Experimental Investigations of Magnetic Reconnection

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Coronal Mass Ejections

Movie from NASA’s Solar Dynamics Observatory (SDO)
Space Weather

The Solar Wind affects the Earth’s environment
The Earth’s Magnetic Shield
The Daily-Show
Magnetic Fusion Devices

International Thermonuclear Experimental Reactor
Reconnection in ITER could destroy the device:

International Thermonuclear Experimental Reactor
The Tokamak Device

*Best known confinement device on Earth*
Sawtooth reconnection in Tokamaks

Neutron yield in a tokamak

H Park, PRL 2005: localized reconnection
Electromagnetism 101

• Faraday’s law:

\[ EMF = -Area \cdot \frac{dB}{dt} \]

• Faraday’s law for a conducting ring: EMF=0.

• The magnetic flux through the ring is trapped

• This also holds if the ring is made of plasma
  \(\rightarrow\) plasma frozen in condition
Reconnection: A Long Standing Problem

Simplest model for reconnection:
\[ \mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{j} \quad [\text{Sweet-Parker (1957)}] \]

\[ - \frac{\partial \Psi}{\partial t} \bigg|_x = E_x = \eta j_x \]
Reconnection: A Long Standing Problem

Simplest model for reconnection:
\[ \mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{j} \]  
[Sweet-Parker (1957)]

Outflow speed:
\[ v_A = \frac{B}{\sqrt{\mu_0 n m_i}} \]
(Alfven speed)

Sweet-Parker: \( L >> \delta \):

\[ t_{sp} = \sqrt{t_{RTA}} = \sqrt{\frac{\mu_0 L^2}{\eta}} \sqrt{\frac{L}{v_A}} \]

Unfavorable for fast reconnection
Two months for a coronal mass ejections
Outline

• The MRX experiment at PPPL
  • 2D reconnection in VTF open configuration
    – Oscillatory reconnection response
  • 3D reconnection in VTF closed configuration
    – Explosive reconnection response
• Conclusions
Family of Reconnection Experiments (H. Ji, PPPL)

Stenzel & Gekelman
Frank et al.

... Wrap SSX Toroidal pieces

2D w/ walls

VTF MRX TS-3

Zoom in Zoom out

local boundary global
steady state process transient
collisionless collisionality collisional

2D Symmetry
The MRX experiment at PPPL

M. Yamada, H Ji, et al.
The MRX experiment at PPPL

Experimental Setup and Formation of Current Sheet

Experimentally measured flux evolution

\[ n_e = 1 - 10 \times 10^{13} \text{ cm}^{-3}, \]

\[ T_e \sim 5 - 15 \text{ eV}, \]

\[ B \sim 100 - 500 \text{ G}. \]
Resistivity increases as collisionality is reduced in MRX

**Effective resistivity**

\[ \eta^* = \frac{E_\theta}{j_\theta} \]

Close to classical Spitzer

\[ \eta^{\text{Spitzer}}_{\perp} = 1.03 \times 10^{-4} T_e^{-3/2} Z \ln \Lambda \]

Enhanced in low collisional plasma

*Ji et al. ‘98*

*Trintchouk et al., ‘03*

*Kuritsyn et al., ‘06*
The measured current sheet profiles agree well with Harris theory.

\[ B_z = -B_0 \tanh \left( \frac{x}{\delta} \right) \]
\[ j_y = \frac{B_0}{\mu_0 \delta} \sech^2 \left( \frac{x}{\delta} \right) \]
\[ p = n_0 (T_e + T_i) \sech^2 \left( \frac{x}{\delta} \right) \]
\[ \delta = \frac{c \sqrt{2(T_e + T_i)/m_i}}{\omega_{pi} (V_i - V_e)} \]
\[ = \frac{c \sqrt{2V_s}}{\omega_{pi} V_{\text{drift}}} \]

Neutral sheet Shape in MRX
Changes from “Rectangular S-P” type to “Double edge X” shape as collisionality is reduced

Rectangular shape
Collisional regime: $\lambda_{mfp} < \delta$
Slow reconnection
No Q-P field

X-type shape
Collisionless regime: $\lambda_{mfp} > \delta$
Fast reconnection
Q-P field present

Yamada et al, PoP 2006
Experimental identification of e-diffusion region

**PIC Simulation**

**Experiment**

The electron diffusion region identified inside of the ion diffusion region in a laboratory plasma

$\leftrightarrow$ The first observation of two-scale diffusion region

[Ren et al, PRL 08, Ji et al GRL, 08, Dorfman et al '10]
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The Versatile Toroidal Facility (VTF)
The Versatile Toroidal Facility (VTF)

*External Coils*

* Vacuum Vessel
The Versatile Toroidal Facility (VTF)

- External Coils
- Vacuum Vessel
- TF Coils
- RF-Power
- Diagnostics
The Versatile Toroidal Facility (VTF)
Magnetic Diagnostics

- Voltage in loops $\sim (dB/dt) A$

- Assuming toroidal symmetry we can use $B_{\text{pol}} = \nabla \times (A_{\phi} e_{\phi})$ and build an array to integrate up $A_{\phi}$

$$\Psi = RA_{\phi}$$

$$\Delta_R \Psi = \Psi(R_1, Z_0) - \Psi(R_0, Z_0) = \int_{R_0}^{R_1} R B_z dR$$

$$\Delta_Z \Psi = \Psi(R_0, Z_1) - \Psi(R_0, Z_0) = - R \int_{Z_0}^{Z_1} \dot{B}_R dZ$$

Kesich et al., RSI 79, 063505 (2008)
Magnetic Array

Measured current & magnetic field
Rogowski Array

- Construction: copper wire wound on teflon tube
- Measures current through each opening
Two different magnetic configurations

An open cusp magnetic field.
Fast reconnection by trapped electrons.

A closed cusp by internal coil.
Passing electrons & spontaneous reconnection events.
Plasma response to driven reconnection
Kinetic modeling

- Why is the experimental current density so small?
- Liouville/Vlasov’s equation: $\frac{df}{dt}=0$
- For a given $(x_0,v_0)$, follow the orbit back in time to $x_1$
- Particle orbits calculated using electrostatic and magnetic fields consistent with the experiment.
- Massively parallel code evaluates $f(x_0,v_0) = f_\infty(|v_1|)$.

Kinetic modeling

• The current is calculated as $j_\parallel = \int v_\parallel f \, dv^3$

• Theory consistent with measurements
  (B-probe resolution: 1.5cm)

• Experimental scaling $j \sim nl_0E_z$ is reproduced

**Theoretical current profile**

**Experimental current profile**
Temporal evolution of the current channel

Eigen response, $f = 10-30$ kHz
The electrostatic potential

Electrostatic potential, $\Phi$

Electron flow:
$$v_{E \times B} = -\nabla \Phi \times B_g \frac{B^2}{B^2}$$

Ideal Plasma:
$$E \cdot B = 0, l \cdot B_{cusp} = 0$$

External fields

- $10V/m$
- $87mT$
- $2mT$
- $\nabla \Phi \sim 500V/m$
The electrostatic potential

Ideal Plasma:

\[ E_\phi B_\phi + E_{pol} \cdot B_{cusp} = 0 \]

Frozen in law is broken where \( E \cdot B \neq 0 \)
Plasma response to driven reconnection

Argon, $C_F = 1.68 \text{ V}$, Klystron @ 35\%, $I_{cusp} = 910 \text{ A}$, $I_0 = 3.6 \text{ m}$

- Dens: $0 - 3 \times 10^{17} \text{ m}^{-3}$
- Current density: $-4 - 4 \text{ kA/m}^2$
- Float Pot: $-14 - 10 \text{ V}$

Loop Voltage: $-50 - 50 \text{ V}$
Total current: $-80 - 80 \text{ A}$

$I_{tot} = 0 \text{ A}$
t = 1481 $\mu$s

Ion polarization currents due to $d\Phi/dt$

**Ion polarization current:**

$$j_\perp = -\frac{nm}{B^2} \nabla \perp \left( \frac{d\Phi}{dt} \right)$$

**Quasi neutrality:**

$$\nabla \cdot (j_\perp + j_\parallel) = 0$$

$$\frac{d}{dl_\parallel} j_\parallel = \frac{nm}{B^2} \nabla^2 \perp \left( \frac{d\Phi}{dt} \right)$$
Model for dynamical response

\[ \nabla \cdot \mathbf{J} = 0 \quad \Rightarrow \quad \Phi \quad \Leftrightarrow \quad A_\phi \quad \text{E} \cdot \text{B} \cong 0 \]

\[ A_\phi = \alpha_1 J_\parallel + A_{\text{ext}} \]

\[ J_\parallel = \alpha_2 \frac{d\Phi}{dt}, \quad \Phi = -\alpha_3 \frac{dA_\phi}{dt} \]

\[ A_\phi = -\alpha \frac{d^2 A_\phi}{dt^2} + A_{\text{ext}}, \quad \alpha = \alpha_1 \alpha_2 \alpha_3 > 0 \]

Oscillating solutions
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Spontaneous Reconnection

- Coronal mass ejections: The most powerful explosions in our solar system

Other Outstanding Problems

- Heating
- 3D effects
- Trigger

Arcade as seen from above
Closed Magnetic Configuration
Plasma in the VTF Closed Configuration

- Visible light of an Argon discharge

- \( n_e \sim 10^{18} \text{ m}^{-3} \),
  \( T_e \sim 15 - 25 \text{ eV} \),
  \( \lambda_e \sim 10 \text{ m} \),
  \( B_g \sim 50 \text{ mT} \),
  \( B_p \sim 5 \text{ mT} \)
Spontaneous reconnection observed

No simple resistivity, \( E \neq \eta^* j \)!
Plasma outflows

Plasma Density

Floating Potential

Current density

Rec. rate, dΨ/dt

t=1μs
Date=Nov28, 2005
shots=116-116
Ns=1
Nbeg=3200
Imax=3.29
Toroidal Asymmetry: Delayed Onset

- Toroidal localized onset
- 5 $\mu$s delay
3D $\partial A_\phi / \partial t$ Data Confirms Asymmetry

- Use 2 fixed arrays & variable onset location to construct full dataset
- Shift onset angle to $\phi = 0$, record relative angle of arrays
3D reconnection (Cartoon)
3D reconnection (Measurements)
Total E-Field is Localized

- Strong toroidal electrostatic E
- $\Phi_x$ measured at x-line, keeps total E localized;
Spontaneous reconnection only for rational $q$

$$q = \frac{\text{toroidal winding \#}}{\text{poloidal winding \#}}$$

$q$-profile of VTF
Large q=2 and q=3 modes observed during reconnection

$V_{\text{float}} \text{ for } q=2$

$t=0\,\mu s$

<table>
<thead>
<tr>
<th>$\phi$</th>
<th>$Z$ (m)</th>
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<tbody>
<tr>
<td>20°</td>
<td>0.4</td>
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<tr>
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$V_{\text{float}} \text{ for } q=3$

$t=0\,\mu s$

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$d\Psi/dt @ Z=0$ (V/m)
Potential maintains $E \cdot B \sim 0$ away from X-line (ohm’s law)

$$E_\phi B_\phi$$

$$E_{pol} \cdot B_{pol} \text{ (from } \nabla V_f \text{)}$$

$$E_{tot} \cdot B_{tot}$$

TV/m

Experiments show

$$- \frac{\partial A_\phi}{\partial t} \propto \phi_{rms}$$
Exponential Growth in the Reconnection Rate

- Growth rate $\gamma \approx 1/(20\mu s \pm 6\mu s)$ at onset location

- Model for Onset

\[
\begin{align*}
\nabla \cdot \mathbf{J} &= 0 \\
\mathbf{J}_\parallel &= \mathbf{A}_\phi \\
\Phi &\leftrightarrow \mathbf{A}_\phi \\
\mathbf{A}_\phi &= \frac{\mu_0}{4\pi} \int \frac{\mathbf{J}_\parallel}{|\mathbf{r}' - \mathbf{r}|} d^3\mathbf{r}'
\end{align*}
\]

Ohm’s Law
Current Continuity: Cartoon

\[ E_{\text{rec}} = -\frac{\partial A_\phi}{\partial t}, \]
Current Continuity: Cartoon

\[ \nabla \cdot \mathbf{J} = \mathbf{V} \cdot \mathbf{J}_\parallel + \nabla \cdot \mathbf{J}_\perp = 0 \]

\[ \mathbf{J}_\perp = \frac{nm \ d\mathbf{E}_\perp}{B^2 \ dt} \]

*Ion polarization current*
q=2 electrostatic mode

- Mode amplitude increases during reconnection onset
Growing $q=2$ Potential

- Ion polarization currents maintain $\nabla \cdot \mathbf{J} = 0$

\[
J_{||}(\mathbf{r}) = \int_{\text{edge}}^{\mathbf{r}} \frac{m_i n}{B^2} \nabla_{\perp}^2 \frac{\partial \phi}{\partial t} \, dl
\]
Model for dynamical response

\[ \nabla \cdot J = 0 \]

\[ J_\parallel \]

\[ \Phi \leftrightarrow A_\phi \]

\[ E \cdot B \cong 0 \]

\[ A_\phi = \alpha_1 J_\parallel + A_{ext} \], \quad \[ J_\parallel = -\alpha_2 d\Phi/dt \], \quad \Phi = -\alpha_3 dA_\phi/dt \],

\[ A_\phi = \alpha d^2 A_\phi / dt^2 + A_{ext} \], \quad \alpha = \alpha_1 \alpha_2 \alpha_3 > 0

Exponentially growing solution!

Conclusions

– Collisional reconnection model and the Hall effect have been verified in MRX

– In the collisionless regime of VTF important collisionless effects become evident

– Experiment offers the opportunity to address the trigger problem

– 3D effects are important!