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The New PUFFIN Generator at MIT

Jack Hare, jdhare@mit.edu

MIT PSFC Plasma Science and Fusion Center

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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

This work is supported by the NSF and NNSA

NNSA National Nuclear Security Administration

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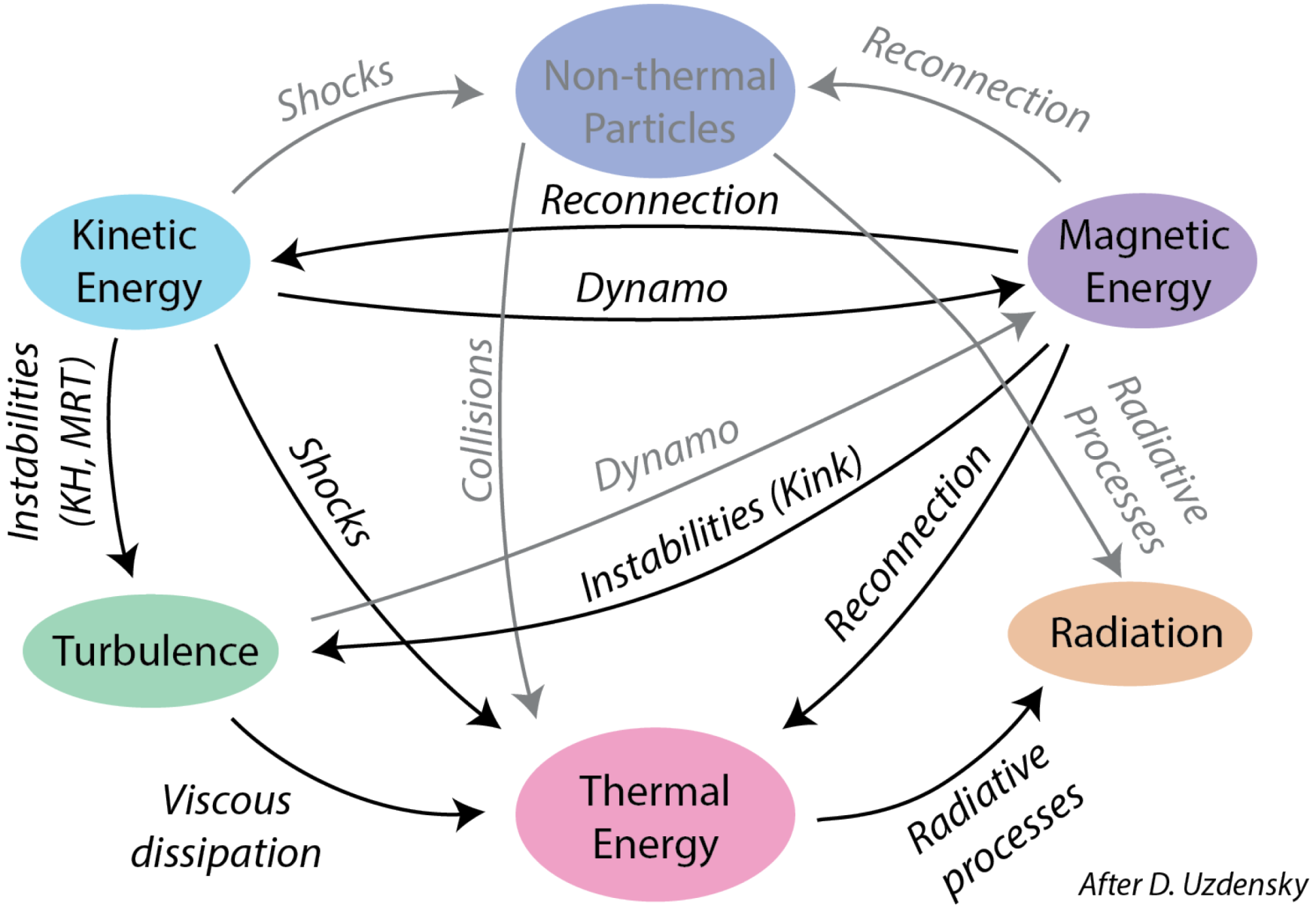
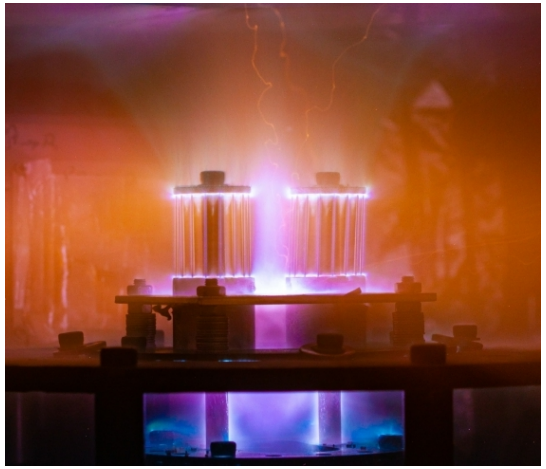
Research Interests: Energy Flows in Plasma



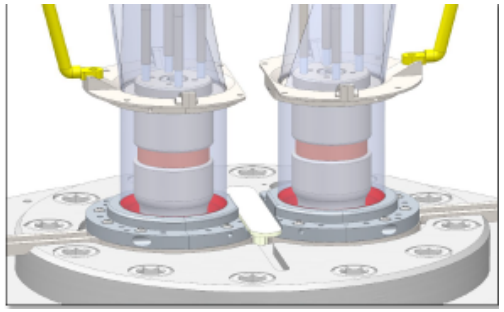
Research paths/talk outline

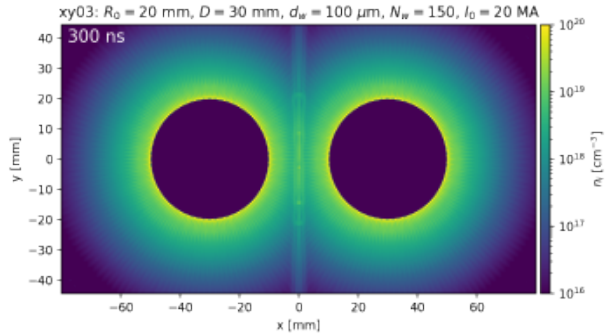
Magnetic reconnection



More current

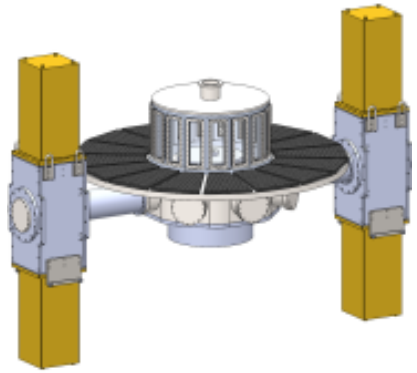
Radiatively cooled reconnection on Z

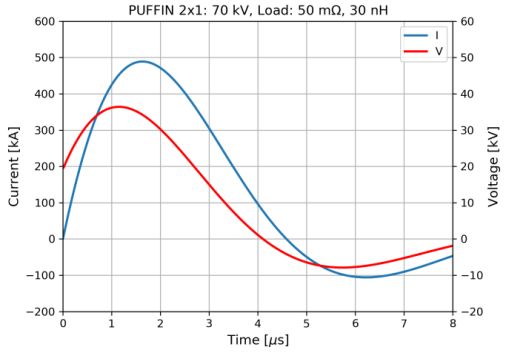




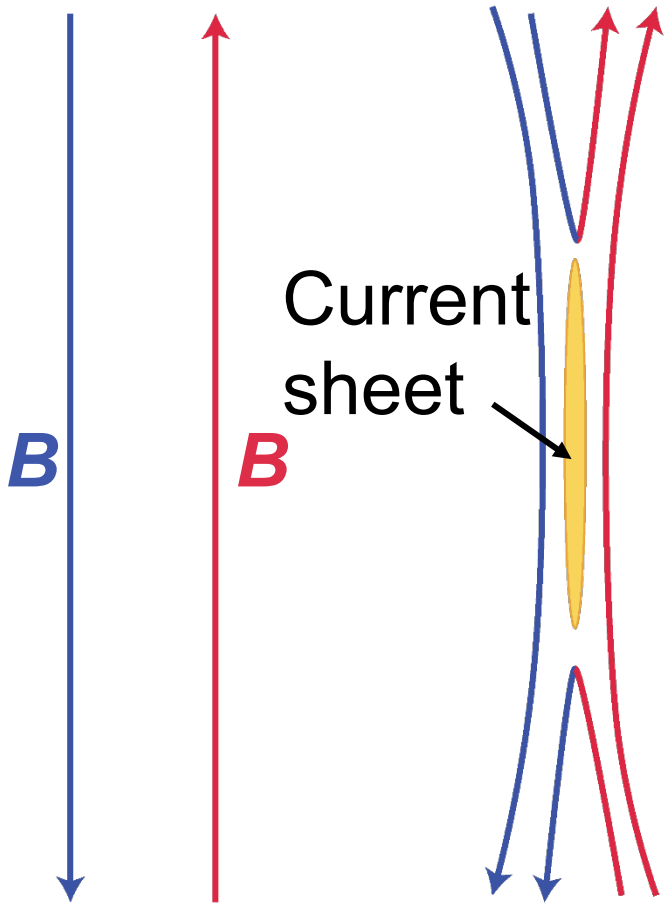
Longer current pulse

PUFFIN: 2 μs, 500 kA at MIT

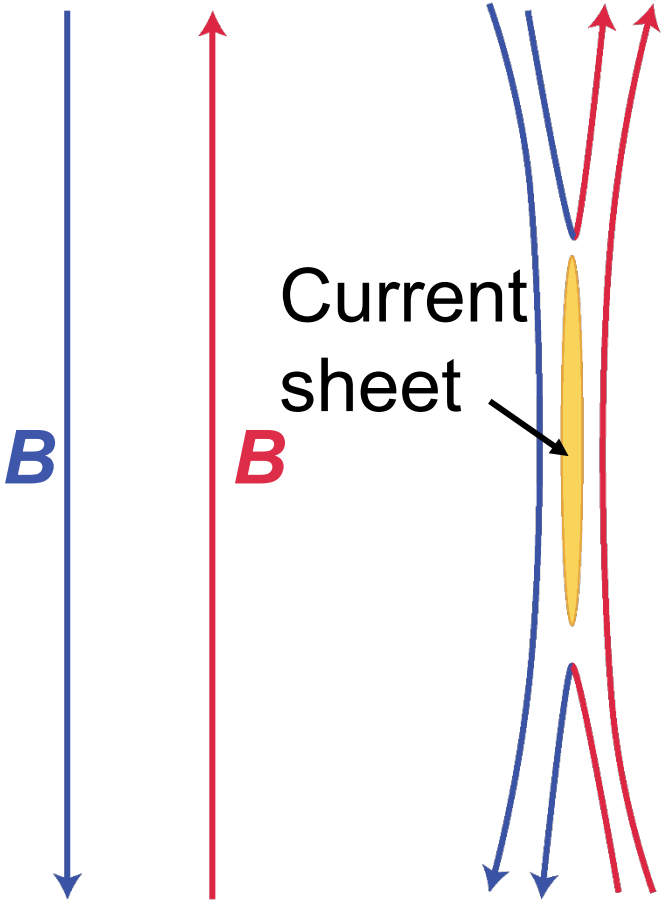




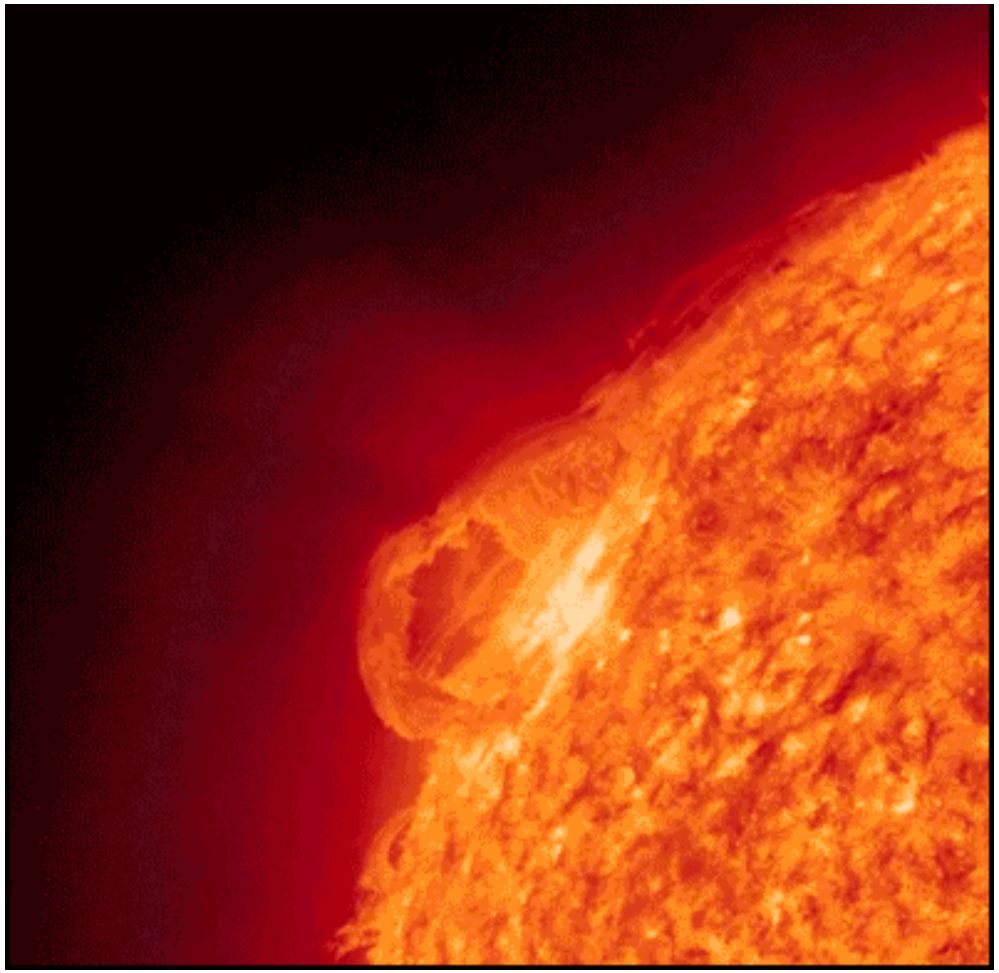
Magnetic Reconnection



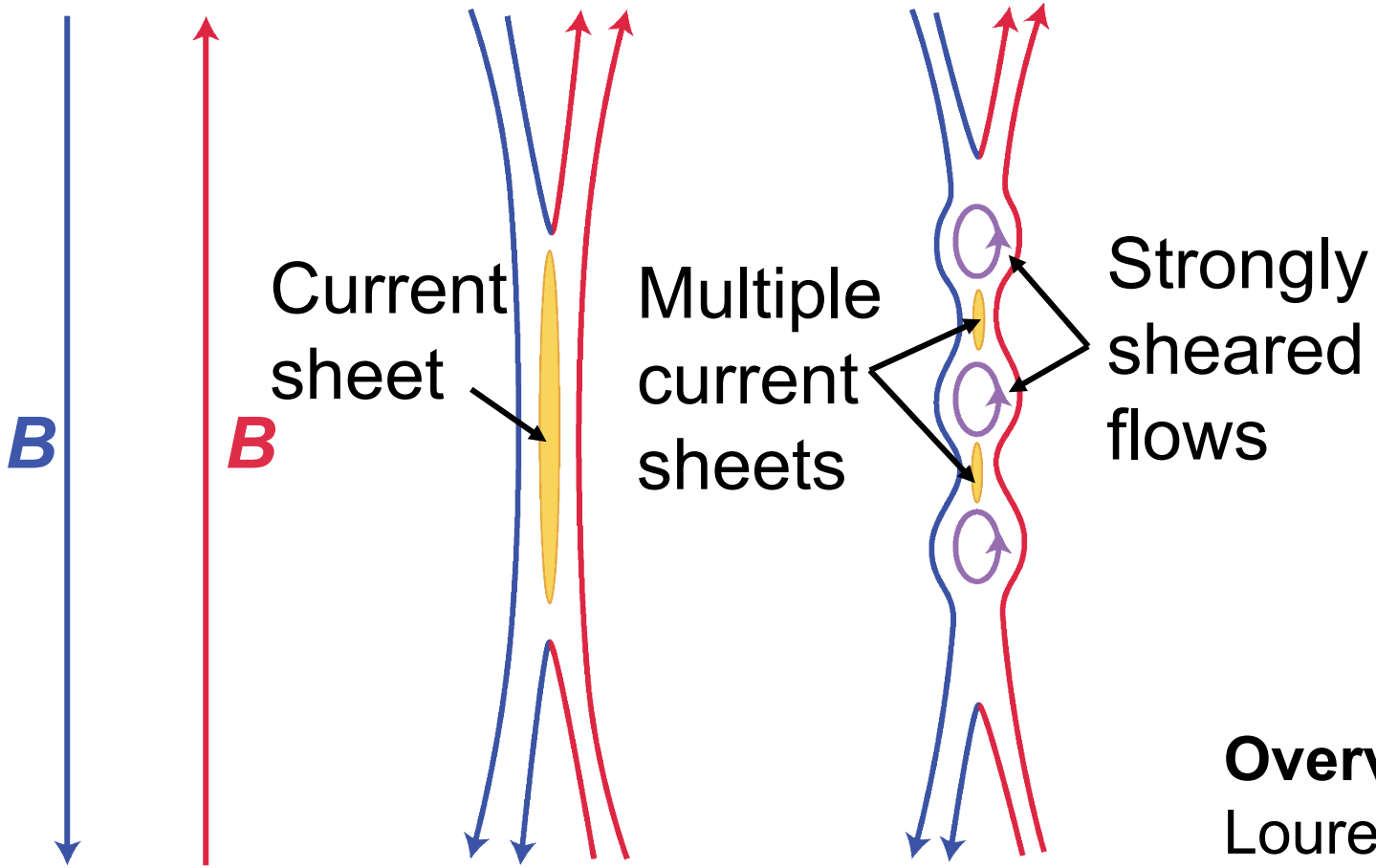
Magnetic Reconnection



Prediction: 1000 yrs. Reality: 10 minutes!

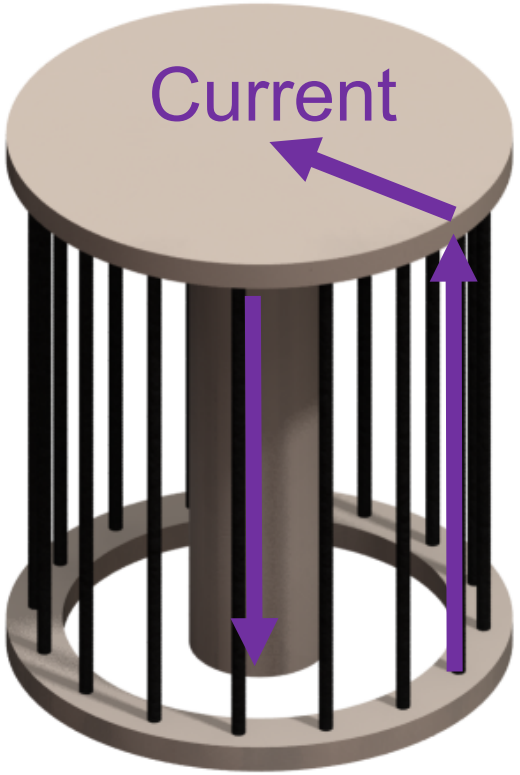


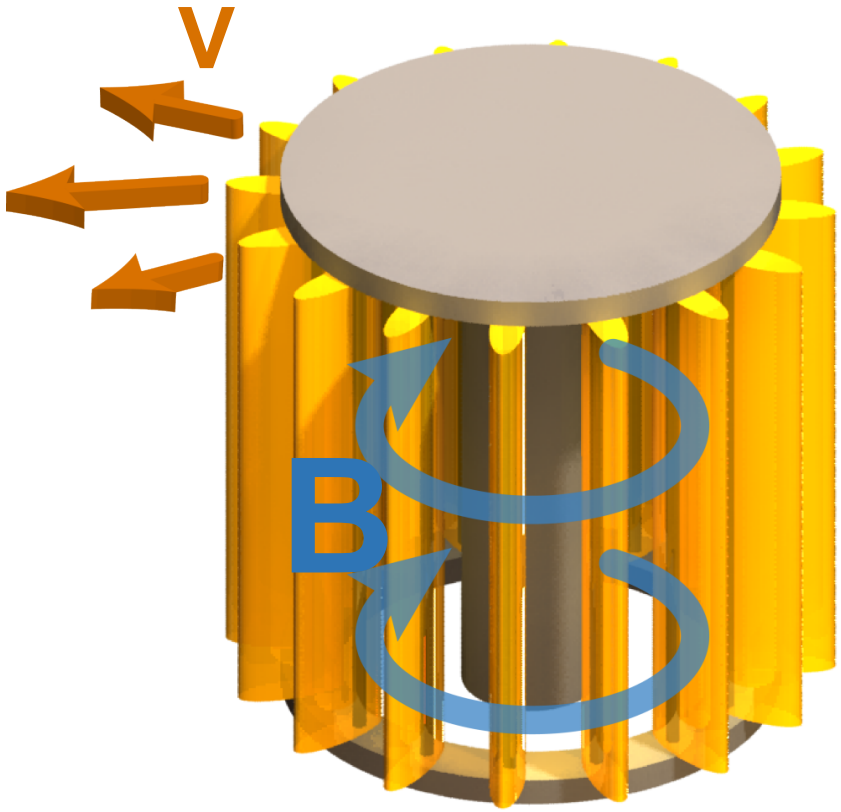
Plasmoids Lead to Fast Reconnection and Anomalous Heating



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

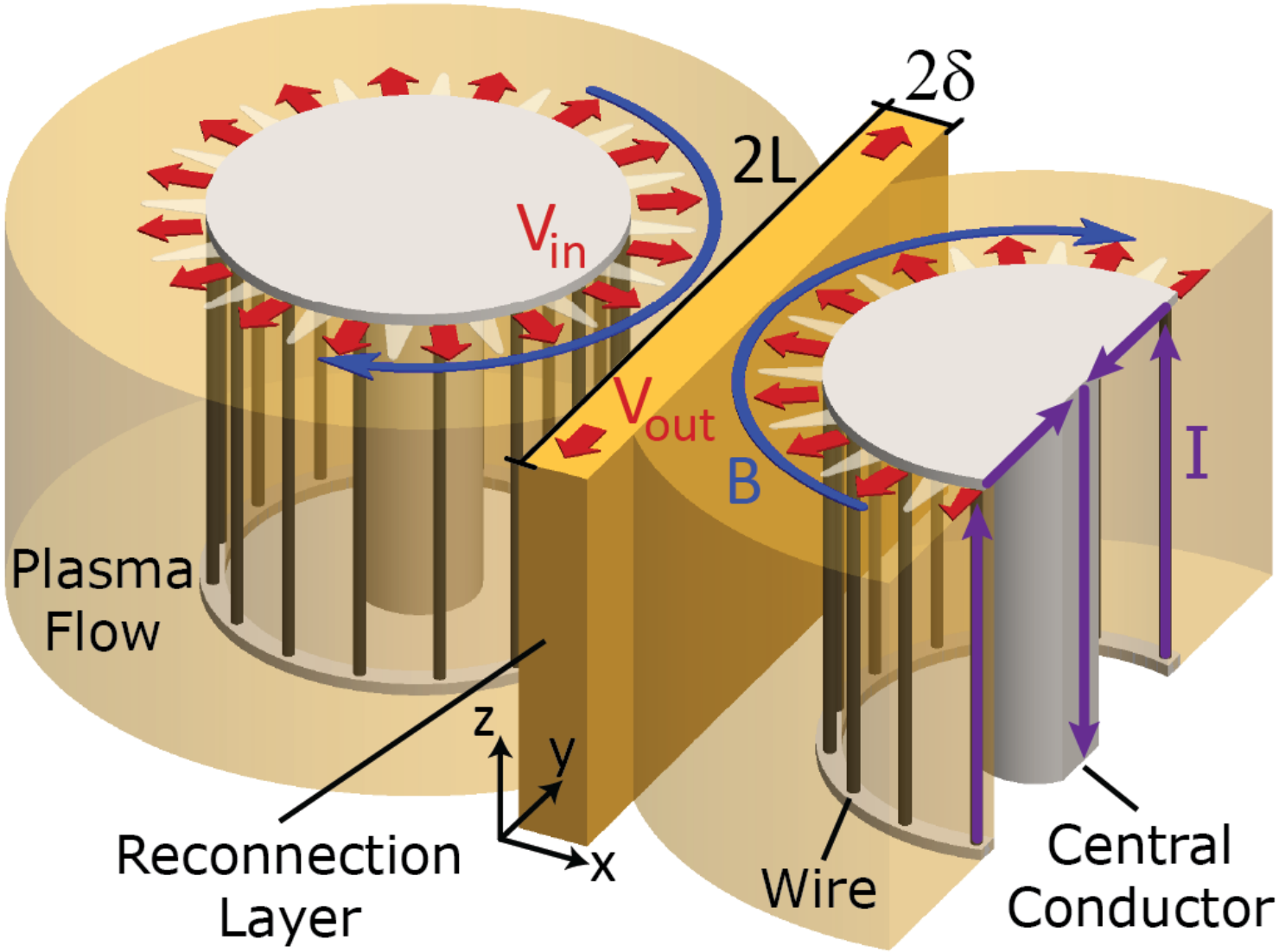
Pulsed-power-driven Magnetic Reconnection





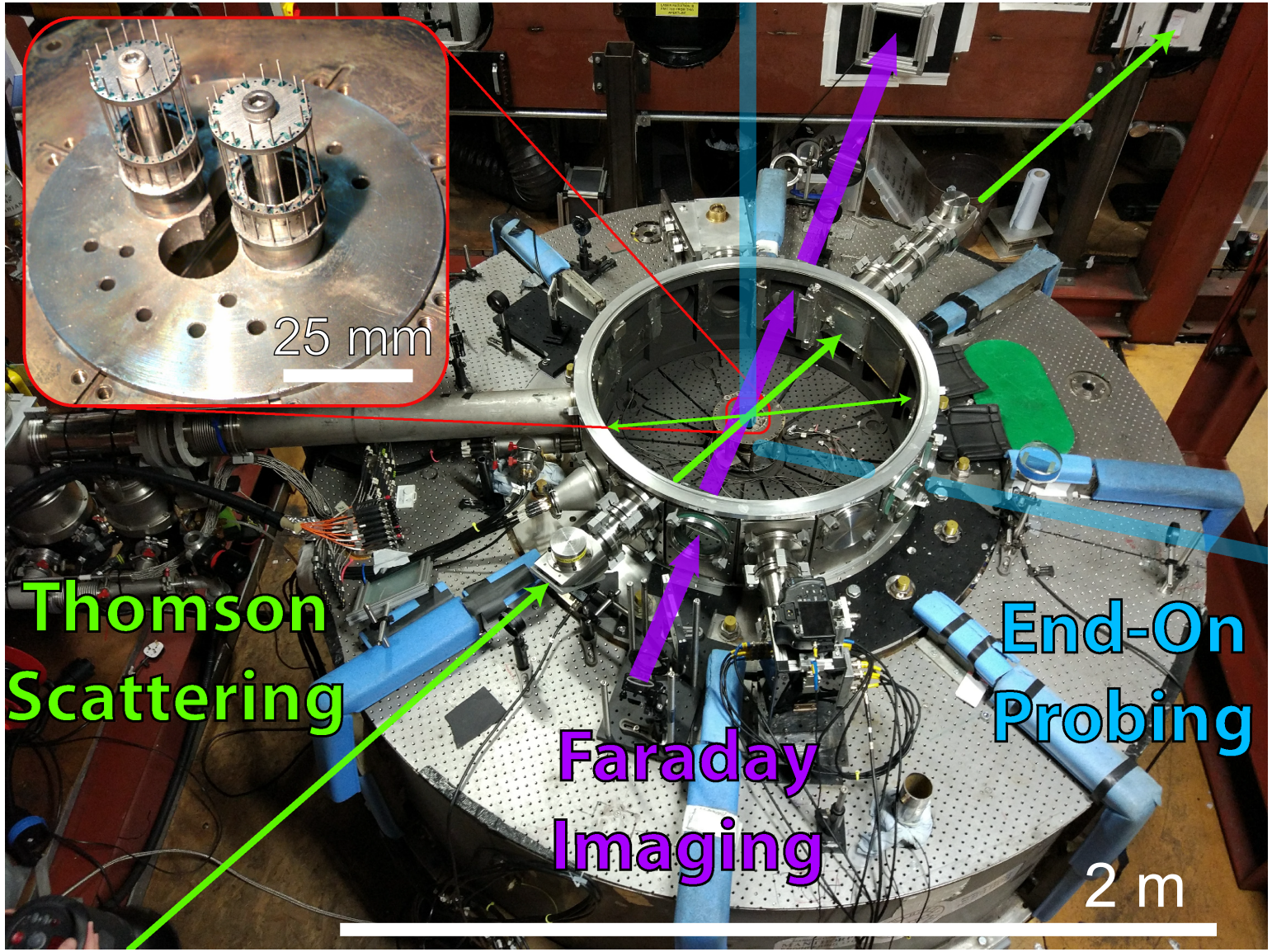
I=1.4 MA, 240 ns rise time

Magnetic Reconnection from Double Exploding Wire Arrays



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

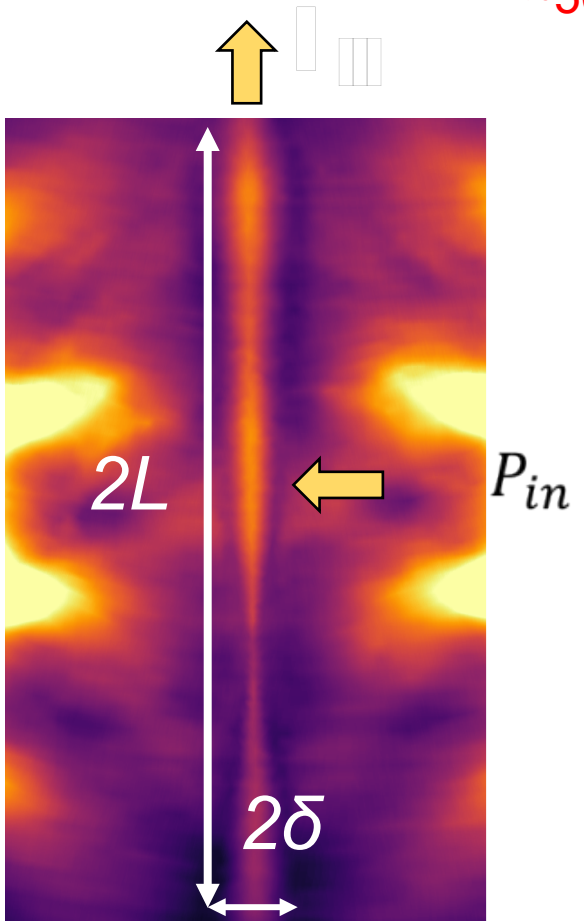
Overview of Diagnostic Suite on MAGPIE at Imperial College

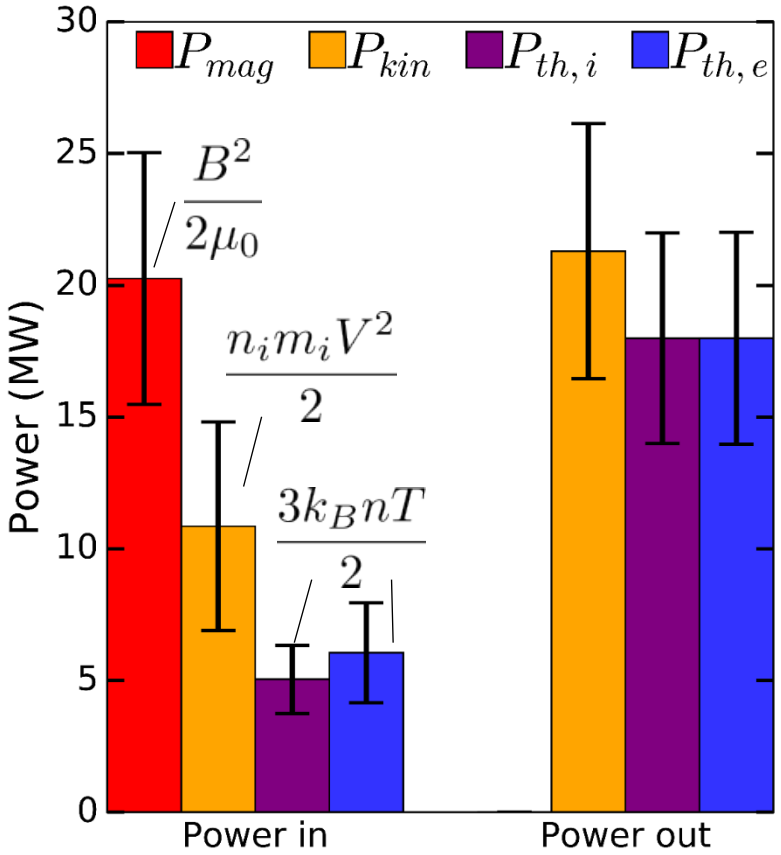


Anomalous Heating in the Reconnection Layer

$$V_{in}Lh\left(E_{mag} + E_{kin} + E_{th,i} + E_{th,e}\right) \approx V_{out}\delta h\left(E_{kin} + E_{th,i} + E_{th,e}\right)$$

~50% ~25% ~25% ~40% ~60%





Classical heating is too slow:

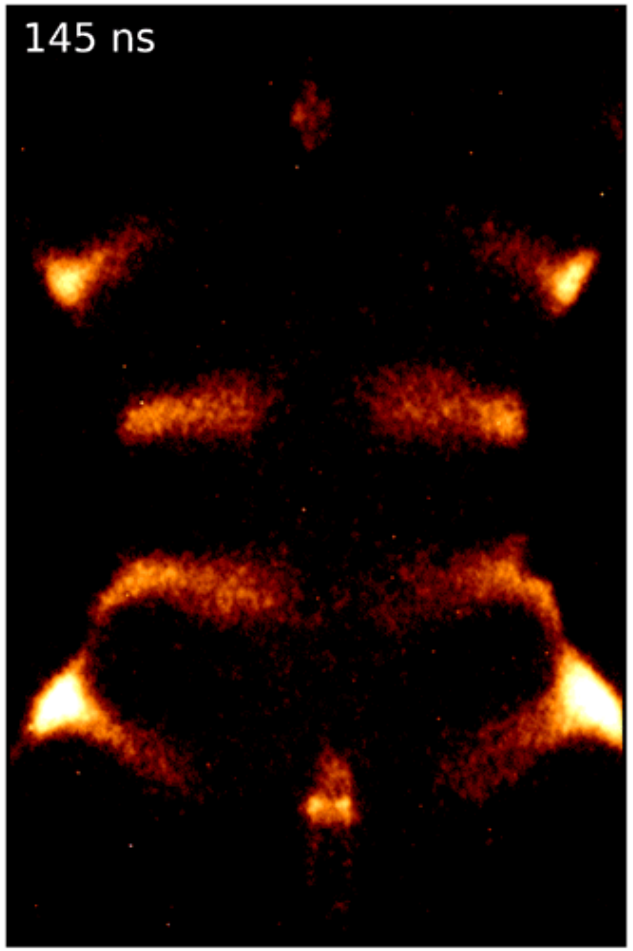
≈ 50 ns

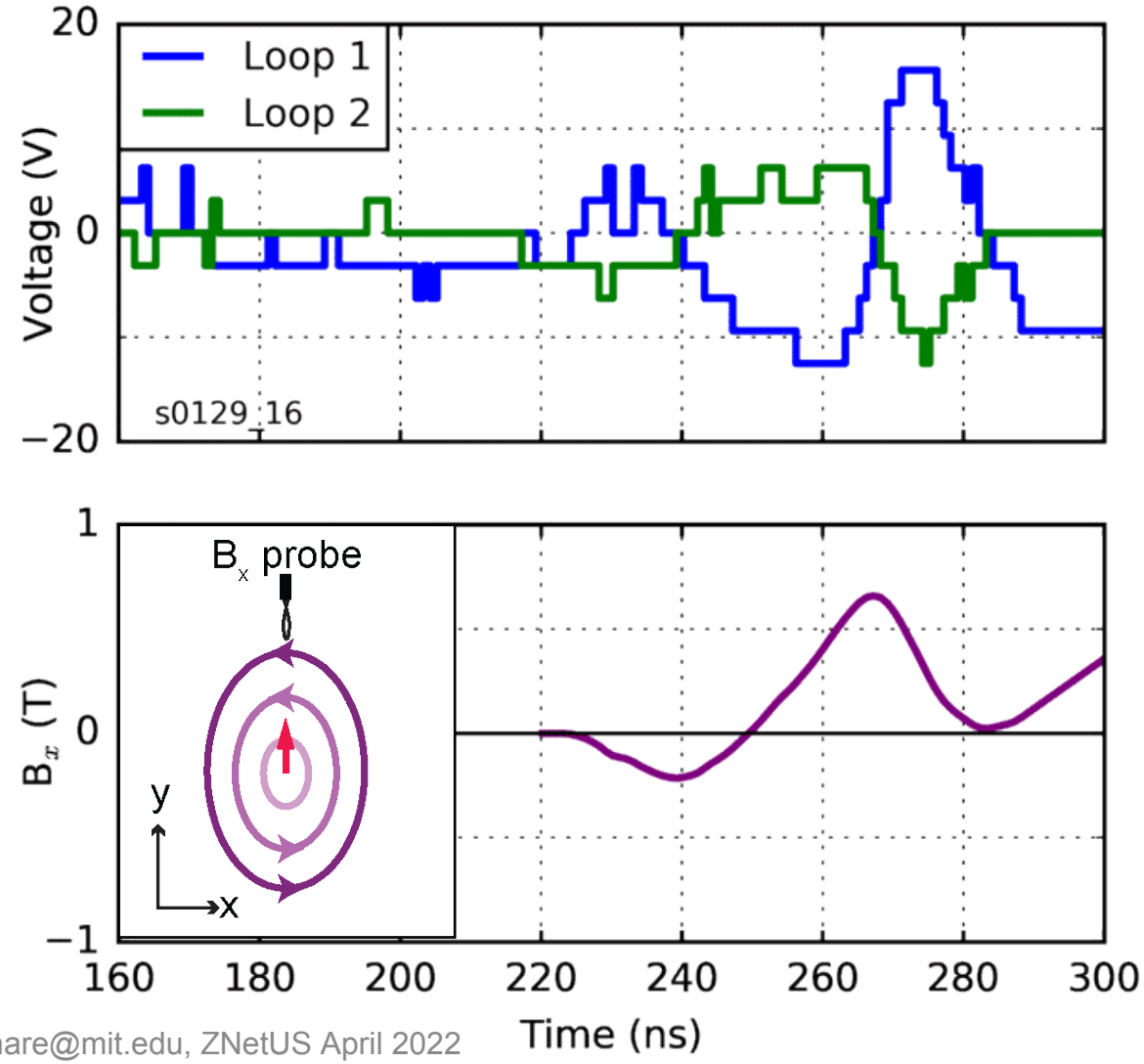
≈ 800 ns

≈ 350 ns

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

Magnetic Structure of Plasmoids





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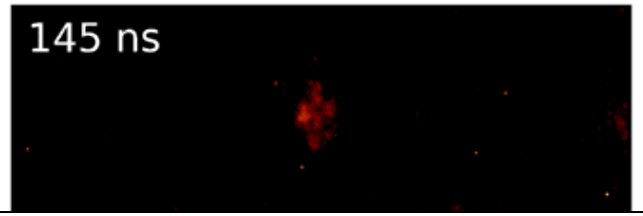
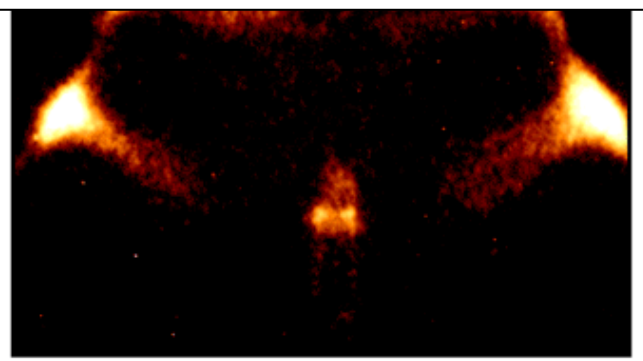
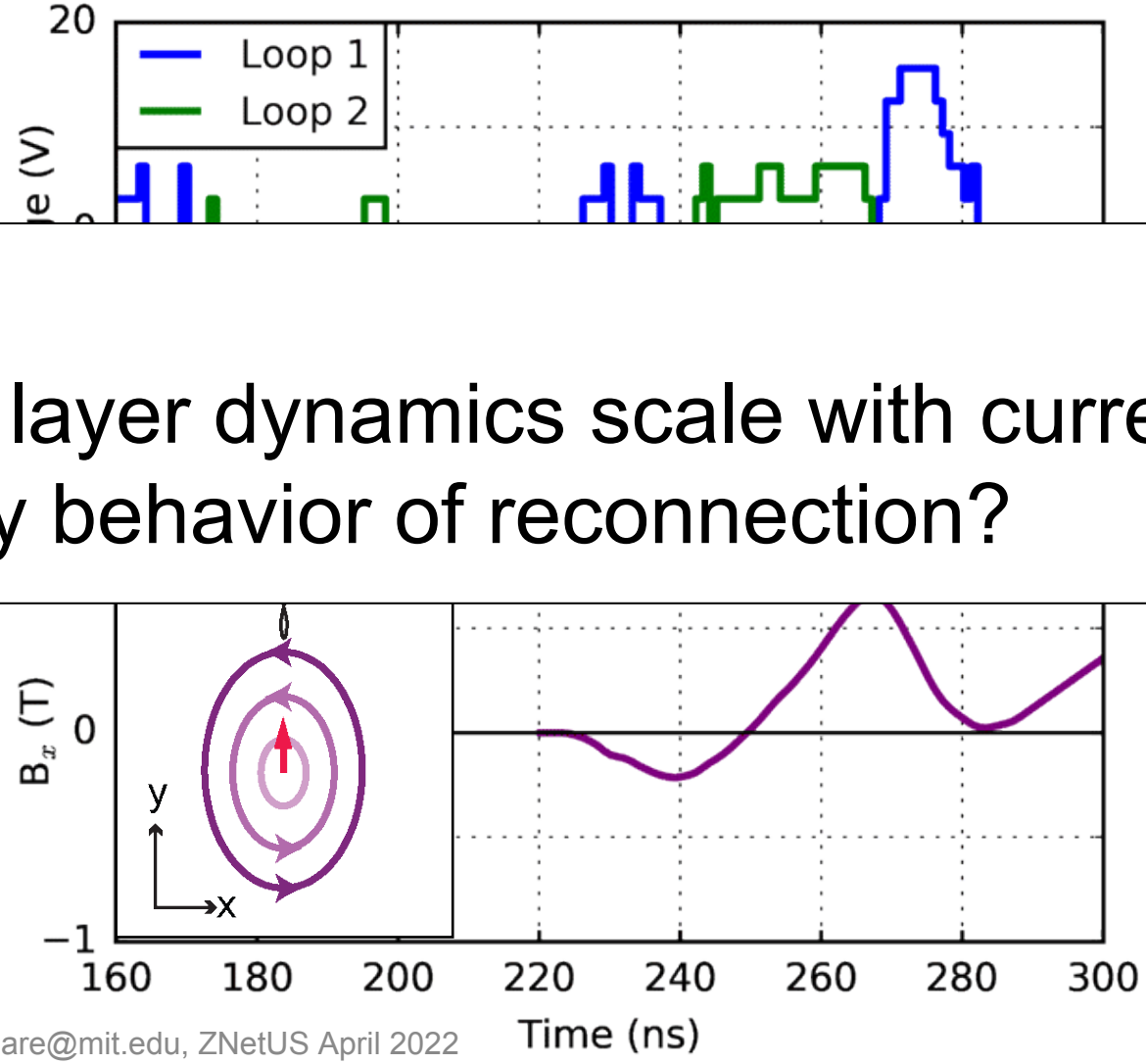




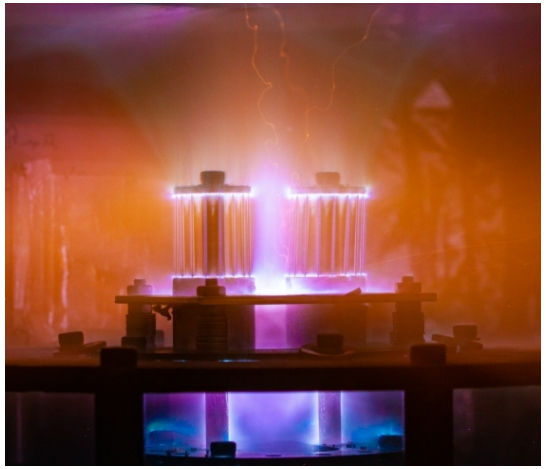


Open questions:

- How does reconnection layer dynamics scale with current?
- What is the quasi-steady behavior of reconnection?

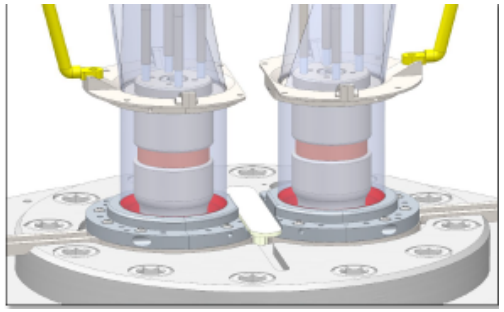
Research paths/talk outline

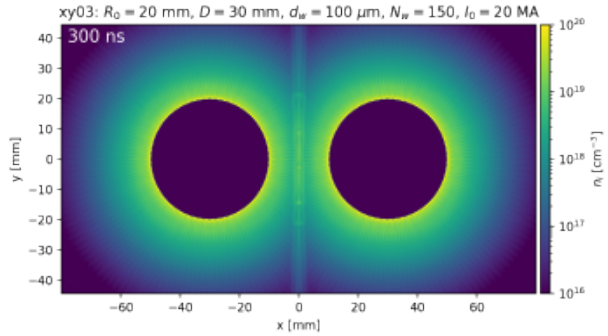
Magnetic reconnection



More current

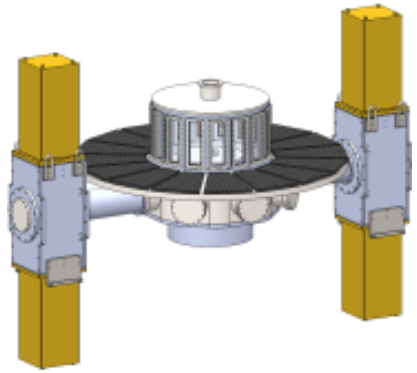
Radiatively cooled reconnection on Z

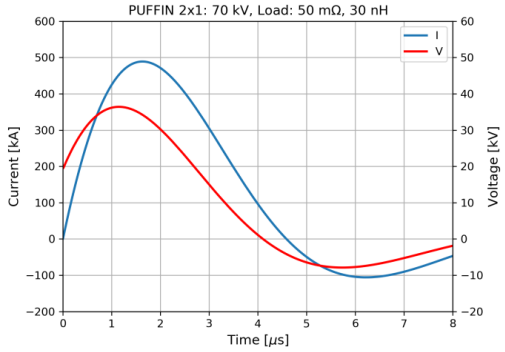




Longer current pulse

PUFFIN: 2 μs, 500 kA at MIT

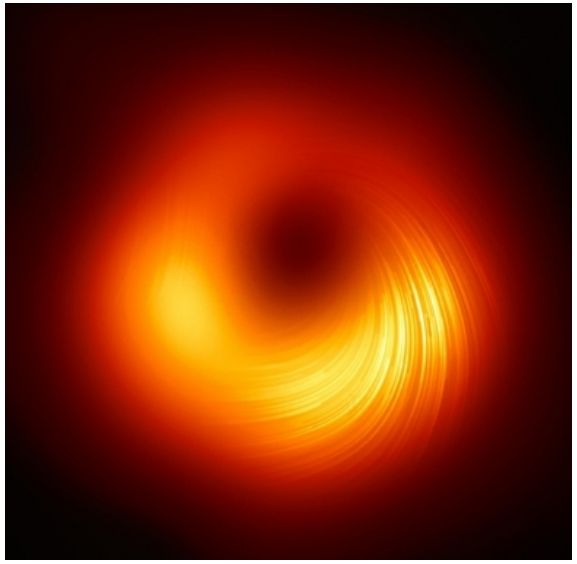




Reconnection in Extreme Astrophysical Environments

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

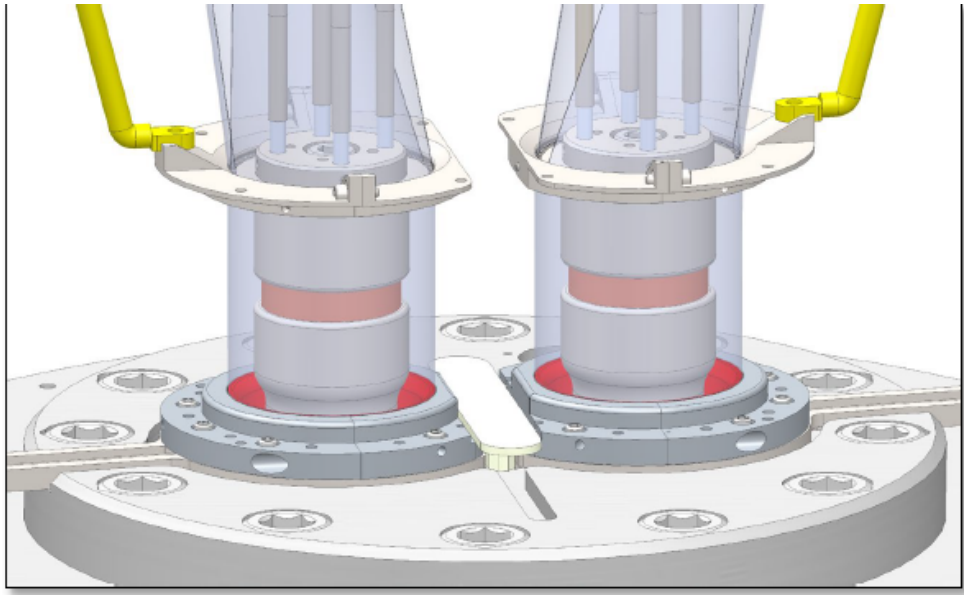
2. X-rays: key observational signature in remote environments:
   - Where and when are X-rays produced – localized bursts?
   - How does this couple back to the reconnection process?

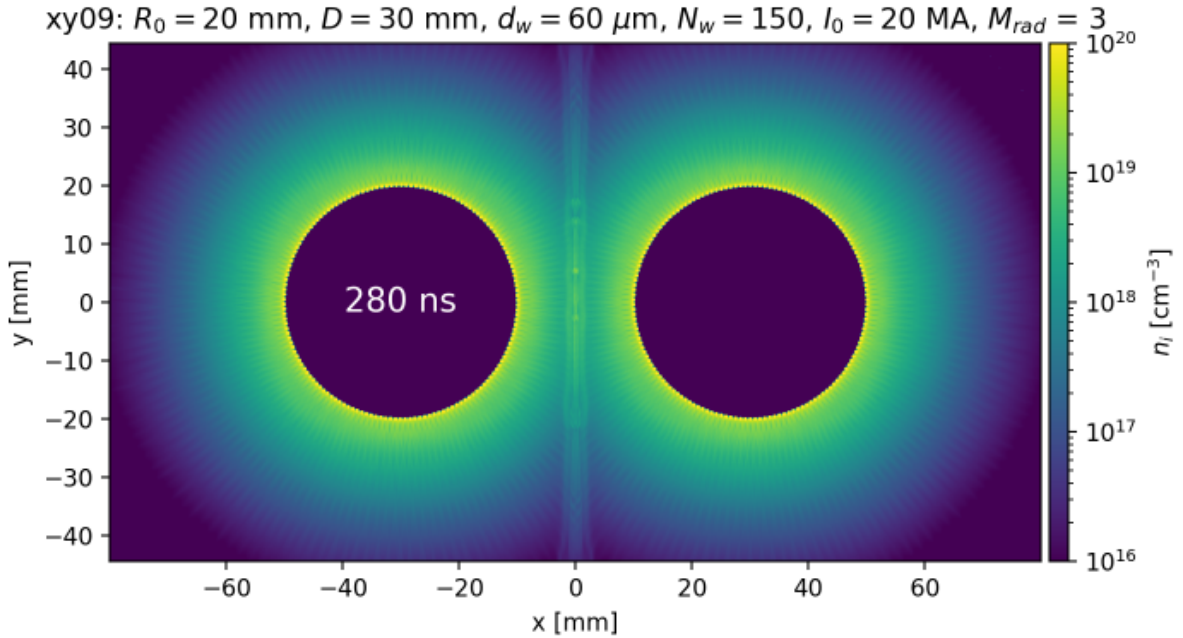
MARZ: Reconnection on Z

Z is the largest pulsed-power machine in the world

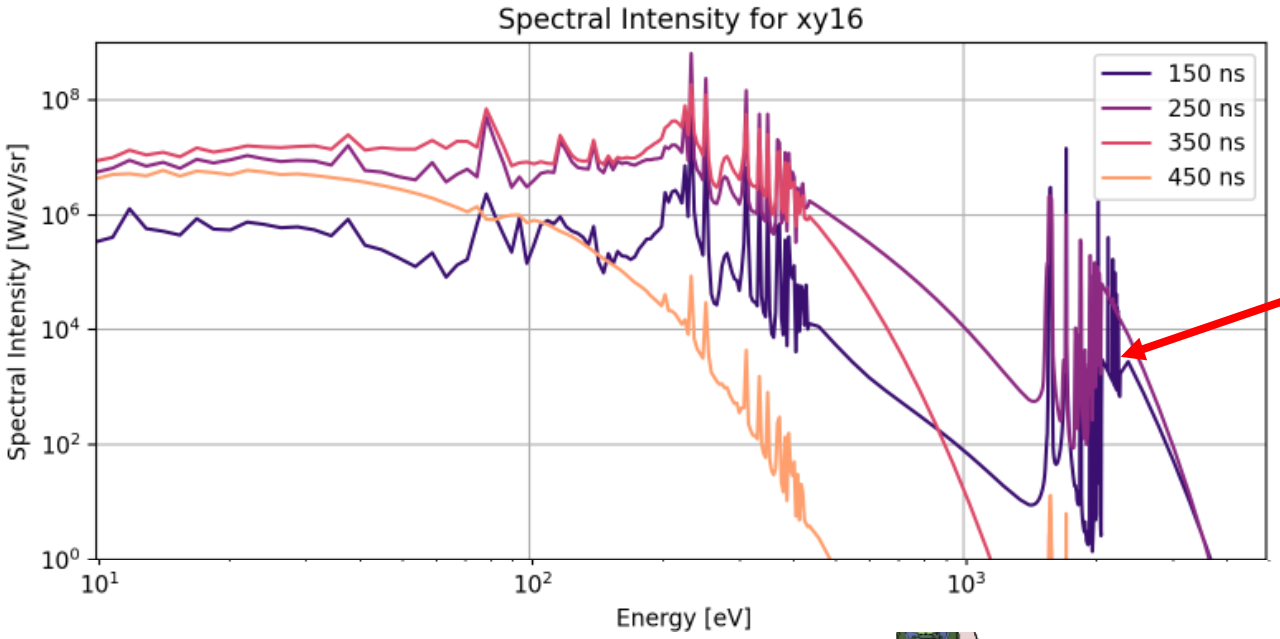
- 20-30 MA peak current compared to 1.4 MA on MAGPIE:
  - **Density** increase by $I^2 \sim 400$
  - **Magnetic energy** increase by $I^2 \sim 400$
  - **Cooling rate** increase by $I^4 \sim 160{,}000$

Unique capability: strongly radiatively cooled reconnection



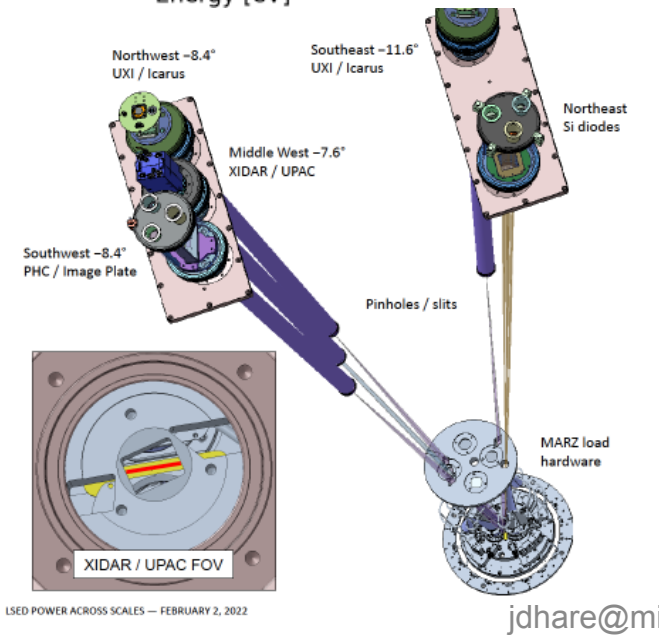


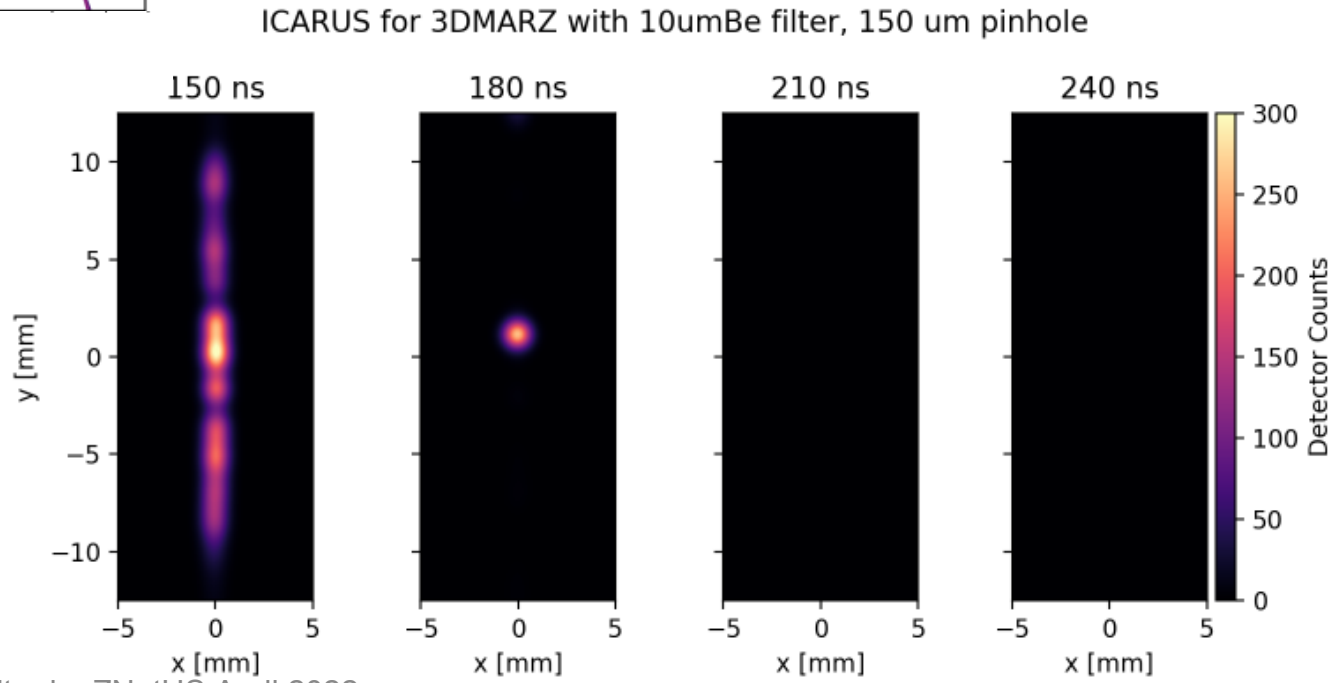
XP2: X-ray Post-Processor by Aidan Crilly & Jerry Chittenden



Al K-shell disappears after collapse

XP2 provides a predictive capability for X-ray diagnostics





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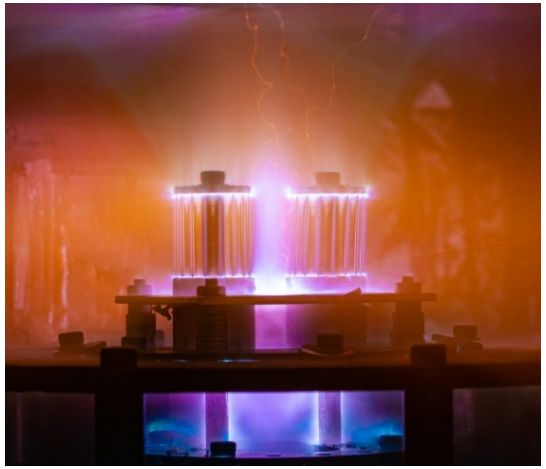

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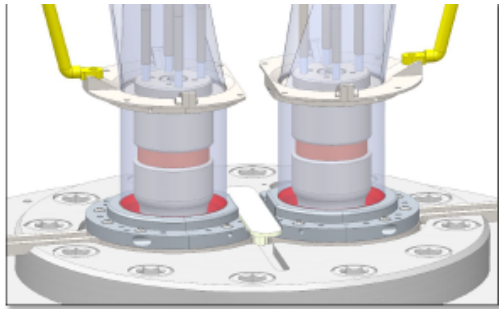

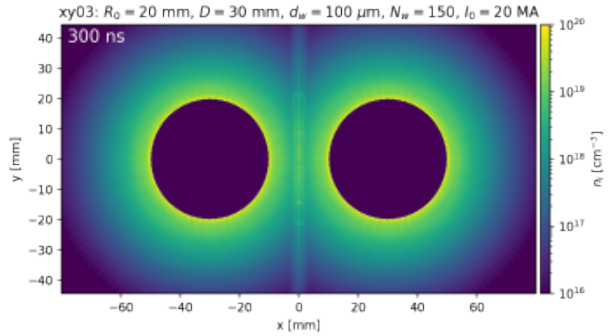

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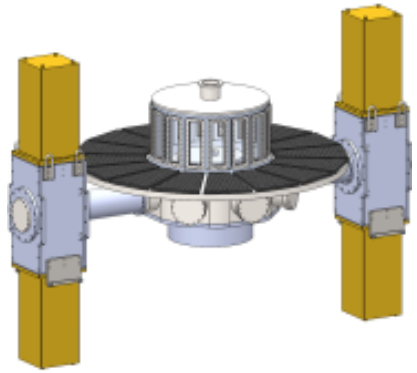
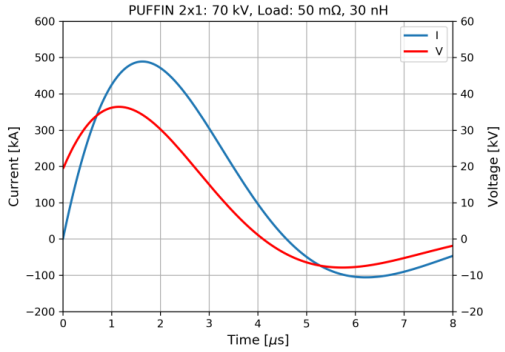
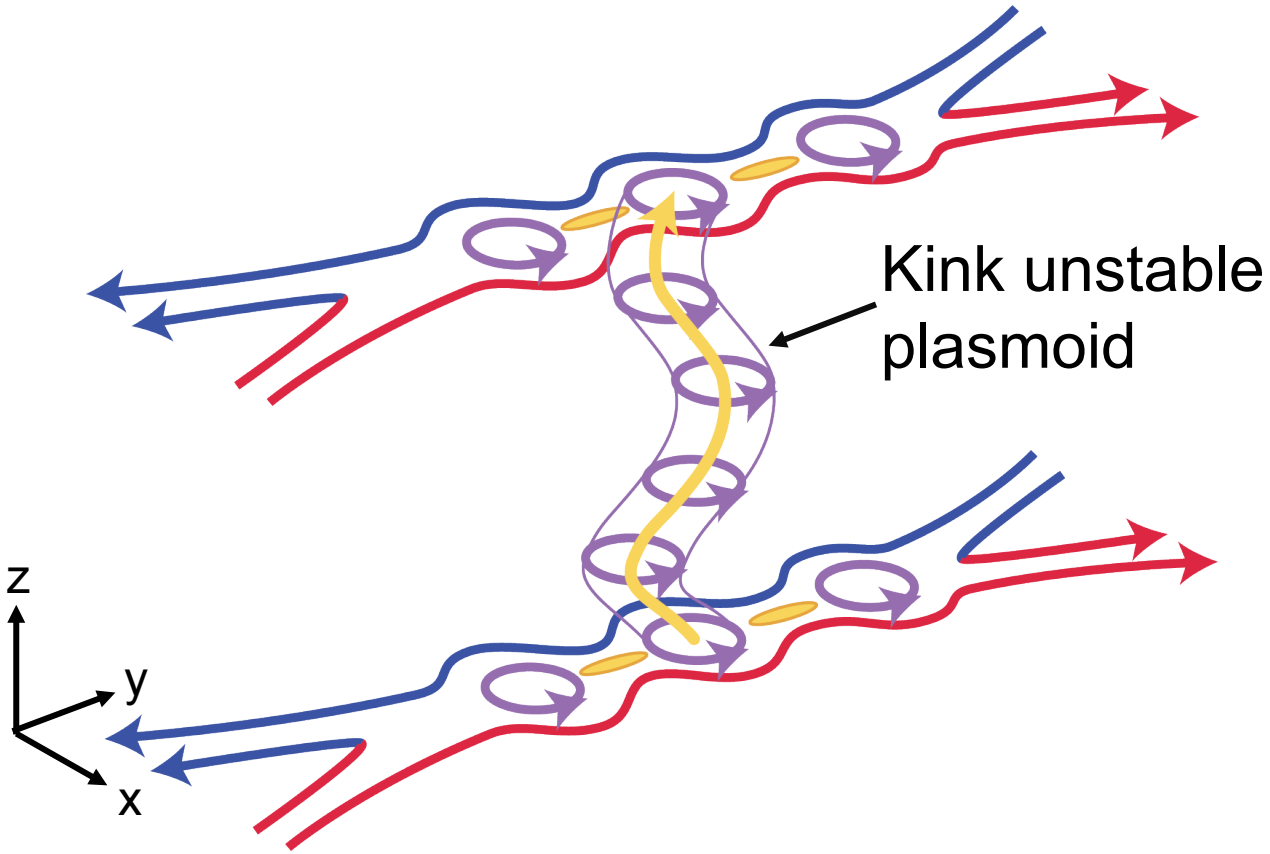


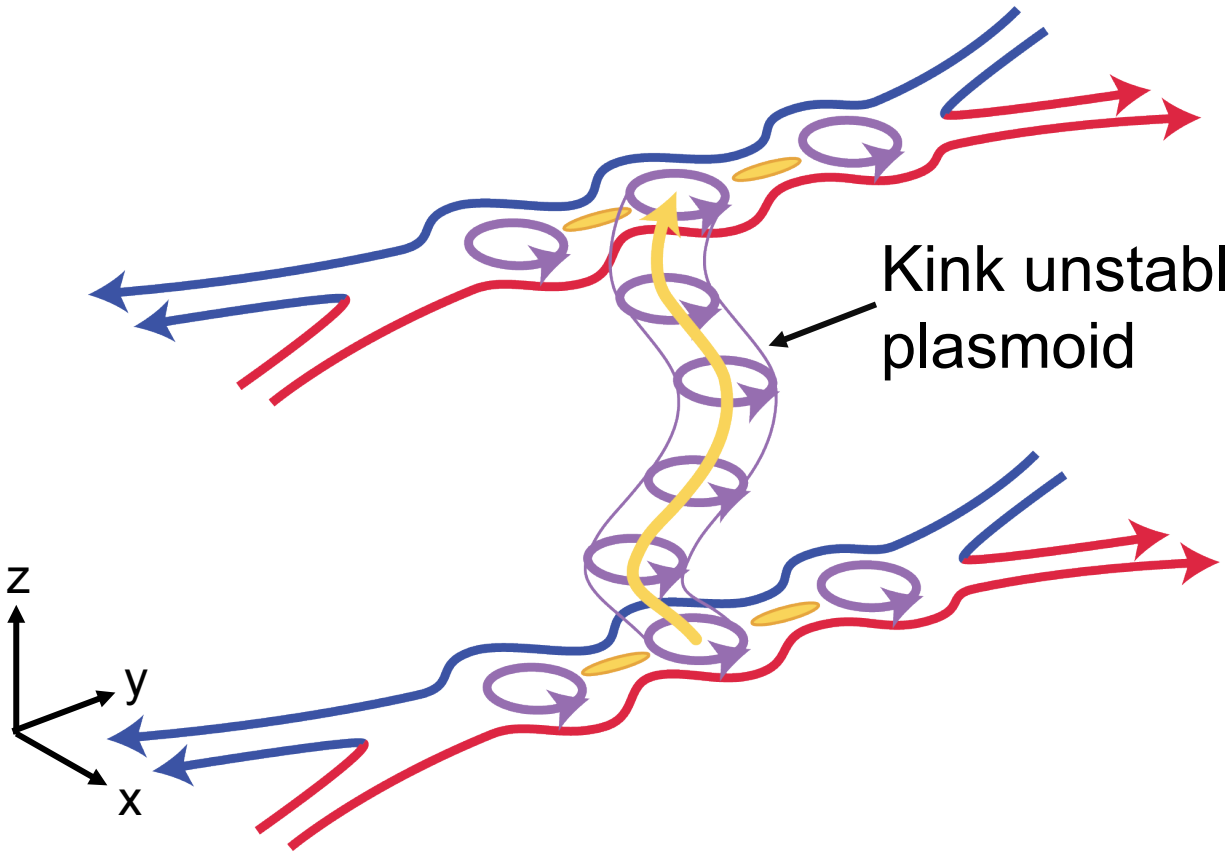


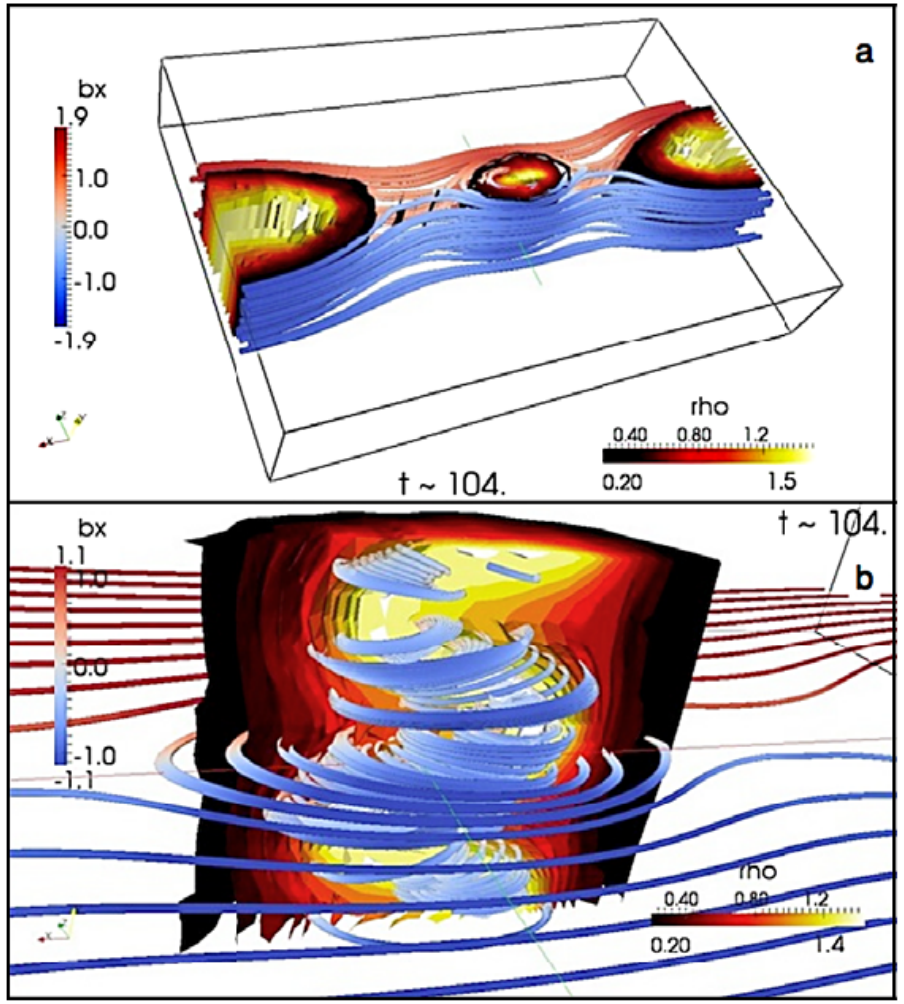
Interesting physics happens on long time scales



Kink Instability Leads to Turbulent Reconnection

Turbulent reconnection over a large volume, as observed in astrophysics

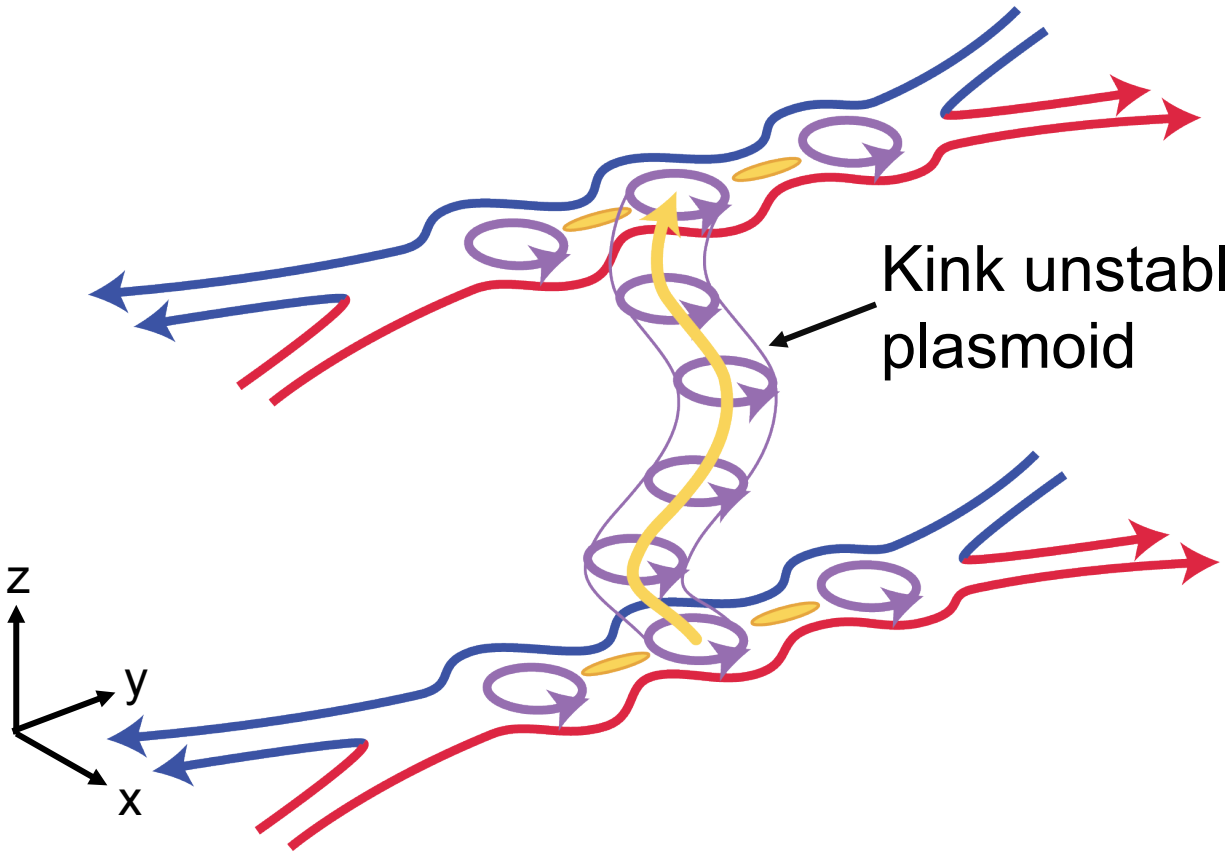


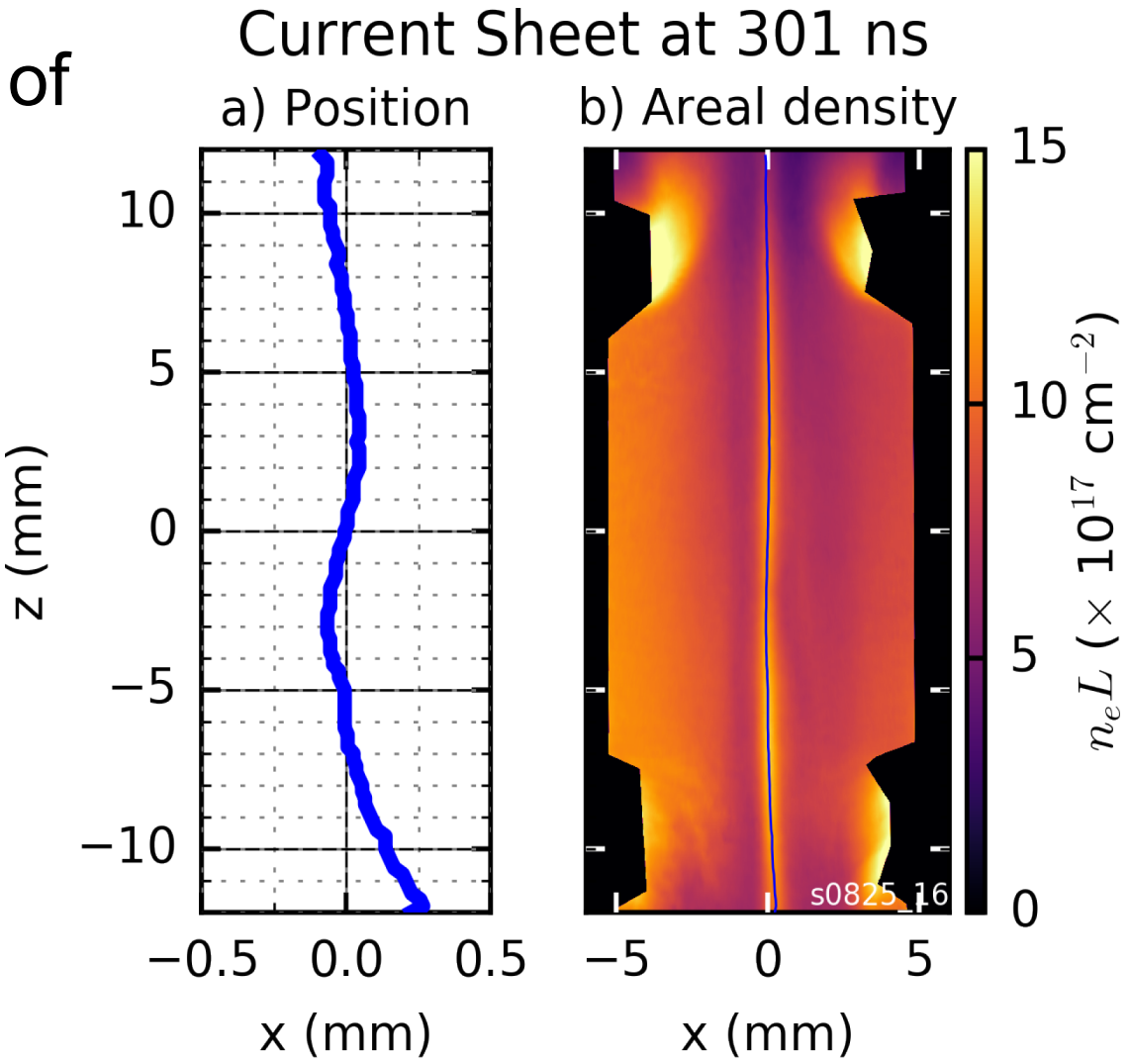


Lapenta, G., and L. Bettarini. *EPL* **93**, 6 (2011)

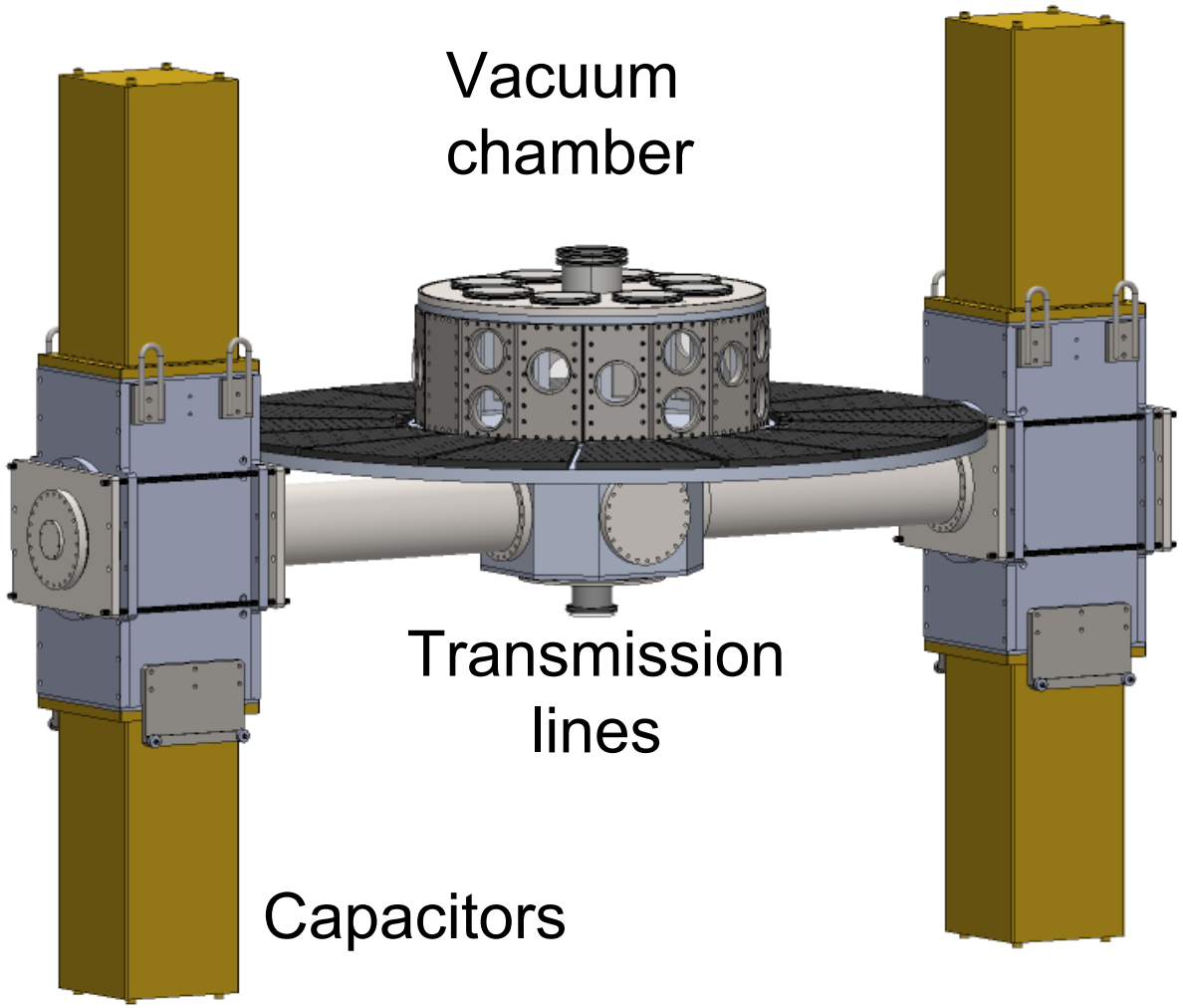
Hints of a kink instability on MAGPIE

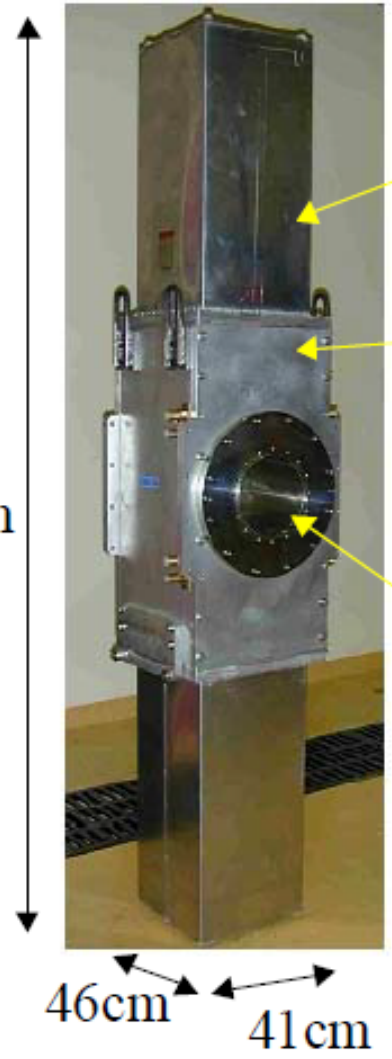
Open question:
What is the long-term behaviour of this kink instability?





PUFFIN uses 2 LTD5 stages from SPHINX (CEA Gramat)



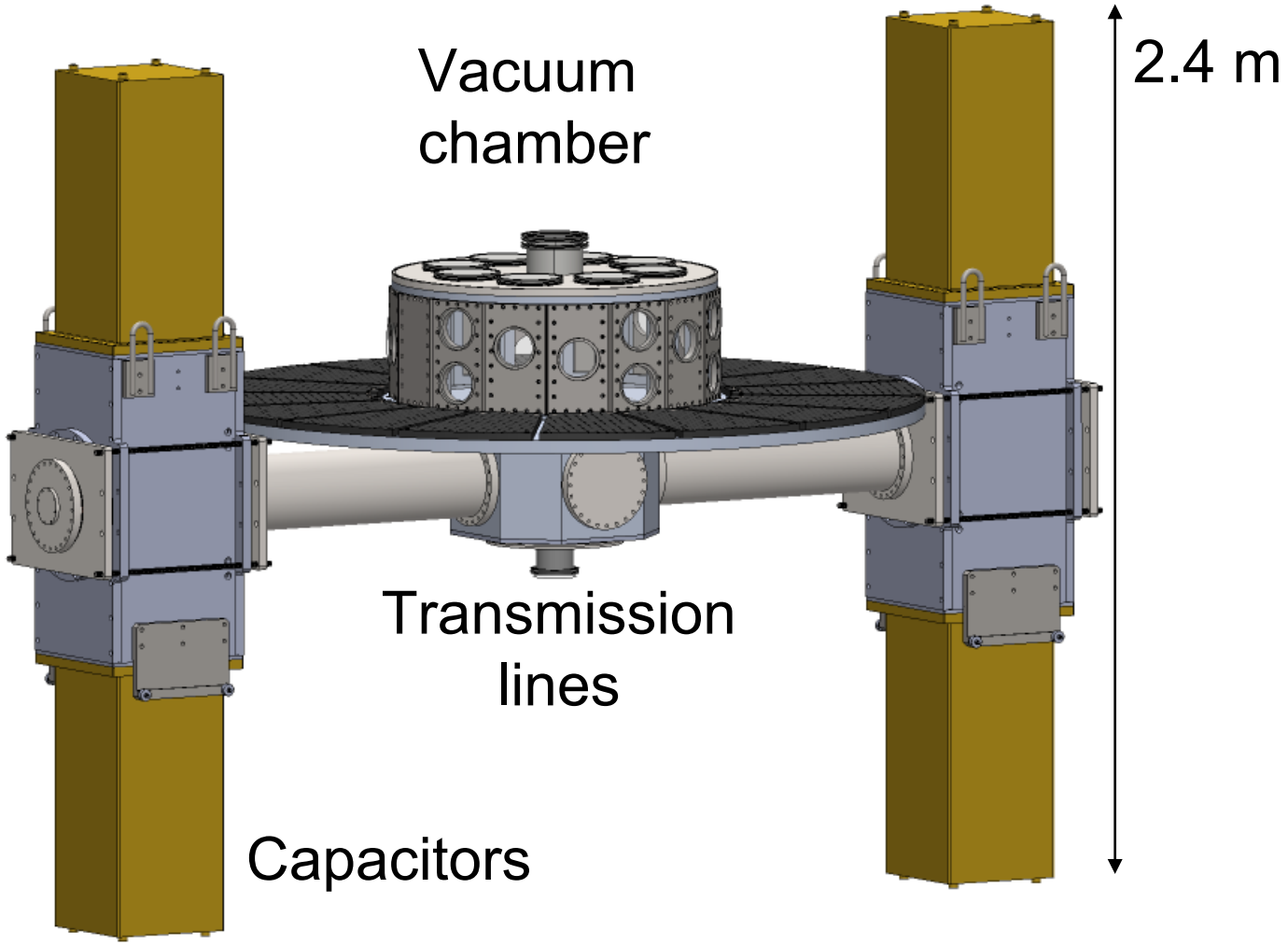


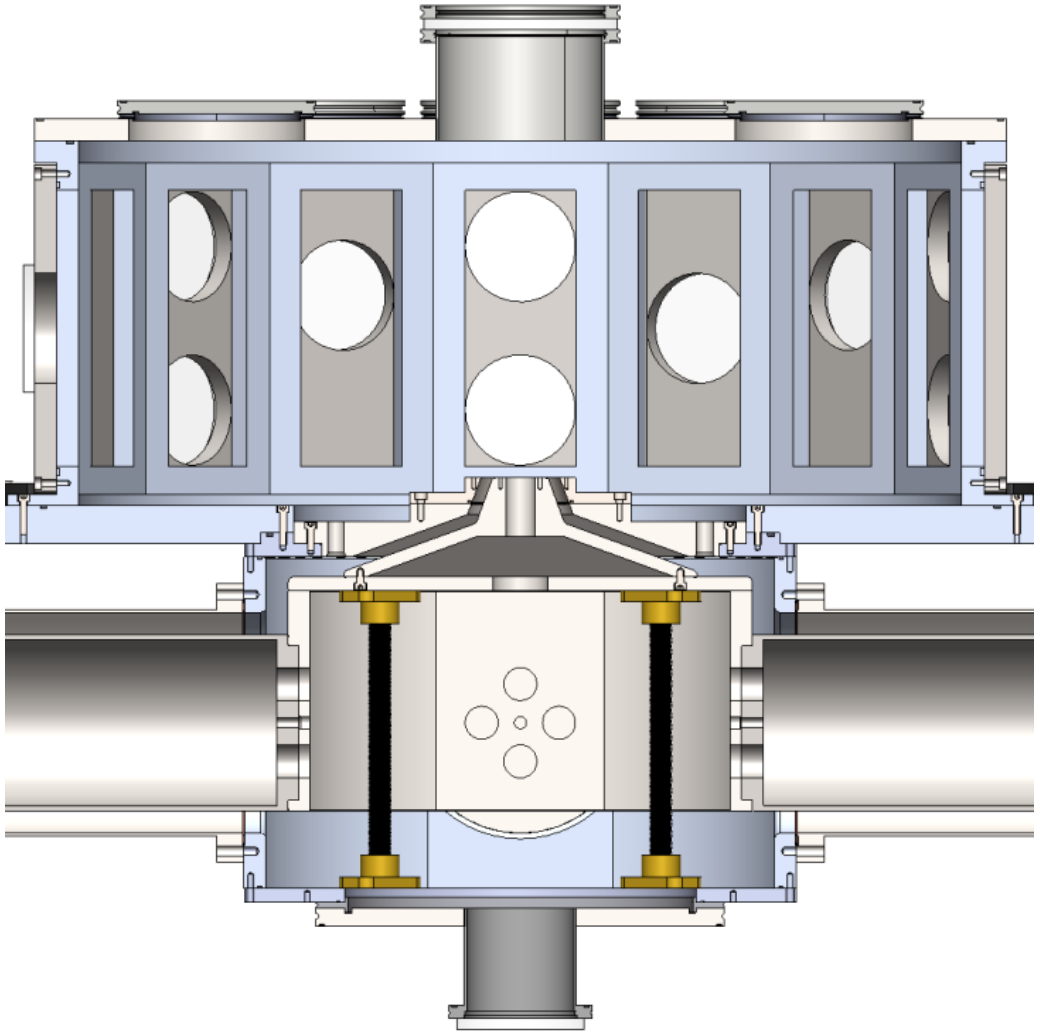
Trench capacitor
4µF; 10nH; 15mΩ

Grounded box enclosing :
2 switches
1 magnetic core
1 vacuum insulator

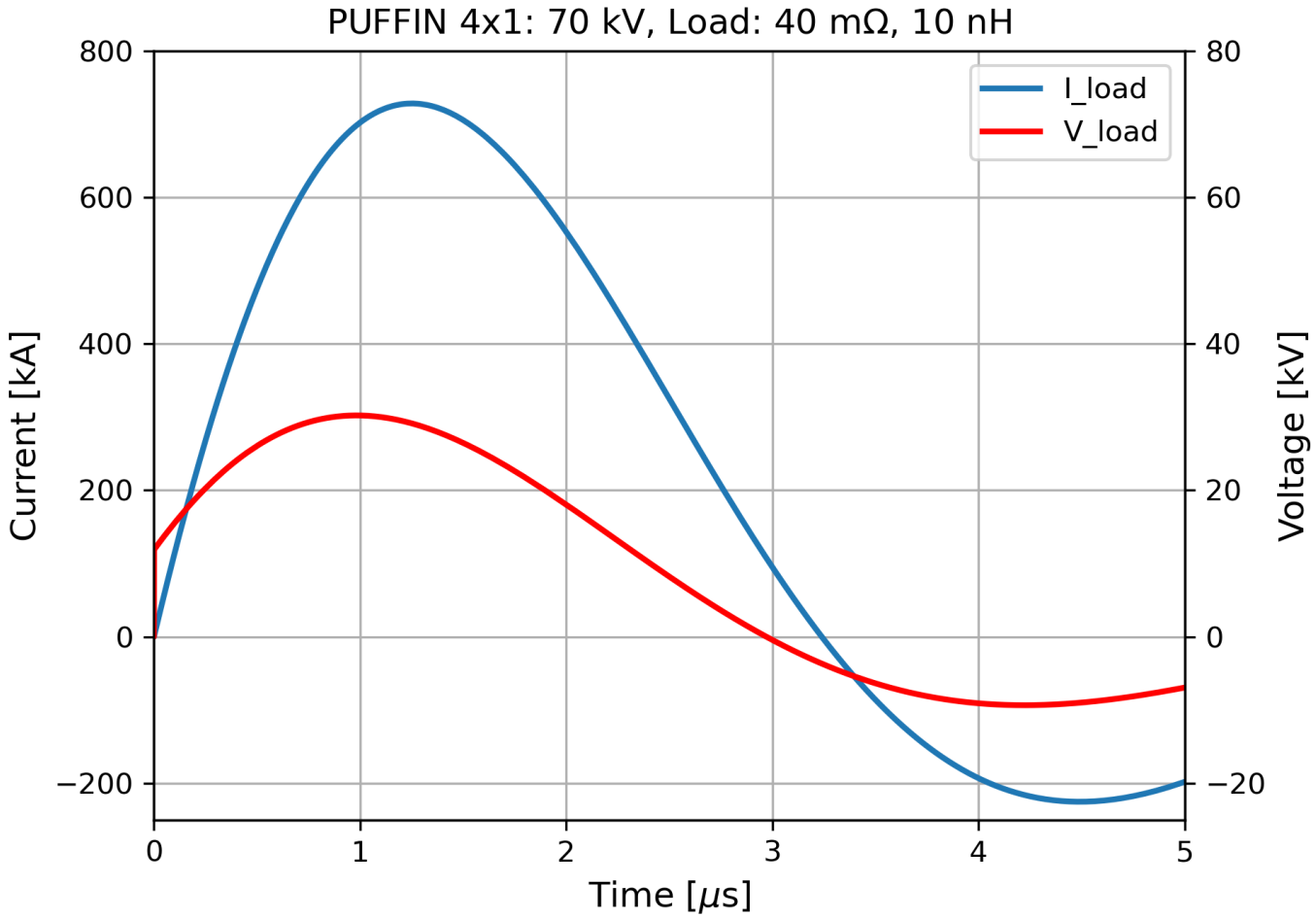
Vacuum line
Dout.200mm, gap 20mm

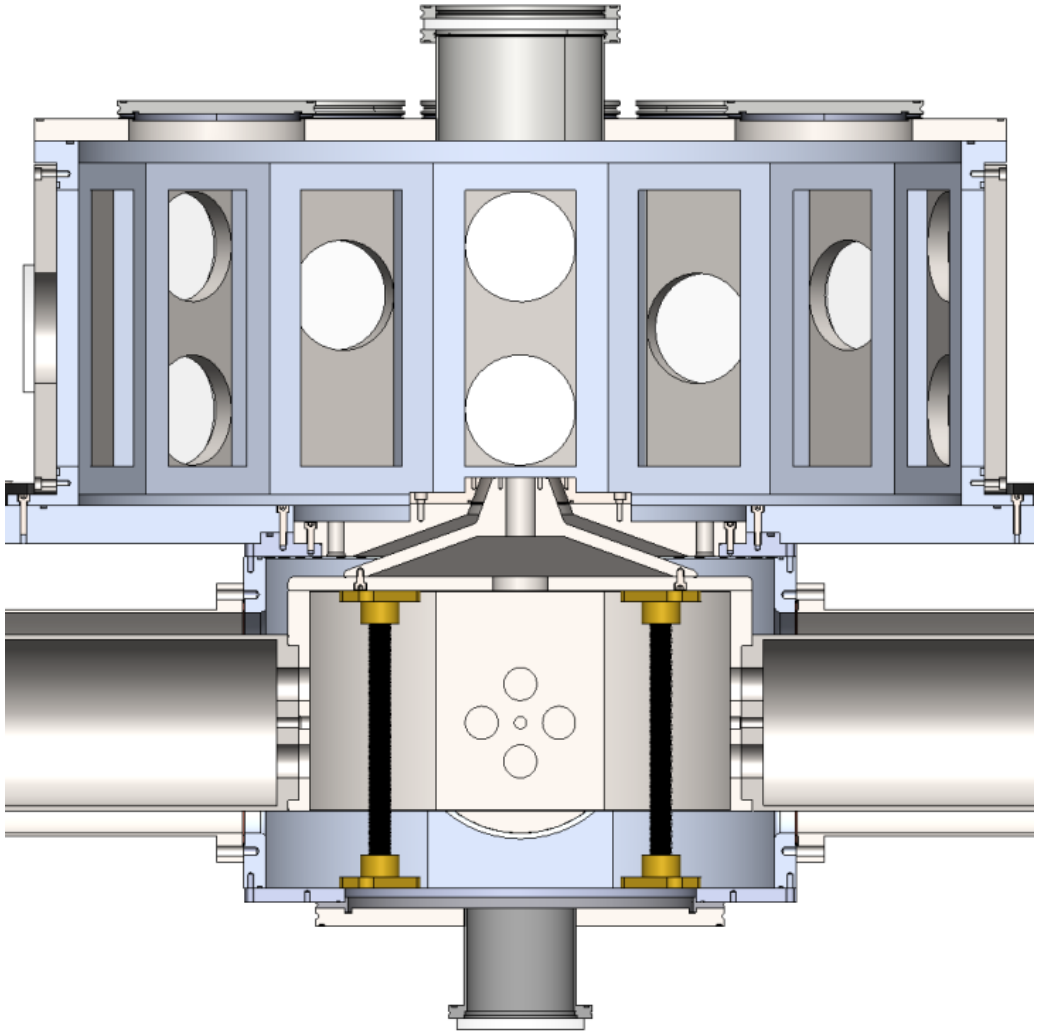
PUFFIN 2x1 will drive around 700 kA with a 1.6 µs rise time



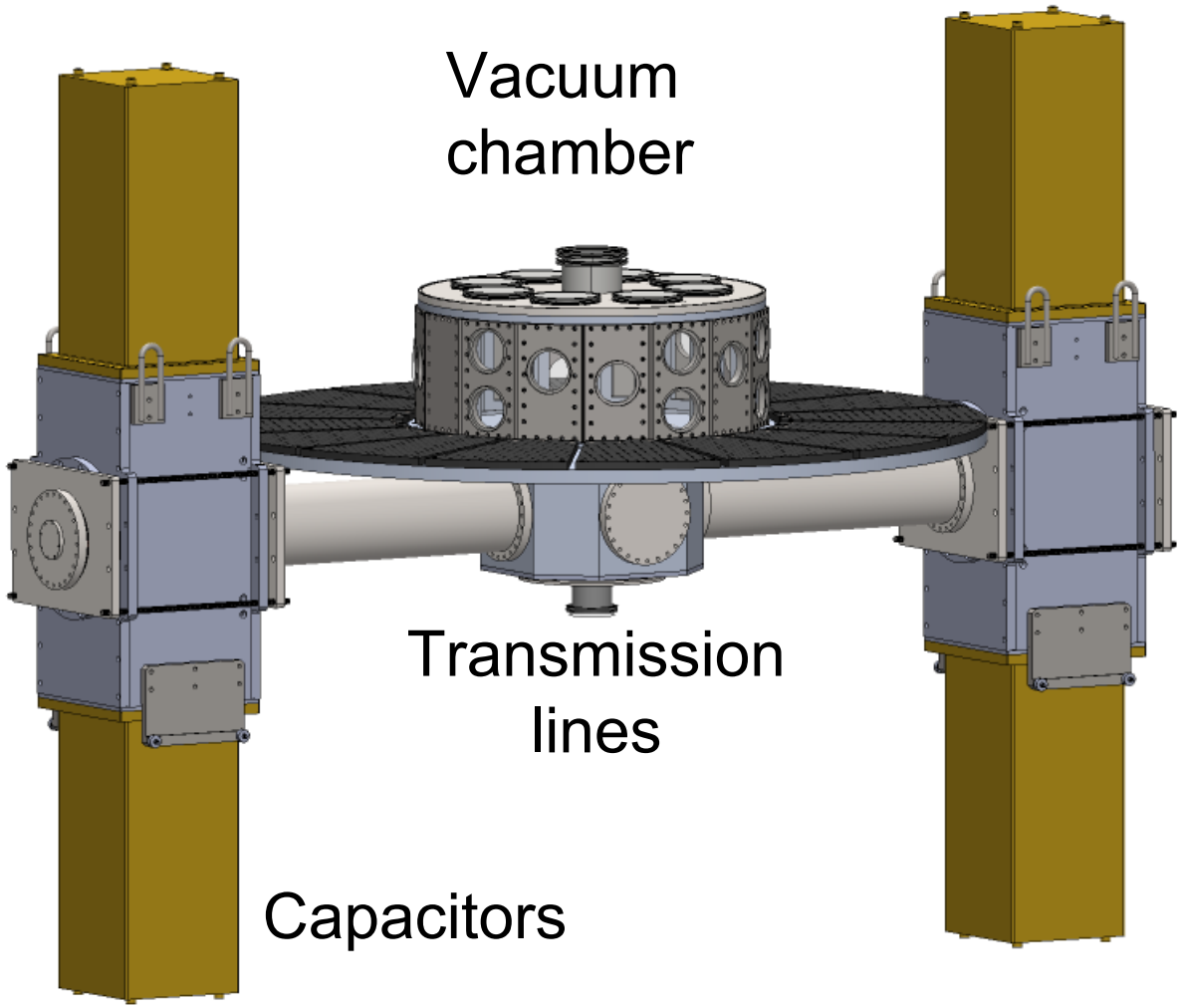


PUFFIN 2x1 will drive ~700 kA with a ~1.5 µs rise time





PUFFIN: a long-pulse driver for fundamental physics



Timeline:

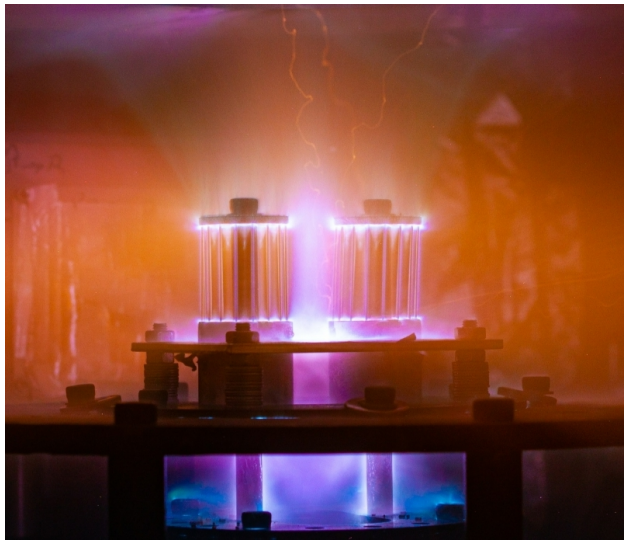
- LTD stages arrive May 2022
- Lab renovation finished December 2022
- Design and construction of power feed expected early 2023
- First experiments in 2023

Diagnostics:

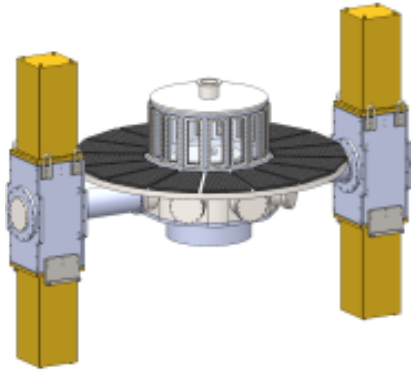
- Laser imaging shadowgraphy, schlieren, interferometry and imaging refractometry
- XUV and optical framing cameras
- Thomson scattering (spatially resolved, ion and electron features)

Summary

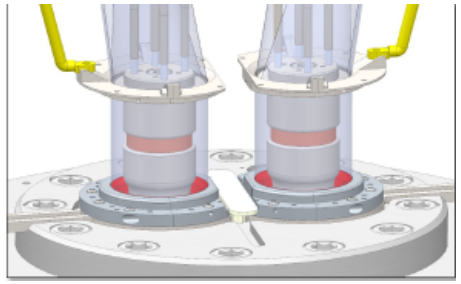
Magnetic reconnection



PUFFIN: 1.6 μs, 700 kA at MIT



Radiatively cooled reconnection on Z



Unifying theme: energy flows in plasmas