

Magnetized High-Energy-Density Plasma Experiments at MIT

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Acknowledgements



MIT

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Imperial College
London



Sandia
National
Laboratories



UNIVERSITY OF MICHIGAN



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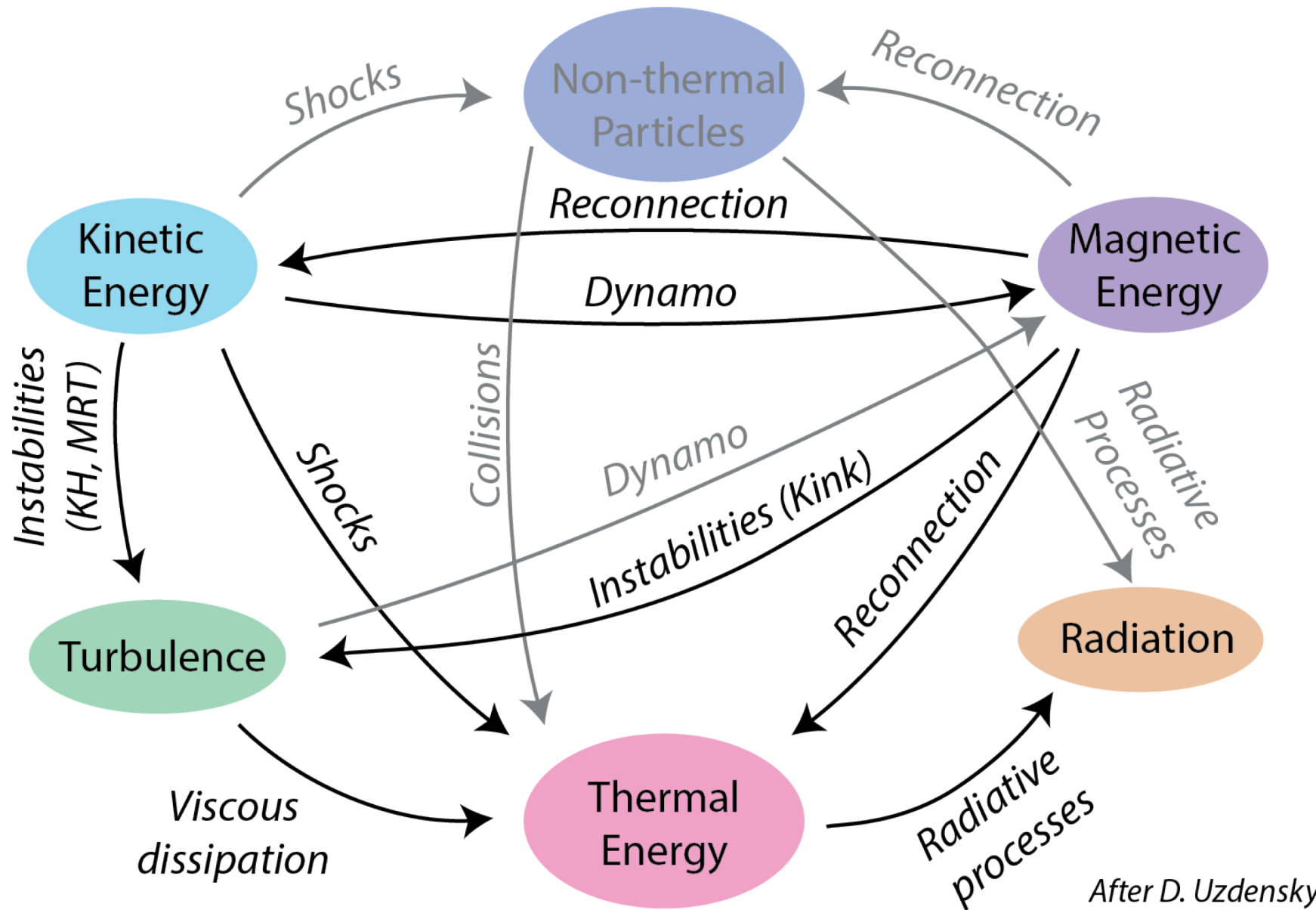


This work is supported by the NSF and the NNSA



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Research Interests: Energy Flows in Plasma



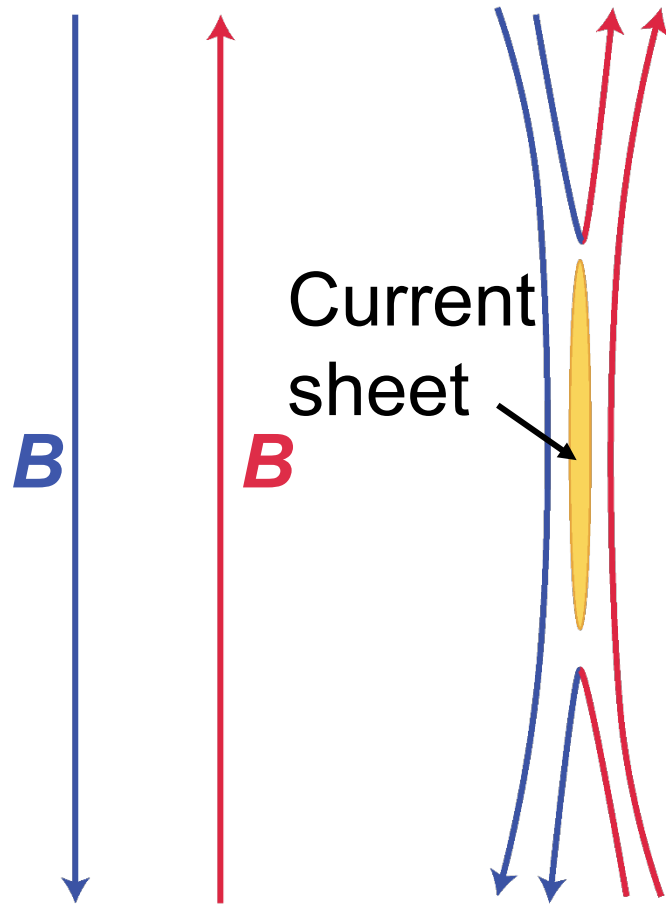
Pulsed-power driven plasmas:

$$U_{mag} \approx U_{th} \approx U_{kin}$$

All energy components important

After D. Uzdensky

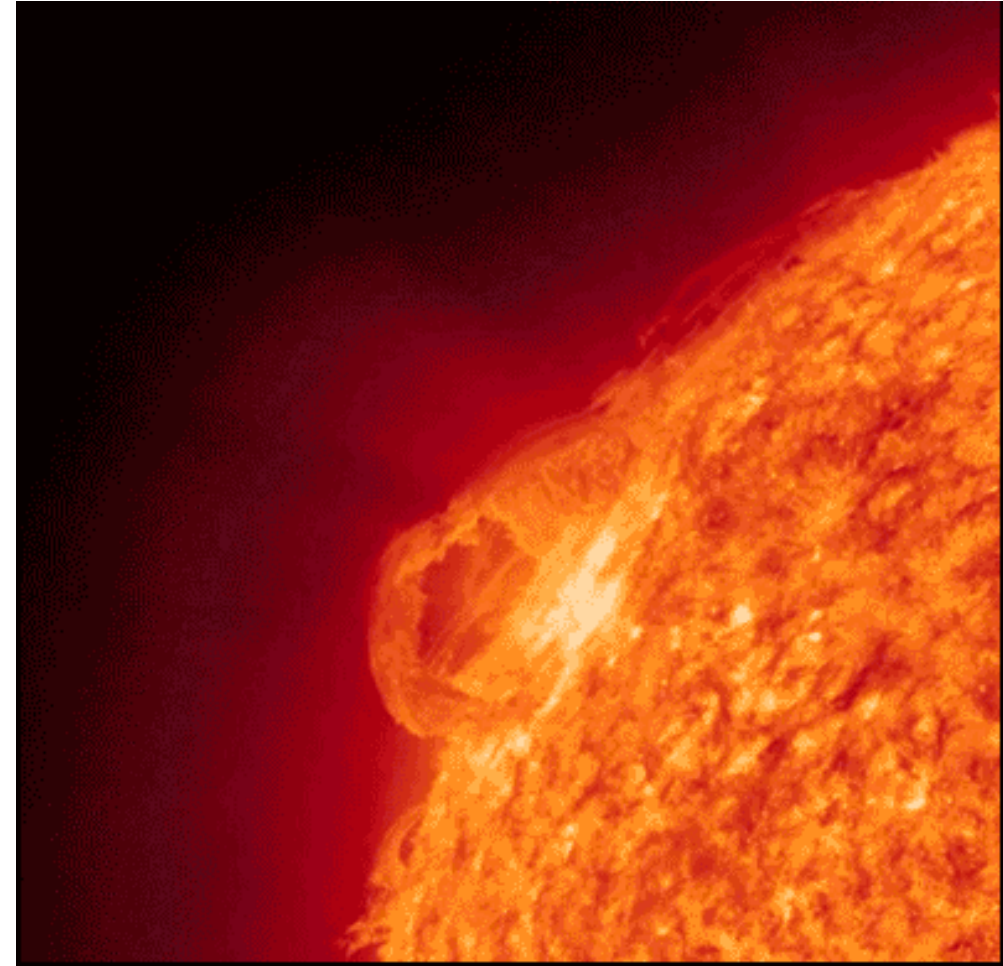
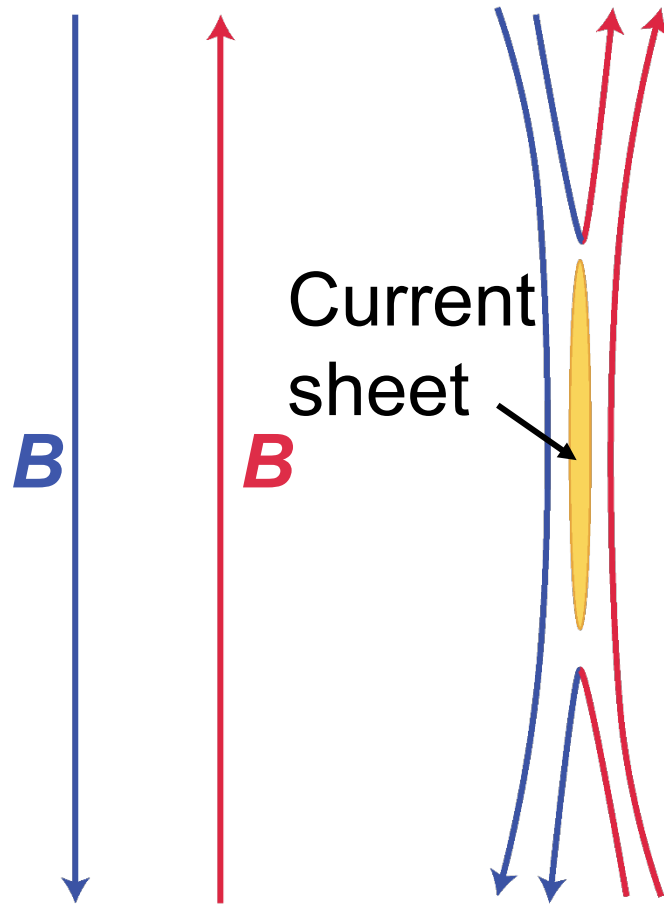
Magnetic Reconnection: field lines break and reform



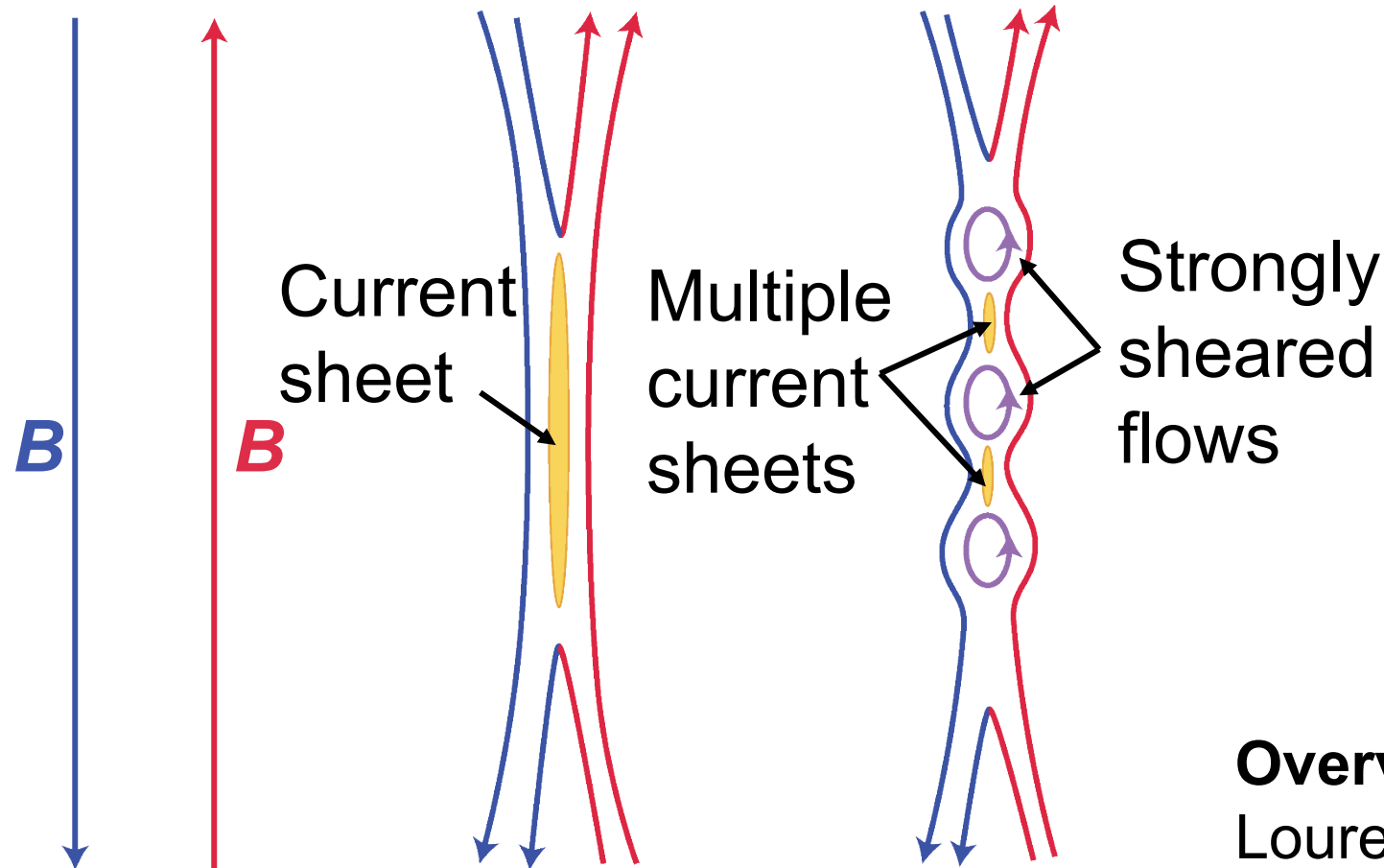
Magnetic Reconnection: theory predicts slow rate



Prediction: 1000 yrs. Reality: 10 minutes!



Plasmoids Lead to Fast Reconnection and Anomalous Heating



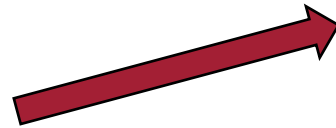
Overview of recent theory:
Loureiro, N. F., & Uzdensky, D.
A.(2015).
PPCF, 58, 014021



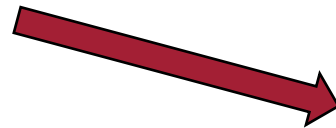
Magnetic
reconnection



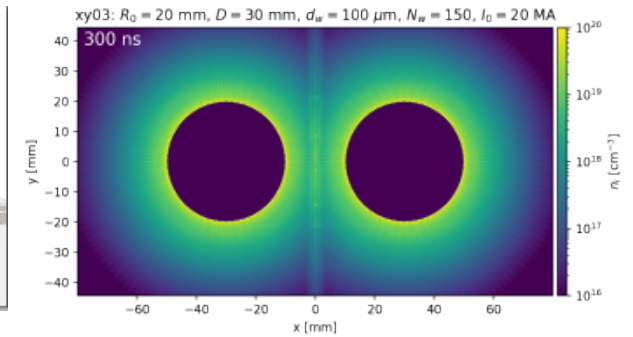
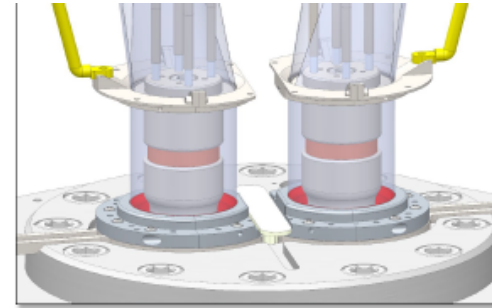
More current



Longer current
pulse

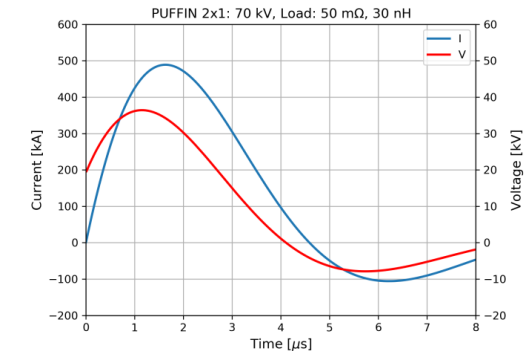
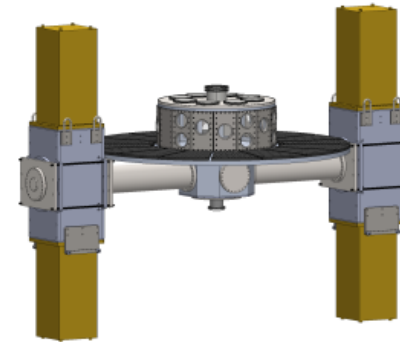


Radiatively cooled reconnection on Z



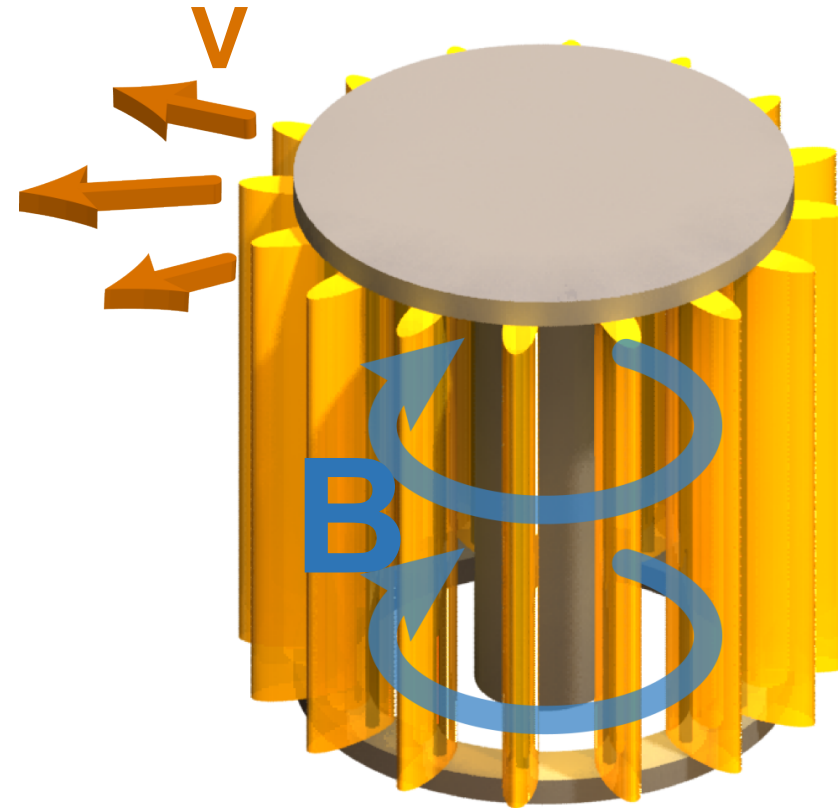
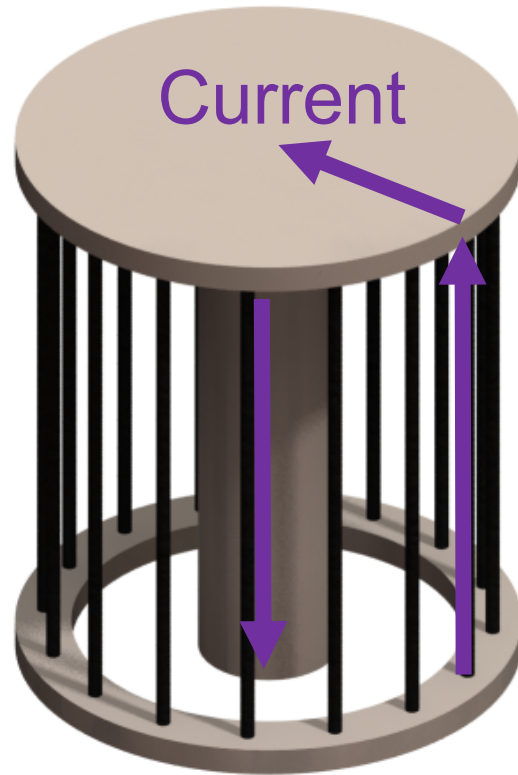
Supported by NSF through PHY2213898

PUFFIN: 1.6 μ s, 700 kA at MIT



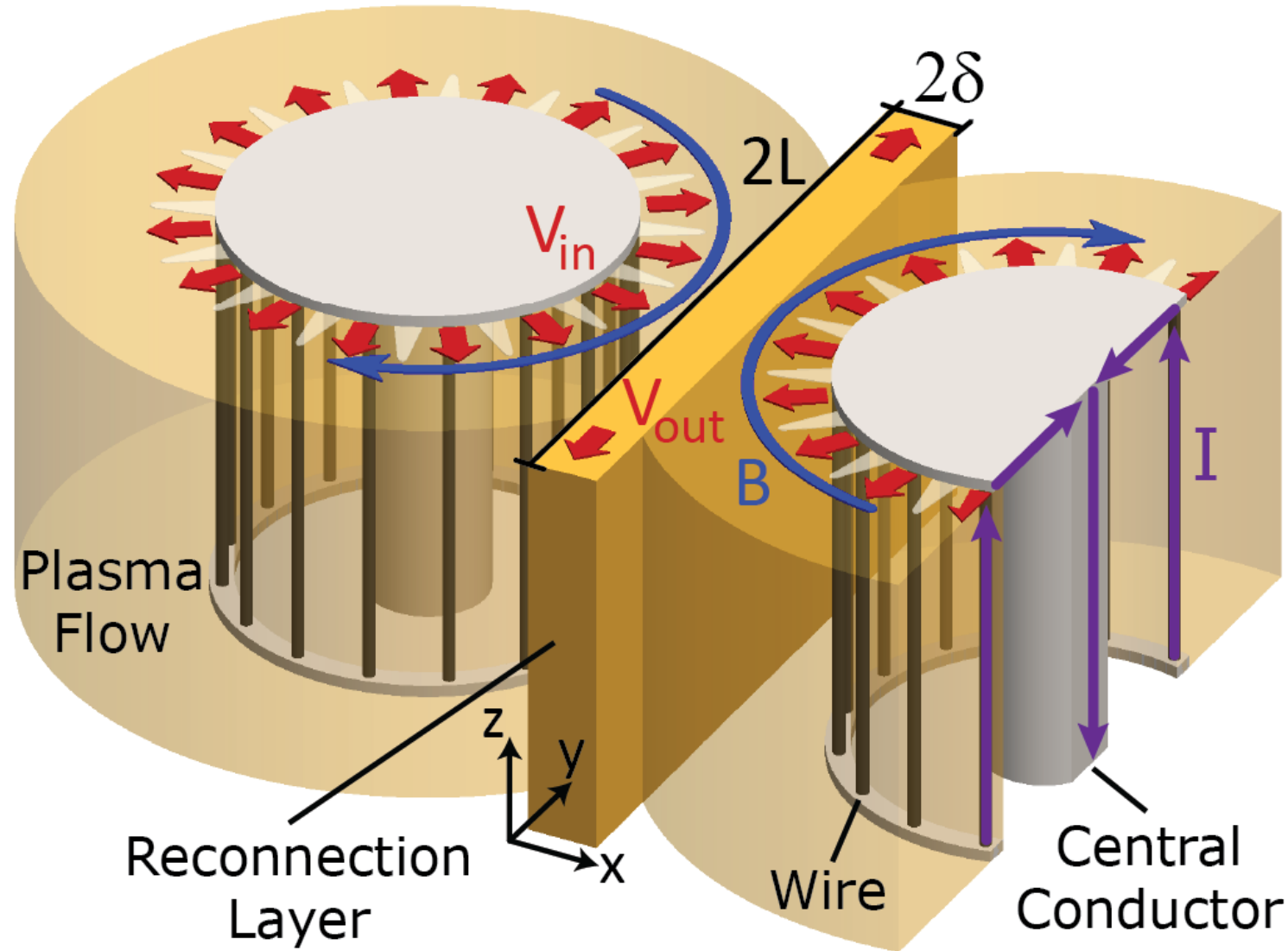
Supported by the NSF and NNSA
through PHY2108050

An exploding wire array: a versatile plasma source

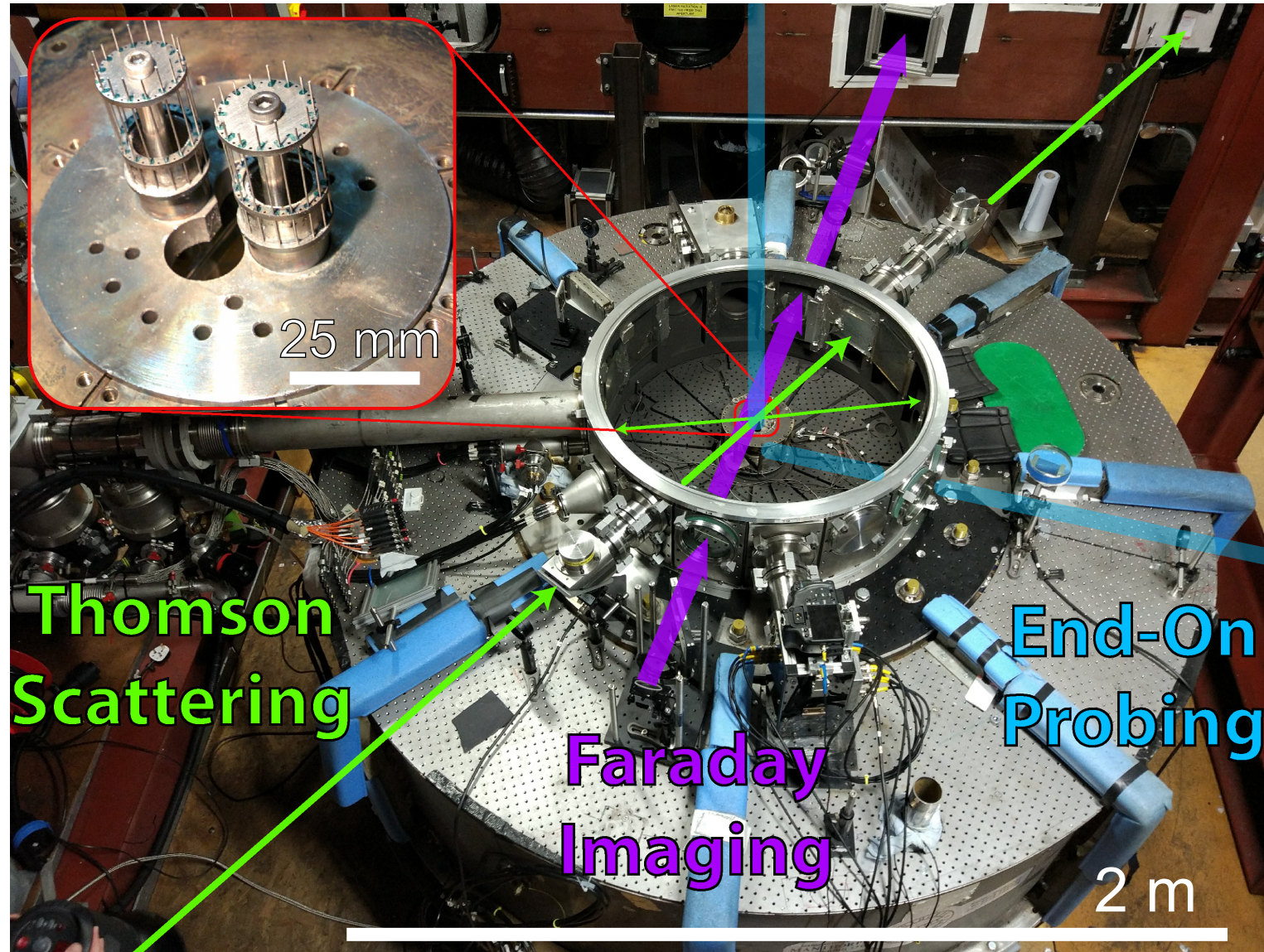


$I=1.4$ MA, 240 ns rise time

Magnetic Reconnection from Double Exploding Wire Arrays



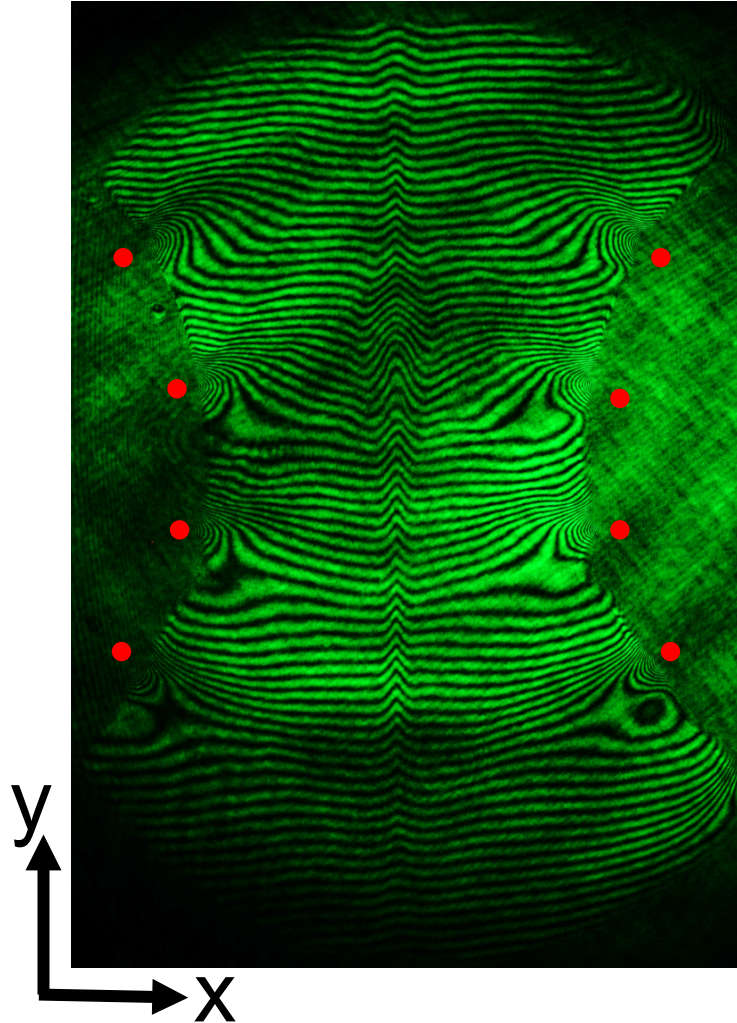
Overview of Diagnostic Suite on MAGPIE at Imperial College



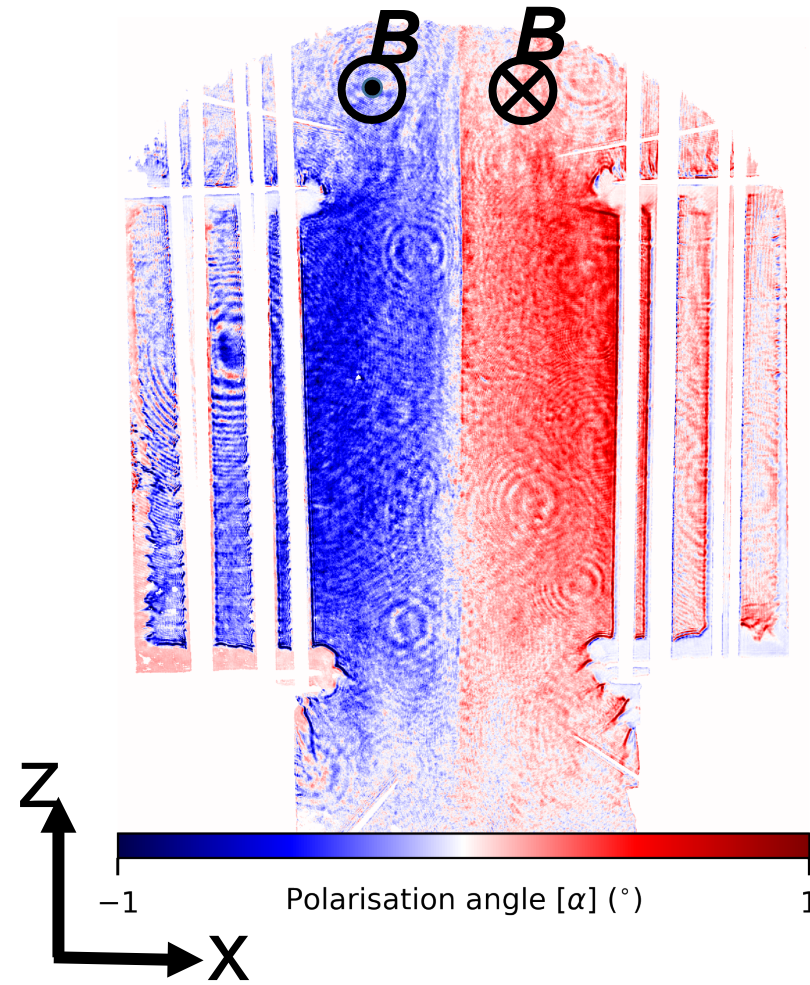
Diagnosing reconnection in the laboratory



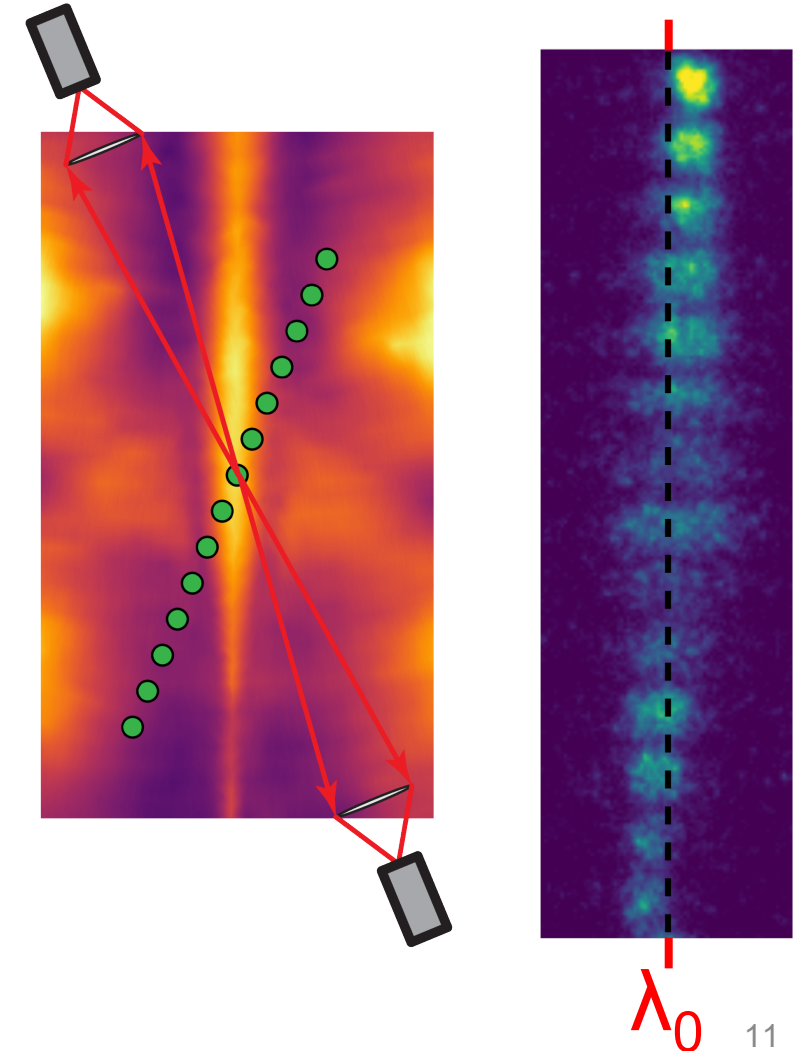
Laser interferometry:
 $\int n_e dl$



Faraday Imaging:
 $\int n_e \mathbf{B} \cdot d\mathbf{l}$



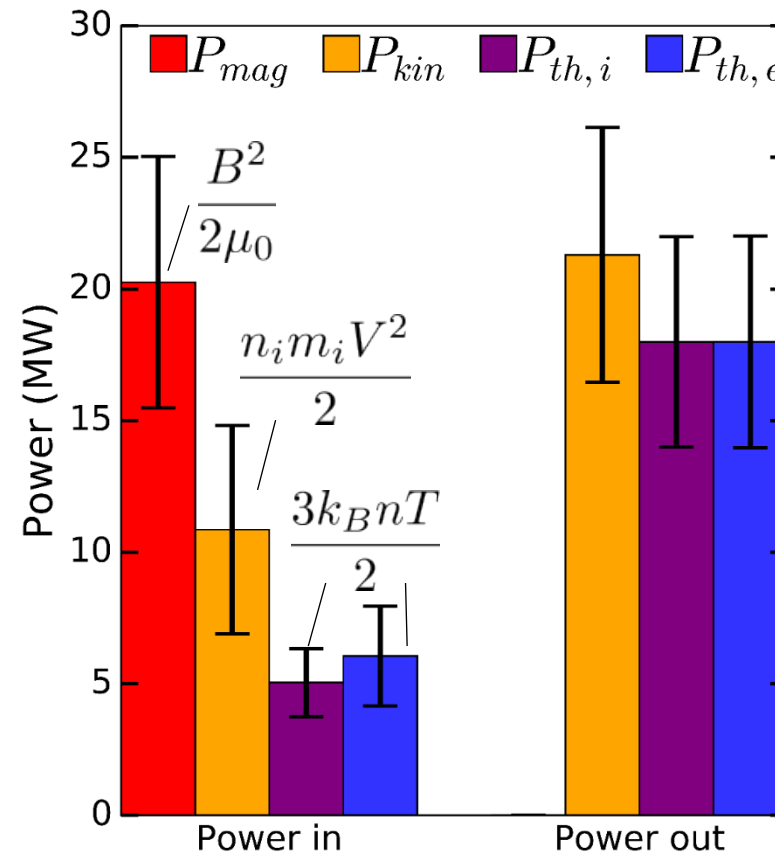
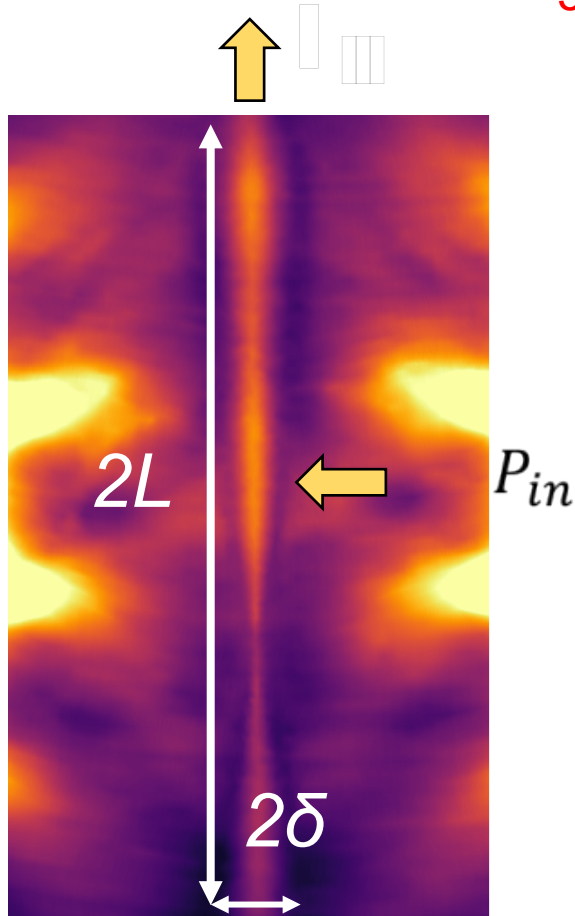
Thomson scattering:
 V, ZT_e, T_i



Anomalous Heating in the Reconnection Layer



$$V_{in} L h \left(\underset{\sim 50\%}{E_{mag}} + \underset{\sim 25\%}{E_{kin}} + \underset{\sim 25\%}{E_{th,i}} + \underset{\sim 40\%}{E_{th,e}} \right) \approx V_{out} \delta h \left(\underset{\sim 40\%}{E_{kin}} + \underset{\sim 60\%}{E_{th,i}} + \underset{\sim 60\%}{E_{th,e}} \right)$$



Classical heating is too slow:

≈ 50 ns

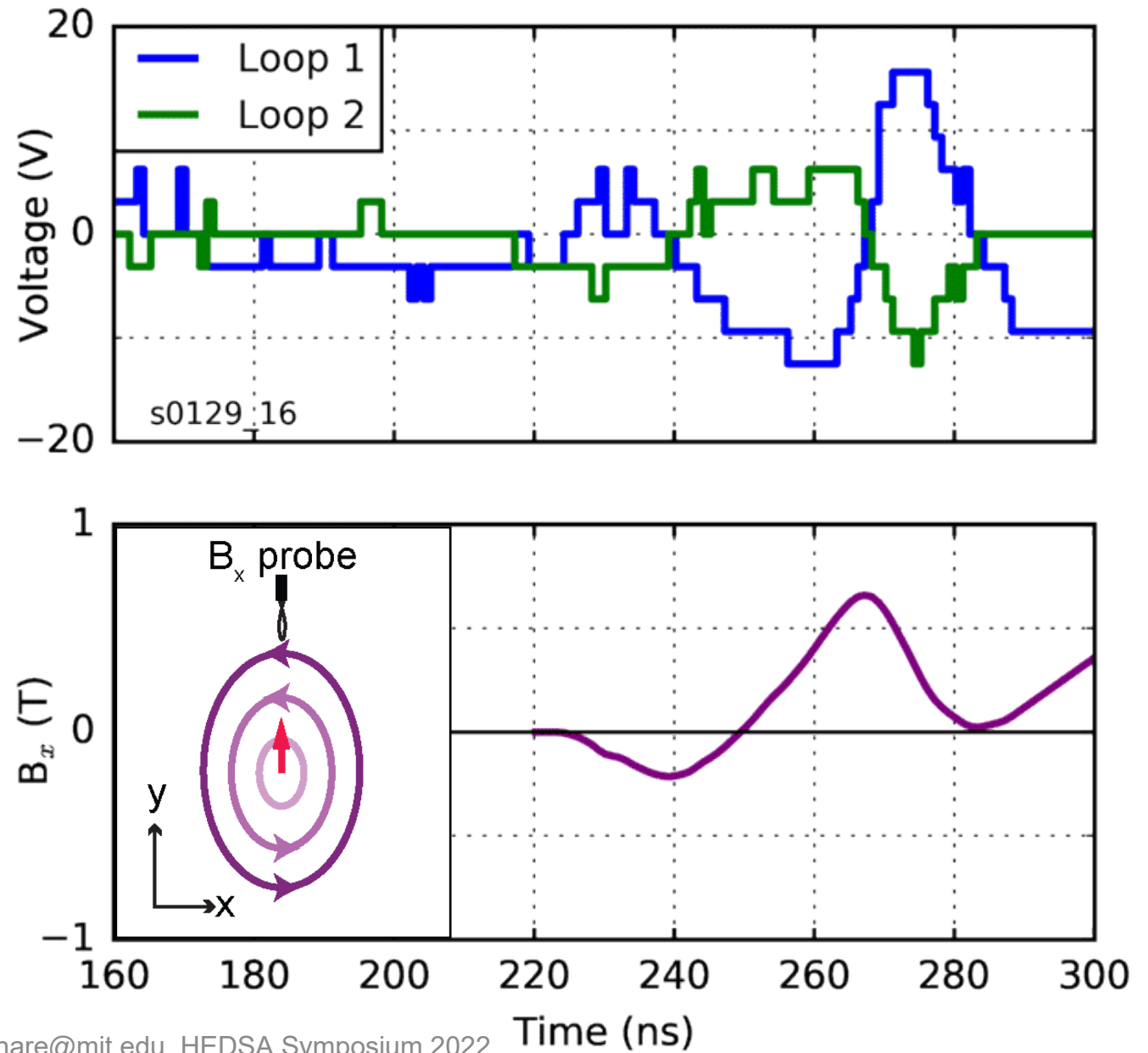
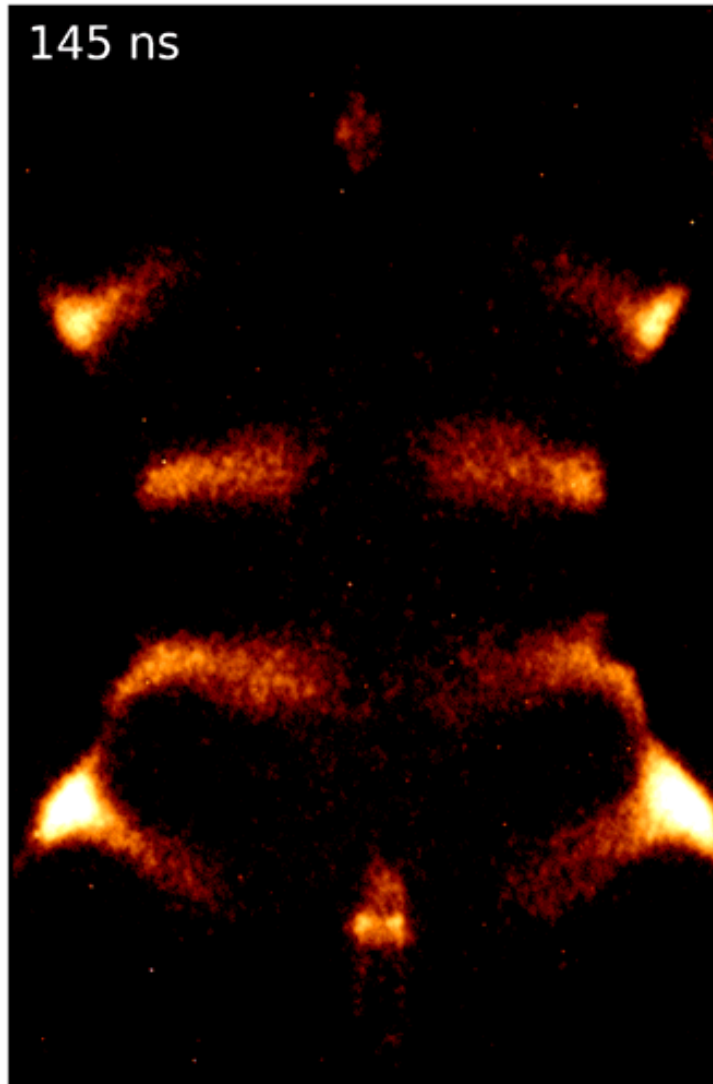
≈ 800 ns

≈ 350 ns

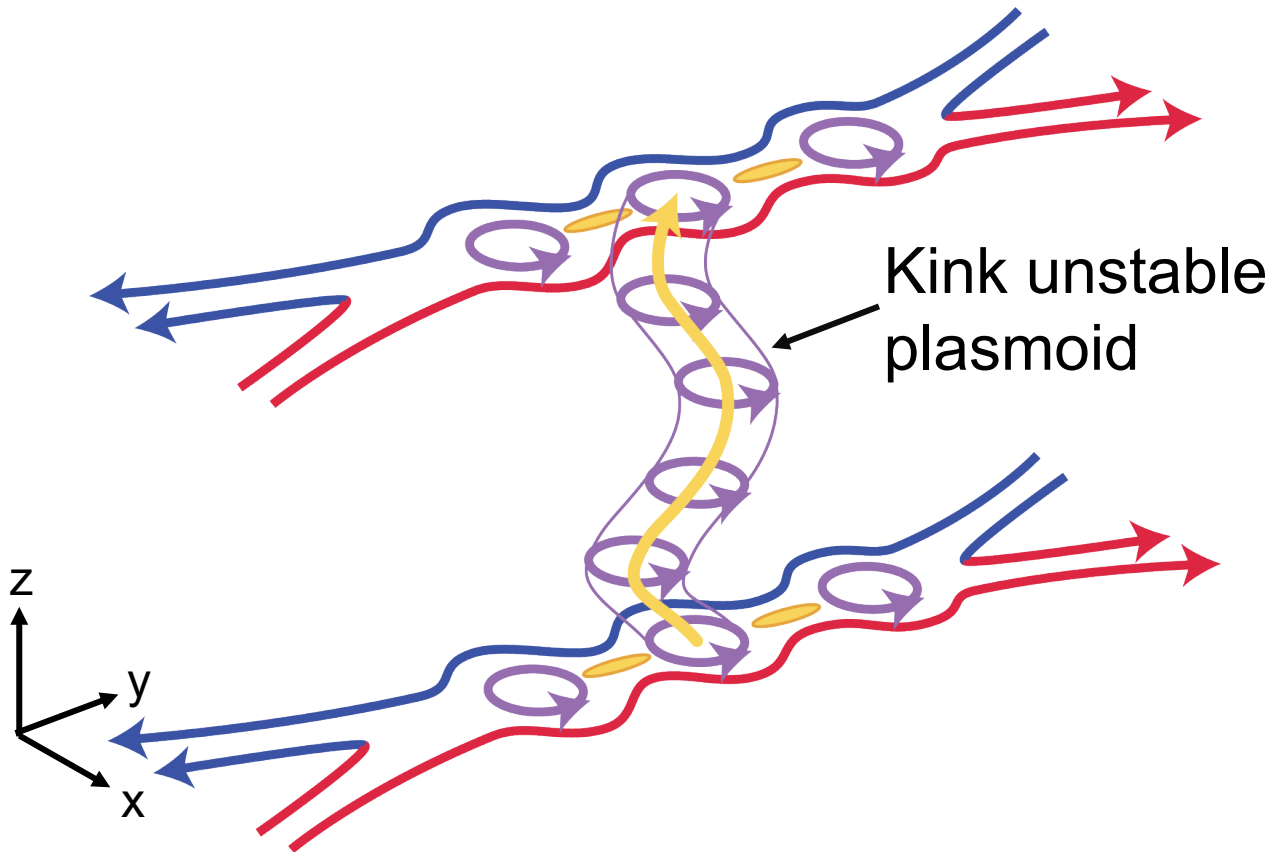
$$\tau_{exp} \ll \tau_{visc}, \tau_{res}$$

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

Magnetic Structure of Plasmoids



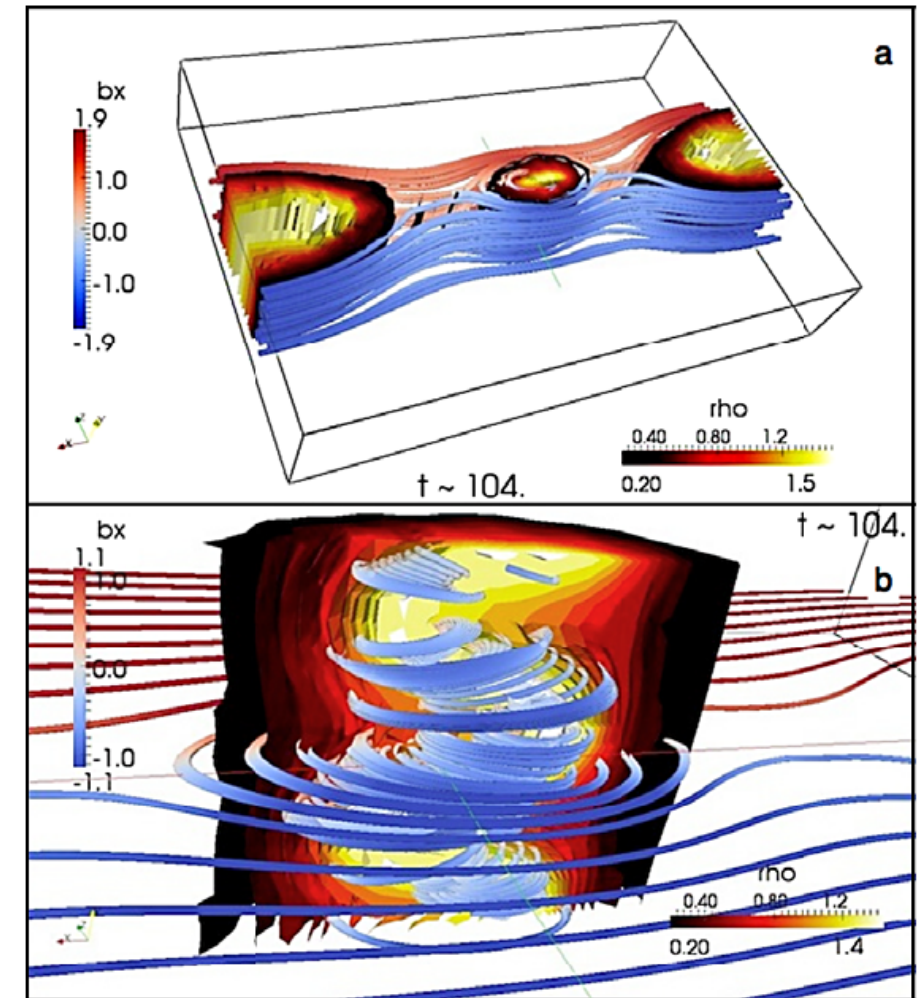
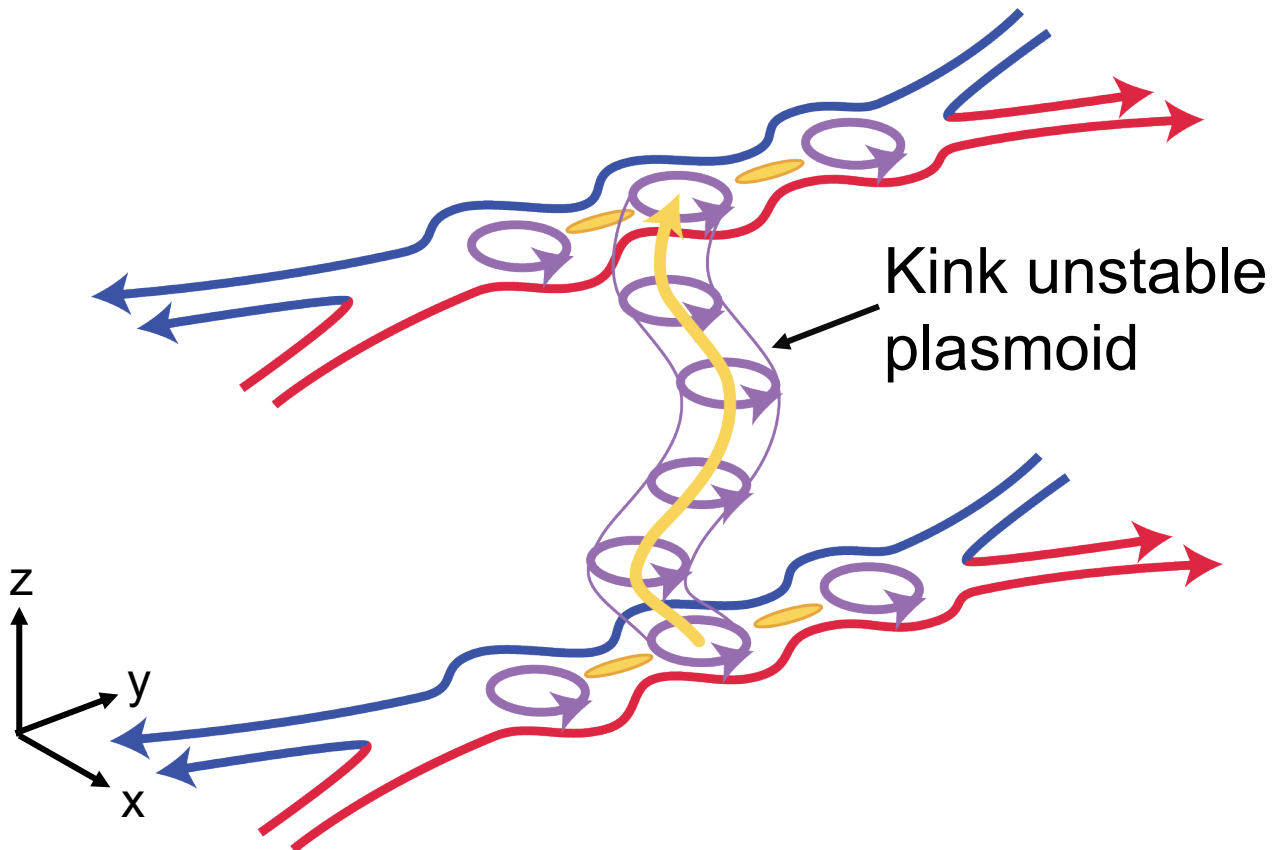
What does a plasmoid look like in 3D?



Kink Instability Leads to Turbulent Reconnection

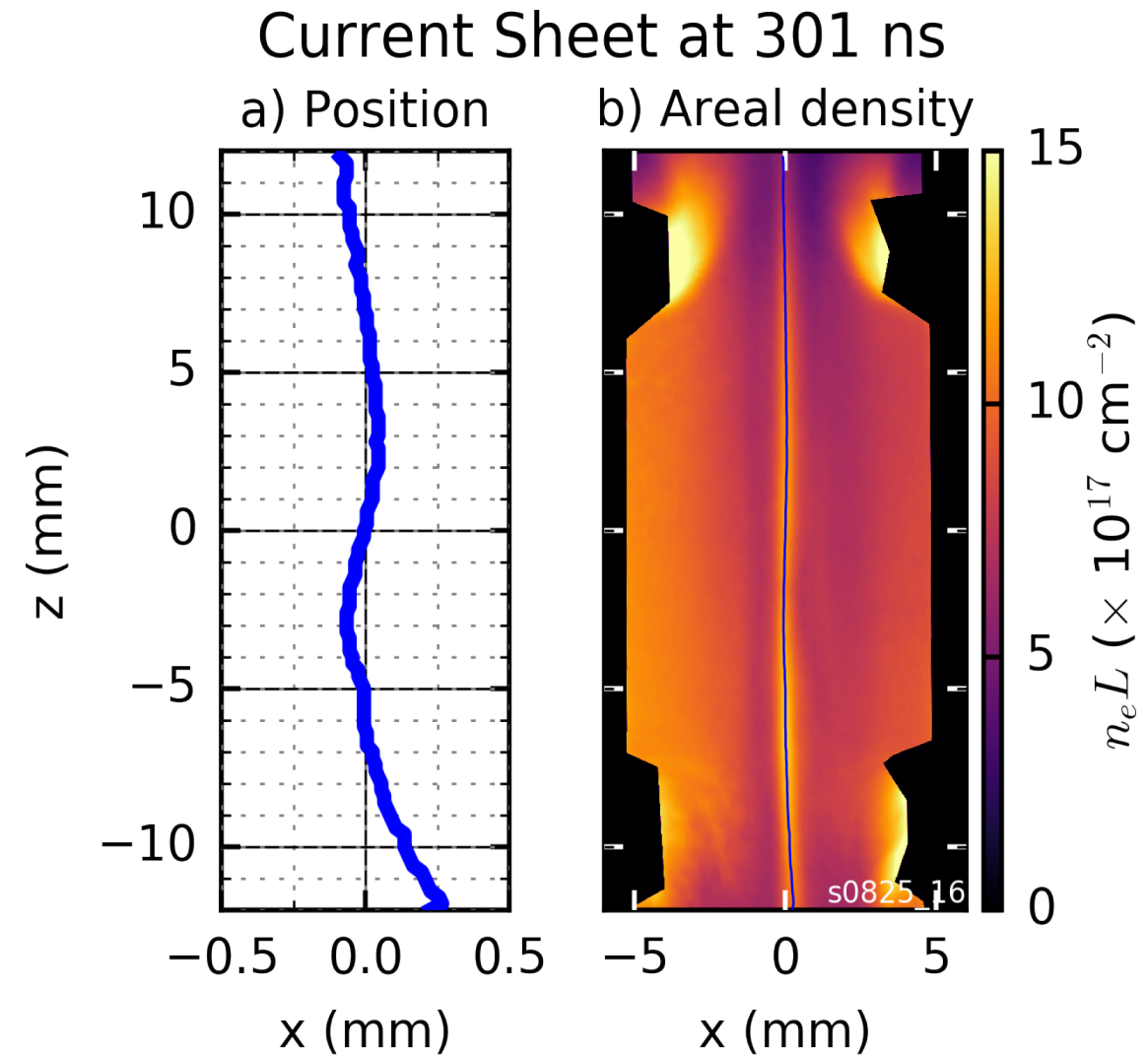
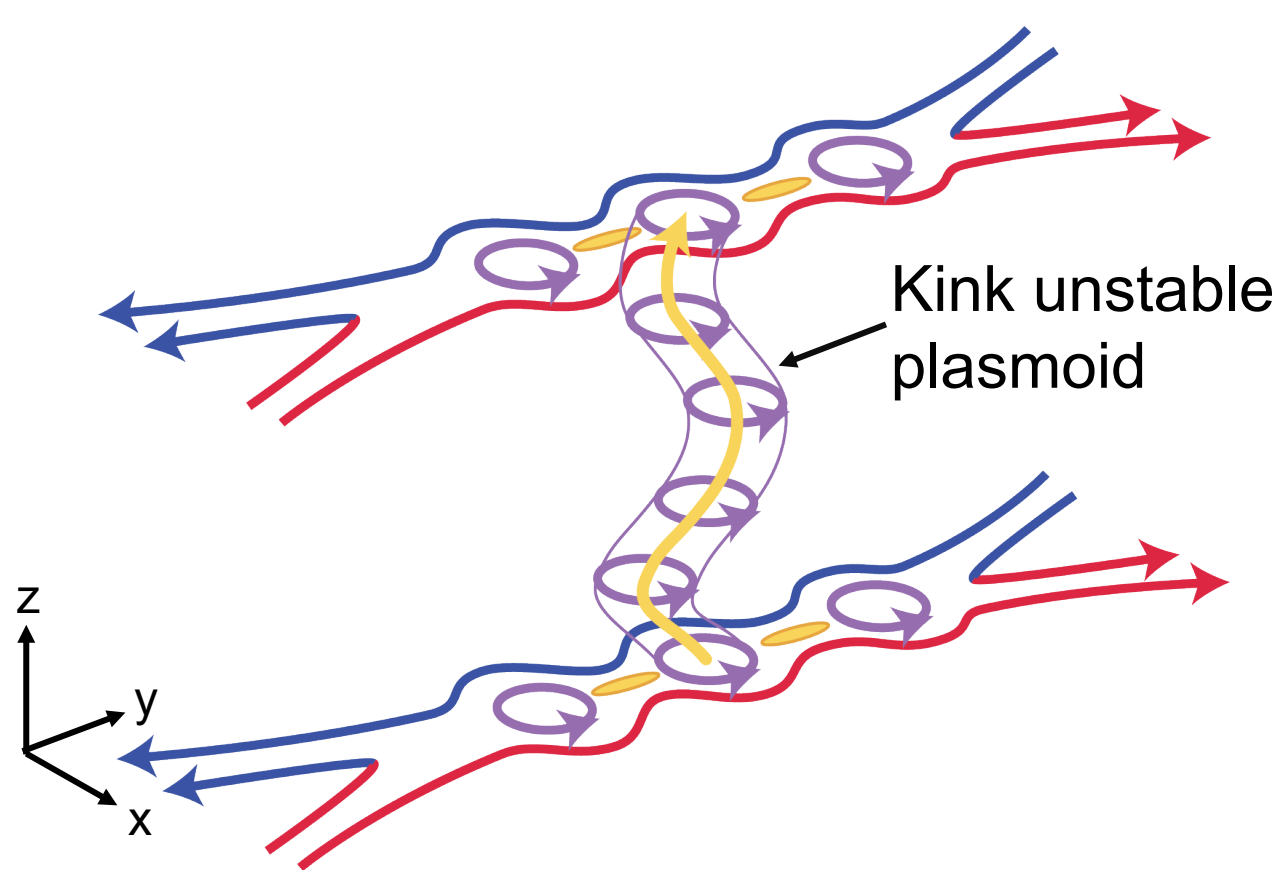


Turbulent reconnection over a large volume,
as observed in astrophysics



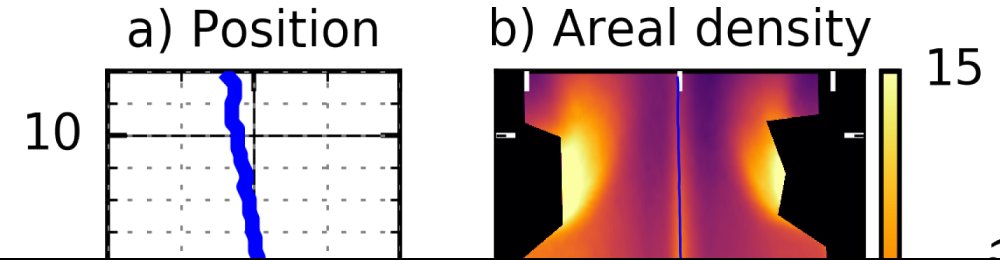
Lapenta, G., and L. Bettarini. *EPL* **93**, 6 (2011)

Hints of a kink instability on MAGPIE



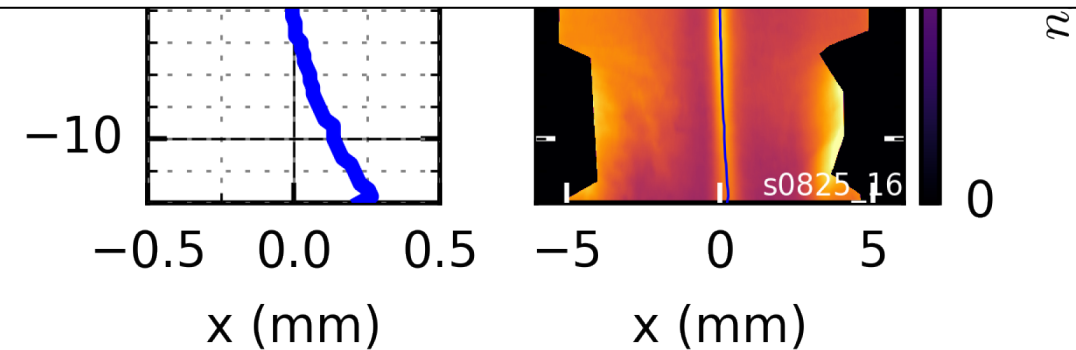
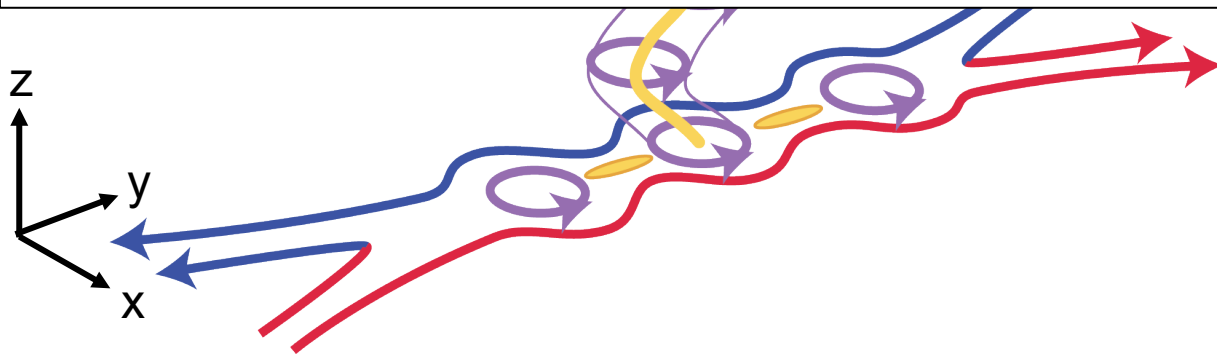


Current Sheet at 301 ns



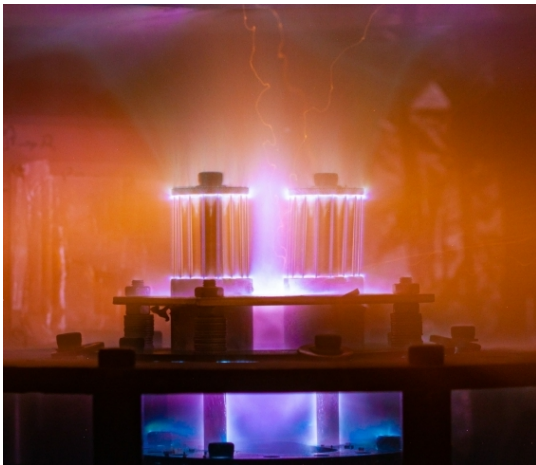
Open questions:

- How do the reconnection layer dynamics scale with current?
- What other instabilities can grow on long timescales?

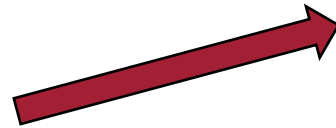




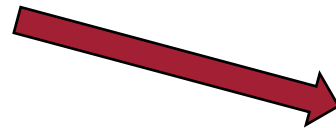
Magnetic
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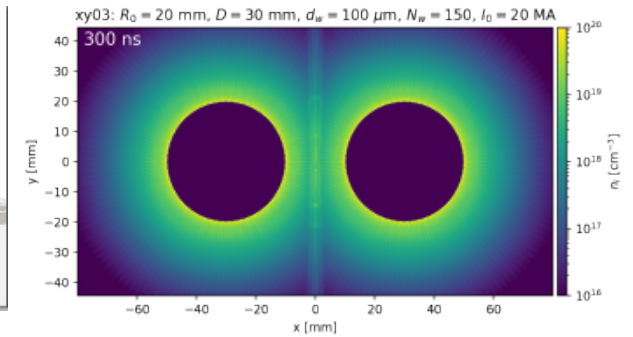
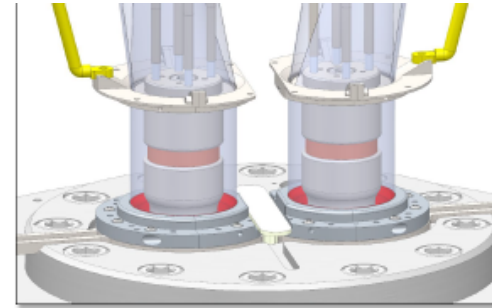
More current



Longer current
pulse

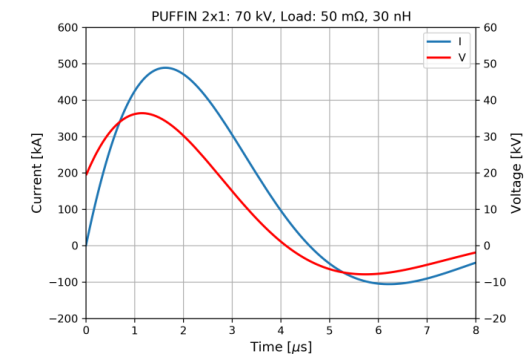
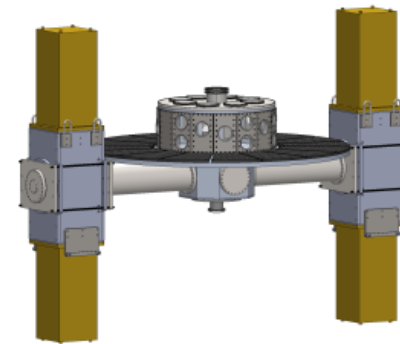


Radiatively cooled reconnection on Z



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PUFFIN: 1.6 μ s, 700 kA at MIT



Supported by the NSF and NNSA
through PHY2108050

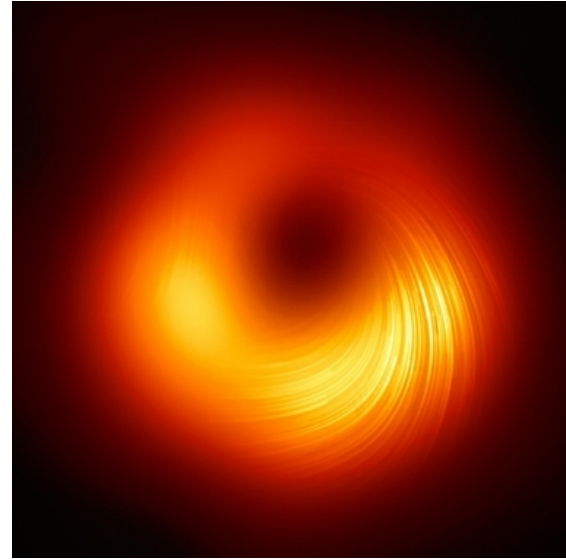
Reconnection in Extreme Astrophysical Environments



Artist's impression of a black hole



M87 (EHT)

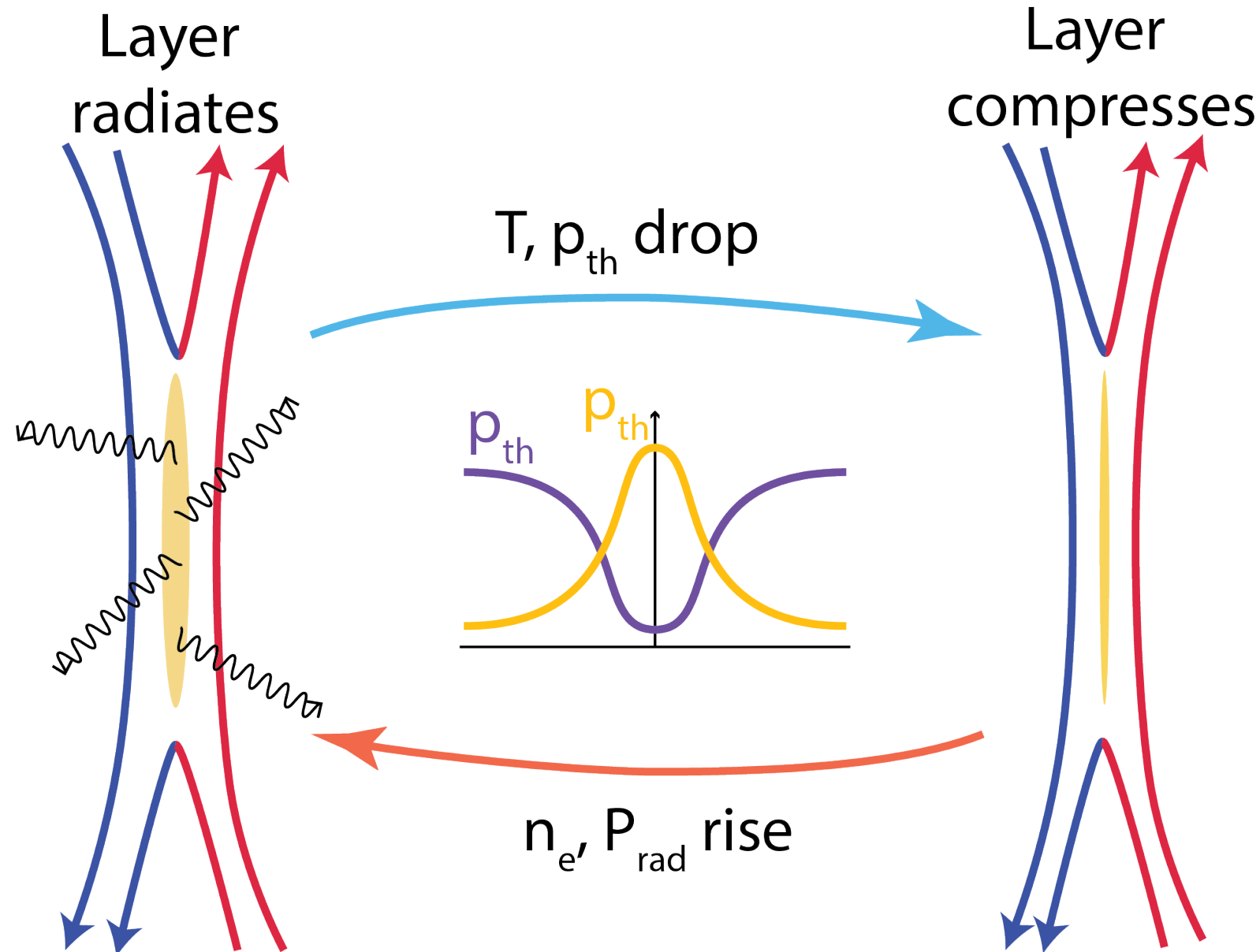


Crab Pulsar (Hubble/Chandra)



1. Cooling is a significant loss mechanism:
 - Modifies partition of magnetic energy between electrons, ions, kinetic
 - Leads to cooling instabilities, radiative collapse, termination of reconnection
2. X-rays: key observational signature in remote environments:
 - Where and when are X-rays produced – localized bursts?
 - How does this couple back to the reconnection process?

Radiative Cooling Instabilities in Reconnection



Uzdensky & McKinney PoP 2011

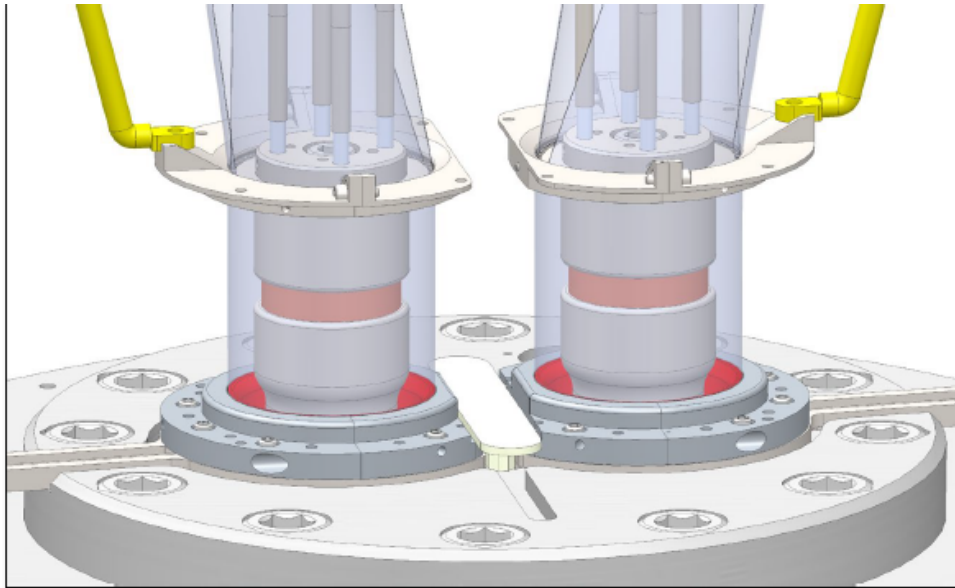
- Layer ohmically heated
- Layer radiatively cools
- Layer compresses
- Layer radiates more
- Runaway process



Z is the largest pulsed-power machine in the world

- 20-30 MA peak current compared to 1.4 MA on MAGPIE:
 - **Density** increase by $I^2 \sim 400$
 - **Magnetic energy** increase by $I^2 \sim 400$
 - **Cooling rate** increase by $I^4 \sim 160,000$

Unique capability: strongly radiatively cooled reconnection



Requires more mass in load:

- 16 $\rightarrow$ 150 wires/array
- 40 μm $\rightarrow$ 75 μm wires
- 16 mm $\rightarrow$ 40 mm arrays



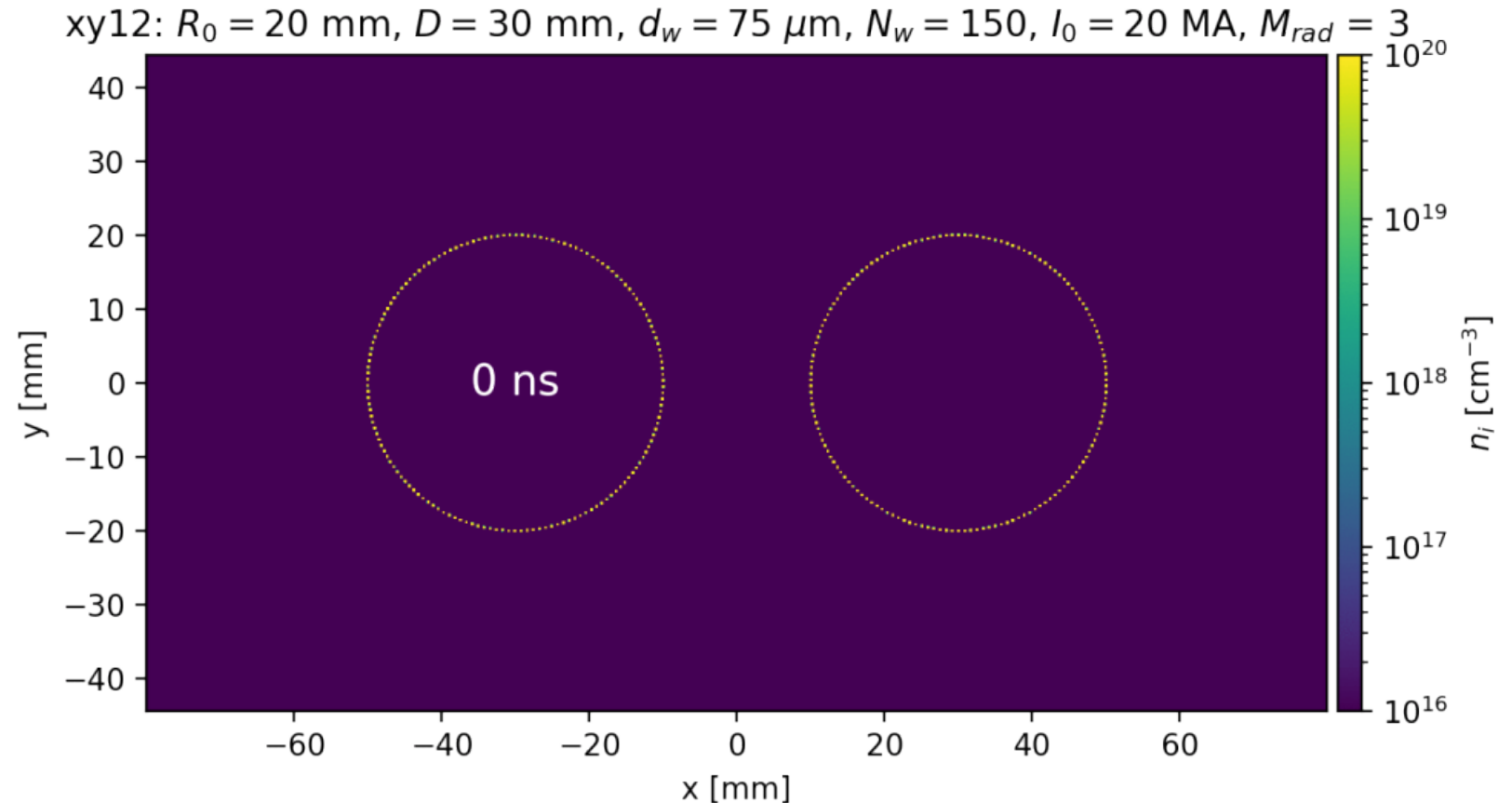
GORGON (J. Chittenden, Imperial) : 3D Eulerian resistive MHD code with several radiation loss models and separate ion and electron energy equations

Wires:

- 150 Al wires
- 75 μm diameter

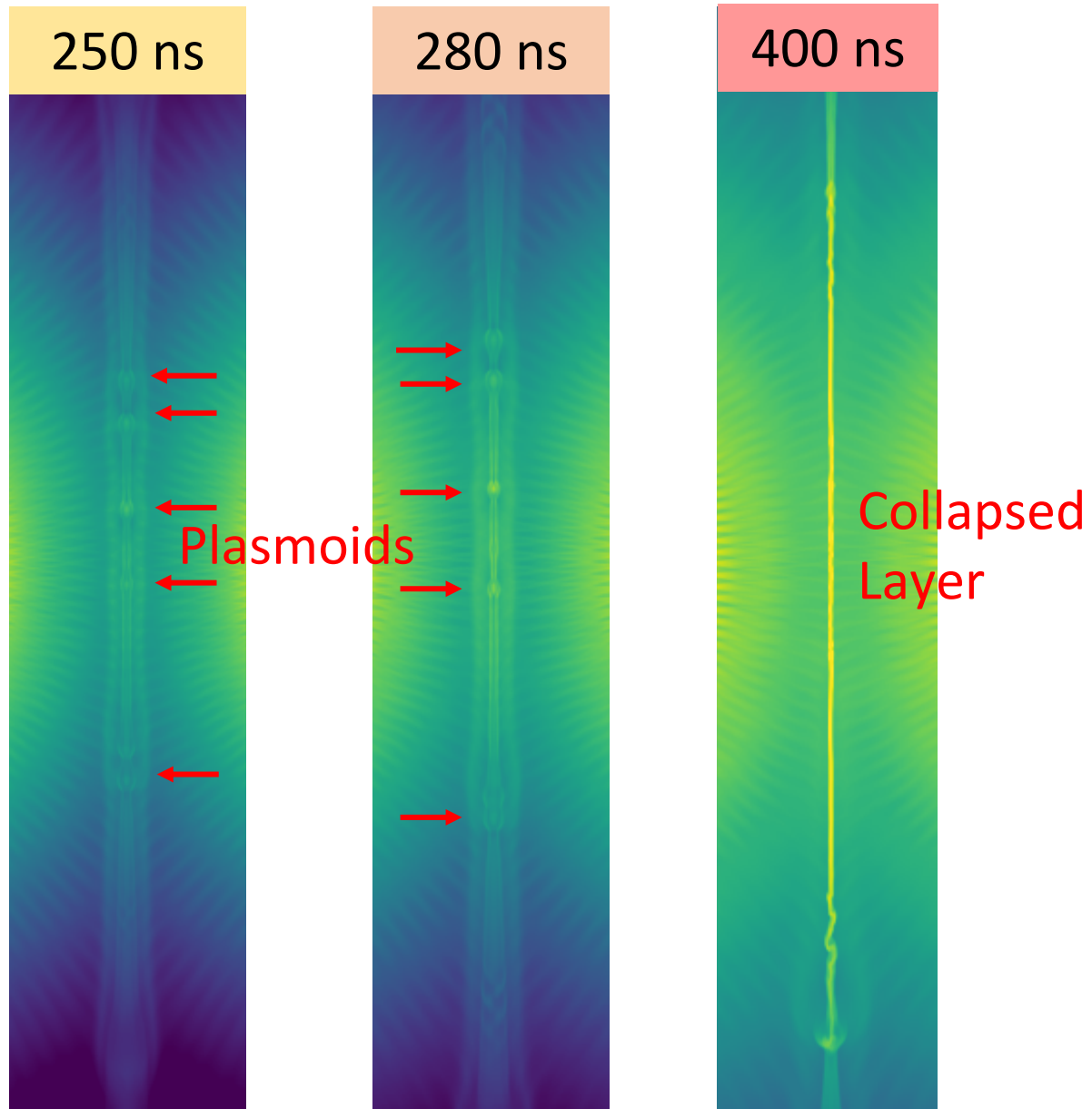
Arrays:

- 40 mm diameter
- 20 mm gap

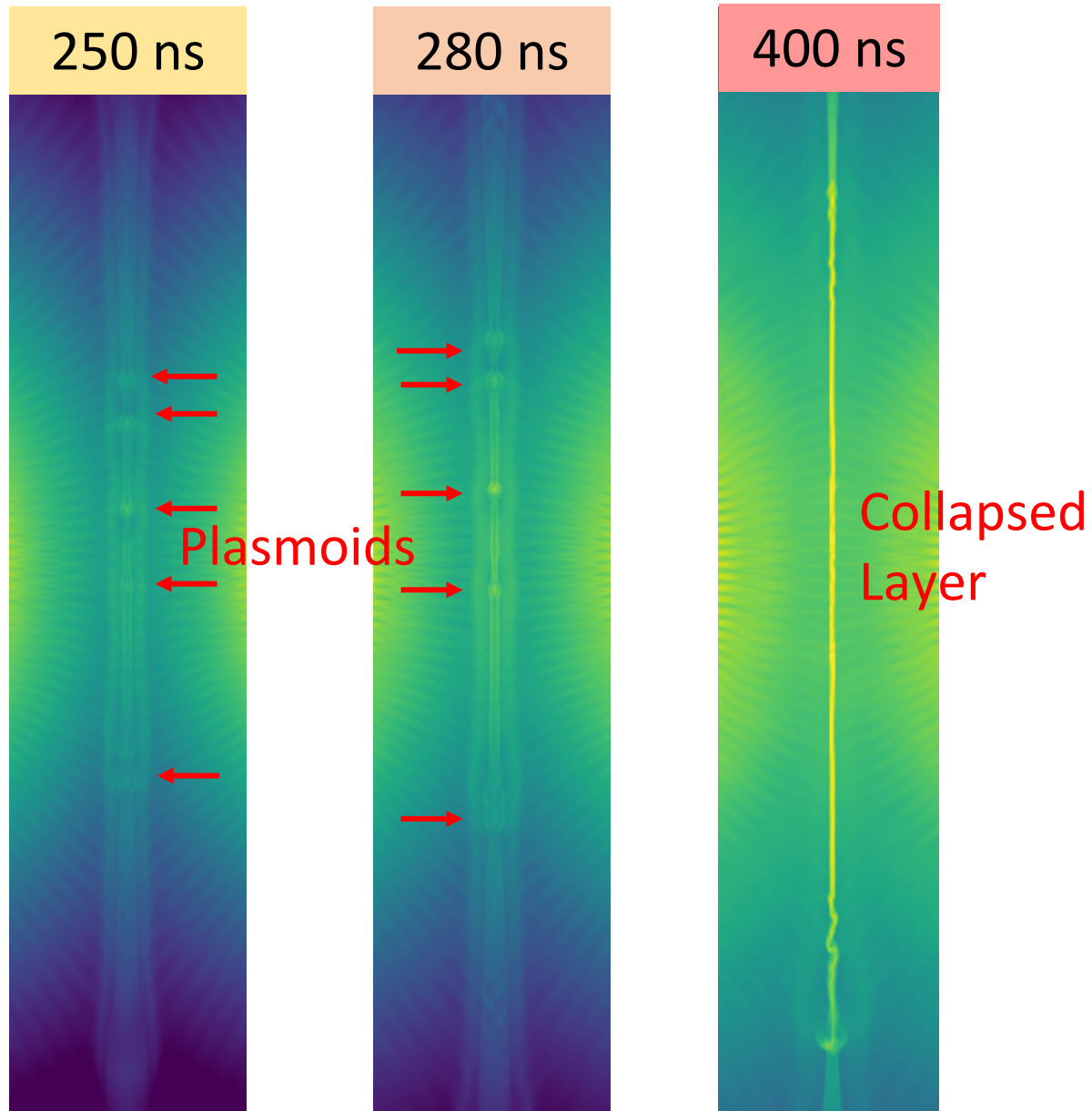


- 2D sims: 50 μm resolution, 180x90 mm. 16 hrs, 256 cores
- Recombination loss: $P_{rad} = M_{rad} C_r n_e T_e^{1/2} (Z^2 n_i E_\infty^{Z-1} / T_e)$, with $M_{rad} \approx 3$

Plasmoids and Collapse



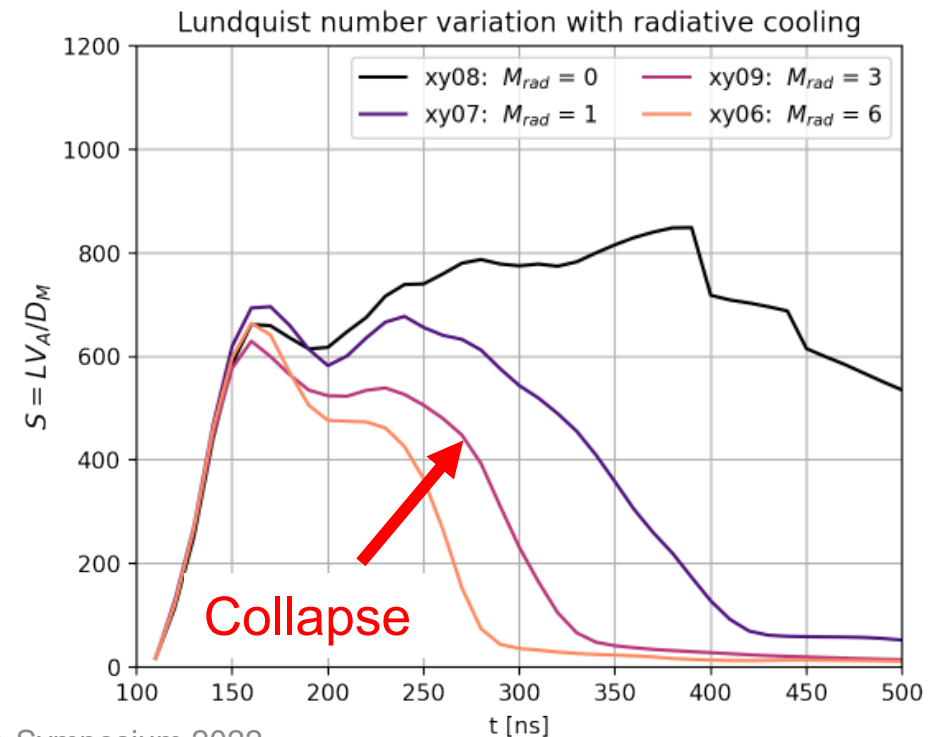
Plasmoids and Collapse



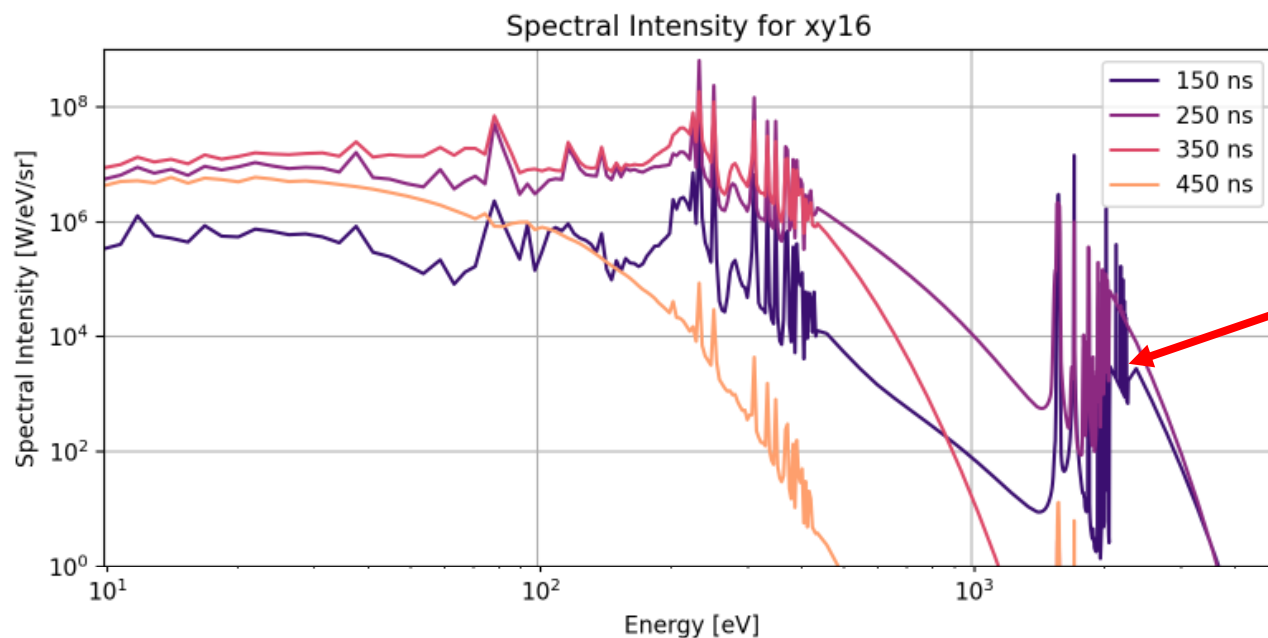
Lundquist number:

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

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



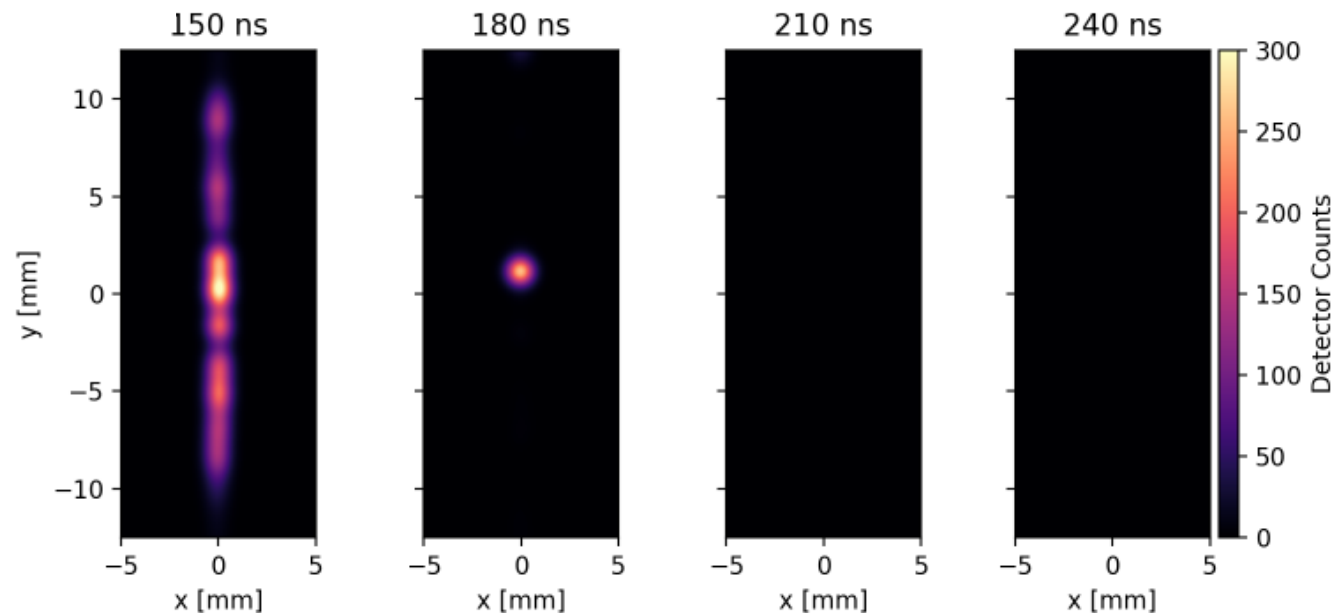
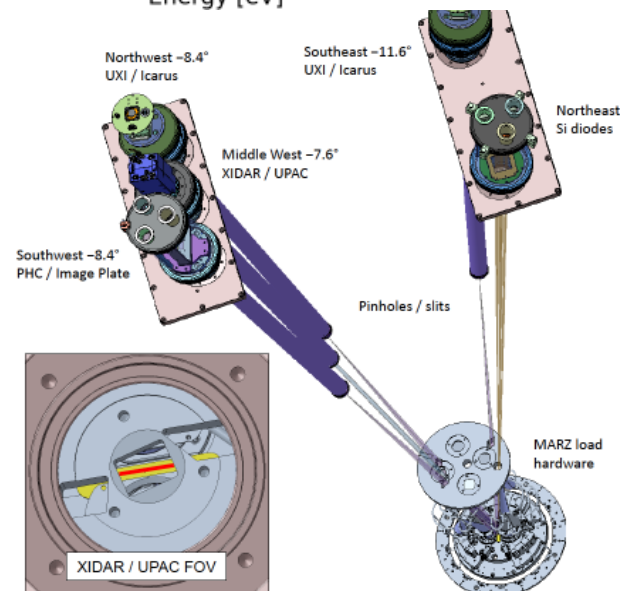
XP2: X-ray Post-Processor by Aidan Crilly & Jerry Chittenden



Al K-shell
disappears
after
collapse

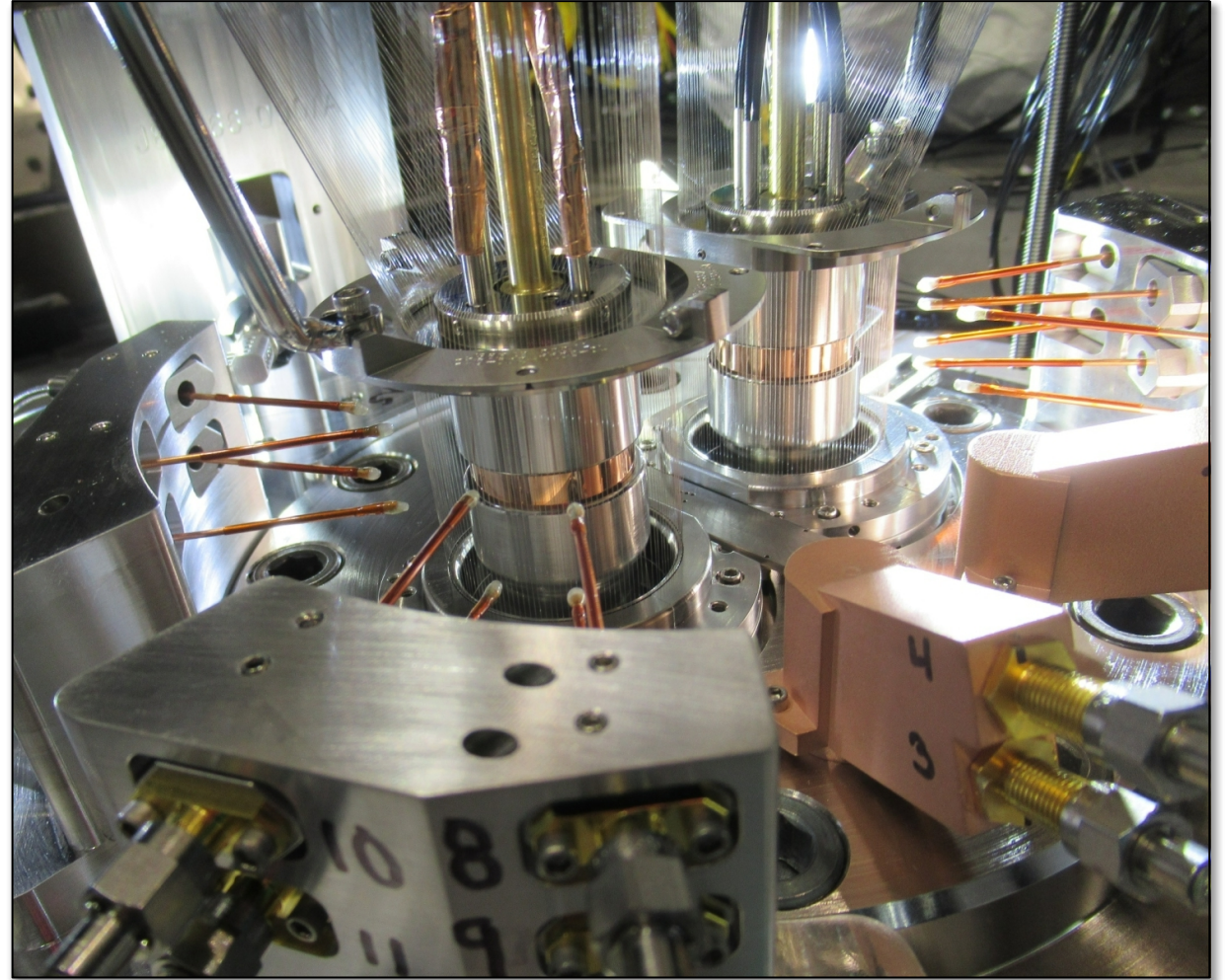
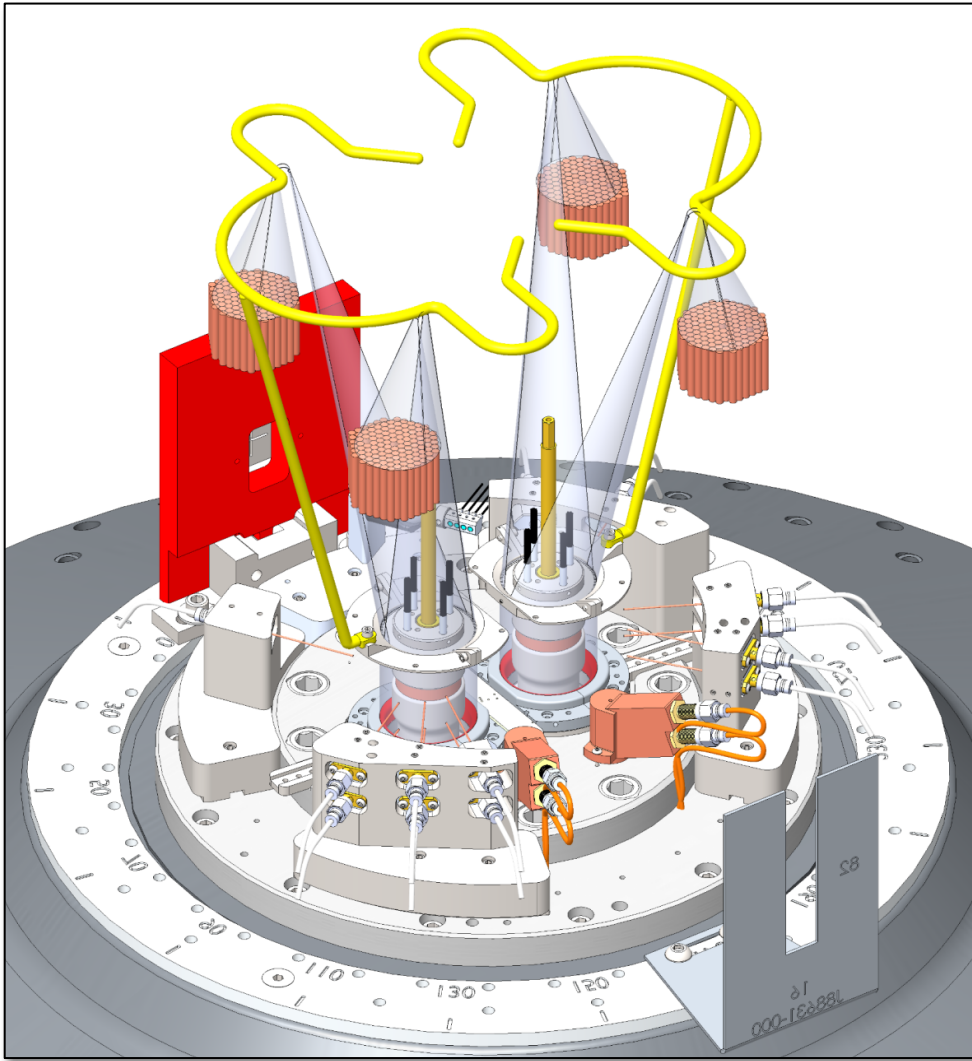
ICARUS for 3DMARZ with 10umBe filter, 150 um pinhole

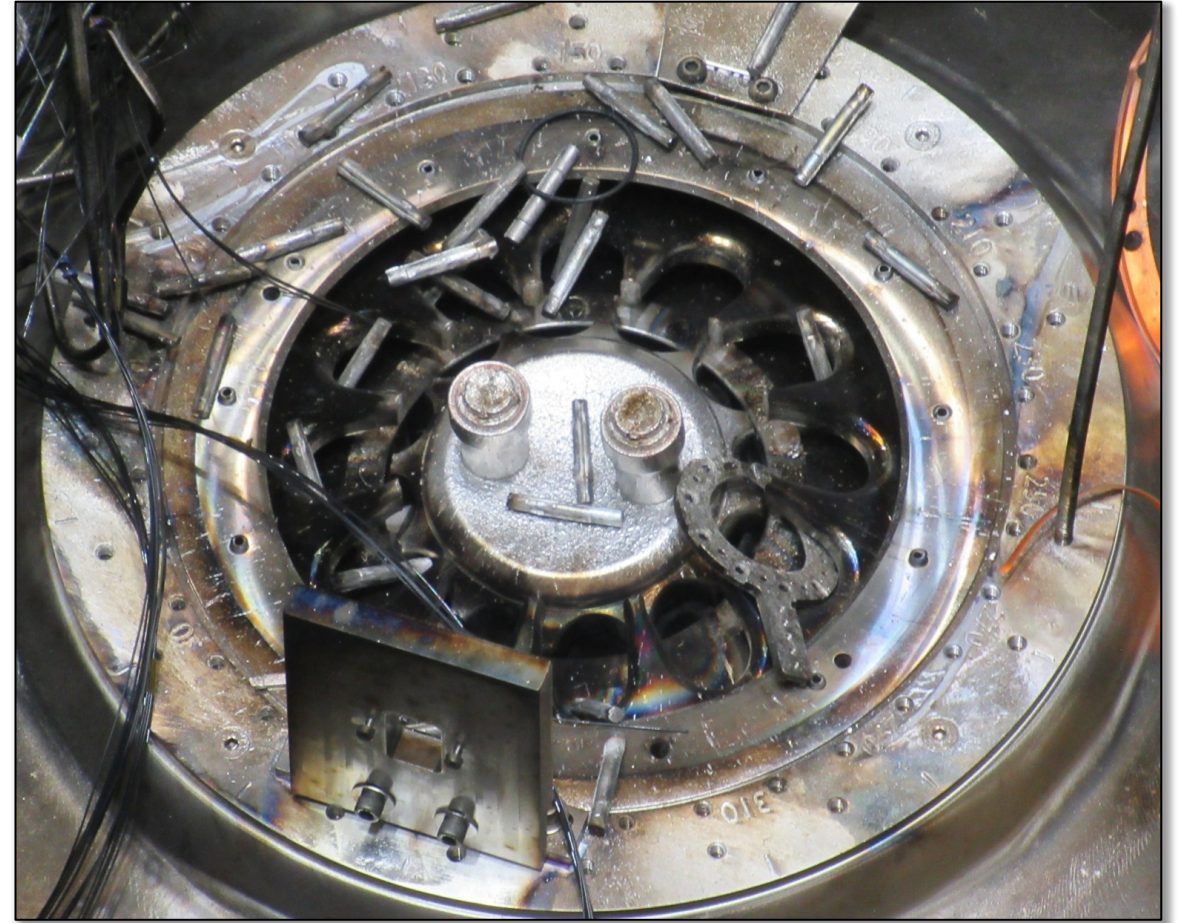
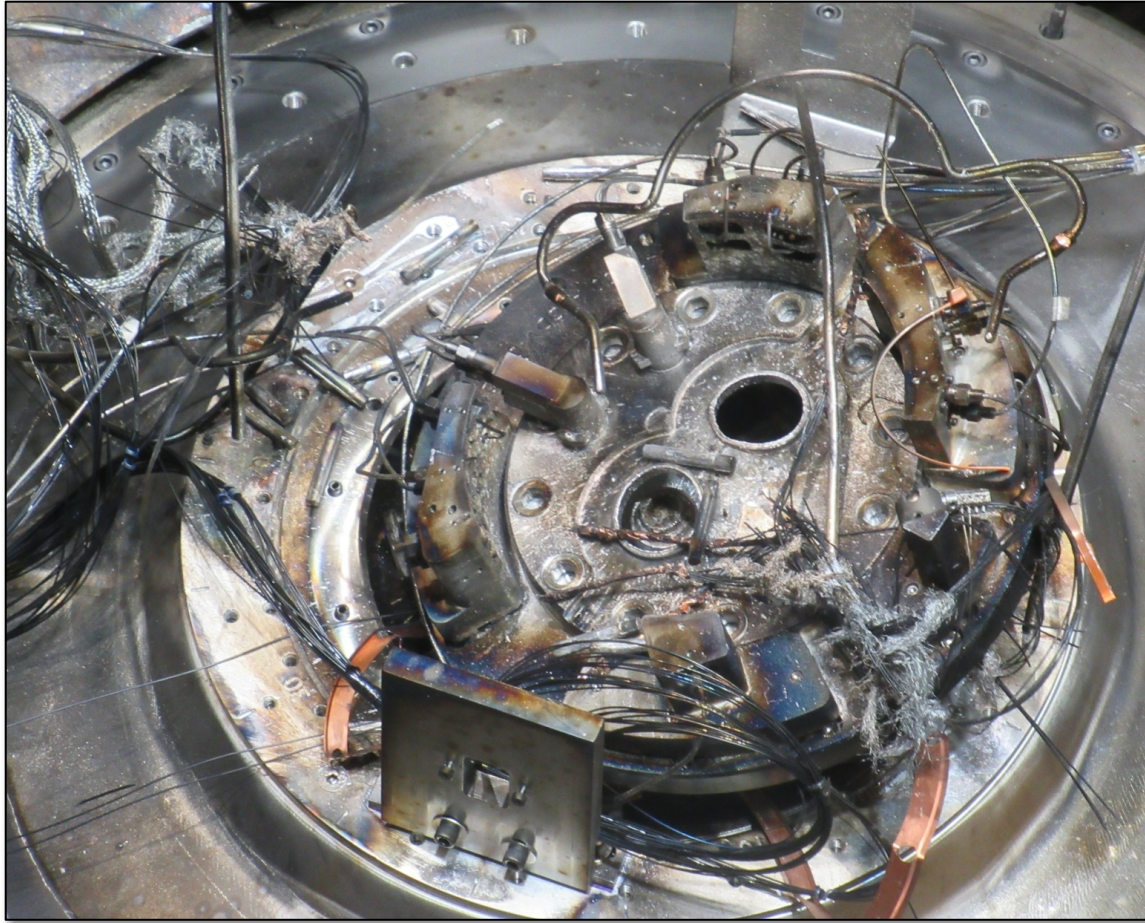
XP2 provides a predictive capability for X-ray diagnostics



USED POWER ACROSS SCALES — FEBRUARY 2, 2022

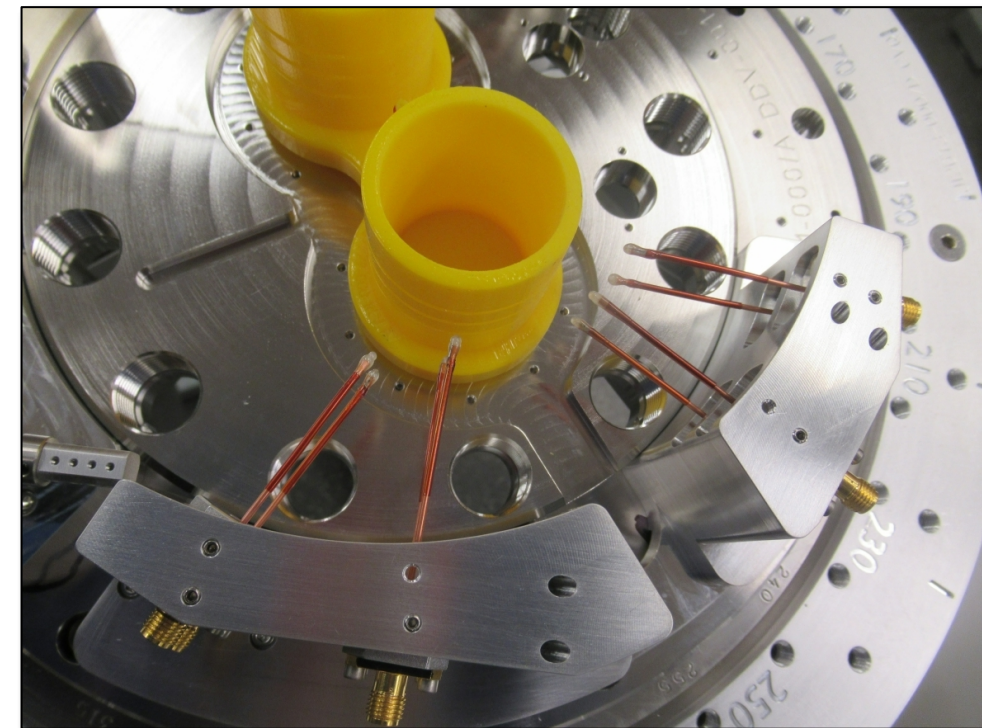
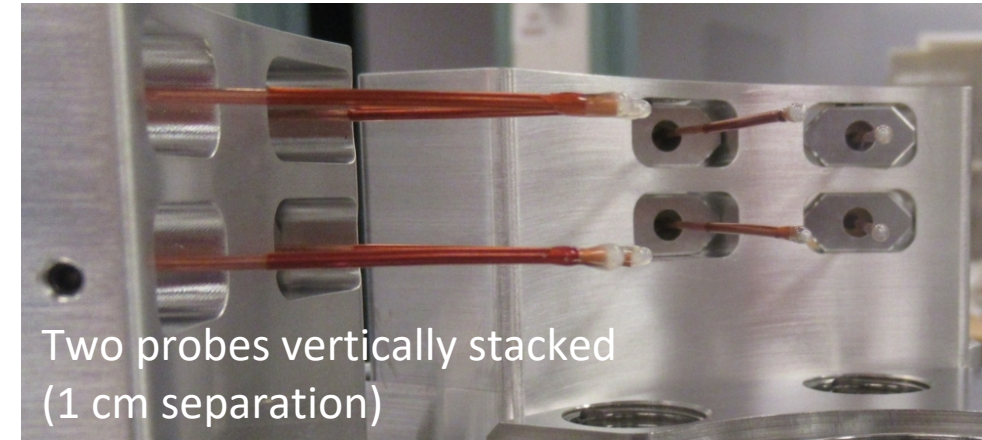
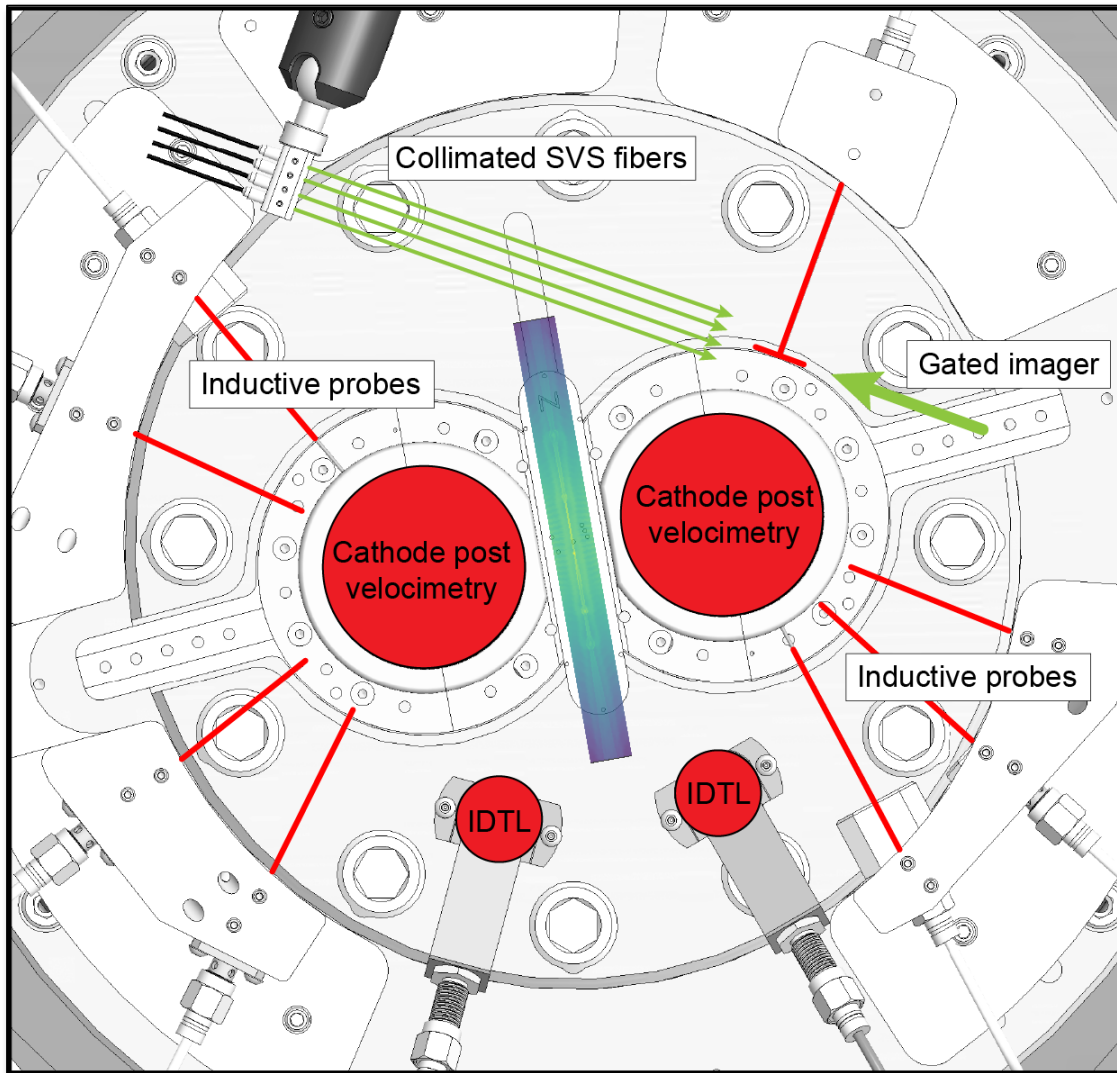
Load Hardware for the first MARZ shot



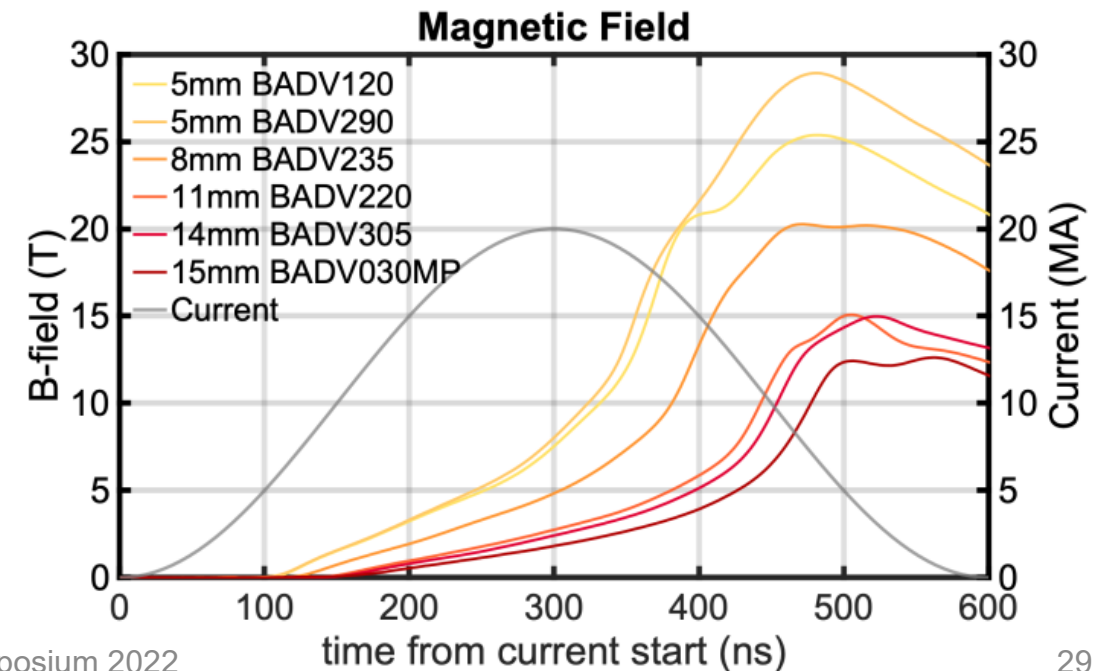
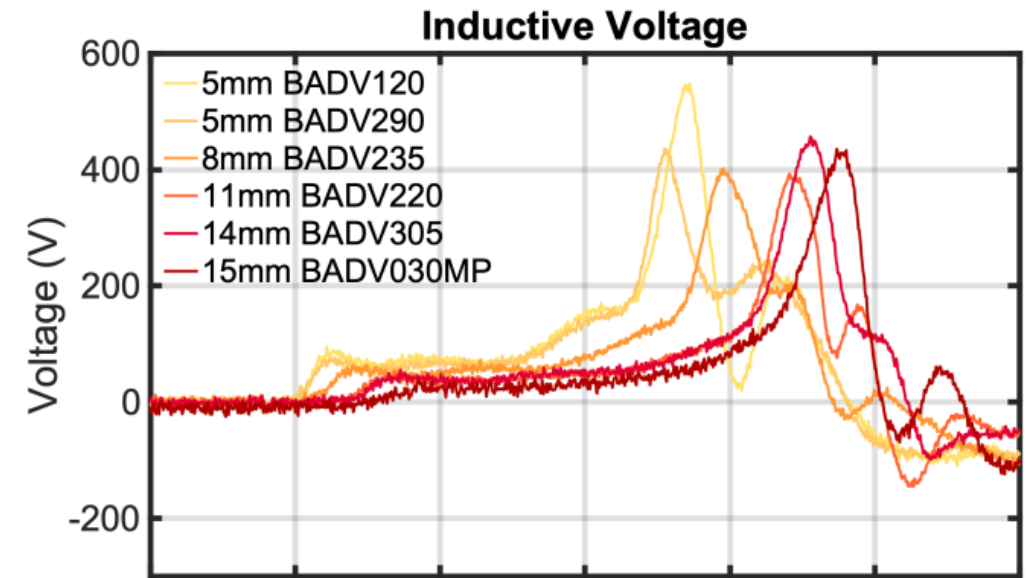
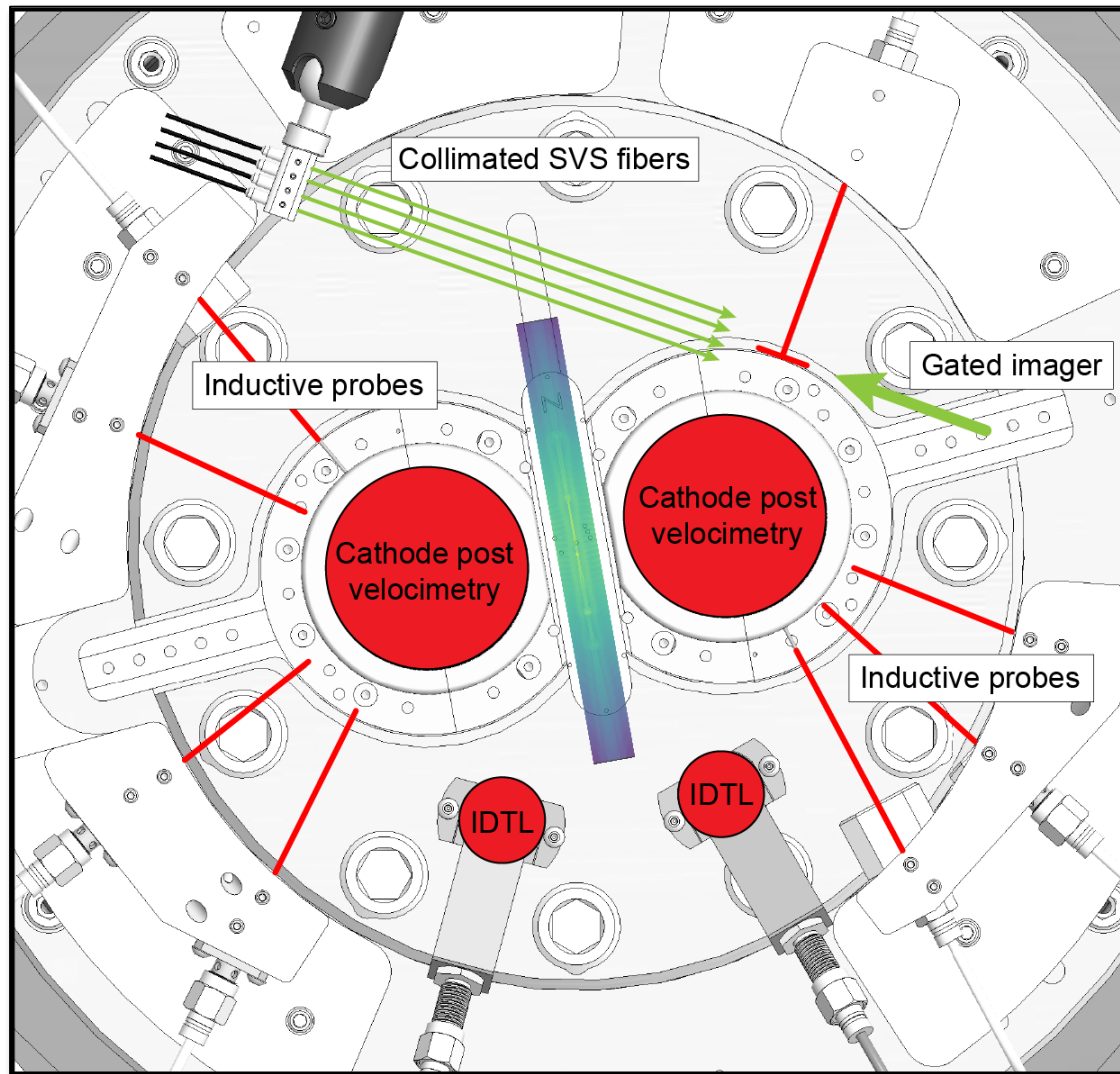


Weeks to build, a microsecond to destroy!

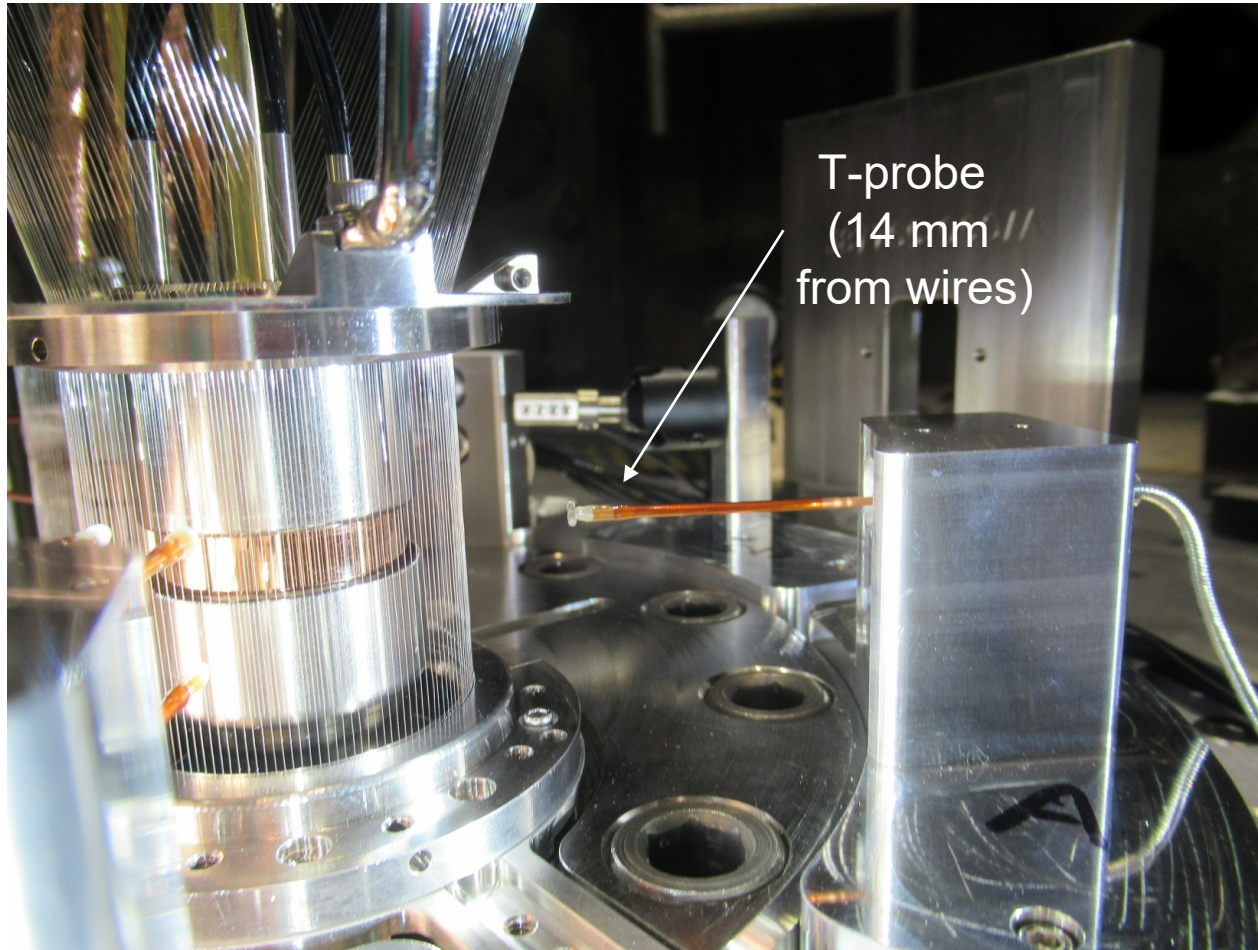
Magnetic Probe Measurements: Plasma Flow



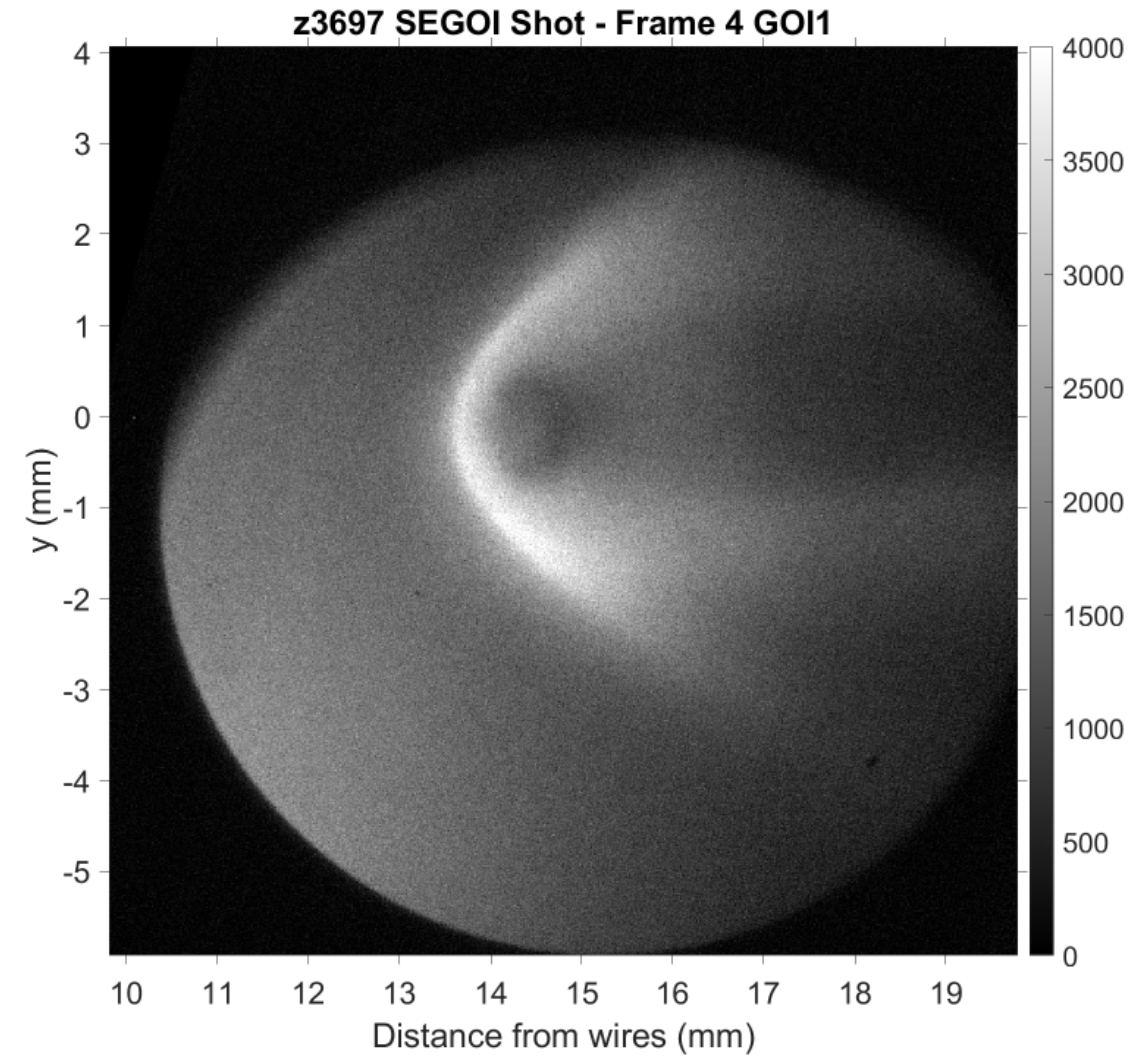
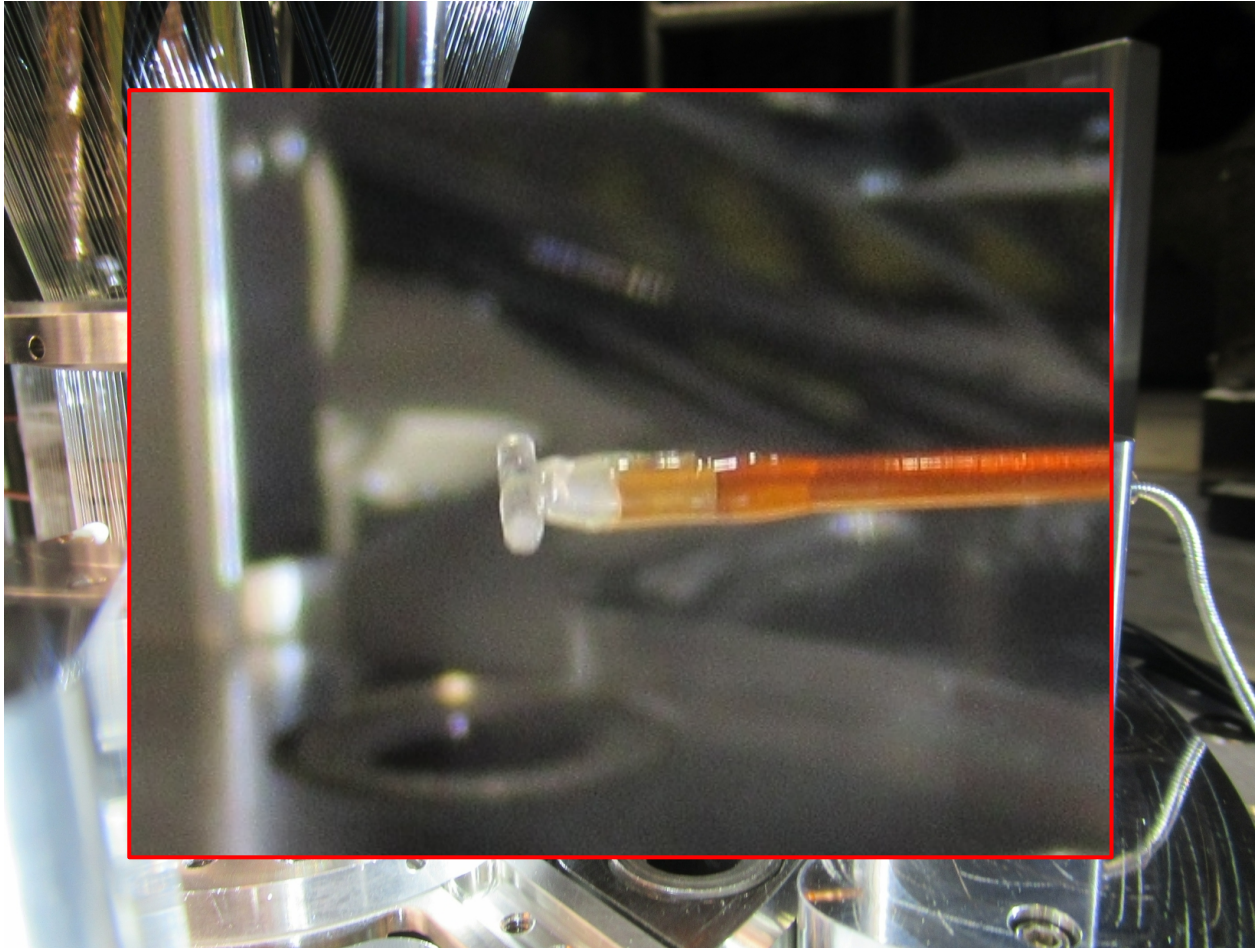
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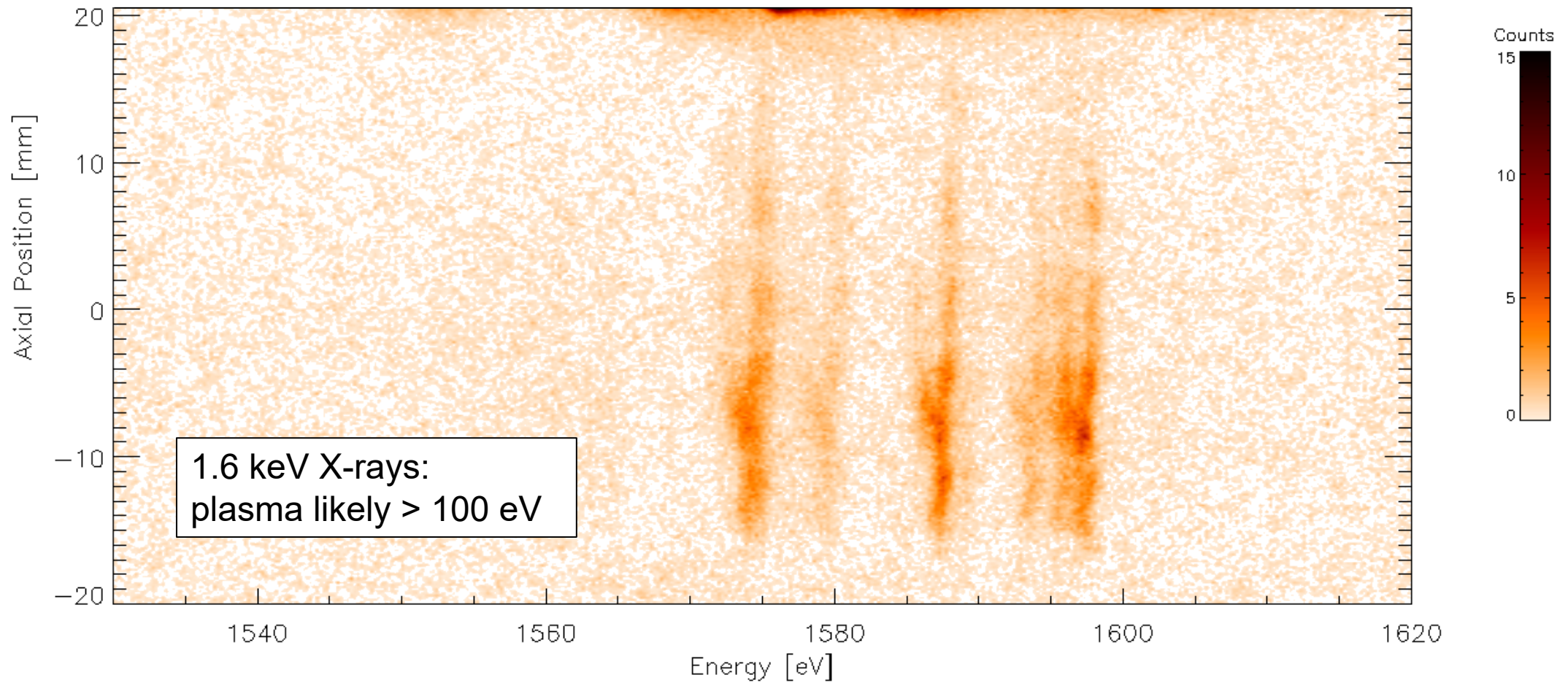
Bow shock around B-dot probe: Plasma Flow



Bow shock around B-dot probe: Plasma Flow

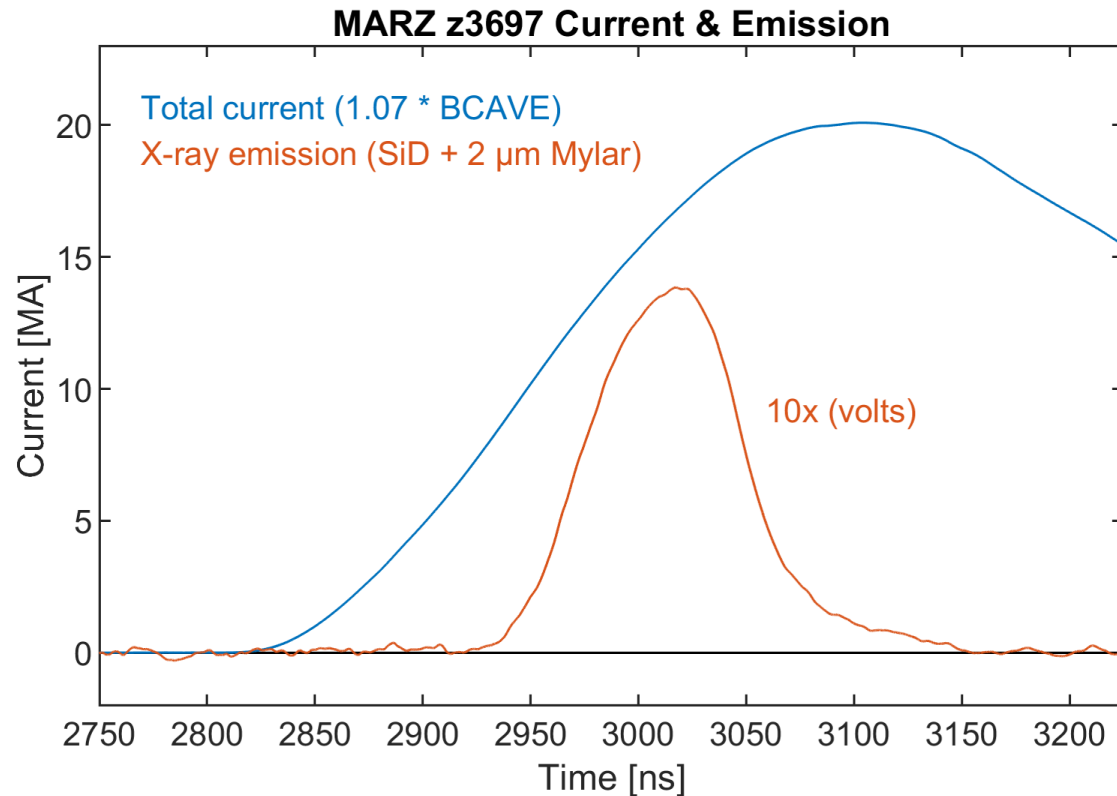


Time Integrated X-ray Spectrum: Hot Plasma

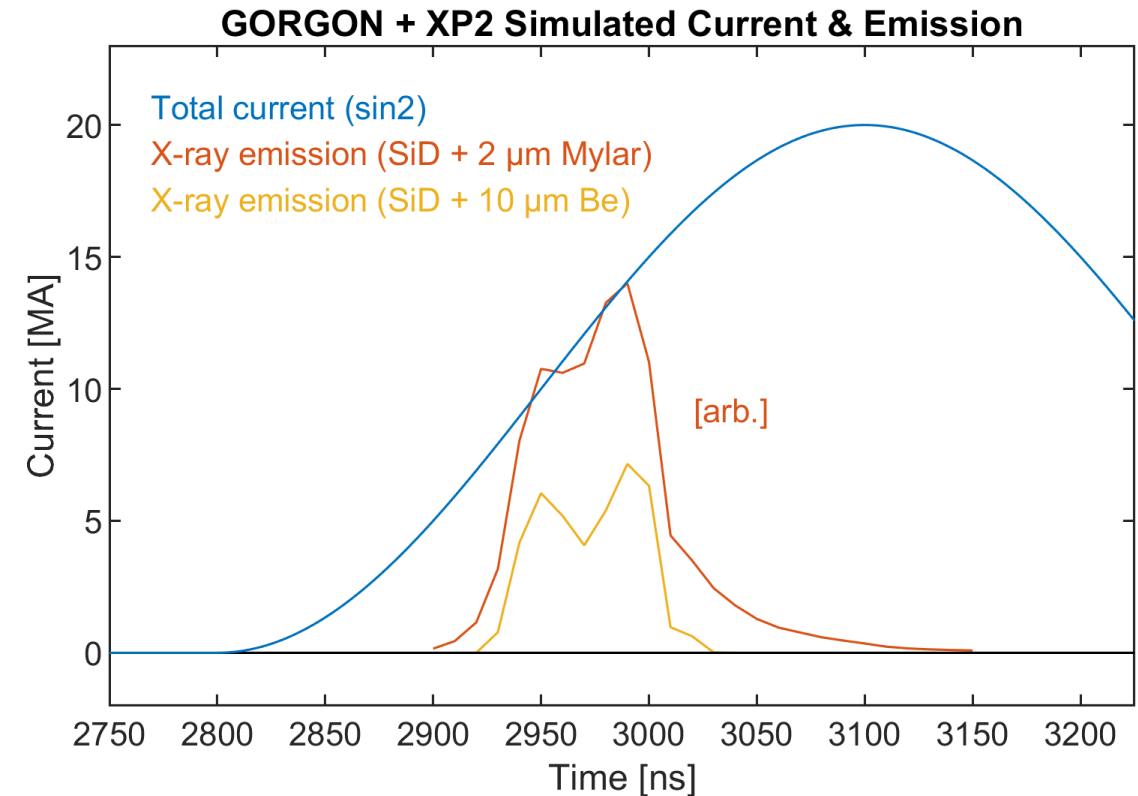




Experiment

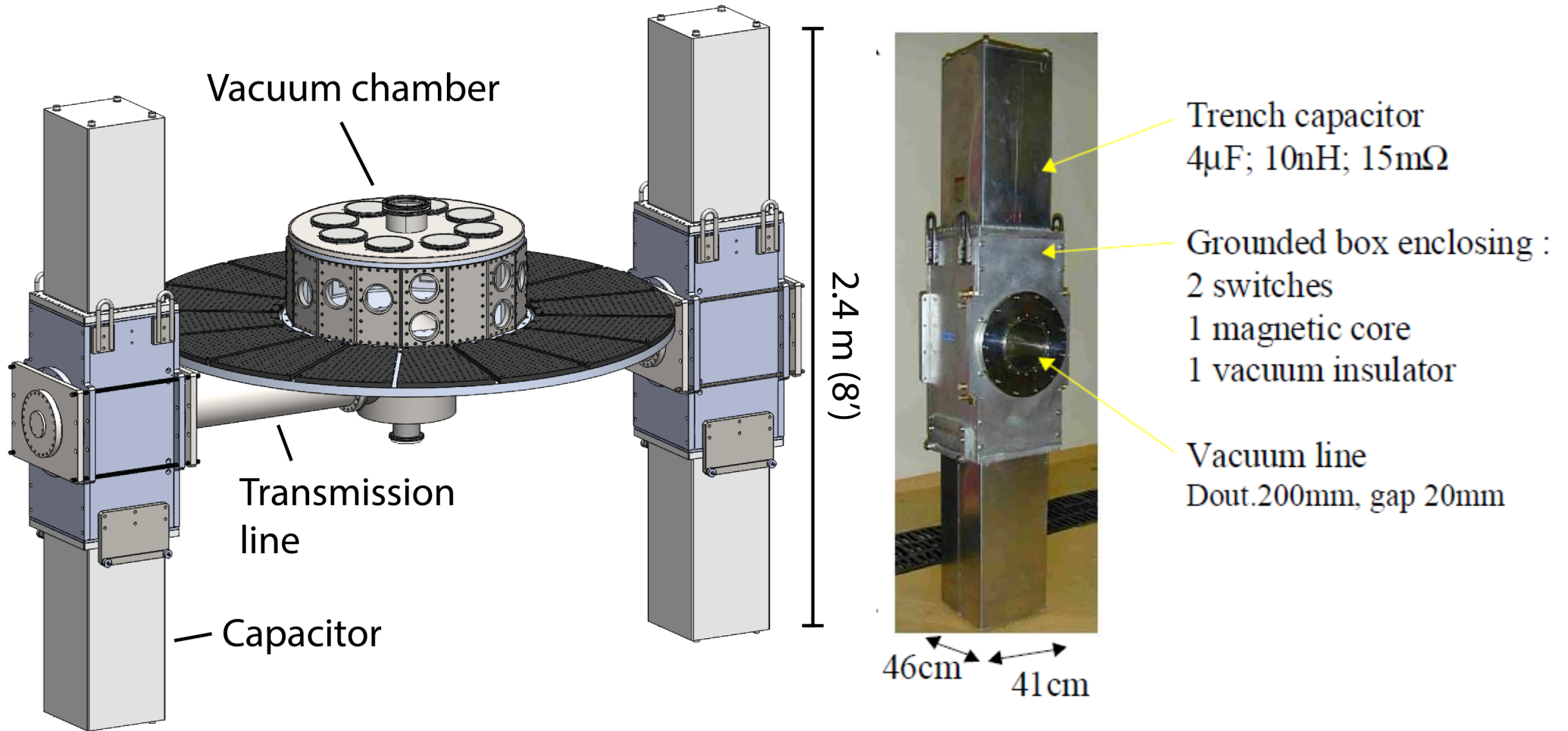


Simulation

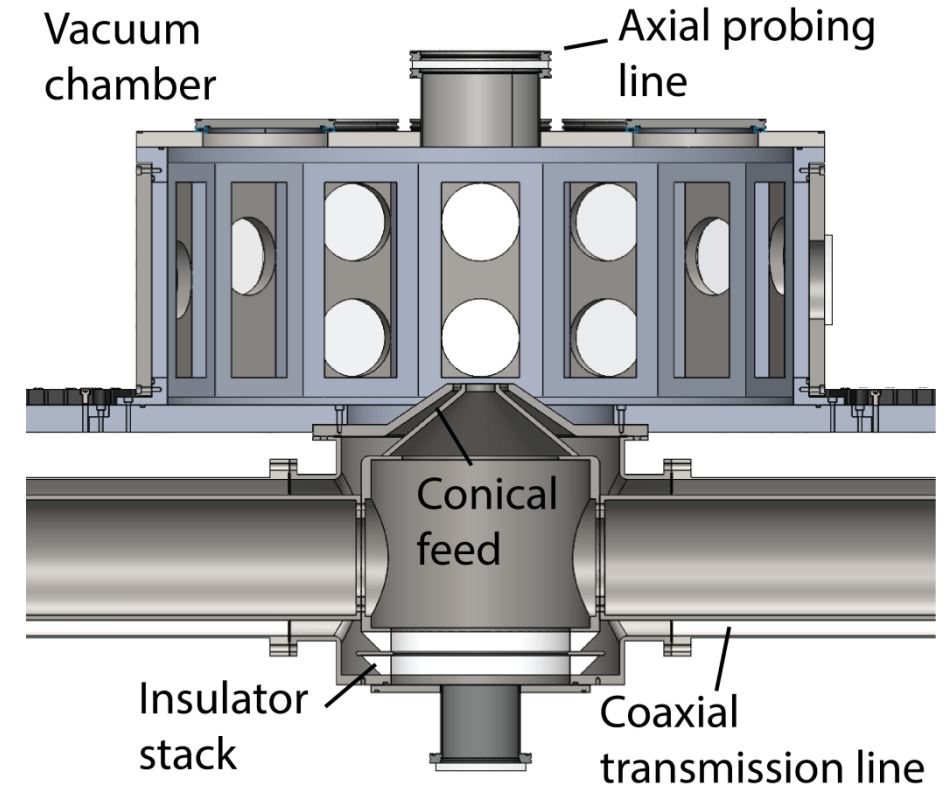
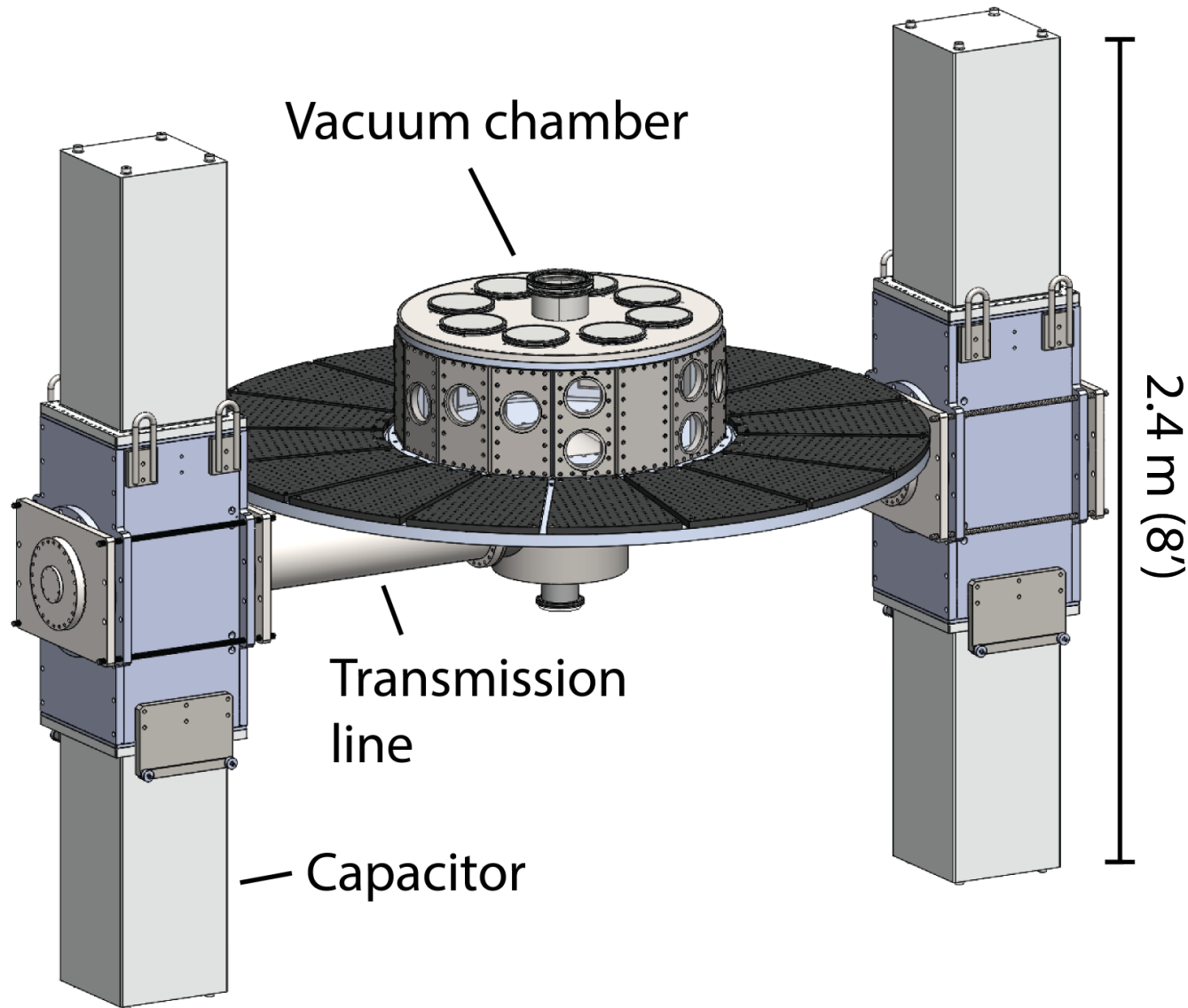


- Radiated power rises after current start, drops before current peak
- X-ray spectra appears softer than simulated: more shots in December

PUFFIN uses 2 LTD5 stages from SPHINX (CEA Gramat)



PUFFIN 2x1 will drive around 600 kA with a 1.5 μ s rise time

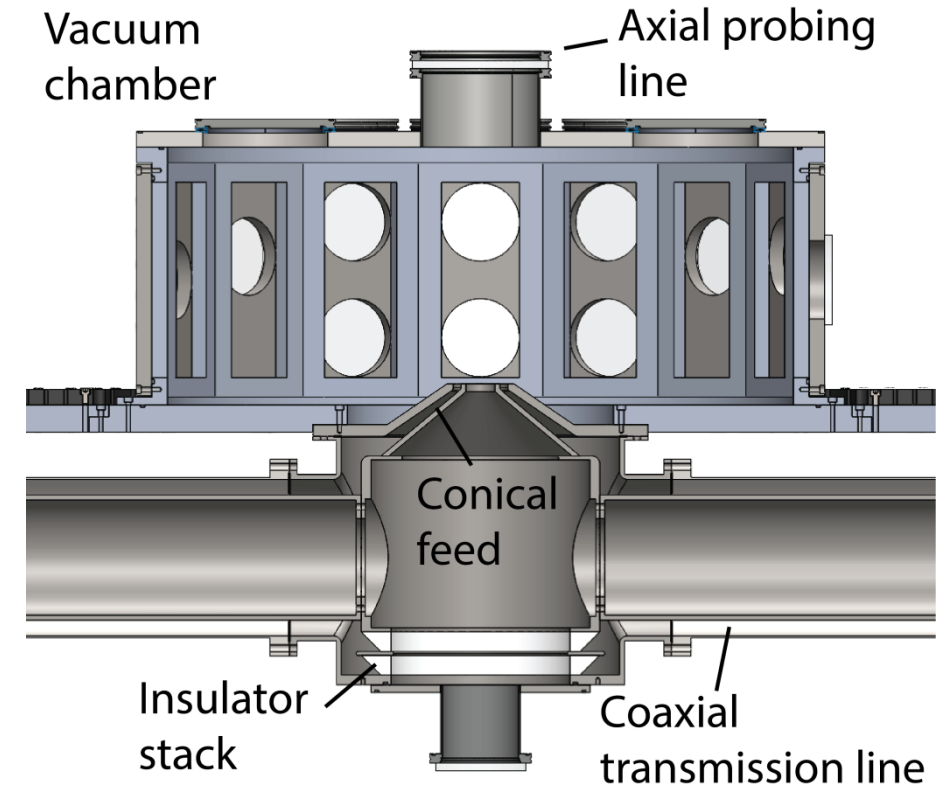
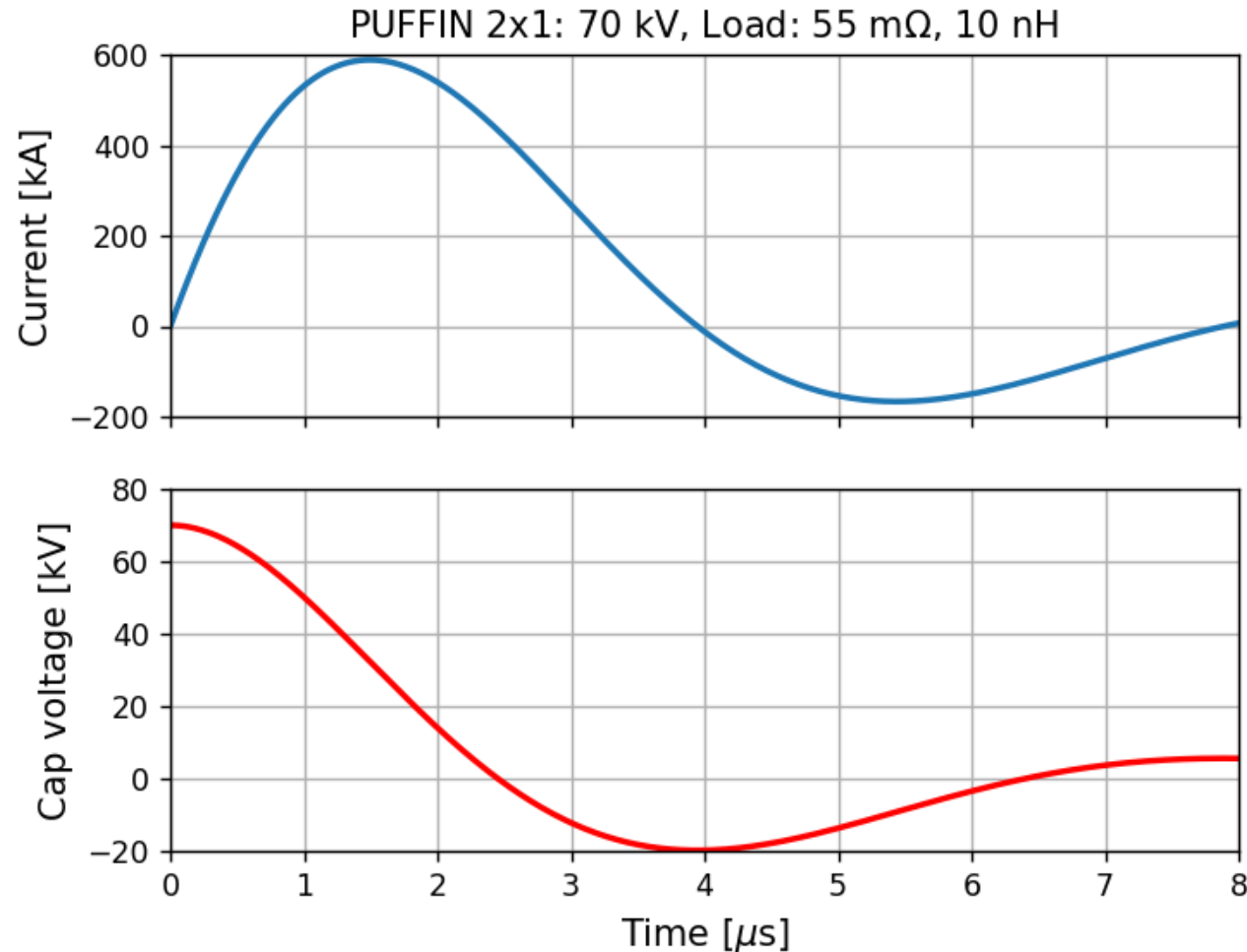


40 kJ energy to load
First plasma in 2023
puffin.mit.edu

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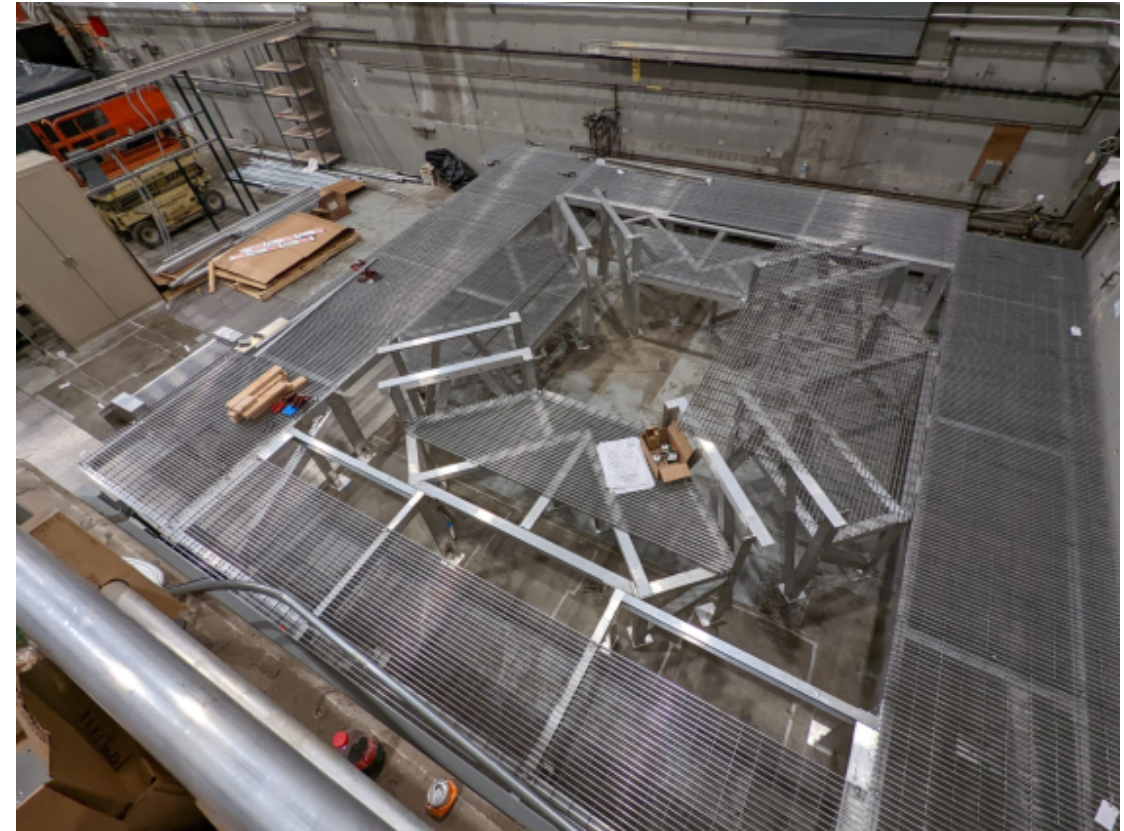


Critically matched load resistance minimizes reverse voltage, but also peak current



40 kJ energy to load
First plasma in 2023
puffin.mit.edu

Construction underway, first plasma 2023!

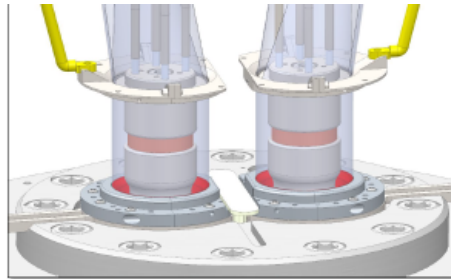




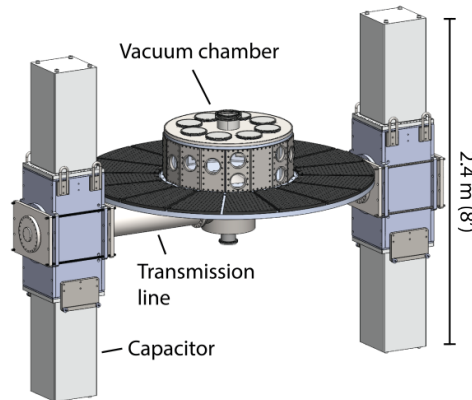
Magnetic reconnection



Radiatively cooled reconnection on Z



PUFFIN: long pulse experiments ($1.5 \mu\text{s}$, 600 kA) @ MIT



Unifying theme: energy flows in plasmas

