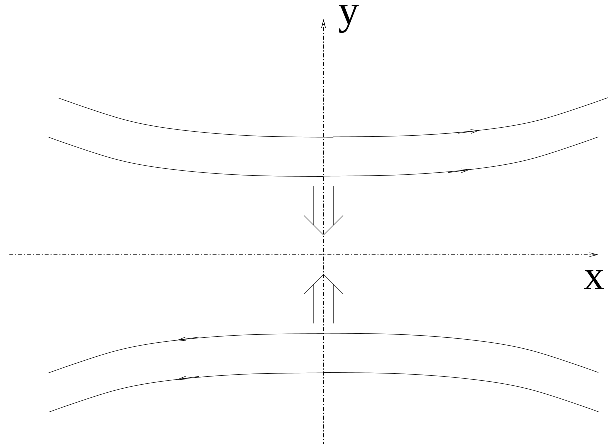
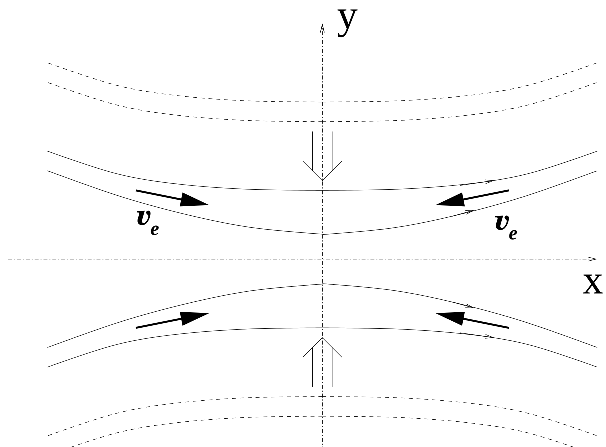
Quadrupole Magnetic Field: Basic Explanation I

(Uzdensky & Kulsrud 2006)





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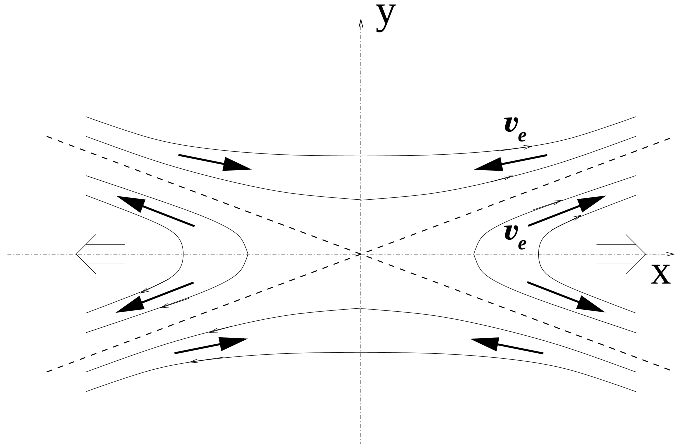
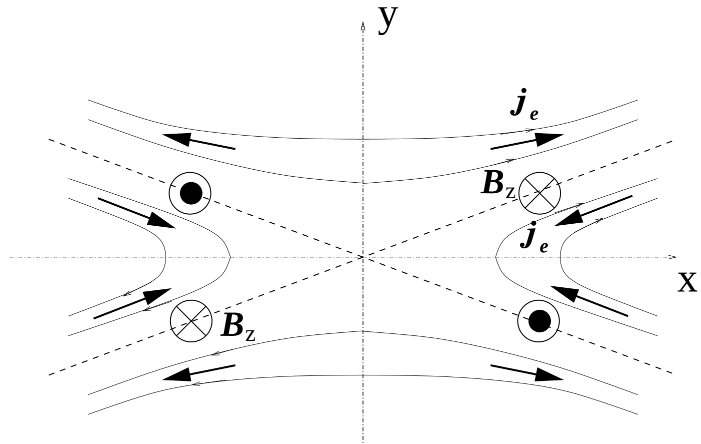
Quadrupole Magnetic Field: Basic Explanation II

(Uzdensky & Kulsrud 2006)





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Ideal Incompressible Electron MHD: General Results

(Uzdensky & Kulsrud 2006)

Three Important Functions:

– volume per flux: $V(x,\Psi) = \int_0^x \frac{dl_{\rm pol}}{B_{\rm pol}} |_\Psi$

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

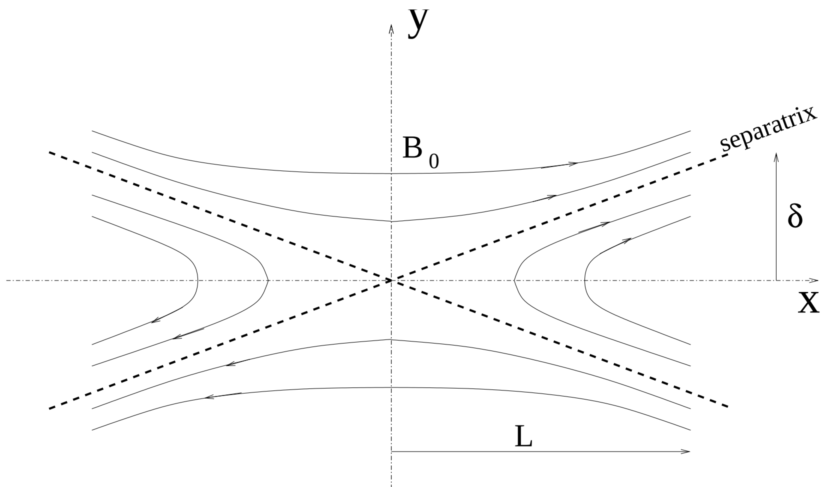
Eqn. (2) $\Rightarrow$ $\mathbf{v}_{\rm pol}^{(e)} \cdot \nabla B_z \equiv 0.$

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 $\mathbf{B}_{\rm pol}$: $\nabla^2\Psi = F(\Psi)$.

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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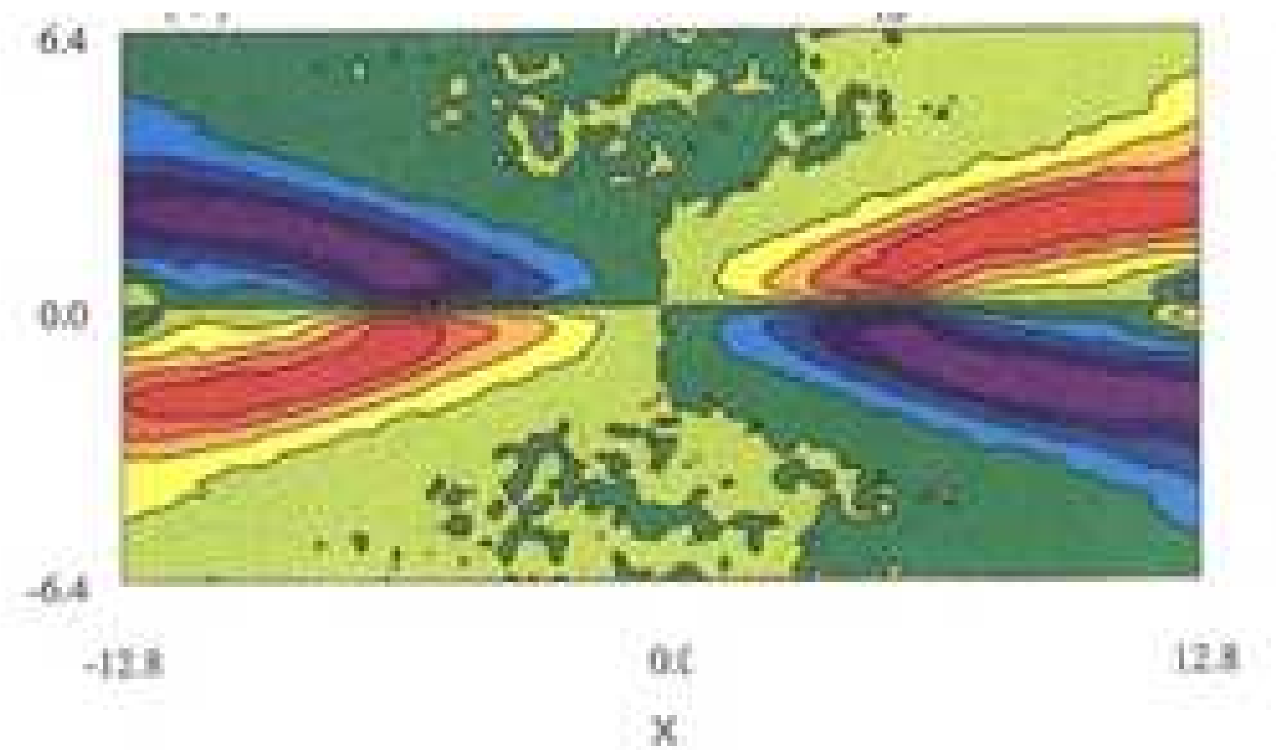
Quadrupole Field in Numerical Simulations

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



Pritchett et al. 2001

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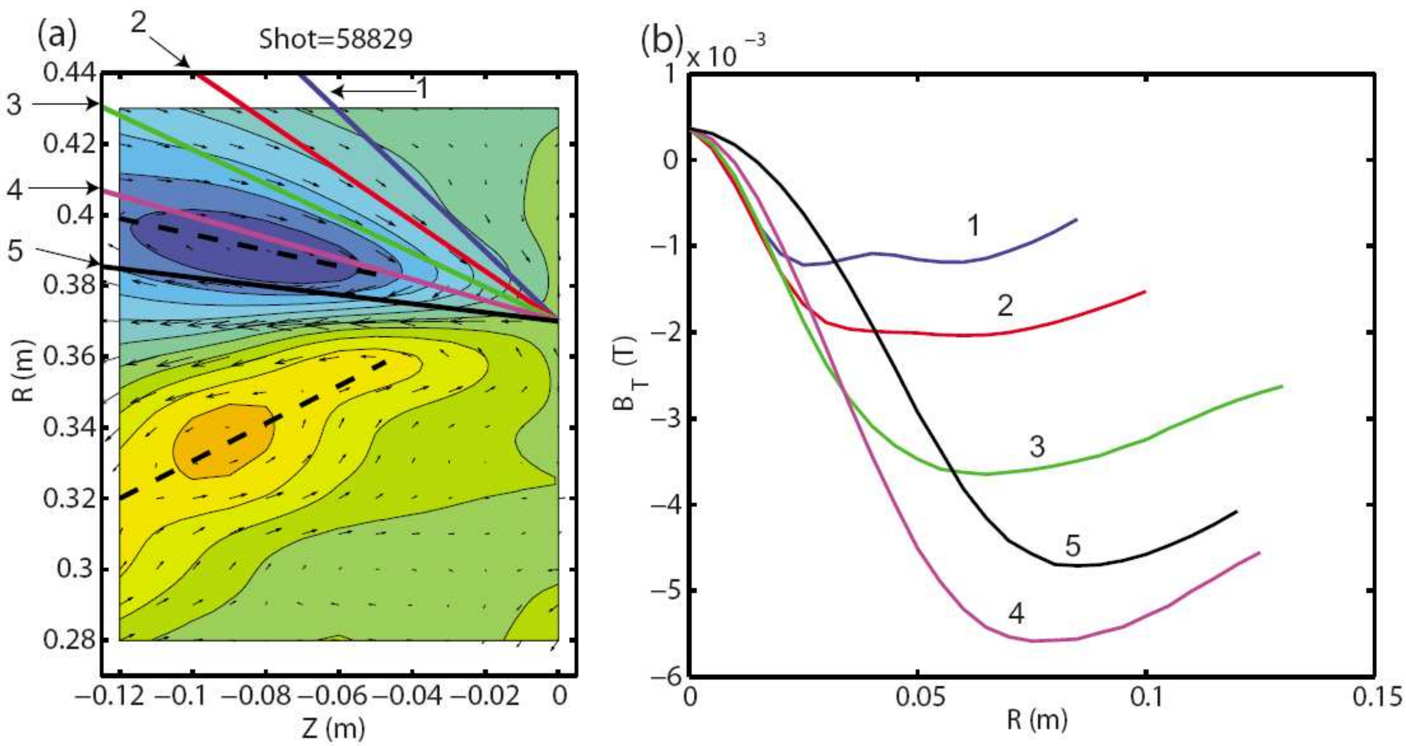
Quadrupole Field in the Laboratory (MRX)

Quadrupole Pattern of Toroidal Magnetic Field in MRX:

082113-6 Ren *et al.*



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 $[X(t), \Psi(t)]$:

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

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

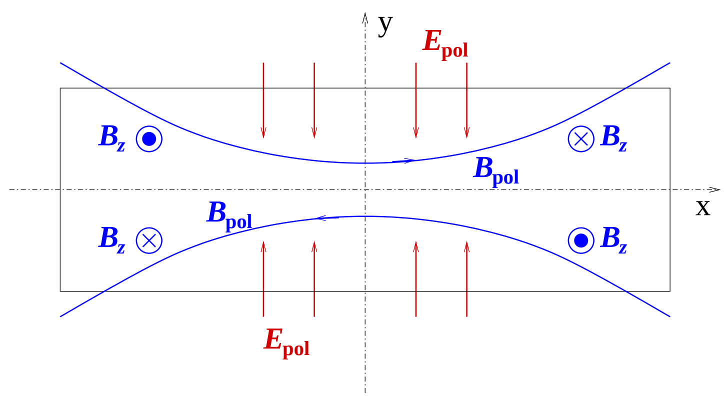
(Uzdensky & Kulsrud 2006)

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:

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

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

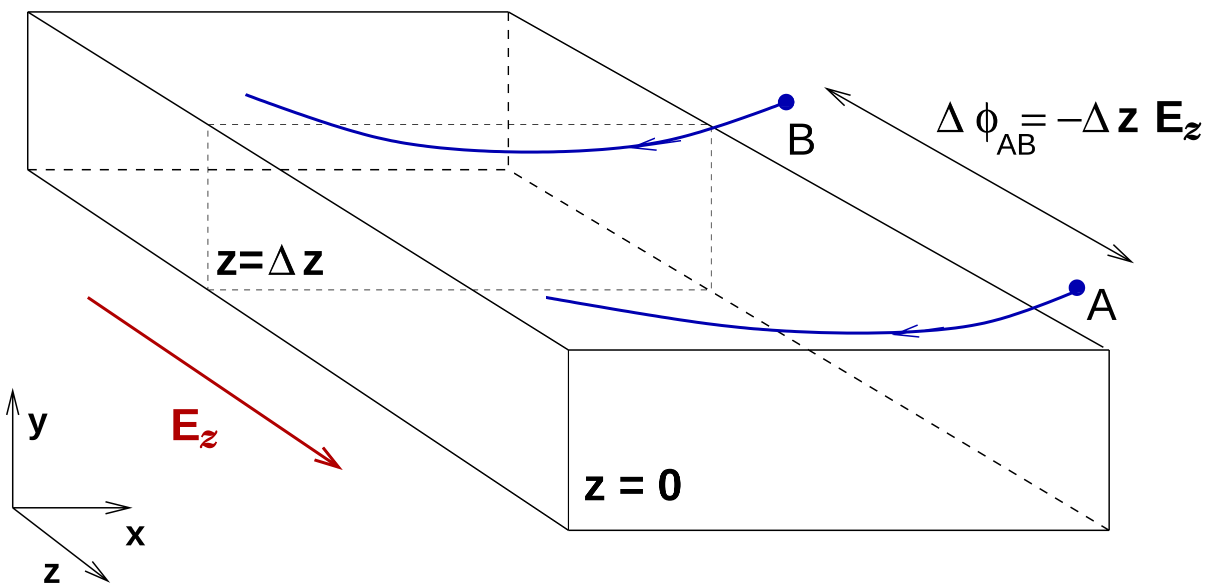


$\mathbf{E}_{\text{pol},\perp}$ is an important signature of Hall reconnection.

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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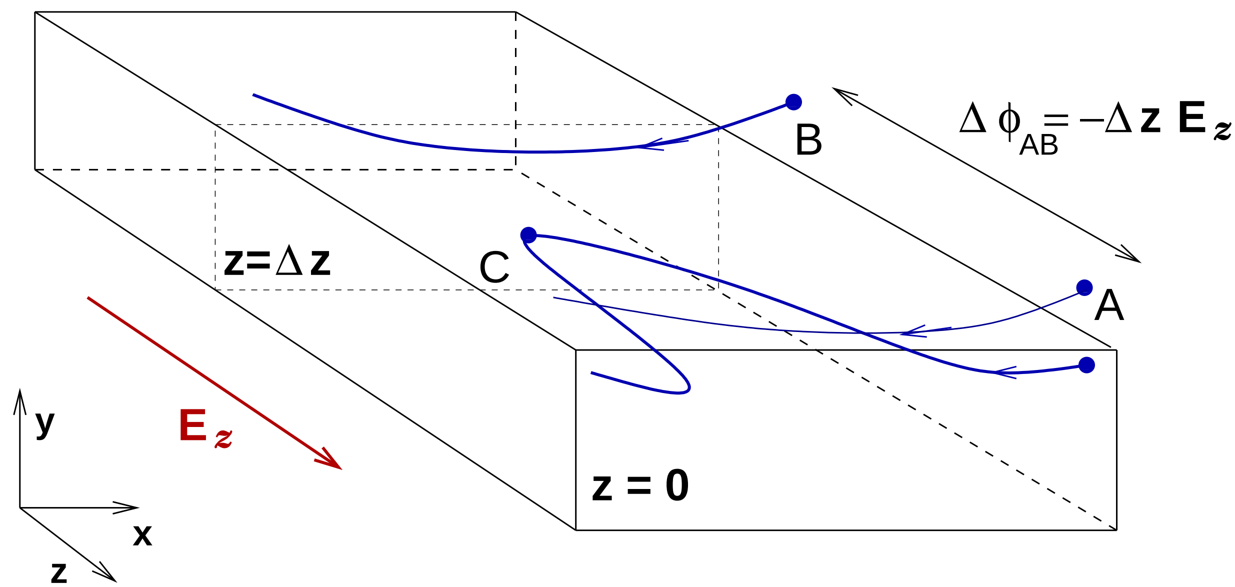
Bipolar In-Plane Electric Field: Basic Picture

(Uzdensky & Kulsrud 2006)



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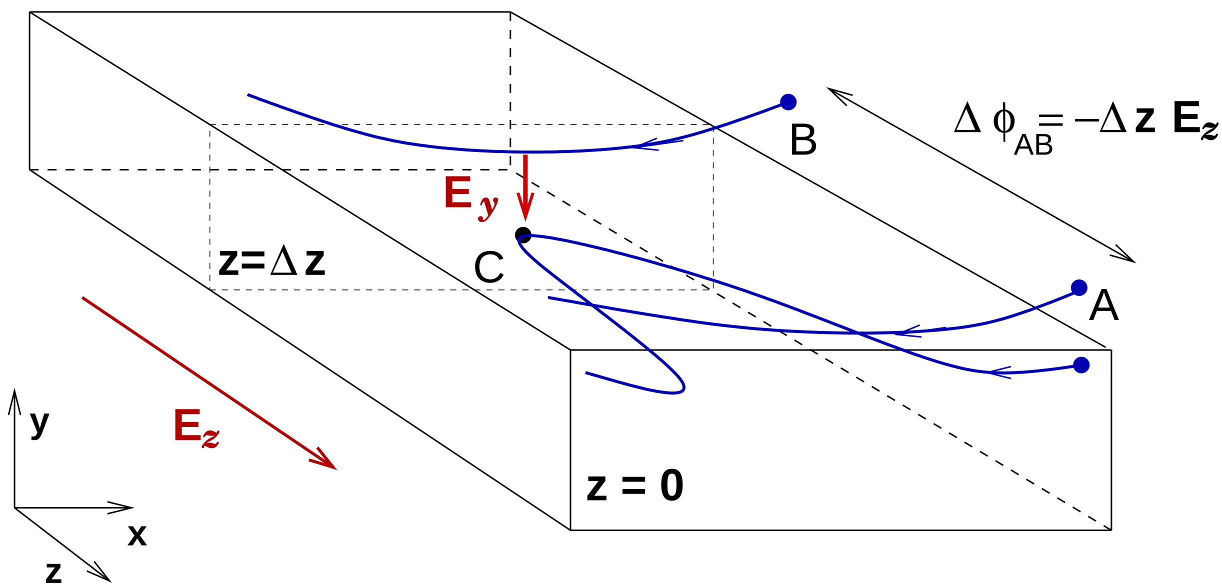
Bipolar In-Plane Electric Field: Basic Picture

(Uzdensky & Kulsrud 2006)



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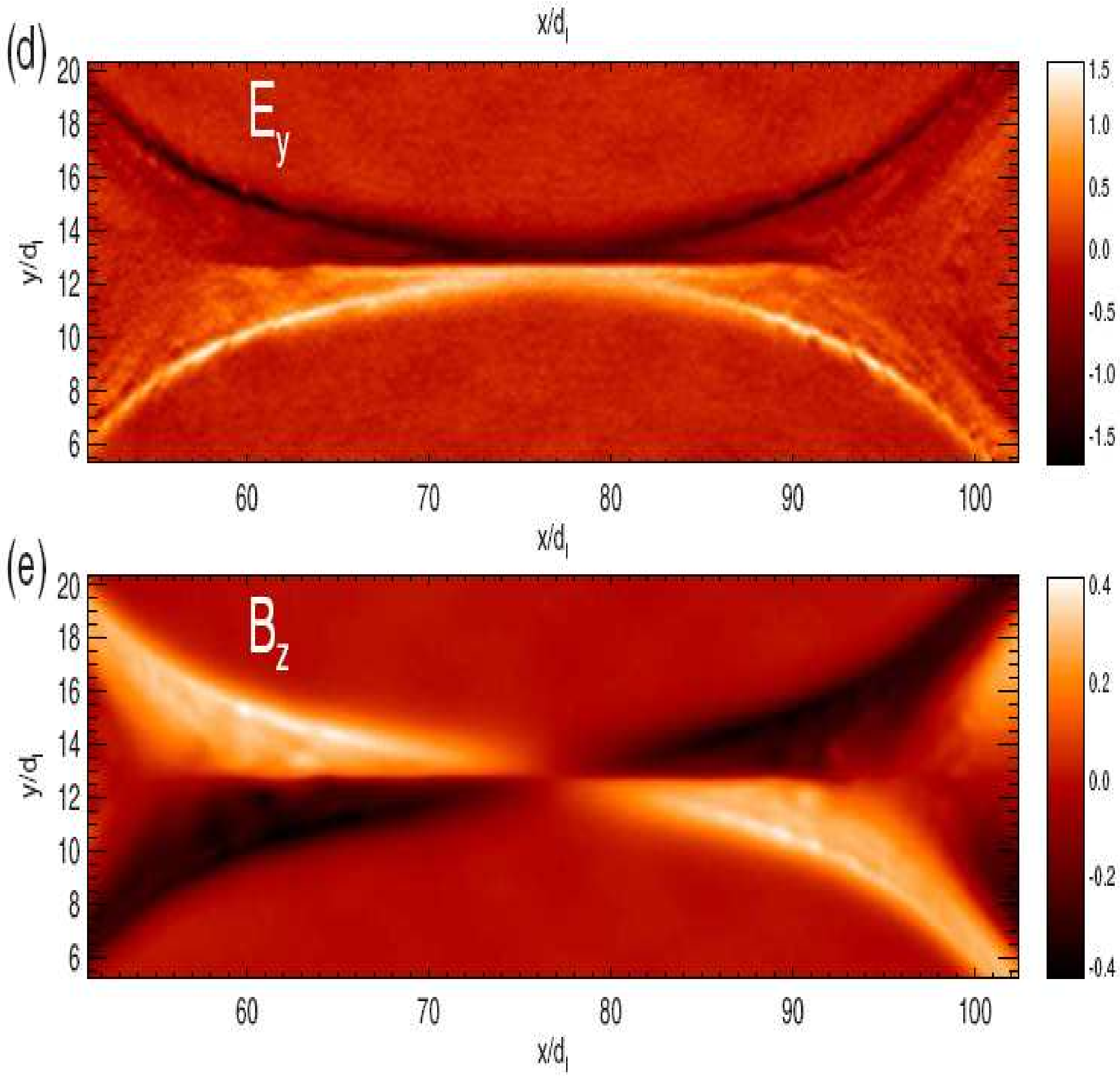
Bipolar In-Plane Electric Field: Numerical Simulations

(Drake et al. 2008)



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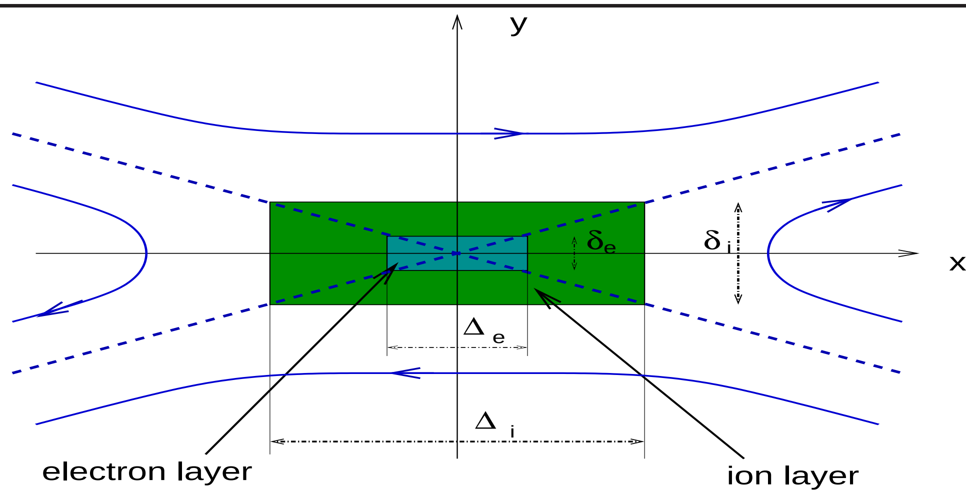
Ion and Electron Heating
and the Strength of the Electron Current Layer



- 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):

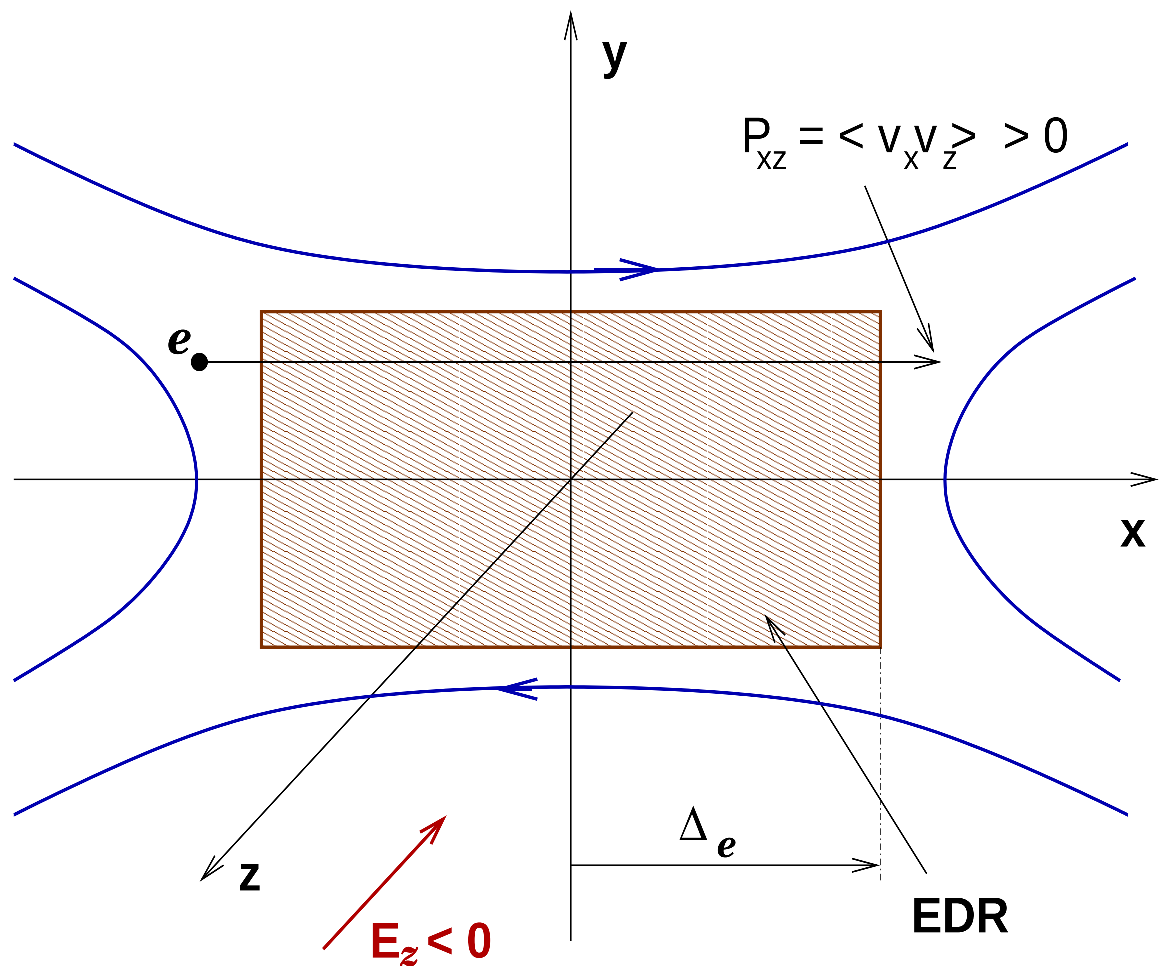
$$\delta_e \sim \rho_e[B_{0e}, T_{e0}] = \sqrt{\frac{T_e}{m_e}} \frac{m_e c}{eB_{0e}} = d_e\sqrt{\beta_{e0}/2}$$

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

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

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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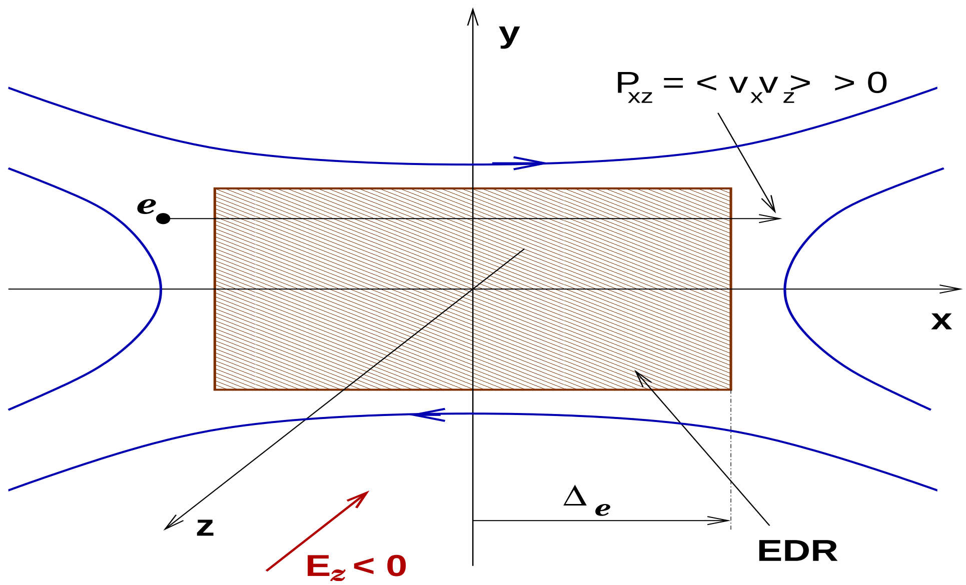
Ohm's Law with Electron Pressure Tensor



- 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: $\tau = \Delta / v_{e,\text{th}}$.
- Thus we get a relationship between Δ_e and E_z:

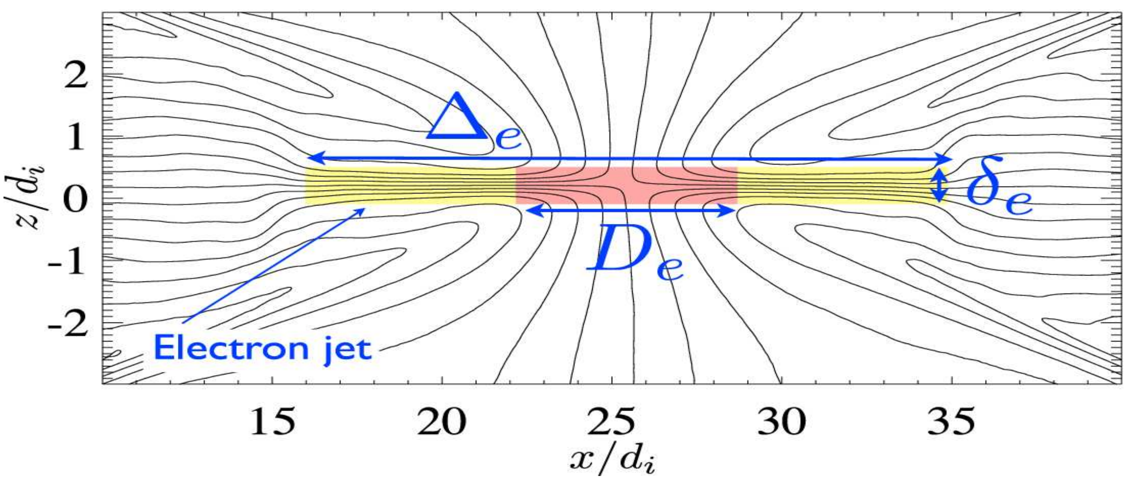
$$E_z = \frac{c}{\omega_{pe}^2} \frac{v_{e,th}}{\Delta_e} \frac{B_{0e}}{\delta_e} = \frac{d_e^2}{\delta_e \Delta_e} \frac{v_{e,\text{th}}}{c} B_{0e} \propto 1/\Delta_e \delta_e \,,$$

or

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

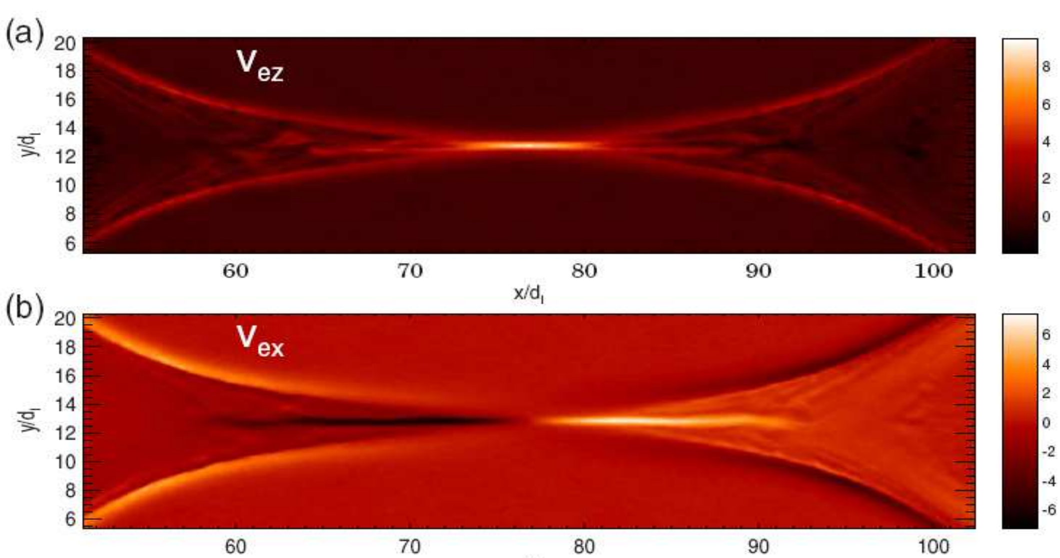
Electron Outflow Jet in PIC Simulations

- <u>PIC simulations</u> *(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)

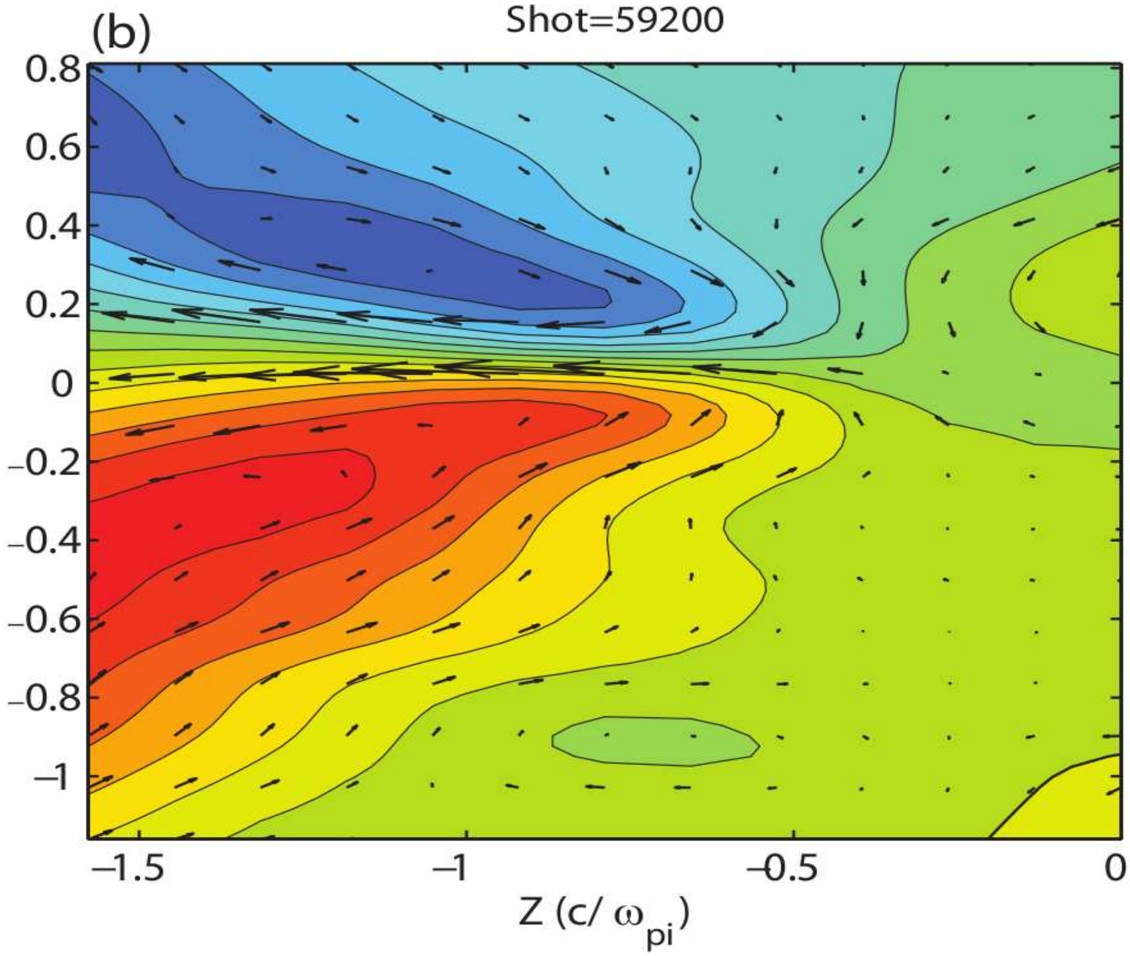
Phys. Plasmas **15**, 042306 (2008)



(Drake et al. 2008)

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 PORTRET

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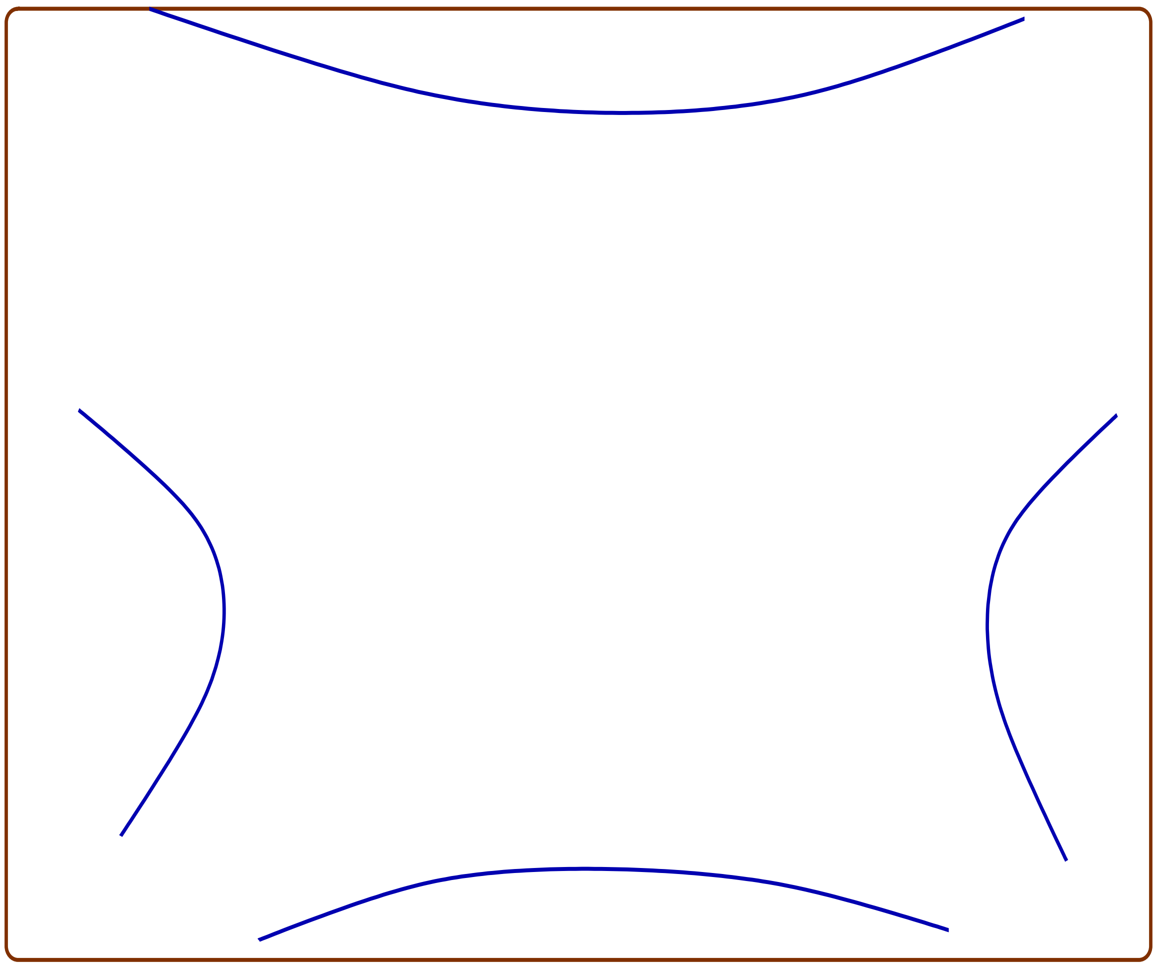
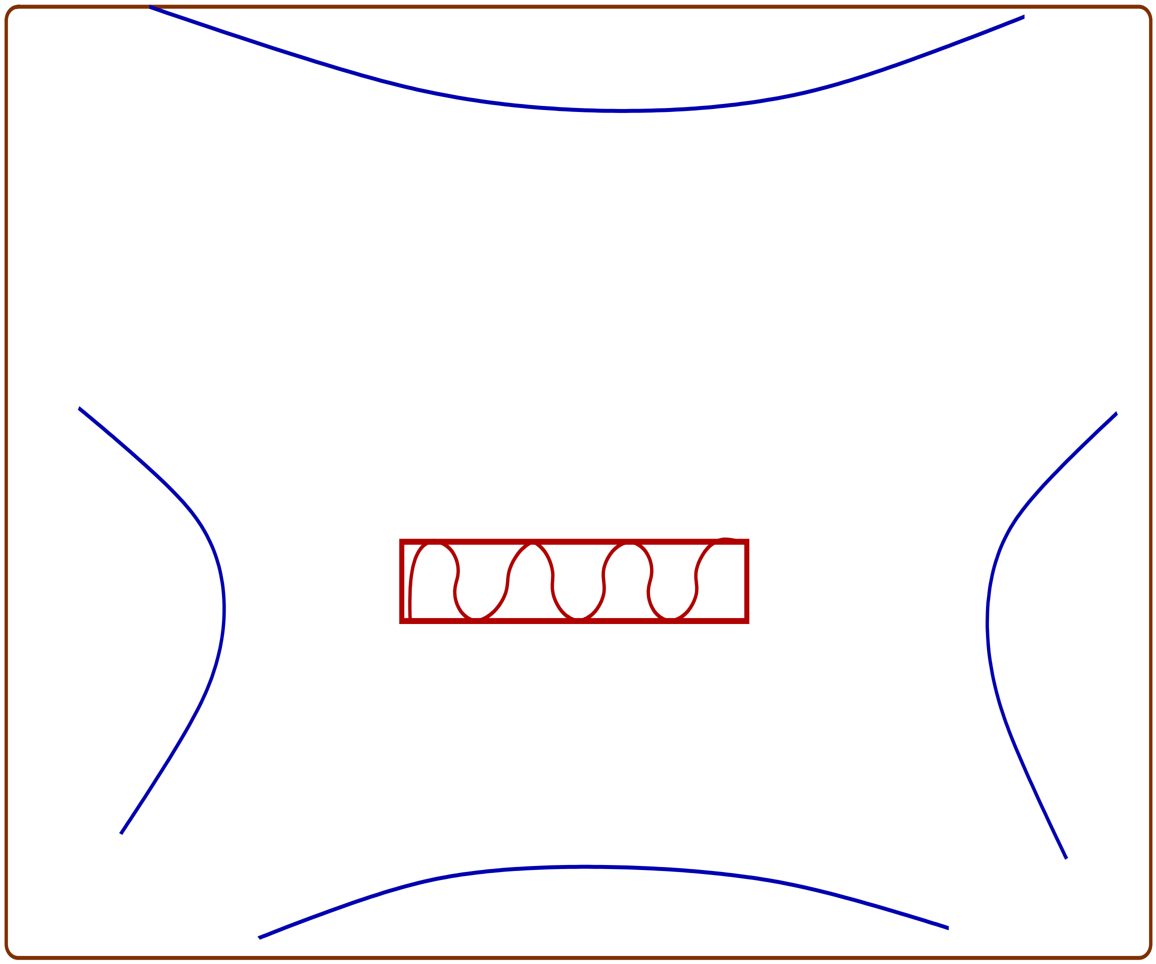
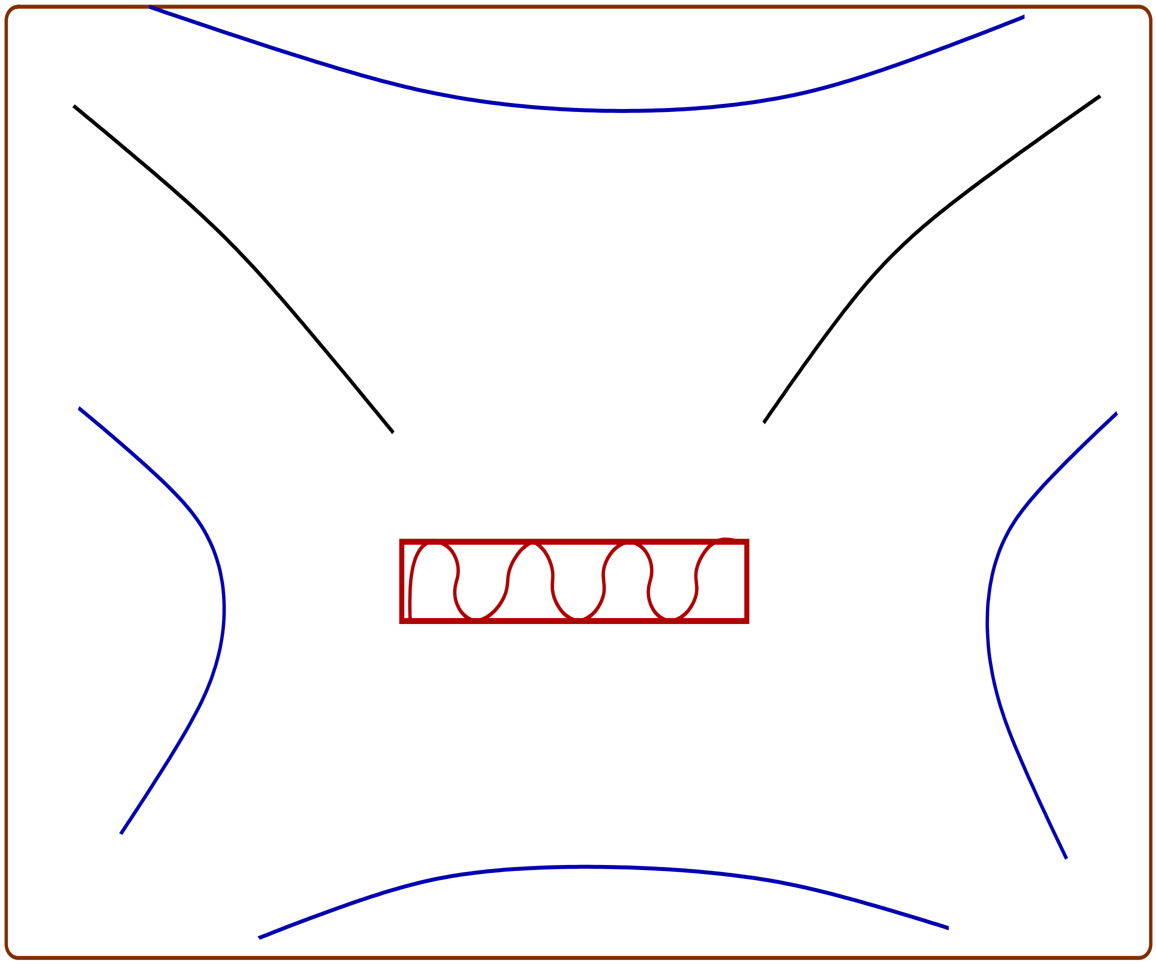


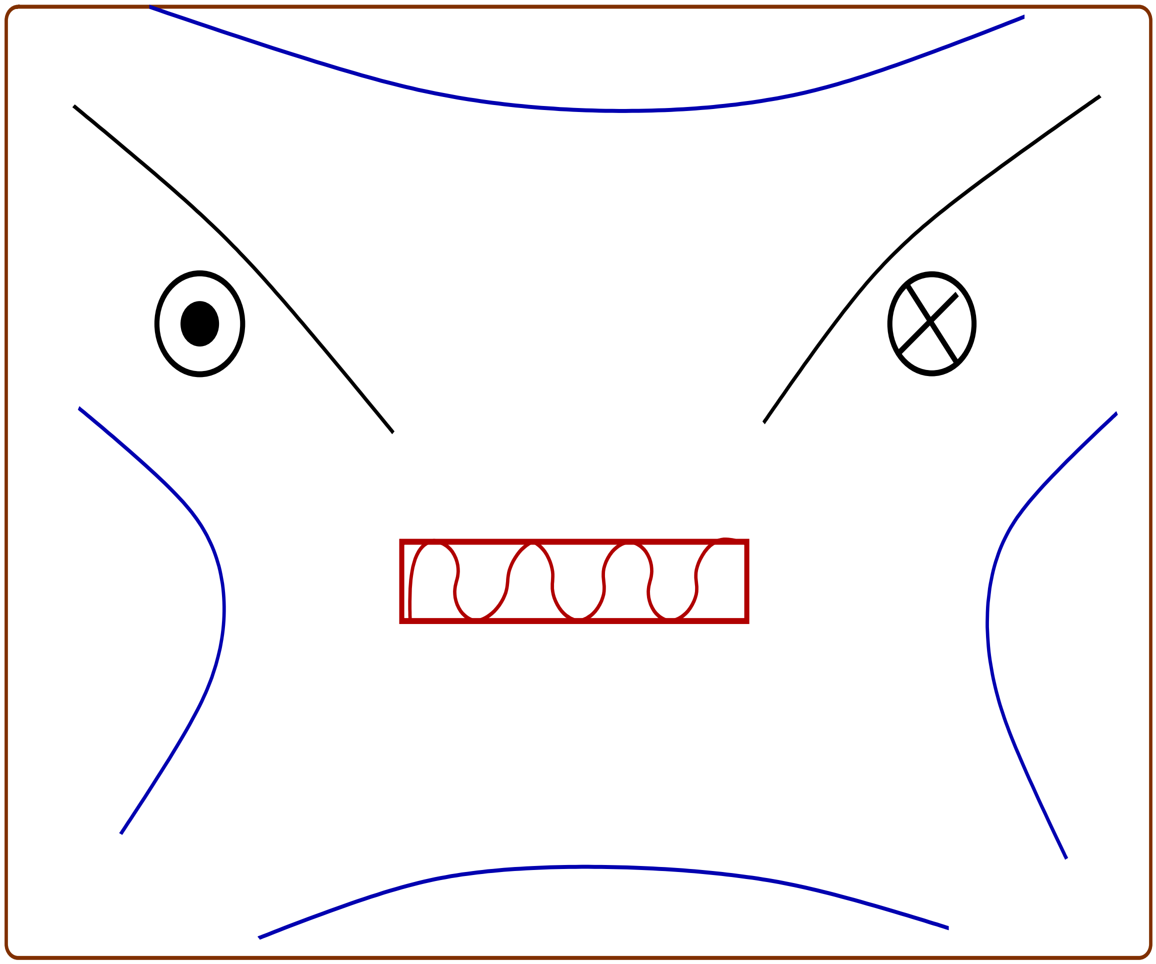
- Outer Ion Layer



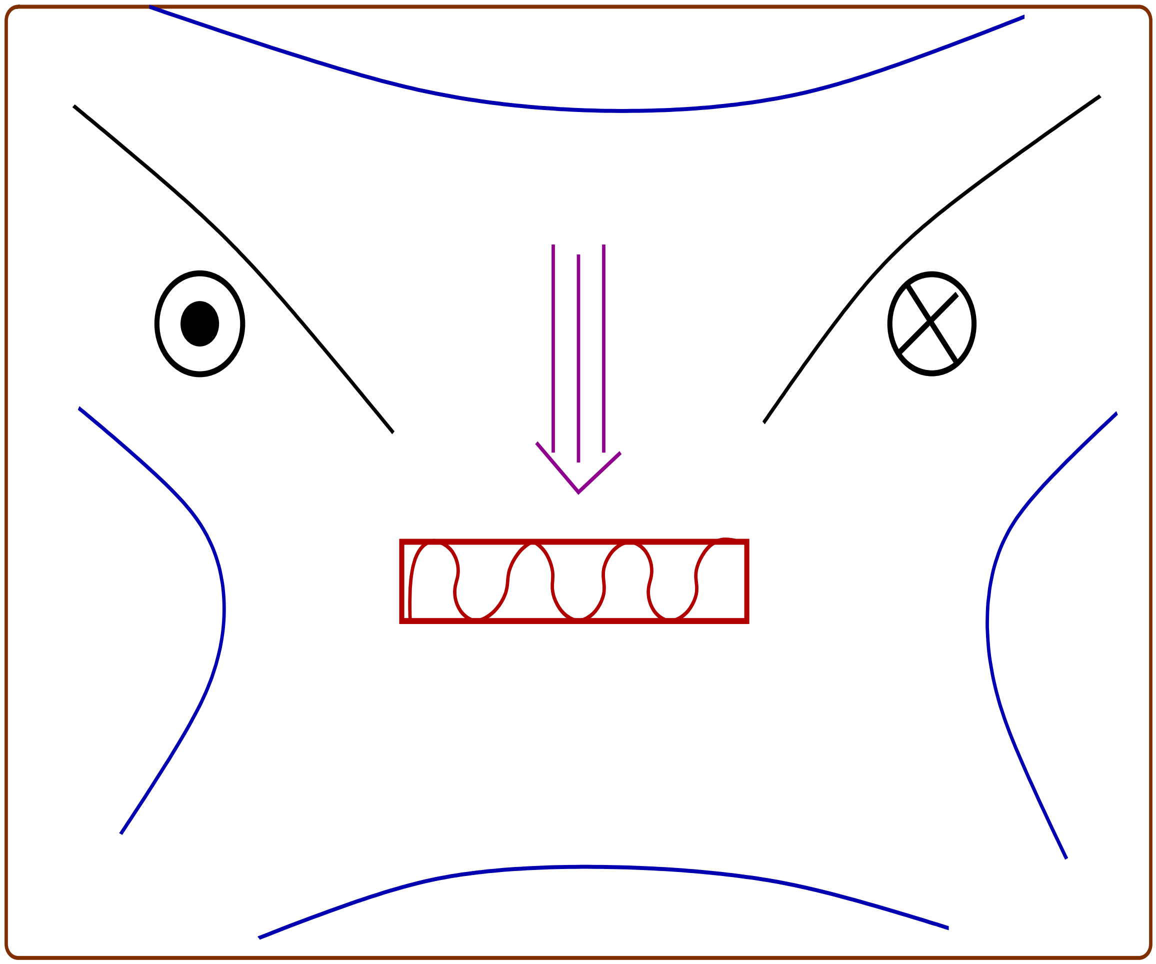
- Outer Ion Layer
- Inner Electron Layer



- 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