Radiatively-Cooled Magnetic Reconnection Experiments at the Z Pulsed-Power Facility

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Talk outline

• What is magnetic reconnection?
  • What is radiatively cooled magnetic reconnection?
  • How do we study it in the laboratory?
  • Results from simulations for experimental design
  • Results from the first MARZ shot on Z
  • Outlook for future MARZ shots
Magnetic Reconnection

Current sheet

B

B

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Magnetic Reconnection

Prediction: 1000 yrs. Reality: 10 minutes!

Current sheet
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1. Cooling is a significant loss mechanism ($\tau_{cool} \ll \tau_A$):
   • Modifies partition of magnetic energy between electrons, ions, kinetic
   • Leads to cooling instabilities, radiative collapse

2. Radiation: key (only?) observational signature in remote environments:
   • Where and when are X-rays produced - localized bursts?
   • How does this couple to the reconnection process? (Plasmoids: localized cooling)

Radiative Cooling Instabilities in Reconnection

Layer radiates

Layer compresses

- Layer ohmically heated
- Radiation/compression loop: runaway process

\[ T, p_{th} \text{ drop} \]

\[ n_e, P_{rad} \text{ rise} \]
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• Experiments require:
  • High $n_e$ for high $P_{rad}$
  • Plenty of $B^2/2\mu_0$ to dissipate
  • Sufficient $t_{drive}$ to see dynamics
• Cooling from Brems + Lines (not synchrotron or inverse Compton!)
  • Cooling rate material dependent
Pulsed-power-driven Magnetic Reconnection

Current

$B$

$V$

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Exploding wire arrays in parallel:

- Sustained flows ($\tau_{drive} \sim 10 \tau_A$)
- Quasi-2D geometry
- Collisional ($\delta \gg \lambda_{mfp}$)
- Inflows: $p_{th} \sim p_B \sim p_{kin}$
- No guide field

**MAGPIE:** 1.4 MA, 250 ns rise time

**Z Machine:** 20 MA, 300 ns rise time

$$n \propto I^2, P_{rad} \propto n^2 \propto I^4$$

**Z’s unique capability: strongly radiatively cooled reconnection**
Radiatively Cooled Reconnection on MAGPIE

Aluminum Wires
Super Alfvénic, Radiatively cooled

Early time $T_i = 300$ eV

Late time $T_i = 40$ eV

16 x 30 um Al wires per array
16 mm diameter, 16 mm tall

Work by L. Suttle: Suttle et al. PRL 2016
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GORGON MHD simulations

GORGON (J. Chittenden, Imperial): 3D Eulerian resistive MHD code with several radiation loss models and separate ion and electron energy equations

Wires:
- 150 Al wires
- 75 µm diameter

Arrays:
- 40 mm diameter
- 20 mm gap

• 2D sims: 50 µm resolution, 180x90 mm. 16 hrs, 256 cores
• Recombination loss: \[ P_{\text{rad}} = M_{\text{rad}} C_r n_e T_e^{1/2} (Z^2 n_i E_{\infty}^{Z-1} / T_e), \] with \( M_{\text{rad}} \approx 3 \)

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Plasmoids and Collapse

- Flows collide at mid-plane
- Plasmoids move within layer
- Inflow density rises with current
- Radiative cooling rises with density
- Thermal pressure removed: layer collapses

250 ns

280 ns

400 ns

Plasmoids

Collapsed Layer

Collapse

\[
\begin{array}{c}
\text{Current [MA]} \\
\hline
0 & 5 & 10 & 15 & 20 & 25 \\
0 & 100 & 200 & 300 & 400 & 500 & 600 \\
\end{array}
\]
Plasmoids and Collapse

Lundquist number:

\[ S = \frac{L V_A}{\mu_0 \eta} \]

Reconnection rate \( \sim \frac{1}{\sqrt{S}} \)

Plasmoids and Collapse

<table>
<thead>
<tr>
<th>Time</th>
<th>Plasmoids</th>
<th>Collapsed Layer</th>
<th>Collapse</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 ns</td>
<td>[ \text{ arrows} ]</td>
<td>[ \text{ yellow line} ]</td>
<td>[ \text{ red arrow} ]</td>
</tr>
<tr>
<td>280 ns</td>
<td>[ \text{ arrows} ]</td>
<td>[ \text{ yellow line} ]</td>
<td>[ \text{ red arrow} ]</td>
</tr>
<tr>
<td>400 ns</td>
<td>[ \text{ arrows} ]</td>
<td>[ \text{ yellow line} ]</td>
<td>[ \text{ red arrow} ]</td>
</tr>
</tbody>
</table>
Pressure balance in the layer

Pre-collapse: flux pile-up decelerates flow

At layer, $P_B = P_{th}$

a) Pressure balance at 250 ns

$M_A = 1$, $\beta_{th} = 1$, $M_S = 1$

$P_{th} = n_e T_e + n_i T_i$, $P_{kin} = \rho V_x^2/2$

$P_B = B_y^2/2\mu_0$, $P_{tot}$
Pressure balance in the layer

Pre-collapse: flux pile-up decelerates flow
At layer, $P_B = P_{th}$

Post-collapse: fast diffusion in cold, resistive plasma removes flux pile-up

![Graph showing pressure balance at 250 ns and 400 ns](image)

- $M_A = 1$
- $\beta_{th} = 1$
- $M_S = 1$

Equations:
- $P_{th} = n_e T_e + n_i T_i$
- $P_{kin} = \rho V_x^2 / 2$
- $P_B = B_y^2 / 2 \mu_0$
- $P_{tot}$
**Plasmoids in the Reconnection Layer**

*Note: Exaggerated aspect ratio*

**Plasmoids:**
- Carry a lot of current
Plasmoids in the Reconnection Layer

Plasmoids:
- Carry a lot of current
- Are hot, with low $\eta$

Note: Exaggerated aspect ratio
Plasmoids in the Reconnection Layer

Plasmoids:
• Carry a lot of current
• Are hot, with low $\eta$
• Are dense
Plasmoids in the Reconnection Layer

Plasmoids:
- Carry a lot of current
- Are hot, with low $\eta$
- Are dense
- Radiate strongly

Note: Exaggerated aspect ratio
Al K-shell disappears after collapse

XP2: predictive capability for X-ray diagnostics
We used XP2 to help design XIDAR, a new diagnostic for Z

Based on linear AXUV Si diode array for MAGPIE by Jack Halliday

On Z, UPAC (Q. Looker): self-contained, 32-pixel linear diode array with 0.25 mm resolution.

Inflow resolved

Outflow resolved
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Load Hardware for first MARZ shot

Thank you to Carlos Aragon, Roger Harmon, Josh Gonzalez, and Leo Molina!

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Load Hardware for first MARZ shot

Thank you to Kraig Leonard, Tommy Mulville, Chris De La O, and many more!

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Load Hardware installation

Wire weights

Wire Arrays

B-dot probe array

Current probes

Weeks to build, a microsecond to destroy!

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Load Hardware Post Shot

Minimal debris, good for future diagnostics!

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Diagnostics for First MARZ Shot

**Diagnostics on MARZ**

- **X-Ray Radiation**
  - X-Ray Imaging
  - Filtered X-Ray diodes
  - X-Ray Diodes
  - Silicon Multi-diode head
  - X-Ray Spectrum

- **Current & Magnetic Field**
  - Load Current
  - PDV & VISAR (Velocimetry)
  - IDTLs / Dual-polarity inductive probes
  - Advected Magnetic Field
  - B-dot probe array

- **Optical Radiation**
  - Gated Self-Emission (8 frame)
  - Streaked Visible Spectroscopy (SVS)

**Reconnection Diagnostics**

- **Side / Along rec. layer**
  - Gated MLM+MCP
  - 2 x UXI-Icarus Pinhole
  - XIDAR-UPAC (diode-array)
  - FOA Pinhole Camera

- **Top-down**
  - X-Ray Spectrum

**Current & Magnetic Field**

- **Load Current**
- **IDTLs / Dual-polarity inductive probes**
- **Advected Magnetic Field**
- **B-dot probe array**

**Optical Radiation**

- **Gated Self-Emission (8 frame)**
- **Streaked Visible Spectroscopy (SVS)**

**Bow Shock Diagnostics**

- **Side / Front and behind shock**
- **XRS3 time-integrated (Al K-shell)**
- **TREX time-gated spectrometer (broadband)**
MARZ1 delivered 10 MA to each wire array

**PDV:** Return on 14/16 channels.

**VISAR:** Return on 13/24 channels.

500 m/s velocities are consistent with pre-shot modeling for 10 MA.
MARZ1 delivered 10 MA to each wire array

Azimuthal asymmetry in current on arrays: indicative of current flowing in reconnection layer?
Magnetic Probe Measurements: Plasma Flow

Two probes vertically stacked (1 cm separation)

Thank you to Gabe Shipley and Derek Lamppa!
Magnetic Probe Measurements: Plasma Flow

Thank you to Gabe Shipley and Derek Lamppa!
Bow shock around B-dot probe: Plasma Flow

T-probe
(14 mm from wires)

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Bow shock around B-dot probe: Plasma Flow
• Four fibers: 6 mm spot size at inductive probe radial locations

Thank you to Sonal Patel and Dan Scoglietti!
Streaked Visible Spectroscopy

- Long time record, spatially localized, broadband spectroscopy
- Use Al II & Al III lines to measure $n_e$ and $T_e$

Thank you to Sonal Patel and Dan Scoglietti!

Pre-shot SEGOI image of SVS 2
1.6 keV X-rays: plasma likely > 100 eV

Thank you to Eric Harding, Andy Maurer, and Stephanie Hansen!
X-ray Spectra are a Rich Source of information

Lots of information on temperature, density (and velocity?) in spectral lines

Intensity (arb. units)

Energy [eV]
Lineout of He-alpha region from $z = -12.81$ mm ($\Delta z = 6$ mm)

Overlay of experiment from $z = -12.81$ mm (red) with optically thick, unshifted SCRAM spectrum with rough best-fit conditions (black; $\tau \sim 15$)

Sat/IC ratio $\rightarrow$ temperature
res/IC ratio $\rightarrow$ $\tau \sim \Delta Y_{\text{LOS}} \times$ density

Experimental spectrum has signatures of opacity broadening (He$\alpha$ resonance broader than and less intense than He$\alpha$ IC)

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• Radiated power rises after current start, drops before current peak
• X-ray spectra appears softer than simulated: more shots in later this year
What didn’t work well

- Most X-ray cameras (gated, time integrated) and diodes (XIDAR, filtered) returned no signal
- Most diagnostics functioned nominally, so red indicates lack of data
- Conclusion: Layer less bright predicted by simulations

<table>
<thead>
<tr>
<th>Diagnostic</th>
<th>Data return</th>
</tr>
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<tbody>
<tr>
<td>IDTLs</td>
<td>4/4 channels</td>
</tr>
<tr>
<td>PDV</td>
<td>14/16 channels</td>
</tr>
<tr>
<td>VISAR</td>
<td>13/24 channels</td>
</tr>
<tr>
<td>Inductive probes</td>
<td>13/15 channels</td>
</tr>
<tr>
<td>SVS</td>
<td>3/4 systems</td>
</tr>
<tr>
<td>SEGOI</td>
<td>Bow shock observed</td>
</tr>
<tr>
<td>LOS 170 diodes</td>
<td>~1/6 diodes</td>
</tr>
<tr>
<td>MLM</td>
<td></td>
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<tr>
<td>XRS3</td>
<td>AI K-shell observed</td>
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<tr>
<td>TREX</td>
<td></td>
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<tr>
<td>TADPoles (2x)</td>
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<tr>
<td>FOA diodes</td>
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<tr>
<td>FOA PHC (UXI, 2x)</td>
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<tr>
<td>FOA PHC (IP)</td>
<td></td>
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<tr>
<td>FOA XIDAR (UPAC)</td>
<td>Image on IP?</td>
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Future work on MARZ

Two more MARZ shots later this year:

1. Improve diagnostics of the reconnection layer
2. Diagnose the outflows from the reconnection layer

Goal: Form a complete picture for publication
Future work on MARZ

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MARZ renewal for CY23-24:
1. New load designs to boost density, magnetic field
2. Change wire material to alter cooling rate
3. Investigate effect of pulse rise-time

Goal: Understand effect of cooling on reconnection

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Future work on MARZ

**New simulation tools:**
- Radiation transport in GORGON (Jerry Chittenden)
- Advanced X-ray post-processing such as Doppler shift (Aidan Crilly)

**New diagnostics:**
- Laser imaging (David Yager-Elorriaga)
- Thomson scattering (Jacob Banasek)
- X-pinch backlighting (Matt Gomez)
- Fe L-shell spectroscopy (Patricia Cho)
- UV spectroscopy, fiber coupled (Mark Johnston)
Conclusions

- Strong radiative cooling important in extreme astrophysical environments:
  - Key signature of reconnection; modifies energy partition; leads to collapse
- HED pulsed-power experiments can reach strong radiative cooling regime
- 2D MHD simulations show rich physics: plasmoid formation, layer collapse
- 3D MHD simulations with radiation transport coming online
- Preliminary experimental results from the Z machine show viability of platform for radiatively cooled reconnection studies: more shots later this year!