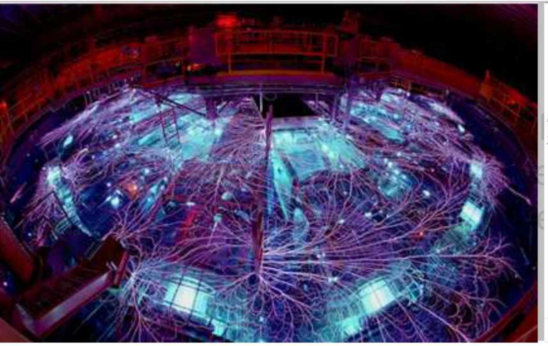
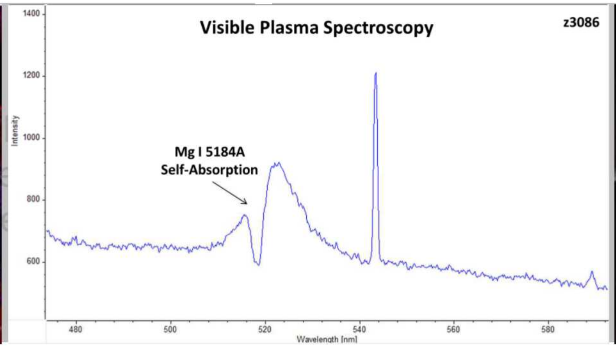
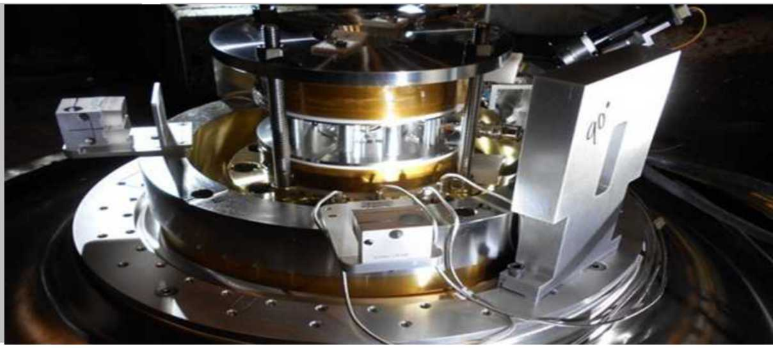
This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

SAND2018-12919C







Spectroscopic Measurements of Plasmas in the Power Flow Regions on the Z Machine

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Abstract

Pulsed power devices depend on the ability to deliver high voltages and currents to a variety of complex loads with minimal transmission losses. The Z Machine at Sandia National Laboratories can deliver up to 26MA within a few 10's of nanoseconds to multiple z-pinch type loads. An effort is underway to measure plasma parameters such as temperatures and densities within the power flow regions on the Z Machine. A proper physics understanding of efficient high current delivery is necessary to ensure that higher current devices such as Z-Next will perform as designed. In the power flow regions, plasmas form on the electrode surfaces and propagate into the vacuum gap, providing a current loss mechanism. These plasmas are measured spectroscopically using a 1m Czerny-Turner spectrometer with a fast (nanosecond) streak camera output. Data is analyzed using detailed, time-dependent, collisional-radiative (CR) and radiation transport modeling. Recent results will be presented.

Motivation

- Obtain measurements of plasmas in the power flow regions on Z.
- Detailed plasma measurements have been made on other pulsed-power machines[1,2]. Want to extend these measurements to the Z-Machine.
- Plasma measurements in the Z convolute region were made by Matt Gomez et. al.[3] Want to expand these measurements to other power flow 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 (Z-Next)[4].

[1] M.D. Johnston, *et al.,* in submission.

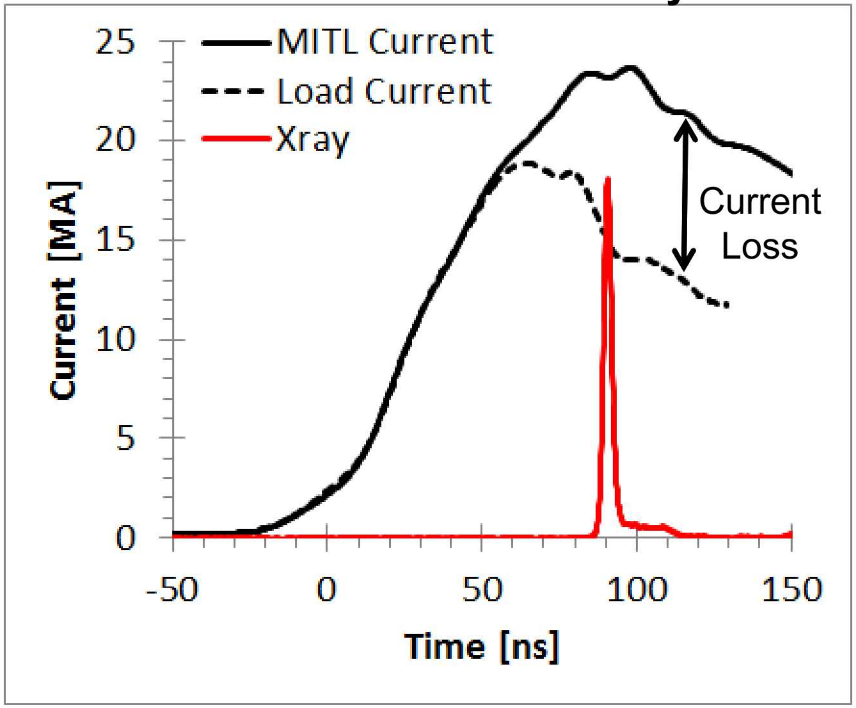
[2] S.G. Patel, M.D. Johnston, *et al., Review of Sci. Instr.,* 89, p. 10D123 (2018).

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

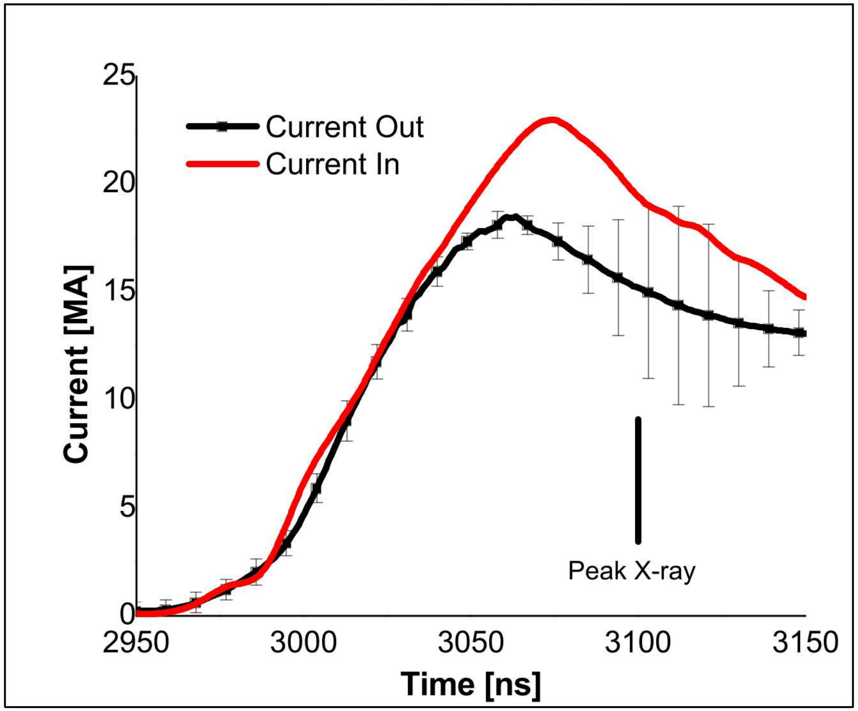
[4] W.A. Stygar *et al.*, *Phys. Rev. STAB,* 18, 110401 (2015).

Current Losses on Z Reduce Power Delivery to the Loads

Stainless Steel Wire Array

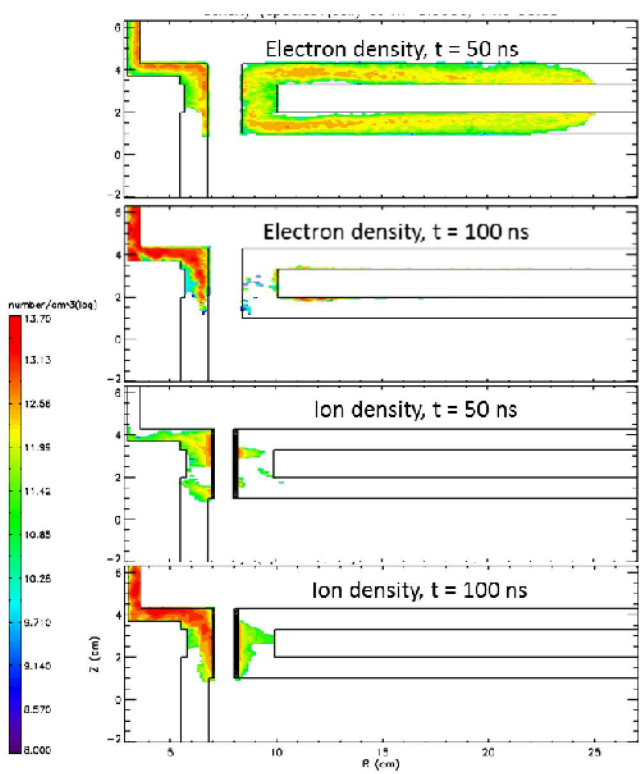


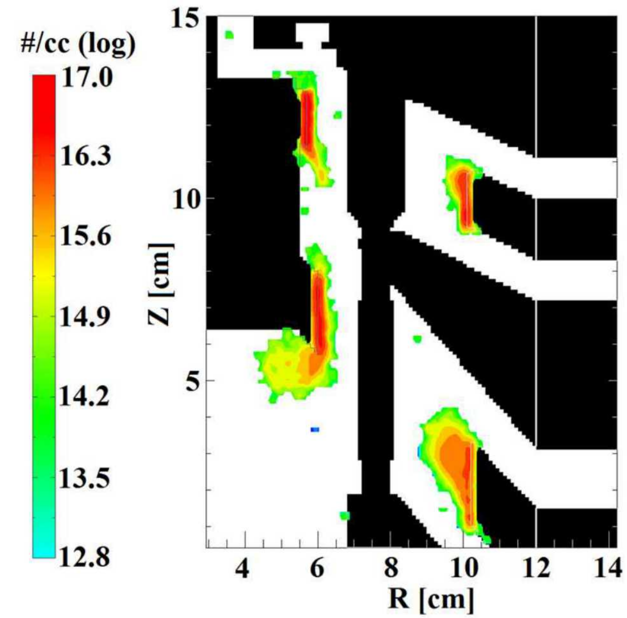
Gas Puff Load



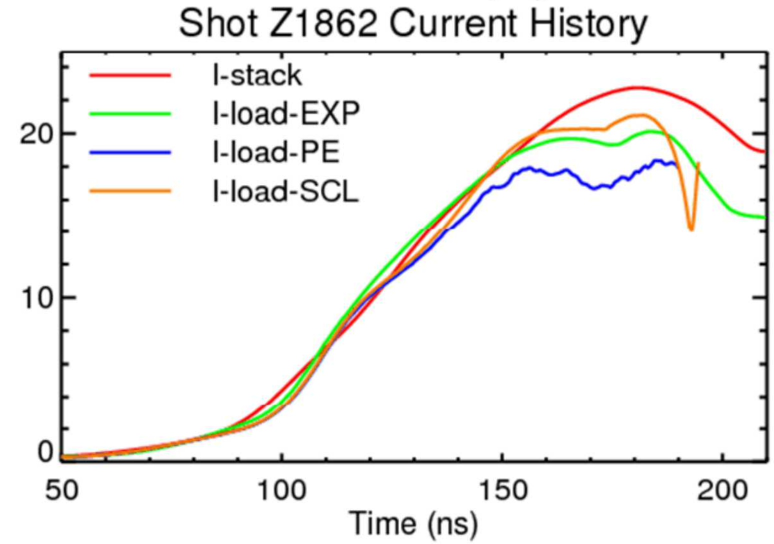
- Up to 5MA current loss is sustained for ~50ns on some loads.
- Surface contaminants, outgassing of electrode materials, and non-ideal geometries affect current delivery to the load.
- Approximately 70% of the total electrical power delivered to the load occurs after peak current, when losses are at their highest.
- Current and voltage near stagnation are more important than the peak current and these are dictated by convolute loss.

Current losses on the Z machine are attributed to plasma formation in the convolute and final current feed[5]



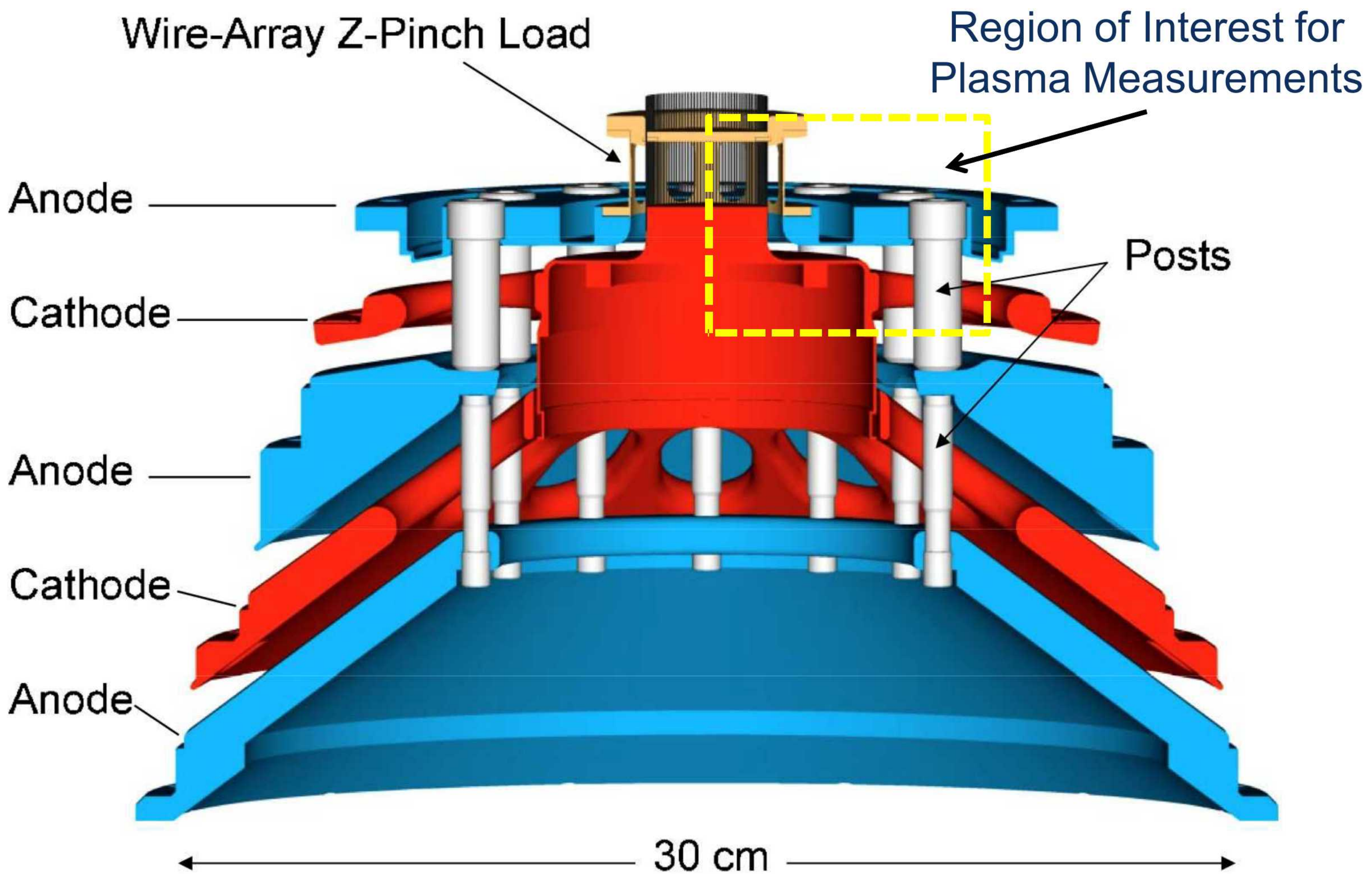


- Plasma models reproduce measured currents, but experimental measurements are needed to verify the physics are correct.



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

Z Hardware Configuration[6]



- 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

[6] D.H. McDaniel, *et al.*, *Proc. 5th International Conf. on Dense Z Pinches,* AIP, Melville, NY p. 23 (2002).

Particle in Cell Modeling of Cathode and Anode Plasma in Quicksilver[7,8]

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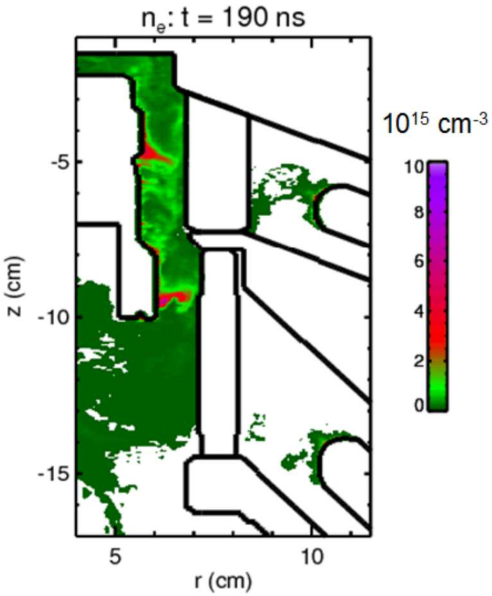
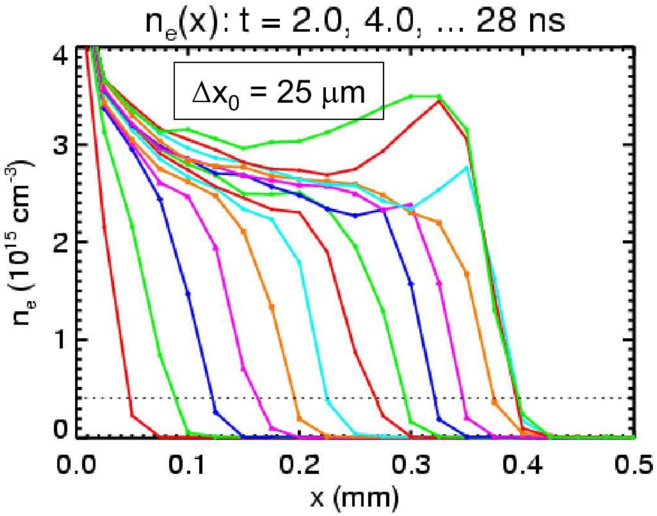
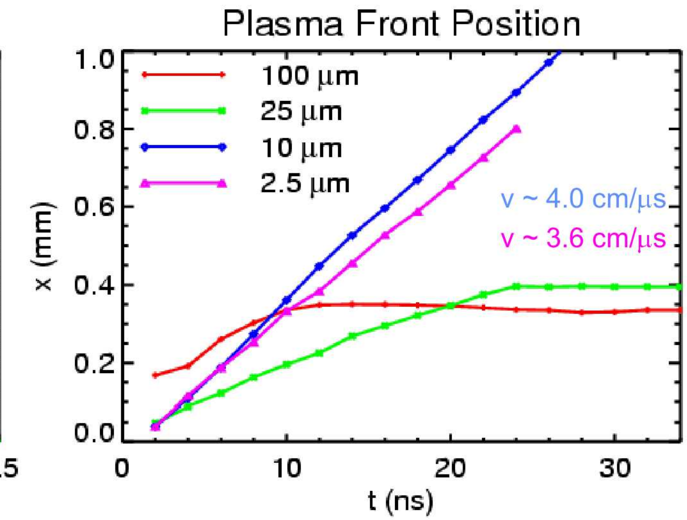
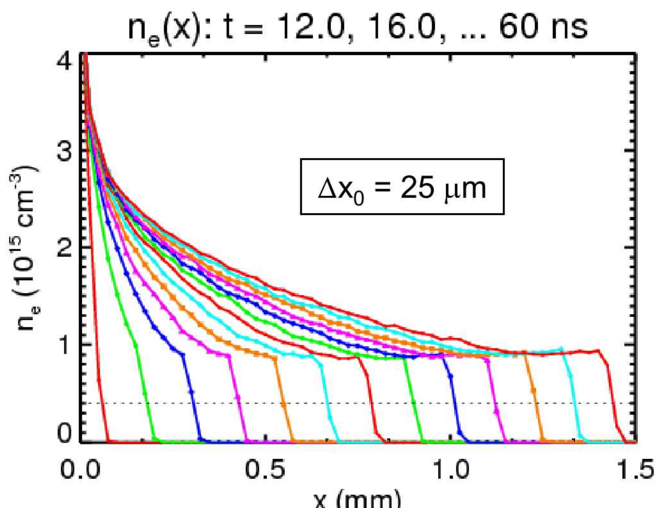


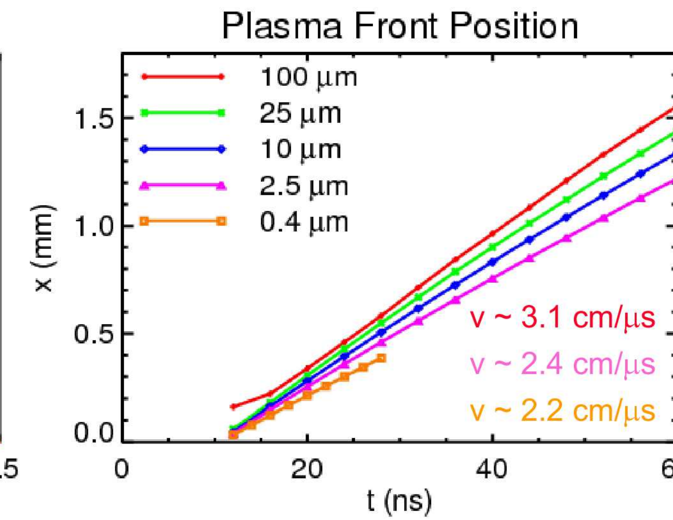
Cathode Plasma





Anode Plasma



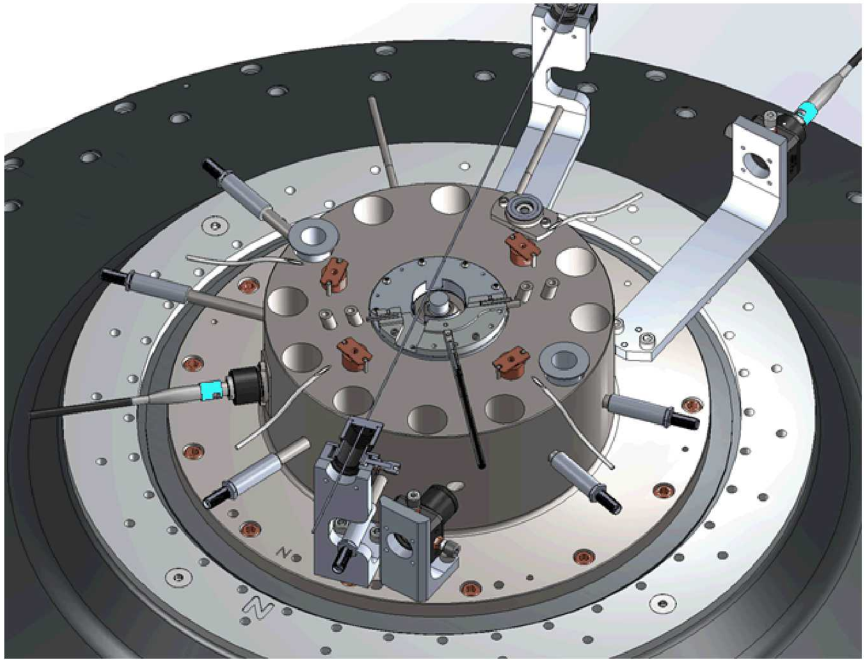


- High density electron structures are observed on the inside of the posts, where B-fields are high.

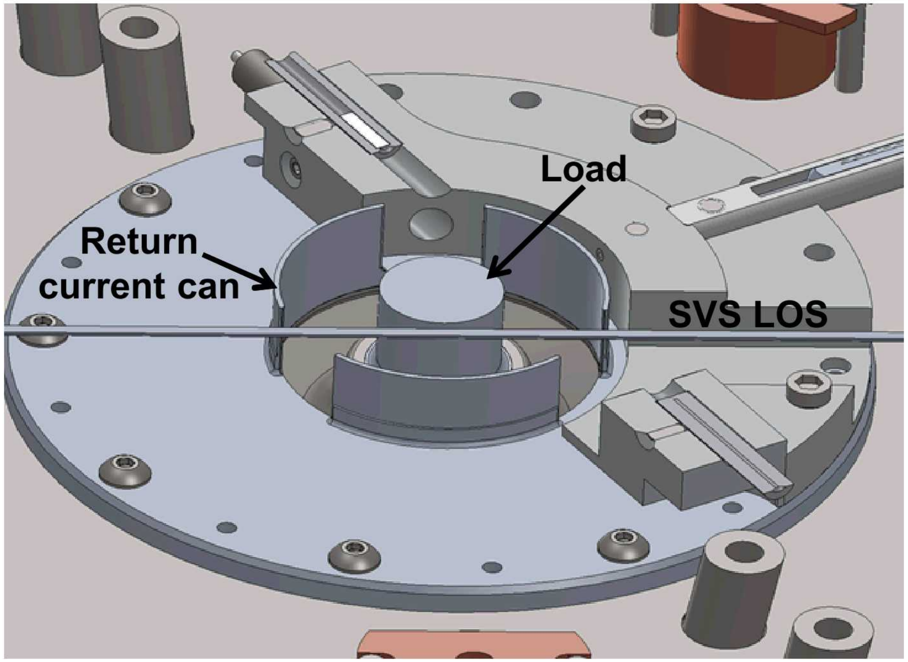
[7] J.P. Quintenz, *et al.*, Laser Part. Beams 12, p. 283 (1994).

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

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

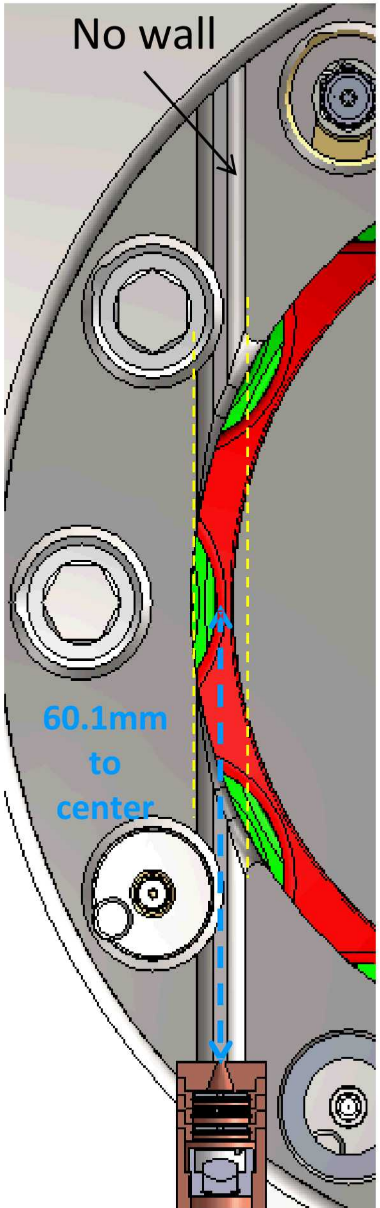


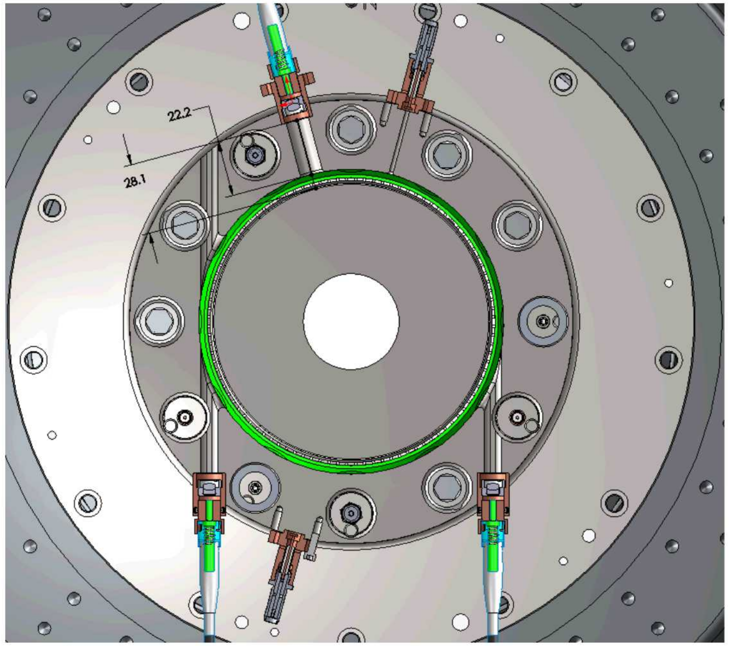
Power Flow Hardware

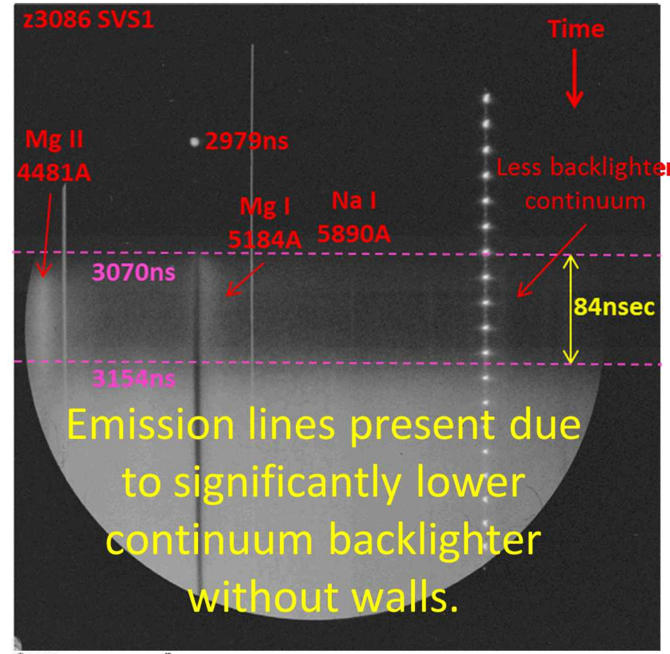


- Experiments are designed to look for plasmas off the surface of a non-imploding load.
- Coatings are applied to the load to measure specific neutral and ion lines.
- Experiments are designed to look in the final feed gap without a backlighting wall.

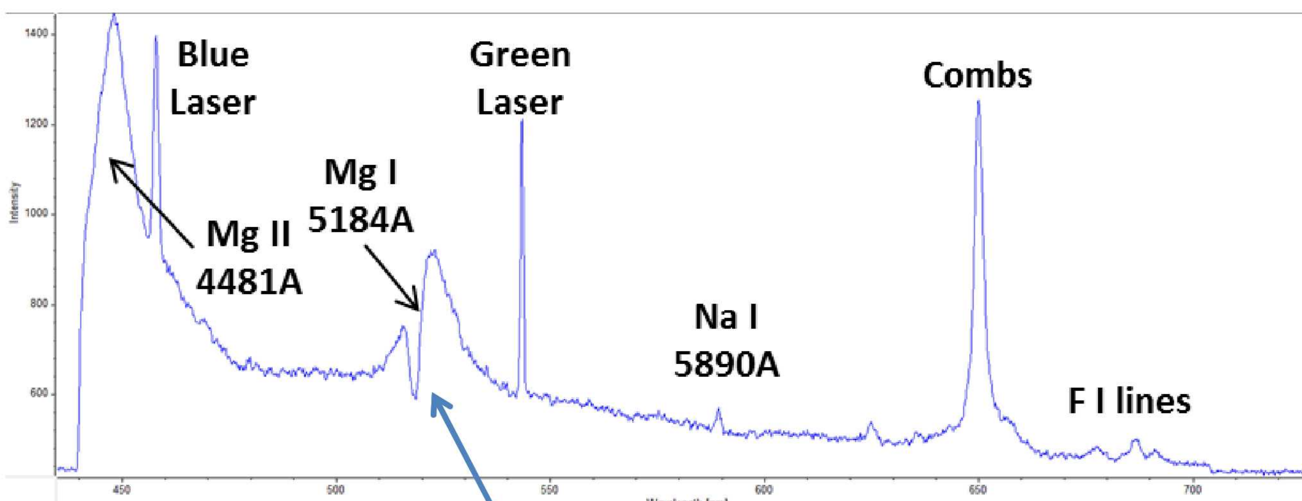
Chordal Line of Sight on Power Flow Shots in the Final Feed







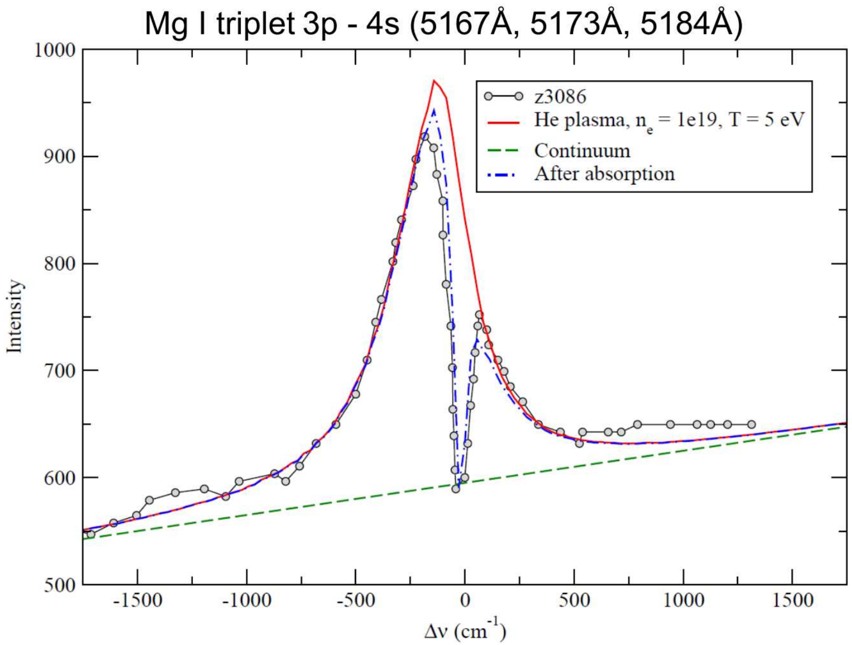
*20nsec combs



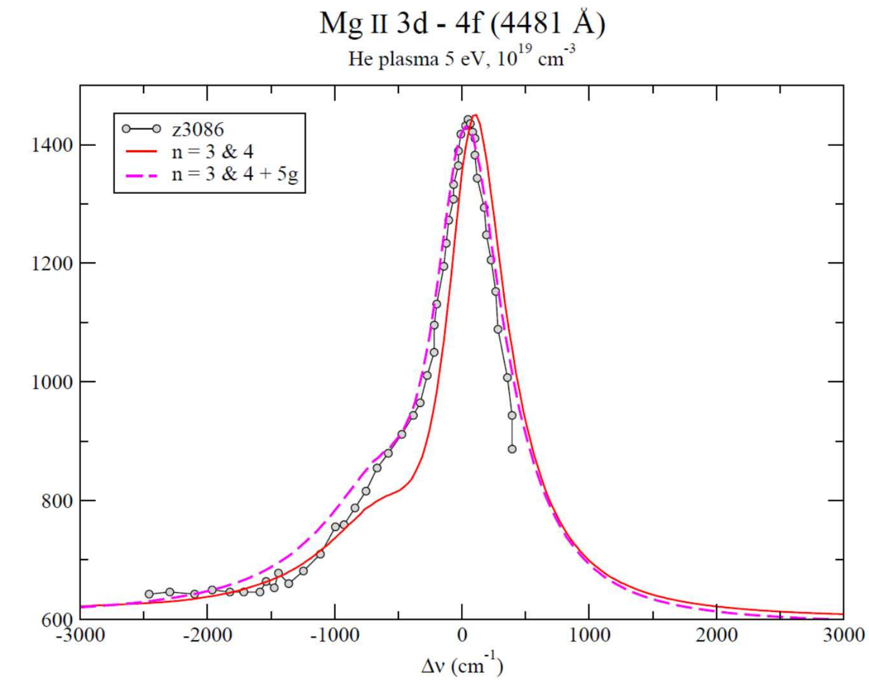
Emission and self-absorption of Magnesium neutral observed.

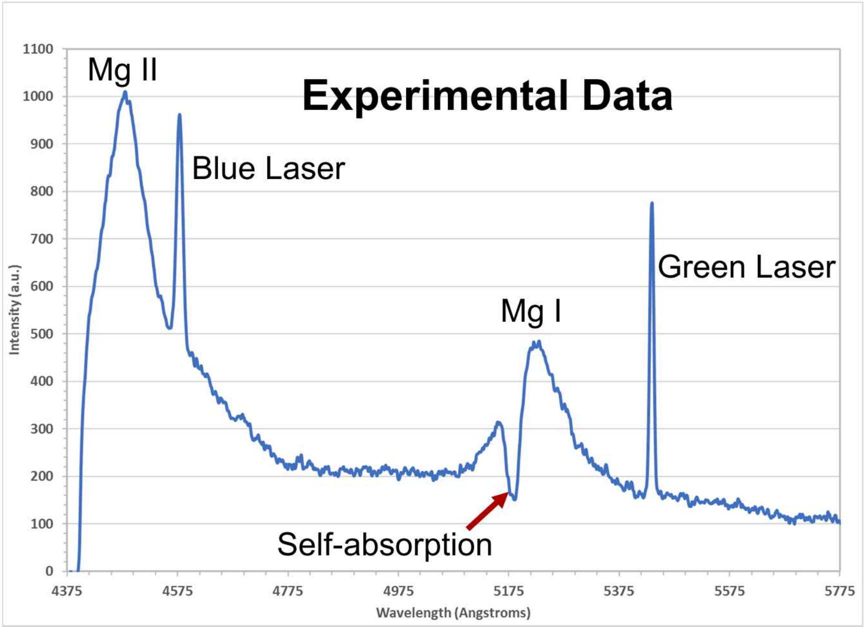
Magnesium Dopant Results

Sandia National Laboratories



- MgF_2 coated optics
- Mg I and Mg II broadened line emission observed
- Two distinct plasma regions present in spectrum
- Colder, more dilute Mg I plasma next to optics
- Hotter, denser plasma, further off the surface
- Light from the hotter, denser plasma is absorbed in the cooler plasma.
- Density of emitting plasma: ~$1x10^{19}$ cm^{-3}
- Density of absorbing plasma: ~ $1x10^{18}$ cm^{-3}
- Plasma temperatures: 1-5eV
- Mg I lines are red-shifted by 5.9Å
- Opacity (τ) = ~0.4
- $1x10^{19}$ cm^{-3} continua fits experimental data





Metastable level in Mg I (steady state, without opacity)

3s3p ^{3}P - *metastable* level

3s3p ^{3}P → 2p6 3s2 ^{1}S – spin-forbidden transition

3s4s ^{1}S → 3s3p ^{1}P; $\lambda =$ 11,828 Å (NIST)

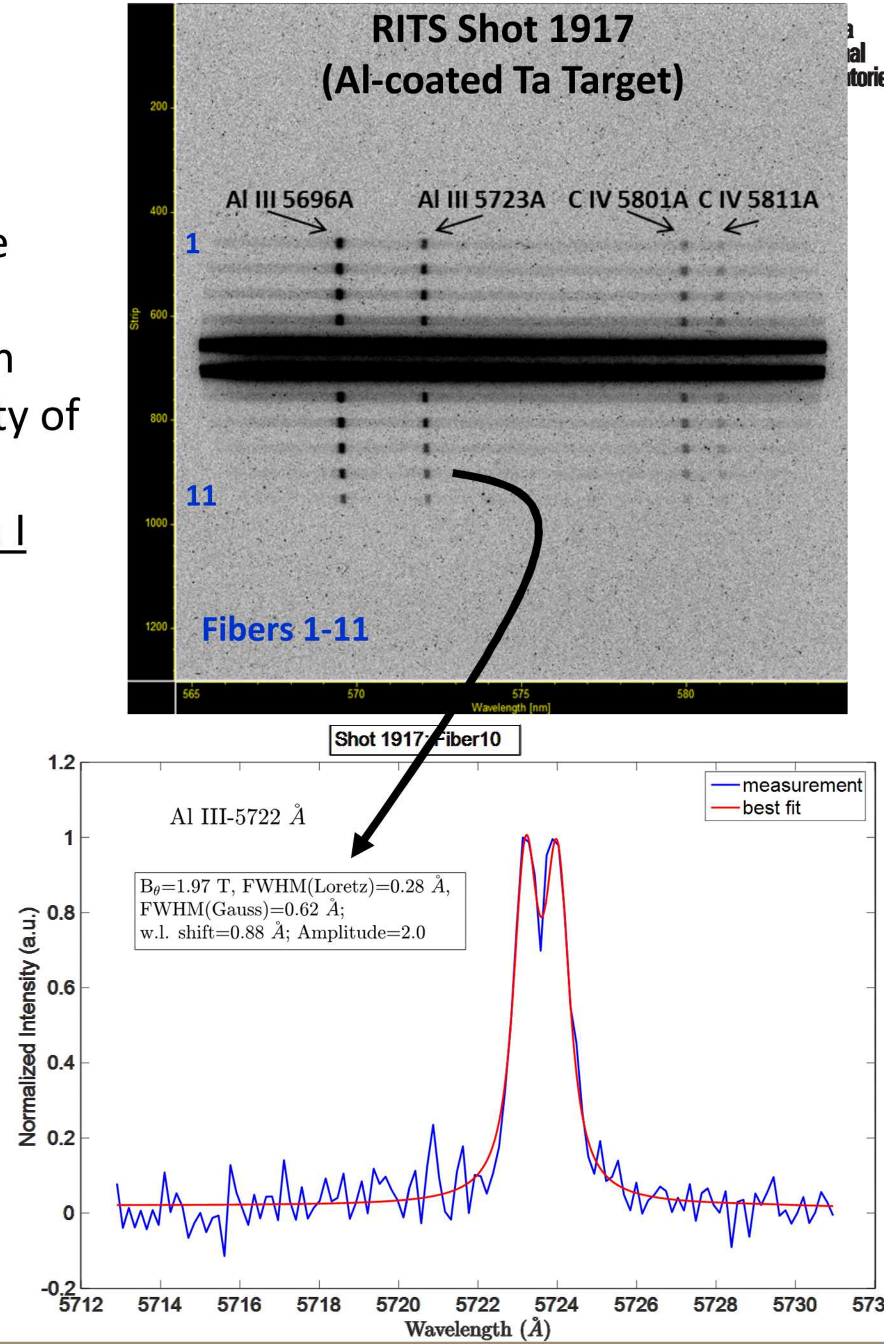
3s4s ^{3}S → 3s3p ^{3}P; $\lambda =$ 5,183 Å (NIST)

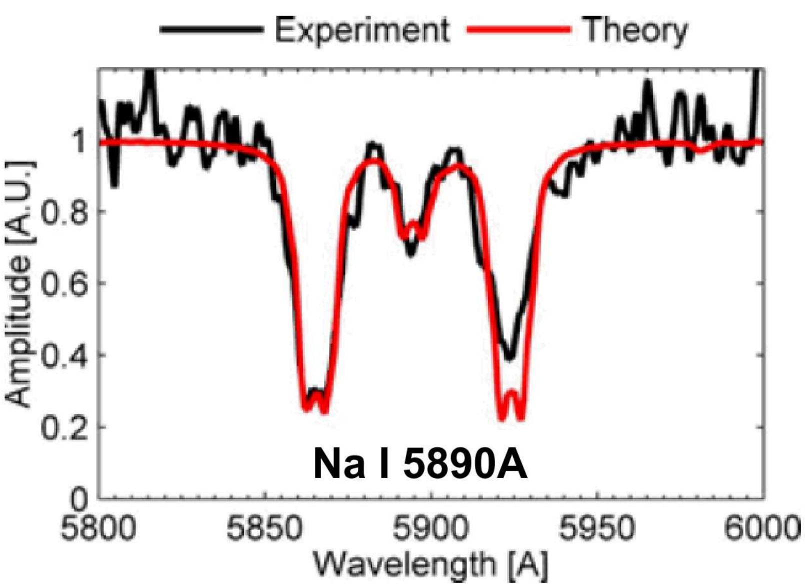
T_e (eV)	Level	N_e (cm^{-3})	POP*	$A_{i \to j}$***
1	3s4s ^{1}S	10^{19}	$1.62 \cdot 10^{-3}$	
	3s4s ^{1}S → 3s3p ^{1}P			$2.85 \cdot 10^{+7}$
	3s3p ^{1}P → 2p6 3s2 ^{1}S		$1.39 \cdot 10^{-2}$	$5.05 \cdot 10^{+8}$
1	3s4s ^{3}S	10^{19}	$6.47 \cdot 10^{-3}$	
	3s4s ^{3}S → 3s3p ^{3}P			$1.23 \cdot 10^{+8}$
	3s3p ^{3}P → 2p6 3s2 ^{1}S		$2.13 \cdot 10^{-1}$	$5.01 \cdot 10^{+1}$
1	gs** - 2p6 3s2 ^{1}S	10^{19}	$3.57 \cdot 10^{-1}$	

* - population, ** - ground states, *** - Einstein coefficient

Zeeman Splitting Diagnostics

- Time and space resolved Zeeman measurements were taken on the SMP diode on RITS-6 as a proof of principle for Z.
- Calculations of Zeeman lineshapes have been done for Al III and C IV covering a wide variety of Z relevant temperature and density regimes.
- Previous work by Gomez et. al. measured Na I splitting in the load region on Z.[9]



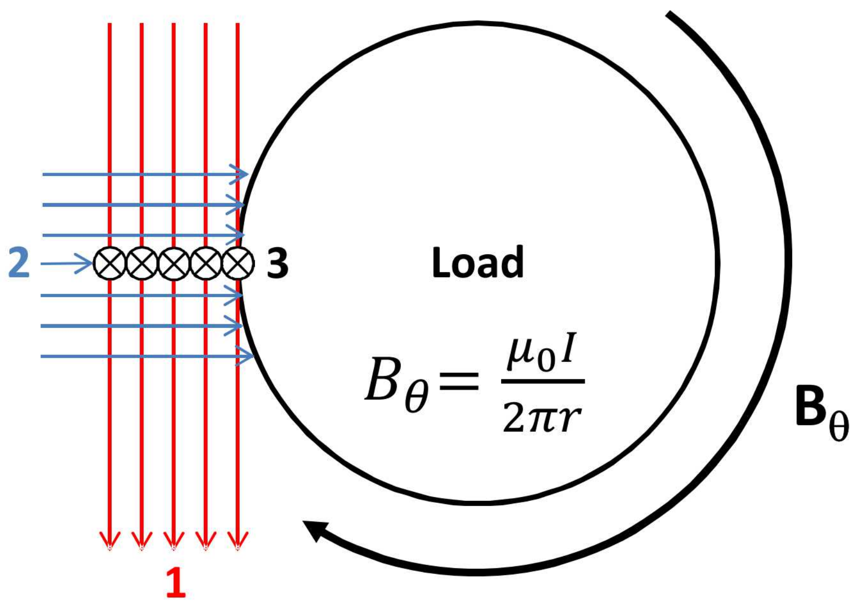


[9] M.R. Gomez, *et al., Rev. Sci. Instr.*, 85, p. 11E609-1-11 (2014).

[10] S. Biswas, M.D. Johnston *et al., POP,* to appear.

Zeeman Splitting Measurements on Z

Three Potential Views at the Load



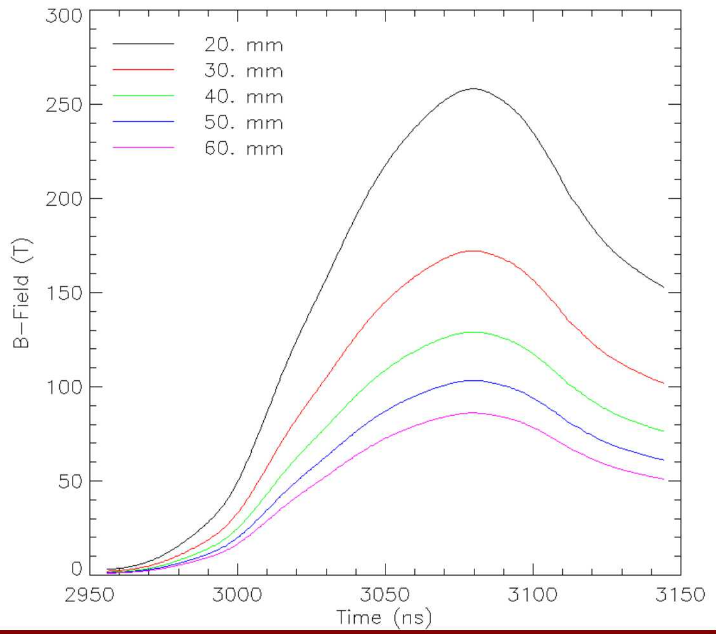
Requirements:

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

Considerations:

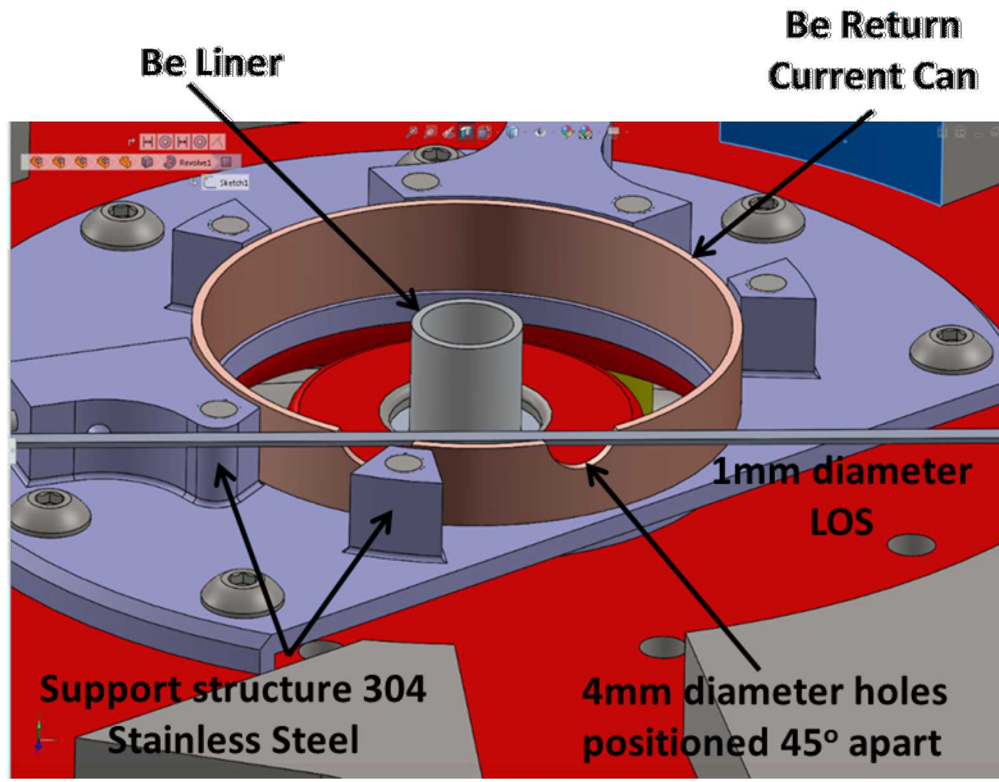
- Polarizations (σ and π)
- Lines of sight vs. B-field orientation
- Weak field/Strong field
- Specific Lines (low Stark)
- Plasma density and temperatures
- Doppler broadening

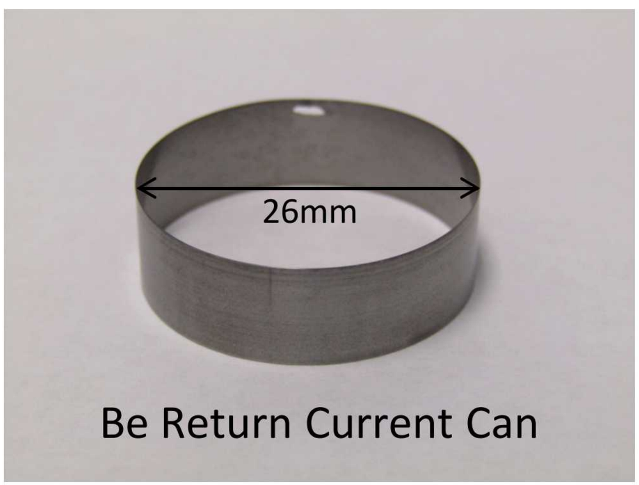
B-field versus Radius

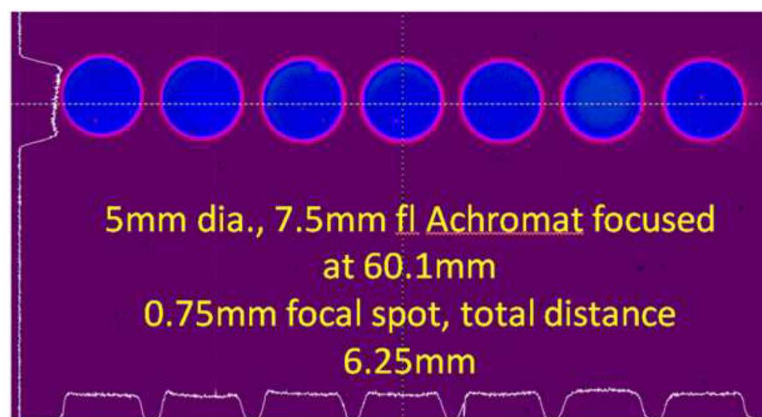


Proposed Zeeman Splitting Measurements Inside the MagLIF Return Current Can

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

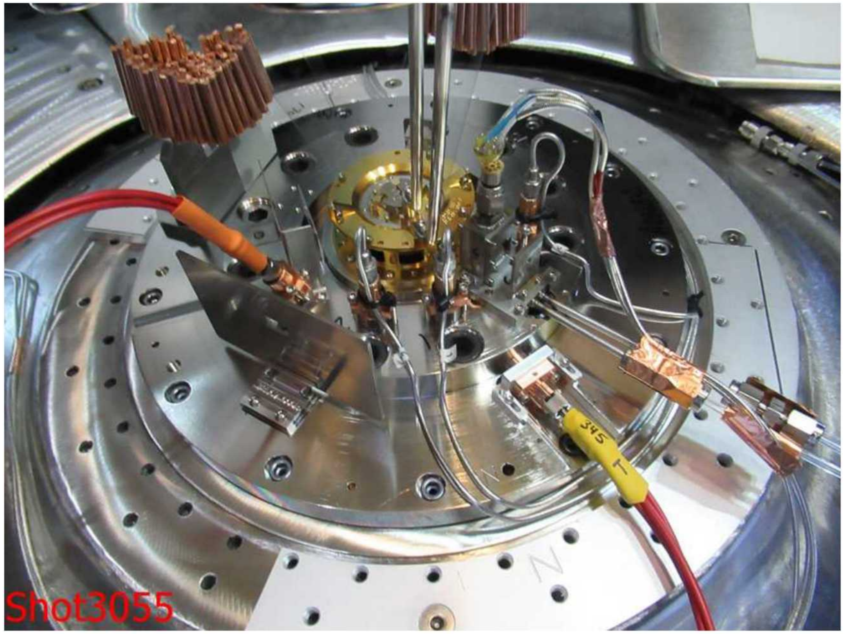




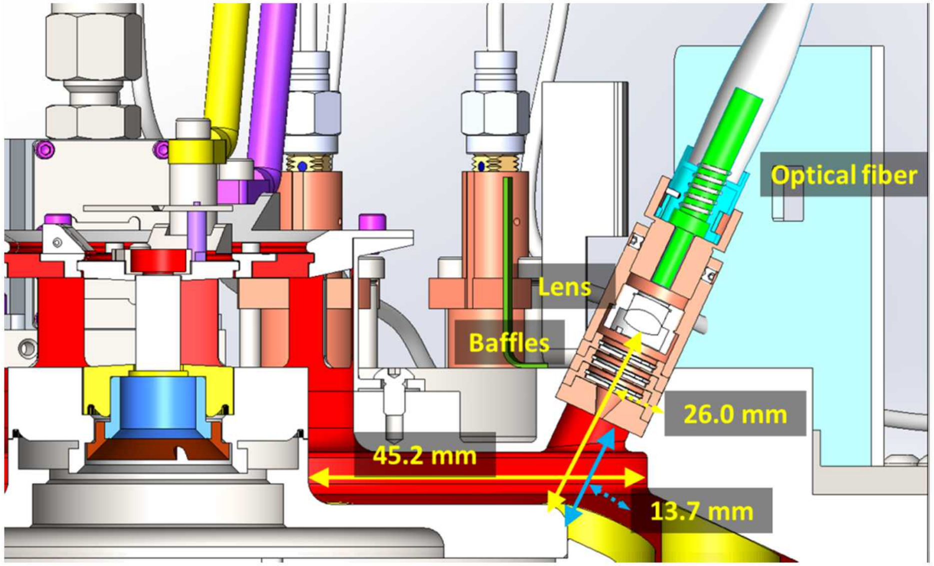


AC050-008-A-ML (f# 1.5, NA 0.32, 18.4° half angle)

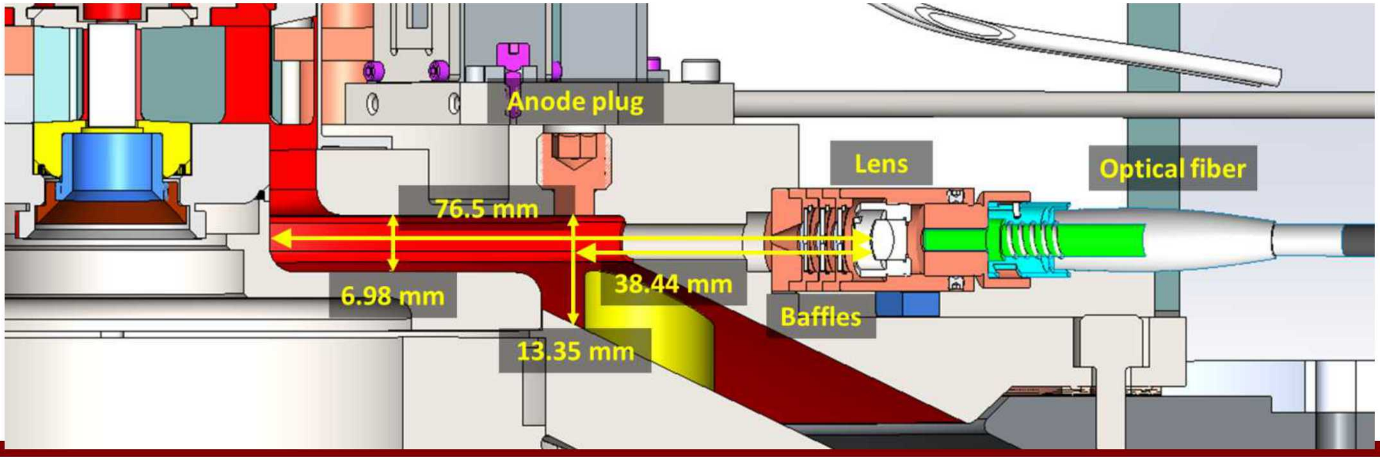
Ride-along Experiments are Fielded on Multiple Z Platforms



Wire Array Experiment

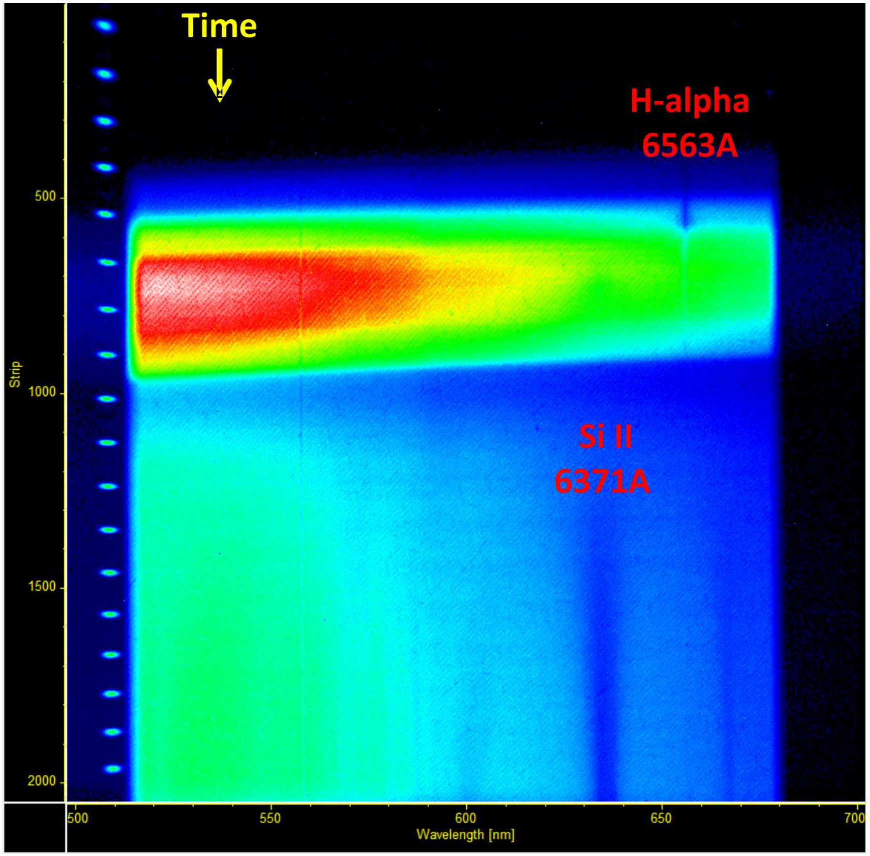


Angled LOS

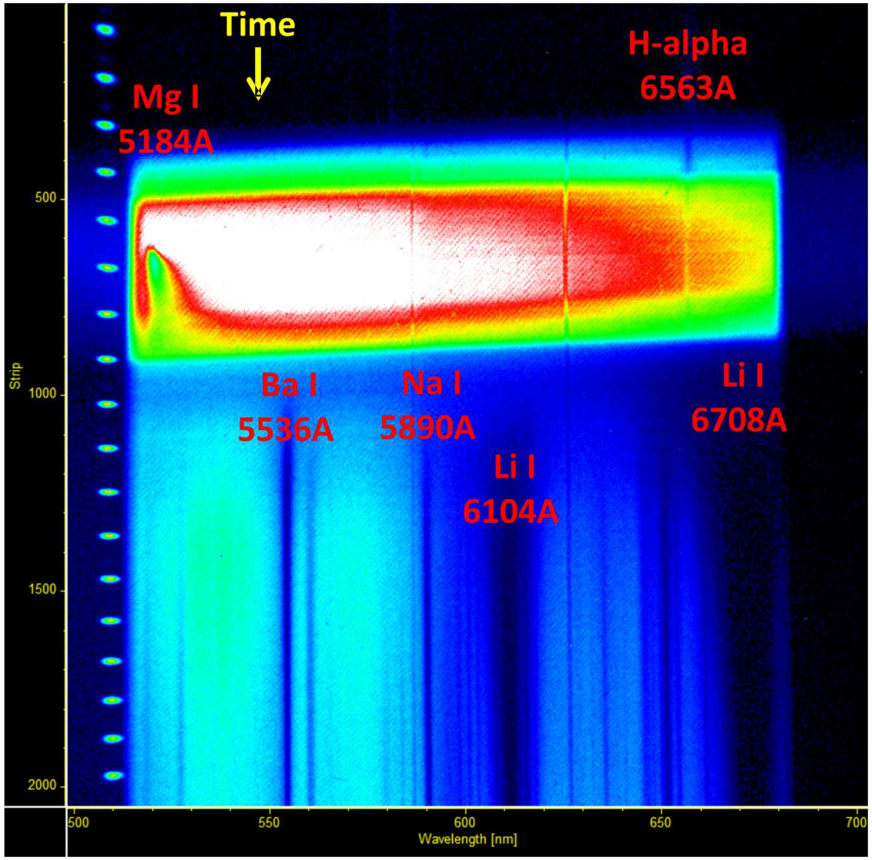


Horizontal LOS

Spectra from Nested Wire Array Experiments



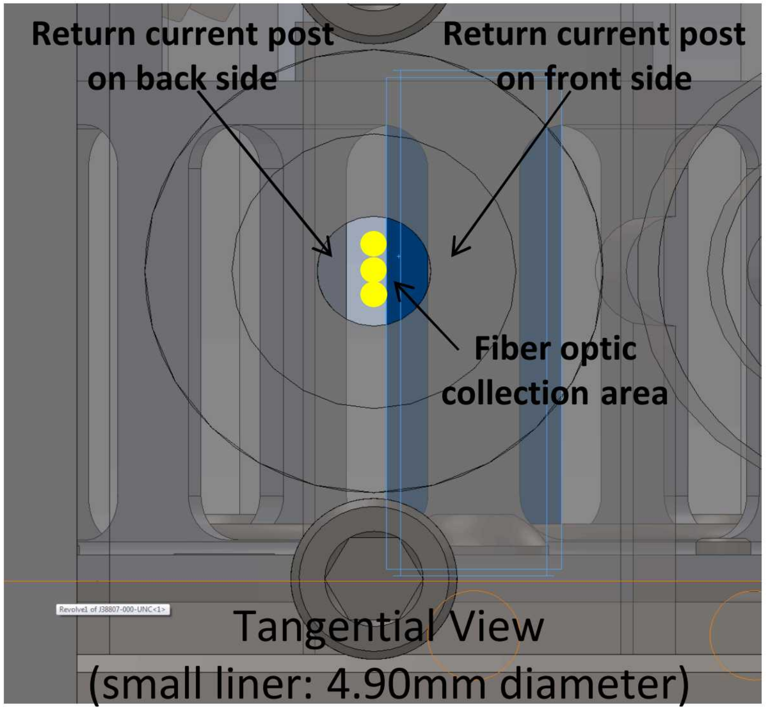
Fused Silica Window-no dopants
Grating: 150g/mm
Center Wavelength: 595nm
Sweep: 500ns
Combs: 35MHz (28ns)

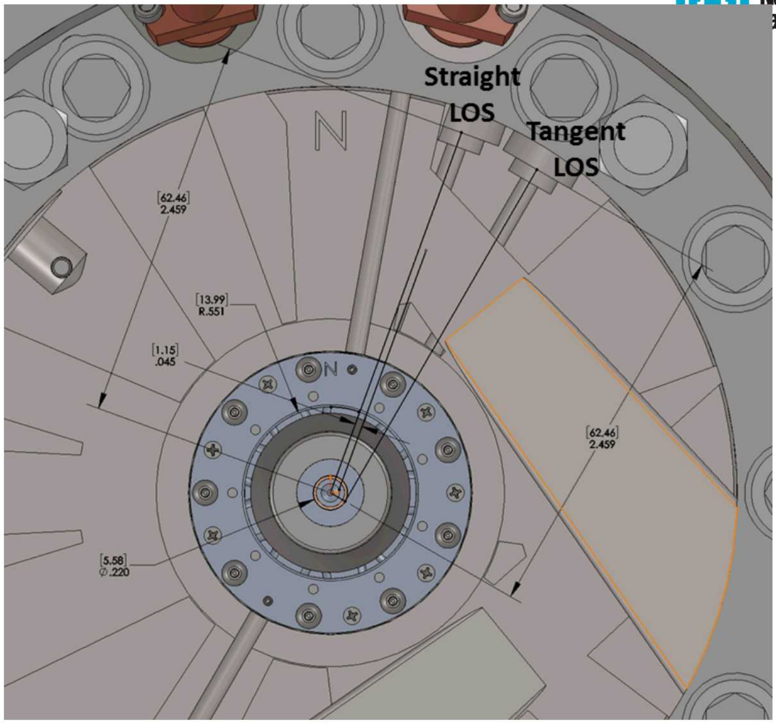


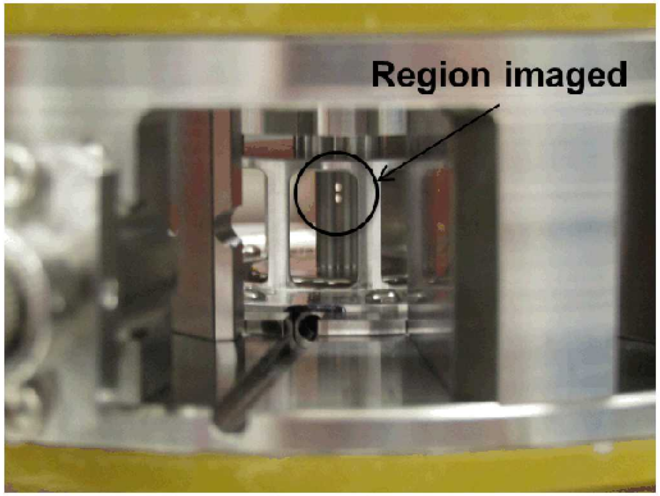
MgF_2 coated optics
Lithium and Sodium Dopants

- Dopants observed from both the anode and cathode, as well as from the optics.
- Highly broadened lithium neutral lines along the anode.

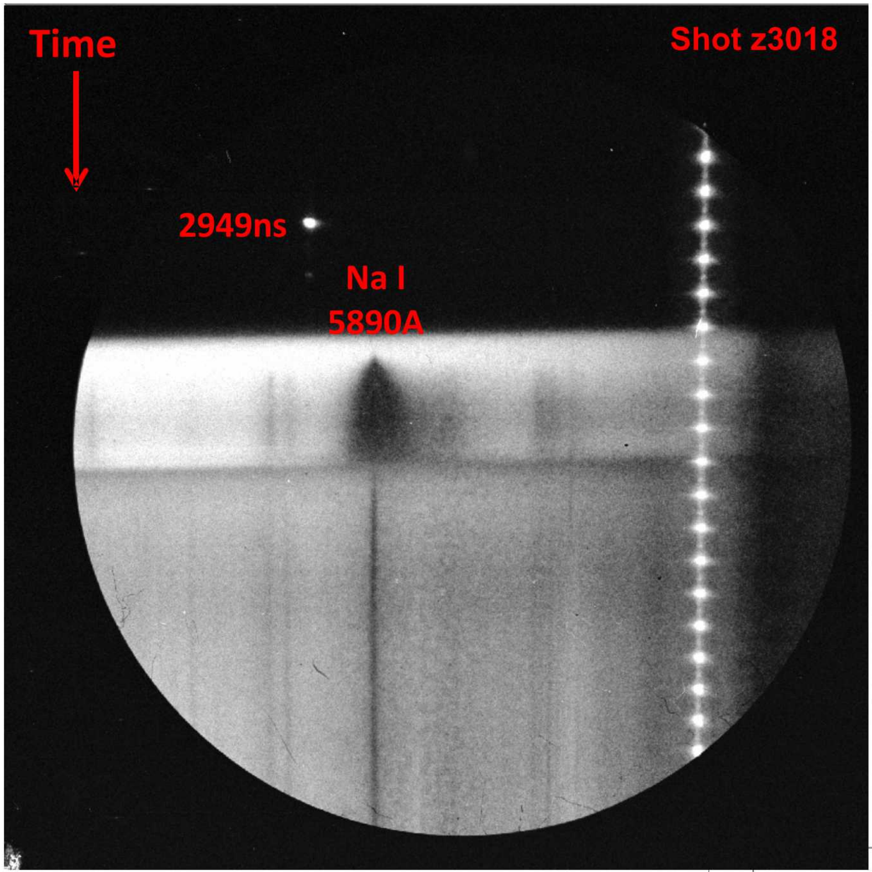
Hardware for MagLIF Liner Experiments with Slotted Return Can







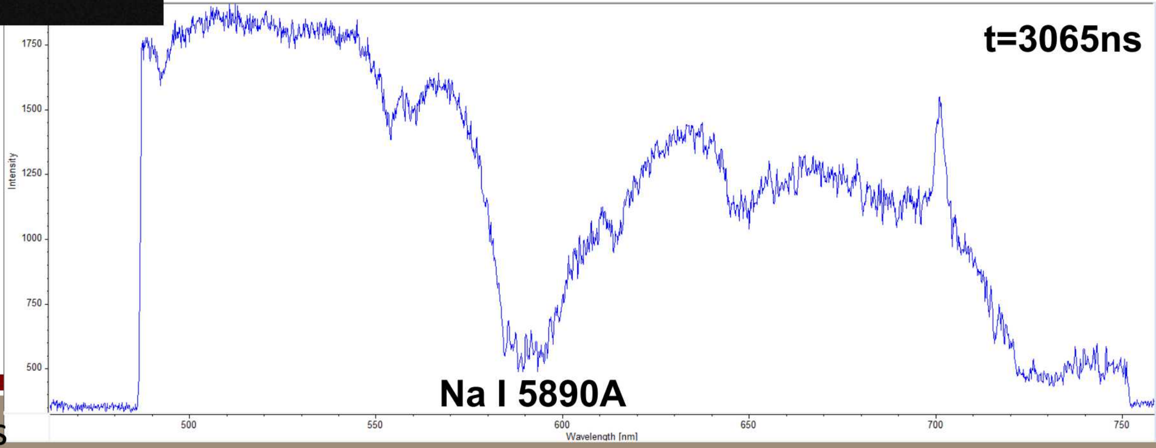
MagLIF Liner Experiments Show Sodium Line Broadening



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

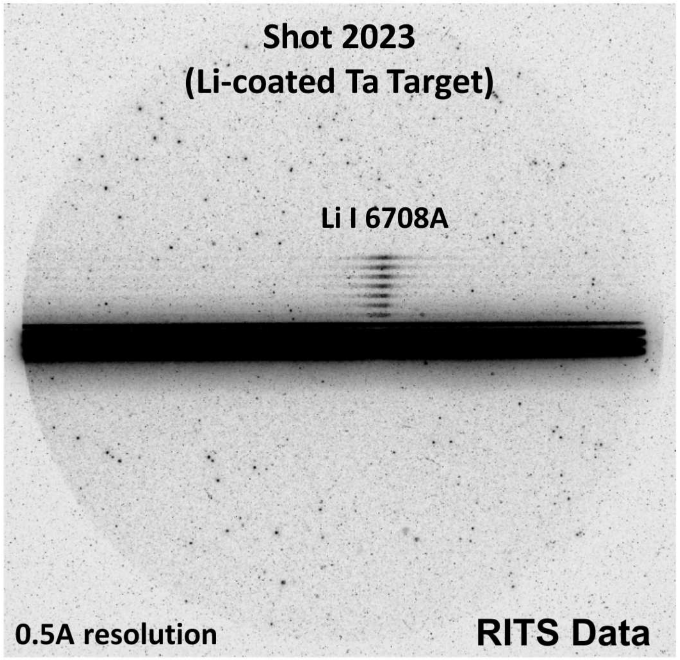
Experimental AR: 9
Uncoated Be Liner OD: 5.23mm

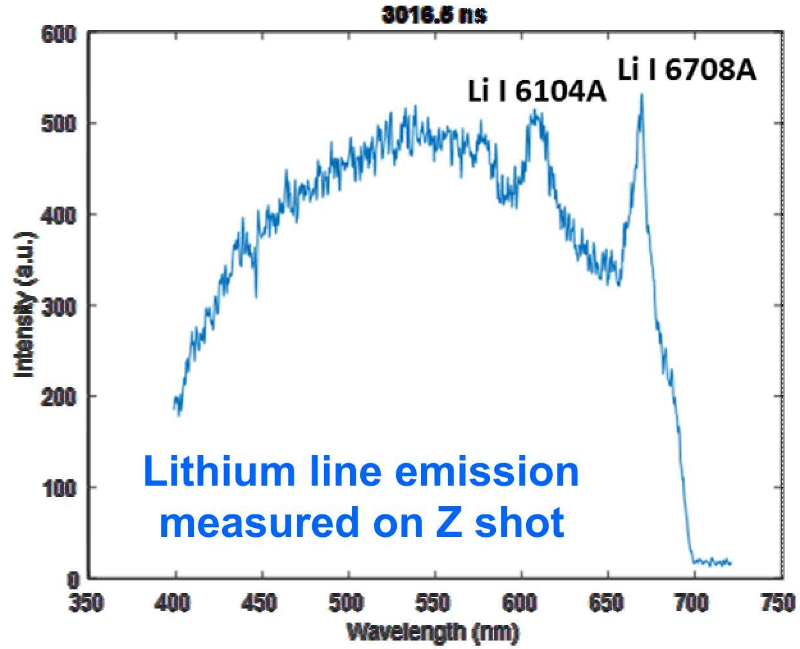
SVS1
Collimated beam, 1mm Aperture
7.5mm fl lens (uncoated)
Max counts: ~2000

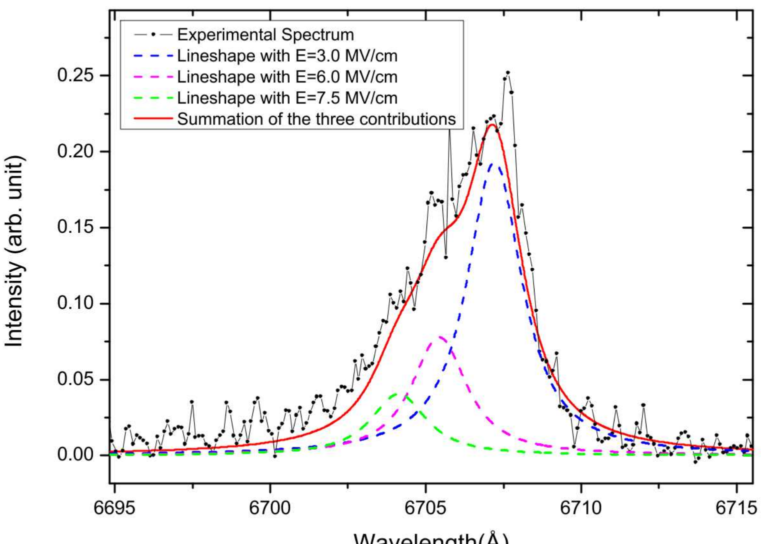


*Film begins to saturate around 3500 counts

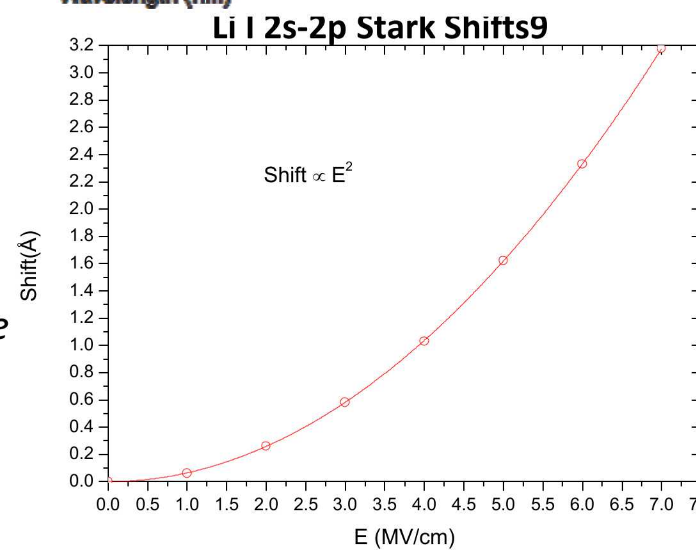
Electric Field Measurements on Pulsed-Power Diodes[11]







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.



[11] S. Biswas, M.D. Johnston *et al., Physical Review E, submitted.*

Summary and Conclusions

- Spectroscopic measurements of plasmas in the power flow regions on Z are ongoing.

- B-fields can be 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[12].

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

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

- Spectral measurements are needed to increase the fundamental physical understanding of plasmas and fields in high power machines.

- 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, such as Z-Next.

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

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.
- Determine plasma parameters such as species, ionization states, densities, and temperatures.
- Measure 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)[13].
- Implement a gated spectroscopy system at high resolution to record the spatial distribution of plasma on a single shot.
- Explore Stark shifts to measure E-fields as a function of time and space.
- Extend spectroscopic methods to other power flow regions.

[13] S. Patel, *et al.*, LDRD Funded Project.