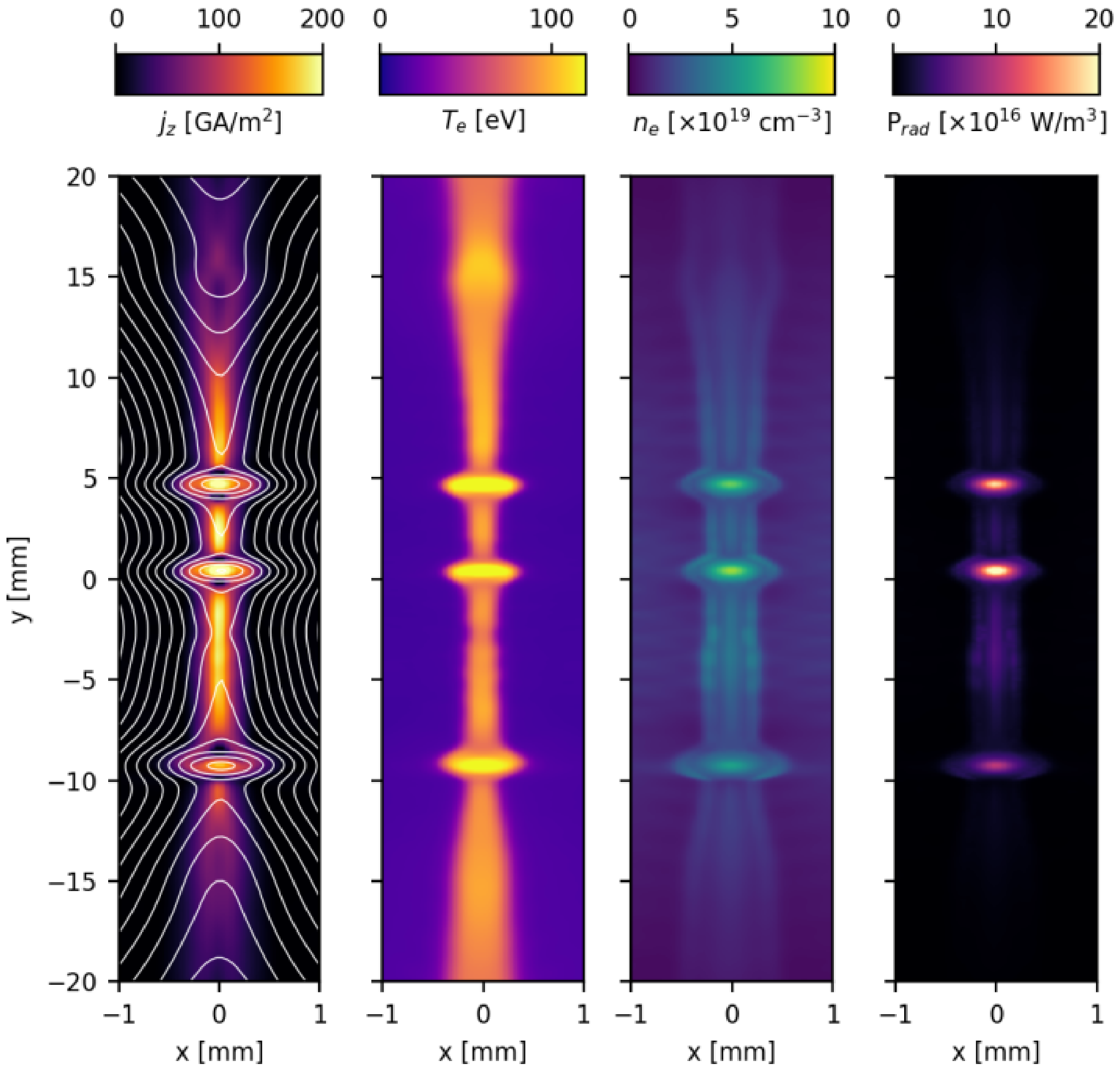
SAND2022-14159C

Simulations of the Magnetically Ablated Reconnection on Z (MARZ) platform



Jack Hare, on behalf of the MARZ collaboration

jdhare@mit.edu

PUFFIN

MIT | PSFC Plasma Science and Fusion Center

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

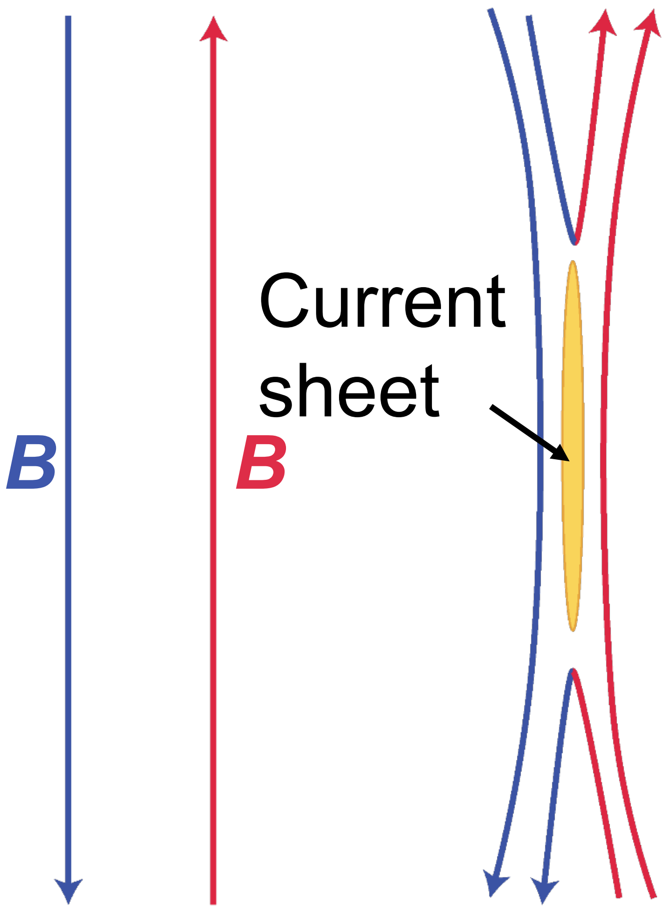
Magnetically Ablated Reconnection on Z (MARZ) collaboration

MIT	Jack Hare and Rishabh Datta
Imperial College	Sergey Lebedev, Jerry Chittenden, Aidan Crilly, Jack Halliday, Simon Bland, Danny Russell, Lee Suttle, and others
Princeton University/PPPL	Will Fox and Hantao Ji
University of Michigan	Carolyn Kuranz
University of Colorado Boulder	Dmitri Uzdensky
Sandia National Laboratories	Katherine Chandler, Clayton Myers, Carlos Aragon, Chris Jennings, Dave Ampleford, Kris Beckwith, Greg Dunham, Aaron Edens, Matt Gomez, Josh Gonzalez, Stephanie Hansen, Eric Harding, Roger Harmon, Michael Jones, Jeff Kellogg, Guillaume Loisel, Quinn Looker, Leo Molina, Michael Montoya, Sonal Patel, Gabe Shipley, Shane Speas, Tim Webb, David Yager-Elorriaga, and many others

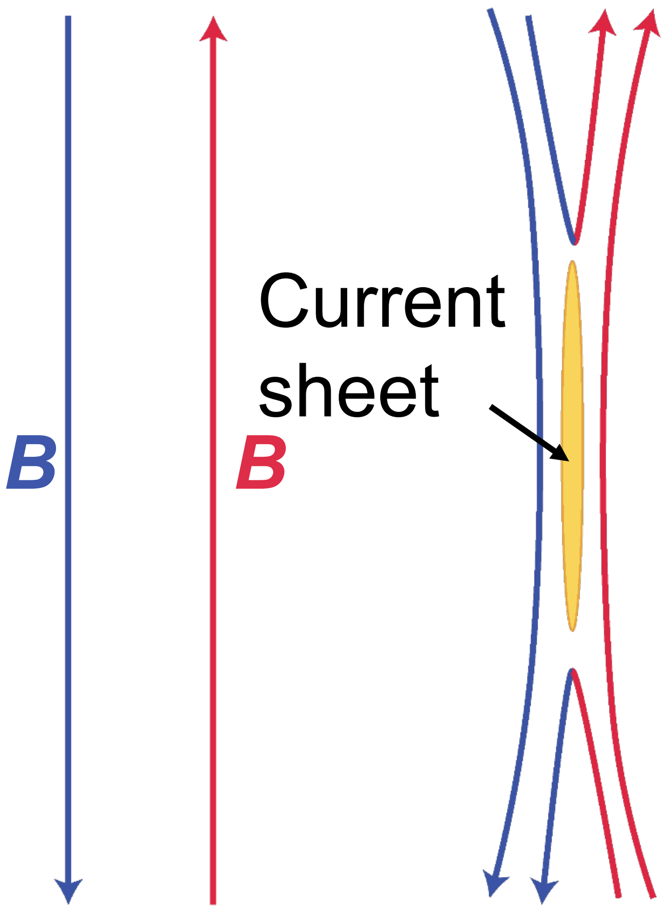
This work is supported by the NSF through an EAGER award

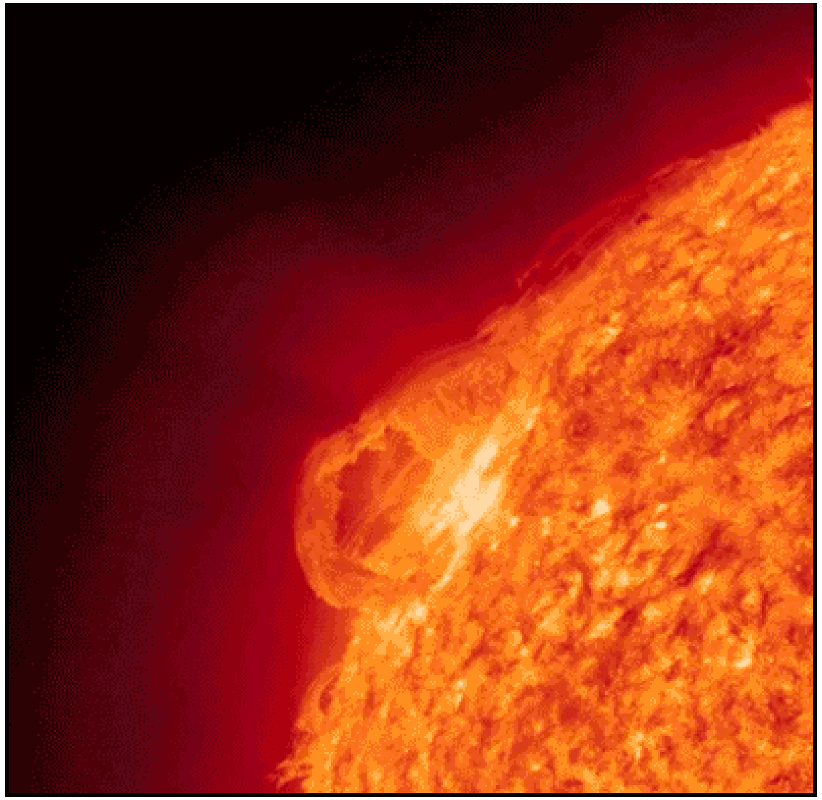
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Magnetic Reconnection

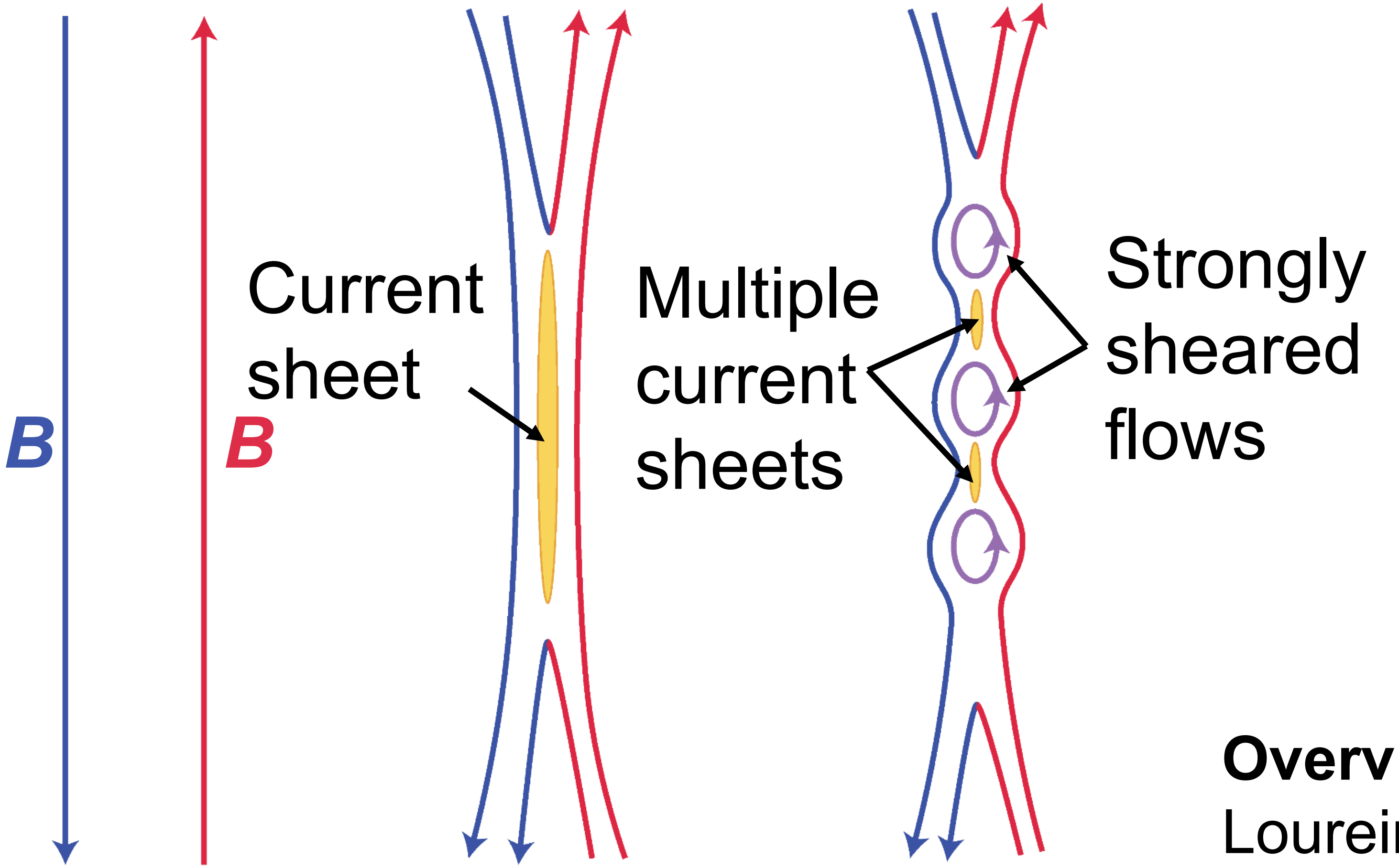


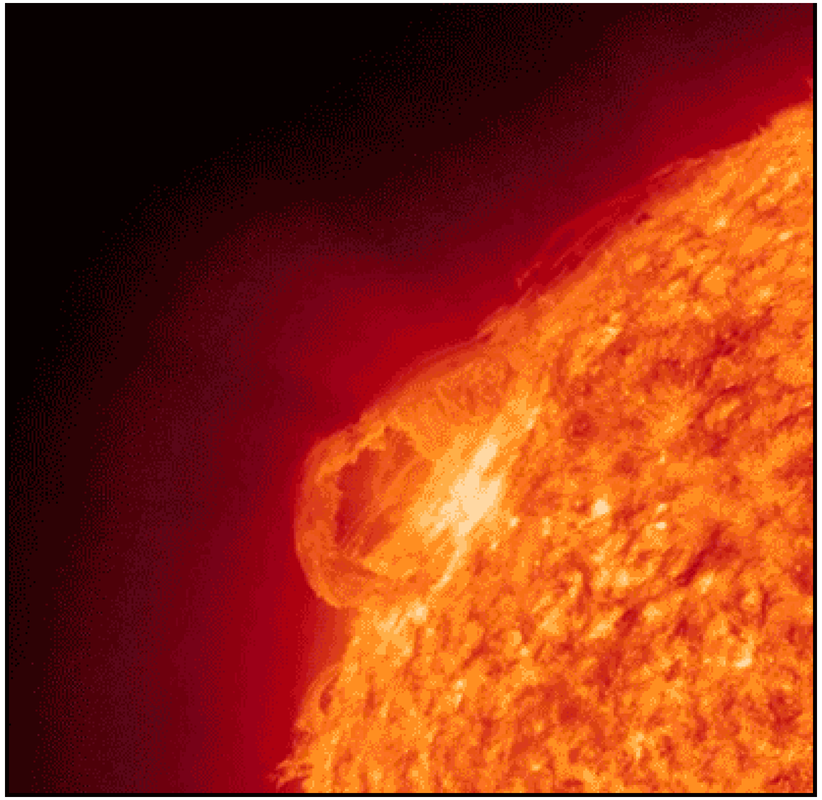
Magnetic Reconnection





Plasmoids Lead to Fast Reconnection and Anomalous Heating



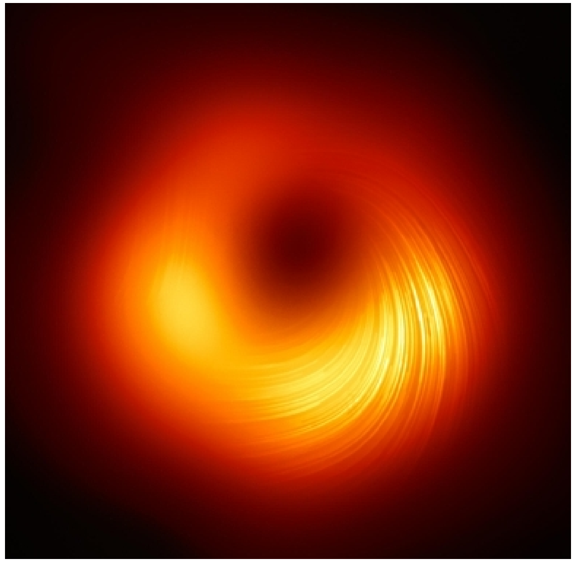


Overview of recent theory:
Loureiro, N. F., & Uzdensky, D. A.(2015).
PPCF, *58*, 014021

Reconnection in Extreme Astrophysical Environments

Artist's impression of a black hole

M87 (EHT)



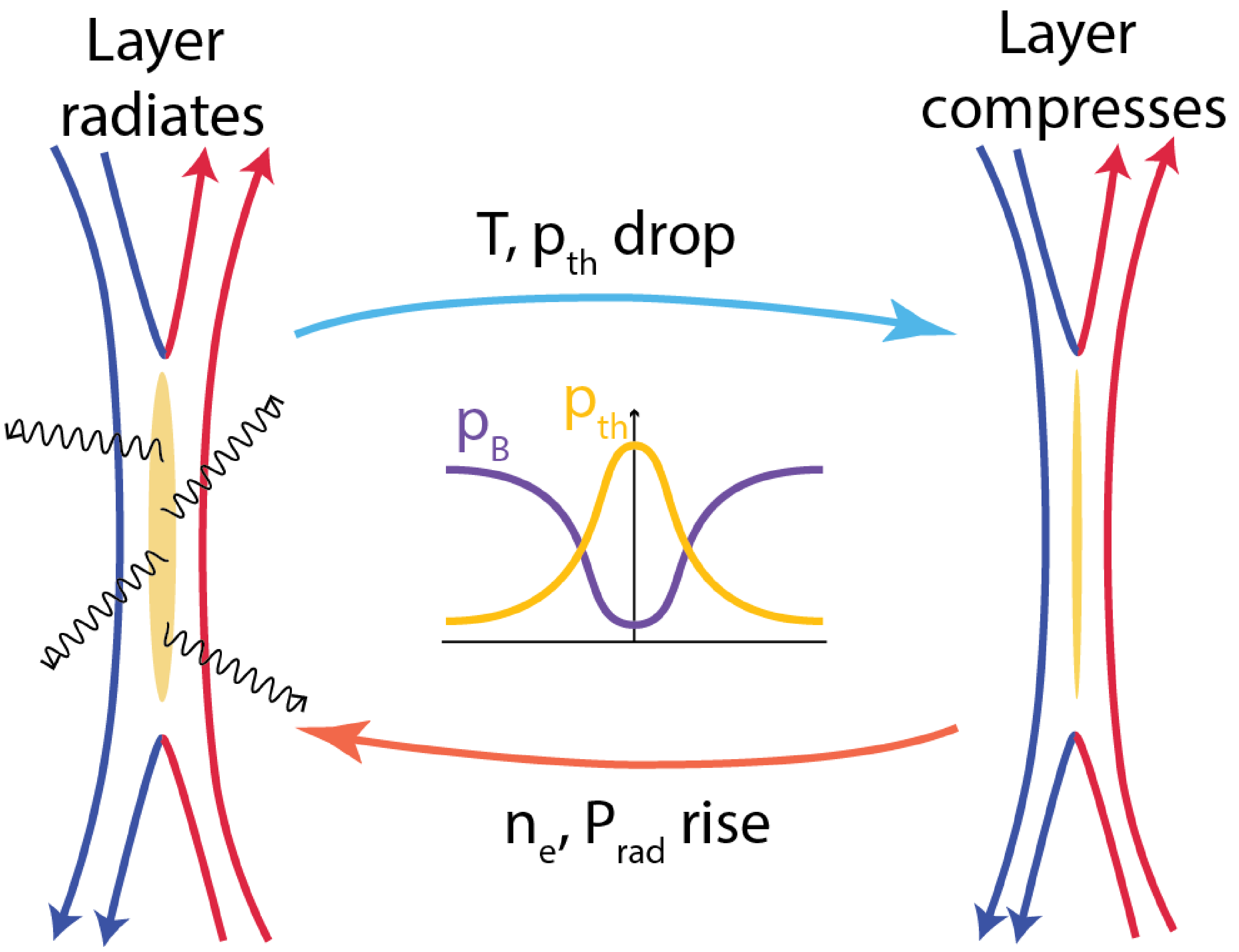
Crab Pulsar (Hubble/Chandra)

See: Uzdenksy in "Magnetic reconnection: Concepts and applications" arXiv:1510.05397 (2016)

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

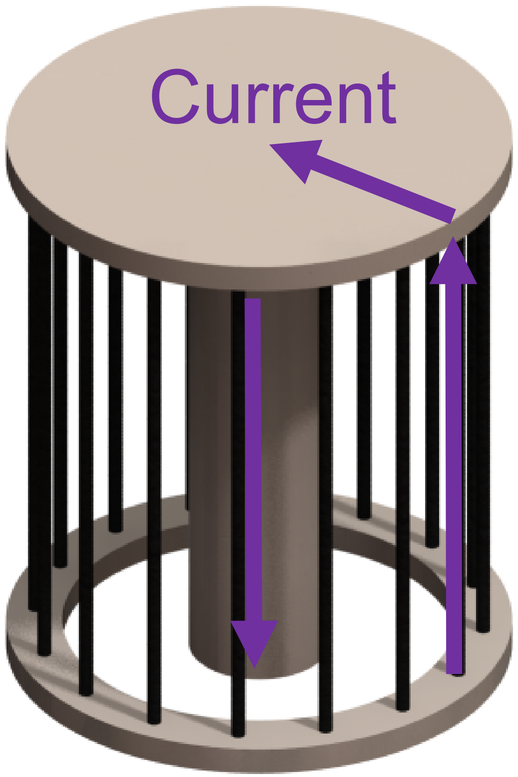
2. Radiation: key (only?) observational signature in remote environments:
   - Where and when are X-rays produced – localized bursts?
   - How does this couple to the reconnection process? (Plasmoids: localized cooling)

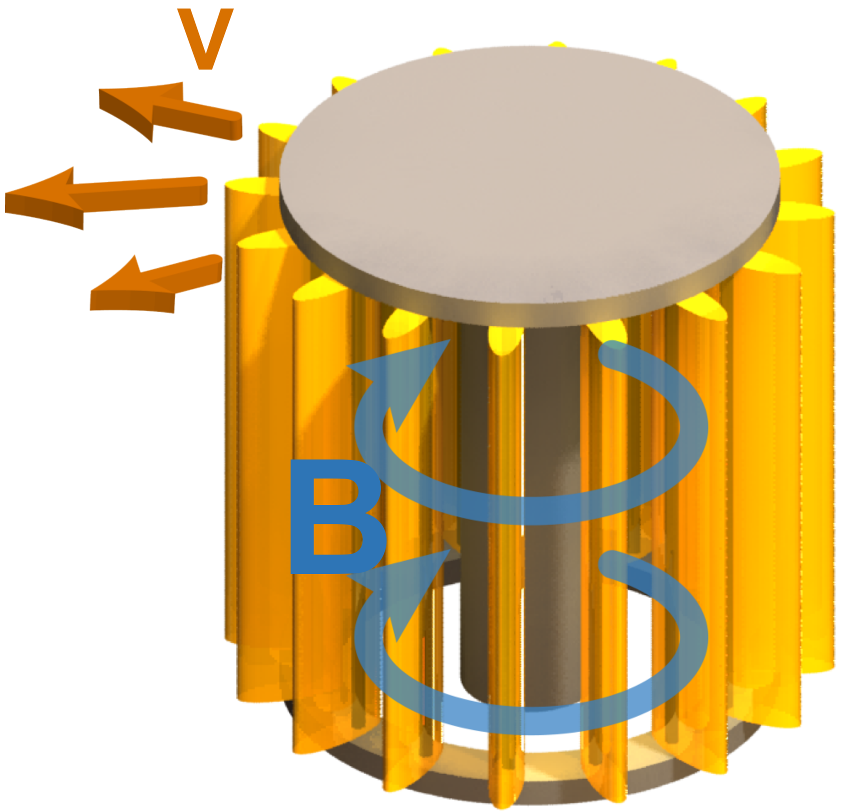
Radiative Cooling Instabilities in Reconnection



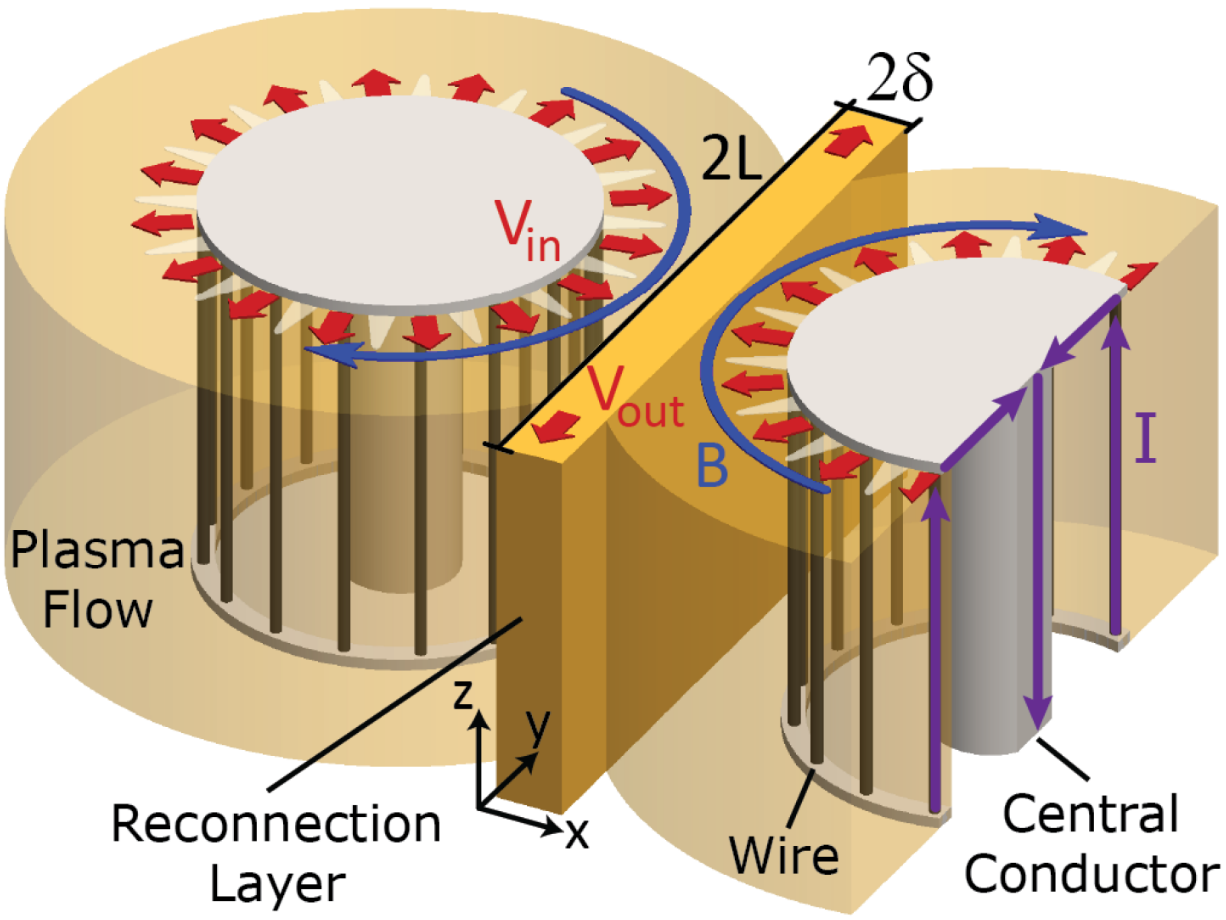
- Layer ohmically heated, radiatively cooled
- Layer radiates, compresses, radiates more: runaway process

Pulsed-power-driven Magnetic Reconnection





Magnetic Reconnection from Double Exploding Wire Arrays



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

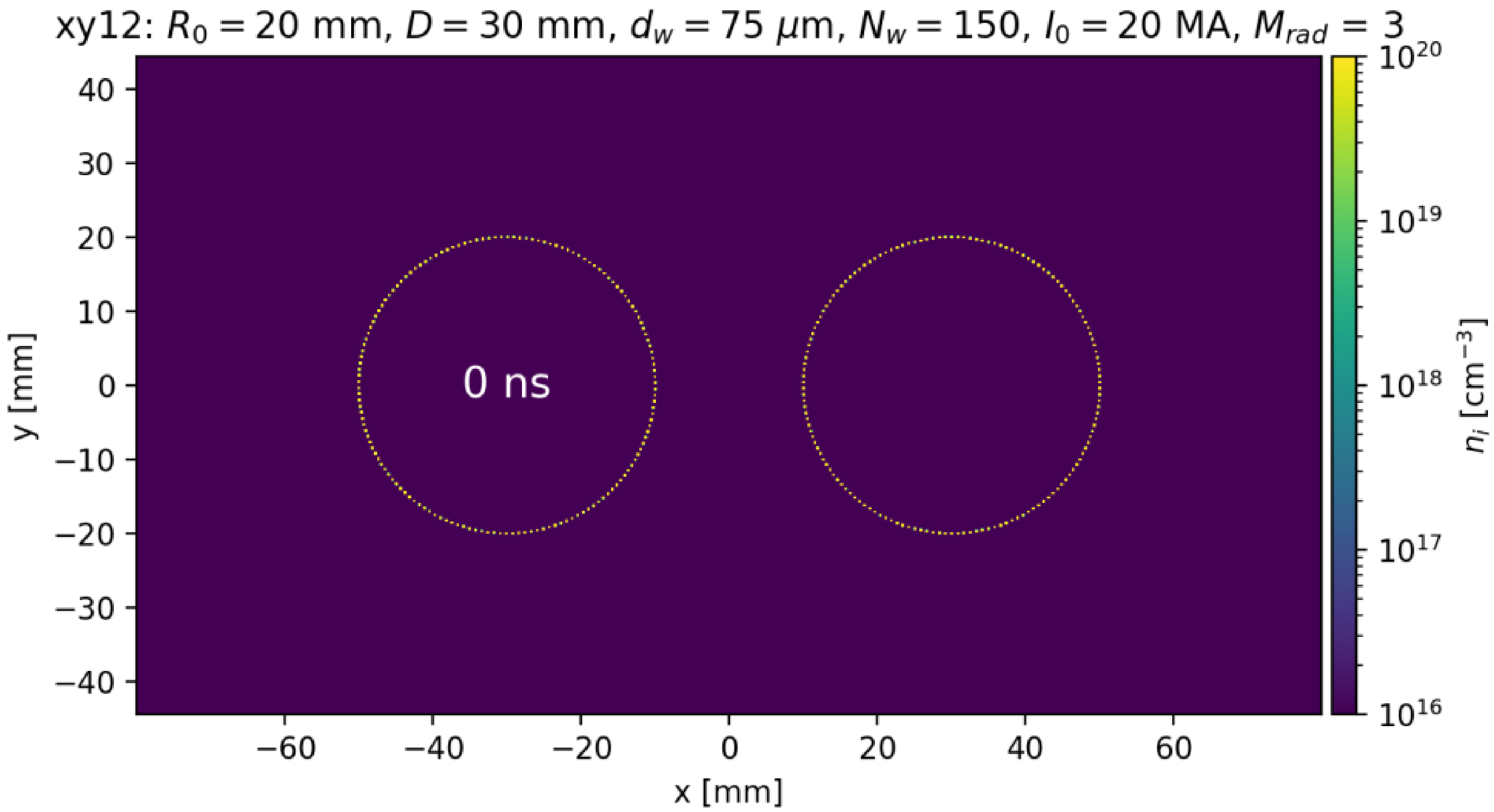
Hare *et al* PRL 2016, PoP 2017, 2018

GORGON MHD simulations

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

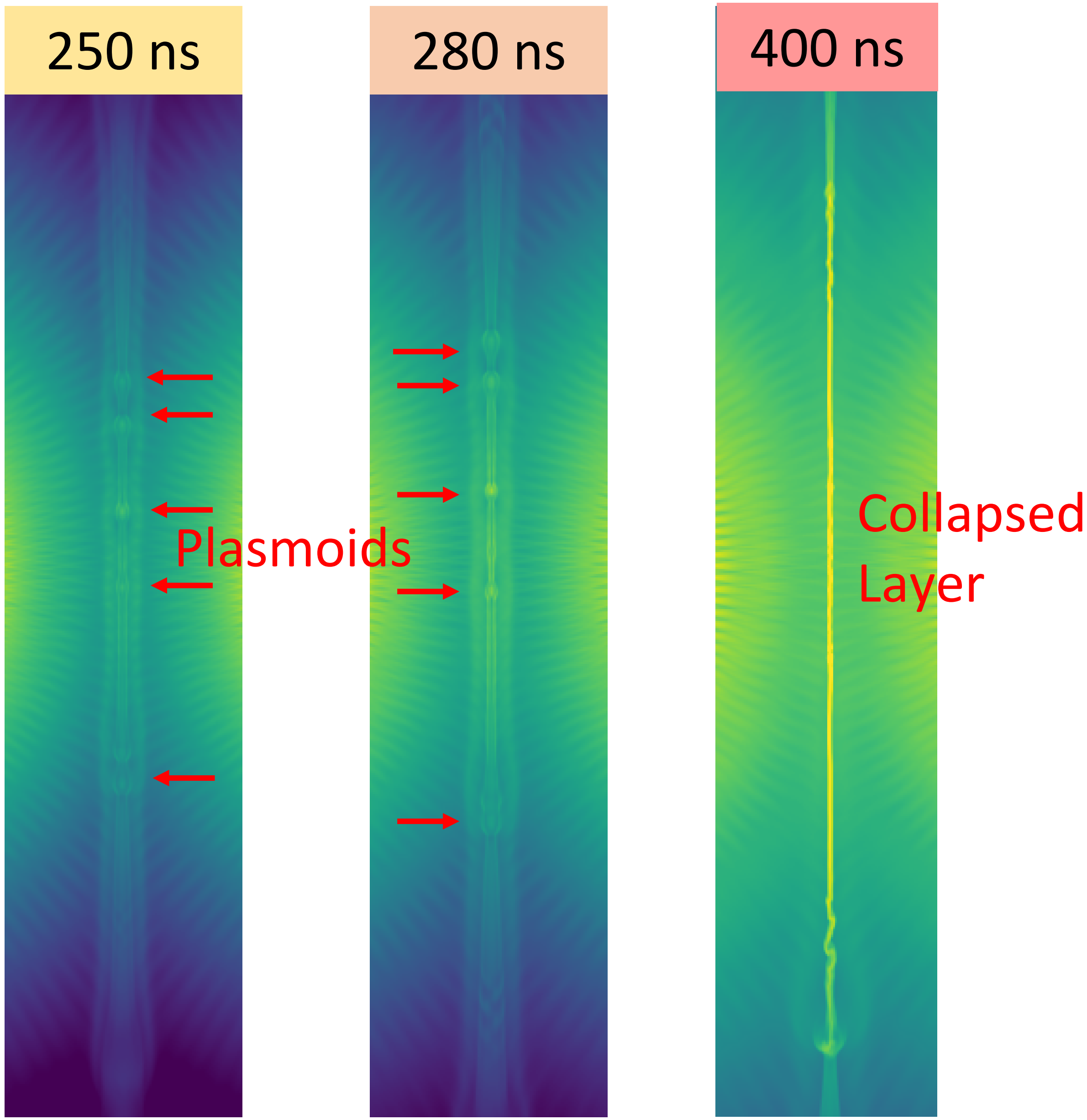
Wires:
- 150 Al wires
- 75 μm diameter

Arrays:
- 40 mm diameter
- 20 mm gap

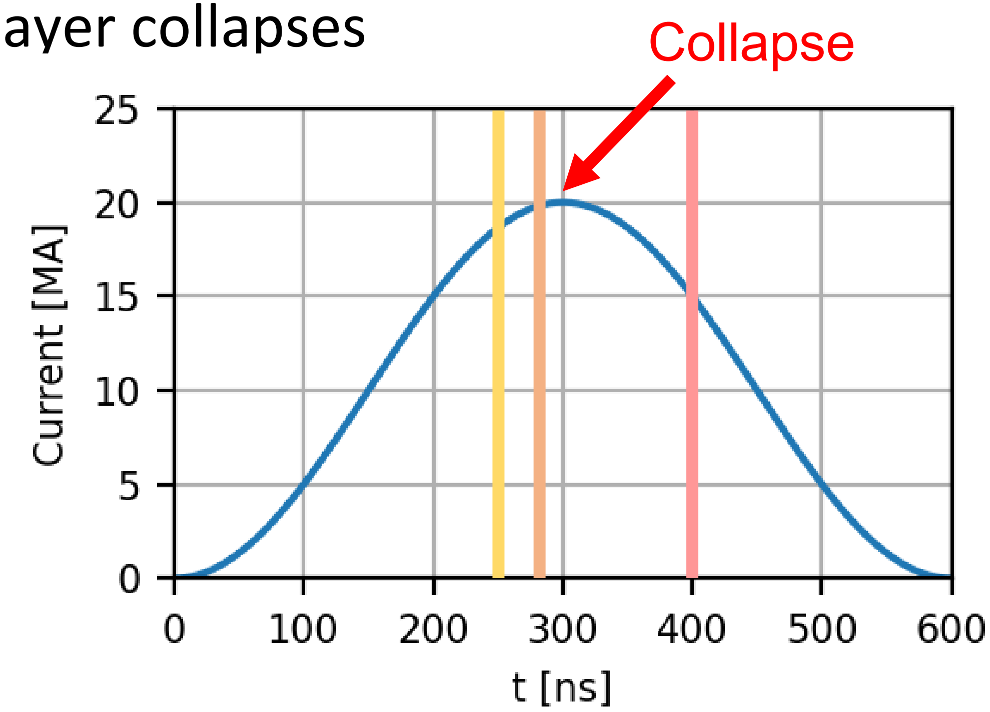


- 2D sims: 50 μm resolution, 180x90 mm. 16 hrs, 256 cores
- Recombination loss: $P_{rad} = M_{rad} C_r n_e T_e^{1/2}(Z^2 n_i E_\infty^{Z-1}/T_e)$, with $M_{rad} \approx 3$

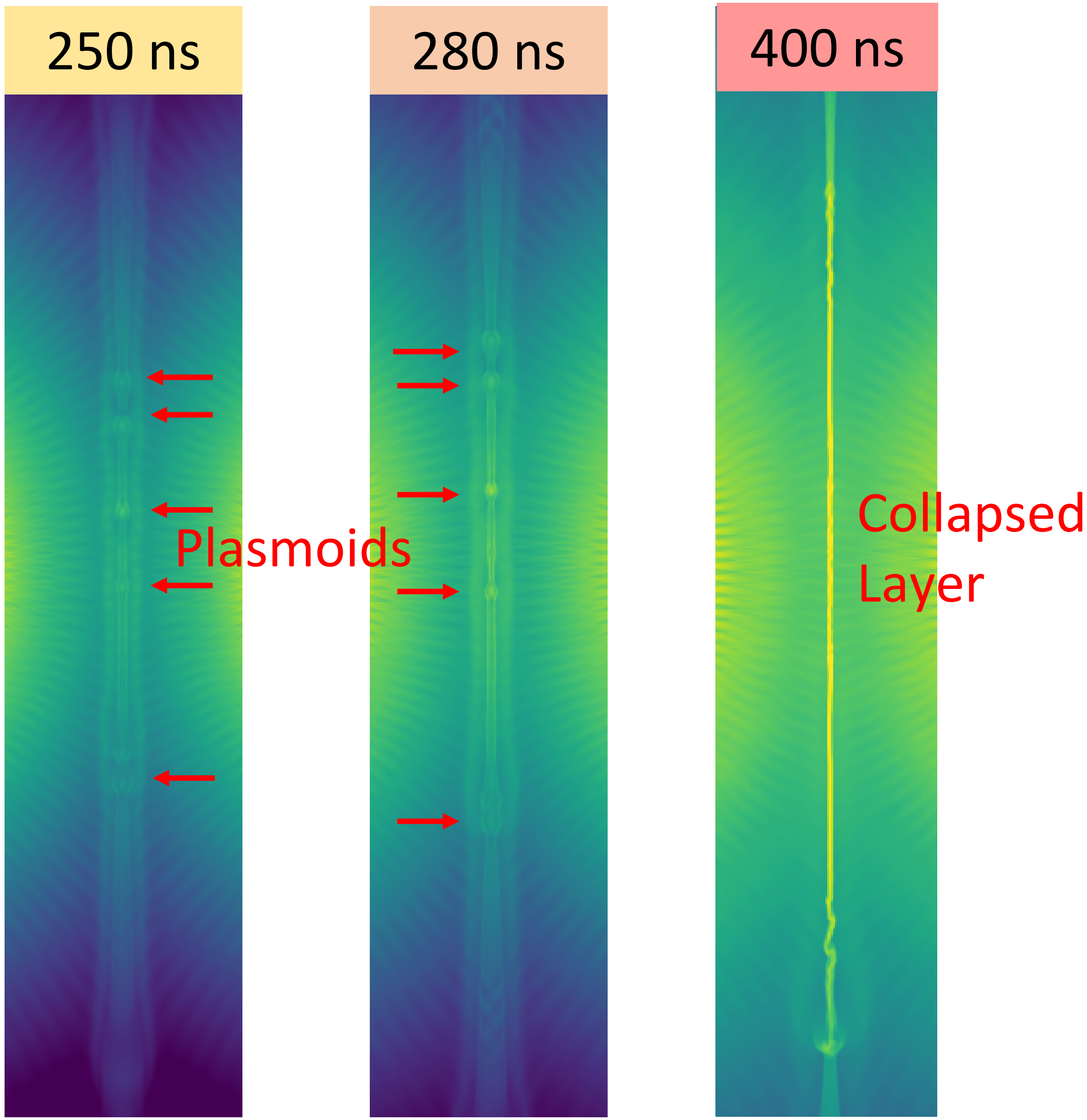
Plasmoids and Collapse



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



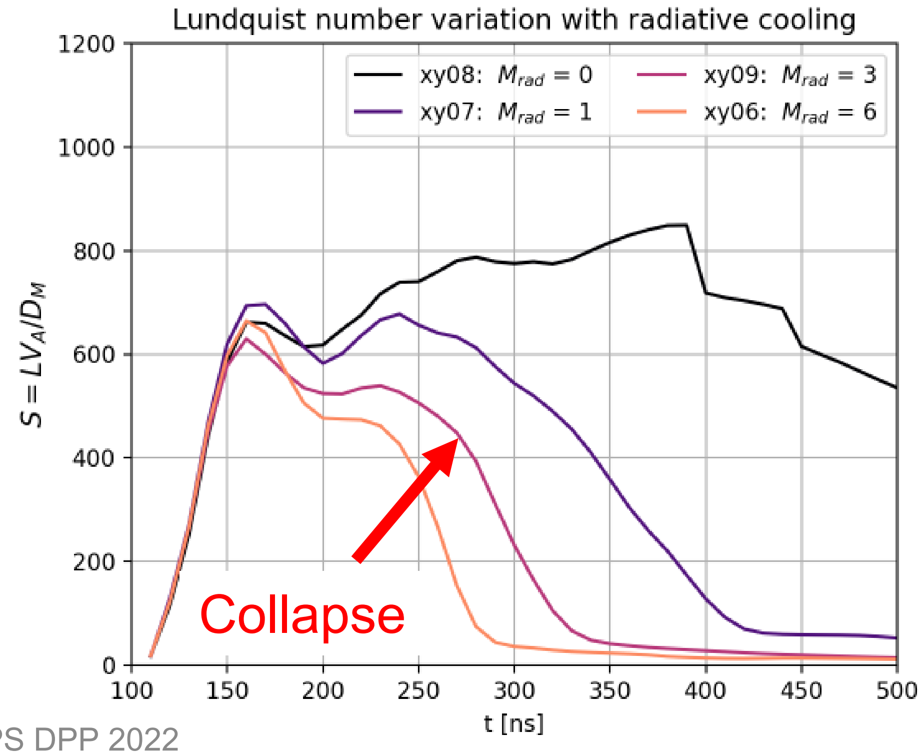
Plasmoids and Collapse



Lundquist number:

$$S = \frac{LV_A}{\mu_0 \eta}$$

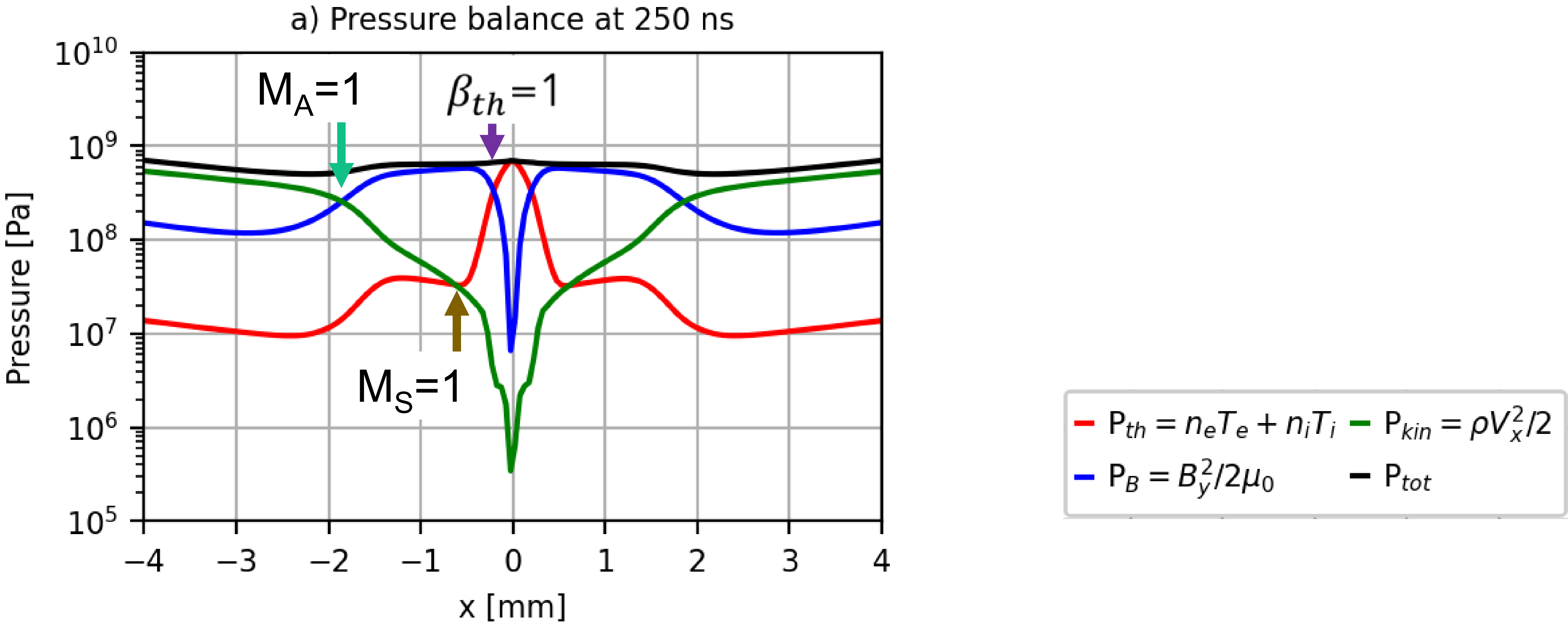
$$\text{Reconnection rate} \sim \frac{1}{\sqrt{S}}$$



Pressure balance in the layer

Pre-collapse: flux pile-up decelerates flow

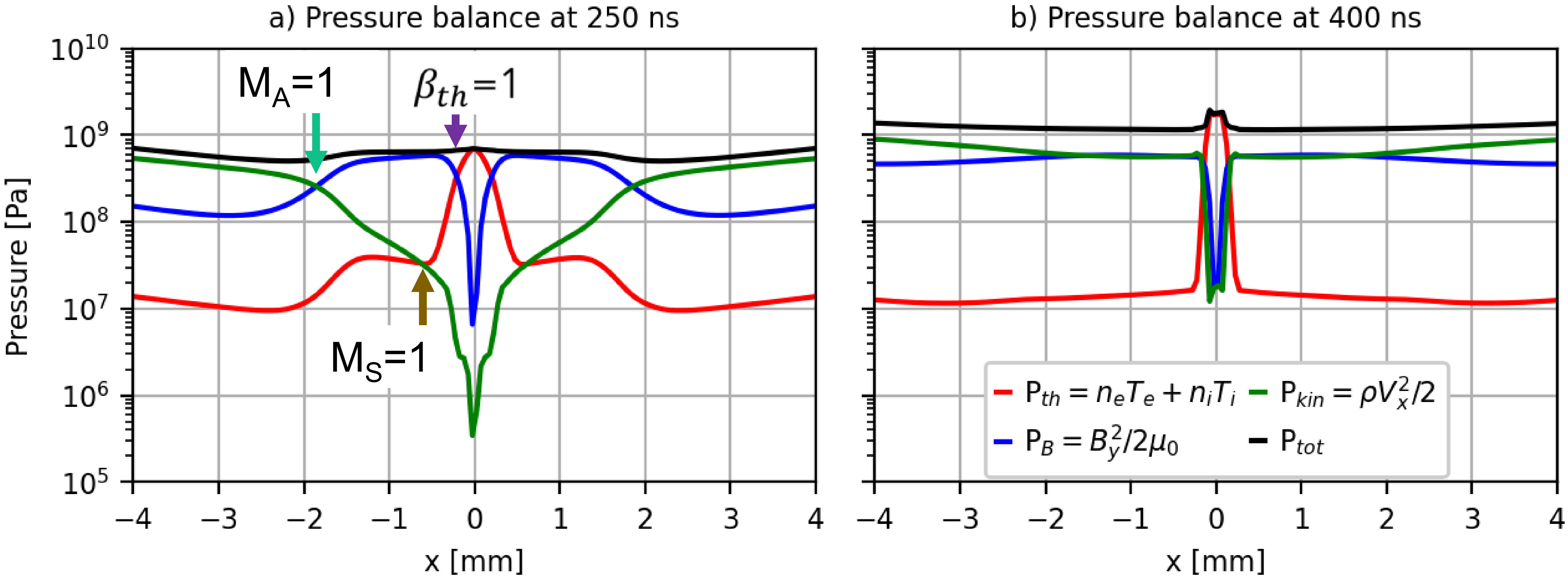
At layer, $P_B = P_{th}$



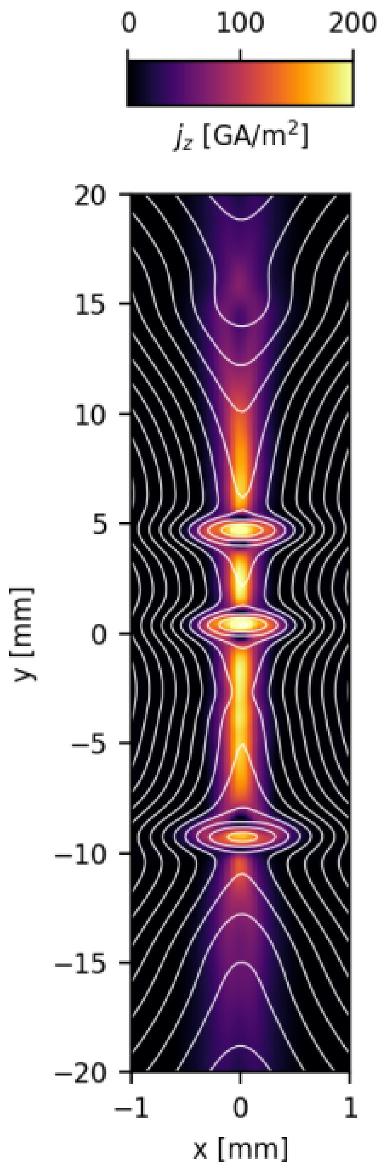
Pressure balance in the layer

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



Plasmoids in the Reconnection Layer

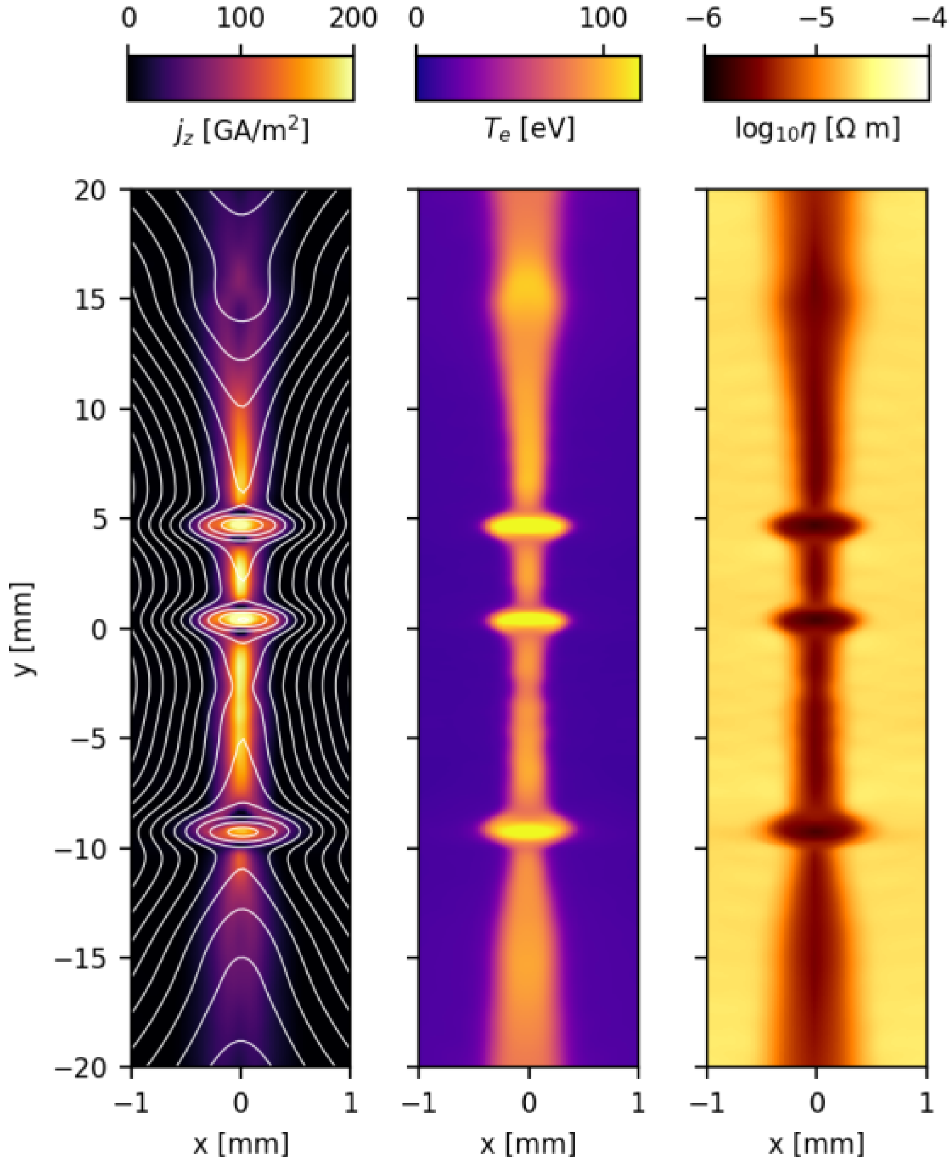


Note: Exaggerated aspect ratio

Plasmoids:

- Carry a lot of current

Plasmoids in the Reconnection Layer

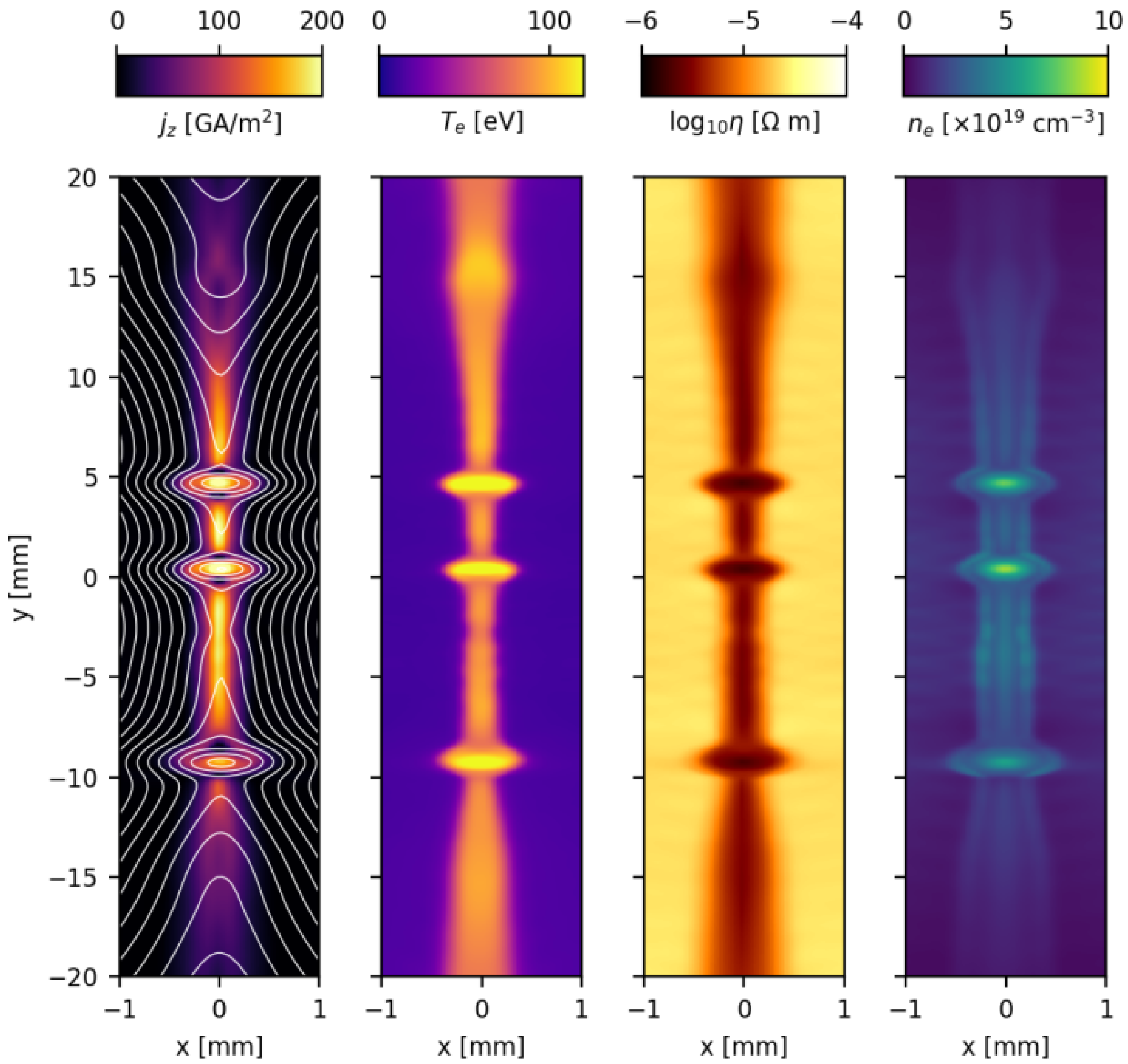


Note: Exaggerated aspect ratio

Plasmoids:

- Carry a lot of current
- Are hot, with low η

Plasmoids in the Reconnection Layer

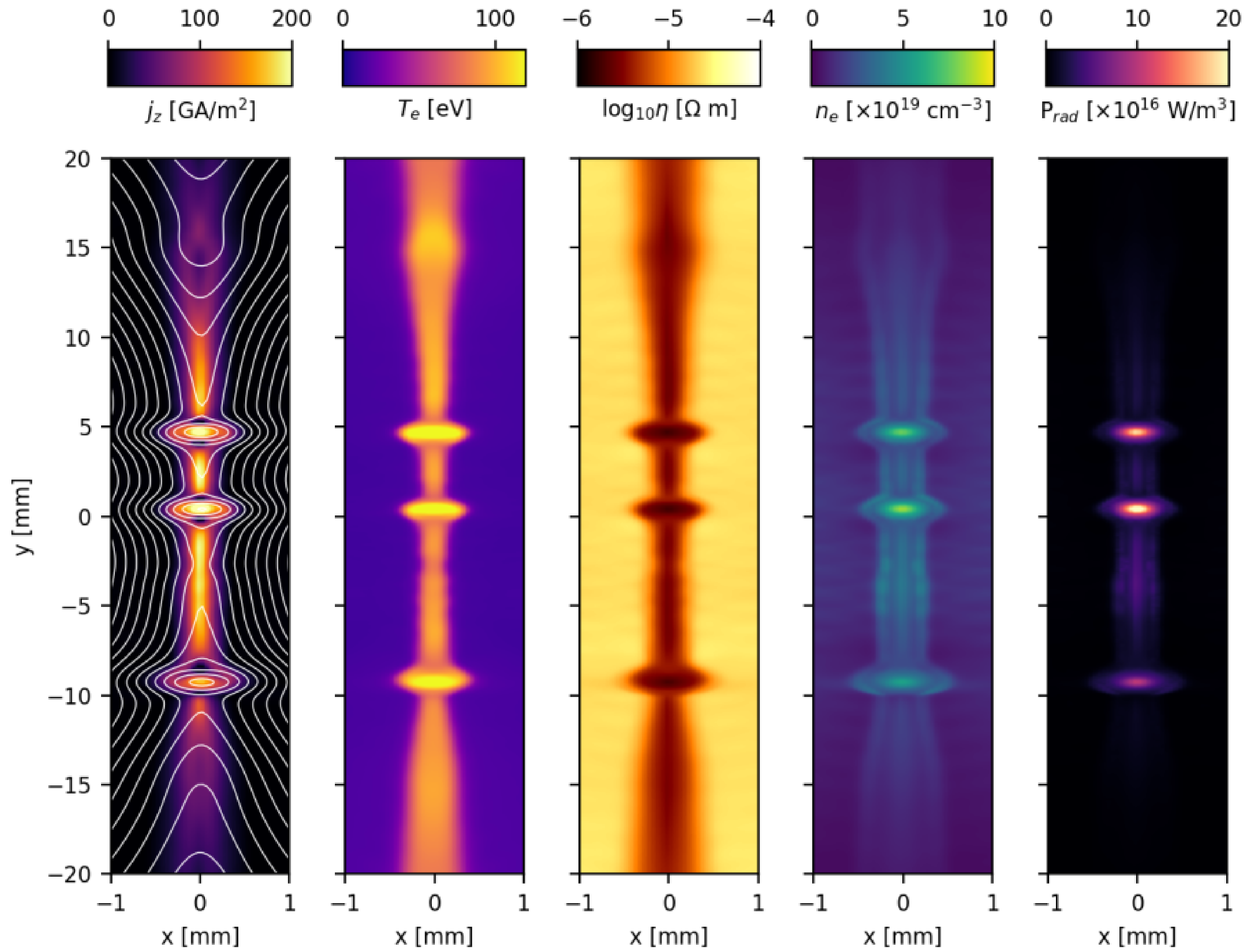


Note: Exaggerated aspect ratio

Plasmoids:

- Carry a lot of current
- Are hot, with low η
- Are dense

Plasmoids in the Reconnection Layer



Note: Exaggerated aspect ratio

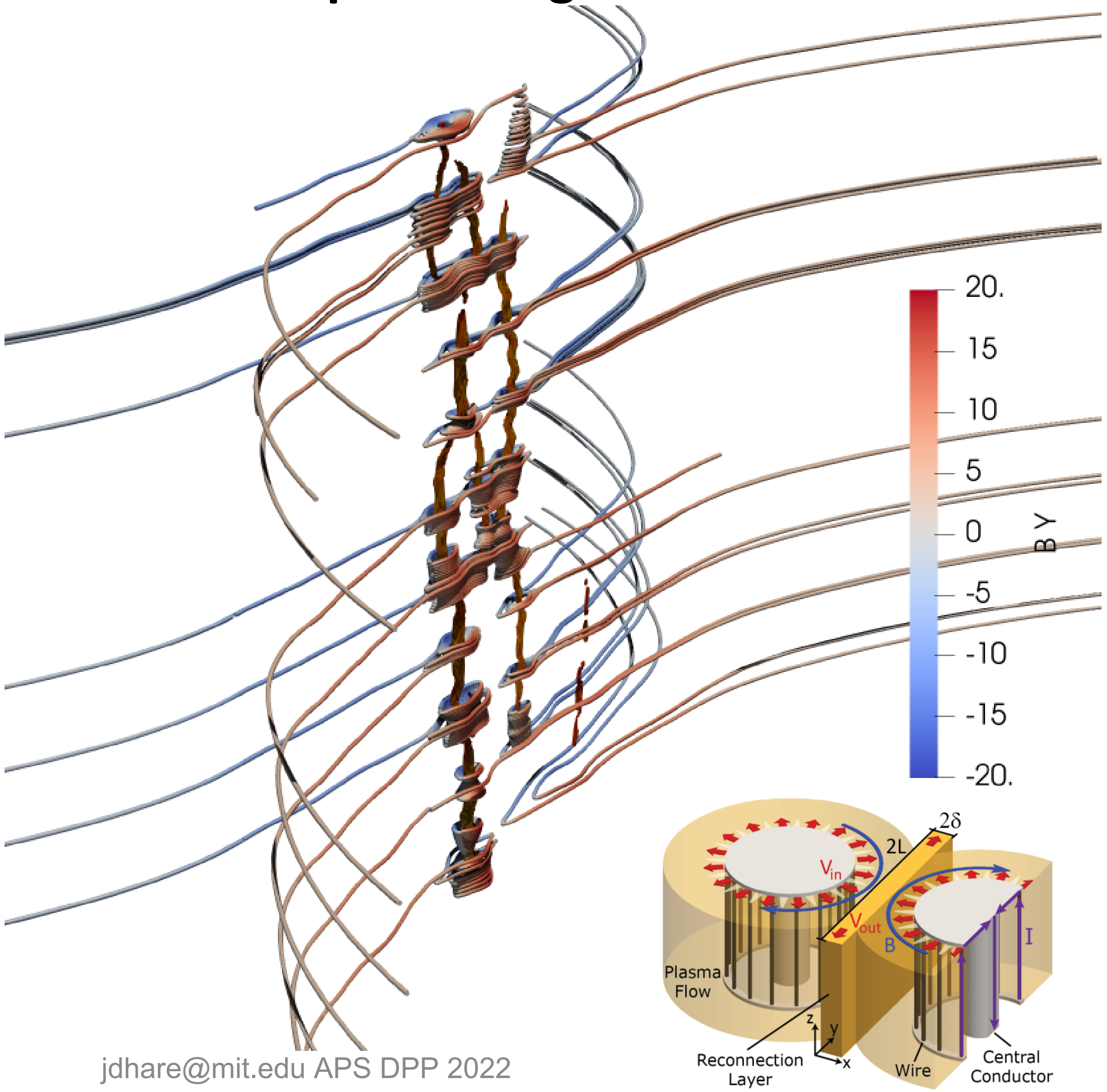
Plasmoids:

- Carry a lot of current
- Are hot, with low η
- Are dense
- Radiate strongly

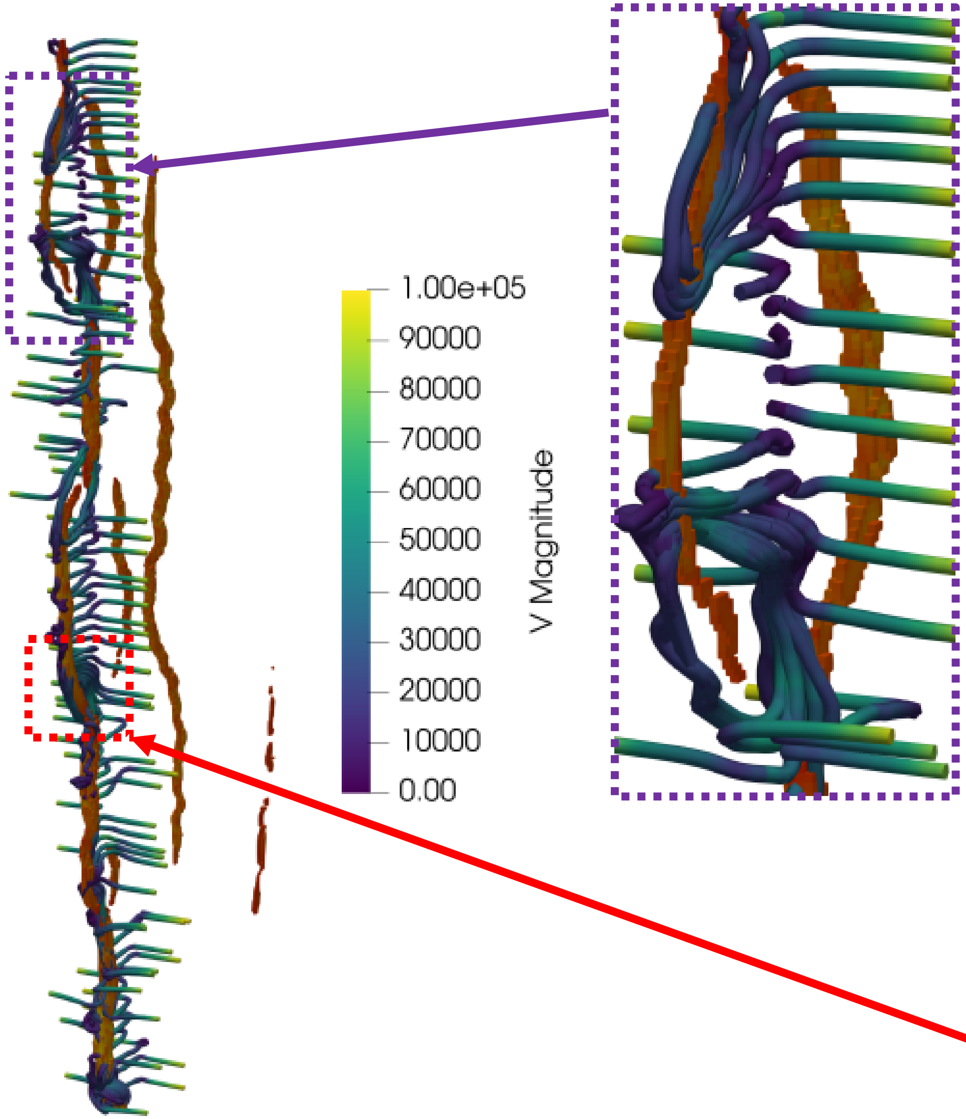
3D GORGON simulations: kinking plasmoids

Plasmoids **kink**…and generate **out-of-plane magnetic fields**

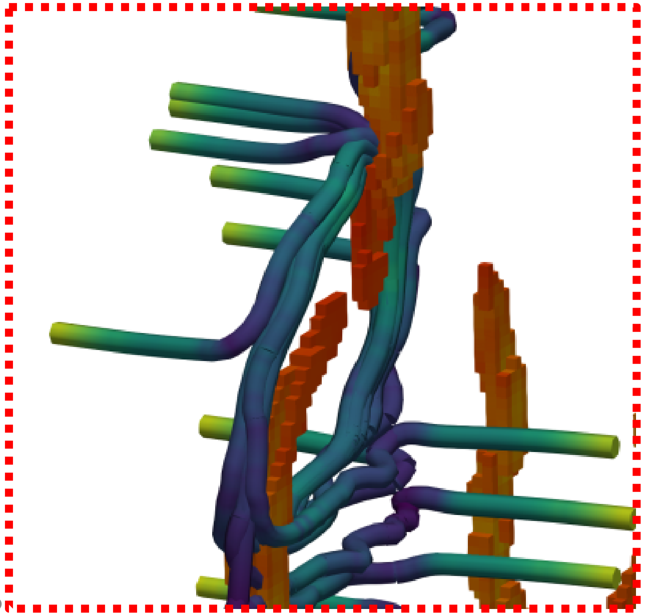
Surfaces of high current



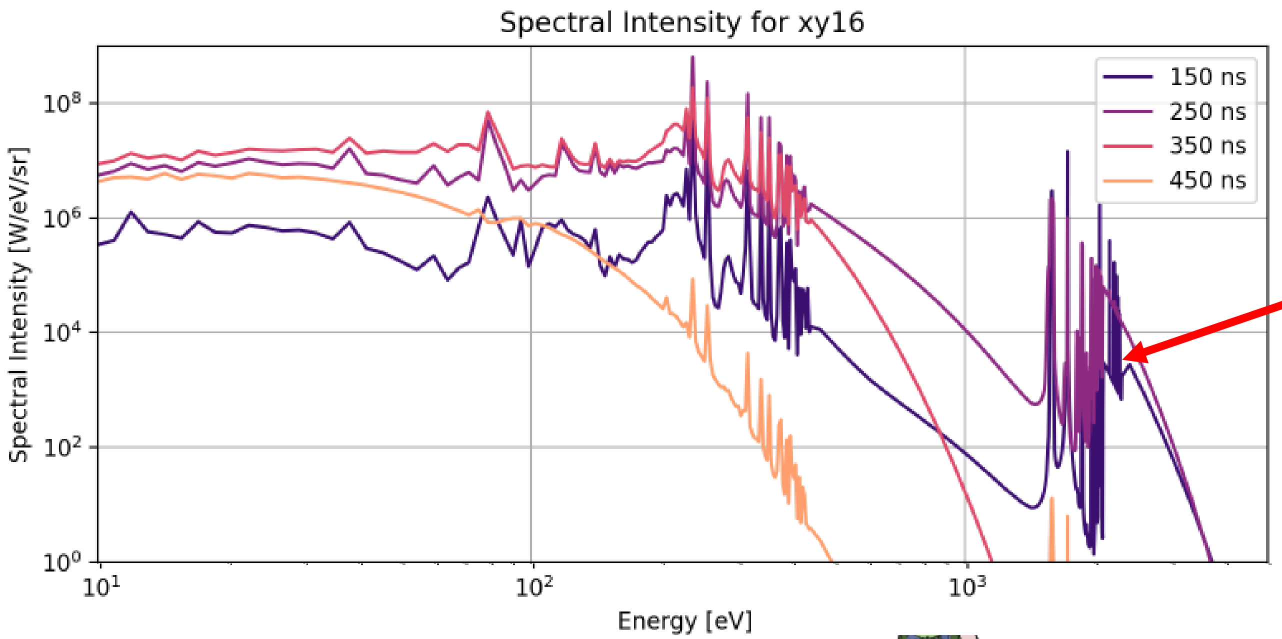
Kink instability generates out-of-plane velocity



Kink instability generates vertical flows: potential spectroscopic signature

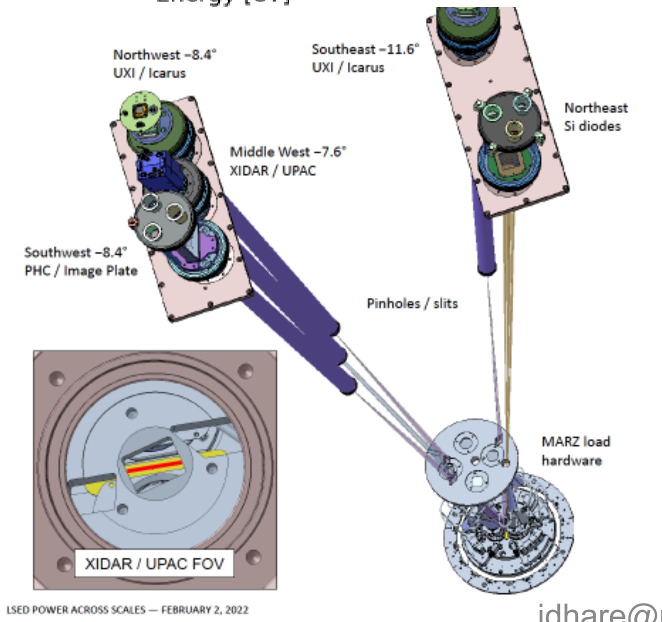


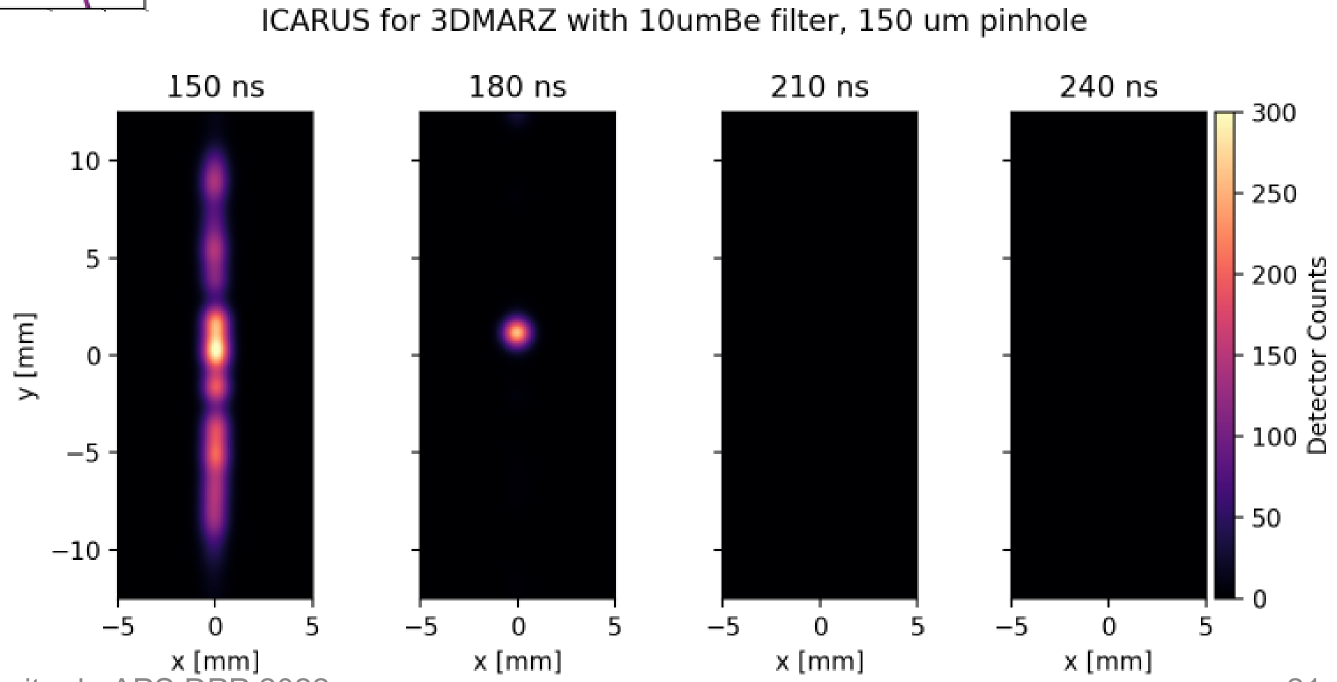
XP2: X-ray Post-Processor by Aidan Crilly & Jerry Chittenden



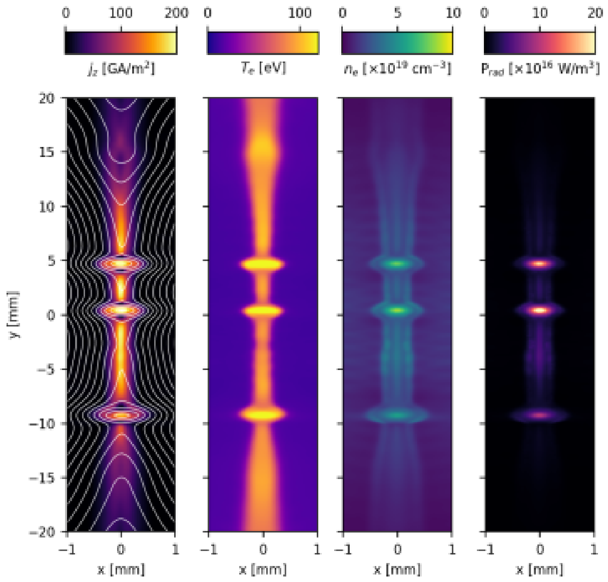
Al K-shell disappears after collapse

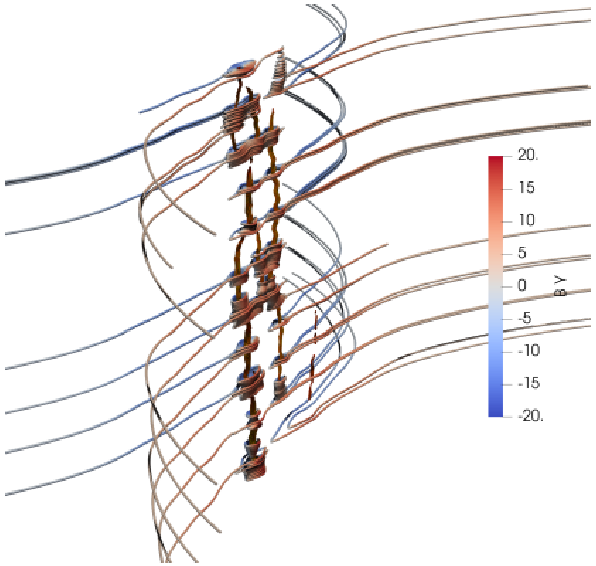
XP2:predictive capability for **X-ray diagnostics**

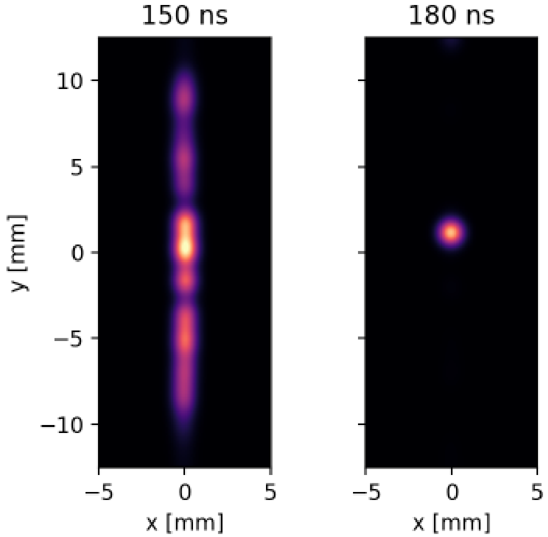




Conclusions







- Radiatively cooled magnetic reconnection is relevant to extreme astrophysical environments
- 2D (and 3D) simulations show hot, dense, strongly radiating plasmoids
- In 3D, plasmoids are kink unstable, generating out-of-plane fields and flows
- Using XP2, we can post-process simulation data to model synthetic diagnostics