Pulsed-Power-Driven Plasma Physics at MIT

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PUFFIN

MIT | PSFC Plasma Science and Fusion Center

Acknowledgements

MIT PSFC — Rishabh Datta, Thomas Varnish, Simran Chowdhry, Nuno Loureiro and others

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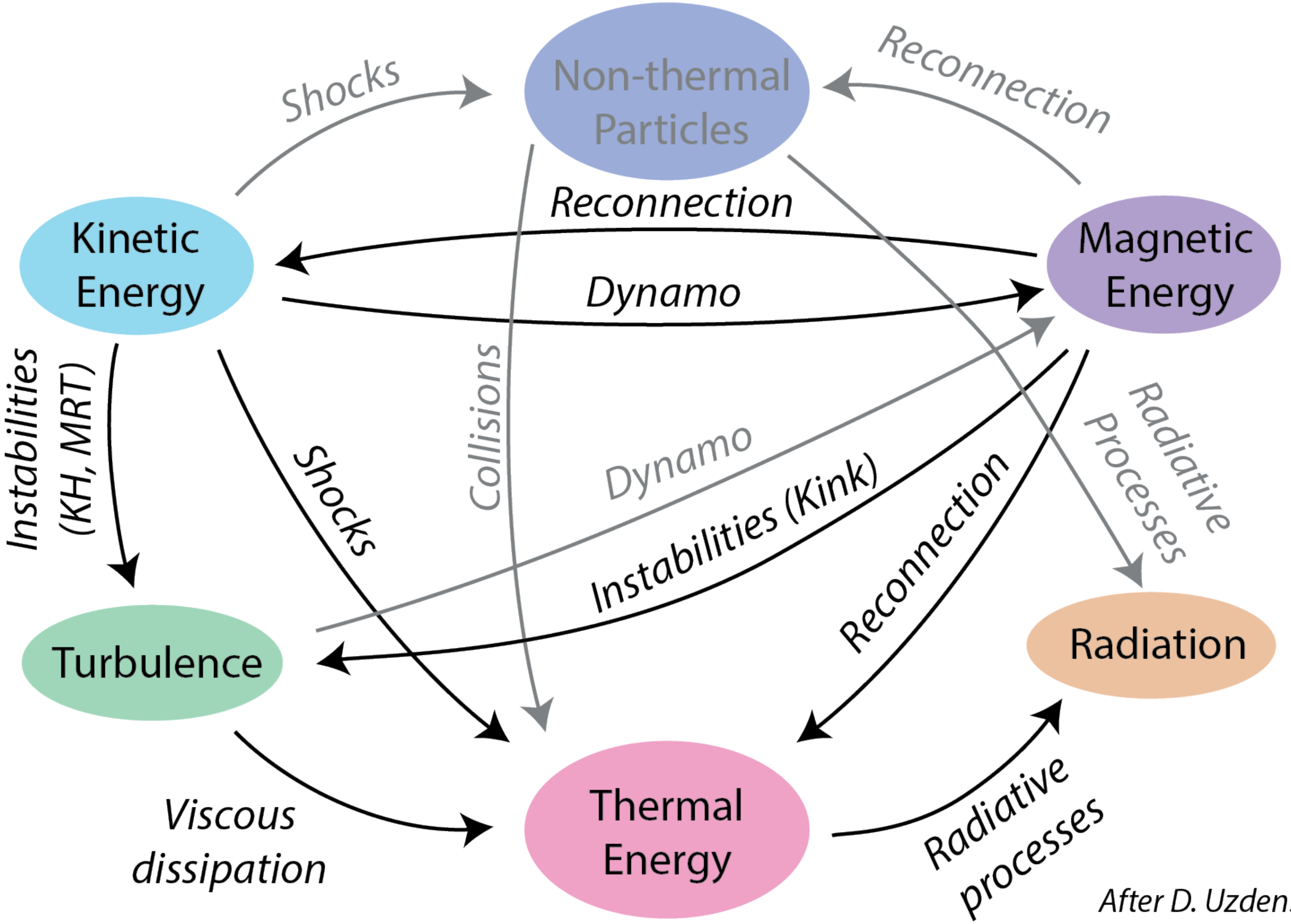
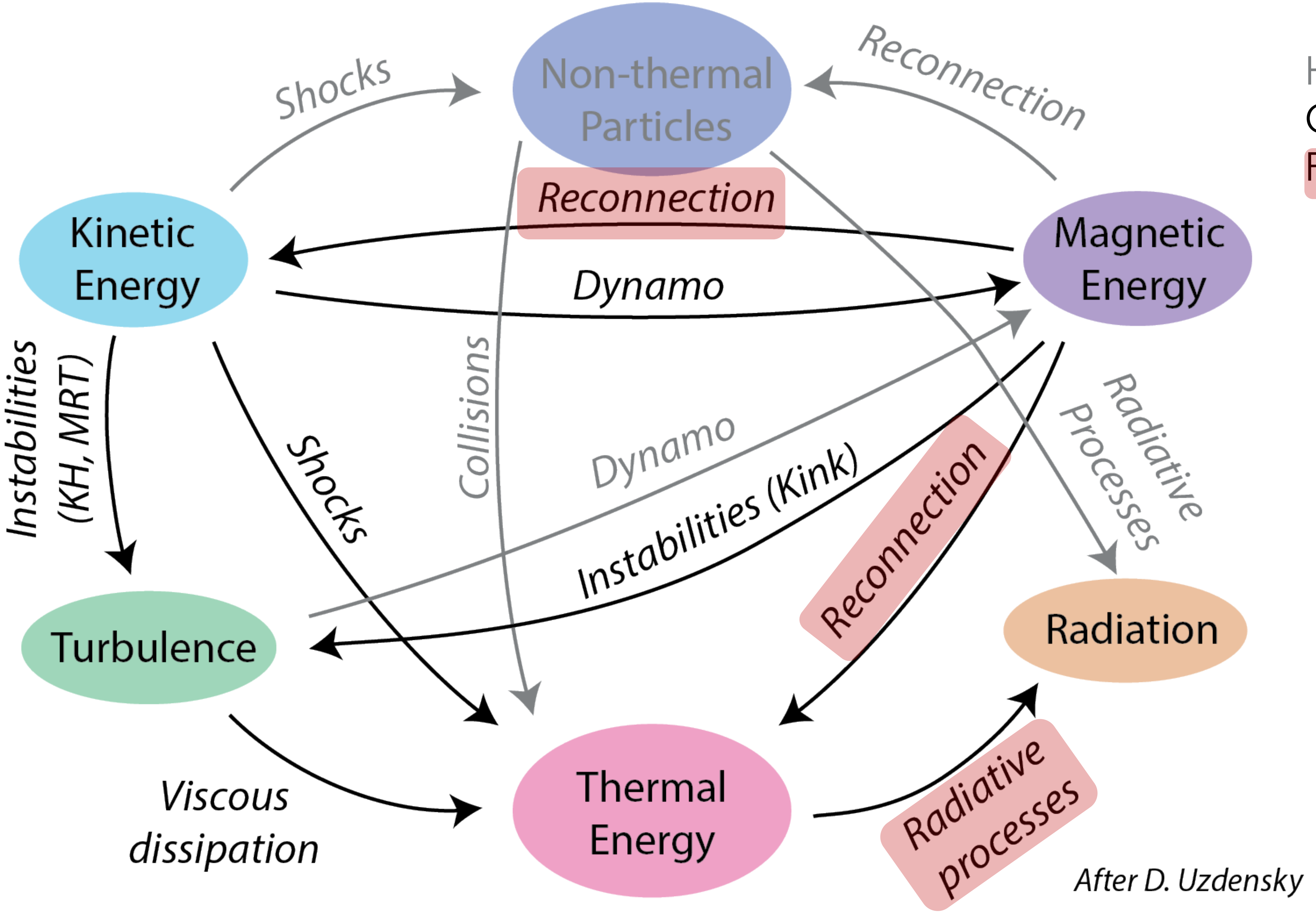
Research Interests: Energy Flows in Plasma



After D. Uzdensky

Research Interests: Energy Flows in Plasma



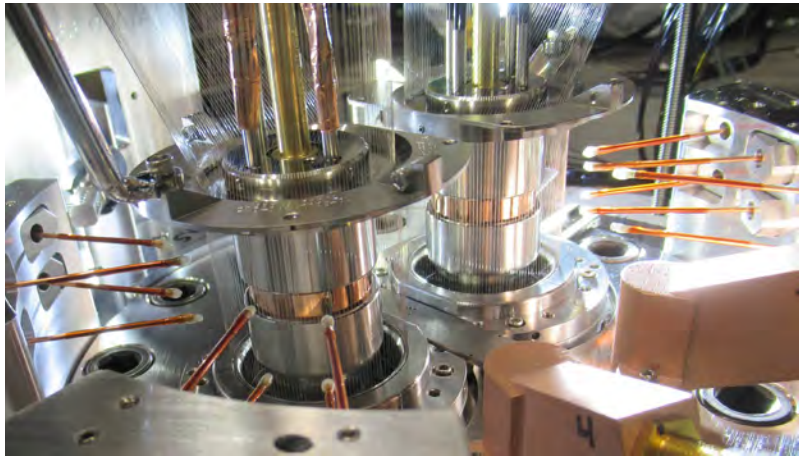
Hard to study with pulsed-power
Can study with pulsed-power
Focus of this talk

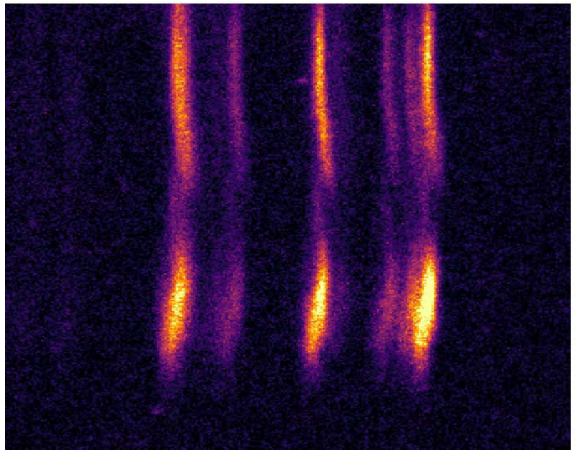
Research paths and talk outline

Magnetic reconnection

Radiative cooling

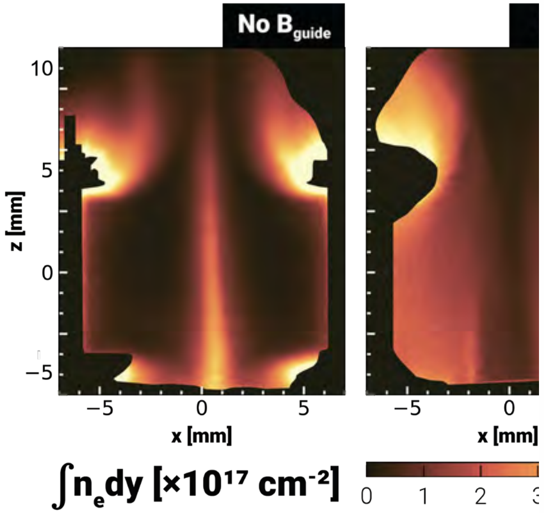
MARZ: Radiatively cooled reconnection on Z



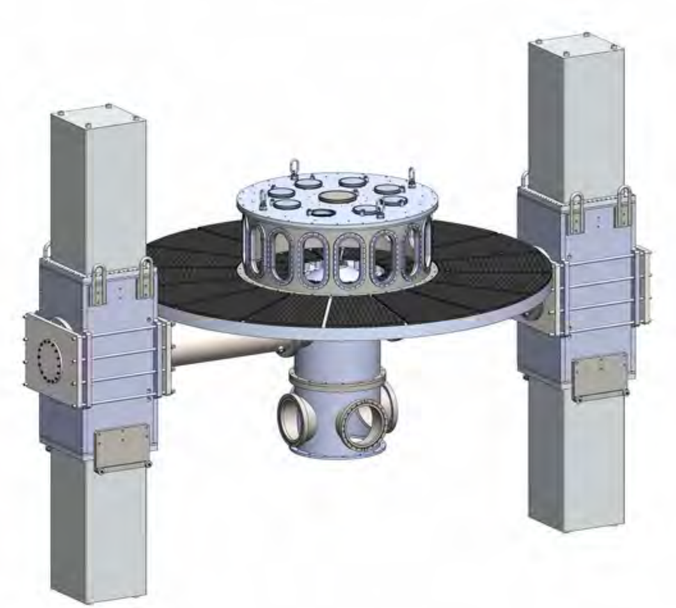


Plasmoids and turbulence

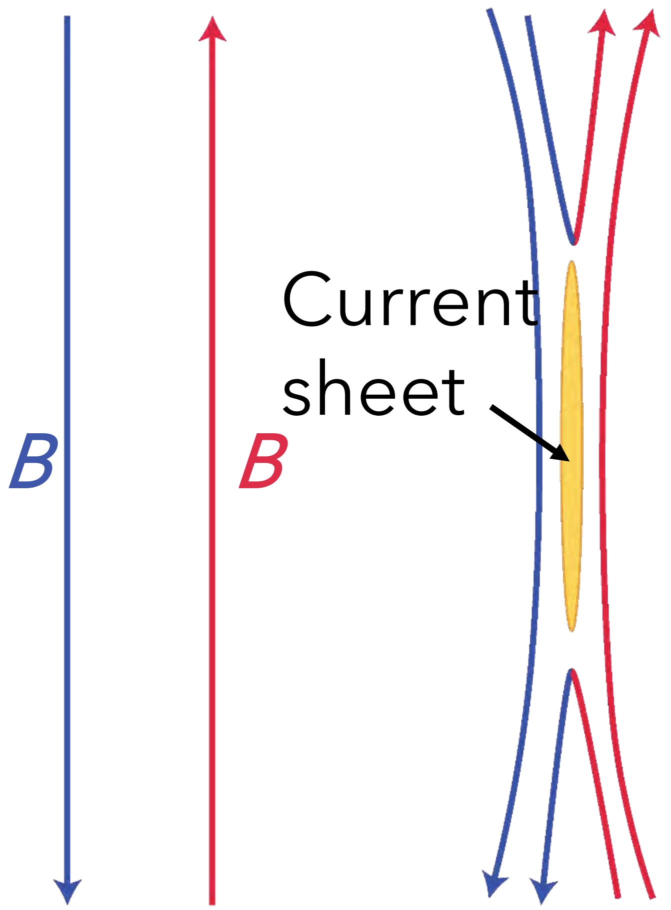
Guide field on MAIZE



Longer timescales on PUFFIN



Magnetic Reconnection



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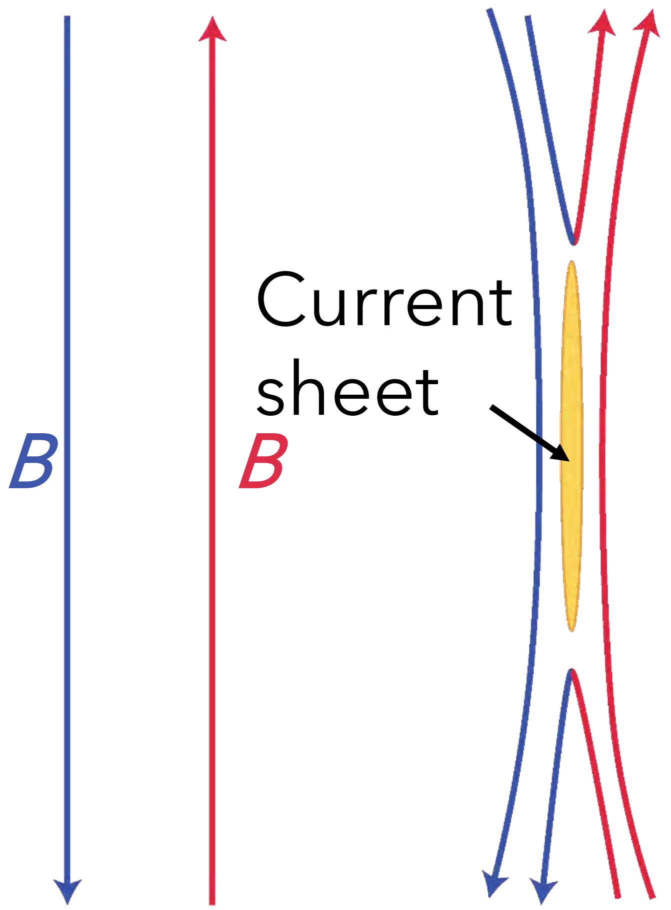
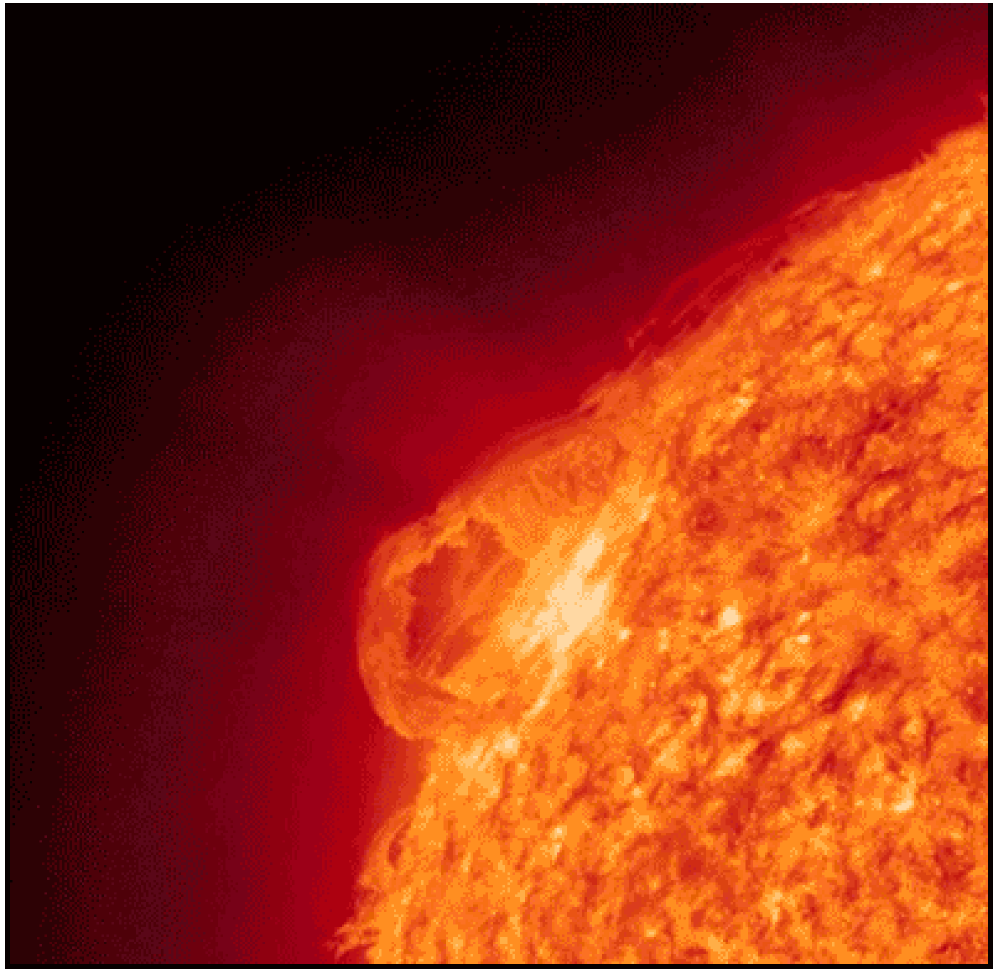
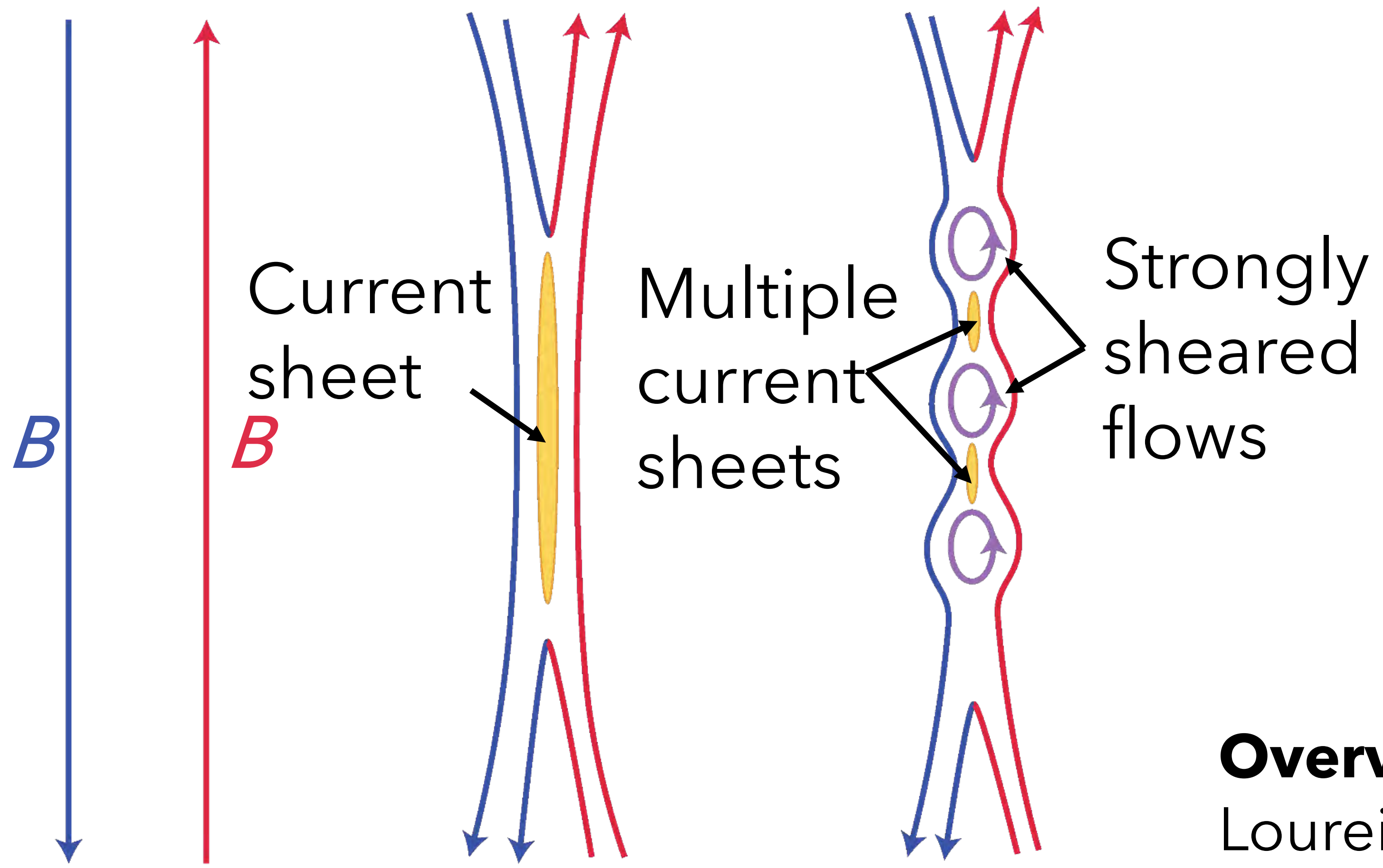


Prediction: 1000 yrs. Reality: 10 minutes!

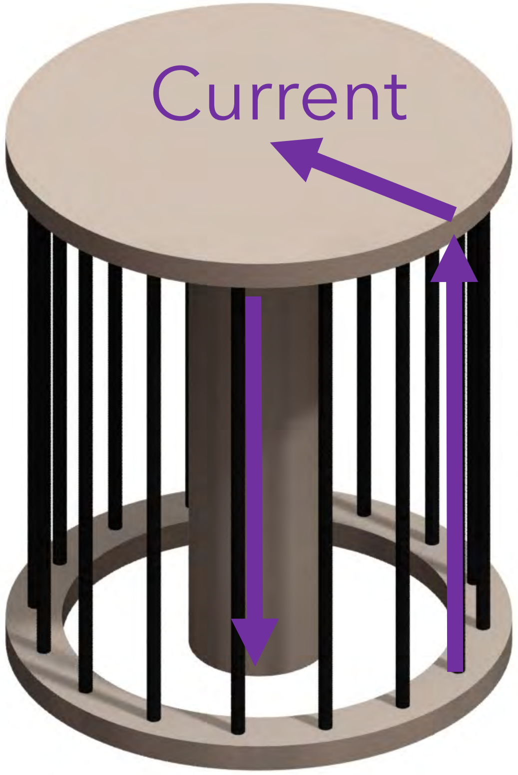


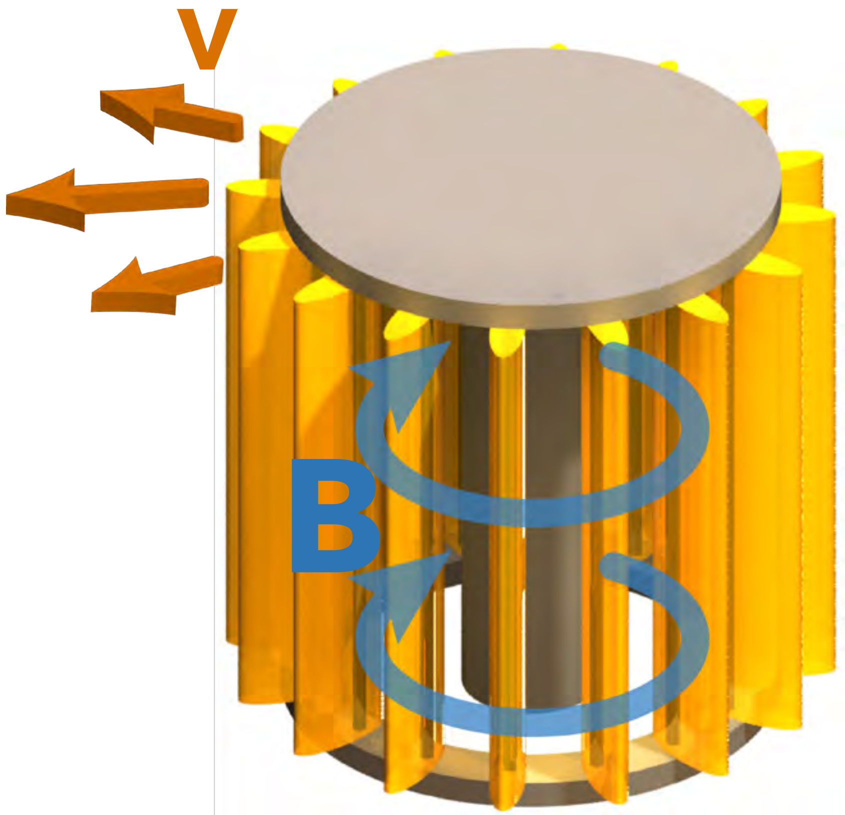
Plasmoids Lead to Fast Reconnection and Anomalous Heating



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

Pulsed-power-driven Magnetic Reconnection





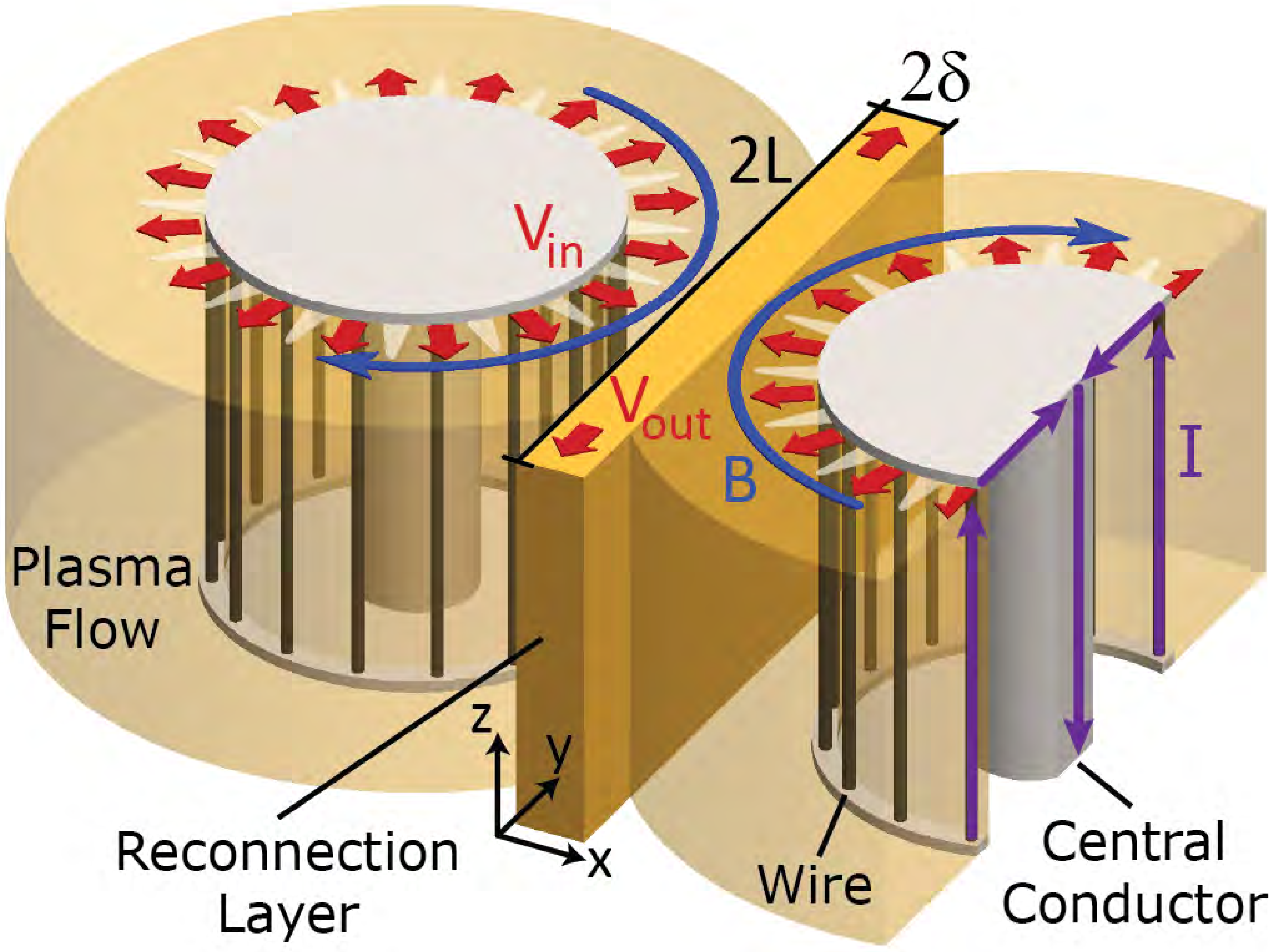
Current **heats** the wires & generates the **magnetic field** which **accelerates** the plasma

Result: energy components in rough equipartition,

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

Similar to astrophysical systems

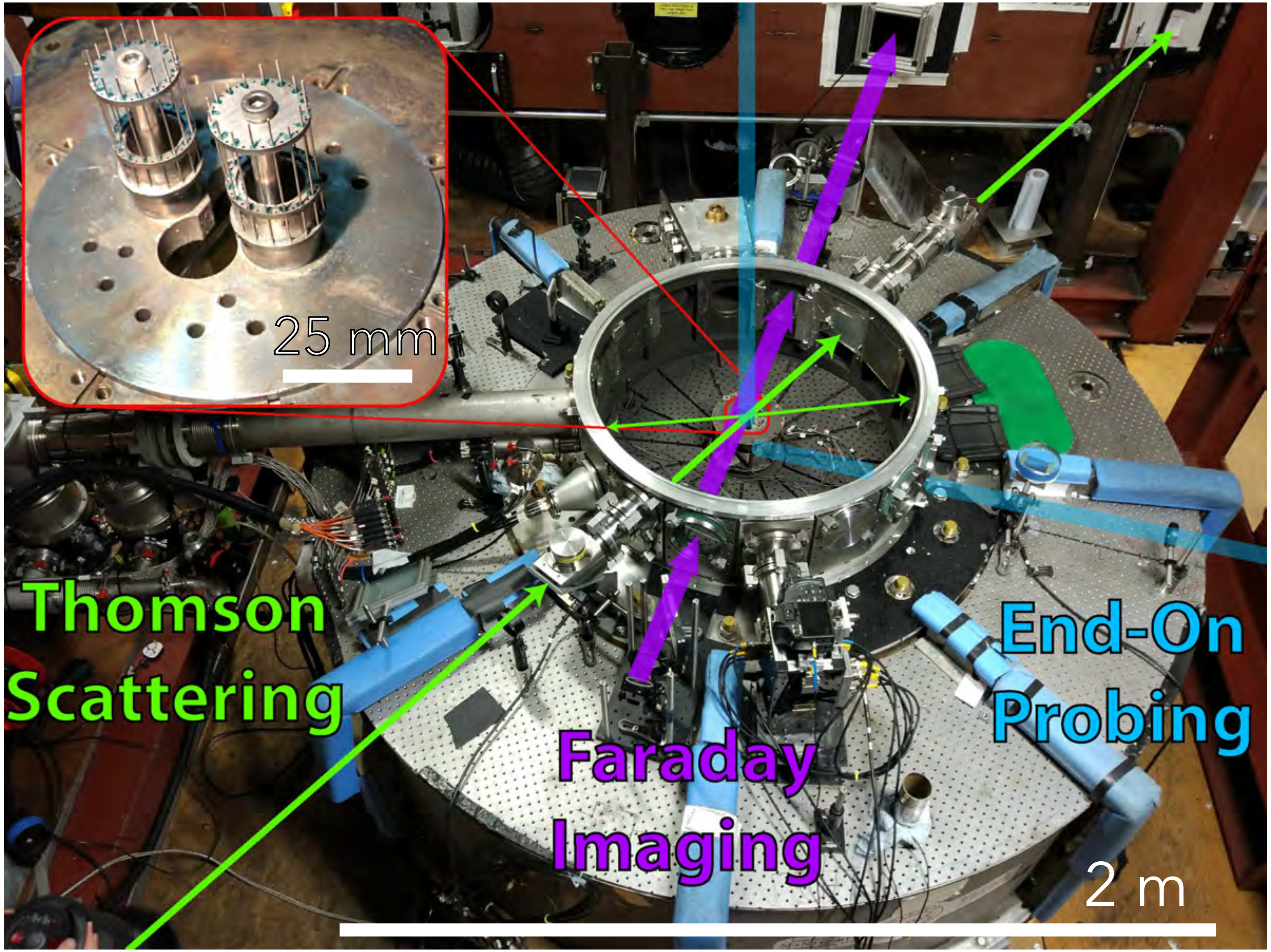
Magnetic Reconnection from Double Exploding Wire Arrays



Drive two exploding arrays in **parallel**: collides flows with **opposite magnetic fields**, forming a **reconnection layer**.

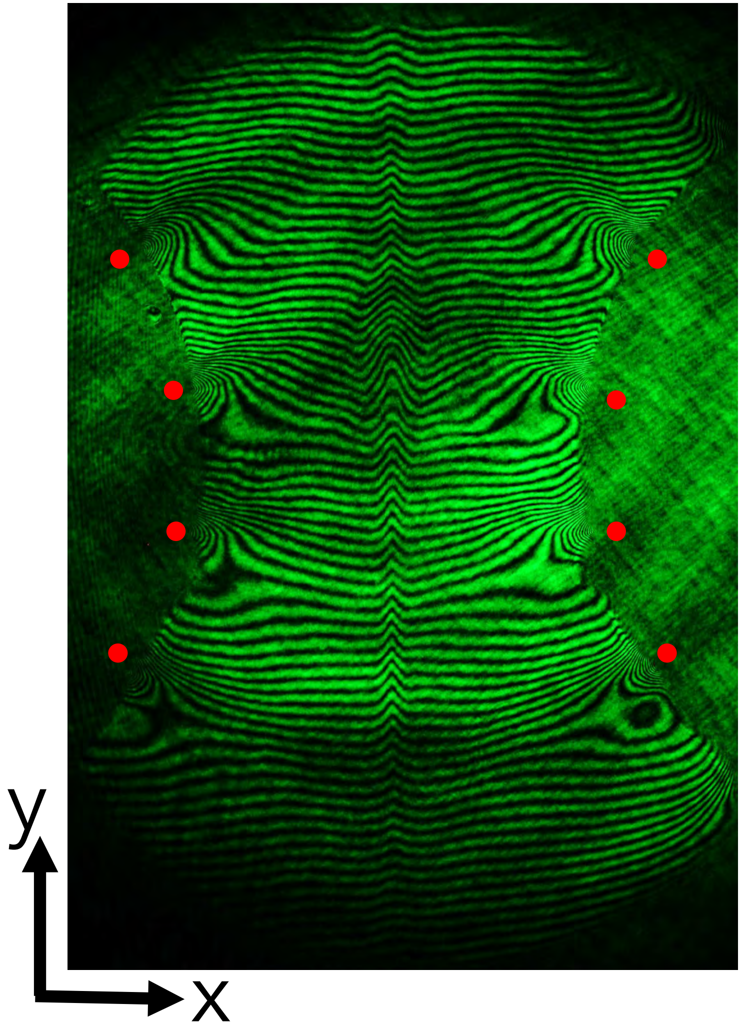
Hare *et al* PRL 2017, PoP 2017, 2018

Overview of Diagnostic Suite on MAGPIE at Imperial College

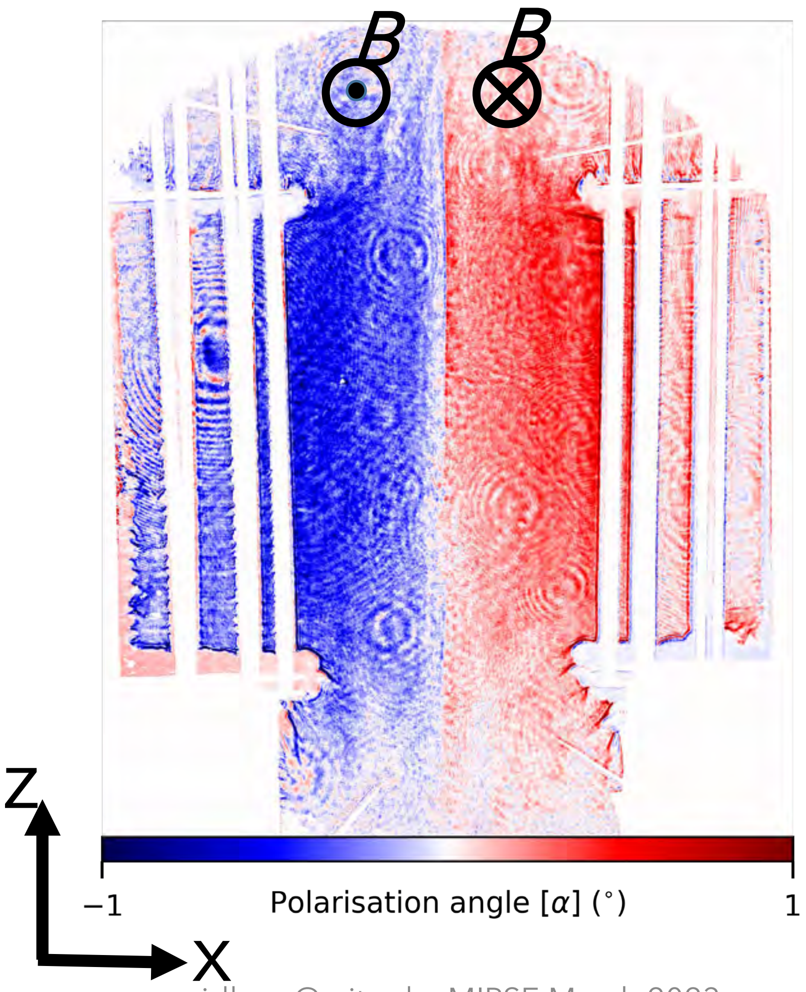


Diagnosing reconnection in the laboratory

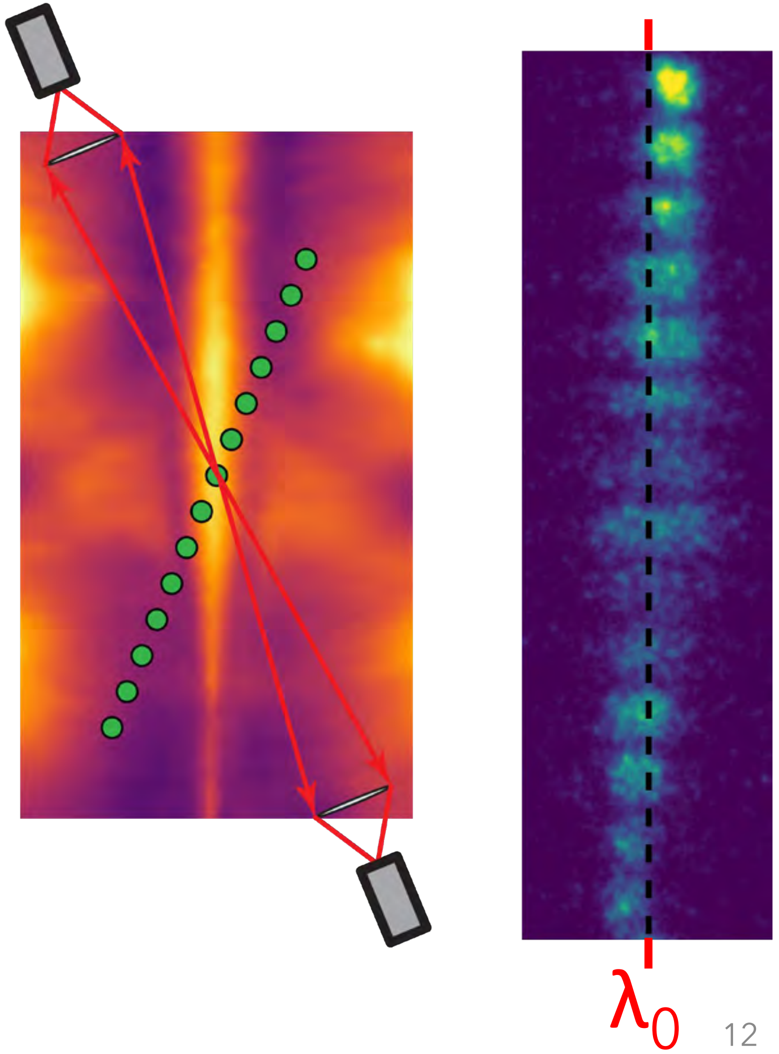
Laser interferometry:
$\int n_e dl$



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

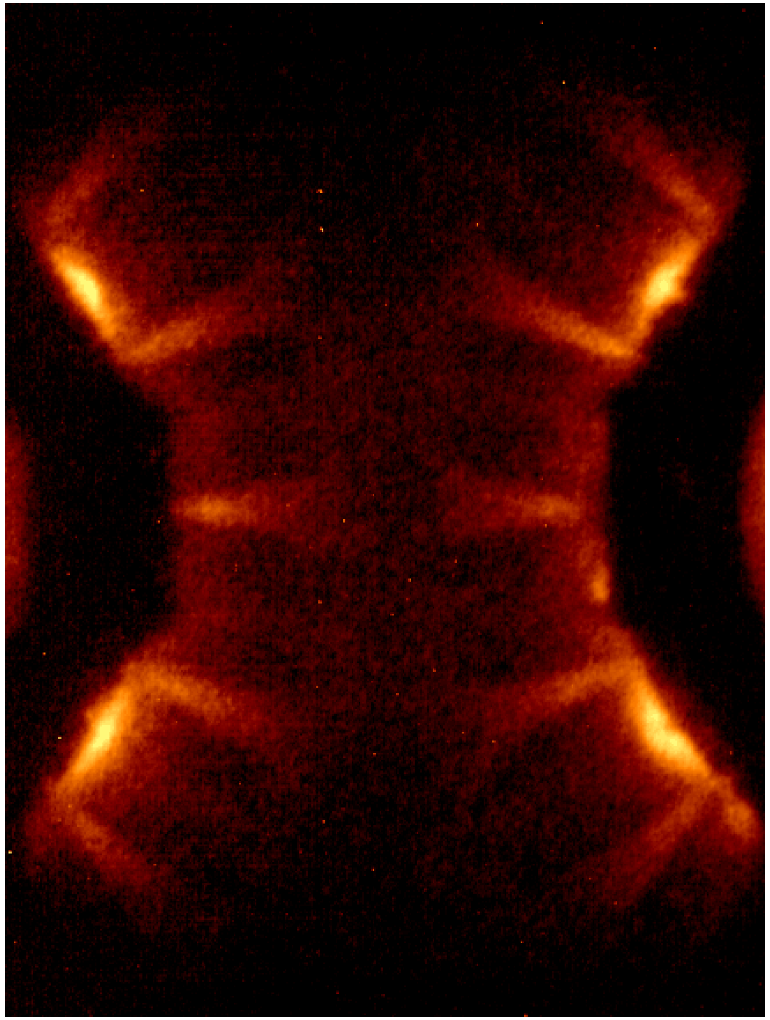


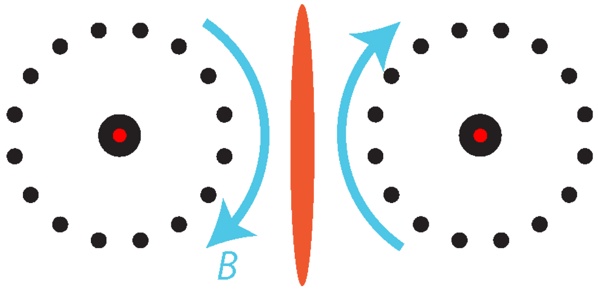
Thomson scattering:
$\boldsymbol{V}, ZT_e, T_i$



Choice of Wire Material

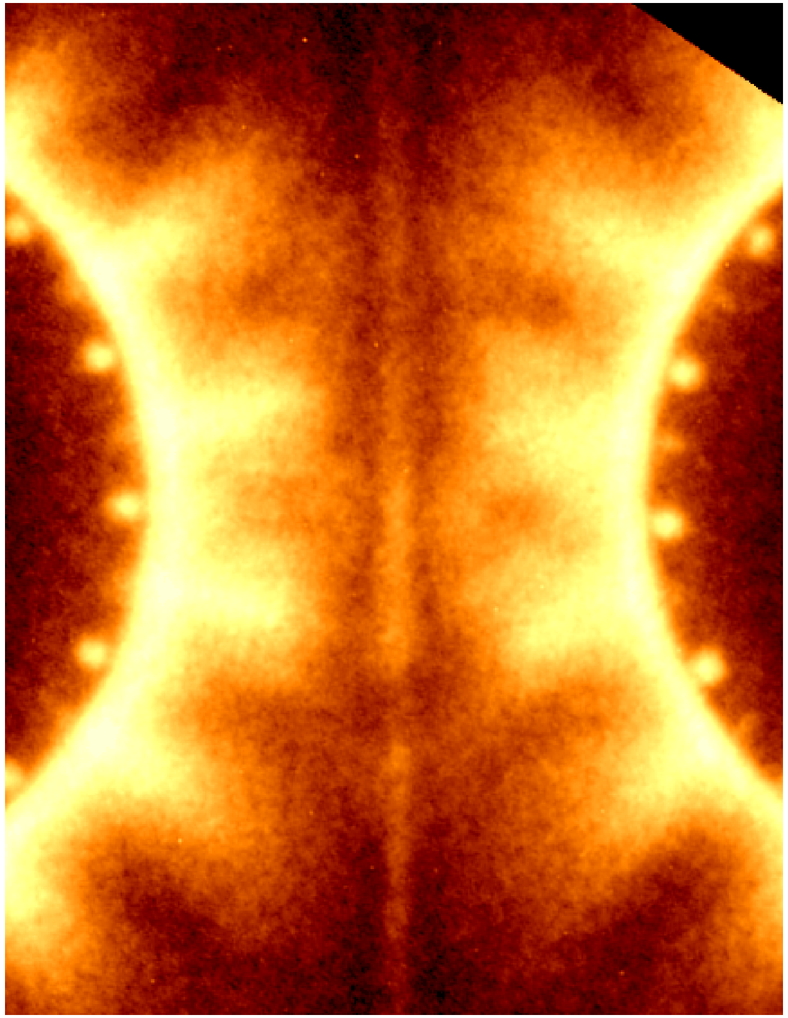
Aluminium Wires
Super Alfvénic, Radiatively cooled





	M_A	L/λ_{ii}	S
Aluminium	2	2000	10
Carbon	0.7	200	120

Carbon Wires
Sub-Alfvénic, Plasmoid instability



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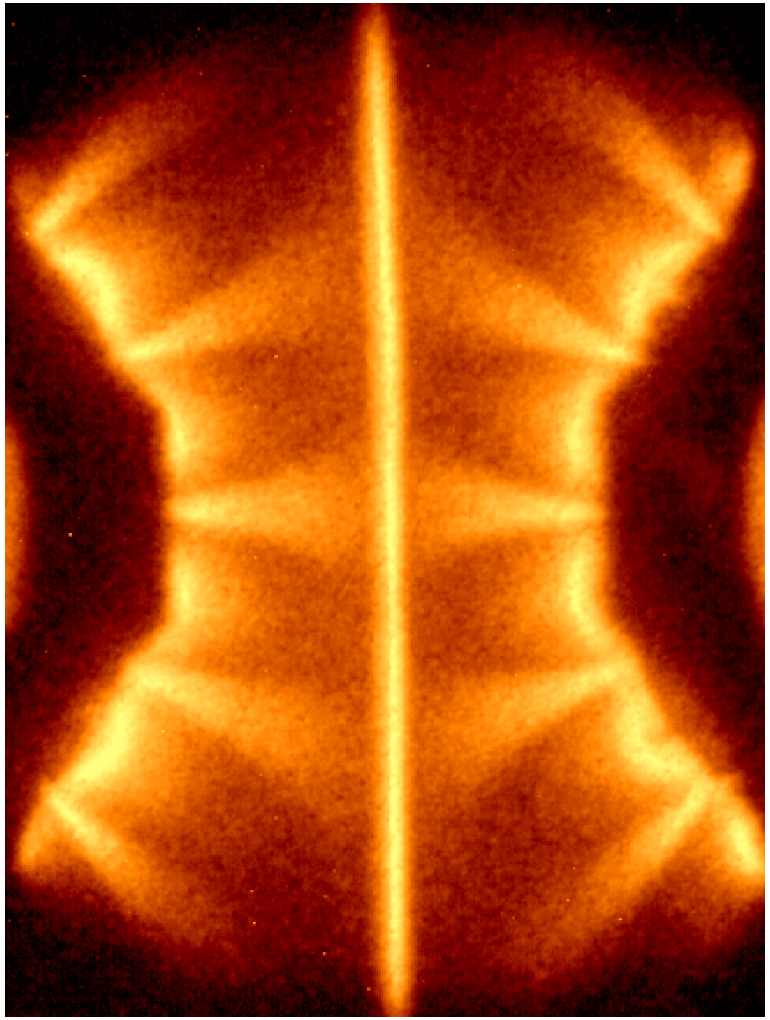

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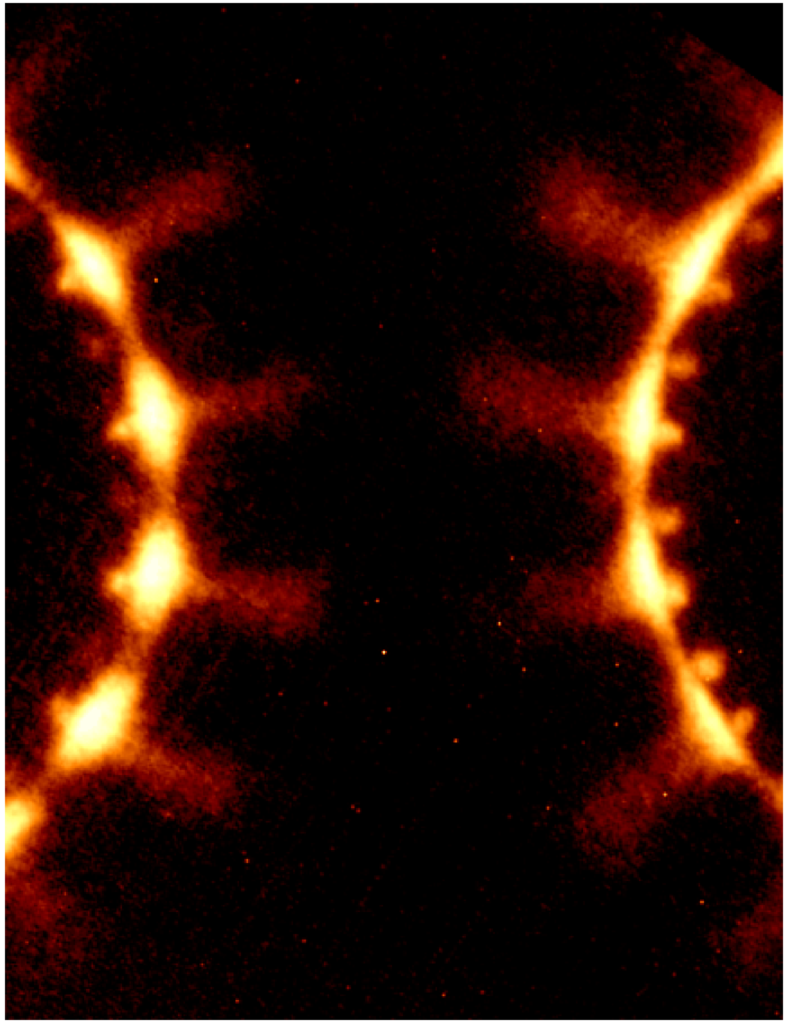

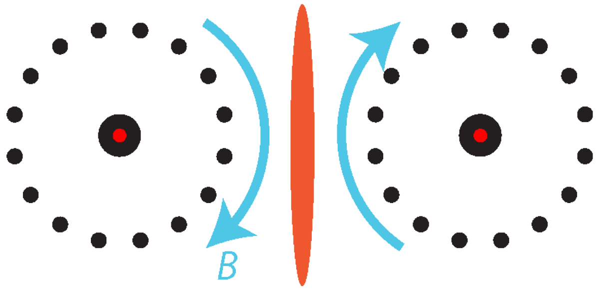

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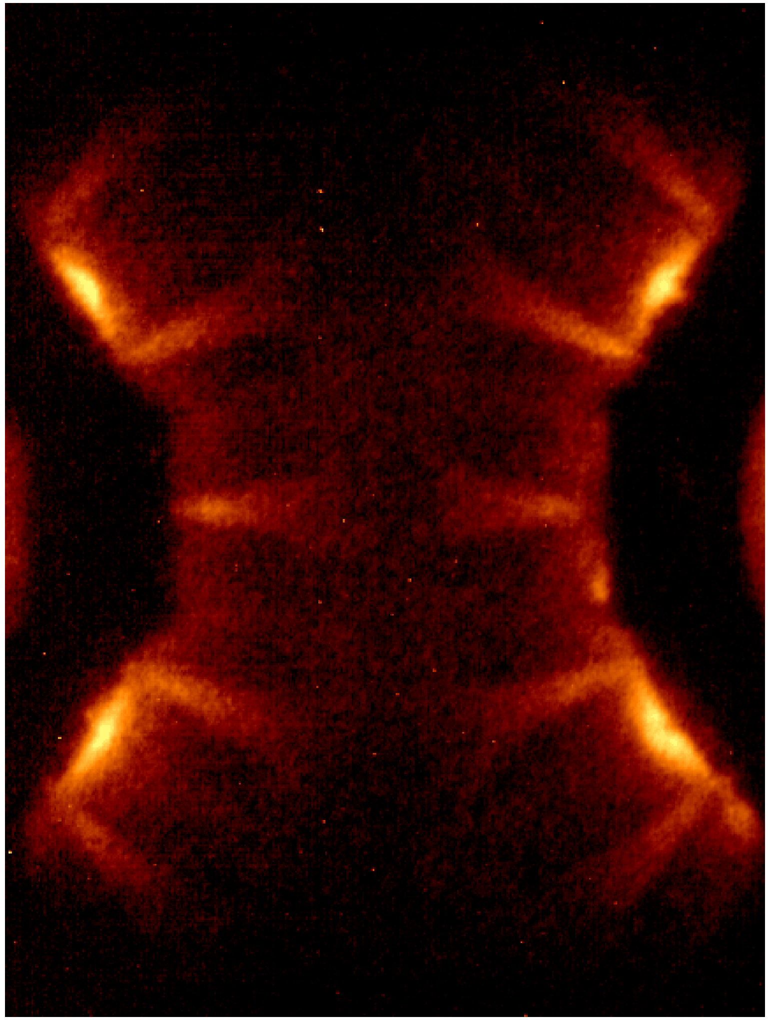

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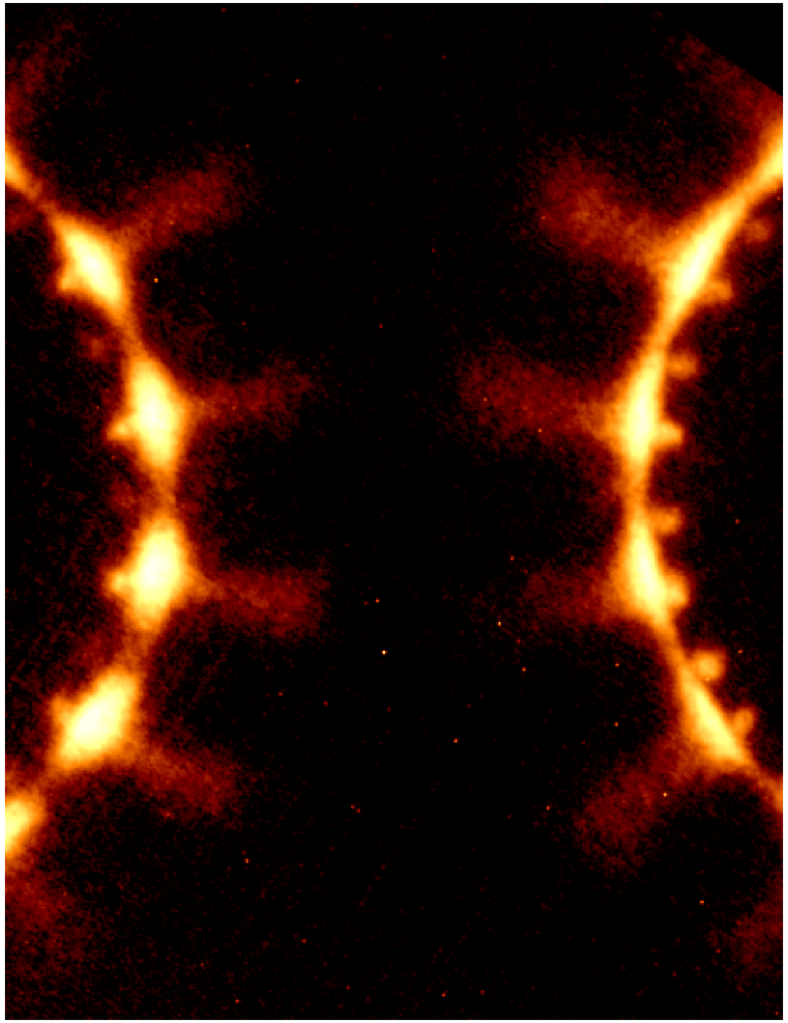

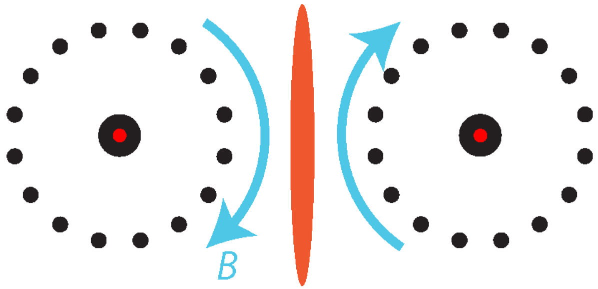

	M_A	L/λ_{ii}	S
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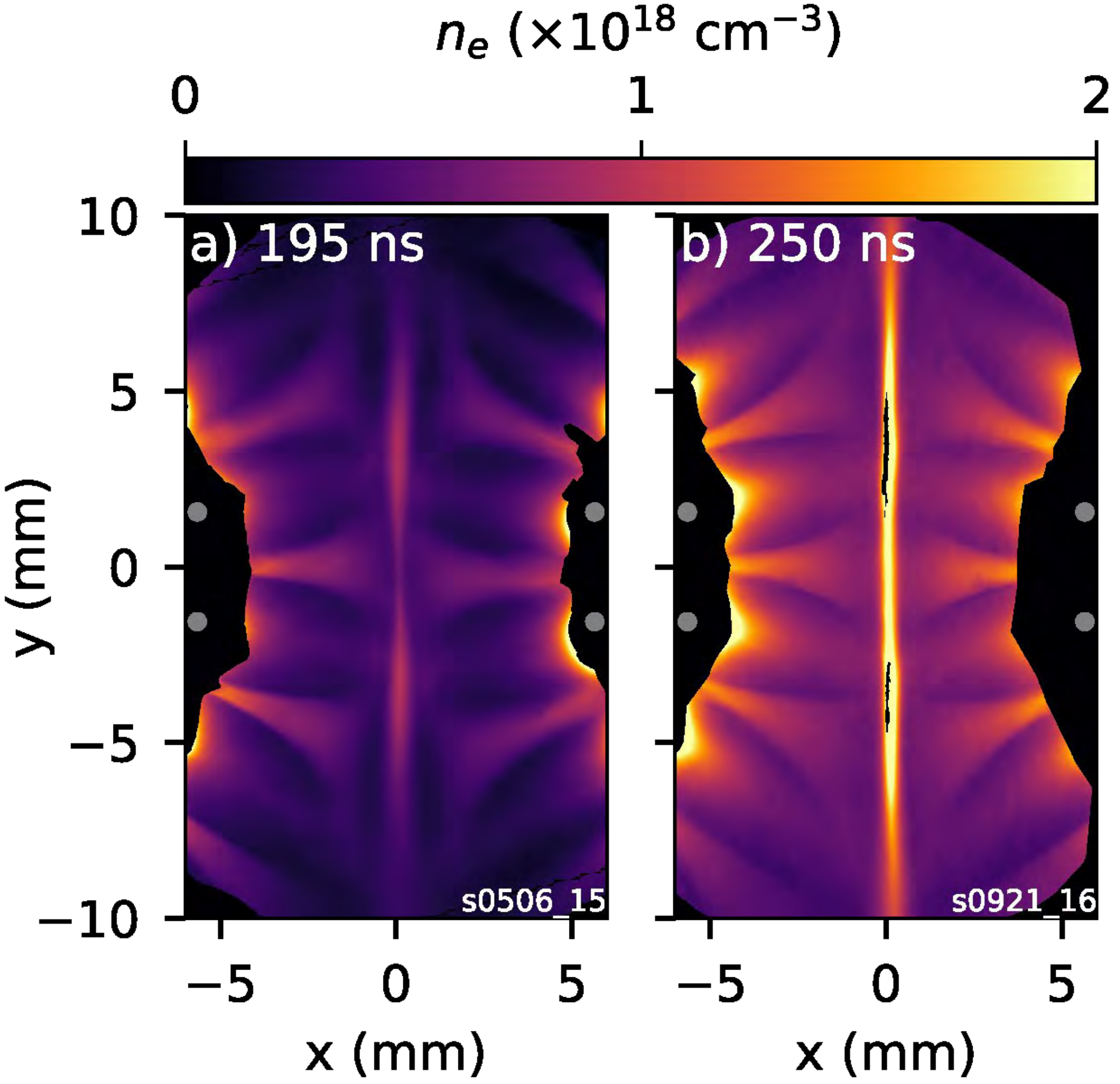
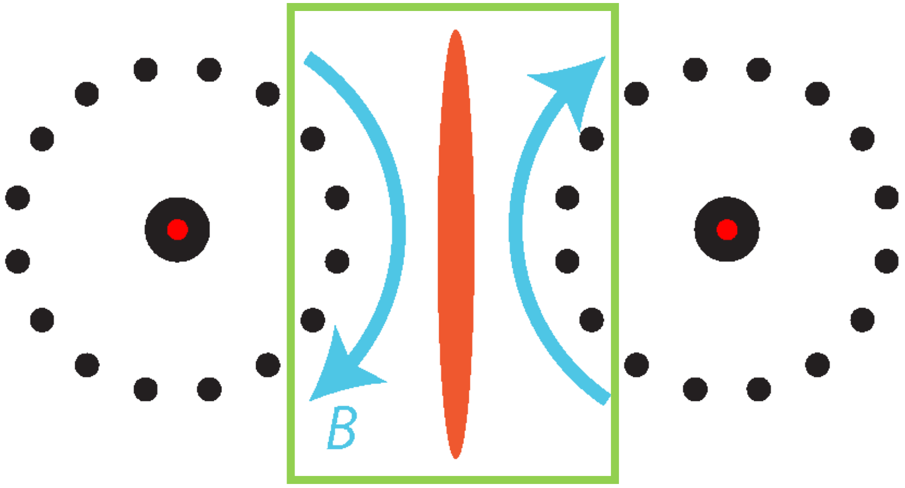
Aluminium: Density increases suddenly

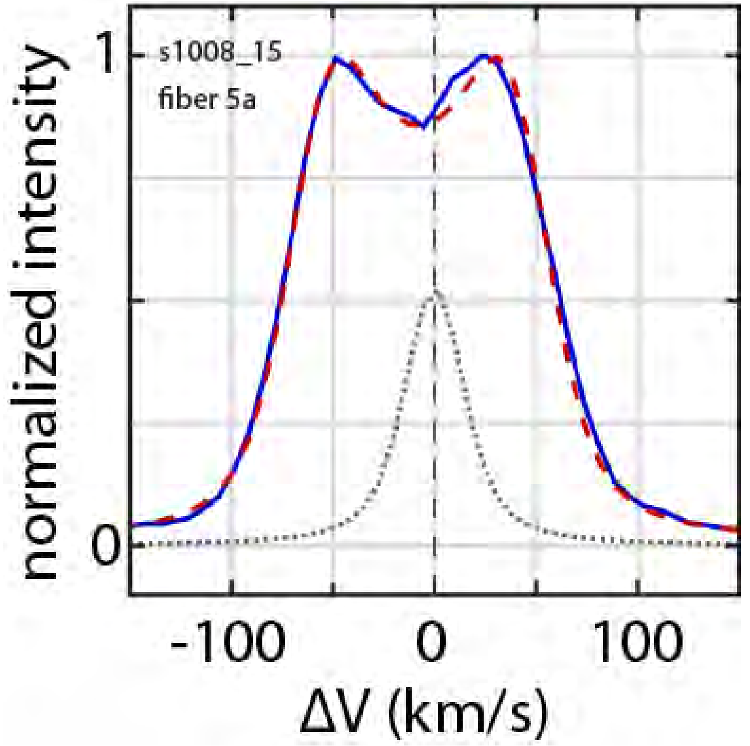


Suttle, L.G. *et al.* ***PRL*** 2016
Suttle, L.G. *et al.* ***PoP*** 2017

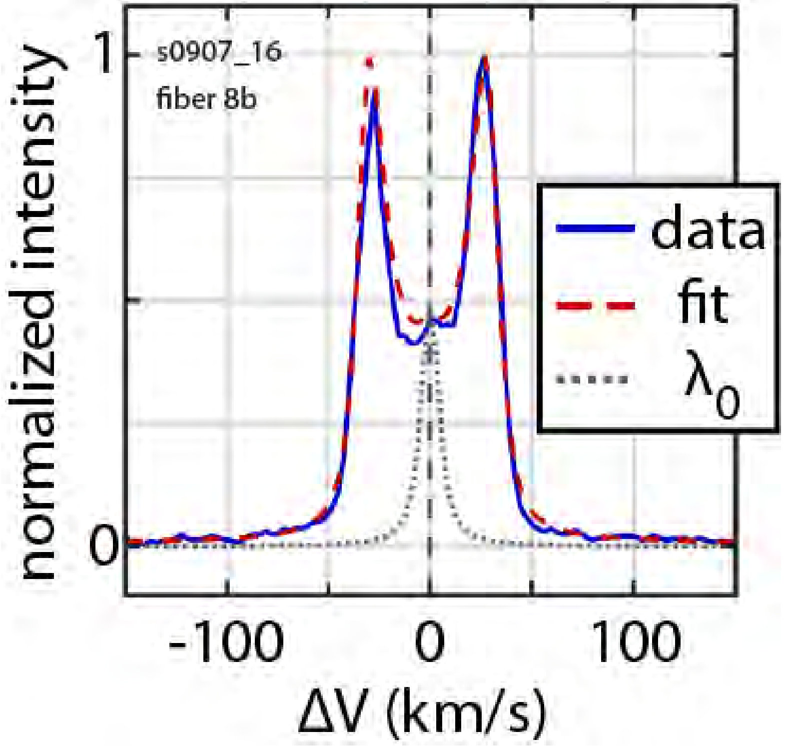


Aluminium: Ion temperature drops suddenly

Early time $T_i = 300$ eV



Late time $T_i = 40$ eV



$T_i >> T_e$ ($T_i \approx ZTe$)

Decrease of ion temperature

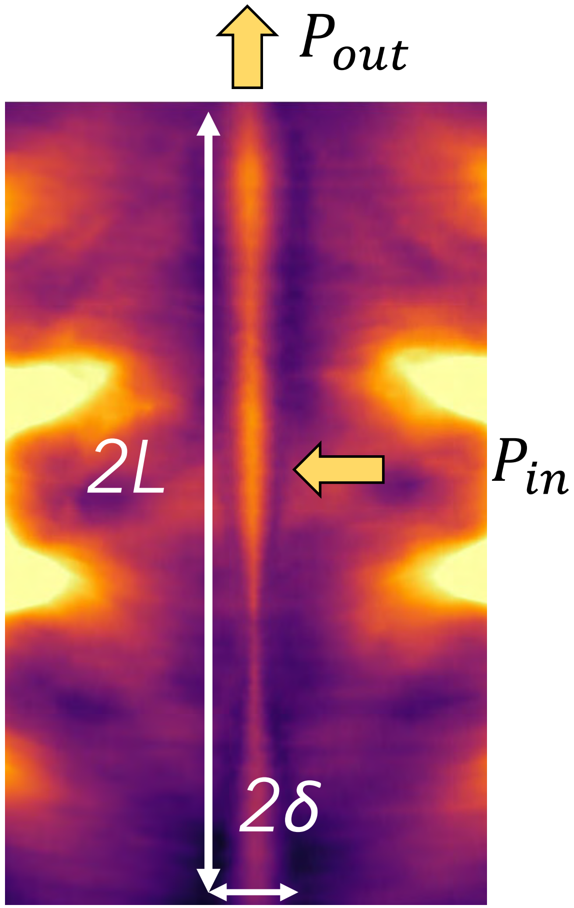
$T_i \approx T_e$

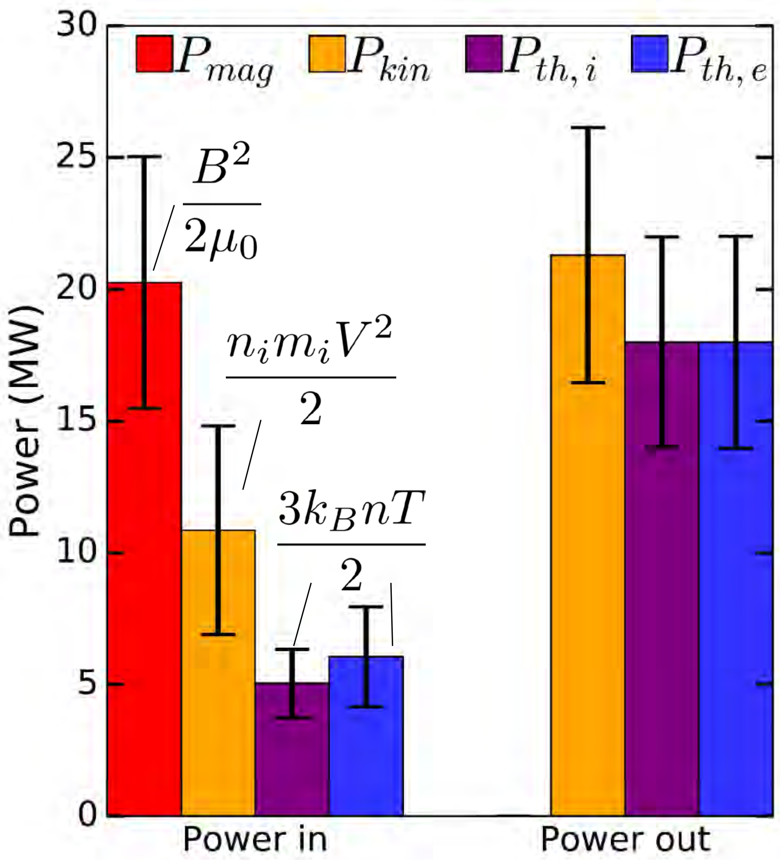
$$t_{ei}{}^{(E)} \propto 1/n_i \qquad t_{cool} \approx 4\,ns$$

Carbon: Anomalous Heating in the Reconnection Layer

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

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





Classical heating is too slow:

$\tau_{exp} \approx 50$ ns

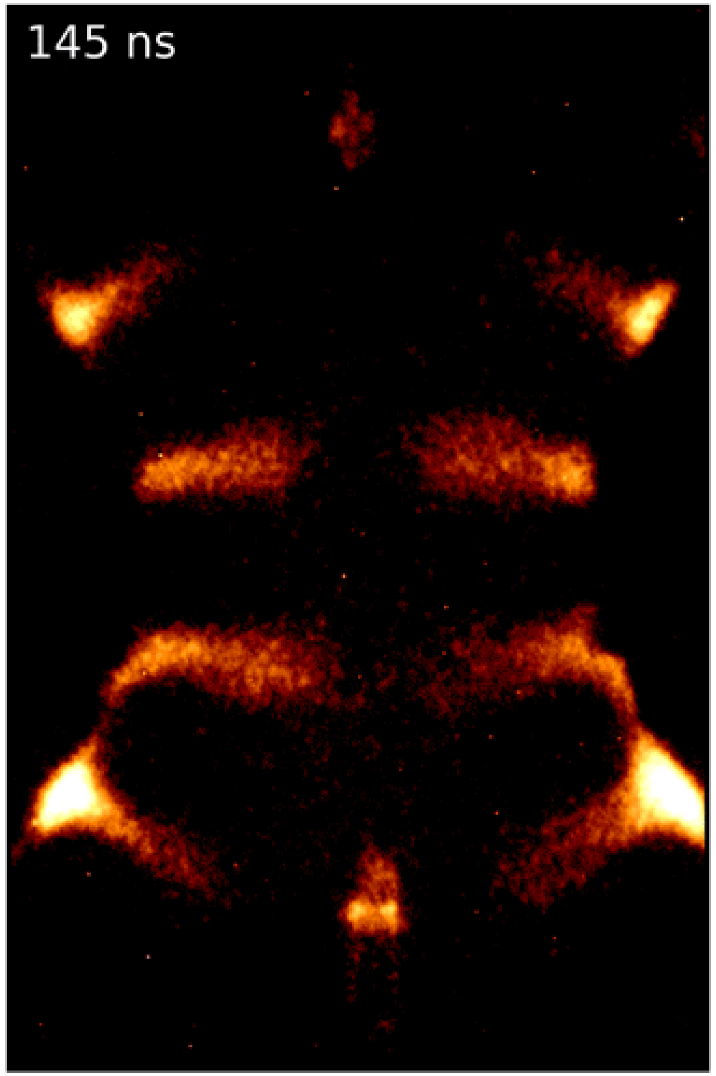
$\tau_{visc} \approx 800$ ns

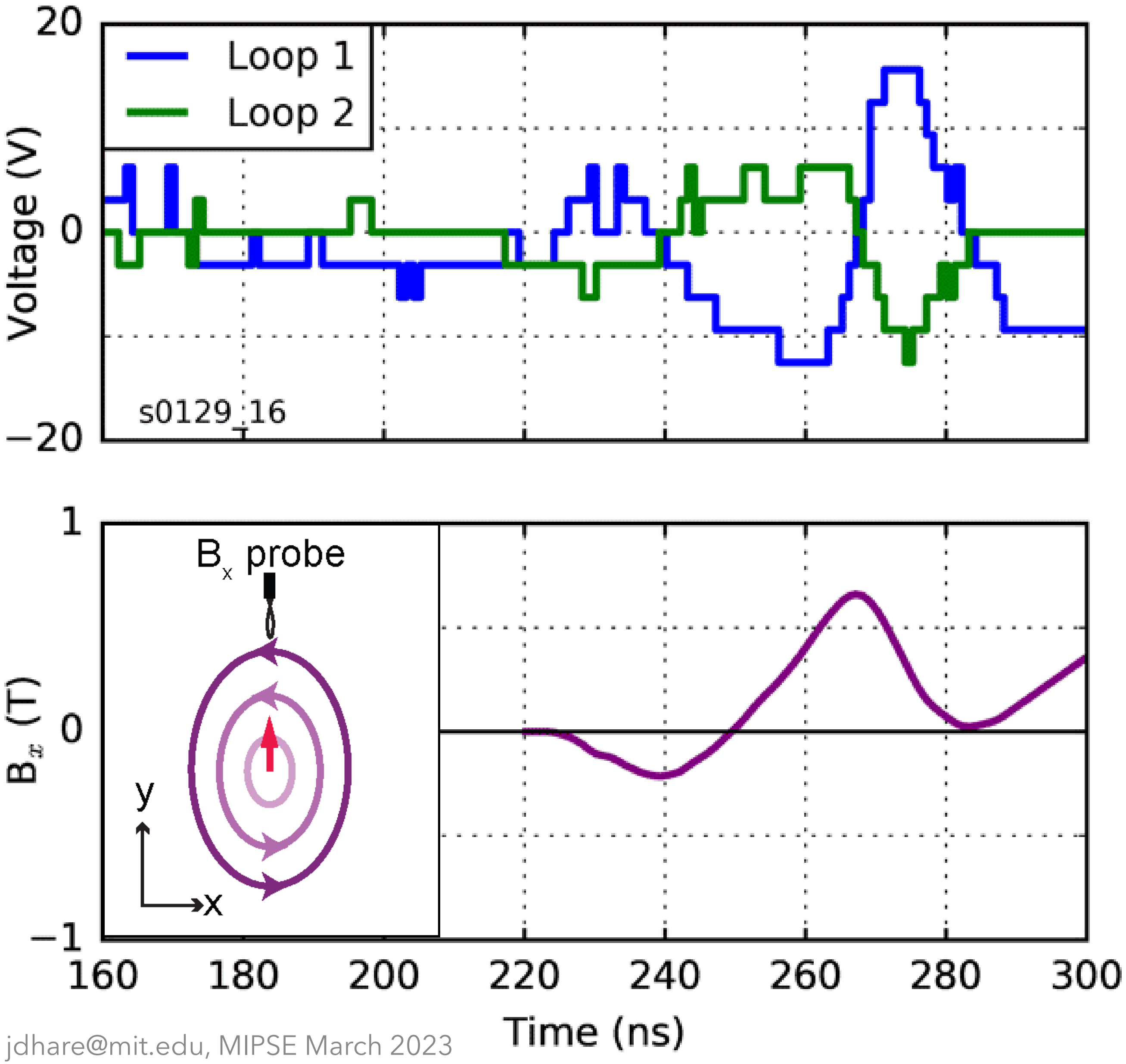
$\tau_{res} \approx 350$ ns

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

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

Plasmoids observed in emission, density & B-field



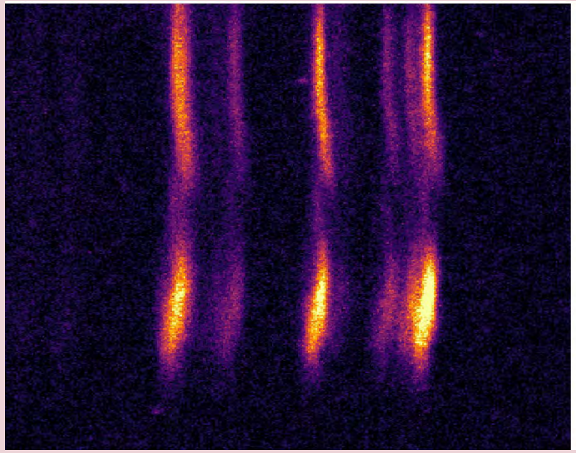


Research paths and talk outline

Magnetic reconnection

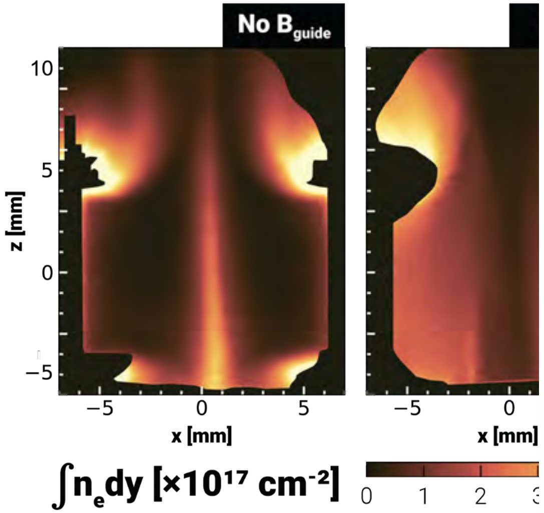
Radiative cooling

MARZ: Radiatively cooled reconnection on Z

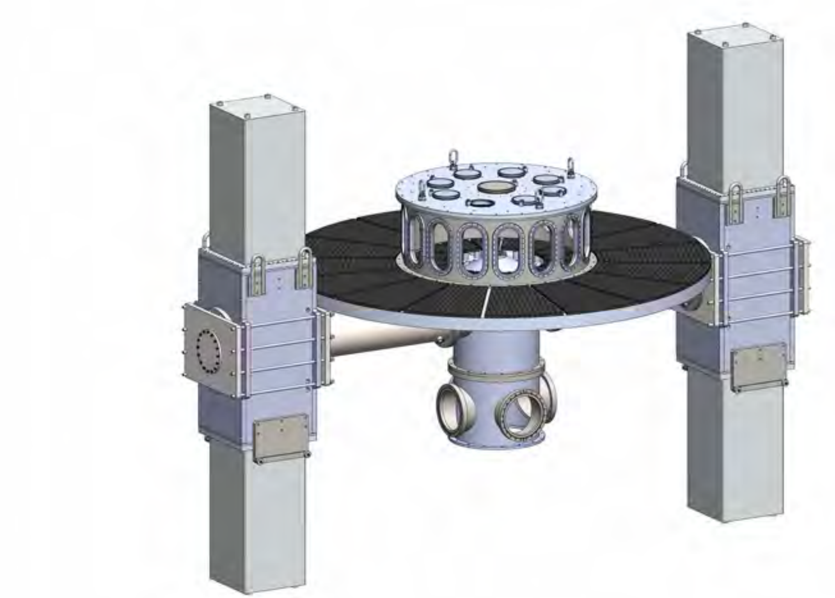


Plasmoids and turbulence

Guide field on MAIZE



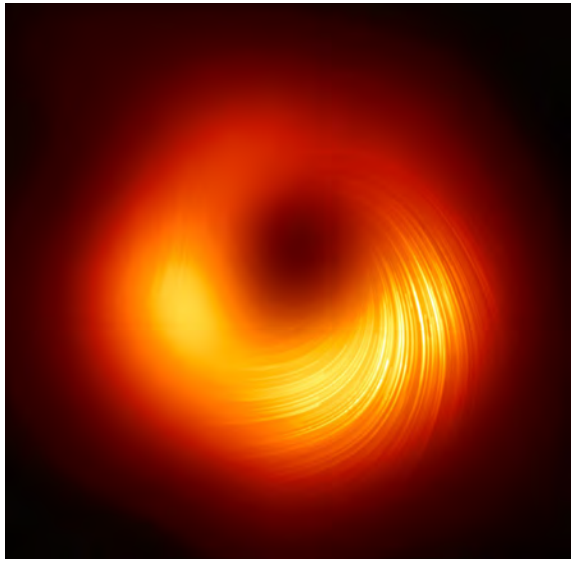
Longer timescales on PUFFIN



Reconnection in Extreme Astrophysical Environments

Artist's impression of a black hole

M87 (EHT)

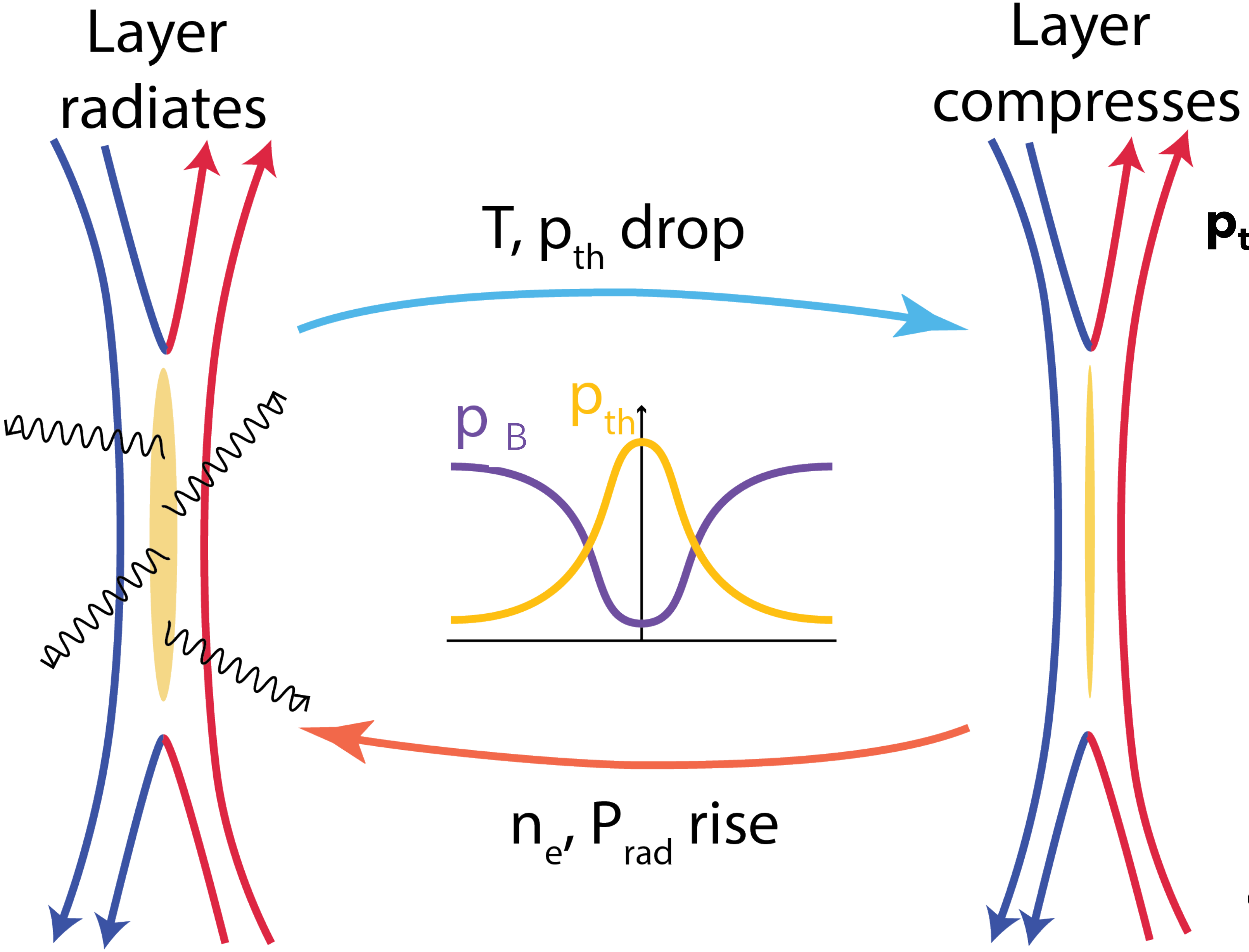


Crab Pulsar (Hubble/Chandra)

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

1. Cooling is a significant loss mechanism:
   - Modifies partition of magnetic energy between electrons, ions, kinetic
   - Leads to cooling instabilities, radiative collapse, rapid 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



p_{th} in layer opposes **p_B** outside

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

Overview of Sweet-Parker radiative reconnection
Uzdensky, D. A & McKinney, J. C (2011).
Phys. Plasmas 18 (4), 042105

MARZ Collaboration: Radiatively Cooled Reconnection on Z

Z is the largest pulsed-power machine in the world

- 20 MA peak current compared to 1.4 MA on MAGPIE:
  - **Ablated mass** $\propto I^2/R \sim 80 \rightarrow$ more, thicker wires; denser layer
  - **Magnetic energy density** $\propto I^2/R^2 \sim 30 \rightarrow$ more energy, hotter layer
  - **Cooling rate** $\propto n_e^2 T_e^{1/2} \sim 60 \rightarrow$ strong radiative cooling

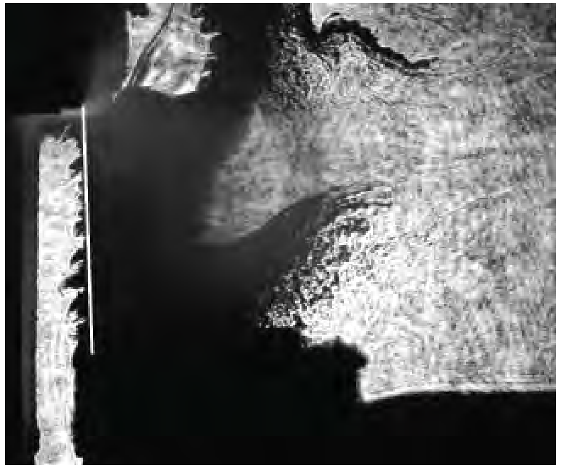
Requires more mass in load:
- $16 \rightarrow 150$ wires/array
- 40 μm → 75 μm or 100 μm wires
- 16 mm → 40 mm arrays

Research paths and talk outline

Magnetic reconnection

Radiative cooling

Planar wire arrays on COBRA



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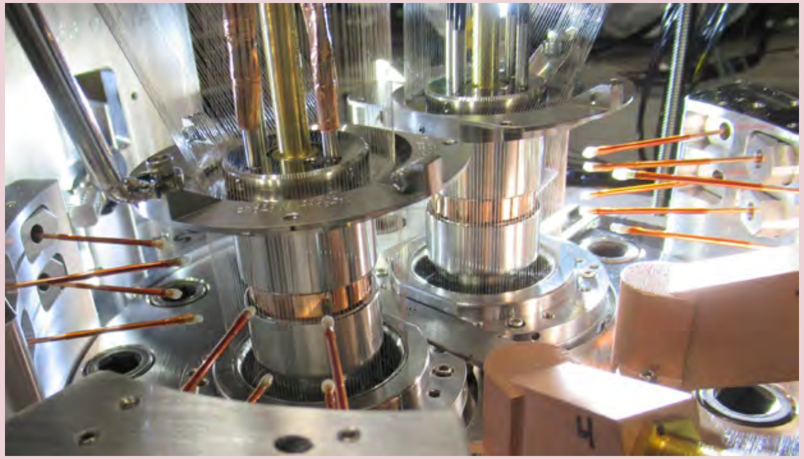

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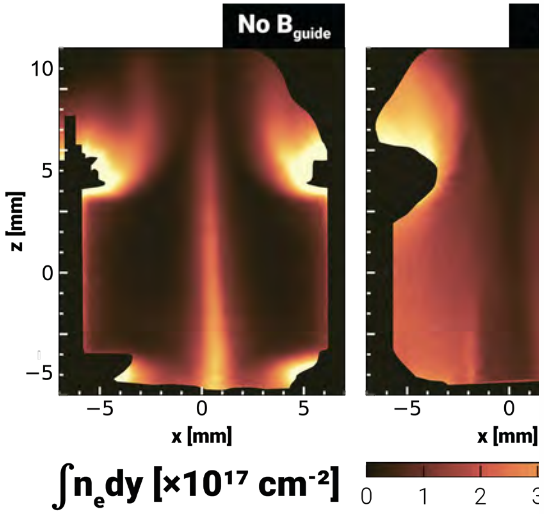
Guide field on MAIZE



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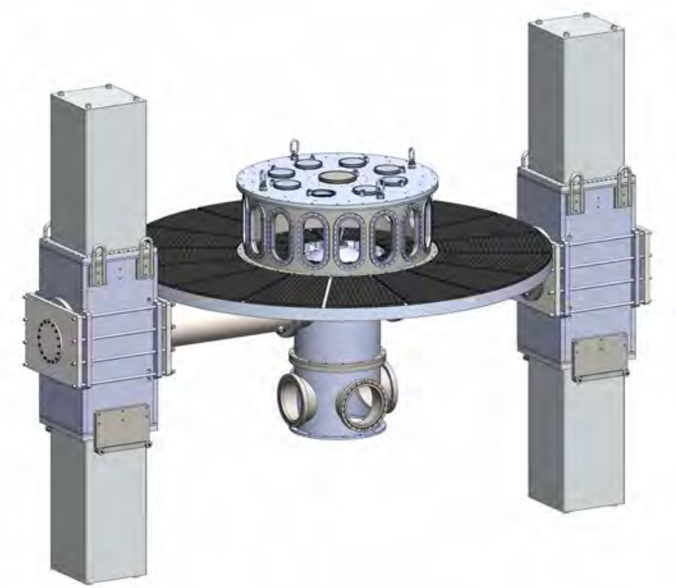
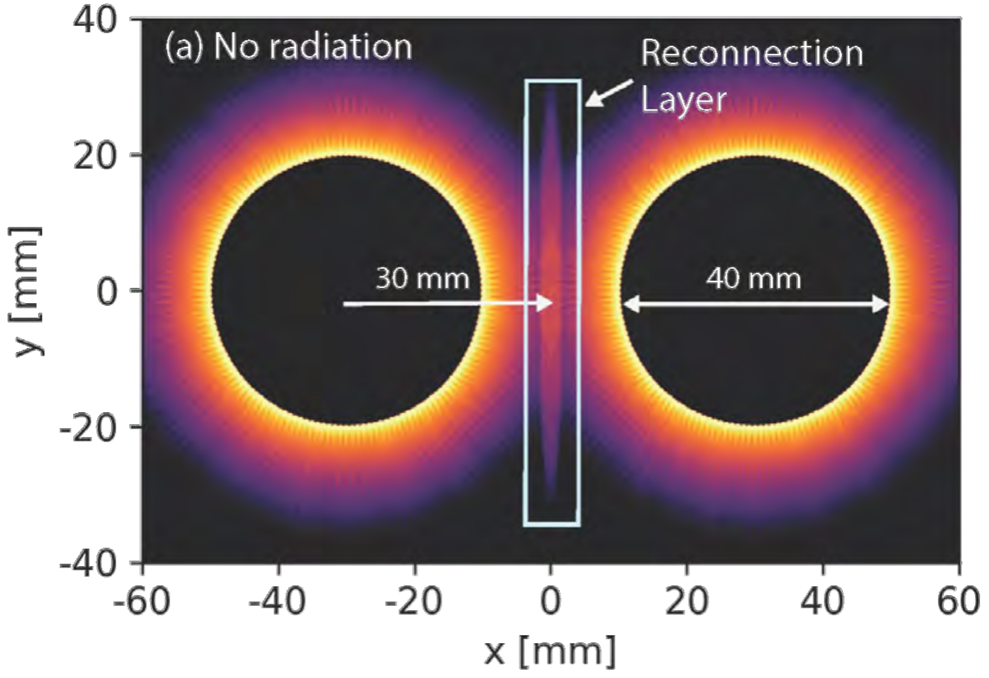


GORGON: 2D MHD Simulation Setup

GORGON (J. Chittenden, Imperial):
2D or 3D Eulerian resistive MHD code with detailed radiation loss models



Analysis by Rishabh Datta & Simran Chowdhry

- 150 Al wires, 75 μm diameter
- 40 mm diameter arrays, 20 mm gap
- 20 MA, 300 ns rise-time current pulse

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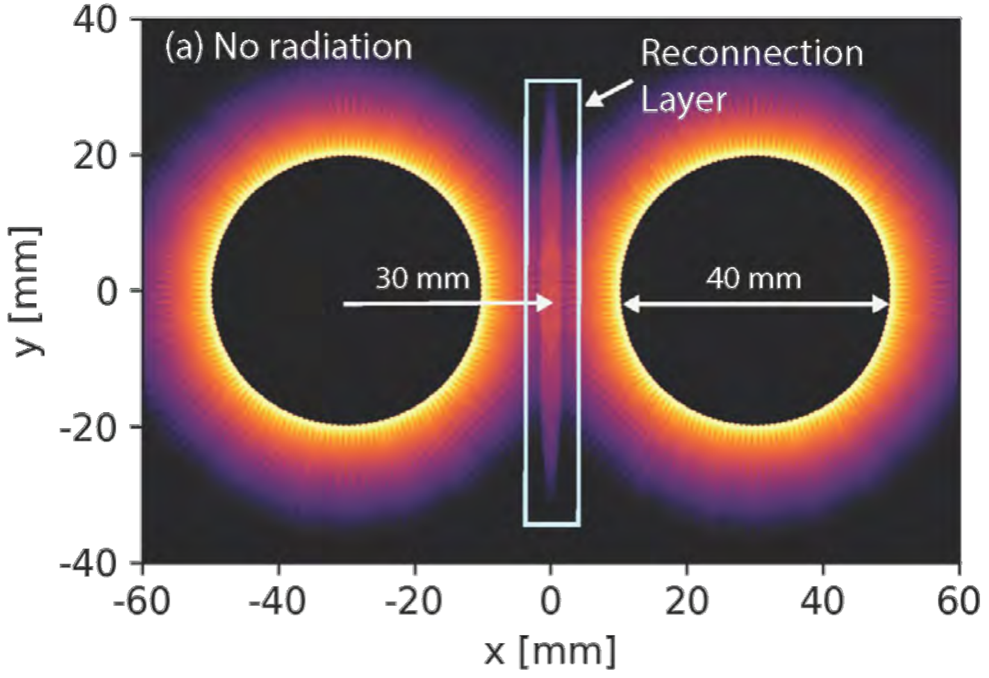
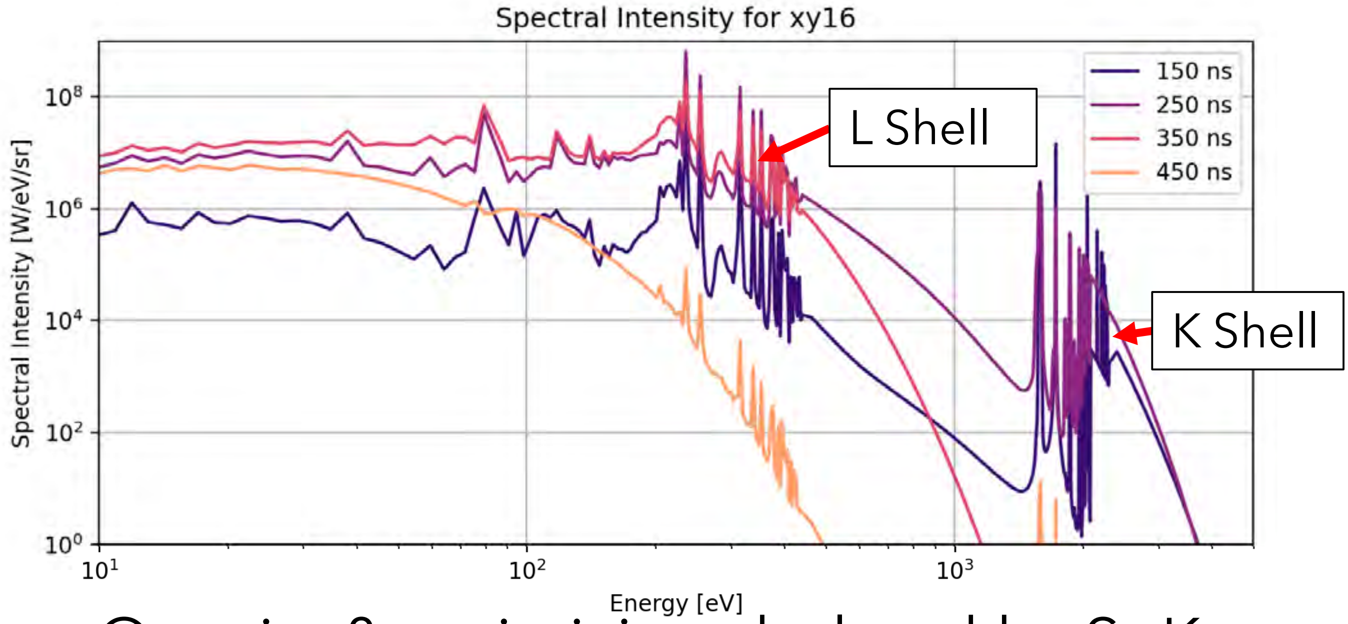
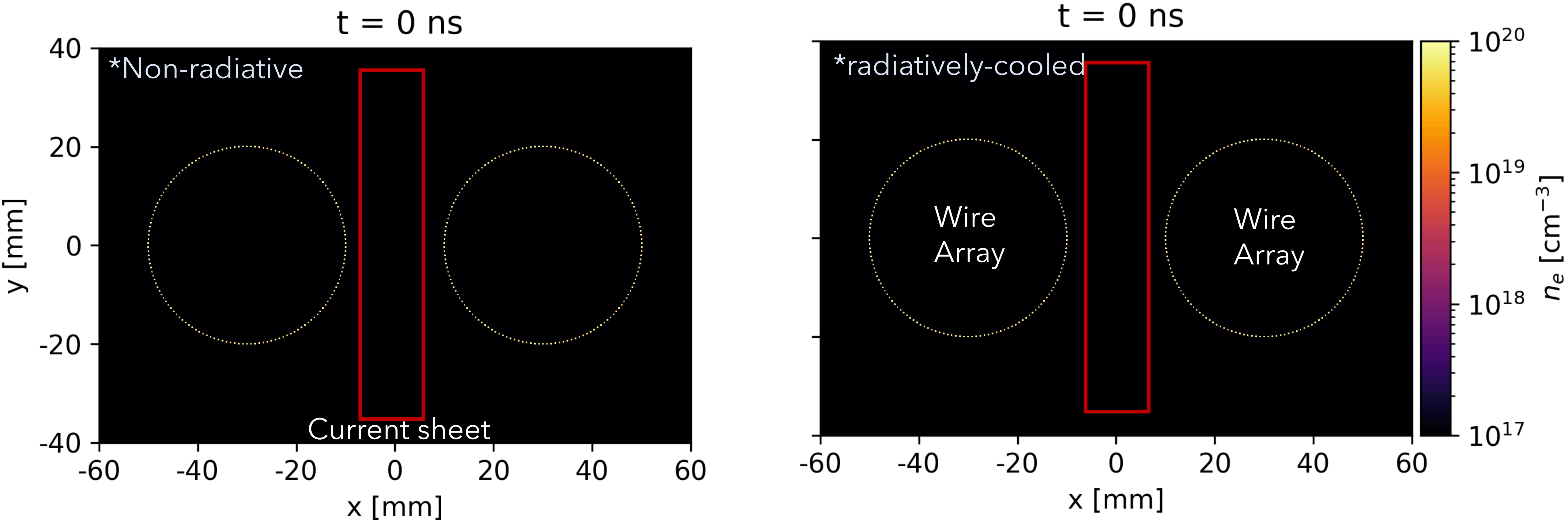




- 150 Al wires, 75 μm diameter
- 40 mm diameter arrays, 20 mm gap
- 20 MA, 300 ns rise-time current pulse

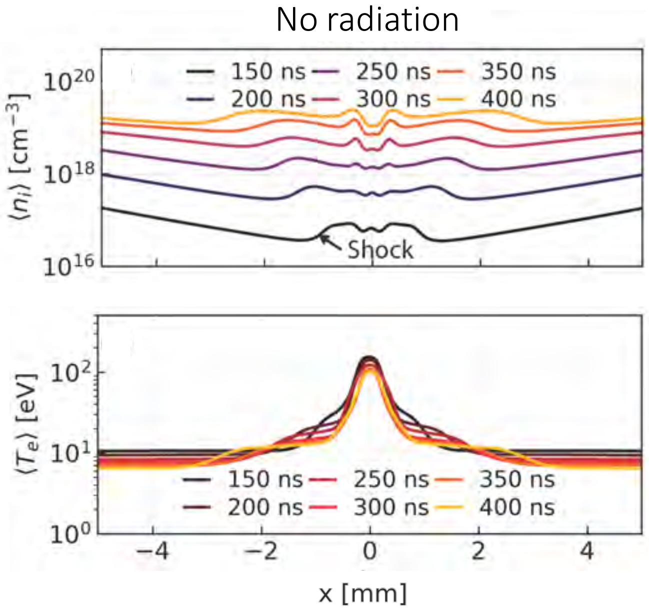
- Opacity & emissivity tabulated by SpK (Crilly 2022)
- Bound-bound, bound-free, and free-free transitions
- Probability of escape model, for photon $\lambda_{mfp} > 25\ \mu m$, cell size

Simulations show radiative collapse



With cooling: strongly-compressed, denser and thinner current sheet,
Consistent with theory (Uzdensky & McKinney, 2011) and previous simulations.

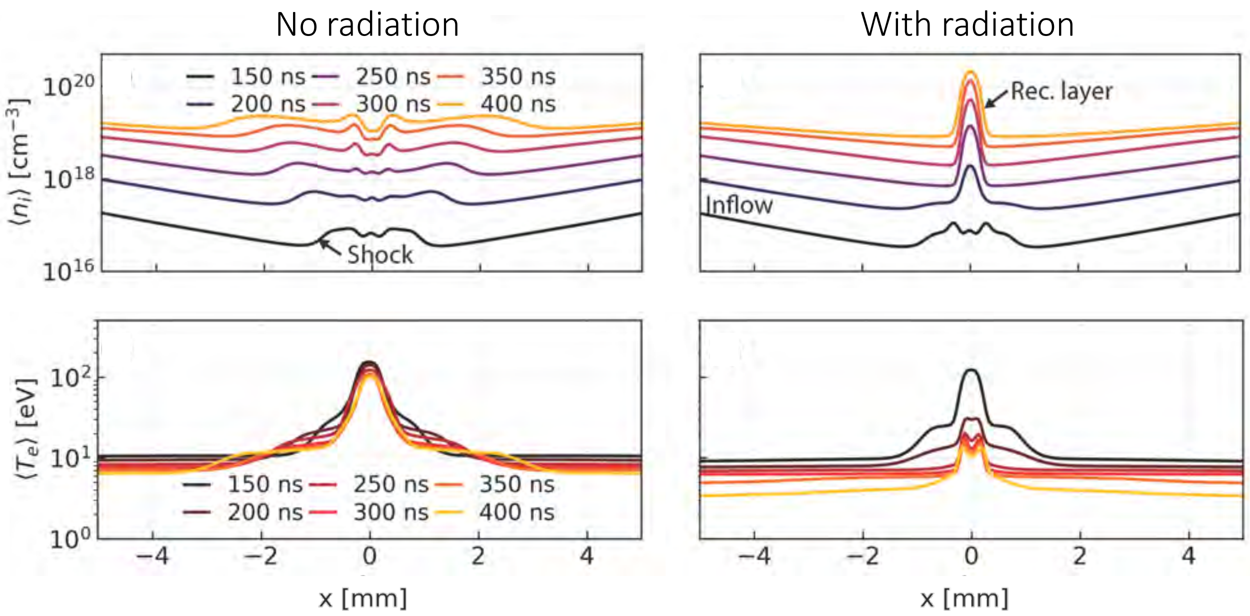
Radiation causes a colder, denser layer



Without radiation:

- Shocks, hotter layer

Radiation causes a colder, denser layer



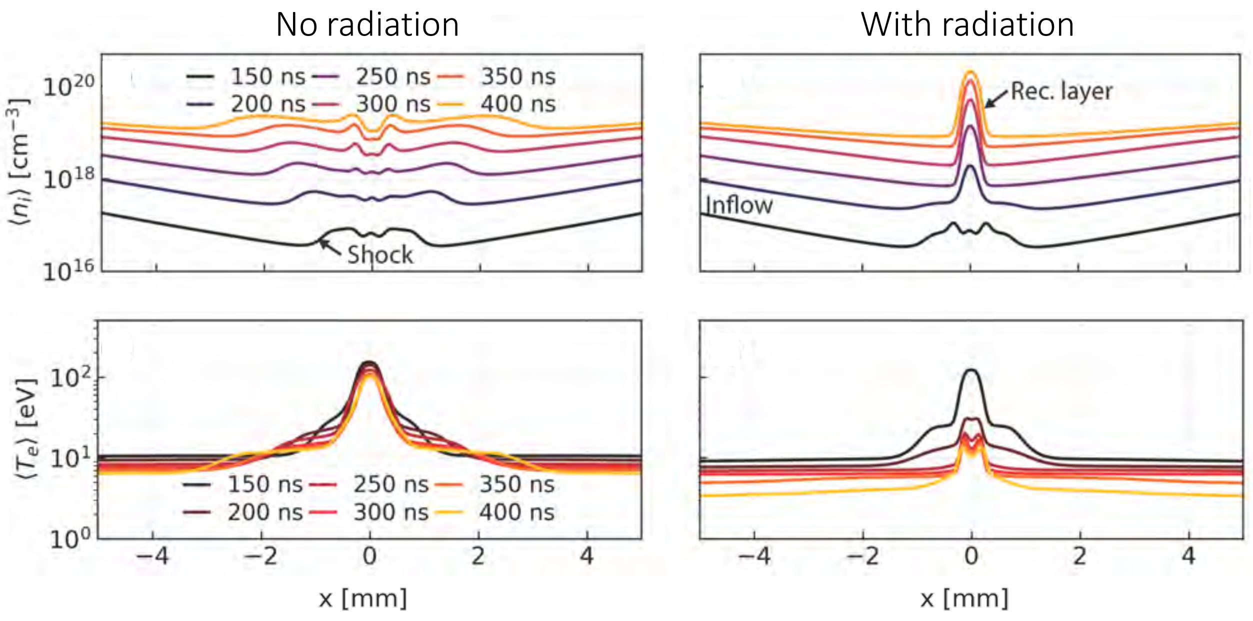
Without radiation:

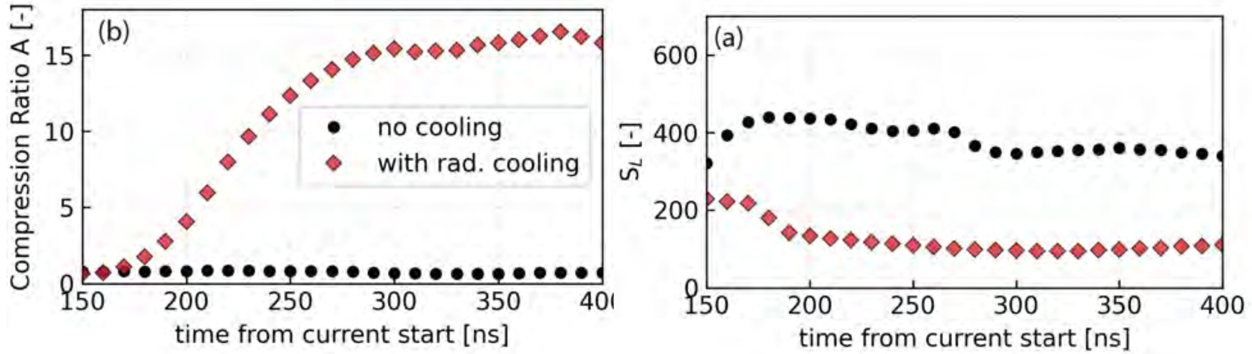
- Shocks, hotter layer

With radiation:

- Cooler, denser layer: strong compression, muted shocks

Radiation causes a colder, denser layer





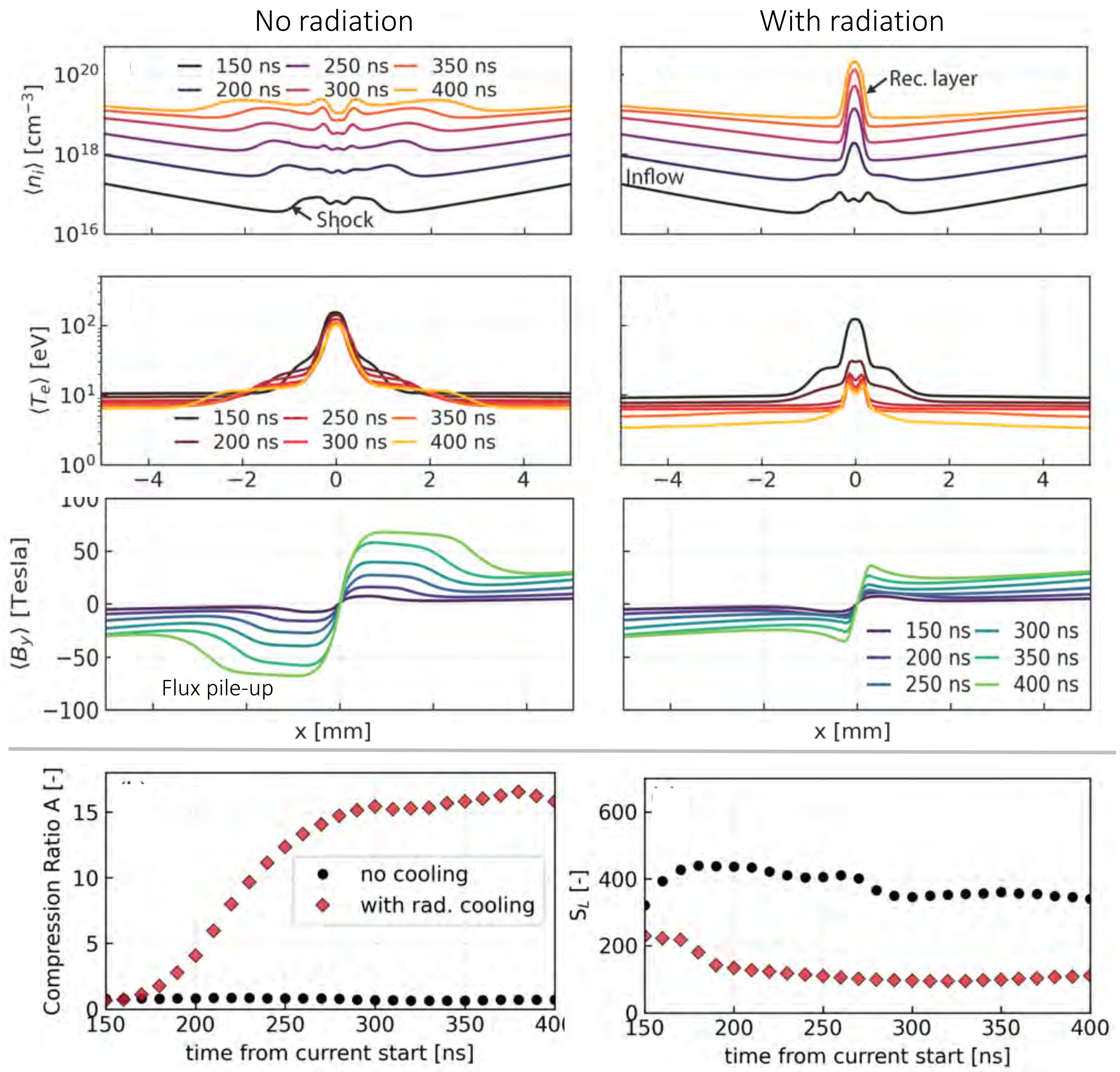
Without radiation:

- Shocks, hotter layer

With radiation:

- Cooler, denser layer: strong compression, muted shocks
- $S_L \downarrow$,A= $\rho_{layer}/\rho_{in} \gg 1 \uparrow$: faster reconnection

Radiation causes a colder, denser layer



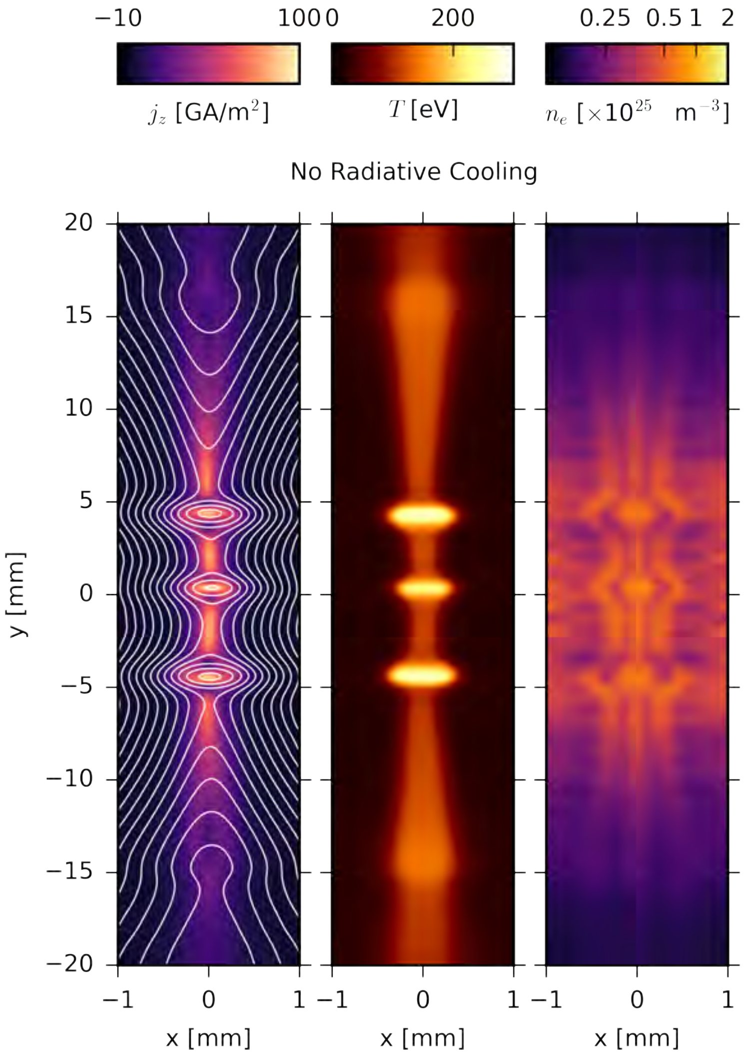
Without radiation:

- Shocks, hotter layer

With radiation:

- Cooler, denser layer: strong compression, muted shocks
- $S_L \downarrow$, A= $\rho_{layer}/\rho_{in} \gg 1 \uparrow$: faster reconnection
- Reduced flux pile-up outside the layer: lower $\langle B_y \rangle$ and n_e just outside the layer

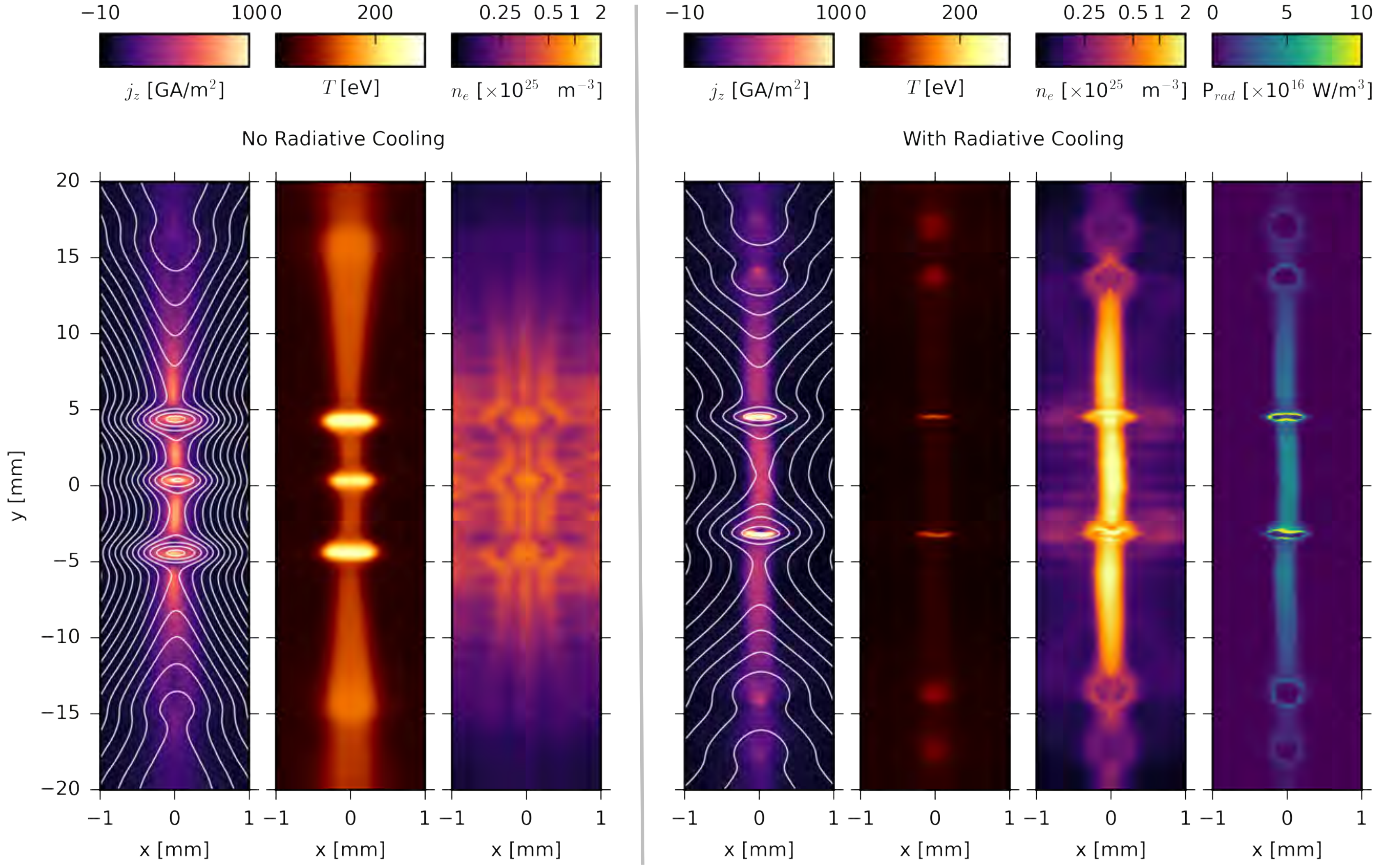
Radiation affects the layer and the plasmoids



Without Cooling:

- n_e, J_z in the layer ~ n_e, J_z in the plasmoids
- T_e in the layer ≪ T_e in the plasmoids

Radiation affects the layer and the plasmoids



Without Cooling:

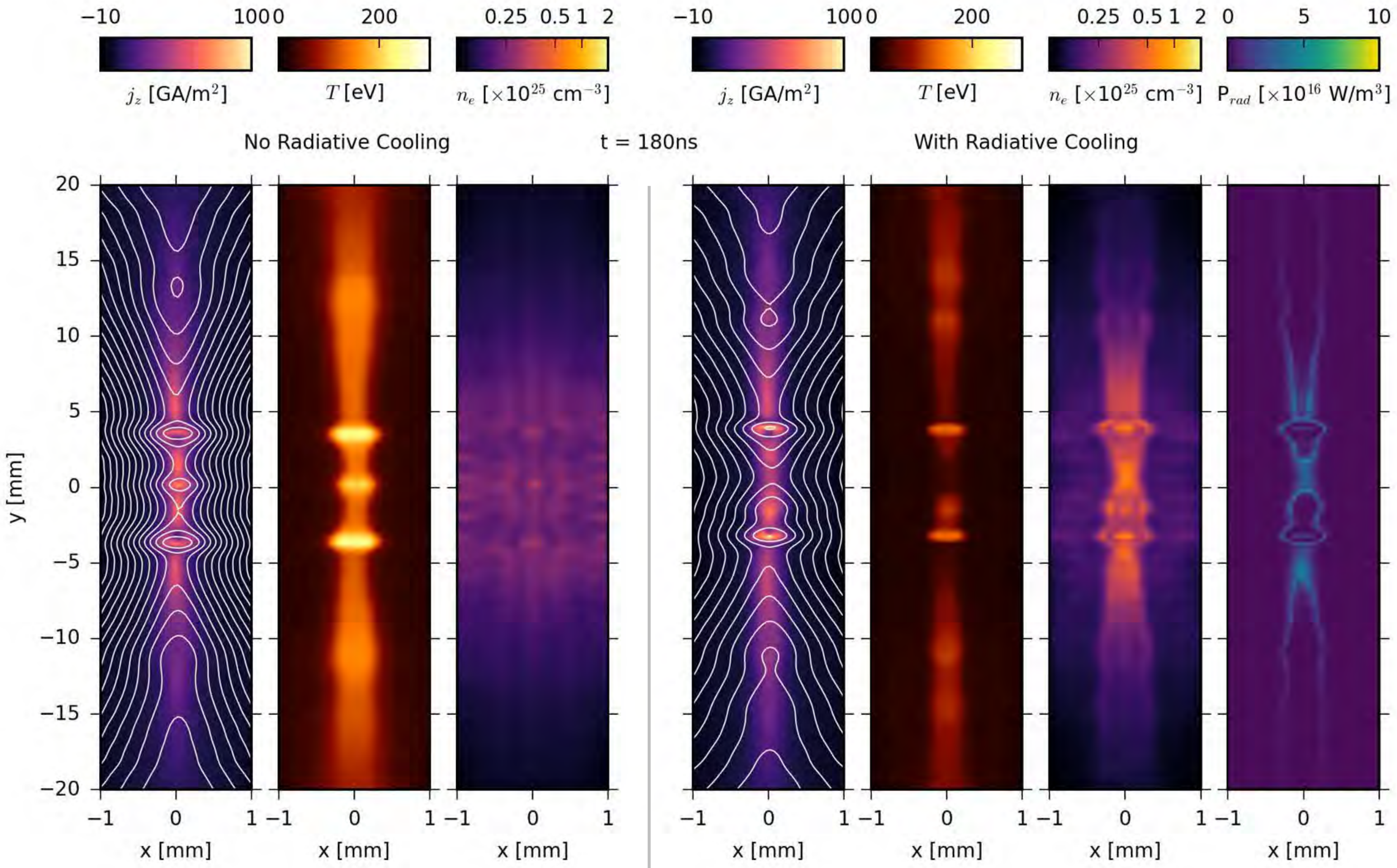
- n_e, J_z in the layer ~ n_e, J_z in the plasmoids
- T_e in the layer ≪ T_e in the plasmoids

With Cooling:

- J_z localized in plasmoids, reduced flux pile up
- Cooler, denser plasmoids and layer
- Plasmoids radiate strongly

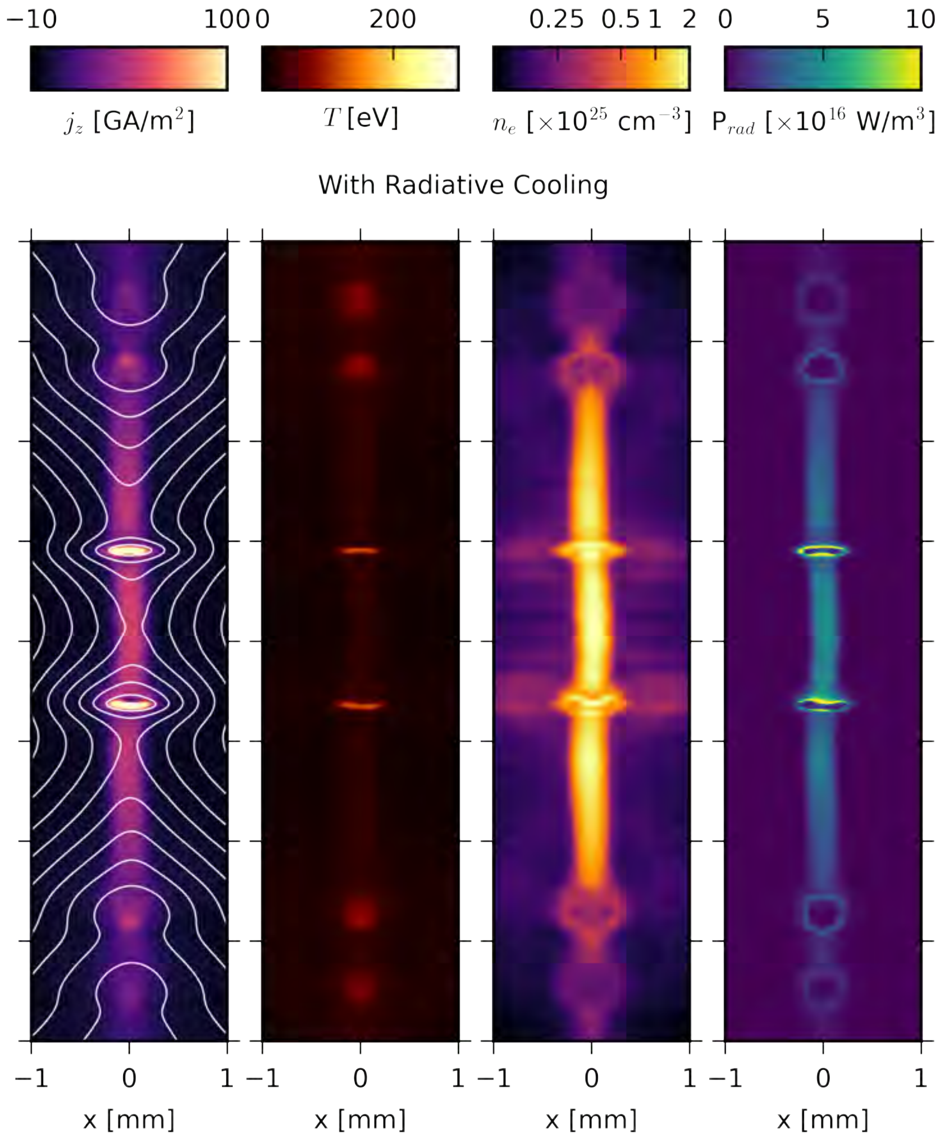
Note: Exaggerated aspect ratio

Global evolution of layer and plasmoid properties



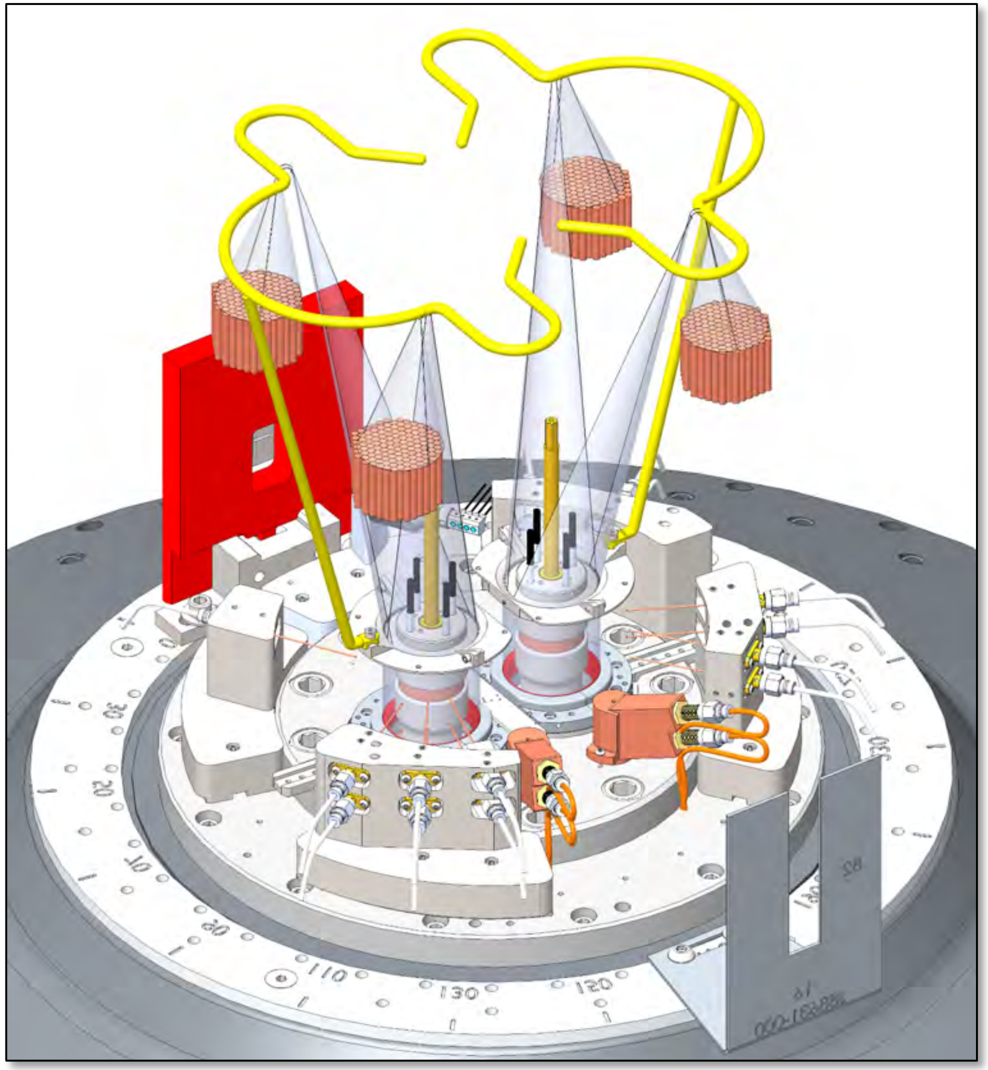
Radiatively Cooled Reconnection Simulation Summary

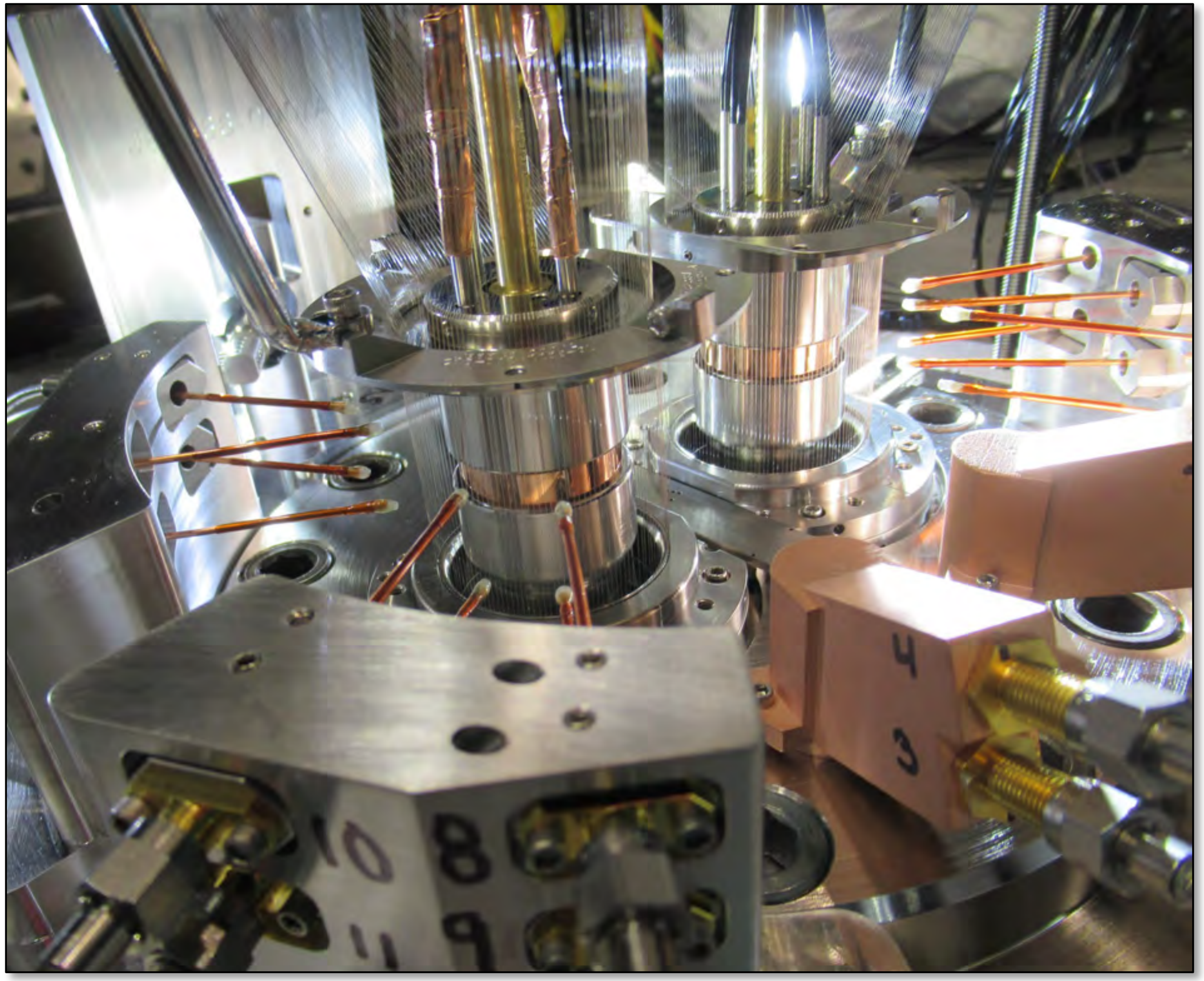
- The inflows to the layer are cold (5 eV) and advect magnetic fields O(10) T
- Layer is initially hot (>100 eV) and contains plasmoids, which are the brightest regions emitting in the Al K-Shell at 1.6 keV
- The layer rapidly collapse before peak current, and ceases to radiate high energy photons



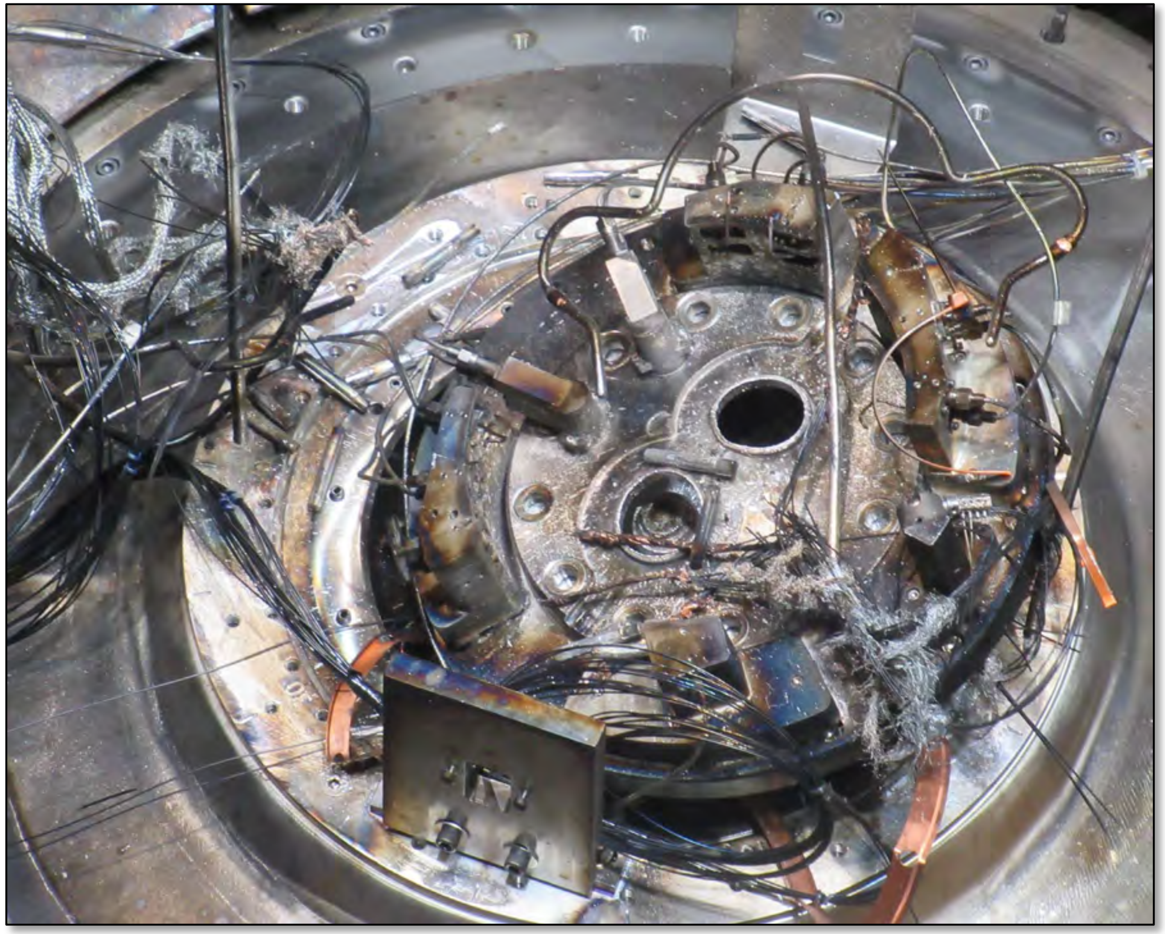
What about the experiments?

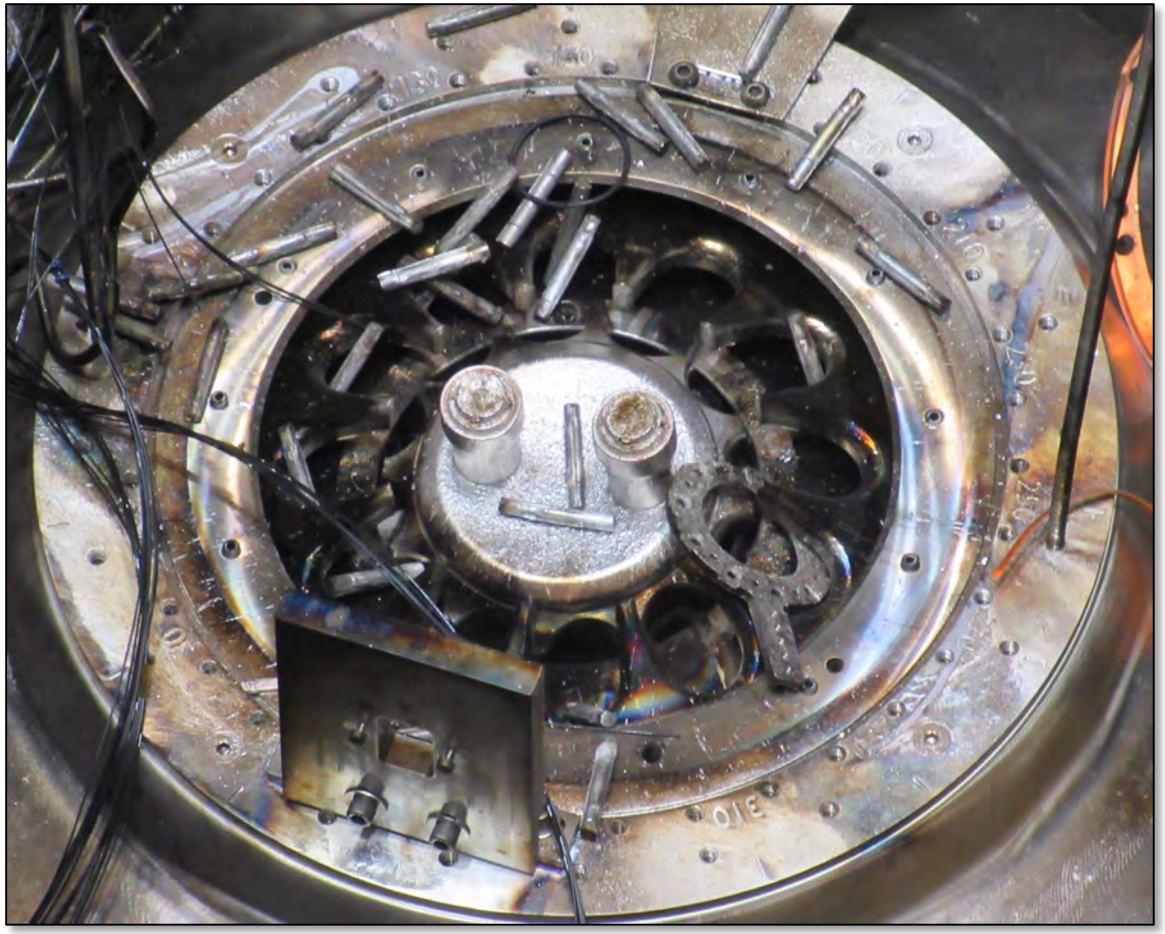
Load Hardware for the first MARZ shot





Load Hardware Post Shot



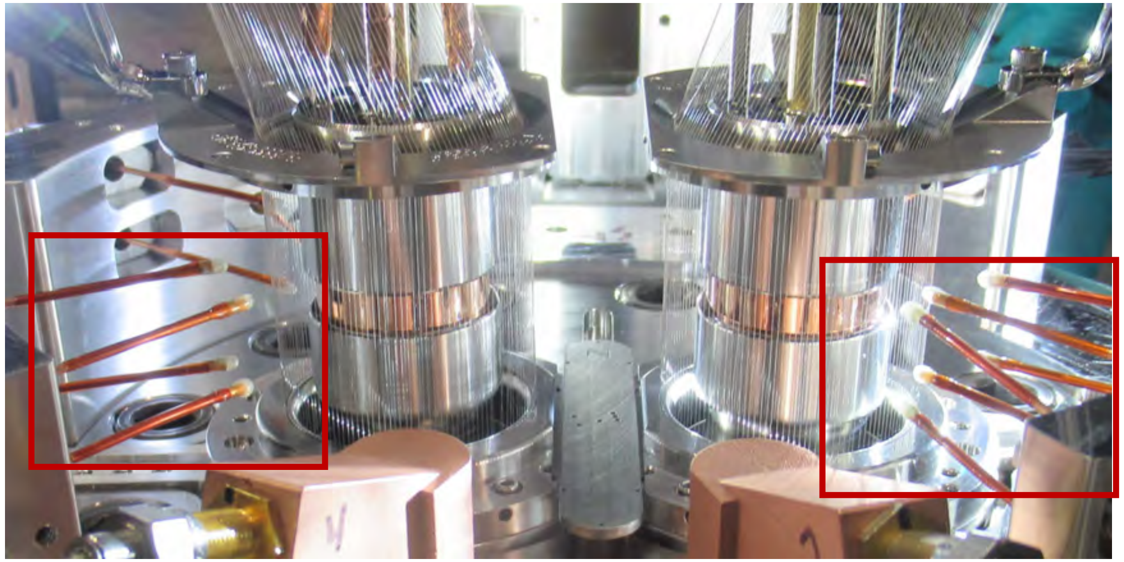


Weeks to build, a microsecond to destroy!

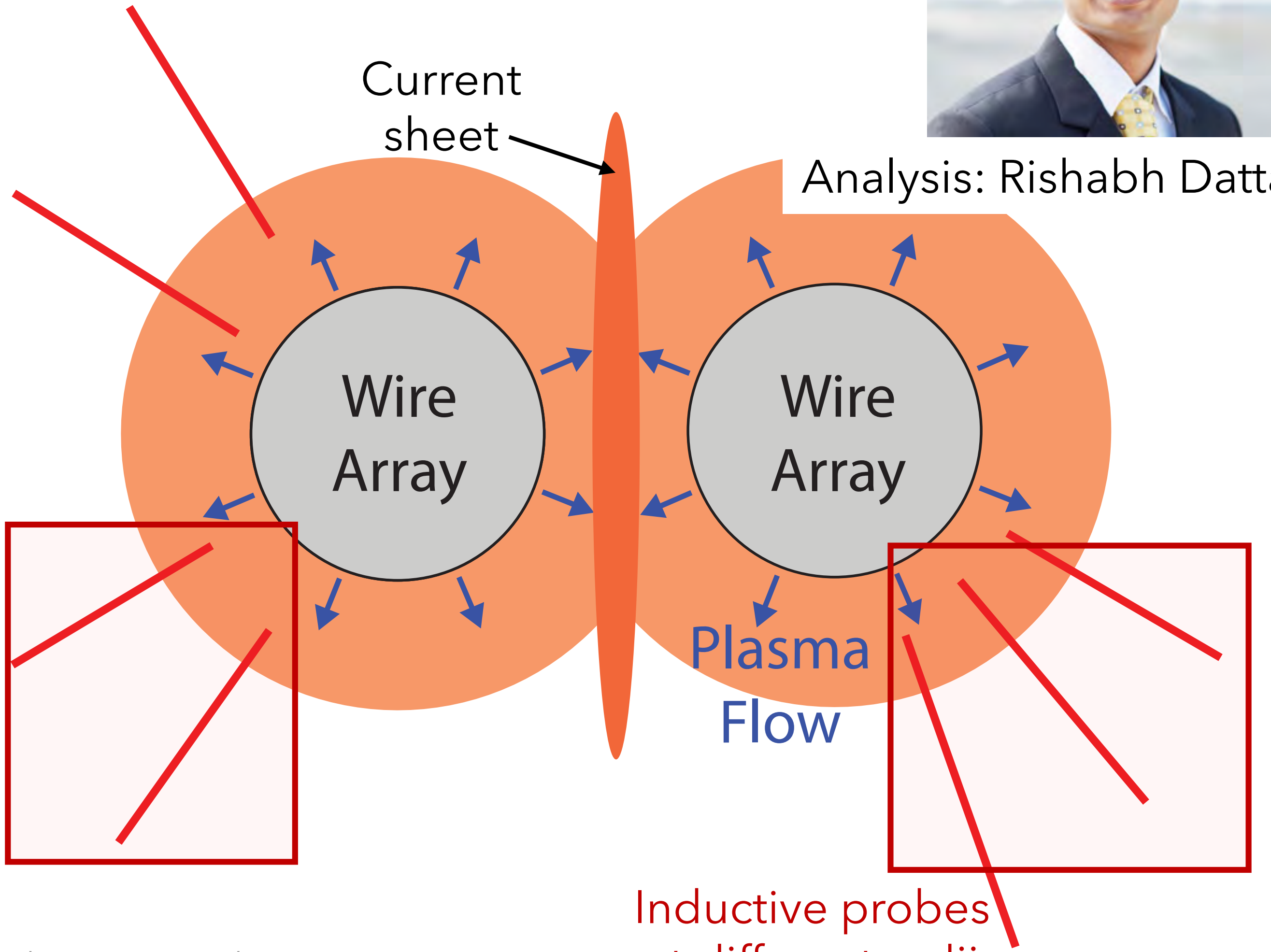
Inductive probes measure advected magnetic fields

Analysis: Rishabh Datta

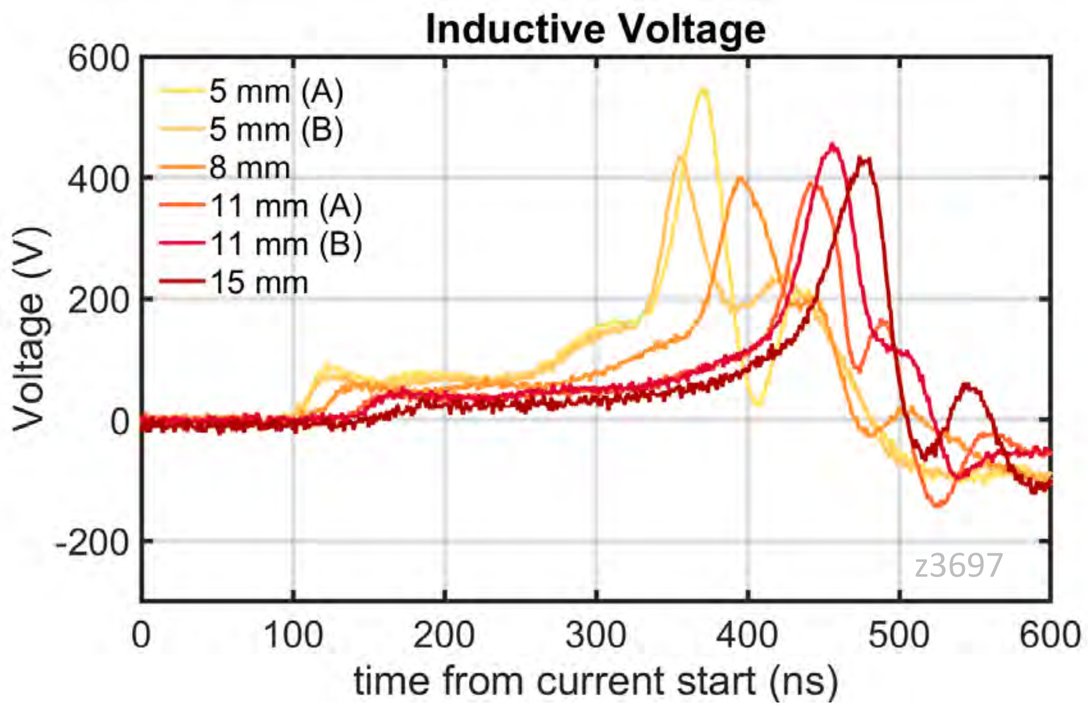
- **Inductive probes (magnetic field & velocity)**

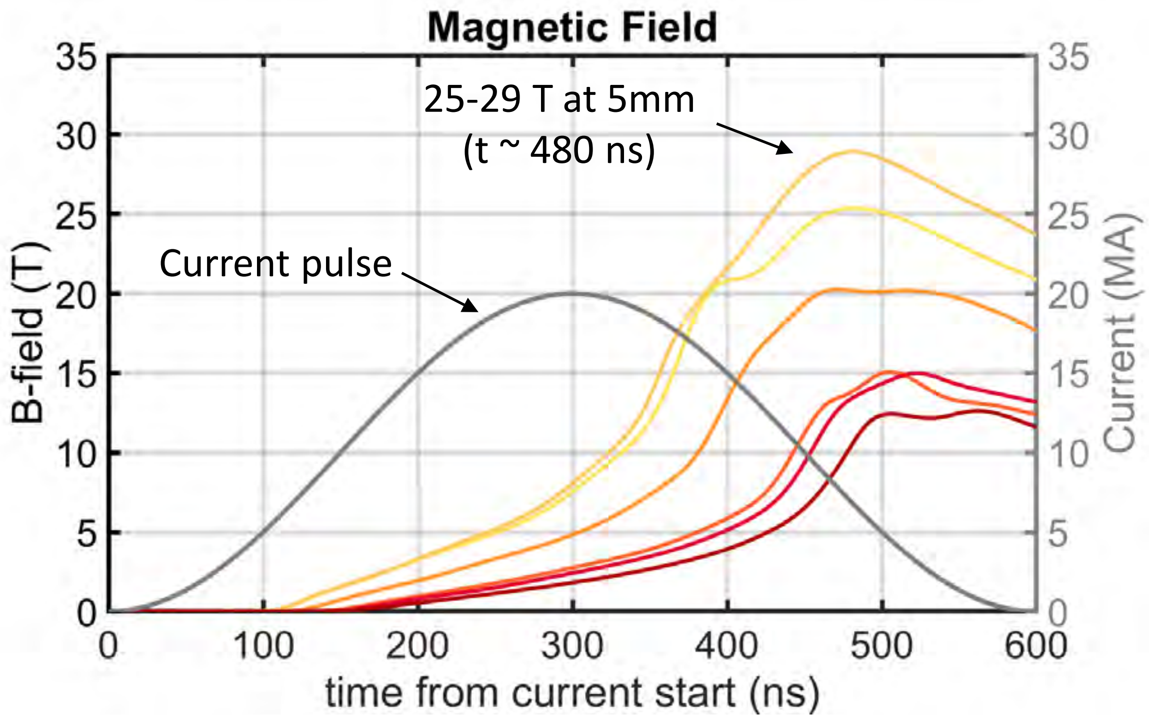


In-chamber View



Magnetic field in layer inflowa

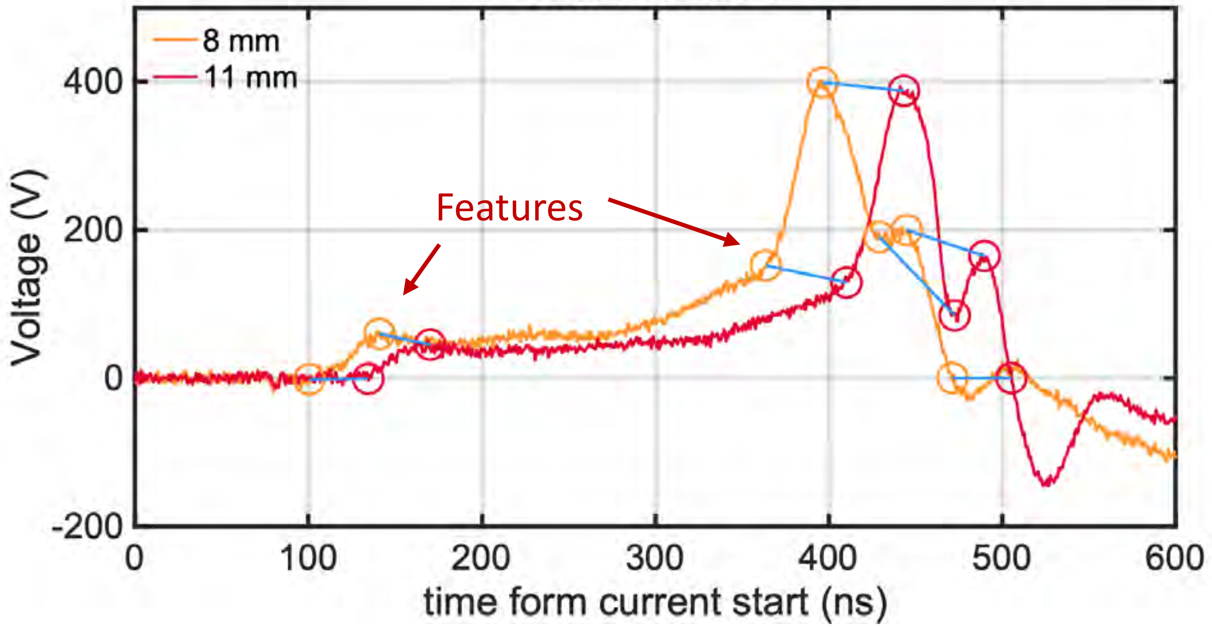


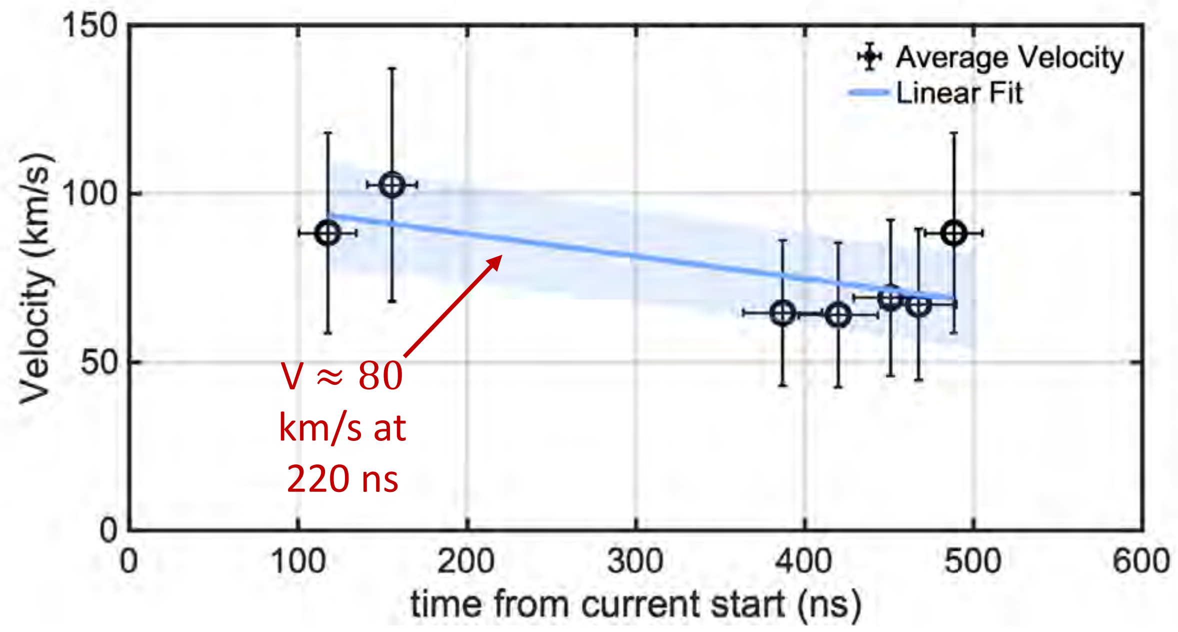


We measure peak field of 25-29 T at 5 mm from wires

Magnetic field strength decreases with distance from wires

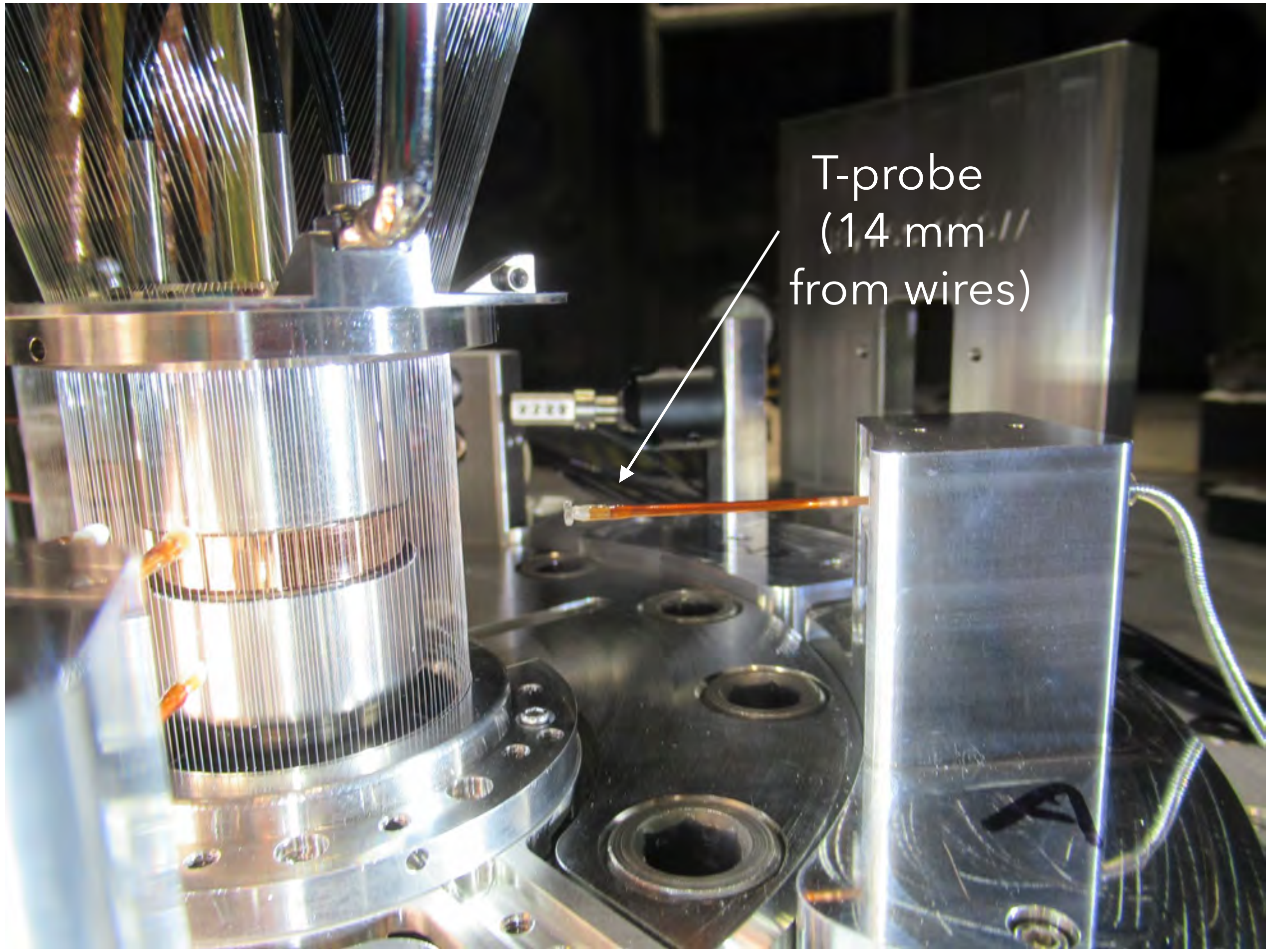
Infer layer inflow velocity from time-of-flight



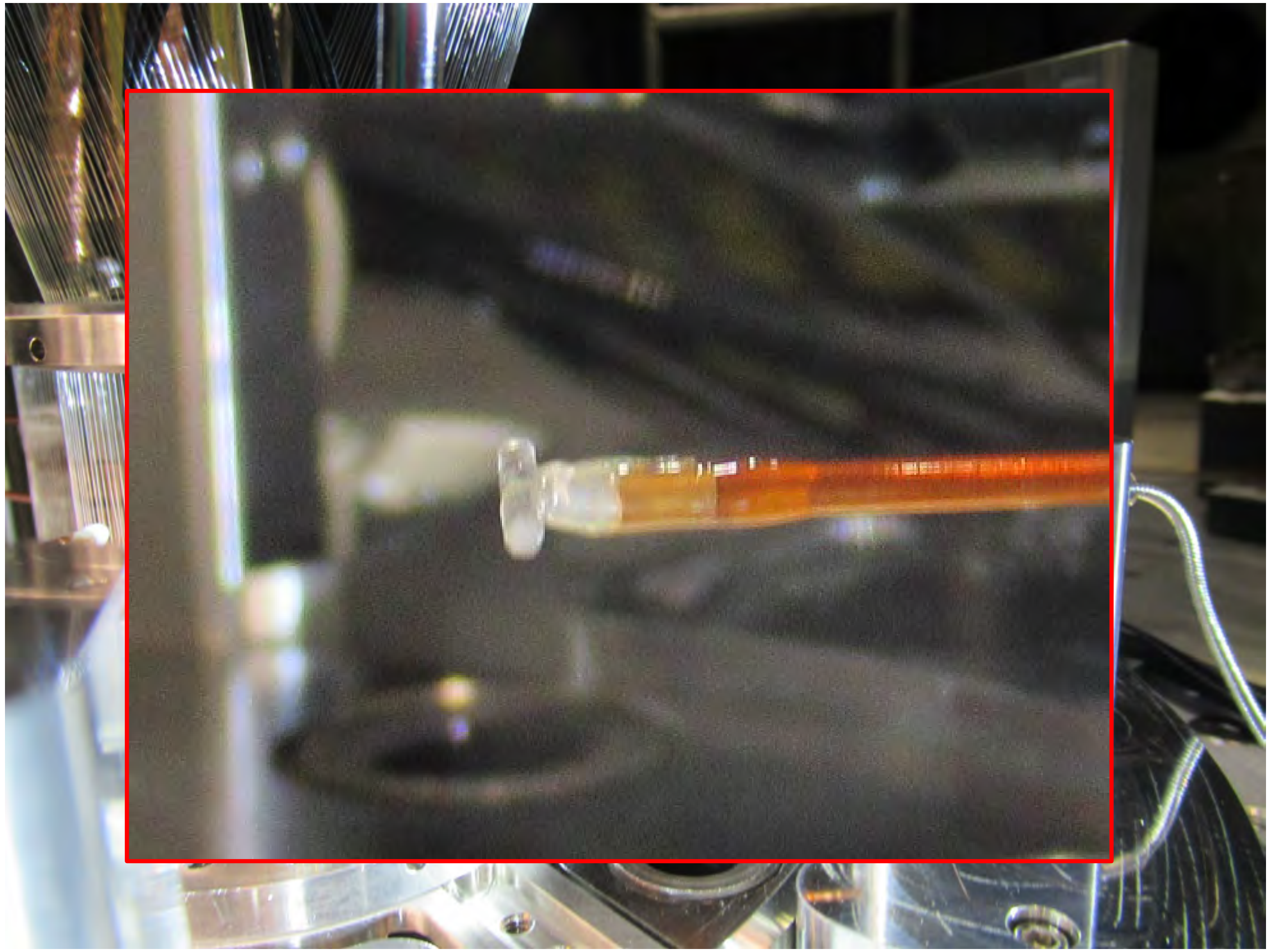


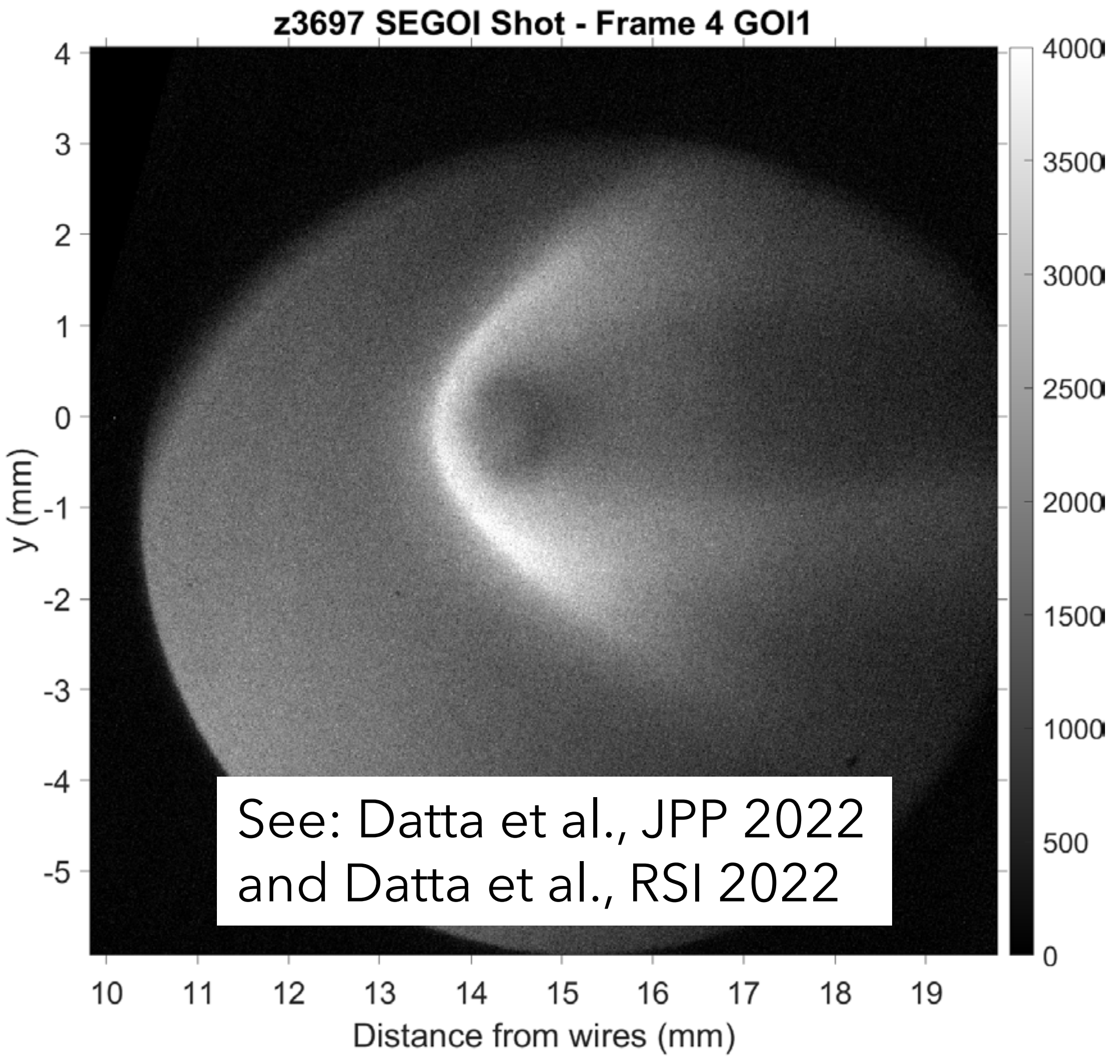
We estimate an inflow velocity of roughly 80 km/s at time of collapse

Bow shock around B-dot probe: Mach number

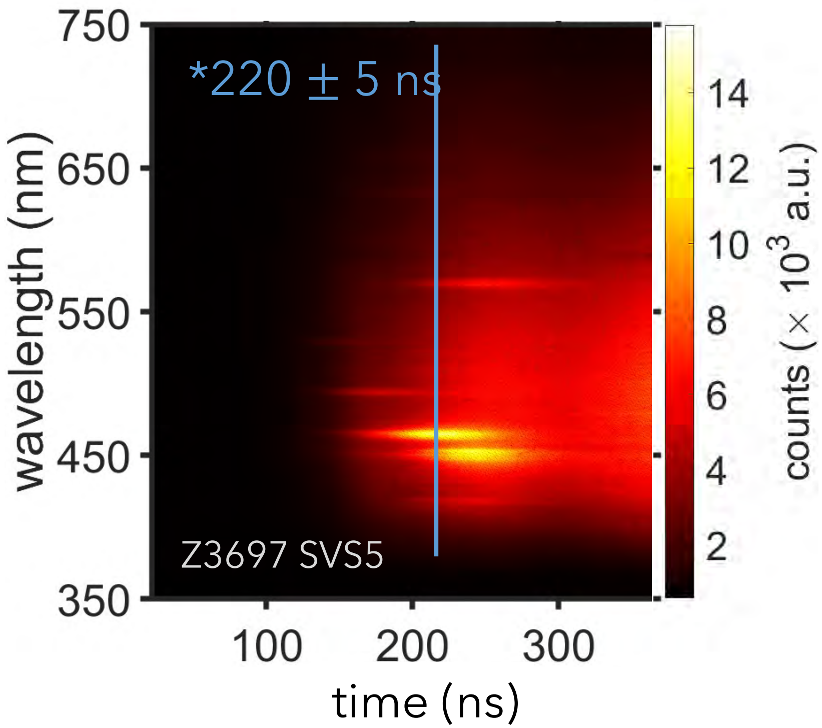


Bow shock around B-dot probe: Mach number

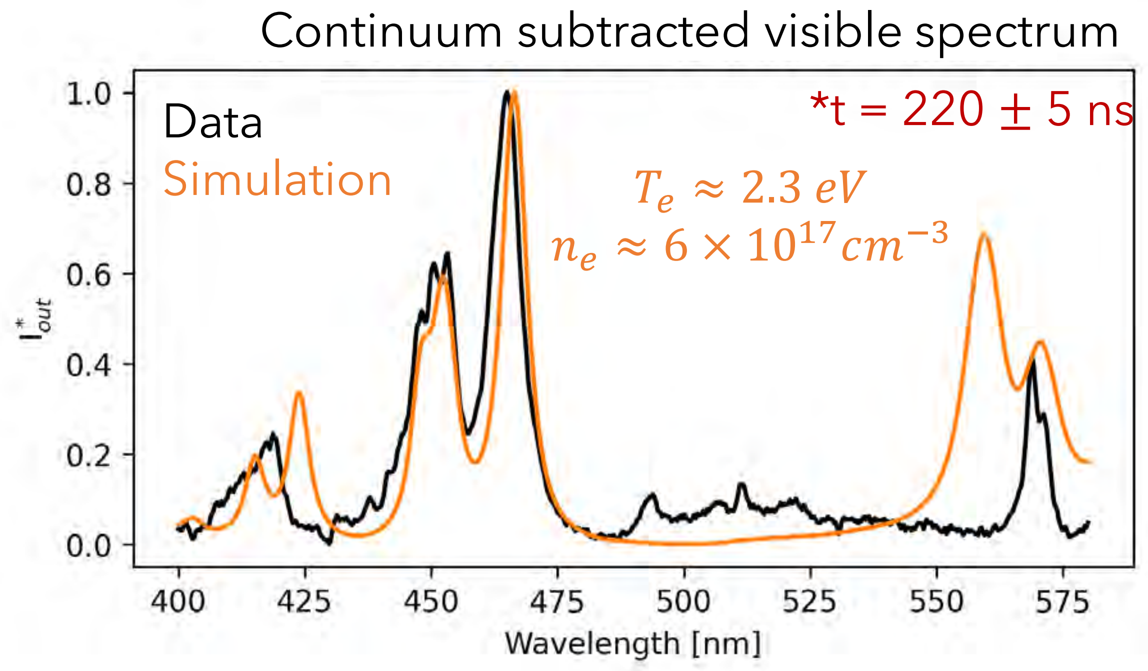




Visible spectroscopy of layer inflows

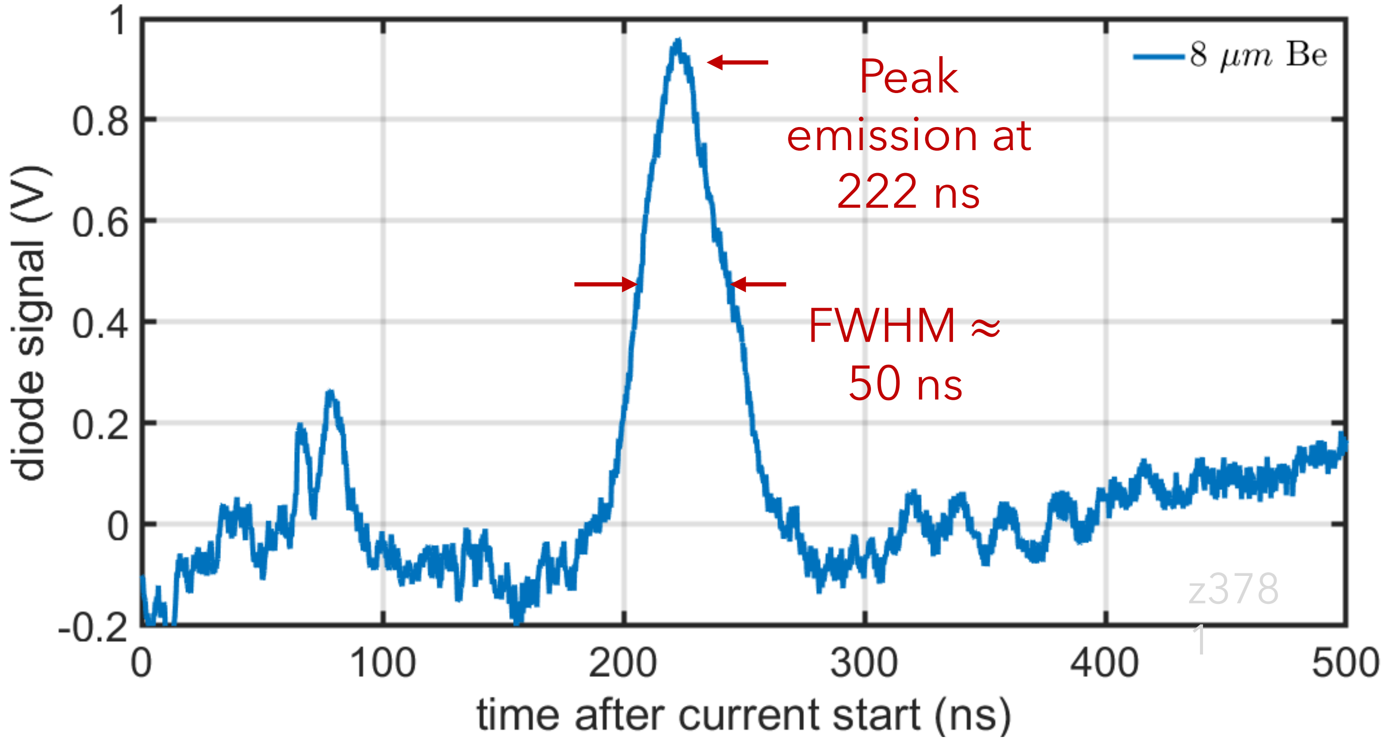


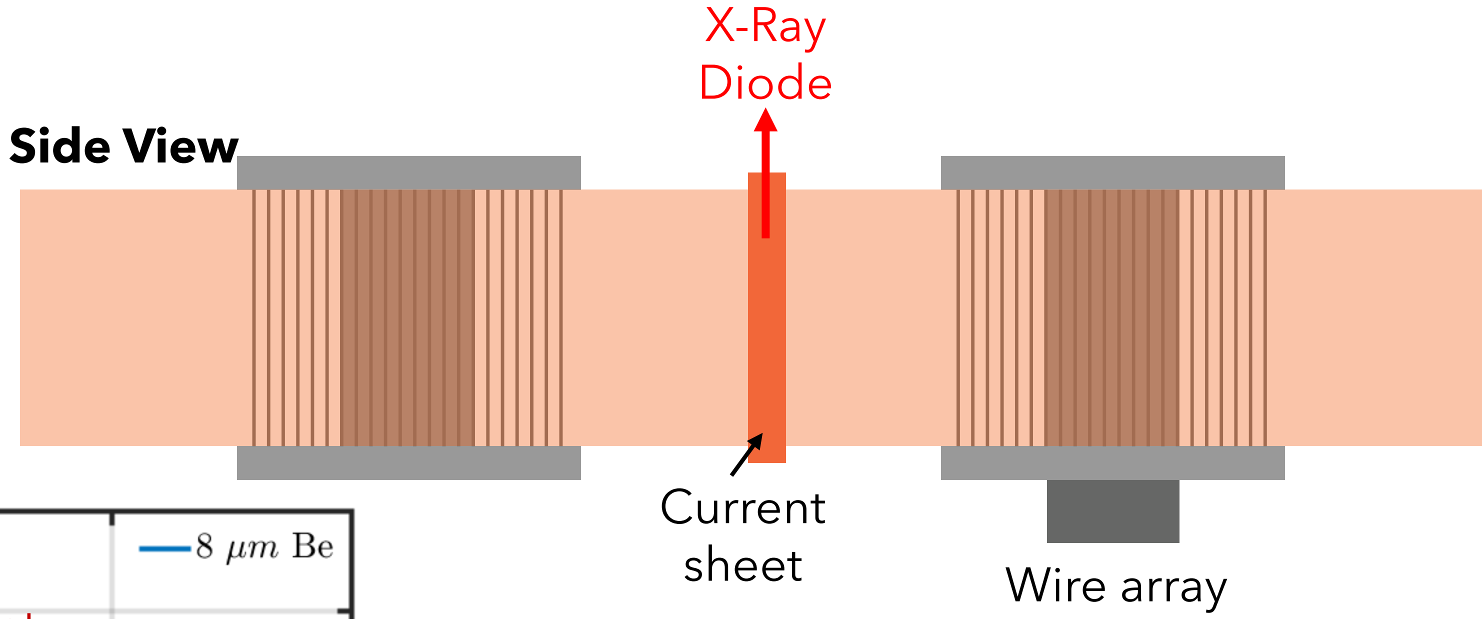
*8 mm from wires



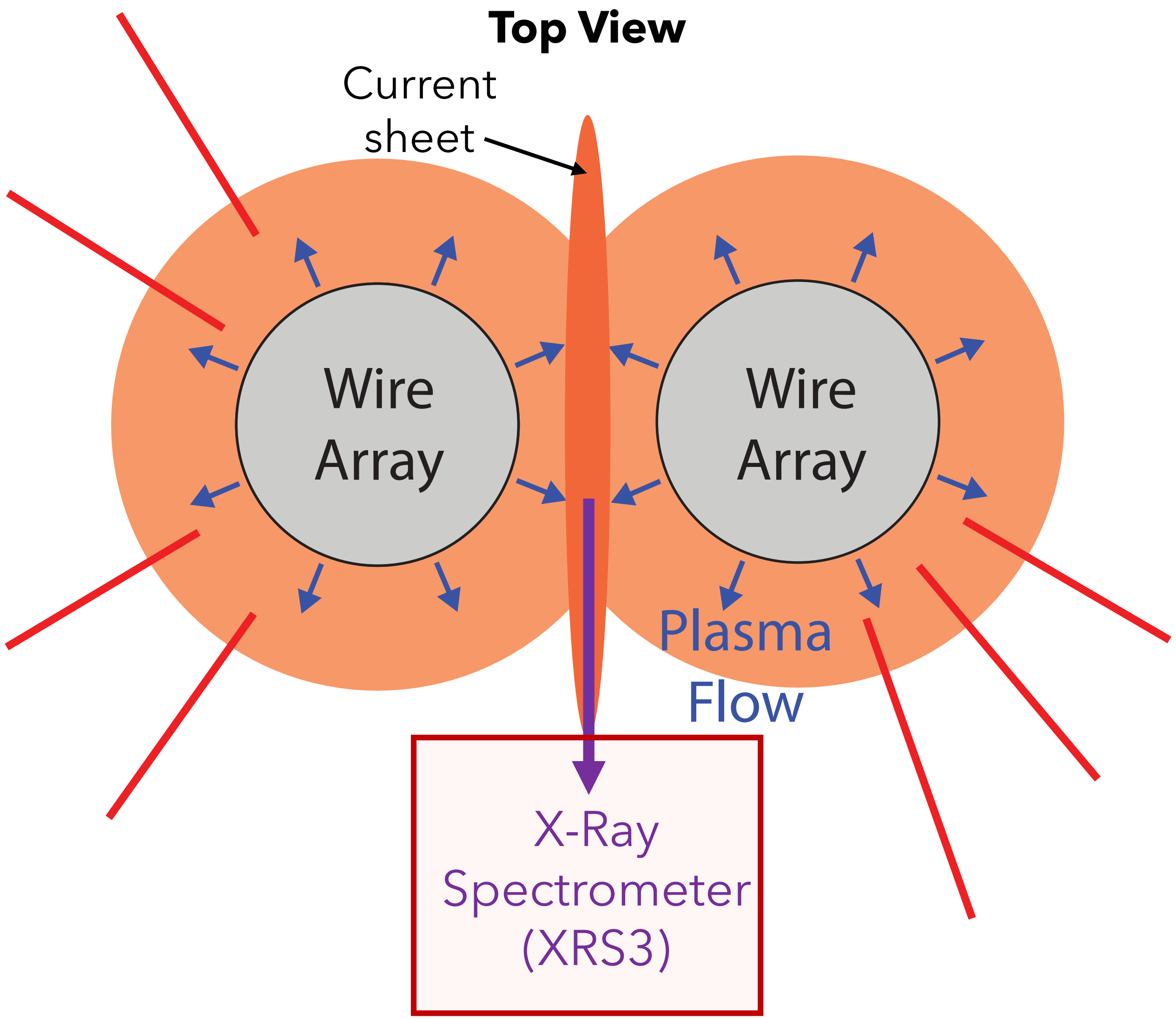
Inflow temperature (2-3 eV), electron density ($6 \times 10^{17}\mathrm{cm}^{-3}$), and average ionization (~2)

X-ray diodes observe the reconnection layer

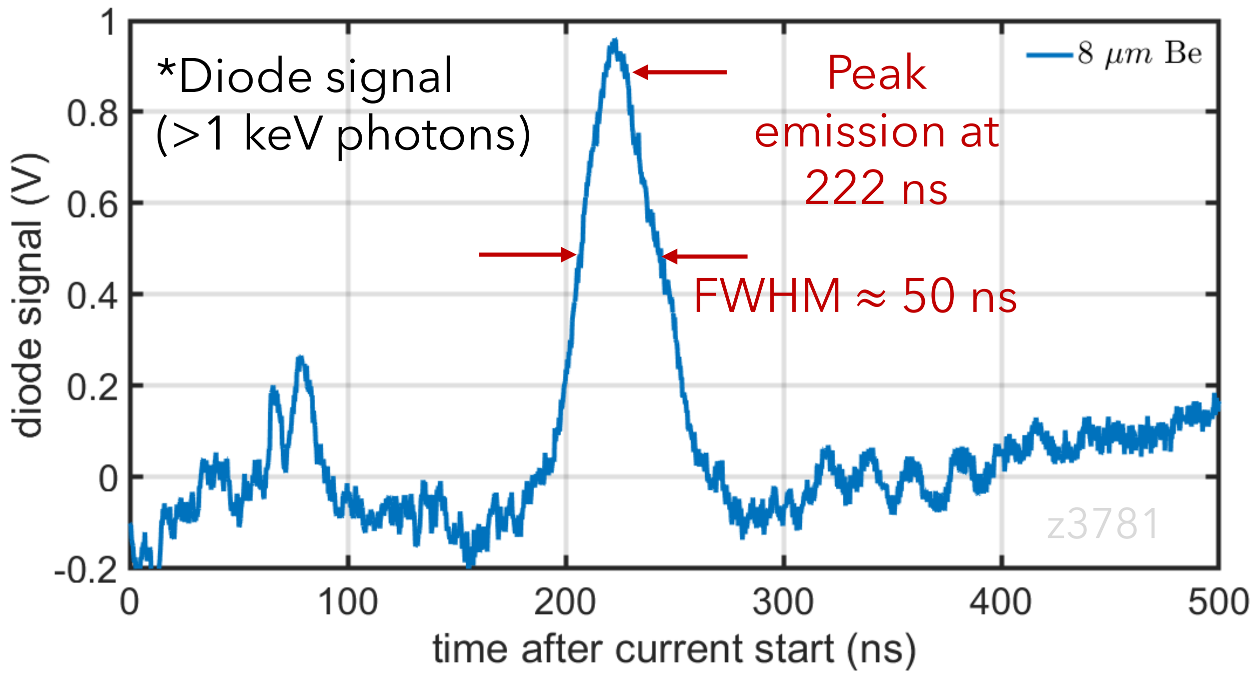


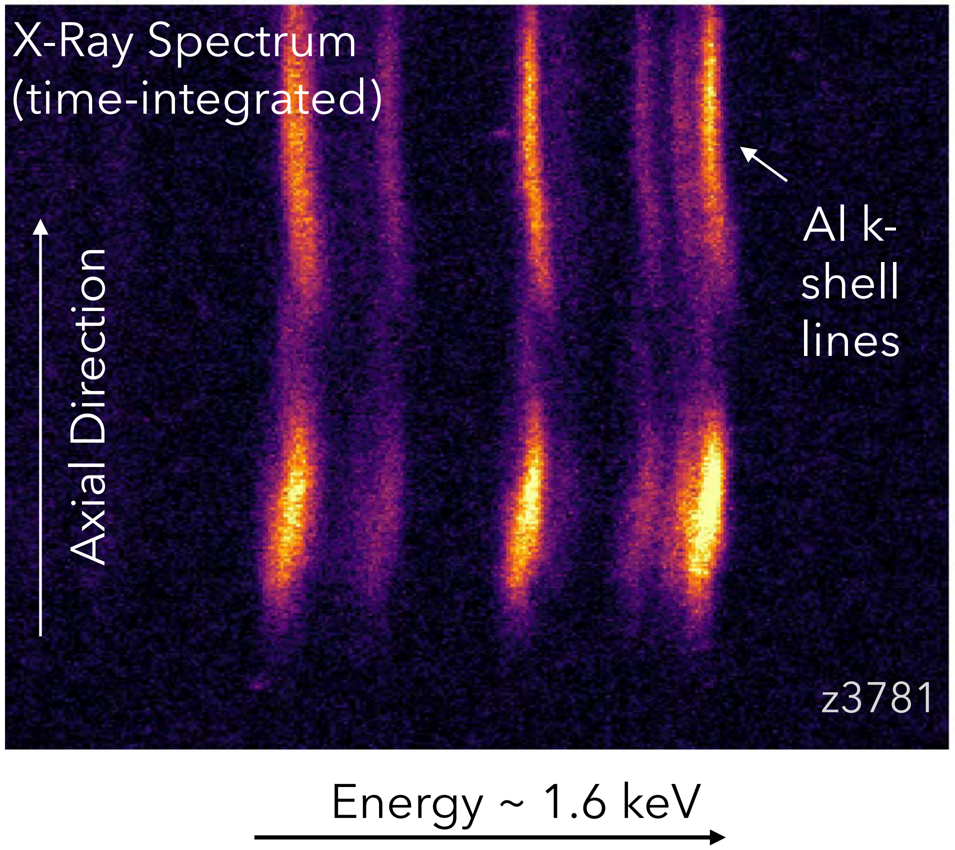


Time integrated X-ray spectra with 1.6 keV photons



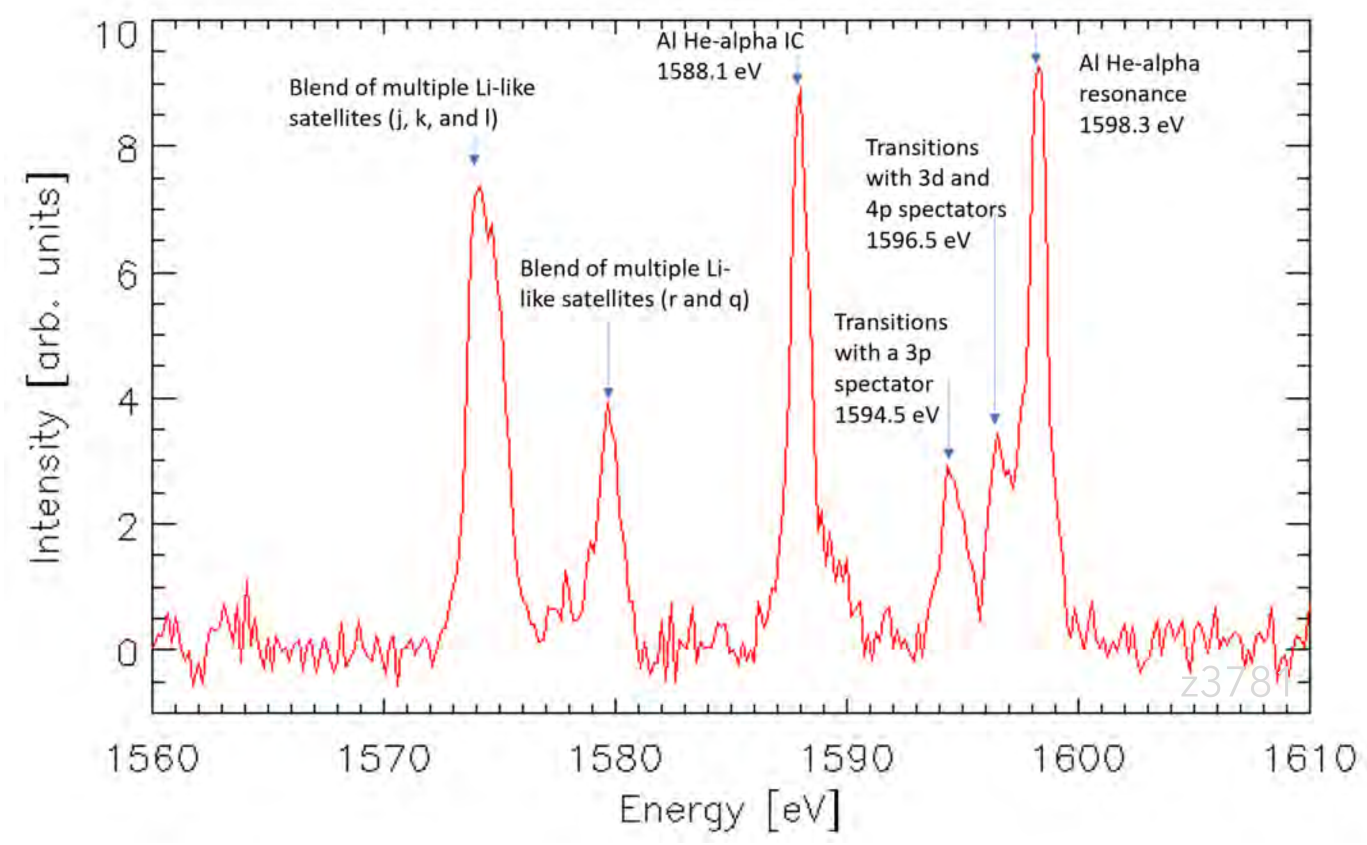
Time integrated X-ray spectra with 1.6 keV photons

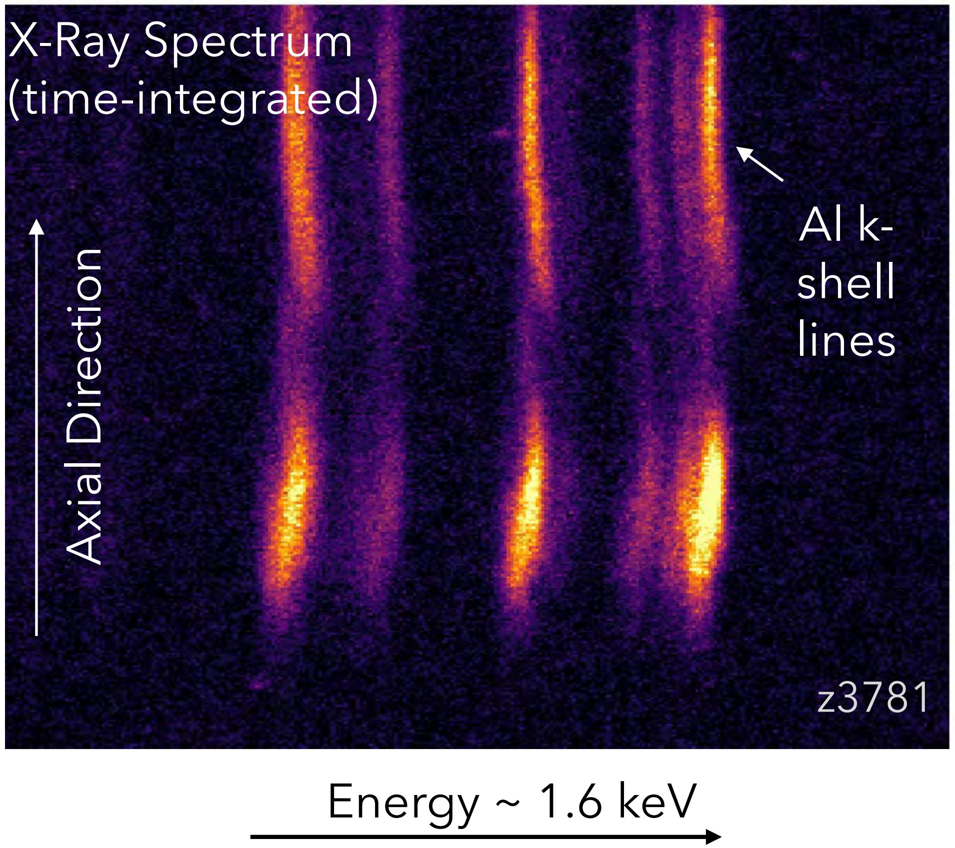




Diode signal suggest that ~1 .6 keV photons measured by the spectrometer are from time of radiative collapse (220 ns ±25 ns)

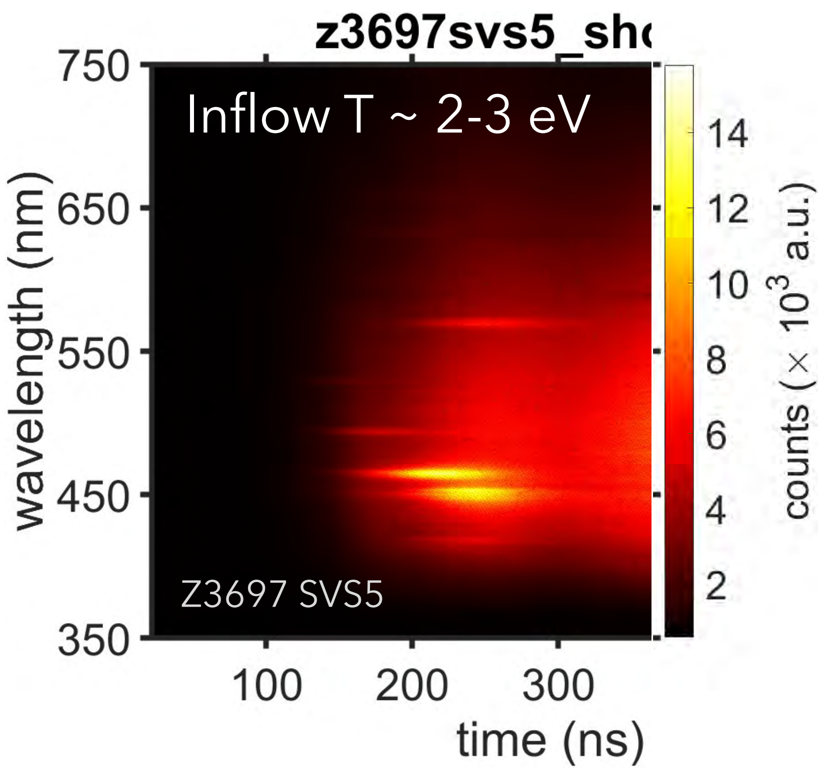
Detailed analysis suggests hot, bright regions in layer

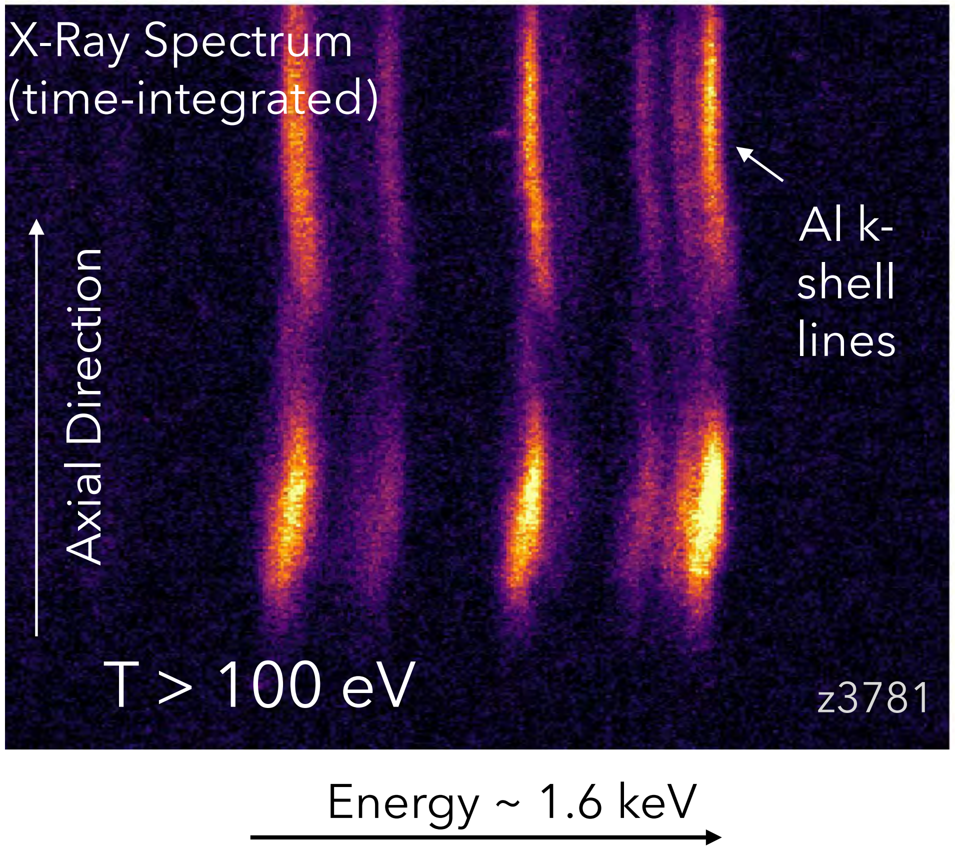




Spectrum corresponds to localized hotspots with T_e >100 eV embedded within a colder reconnection layer – see UXI

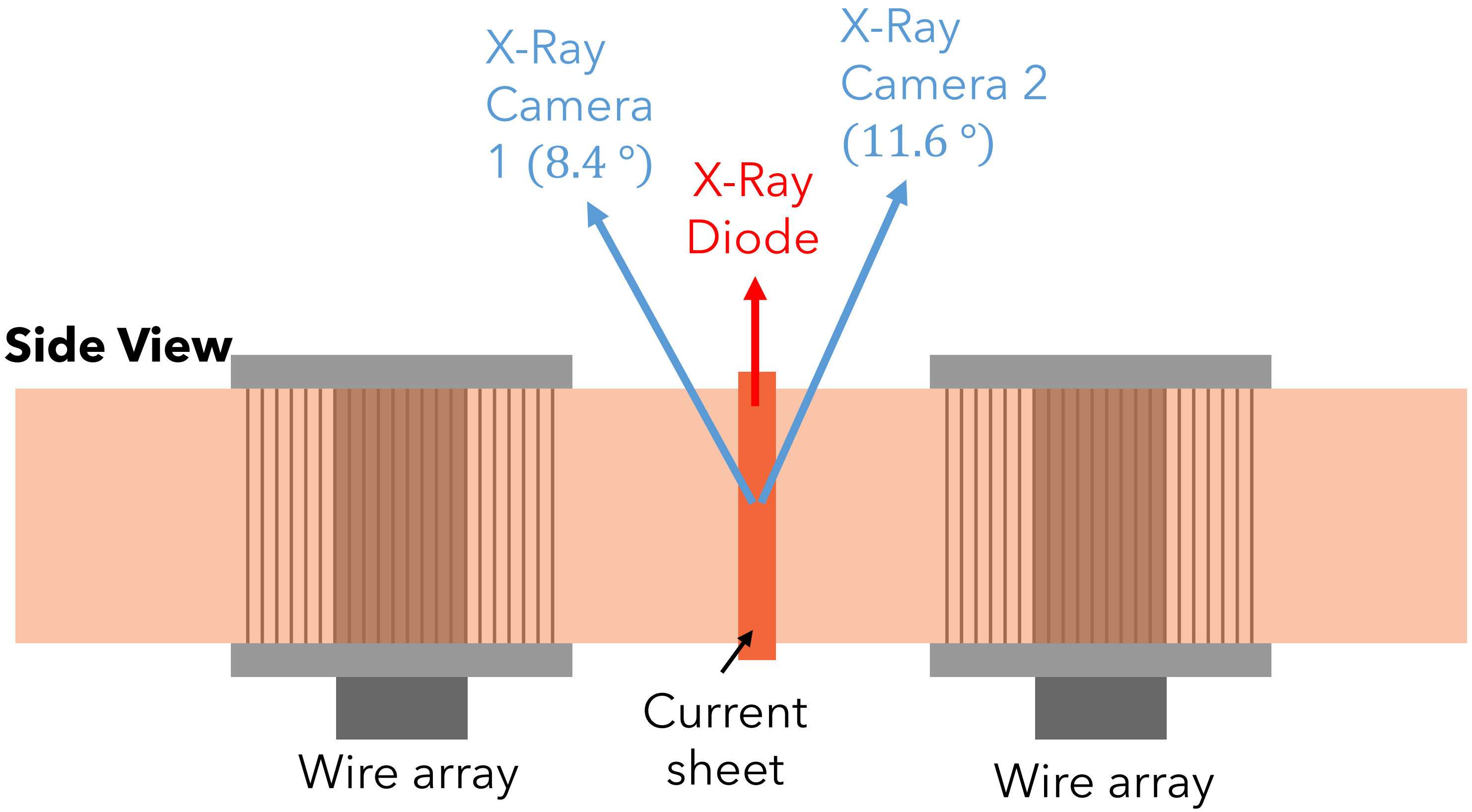
Comparing visible and X-ray spectra shows heating





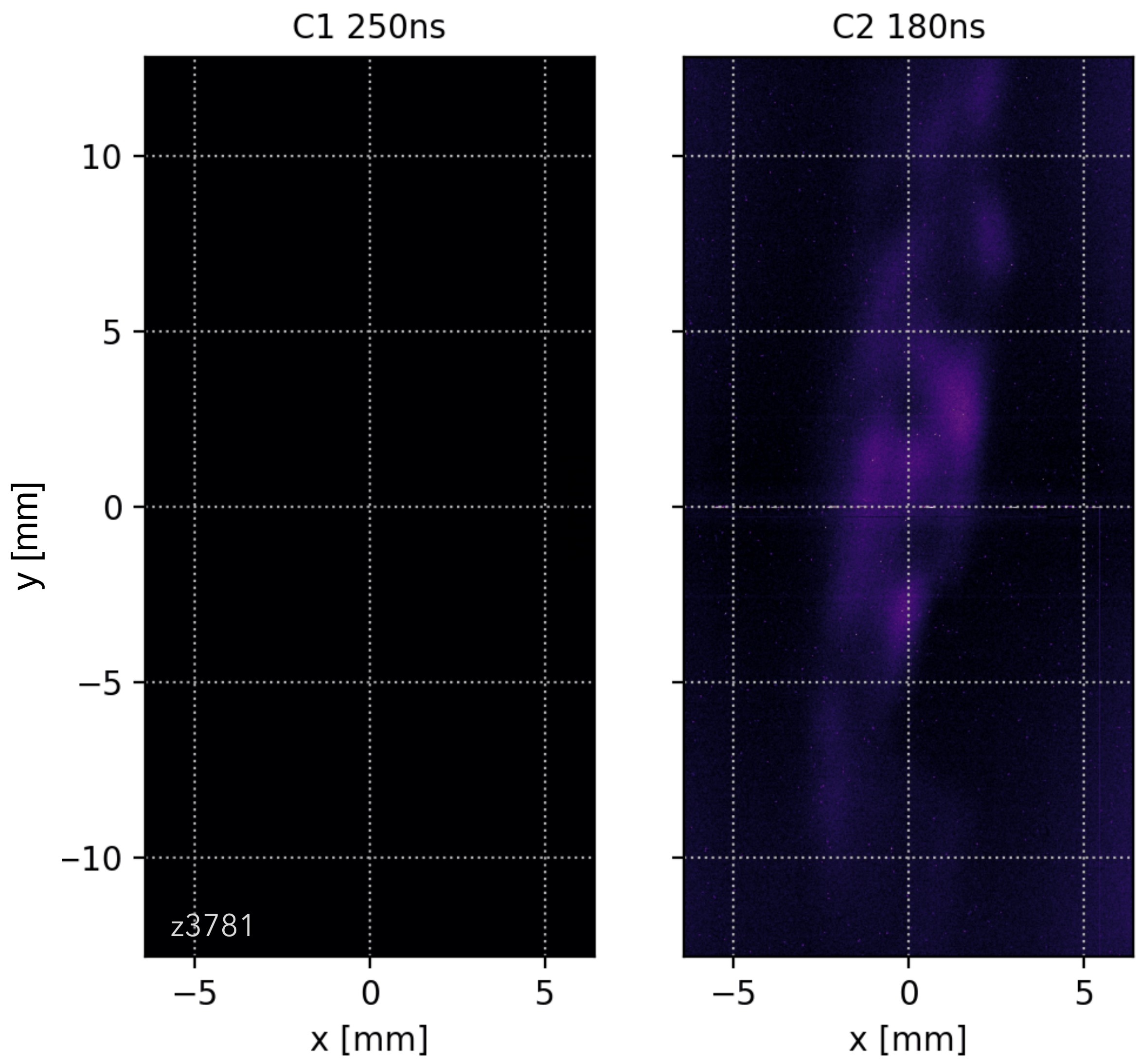
We see strong heating of the layer,
consistent with reconnection

Ultrafast X-ray Imagers study layer dynamics

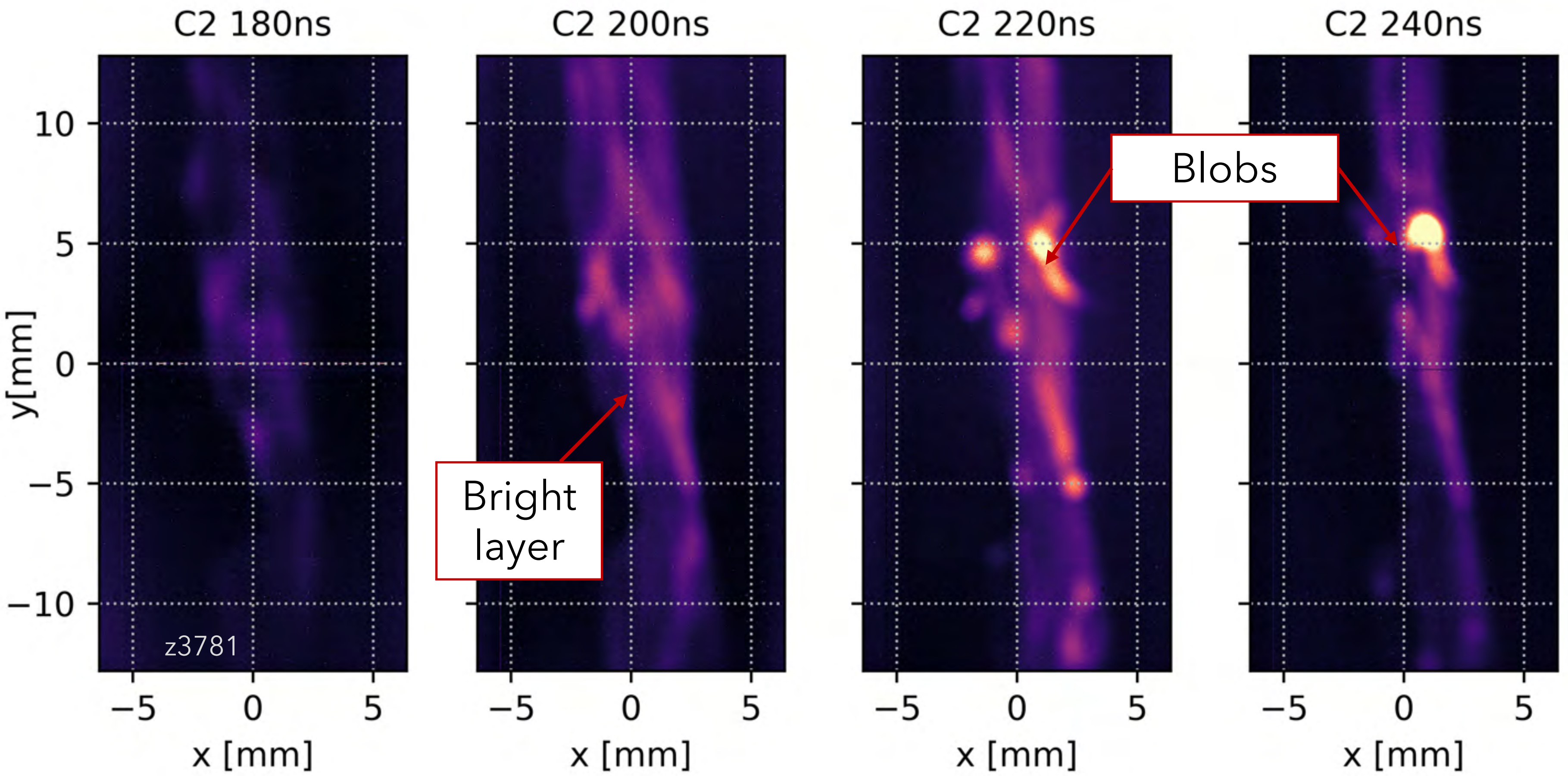


500 um pinhole
>100 eV Photons

Ultrafast X-ray Imagers study layer dynamics

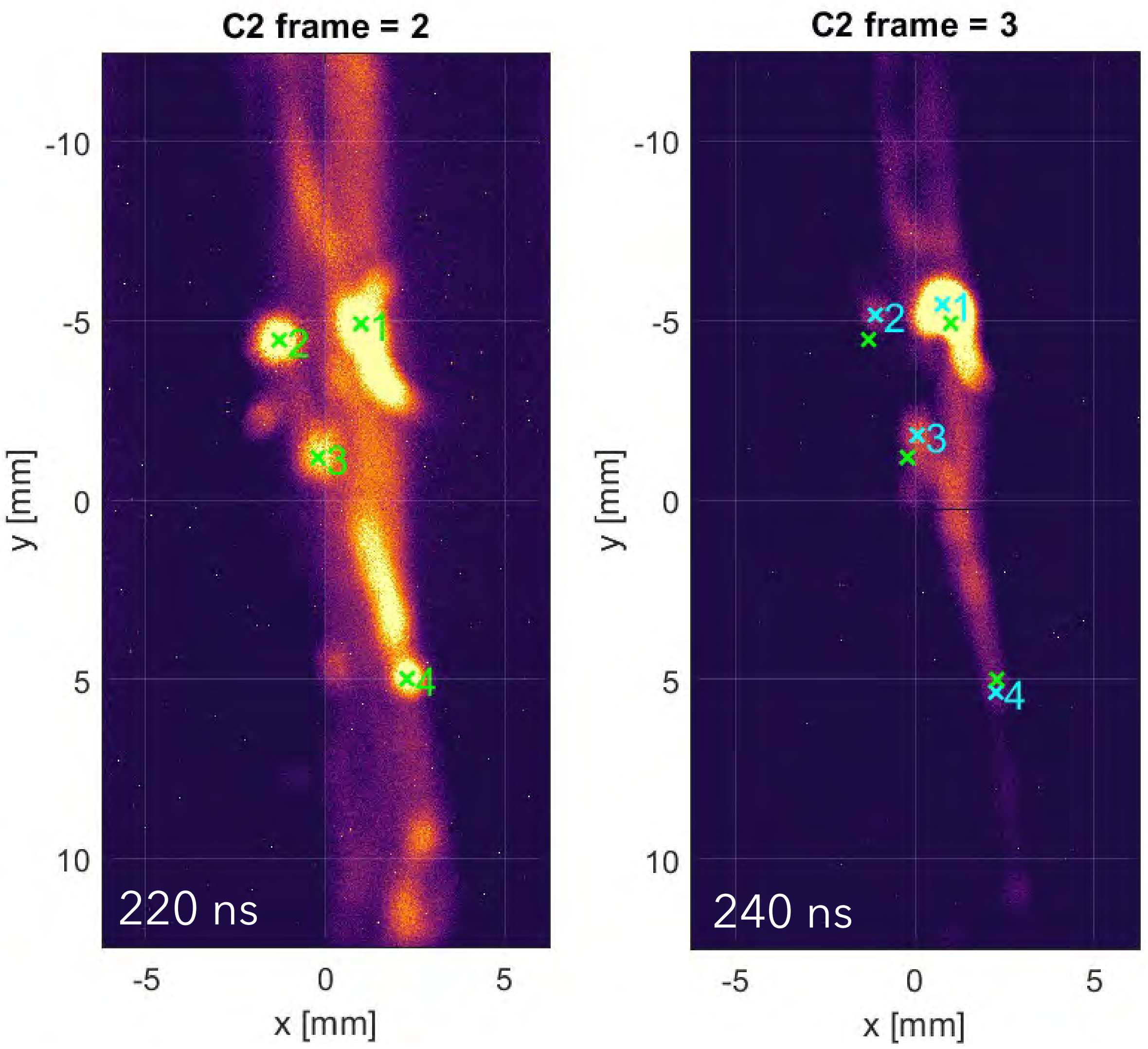


Ultrafast X-ray Imagers study layer dynamics



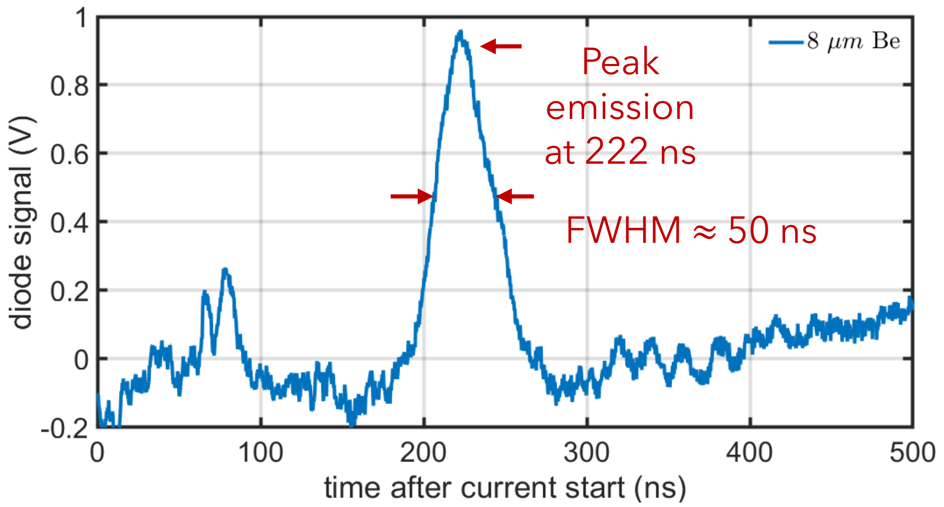
We observe an elongated bright layer with localized regions of intense emission.
Intensity decreases with time, indicating radiative collapse.

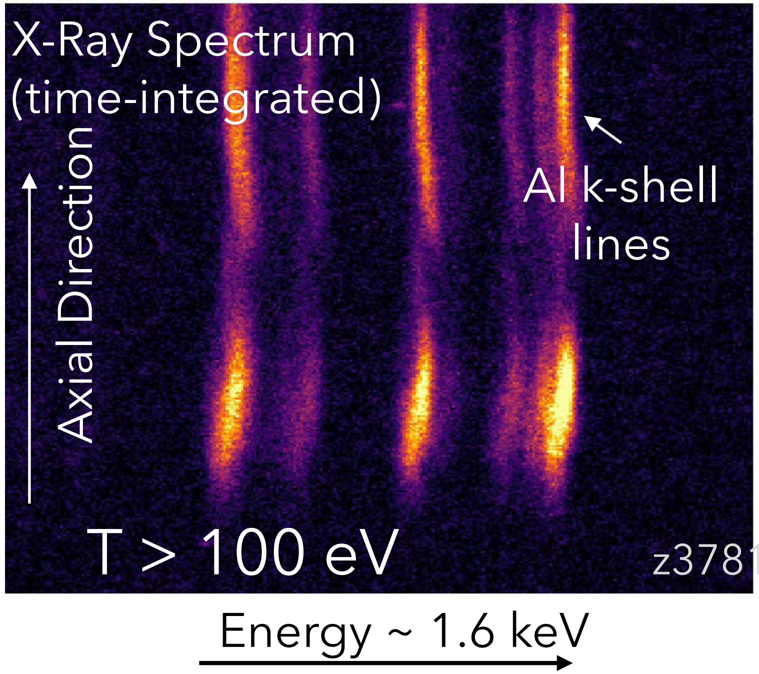
Infer blob velocity from time of flight

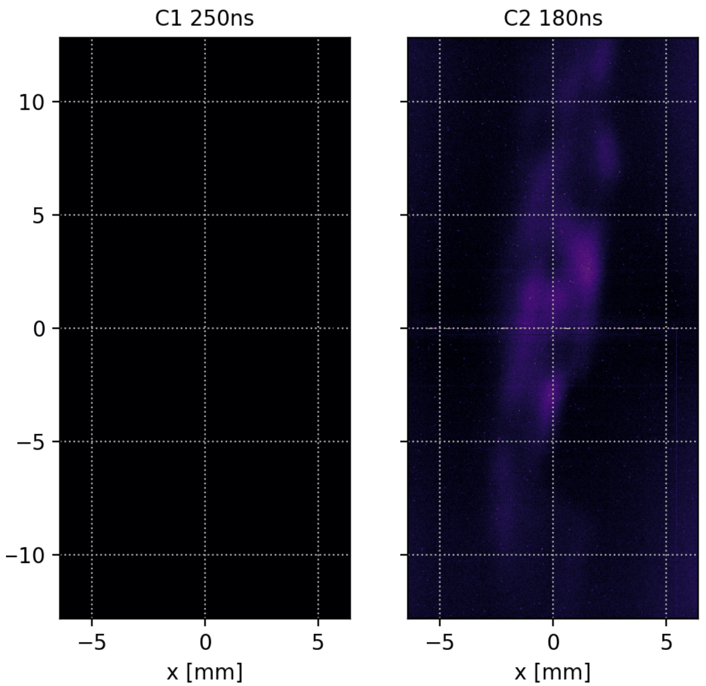


Velocity of blobs varies between 18-35 km/s (magnetosonic velocity ~ 90 km/s)

Summary of Radiatively Cooled Reconnection Experiments







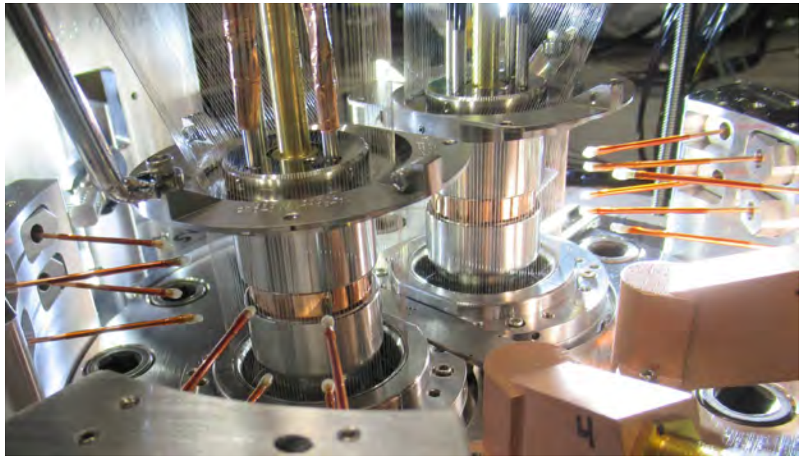
- Diode signal consistent with formation and collapse of layer
- Time integrated X-ray spectrum temporally localized by diode; consistent with >100 eV bright blobs embedded in colder layer
- Ultrafast X-ray cameras shows rich structure in layer, fast moving bright blobs consistent with plasmoids in 3D MHD simulations

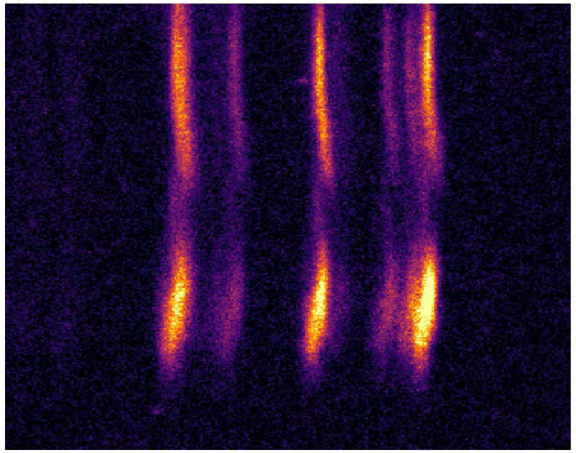
Research paths and talk outline

Magnetic reconnection

Radiative cooling

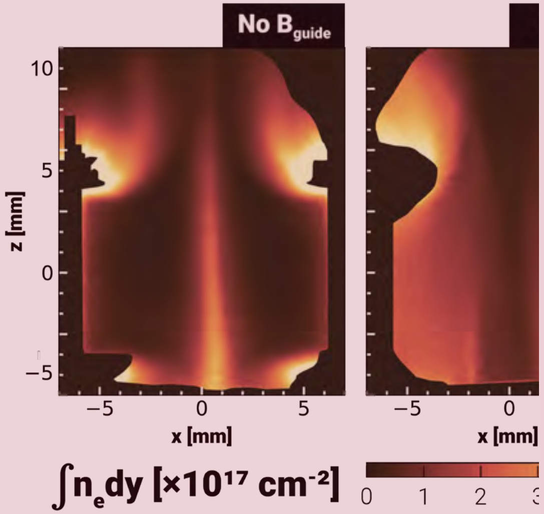
MARZ: Radiatively cooled reconnection on Z



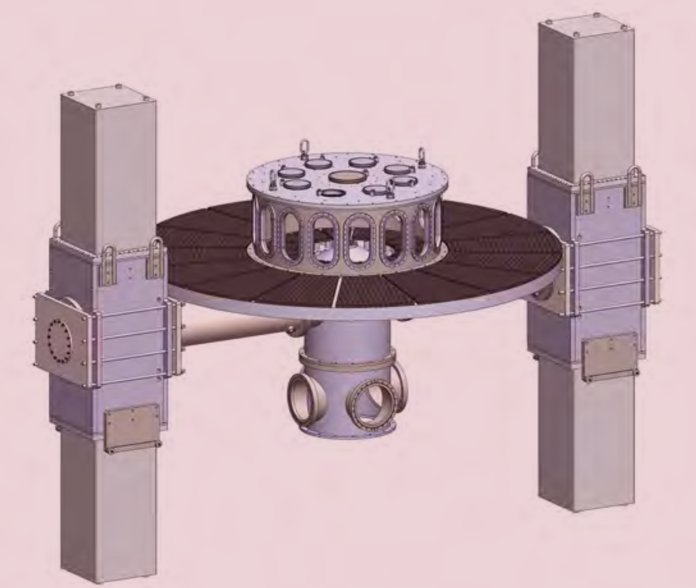


Plasmoids and turbulence

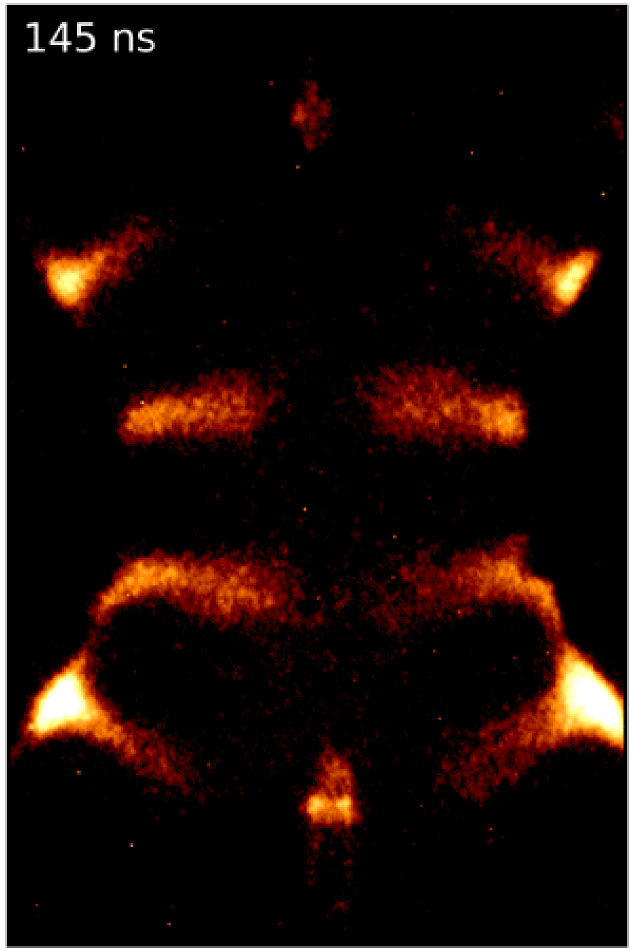
Guide field on MAIZE

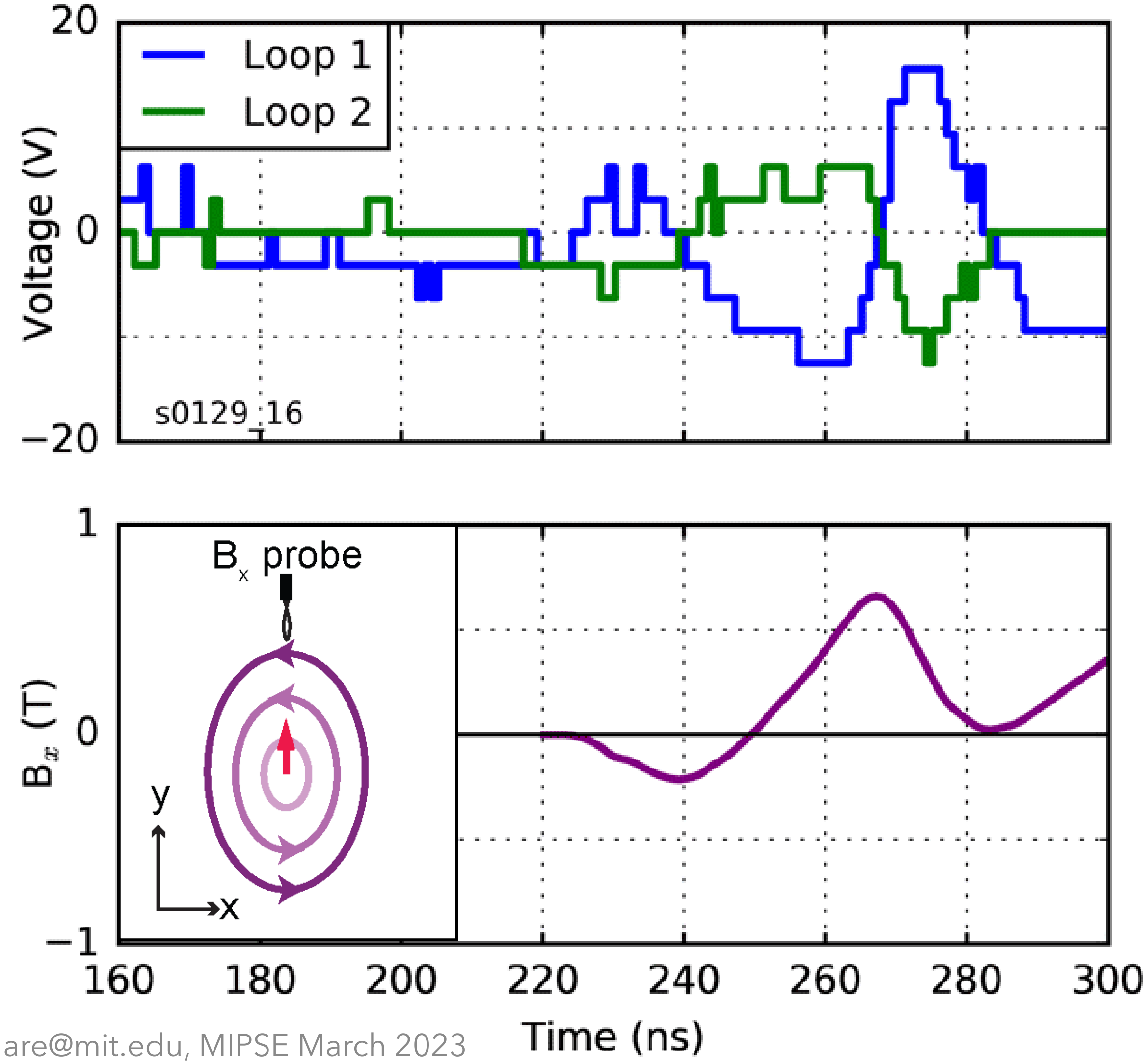


Longer timescales on PUFFIN

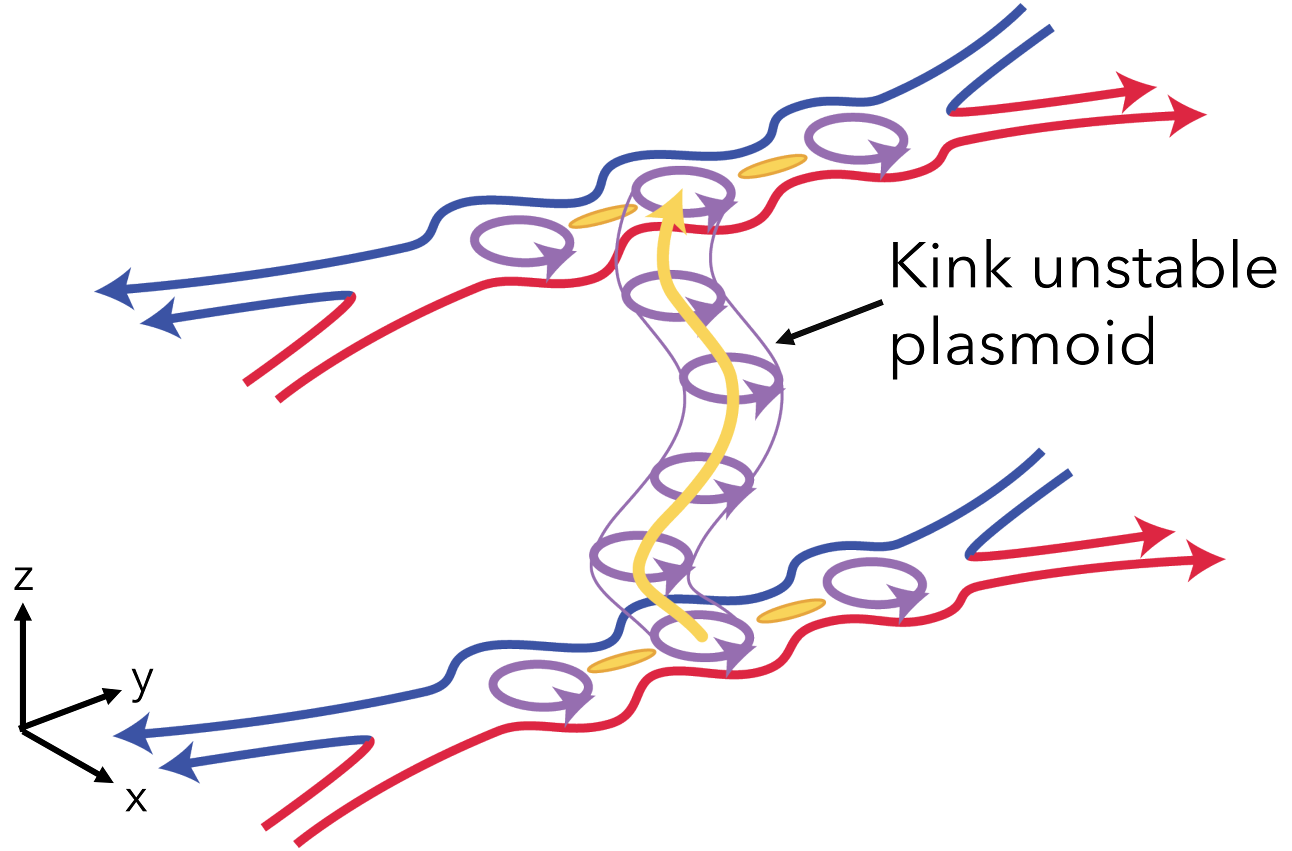


Plasmoids observed in emission, density & B-field



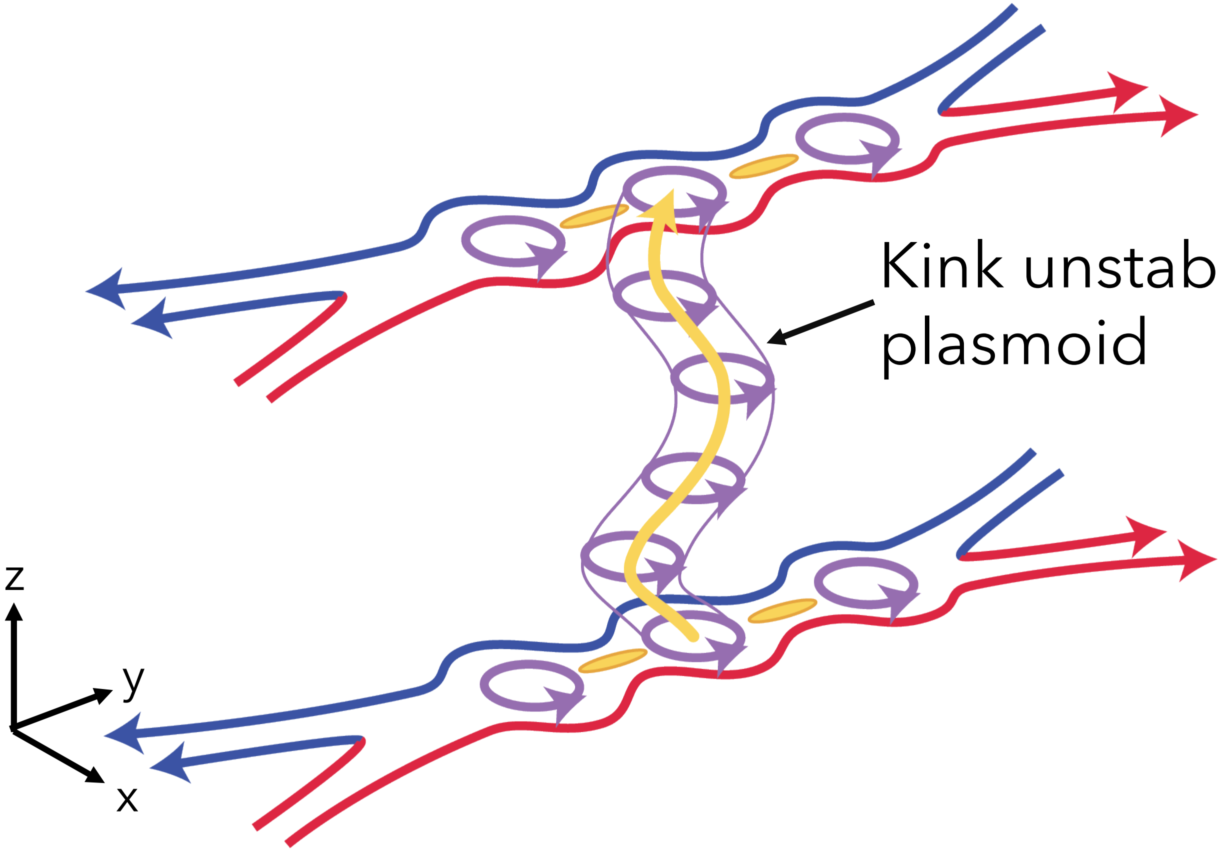


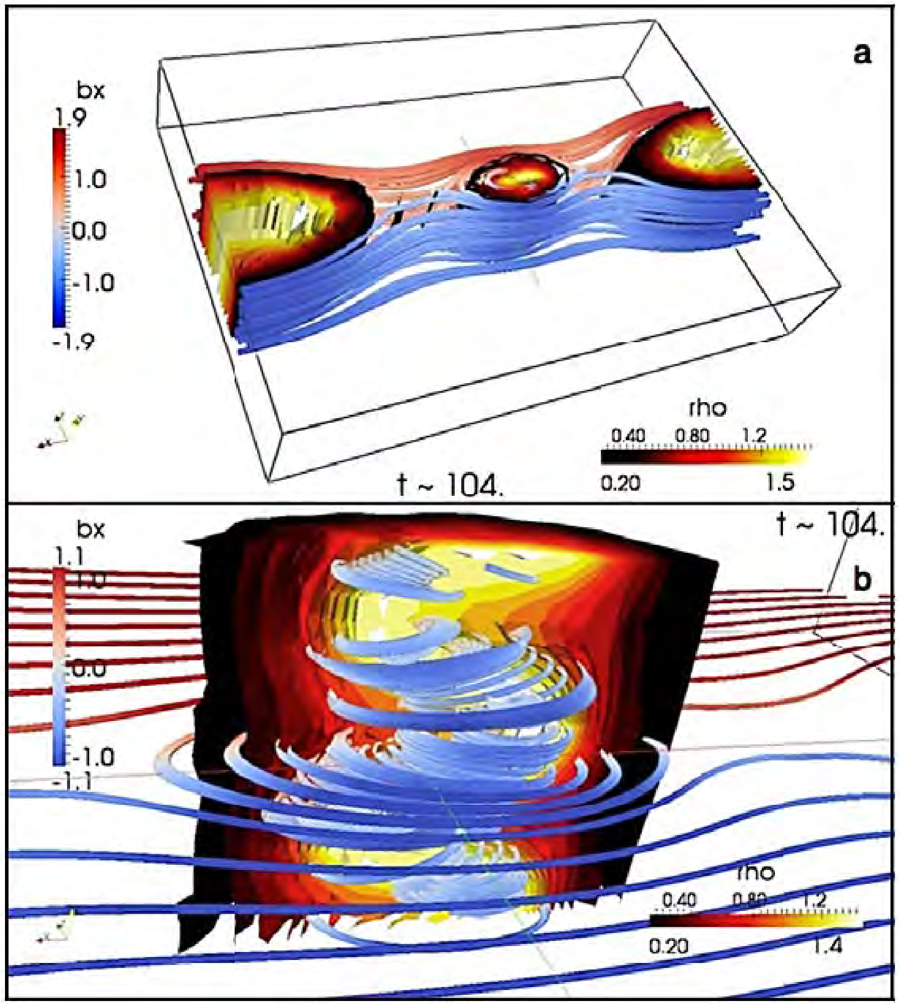
What does a plasmoid look like in 3D?



Kink Instability Leads to Turbulent Reconnection

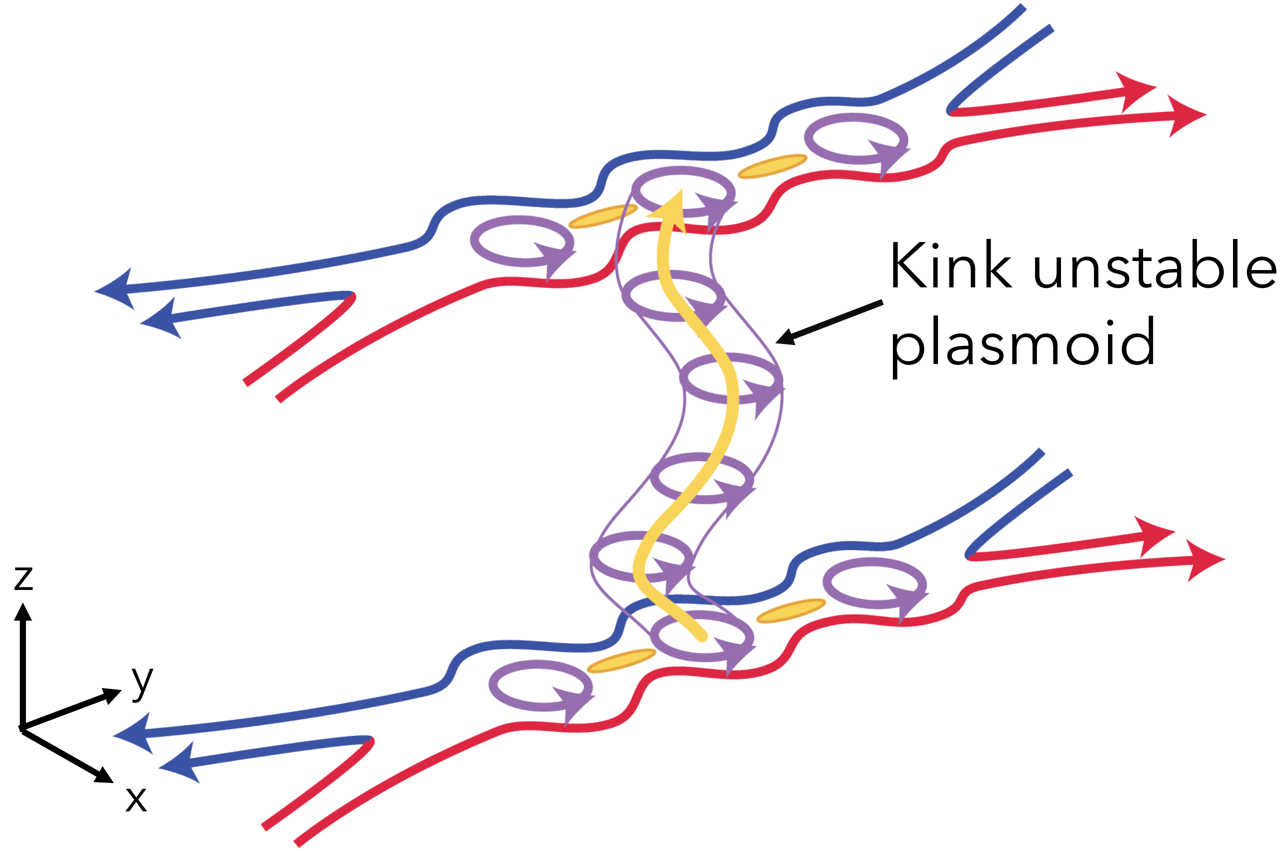
Turbulent reconnection over a large volume, as observed in astrophysics

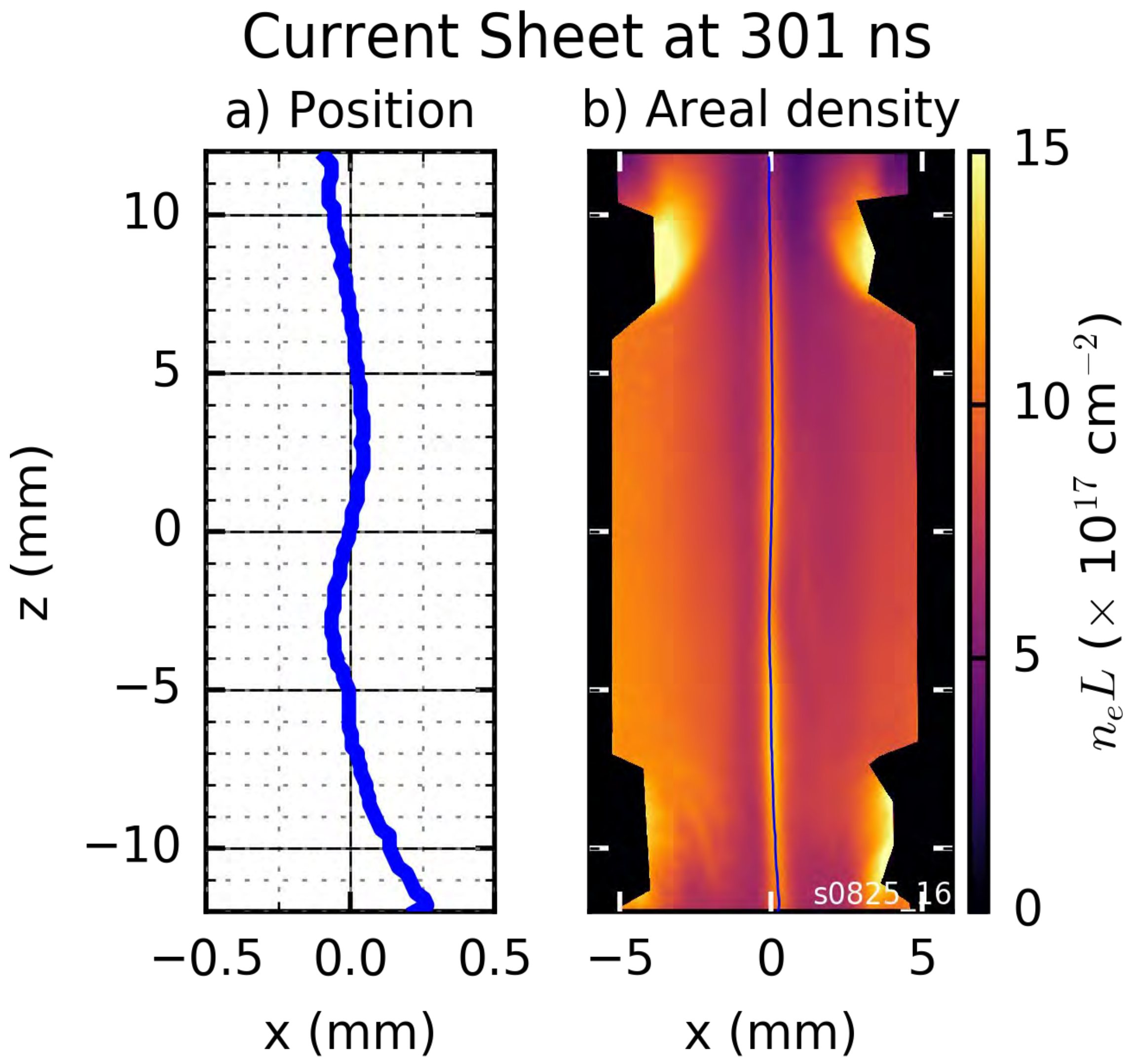




Lapenta, G., and L. Bettarini. *EPL* **93**, 6 (2011)

Hints of a kink instability on MAGPIE

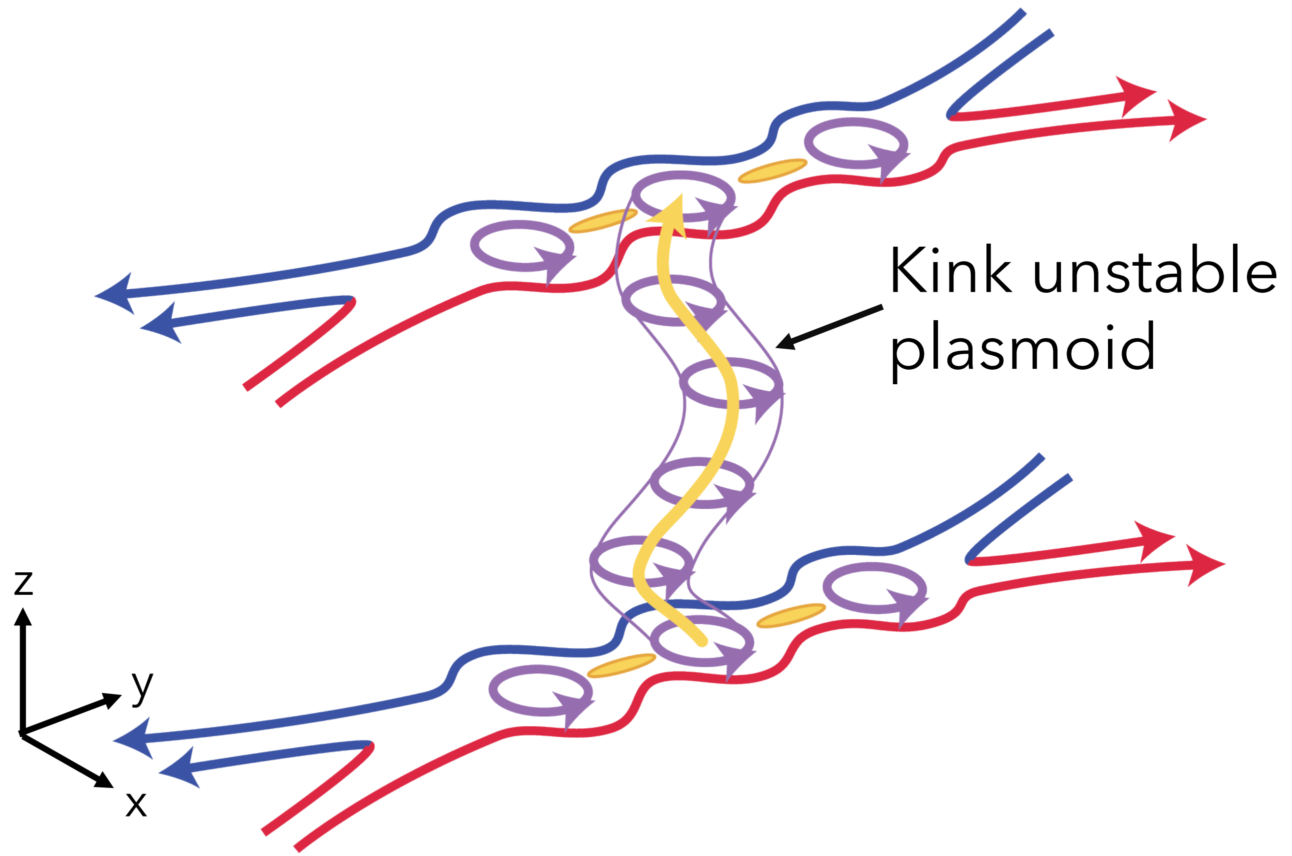


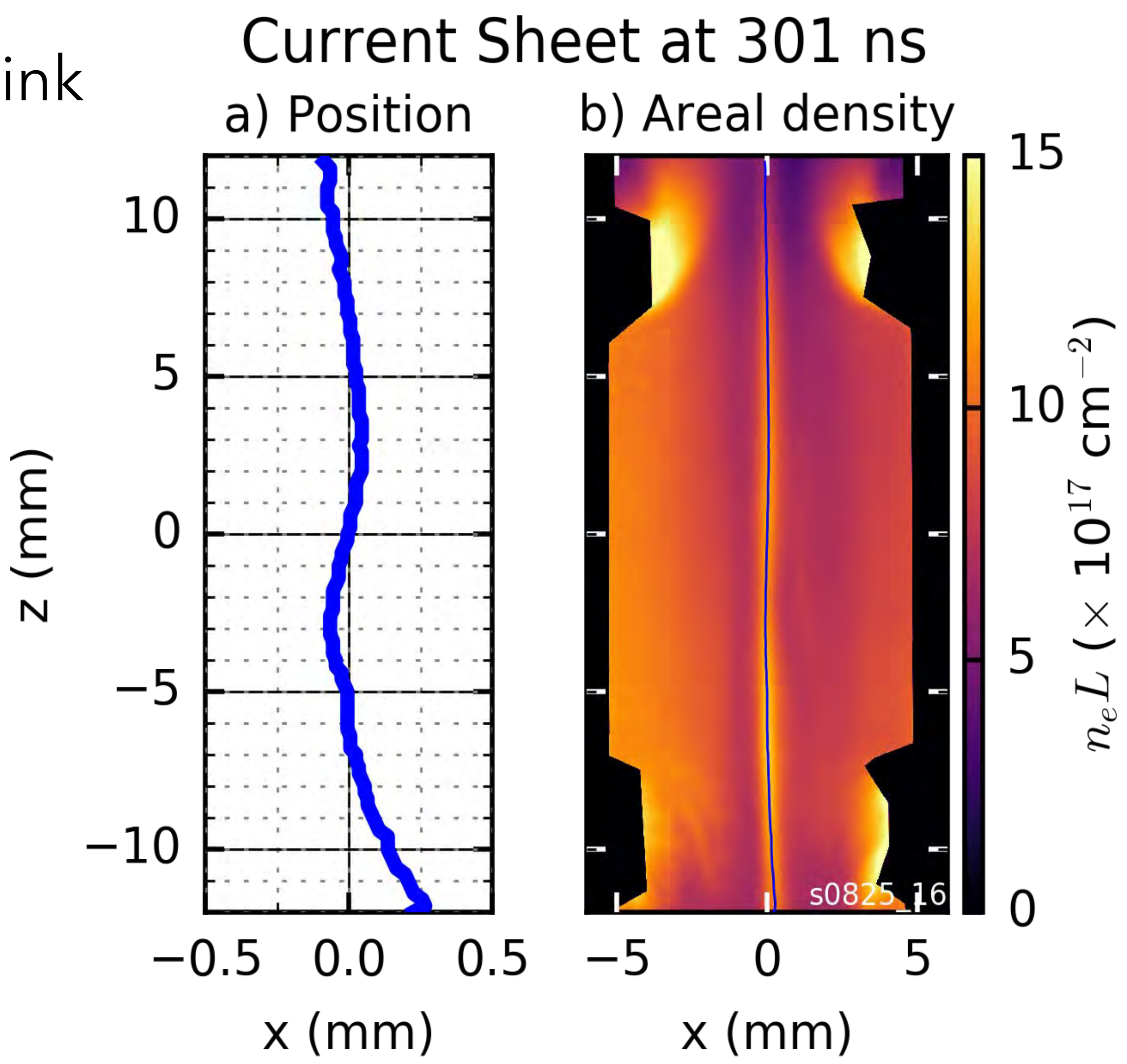


Hints of a kink instability on MAGPIE

Open questions:

- Behavior of plasmoid on long timescales – kink

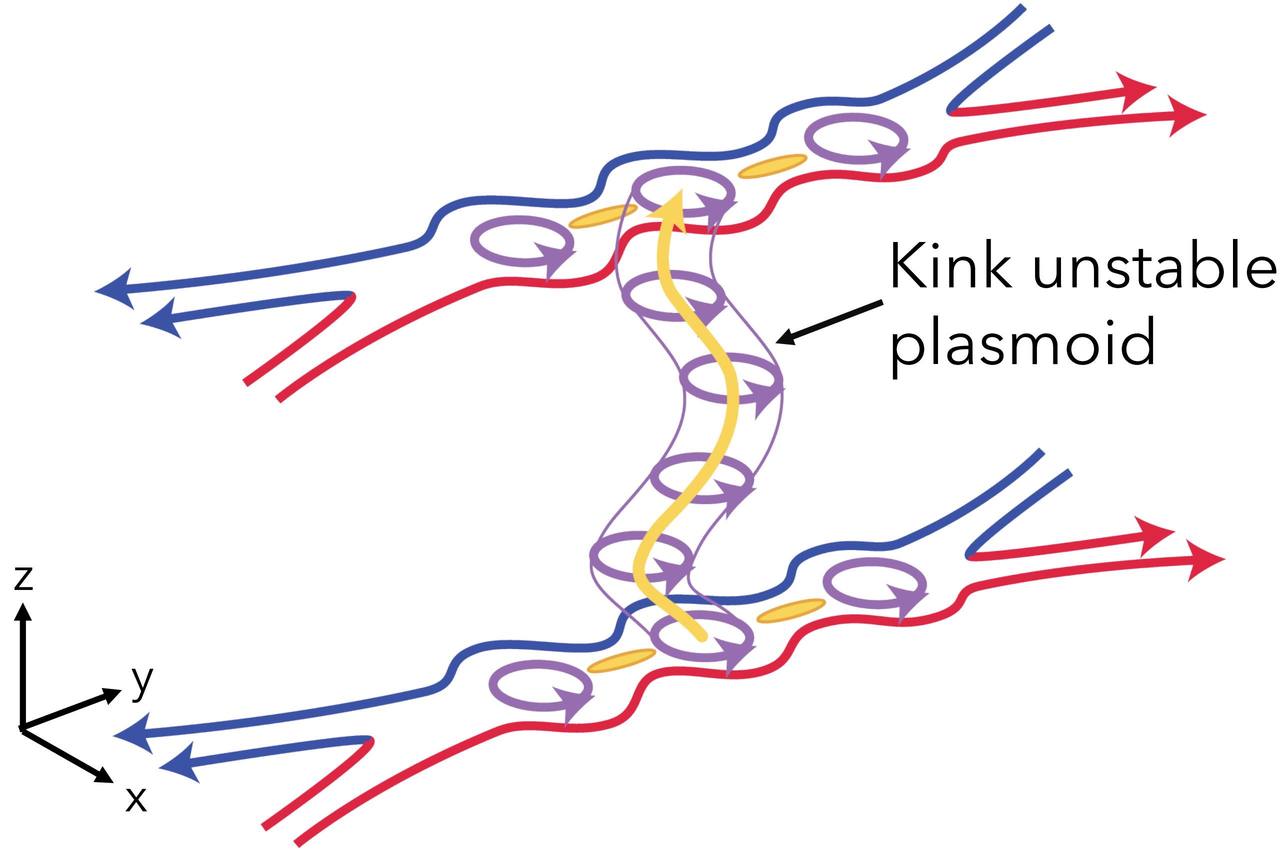


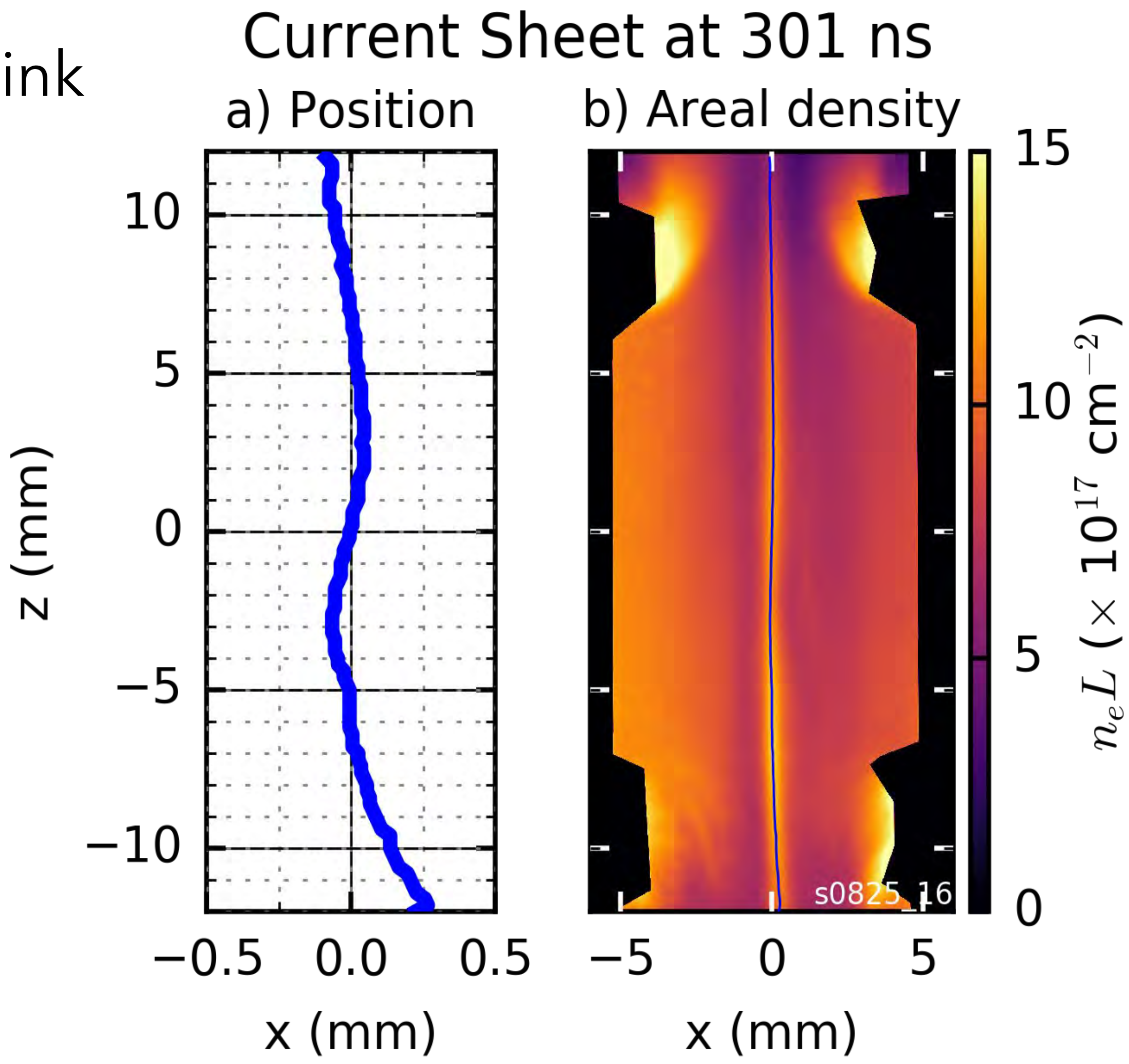


Hints of a kink instability on MAGPIE

Open questions:

- Behavior of plasmoid on long timescales – kink
- Effects of adding B_z on plasmoid stability





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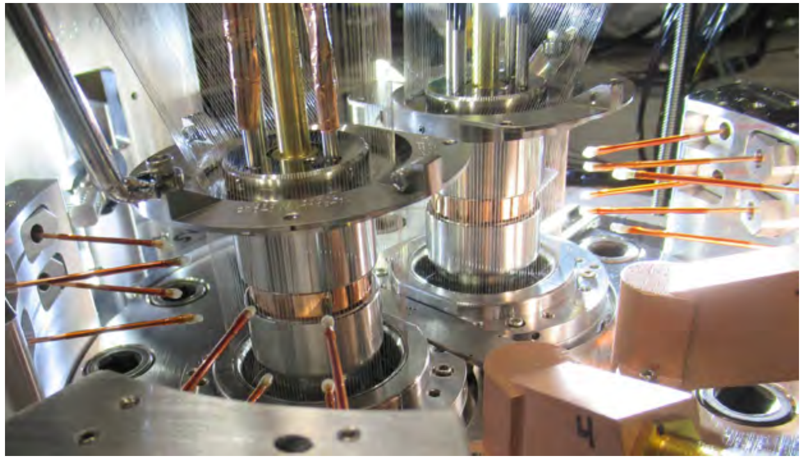
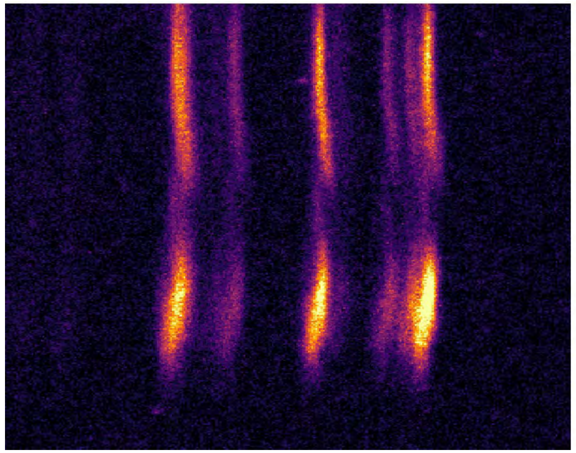
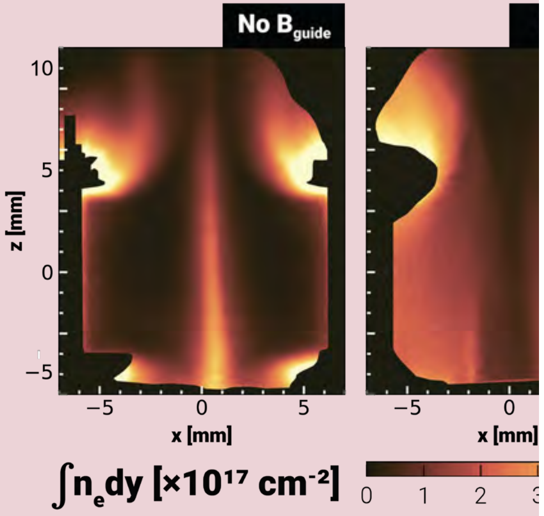




Plasmoids and turbulence

Guide field on MAIZE



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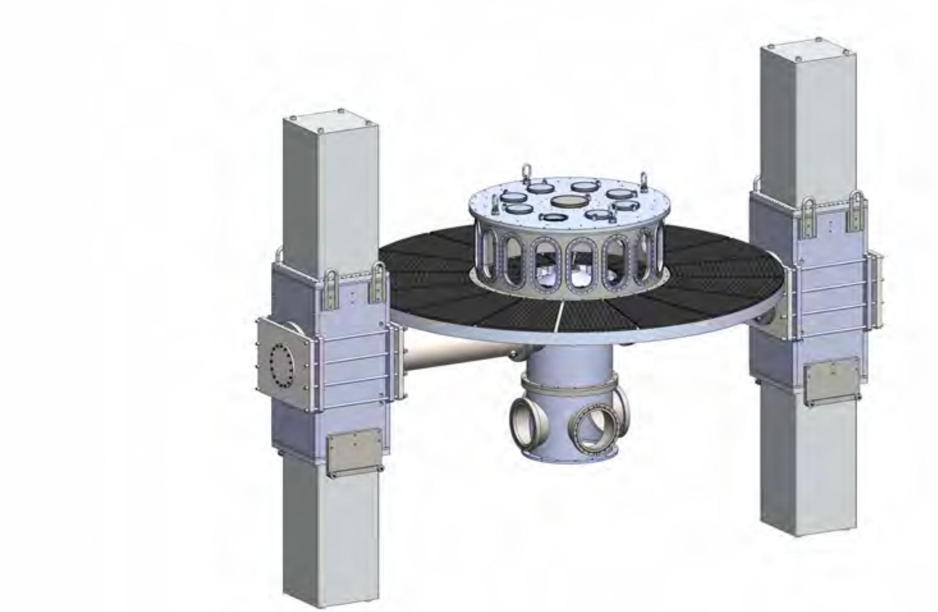
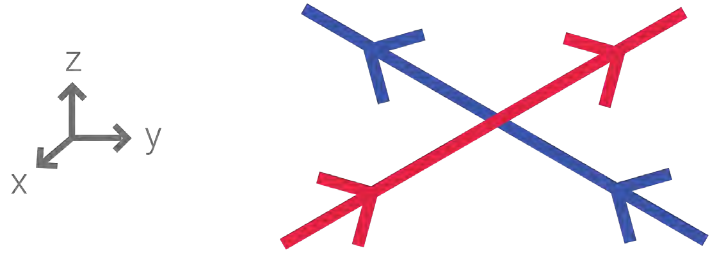
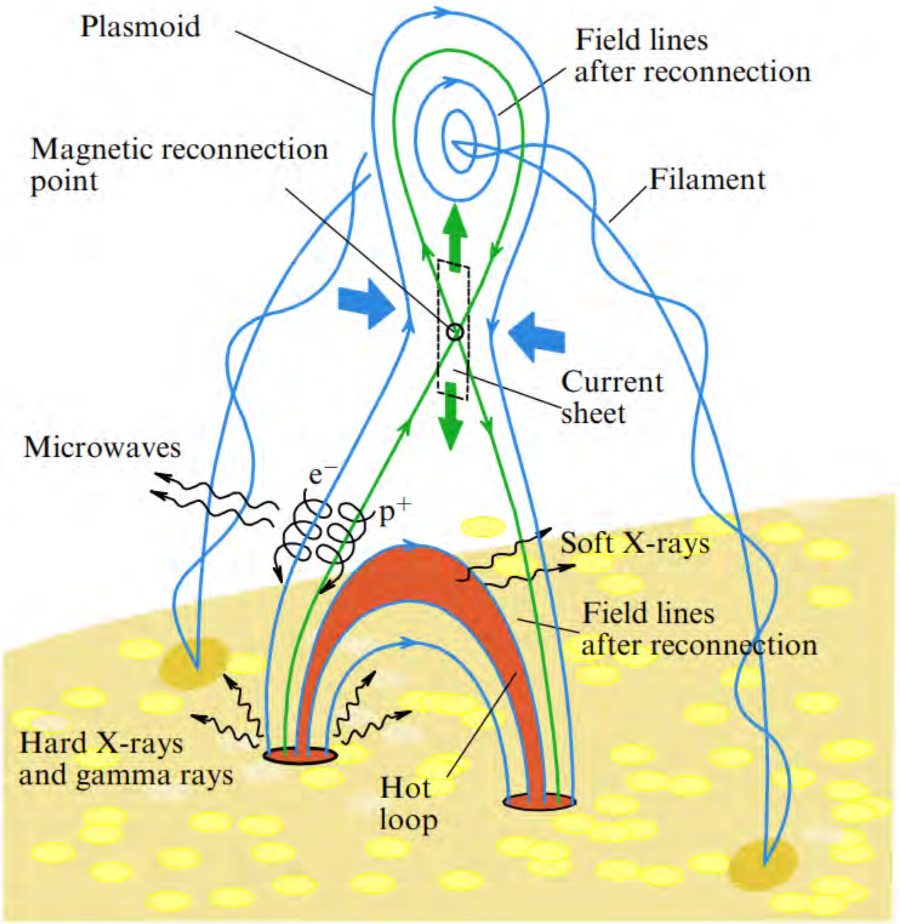
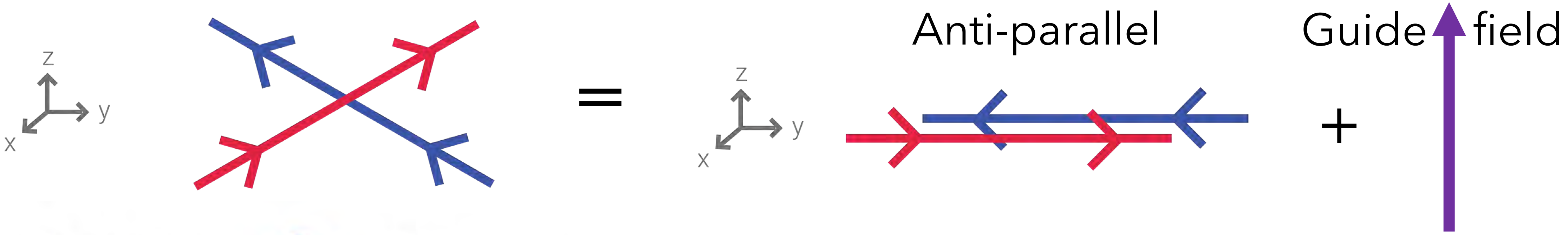


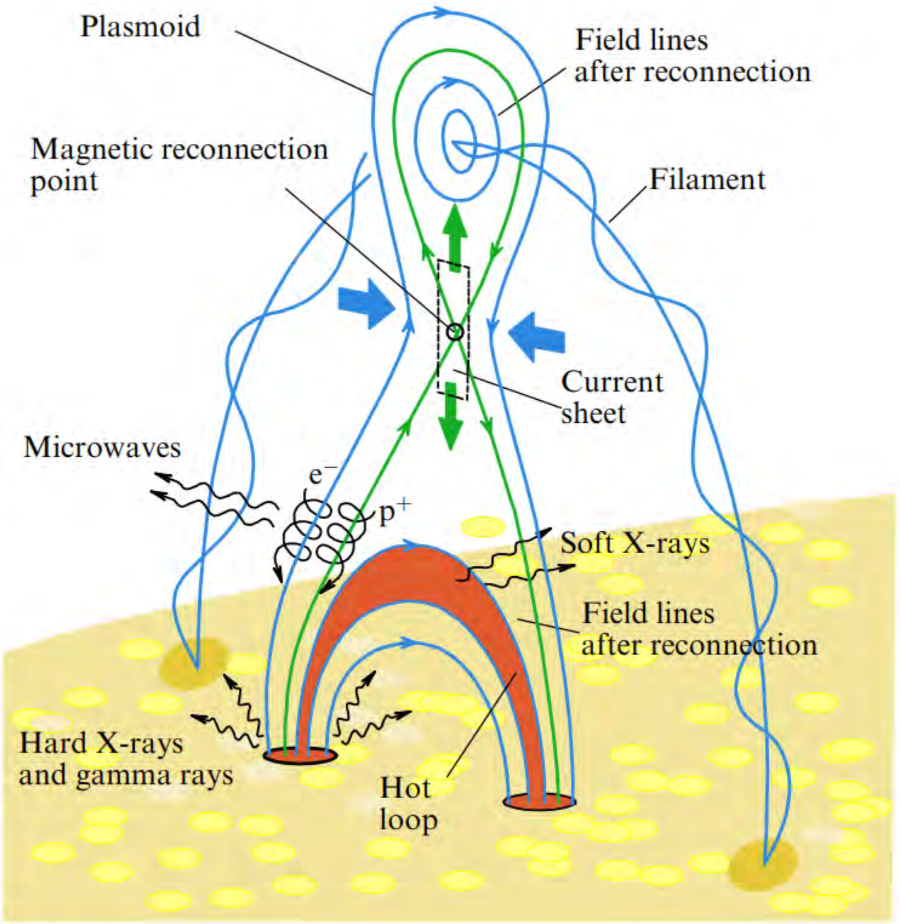
Guide field reconnection





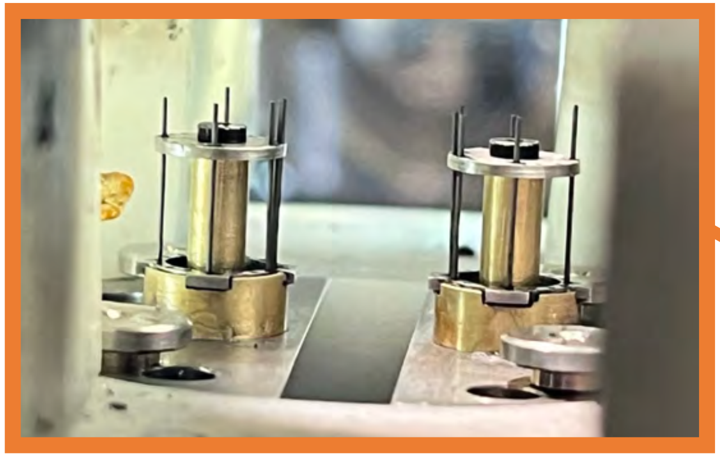
Guide field reconnection





Guide field: *non-reconnected B-field. Magnetizes particles, gyro motion.*

Preliminary guide field experiments on MAIZE

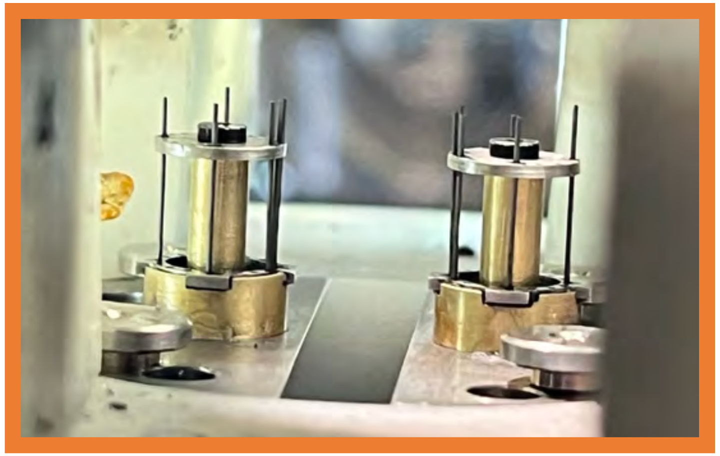


Thomas Varnish

Parameter	MAGPIE	MAIZE
Peak Current [MA]	1.4	0.5*
Rise Time [ns]	240	240

**lower than usual current now fixed*

Preliminary guide field experiments on MAIZE



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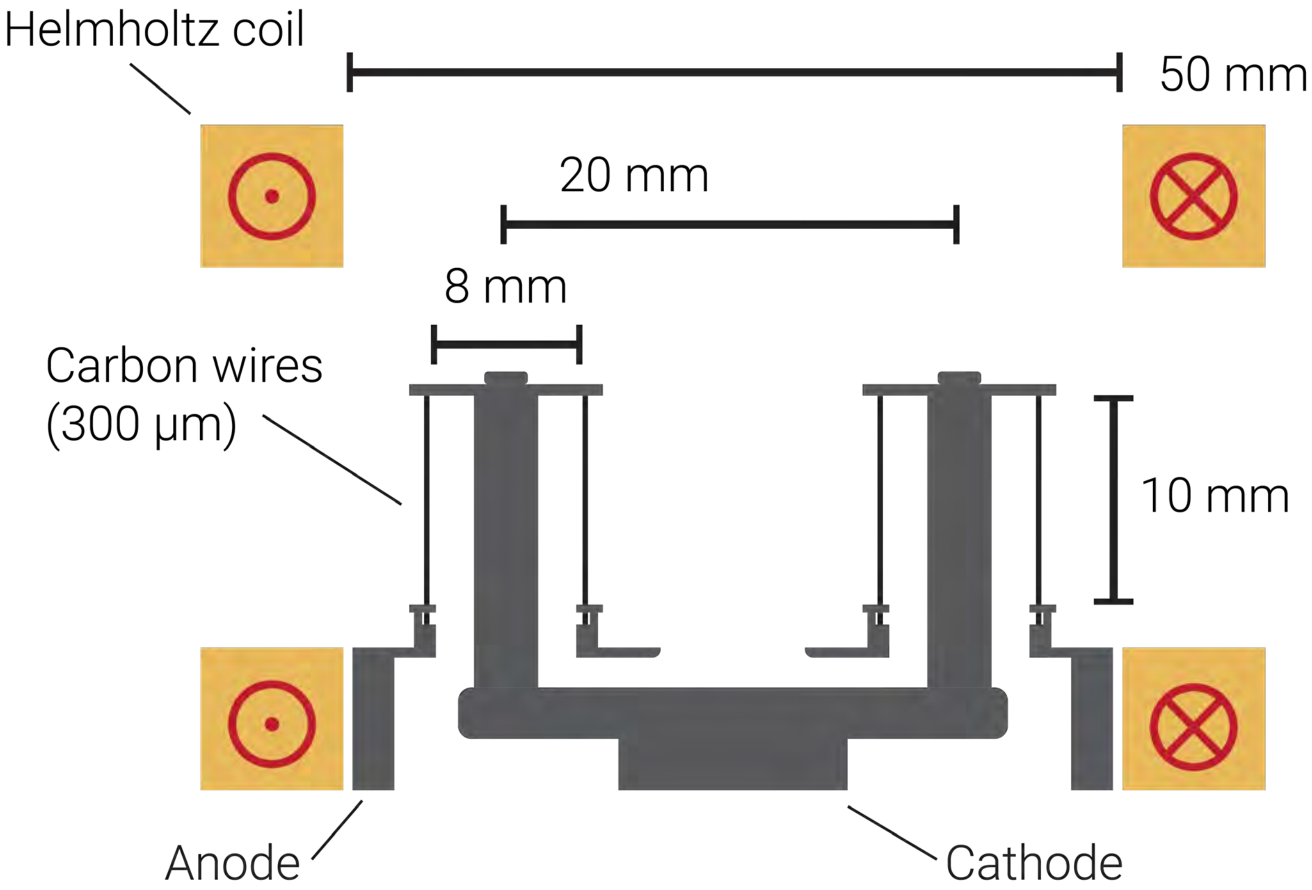

Preliminary guide field experiments on MAIZE

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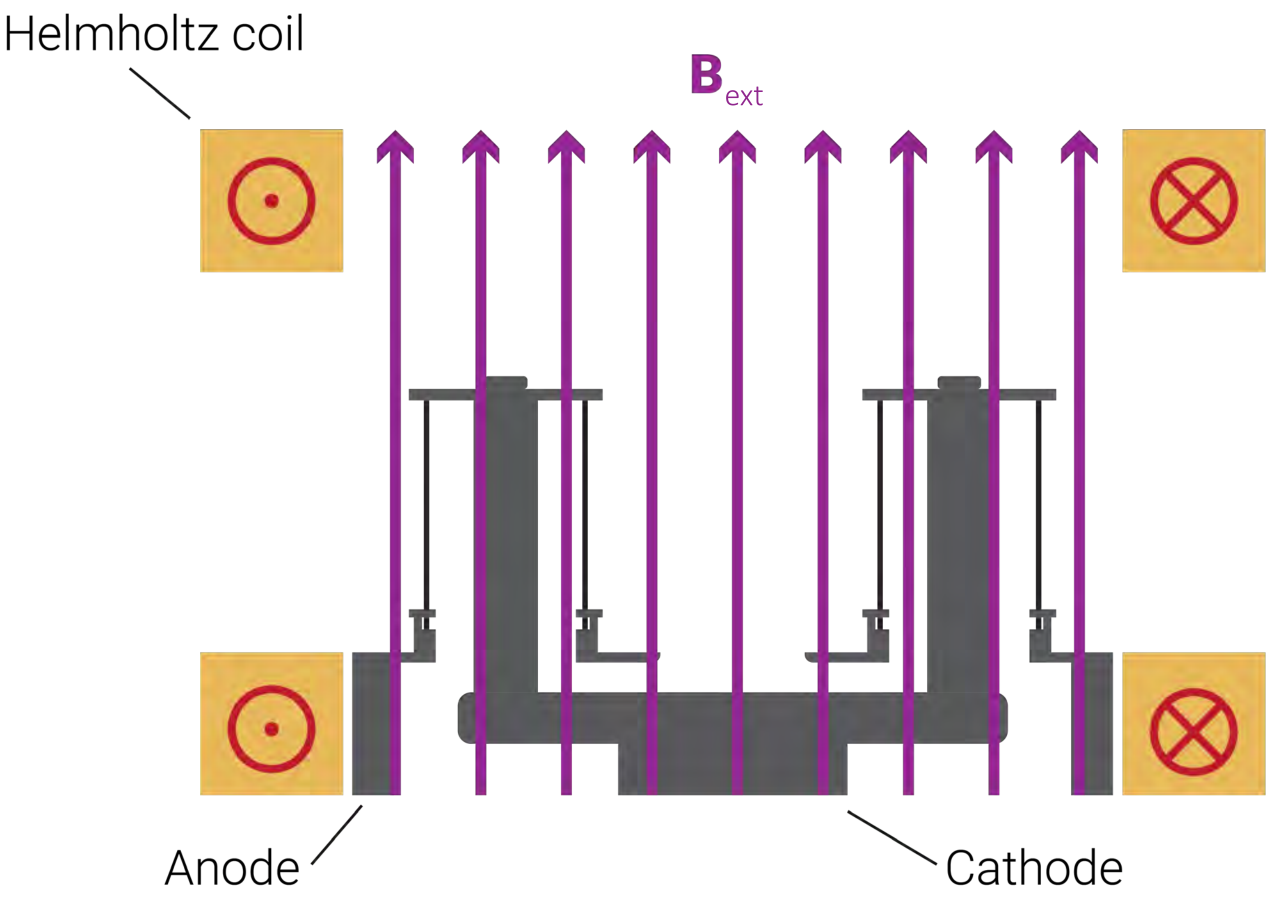

Preliminary guide field experiments on MAIZE

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Peak Current [MA]	1.4	0.5*
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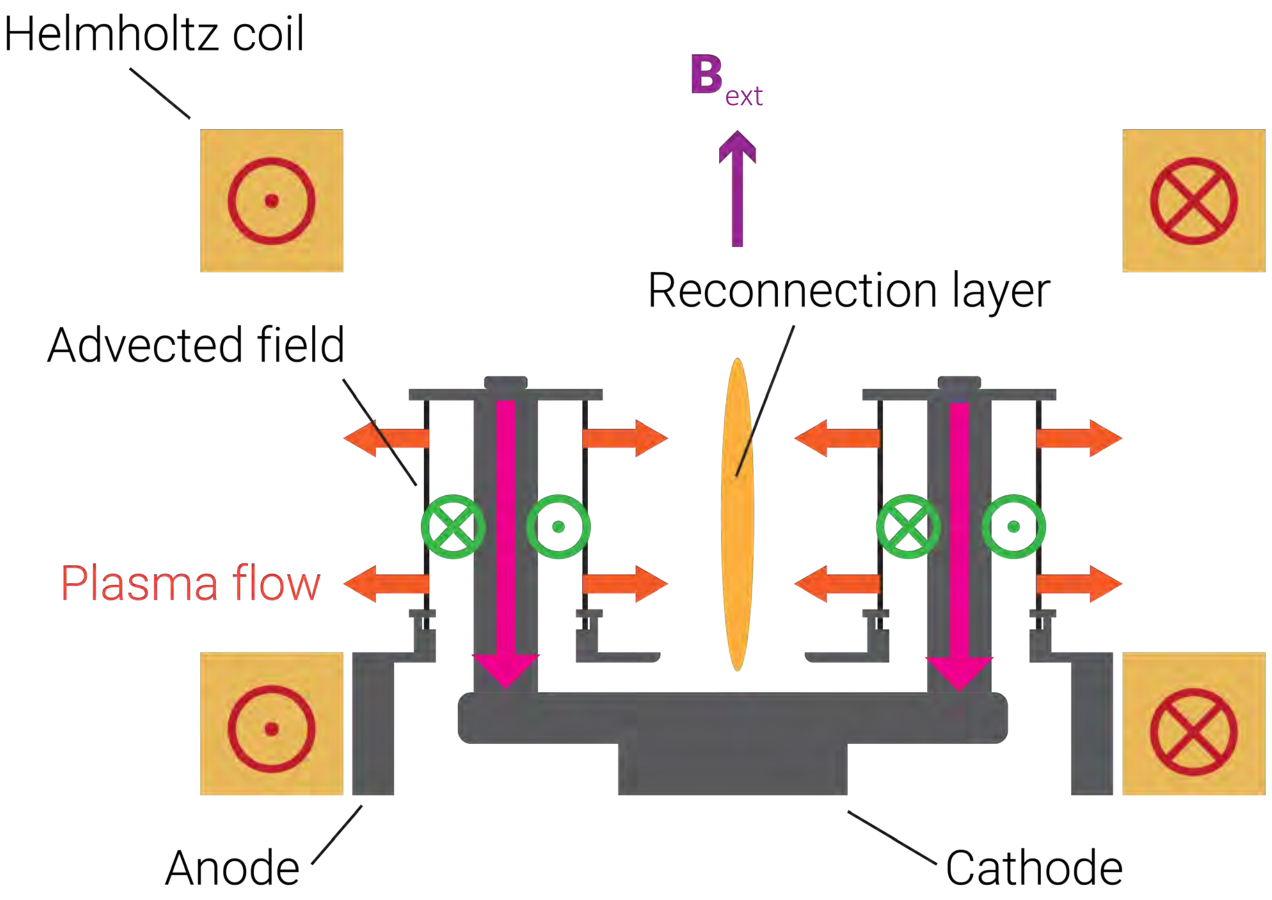
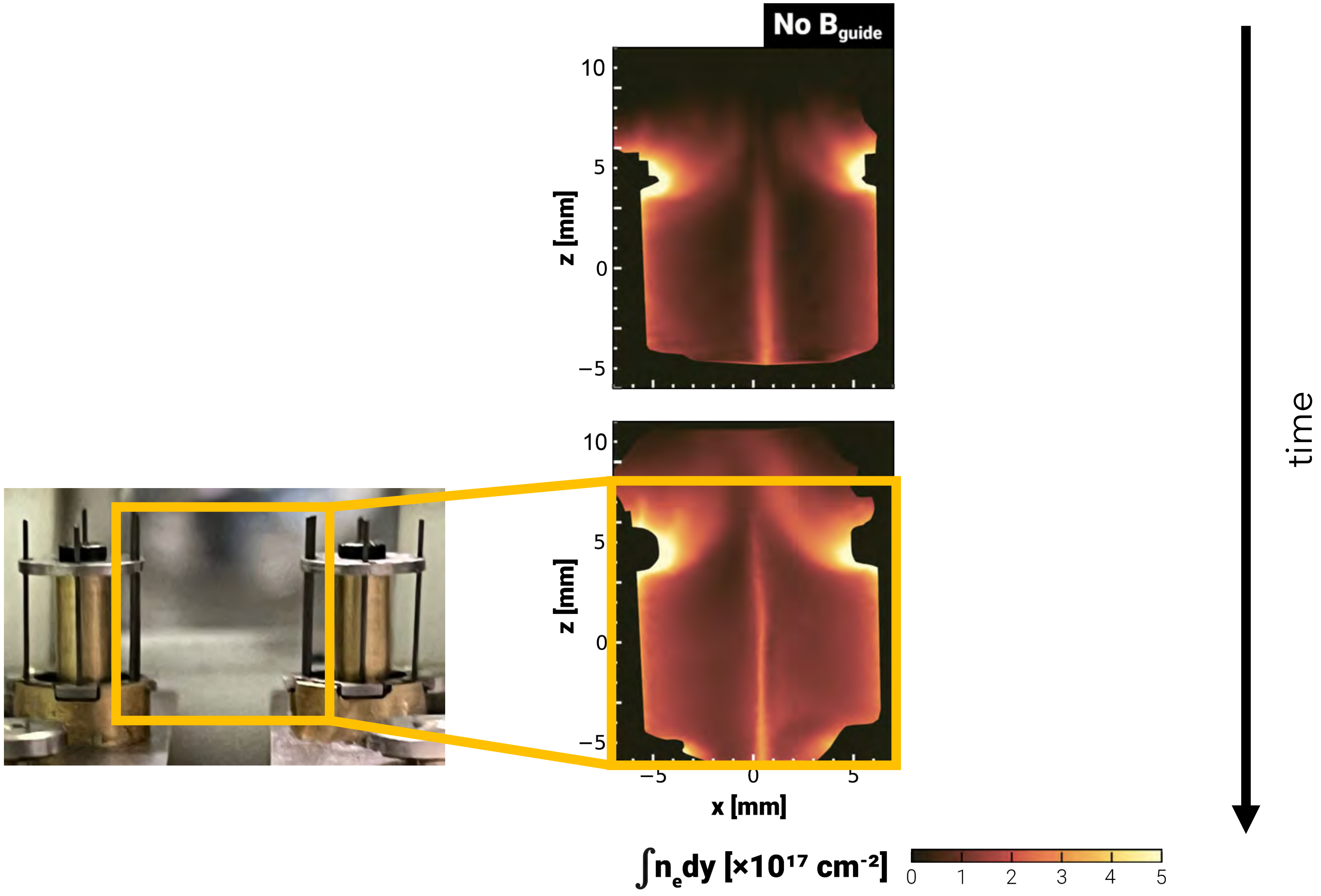
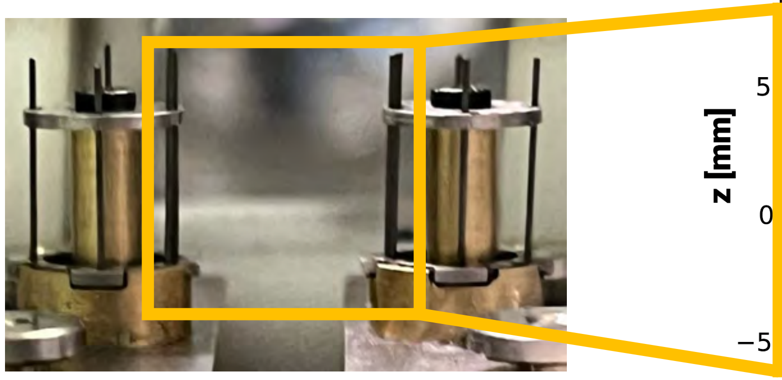


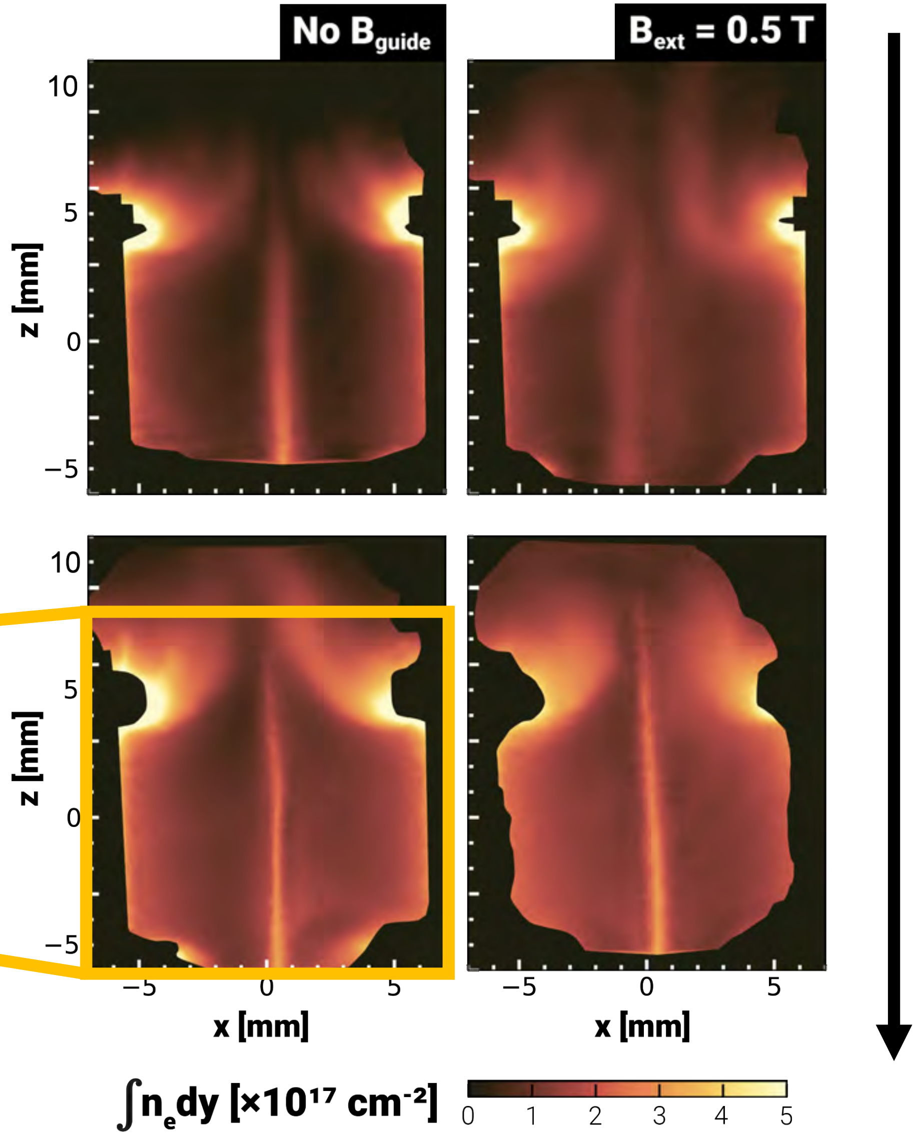
Results without external field



Small external fields delay onset of reconnection

$$\frac{B_{ext}}{B_{rec}} \sim 0.25 - 0.5$$



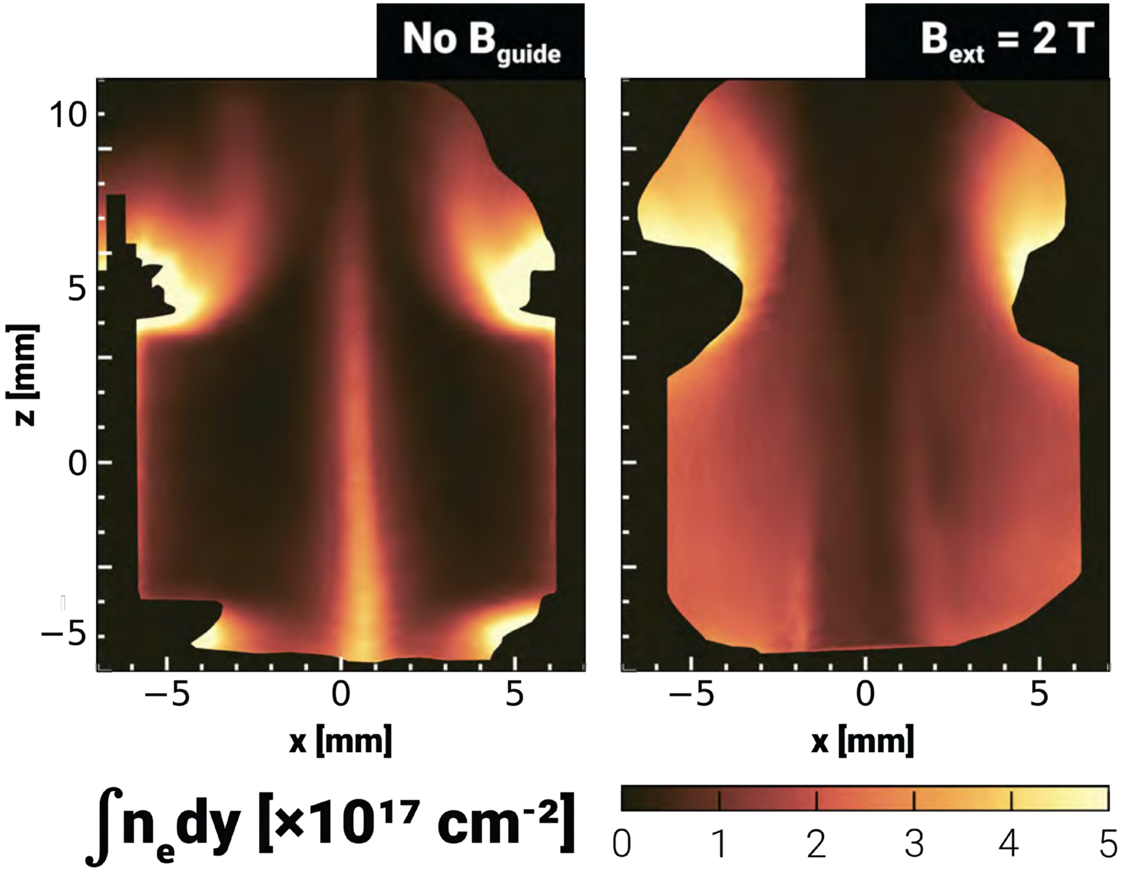


Layer not fully formed in external field

Layer now formed in both

Large external fields prevent reconnection

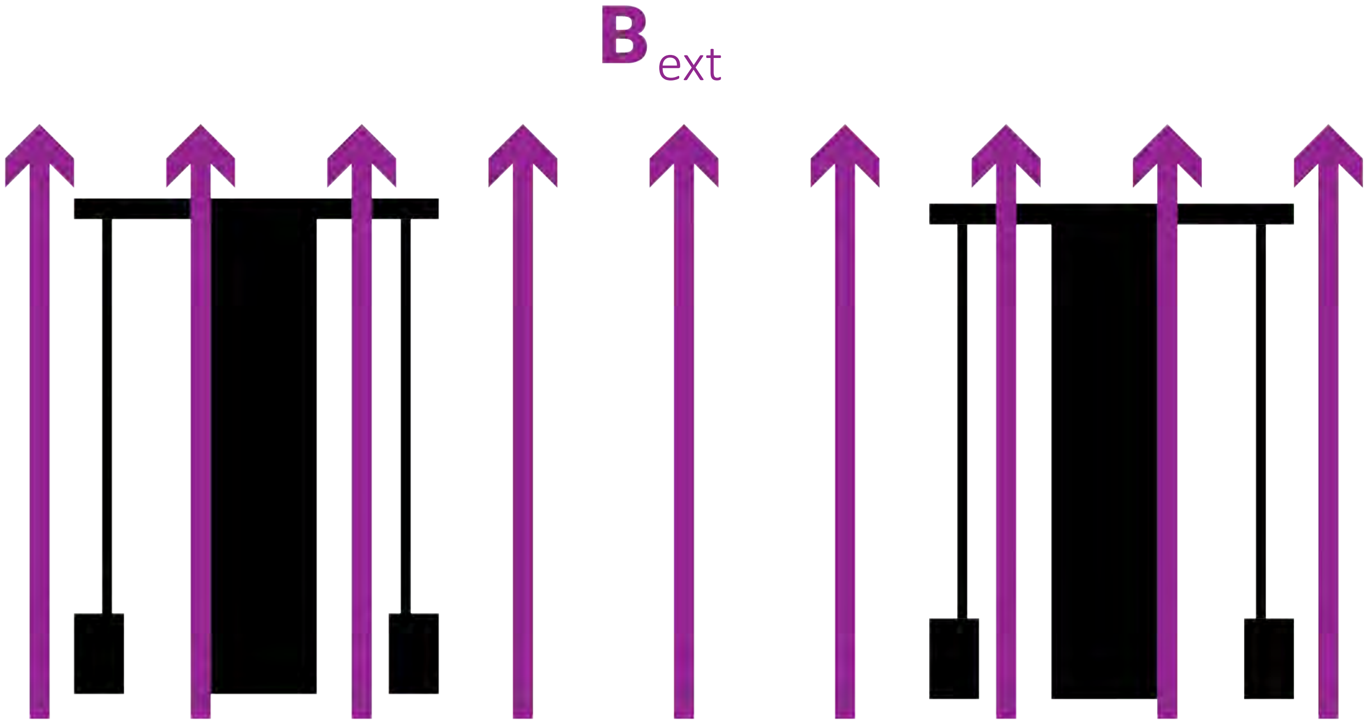
$$\frac{B_{ext}}{B_{rec}} \sim 1 - 2$$



Void observed instead of layer →
No reconnection with external field

Externally-applied fields are frozen-out of the plasma flows

Helmholtz coil provides uniform B_z across entire platform



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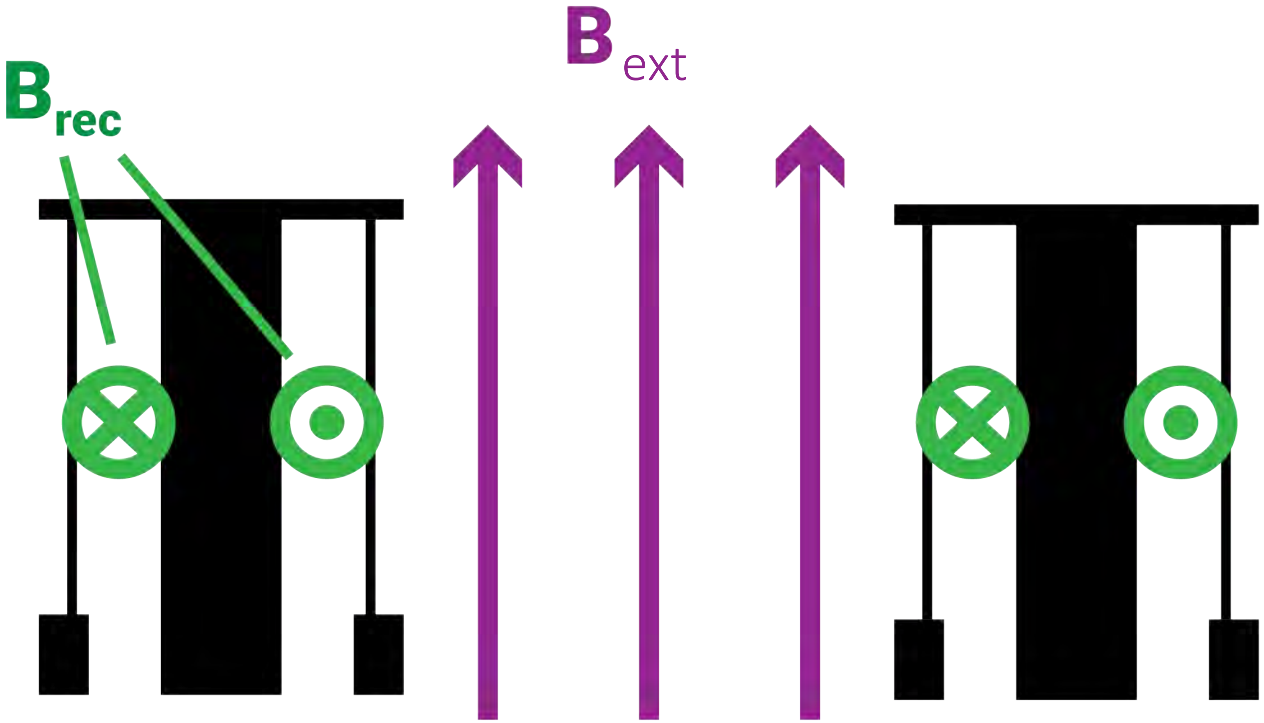
Flows advect B_{rec} into region filled with B_{ext}



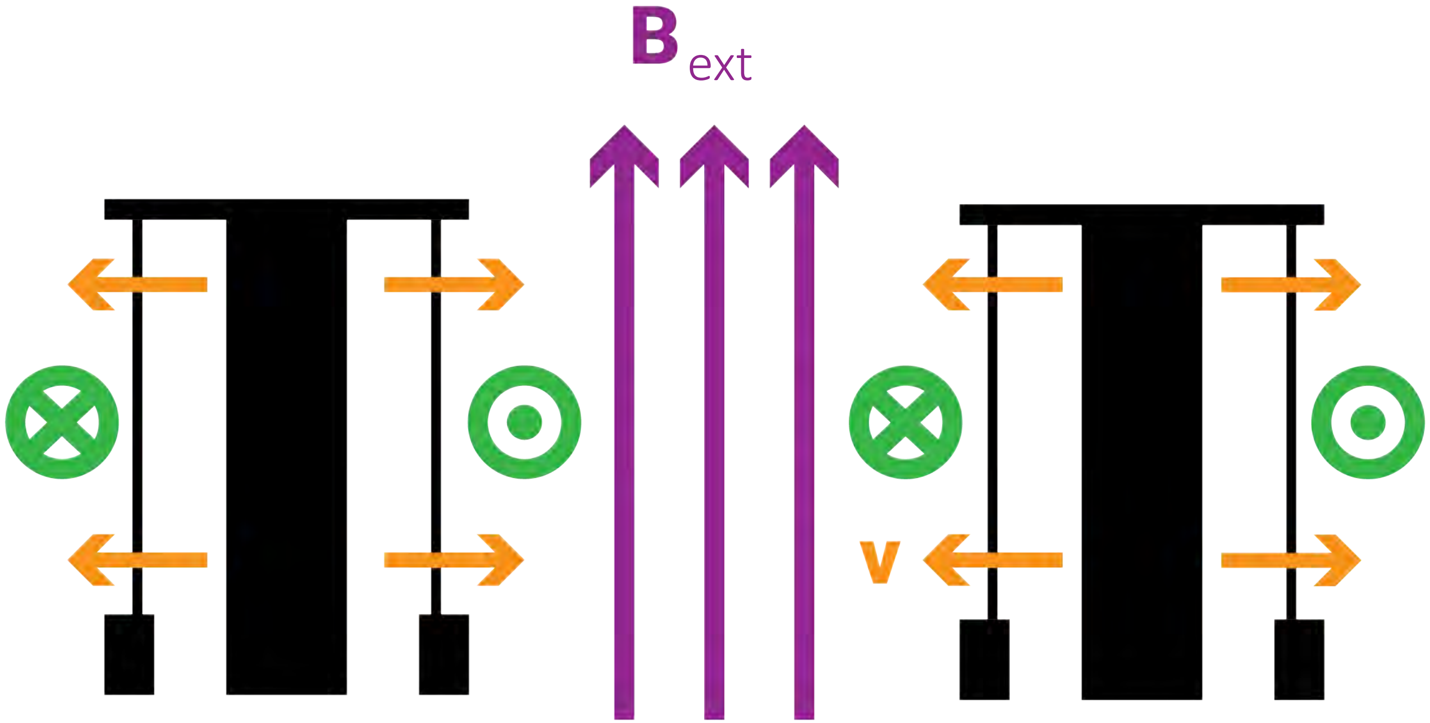
Externally-applied fields are frozen-out of the plasma flows

Helmholtz coil provides uniform B_z across entire platform

Flows advect B_{rec} into region filled with B_{ext}

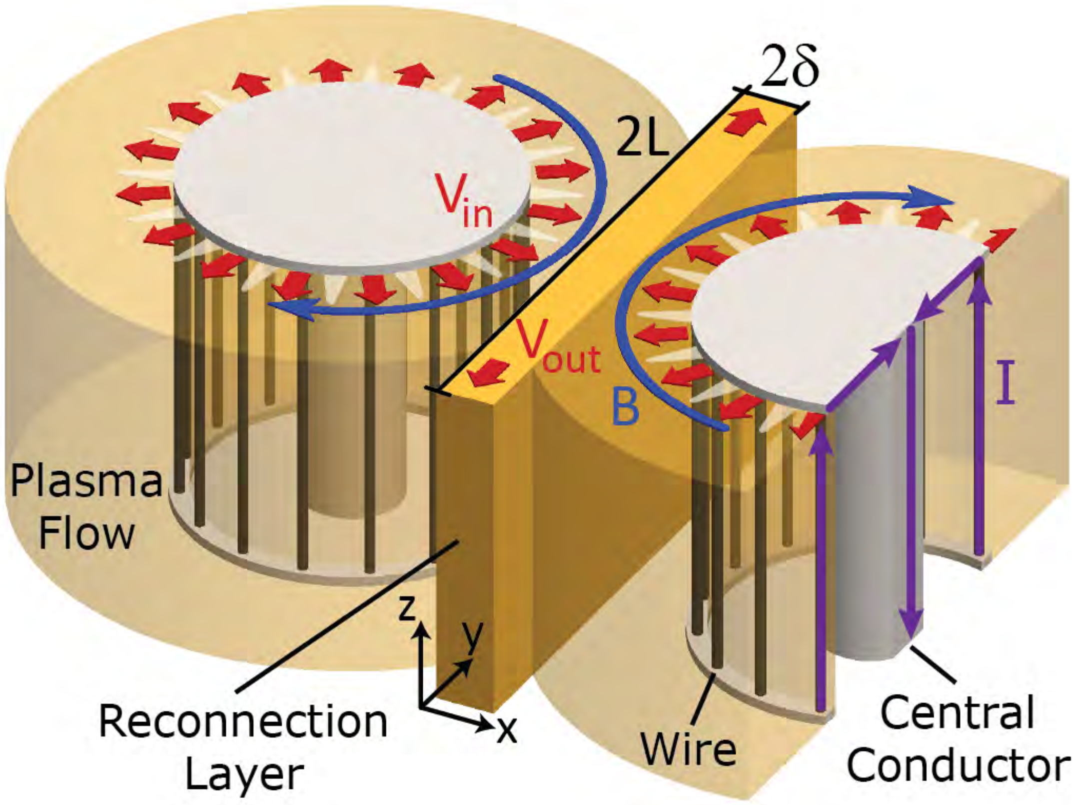
$$\tau_{hydro} \sim \frac{L}{V} = 160 \text{ ns}$$

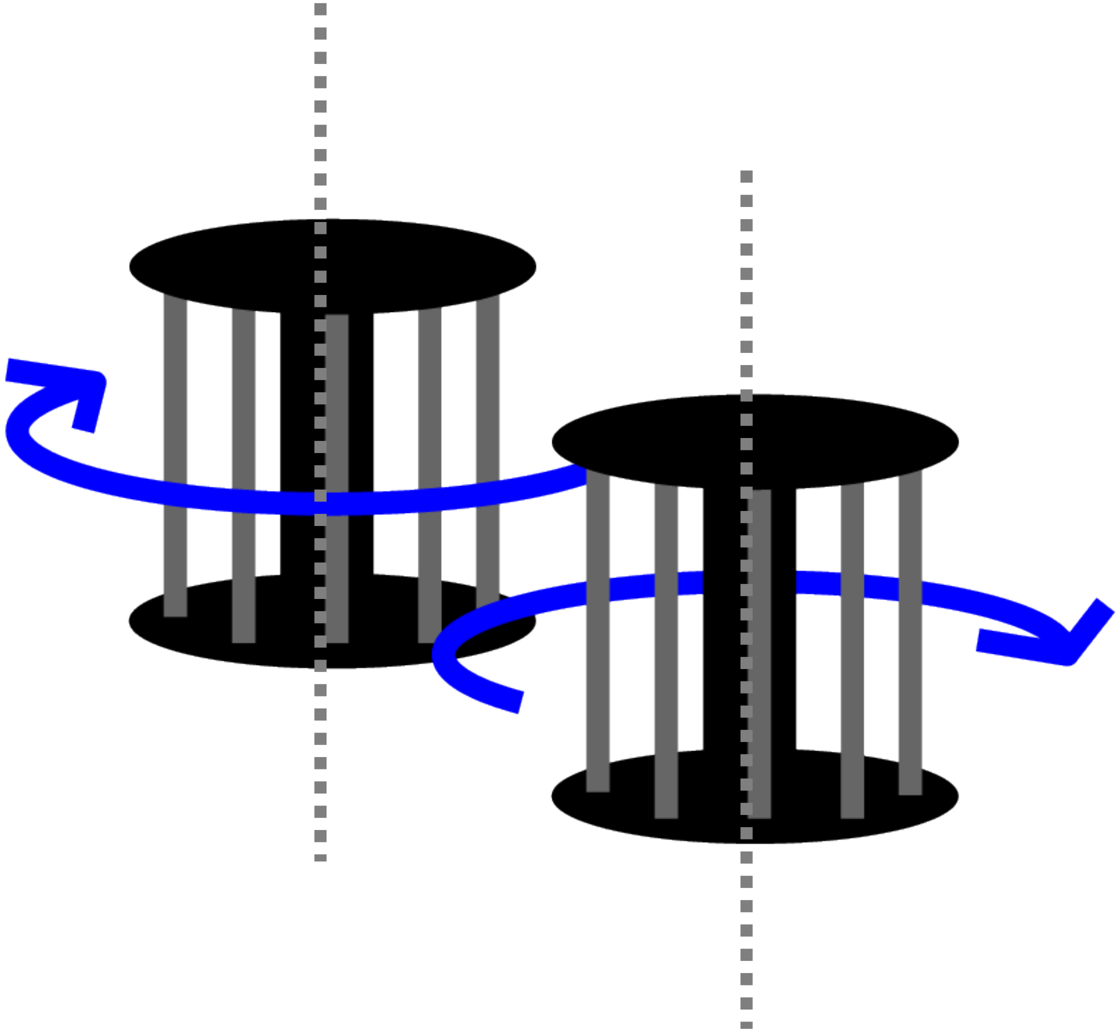
$$\tau_D \sim \frac{L^2}{\bar{\eta}} = 550 \text{ ns}$$



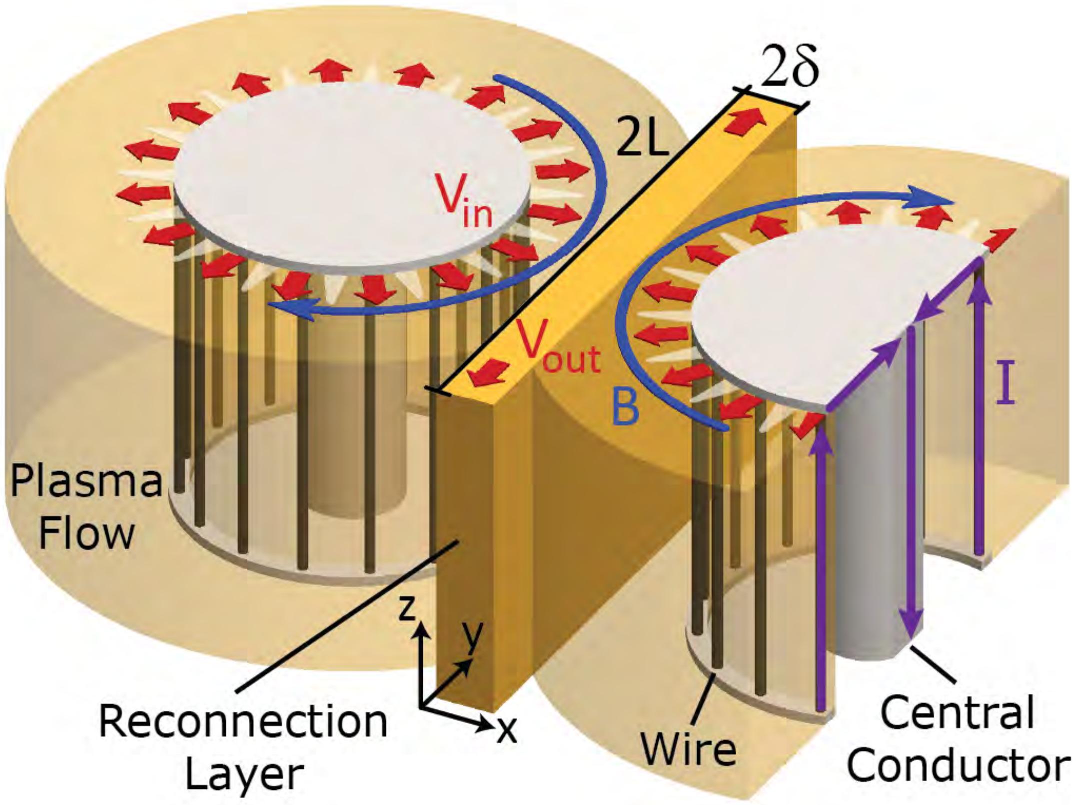
The external field does NOT have time to diffuse into the plasma flows

Embed guide field into plasma flows

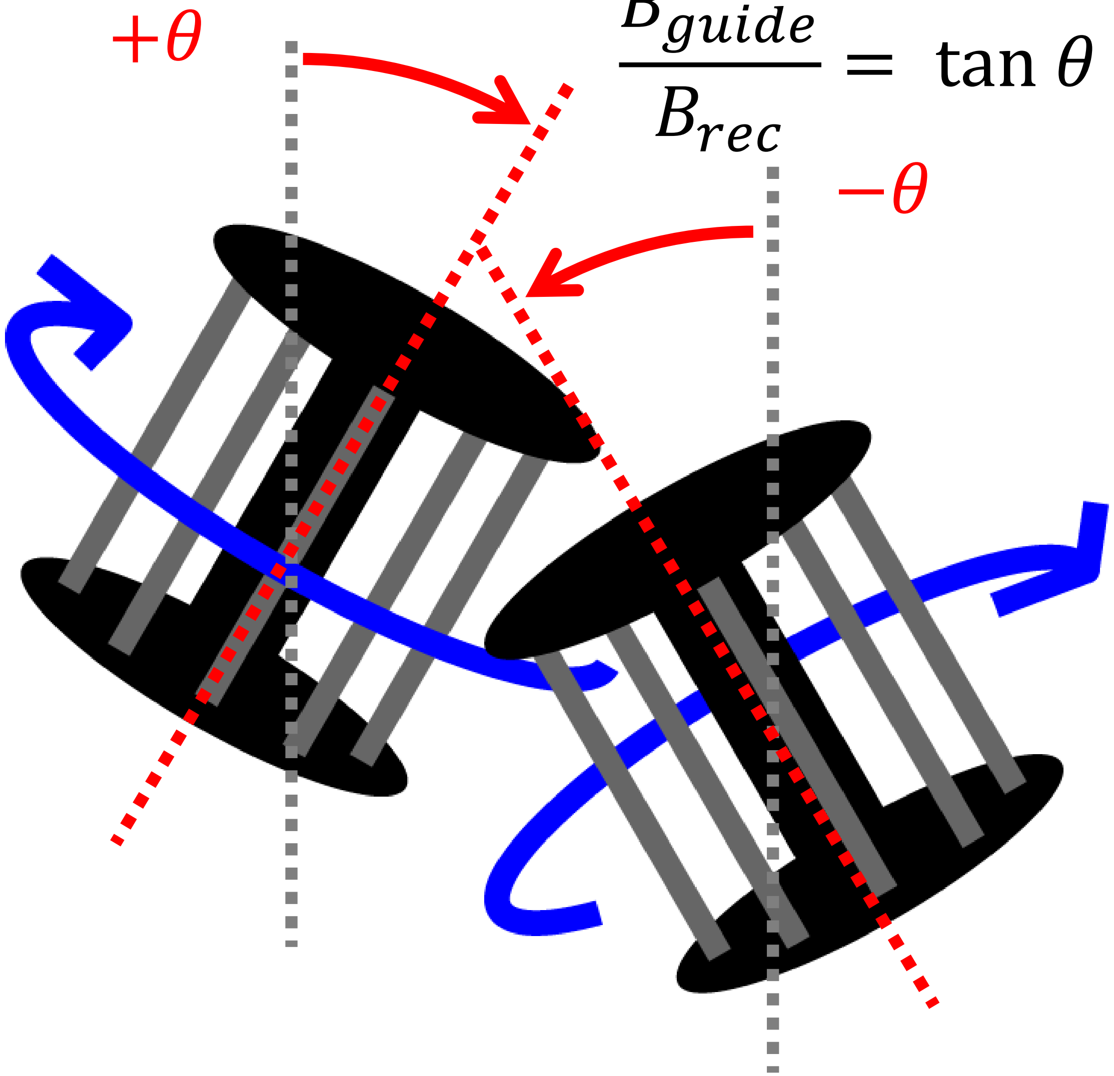




Embed guide field into plasma flows



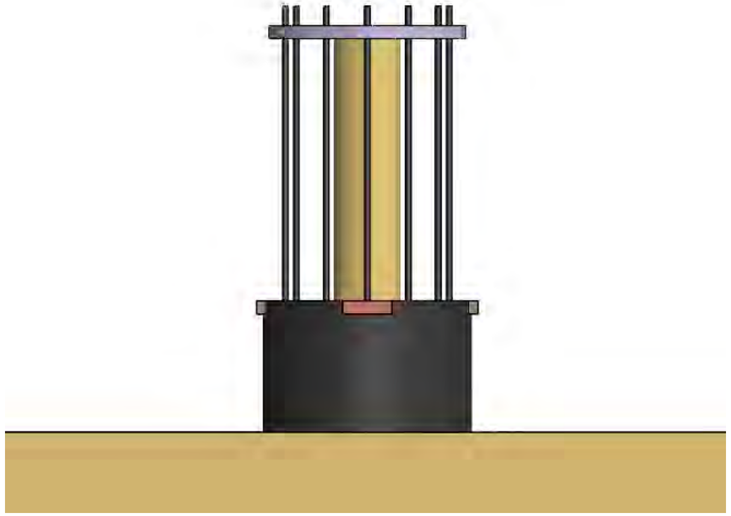
$$\frac{B_{guide}}{B_{rec}} = \tan\theta$$



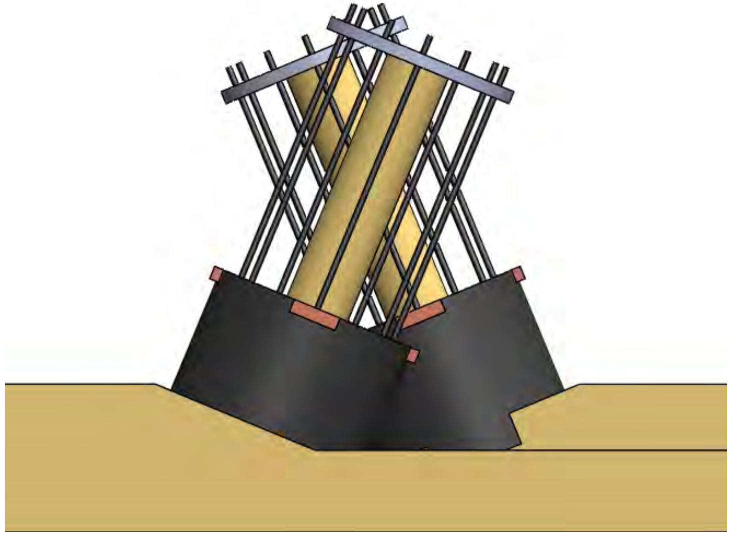
Testing on MAIZE right now!

Experimental lead: Thomas Varnish
With help from Simran Chowdhry and Lansing Horan IV

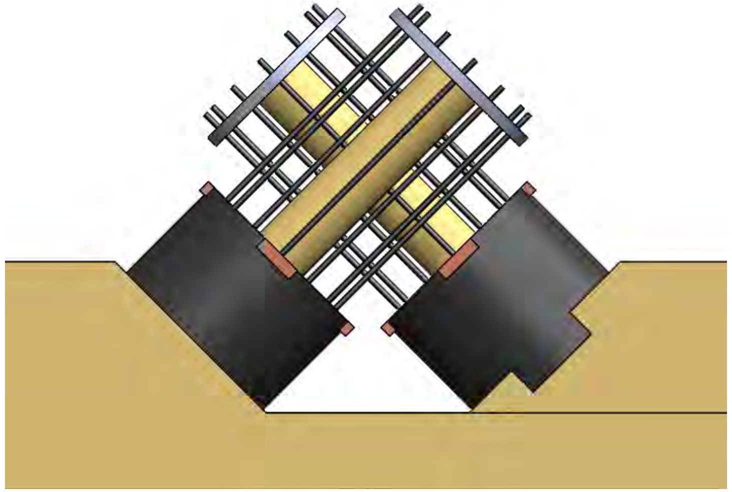
0° $\frac{B_{guide}}{B_{rec}} = 0$



22.5° $\frac{B_{guide}}{B_{rec}} \sim 0.4$



45° $\frac{B_{guide}}{B_{rec}} = 1$

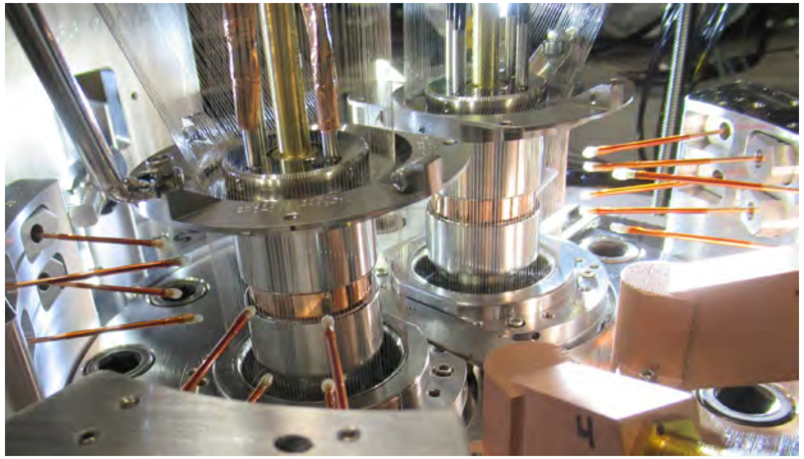


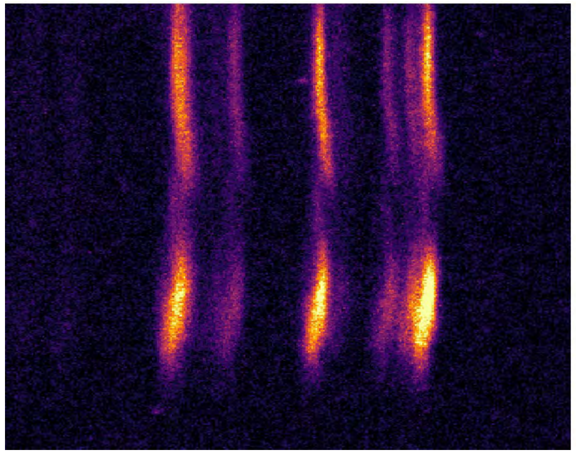
Research paths and talk outline

Magnetic reconnection

Radiative cooling

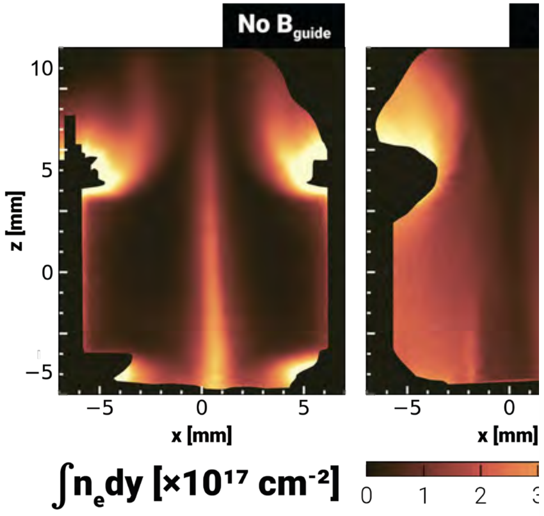
MARZ: Radiatively cooled reconnection on Z



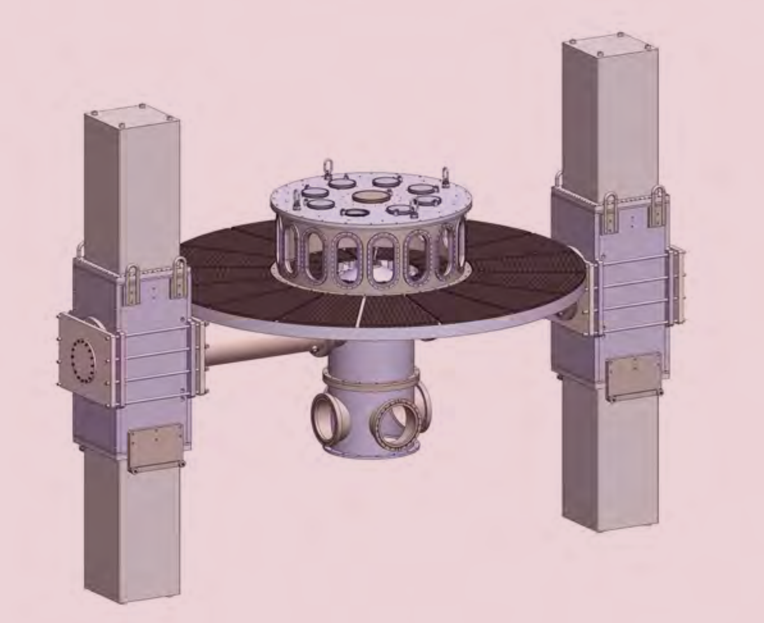


Plasmoids and turbulence

Guide field on MAIZ

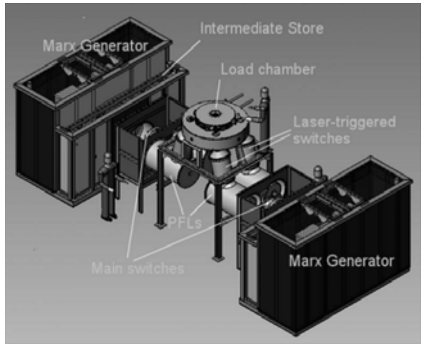


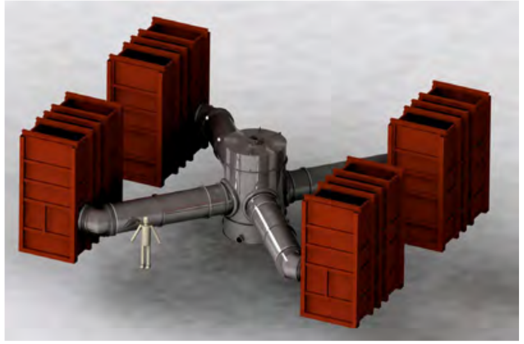
Longer timescales on PUFFIN

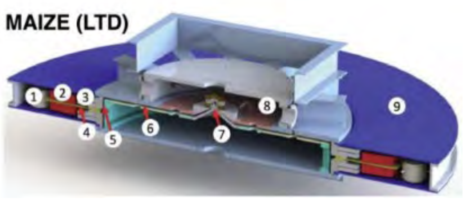


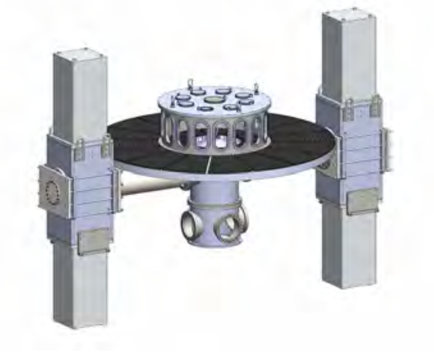
PUFFIN's Unique Purpose: Sustained Magnetized Flows

COBRA:	MAGPIE:	MAIZE:	HADES:	PUFFIN:
1 MA, 100-200 ns	1.4 MA, 240 ns	1 MA, 100 ns	1 MA, 300 ns	1 MA, 1500 ns



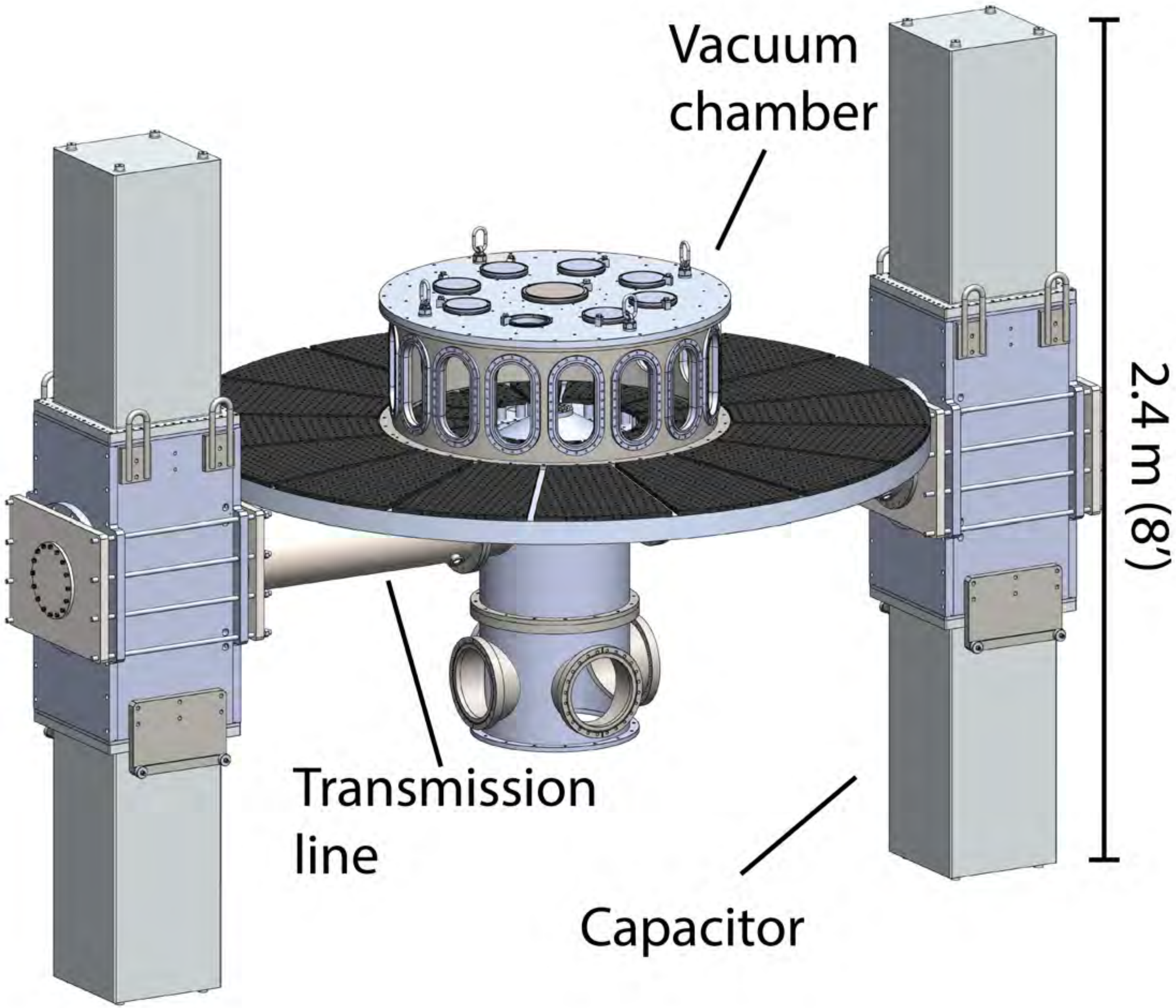


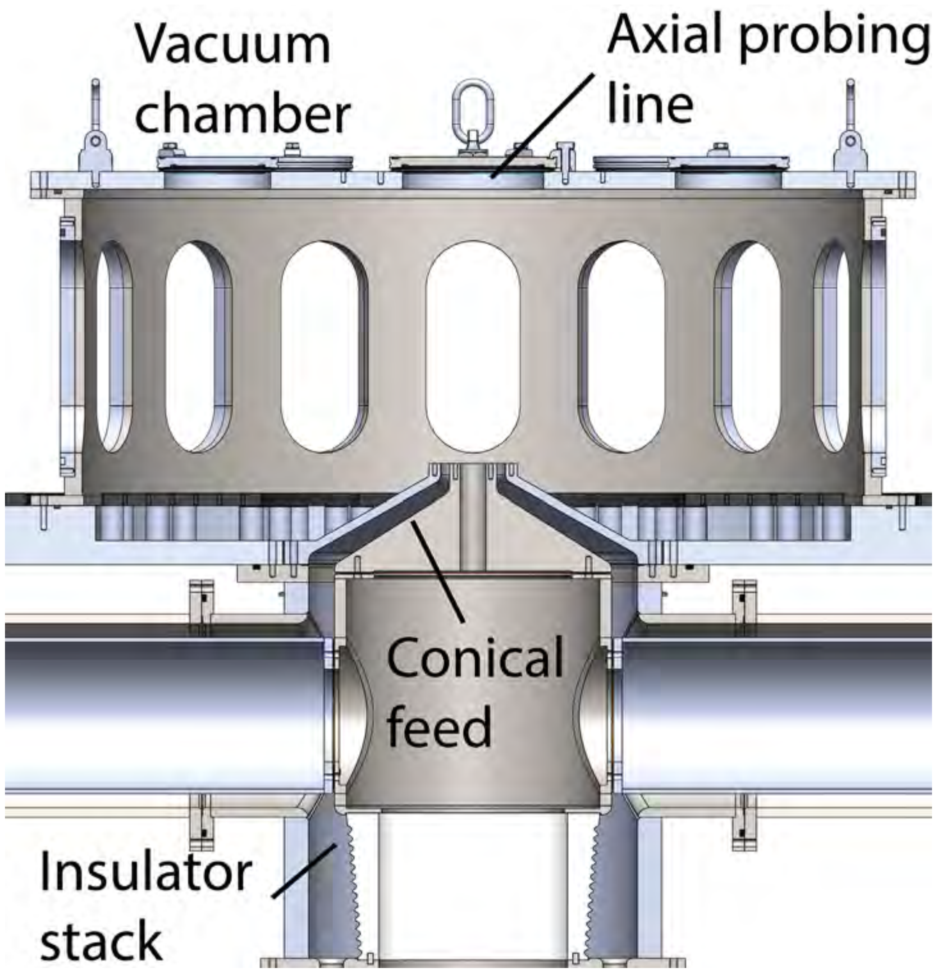




- Existing pulsers optimized for fast implosions, short drive time
- But interesting physics may take longer to develop
- Need to sustain drive for much longer to see "steady state" behavior, or development of slow growing instabilities

PUFFIN 2x1 will drive around 1 MA with a 1.5 μs rise time

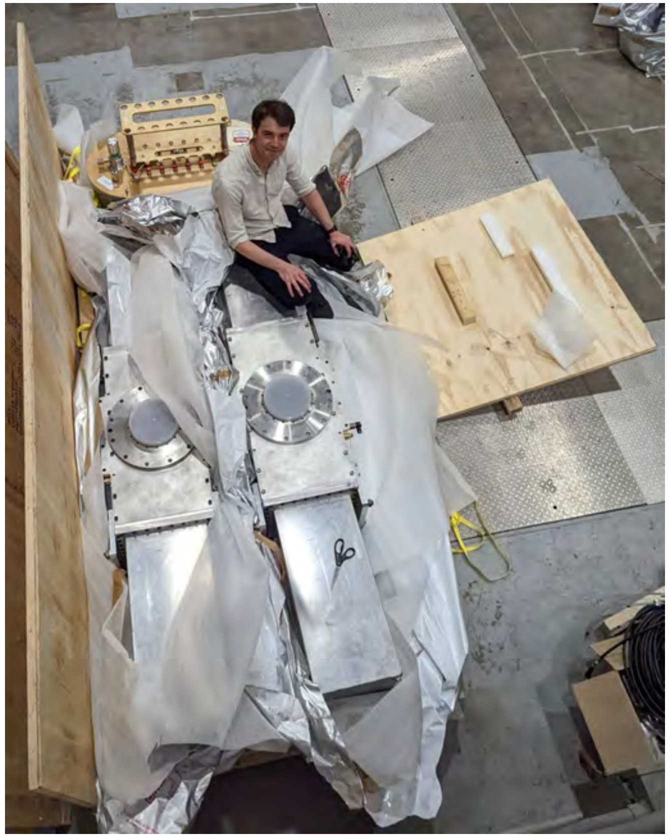


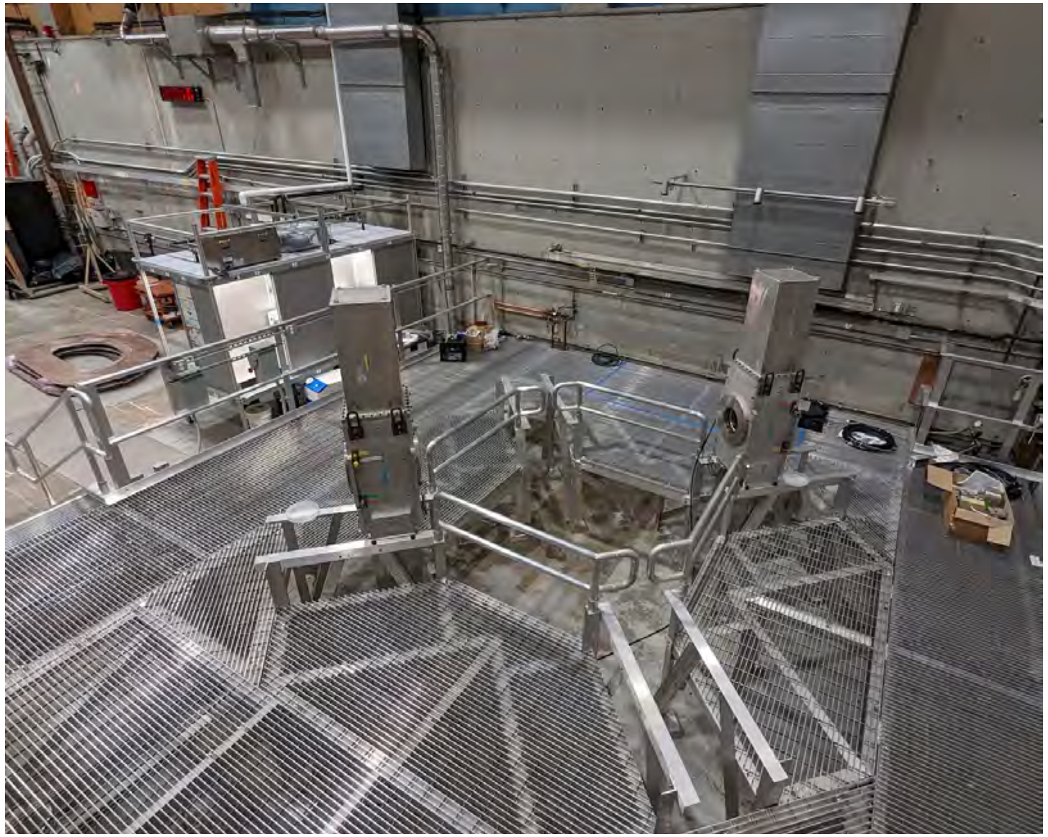


40 kJ energy to load

puffin.mit.edu

Construction underway, aiming for first plasma in 2023


LTD5 modules arrived
May 2022

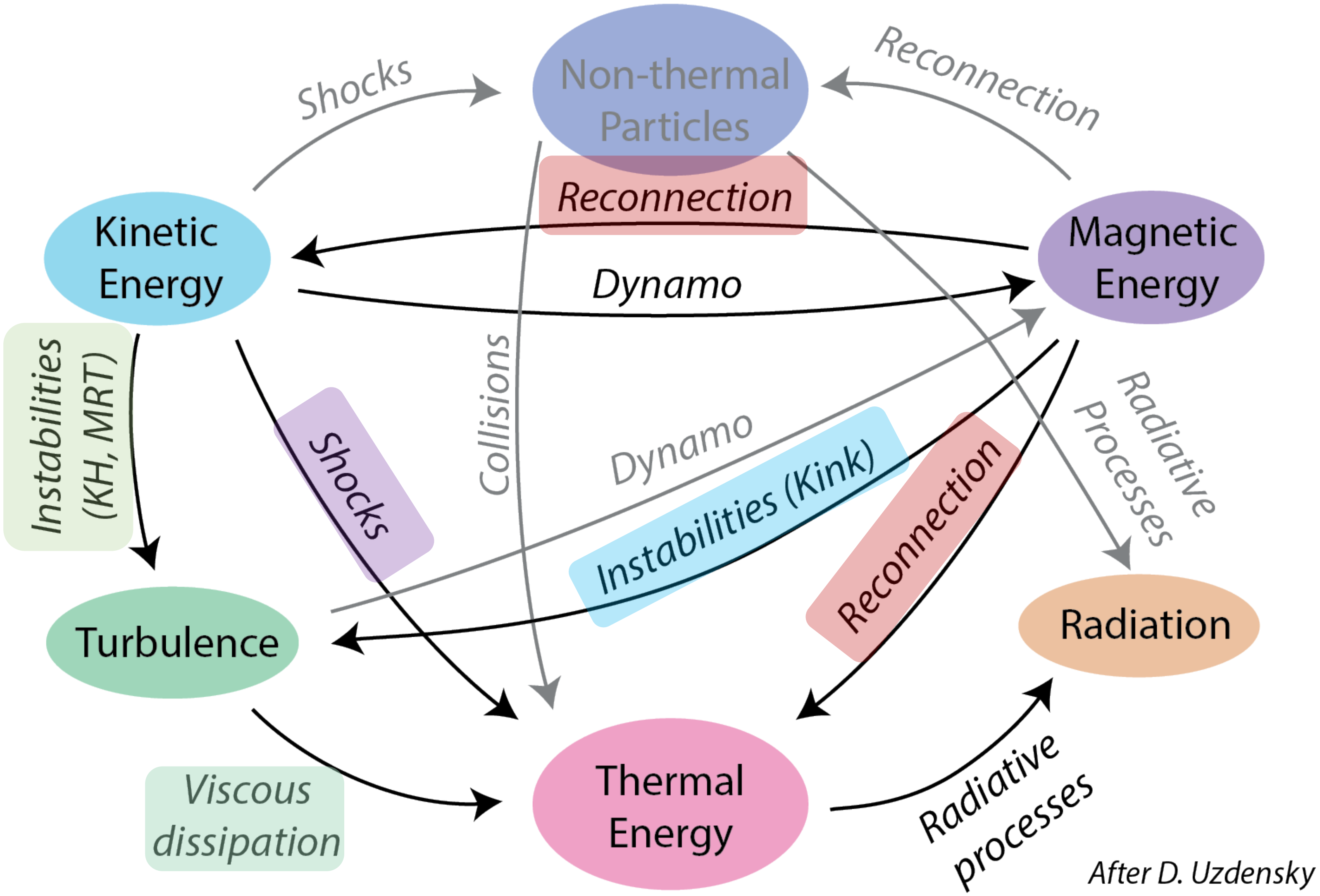

Mezzanine construction finished
September 2022


Laser barrier finished
March 2023

Research directions for PUFFIN

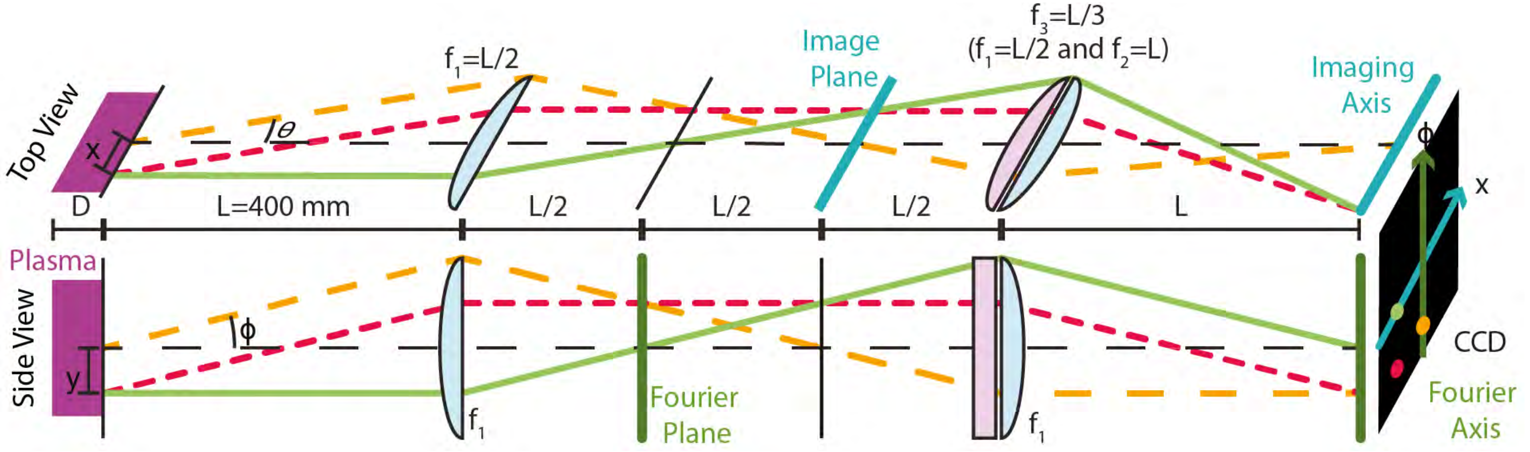
1. Reconnection
2. Shocks
3. Jets
4. Instabilities
5. Turbulence

…and diagnostic development for all of the above!



Diagnostics on PUFFIN

- EKSPLA diagnostic laser, 100 mJ, 2 ns pulses simultaneously in 1064 nm, 532 nm and 355 nm
  - Shadowgraphy and schlieren imaging
  - Interferometry (side on and axial)
  - Faraday rotation imaging
  - Imaging refractometer: Hare, Burdiak, Lebedev et al, RSI 2020

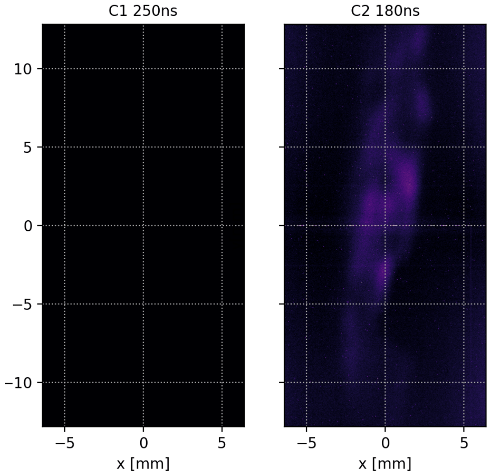


- Upgrades planned for:
  - Optical Thomson scattering: multi-fiber for high spatial or angular resolution
  - Ultra-high speed self emission imaging

Summary

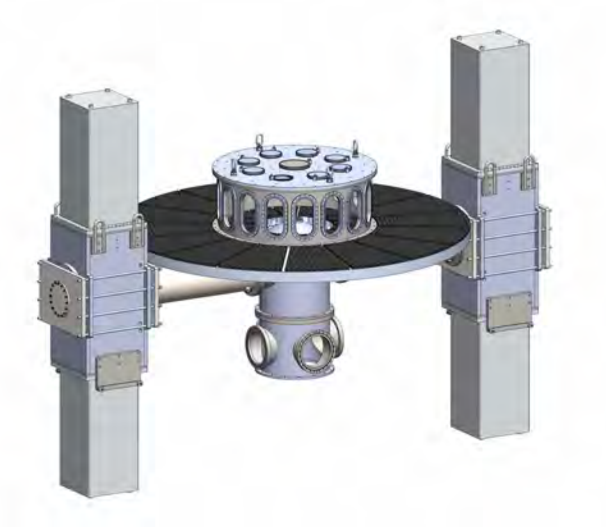
Magnetic reconnection

MARZ: Radiatively cooled reconnection on Z

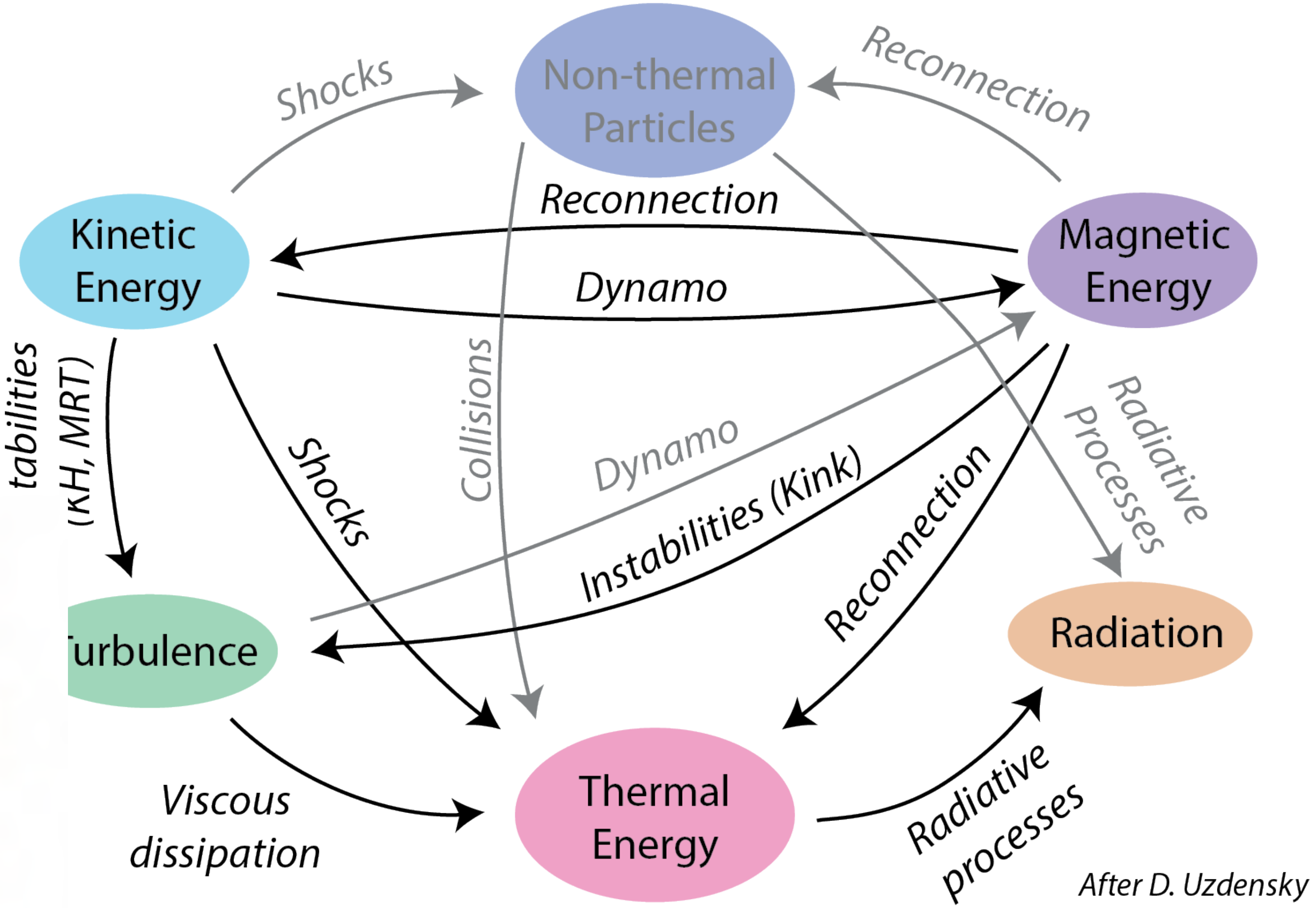


Guide field reconnection on MAIZE

PUFFIN: long pulse 1.5 μs, 1 MA @ MIT



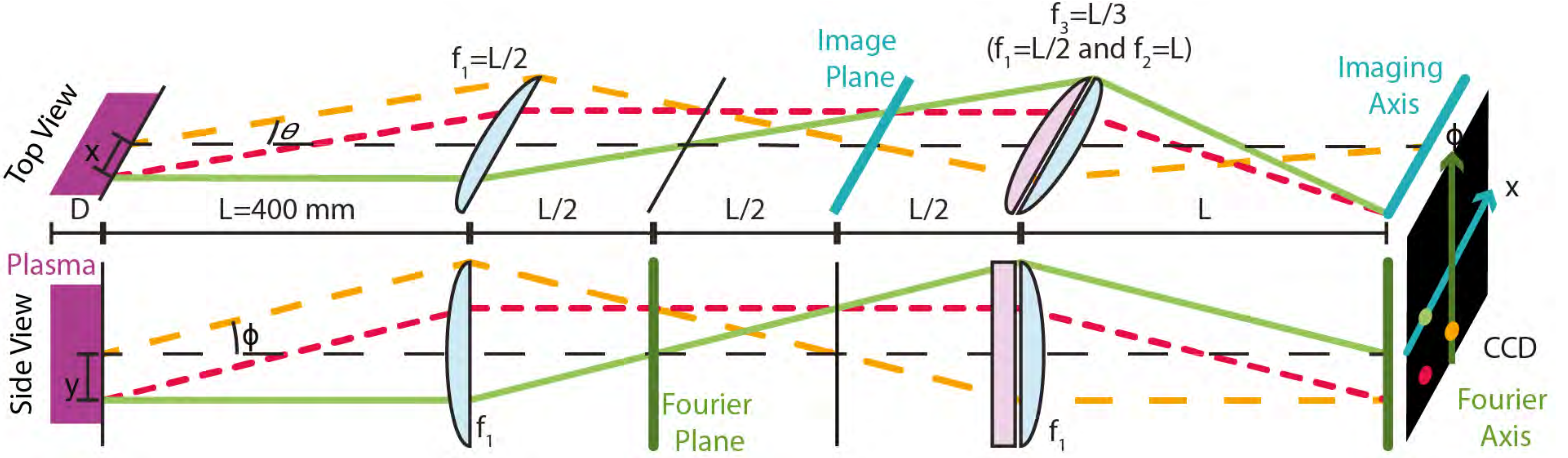
Unifying theme: energy flows in plasmas



Bonus slides

Advanced Refractometry Diagnostics

With Guy Burdiak and Sergey Lebedev

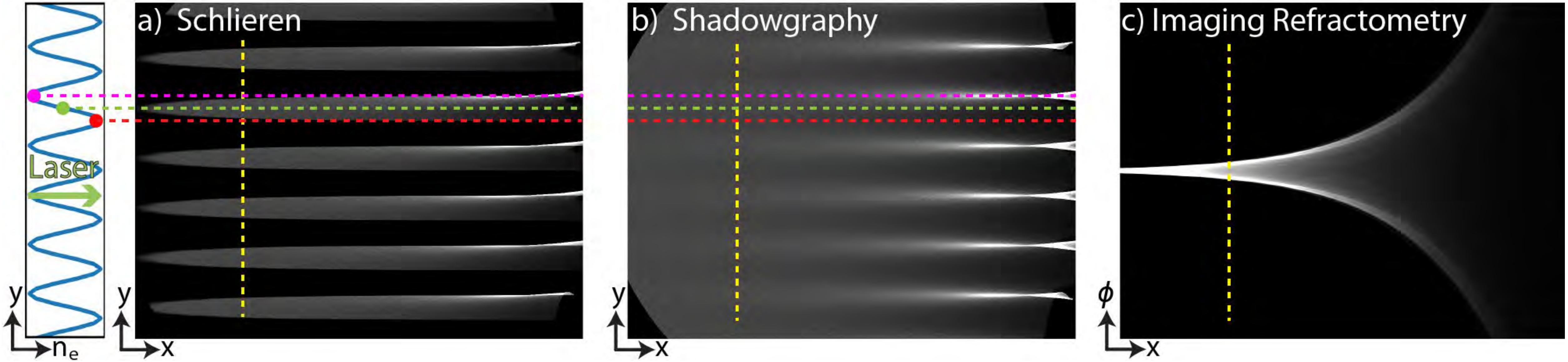


Cylindrical lens forms

- Image along one axes: spatial resolution
- Analog Fourier transform along the other: angular resolution

Synthetic Diagnostics using 3D ray tracer

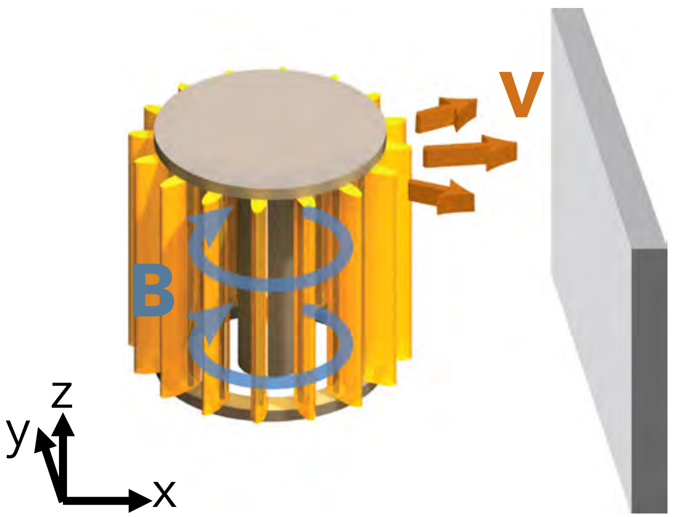
With Aidan Crilly

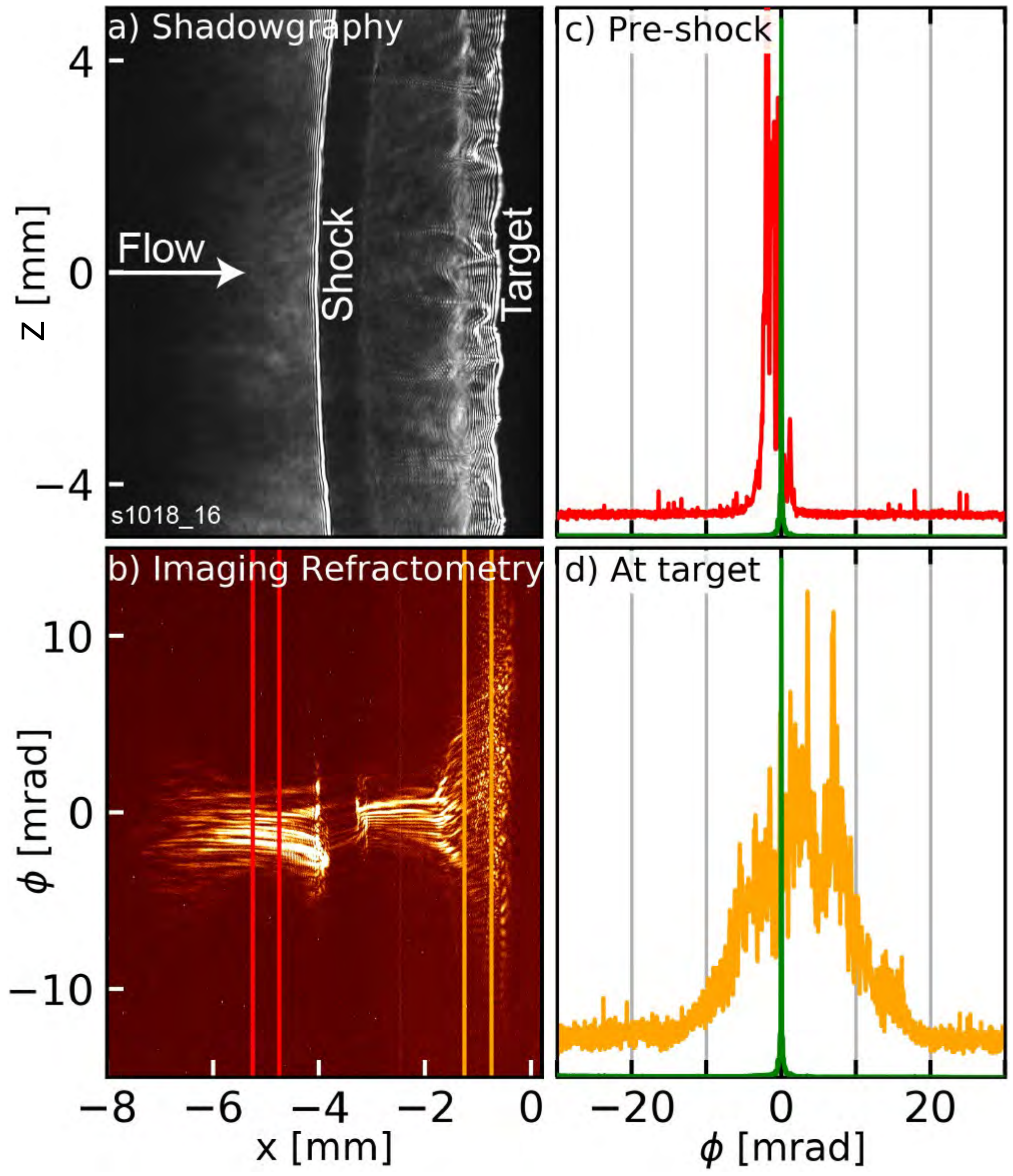


Synthetic ray tracing capability includes:

- Finite aperture of lenses: rays refracted out of system are lost
- Stops and knife edges for schlieren
- Inverse bremsstrahlung absorption model
- 3D array of electron density: analytical formulas for testing, GORGON for synthetic diagnostics

Imaging refractometry: sensitive to small density fluctuations



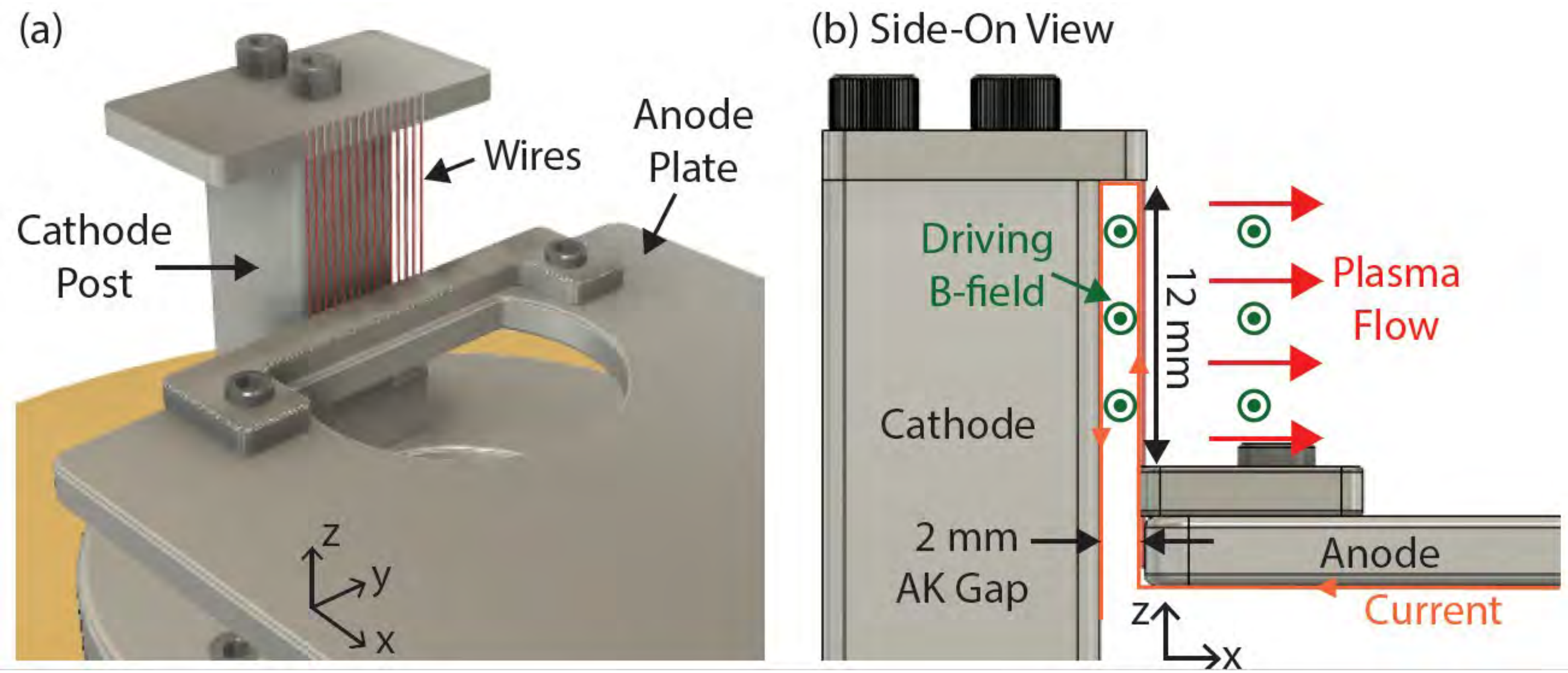


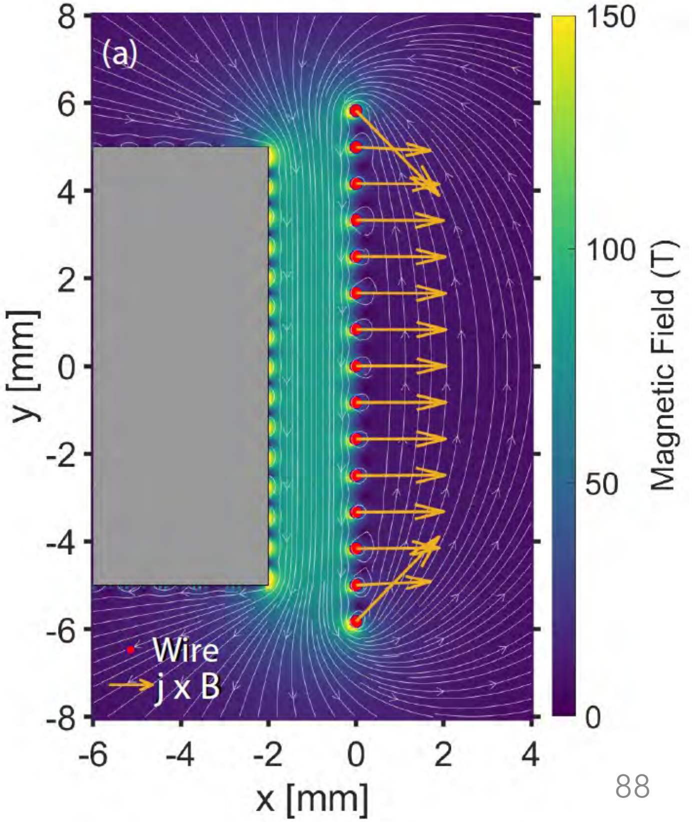
- Shadowgraphy:
  shock and stagnated plasma qualitatively
- Imaging refractometer:
  density fluctuations increase significantly in stagnated plasma

Diversion: Can we ablate such thick wires?

- Scaled planar wire arrays on COBRA matched Z conditions:
  - current per wire, 70 kA
  - magnetic field on wire, 100 T (2 mm AK gap!)
  - wire spacing, 0.8 mm

Lead: Rishabh Datta





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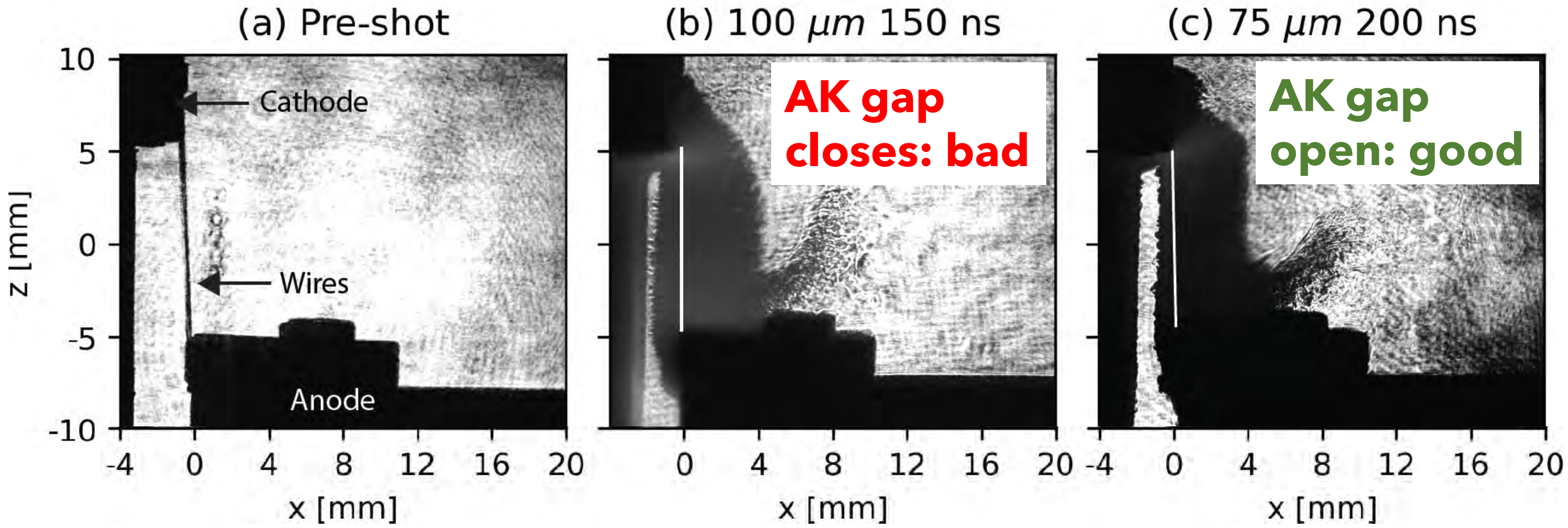
- Found **good ablation** for $\leq 75\ \mu m$ wires



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- Found **good ablation** for $\leq 75\ \mu m$ wires
- And lots of other interesting stuff: instabilities, properties of exploding planar wire arrays: paper coming soon!