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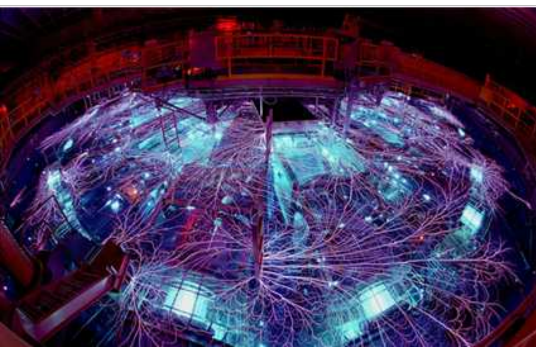

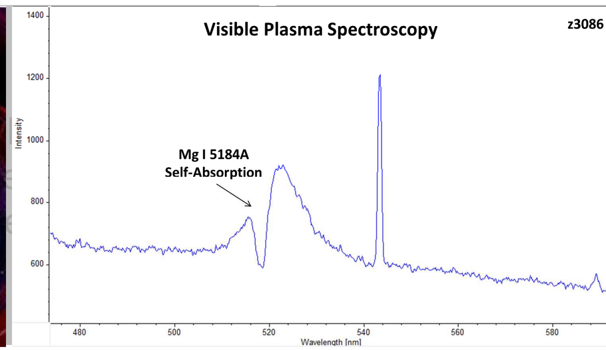

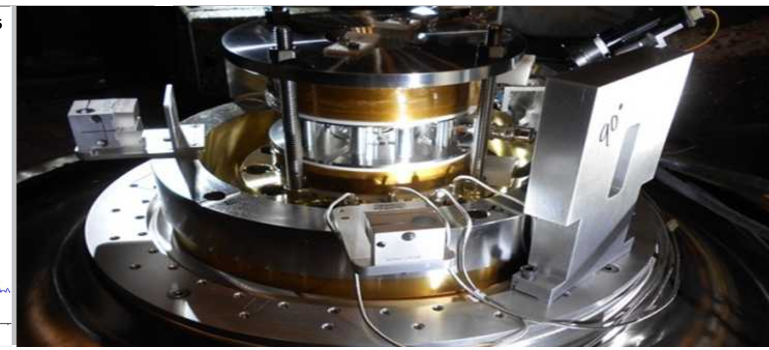

Visible Spectroscopy Measurements of Plasmas and Fields on the Z-Machine at Sandia National Laboratories

M.D. Johnston[1], S.G. Patel[1], R.E. Falcon[1], D.E. Bliss[1], G.R. Laity[1], M.L. Kiefer[1], M.E. Cuneo[1], S. Biswas[2], R. Doron[2], D. Mikitchuk[2], E. Stambulchik[2], and Y. Maron[2]

[1]Sandia National Laboratories, Albuquerque, NM 87185, USA

[2]Weizmann Institute of Science, Rehovot, Israel

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ABSTRACT

Pulsed power devices depend on the ability to deliver high voltages and high currents to a variety of loads with minimal transmission losses. The Z-Machine at Sandia National Laboratories can deliver up to 26MA in approximately 100 nanoseconds to many types of z-pinch loads. This capability is used to conduct a variety of physics-based experiments, investigating such things as inertial confinement fusion, stellar opacities, radiation effects, and materials at extreme conditions, to name a few. In order to better understand the physics involved with efficient high current delivery to a load, there is an effort underway at Sandia to study plasma formation and propagation in the power flow regions on Z. Experiments are being conducted using streaked, visible spectroscopy to obtain time histories of plasma formation and propagation throughout the final power flow regions, where currents and fields are at their highest. Electron and ion bombardment of electrode surfaces are sufficient to create plasmas which can migrate into the vacuum gap on the timescales of the current pulse (~100nsec). These plasmas drain current away from the load, causing the machine to be less efficient. Depending on the specific load, losses of up to 20% can occur. Visible spectroscopy is a good technique for exploring these early-time plasmas, as it can observe species and charge states at lower energies (a few electron Volts) and densities (10^{16} cm^{-3} or less), then would be possible from diagnostics measuring in other regions of the radiation spectrum. In addition, electric and magnetic field effects on spectral lines (Stark and Zeeman) can provide detailed information into the distribution of fields and currents within the power flow regions, which may not be possible to obtain using other techniques such as V and B-dot monitors. Other effects such as Doppler broadening provide information into plasma motion and velocity. This paper describes the first comprehensive attempt to characterize plasma formation and propagation in the pulsed-power regions on Z. The first portion of the paper outlines the experimental techniques used to make these measurements and lists some of the difficulties and challenges encountered while working in such a hostile environment. The second portion provides results obtained to date, comparisons with hybrid fluid-PIC simulations, and conclusions. The final section outlines plans for future work.

MOTIVATION

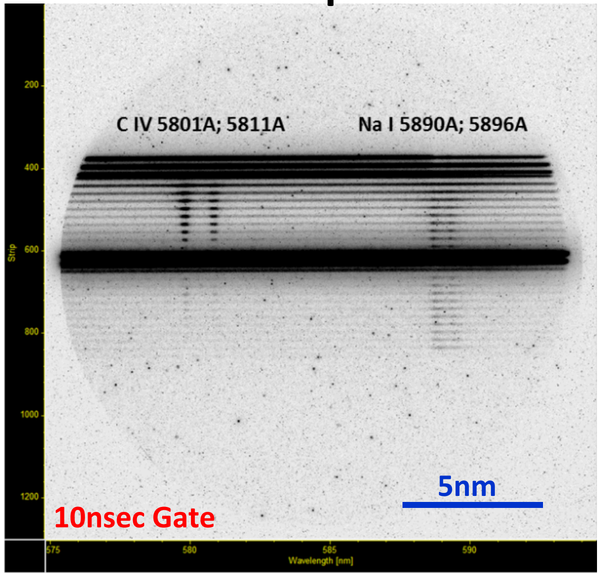
- Provide quantitative measurements of plasmas and fields generated in the power flow regions on Z.
- Detailed plasma measurements have been made on the SMP diode on RITS-6. Want to extend these measurements to Z.
- Plasma measurements in the Z convolute were made by Matt Gomez et. al.[1] Want to expand these measurements to other regions.
- Gain a physics understanding of plasma formation on Z.
- Input experimental data into particle in cell (PIC) codes to better predict plasmas and fields in high power devices.
- Use this information to improve present pulsed power designs and as a predictive capability for future, next generation capabilities (ex. Z300, Z800, and Jupiter).

[1] M.R. Gomez, et al., *Physical Rev. Accel. and Beams,* 20, p. 010401-1-21 (2017).

Plasma Measurements Taken on the SMP Diode at SNL

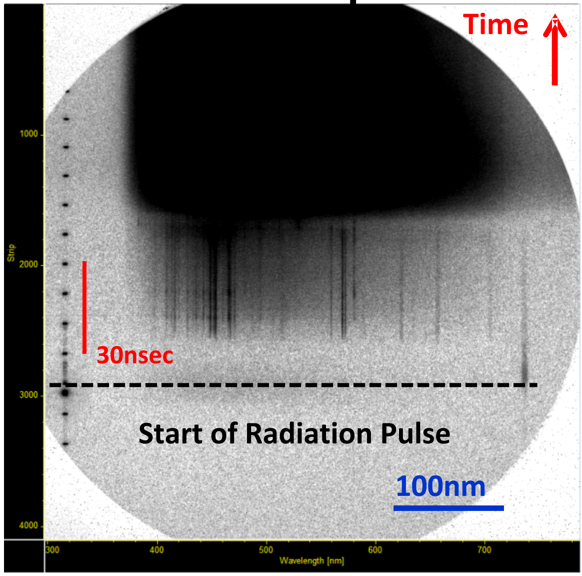
- Multi-Fiber Gated spectra
- Streaked spectra
- Avalanche Photodiodes

Gated Spectra

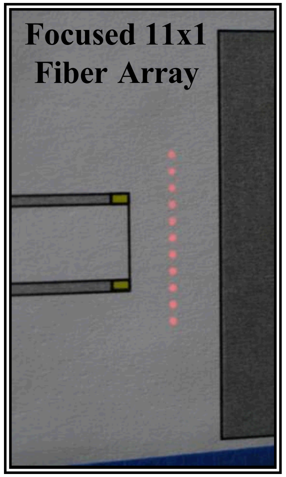


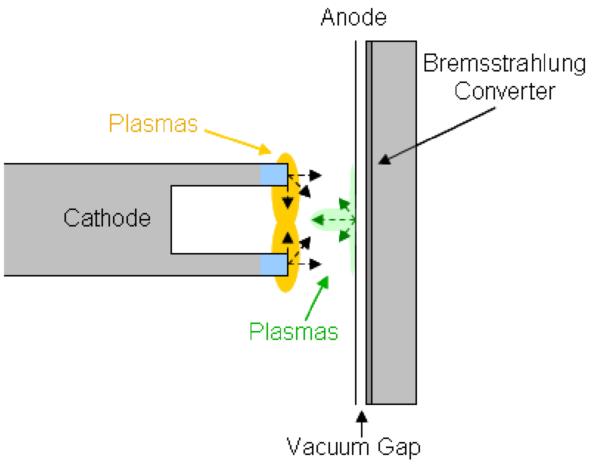
High Spectral Resolution (0.5A)

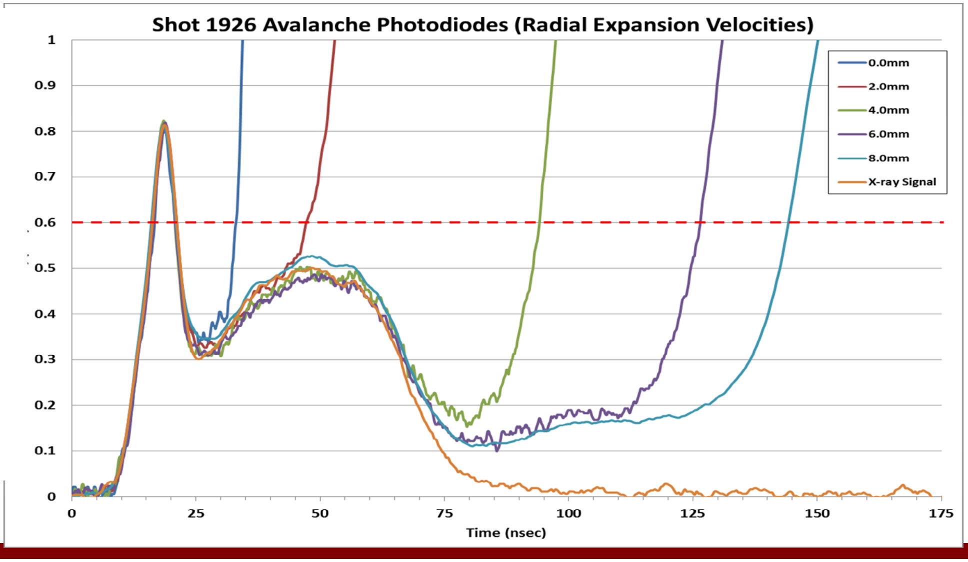
Streaked Spectra



Lower Spectral Resolution (10A)

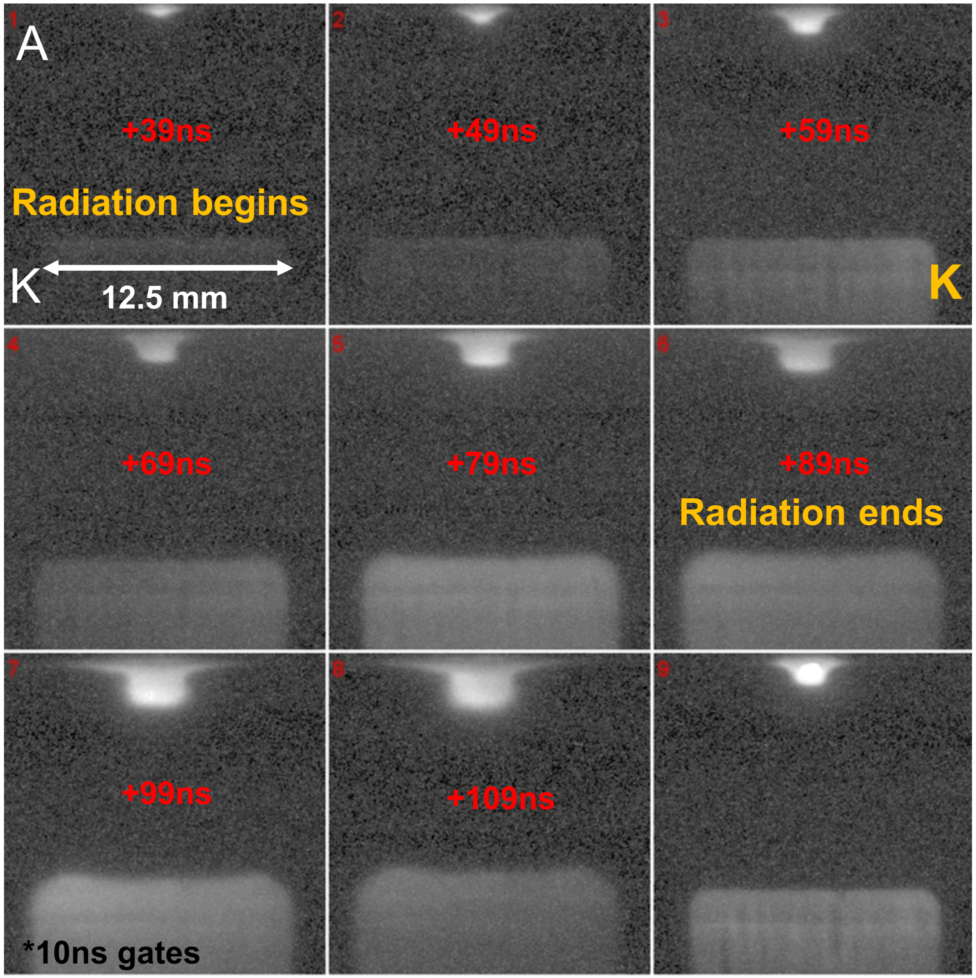


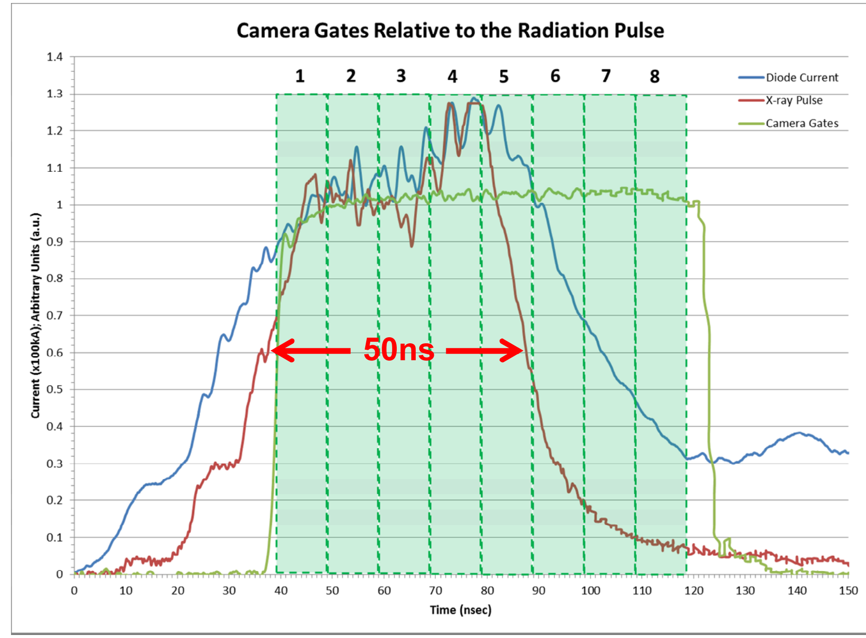




Avalanche Photodiodes

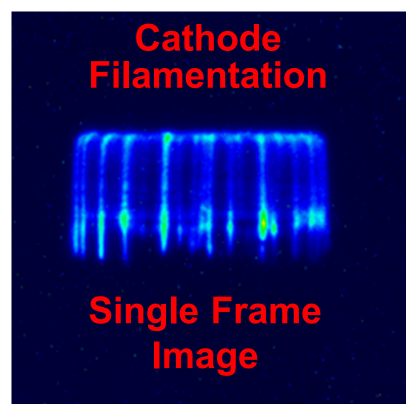
Self-Emission Images Reveal Structure and Apparent Closure Velocities of Diode Plasmas





FWHM of Radiation Pulse: 50ns

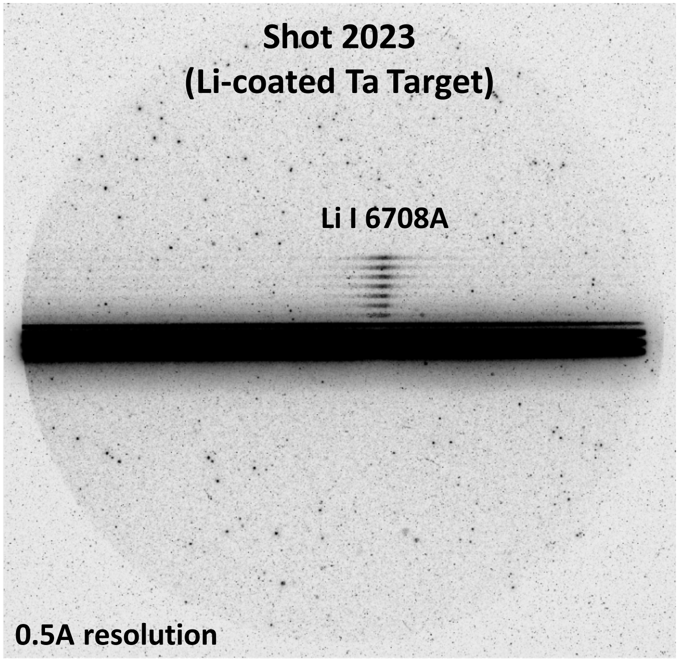
- Want similar diagnostics on Z.

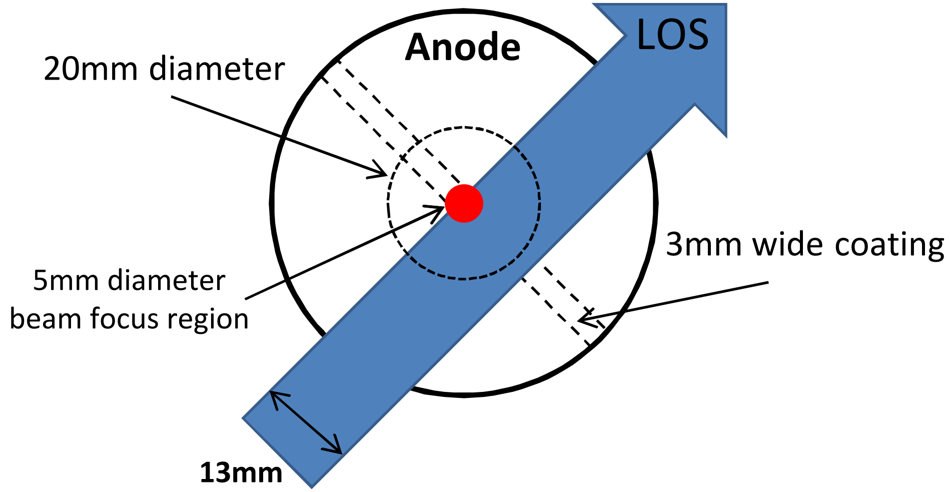


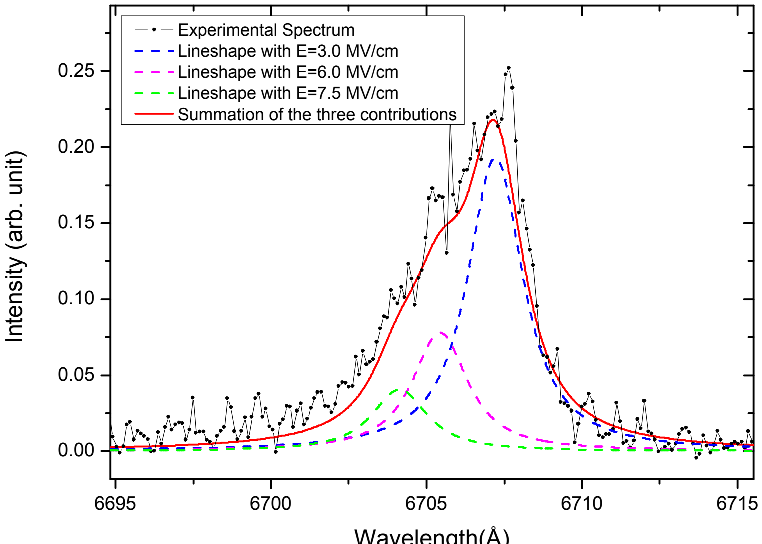
Filament formation on cathode could drive:

- Non-uniform anode plasma
- Field fluctuations
- Thermal instability

Electric Field Measurements on Pulsed-Power Diodes

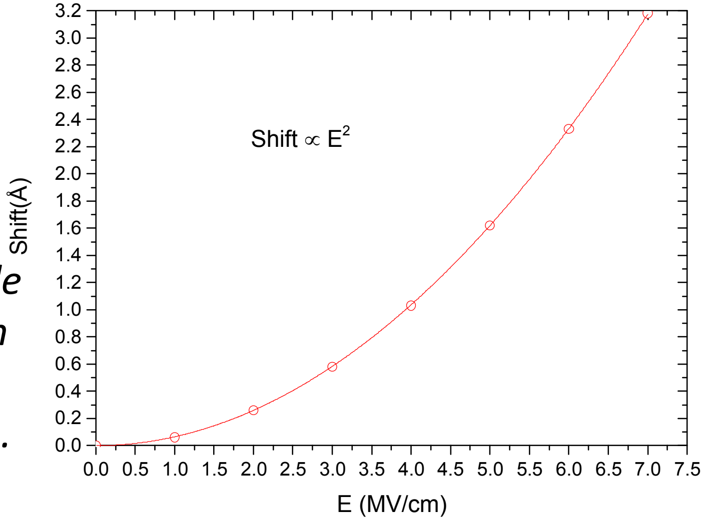






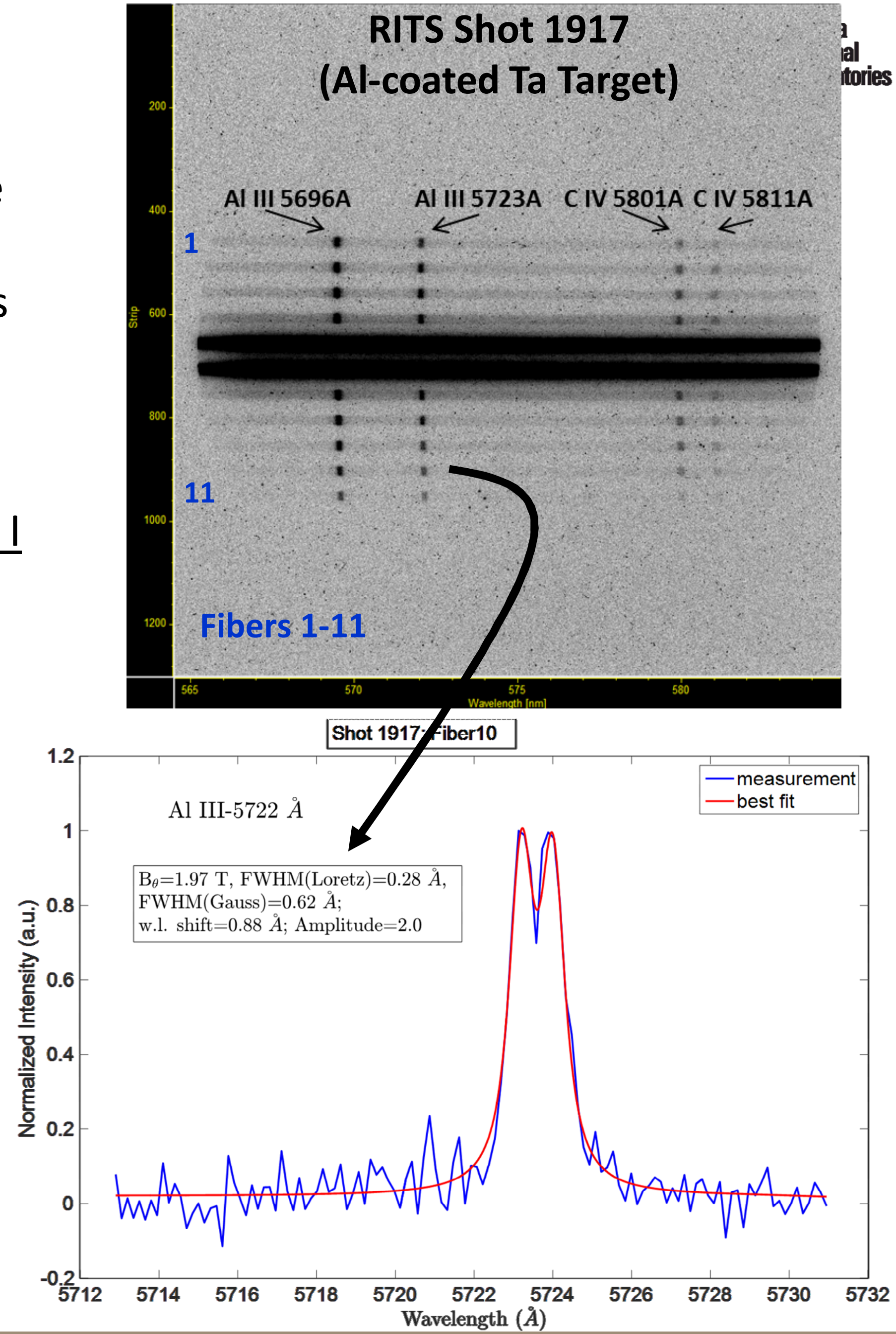
Large electric fields (MV/cm) cause a shift of the line-center towards shorter wavelengths. Since these spectra are integrated across multiple field lines, the result is an asymmetric line profile skewed towards the blue.

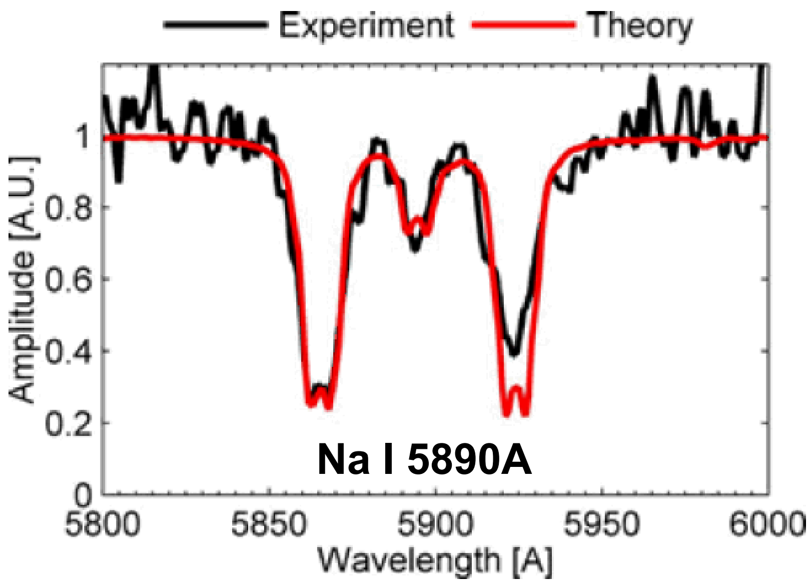
Li I 2s-2p Stark Shifts*



Zeeman Splitting Measurements

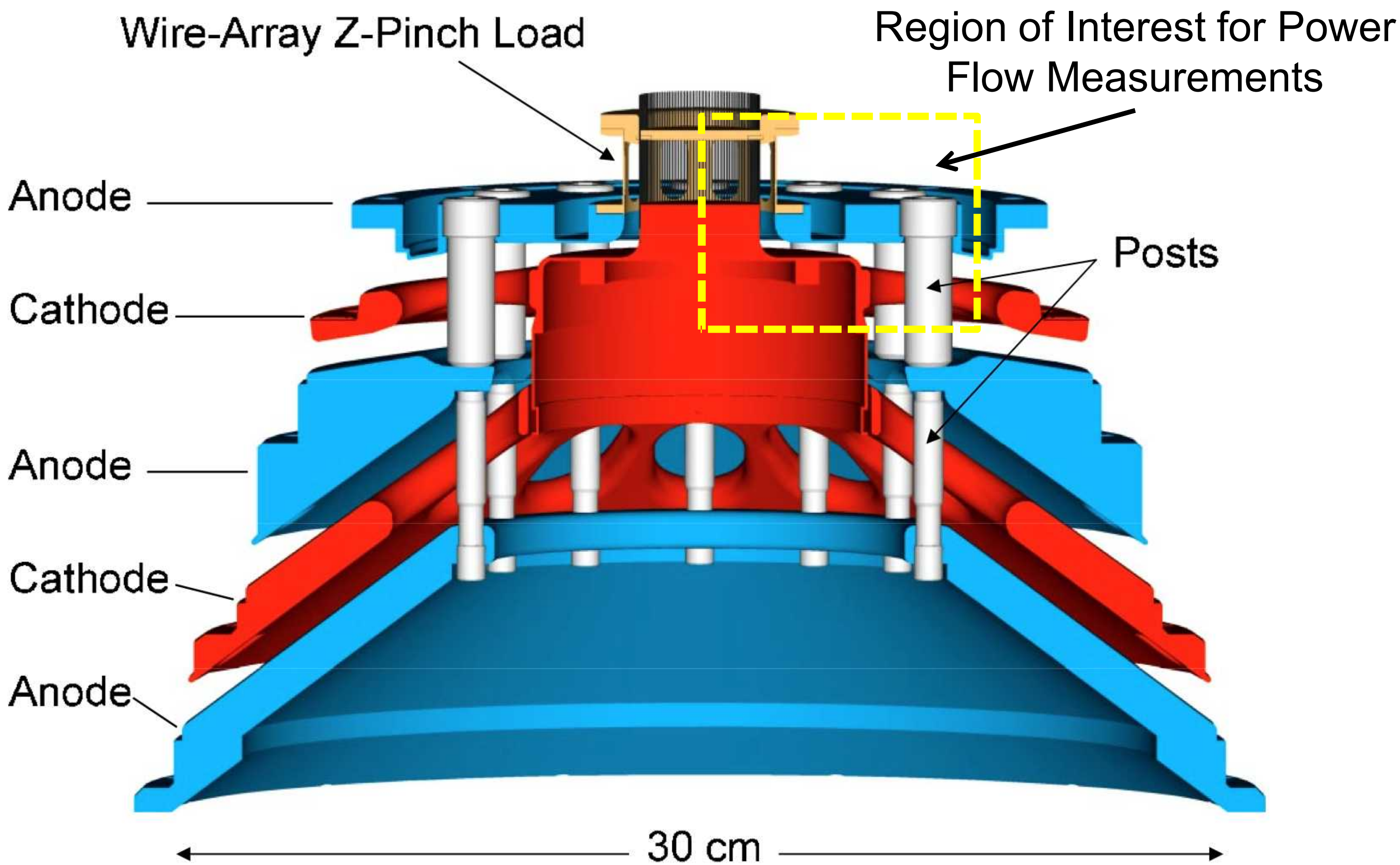
- Time and space resolved Zeeman measurements were taken on the SMP diode on RITS-6 as a proof of principle for Z.
- From RITS, calculations of Zeeman lineshapes have been done for Al III and C IV covering a wide variety of temperatures and density regimes.
- Previous work by Gomez et. al. measured Na I splitting in the load region on Z.[2]





[2] M.R. Gomez, et al., *Rev. Sci. Instr.*, 85, p. 11E609-1-11 (2014).

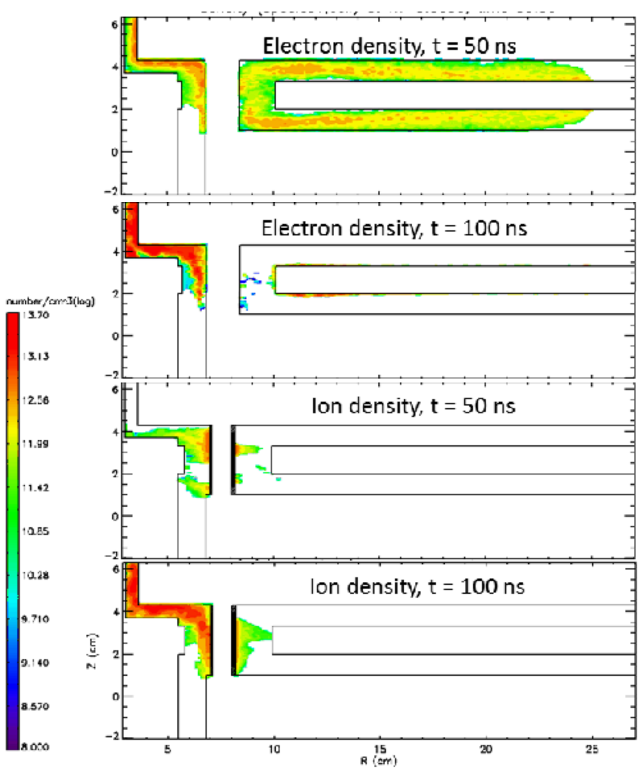
Z Hardware Configuration[3]

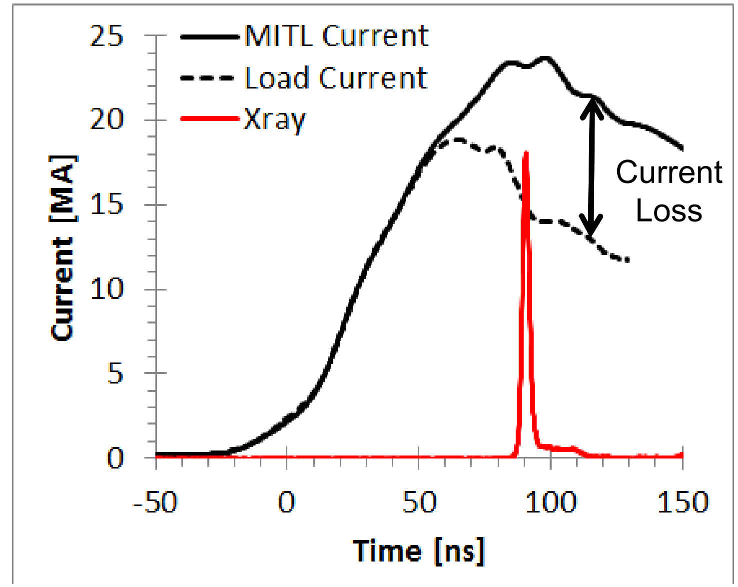


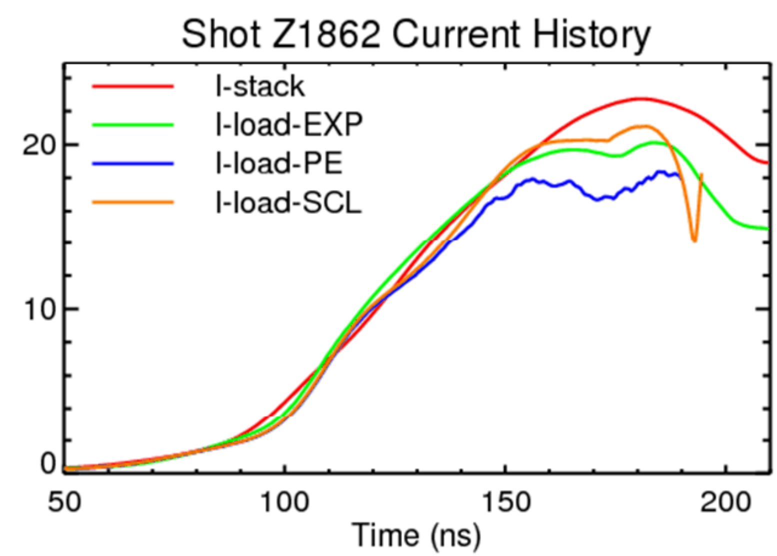
- B-dot measurements are made at 6 cm from the axis
- Vacuum gap decreases to 3 mm in the MagLIF hardware
- Plasma velocity > 10 cm/µs measured in the convolute

[3] D.H. McDaniel, et al., *Proc. 5th Inter. Conf. on Dense Z Pinches, AIP*, New York, p. 23 (2002).

Current losses on the Z machine are attributed to plasma formation in the convolute and final current feed[4]



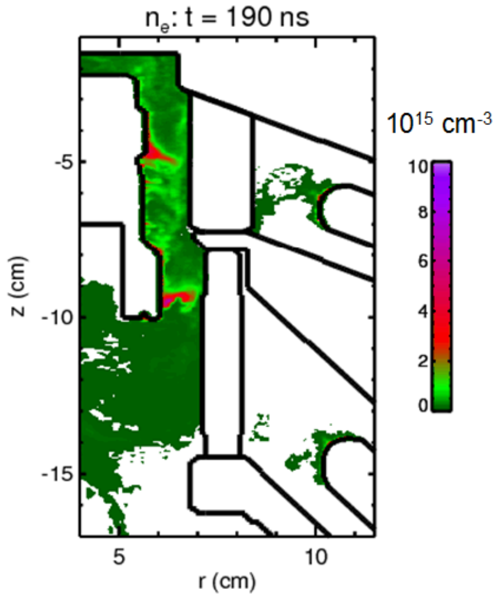




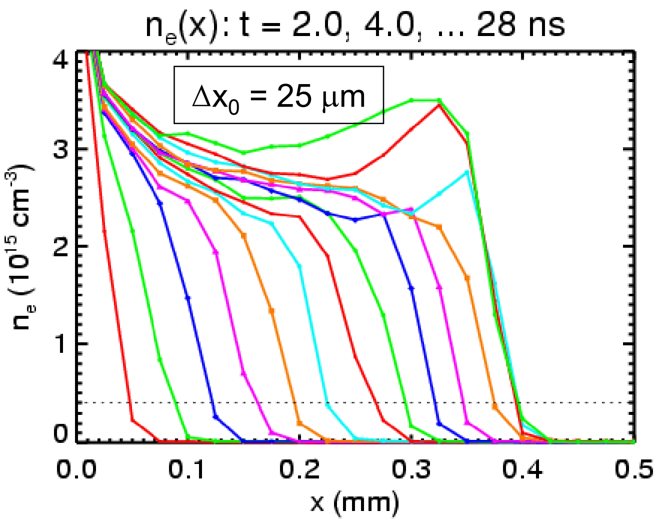
- Current losses of <u>up to 20%</u> have been observed on some Z loads.
- Plasma models can reproduce measured currents, but experimental measurements are needed to verify the correct physics.

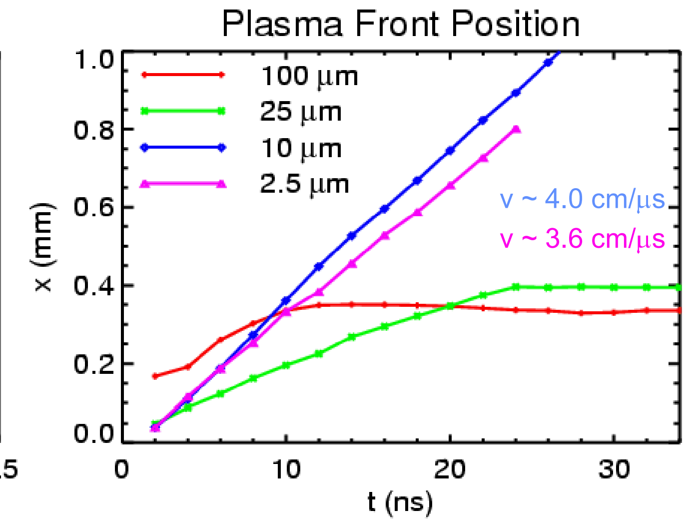
[4] D.V. Rose, et al., *Physical Rev. Special Topics-Accel. and Beams*, <u>18</u>, p. 030402-1-10 (2015).

Particle in Cell Modeling of Cathode and Anode Plasma on Z[5]

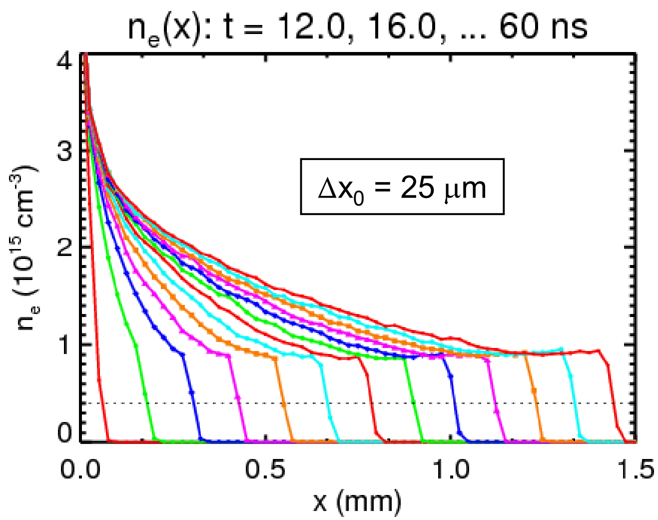


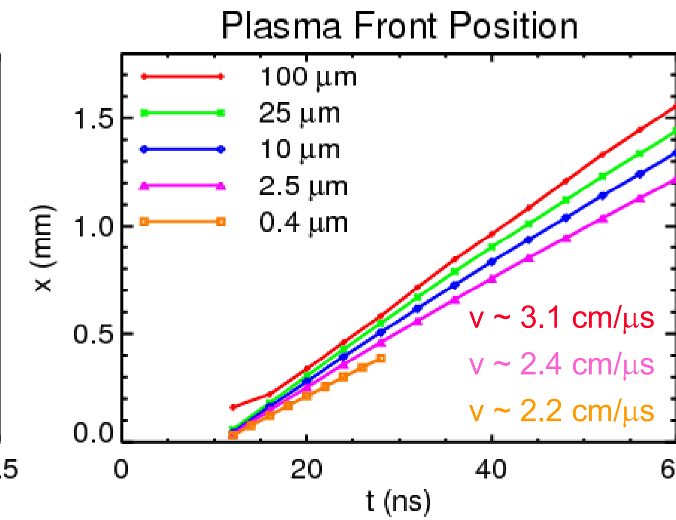
Cathode Plasma





Anode Plasma

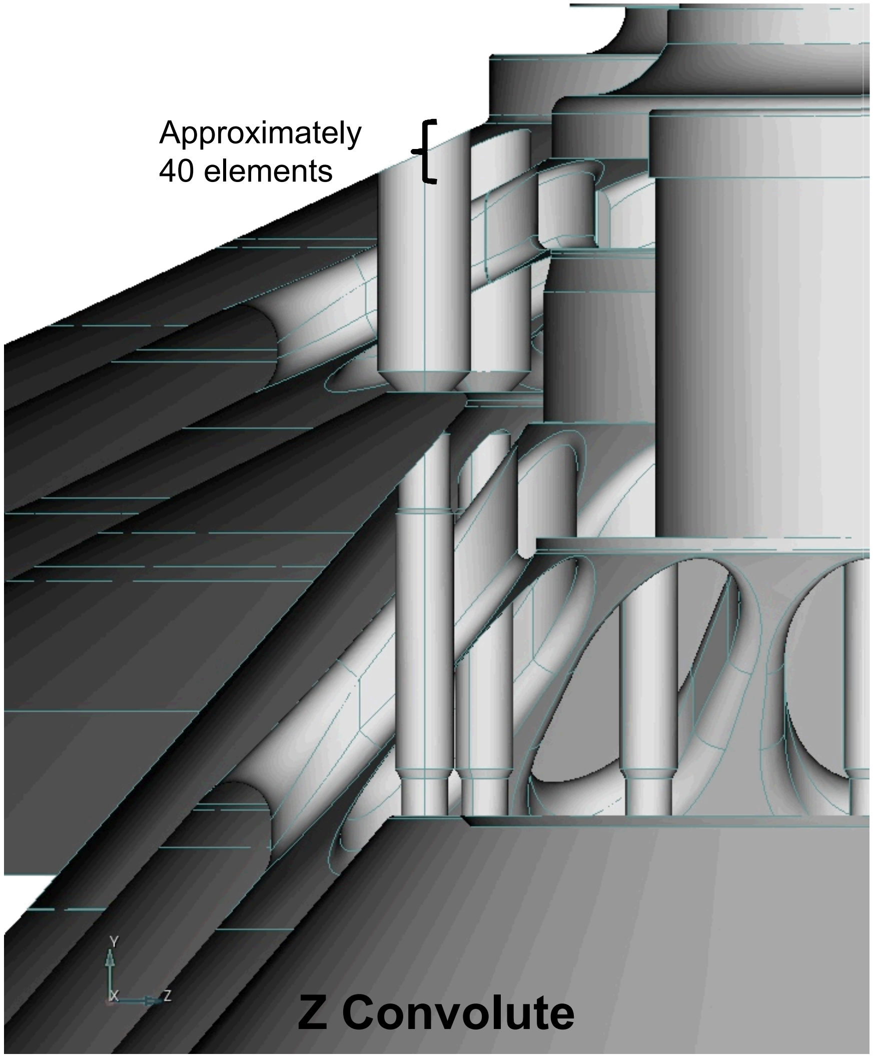


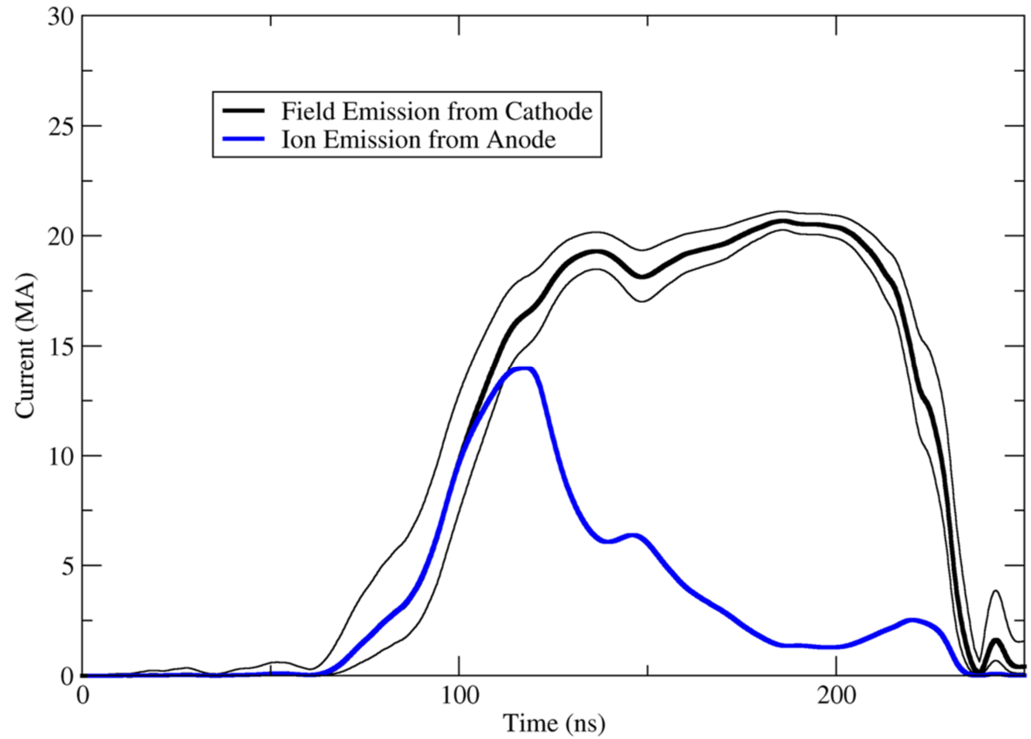


- High density electron structures are observed on the inside of the posts, where B-fields are high.

[5] T.D. Pointon, *52nd Annual Meeting of the APS Division of Plasma Physics,* Nov. 8-12, 2010.

EMPHASIS[6] simulations are focused on final-feed gap and provide guidance for plasma experiments



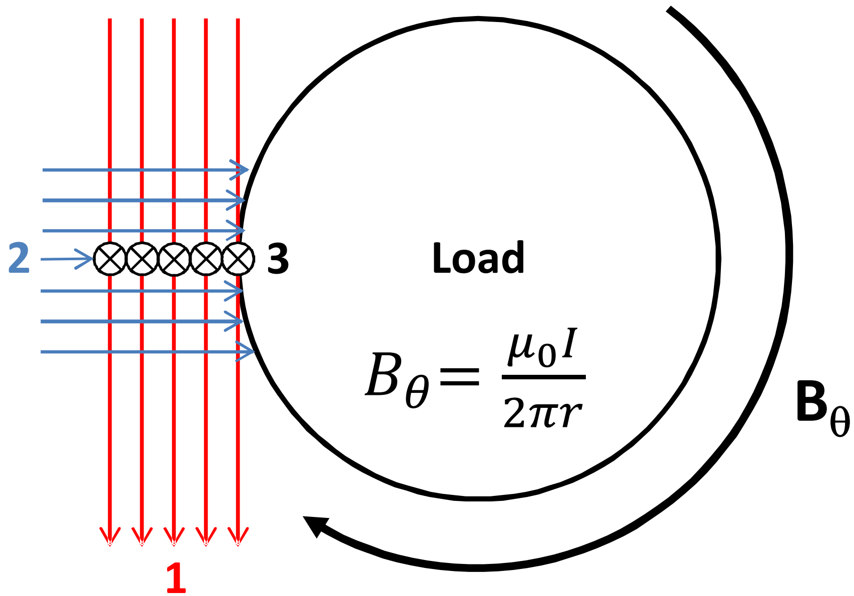


Initial bounding calculations of geometry

- Showing best, ***largest*** current case with uncertainty (black)
- Showing ***lowest*** current case (blue)

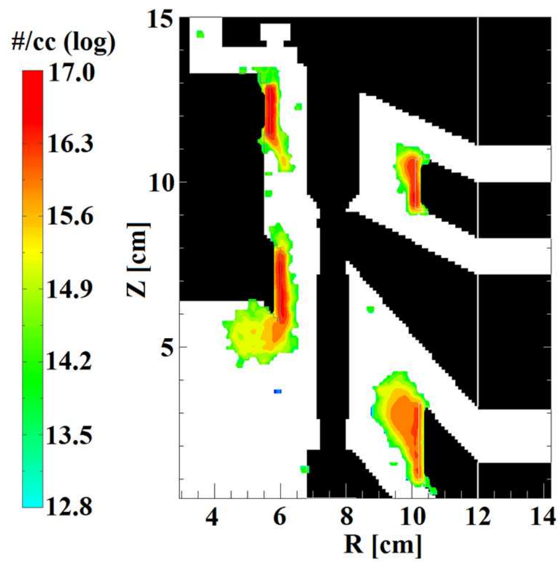
Proposed Zeeman Splitting Measurements on Z

Three Potential Views at the Load



Requirements:

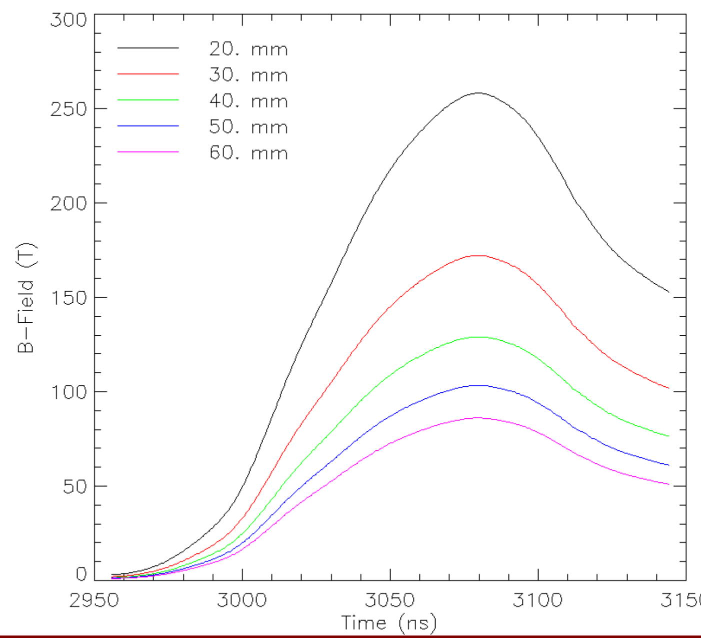
- Slotted return current can
- Multifiber array
- Detectors (Streaked spectra, gated spectra, photodiodes)
- Dopants (NaCl, Al, C, others)
- Compare with VISAR measurements at the load
- Compare with B-dot monitors at r=6cm



Considerations:

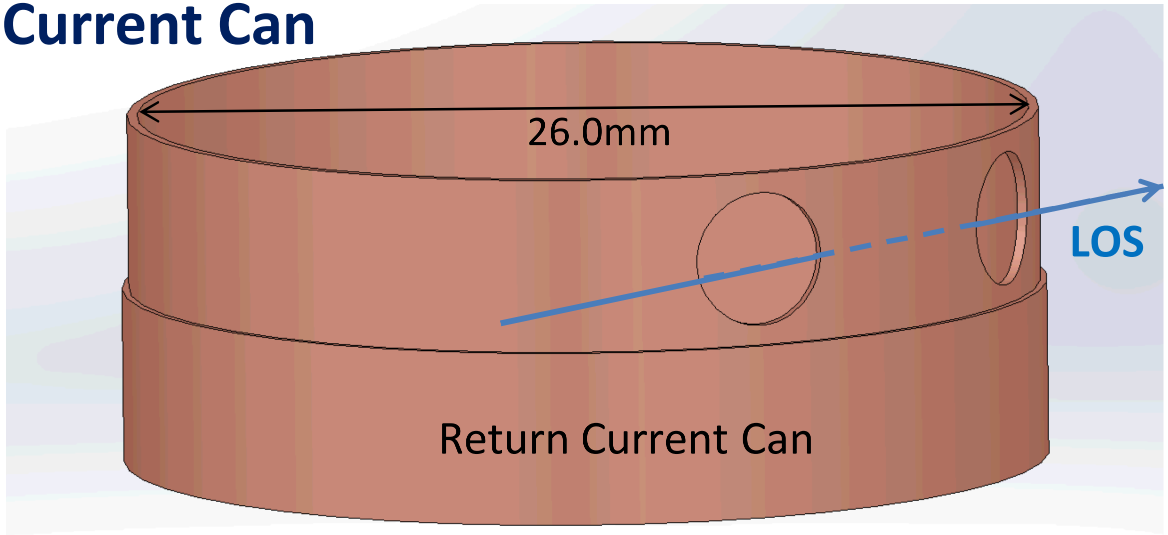
- Polarizations (σ and π)
- Lines of sight vs. B-field orientation
- Weak field/Strong field
- Specific Lines (low Stark)
- Plasma density and temperatures
- Doppler broadening

B-field versus Radius

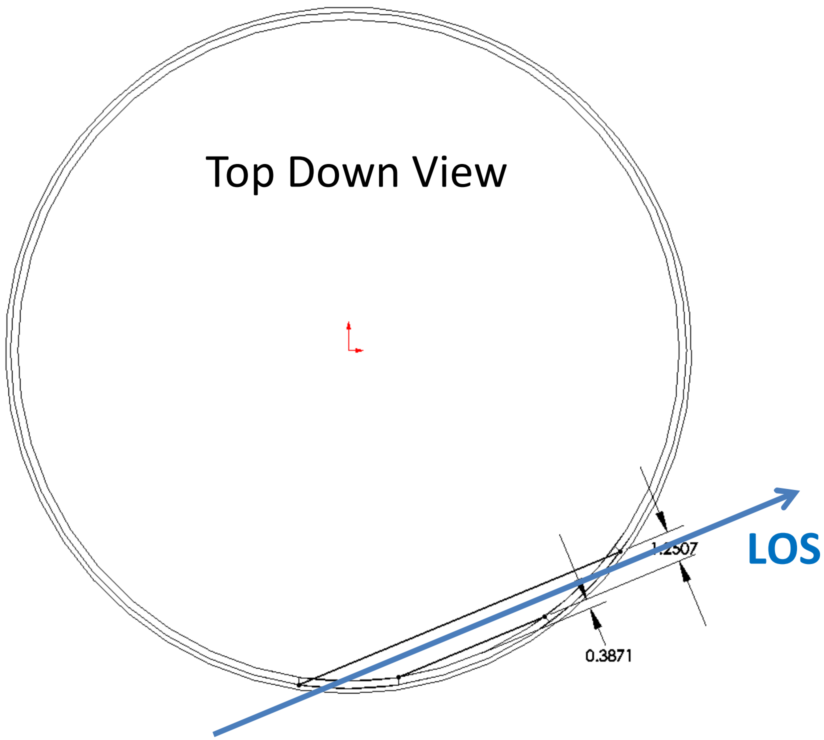


*LSP simulation of the convolute courtesy of Dave Rose, Proceedings IEEE Pulsed Power Conf. (2009).

Proposed Zeeman Splitting Measurements near the MagLIF Return Current Can



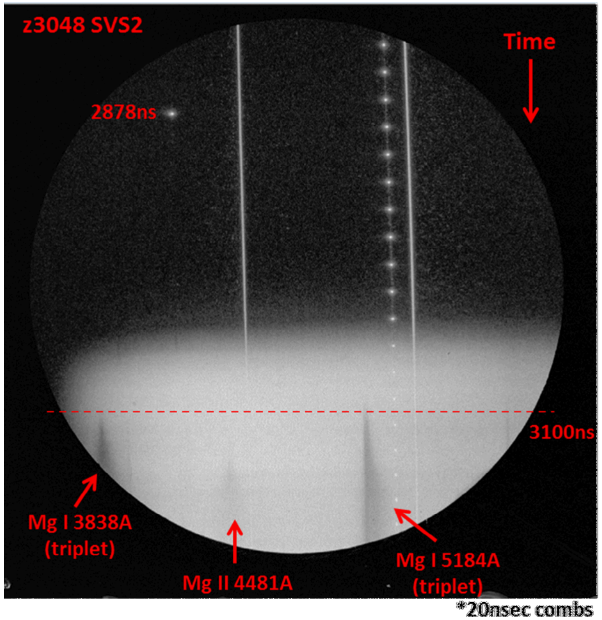
- Dopants will be applied to the inside and outside of the return current can, around the holes.
- A horizontal array of fibers will be used to allow for measurements at different distances from the surface.
- Various dopants will cover both neutral and ion species.

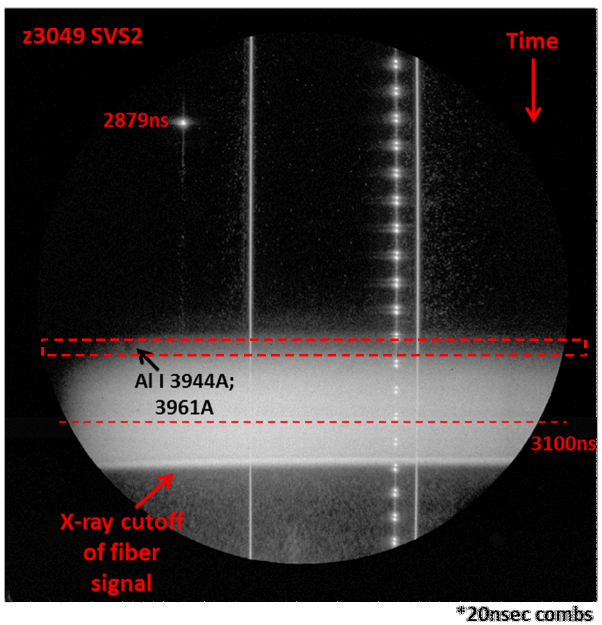


4mm diameter holes offset by 45°

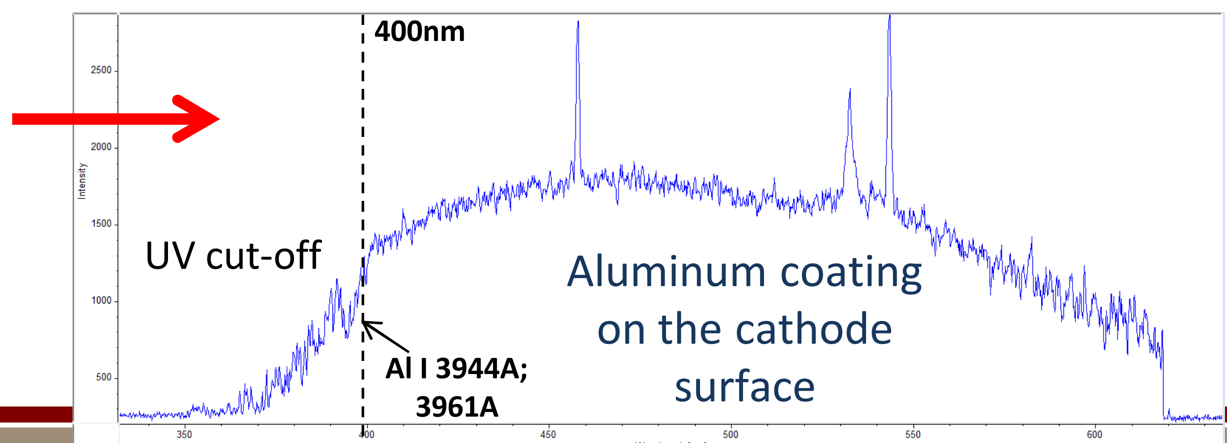
Be Return Current Can

Initial Visible Spectroscopy Experiments on Z

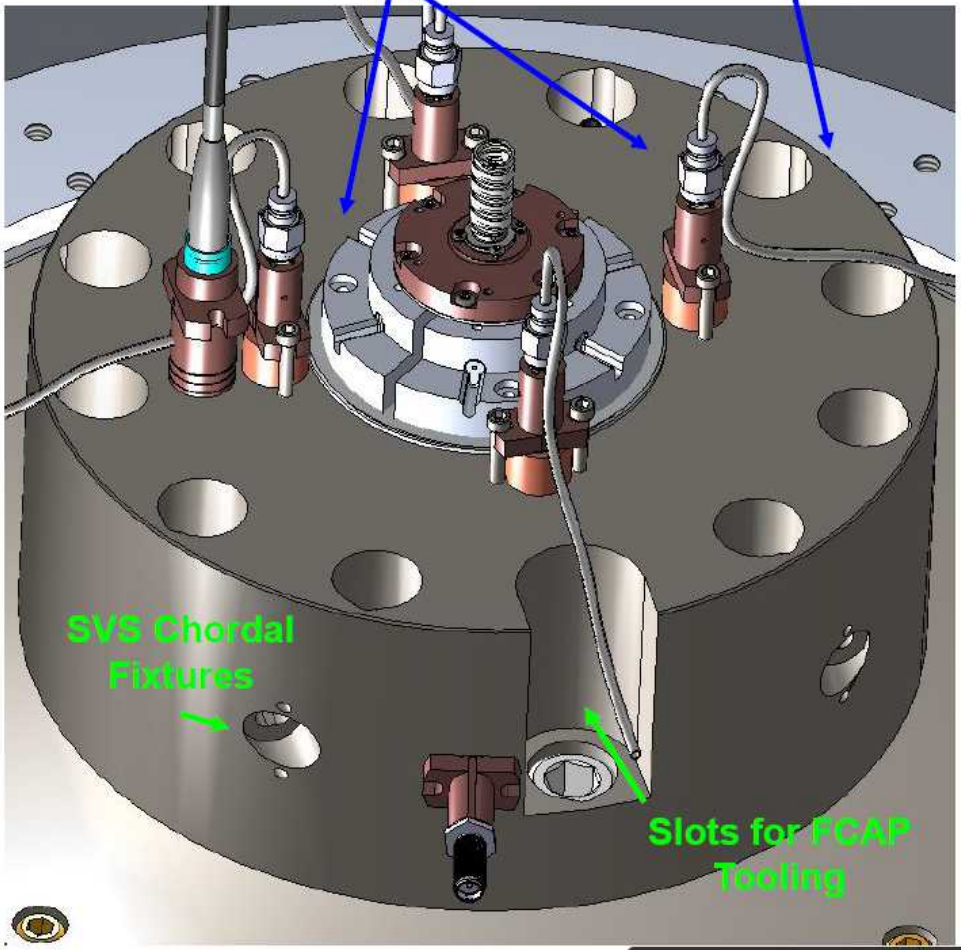


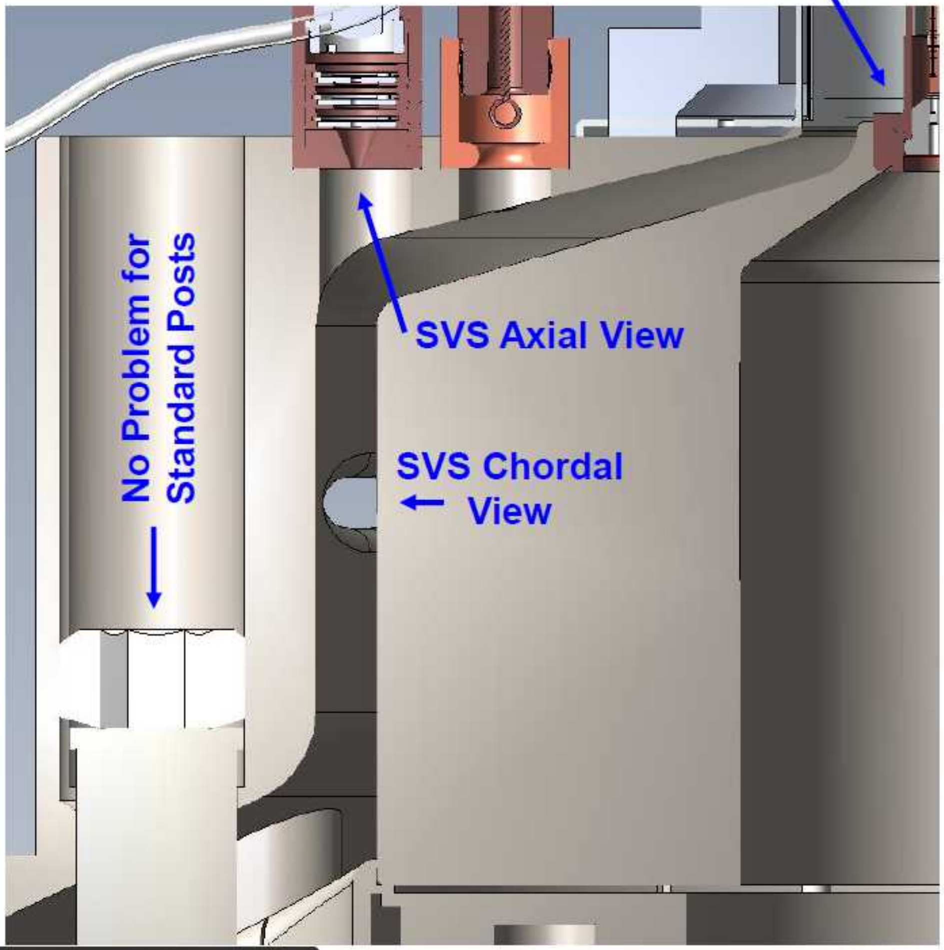


- Spectra collected using two anode post LOS without optics (turning mirror, but no lenses).
- Adjusted the spectral window to measure the uv cutoff for the present SVS systems.
- Looking for Aluminum and Magnesium lines.
- Comparison of aqueous dopants versus solid thin film coatings.
- Measured Mg I lines from the mirror surface following peak current.
- Measured Al I lines during the current risetime on the cathode surface in the post-hole convolute region.
- X-ray signal cuts-off the optical fiber transmission late in the pulse (may require shielding on future shots).
- APD signals measured time-evolution of plasma light.



Dedicated Experiments for Power Flow Physics are now Being Conducted on Z.

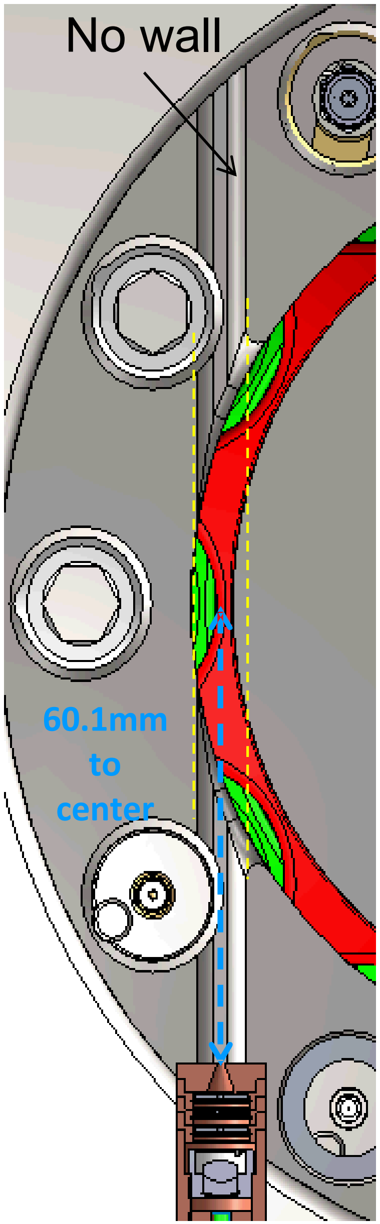


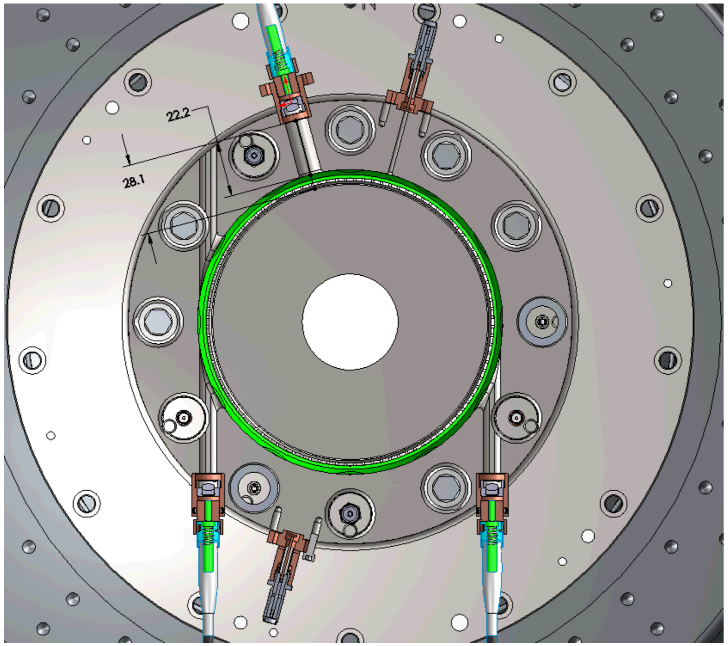


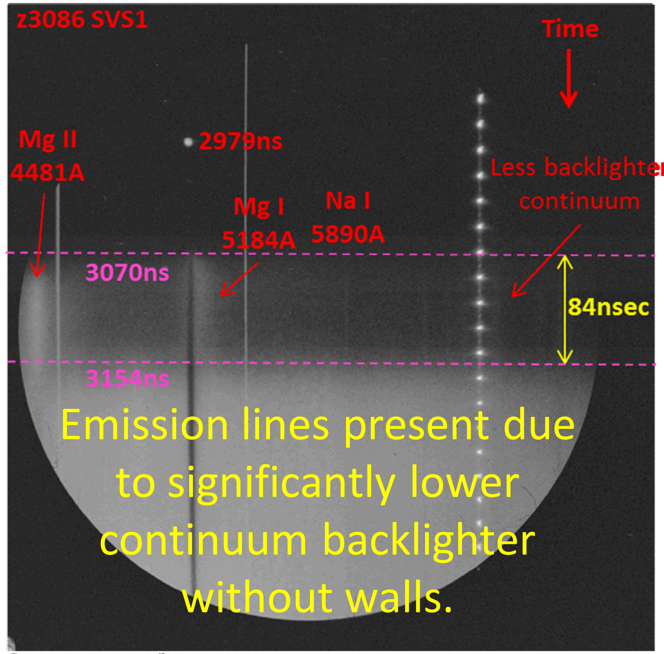
*Slide courtesy of George Laity

**First shots were conducted in May.

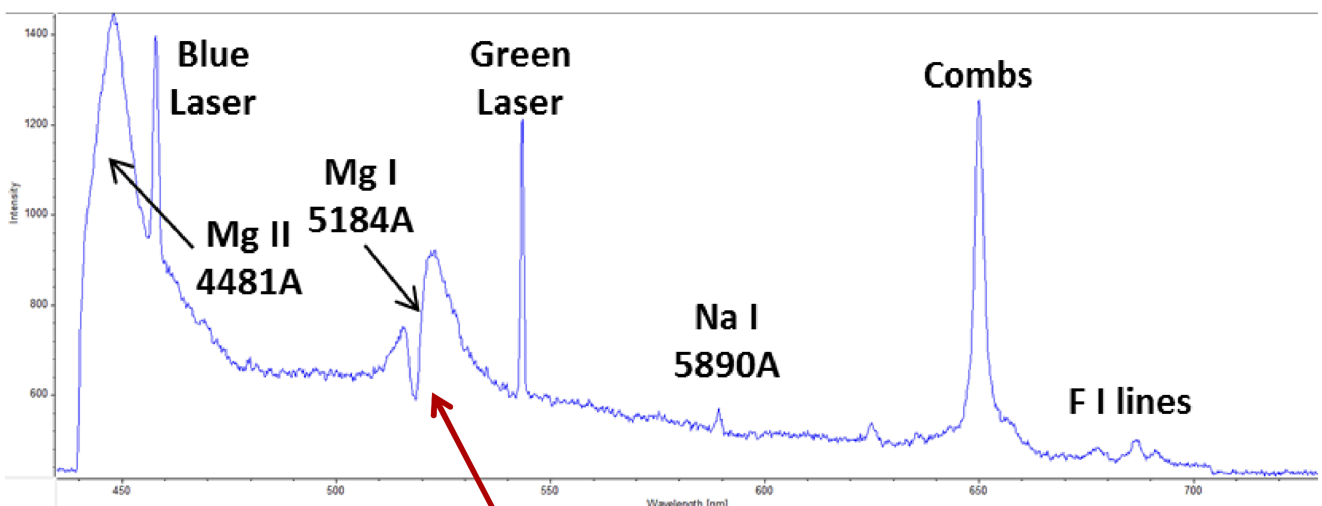
SVS Chordal Line of Sight (LOS) without Walls





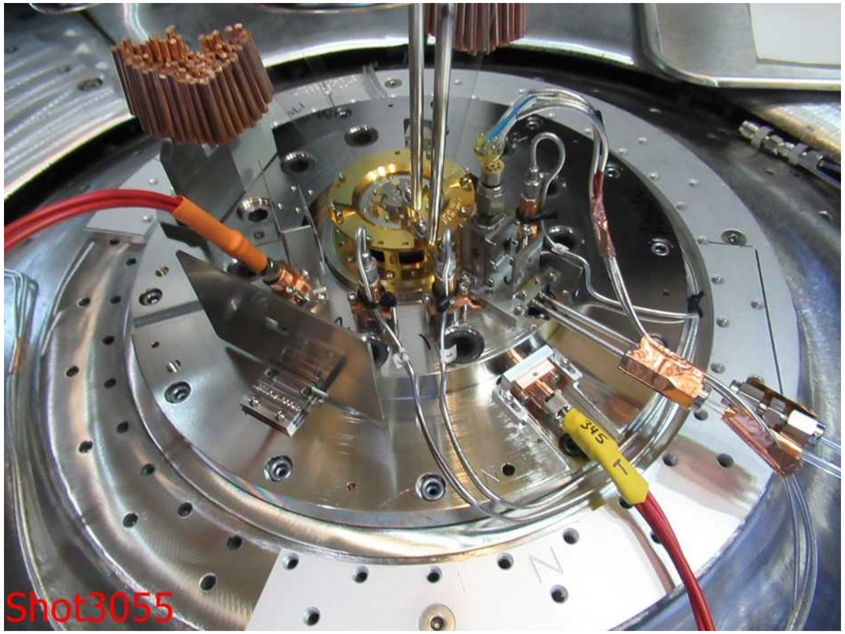


*20nsec combs

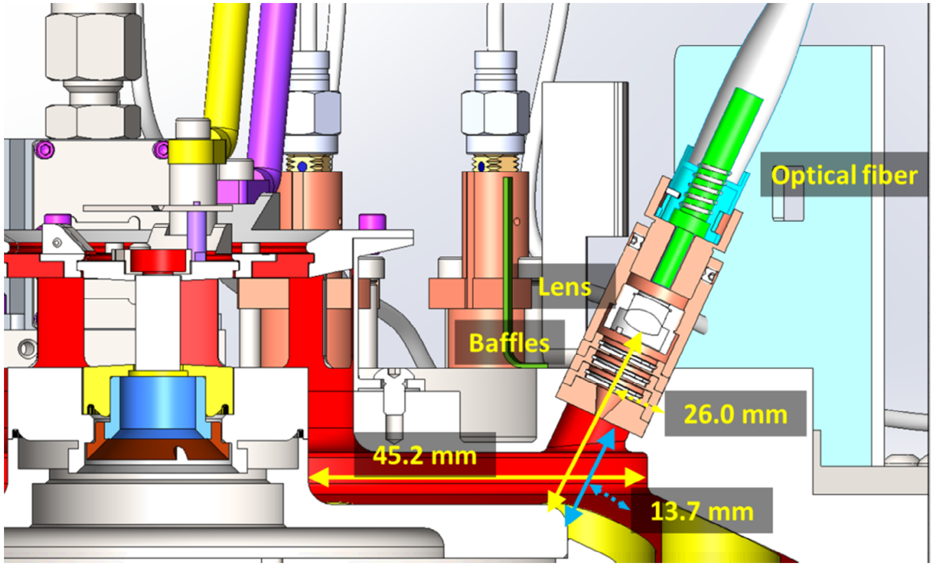


Emission and self-absorption observed.

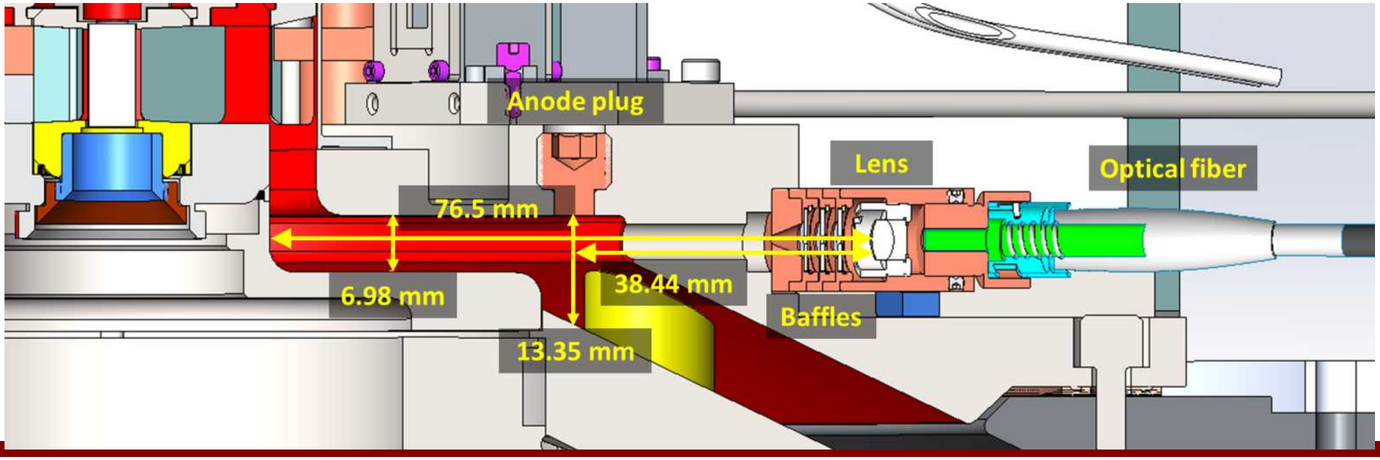
Ride-along Experiments are being Fielded on Multiple Z Platforms (Wire Arrays Experiments)



Wire Array Experiment

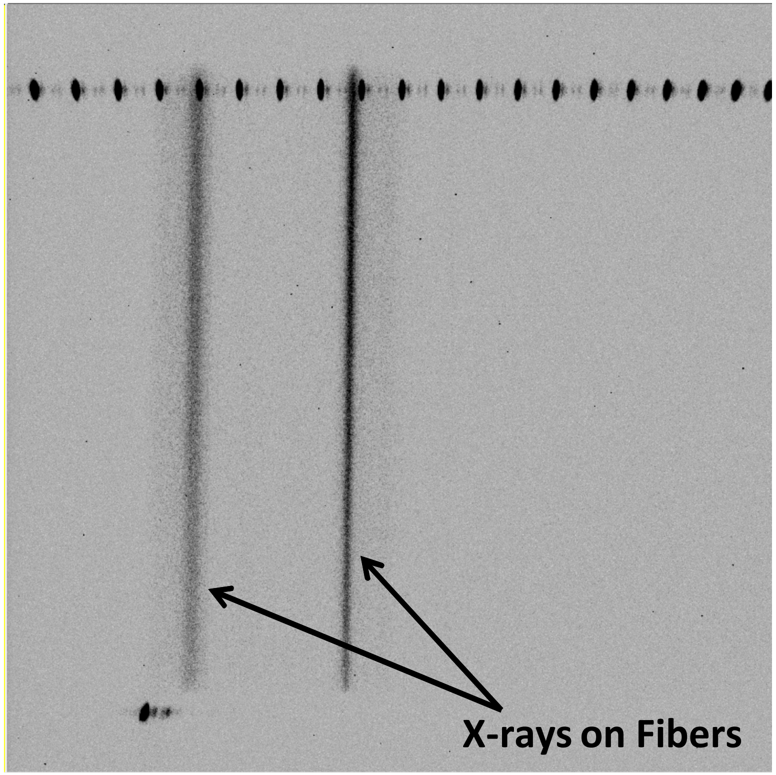


Angled LOS

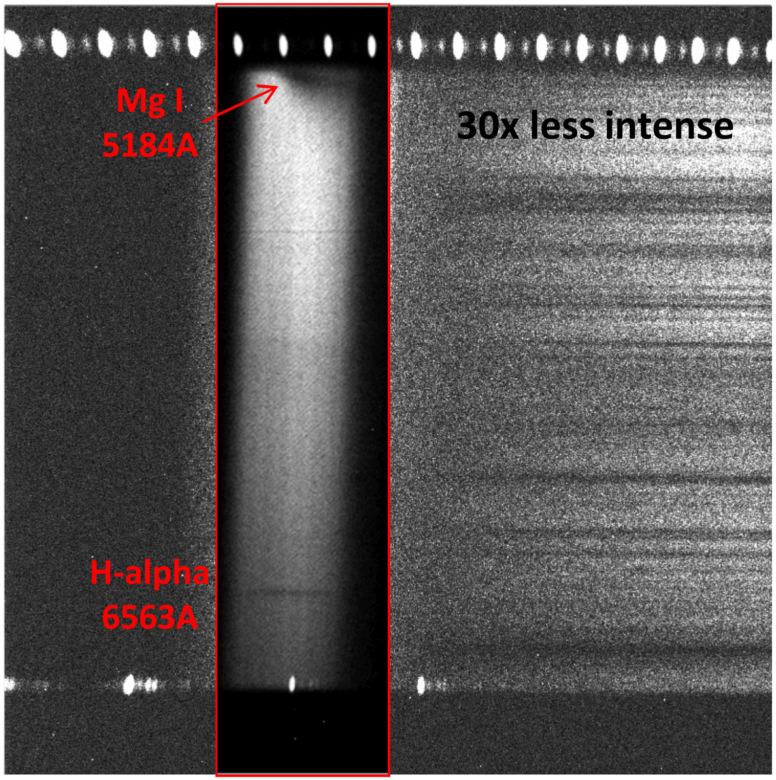


Horizontal LOS

Initial Spectra from Wire Array Experiments (Nested Array)



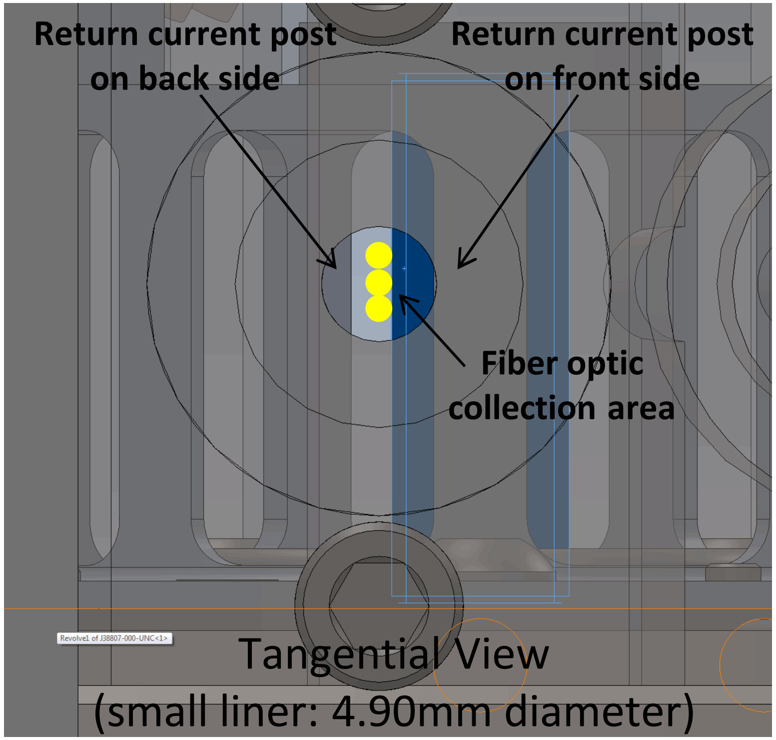
SVS4 (Angled Probe)
No dopants, MgF_2 coated 7.5mm fl lens
Grating: 150g/mm
Center Wavelength: 600nm
Sweep: 500ns
Combs: 35MHz (28ns)

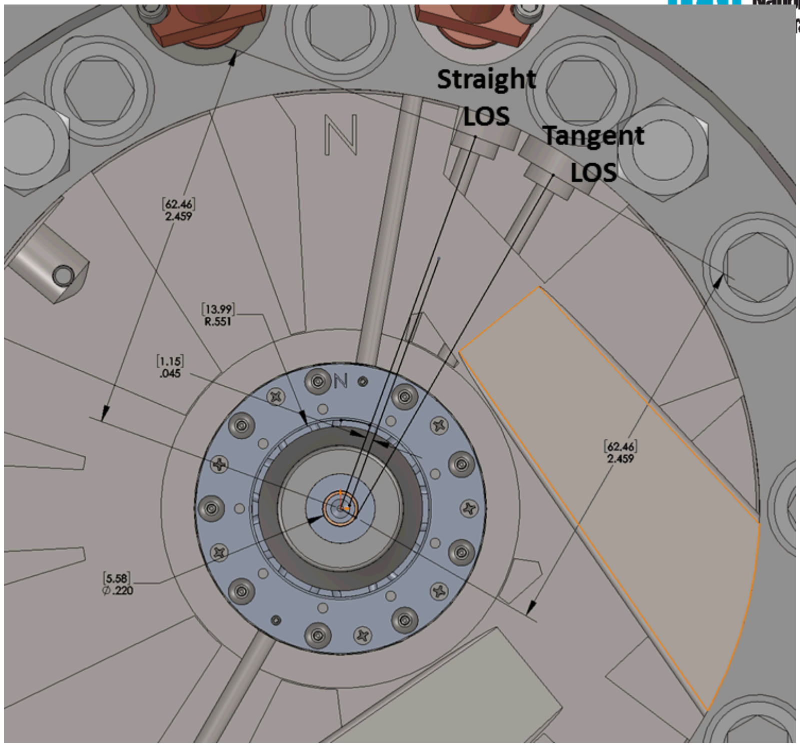


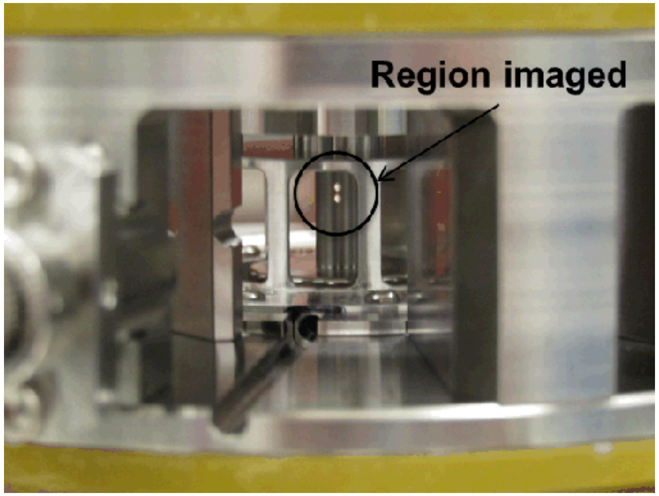
SVS5 (Horizontal Probe)
No dopants, MgF_2 coated 7.5mm fl lens
Grating: 150g/mm
Center Wavelength: 600nm
Sweep: 500ns
Combs: 35MHz (28nsec)

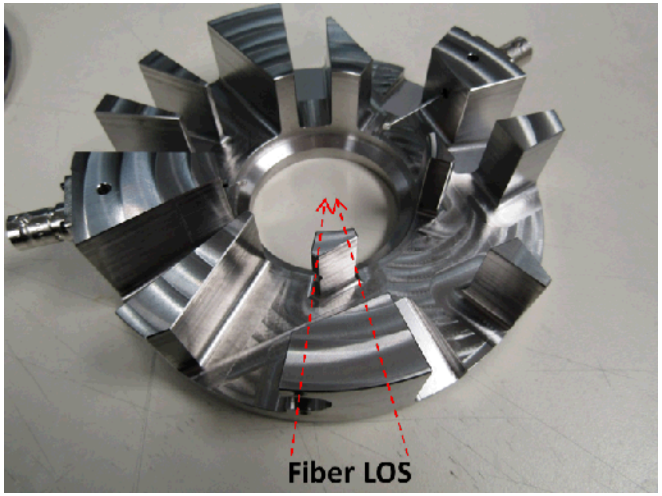
* No APDs fielded on this shot

Hardware Setup for MagLIF Liner Experiments

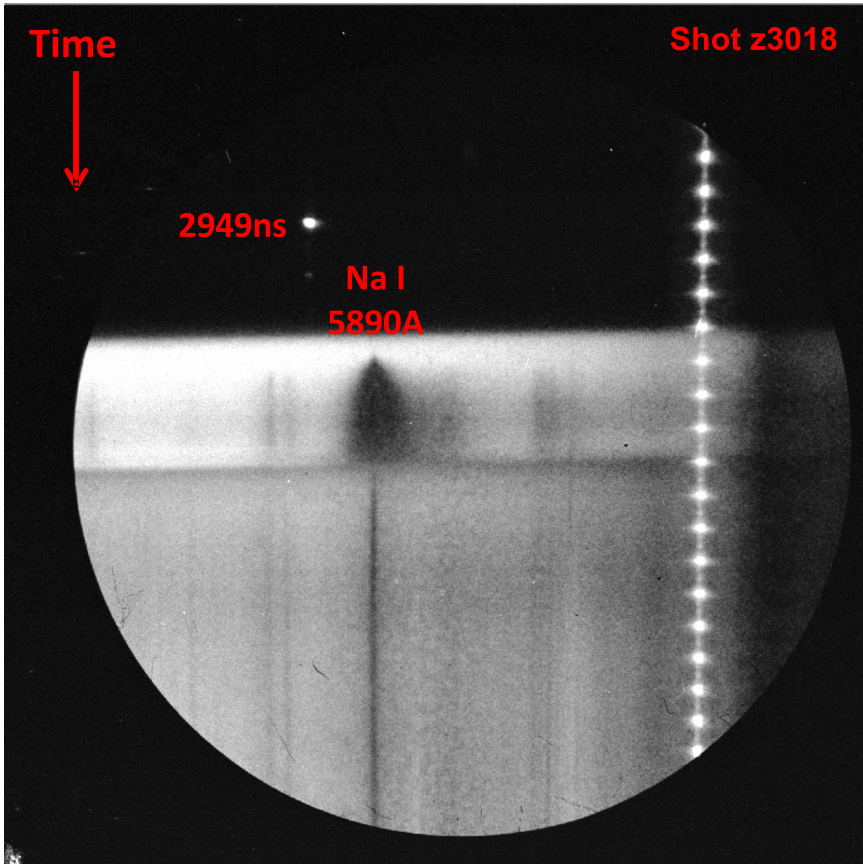








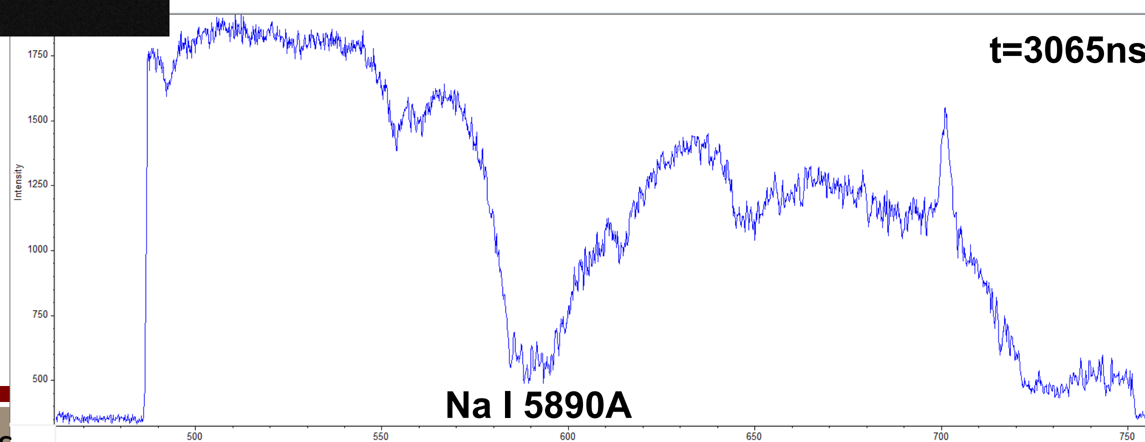
MagLIF Liner Experiments Show Sodium Line Broadening



Grating: 150g/mm
Center Wavelength: 618nm
Sweep: 480ns
Combs: 20nsec
Start of sweep: 2870ns
Impulse: 2949ns
Slit: 100 microns
Fiber: 100 microns
ND: 0.4 (40% transmission)
MCP Gain: 600V
LOS: 110
Green Laser: 5435A
Red Laser: 6328A

Experimental AR: 9
Uncoated Be Liner OD: 5.23mm

SVS1
Collimated beam, 1mm Aperture
7.5mm fl lens (uncoated)
Max counts: ~2000



*Film begins to saturate around 3500 counts

Summary and Conclusions

- Spectroscopic measurements of plasmas and local magnetic and electric fields have begun on Z.

- Local B-fields are measured using the Zeeman effect, even when Stark and Doppler broadening is present, and for arbitrary B-field orientations, using techniques developed at the Weizmann Institute[7].

- Measurements of the magnetic field provide needed information regarding local current distributions, including current loss mechanisms, on Z.

- Additional techniques are being developed at the Weizmann Institute to analyze spectral data, taking into account opacities, impurities, signal to noise, and continua.

- These types of spectral measurements are needed to increase the fundamental physical understanding of plasmas and fields in high power diodes. Until now only global B-fields have been inferred from current probe measurements.

- Present and future understanding and design of high power diodes relies heavily on kinetic PIC and hybrid (PIC/fluid) simulation models (ex. LSP and EMPHASIS). Experimental measurements are necessary to validate these models, and for accurate prediction of the performance of the next generation pulsed-power machines.[8]

[7] R. Doron, et al., *High Energy Density Phys.,* 10, p. 56-60 (2014).

[8] W.A. Stygar, et al., *Phys. Rev. Spec. Topics Accel. and Beams.,* 18, p. 110401-1-30 (2015).

Future Work

- Continue to develop advanced techniques of spectral analyses, which include effects due to opacities, impurities, signal to noise, line emission, absorption, continua, and shielding.
- Map magnetic fields and currents in the A-K gap on Z. This will require greater signal to noise and/or plasma injection scheme (active dopants).
- Implement a gated spectroscopy system at high resolution to record the spatial distribution of fields on a single shot.
- Further explore Stark shifts to measure E-fields as a function of time and space.
- Extend these spectroscopic methods to other power flow regions.

Experimental measurements are necessary to validate models.