Experimental Study of Magnetic Reconnection on MRX

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Outline

• Introduction
  – dedicated reconnection experiments
• Recent results from Magnetic Reconnection Experiment (MRX)
  – Collisionless reconnection => Two fluids physics
  – Two-scale diffusion region
  – MRX scaling regarding collisionality
• Outstanding issues on reconnection
• New experiment for solar flare dynamics
Goals of Lab Experiments

• Learn the physics of fundamental processes from plasmas
  (Not to simulate space phenomena)

• Check/verify theoretical concepts

• Compare data with observations/simulations

• Discover new physics
## Dedicated Reconnection Experiments

<table>
<thead>
<tr>
<th>Device</th>
<th>Site</th>
<th>Built</th>
<th>PI’s</th>
<th>Geometry</th>
<th>Res. Thrust</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D-CS</td>
<td>Russia</td>
<td>1970</td>
<td>Syrovatskii, Frank</td>
<td>Linear</td>
<td>Guide field</td>
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<tr>
<td>LPD, LAPD</td>
<td>UCLA</td>
<td>1980</td>
<td>Stenzel, Gekelman</td>
<td>Linear</td>
<td>Heating, waves</td>
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<td>TS-3/4</td>
<td>Tokyo</td>
<td>1990</td>
<td>Katsurai, Ono</td>
<td>Toroidal Merging</td>
<td>Heating</td>
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<tr>
<td>MRX</td>
<td>Princeton</td>
<td>1995</td>
<td>Yamada, Ji</td>
<td>Driven, merging</td>
<td>2-fluid effects, waves, scaling</td>
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<td>SSX</td>
<td>Swarthmore</td>
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<td>Brown</td>
<td>Merging</td>
<td>Heating</td>
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<td>VTF</td>
<td>MIT</td>
<td>1998</td>
<td>Egedal</td>
<td>Toroidal with guide B</td>
<td>Trigger, waves</td>
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<td>RSX</td>
<td>Los Alamos</td>
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<td>Intrator</td>
<td>Linear</td>
<td>Boundary</td>
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<tr>
<td>RWX</td>
<td>Wisconsin</td>
<td>2002</td>
<td>Forest</td>
<td>Linear</td>
<td>Line-tying</td>
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</table>
Magnetic Reconnection: Recent Progress

- Two-fluid effects in the local reconnection layer analyzed thru strong collaboration between space and lab research
  - Ion diffusion region and electron diffusion regions identified: in 2-scales
  - Electromagnetic and electrostatic fluctuations analyzed
- Transition from collisional MHD to collisionless regime established
- Role of reconnection in magnetic self-organization investigated
- Multiple reconnection layers $\iff$ Global reconnection
Magnetic reconnection happens at both magnetopause and magnetotail.

Two fluid effects are dominant when $\delta_{ns} \sim c/\omega_{pi}$

Magnetic Reconnection Experiment (MRX).
Goals: Create a prototypical reconnection layer to study the elementary processes
Experimental Setup and Formation of Current Sheet on MRX

Experimentally measured flux evolution

\[ n_e = 1 - 10 \times 10^{13} \text{ cm}^{-3}, \]
\[ T_e \sim 5 - 15 \text{ eV}, \]
\[ B \sim 100 - 500 \text{ G}, \]
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
- Hall effects
Evolution of magnetic field lines during reconnection in MRX
Two-scale Diffusion Region measured in MRX

The electron diffusion region identified inside of the ion diffusion region

\(<=>\) The first observation of two-scale diffusion region

[Ren et al, PRL 08]

\[ d \sim 5-7 \left( c/\omega_{pe} \right) \gg d_{\text{Theory}} \]

EM (LHW) fluctuations observed

\(\Rightarrow\) Close collaboration with space physics community
Electrostatic waves observed at CS Edge: Electromagnetic waves at the center appear to be more important

Carter et al. PRL ('02) Identified as LHDW

EM waves => S. Dorfman

Bale et al. GRL ('02) Vaivads et al. GRL ('04)
MRX Scaling: $\eta^* \text{ vs } (c/\omega_i)/\delta_{sp}$

A linkage between space and lab on reconnection

$\eta^* \equiv \frac{E_\theta}{j_\theta}$

$\frac{(c/\omega_{pi})}{\delta_{sp}} \sim 5(\lambda_{mfp}/L)^{1/2}$

MRX scaling shows a transition from the MHD to 2 fluid regime based on $(c/\omega_{pi})/\delta_{sp}$

Yamada et al, PoP 2006
**Linkages between space and lab on reconnection**

<table>
<thead>
<tr>
<th>System</th>
<th>L (cm)</th>
<th>B (G)</th>
<th>( \frac{d_i}{c/\omega_{pi}} ) (cm)</th>
<th>( \delta_{sp} ) (cm)</th>
<th>( \frac{d_i}{\delta_{sp}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRX/SSX</td>
<td>10</td>
<td>100-500</td>
<td>1-5</td>
<td>0.1-5</td>
<td>.2-100</td>
</tr>
<tr>
<td>MST/Tokamak</td>
<td>30/100</td>
<td>( 10^3/10^4 )</td>
<td>10</td>
<td>0.1</td>
<td>100</td>
</tr>
<tr>
<td>Magnetosphere</td>
<td>( 10^9 )</td>
<td>( 10^{-3} )</td>
<td>( 10^7 )</td>
<td>( 10^4 )</td>
<td>1000</td>
</tr>
<tr>
<td>Solar flare</td>
<td>( 10^9 )</td>
<td>100</td>
<td>( 10^4 )</td>
<td>( 10^2 )</td>
<td>100</td>
</tr>
<tr>
<td>ISM</td>
<td>( 10^{18} )</td>
<td>( 10^{-6} )</td>
<td>( 10^7 )</td>
<td>( 10^{10} )</td>
<td>0.001</td>
</tr>
<tr>
<td>Proto-star</td>
<td></td>
<td></td>
<td>( \frac{d_i}{\delta_s} \gg 1 )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[
\frac{d_i}{\delta_{sp}} \sim 5 \left( \frac{\lambda_{mfp}}{L} \right)^{1/2}
\]
Future main issues for magnetic reconnection research

- **Identify main mechanisms for energy dissipation in the 2-fluid diffusion region**
  - Particle acceleration and heating
- **Effects of guide field (2D & 3D)**
- **Effects of EM/ES fluctuations**
- **Effects of boundary conditions**

- **Find guiding principles for 3-D global reconnection phenomena**
  - Global energy flows
  - Multiple current sheets
  - Magnetic self-organization
  - Impulsive reconnection

⇒ Yamada, Kulsrud, Ji; Rev. Mod. Phys. (2009)
Zweibel & Yamada; Ann Rep AA. (2009)
New Setup for MRX-Solar Flare Experiment

- Electrodes ~ 15 cm diameter
- \( R = 15-30 \) cm
- Angle \( 90^\circ-180^\circ \)
- \( B_t \): Toroidal field 0 -1200 Gauss
- \( B_z \): Strapping field 0-100 Gauss
- The flux cores were not utilized in the experiments
Electrodes inside the MRX vacuum vessel

Flare photos taken with a commercial Canon Powershot 100 µs exposure
Safety factor $q$ determines the stability of simulated flux loop in MRX

$B_p$ vectors & $j$ counters (color): Framing camera photos

**Stable**

- $B_{\text{toroidal}} = 1055 \text{ G}$

**Unstable**

- $B_{\text{toroidal}} = 360 \text{ G}$

- $R_p$, $q_a$ value

![Graphs showing stability and instability with $B_{\text{toroidal}}$ values and $q_a$ plots.](image)