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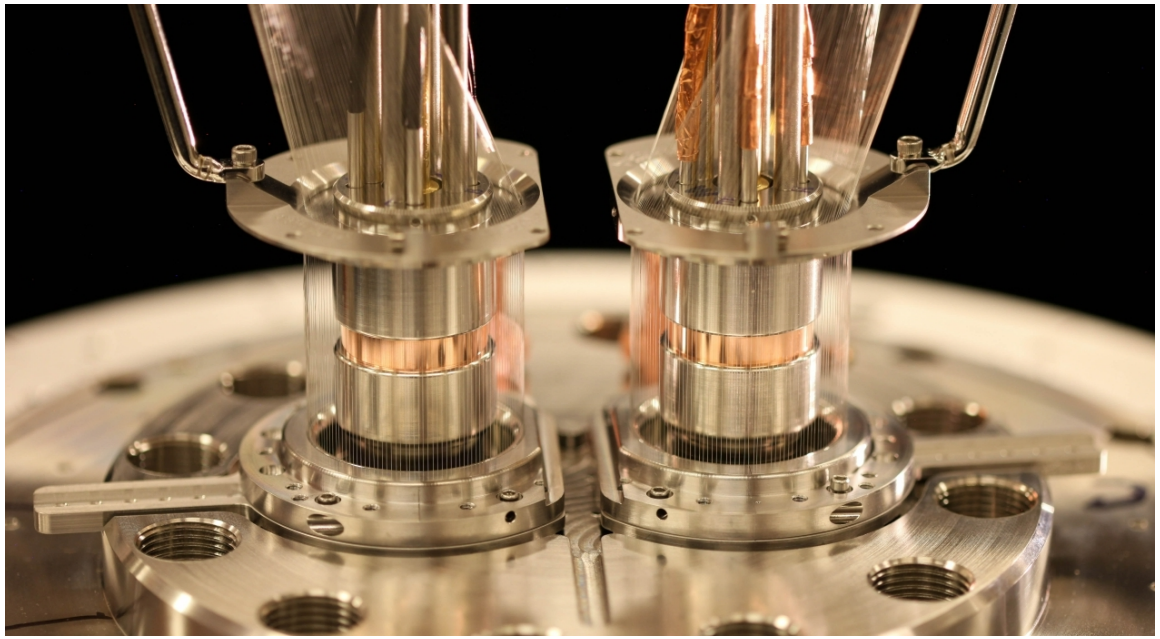


Plasma flows from dual exploding wire arrays for the MARZ campaign on Z

Rishabh Datta, J P Chittenden, A C Crilly, W R Fox, J W Halliday, C A Jennings, H Ji, C C Kuranz, R F Meelan, S V Lebedev, D A Uzdensky, C E Myers, K Chandler, J D Hare

APS DPP Annual Meeting, Oct. 20th, 2022

Magnetically Ablated Reconnection on Z (MARZ) collaboration

MIT	Jack Hare and Rishabh Datta
Imperial College	Sergey Lebedev, Jerry Chittenden, Simon Bland, Aidan Crilly, Jack Halliday, Danny Russell, Lee Suttle, and others
Princeton University/PPPL	Will Fox and Hantao Ji
University of Michigan	Carolyn Kuranz
University of Colorado Boulder	Dmitri Uzdensky
Sandia National Laboratories	Katherine Chandler, 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

Imperial College London

Sandia National Laboratories

PRINCETON UNIVERSITY

UNIVERSITY OF MICHIGAN

PPPL PRINCETON PLASMA PHYSICS LABORATORY

University of Colorado Boulder

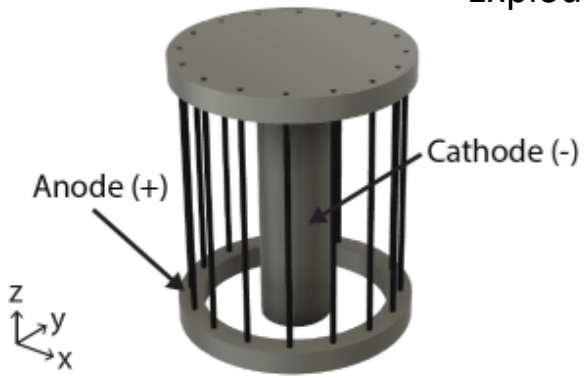
MIT PSFC Plasma Science and Fusion Center

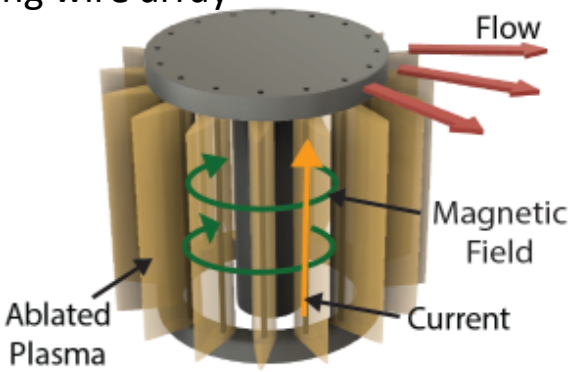
This work is supported by the NSF through an EAGER award

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.

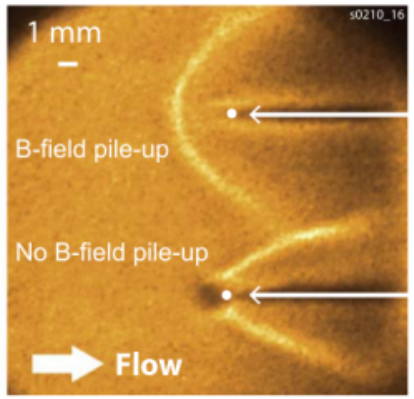
Wire Arrays for Laboratory Astrophysics

Exploding wire array





Magnetic Flux Pile-up

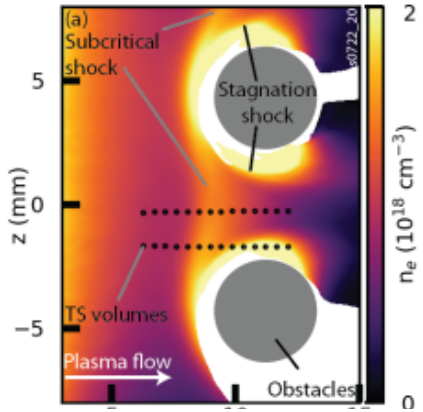


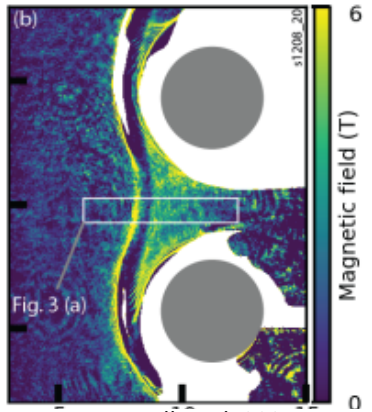
500 μm conducting cylinder

500 μm non-conducting cylinder

Burdiak et al. 2017. PoP.

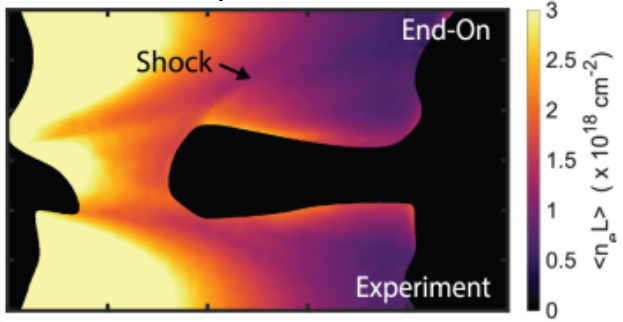
Subcritical MHD shocks





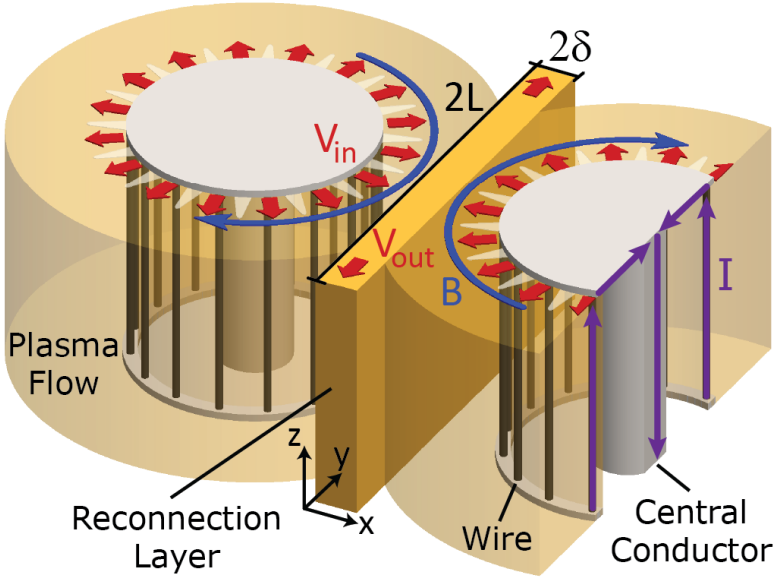
Russell et al. 2021.

Anisotropic 3D Shocks

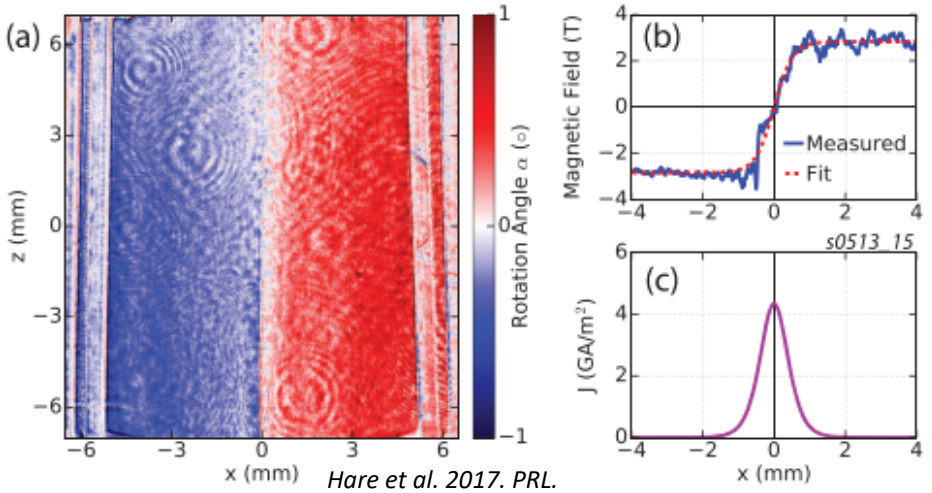


Datta et al. 2022.

Dual Exploding Wire Array

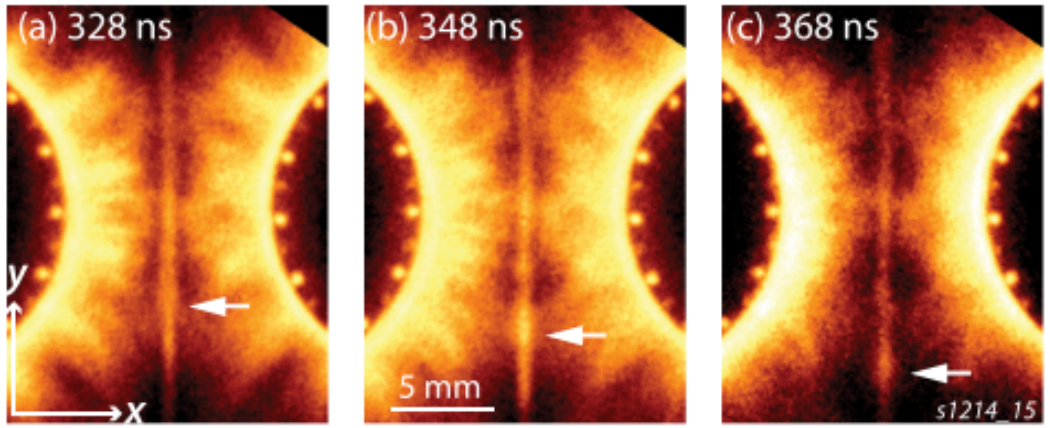


Harris Sheet Magnetic Field Profile



Hare et al. 2017. PRL.

Plasmoid Motion in Reconnection Layer

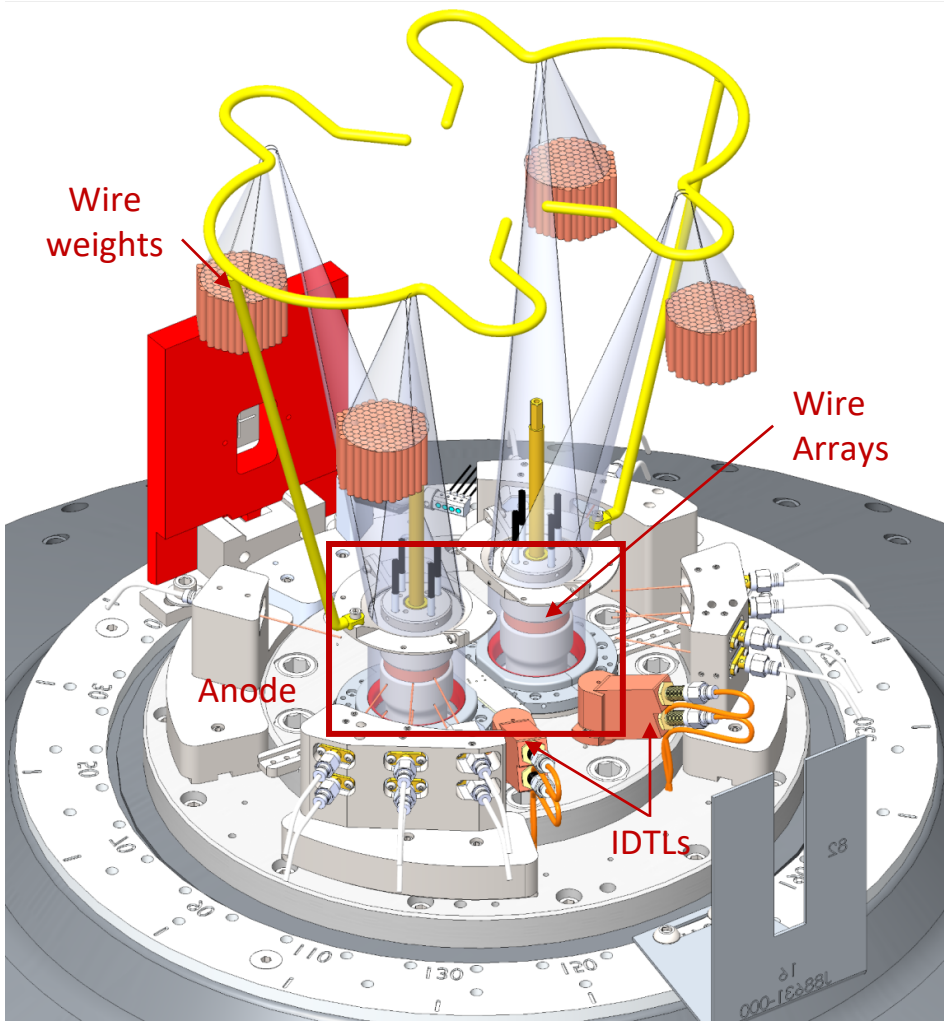


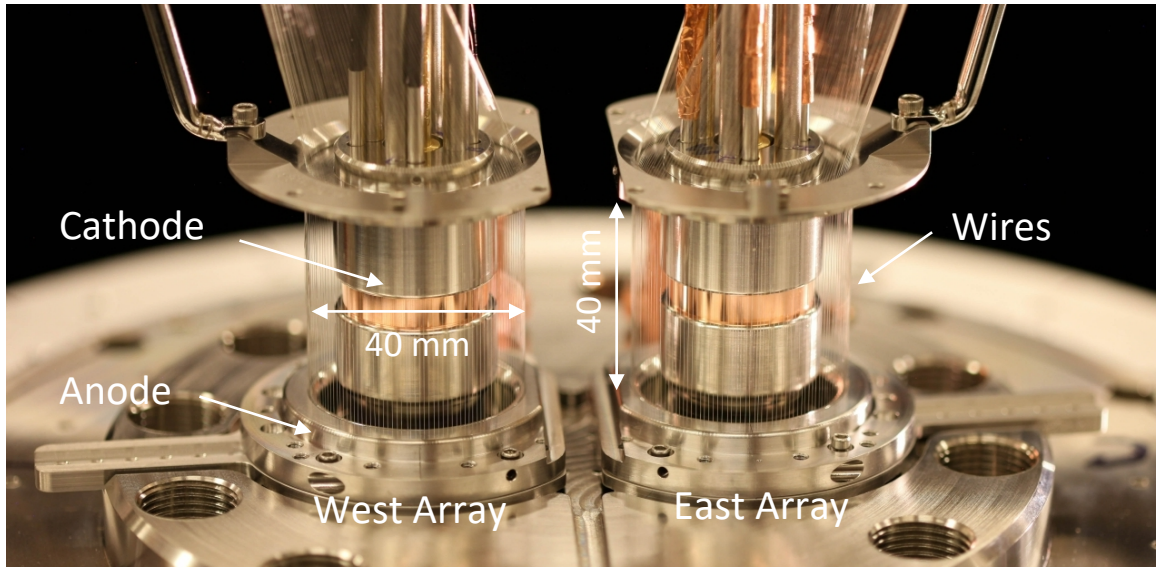
Hare et al. 2017. PRL.

On ~1MA University scale facilities, wire arrays generate plasma that is:

- Highly-collisional ($\lambda_{ii}/L \sim 10^{-6} - 10^{-4}$)
- Supersonic ($M_S \sim 2 - 7$)
- Super-Alfvenic ($M_A \sim 1 - 2$)
- Magnetized ($\rho_e/L \sim 10^{-4}, \rho_i/L \sim 10^{-2}$)
- Frozen-in flux ($Re_M > 10$)

A Dual Exploding Wire Array on Z





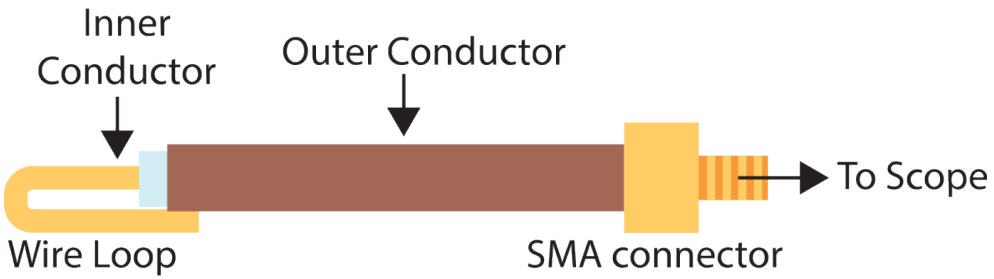
For each array:

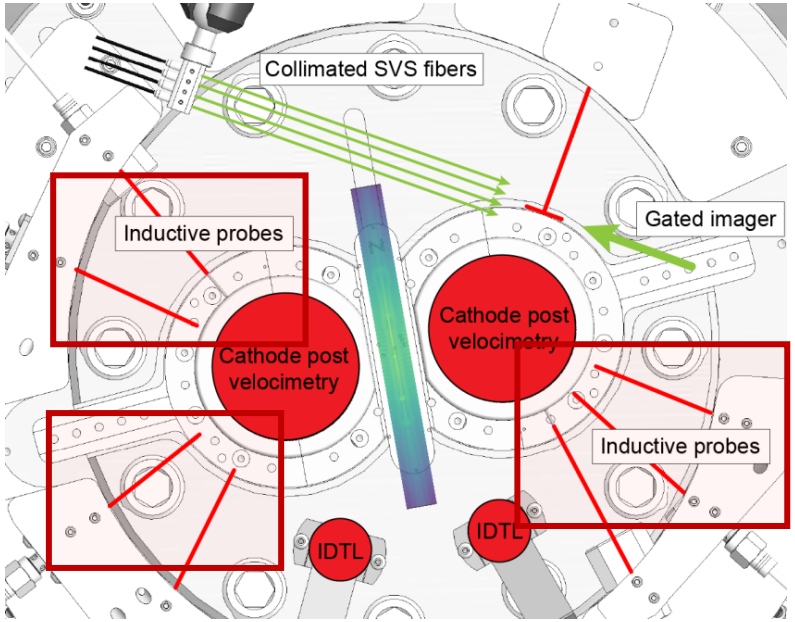
# Wires	150
Wire Diameter & Material	75 um Al
Array Diameter	40 mm
Array Height	40 mm
AK Gap	10 mm
Array Separation	20 mm

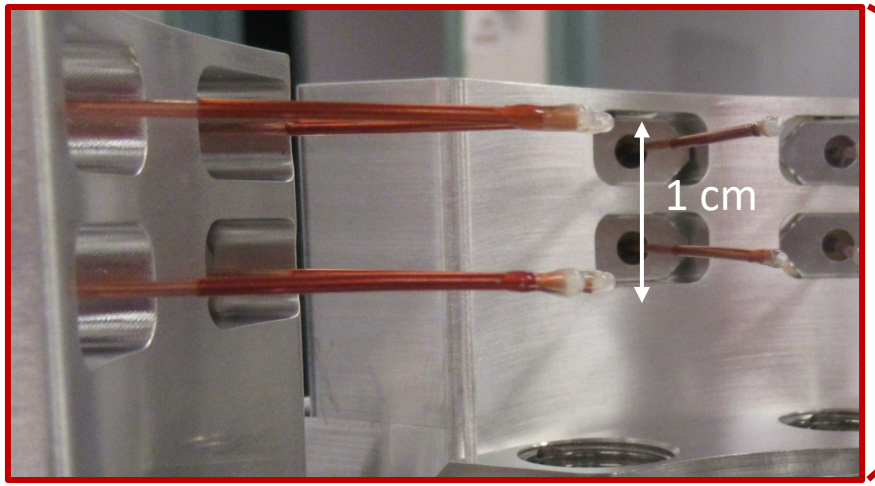
Current:
10 MA per array,
300 ns rise time

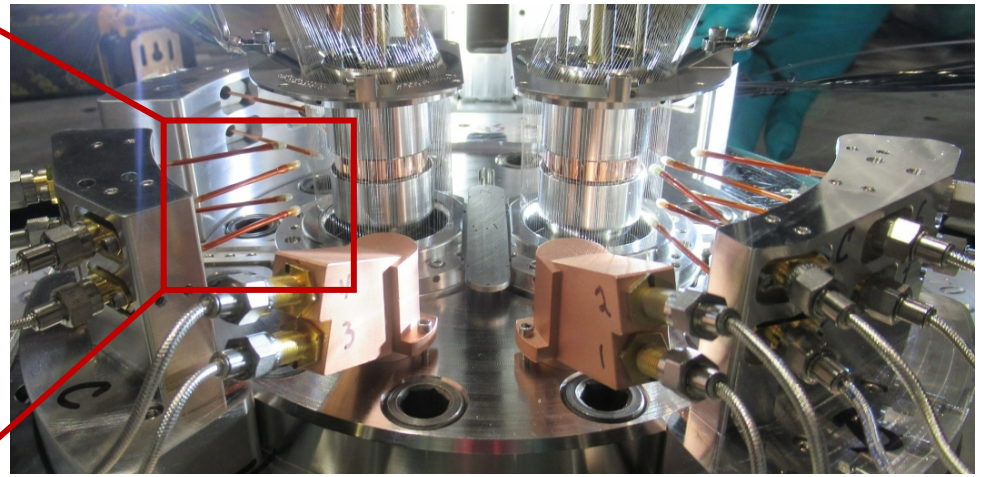
Inductive Probe Array

- Measure time- and space-resolved magnetic field
- Measure flow velocity from time-of-flight of B-field
- Single-looped probes of OD ~1.5 mm
- Probes placed at 4 radii (5, 8, 11, and 15 mm from wires)
- At each location, vertically stacked 2 probes of opposite polarity

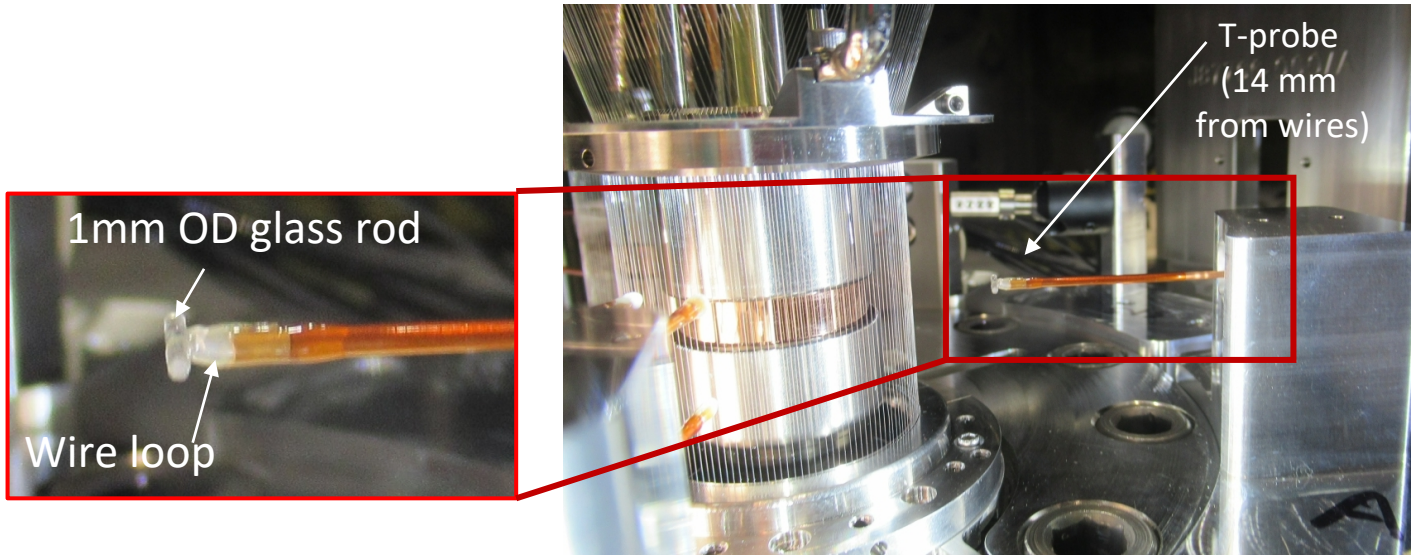


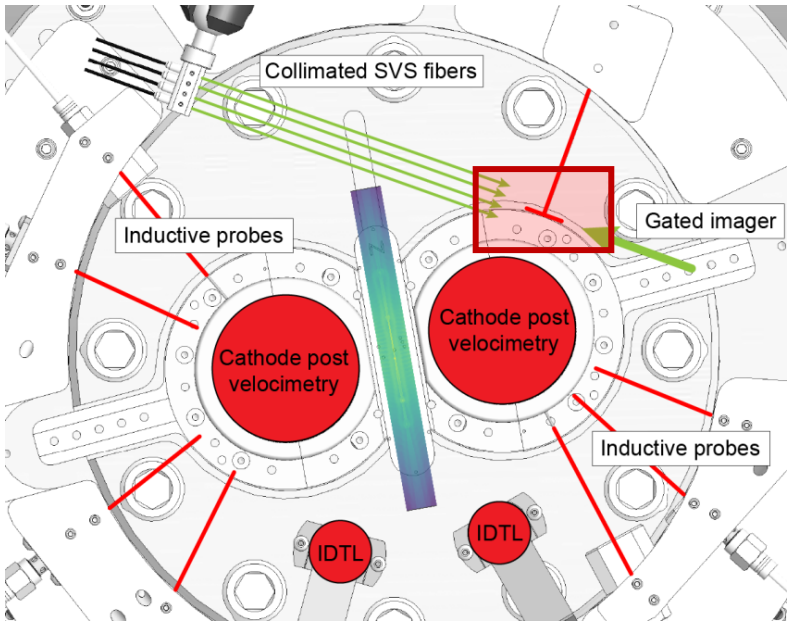






Inductive Probe with Target for Bow Shock Generation

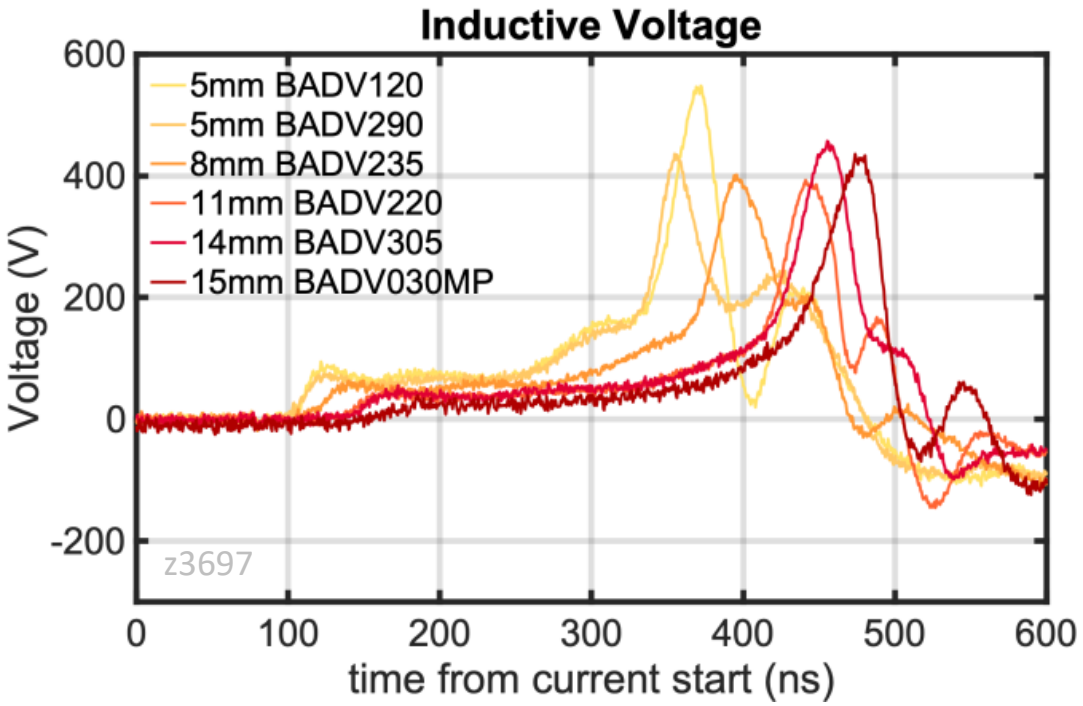


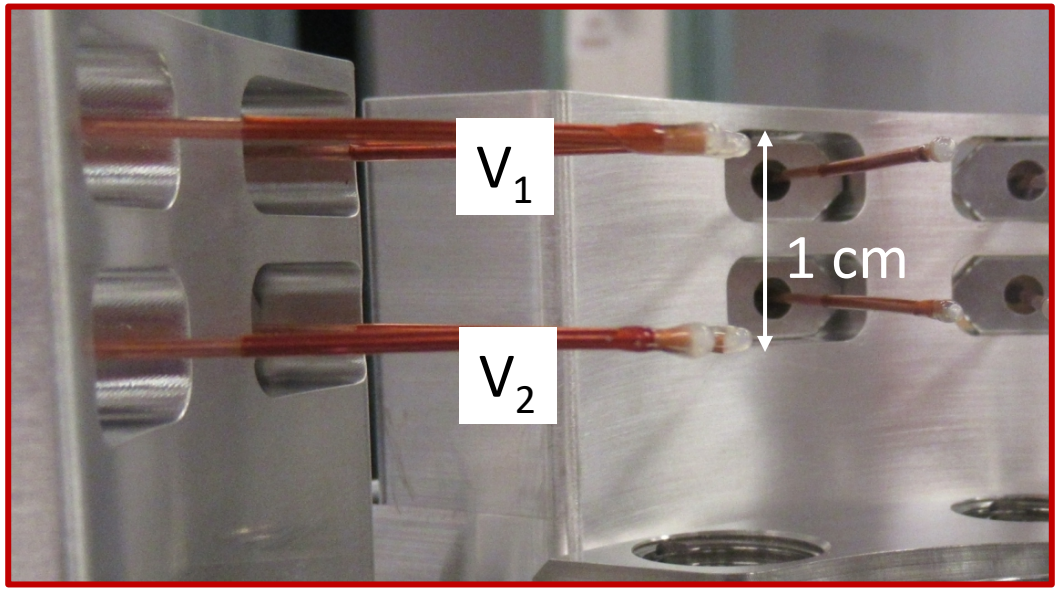


A bow shock forms around the b-dot probe with a glass rod (“T-probe”)

Structure of shock provides information about the upstream Mach no.

Magnetic Field Measurements

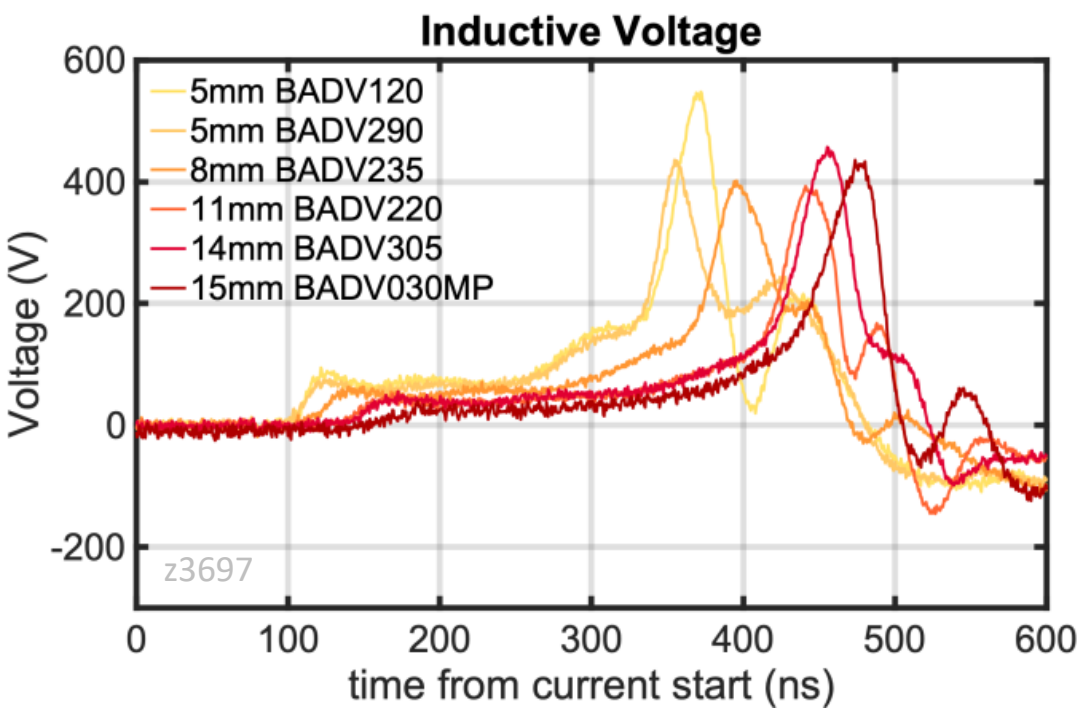


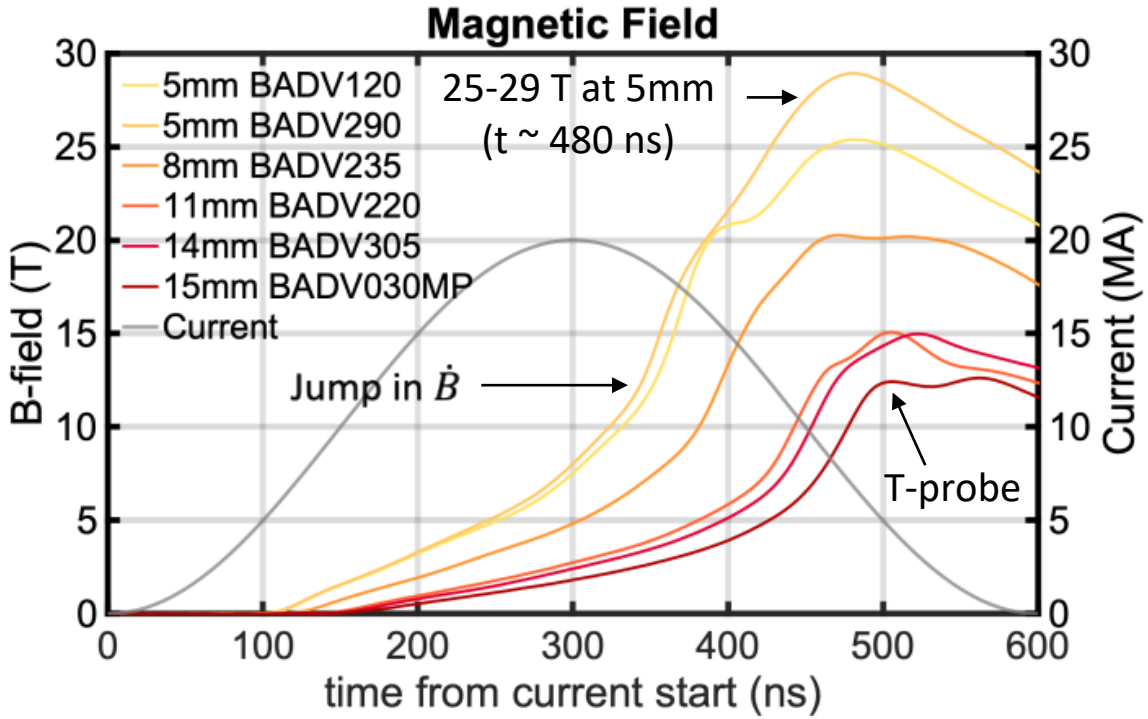


Common mode rejection:

$$\bar{V} = 0.5(V_2 - V_1) = \frac{A_1 + A_2}{2}\dot{B}$$

Magnetic Field Measurements





As expected, magnetic field strength decreases with distance from wires

Rate of change of B exhibits a jump, which suggests an abrupt increase in ablation rate

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

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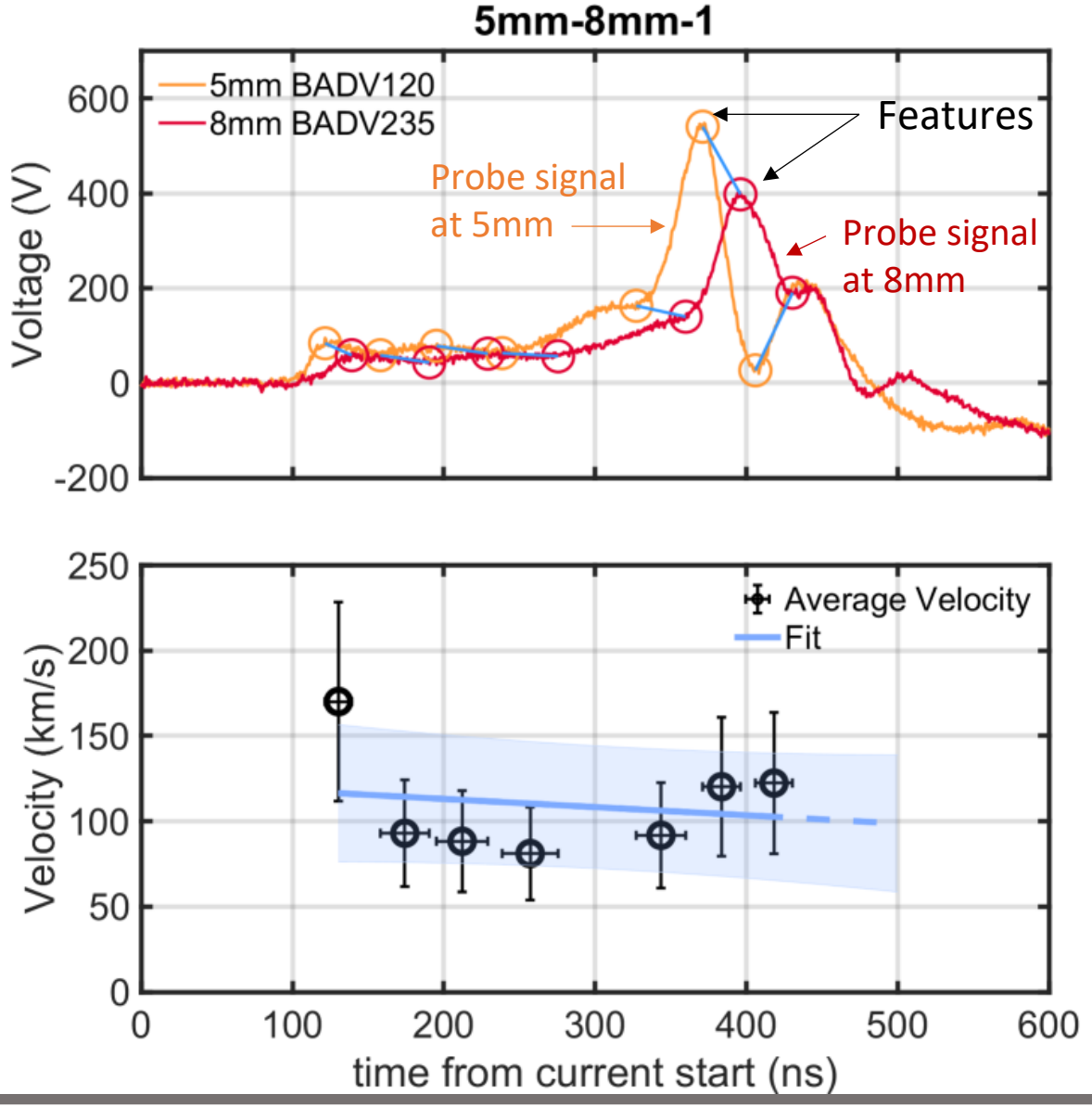
Average Velocity from Time of Flight

Average velocity of a magnetized fluid parcel:

$$\bar{u} = \frac{s}{\tau} = \frac{1}{\tau}\int_0^{\tau} \frac{dx_p(x_0,t)}{dt} dt$$

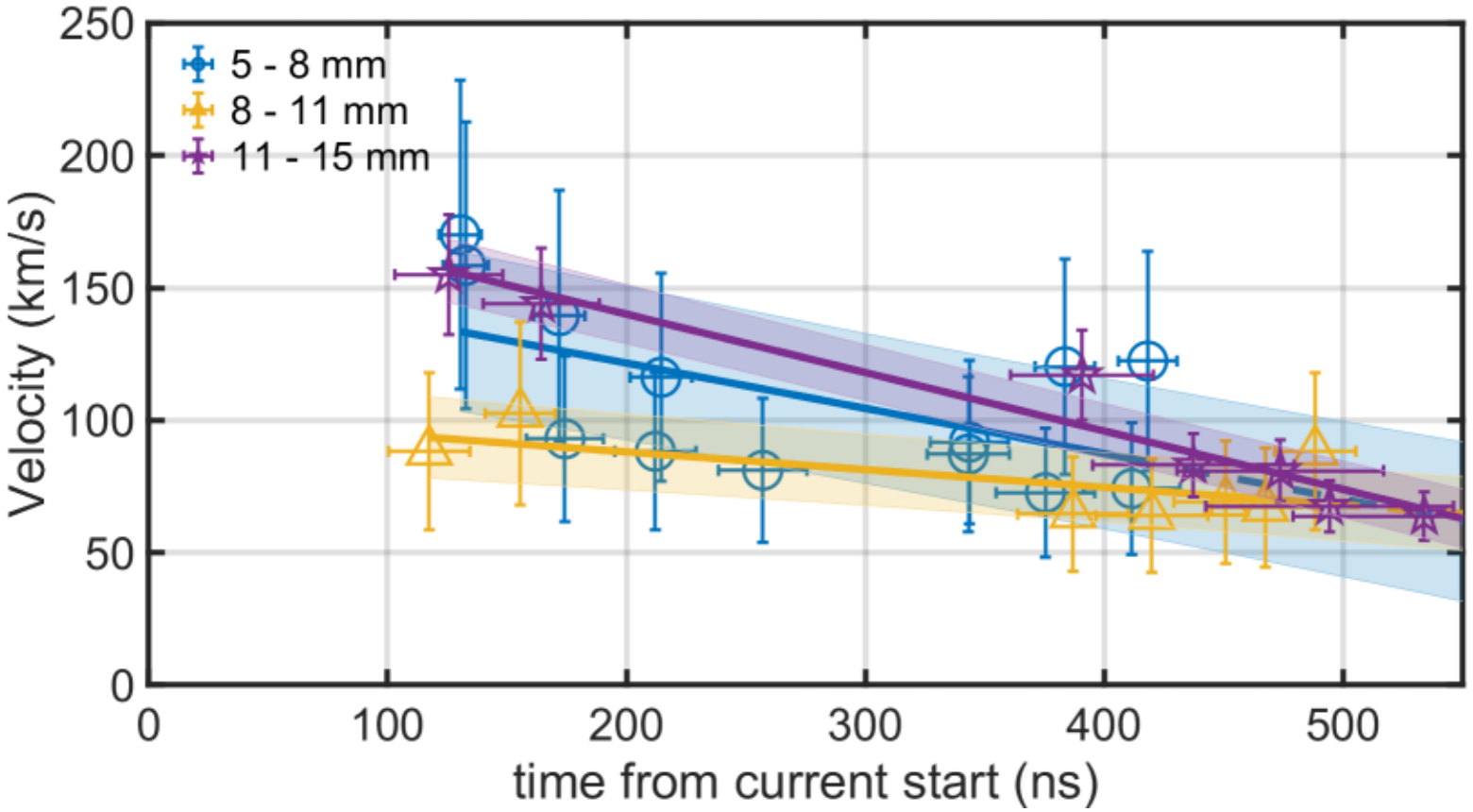
$$s = 3 \pm 1\text{mm}$$

Average flow velocity ~ 120 km/s
between 5 mm < r < 8 mm



See Datta et al. HTPD (Accepted) for details

Average Velocity from Time of Flight



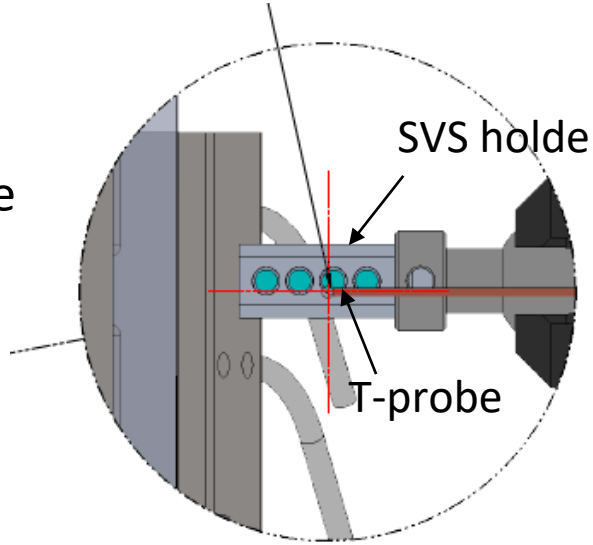
Average flow velocity ranges between ~ 70 – 150 km/s

Velocity decreases with time, similar to what we see in simulations

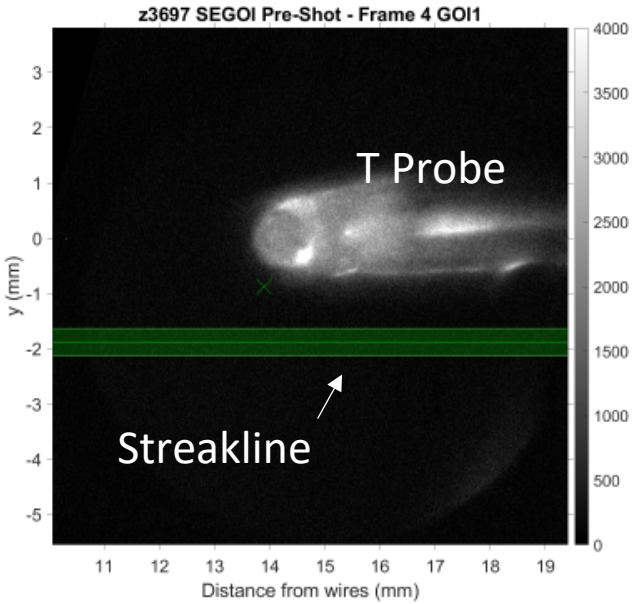
Self-emission gated optical imager (SEGOI)

- Records time-gated and 2D space-resolved visible emission
- Monitors the time-evolution of the bow shock around the T-probe
- 8 frames recorded on 8 separate MCPs with 7 ns inter-frame time
- A streak camera records 1D space-resolved emission from SEGOI

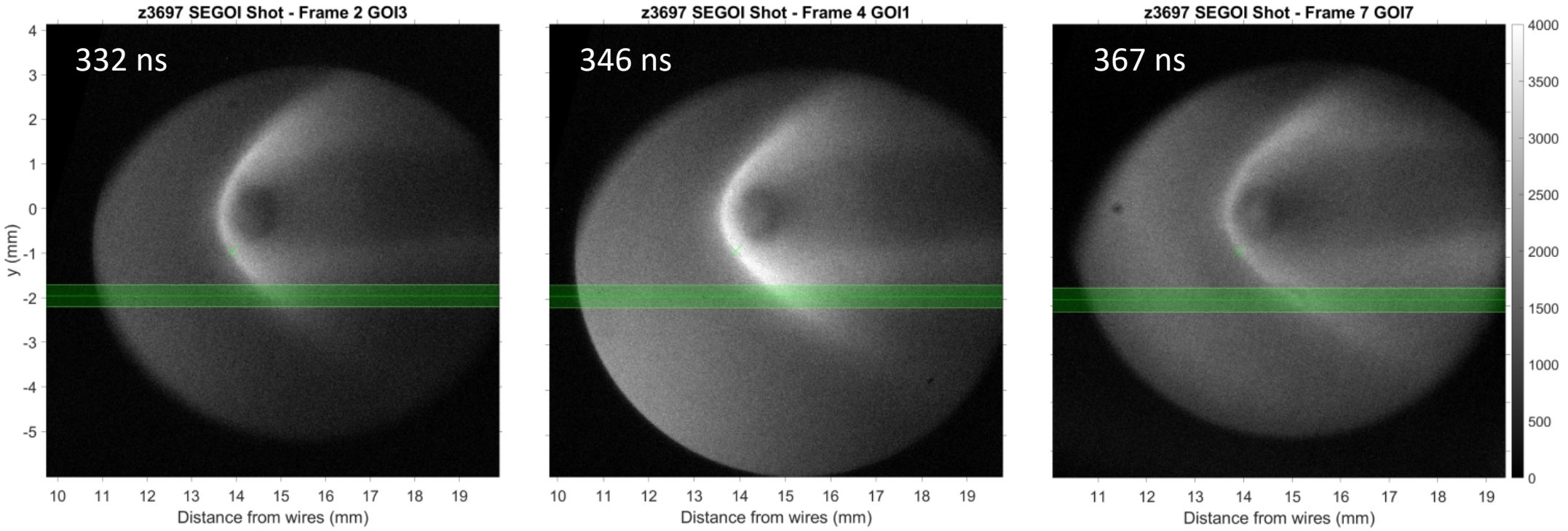
SEGOI Field of View



Preshot image



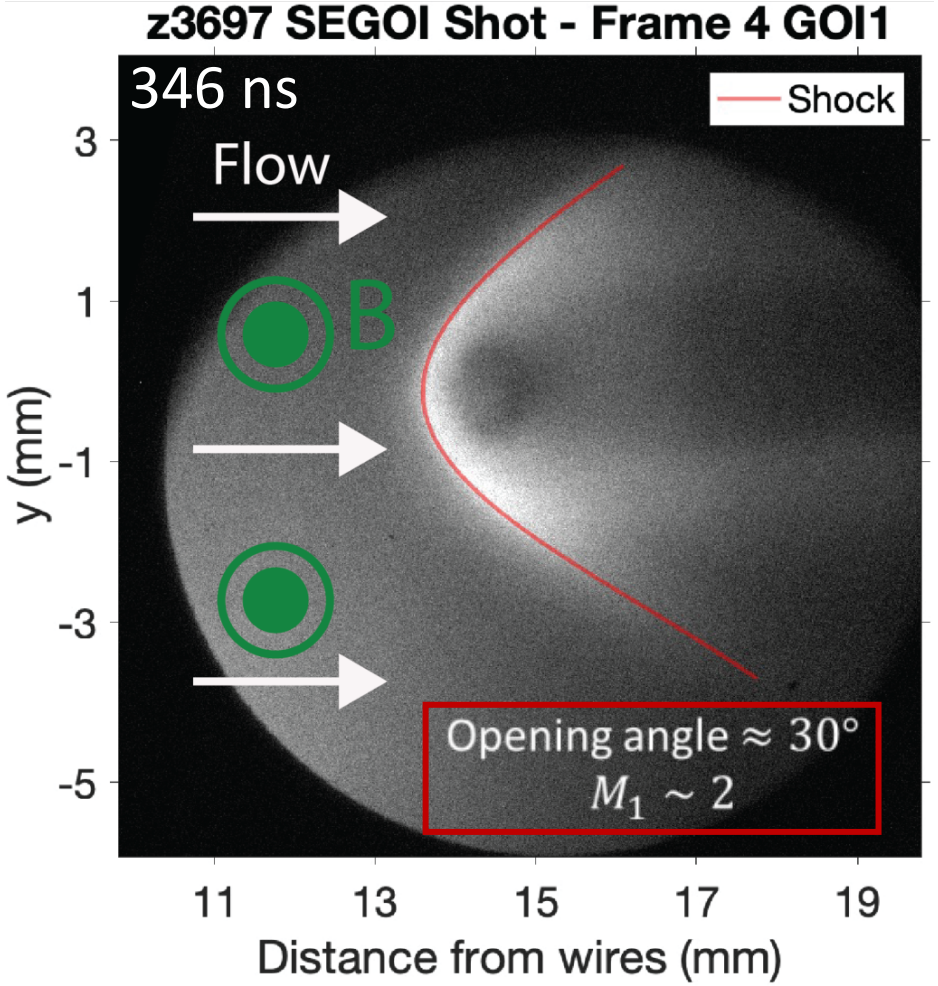
A bow shock is clearly visible ahead of the T-probe



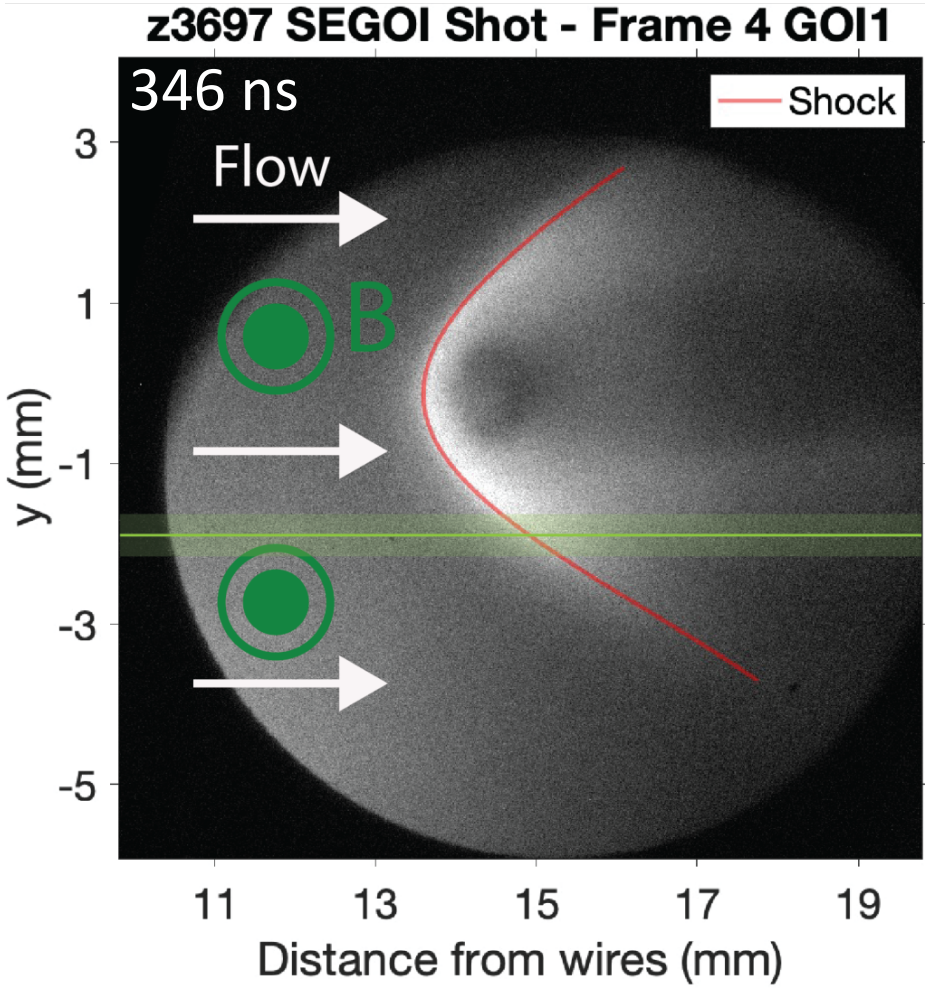
The shock shape remains roughly invariant during the observation window

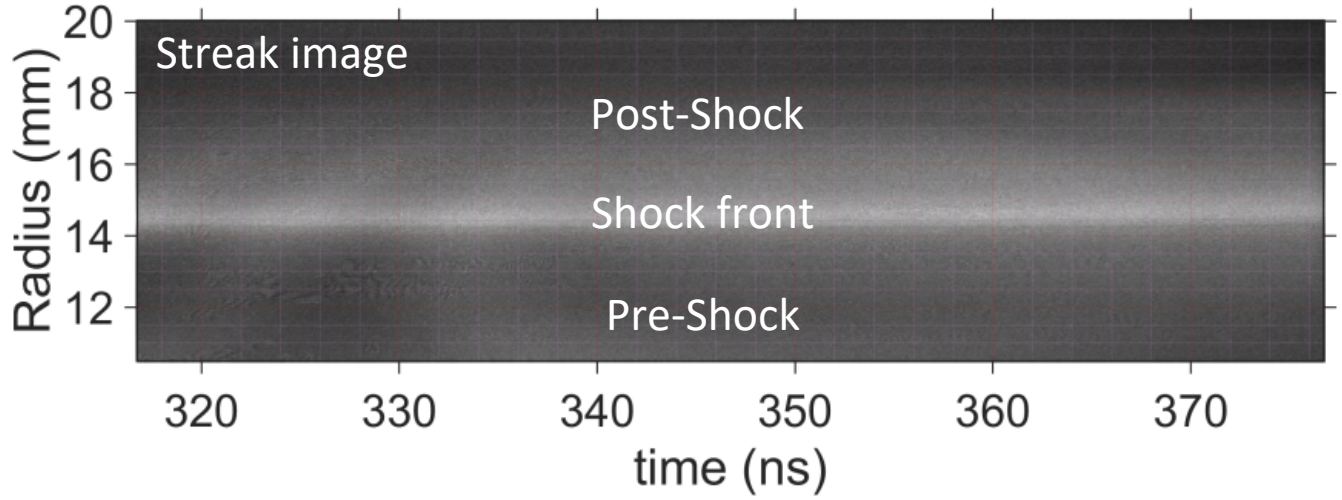
**images have been scaled, rotated, and centered*

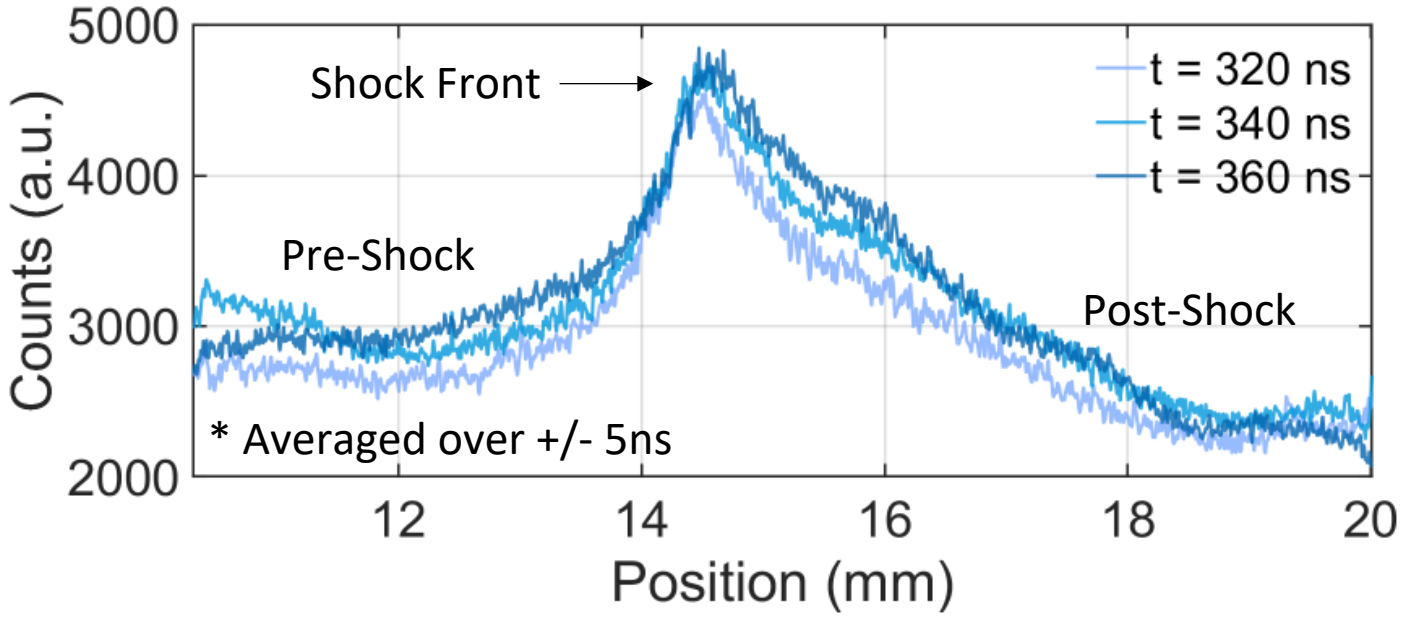
Mach Number of Upstream Flow



Position of shock remains invariant in time

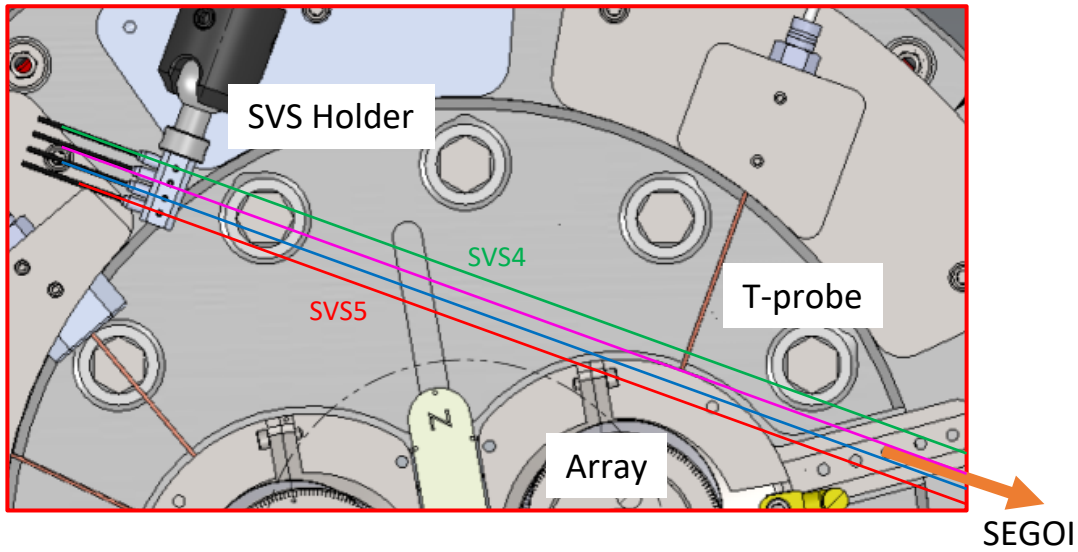


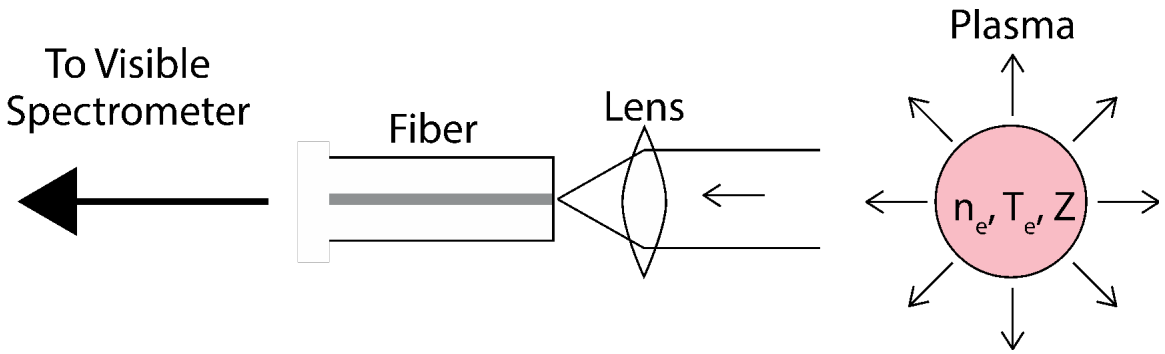


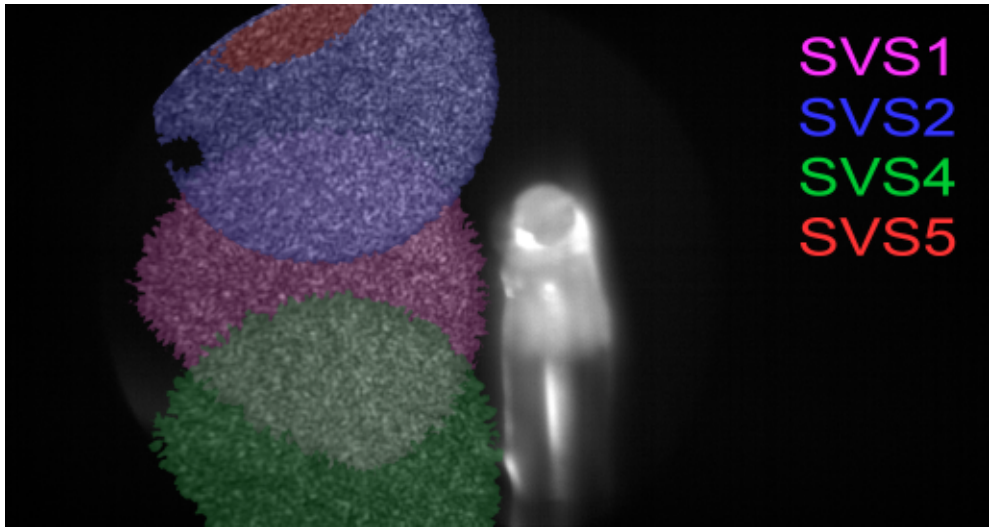


Streaked Visible Spectrometry (SVS)

- 4 SVS fibers make chordal measurements of visible spectra
- Spectra with Al-II and Al-III lines will allow for density and electron temperature measurements

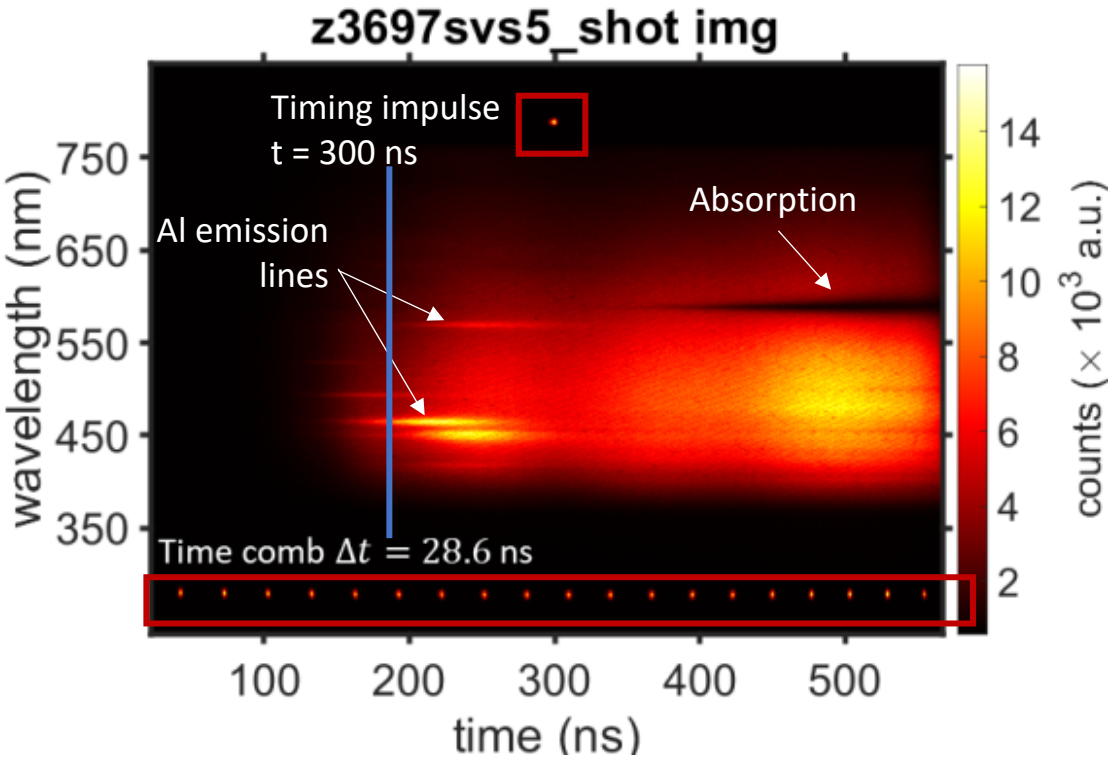


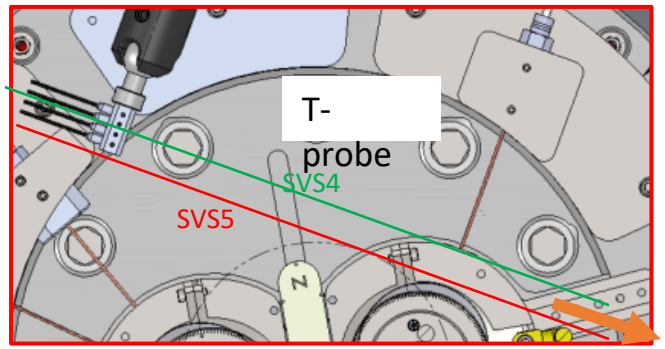




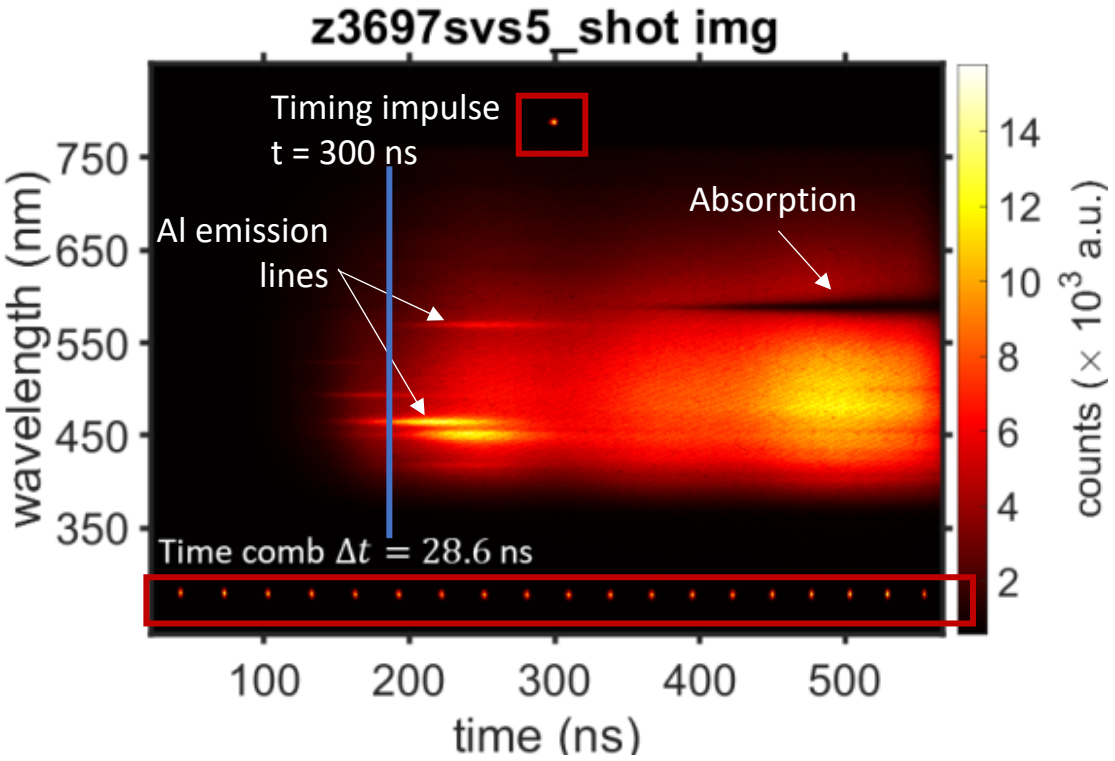
SEGOI alignment camera view with Backlit SVS Fibers

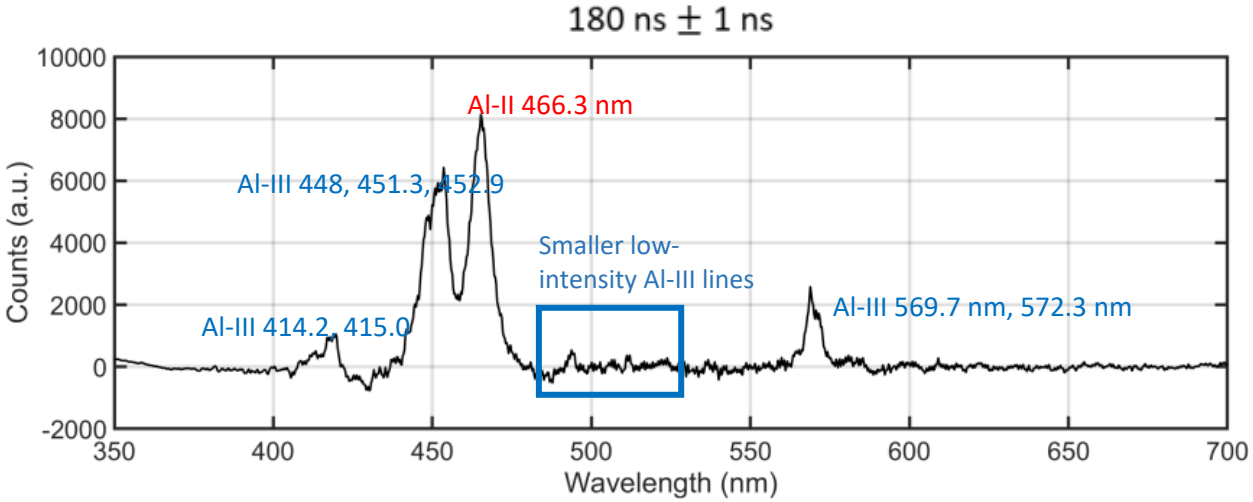
Streaked Optical Spectra

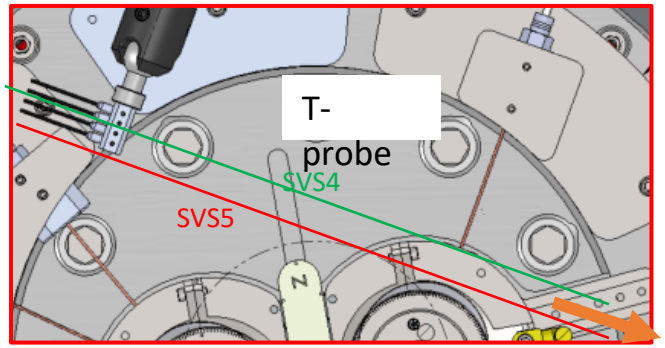




Streaked Optical Spectra



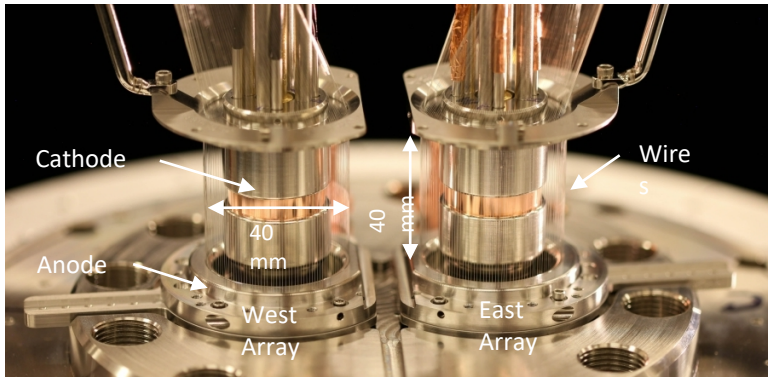


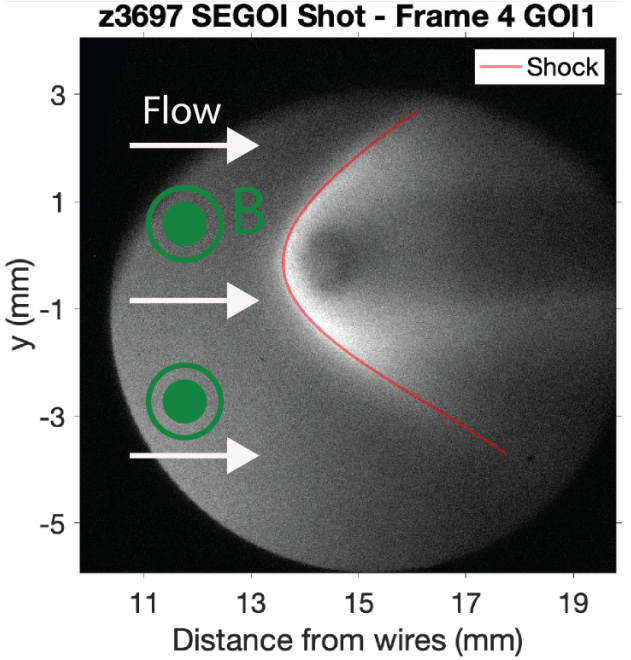


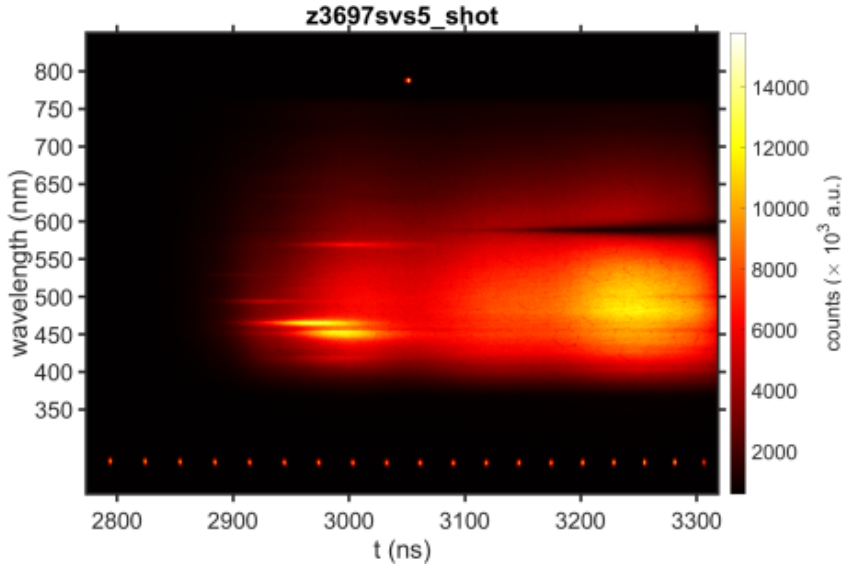
PRISMspect simulations will be used to determine electron density and temperature from the SVS spectra

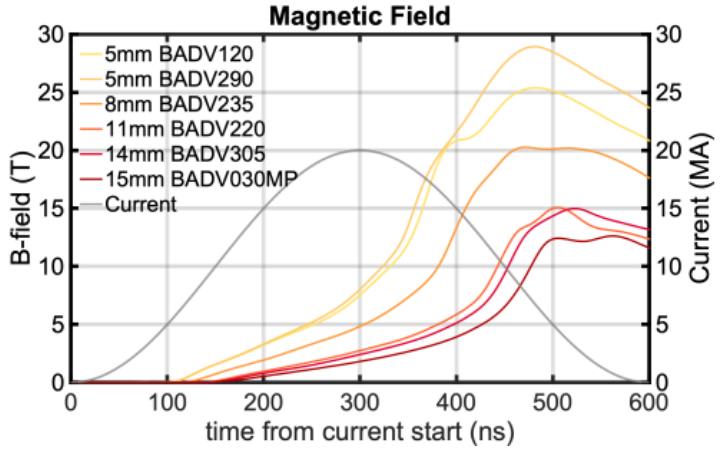
Summary

- We characterize the plasma flows from the first dual wire array load on the Z machine
- Magnetic field of upto 29T and flow velocities of ~70-150 km/s
- Image a bow shock of Mach no. ~ 2
- Visible specta show well-defined Al-II and Al-III lines





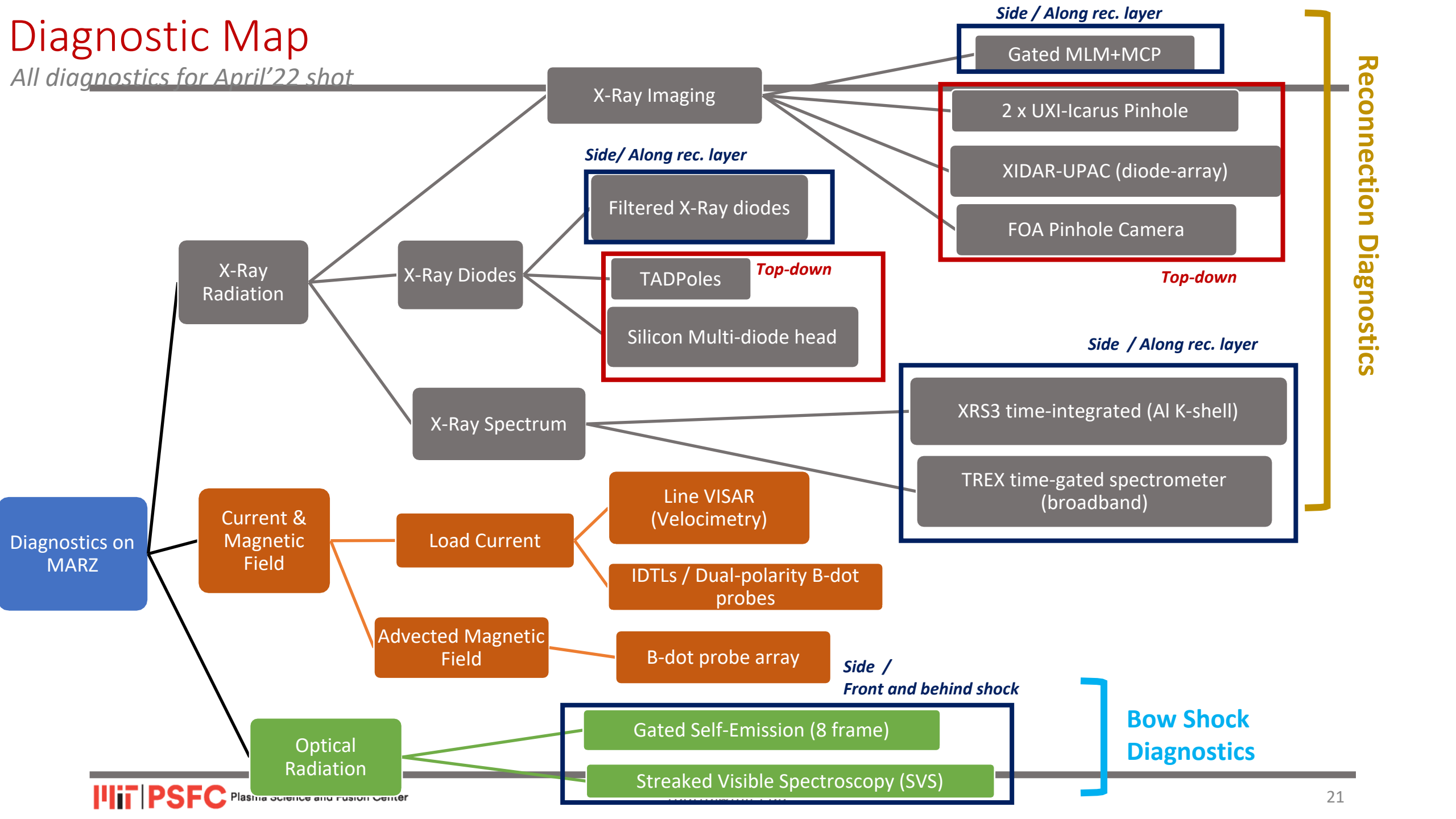




Supplementary Slides

Diagnostic Map

All diagnostics for April'22 shot



Z Line VISAR (Velocimetry)

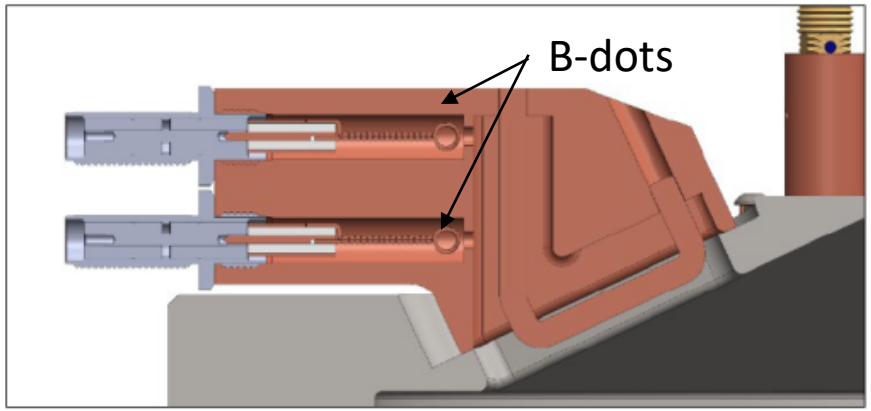
Measured Quantities	Spatially and temporally resolved velocity history of a flyer plate
Inferred Quantities	Time-resolved current in the load
Line-Of-Sight	n/a
Diagnostic Output	Current vs time
Details	

Specifications:

Spectral band(s)	N/A
Spatial resolution	1–4 μm
Temporal resolution	10–40 ps
Field of view	1–4mm
Physical Location(s)	983/1307, Z High-bay, custom final optics
Number of Channels	Two streaked VISAR interferometer channels, 8 gated optical imager (GOI) channels
Dynamic Range	

IDTLs with Dual-Polarity B-dot Probes

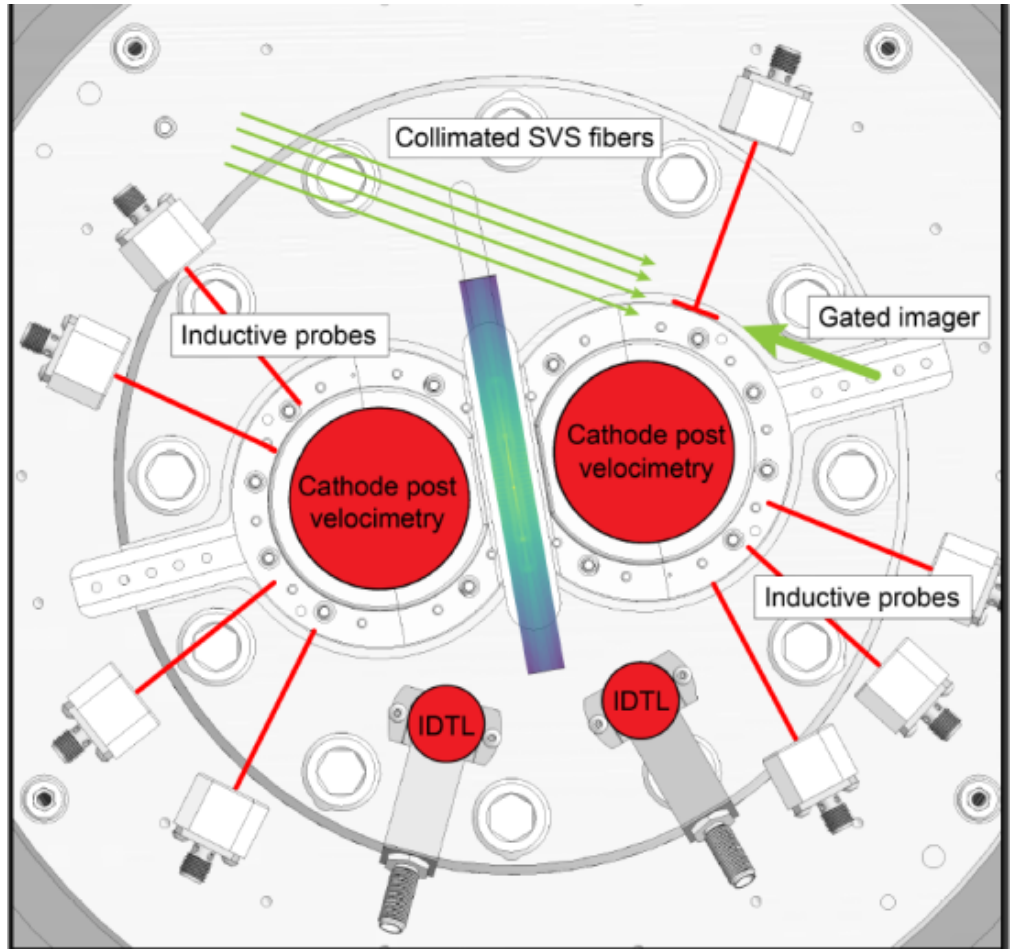
Measured Quantities	Rate of change of magnetic flux
Inferred Quantities	Time-resolved inner MITL current
Line-Of-Sight	n/a
Diagnostic Output	Current vs time
Details	



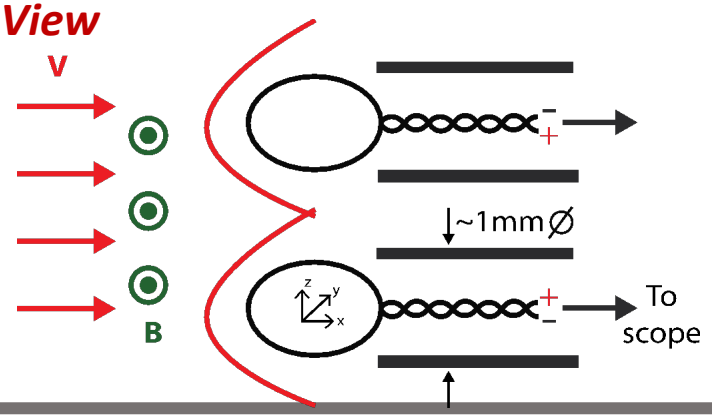
Images courtesy C. Myers, Z Diagnostic Manual (SNL)

Inductive Probes

Measured Quantities	Rate of change of magnetic flux
Inferred Quantities	Time- and space-resolved magnetic field & velocity
Line-Of-Sight	n/a
Diagnostic Output	Voltage vs time (4 radial locations 5, 8, 11 & 14 mm from array)
Details	16 probes total; 2 probes stacked vertically; 1mm diameter



Side-View



Two probes vertically stacked

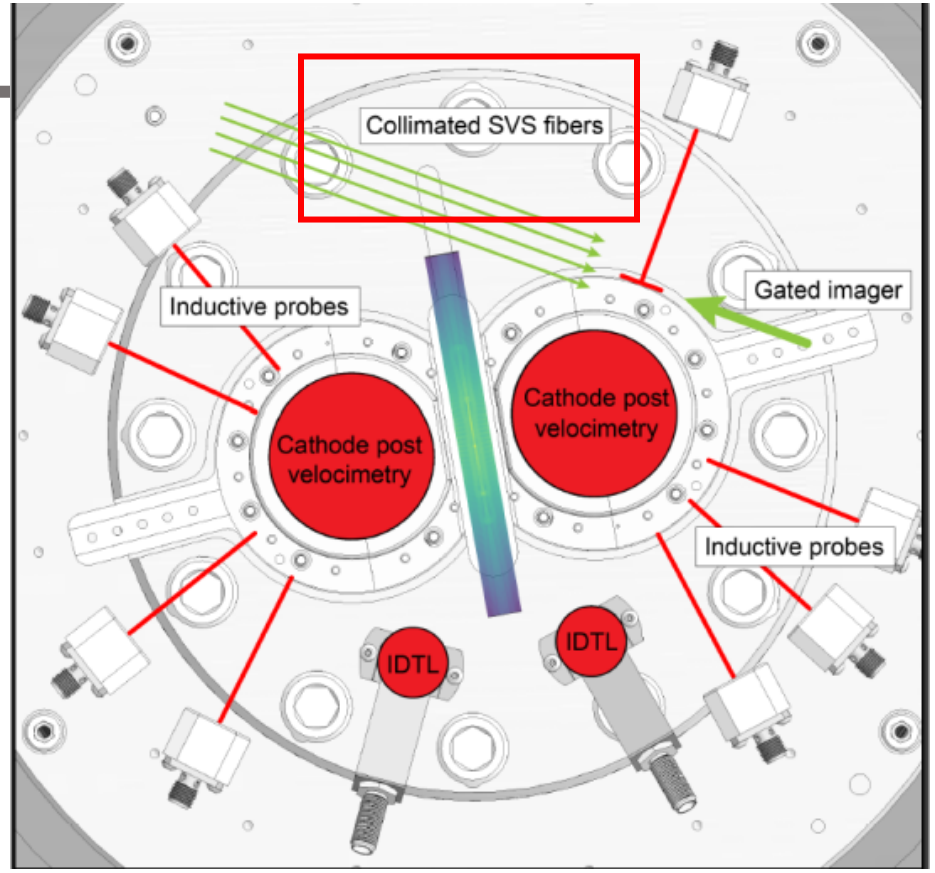
**not to scale*

rdatta@mit.edu

Images courtesy C. Myers, Z Diagnostic Manual (SNL)

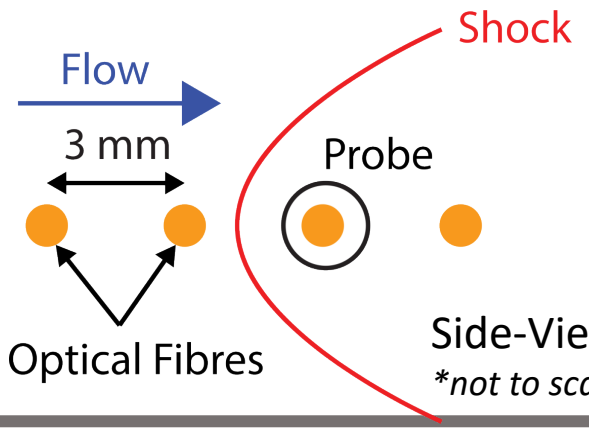
Streaked Visible Spectroscopy (SVS)

Measured Quantities	Time-resolved & Space-resolved Optical Power Spectrum
Inferred Quantities	Bow shock formation; Density & Temperature
Line-Of-Sight	Side-on (front and behind shock)
Diagnostic Output	Counts vs wavelength vs time at 4 spatial locations
Details	Same 4 radii as the inductive probes



Specifications:

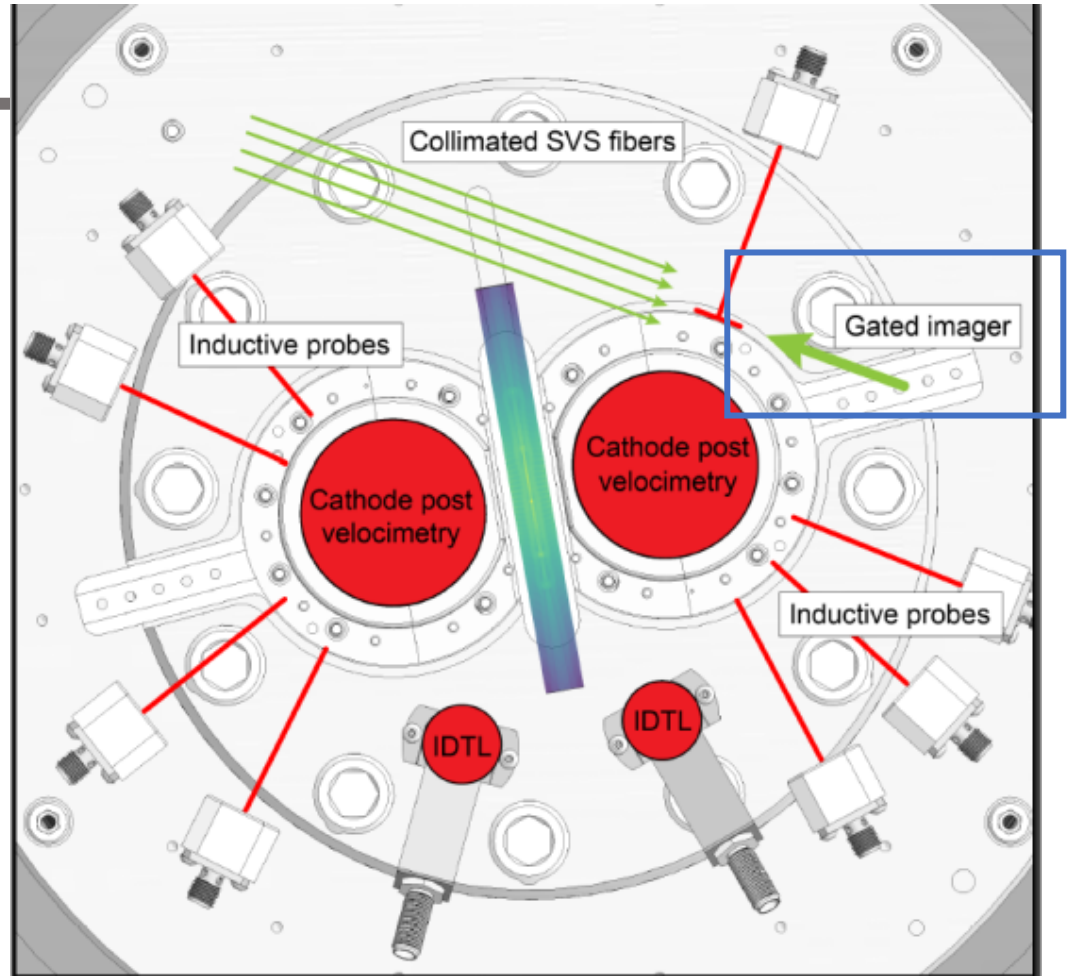
Spectral band(s)	Visible Light, 400 – 800 nm
Spatial resolution	Non-Imaging but FOV can be limited to ~20 um
Temporal resolution	100 ps
Field of view	20 um – 10 cm
Physical Location(s)	Room 1307 Mezzanine
Number of Channels	4
Dynamic Range	~30 dB



Images courtesy C. Myers, Z Diagnostic Manual (SNL)

Self-emission Gated Imager (SEGOI)

Measured Quantities	Time- gated and space-resolved optical Self-emission
Inferred Quantities	Bow shock formation & shape
Line-Of-Sight	Side-on (front and behind shock)
Diagnostic Output	Optical image (8 frames)
Details	



Specifications

Spectral Band(s)	Green light 540-600 nm
Spatial Resolution	30-50 um
Field of View	1 cm
Details	Upto 8 gated optical imagers and 2 streak cameras of Z Line VISAR

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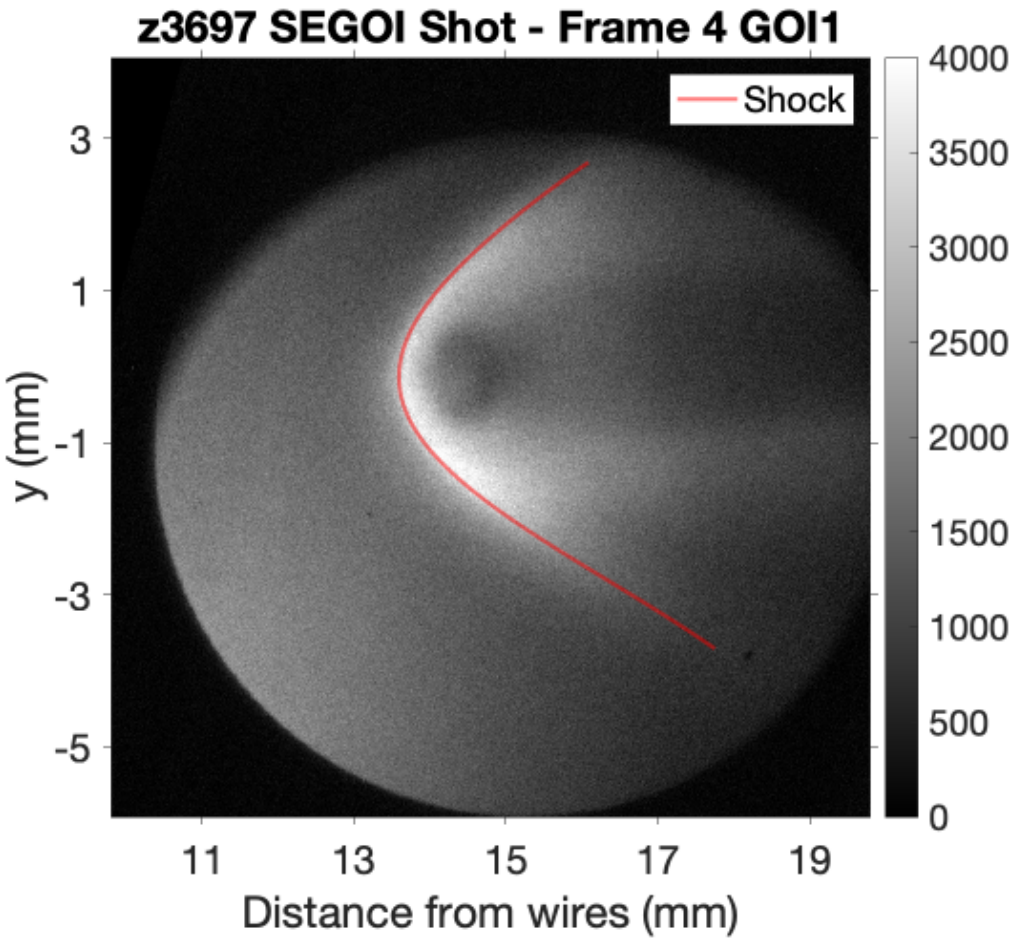
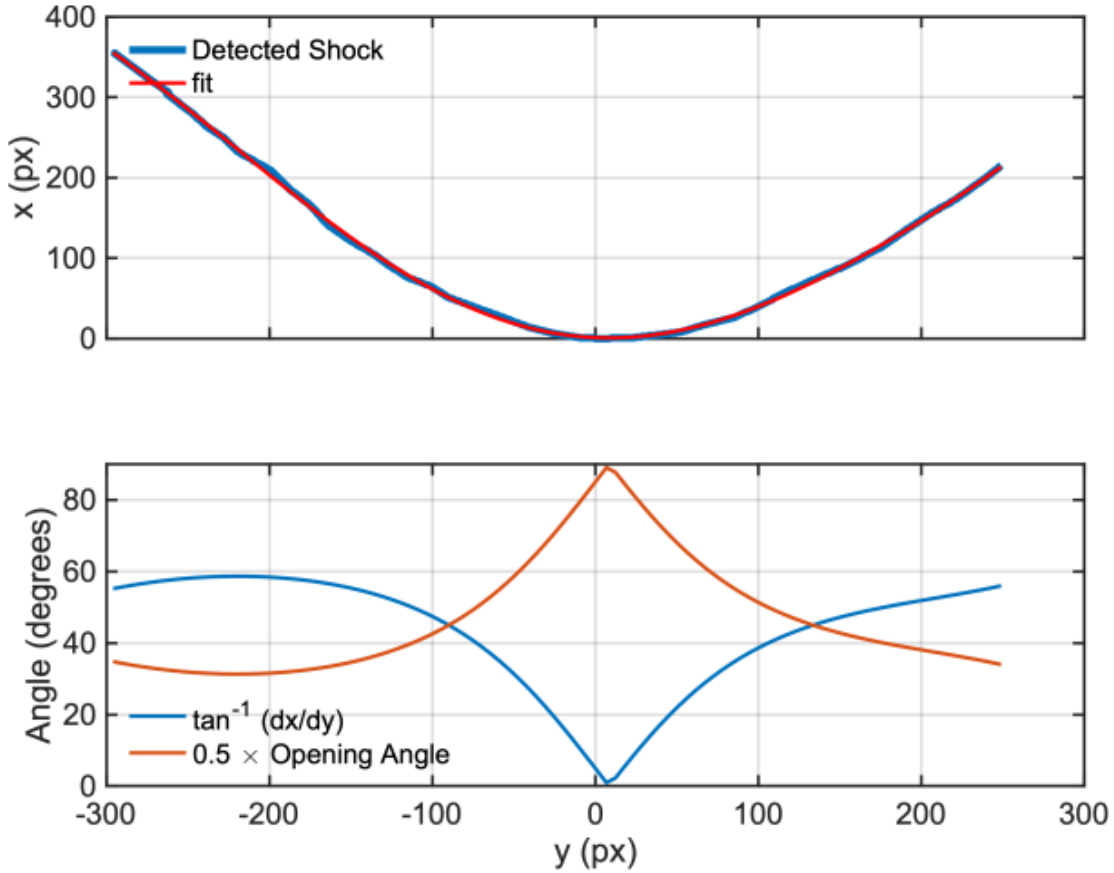
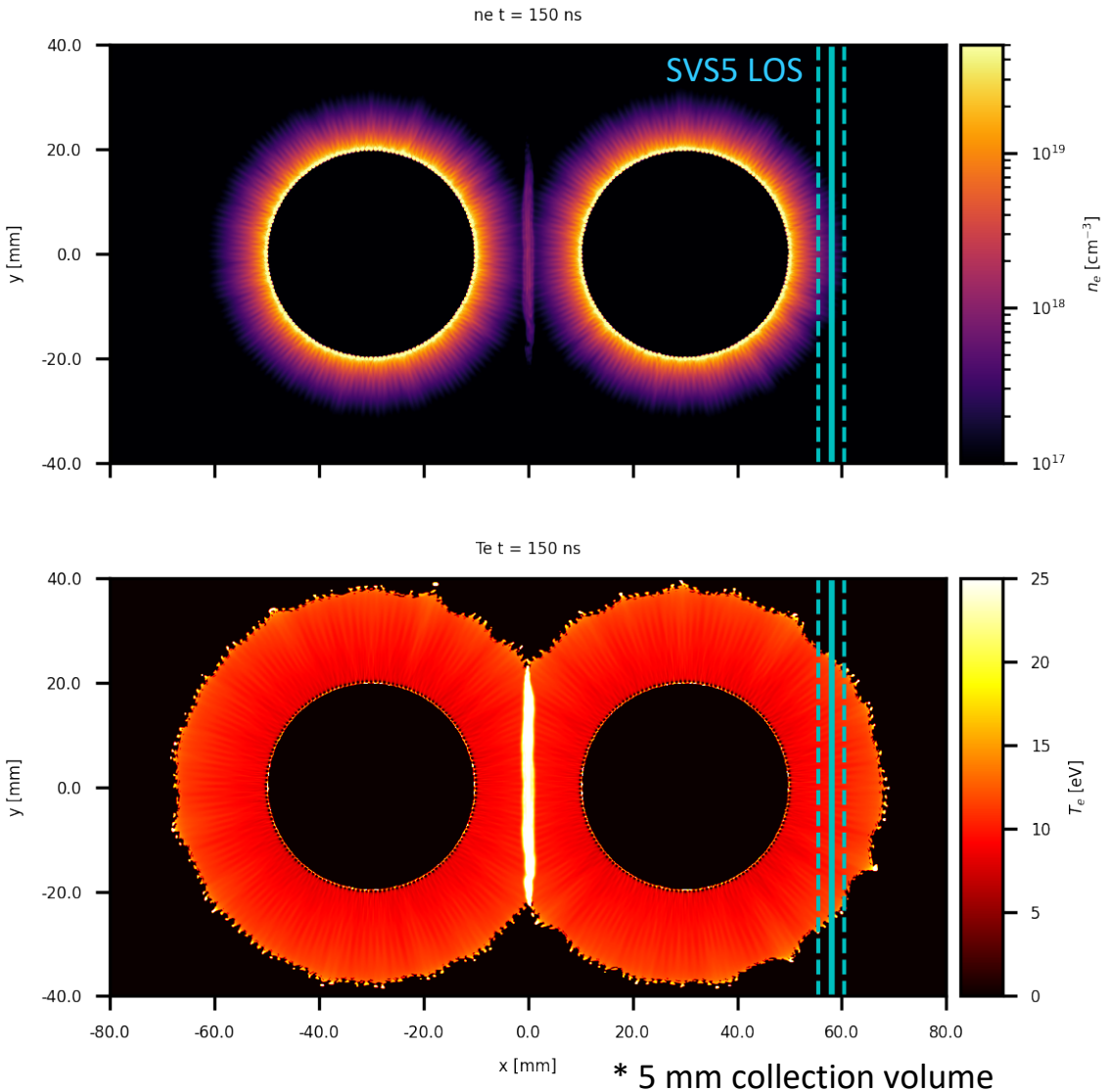
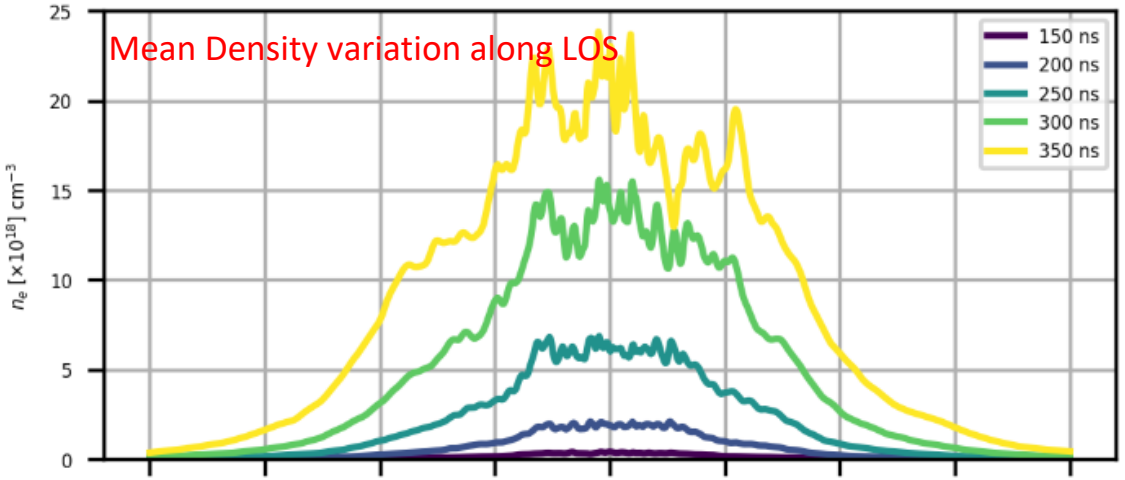
Images courtesy C. Myers, Z Diagnostic Manual (SNL)

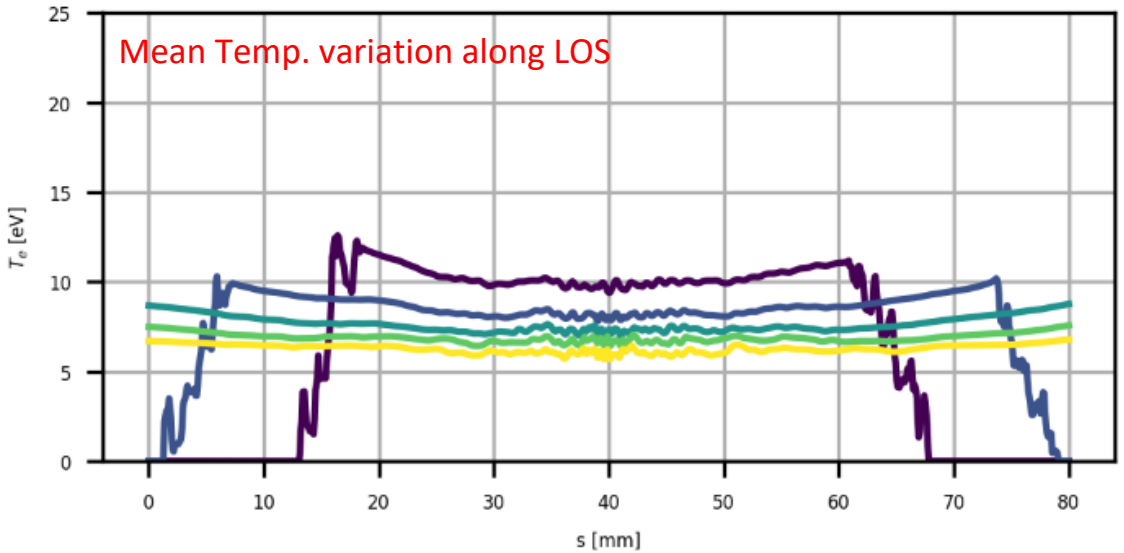
Shock Opening Angle





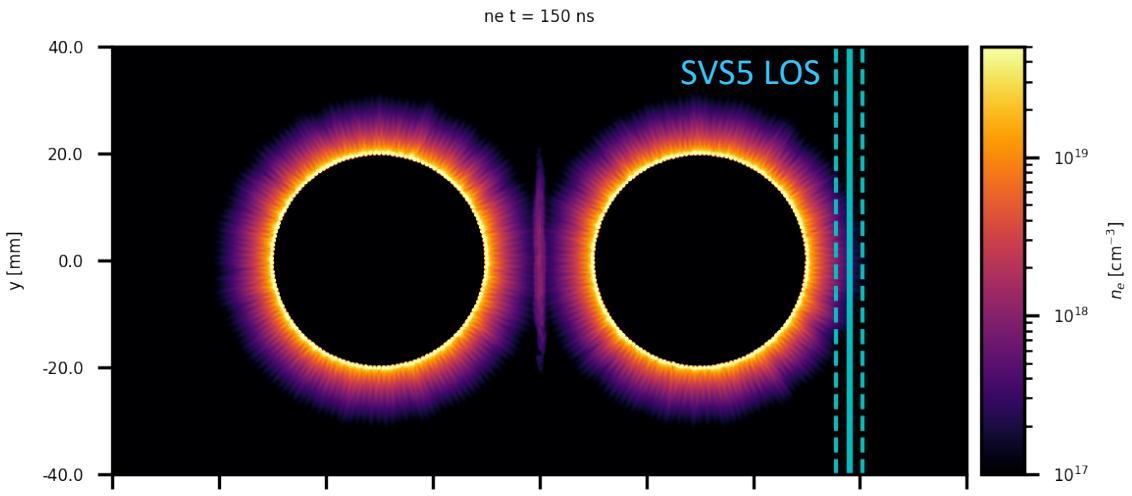


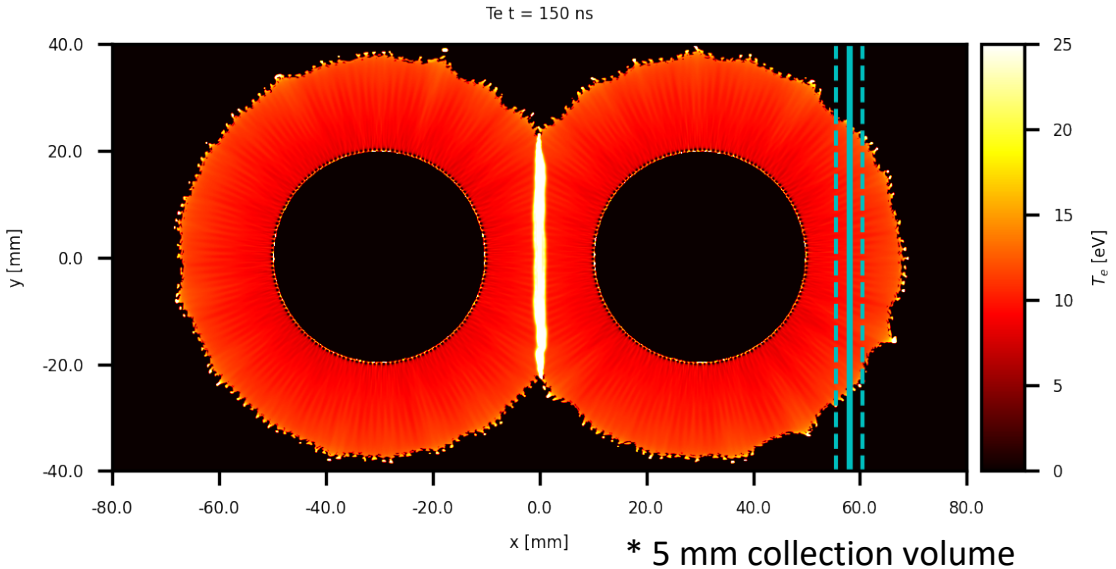




* 5 mm collection volume

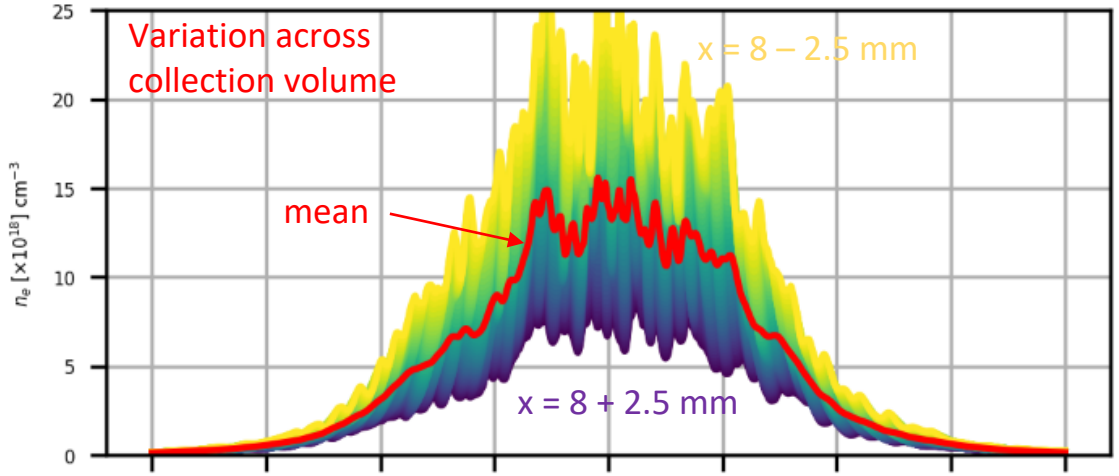
* Averaged over collection volume

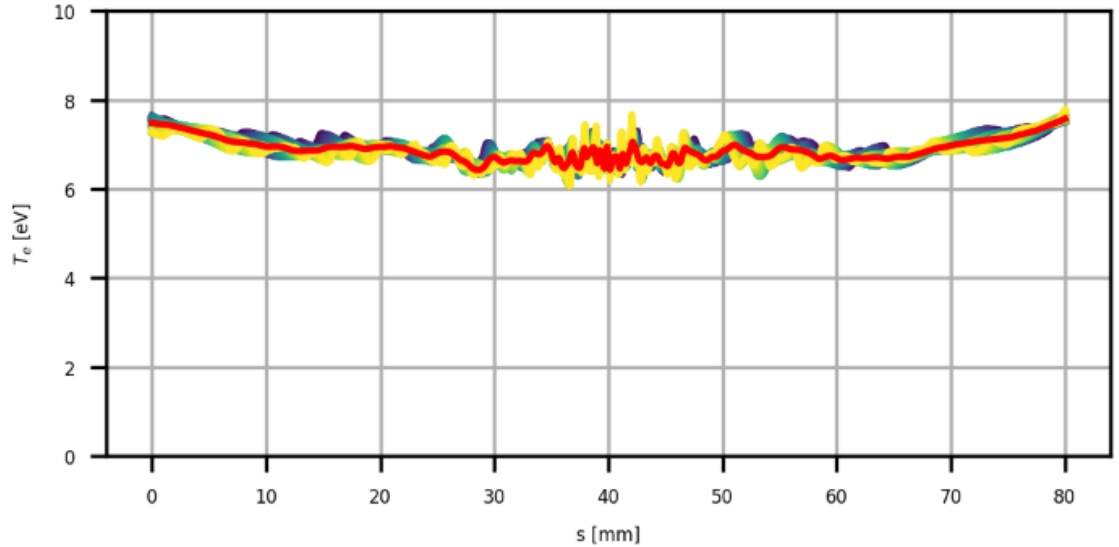




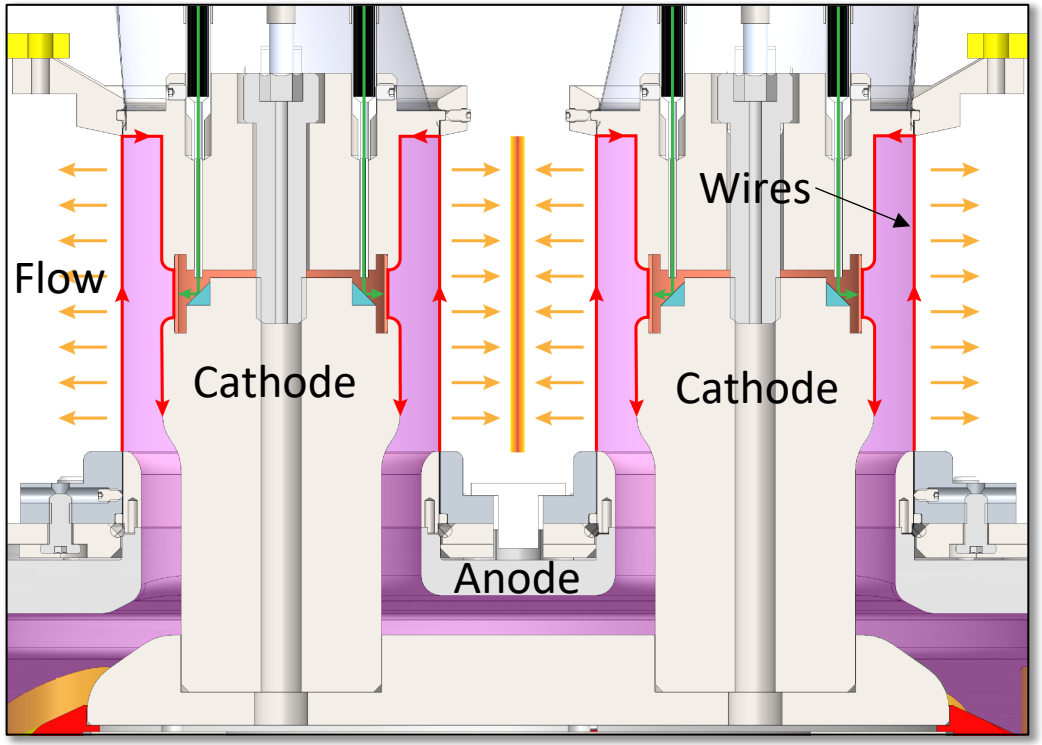
* 5 mm collection volume

t = 300 ns

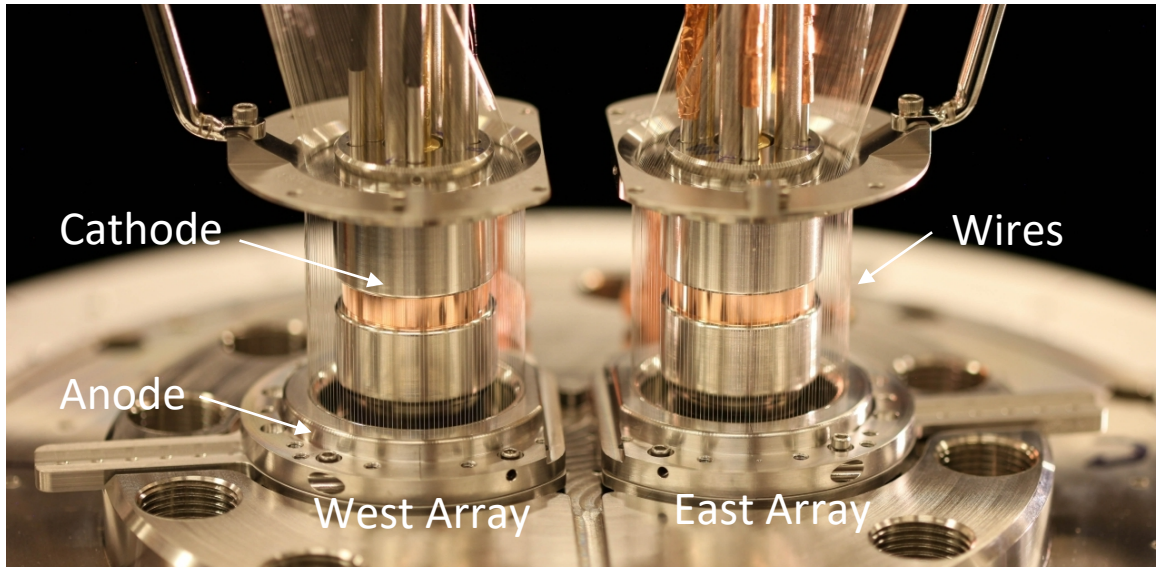


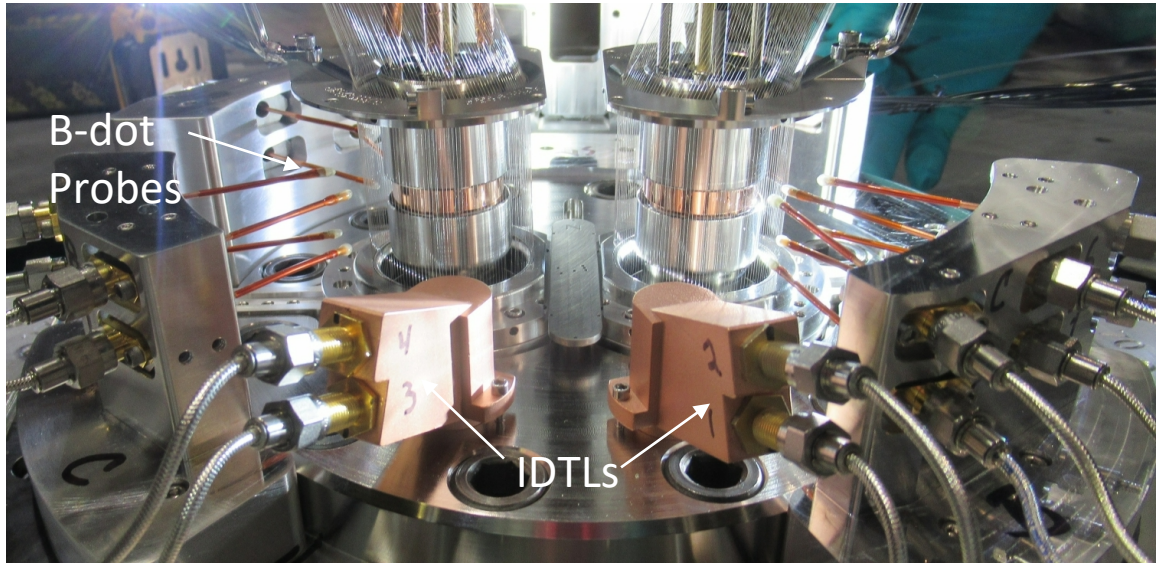


A Dual Exploding Wire Array on Z



Velocimetry





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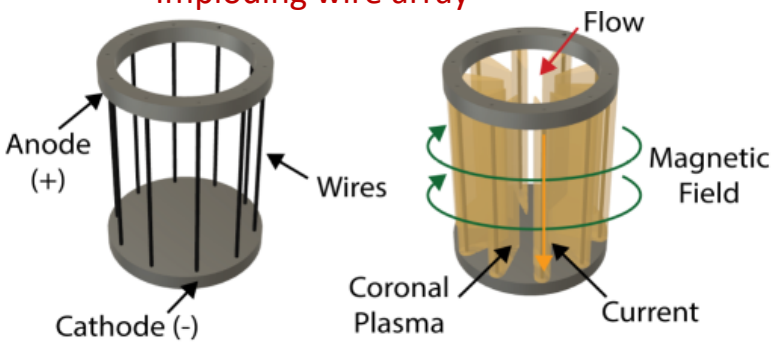
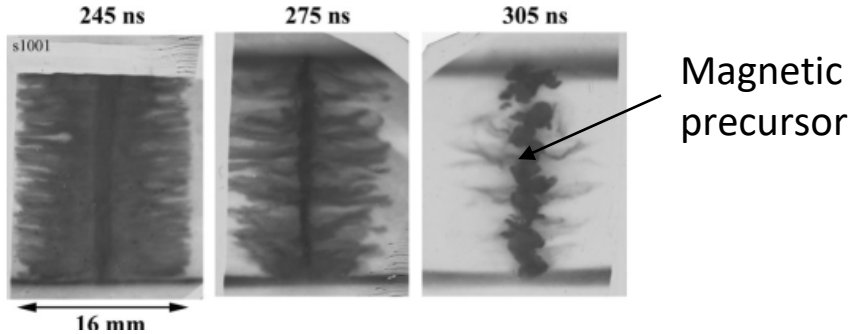
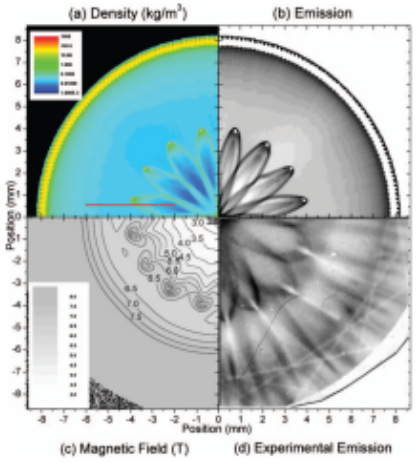
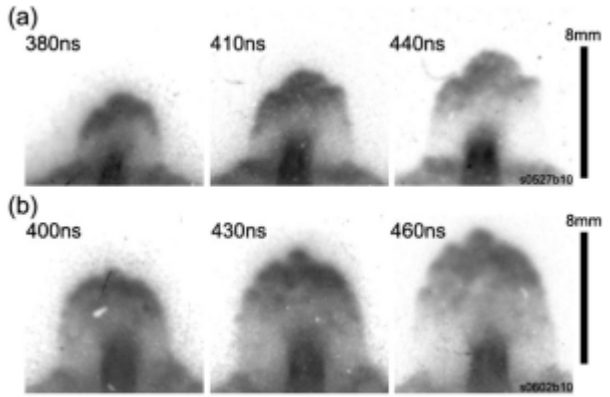
Wire Arrays for Laboratory Astrophysics

Imploding wire array



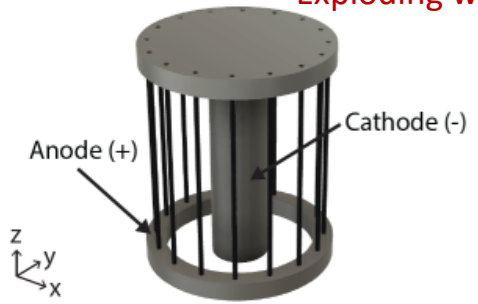


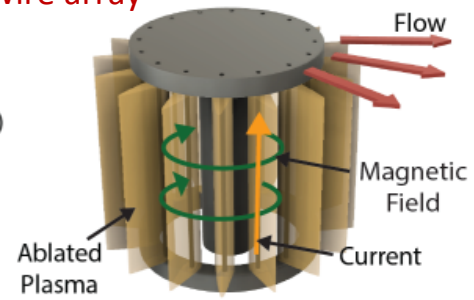




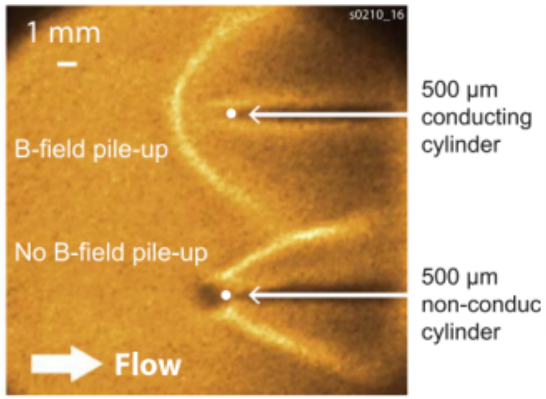
Jet and Bow Shock

Exploding wire array

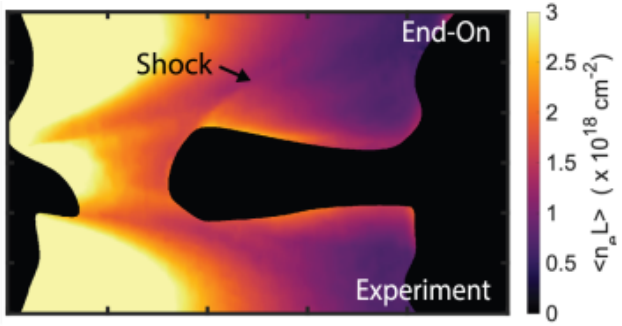


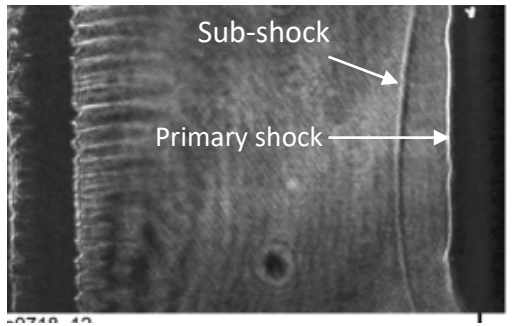


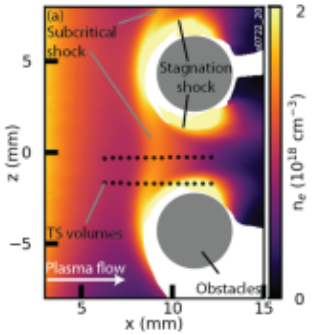
Magnetic Flux Pile-up

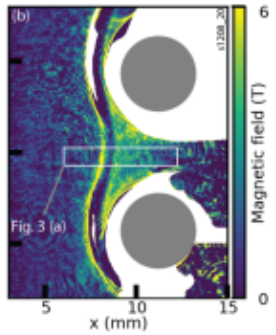


Anisotropic 3D Shocks

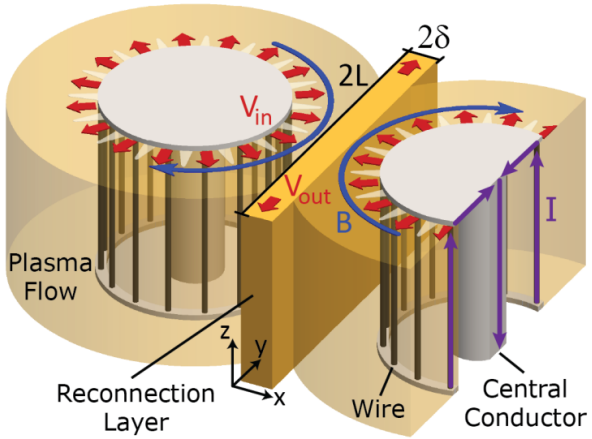


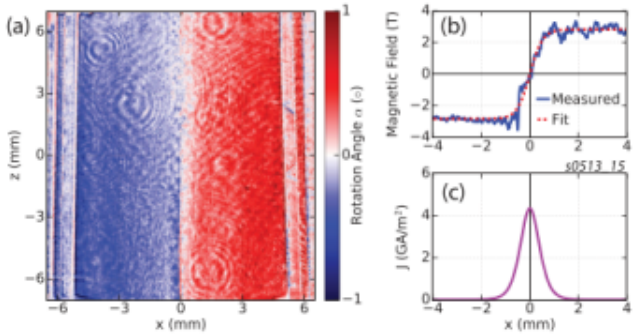


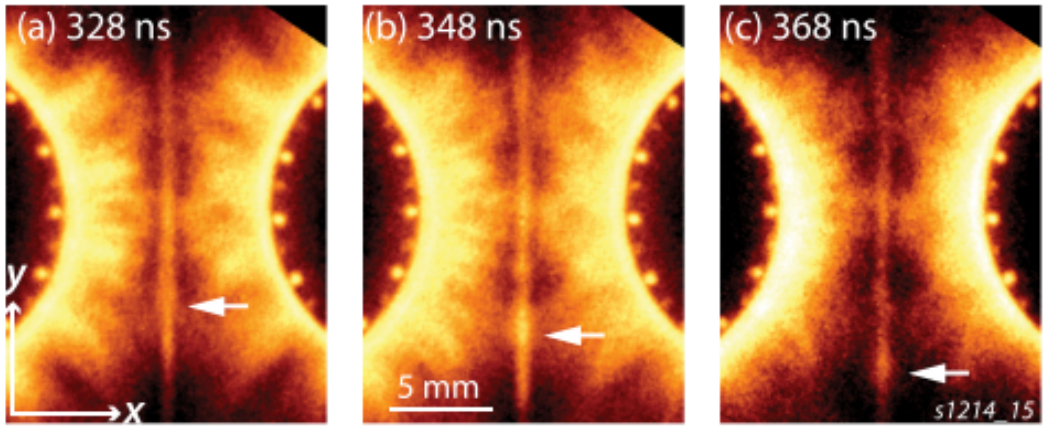




Dual Exploding Wire Array







Characteristic Parameters of Ablated Plasma in Exploding Wire Arrays (Suttle et al. 2019)

Parameter	Symbol	Material C	Material Al	Material W
Electron density (cm^{-3})	n_e	(2–5) × 10^{17}	(0.3–2) × 10^{18}	(0.3–2) × 10^{18}
Magnetic field (T)	B	3	2–4	2–4
Flow velocity ($km\ s^{-1}$)	V	50	50–150	50–150
Ion temperature (eV)	T_i	50	20	—
Electron temperature (eV)	T_e	15	15	<6
Average ionization	$\overline{Z}$	4	3.5	<6
Ion sound speed ($km\ s^{-1}$)	c_S	30	20	5
Alfvén speed ($km\ s^{-1}$)	V_A	70	30	10
Ion-ion mean free path (mm)	λ_{ii}	10^{-2}	10^{-3}	10^{-5}
Radiative cooling time (ns)	τ_{rad}	100	20	<1
Reynolds number	Re	10^5	10^5	10^7
Magnetic Reynolds number	Re_M	20	50	10
Dynamic Beta	β_{dyn}	1	10–100	100–1000
Thermal Beta	β_{th}	0.4	1	0.5
Localization	L/λ_{ii}	10^3	10^4	10^6

On ~1MA University scale facilities, wire arrays generate highly-collisional ($\lambda_{ii} \sim 10^{-5} - 10^{-3}\ mm$), supersonic ($M_S \sim 2 - 7$) & super-Alfvenic ($M_A \sim 1 - 2$), magnetized ($B \sim 5 - 10\ T$) plasma flows with frozen-in flux ($Re_M > 10$)

Diagnostics of Ablated Plasma

Inductive probe array:

- Measure time- and space-resolved magnetic field of ablated plasma
- Measure flow velocity from time-of-flight of magnetic field

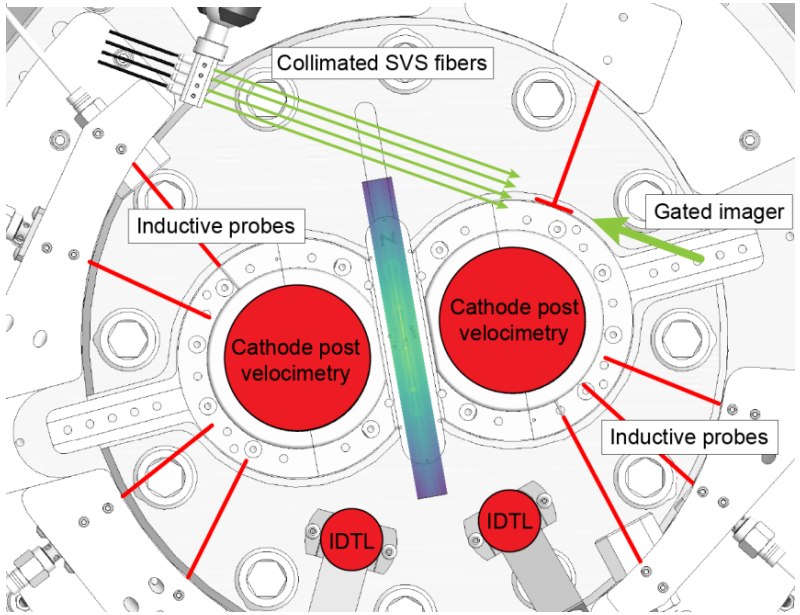
Self-emission gated optical imager (SEGOI)

- Records time-gated and 2D space-resolved visible emission
- Monitors evolution of bow shock around T-probe
- Structure of shock provides information about the Mach no.

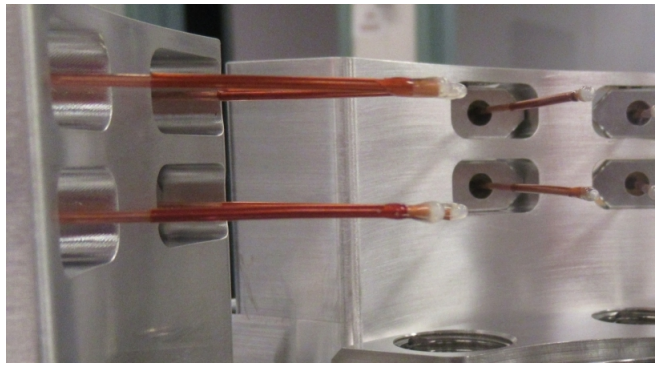
Streaked visible spectroscopy (SVS)

- Space- and time-resolved emission spectra of visible radiation

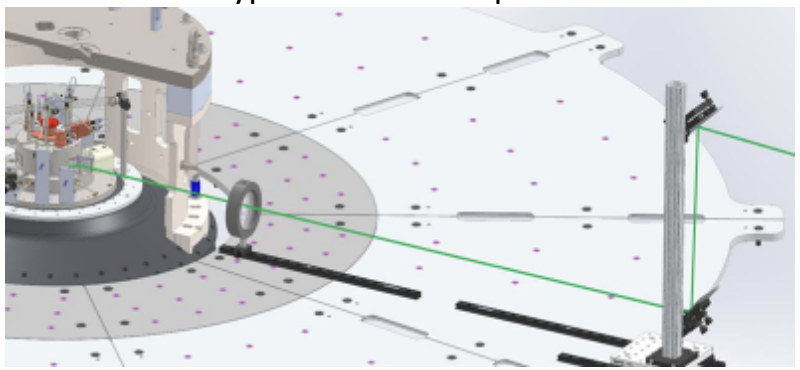
Diagnostic Setup for z3697



Inductive ('b-dot') probes on z3697

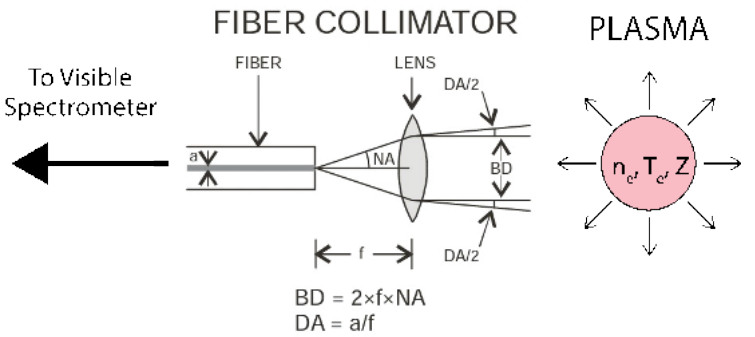


Typical SEGOI setup on Z



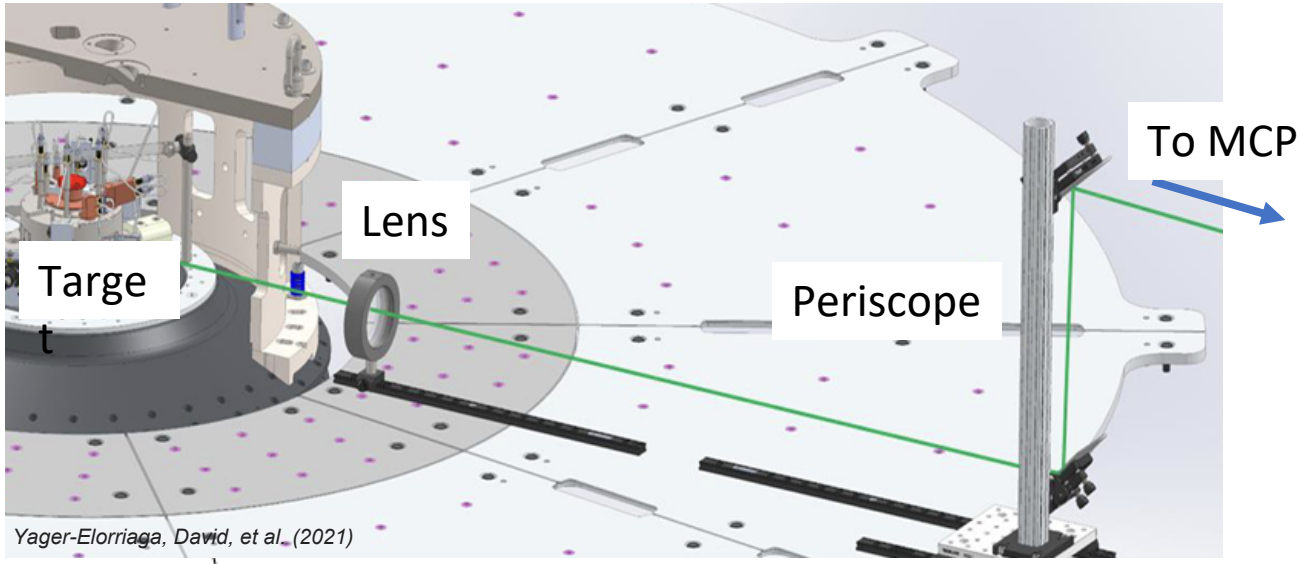
Yager-Elorriaga, David, et al. (2021)

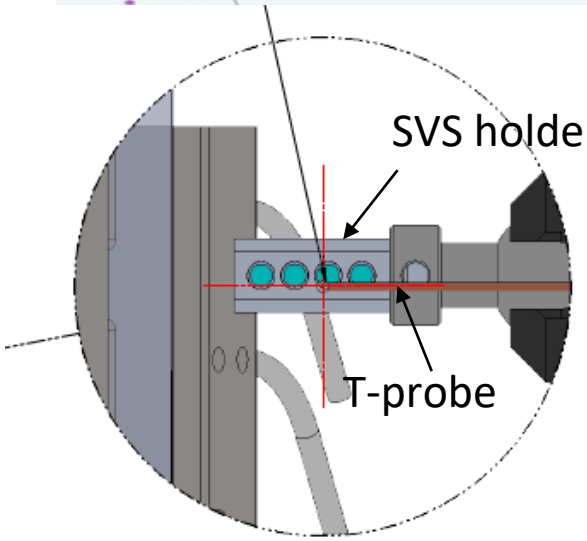
Visible Spectrometry with Fiber Collimator



Self-emission gated optical imager (SEGOI)

- Records time-gated and 2D space-resolved visible emission
- Monitors the time-evolution of the bow shock around the T-probe
- 8 frames recorded on 8 separate MCPs with 7 ns inter-frame time
- A streak camera records 1D space-resolved emission from SEGOI





SEGOI Field of View