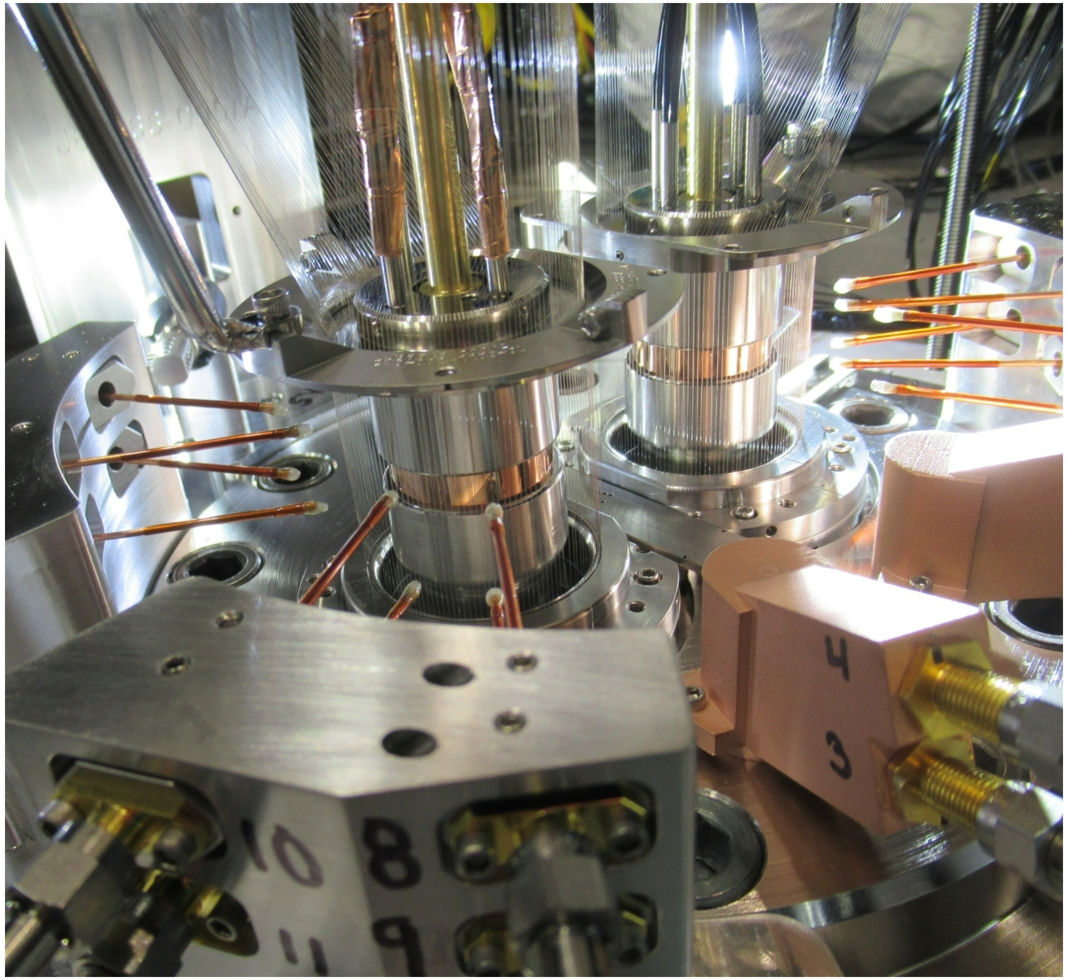
SAND2022-6698C

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



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MIT | PSFC Plasma Science and Fusion Center

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MARZ Collaboration

MIT	Jack Hare (Academic PI) and Rishabh Datta
Imperial College	Sergey Lebedev, Jerry Chittenden, Simon Bland, Aidan Crilly, Jack Halliday, 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	Clayton Myers (Sandia PI), 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 others

Imperial College London

Sandia National Laboratories

PRINCETON UNIVERSITY

UNIVERSITY OF MICHIGAN

PPPL PRINCETON PLASMA PHYSICS LABORATORY

University of Colorado Boulder

MIT PSFC Plasma Science and Fusion Center

NSF

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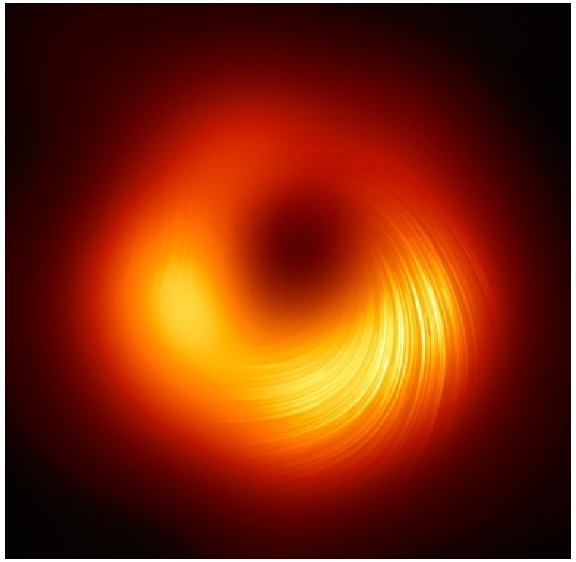
Reconnection in Extreme Astrophysical Environments

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)

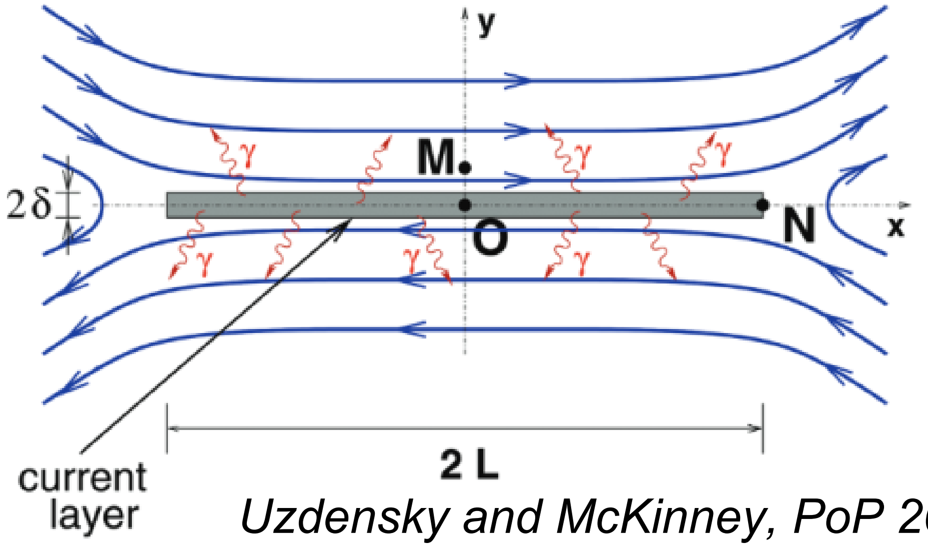
1. Cooling is a significant loss mechanism ($\tau_{cool} \ll \tau_A$):
   - Modifies partition of magnetic energy between electrons, ions, kinetic
   - Leads to cooling instabilities, radiative collapse

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

Radiatively Cooled Reconnection in the Laboratory

Uzdensky-McKinney model:

- Sweet-Parker with $\nabla . \boldsymbol{u} = 0$ replaced by
$$\eta j^2 = P_{rad}$$
- Radiative collapse for Bremsstrahlung emission



Uzdensky and McKinney, PoP 2011

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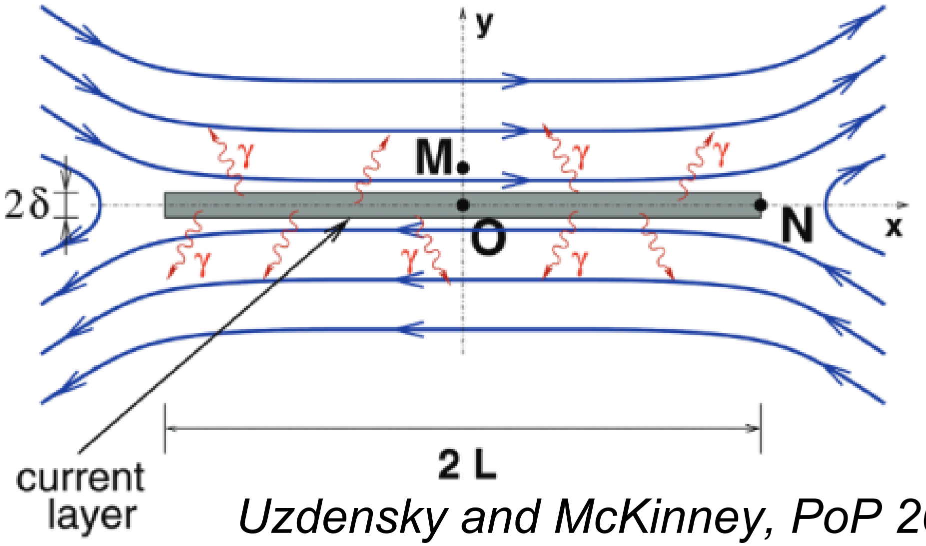
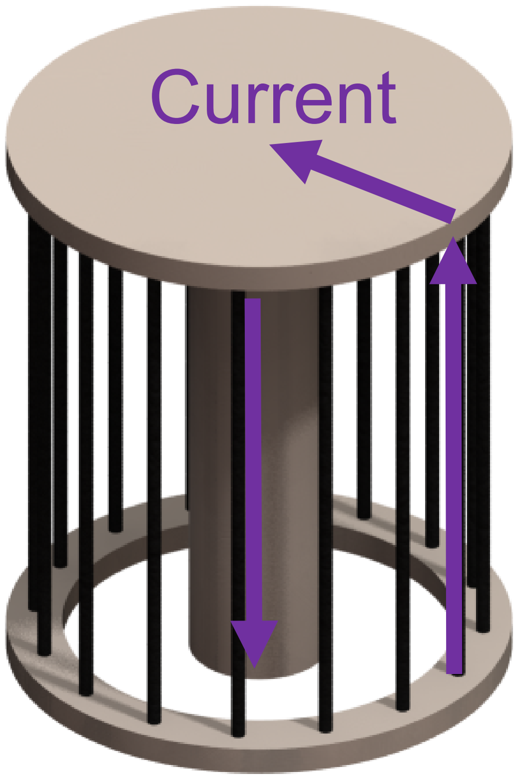


Uzdensky and McKinney, PoP 2011

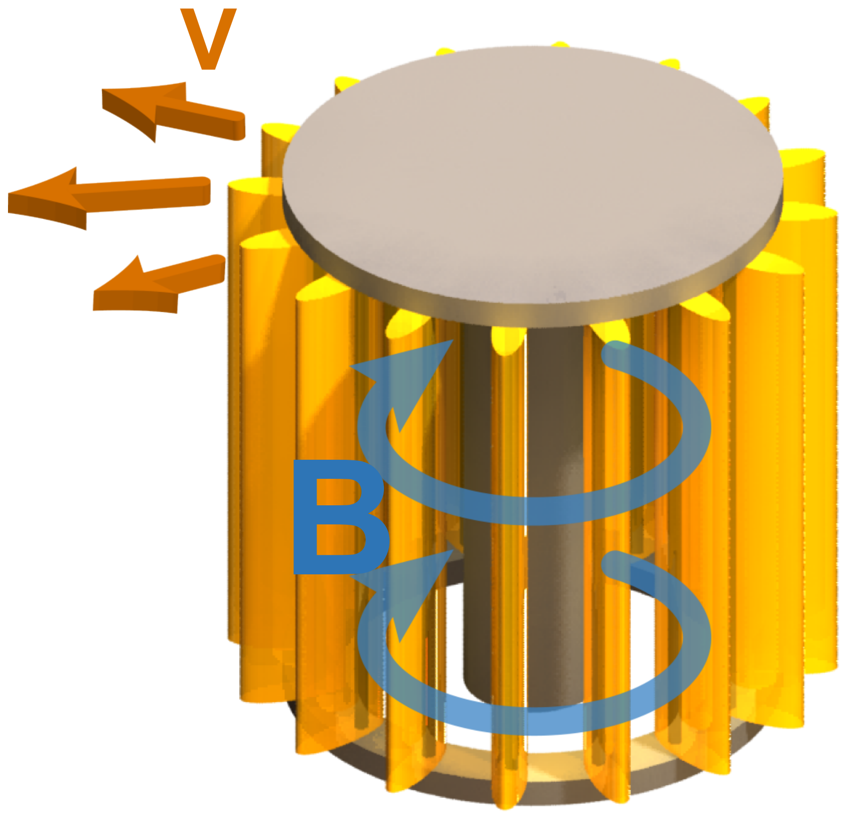
- Experiments require:
  - High density to radiate strongly
  - Plenty of magnetic energy to dissipate
  - Sufficient time-scales to see dynamics
- Synchrotron → Bremsstrahlung + Line radiation
  - Modify cooling rate through material choice
  - No radiation reaction, cooling only

High-energy-density experiments: Lasers and pulsed-power

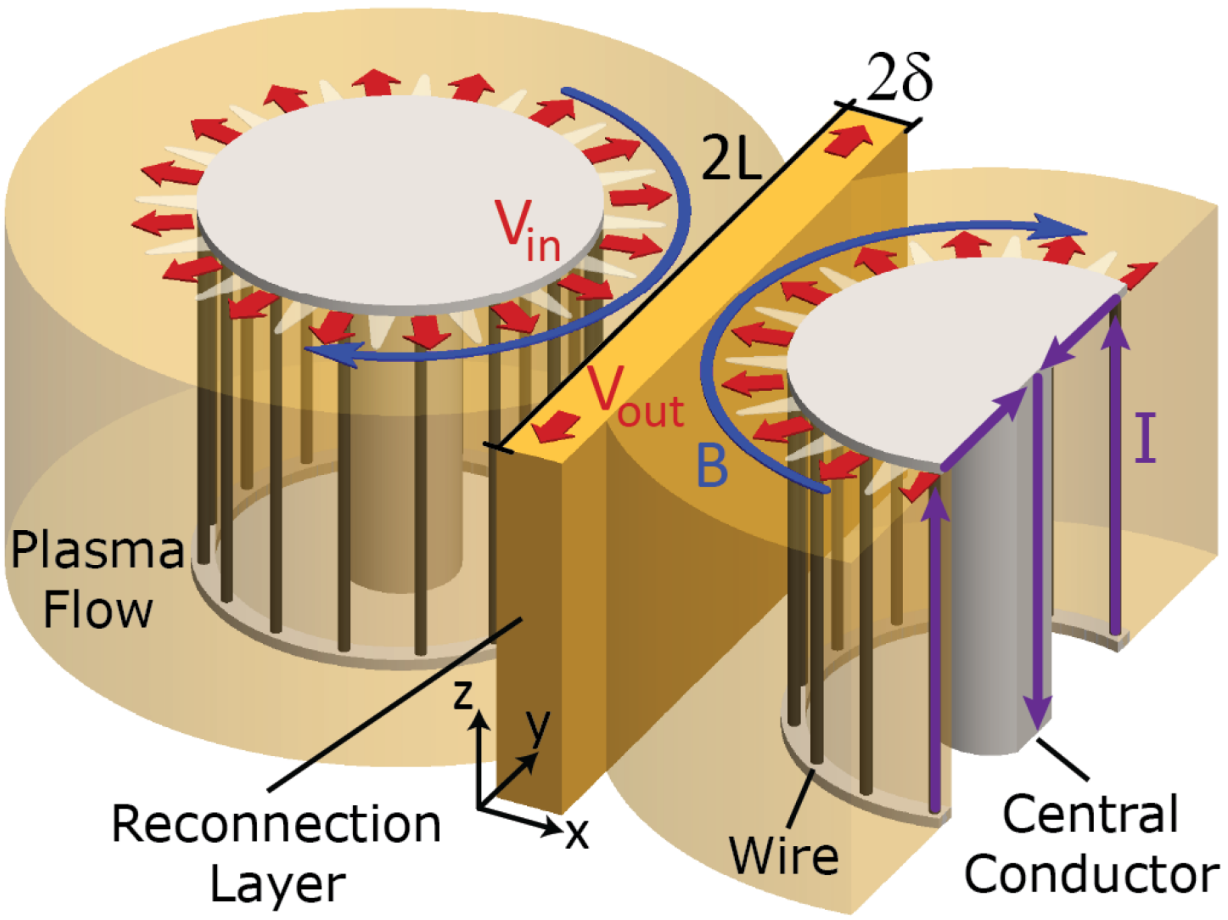
Pulsed-power-driven Magnetic Reconnection



I=1 to 10 MA,
100 to 300 ns rise time



Magnetic Reconnection from Double Exploding Wire Arrays

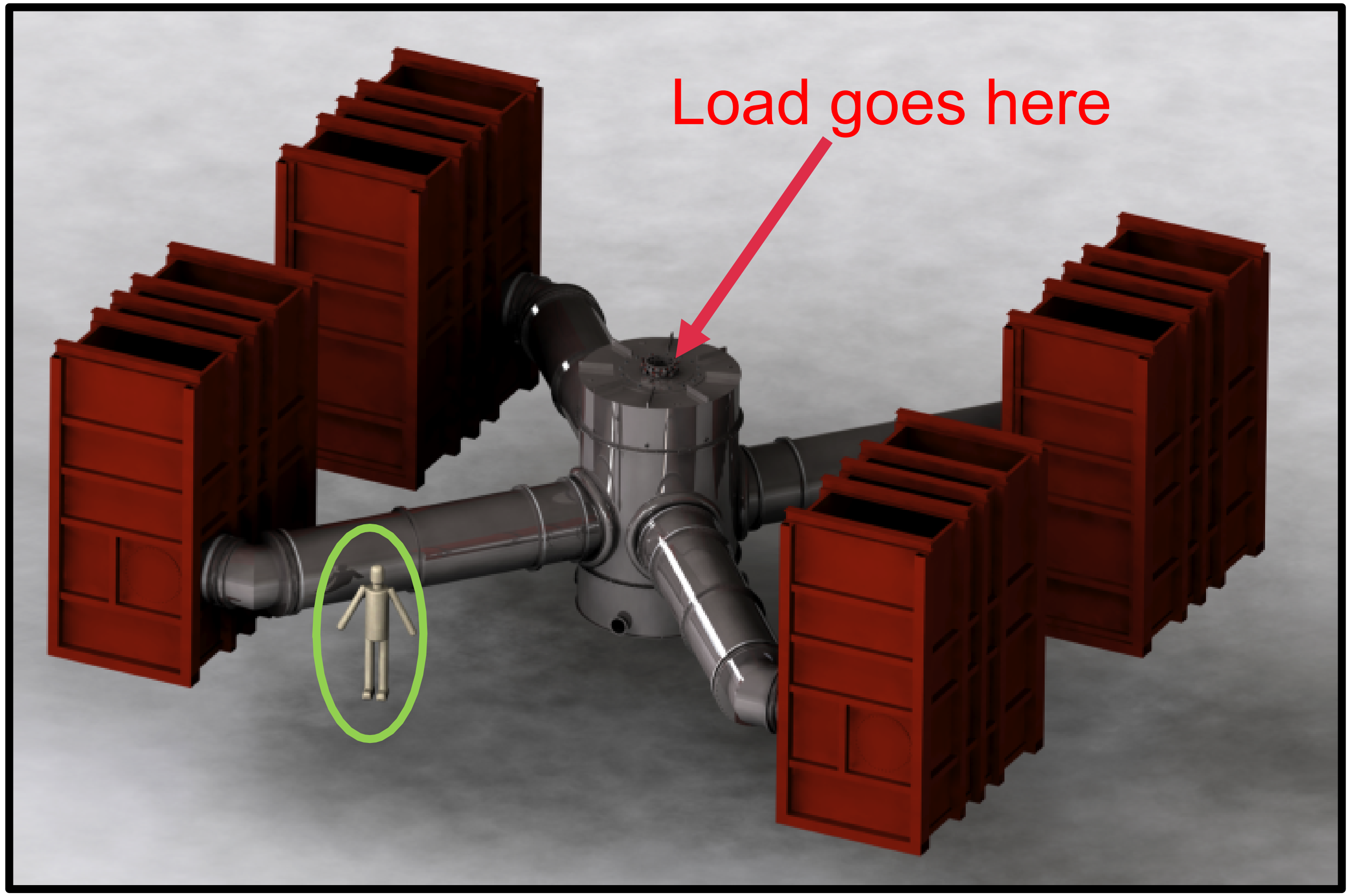


Exploding wire arrays in parallel:

- 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
  (but see Thomas Varnish's poster)

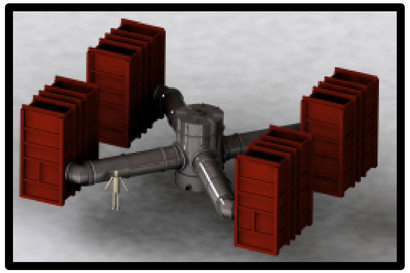
Hare *et al* PRL 2017, PoP 2017, 2018

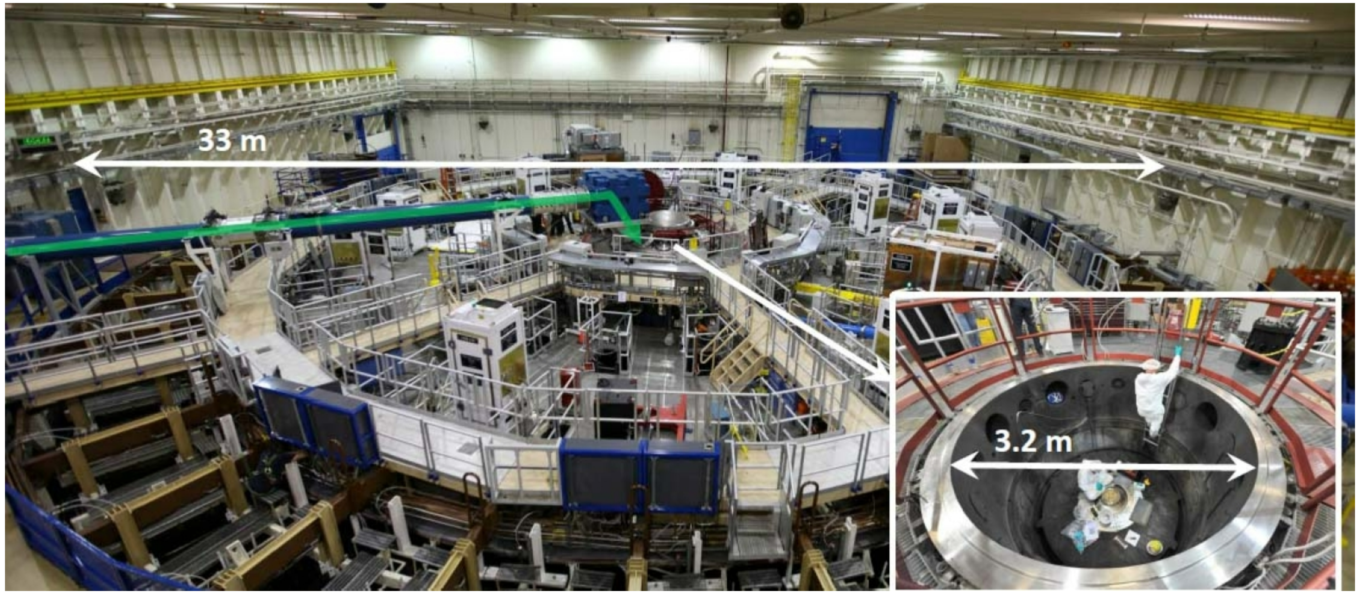
Magnetic Reconnection from Double Exploding Wire Arrays



MAGPIE: 1.4 MA, 250 ns rise time

Magnetic Reconnection from Double Exploding Wire Arrays





MAGPIE: 1.4 MA, 250 ns rise time

Z Machine: 20 MA, 300 ns rise time

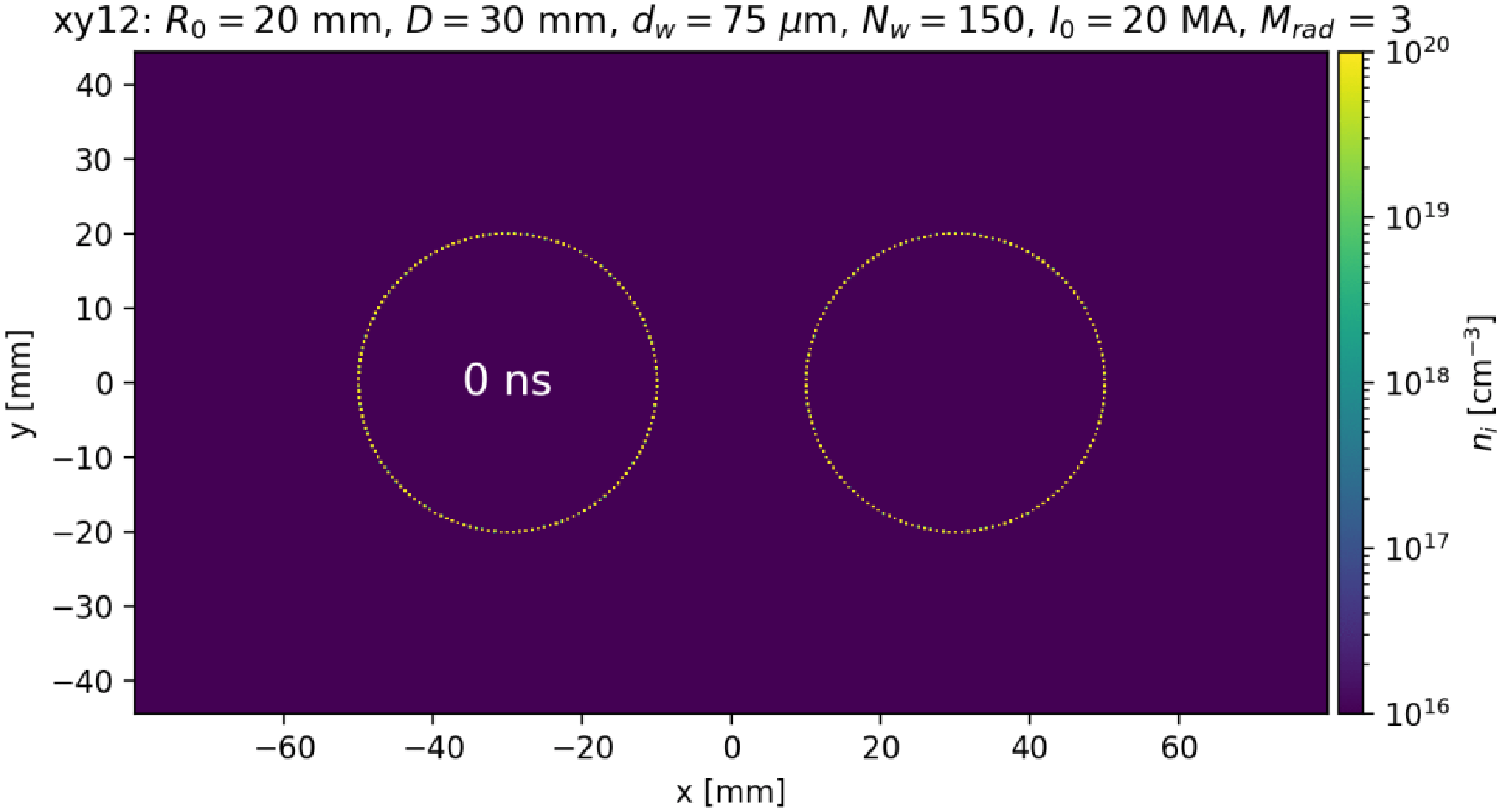
$$n \propto I^2, P_{rad} \propto n^2 \propto I^4$$

Z's unique capability: strongly radiatively cooled reconnection

GORGON MHD simulations

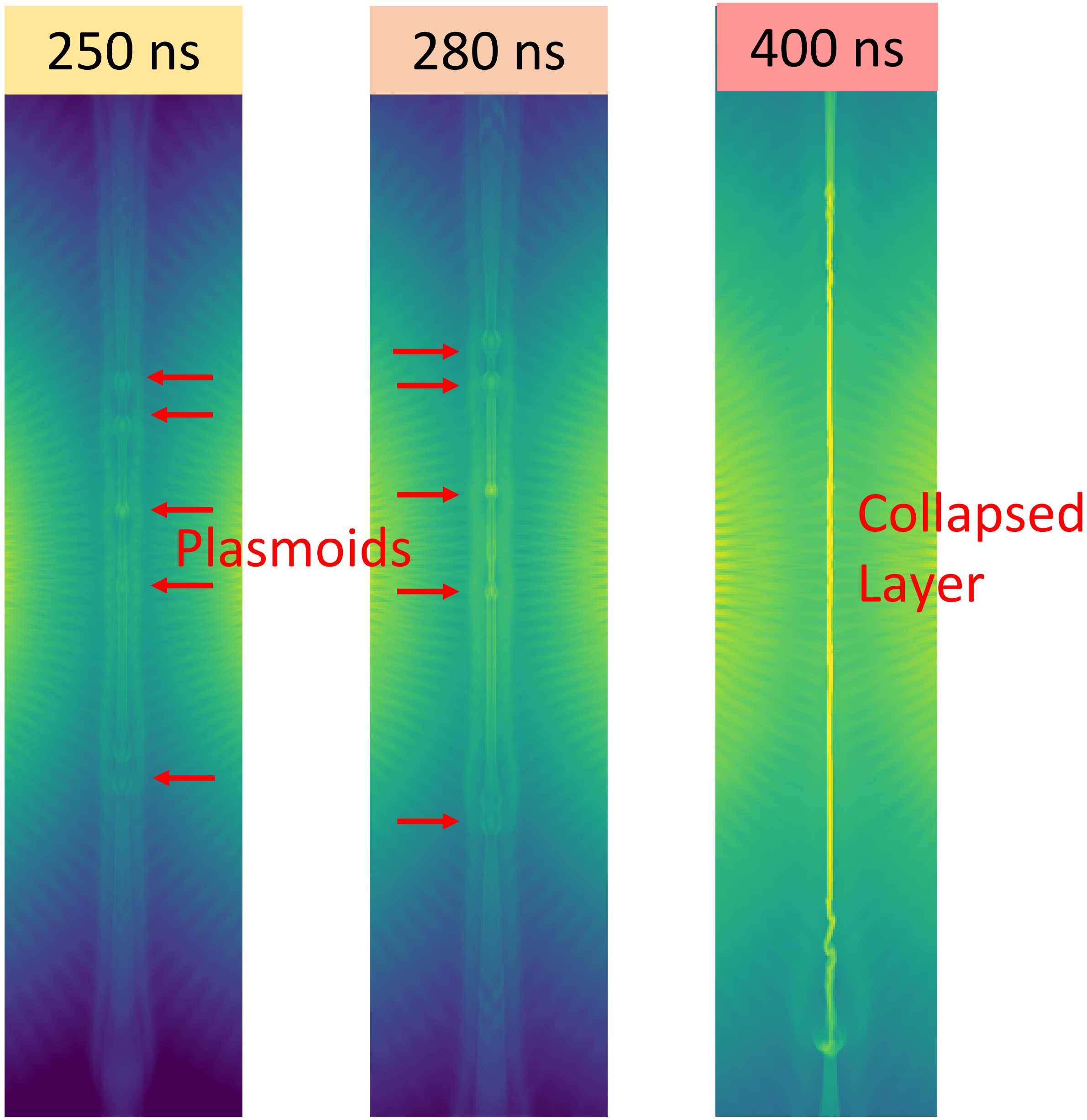
GORGON (J. Chittenden, Imperial) : 3D Eulerian resistive MHD code with radiation loss and separate ion and electron energy equations

2D sims:
50 μm resolution
180x90 mm
16 hrs, 256 cores

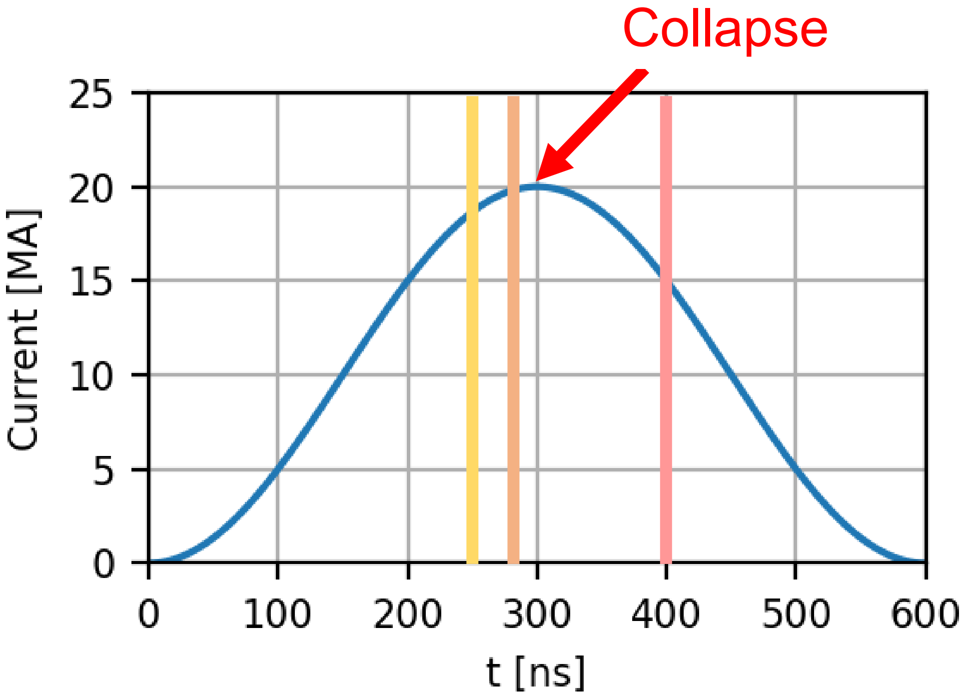


- Recombination loss: $P_{rad} = M_{rad} C_r n_e T_e^{1/2} (Z^2 n_i E_\infty^{Z-1} / T_e)$, with $M_{rad} \approx 3$
- More complex loss models possible!

Plasmoids and Collapse



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



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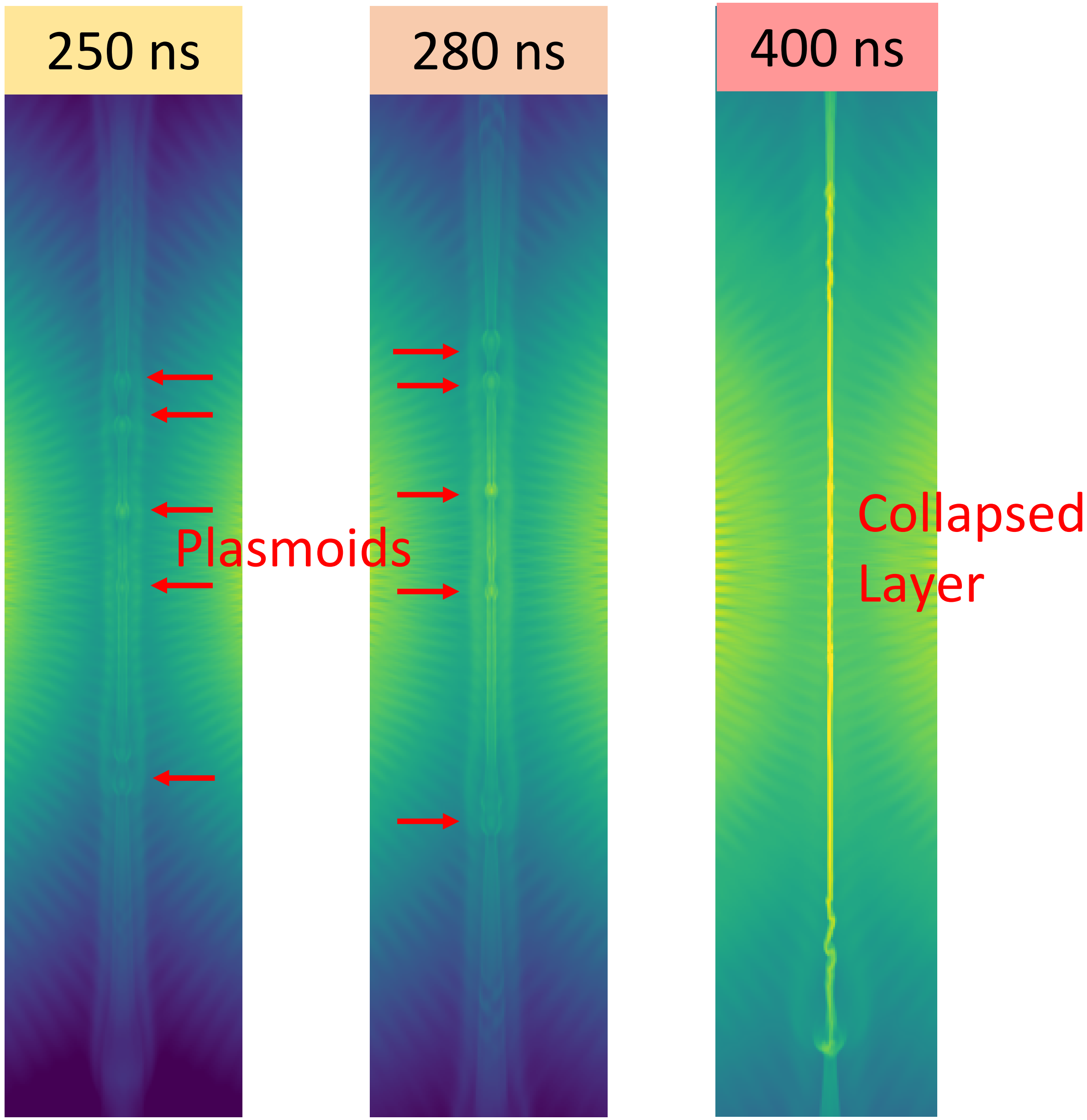

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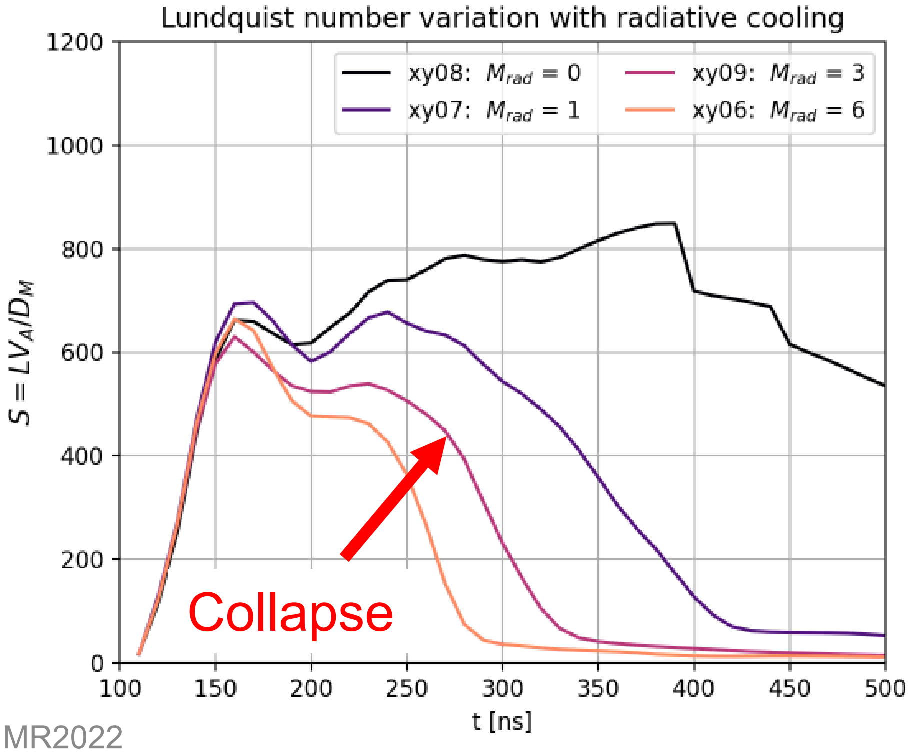
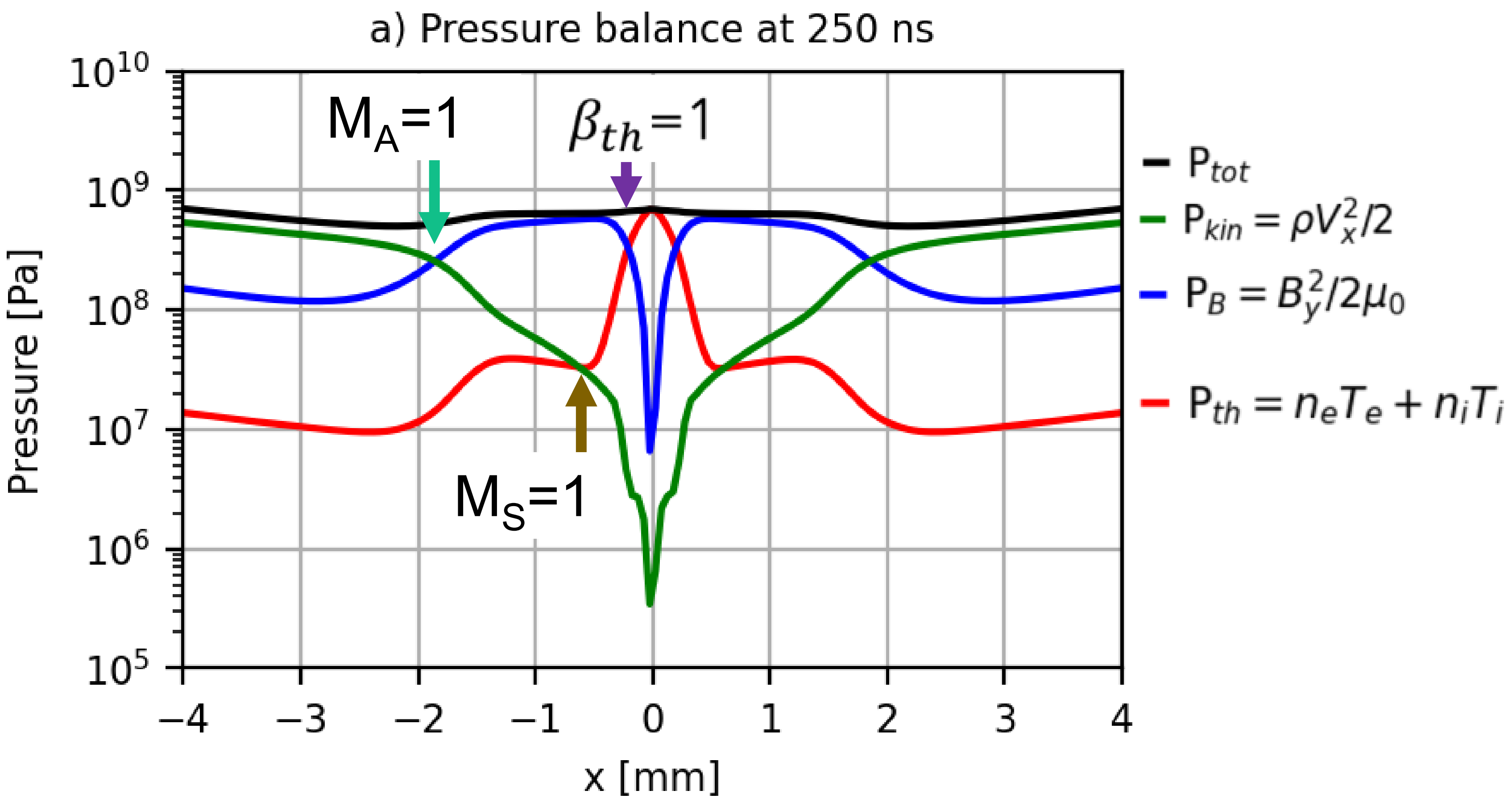


Pressure balance in the layer

Pre-collapse: flux pile-up decelerates flow

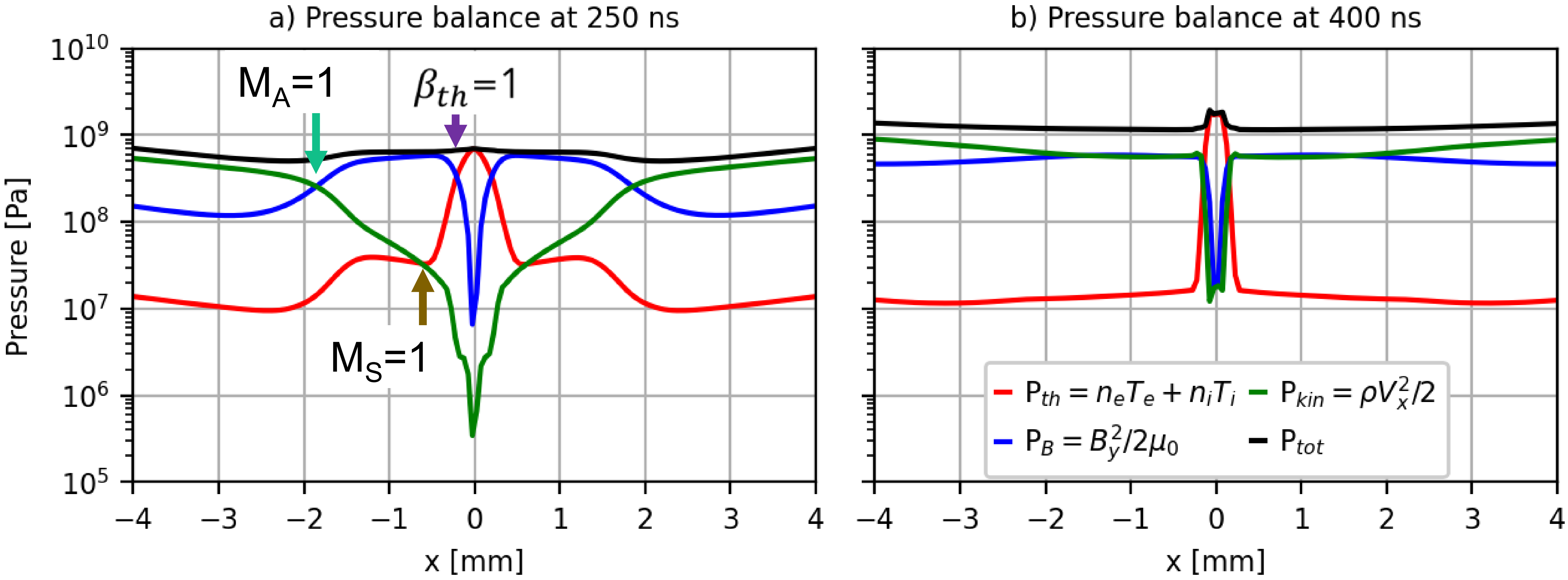
Fox PRL 2011, Suttle PRL 2016



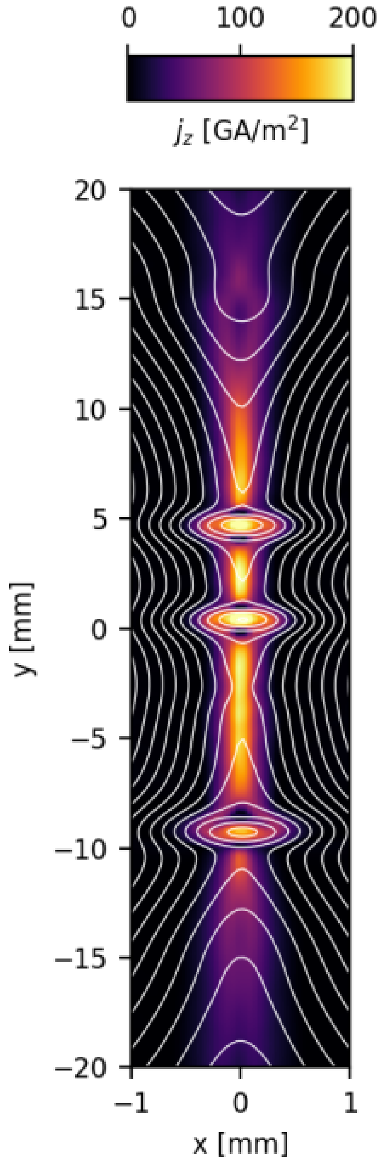
Pressure balance in the layer

Pre-collapse: flux pile-up decelerates flow
Fox PRL 2011, Suttle PRL 2016

Post-collapse: fast reconnection removes flux pile-up



Plasmoids in the Reconnection Layer

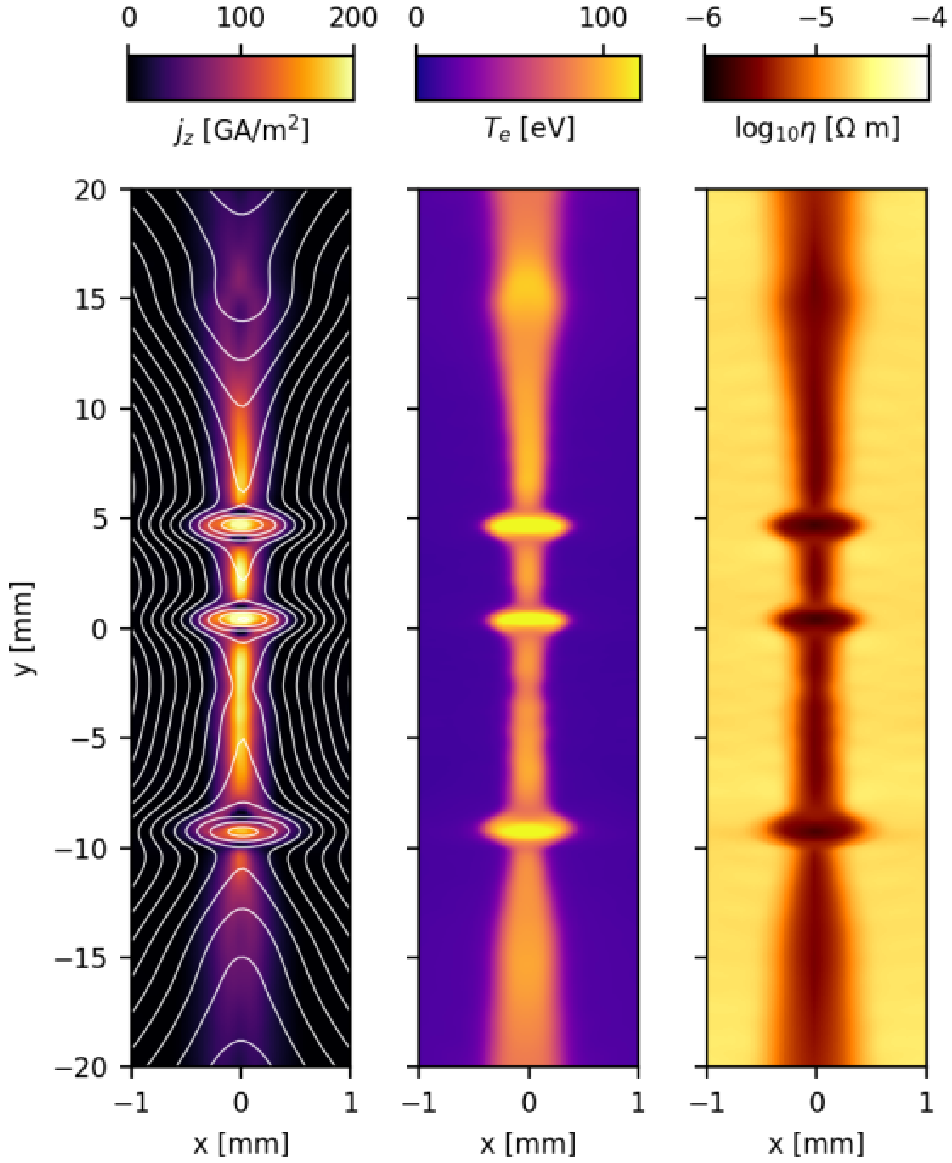


Note: Exaggerated aspect ratio

Plasmoids:

- Carry a lot of current

Plasmoids in the Reconnection Layer

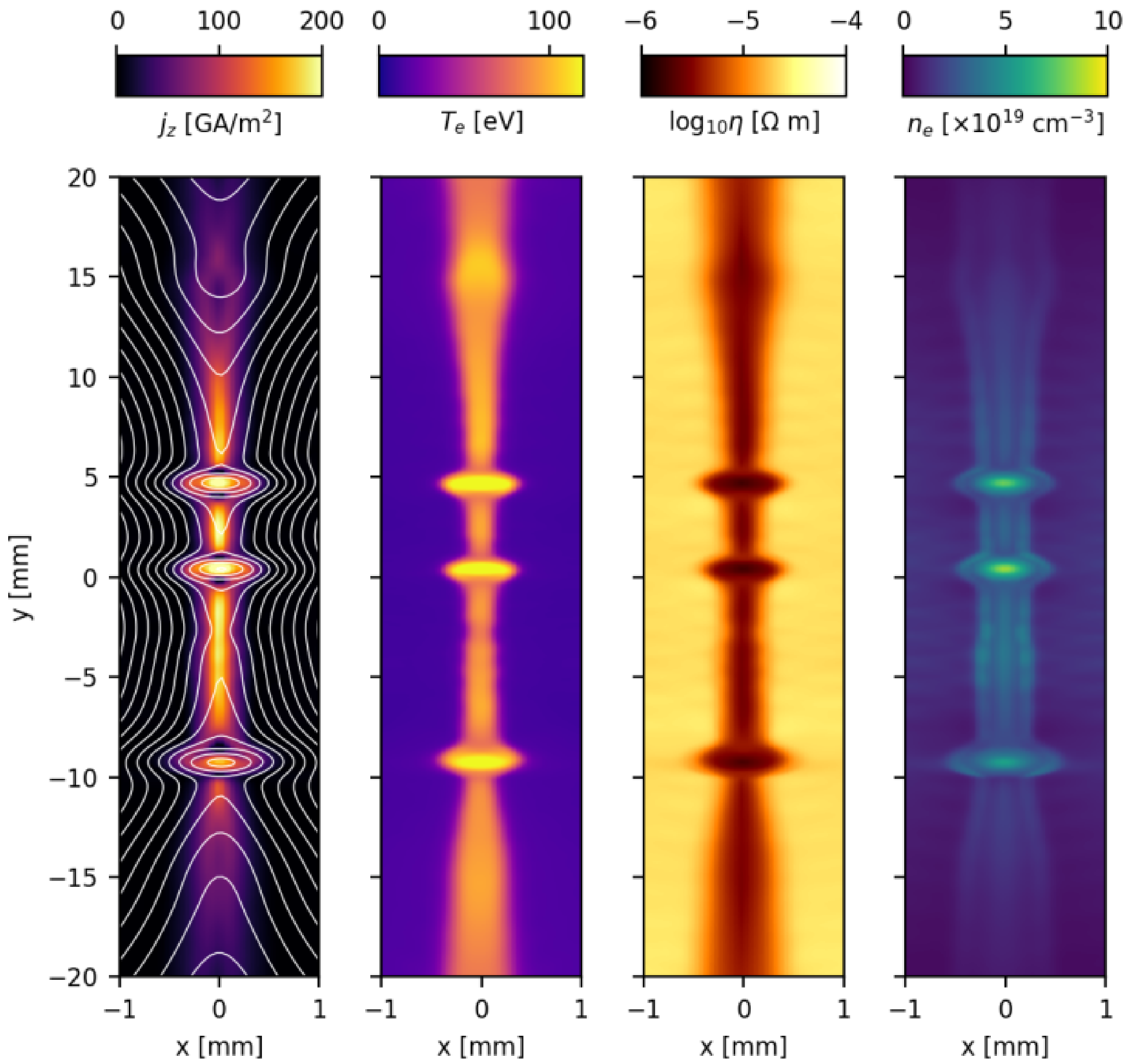


Note: Exaggerated aspect ratio

Plasmoids:

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

Plasmoids in the Reconnection Layer

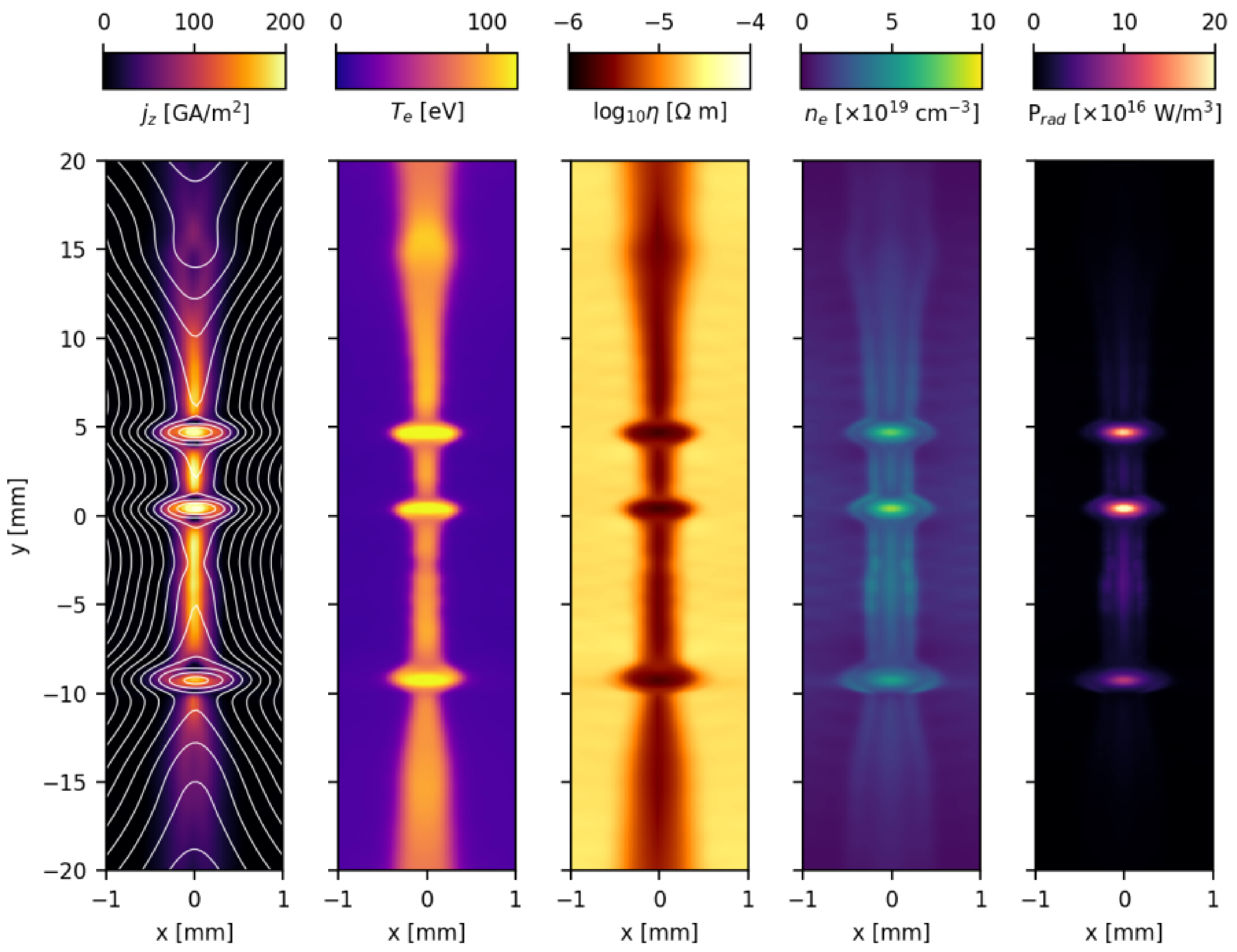


Note: Exaggerated aspect ratio

Plasmoids:

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

Plasmoids in the Reconnection Layer



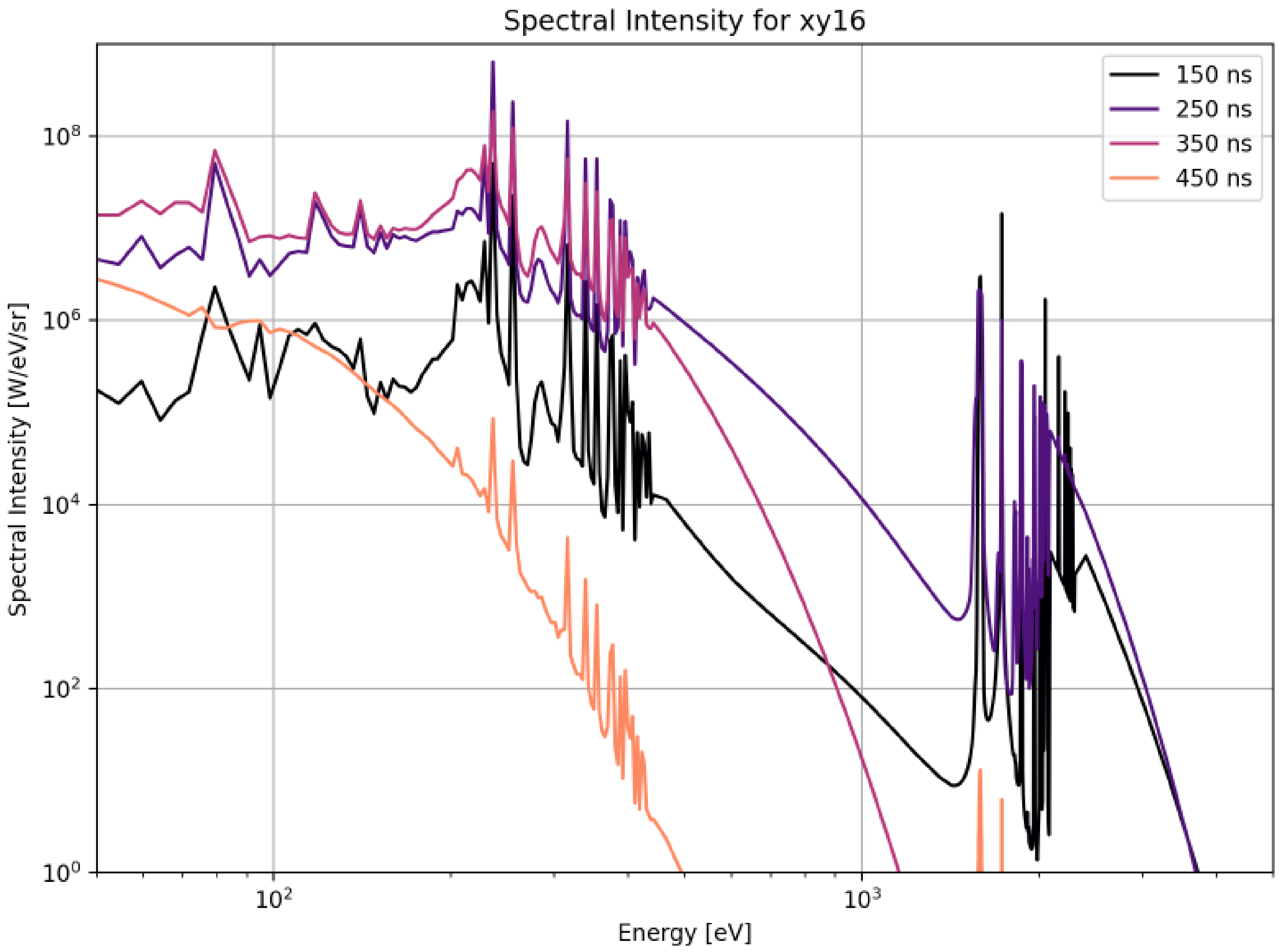
Note: Exaggerated aspect ratio

Plasmoids:

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

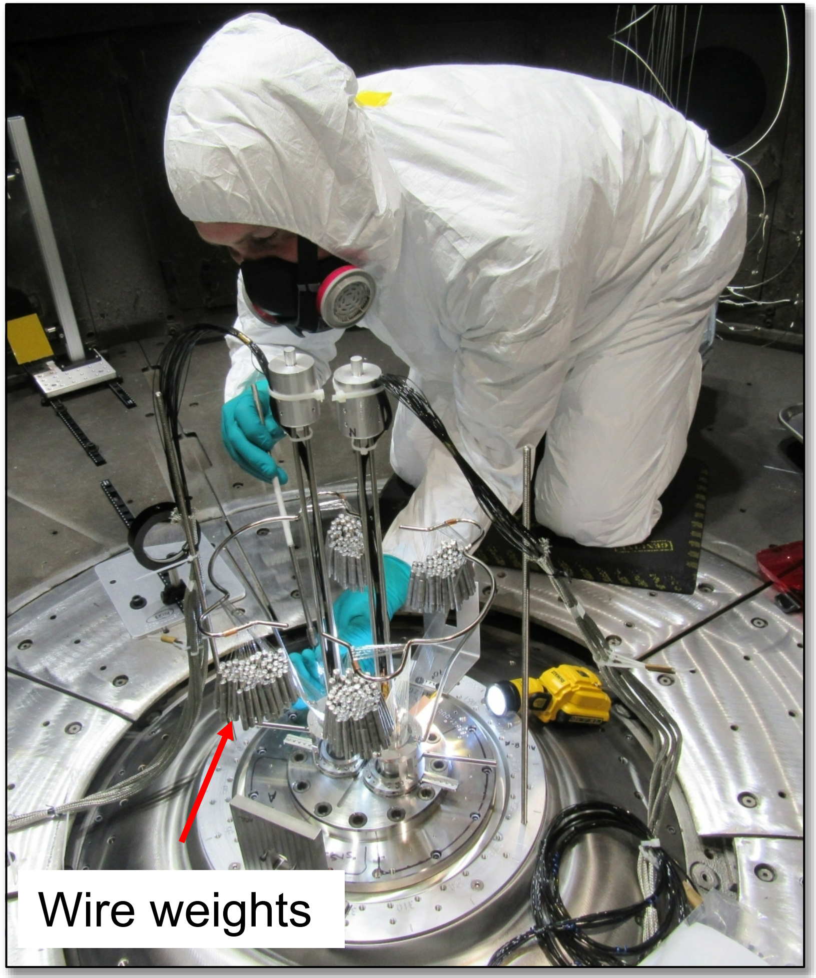
Post Processing to Determine Spectral Intensity

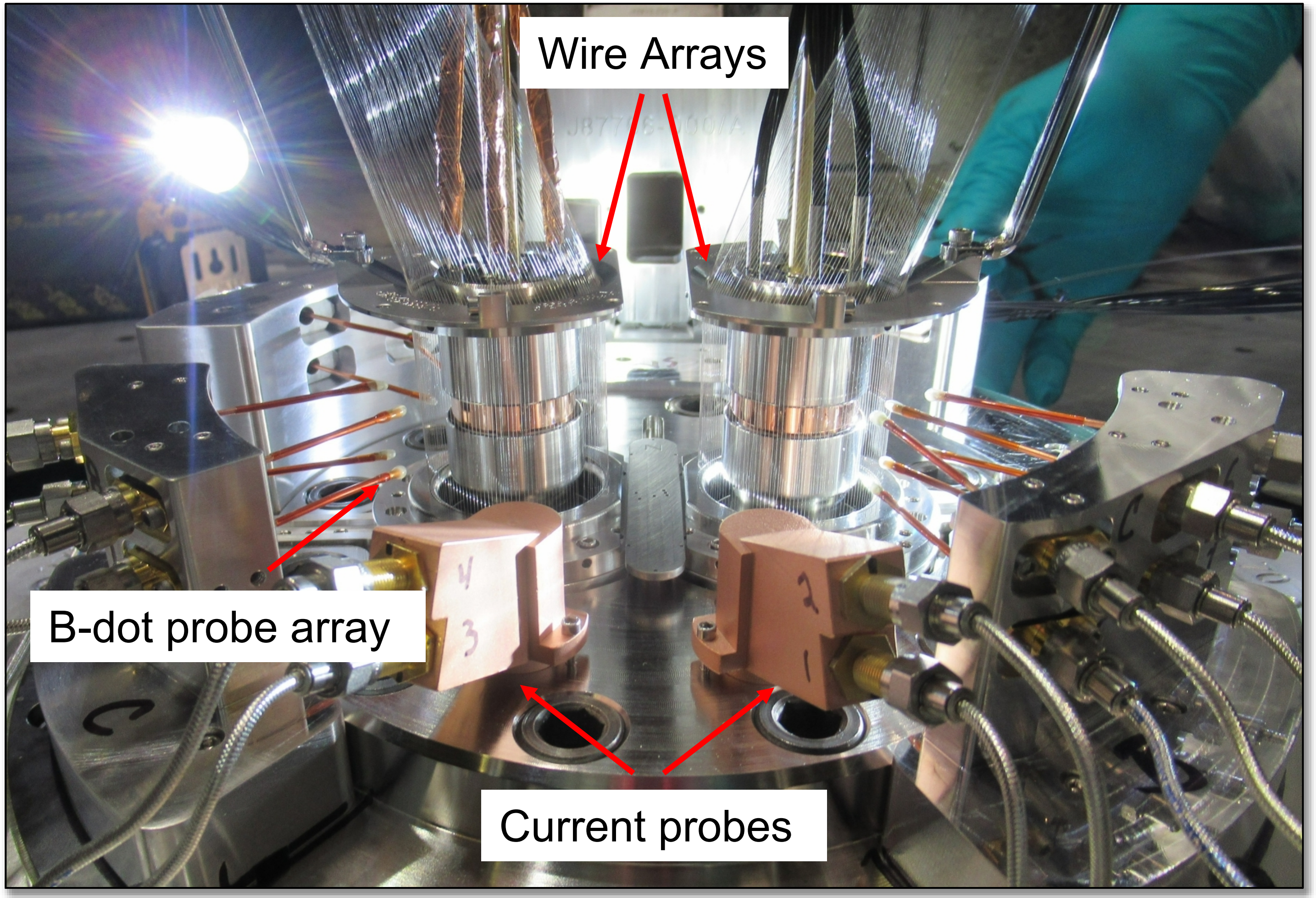
Using the XP2 code from Aidan Crilly and Jerry Chittenden



Experimental Hardware from First Shot on April 21st

Weeks to build, a microsecond to destroy!

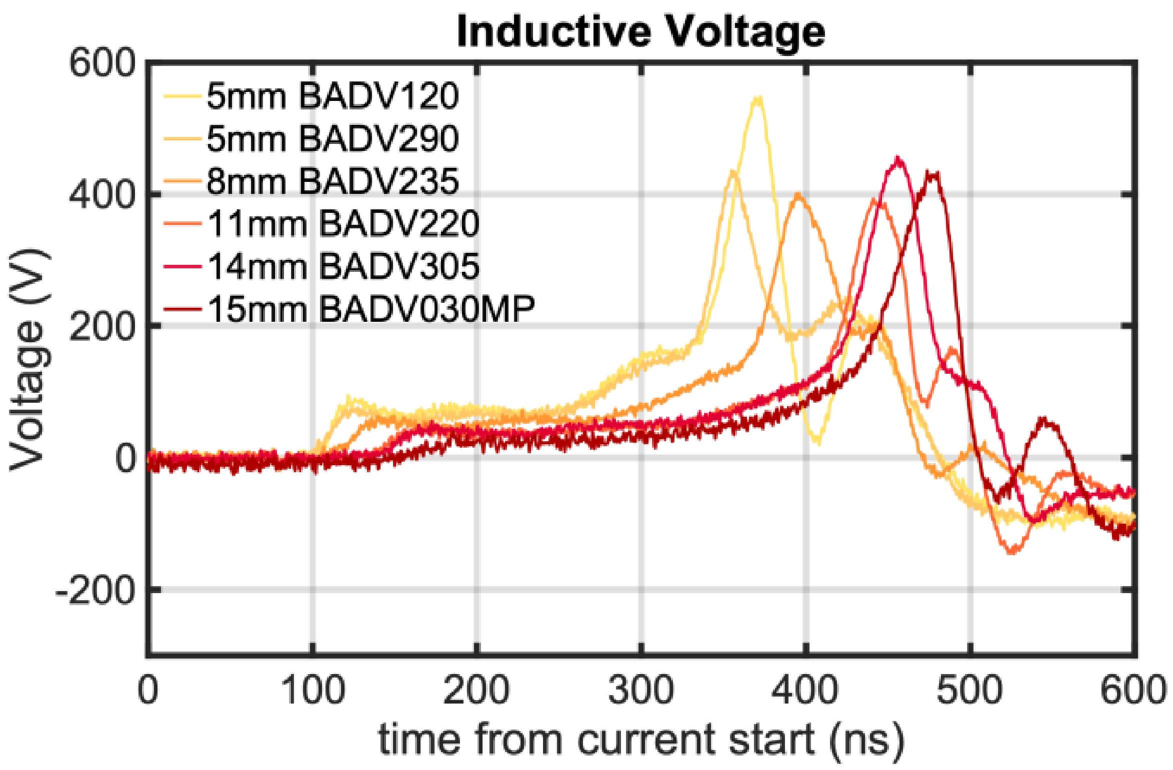


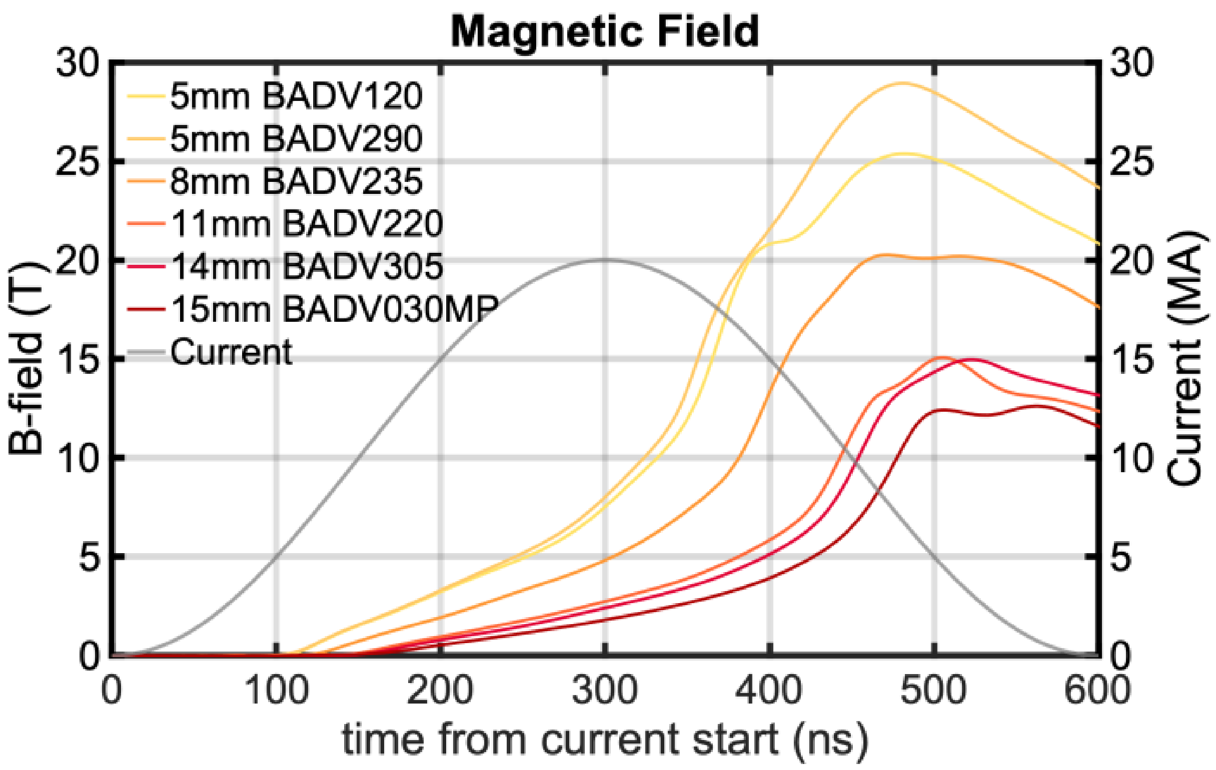


Many diagnostics, can only present an overview

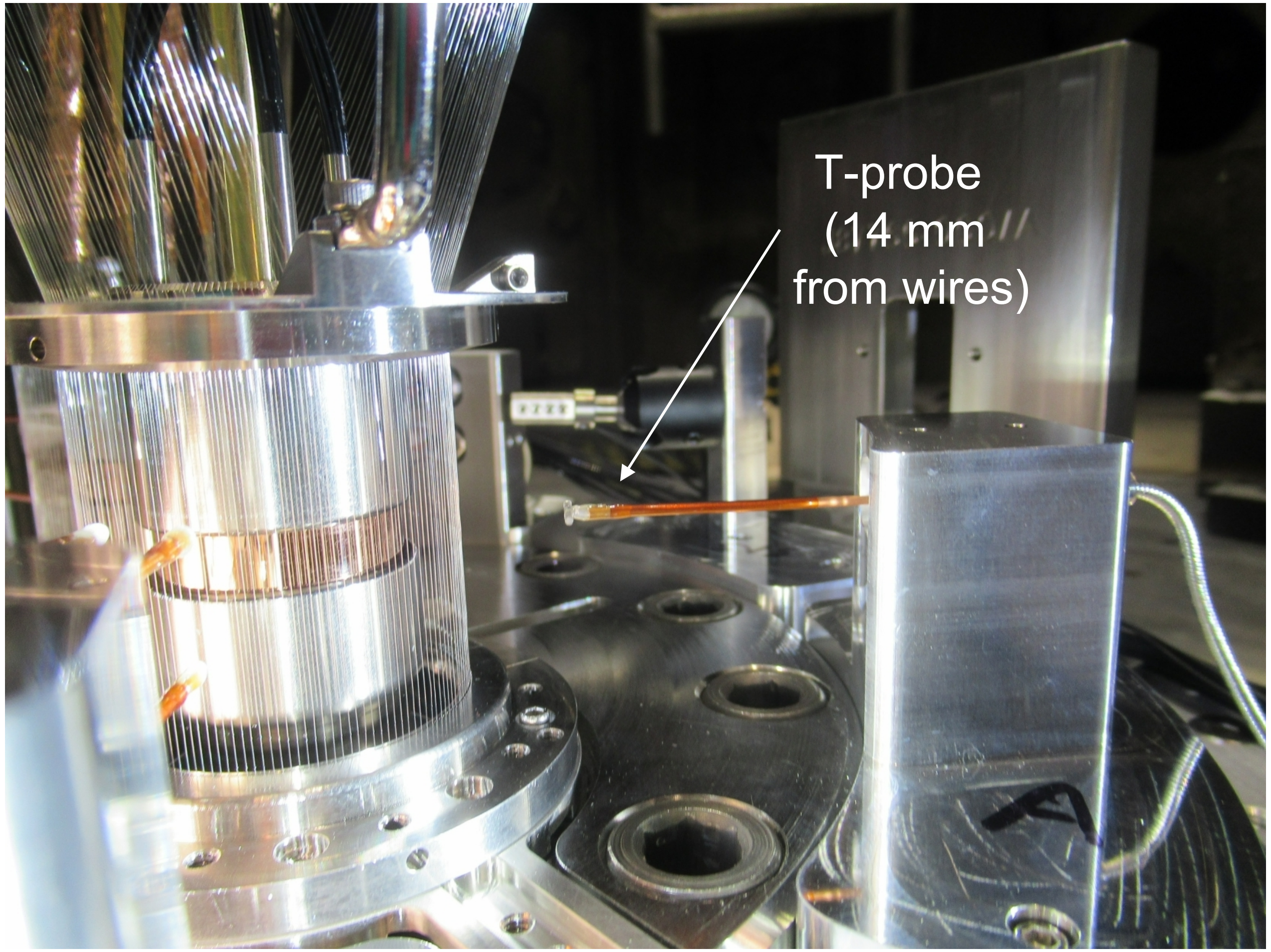
Magnetic Probe Measurements: Plasma Flow

Analysis by R. Datta





Bow shock around B-dot probe: Plasma Flow



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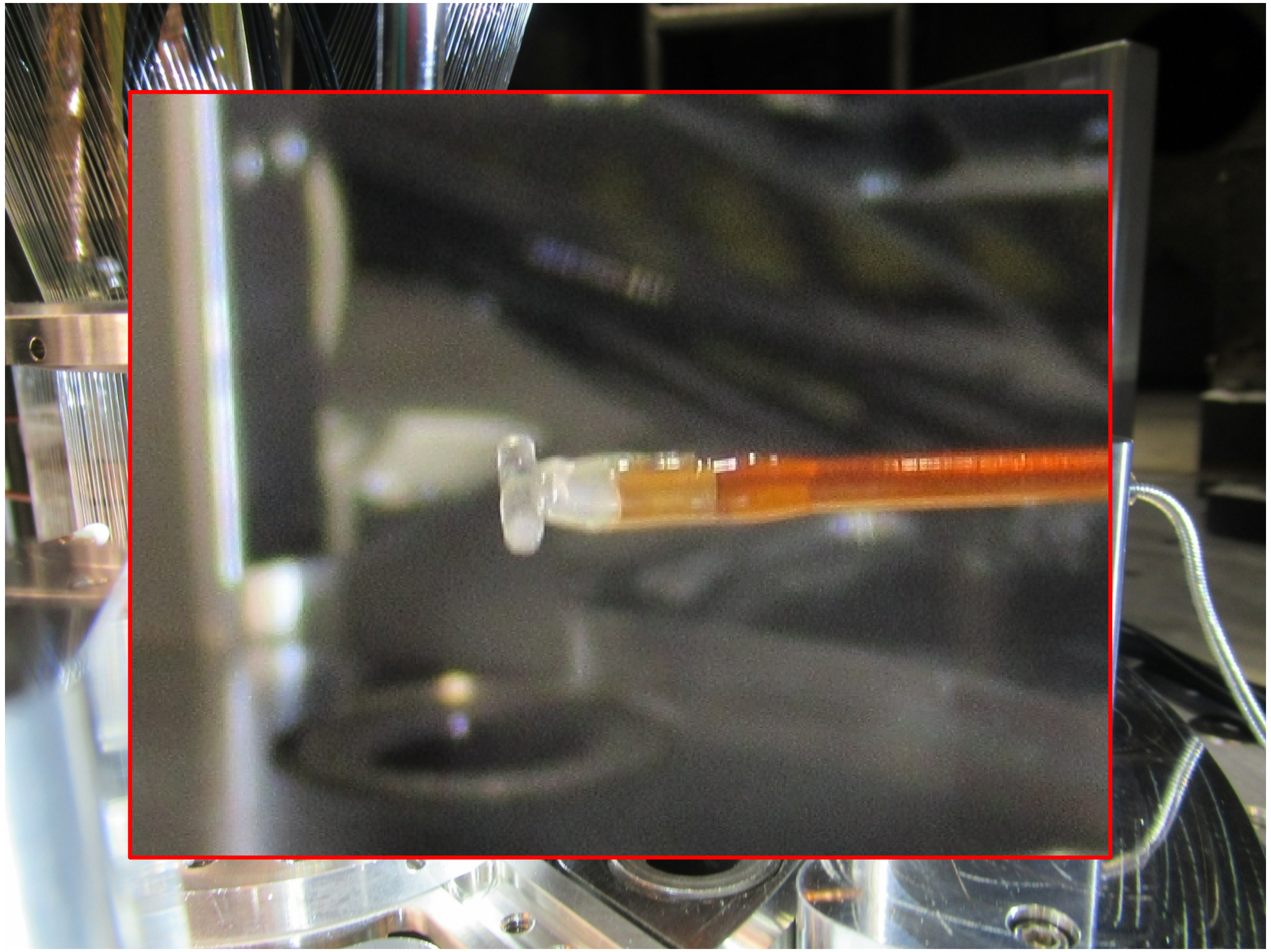
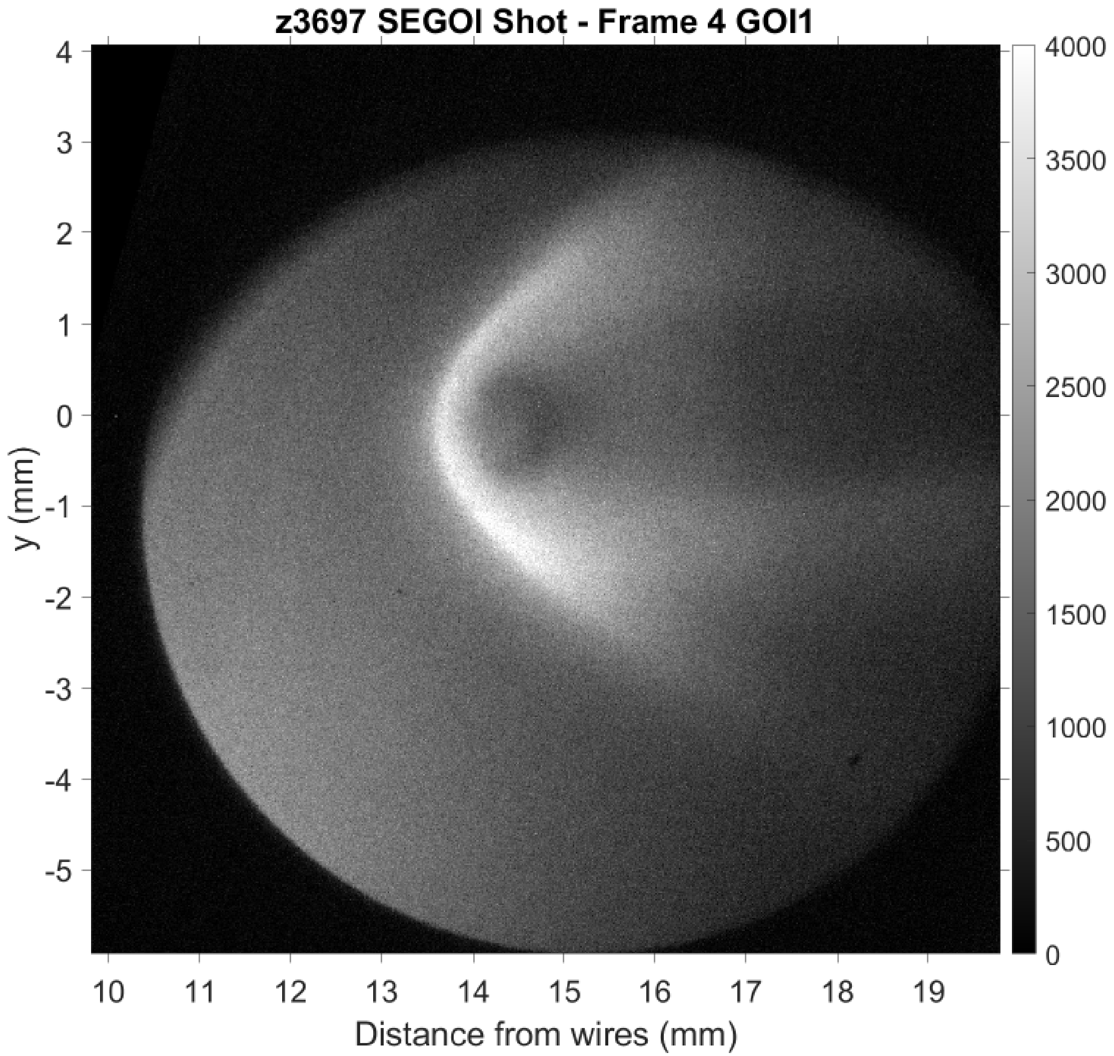
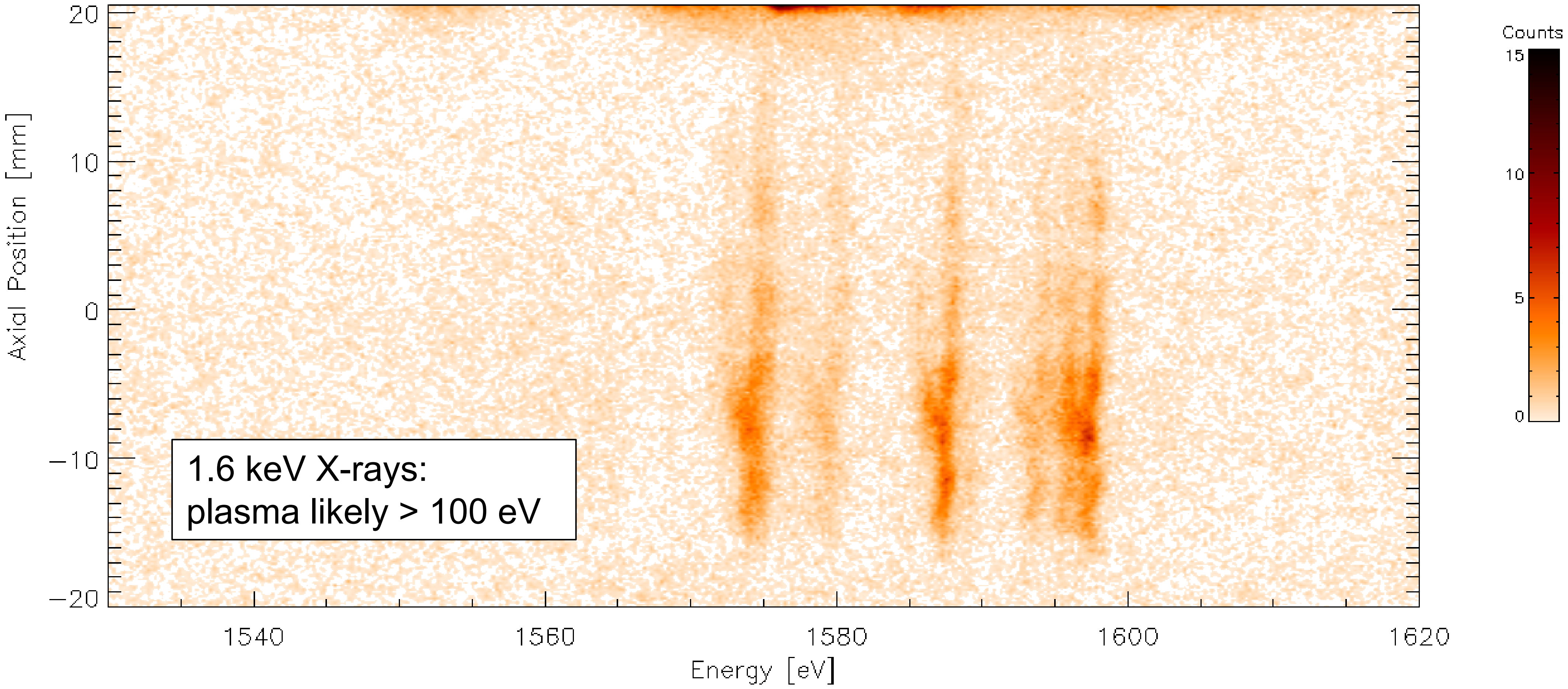
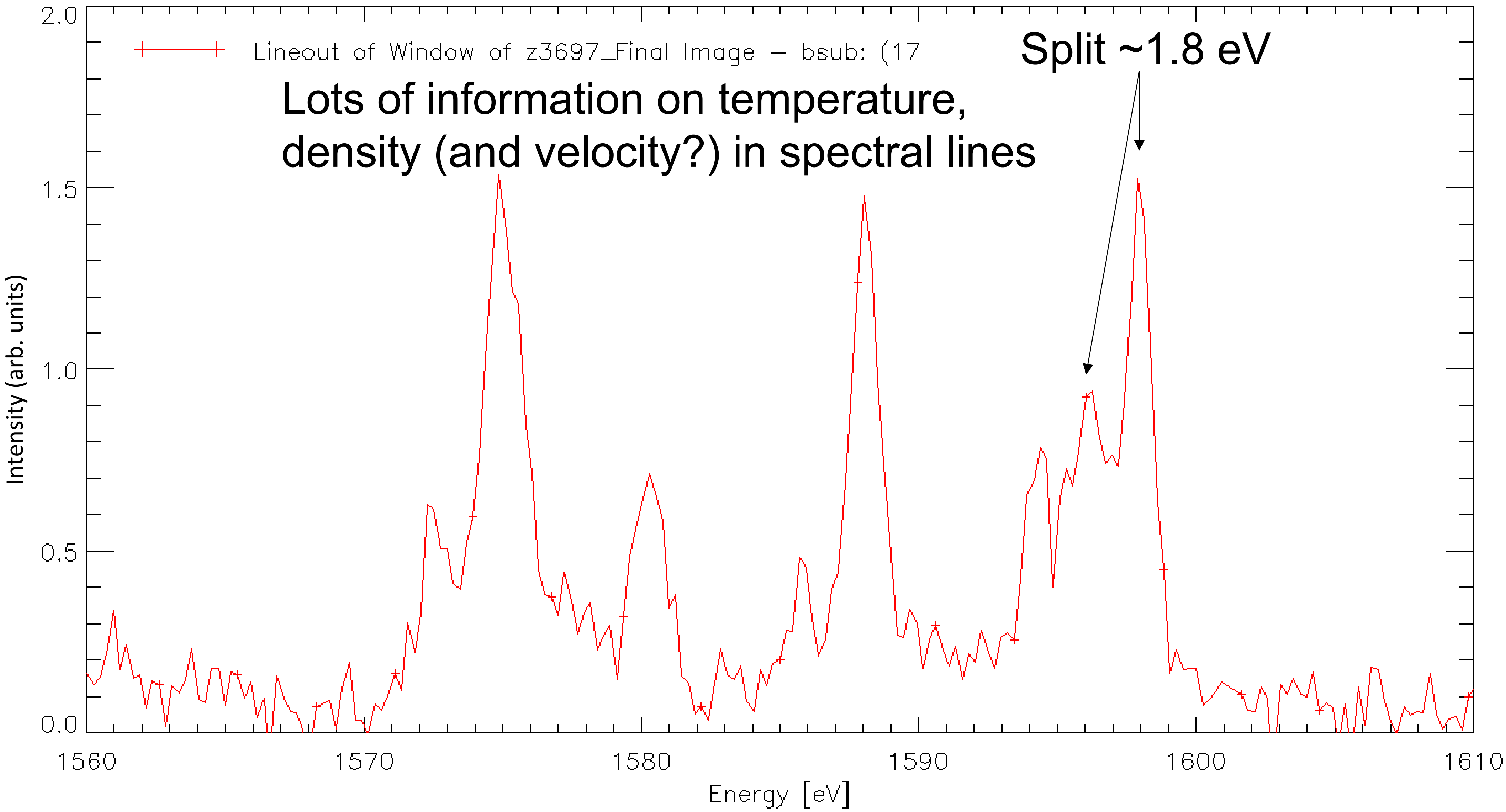




Time Integrated X-ray Spectrum: Hot Plasma

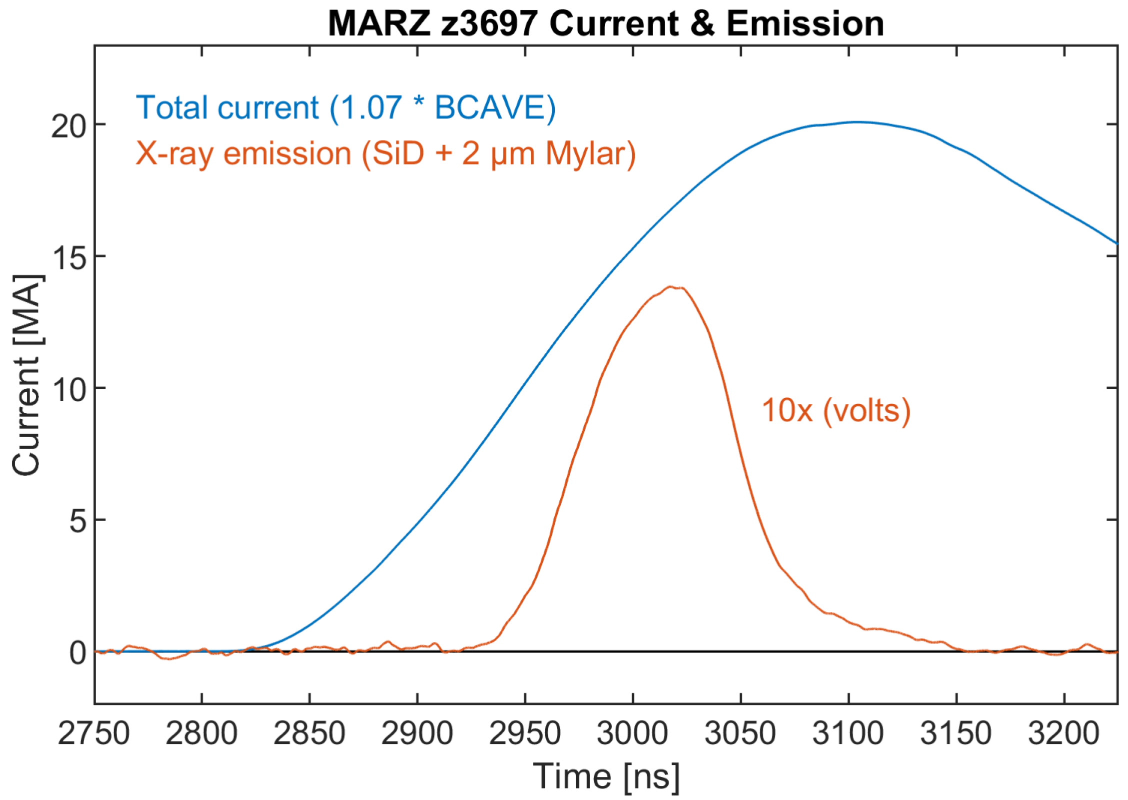


X-ray Spectra are a Rich Source of information

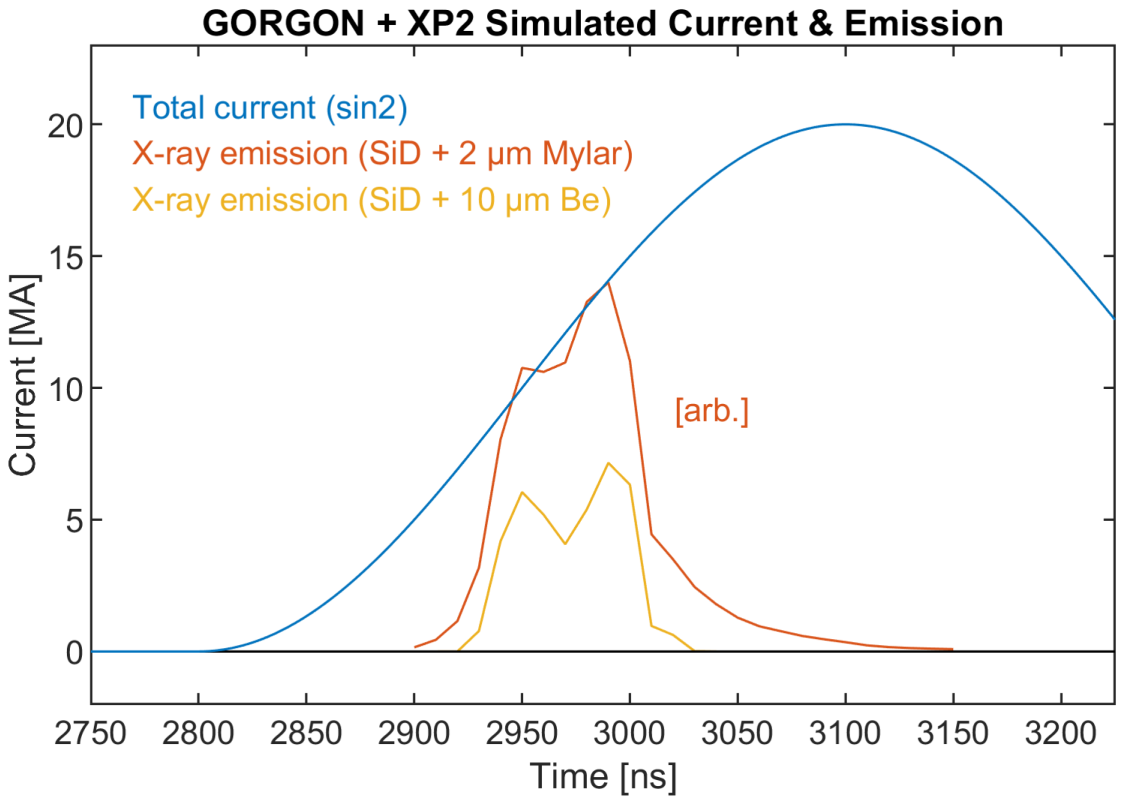


Filtered Diode Signals: Layer Formation, Collapse

Experiment

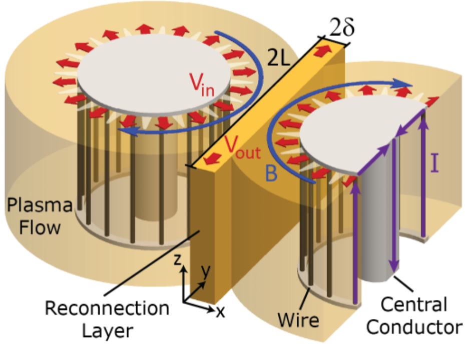


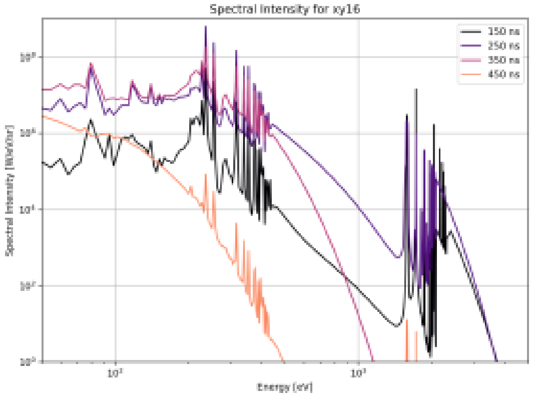
Simulation

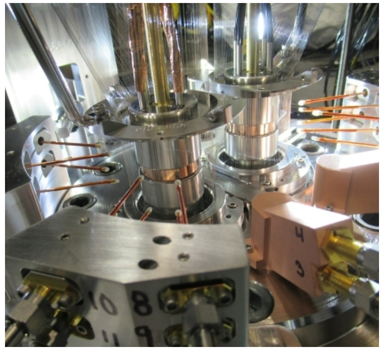


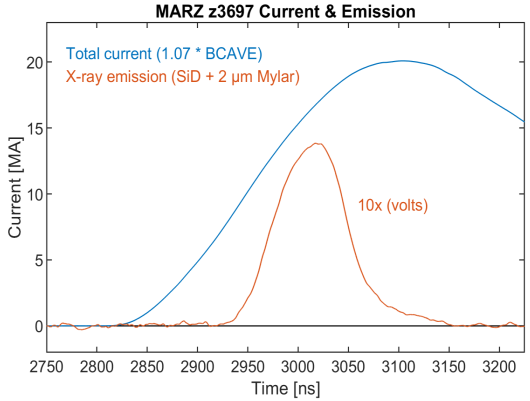
- Radiated power rises after current start, drops before current peak
- X-ray spectra appears softer than simulated: more shots in November

Conclusions









- Strong radiative cooling important in extreme astrophysical environments:
- Key signature of reconnection; modifies energy partition; leads to collapse
- High-energy-density pulsed-power experiments can reach strong radiative cooling regime
- 2D MHD simulations show rich physics: plasmoid formation, layer collapse
- Preliminary experimental results from the Z machine show viability of platform for radiatively cooled reconnection studies: more shots in November