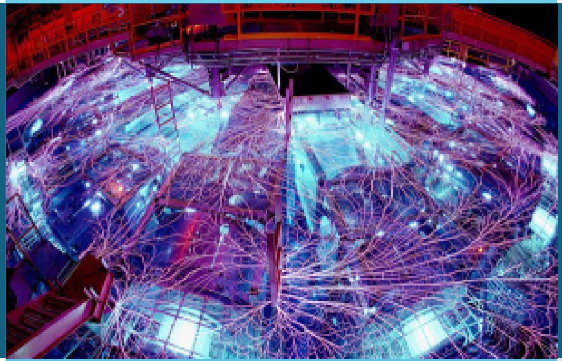
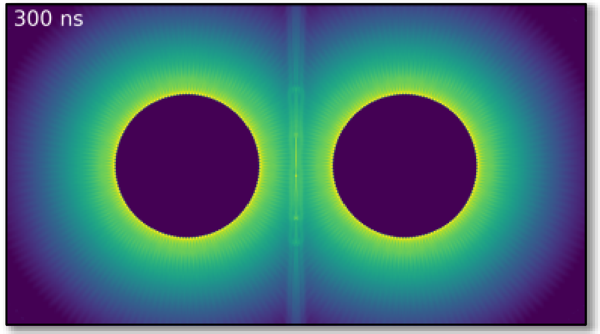
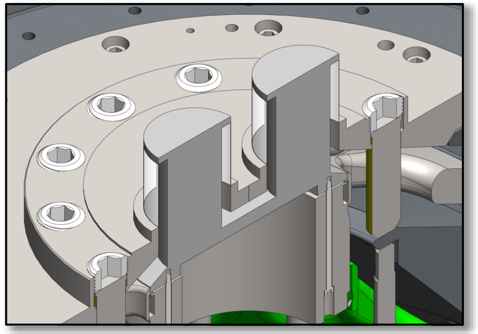
SAND2021-9729C

Sandia National Laboratories



Simulations and design of MARZ
Magnetically Ablated Reconnection on Z





PRESENTED BY

Jack Hare, Clayton Myers, and the MARZ team

Z Fundamental Science Workshop – August 10, 2021

The MARZ collaboration has been awarded four ZFS shots over two years

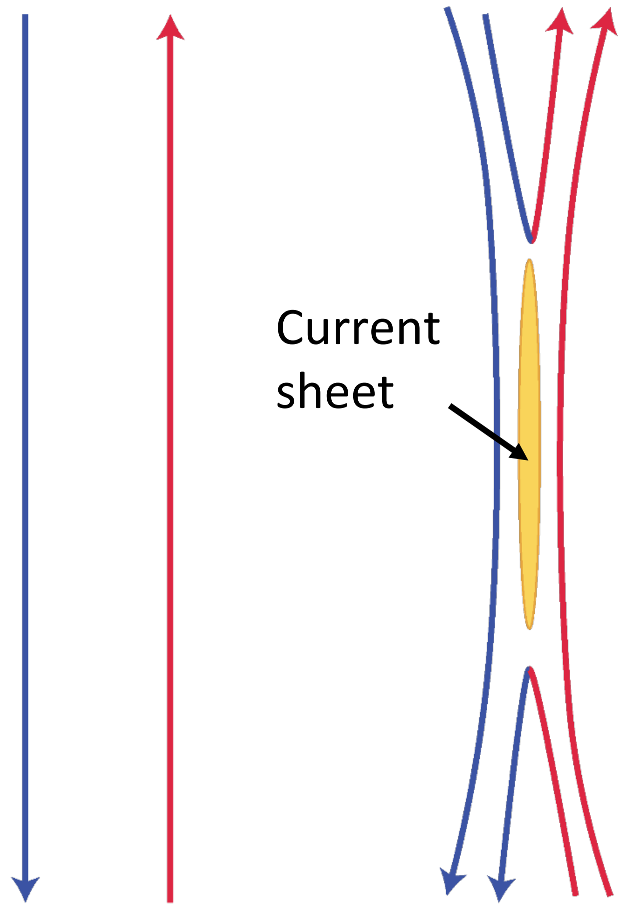
MIT	Jack Hare (PI) and Rishabh Datta
Imperial College	Sergey Lebedev, Jerry Chittenden, Jack Halliday, and Aidan Crilly
Princeton University / PPPL	Will Fox and Hantao Ji
University of Michigan	Carolyn Kuranz and Raul Melean
University of Colorado Boulder	Dmitri Uzdensky
Sandia National Laboratories	Clayton Myers (PI), Chris Jennings (PD), Dave Ampleford (PM), Carlos Aragon (LH), Kris Beckwith, Tony Colombo, Greg Dunham, Aaron Edens, Matt Gomez, Josh Gonzalez, Stephanie Hansen, Eric Harding, Roger Harmon, Michael Jones, Jeff Kellogg, Guillaume Loisel, Quinn Looker, Leo Molina, Sonal Patel, Gabe Shipley, Tim Webb, and David Yager-Elorriaga.

MARZ grew out of discussions in the Magnetized HED breakout session at the 2020 ZFS Workshop.

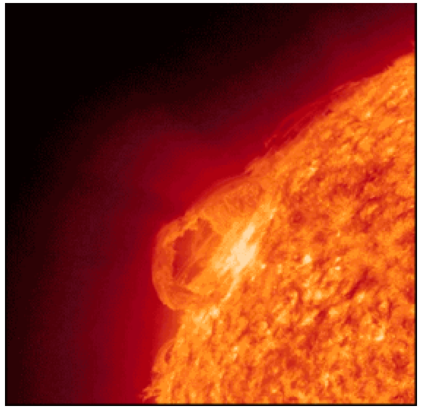
The first of four MARZ experiments is scheduled for December 2021.

Fri 12/03/21	18	FS	Hare MARZ	A1128A	Planned		Myers, C.

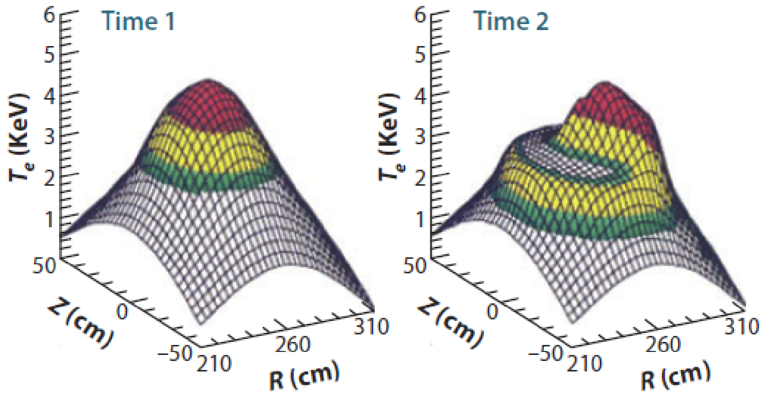
Magnetic Reconnection: a Fundamental Plasma Physics Process



Solar flare



Sawtooth crash (TFTR)

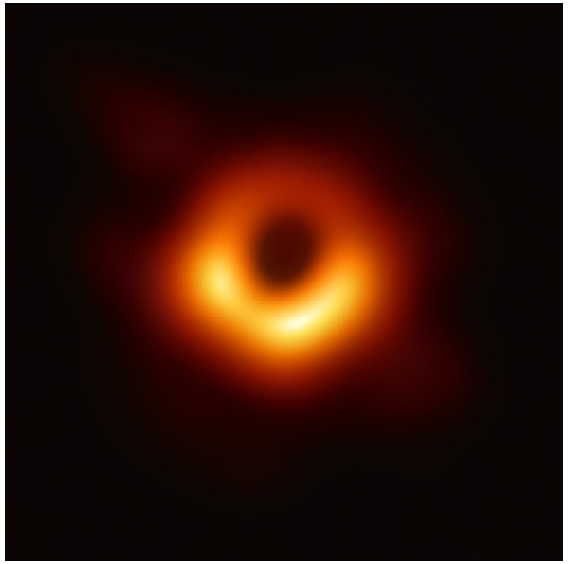


- Changes topology of field lines, allowing for sudden eruptions
- Converts magnetic energy into thermal and kinetic energy, and accelerates particles to high energies
- Important in:
    - Magnetic confinement fusion
    - Space weather: CMEs, damage to satellites
    - Astrophysics: drives rapid change in astrophysical objects

Radiatively Cooled Magnetic Reconnection

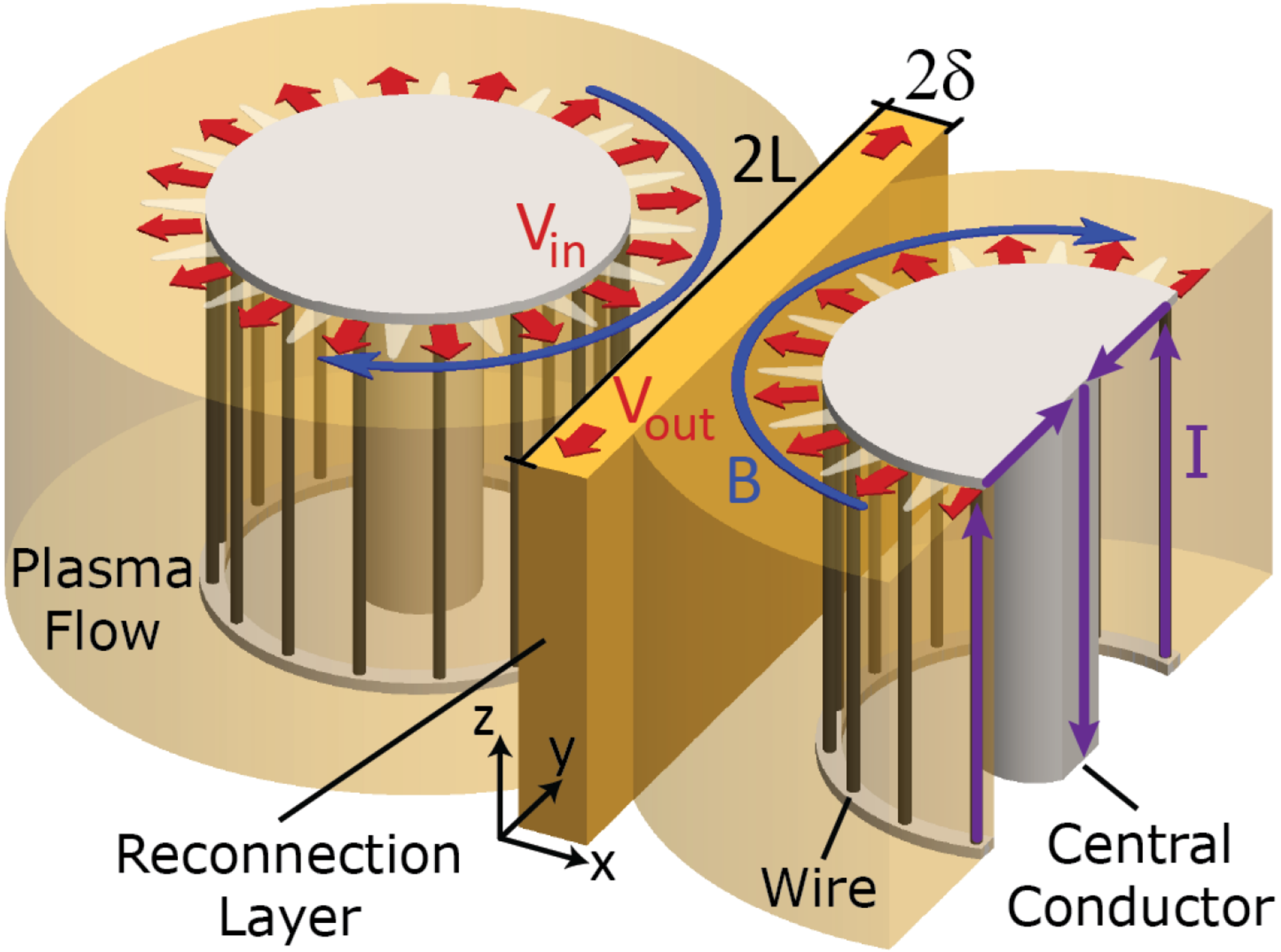
Artist's impression of a black hole

M87 EHT



- Cooling is a **significant loss mechanism**, modifies energy partition
- Cooling can lead to **instabilities**, radiative collapse, cessation of reconnection
- See Uzdensky & McKinney "Magnetic reconnection with radiative cooling. I. Optically thin regime." *Physics of Plasmas* **18**, 042105 (2011).

Scaling up the MAGPIE Platform



Double exploding wire arrays

- Sustained flows
- Quasi-2D
- Collisional
- No guide field

Scaling from 1 MA to 20 MA:

- Density ~ I^2
- Magnetic Field ~ I

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

Hare, J. D. *et al.* ***PRL*** 2017

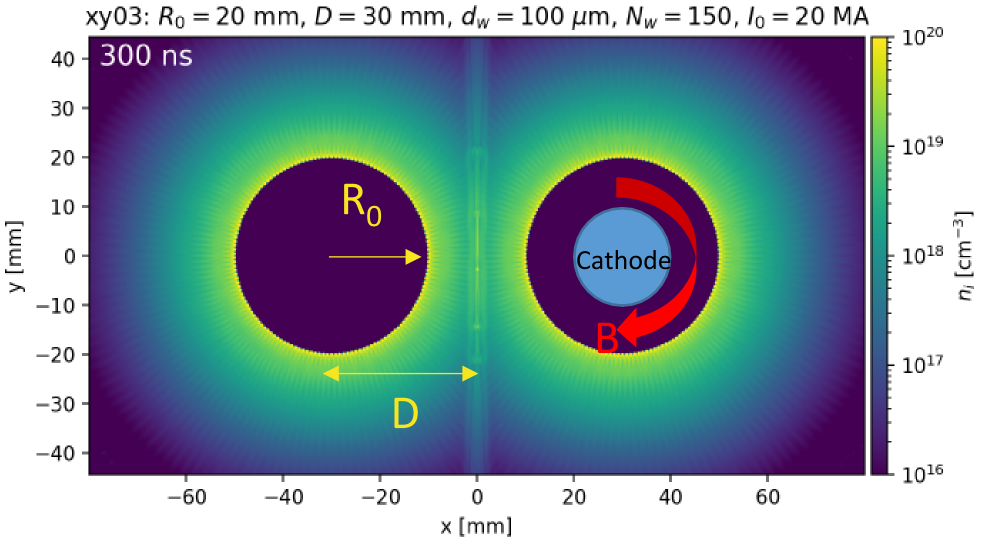
Suttle, L.G. *et al.* ***PoP*** 2017

Hare, J. D. *et al.* ***PoP*** 2018

Hare, J. D. *et al.* ***PoP*** 2018

Simulations: GORGON MHD in 2D

GORGON is a 3D Eulerian resistive MHD code with radiation loss and separate ion and electron energy equations



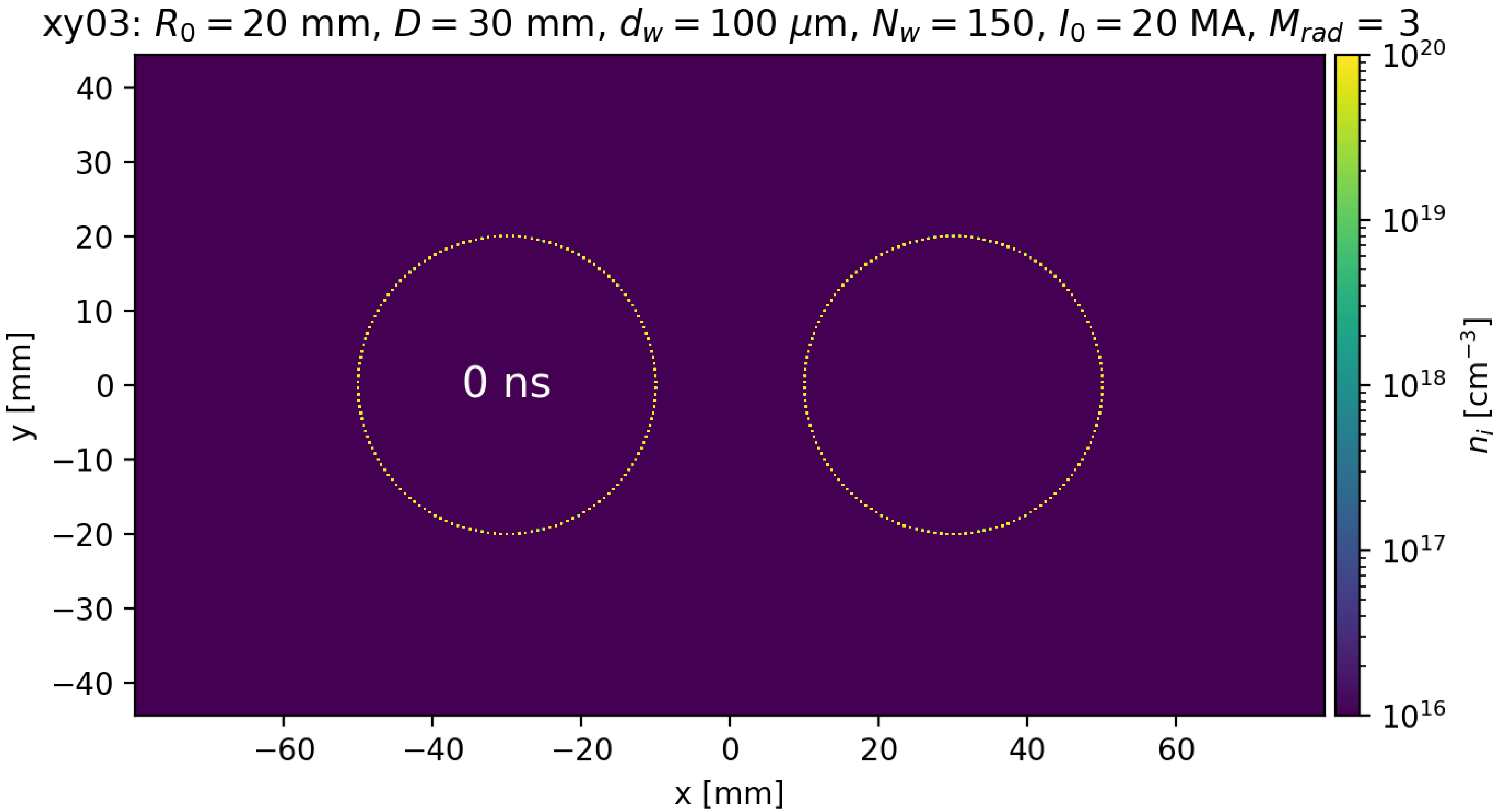
See A. Crilly, 11:30 am today in Theory/Modeling/Computation session

- Two exploding wire arrays, driven by Z current pulse (20 MA, 300 ns rise)
- 2D sims, 50 um resolution, 180x90 mm: 16 hrs on 256 cores.
- Resistive MHD with recombination radiation loss:

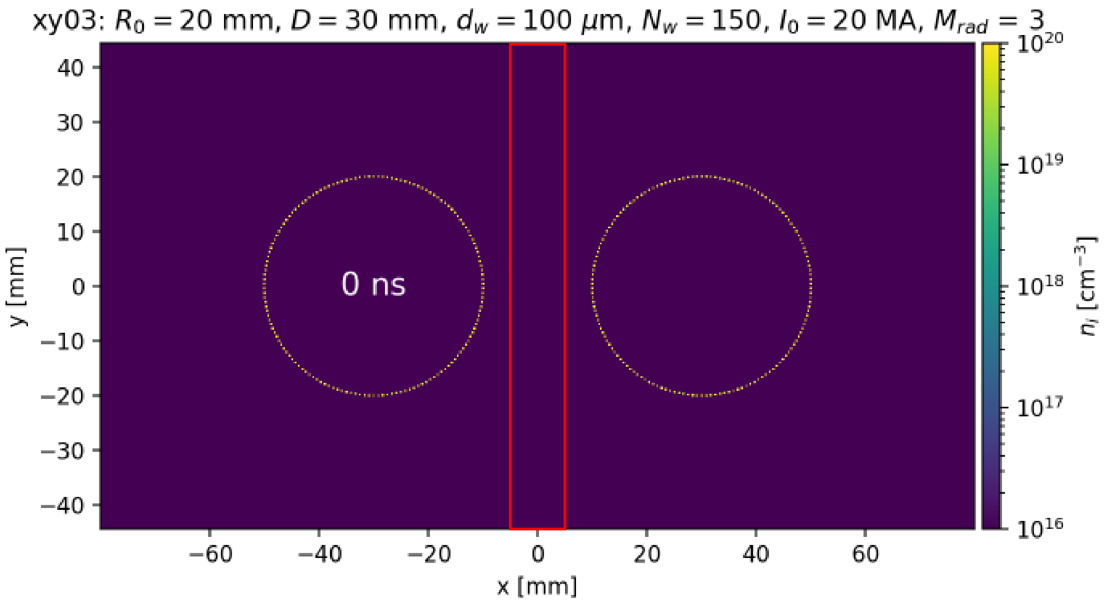
$$P_{rad} = M_{rad} n_e\, T_e^{1/2} (Z^2 n_i E_\infty^{Z-1}/T_e),\ \text{where } M_{rad} \approx 3$$

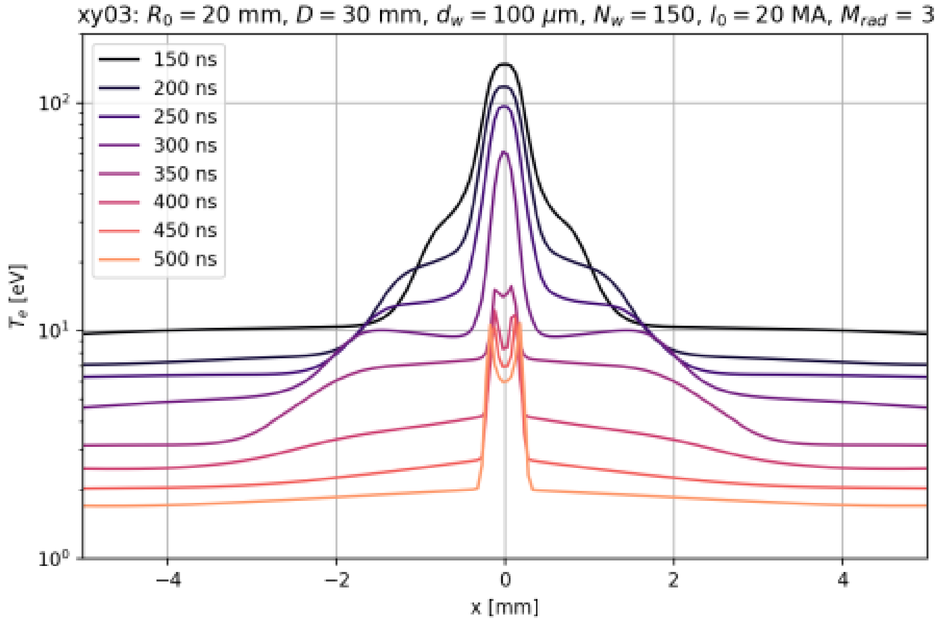
- More advanced calculations now available with tabulated emissivities

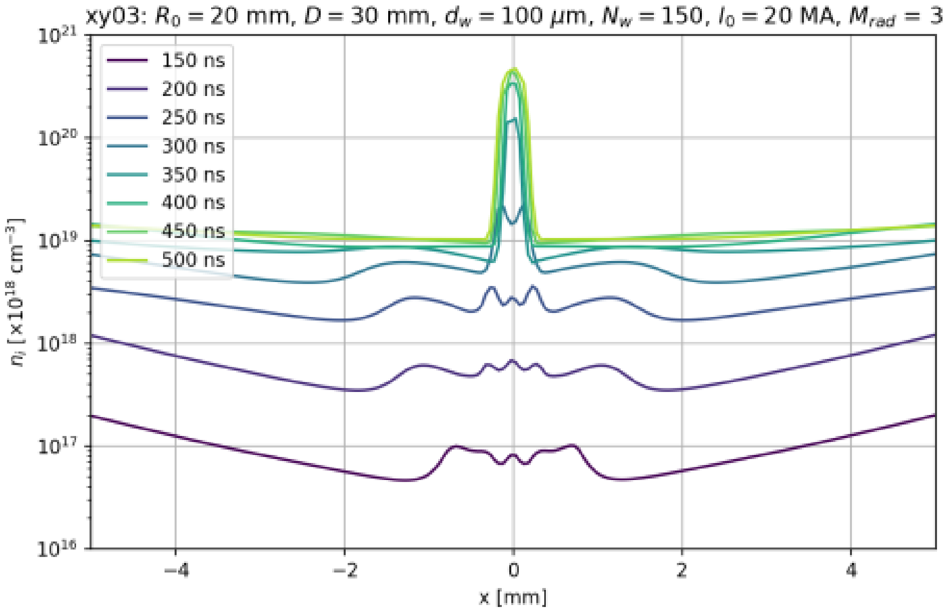
Plasmoids and Radiative Cooling

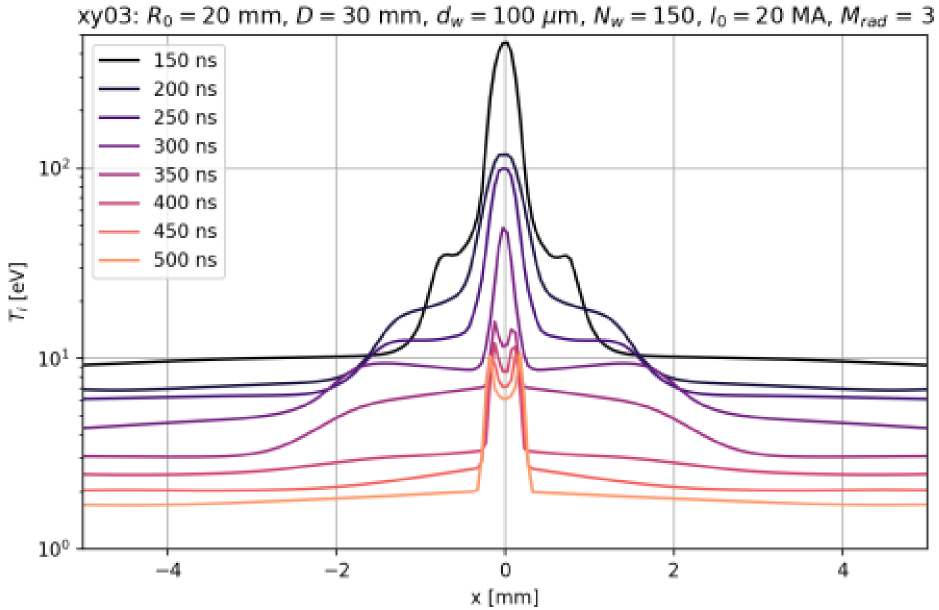


Plasmoids and Radiative Cooling

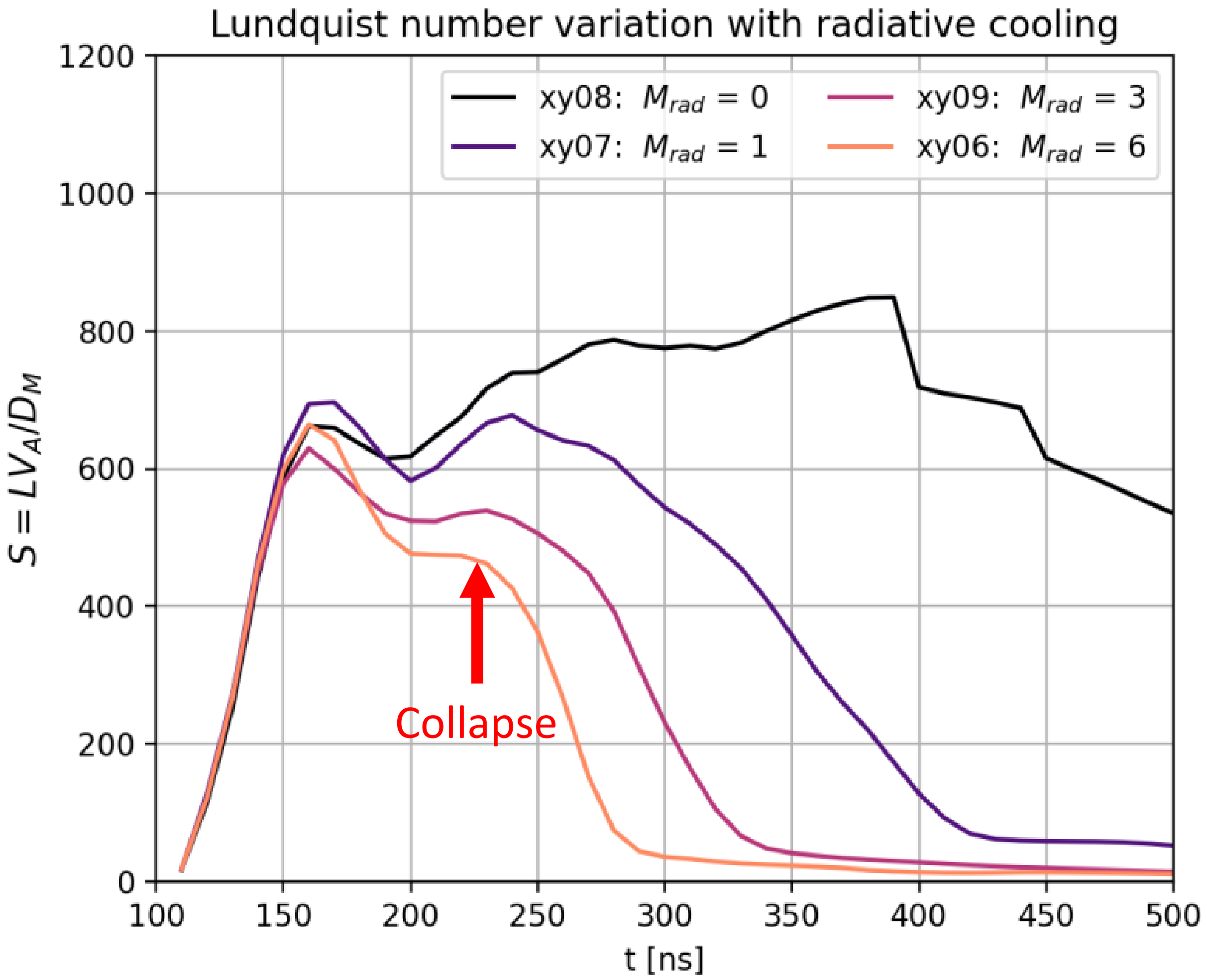








Collapse process due to radiative cooling

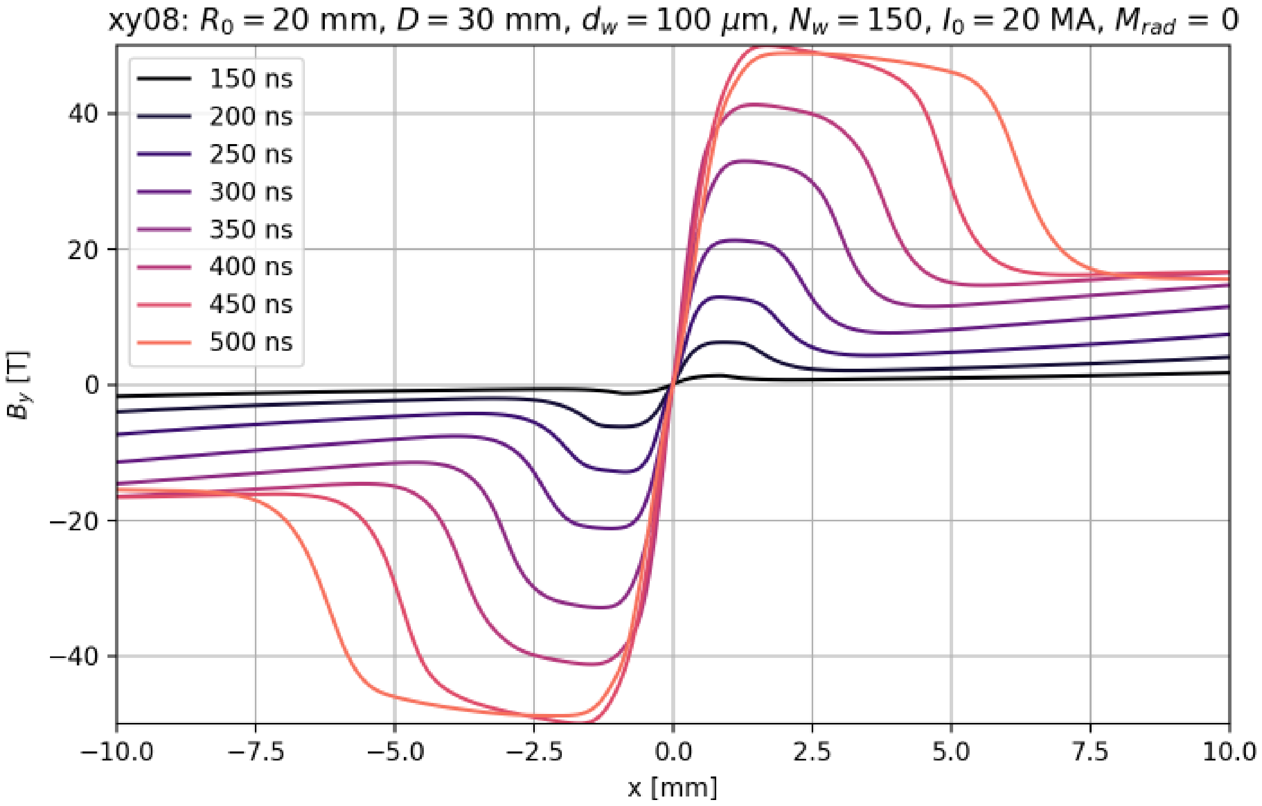


- S calculated with $j(L) = j(0)/2$
- Initially high S in hot layer. Plasmoids form below $S_c = 10^4$ due to density perturbations.
- Collapse time depends on radiative cooling strength
- System transitions from a 2D reconnecting to 1D diffusive

Magnetic fields: radiative collapse limits B-field pileup

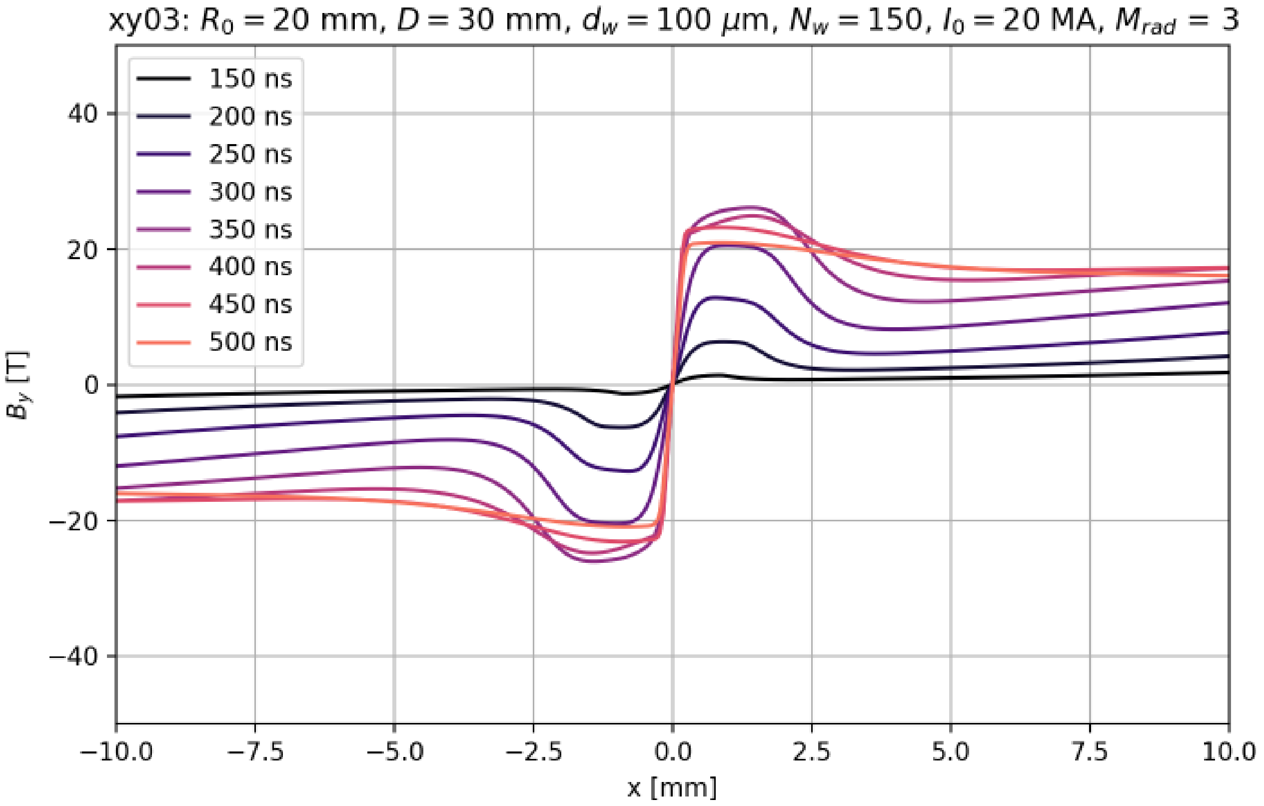
No Cooling

Pileup continues

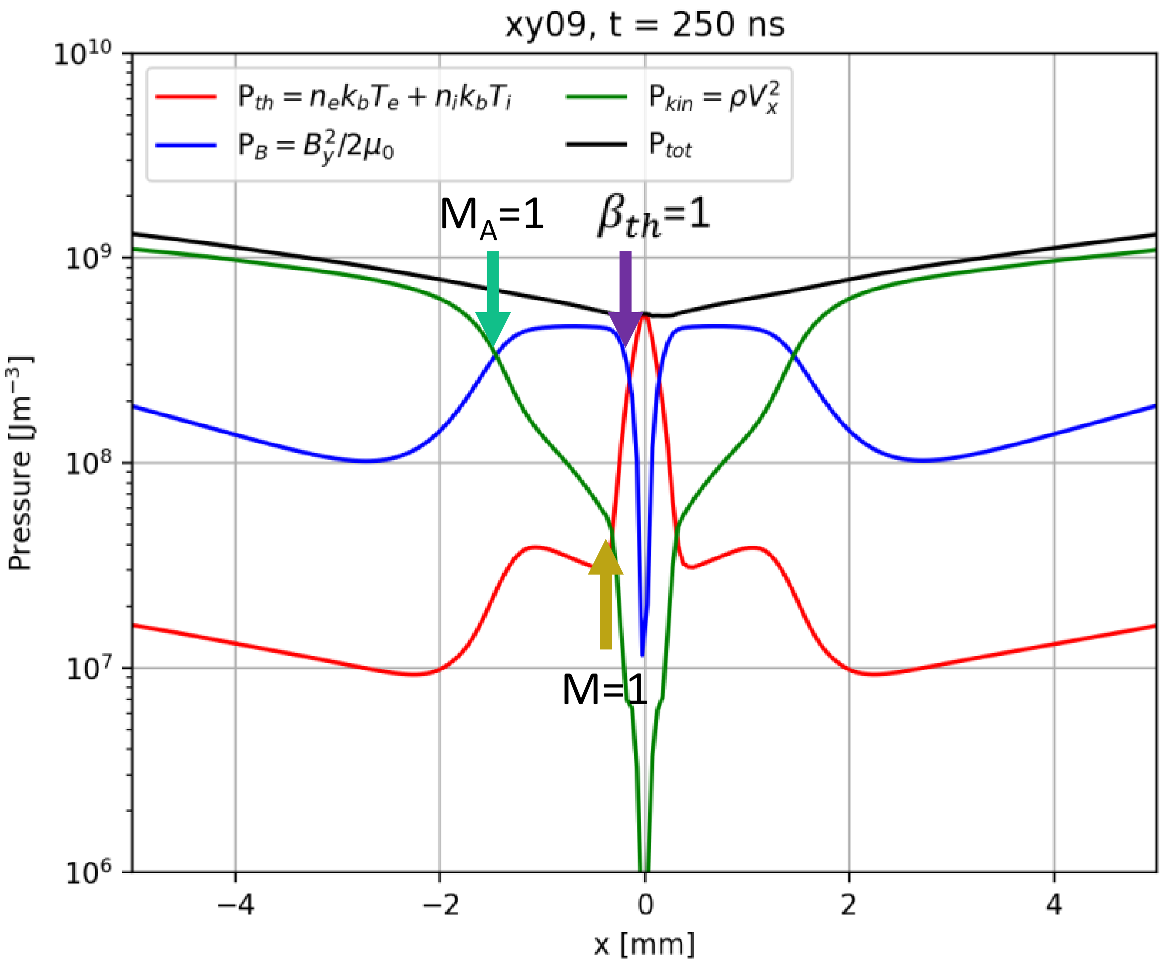


Cooling

Pileup ceases after collapse



Magnetic precursor decelerates flow, thermal beta low



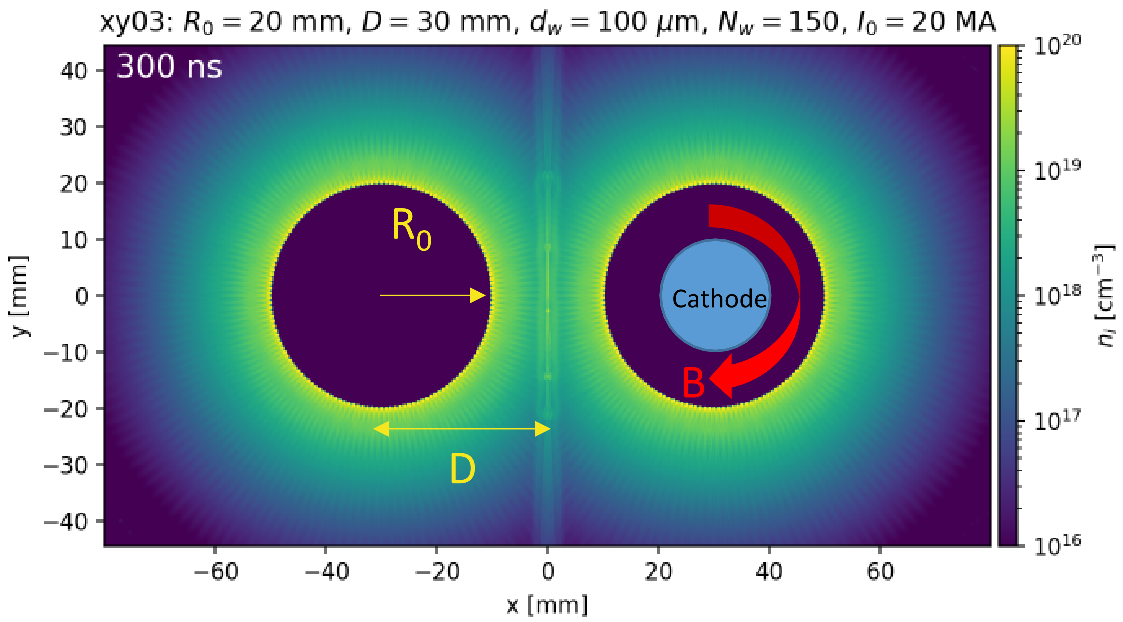
Experimental objectives for MARZ

Primary objectives:

1. Test whether an inverse wire array magnetized ablation platform can be scaled up to Z.
2. Test whether the plasma conditions and the radiative evolution of the MARZ reconnection layer can be diagnosed.

Secondary objectives:

1. Characterize magnetic shock formation in front of obstacles placed in the ablation stream.

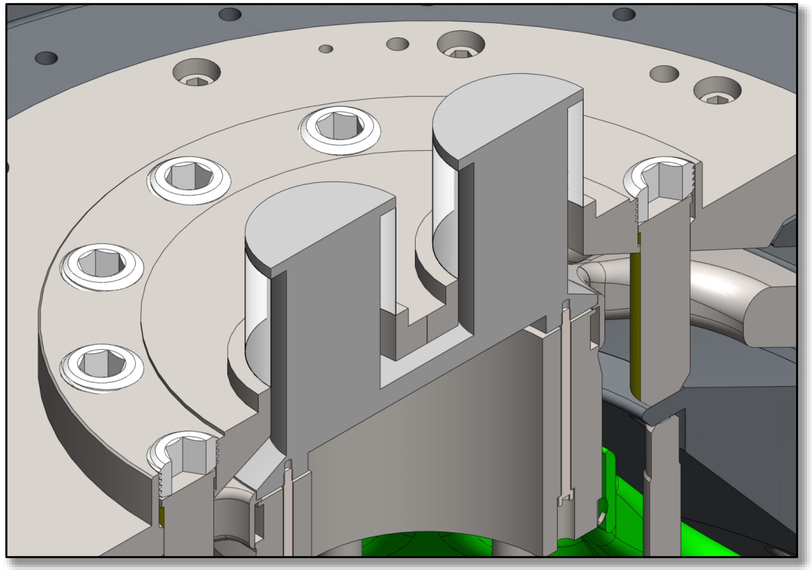


We need to develop a new (to Z) inverse wire array source for these experiments.

The MARZ objectives and diagnostics are chosen to distribute risk and provide information on potential failure modes.

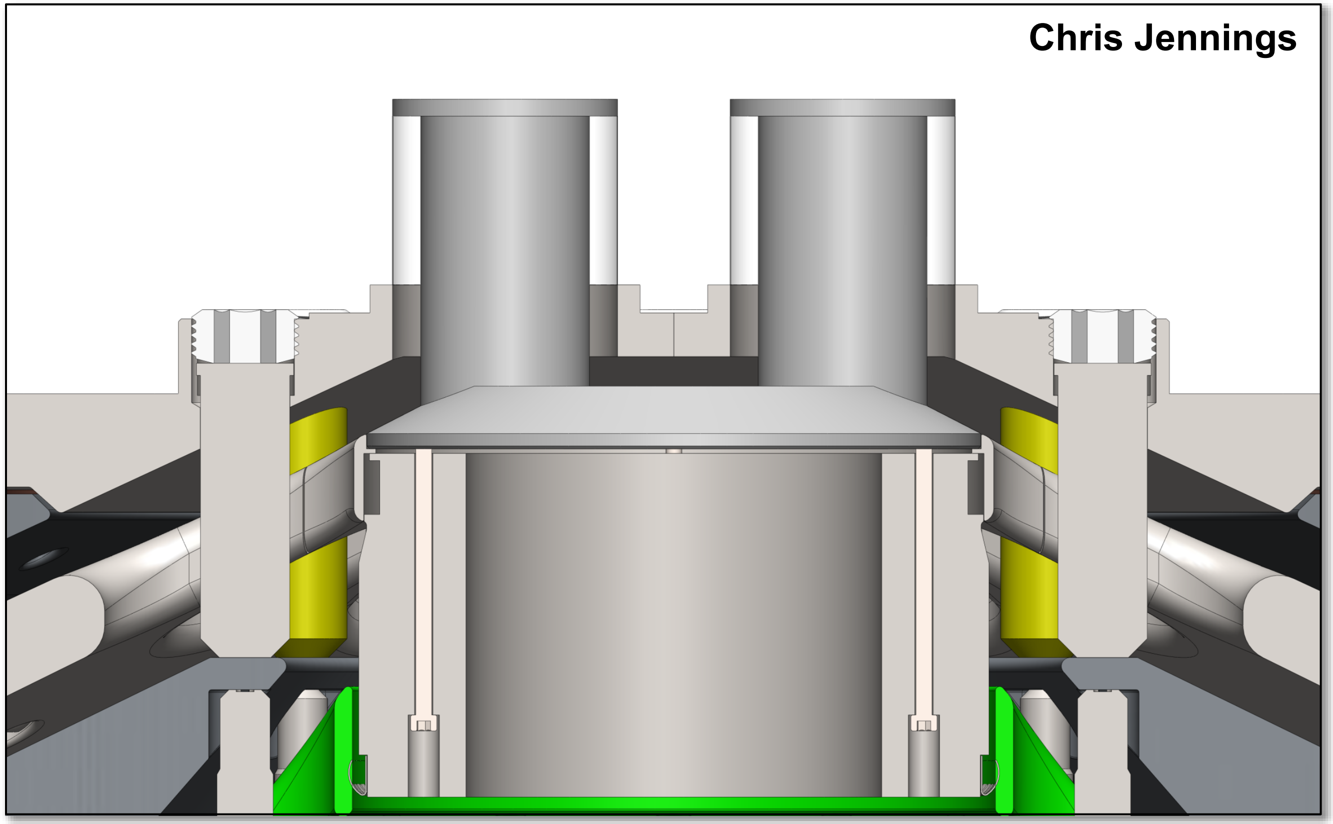
The complexity of the diagnostic load for the first experiment is still being evaluated.

We will attempt to split the inner MITL and deliver ~10 MA to two side-by-side inverse wire arrays in 300 ns.



Inverse wire arrays: 150 wires each, 75 µm aluminum, 40 mm array diameter, 60 mm center-to-center distance, 40 mm tall.

Expect an inner-MITL inductance of 2–3 nH (quite low).



This type of split inner MITL has not been fielded before on Z.

The most insidious feature is a magnetic null on axis.

Expect current loss to saturate rather than run away.

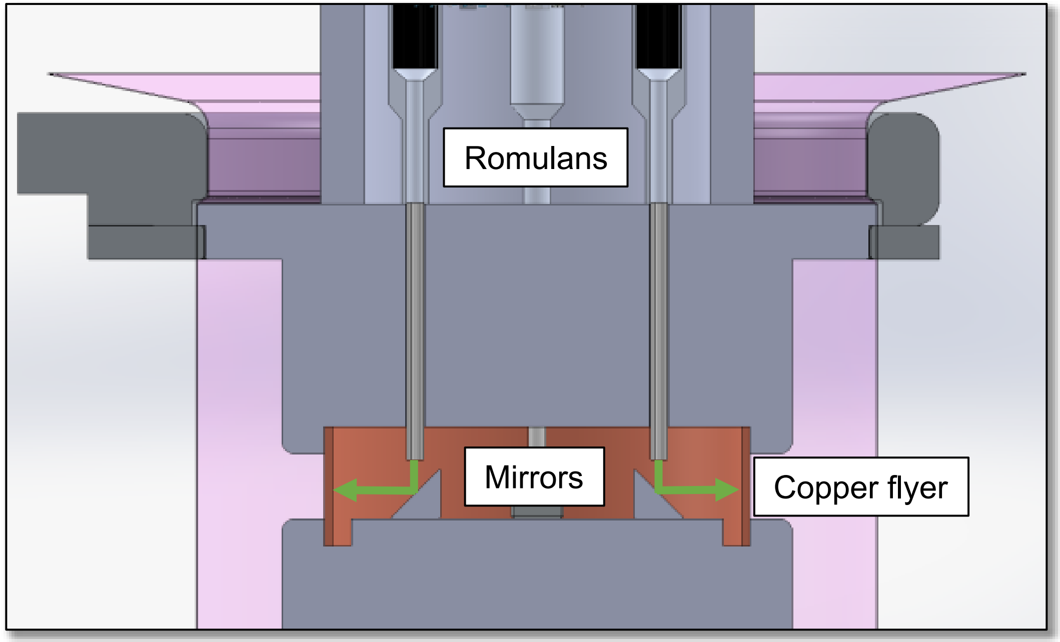
Diagnosing current delivery [P1]

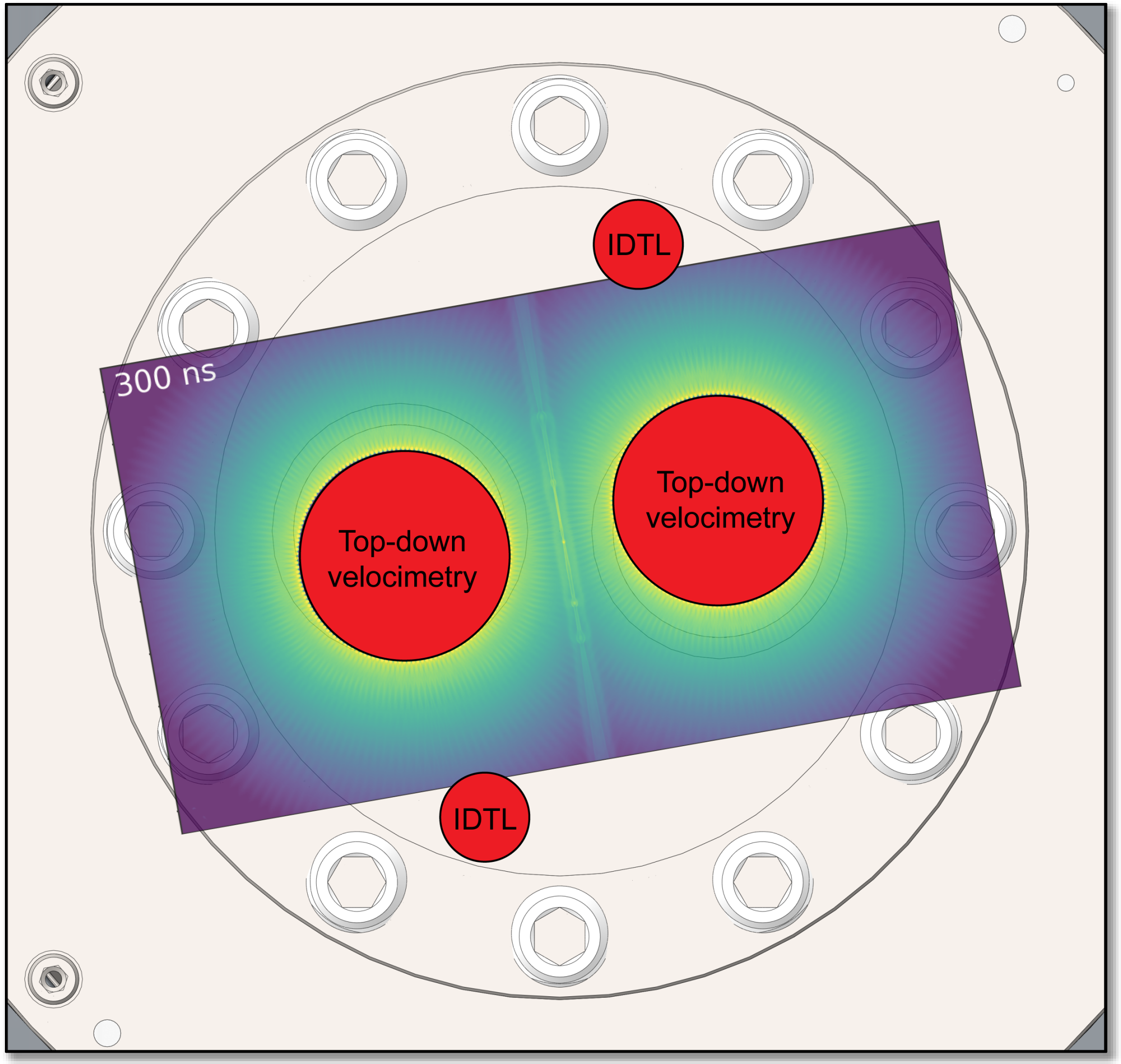
Inner MITL current delivery:

- 2x IDTLs (inductively driven transmission lines).

Load current velocimetry:

- Embed imploding flyer in center post.





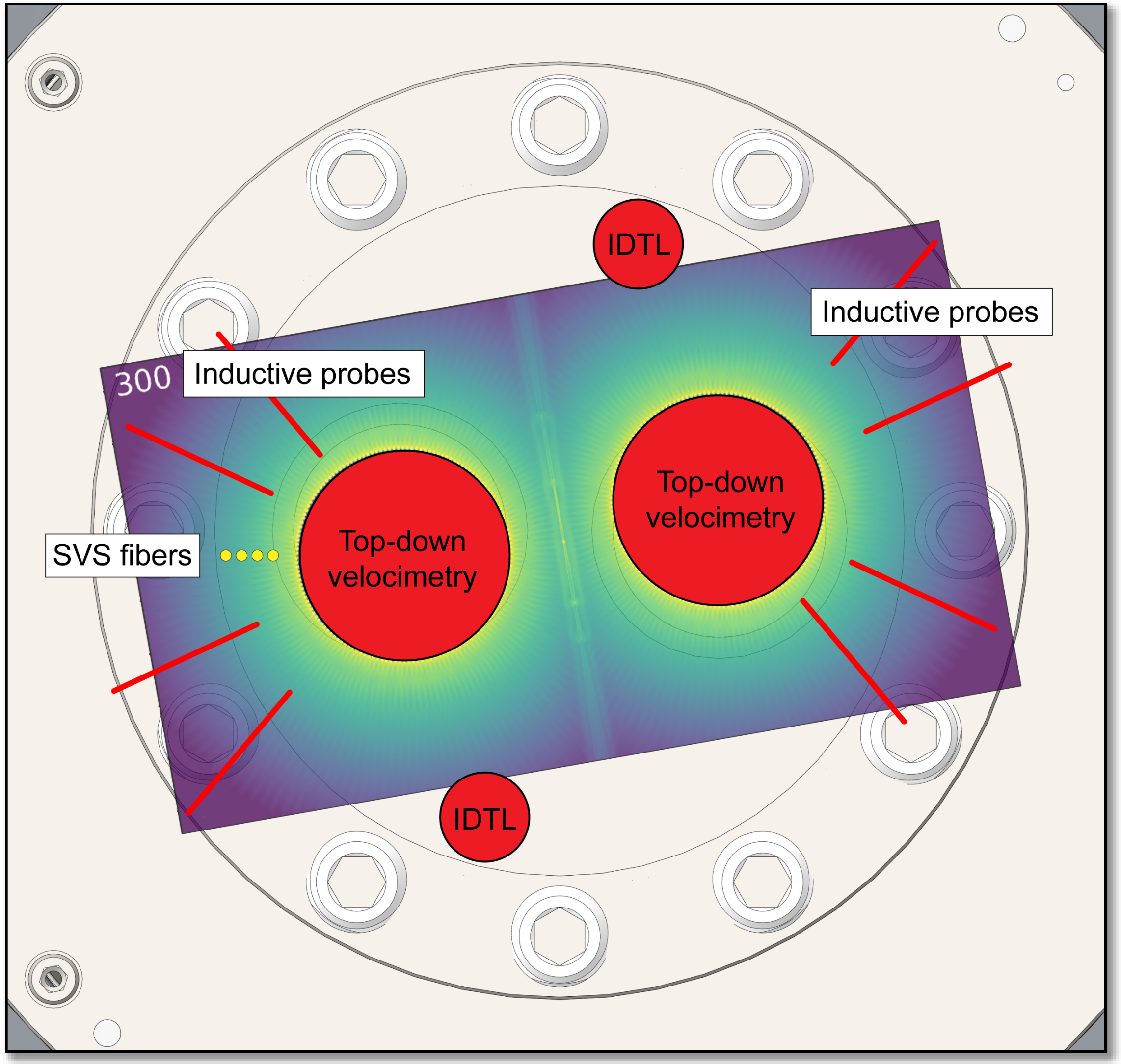
Diagnosing the ablation streams [P1]

Inductive probe array:

- 8x probes (four per wire array) in the unperturbed ablation streams.
- Measure the advected magnetic field at different radial positions.
- Radial locations = 25, 28, 31, 34 mm from the center of each array.
- Azimuthal spacing = 25° as shown.

Streaked Visible Spectroscopy (SVS) fibers:

- Four top-down SVS fibers at the same four radii as the inductive probes.
- Look for ablation stream arrival time to correlate with inductive probes.
- Attempt to measure the magnetic field via Zeeman splitting of the Al-III line.



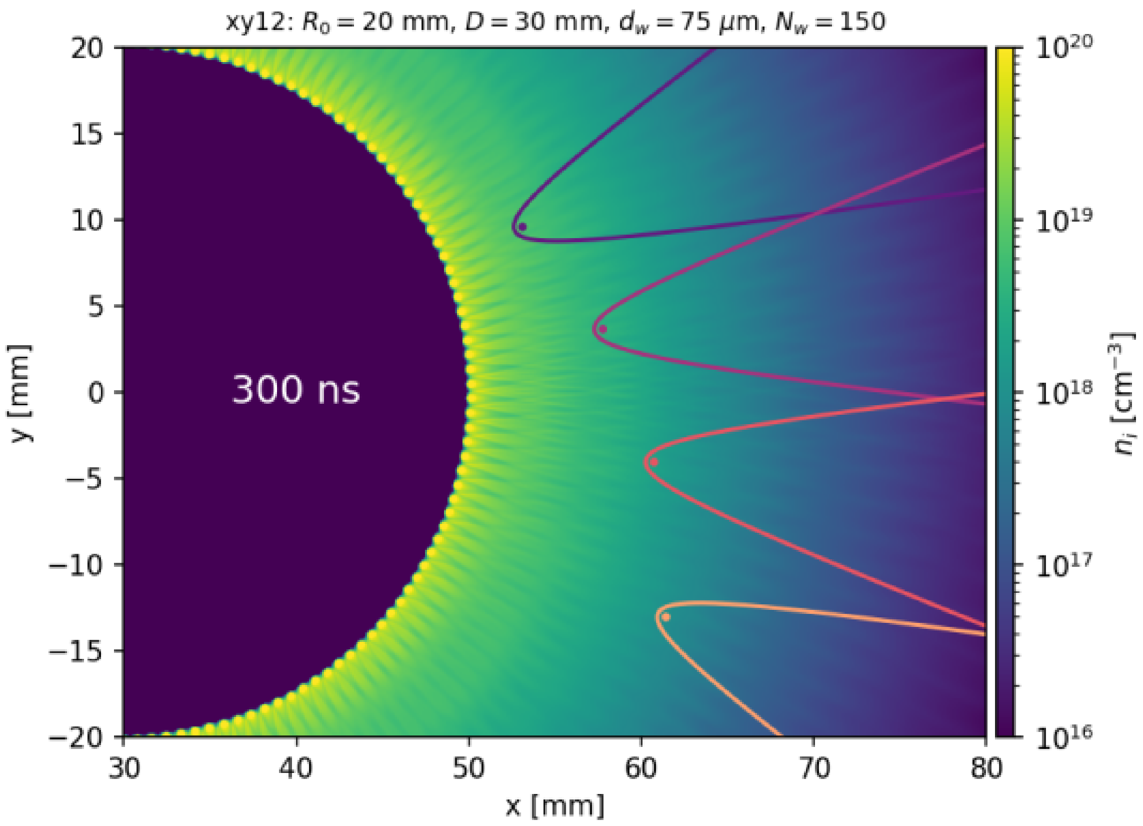
B-dot measurements to determine field strength and flow velocity [P1]

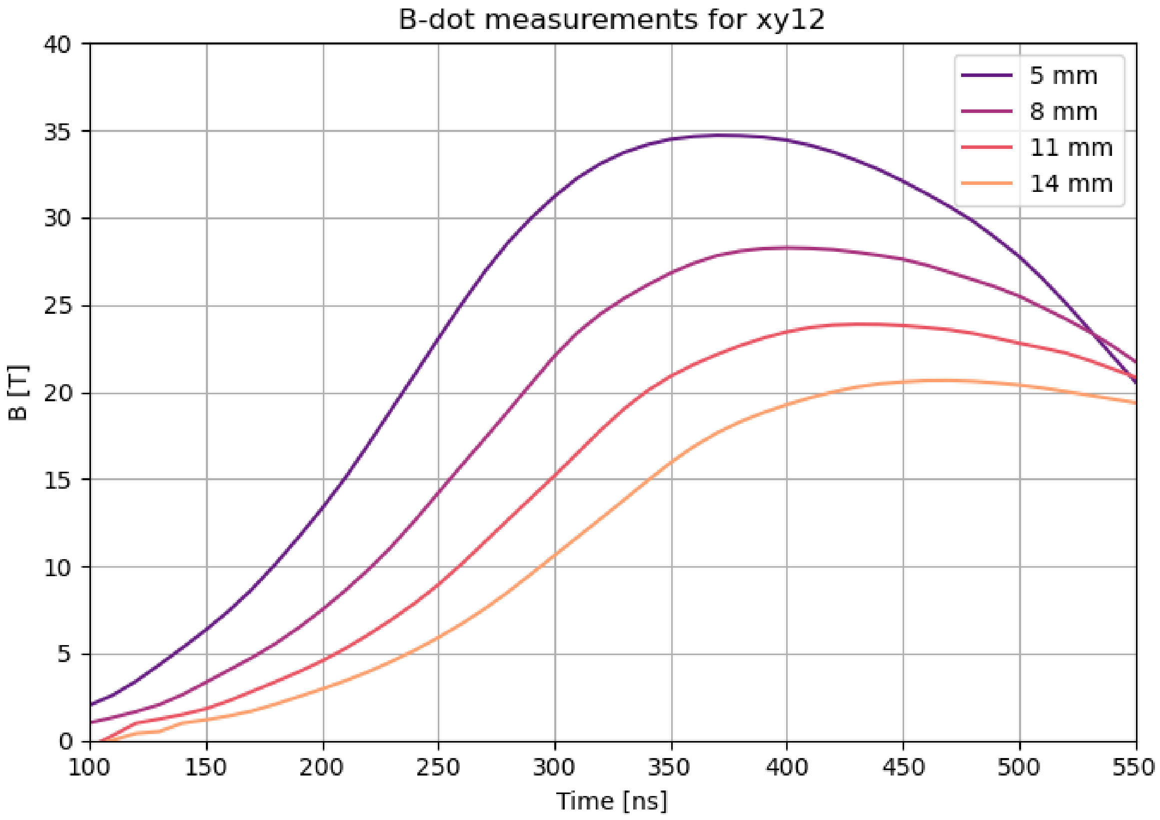
B-dots located 5, 8, 11 and 14 mm from wires

Expected half-opening-angle of Mach cones $< 14^o$, so probe separation must be $>15^o$.

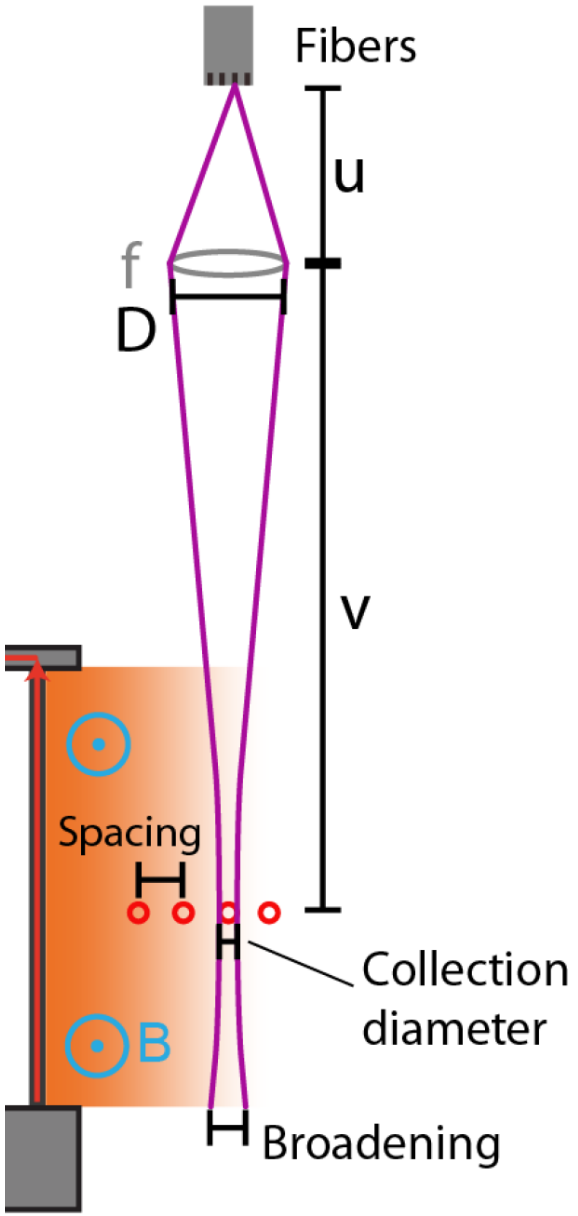
ToF gives $V \approx 100$ km/s ($V \approx 75$ km/s in sims)

$$R_M \approx 20$$





SVS will image optical self emission at the B-dot radial locations [P1]



SVS = Streaked visible spectroscopy

Four fibers coupled to streaked visible spectrometer:

- Time of flight from spectrally integrated signal
- Constrain density and temperature using atomic lines
- Possibility to use Zeeman splitting of Al III to measure B-field

Use a single lens imaging system onto a four-fiber linear array. Constraints:

- Collection volume diameter < 0.5 mm, $M < 5$ for 100 um fibers.
  M=5
- Must fit within blast shield, $u + v < 400$ mm:
  f= 50 mm, u = 300 mm, v = 60 mm
- Spacing of collection volumes = 3 mm = M x fiber spacing.
  0.6 mm fiber spacing
- Minimize broadening of collection volumes,
  D = 12.5 mm, 0.1 NA

In-plane diagnostics for the reconnection layer [P2]

Diodes and imaging:

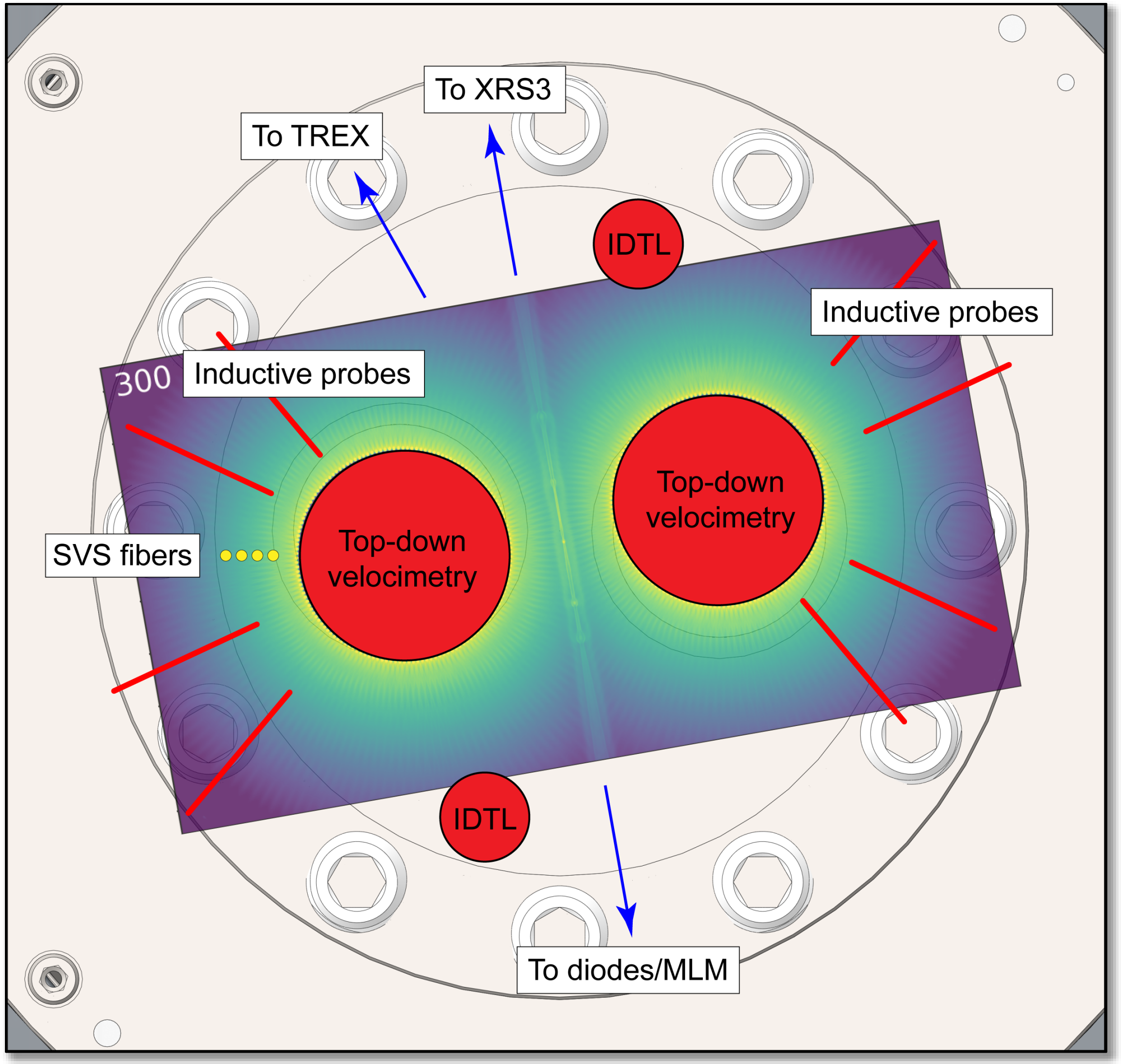
- LOS 170 diodes (6 slots).
- MLM (multi-layer mirror) for gated X-ray imaging (24 frames across three MCPs).

Spectroscopic survey:

- XRS3-RR at LOS 350 for time-integrated Al K-shell spectra.
- TREX at LOS 330 for time-integrated and MCP gated spectral survey.

TADPole stand-alone diodes (3x).

- Look for background, reconnection layer, and bow shock emission.
- Build mounts into the blast shield lid.

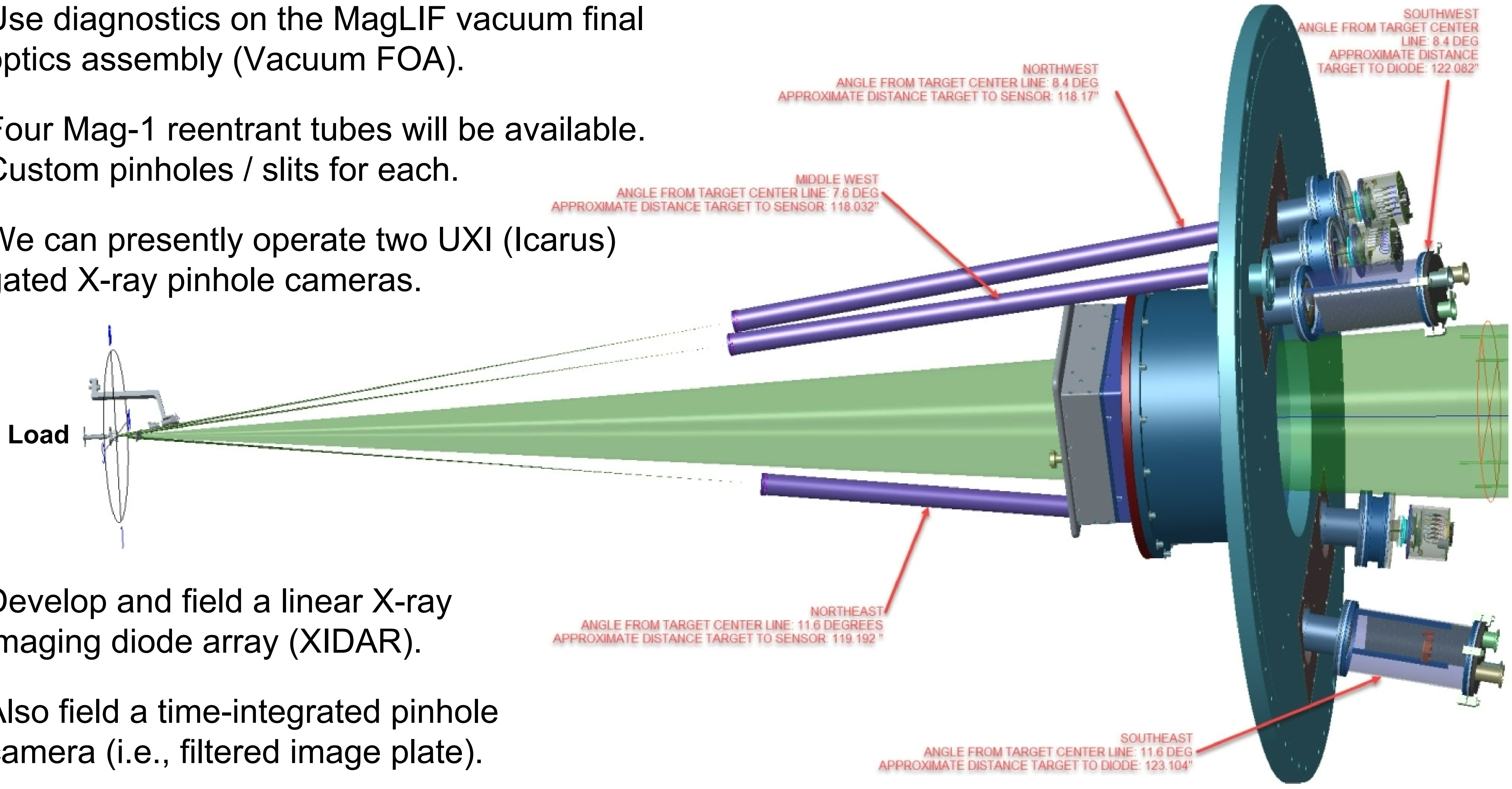


Top-down diagnostics for the reconnection layer [P2] → MagLIF FOA

Use diagnostics on the MagLIF vacuum final optics assembly (Vacuum FOA).

Four Mag-1 reentrant tubes will be available. Custom pinholes / slits for each.

We can presently operate two UXI (Icarus) gated X-ray pinhole cameras.

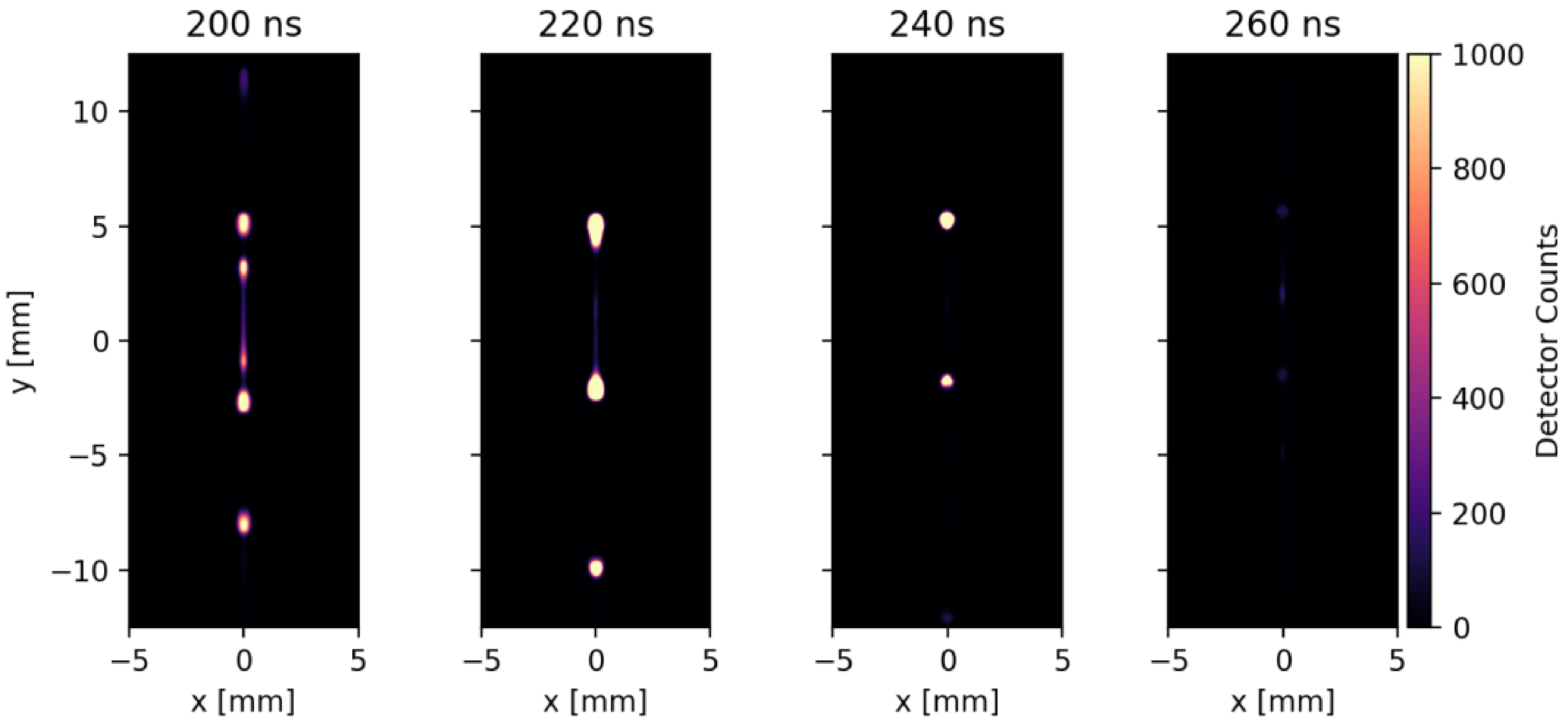


Develop and field a linear X-ray imaging diode array (XIDAR).

Also field a time-integrated pinhole camera (i.e., filtered image plate).

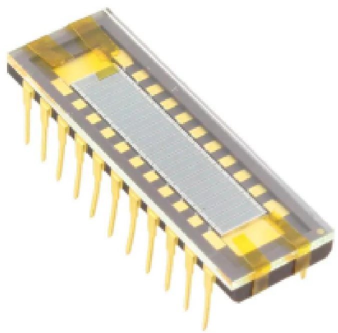
Synthetic Data for the UXI (Icarus) gated X-ray cameras [P2]

We can post-process sims with XP2 (Crilly, Chittenden) to generate synthetic diagnostic images



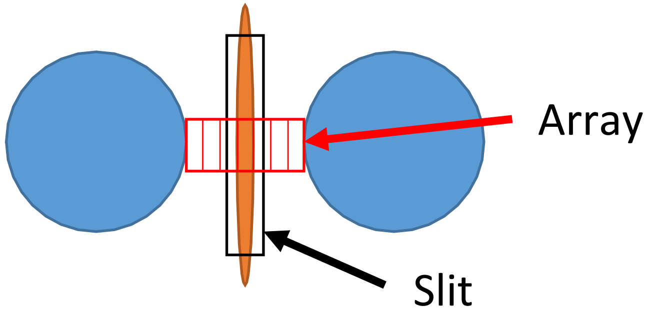
- ICARUS: 1024x512 px, 25.6 x 12.8 mm, Mag 1 axial pinhole imaging.
- 4 or 8 frames, <2 ns exposure.
- Broadband response, here filtered with 2 um V to preserve Al K-shell.

X-ray Imaging Diode Array (XIDAR) [P2]

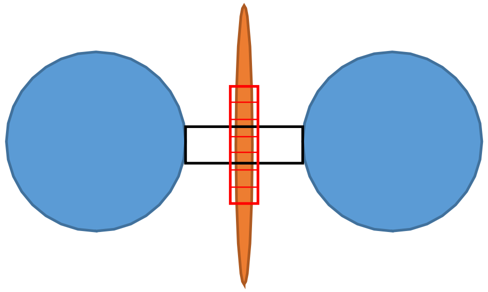


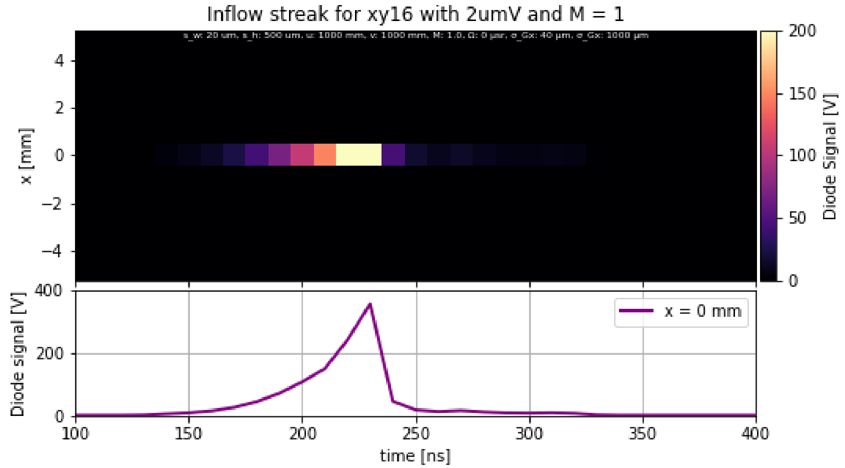
AXUV20ELG

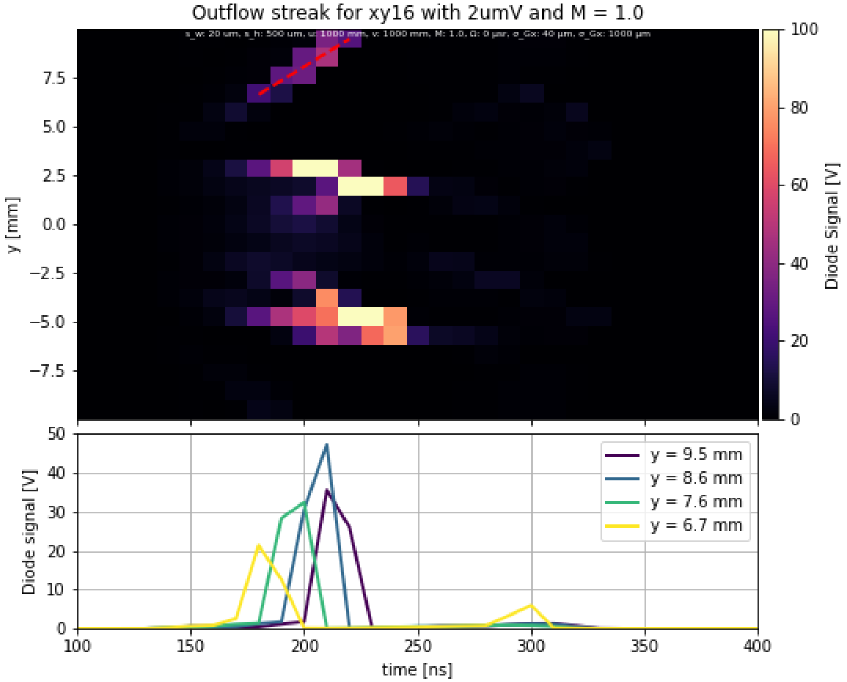
Inflow resolved



Outflow resolved







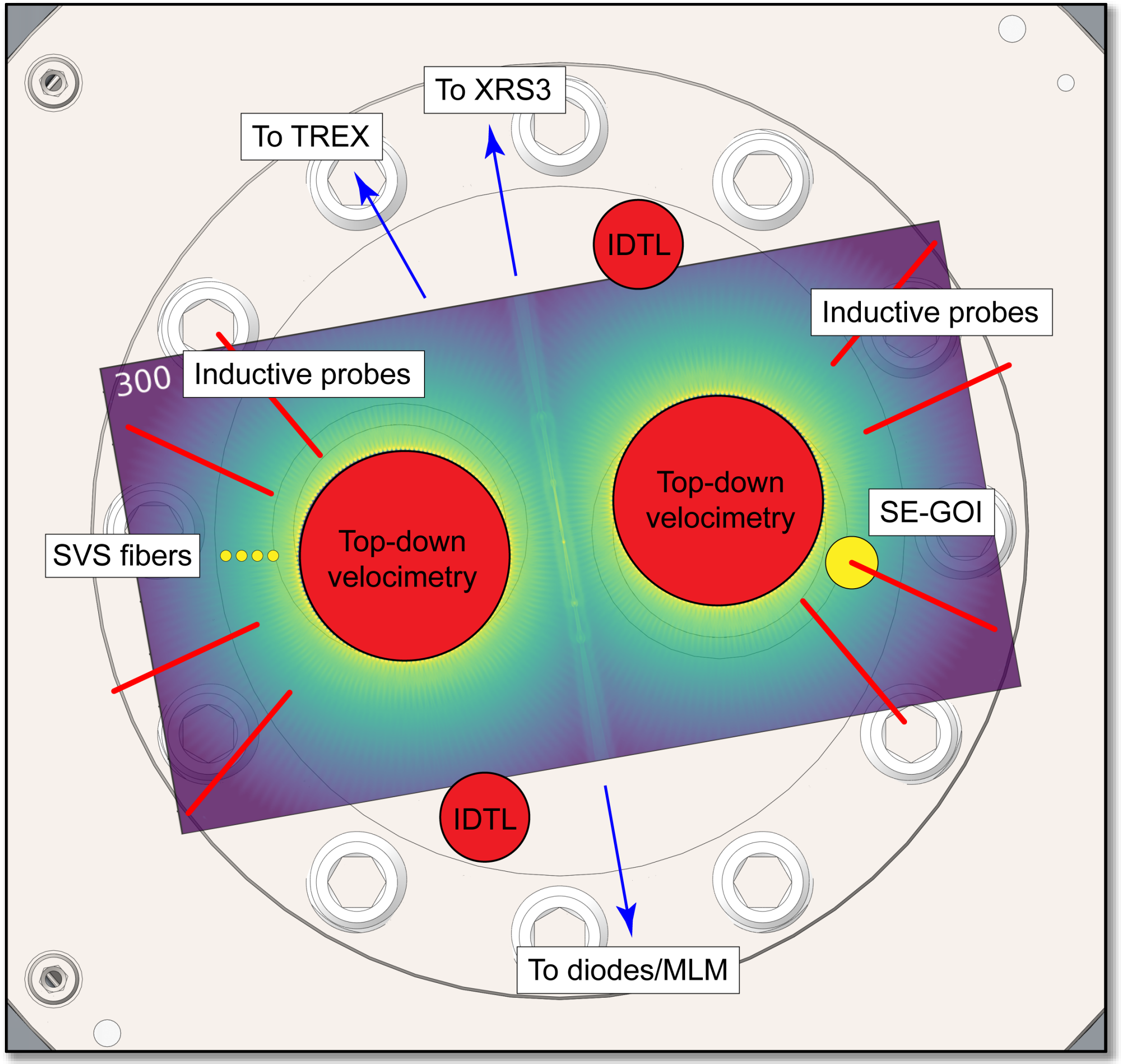
- Linear 20-channel AXUV Si diode used on MAGPIE for reconnection experiments.
- Slit imaging reduces alignment requirements, can resolve in inflow or outflow direction.

Bow shock imaging [S2]

Self-emission gated optical imager:

- Use the eight-frame self-emission gated optical imager (SE-GOI) built into the Z Line VISAR instrument.
- Top-down view bow shock that forms around one of the inductive probes.
- Like the SVS probes, need to find clear vertical line of sight past wire weights, Romulan fibers, etc.
- Use David Yager-Elorriaga's existing optical configuration for the SE-GOI.

Simulations will inform expected footprint of bow shock, etc. [R. Datta, MIT].



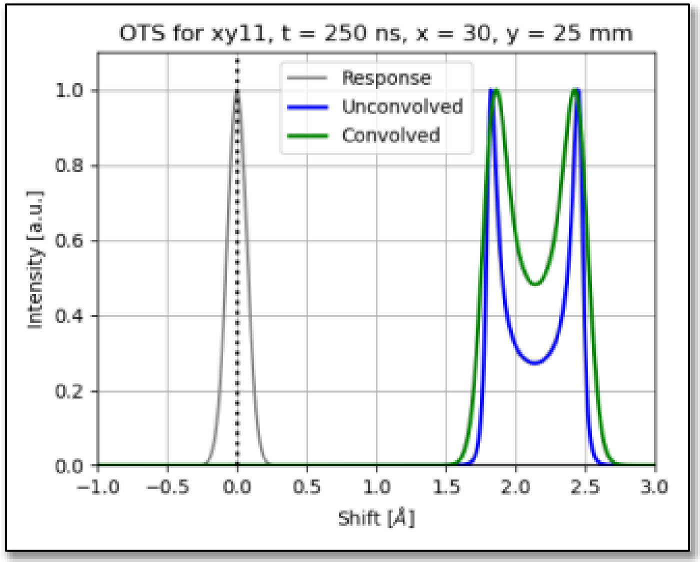
We're looking forward to the first MARZ experiment in December 2021!

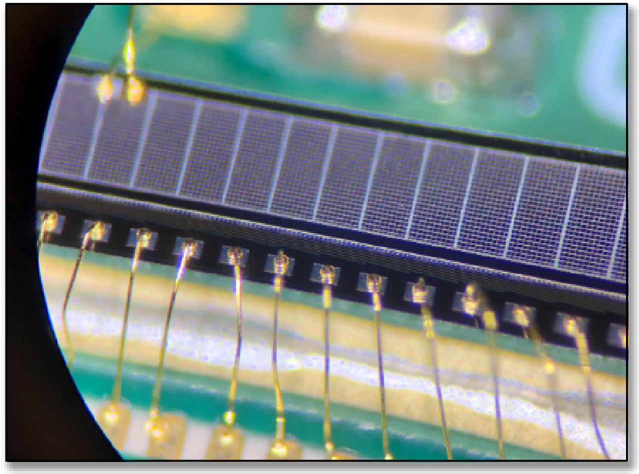
Overarching objectives and challenges:

- MARZ is the first experiment with the potential to access and study the radiative reconnection regime in the laboratory.
- MARZ requires a new (to Z) inverse wire array plasma source. Diagnostics have been chosen to assess source performance in addition to reconnection behavior.
- We're in the final phases of the design process for the first experiment. We're continuing to evaluate the complexity of the diagnostic load.

Future diagnostic development:

Optical Thomson Scattering (OTS) using Z Petawatt and the Gated Visible Spectrometer (GVS).





Ultrafast Pixel Array Camera (UPAC) is a UXI-based linear image diode array. [Quinn Looker]