An overview of recent results from the PUFFIN group at MIT

Jack D. Hare[1], Simran Chowdhry[1], Rishabh Datta[1], Lansing Horan IV[1], Emily Neill[1], Thomas Varnish[1], the MARZ collaboration, the MAIZE team, and the COBRA team

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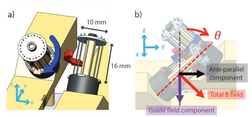
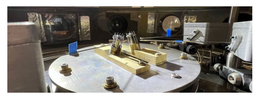
Guide-field reconnection using tilted arrays on MAIZE

See Thomas' poster, two down from this one at BP12. 126!

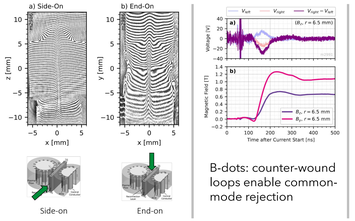


Tilt Angle (°)	$b = \frac{B_{guide}}{B_{rec}} = \tan\theta$
0	0
22.5	0.4
45	1

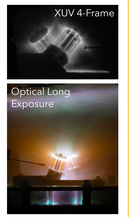
- Guide field component embedded into the flow rather than applied externally
- MAIZE: 500 kA, 200 ns



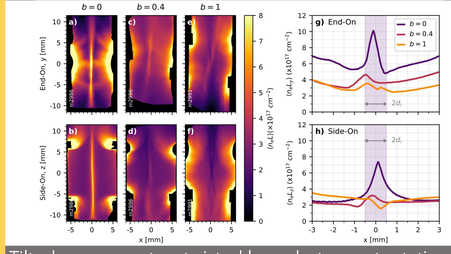
Diagnostic setup and results



B-dots: counter-wound loops enable common-mode rejection



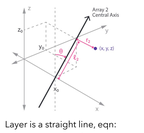
Interferometry shows rotated layer with increasing guide-field



Tilted arrays create a twisted layer, but no net rotation

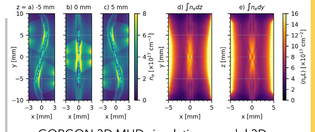
Based on Lebedev's rocket model, assume rotated layer forms where:

$$\rho(r_1) = \rho(r_2)$$



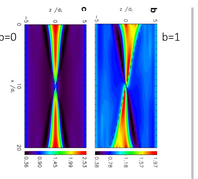
Layer is a straight line, eqn:

$$y = -\frac{x_0(1+b^2)}{b} \cdot \frac{1}{z} \cdot x$$

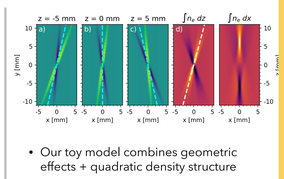


- GORGON 3D MHD simulations model 3D load hardware
- Layer rotation in x-y slices matches geometric model (cyan dashed lines)
- No overall rotation seen in line-integrated maps, unlike experimental results

2-fluid effects explain layer rotation and side-on structure

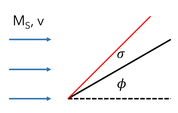


Simulations (Yang+ 2008, Huba+ 2005) show quadrupolar density structure in 2-fluid GF reconnection



- Our toy model combines geometric effects + quadratic density structure
- Qualitatively matches experimental data: quadrupolar end-on n_e, and void/peak in side-on n_e.

Oblique shock experiments on COBRA

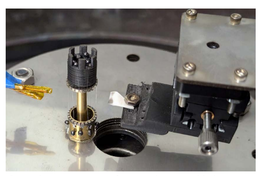


- Use exploding wire array to drive supersonic plasma flow into an obstacle at angle ϕ to flow
- Measure the angle σ of the shock
- With two obstacles, eliminate M_s and measure γ directly

$$\tan\phi_{1,2} = 2\cot\sigma_{1,2}\frac{M_S^2\sin^2\sigma_{1,2}-1}{M_S^2(\gamma+\cos 2\sigma_{1,2})+2}$$

Experiments carried out on COBRA, supported by NNSA through ZNetUS
Work led by Rishabh Datta, with Emily Neill (undergrad)

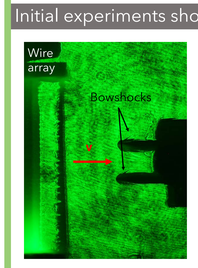
Load Hardware and Diagnostic Setup



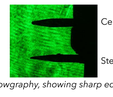
Original setup: segment of ceramic boxcutter blade, mounted at a precise angle to get two oblique surfaces

- 33 um Al wires
- 20 mm tall, 10 mm diameter overmassed exploding wire array
- Diagnostics
  - Laser interferometry
  - Laser Shadowgraphy
  - Thomson Scattering
  - Side-on and end-on XUV
  - High speed optical camera
  - In situ b-dot probes

Initial experiments showed bow (not oblique) shocks



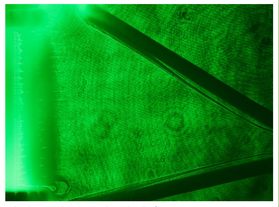
- Knife edge targets produced bow shocks, not oblique shocks
- Behaviour independent of target material – steel and ceramic knives tested
- Possible cause: photo-ionization or ablation of material from leading tip, creating a dense, cold, plasma: a blunt obstacle



Pre-shot shadowgraphy, showing sharp edge of targets

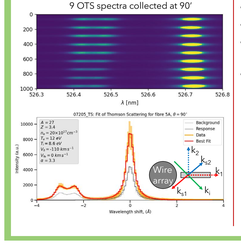
New approach: the crocodile, a shocking improvement

Two angled aluminium targets, with the leading edge out of the plasma

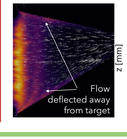


Shadowgraphy shows clear shocks forming on upper and lower surface, with different shock angles

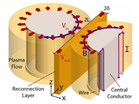
Thomson Scattering and Simulations



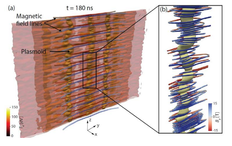
- Simulations and OTS agree flow is $M_s \approx 6$
- Shadowgraphy shock angles: $M_s \approx 10$
- In simulations, magnetic field pile-up deflects flow away from target,
- Decreases effective target angle and hence shock angle



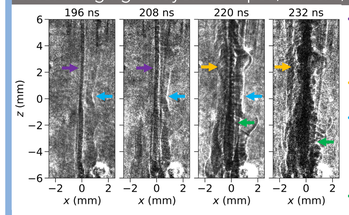
The Magnetic Reconnection on Z (MARZ) Platform



- First exploding wire array load on Z
- Reconnection experiment with both strong radiative cooling (Al K-shell) and plasmoid instability present



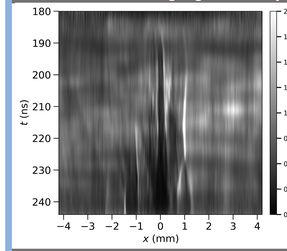
Laser imaging of layer: collapse, shocks, and instabilities



- **Dark central void:** beam deflected away from the peaked layer density
- **Void grows wider:** layer radiative collapse
- **Bright bands outside layer:** MHD shocks just outside the layer causes local beam focusing
- **Smal;-scale axial structures:** layer instabilities such as kinking plasmoids

See Lansing's poster, next to this one at BP12. 125!

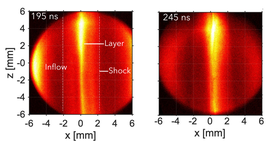
Streaked laser imaging of the layer: collapse and shocks



Streak image (180 – 245 ns) of reconnection layer:

- Also exhibits **dark central void** (**that widens in time**)
- And a **bright band outside the layer**
- Laser speckle difficult to remove

Optical self-emission from the layer: shocks

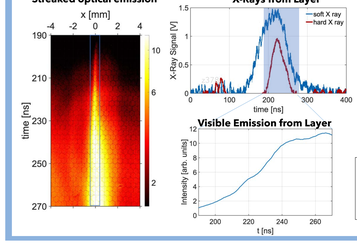


- Thin bright central region: reconnection layer
- Jump in emission at $x = \pm 2$ mm: planar shocks

Shock formation is consistent with magnetic flux pile-up due to super-Alfvénic super-sonic inflows

See Rishabh Datta's talk, Tuesday PM JO08.08!

Optical self-emission from the layer: radiative collapse

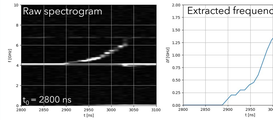


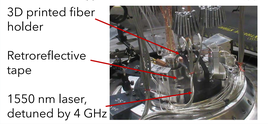
Falling X Ray emission: Falling temperature

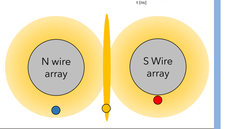
Rising visible emission: Rising density

Temperature falls as density rises rapidly: evidence for radiative collapse of layer

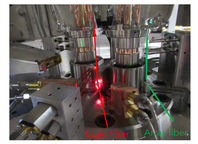
Temporally Heterodyned Interferometry (PDV)

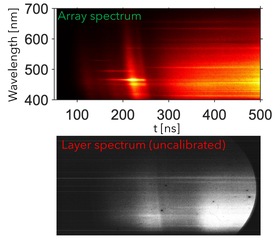






Axial Streaked Visible Spectroscopy





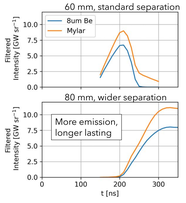
- New configuration: axial rather than chordal measurement
- Uses 45° mirrors to collect light at fixed r from wires

MARZ 5: separate arrays for a hotter, longer-lasting layer

MARZ 5 (December, 2024): move arrays further apart (from 60 mm to 80 mm, center to center)

Simulations suggest:

- Flows accelerated over longer distance
- More heating by shocks
- Hotter reconnection layer
- More X-rays – easier to diagnose
- Longer plasmoid phase before collapse
- More time for instability growth

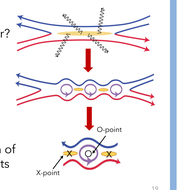


Radiatively Cooled Reconnection and Plasmoids in Athena++

See Simran Chowdhry's poster, Wednesday AM NP12.33!

Aim : Develop a fundamental understanding of the interaction of radiation with reconnection processes through analytic work and numerical studies

1. How do different optically thin radiative cooling processes affect the stability of the reconnection layer?
2. How is the formation and evolution of plasmoids modified in the presence of strong radiative cooling processes?
3. How does strong radiative cooling affect the partition of energy and the acceleration of particles at the X-points and O-points?



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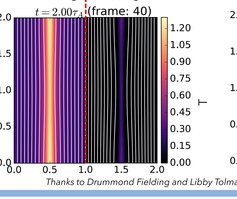
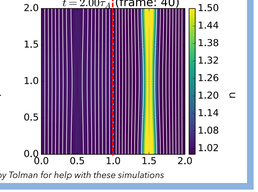
First steps – radiatively cooled Double Harris sheets

Optically thin bremsstrahlung cooling: $P_{rad} = An^2T^{1/2}$, A chosen such that $R = \frac{\tau_A}{\tau_{cool}} \sim 2$

Significant temperature decrease…

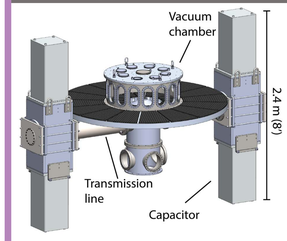


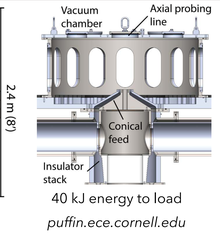
…leads to large compression in layer



Thanks to Drummond Fielding and Libby Tolman for help with these simulations

The new long-pulse PUFFIN facility at MIT (soon Cornell), 800 kA in 2 μs

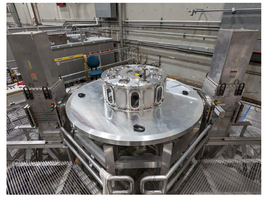




40 kJ energy to load

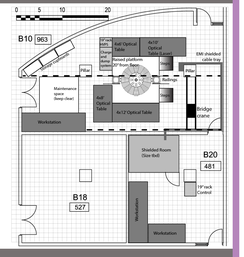
puffin.ece.cornell.edu

Photographs of PUFFIN assembly



Moving PUFFIN to Cornell

- The PUFFIN group is moving to Cornell in January 2025 to join the Laboratory for Plasma Studies
- Lab space is being prepared in the basement of Rhodes Hall, just down the corridor from the COBRA and XP facilities
- Currently at 90% CDs, renovation completion expected in Summer 2025
- We are recruiting graduate students to start in Fall 2025 – apply to Cornell ECE or AEP!



Recent publications

- R. Datta, K. Chandler, C.E. Myers, J. P. Chittenden, A. J. Crilly, C. Aragon, D. J. Ampleford, J. T. Banasek, A. Edens, W. R. Fox, S. B. Hansen, E. C. Harding, C. A. Jennings, H. Ji, C. C. Kuranz, S. V. Lebedev, Q. Looker, S. G. Patel, A. Porwitzky, G. A. Shipley, D. A. Uzdensky, D. A. Yager-Elorriaga, and J.D. Hare, *"Plasmoid formation and strong radiative cooling in a driven magnetic reconnection experiment"*, Physical Review Letters, 2024.
- R. Datta, K. Chandler, C.E. Myers, J. P. Chittenden, A. J. Crilly, C. Aragon, D. J. Ampleford, J. T. Banasek, A. Edens, W. R. Fox, S. B. Hansen, E. C. Harding, C. A. Jennings, H. Ji, C. C. Kuranz, S. V. Lebedev, Q. Looker, S. G. Patel, A. Porwitzky, G. A. Shipley, D. A. Uzdensky, D. A. Yager-Elorriaga, and J.D. Hare, *"Radiatively Cooled Magnetic Reconnection Experiments Driven by Pulsed Power"*, Physics of Plasmas, 2024.
- R. Datta, A. J. Crilly, J. P. Chittenden, S. Chowdhry, K. Chandler, N. Chaturvedi, C. E. Myers, W. R. Fox, S. B. Hansen, C. A. Jennings, H. Ji, C. C. Kuranz, S. V. Lebedev, D. A. Uzdensky, and J. D. Hare, *"Simulations of Radiatively Cooled Magnetic Reconnection Driven by Pulsed Power"*, Journal of Plasma Physics, 2024.
- R. Datta, F. Ahmed, and J. D. Hare, *"Machine learning assisted analysis of visible spectroscopy in pulsed-power-driven plasmas"*, IEEE Transactions in Plasma Science, 2024.

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