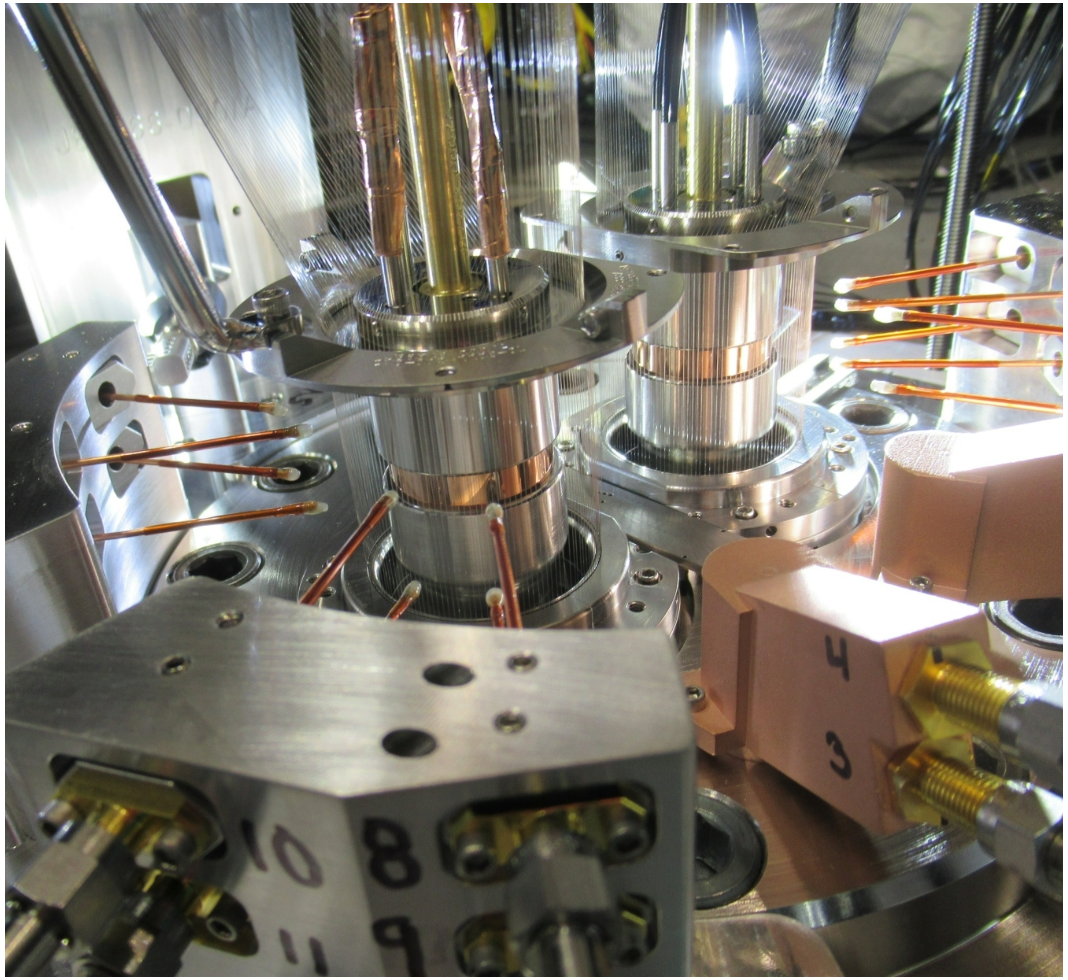
SAND2022-10317C

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

Jack Hare, jdhare@mit.edu



PUFFIN

MIT | PSFC Plasma Science and Fusion Center

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

Acknowledgements

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

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Talk outline

- What is magnetic reconnection?
- What is radiatively cooled magnetic reconnection?
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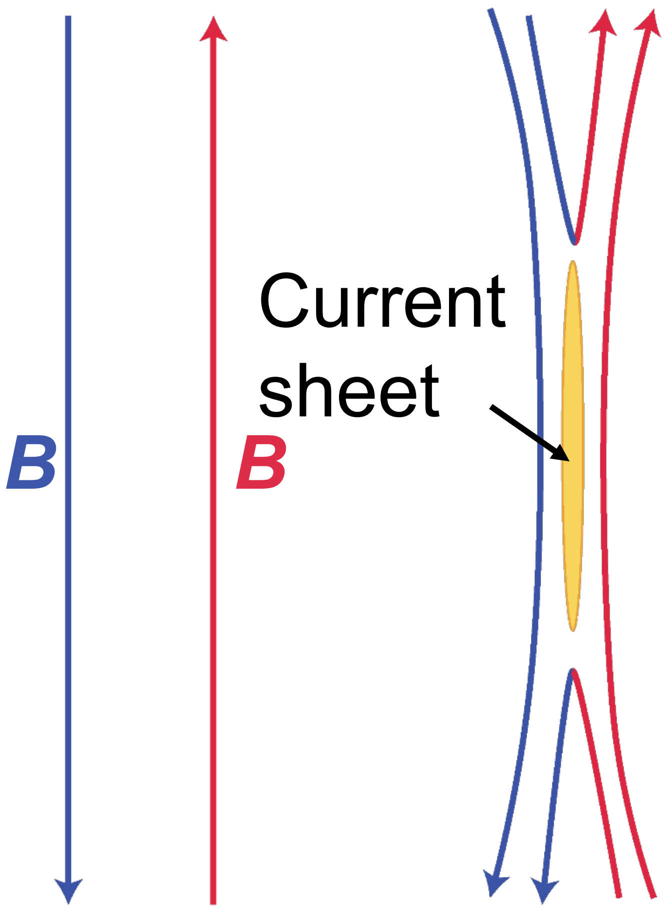
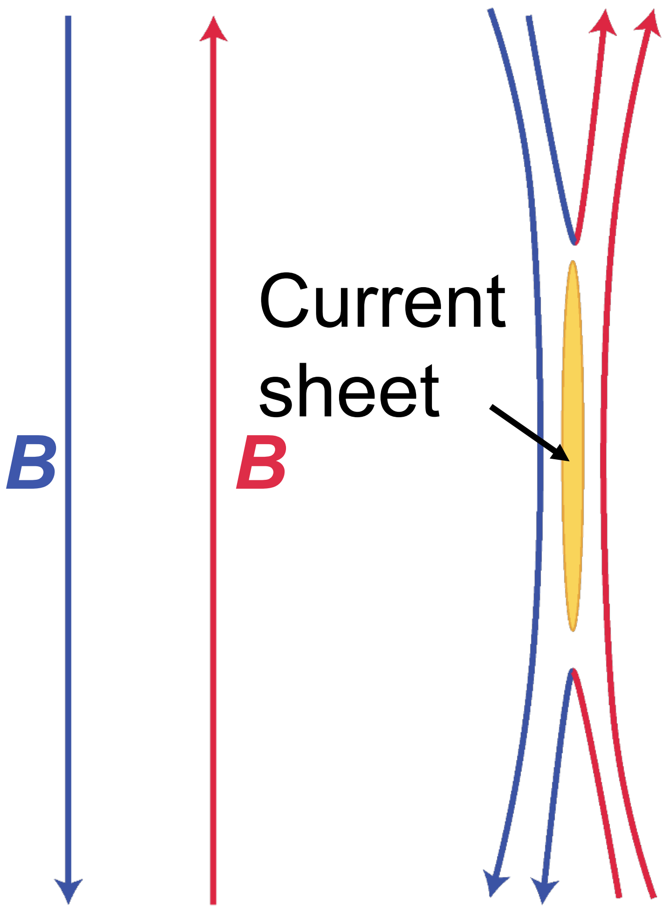
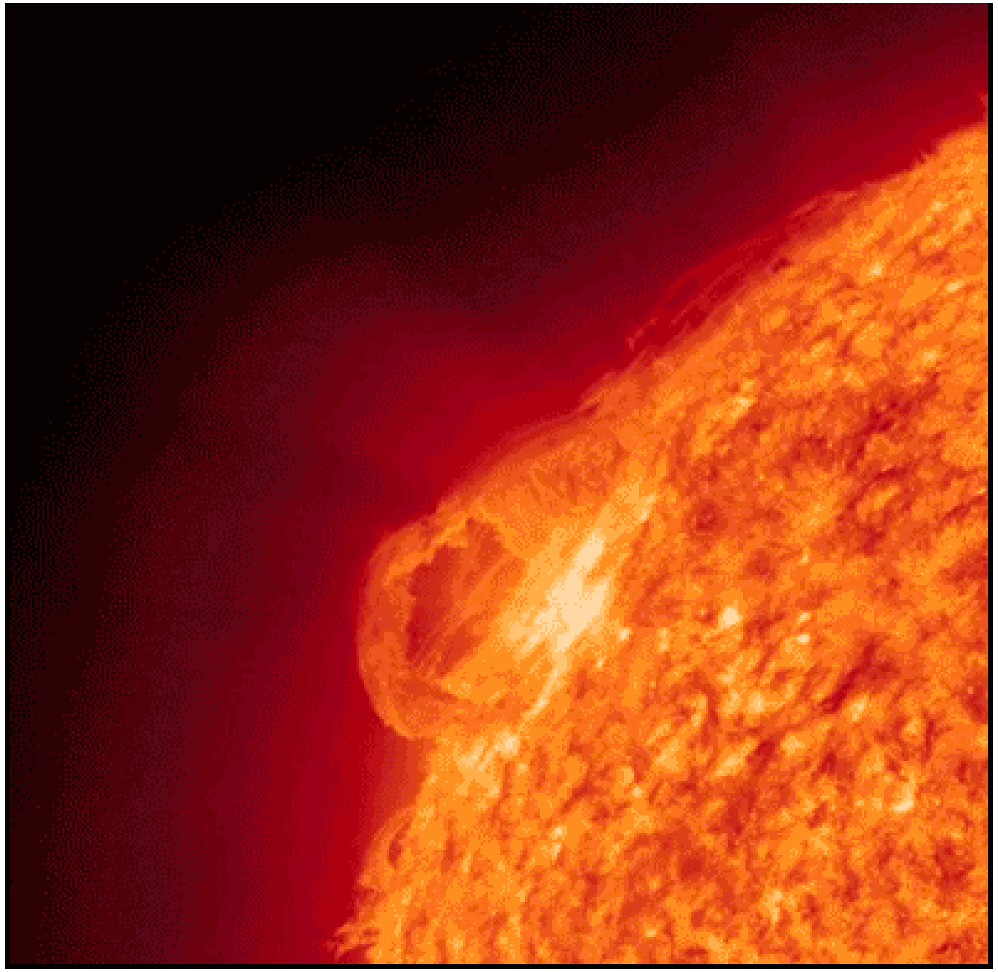
Magnetic Reconnection



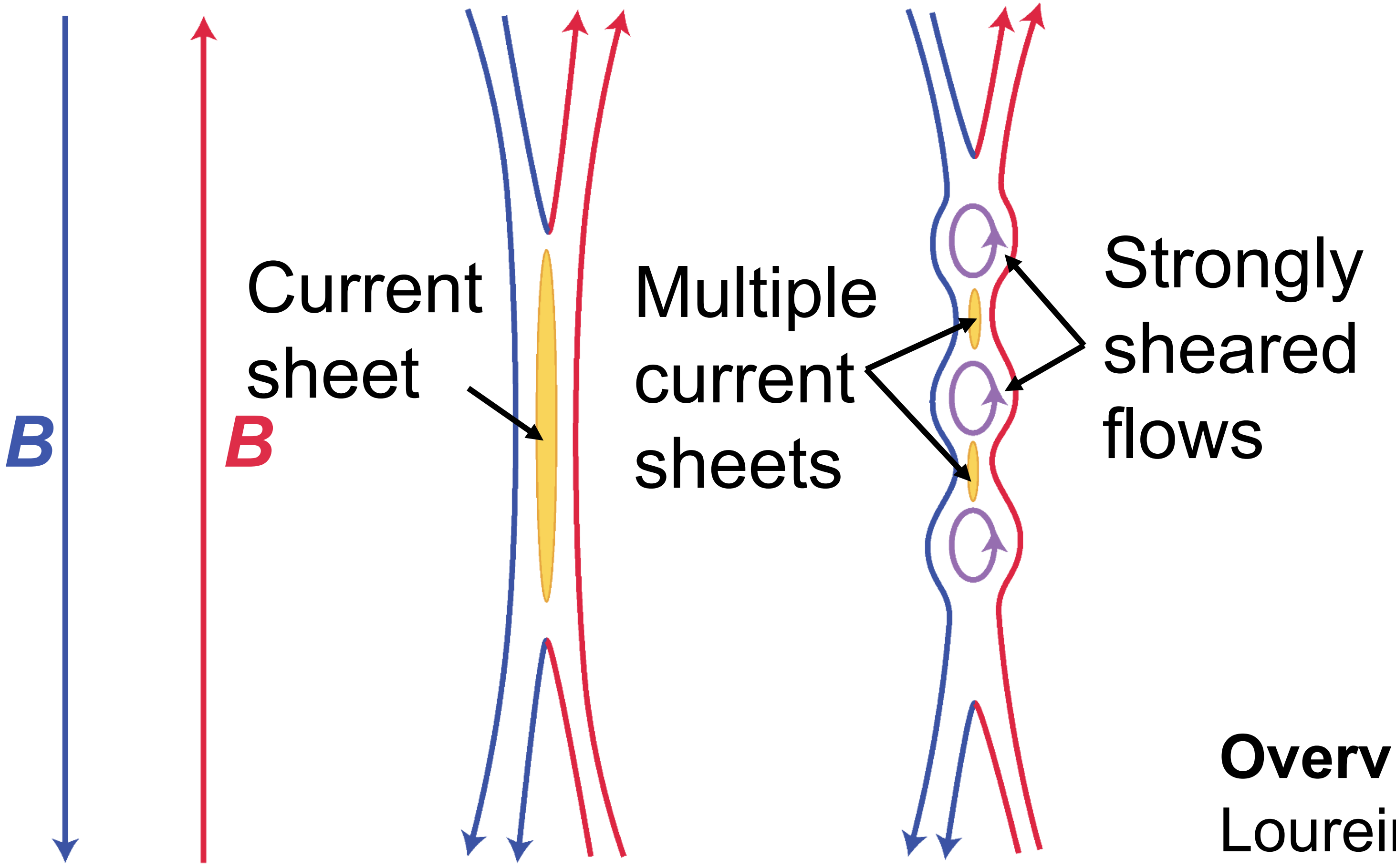
Magnetic Reconnection



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

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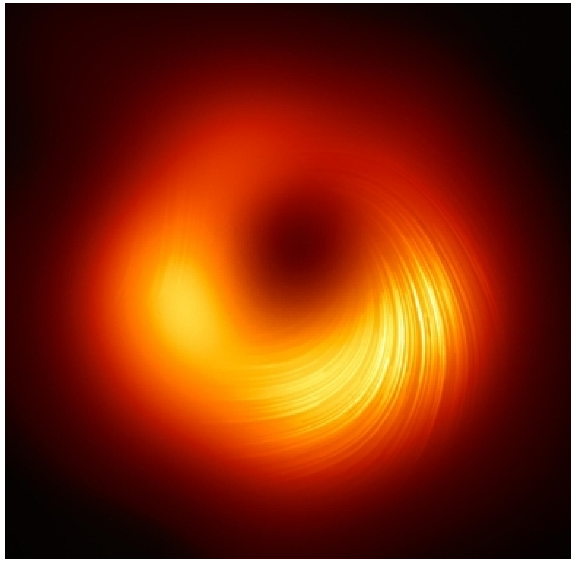
Reconnection in Extreme Astrophysical Environments

Artist's impression of a black hole

M87 (EHT)



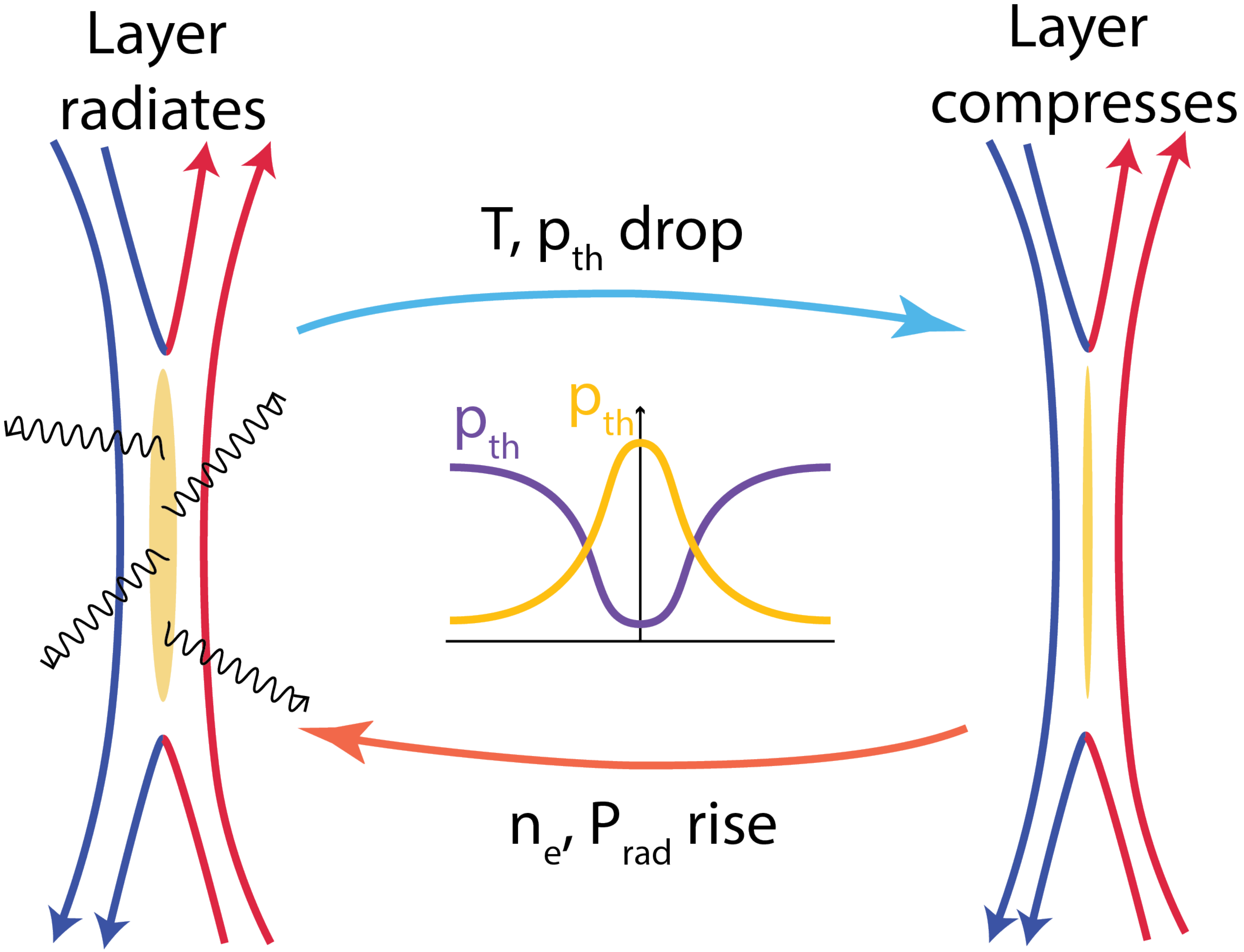
Crab Pulsar (Hubble/Chandra)

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

Radiative Cooling Instabilities in Reconnection



- Layer ohmically heated
- Radiation/compression loop: runaway process

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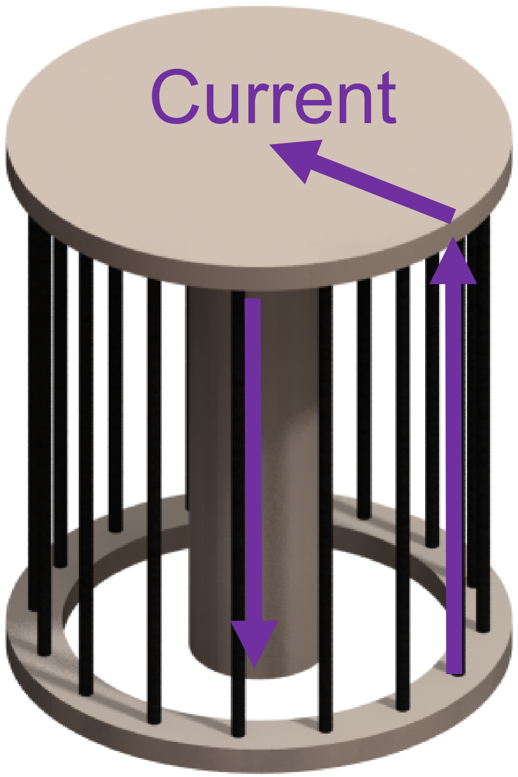
Studying Radiatively Cooled Reconnection in the Lab

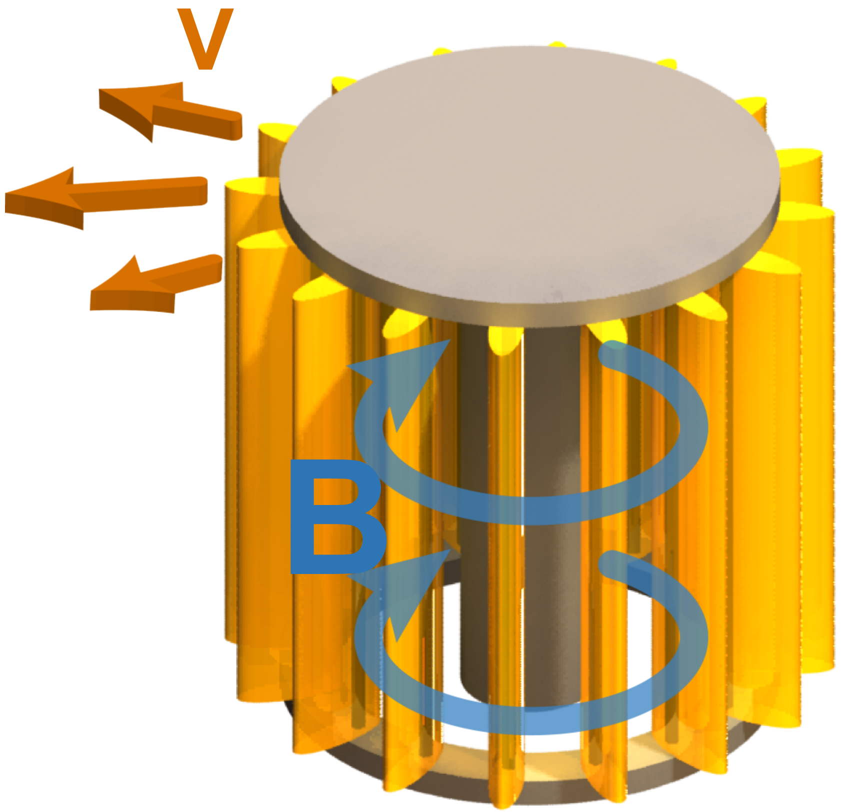
- Experiments require:
  - High n_e for high P_{rad}
  - Plenty of $B^2/2\mu_0$ to dissipate
  - Sufficient t_{drive} to see dynamics
- Cooling from Brems + Lines
  - Cooling rate material dependent

→

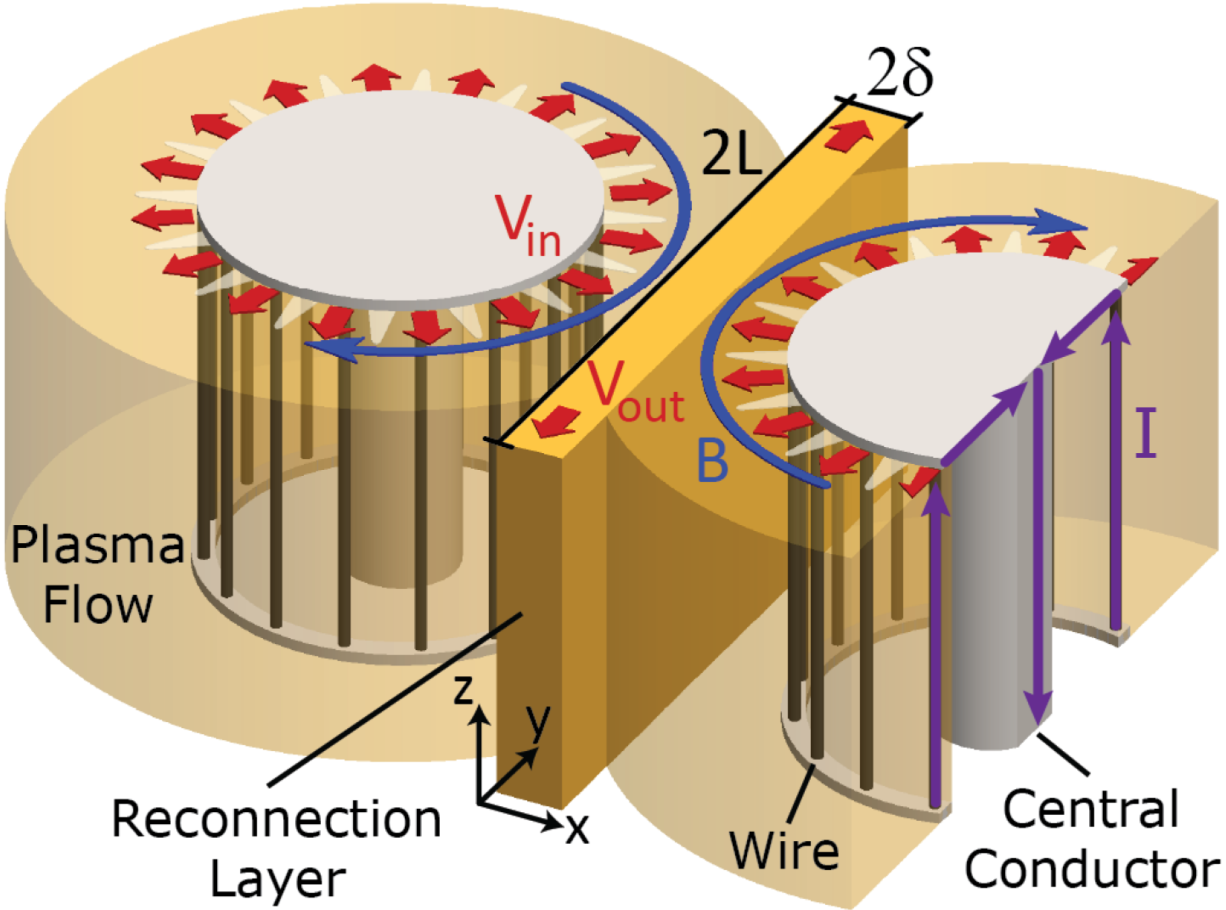
High-energy-density experiments:
Lasers and pulsed-power

Pulsed-power-driven Magnetic Reconnection





Magnetic Reconnection from Double Exploding Wire Arrays



Exploding wire arrays in parallel:

- Sustained flows ($\tau_{drive} \sim 10\ \tau_A$)
- Quasi-2D geometry
- Collisional ($\delta \gg \lambda_{mfp}$)
- Inflows: $p_{th} \sim p_B \sim p_{kin}$
- No guide field

MAGPIE: 1.4 MA, 250 ns rise time

Z Machine: 20 MA, 300 ns rise time

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

Z's unique capability: strongly radiatively cooled reconnection

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

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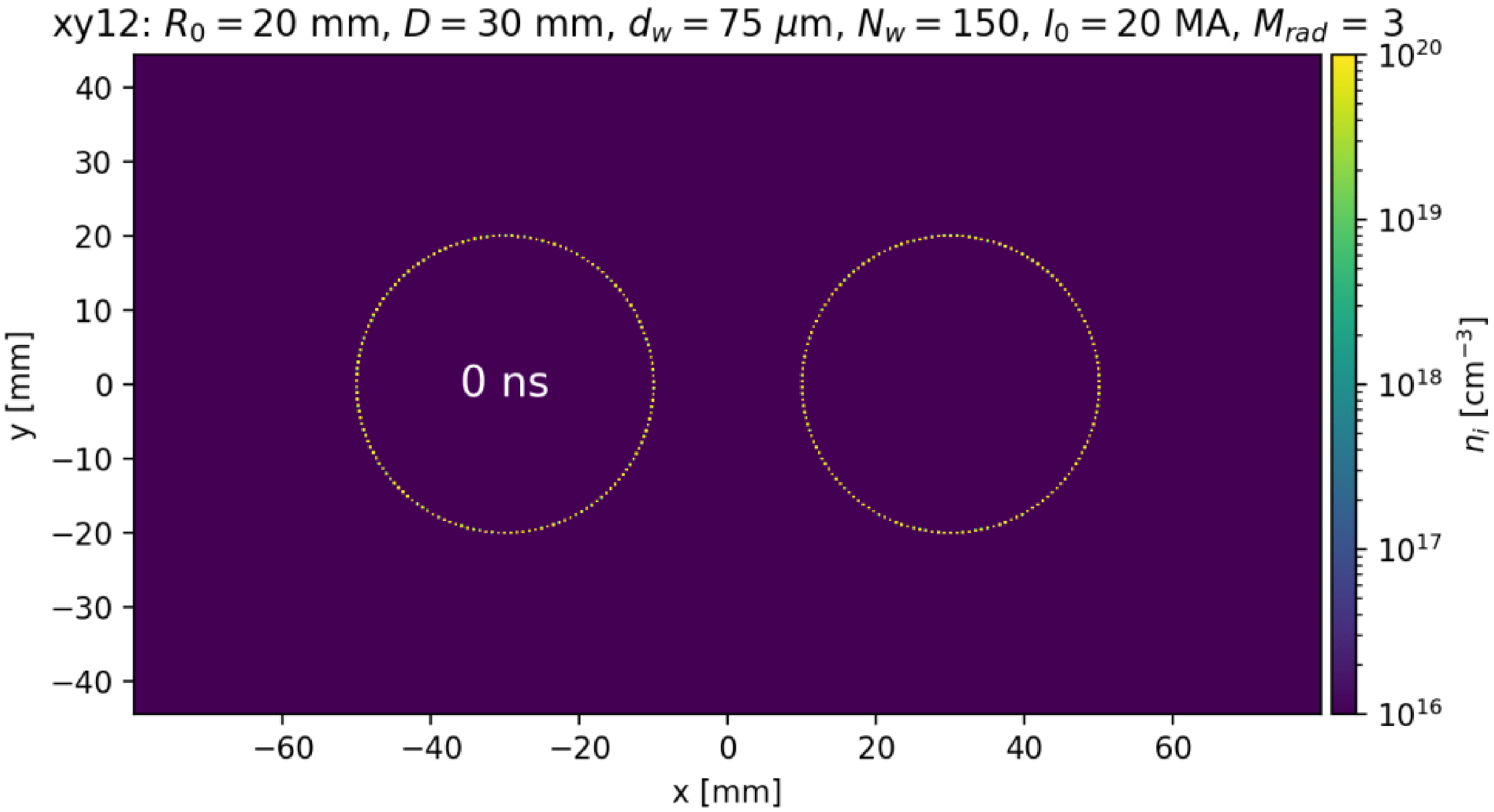
GORGON MHD simulations

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

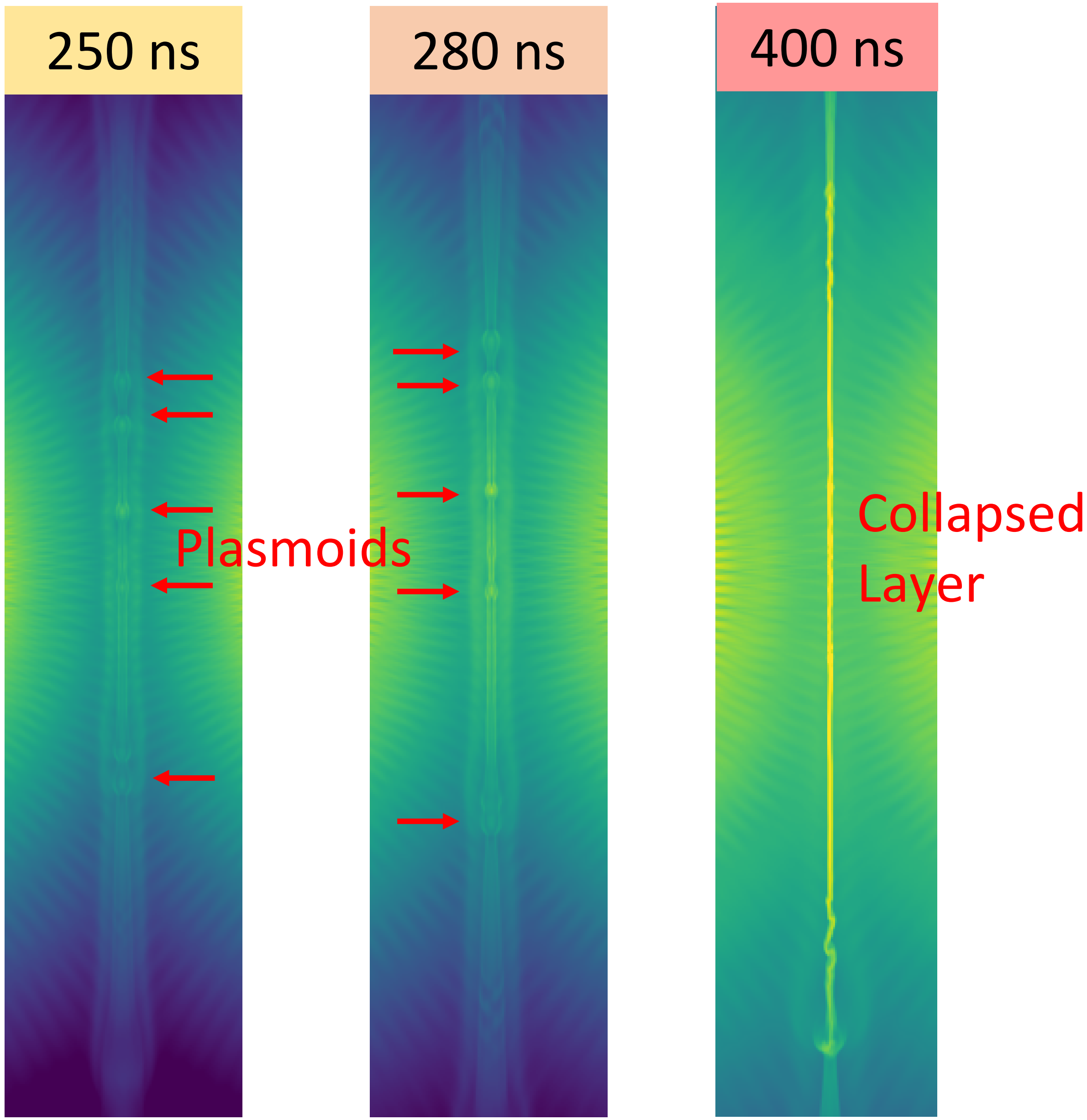
Wires:
- 150 Al wires
- 75 μm diameter

Arrays:
- 40 mm diameter
- 20 mm gap

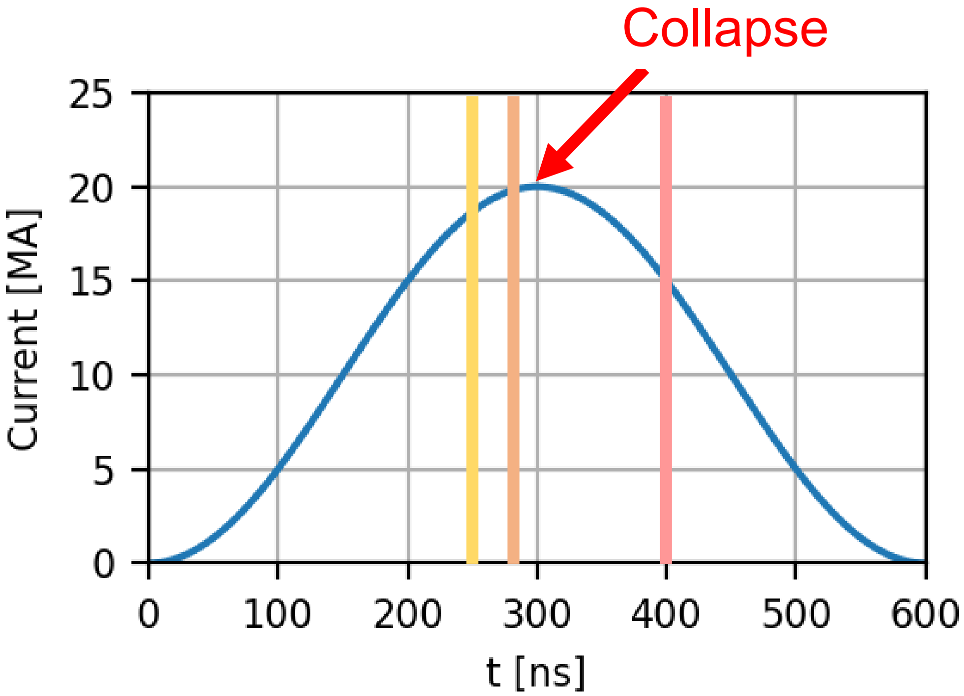


- 2D sims: 50 μm resolution, 180x90 mm. 16 hrs, 256 cores
- Recombination loss: $P_{rad} = M_{rad} C_r n_e T_e^{1/2} (Z^2 n_i E_\infty^{Z-1} / T_e)$, with $M_{rad} \approx 3$

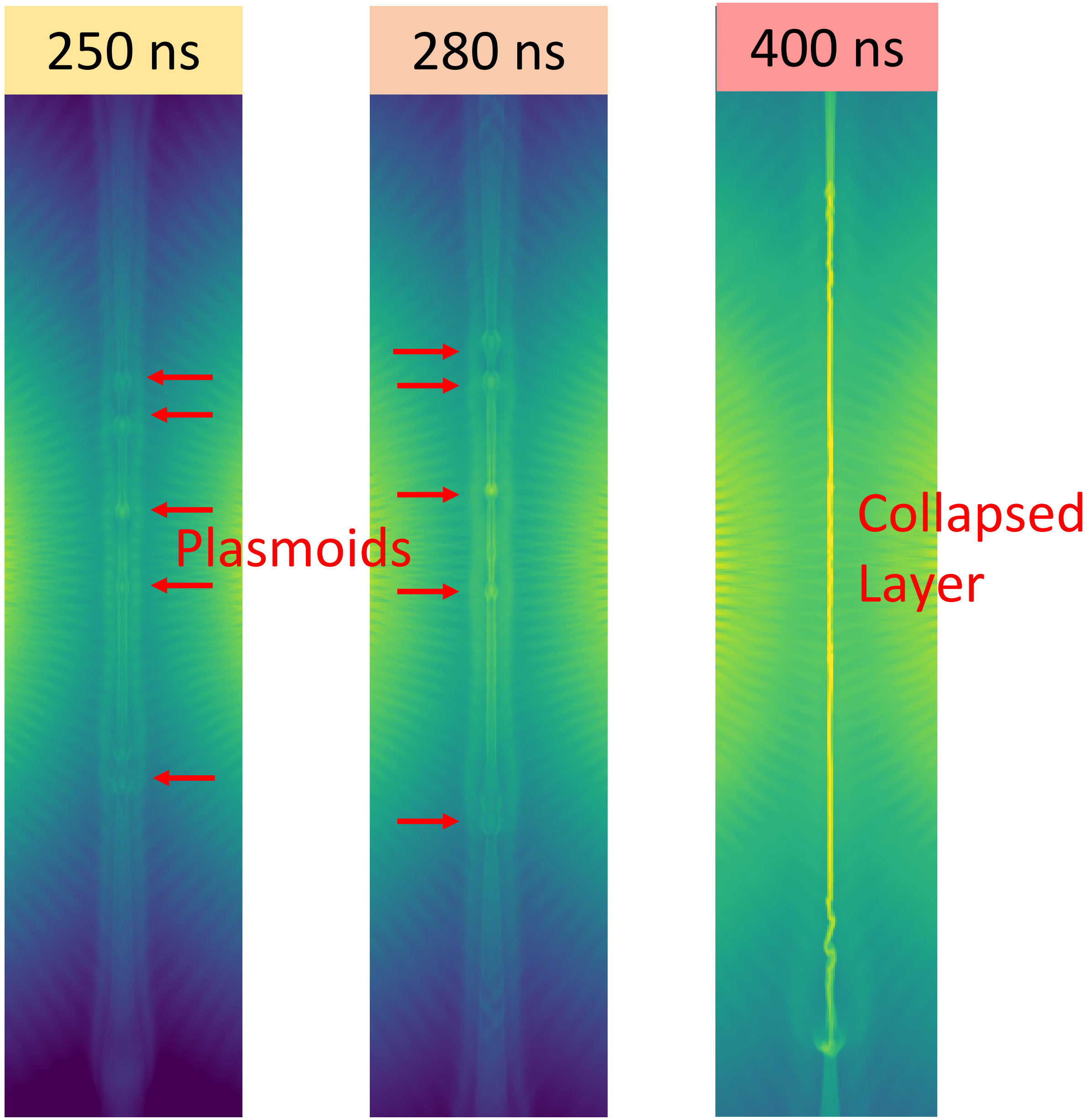
Plasmoids and Collapse



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



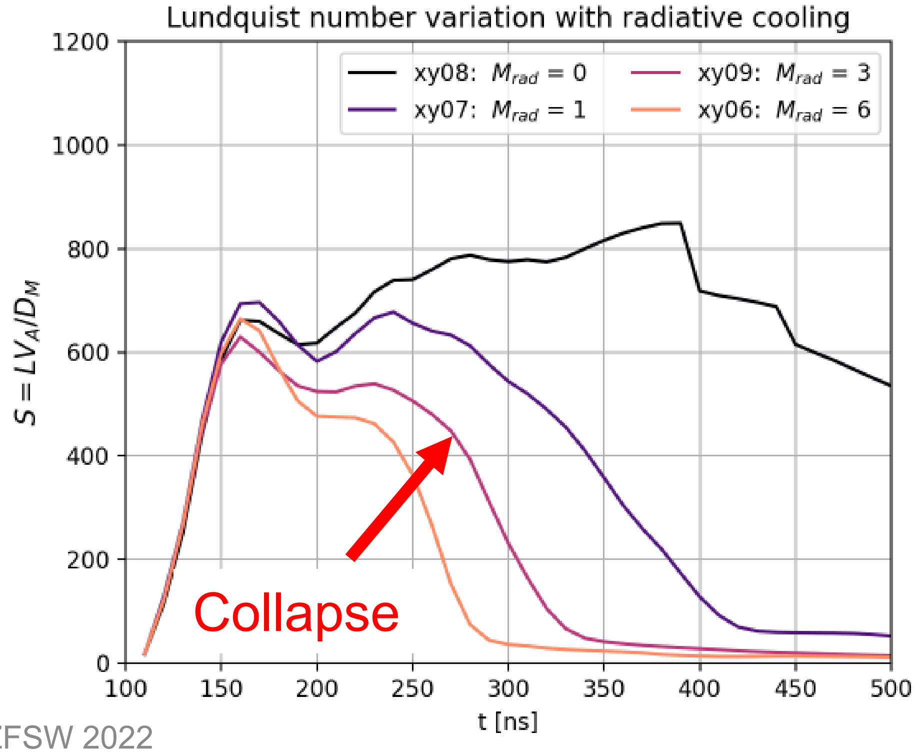
Plasmoids and Collapse



Lundquist number:

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

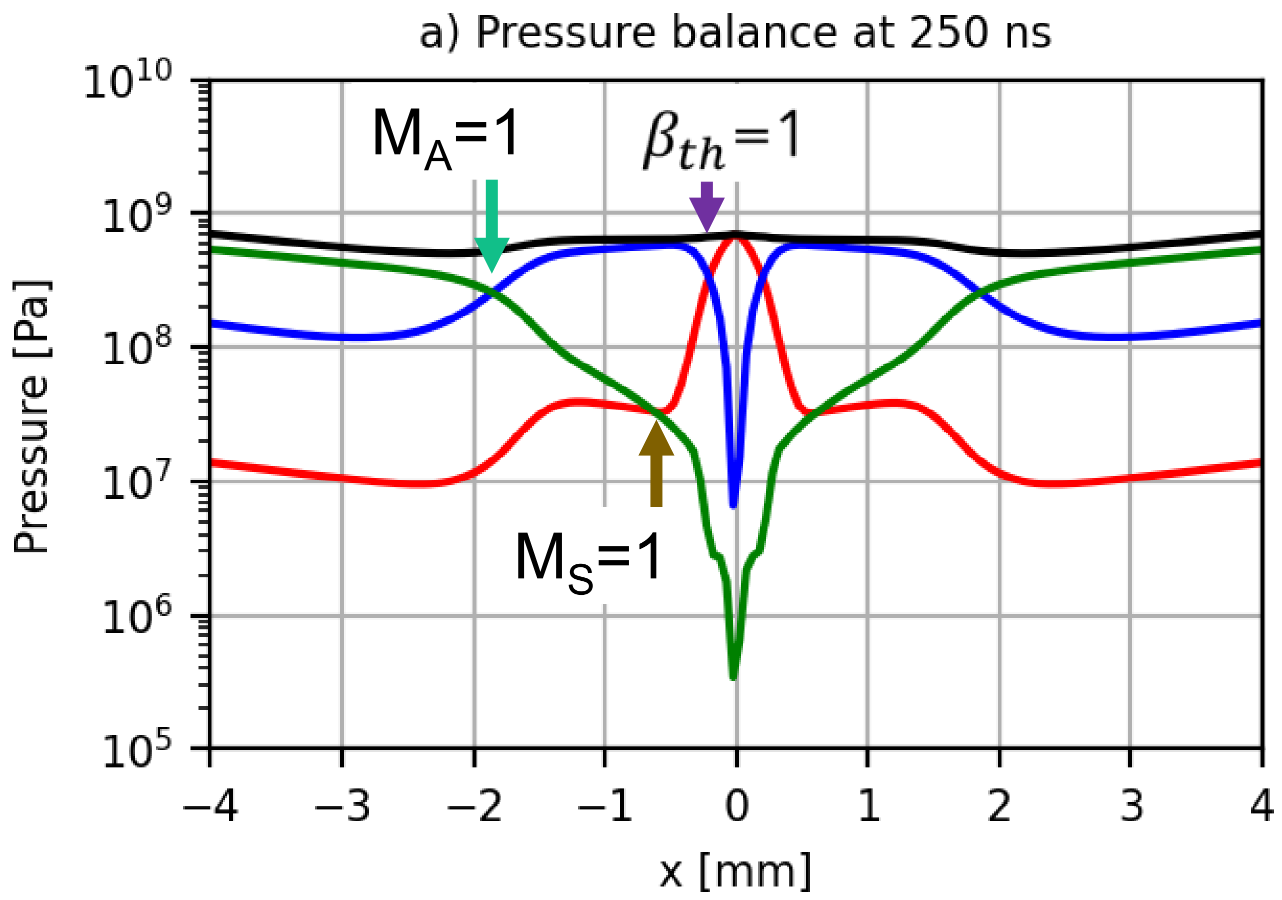
Reconnection rate ~ $1/\sqrt{S}$



Pressure balance in the layer

Pre-collapse: flux pile-up decelerates flow

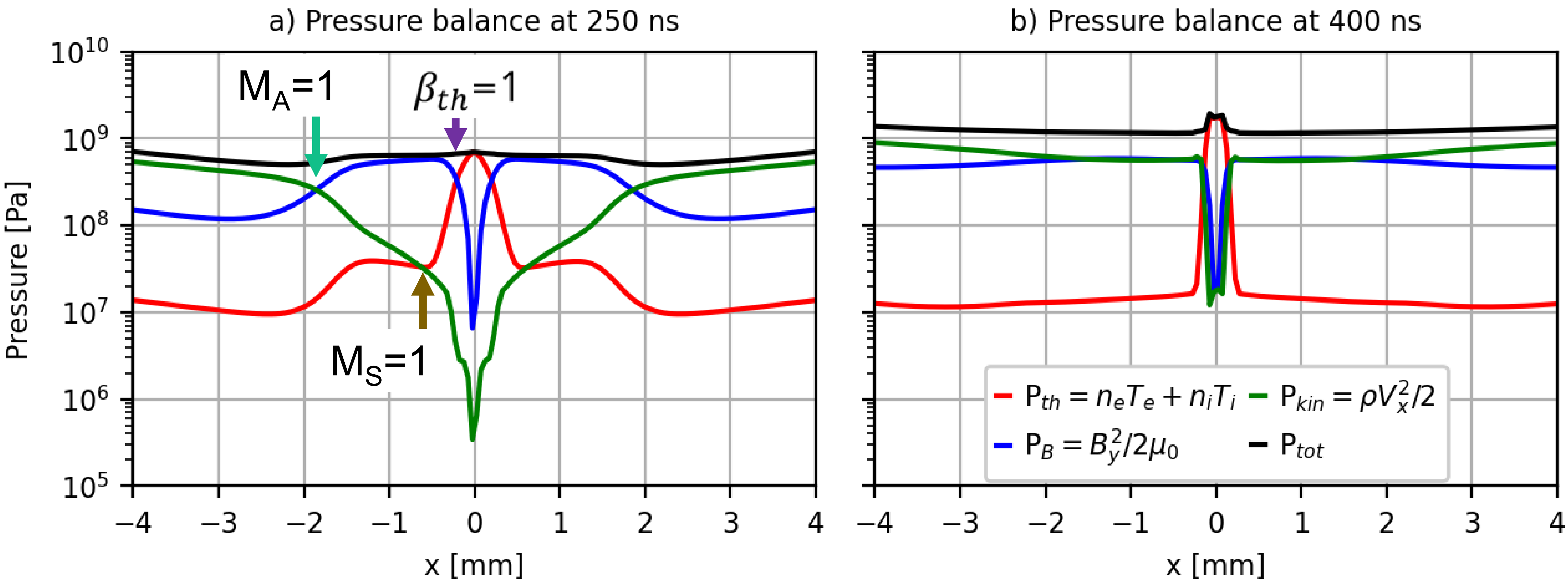
At layer, $P_B = P_{th}$



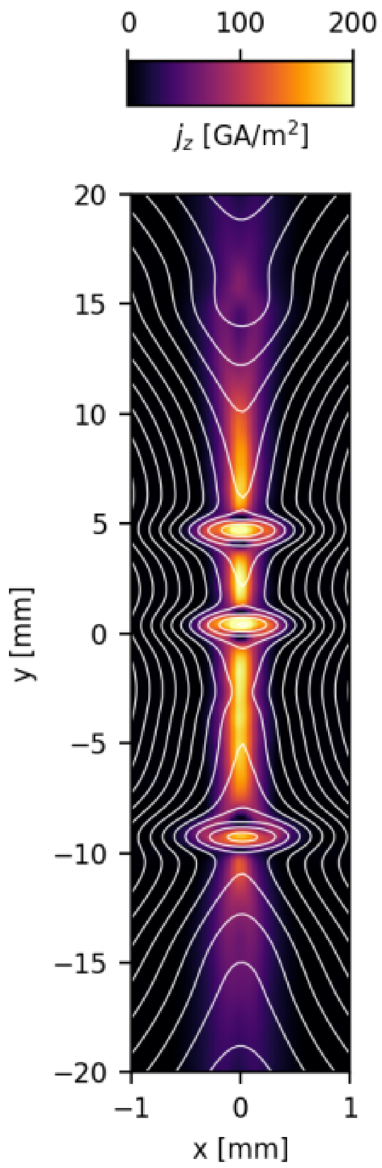
Pressure balance in the layer

Pre-collapse: flux pile-up decelerates flow
At layer, $P_B = P_{th}$

Post-collapse: fast reconnection removes flux pile-up



Plasmoids in the Reconnection Layer

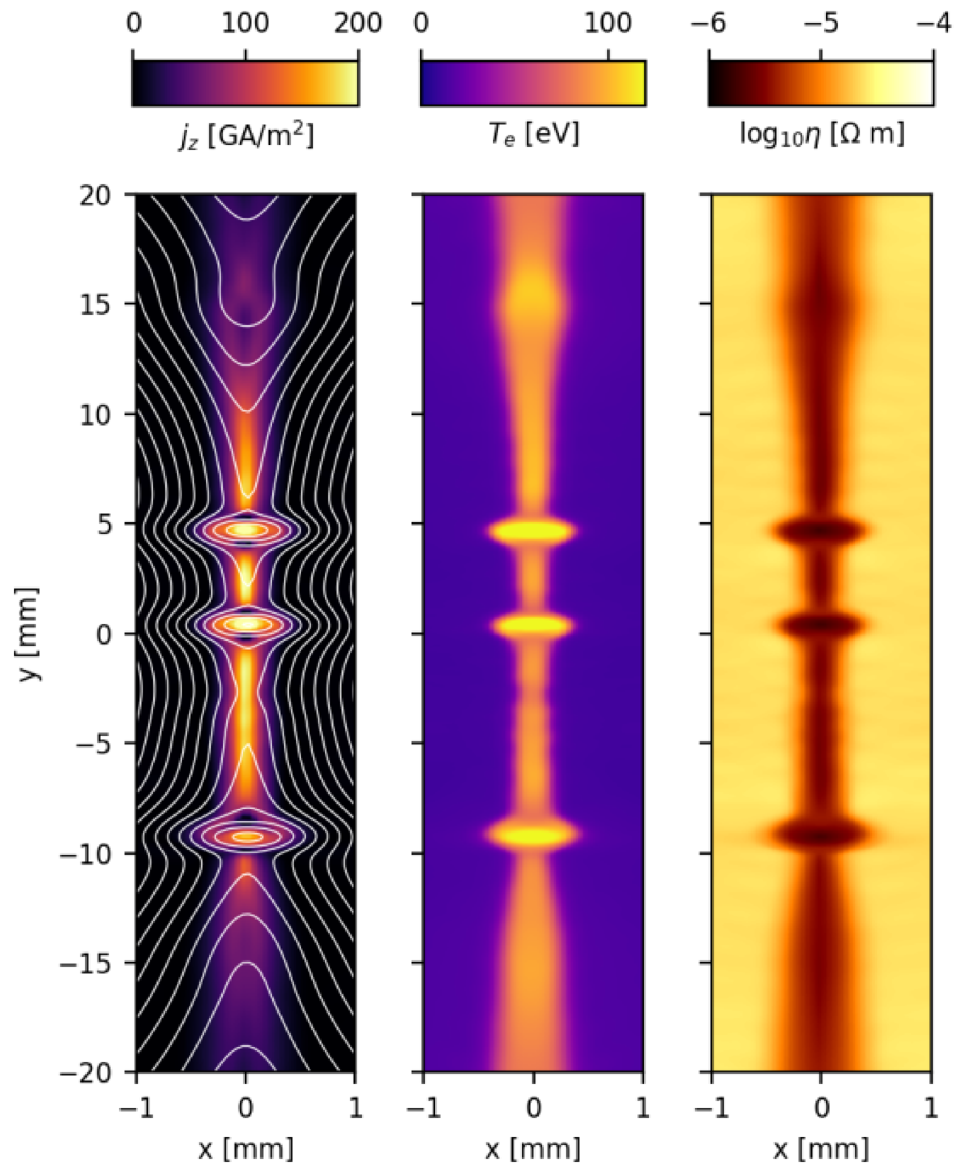


Plasmoids:

- Carry a lot of current

Note: Exaggerated aspect ratio

Plasmoids in the Reconnection Layer

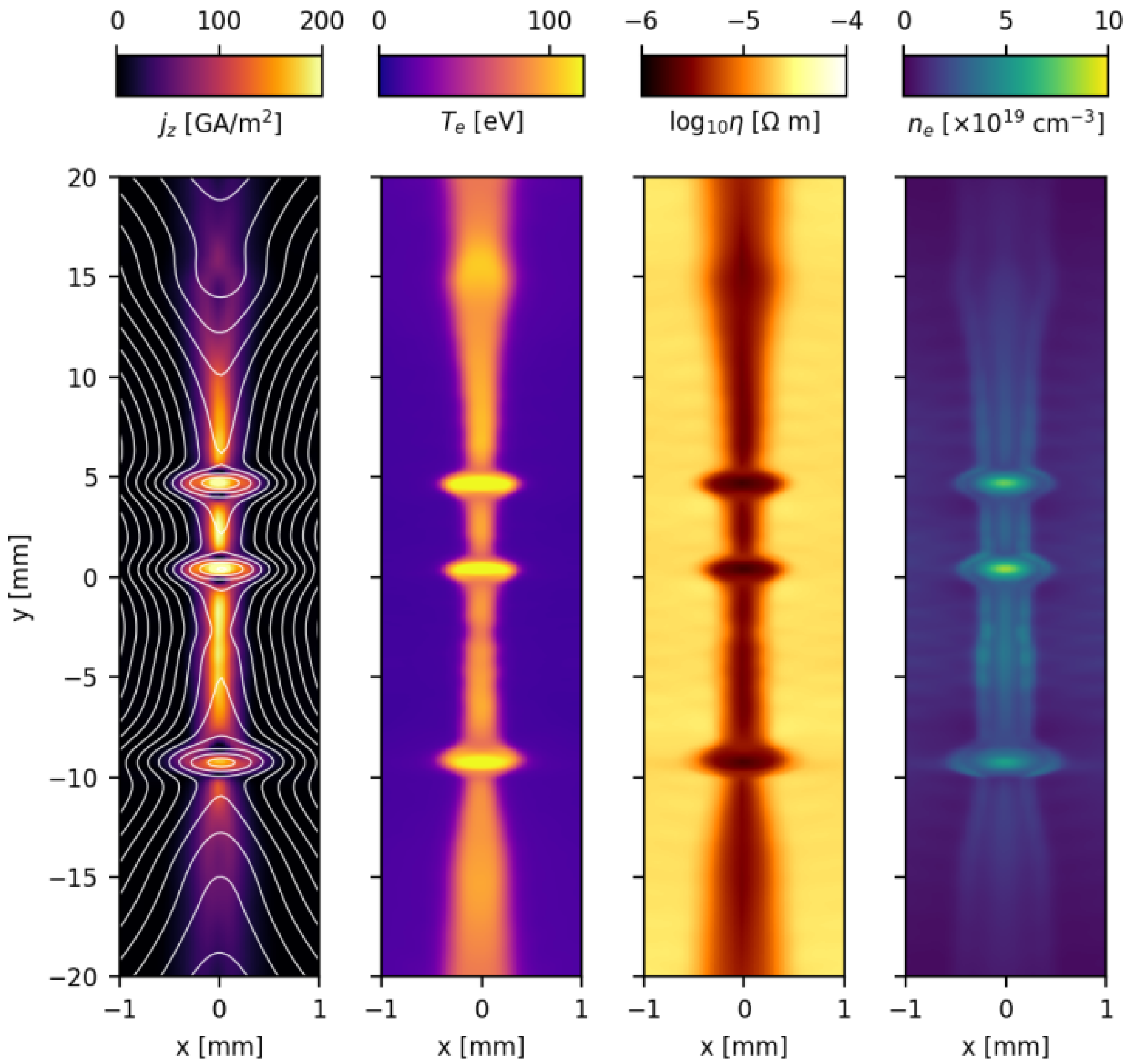


Note: Exaggerated aspect ratio

Plasmoids:

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

Plasmoids in the Reconnection Layer

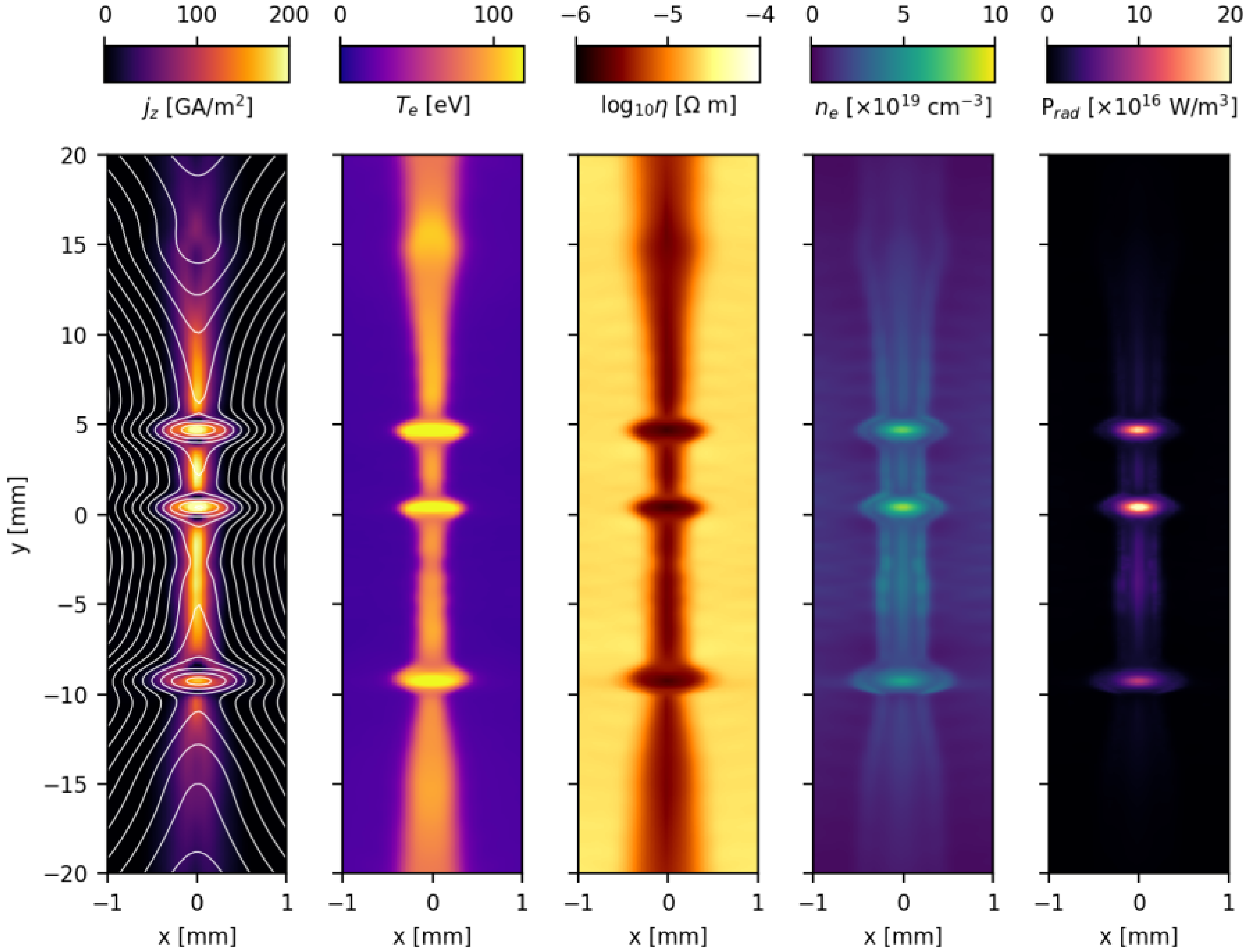


Note: Exaggerated aspect ratio

Plasmoids:

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

Plasmoids in the Reconnection Layer

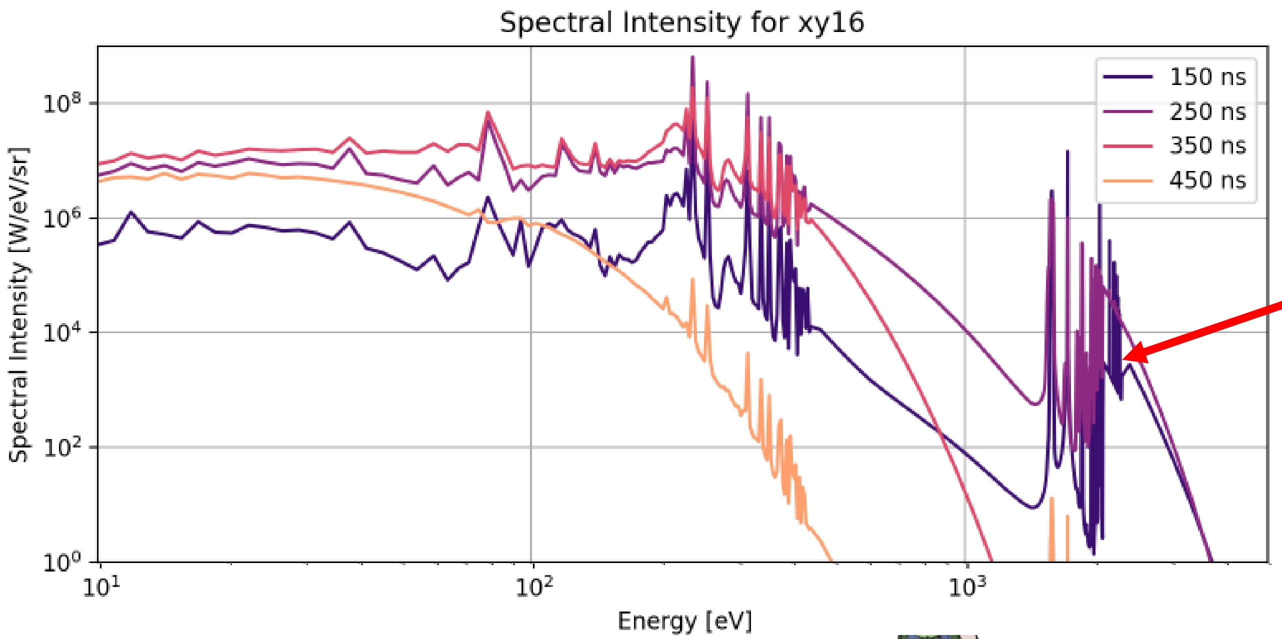


Note: Exaggerated aspect ratio

Plasmoids:

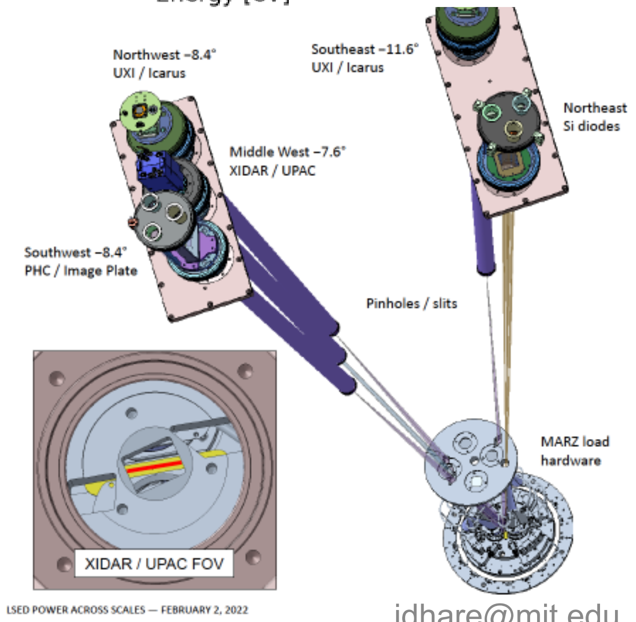
- Carry a lot of current
- Are hot, with low η
- Are dense
- Radiate strongly

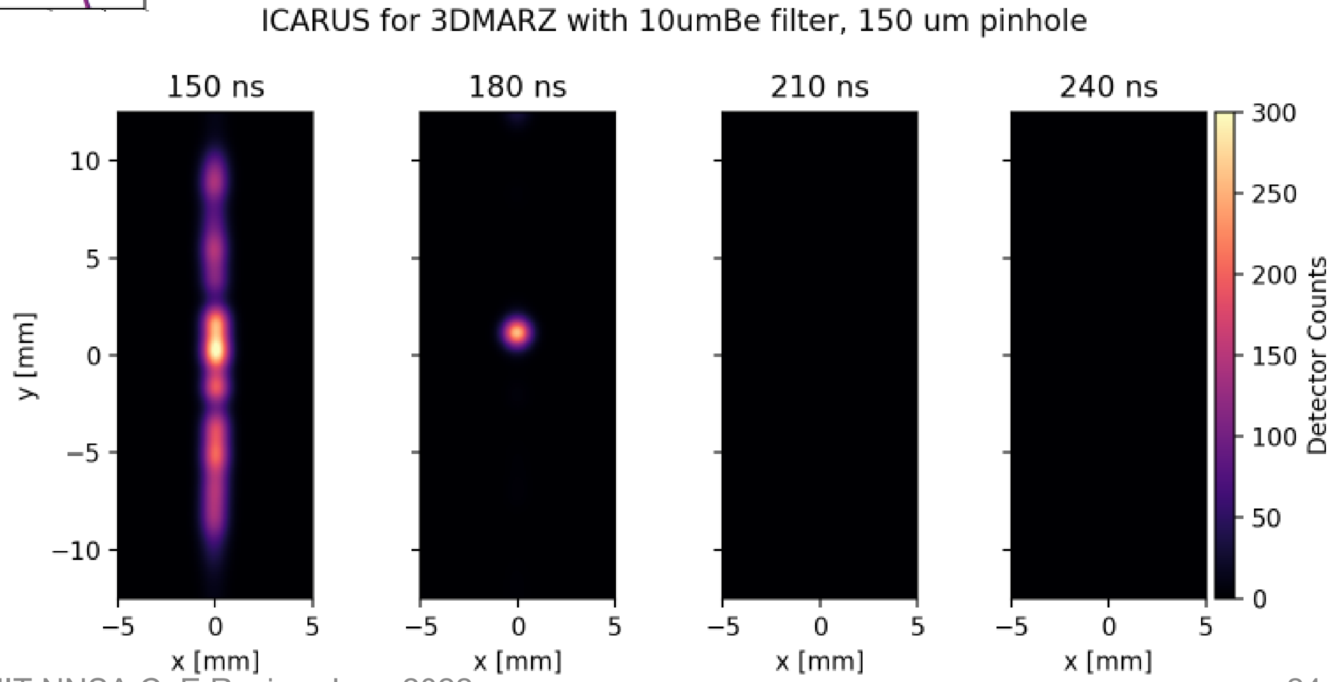
XP2: X-ray Post-Processor by Aidan Crilly & Jerry Chittenden



Al K-shell disappears after collapse

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

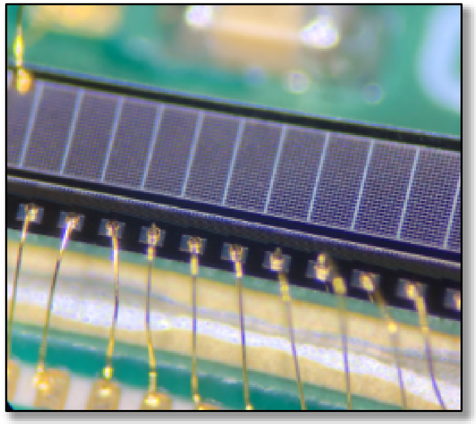


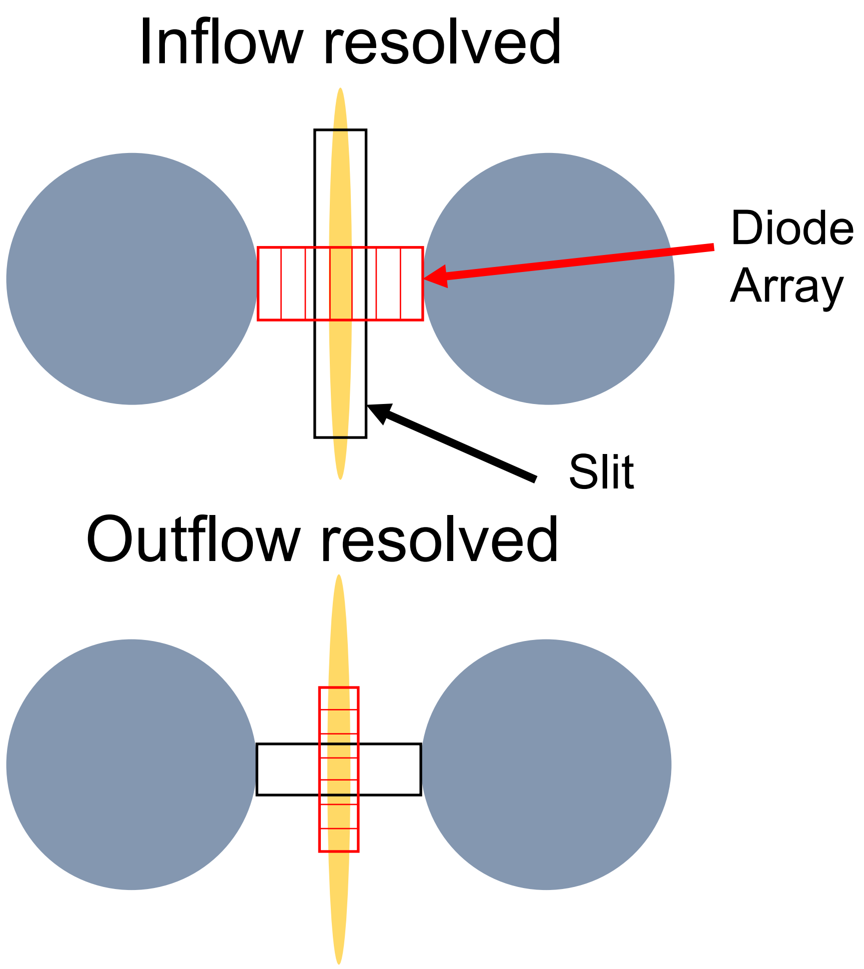


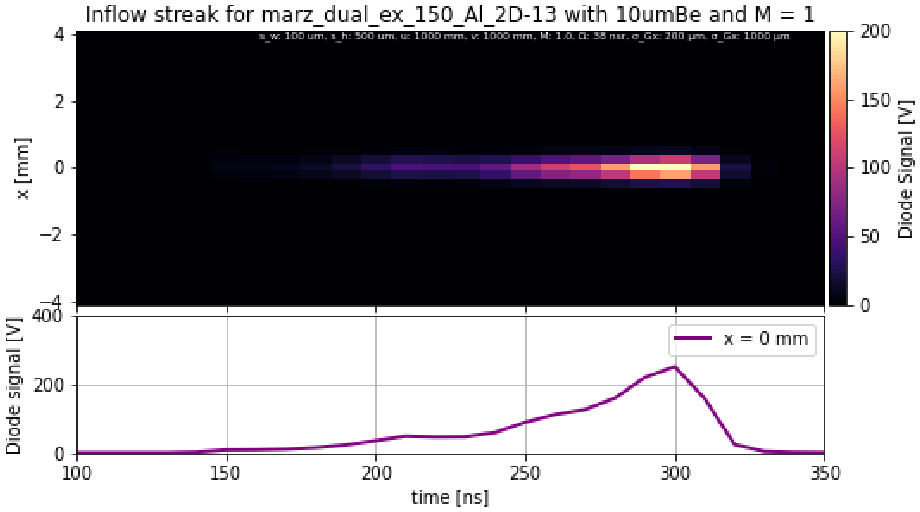
We used XP2 to help design XIDAR, a new diagnostic for Z

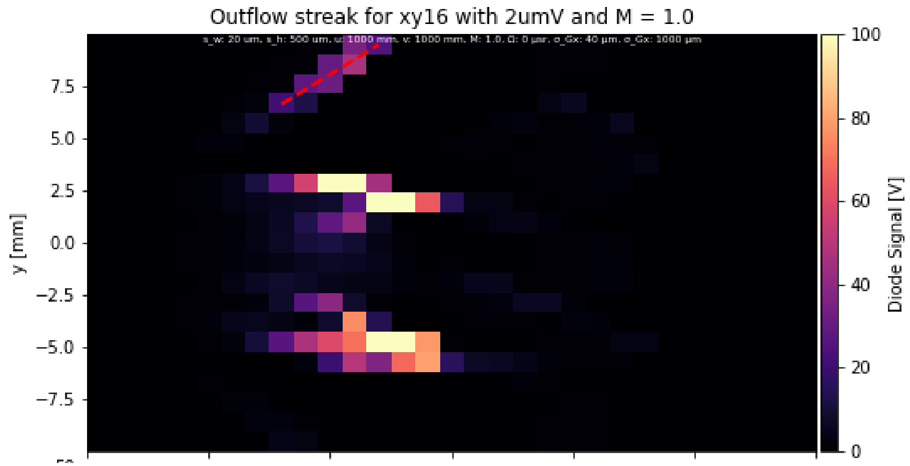
Based on linear AXUV Si diode array for MAGPIE by Jack Halliday

On Z, UPAC (Q. Looker): self-contained, 32-pixel linear diode array with 0.25 mm resolution.









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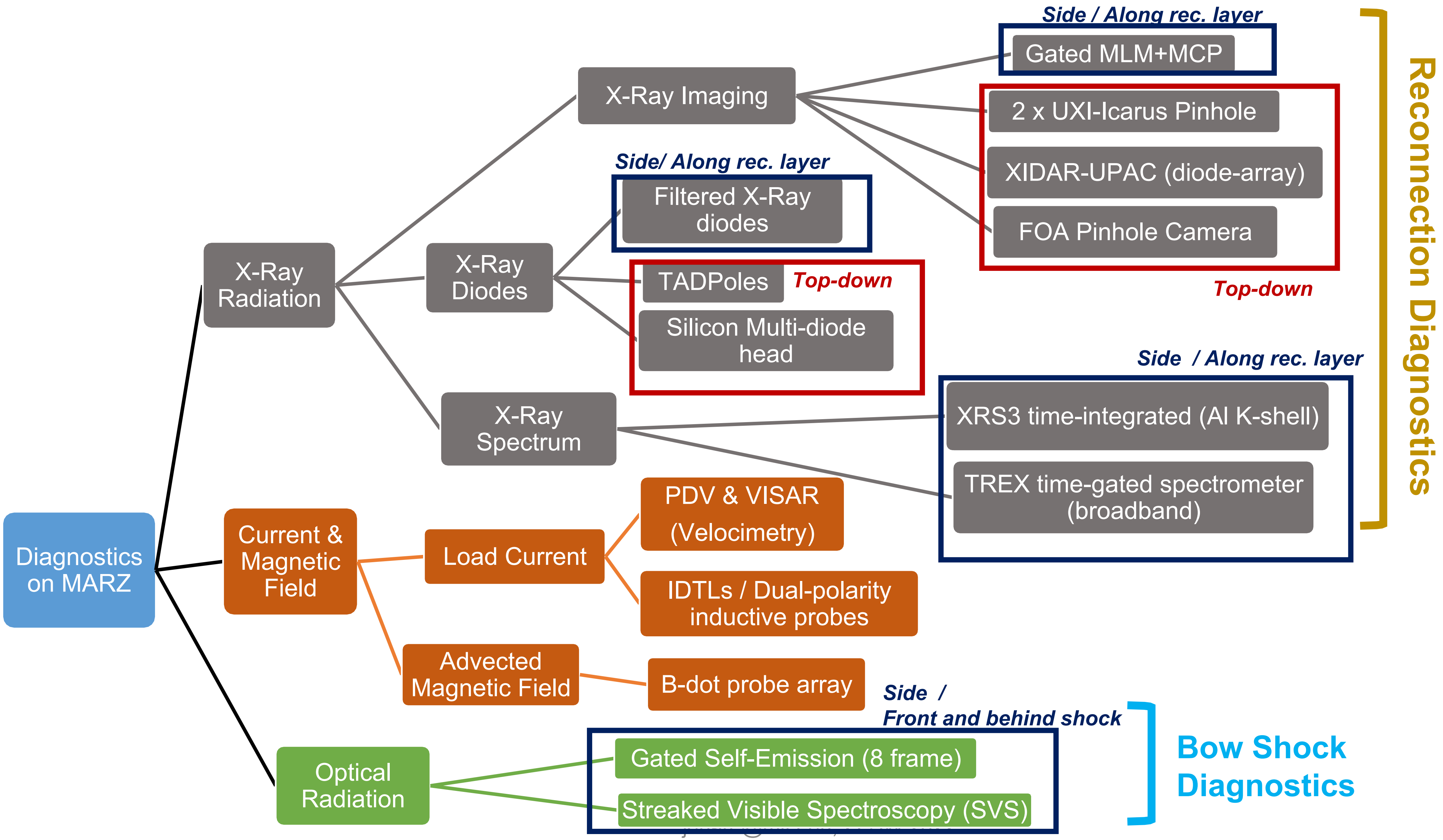
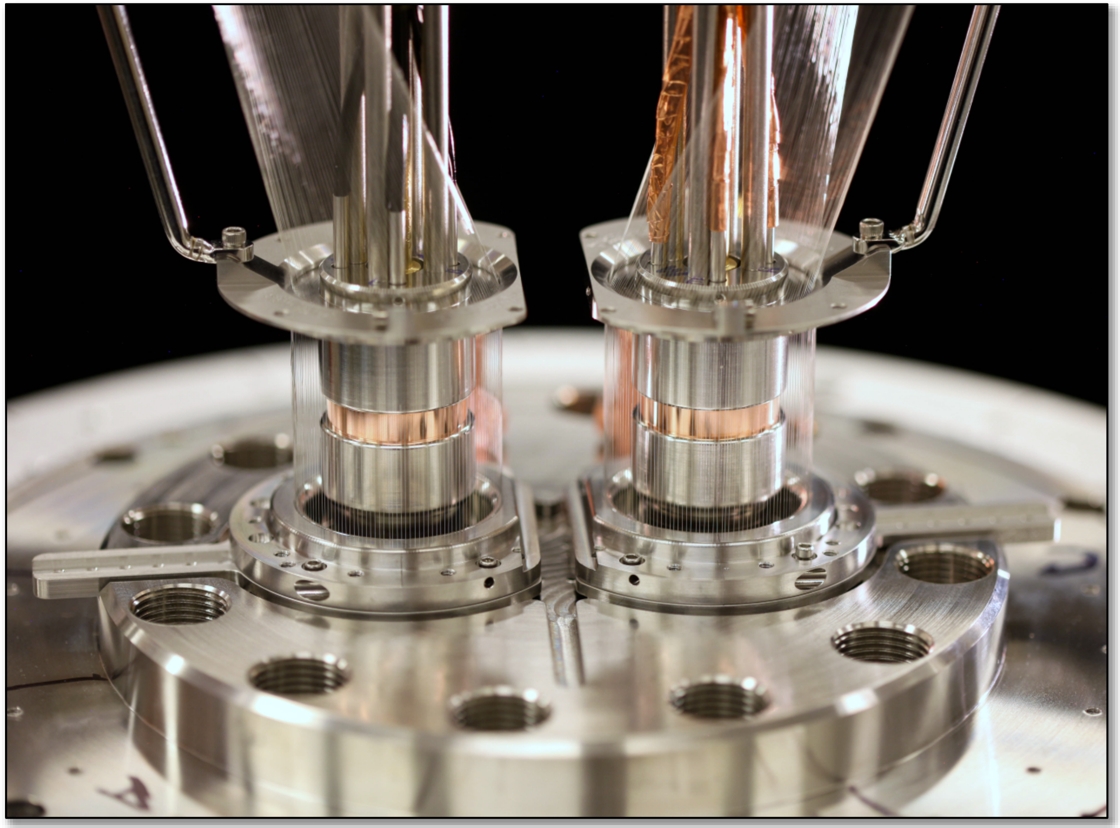
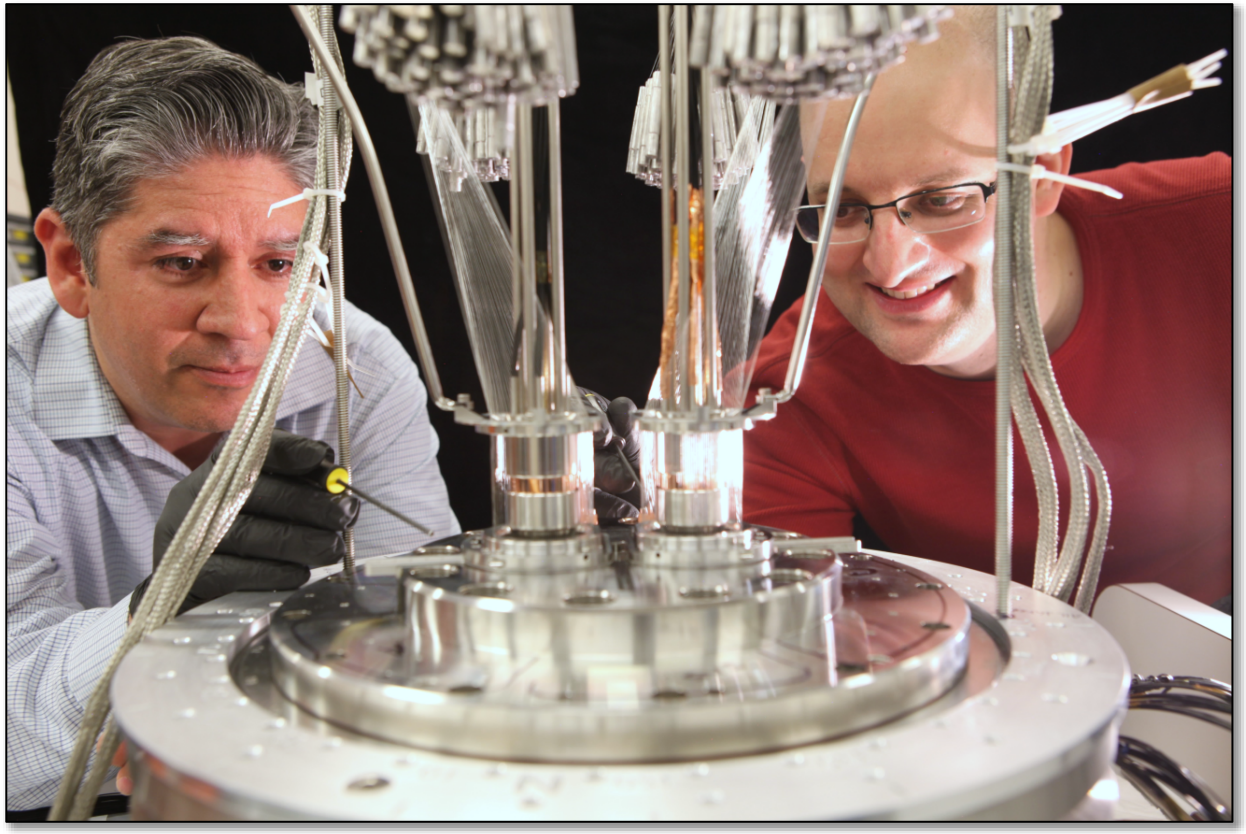
Diagnostics for First MARZ Shot



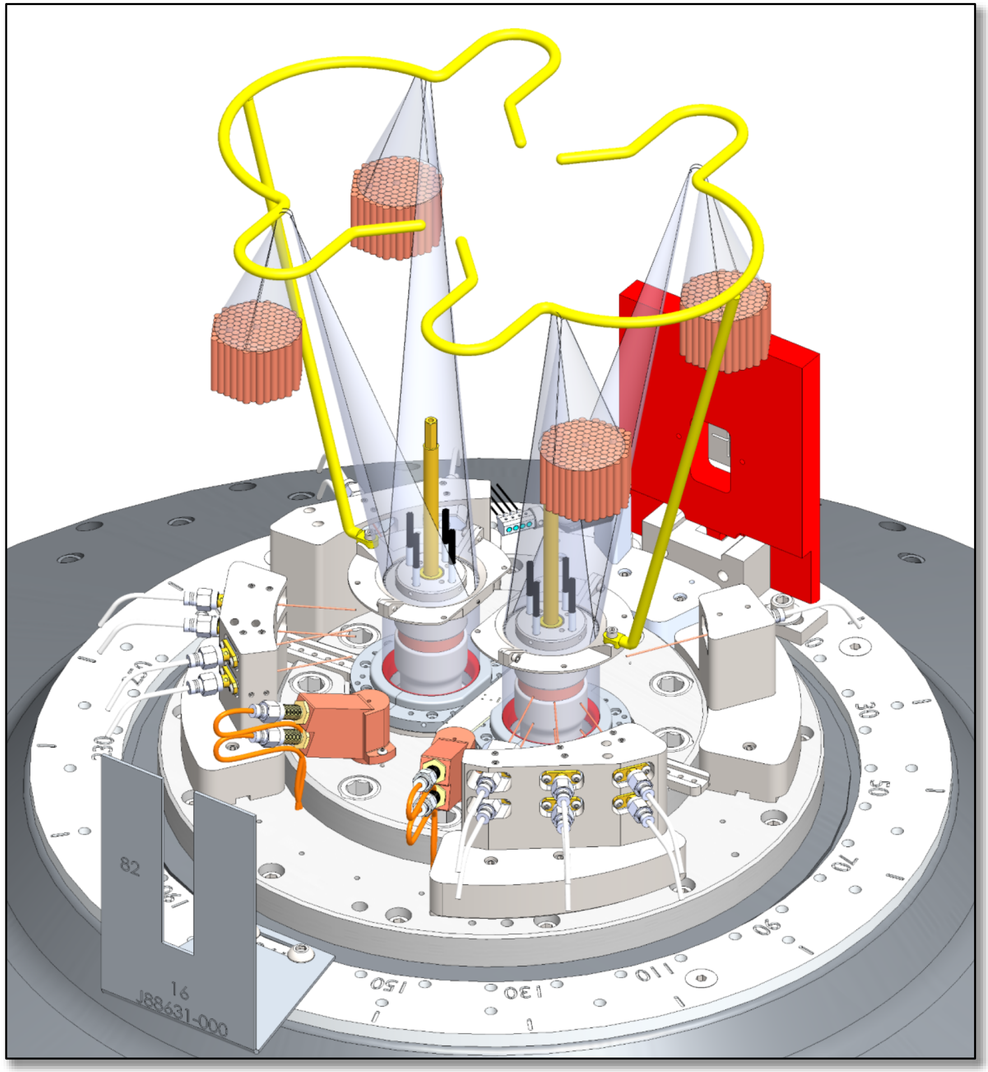
Load Hardware for first MARZ shot

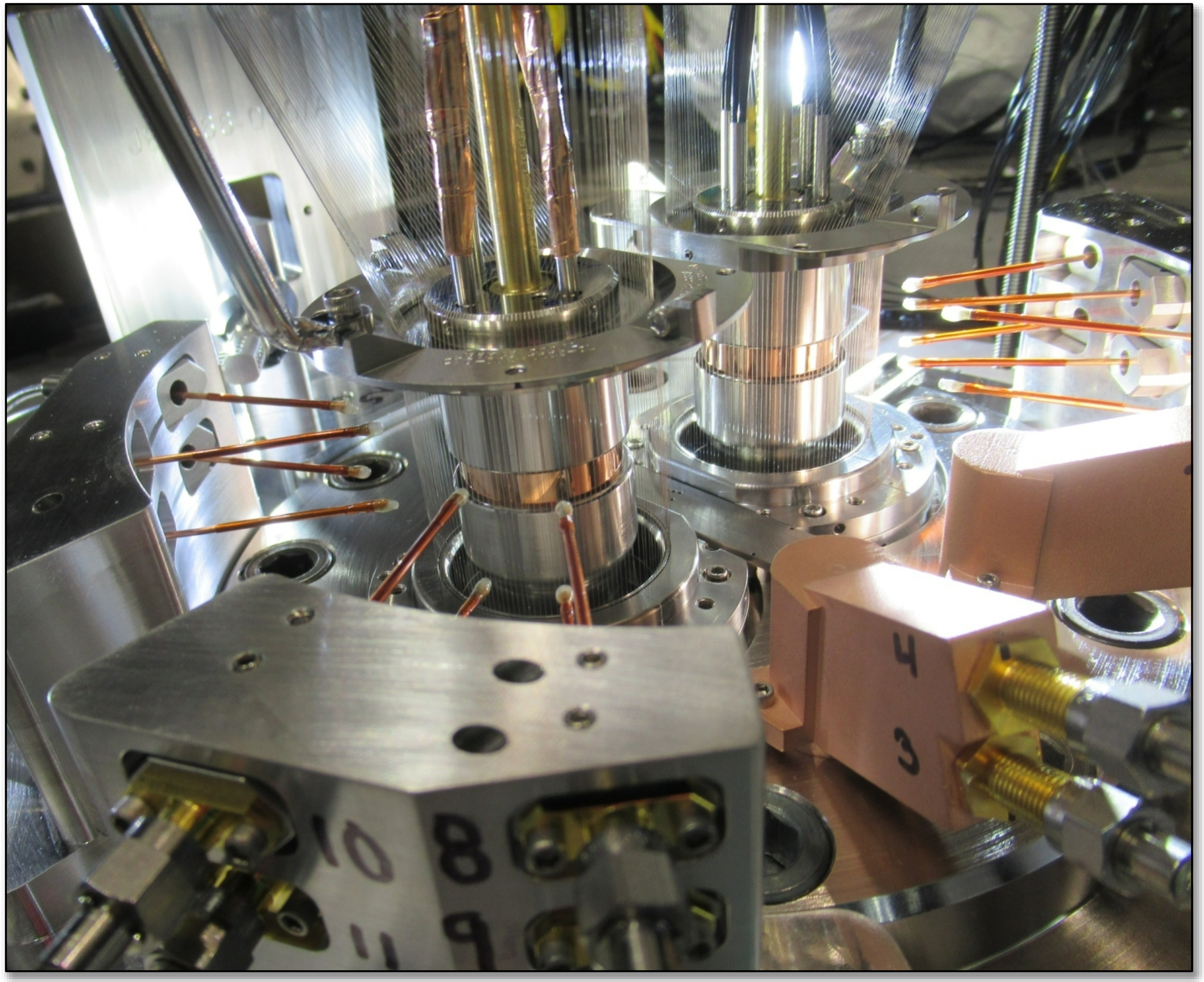




Thank you to Carlos Aragon, Roger Harmon, Josh Gonzalez, and Leo Molina!

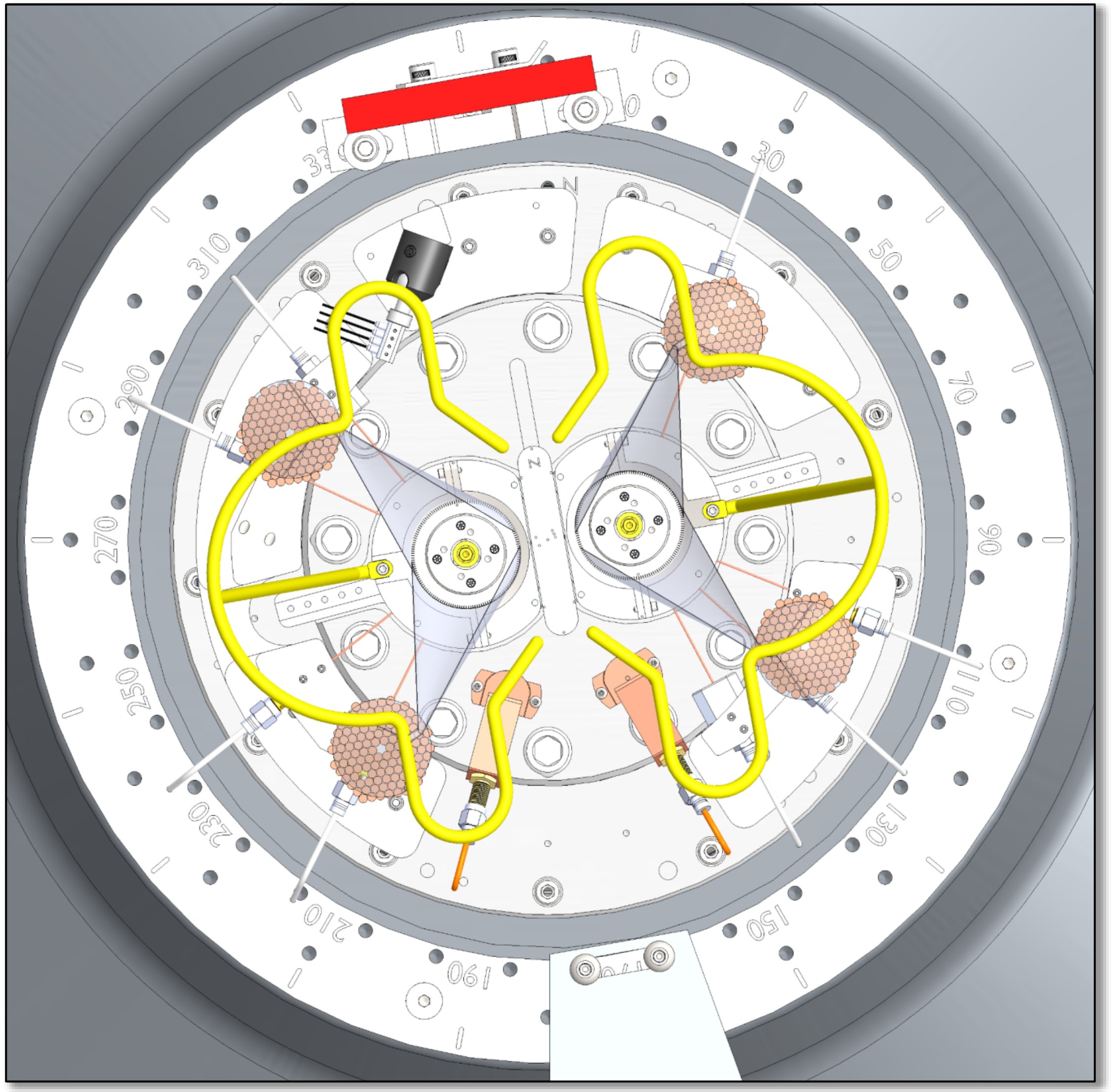
Load Hardware for first MARZ shot

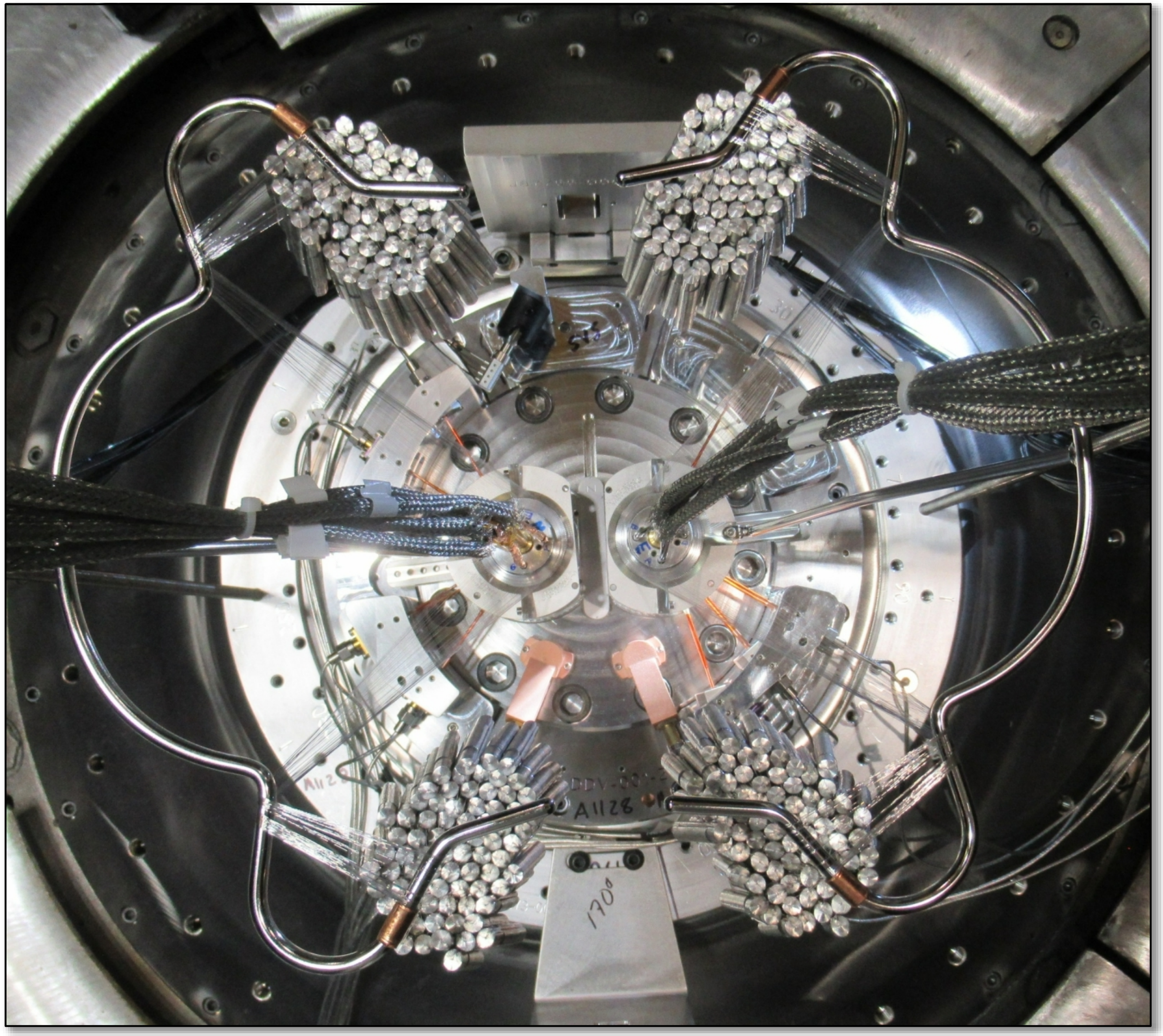




Thank you to Kraig Leonard, Tommy Mulville, Chris De La O, and many more!

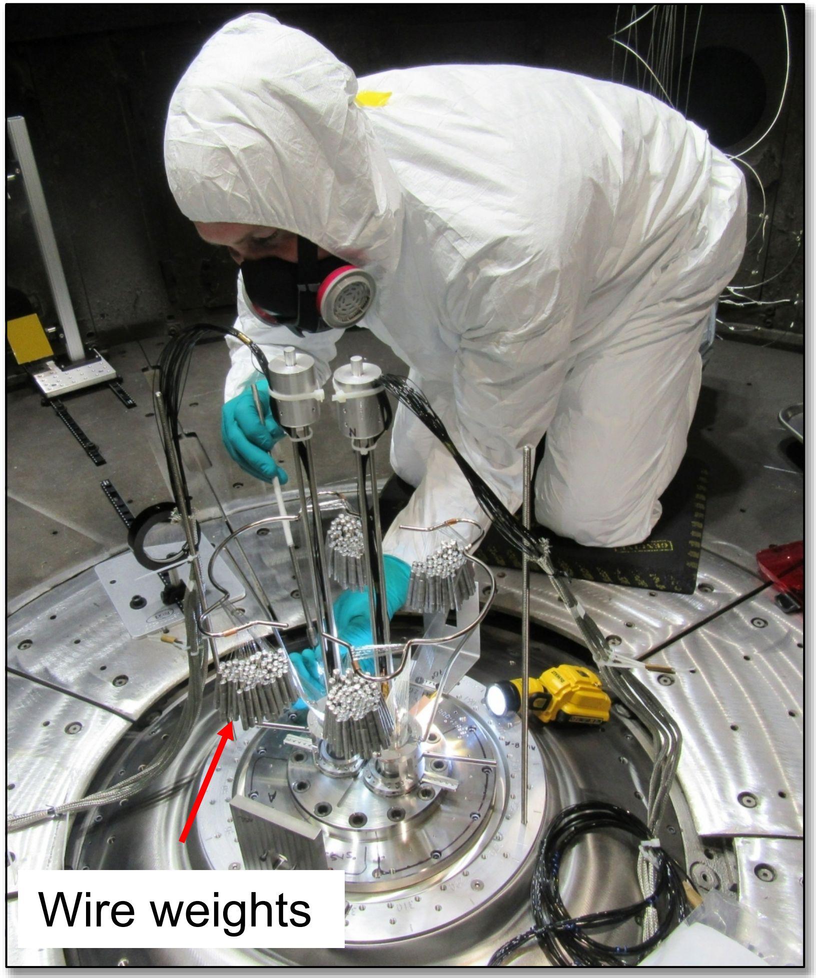
Load Hardware for first MARZ shot

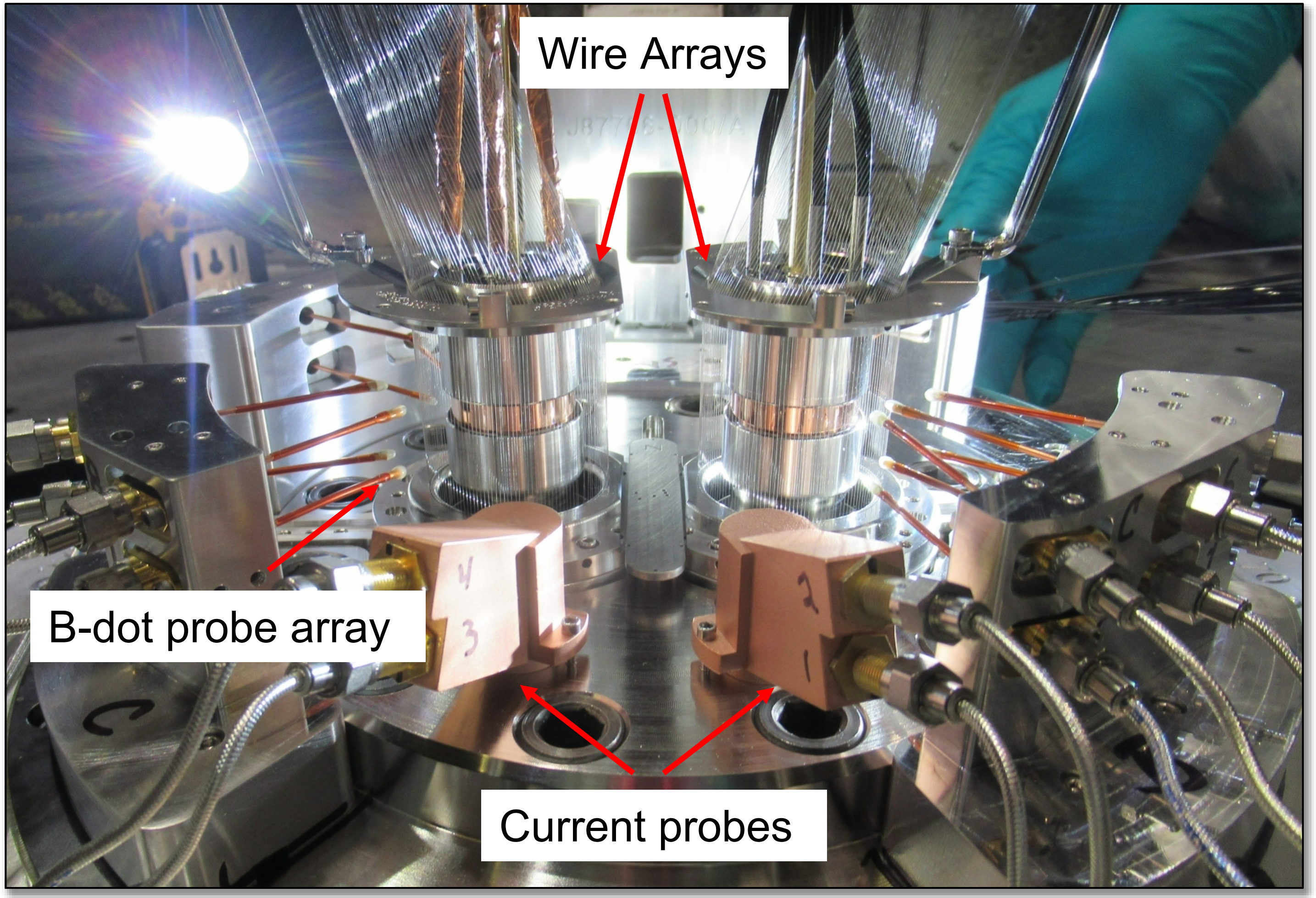




Thank you to Kraig Leonard, Tommy Mulville, Chris De La O, and many more!

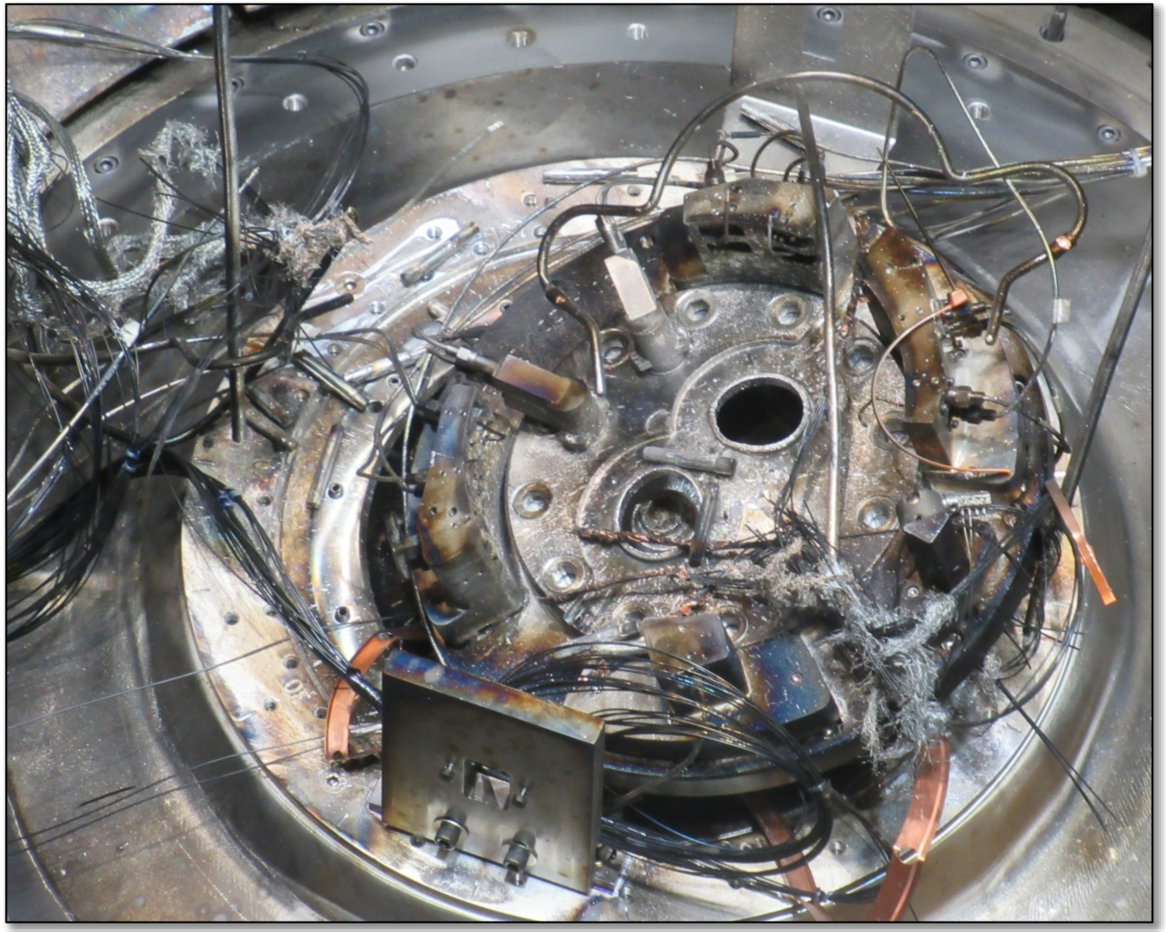
Load Hardware installation

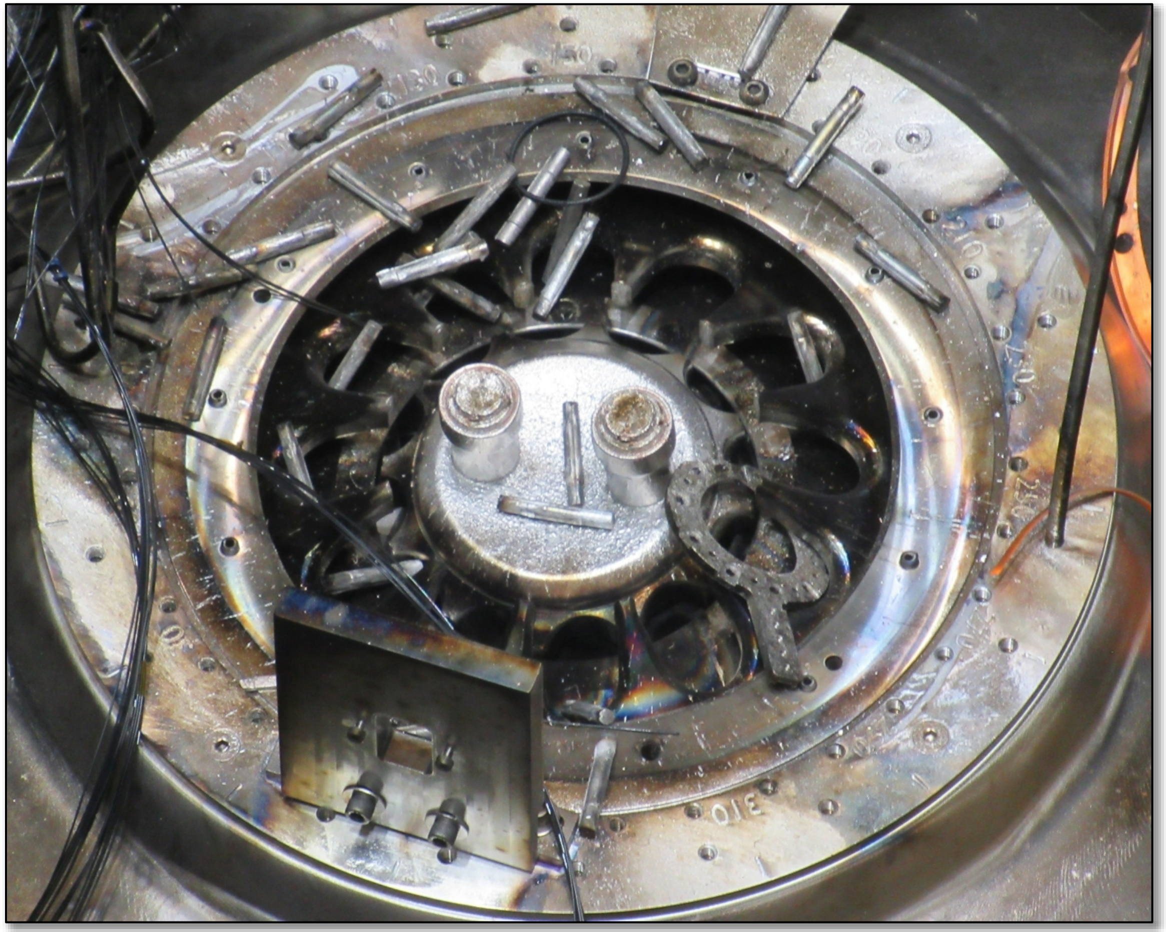




Weeks to build, a microsecond to destroy!

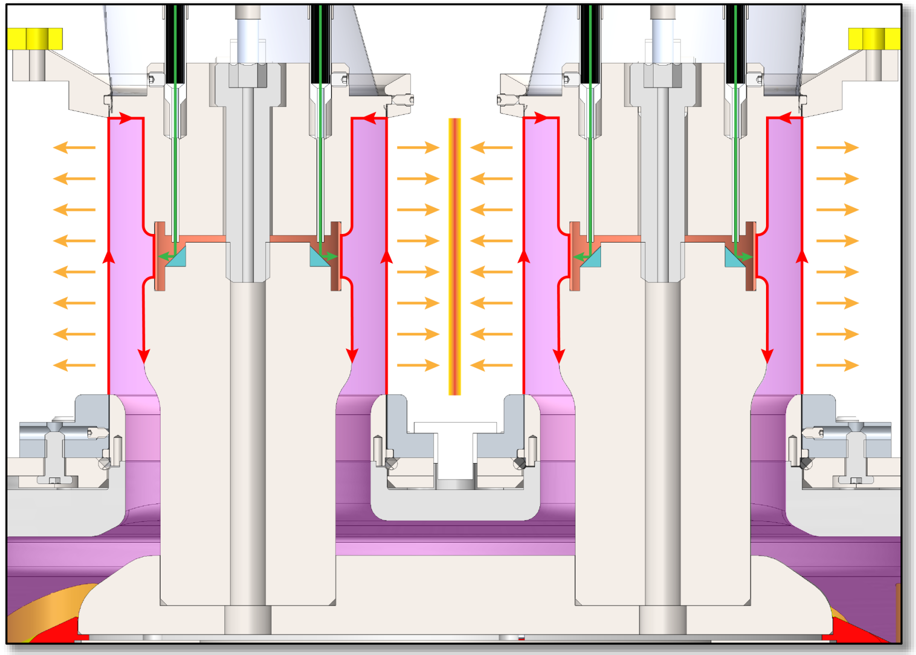
Load Hardware Post Shot

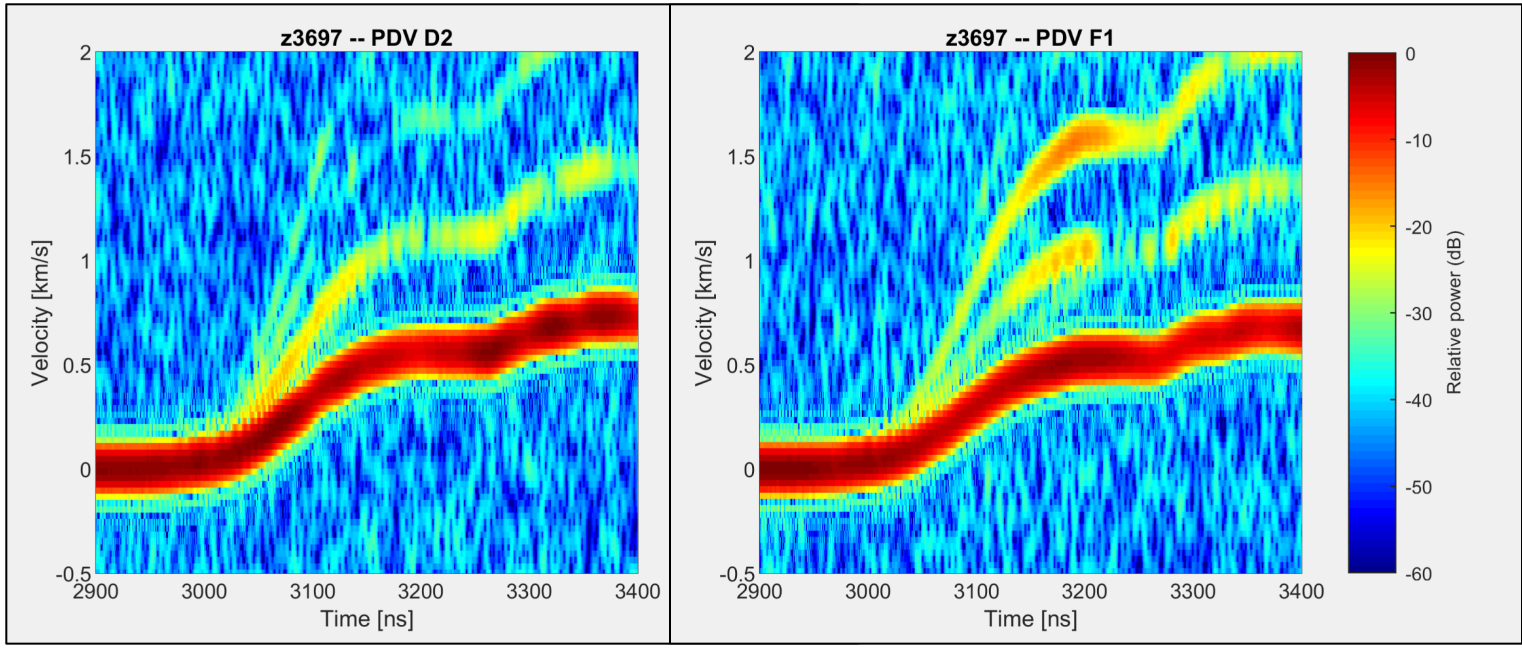




Minimal debris, good for future diagnostics!

MARZ1 delivered 10 MA to each wire array



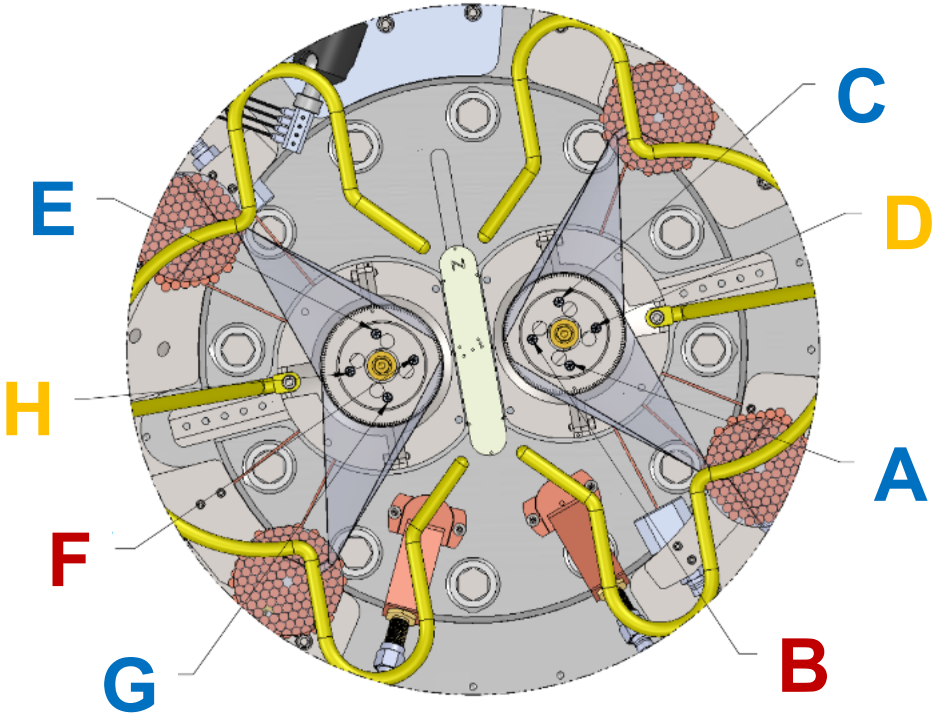


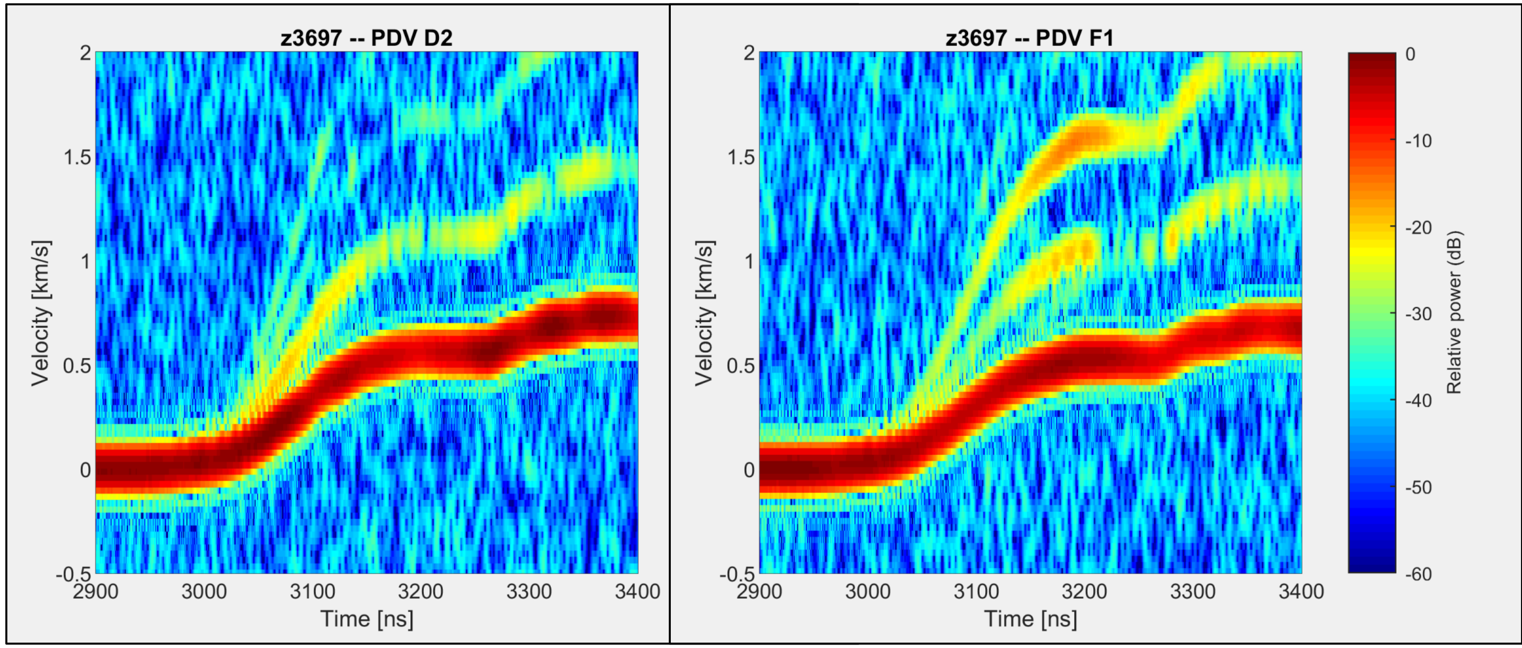
PDV: Return on 14/16 channels.

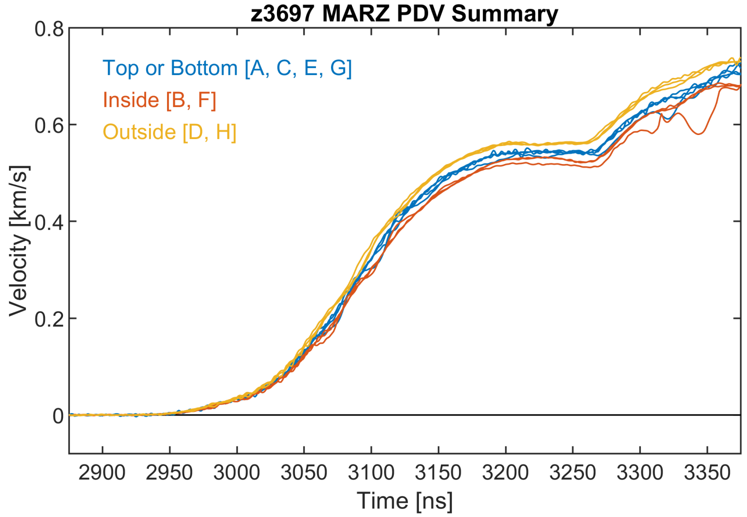
VISAR: Return on 13/24 channels.

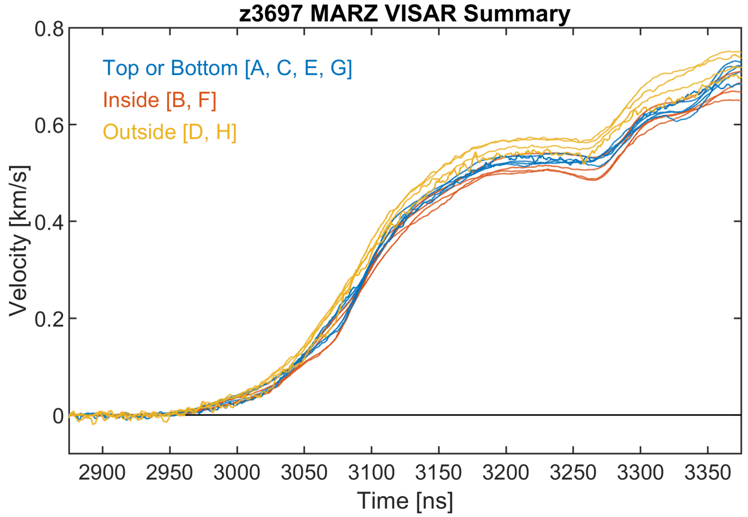
500 m/s velocities are consistent with pre-shot modeling for 10 MA.

MARZ1 delivered 10 MA to each wire array



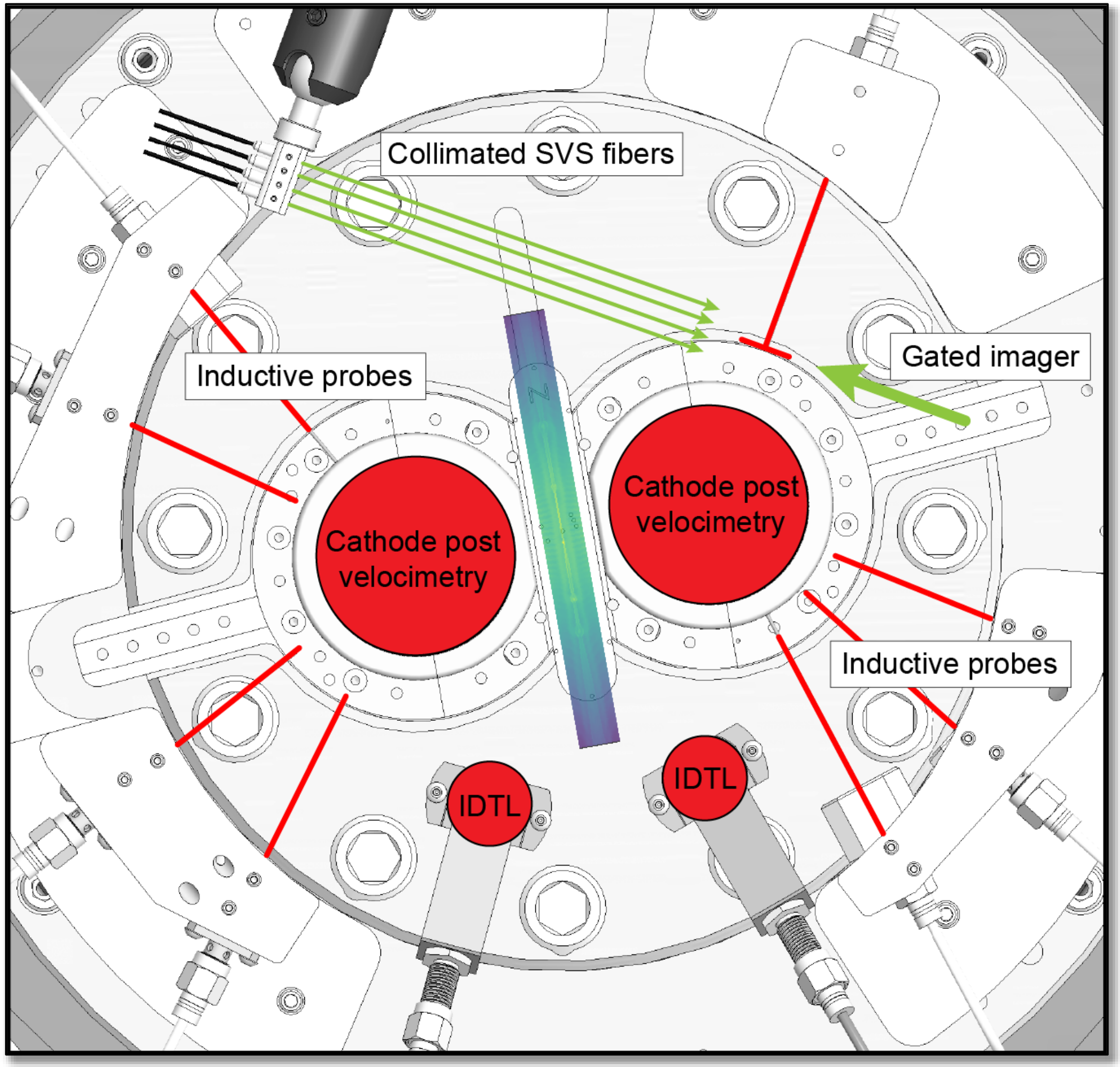


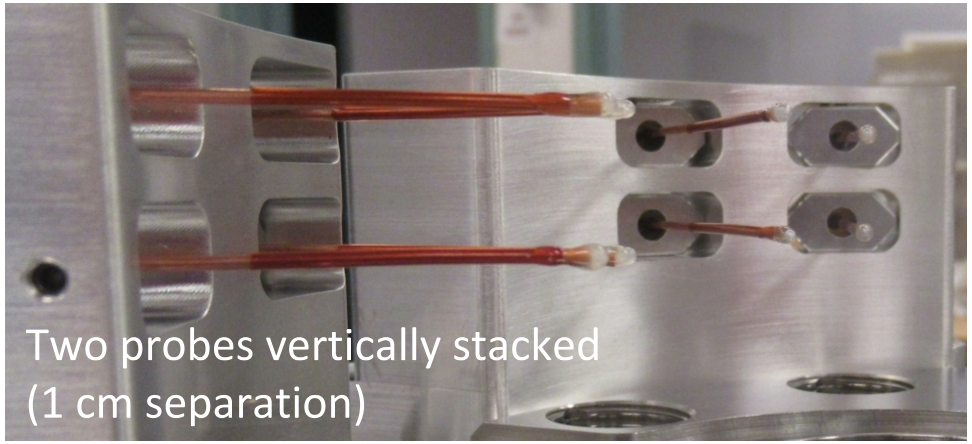


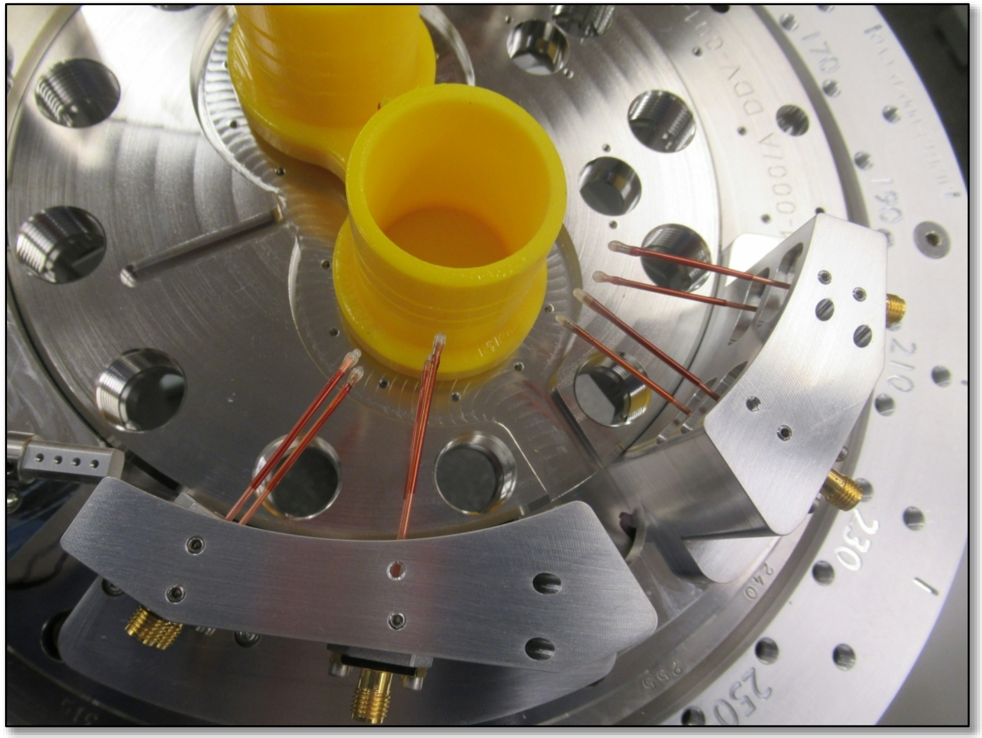


Azimuthal asymmetry in current on arrays:
indicative of current flowing in reconnection layer?

Magnetic Probe Measurements: Plasma Flow

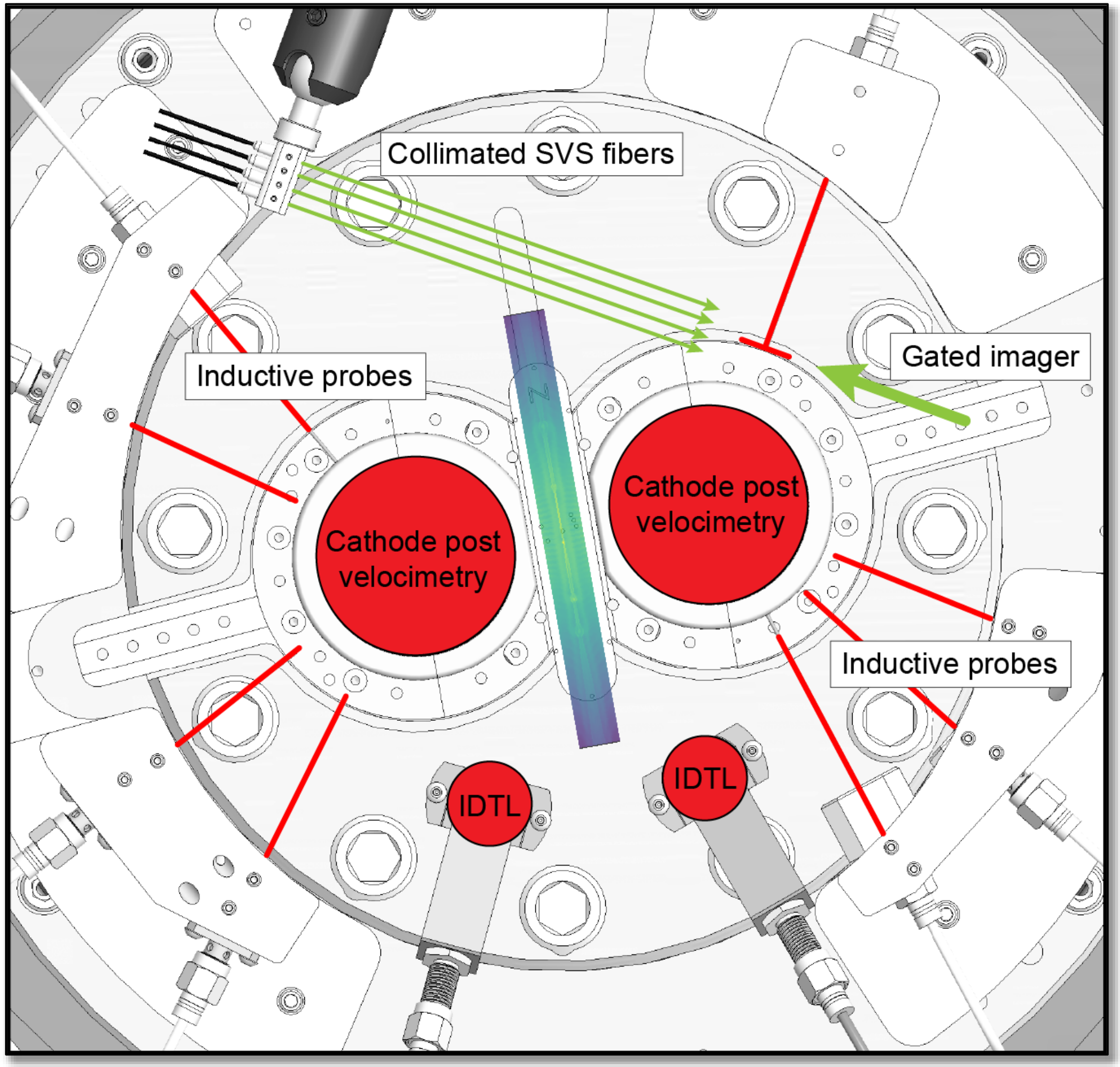


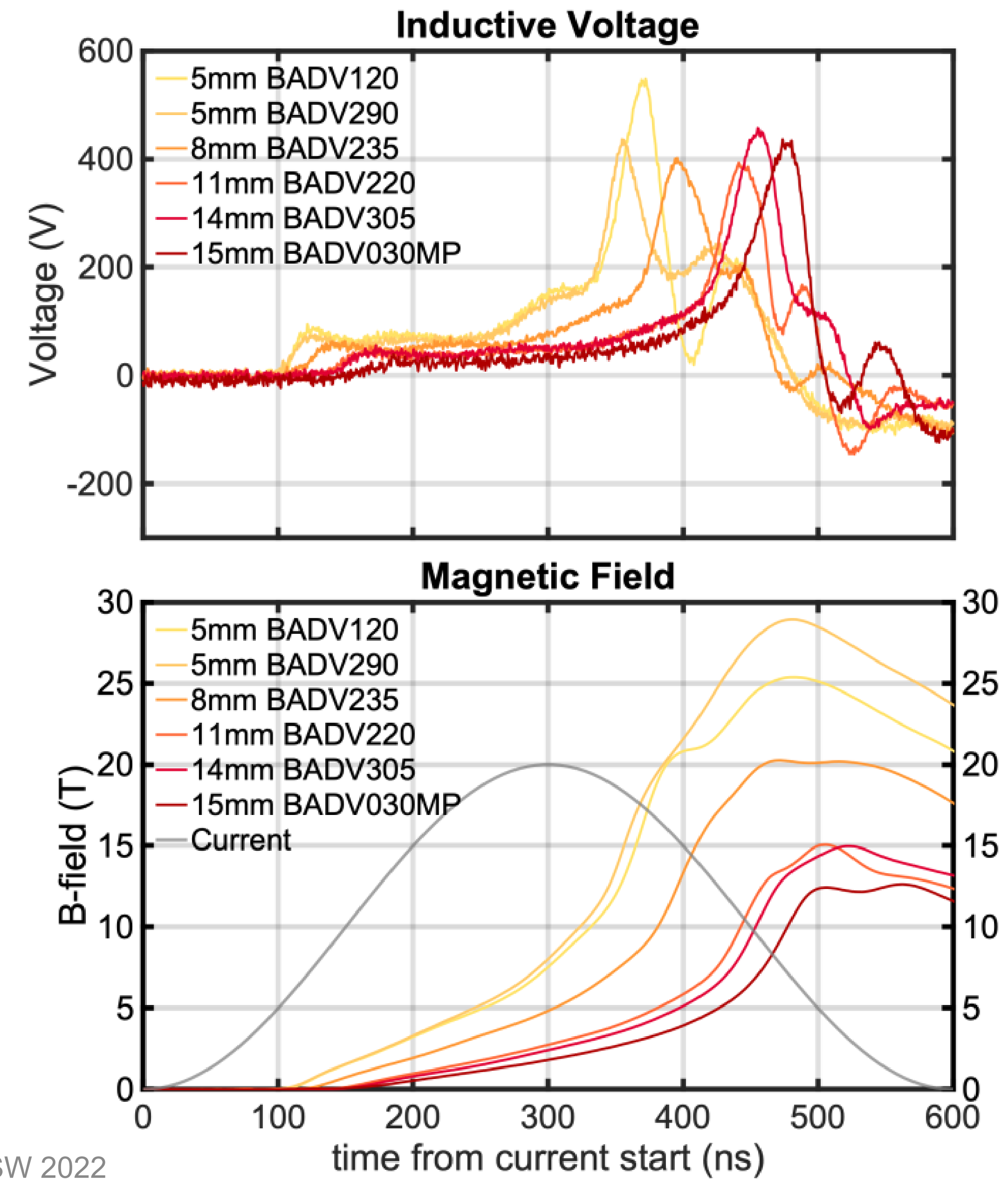




Thank you to Gabe Shipley and Derek Lamppa!

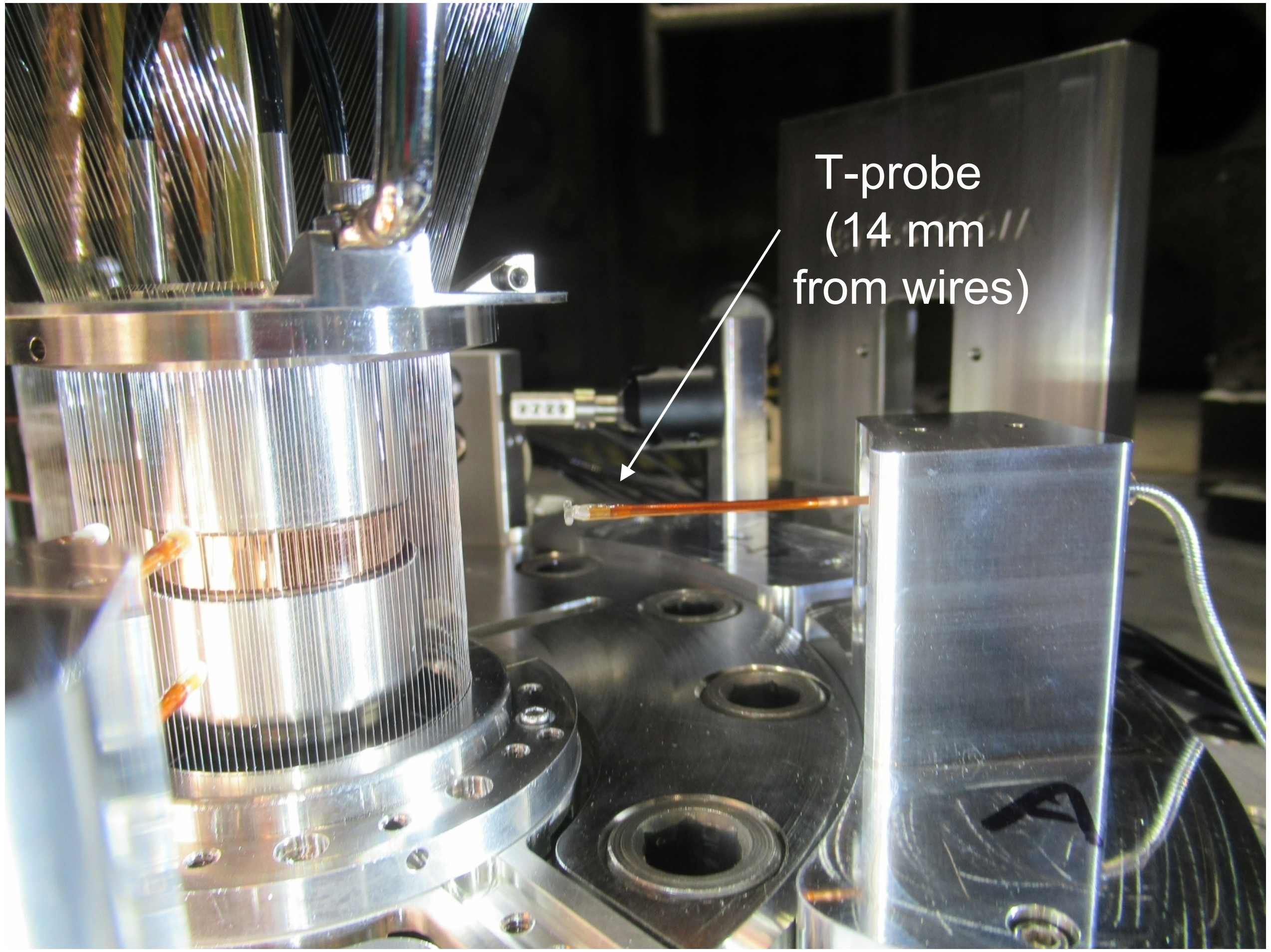
Magnetic Probe Measurements: Plasma Flow



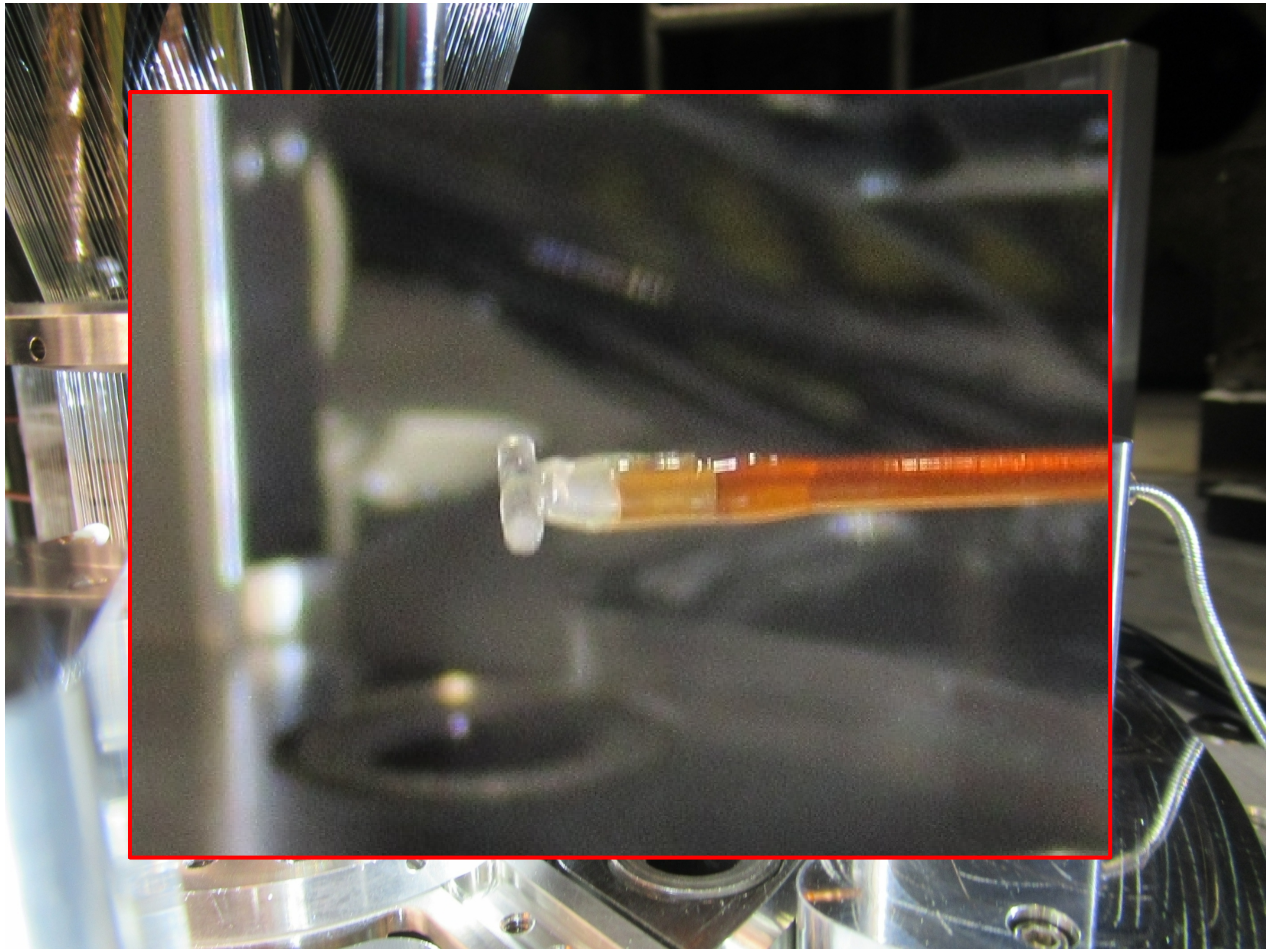


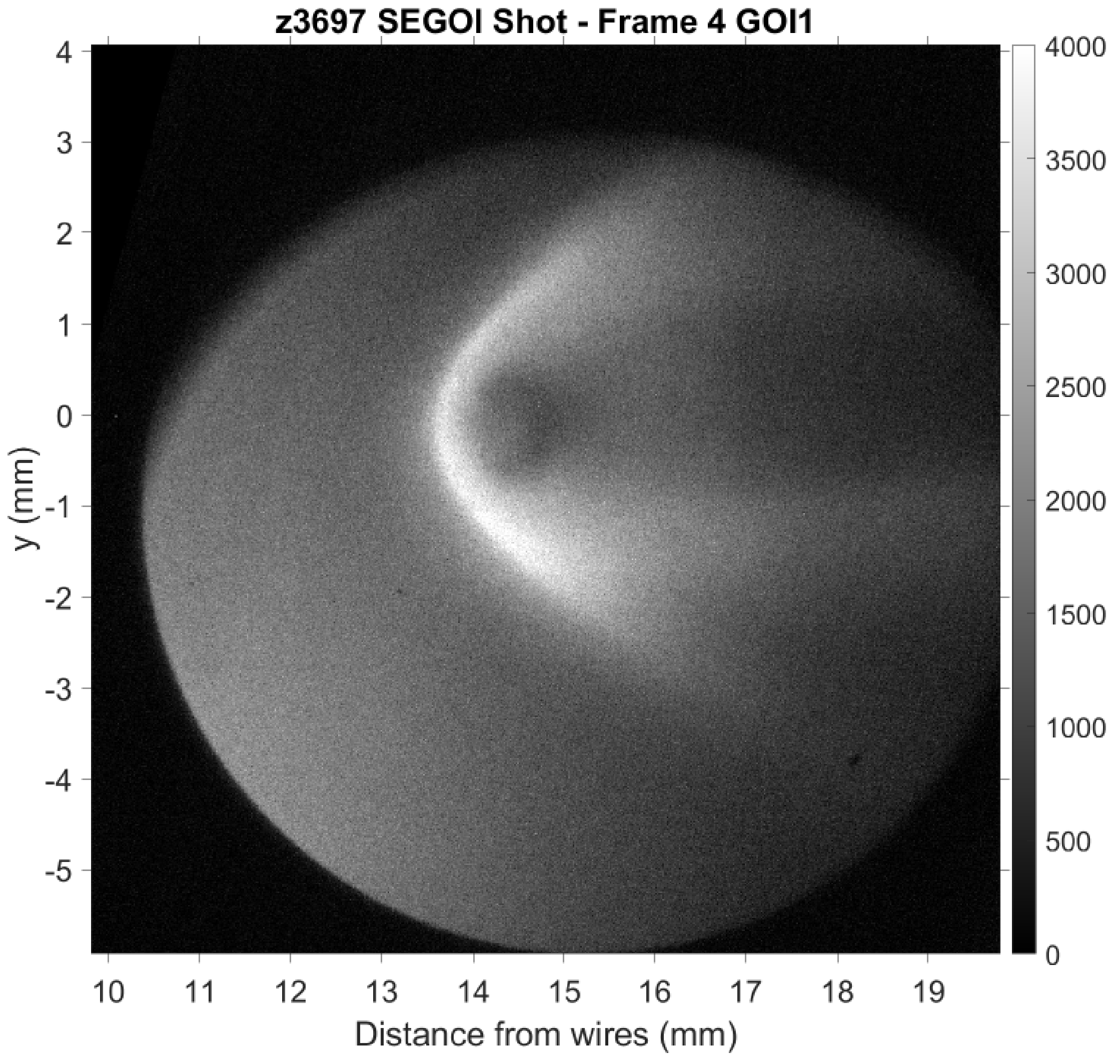
Thank you to Gabe Shipley and Derek Lamppa!

Bow shock around B-dot probe: Plasma Flow

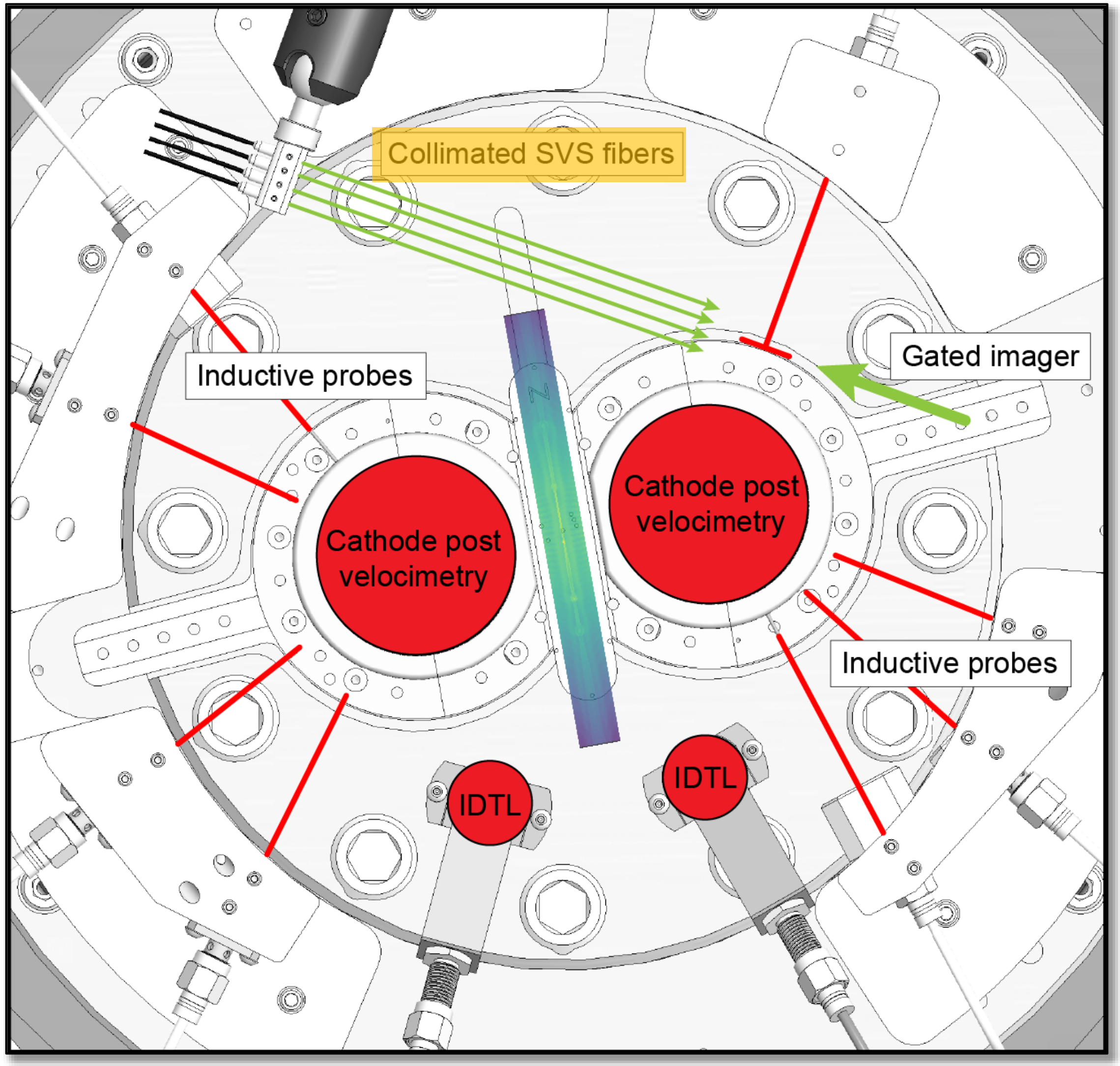


Bow shock around B-dot probe: Plasma Flow

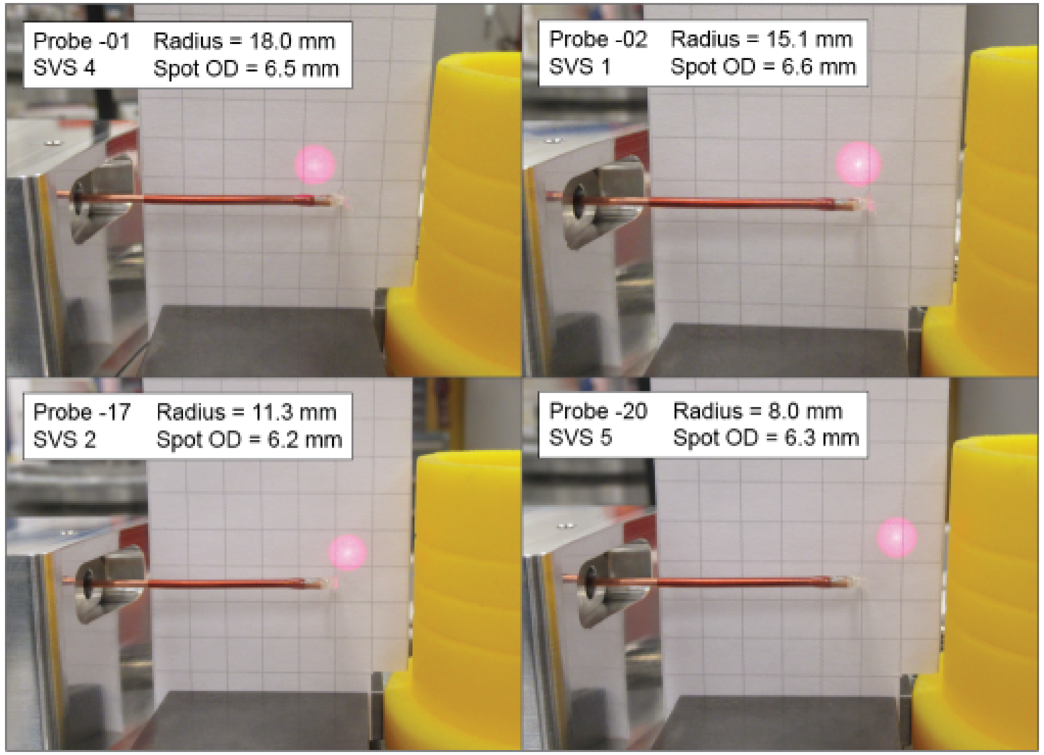




Streaked Visible Spectroscopy



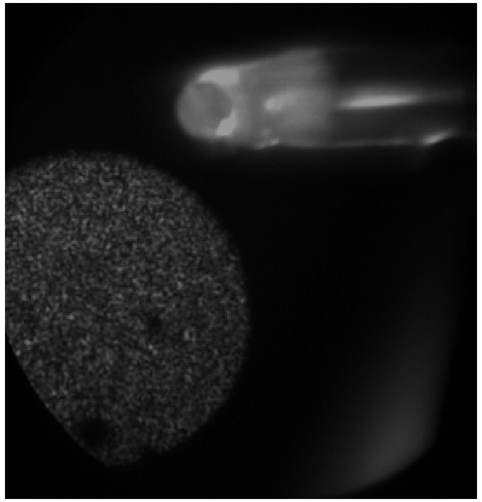
- Four fibers: 6 mm spot size at inductive probe radial locations



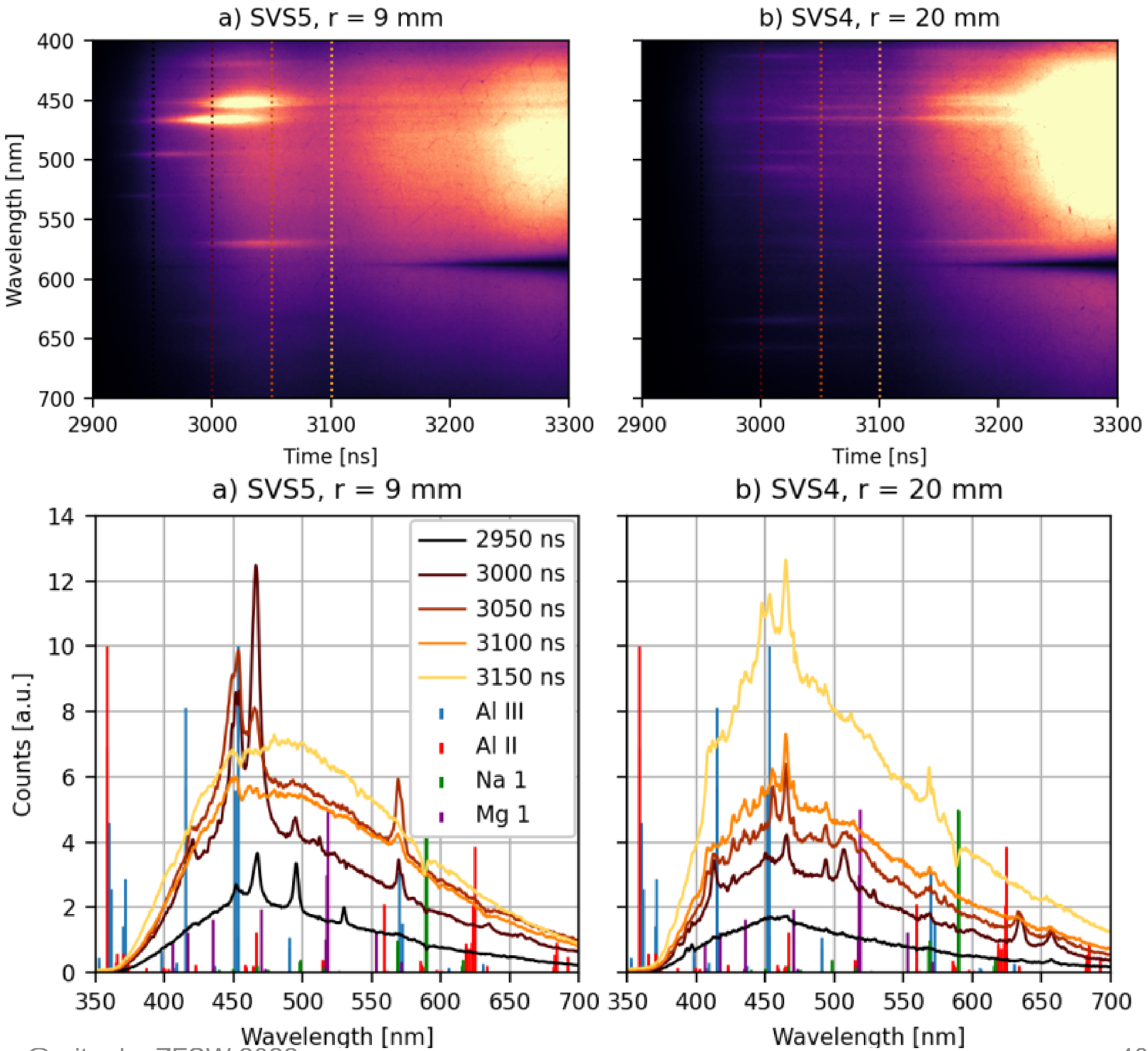
Thank you to Sonal Patel and Dan Scoglietti!

Streaked Visible Spectroscopy

- Long time record, spatially localized, broadband spectroscopy
- Al II & Al III lines to measure n_e and T_e

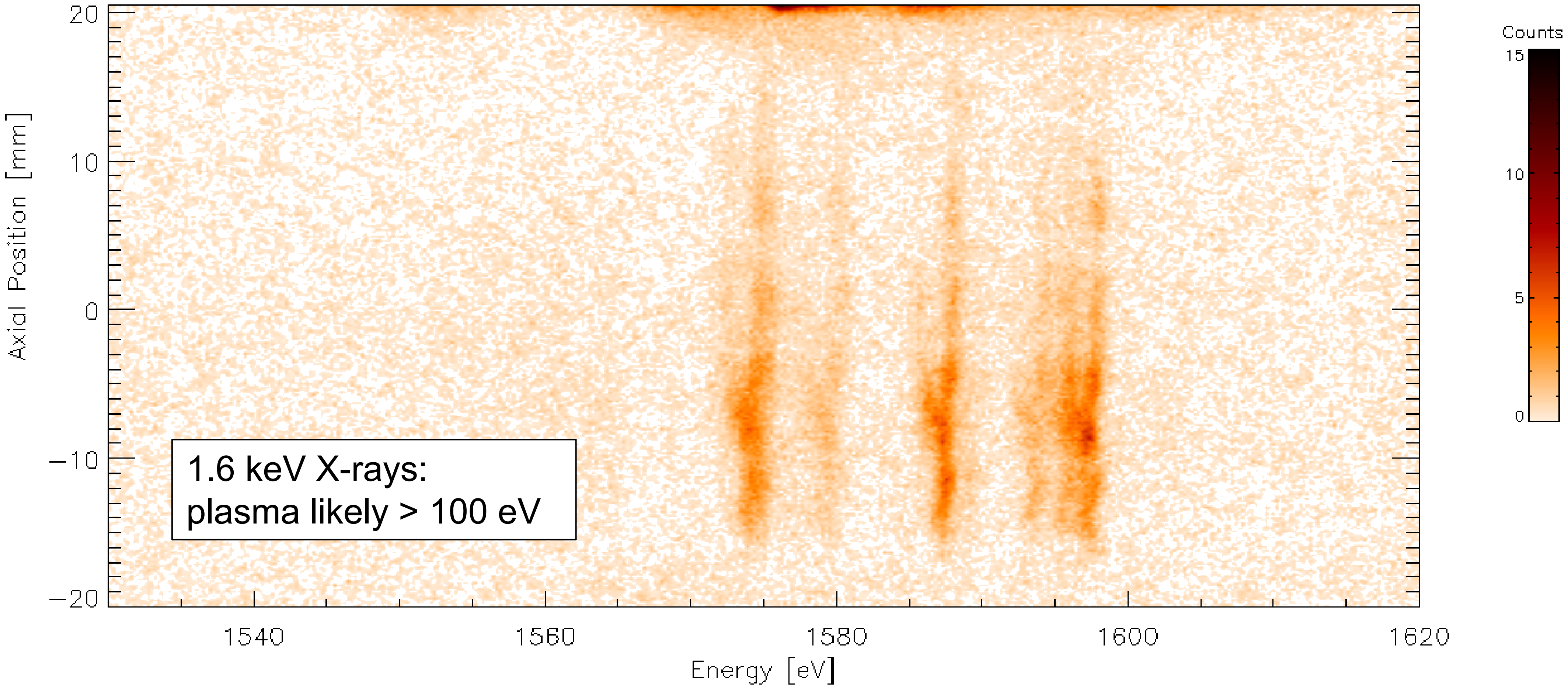


Pre-shot SEGOI image of SVS 2



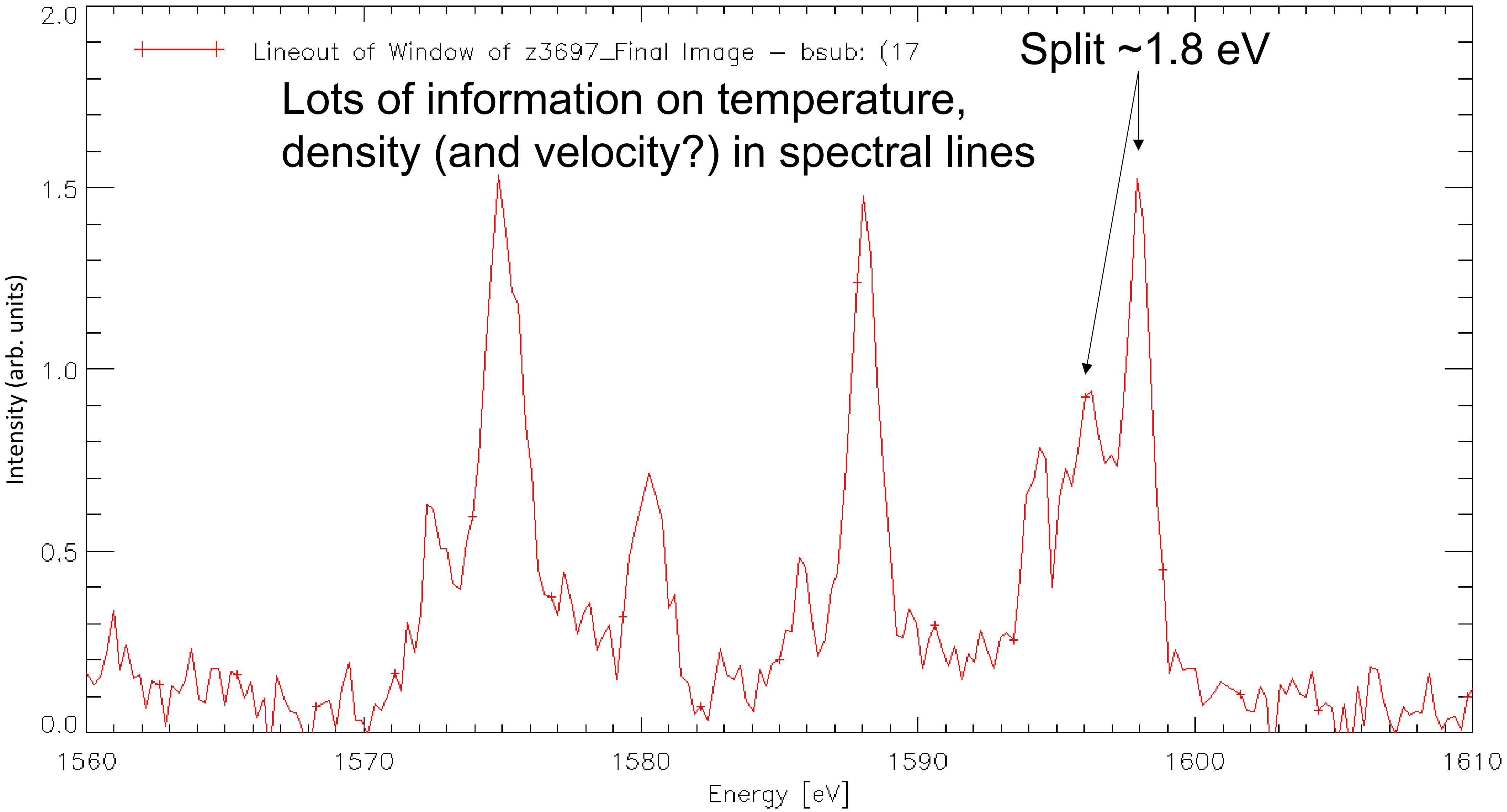
Thank you to Sonal Patel and Dan Scoglietti!

Time Integrated X-ray Spectrum: Hot Plasma



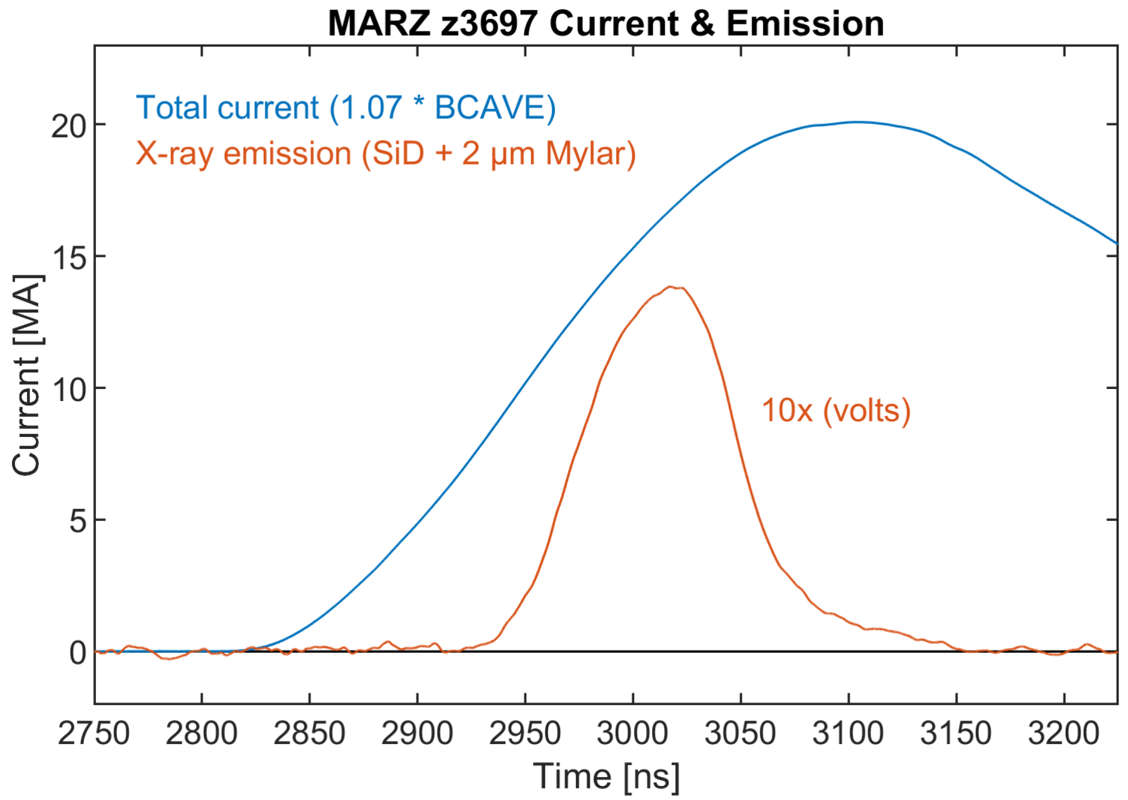
Thank you to Eric Harding, Andy Maurer, and Stephanie Hansen!

X-ray Spectra are a Rich Source of information

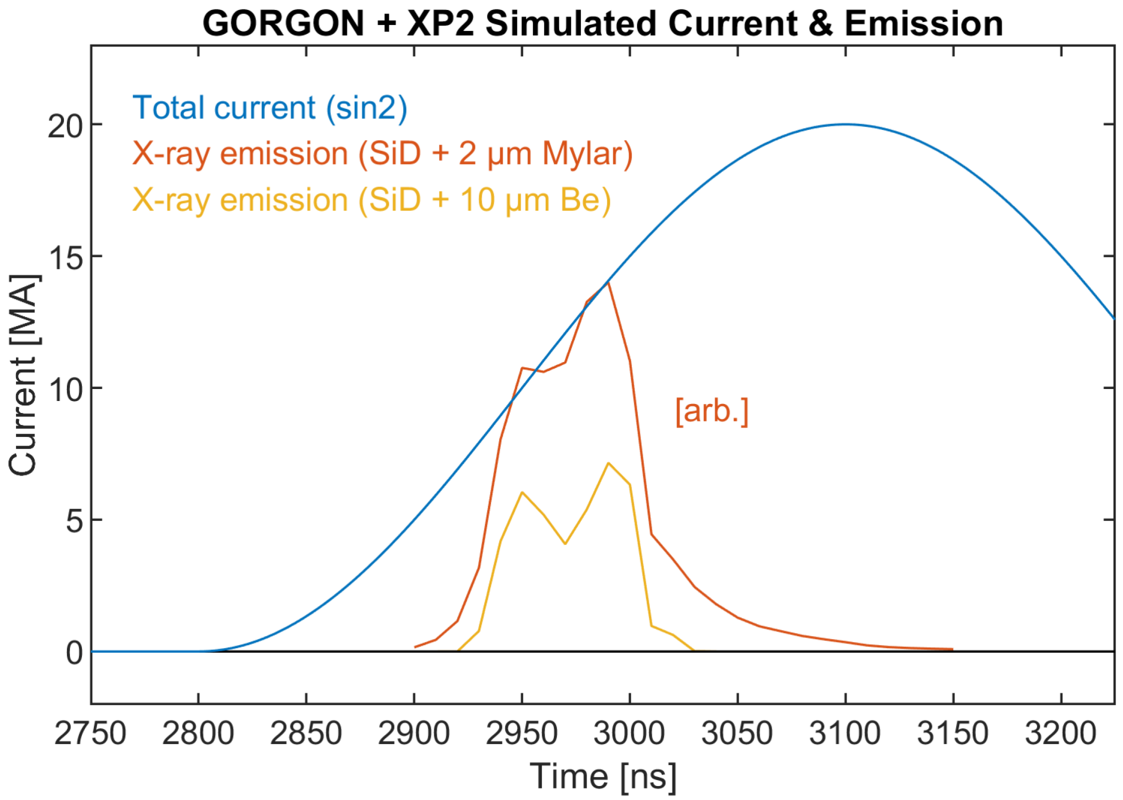


Filtered Diode Signals: Layer Formation, Collapse

Experiment



Simulation

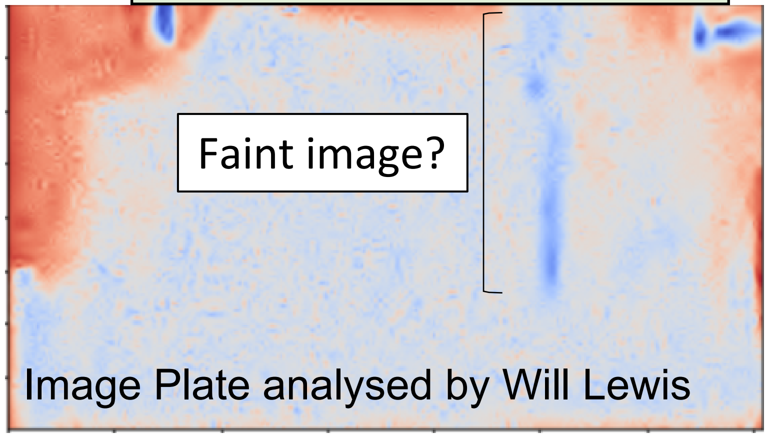


- Radiated power rises after current start, drops before current peak
- X-ray spectra appears softer than simulated: more shots in later this year

What didn't work well

- Most X-ray cameras (gated, time integrated) and diodes (XIDAR, filtered) returned no signal
- Most diagnostics functioned nominally, so red indicates lack of data
- Conclusion:
  Layer less bright predicted by simulations

UPAC Sensor Location



Our only image of the layer

Diagnostic	Data return
IDTLs	4/4 channels
PDV	14/16 channels
VISAR	13/24 channels
Inductive probes	13/15 channels
SVS	3/4 systems
SEGOI	Bow shock observed
LOS 170 diodes	~1/6 diodes
MLM	
XRS3	Al K-shell observed
TREX	
TADPoles (2x)	
FOA diodes	
FOA PHC (UXI, 2x)	
FOA PHC (IP)	
FOA XIDAR (UPAC)	Image on IP?

Talk outline

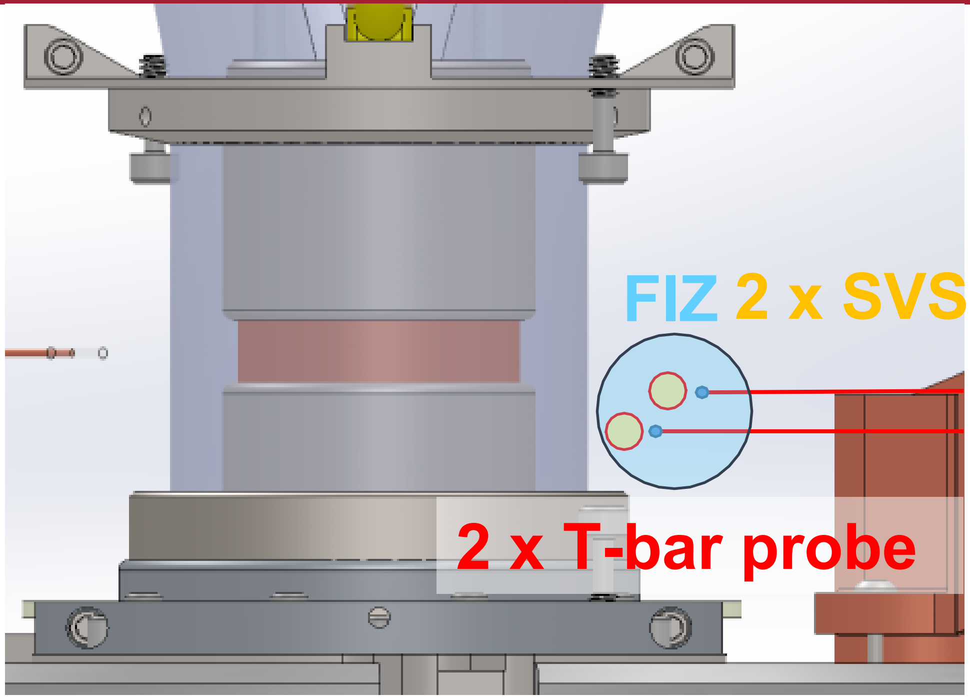
- What is magnetic reconnection?
- What is radiatively cooled magnetic reconnection?
- How to we study it in the laboratory?
- Results from simulations for experimental design
- Results from the first MARZ shot on Z
- Outlook for future MARZ shots

Future work on MARZ

Two more MARZ shots later this year:

1. Improve diagnostics of the reconnection layer
2. Diagnose the outflows from the reconnection layer

Form a complete picture for publication



Future work on MARZ

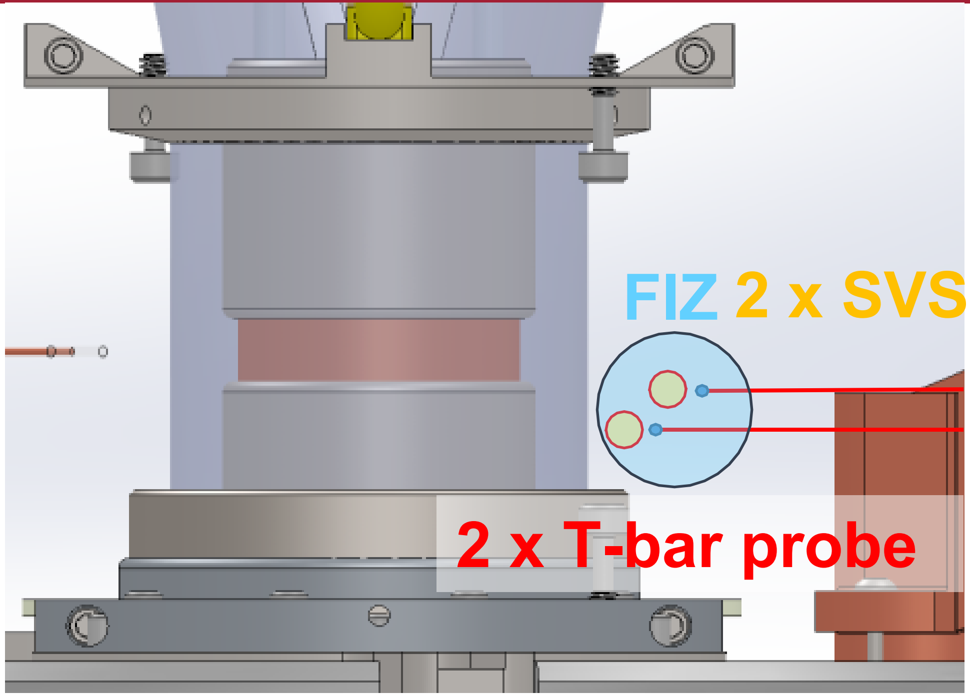
Two more MARZ shots later this year:

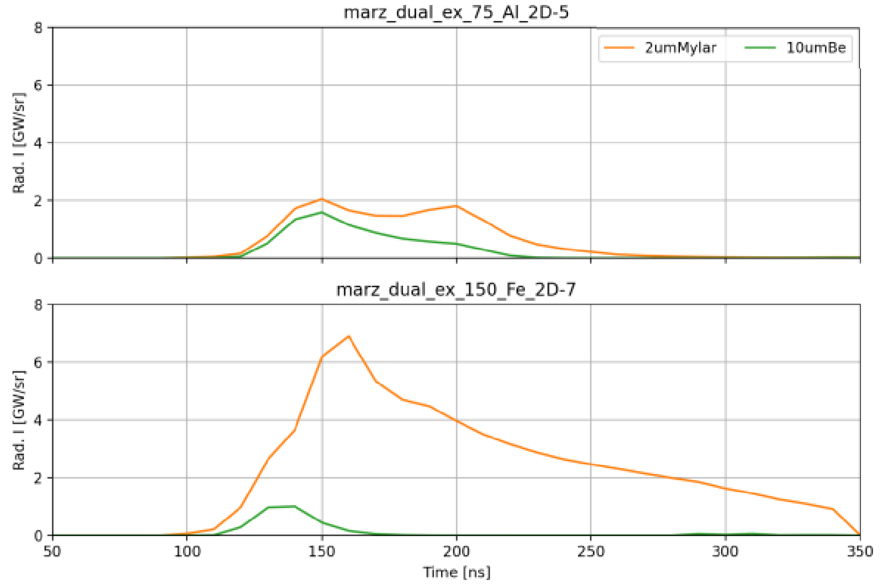
1. Improve diagnostics of the reconnection layer
2. Diagnose the outflows from the reconnection layer

Form a complete picture for publication

MARZ renewal for CY23-24:

1. New load designs to boost density, magnetic field
2. Change wire material to alter cooling rate
3. Investigate effect of pulse rise-time





Future work on MARZ

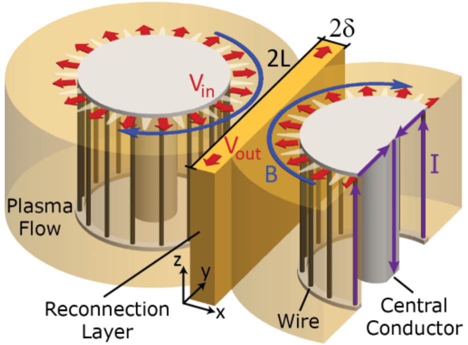
New simulation tools:

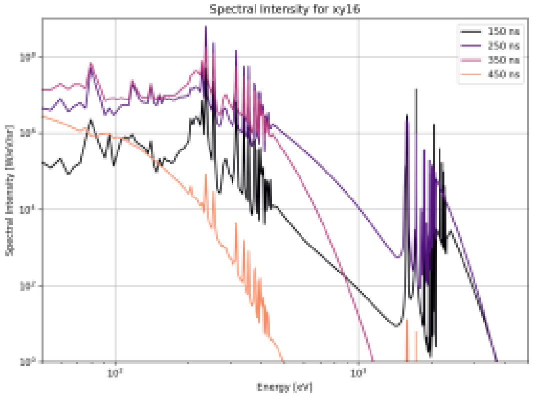
- Radiation transport in GORGON (Jerry Chittenden)
- Advanced X-ray post-processing such as Doppler shift (Aidan Crilly)

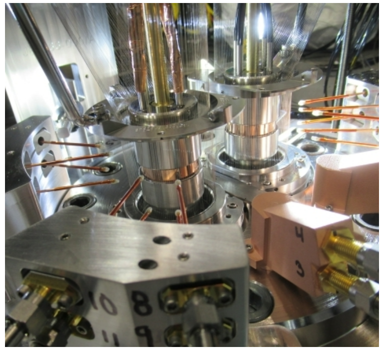
New diagnostics:

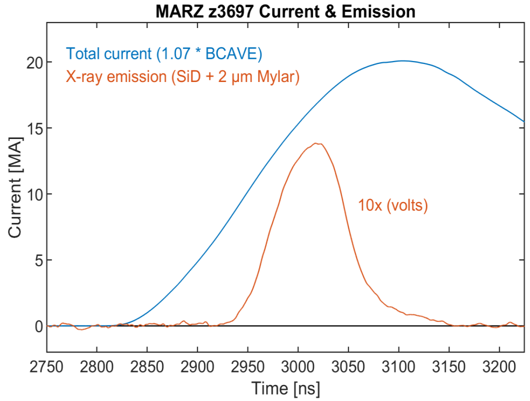
- Laser imaging (David Yager-Elorriaga)
- Thomson scattering (Jacob Banasek)
- X-pinch backlighting (Matt Gomez)
- Fe L-shell spectroscopy (Patricia Cho)
- UV spectroscopy, fiber coupled (Mark Johnston)

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 later this year!

Future work on MARZ

New simulation tools:

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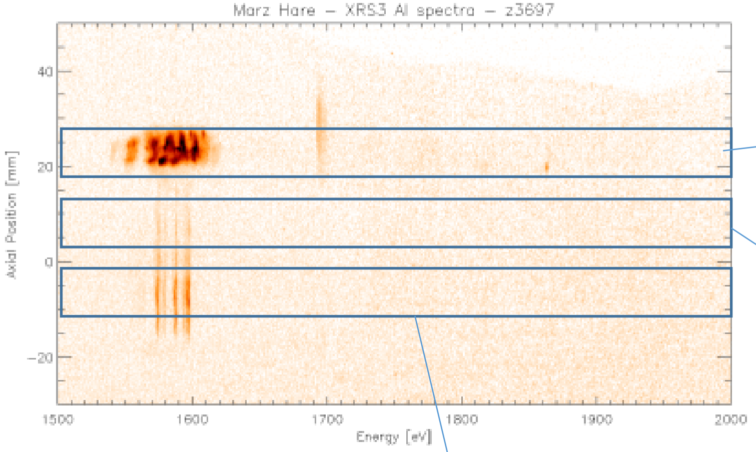
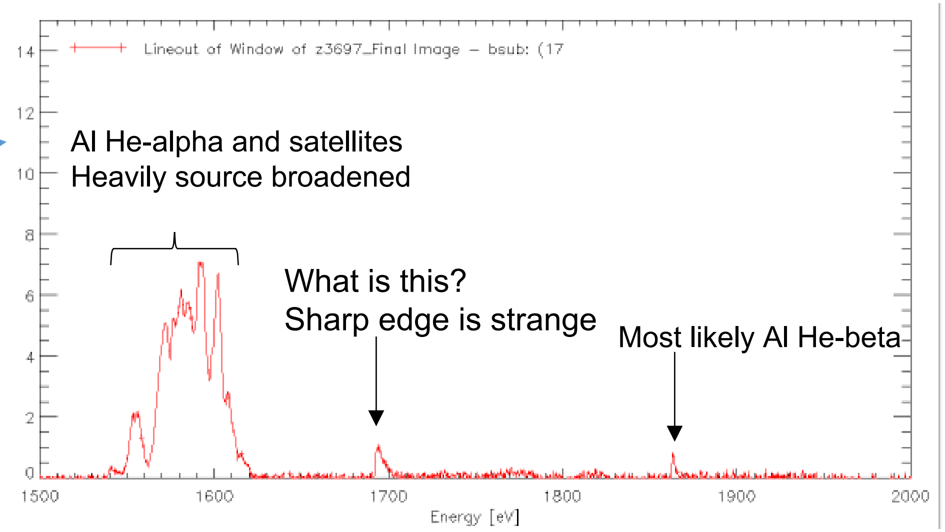
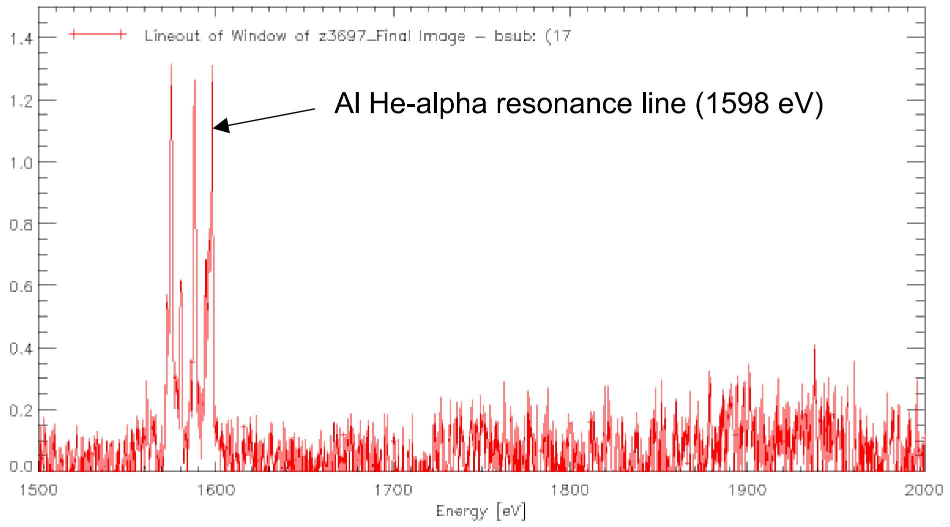
Survey of axially resolved XRS3

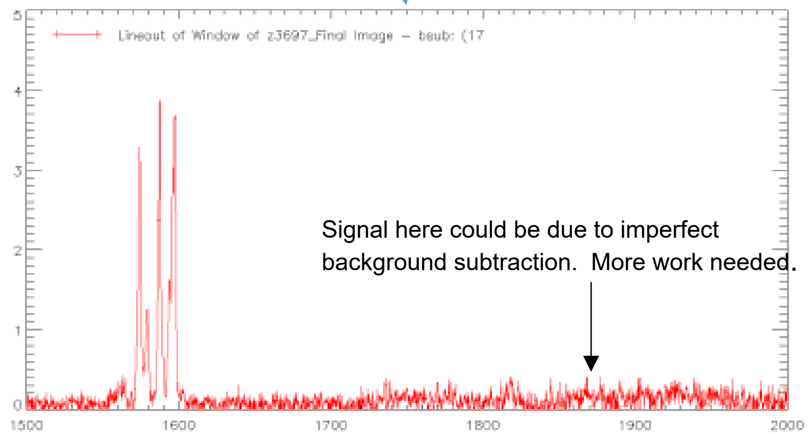
Focusing crystal and proximity to target make this our most sensitive X-ray diagnostic

K-shell emission from top of target could interfere with top-down imaging unless it's late-time

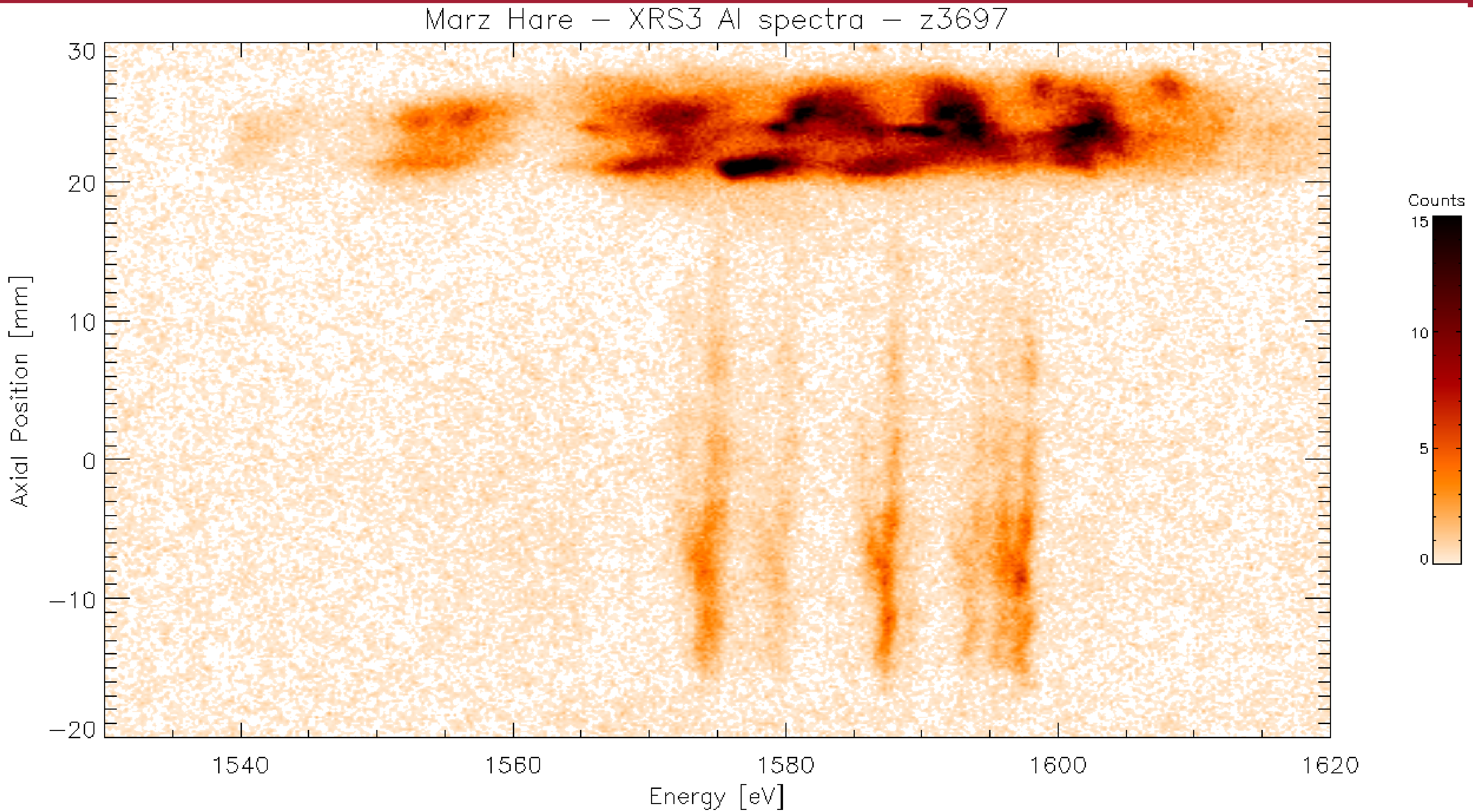






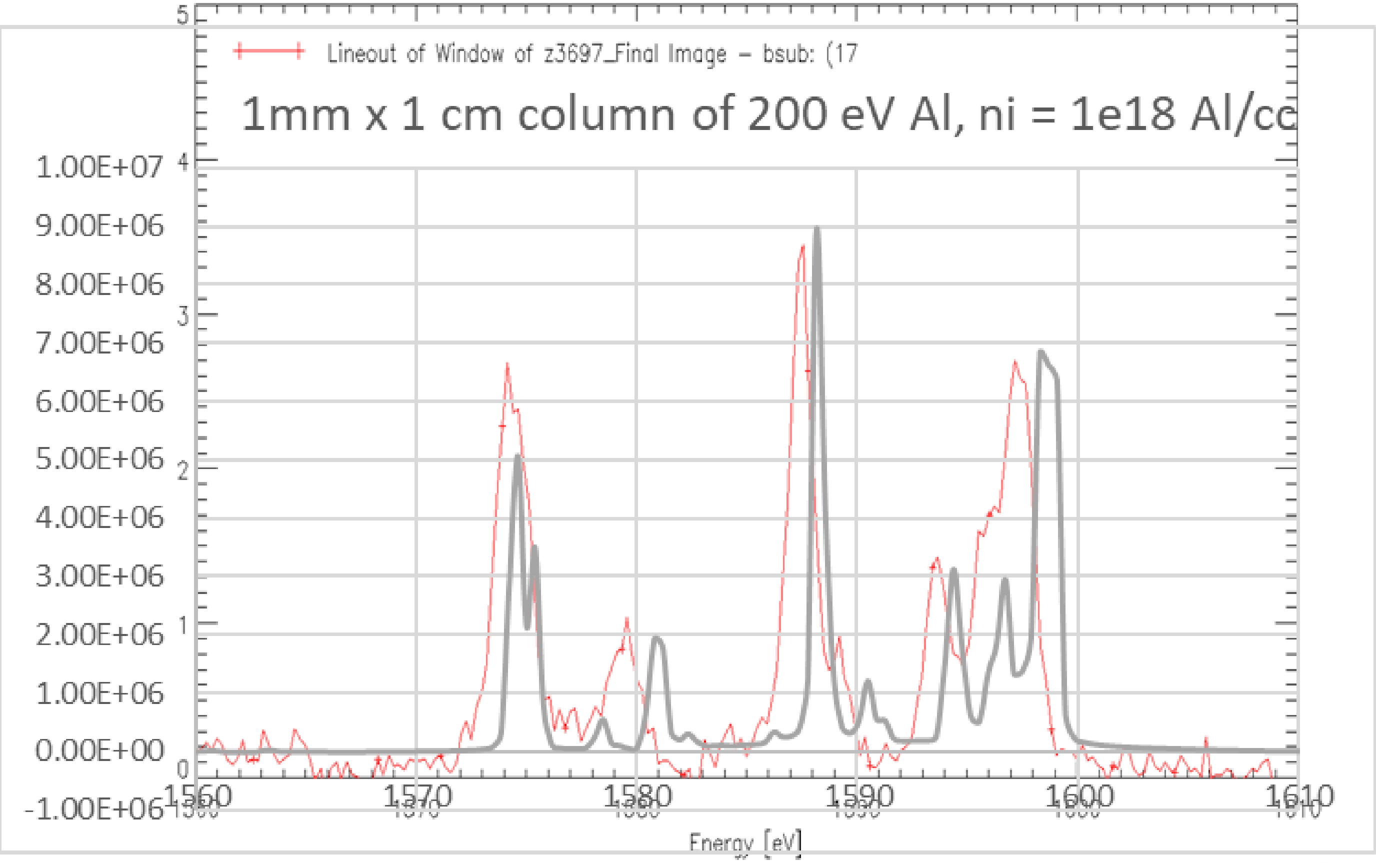


Processed data. Zoomed-in on Al He-alpha



Notes: Lines appear to split at z = -6 mm position. This could be due to the imaging in the dispersion plane where XRS3 sees two sources separated in the horizontal plane, or Doppler shifts.

Lineout of He-alpha region from z = -12.81 mm (Δz = 6 mm)

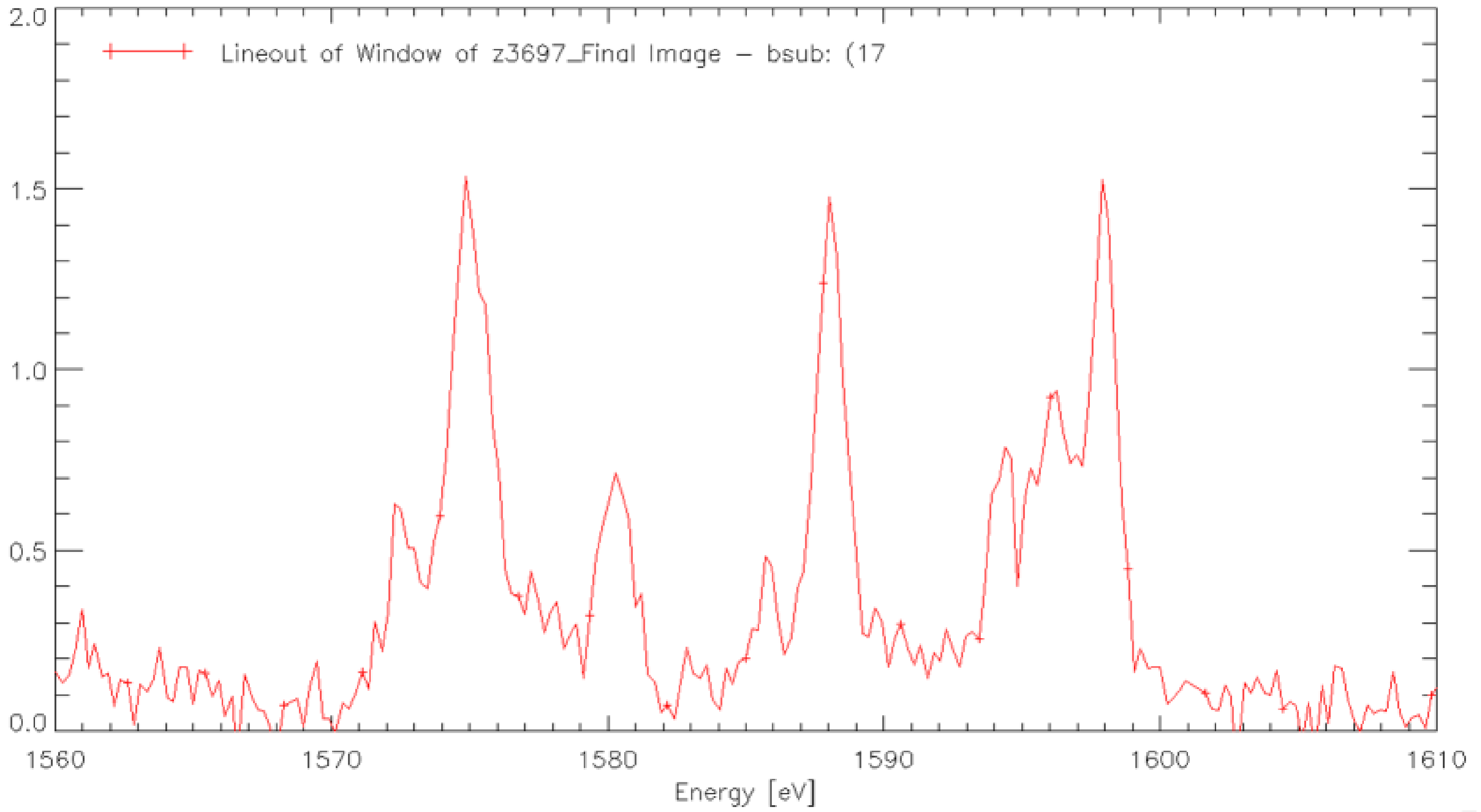


Overlay of experiment from z = -12.81 mm (red) with optically thick, unshifted SCRAM spectrum with rough best-fit conditions (black; $\tau \sim 15$)

Sat/IC ratio → temperature
res/IC ratio → $\tau \sim \Delta Y_{LOS}$ x density

Experimental spectrum has signatures of opacity broadening (Heα resonance broader than and less intense than Heα IC)

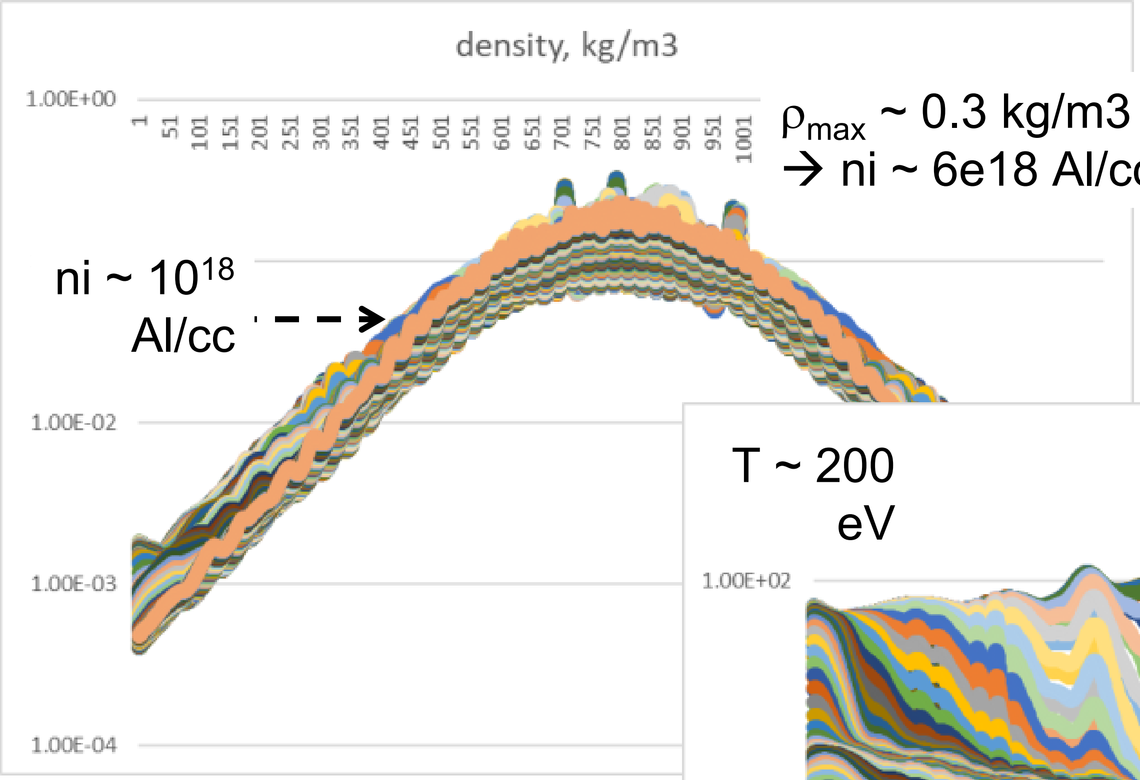
Lineout of He-alpha region from z = 4.27mm (Δz = 10 mm)

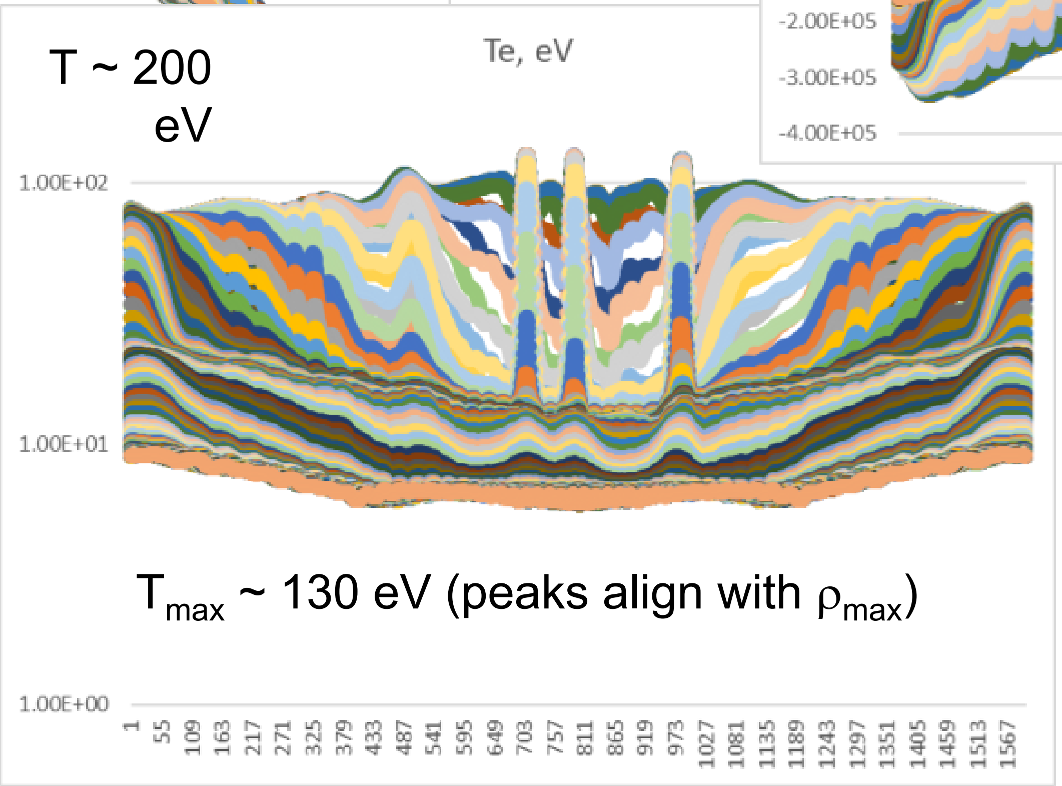


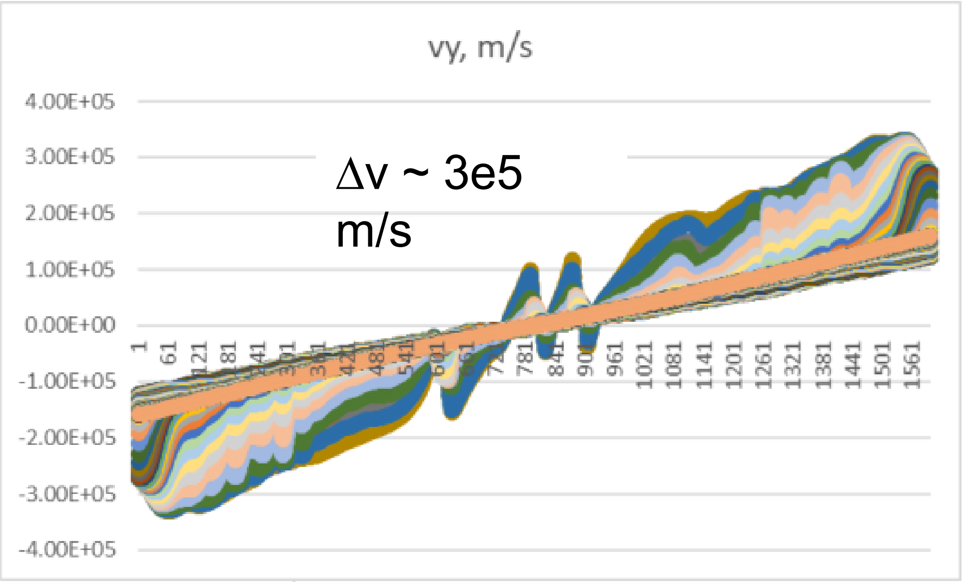
Split ~1.8 eV
→ Δv ~ 3e5 m/s,

Probably a little cooler and less optically thick than previous spectrum

XY Lineouts from Simulations

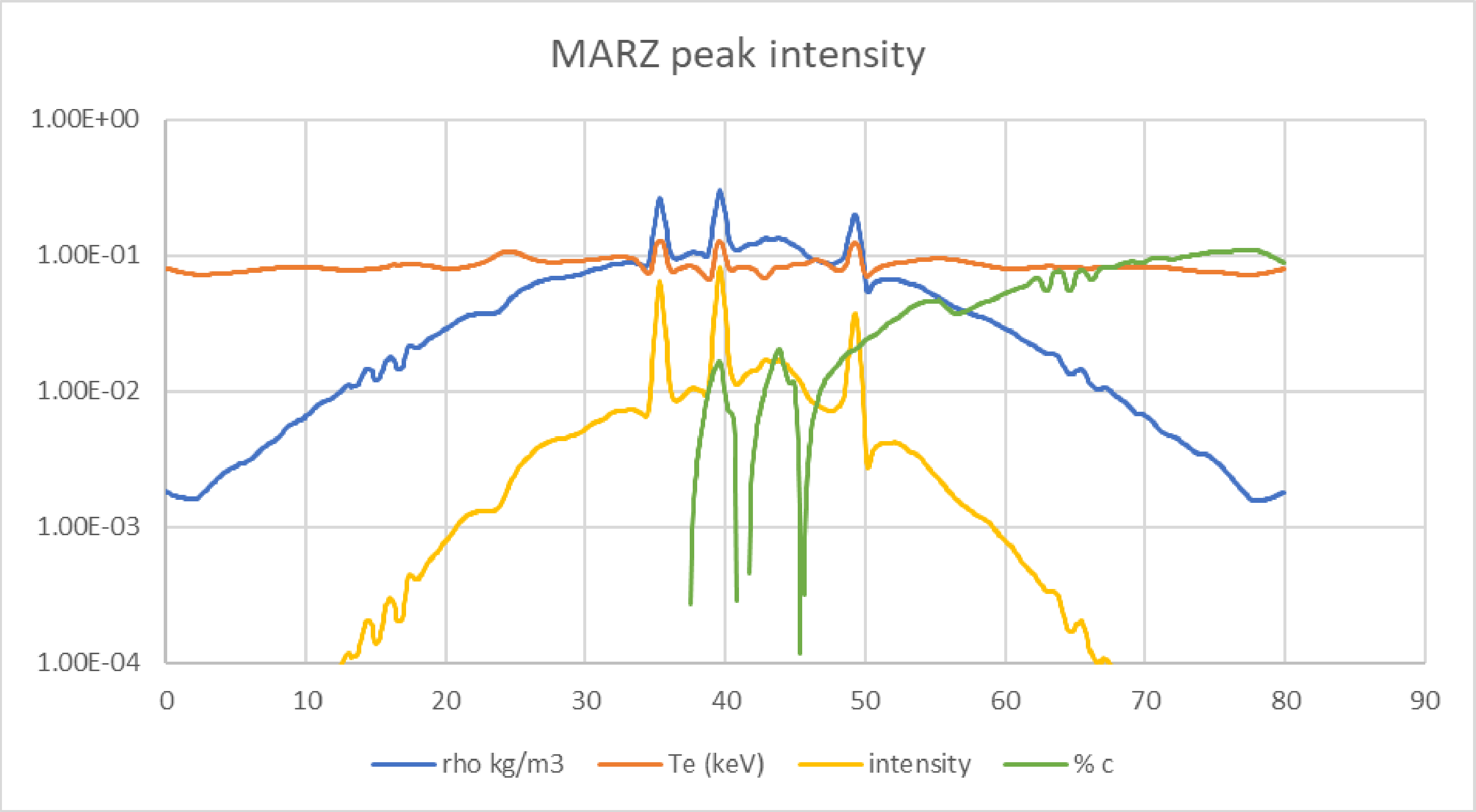






Density, temperature, and velocities are in pretty good agreement with rough first-cut analysis:
~1mm @ ni ~ 1e18 Al/cc
T <~ 200 eV,
Δv_Y ~ 3e5 m/s

Select X column with peak intensities ~ $n_i^2 e^{-1.6keV/T}$



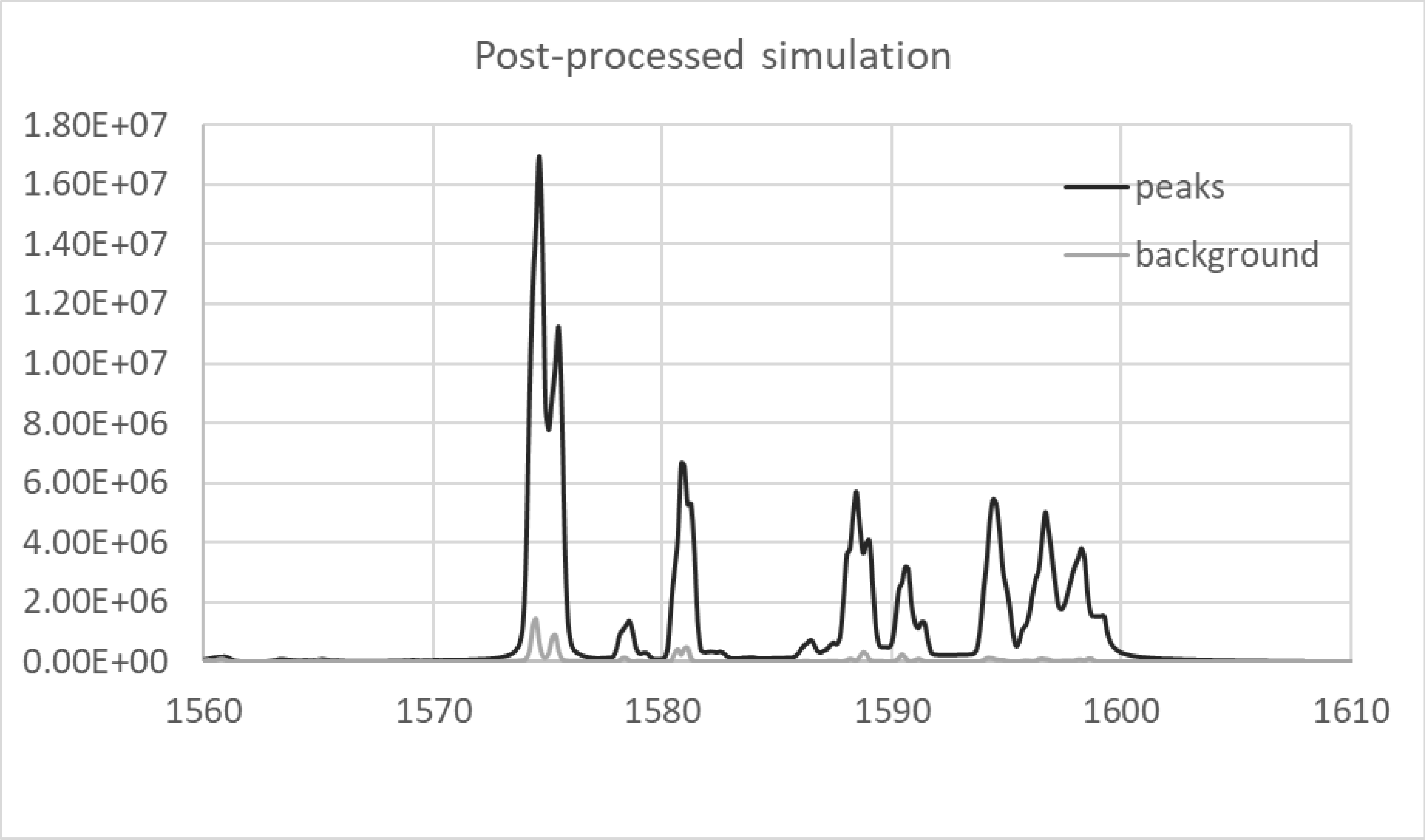
Model plasma as three 1 cm x 0.6 mm columns of 5e18 Al/cc plasma (τ ~ 60) with ~ 20 mm low-level background

Peaks: 130 eV with Doppler shifts from v_Y

1. -0.17 eV
2. +0.26 eV
3. +0.31 eV

Background: 90 eV, 2e18 Al/cc (thin)

Post-processed simulation



(3) 1 cm x 0.6 mm columns of 130 eV, 5e18 Al/cc plasma ($\tau \sim 60$) :

Temperature seems a bit too low (satellites)

Optical depth (density?) seems a bit too high

Doppler shift (net 0.5 eV) seems a bit too small (broadens but doesn't split lines)

Background contributes negligible emission