Relaxation of flux ropes and magnetic reconnection in RSX

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Outline

1. Motivations
2. The RSX device and diagnostics
3. Experimental measurements
   - Single flux rope
   - Two flux ropes
4. Conclusions and discussion
Flux ropes are ubiquitous in Nature

Early stage of spheromak formation
P.M. Bellan, this workshop

Solar arcades
Solar flares

Formation of spheromak through kink instability
S. Hsu and P.M. Bellan, PRL 90, 2003

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RSX device

The plasma source: the plasma gun

- $V_{\text{bias}} \sim 300\text{V}$, $I_{\text{bias}} \sim 600\text{kA}$, $V_{\text{arc}} \sim 100\text{V}$, $I_{\text{arc}} \sim 1\text{kA}$.

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Schematics of RSX

3D schematic view of RSX

- linear vacuum vessel ⇒ easy of diagnostics, 3D experiment
- 12 magnet coils: $B_z = 0$-1000 Gauss ⇒ can be varied independently
- 4 movable plasma guns ⇒ single and multiple flux rope interaction
Discharge sequence

- Plasma formation
- Flux rope formation

Graphs showing:
- Arc Voltage
- Arc Current
- Bias Voltage
- Ext. anode current

Time [ms]: 10 to 25
## Plasma parameters and diagnostics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>$n_e \approx 10^{12}-10^{14}$ cm$^{-3}$</td>
</tr>
<tr>
<td>El. Temperature</td>
<td>$T_e \approx 3-15$ eV</td>
</tr>
<tr>
<td>Poloidal field</td>
<td>$B_{pol} &lt; 50$ Gauss</td>
</tr>
<tr>
<td>Scale size</td>
<td>$d \approx 10$ cm, $L \approx 30-300$ cm</td>
</tr>
<tr>
<td>Ion skin depth</td>
<td>$\delta_i = c/\omega_{pi} \approx 2$ cm</td>
</tr>
<tr>
<td>electron skin depth</td>
<td>$\delta_i = c/\omega_{pi} \approx 1.7$ mm</td>
</tr>
<tr>
<td>Ion gyro radius</td>
<td>$r_{Gi} \approx 0.35-1.4$ cm</td>
</tr>
<tr>
<td>electron gyro radius</td>
<td>$r_{Ge} \approx 1-4$ mm</td>
</tr>
</tbody>
</table>

- Gun parameters (current, voltage)
- Multi-2D magnetic probe (2.5mm space resolution, 20MHz acq. Freq.) $\Rightarrow$ B field
- Triple electrostatic probe (2 mm space resolution, 20MHz acq. Freq.) $\Rightarrow$ $T_e$, $n_e$
- Poloidal and axial arrays of magnetic probes (8 mm diameter, time response 100 ns) $\Rightarrow$ mode number (m, n)
Cook Dicam, fast gated CCD camera

- visible light emission
- global dynamics

2 frames per shot
1280×1024 pixels, 12bit
40 ns min. exposure
(<t_{Alf}=0.5-1 micro-sec)

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Physics questions we want to address and critical features of RSX

• How does the plasma relaxed state depend on $\beta$? 
  In RSX, $\beta$ can be scaled ($\beta \ll 1$ to $\beta \sim 1$) by varying plasma density, external magnetic field, and total plasma current.

• How does relaxation depend on the external drive? 
  In RSX, the rate of change of $V_{\text{bias}}$ can be controlled externally ($dV_{\text{bias}}/dt > 0$, $dV_{\text{bias}}/dt = 0$, ...)

• How is the relaxed state influenced by boundary conditions (see for example D.D. Ryutov, ICC-2004)? 
  In RSX, it is easy to implement different boundary conditions (i.e. shaped anode, flux conserver).
Preliminary studies of single flux rope relaxation

<p>| | |</p>
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<tbody>
<tr>
<td><strong>Density</strong></td>
<td>$n_e \sim 0.6 \text{e}^{13} \text{cm}^{-3}$</td>
</tr>
<tr>
<td><strong>El. Temperature</strong></td>
<td>$T_e \sim 3 \text{-} 15 \text{eV}$</td>
</tr>
</tbody>
</table>
| **Scale length**            | $L \sim 100 \text{ cm}$  
                          | $r \sim 2 \text{ cm}$ |
| **Guide field**             | $B_z = 200 \text{ Gauss}$ |
| **Ion skin depth**          | $\delta_i = c/\omega_{pi} \sim 2 \text{ cm}$ |
| **Electron skin depth**     | $\delta_i = c/\omega_{pi} \sim 1.7 \text{ mm}$ |
| **Ion gyro radius**         | $r_{Gi} \sim 0.35 \text{-} 1.4 \text{ cm}$ |
| **Electron gyro radius**    | $r_{Ge} \sim 1 \text{-} 4 \text{ mm}$ |

![Graph of I_anode vs time](image-url)
Single and multiple helicity states are observed during current ramp up \((dV_{\text{bias}}/dt > 0)\)

- Onset of \(m/n=1/1\) consistent with KS limit \(q_{\text{edge}} = 1\)
- \(q_{\text{edge}} = 2\) at onset of \(n=2\) ?
- Saturated state for \(n=1\) and \(n=2\) is observed, no disruption
- Plasma increases its inductance at \(n=2\) onset
Open questions

- Identify the saturation mechanism (field line bending, wall).
- Non linear mode coupling.
- Influence of external drive on the relaxed state.
- How does relaxation change with $\beta$?
Relaxation of two flux ropes and magnetic reconnection

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<tr>
<td>Density</td>
<td>$n_e \sim 0.6 - 3 \times 10^{13} \text{cm}^{-3}$</td>
</tr>
<tr>
<td>Guide field</td>
<td>$B_z = 100 - 400 \text{Gauss}$</td>
</tr>
<tr>
<td>Reconnection field</td>
<td>$B_{rec} \sim 10 \text{ Gauss}$</td>
</tr>
<tr>
<td>El. Temperature</td>
<td>$T_e \sim 3 - 15 \text{eV}$</td>
</tr>
</tbody>
</table>
| Scale size         | $d \sim 8 \text{ cm}$  
          | $L \sim 100 \text{ cm}$ |

- High guide field ($B_z / B_{rec} = 20-60$)
- 2 plasma guns at $z = 0$, spaced by 8 cm
- External anode at $z = 1 \text{ m}$
- Measurements in the reconnection plane at $z = 0.5 \text{m}$
Coalescence of the flux ropes is observed during current ramp-up.

- Plasma formation at $t=-1\text{ms}$
- Current channel formation
- $V_{\text{bias}}$ turns on
- Distance between the two flux ropes:
  - Initial distance: 8 cm
  - Final distance: 6 cm
- Kink dynamics
- Starting of coalescence

Graph showing gun current [A] against time [μs].
Magnetic reconnection is observed

Bz / B_{rec} = 25

B field

Flux ropes

X-Point

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Current sheet shrinks to a size between $\delta_i$ and $\delta_e$

- Ion skin depth $\delta_i \approx 9\text{cm}$
- Electron skin depth $\delta_e \approx 2\text{mm}$
- Ion Gyroradius $\rho_i \approx 0.7\text{cm}$
- Ion sound radius $\rho_s \approx 1.7\text{cm}$

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3D effect: observation of zipper effect and density wave in the current sheet

- **Zipper effect**: coalescence and twisting start at the external anode and propagates towards the guns
- A **pressure rarefaction wave** is observed in the current sheet that propagates in the direction of the electron drift velocity (from external anode to plasma gun)

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Guide magnetic field scan

- 3 magnetic fields: $B_z=100, 200, 400$ Gauss
- Gun pressure adjusted to have same $n_e$
- No strong dependence of the current sheet thickness on $B_z$ is observed
- $J_0$ in the current sheet increases and saturates with $B_z$
- This observation may be interpreted in terms of increased electron mobility in the $z$ direction due to a reduced Larmor radius [Ricci P. et al, Physics of Plasmas 10, p.3554 (2003)].
Summary

• On RSX, relaxation of single and double flux rope is studied in the presence of a high guide magnetic field.

• Single and multiple helicity relaxed state are identified in single flux rope relaxation.

• Magnetic reconnection play an important role in two flux rope relaxation.

• A current sheet is observed on a scale length intermediate between $\delta_i$ and $\delta_e$. No strong dependence of the current sheet thickness on $B_z$.

• The peak current density in the current sheet increases and saturates with $B_z$.

• 3D effects: propagation of density wave and zipper effect