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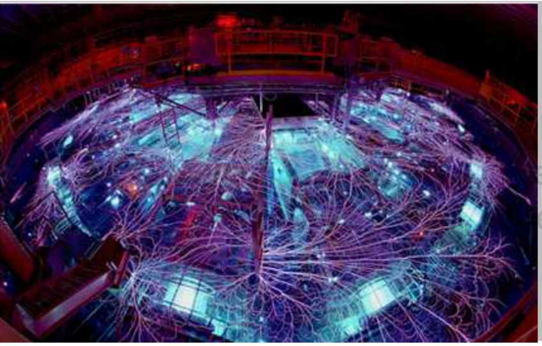

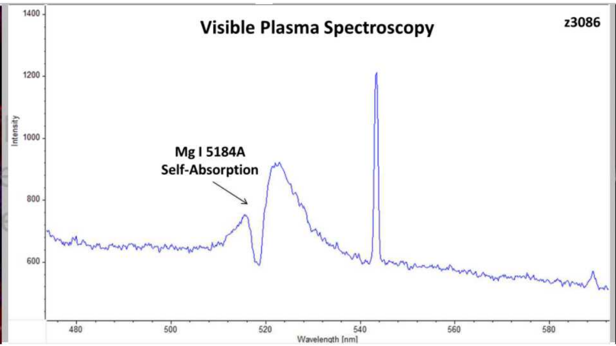

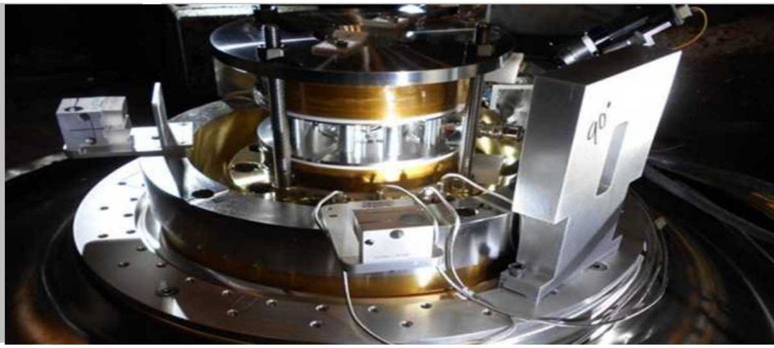

Visible Spectroscopy Techniques for Diagnosing Plasmas in High-Energy-Density Power-Flow Systems

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Abstract

Pulsed power devices rely 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 ~100 nanoseconds to multiple physics targets. This type of current flow combined with MeV potentials across millimeter A-K vacuum gaps lead to a variety of extreme electrode heating conditions, which liberate both surface and entrained gases, forming plasmas that propagate into the vacuum gap and draw current from the load. Losses of up to 20% have been observed on Z for certain load configurations. An effort is underway to investigate plasma generation in the power flow regions of the Z Machine. Visible plasma spectroscopy is employed to spatially and temporally determine plasma formation and propagation, and to measure plasma parameters such as densities and temperatures. In addition to plasma parameters, measurements of magnetic and electric fields by Zeeman splitting and Stark shifts, respectively, are also conducted [1]. Measurements are made using multifiber arrays, input into streak and fast-gated spectrometers. Line shape analyses are performed using detailed, time-dependent, collisional-radiative (CR) and radiation transport modeling. Recent results will be discussed.

[1] S. Biswas, M.D. Johnston, et. al., "Shielding of the Azimuthal Magnetic Field by the Anode Plasma in a Relativistic Self-Magnetic-Pinch Diode," Physics of Plasmas, 25, 113102 (2018).

Outline

- Power Flow Studies on Z
- Current Loss Mechanisms
- Initial Experimental Results
- Zeeman Measurements with Hydrogen
- Zeeman and Stark Measurements with Lithium
- Other Experimental Platforms on Z
- Summary and Conclusions
- Z-Next
- Future Work

Motivations for Power Flow Studies on the Z Machine

- Obtain measurements of plasmas in the power flow regions on Z for the purpose of gaining a comprehensive physics understanding of plasma formation on Z.

- Detailed plasma measurements have been made on other pulsed-power machines [2]. Want to extend these measurements to the Z-Machine.

- Current losses on Z are attributed to plasmas in the vacuum gap of the final feed section.

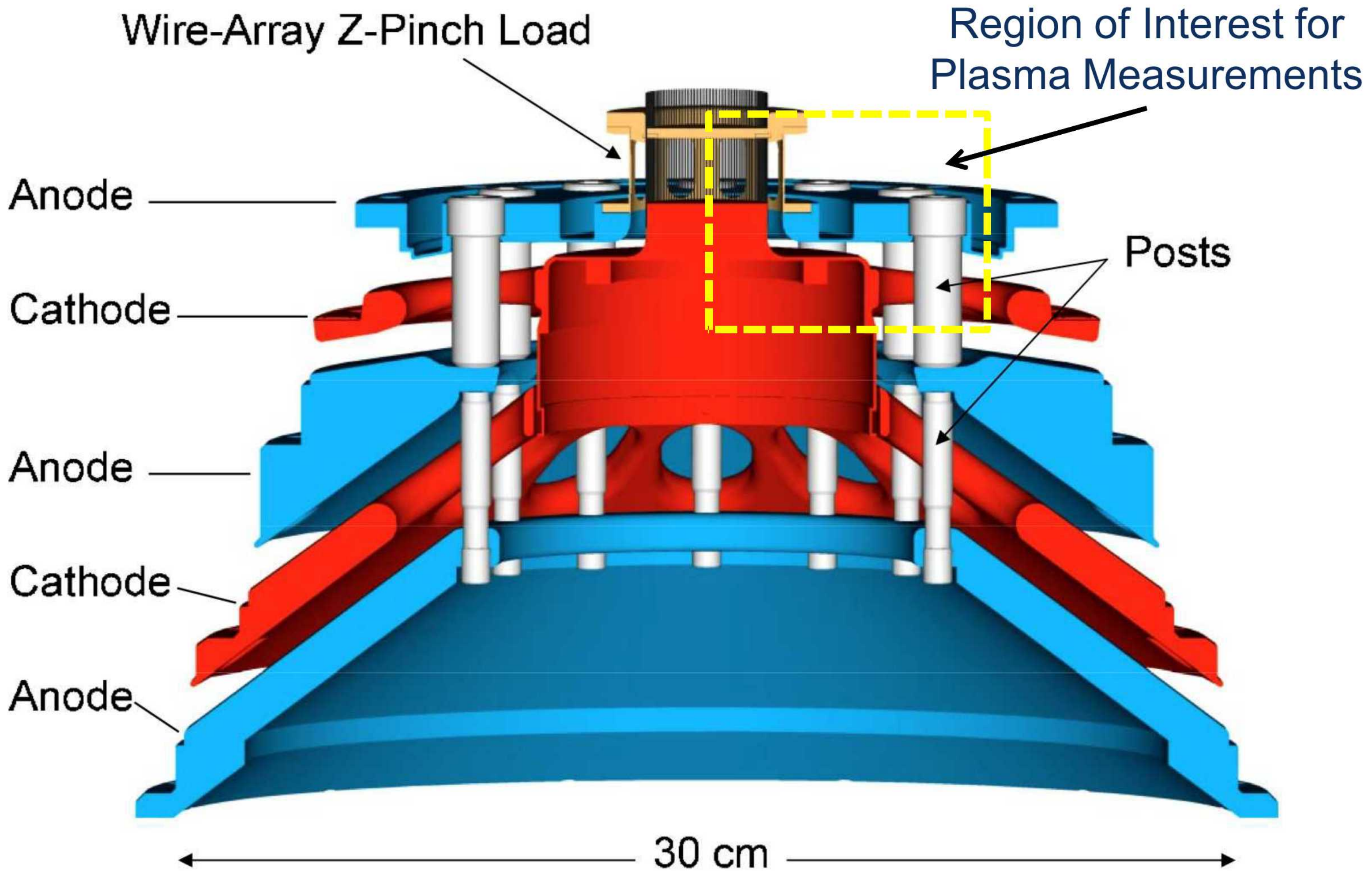
- Input experimental data into particle in cell (PIC) codes to better predict plasmas and fields in high power devices.

- Use this information to improve present pulsed power designs, and as a predictive capability for future, next generation facilities such as Z-Next [3].

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

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

Z Load Hardware Configuration [4]



- 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

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

Current Losses on Z Reduce Power Delivery to the Loads

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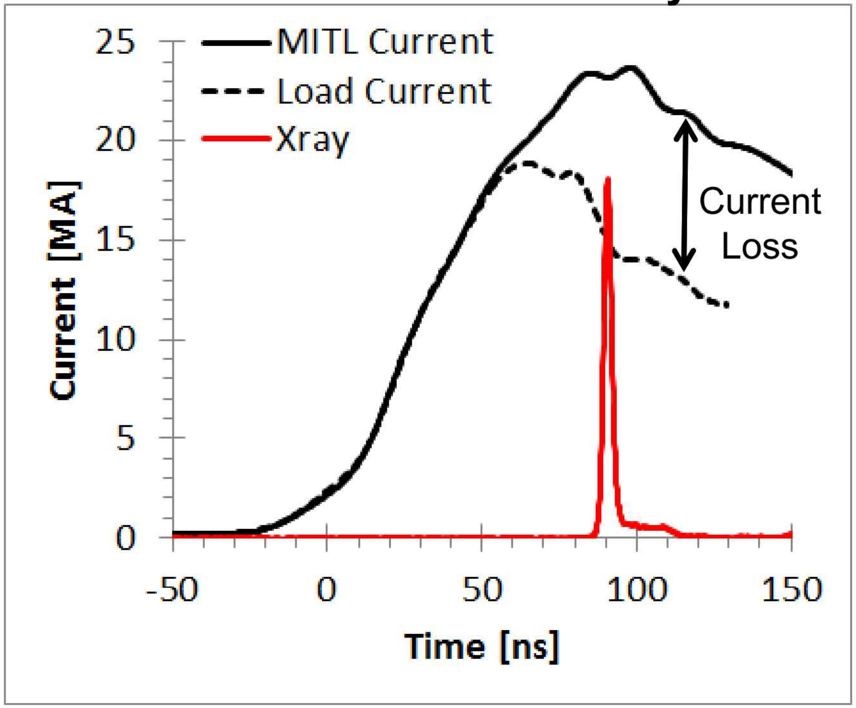
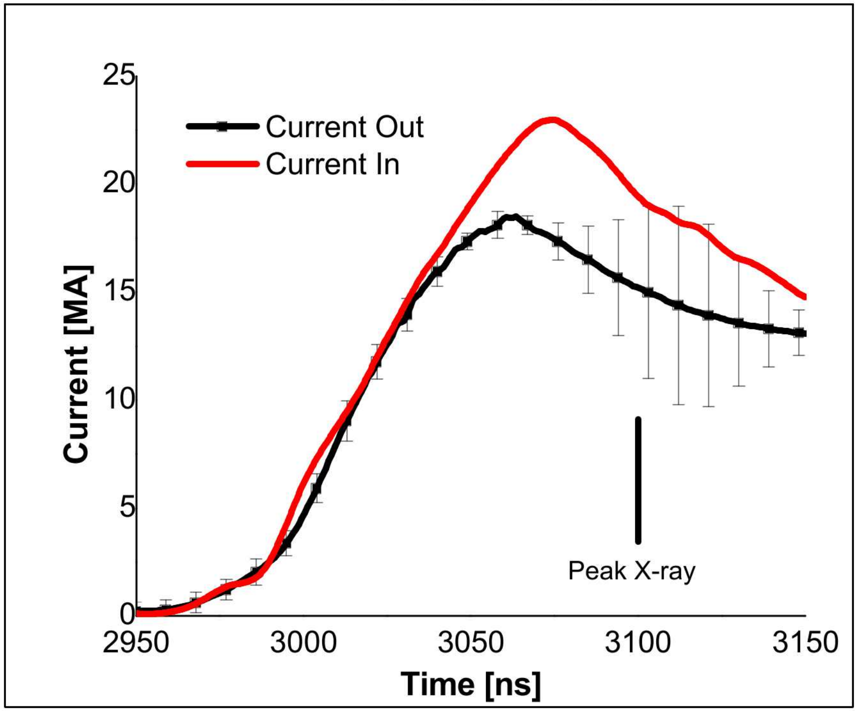
Stainless Steel Wire Array

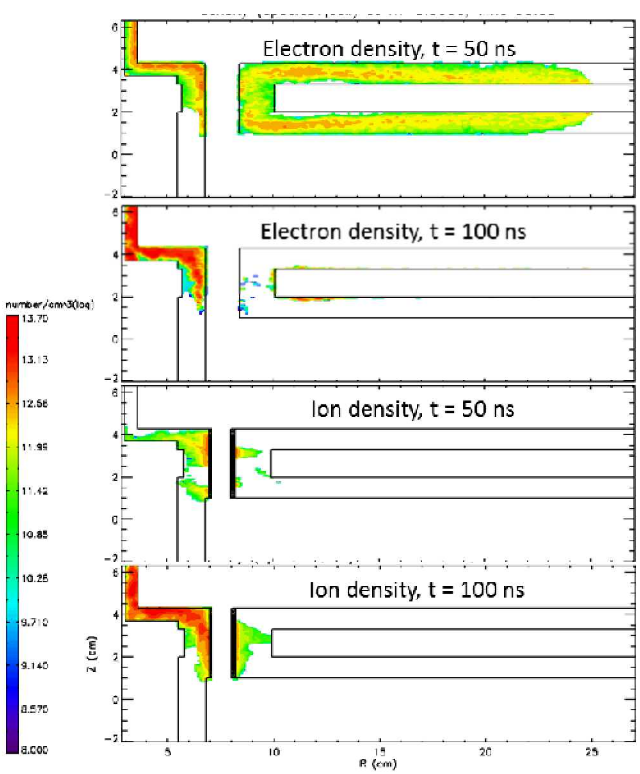


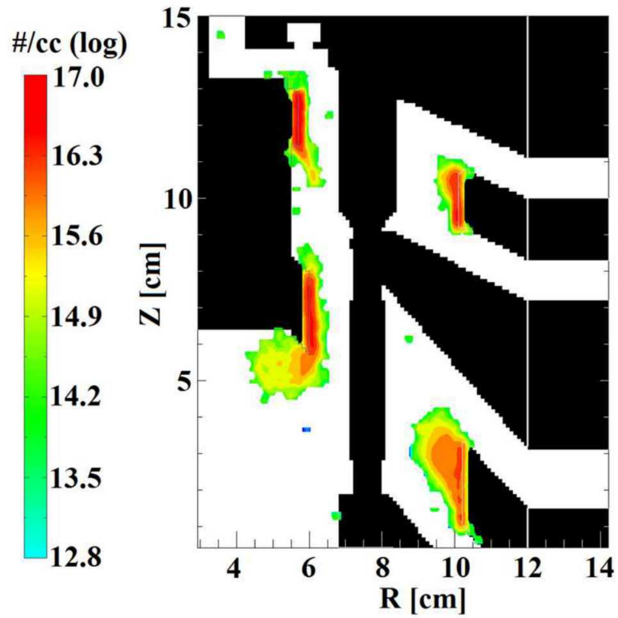
Gas Puff Load

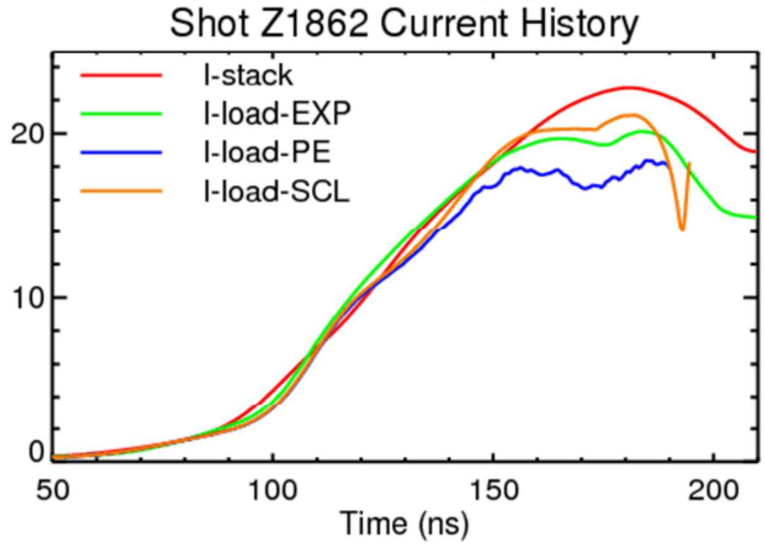


- Up to 5MA current loss is sustained for ~50ns on some loads.
- Surface contaminants, outgassing of electrode materials, and non-ideal geometries affect current delivery to the load.
- Approximately 70% of the total electrical power delivered to the load occurs after peak current, when losses are at 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).

Particle in Cell Modeling of Cathode and Anode Plasma in Quicksilver [6,7]

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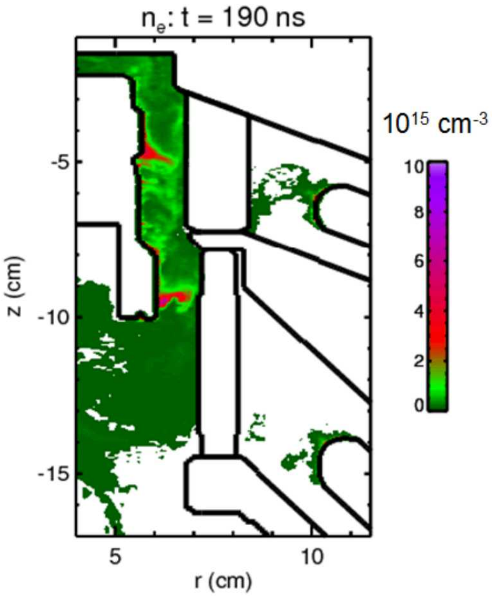
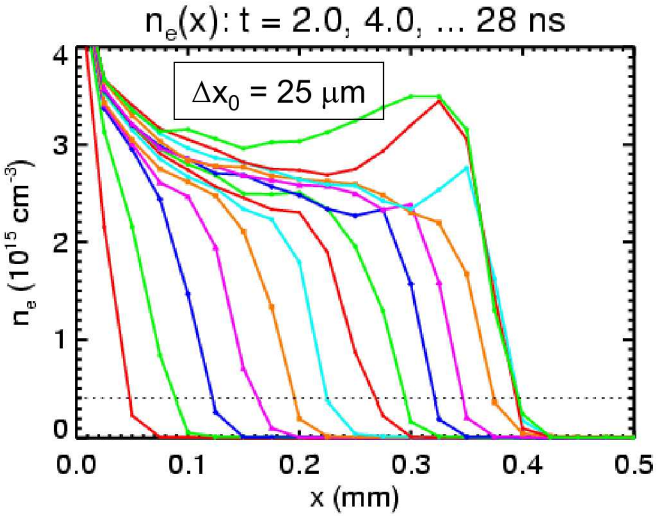
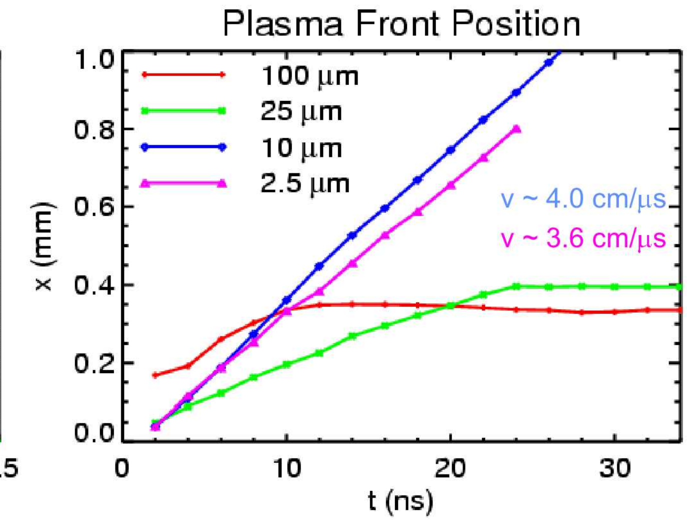
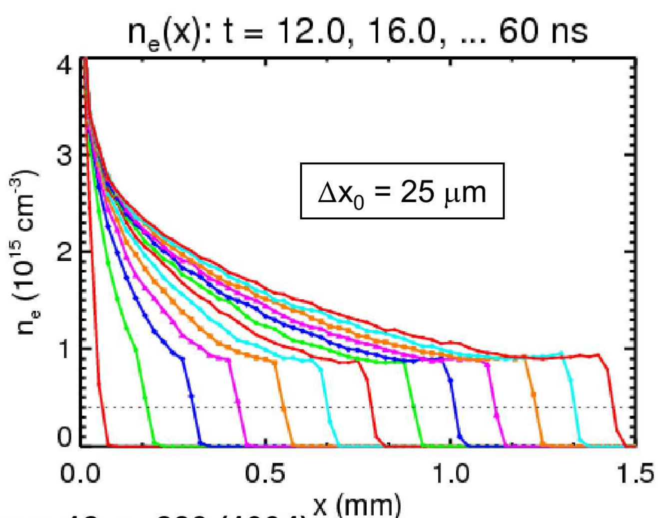


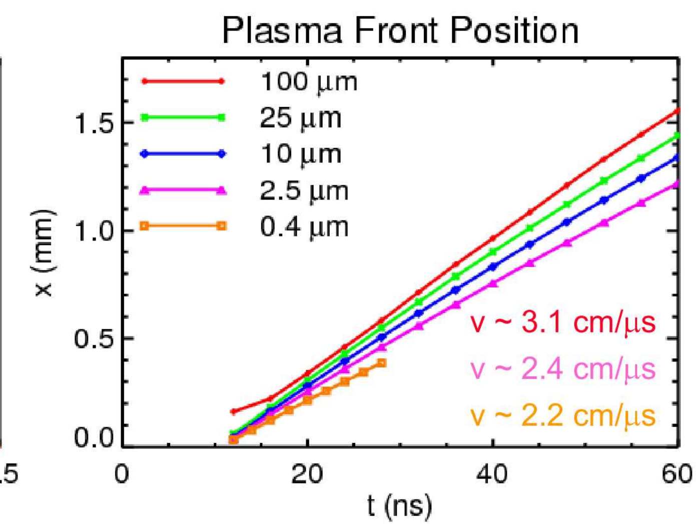
Cathode Plasma





Anode Plasma



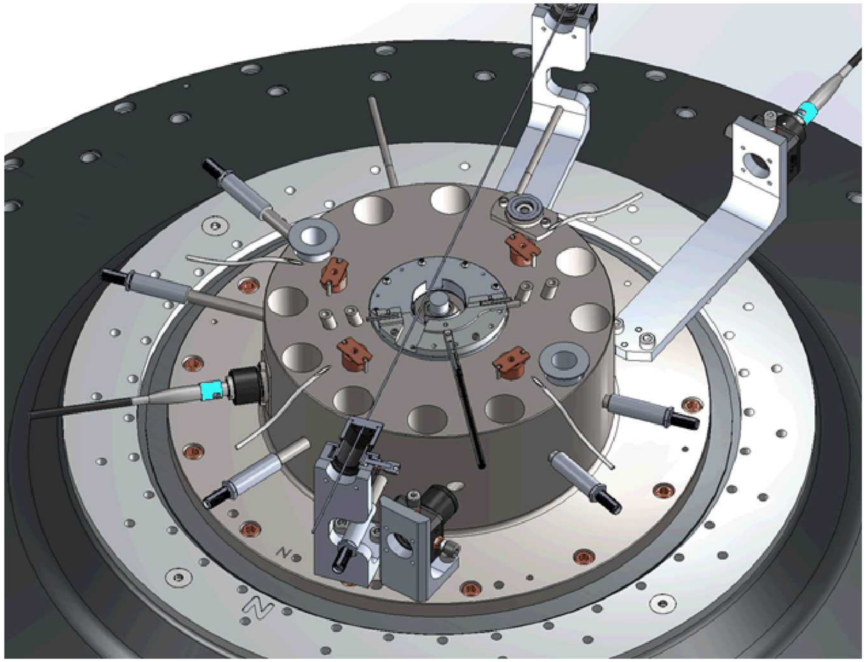


- High density electron structures are observed on the inside of the posts, where B-fields are high.

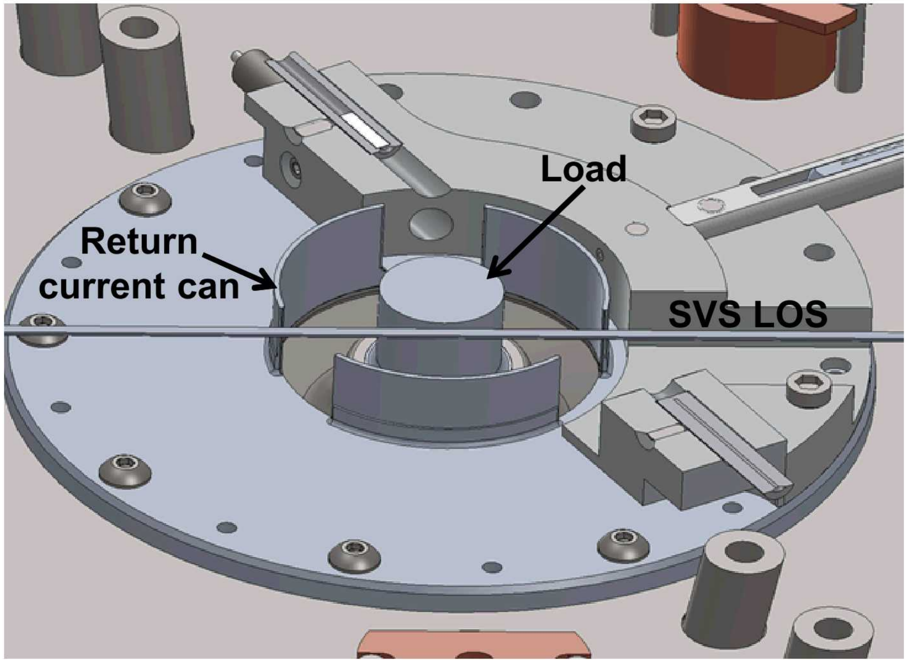
[6] J.P. Quintenz, *et al*., Laser Part. Beams 12, p. 283 (1994).

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

Dedicated Experiments for Power Flow Physics are Being Conducted on Z



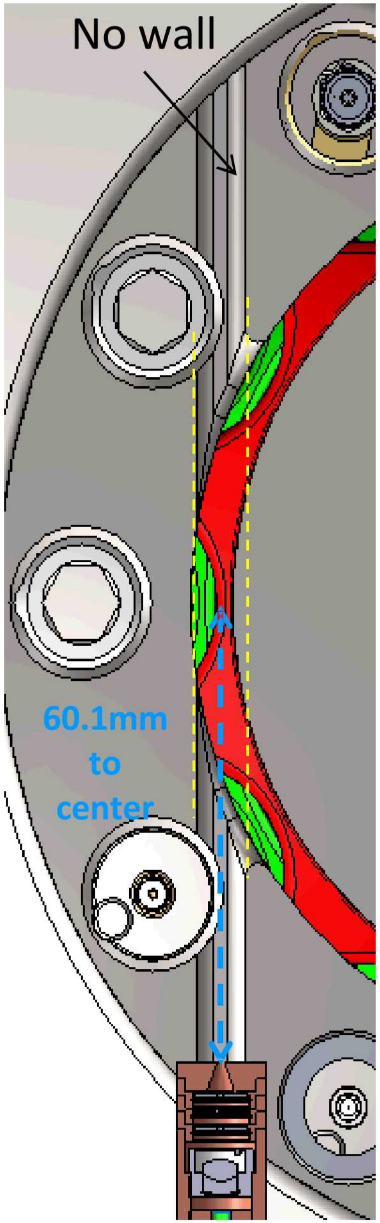
Power Flow Hardware

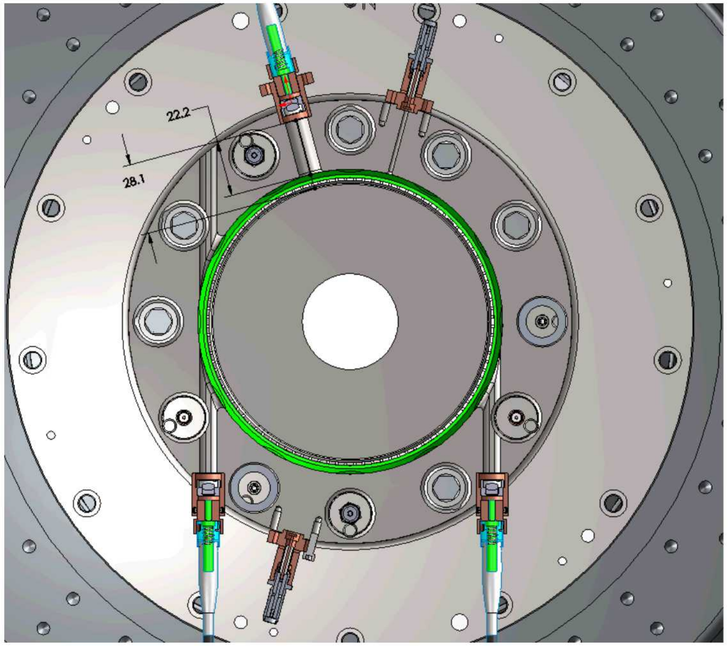


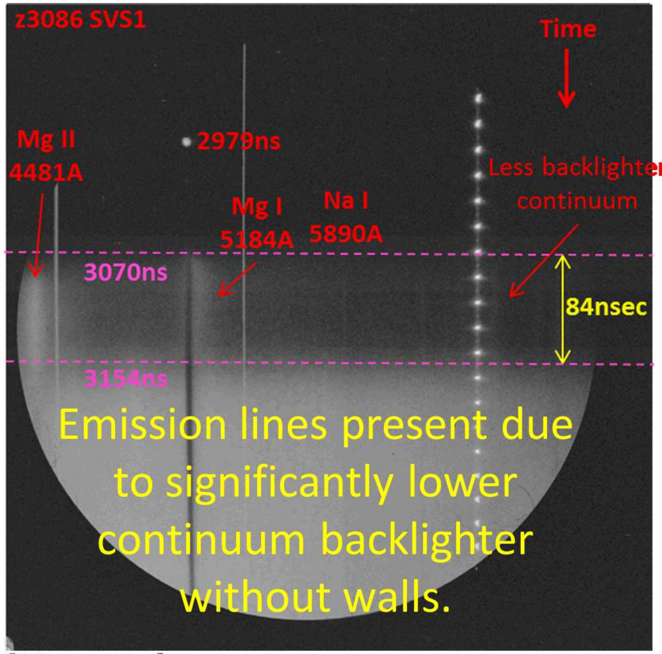
Non-Imploding Load

- 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.

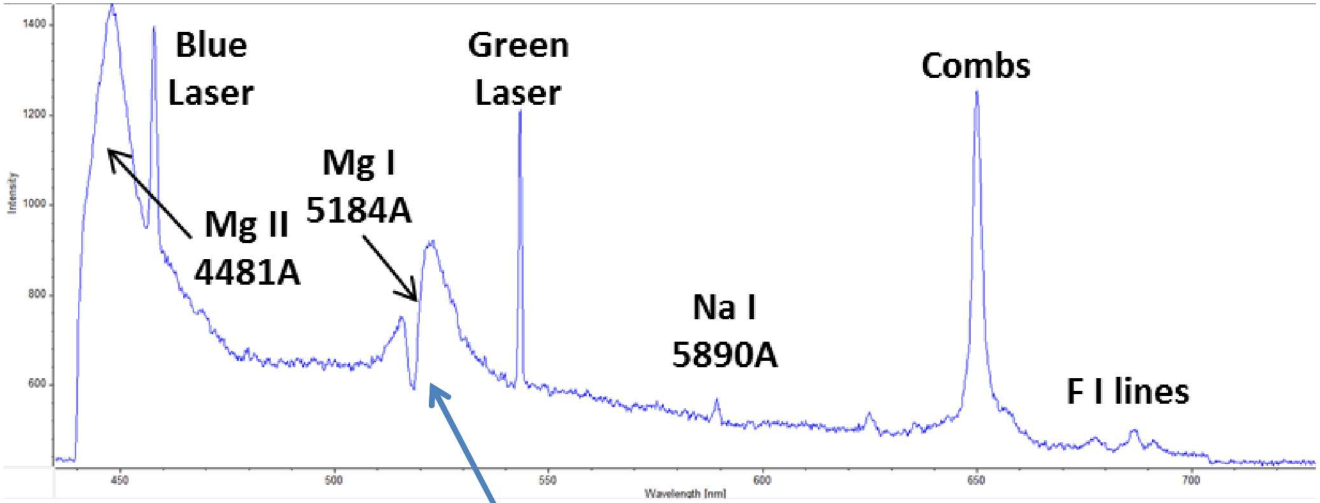
Chordal Line of Sight on Power Flow Shots in the Final Feed







*20nsec combs

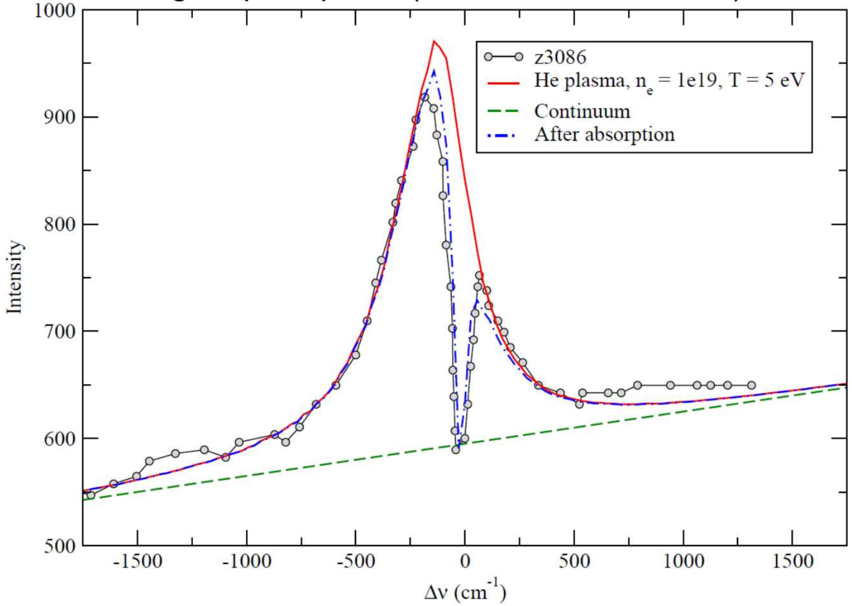


Emission and self-absorption of Magnesium neutral observed.

Magnesium Dopant Results

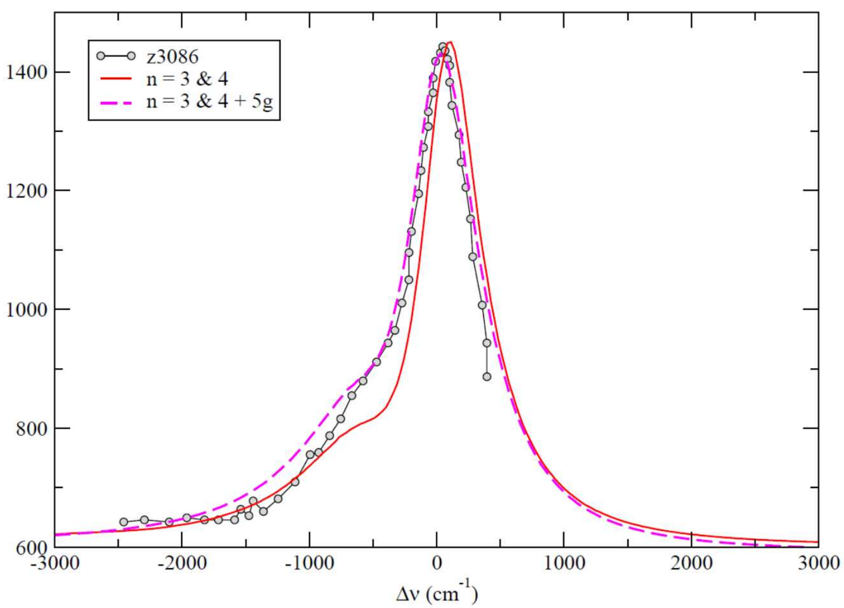
- MgF_2 coated optics
- Mg I and Mg II broadened line emission observed
- Two distinct plasma regions present in spectrum
- Colder, more dilute Mg I plasma next to optics
- Hotter, denser plasma, further off the surface
- Light from the hotter, denser plasma is absorbed in the cooler plasma.
- Density of emitting plasma: ~1×10^{19} cm^{-3}
- Density of absorbing plasma: ~ 1×10^{18} cm^{-3}
- Plasma temperatures: 1-5eV
- Mg I lines are red-shifted by 5.9Å
- Opacity (τ) = ~0.4
- 1×10^{19} cm^{-3} continua fits experimental data

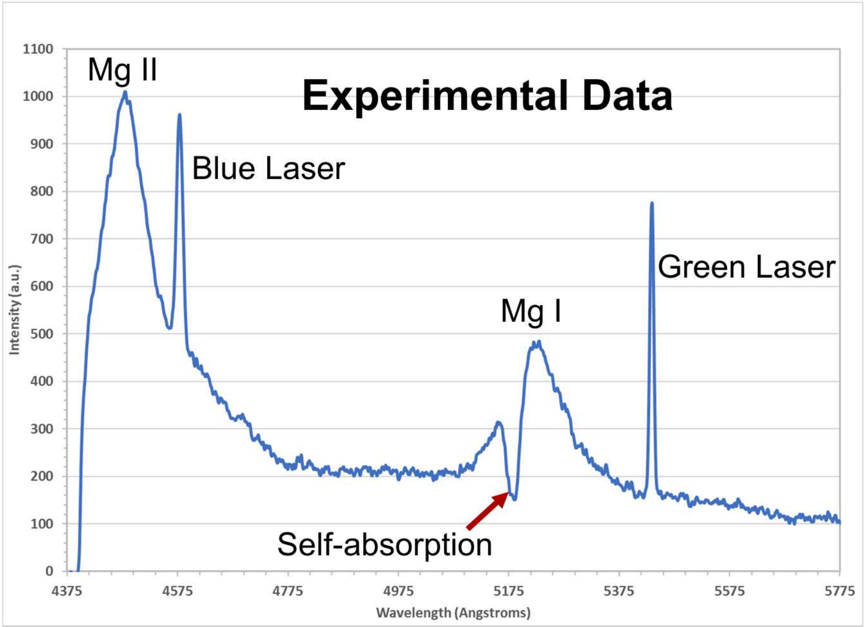
Mg I triplet 3p - 4s (5167Å, 5173Å, 5184Å)



Mg II 3d - 4f (4481 Å)

He plasma 5 eV, 10^{19} cm^{-3}





CRE Calculations

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

3s3p ^3P - *metastable* level

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

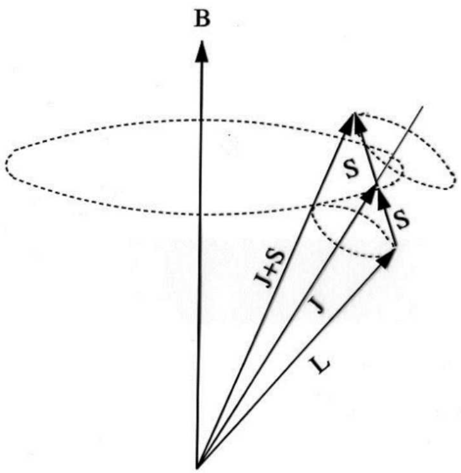
3s4s ^1S → 3s3p ^1P; λ = 11,828 Å (NIST)

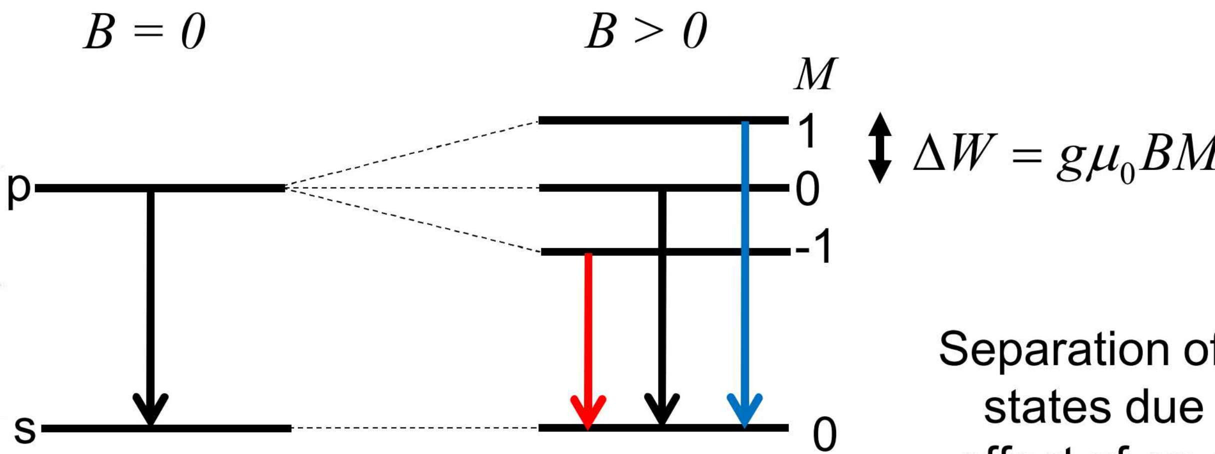
3s4s ^3S → 3s3p ^3P; λ = 5,183 Å (NIST)

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

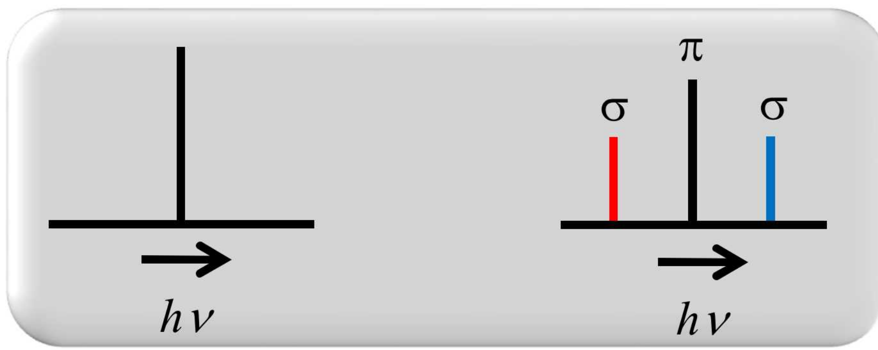
* - population, ** - ground states, *** - Einstein coefficient

Zeeman Splitting is a Useful Technique for Magnetic Field Measurements in Plasmas





Observed

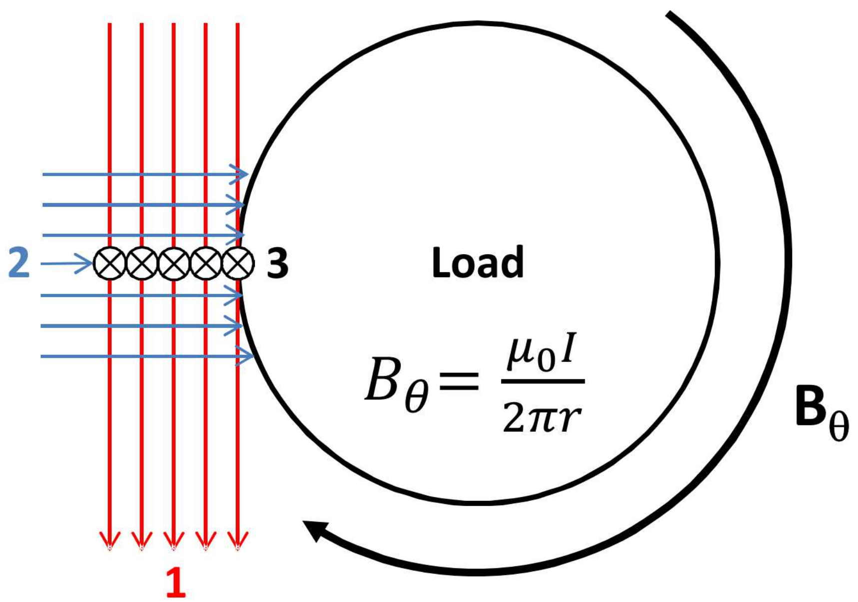


Separation of energy states due to the effect of an applied B-field on the magnetic moment of an atom or ion.

$$h\Delta\nu = \mu_0 B\left(g_u M_u - g_l M_l\right), \begin{bmatrix} \Delta M = 0, \ \pi \\ \Delta M = \pm 1, \ \sigma \end{bmatrix}$$

Zeeman Splitting Measurements on Z

Three Potential Views at the Load



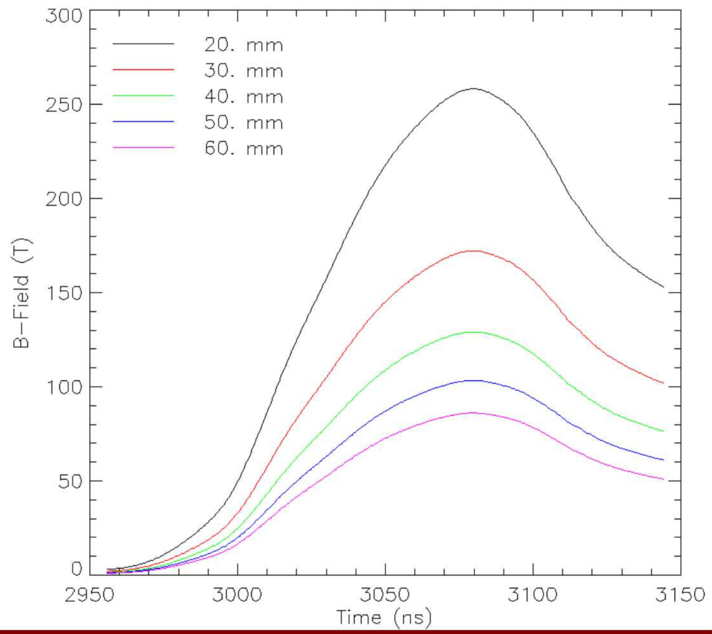
Considerations:

- 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

Requirements:

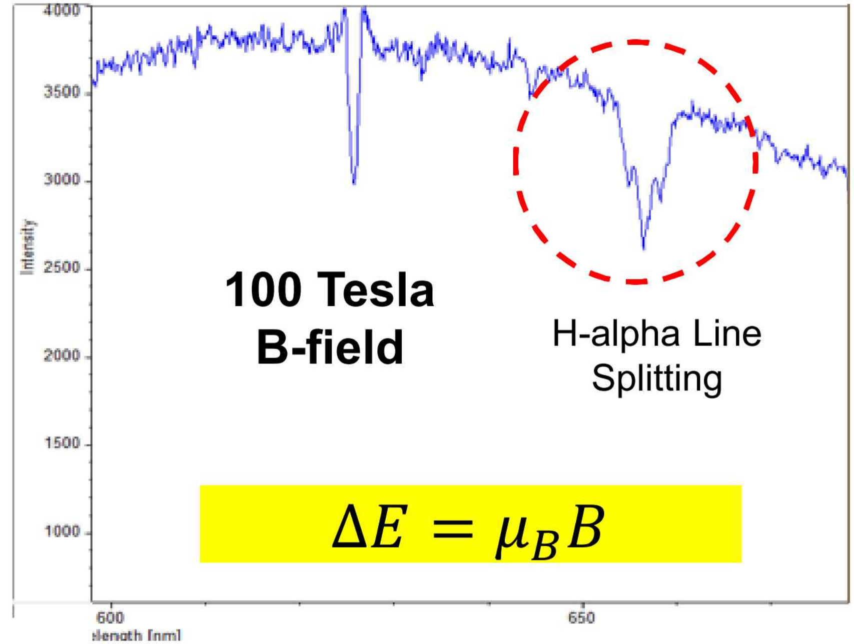
- Slotted return current can
- Multifiber array
- Detectors (Streaked spectra, gated spectra, photodiodes)
- Dopants (Na, Li, Al, C, others)
- Compare with VISAR measurements at the load
- Compare with B-dot monitors at r=6cm

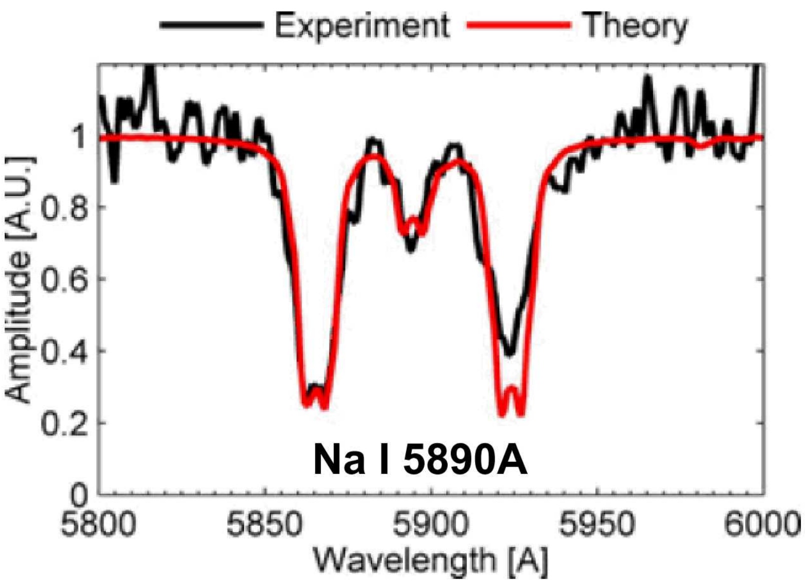
B-field versus Radius



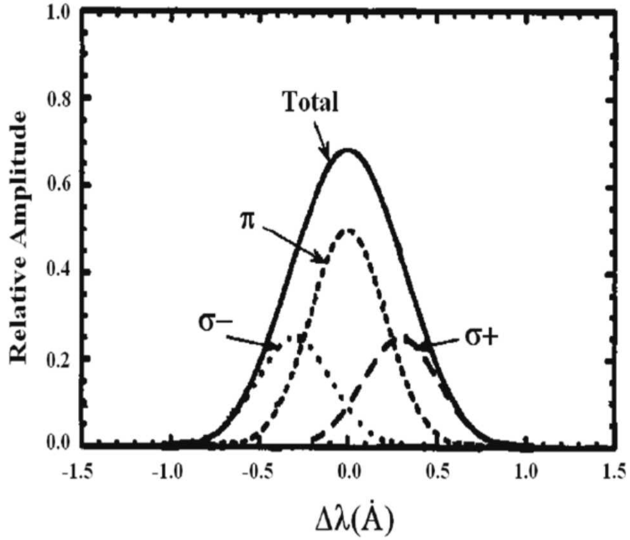
Zeeman Splitting on Z

- 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 Z relevant temperature and density regimes.
- Previous work by Gomez et. al. measured Na I splitting in the load region on Z [8].



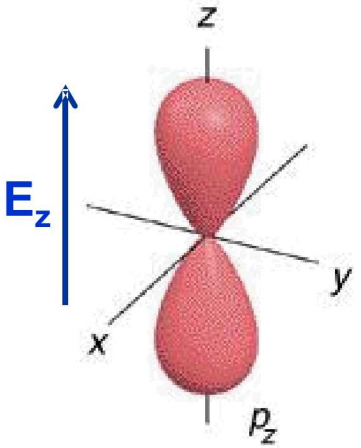


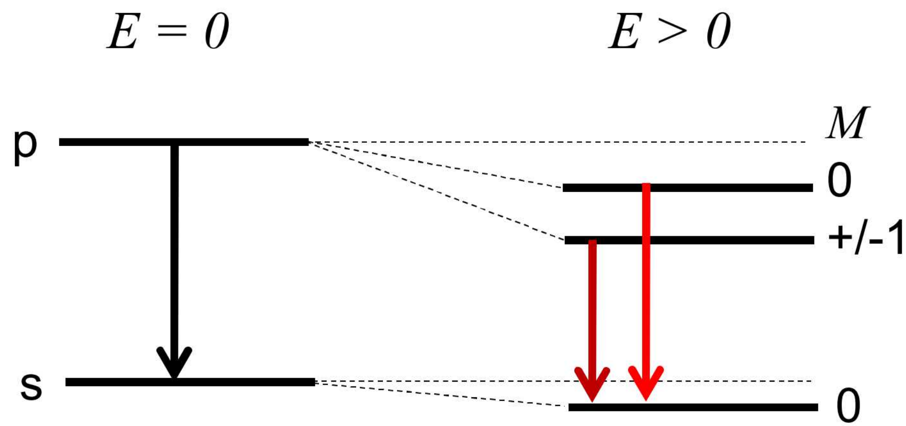
λ_o = 6563Å
$\Delta\lambda$ = 1.2Å/T
m = 0, +/- 1
B = 100T



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

Quadratic Stark Shift is a Useful Technique for Electric Field Measurements in Plasmas



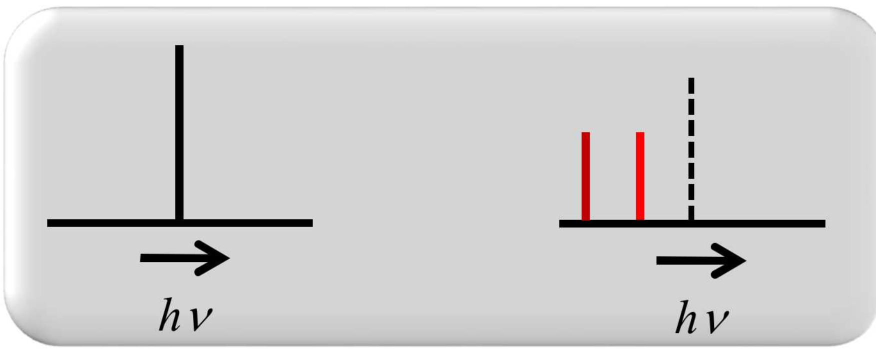


$$\Delta W = -\frac{1}{2}\alpha|E|^2$$

$$\alpha \propto M^2$$

Separation of energy states due to an external E-field inducing a dipole moment in an atom or ion.

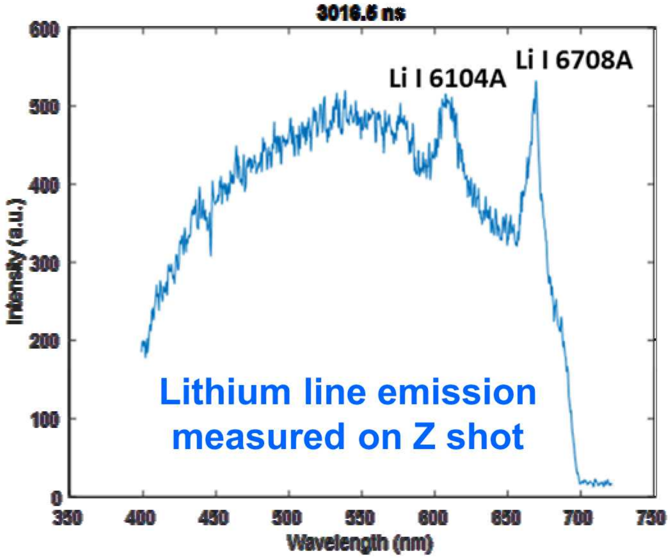
Observed

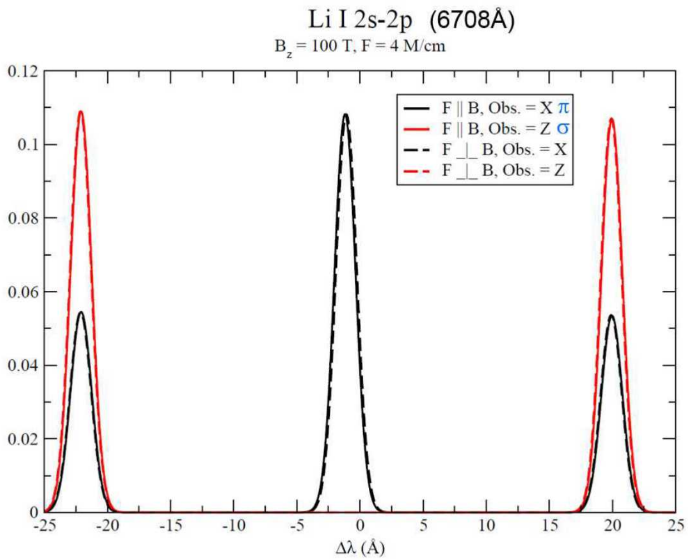


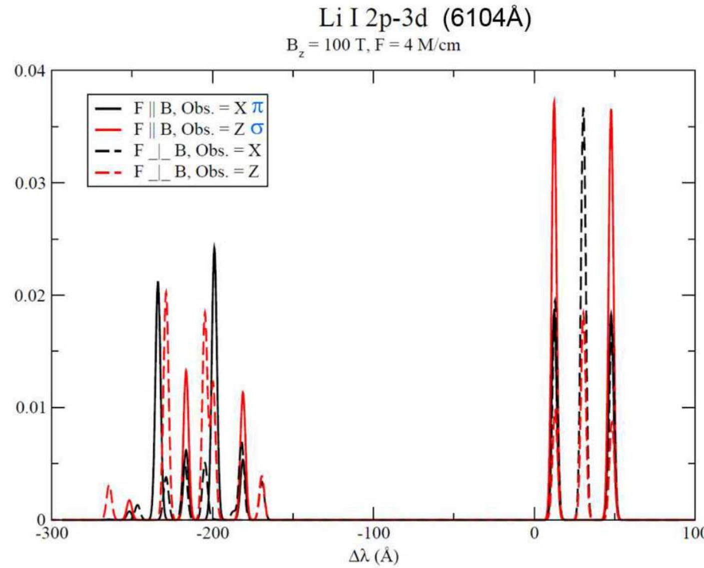
$$h\Delta\nu = h\nu_0 - (\Delta W_u - \Delta W_l)$$

Lithium Dopant for Electric and Magnetic Field Measurements

Lithium neutral lines (6708Å and 6104Å) used in combination, provide a means of measuring local electric and magnetic fields in Z power flow regions*.

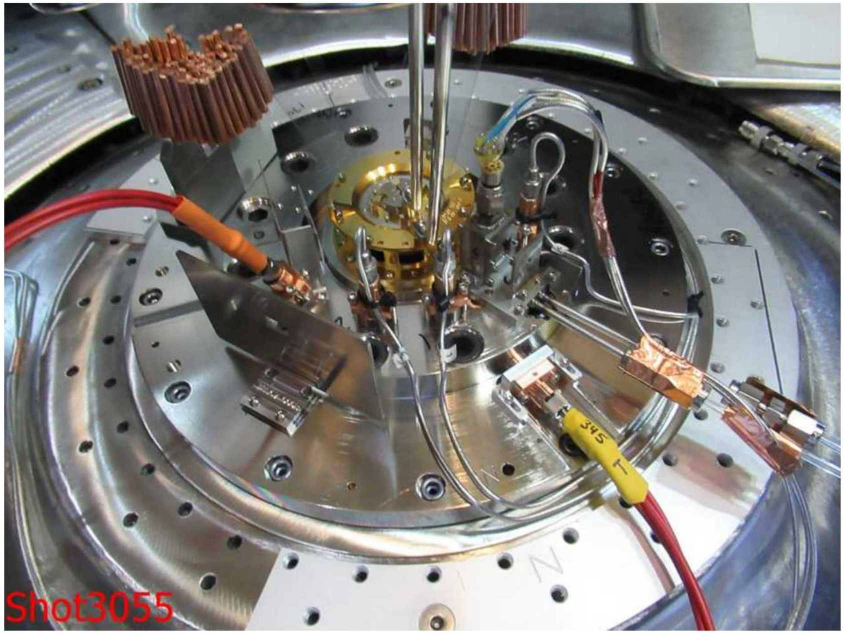




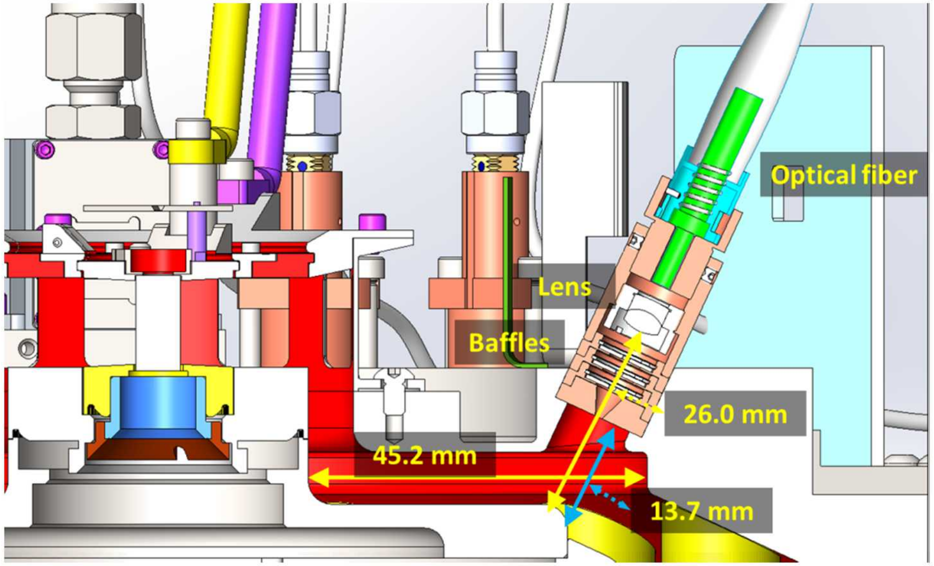


*S. Biswas, M.D. Johnston, *et al.*, "Shielding of the Azimuthal Magnetic Field by the Anode Plasma in a Relativistic Self-Magnetic-Pinch Diode," *Physics of Plasmas, 25, 113102 (2018).*

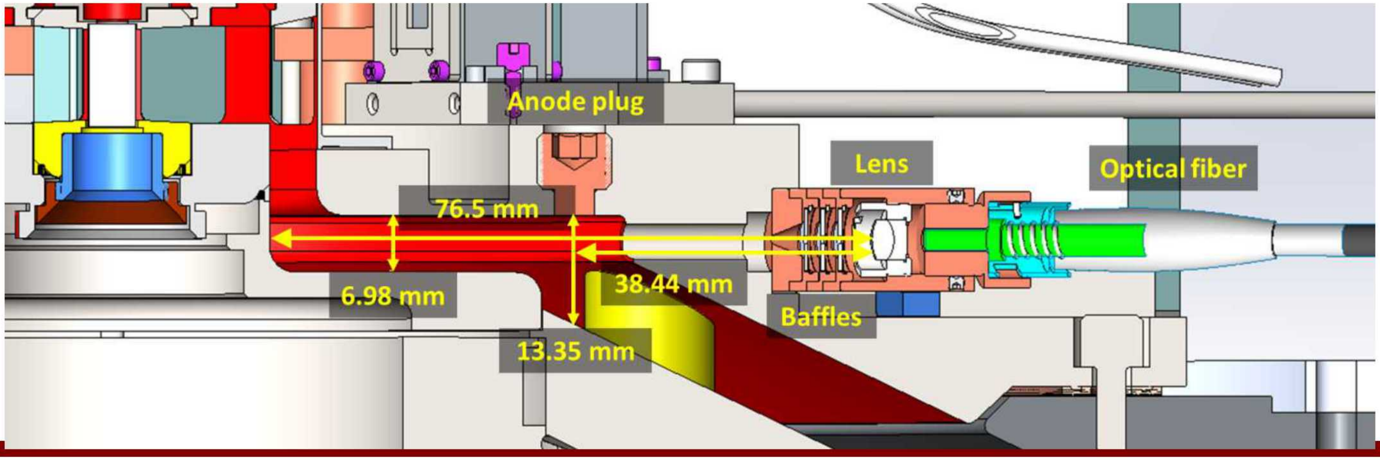
Ride-along Experiments are Fielded on Multiple Z Platforms



Wire Array Experiment

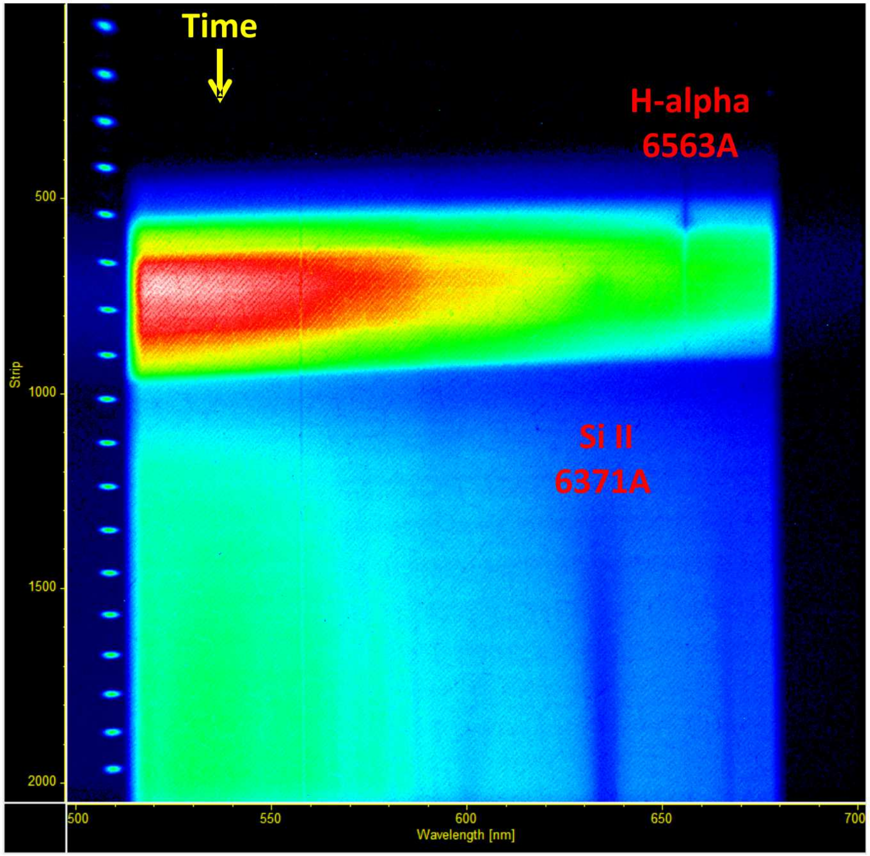


Angled LOS

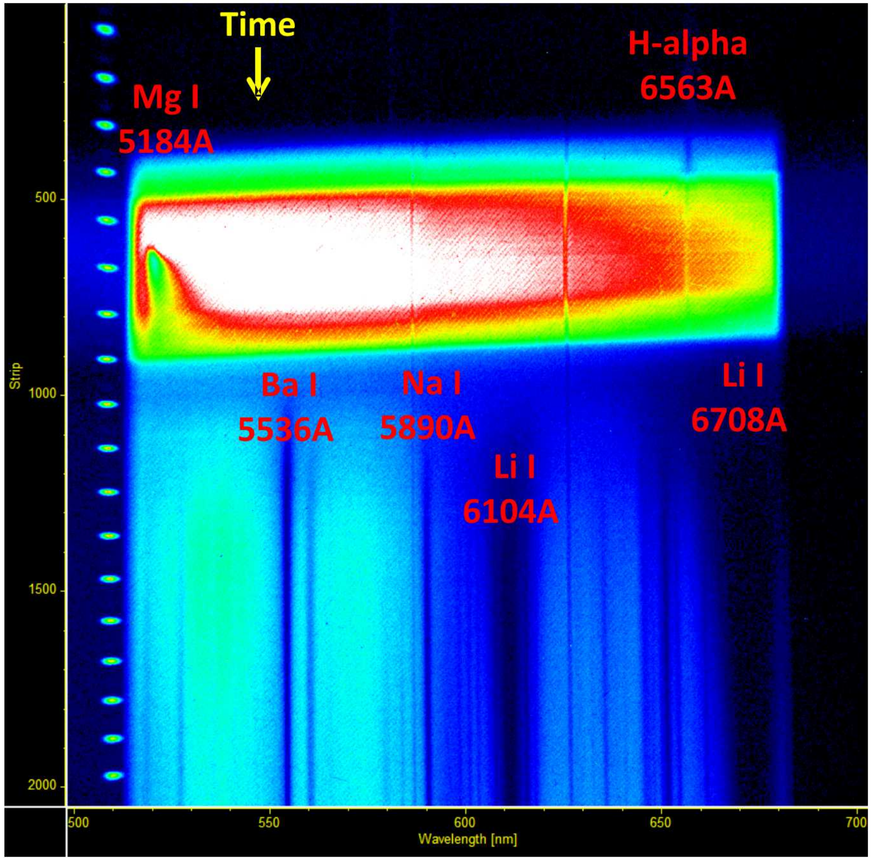


Horizontal LOS

Spectra from Nested Wire Array Experiments



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

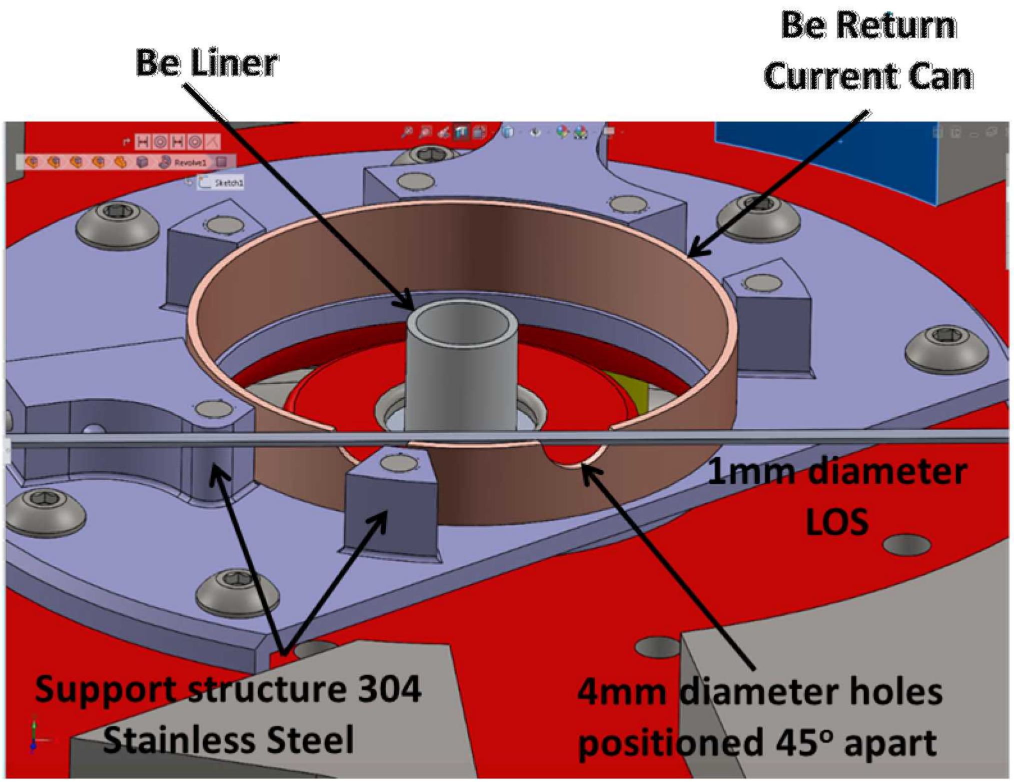


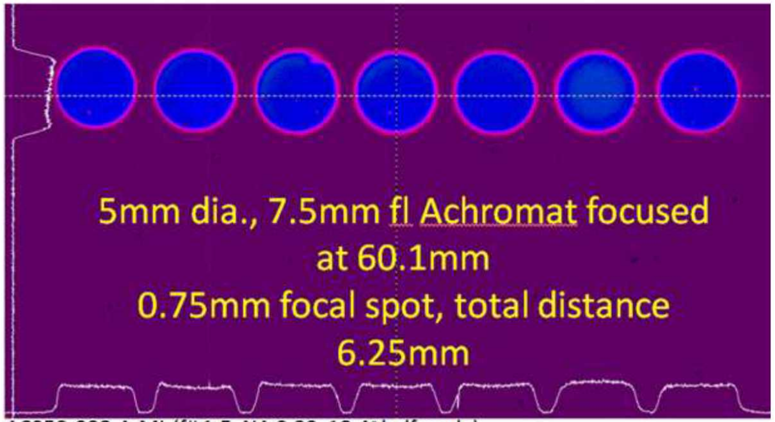
MgF_2 coated optics
Lithium and Sodium Dopants

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

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)

Determination of Current Flow in Pulsed-Power Systems

- Current distribution is important in the design of new pulsed-power machines and in the understanding of existing machines like Z.

- The only way to obtain line emission from the A-K gap of a power-flow transmission line is to use neutrals, which requires:
  - Sufficient number of neutrals in the gap
  - Using neutrals that are not field-ionized in the gap, or more precisely, the atomic level of interest (that provides the radiative decay) should not be field ionized.

- In order to observe the Zeeman effect, one needs line emission in the gap that is <u>not</u> Stark shifted.

- To prove the neutral atoms emitting the line(s) are in the gap (rather than in the plasma) one also needs an emission line from the same atom that <u>is</u> Stark shifted.

- We prove, both experimentally and theoretically, that Li neutrals fulfill these requirements, namely:
  - The 2p-2s transition is <u>not</u> Stark shifted and demonstrates the Zeeman effect.
  - The 3d-2p transition <u>is</u> Stark shifted and proves the presence of the emitting neutrals in the gap.
  - The upper, n=3 level of Li I (also the 2p level) does not field ionize in the gap.

- **In Summary, we demonstrated a promising new method to reliably determine the current distribution in the final feed section on Z.**

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.
- 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 needed to validate the models, and to accurately predict the performance of the next generation pulsed-power machines, such as Z-Next.

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 in the power flow region on Z.

- Measure magnetic fields and currents in the A-K gaps on Z. This will require greater signal to noise and/or plasma injection scheme (ex. active dopants) [9].

- 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.

[9] S. Patel, *et al.*, LDRD Project.