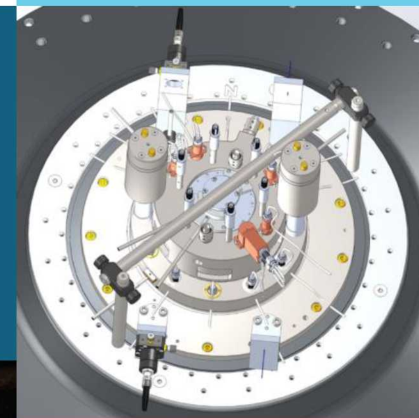
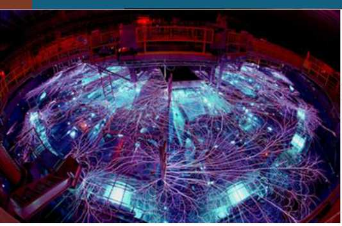
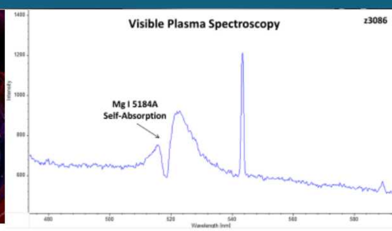
Sandia National Laboratories

SAND2019-12874C



Spectroscopic Investigations of Power Flow Plasmas on the Z-Machine at Sandia National Laboratories





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Fort Lauderdale, FL

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Abstract

Investigations are underway to study plasmas formed in the power flow region of the Z-Machine at Sandia National Laboratories. High current densities (MA/cm^2) during a ~100 nsec pulse, rapidly heat electrode surfaces, desorbing contaminants and entrained gases. These species quickly form a dense (10^{19} cm^{-3}) surface plasma layer composed of neutrals and low charge state ions. Ions that get outside of this layer are subject to MV/cm electric fields, can cross the A- K vacuum gap, and carry current away from the load. Steaked visible spectroscopy using multifiber arrays allow for time and space resolved measurements of the plasma boundary region. The addition of surface dopants such as magnesium and lithium provide a means of measuring localized electric and magnetic fields near the boundary based on Zeeman and Stark affected lineshapes[1]. Data is analyzed using detailed, time-dependent, collisional-radiative and radiation transport modeling.

[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," Phys. of Plasmas, 25, 113102 (2018).

Outline

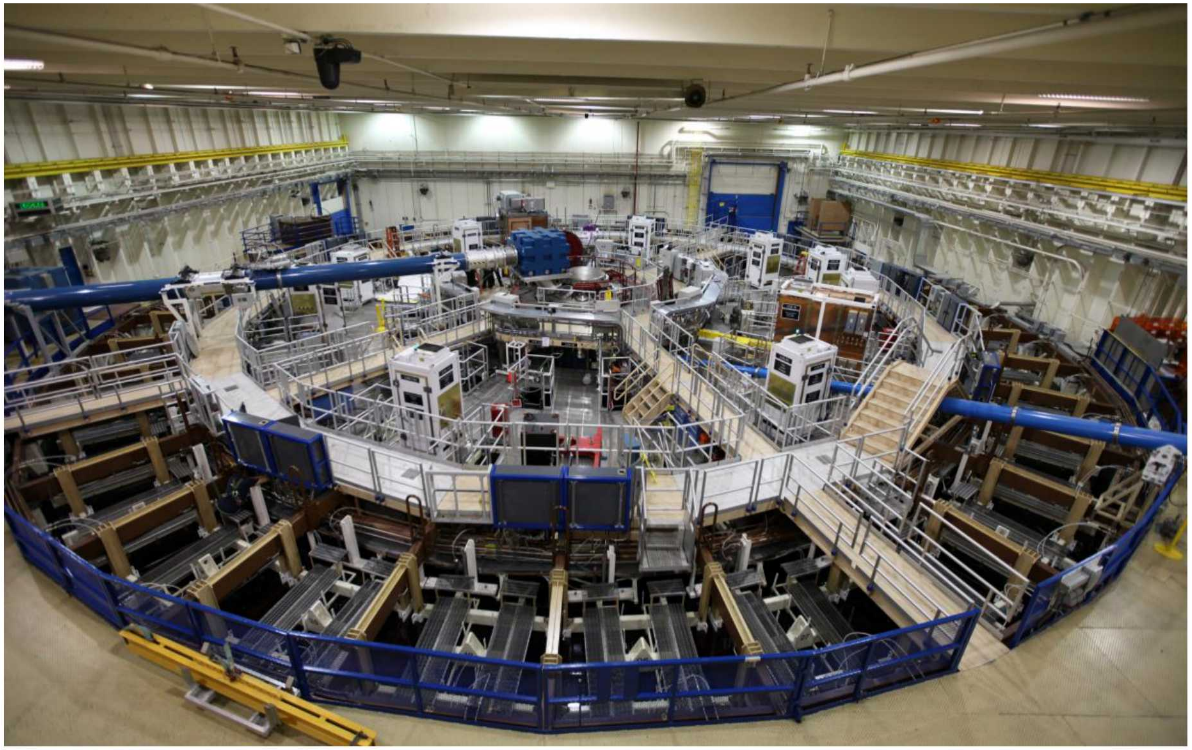
- Power Flow Studies on Z
- Current Loss Mechanisms and Simulations
- Experimental Hardware and Diagnostics
- Initial Experimental Results
- Zeeman Measurements with Hydrogen
- Method to Determine Localized Current Flow
- Zeeman and Stark Measurements with Lithium
- Other Experimental Platforms on Z
- Summary and Conclusions

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]. These measurements are now being extended to the Z Machine.
- Current losses on Z, which affect overall machine efficiency, are attributed to plasmas in the vacuum gap of the final feed section.
- Experimental data is required to benchmark particle in cell (PIC) codes which predict plasmas and fields in high power devices.
- This information is necessary to improve present pulsed power designs, and as a predictive capability for future, next generation facilities [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).

The Z Machine at Sandia National Laboratories



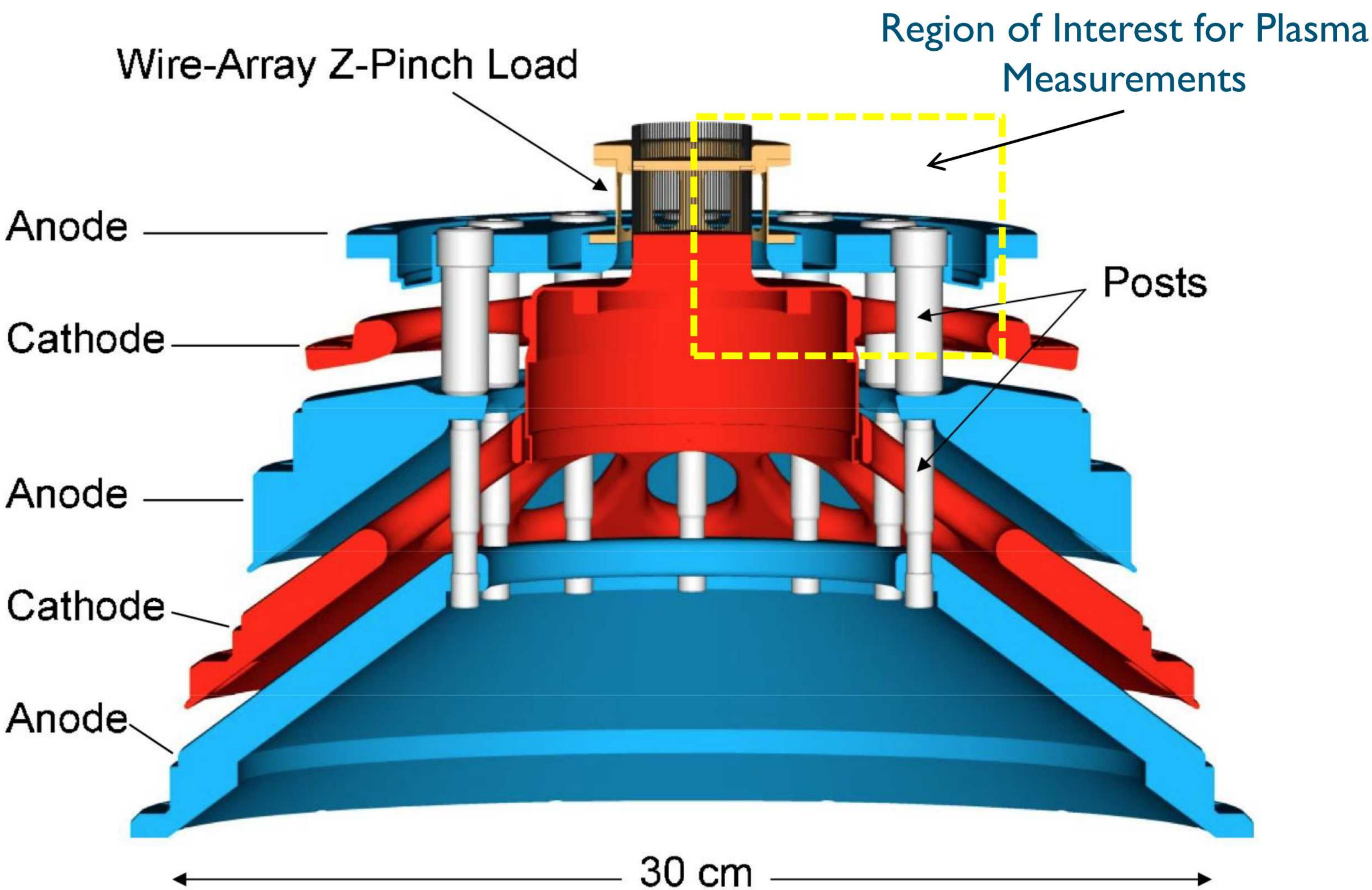
Z Facility

- 22 MJ stored energy
- 3MJ delivered to the load
- 26 MA peak current
- 1-100 Megabar
- 100-600 ns pulse length

Z Target

Z is used extensively for NNSA’s stockpile stewardship program to study dynamic material properties, radiation effects, and fusion.

Power Flow Regions on Z [4]

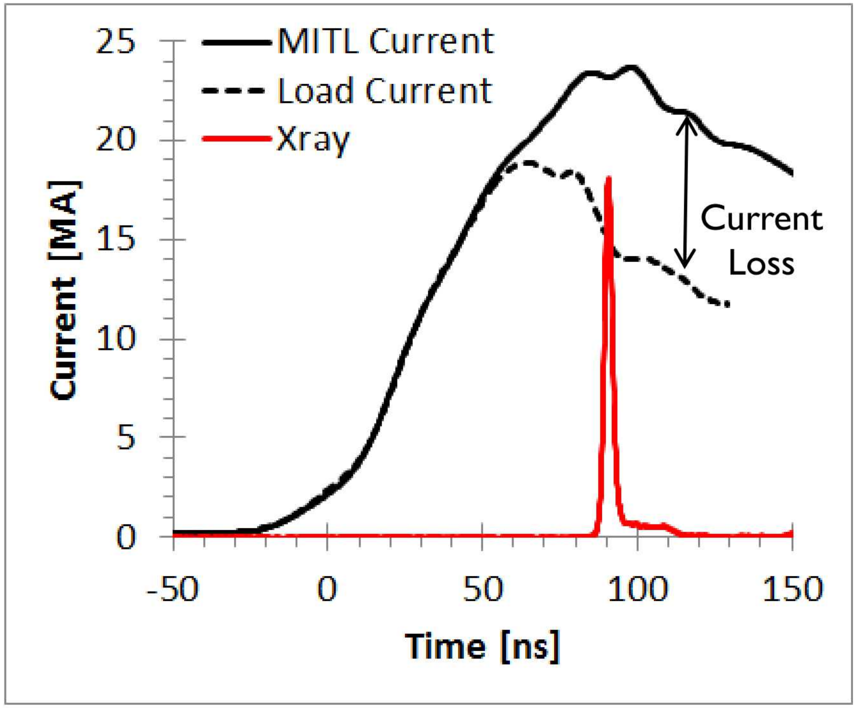


- B-dot measurements are made at 6 cm from the axis
- Vacuum gap decreases to 3 mm in the MagLIF hardware
- Plasma velocity > 10 cm/μs measured in the convolute [5]

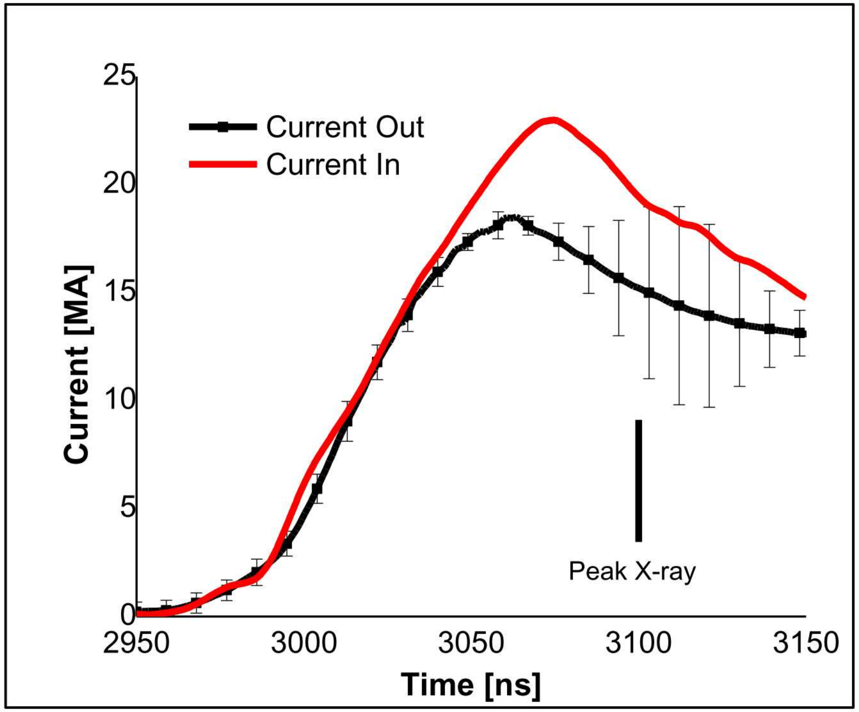
[4] D.H. McDaniel, *et al.*, *Proc. 5th International Conf. on Dense Z Pinches*, AIP, Melville, NY p. 23 (2002).
[5] M.R. Gomez, *et al.*, *Phys. Rev. Accel. and Beams*, 20, 010401 (2017).

Current Losses on Z Reduce Power Delivery to the Loads

Stainless Steel Wire Array



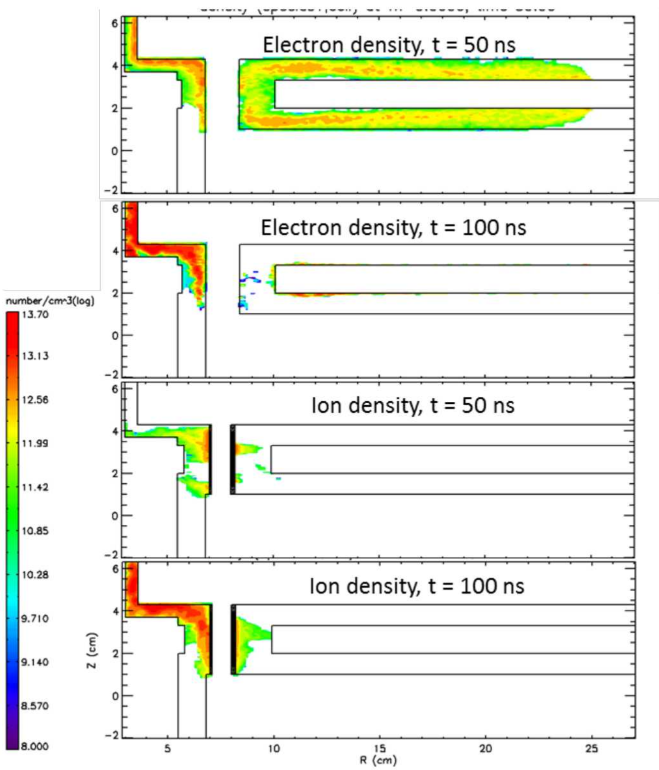
Gas Puff Load

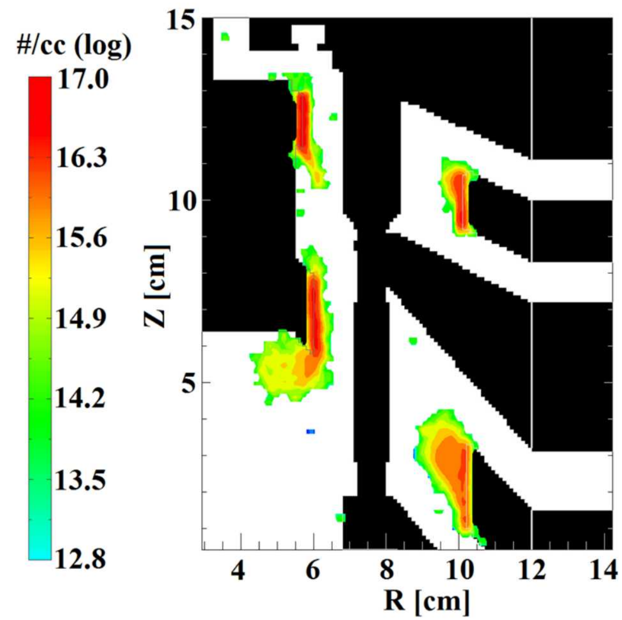


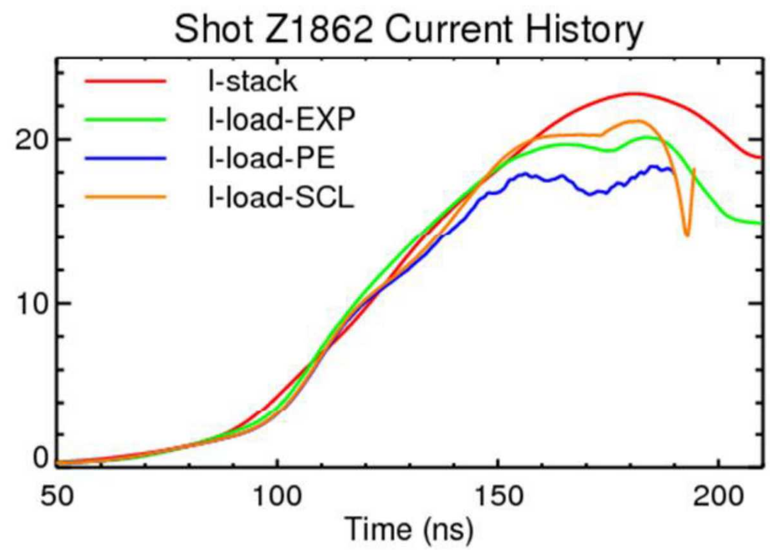
- Up to 5MA current loss is sustained for up to 50ns on some loads.
- Surface contaminants, outgassing of electrode materials, and non-ideal geometries affect current delivery to the load.

- 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 losses.

Current losses on the Z machine are attributed to plasma formation in the convolute and final current feed [6,7]



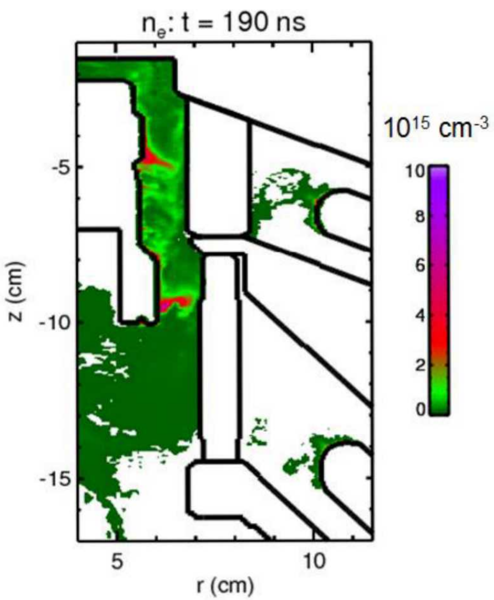




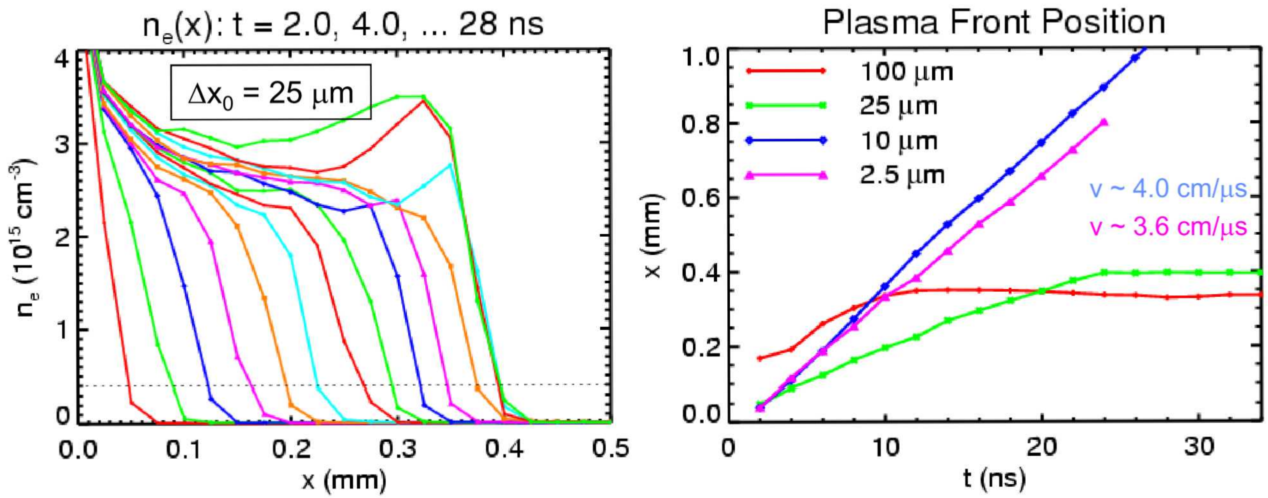
- Plasma models reproduce measured currents, but experimental measurements are needed to verify the physics are correct.

[6] D.V. Rose, *et al.*, *Physical Rev. Special Topics-Accel. and Beams*, 18, 030402 (2015).
[7] D.R. Welch, *et al.*, *Physical Rev. Accel. and Beams*, 22, 070401 (2019).

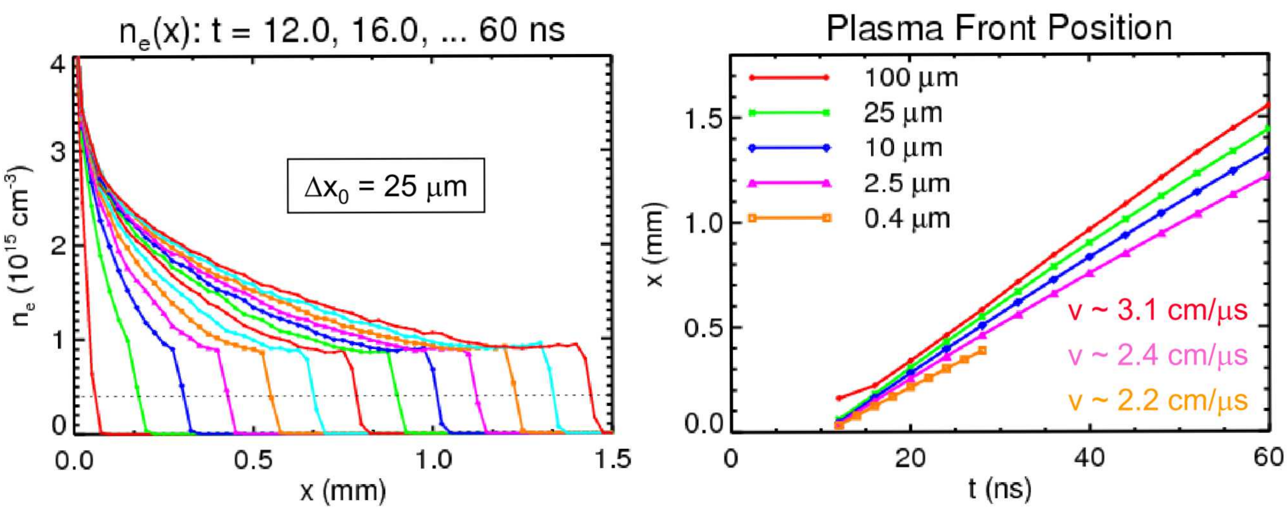
Particle in Cell Modeling of Cathode and Anode Plasma in Quicksilver [8,9]



Cathode Plasma



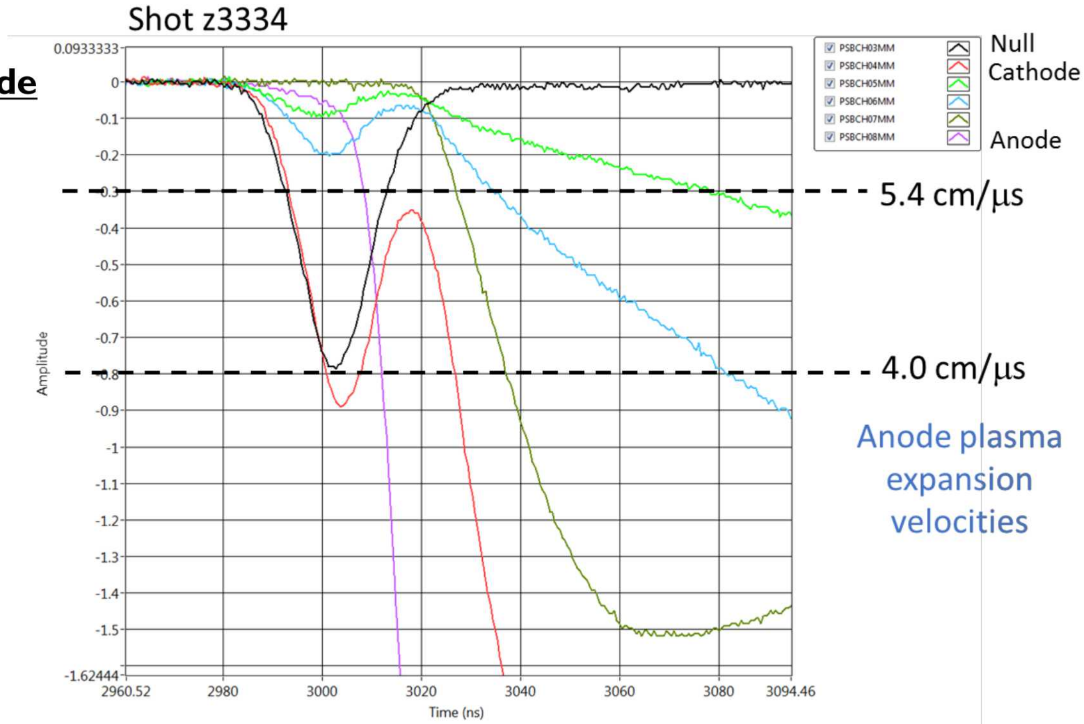
Anode Plasma



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

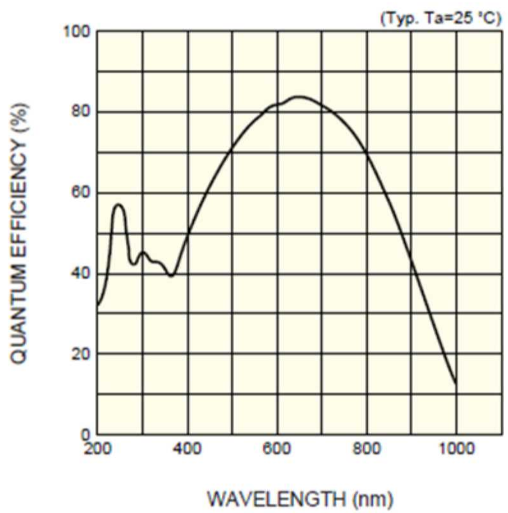
[8] J.P. Quintenz, *et al.*, Laser Part. Beams 12, p. 283 (1994).
[9] T.D. Pointon, *52nd Annual Meeting of the APS Division of Plasma Physics*, Nov. 8-12, 2010.

Plasma Expansion from Silicon Avalanche Photodiodes (APDs)



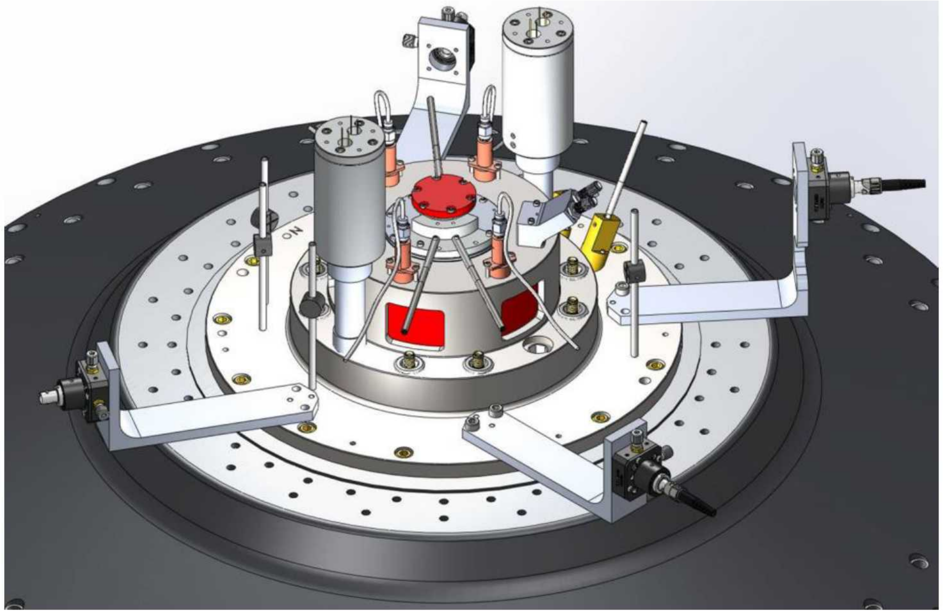
NSTec Model H-EO-53 Avalanche Photodiode

- Hamamatsu Model S5343 Silicon Photodiode
- Bandwidth: 180MHz
- Optical Input Power: 1-100 µW
- Output Impedance: 50 Ohms
- Responsivity: 0.33-20 kV/W
- Linearity: +/- 5%
- Error: +/- 10% (between 8-100µW)
- Scaling Ratio: 1mV/µW
- Wavelength Range: 200-1000nm
- Gain (M): 1-50x
- Quantum Efficiency: 80% @ 620nm
- Photosensitivity: 0.42 A/W @620nm (M=1)
- H-PS-17 Power Supply (120V rms, 1.5A peak)

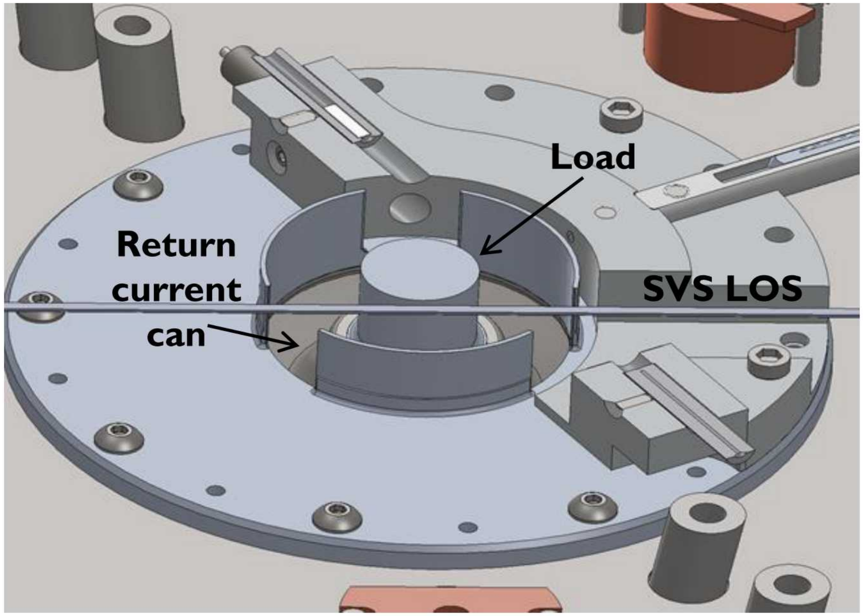


Avalanche Photodiodes can be used to determine plasma expansion velocities.

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



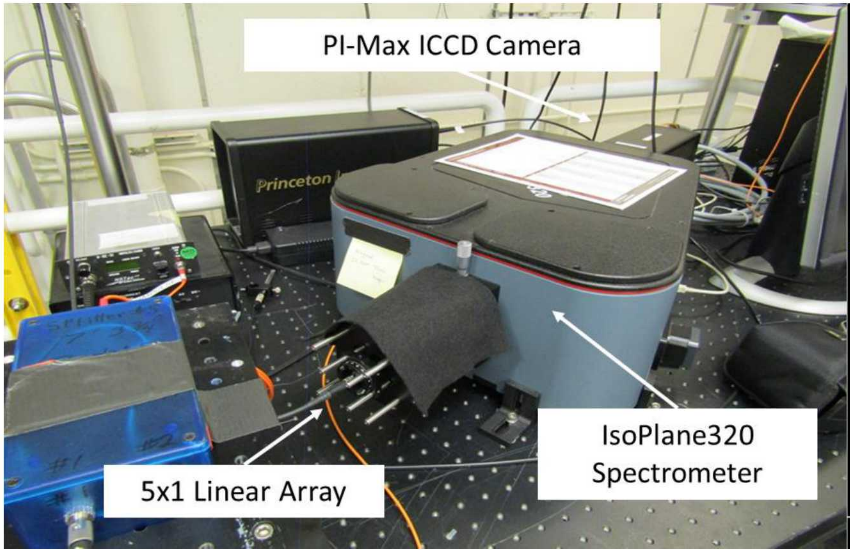
Power Flow Hardware

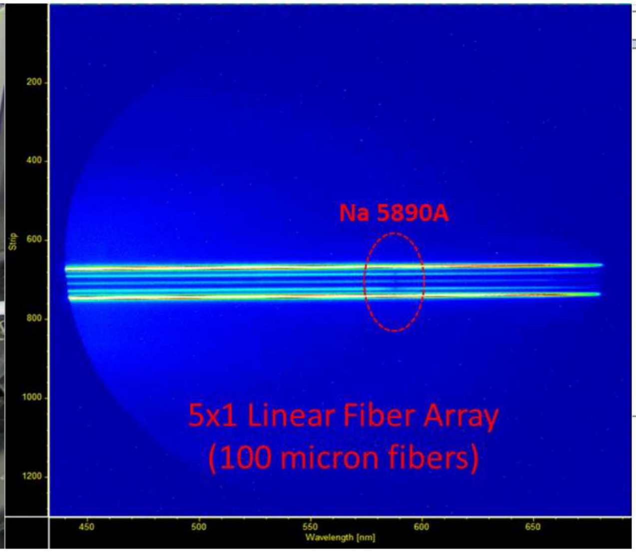


Non-Imploding Load

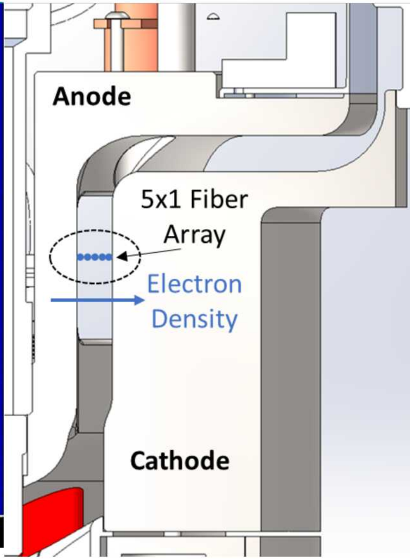
- Experiments are designed to look for plasmas off the surface of a non-imploding load.
- Coatings are applied to power flow surfaces to measure specific neutral and ion lines.
- Experiments are designed to look in the final feed gap without a backlighting wall or other obstructions.

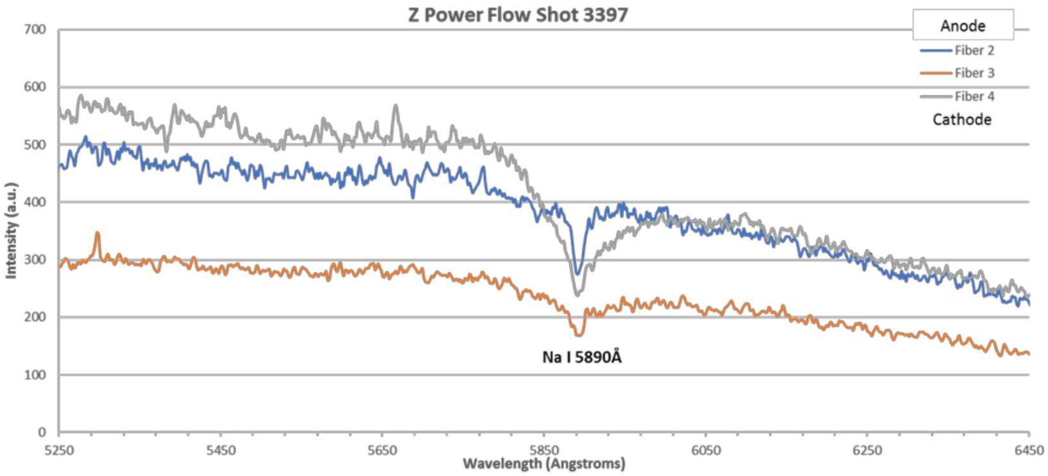
Time and Space Resolved Spectroscopy on Z





Final Feed Section on Z

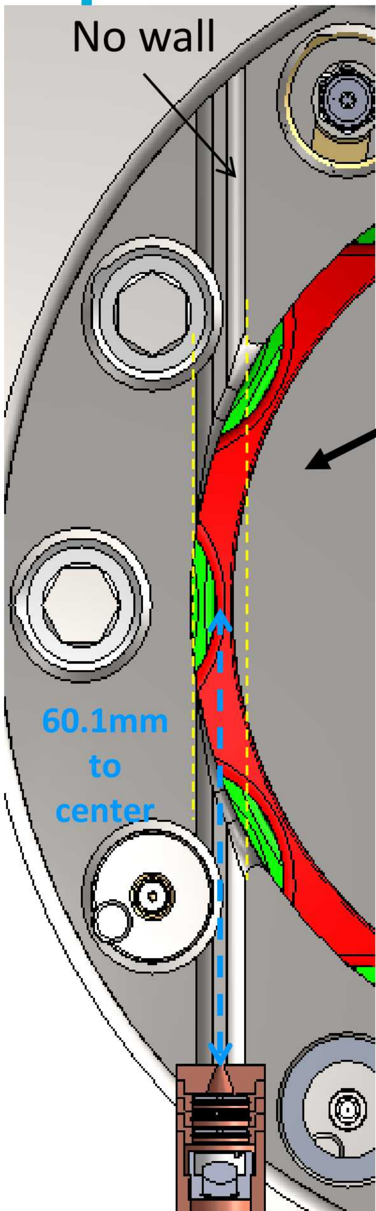


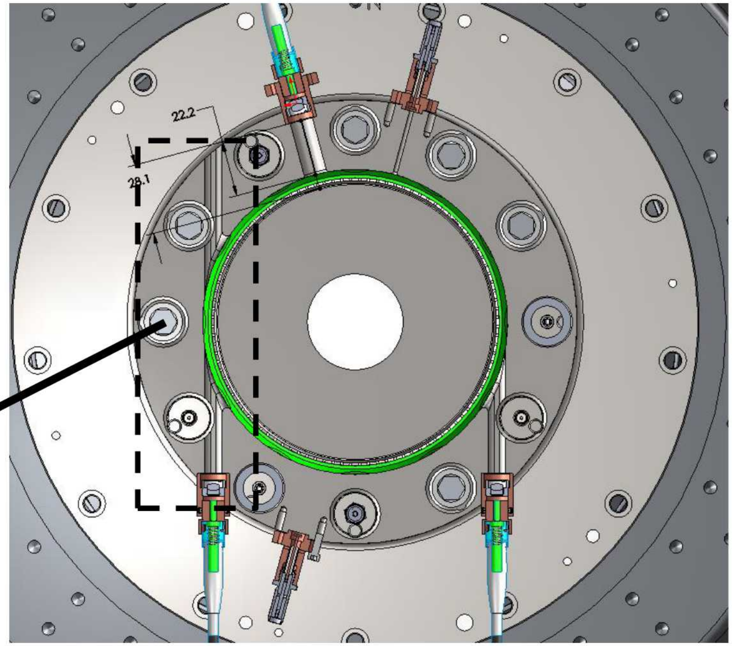


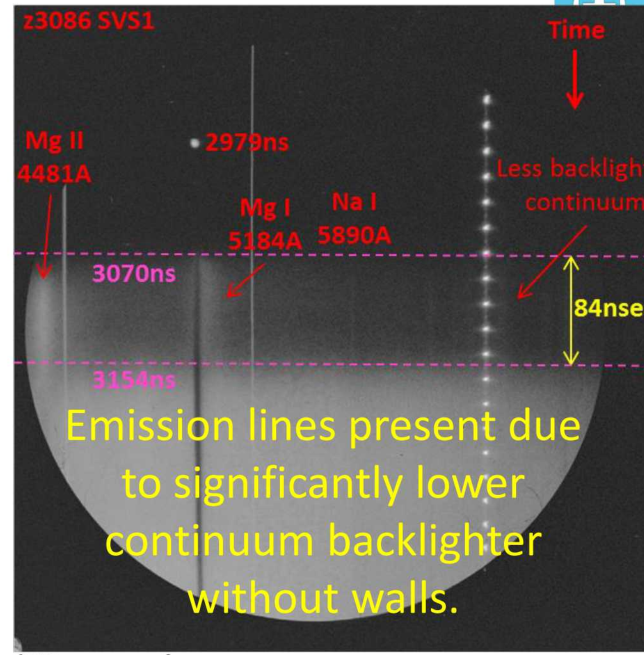
Spatially-resolved Spectra

- Continua plus Line Emission and Absorption
- Schmidt-Czerny-Turner (SCT) Spectrometer, F/4.6 optics
- Wavelengths from <u>350nm-750nm</u>
- Spectral Resolution down to <u>0.5 Angstroms</u>
- Time gates as short as <u>7.0 nanoseconds</u>

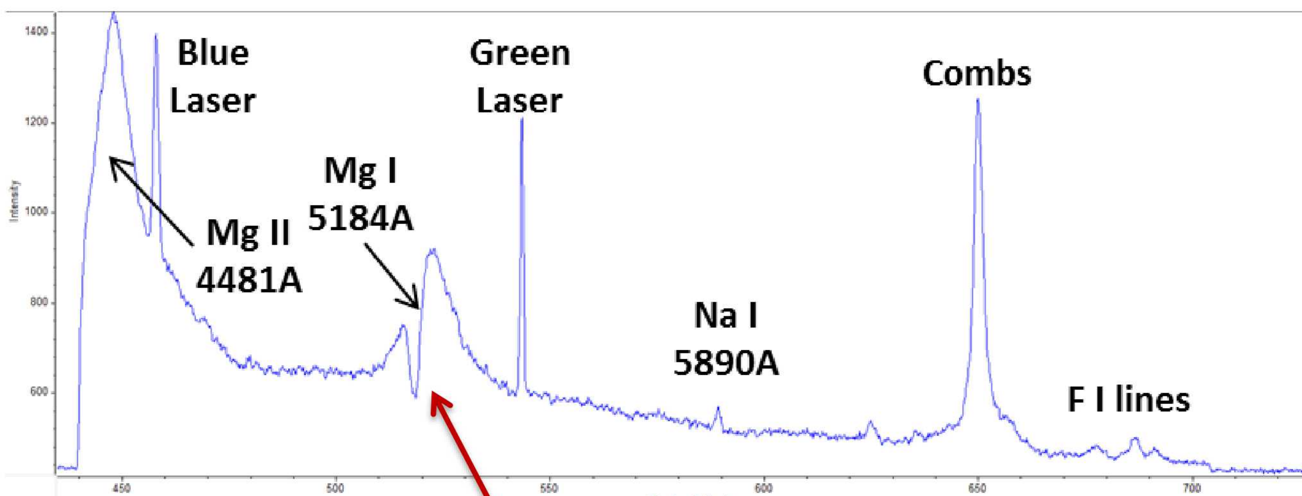
Chordal Line of Sight on Power Flow Shots in the Final Feed







*20nsec combs



Emission and self-absorption of Magnesium neutral line.

Observation of Metastable Level in Mg I

3s3p ^3P - *metastable* level

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

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

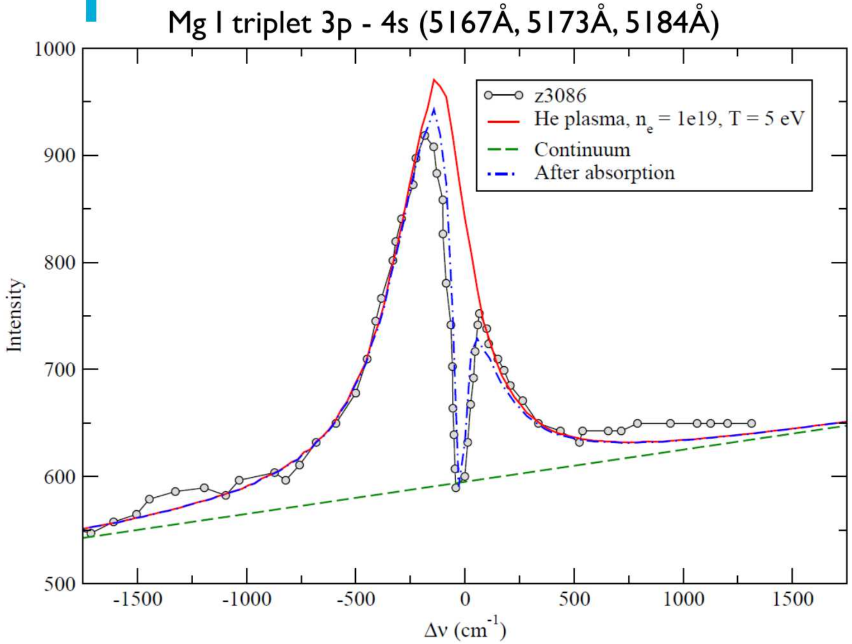
3s4s ^3S → 3s3p ^3P; λ = 5,183 Å (NIST)

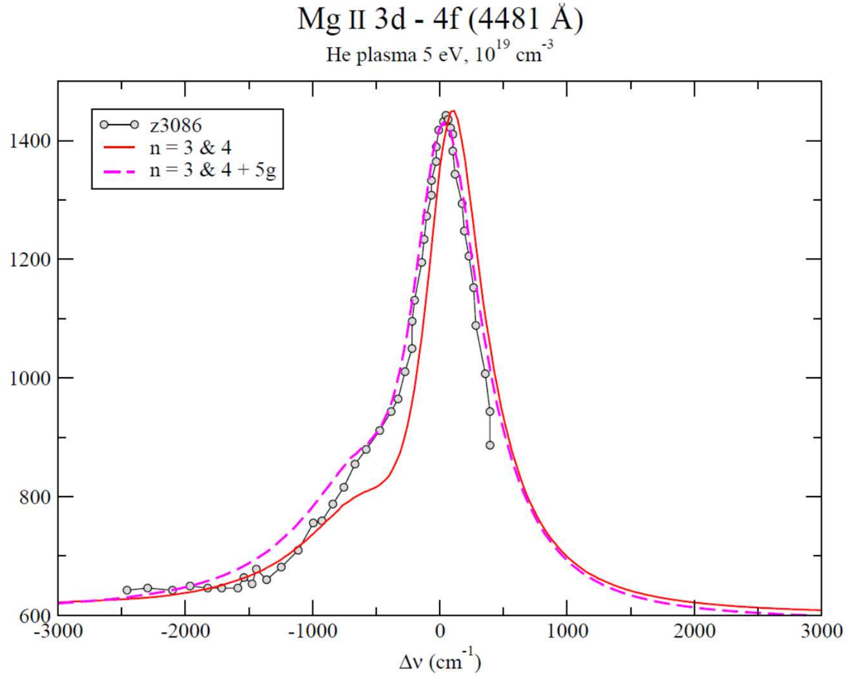
T_e (eV)	Level	N_e (cm^{-3})	POP*	$A_{i \to j}$***
1	3s4s ^1S	10^{19}	$1.62 \cdot 10^{-3}$	
	3s4s ^1S → 3s3p ^1P			$2.85 \cdot 10^{+7}$
	3s3p ^1P → 2p6 3s2 ^1S		$1.39 \cdot 10^{-2}$	$5.05 \cdot 10^{+8}$
1	3s4s ^3S	10^{19}	$6.47 \cdot 10^{-3}$	
	3s4s ^3S → 3s3p ^3P			$1.23 \cdot 10^{+8}$
	3s3p ^3P → 2p6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

(steady state, without opacity)

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

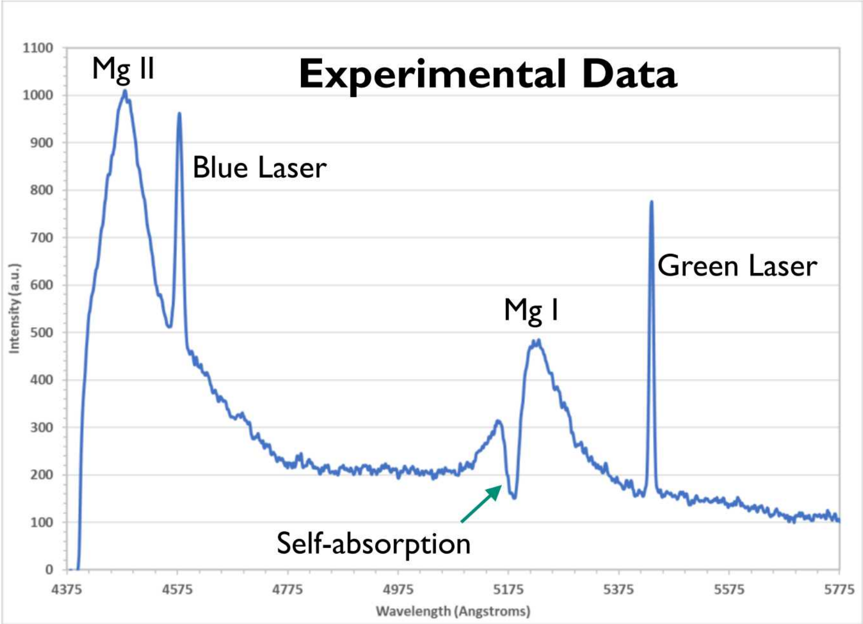
Magnesium Results



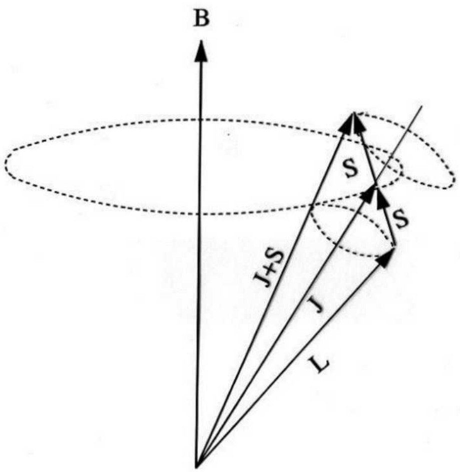


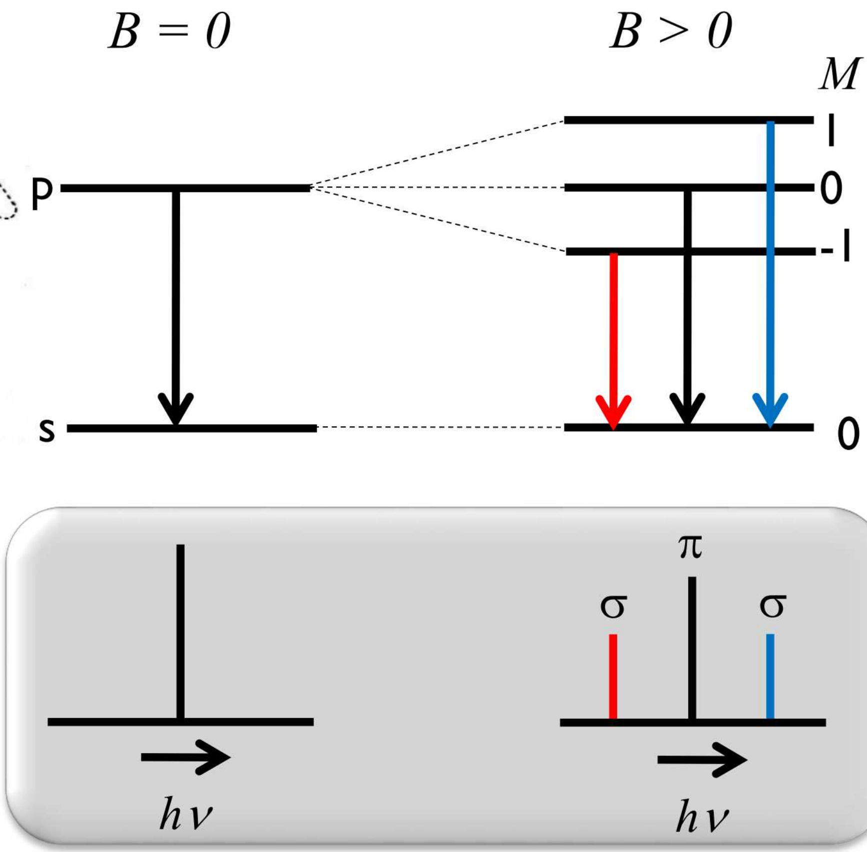
Collisional-Radiative Equilibrium (CRE) Calculations

- 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



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





$$\Delta W = g\mu_0 BM$$

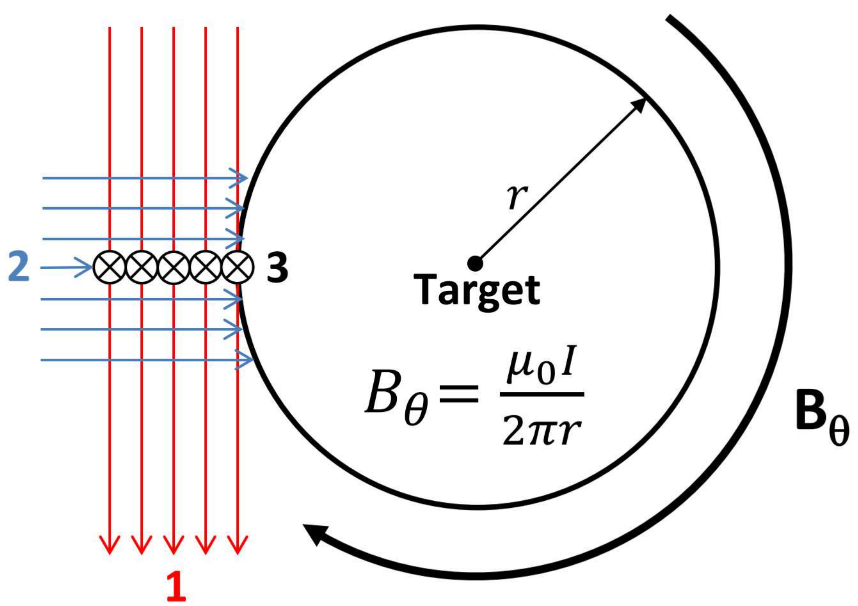
Separation of energy states due to the effect of an applied B-field on the magnetic moment of an atom or ion.

Observed

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

Zeeman Splitting Orientation on Z

Three Potential Views



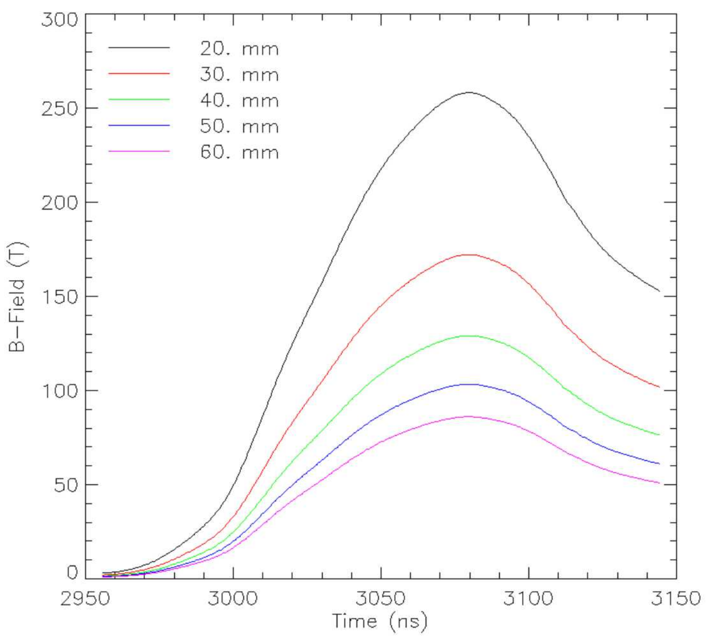
Considerations:

- 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:

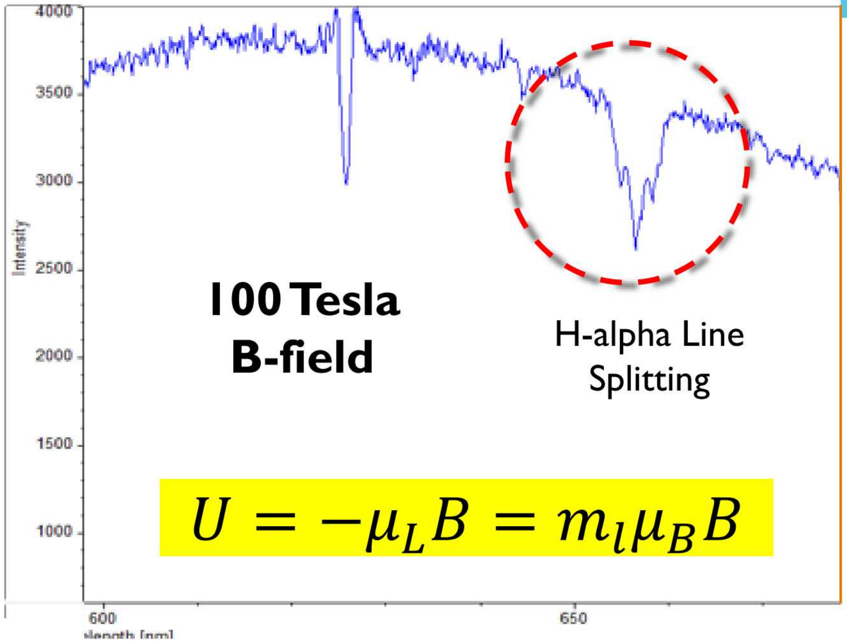
- Slotted anode
- Multifiber array
- Detectors (Streaked spectra, gated spectra, photodiodes)
- Dopants (Na, Li, Al, C, Mg, others)
- Compare with VISAR measurements
- Compare with B-dot monitors at r=6cm

B-field versus Radius

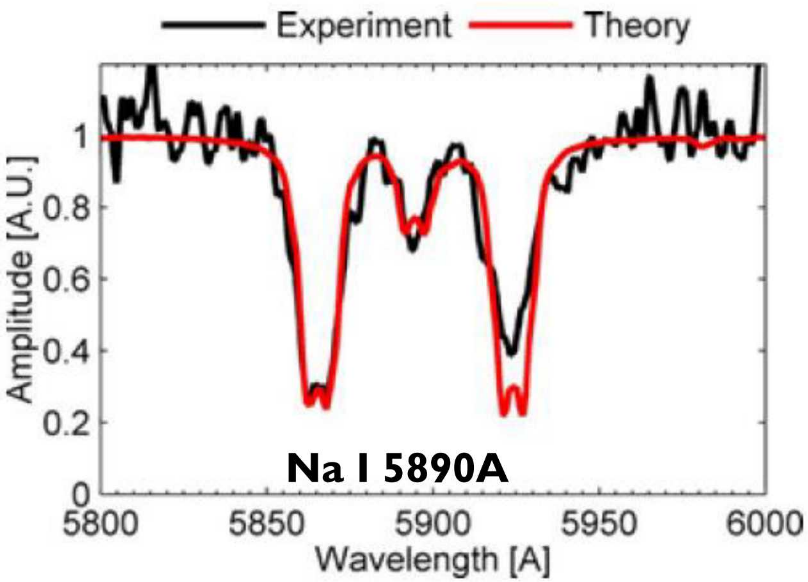


Zeeman Splitting Measurements on Z

- Time and space resolved Zeeman B-field measurements were taken on the SMP diode on RITS-6.
- 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 [10].



$$U = -\mu_L B = m_l \mu_B B$$



$$E = -13.6eV\left(\frac{1}{3^2} - \frac{1}{2^2}\right) = 1.89\text{eV}$$

$$\lambda = \frac{hc}{E} = \frac{1240eV \cdot nm}{1.89eV} = 656.1\text{nm}$$

$$\Delta E = \mu_B B = (9.27 \times 10^{-24})(100T) = 9.27 \times 10^{-22} J$$

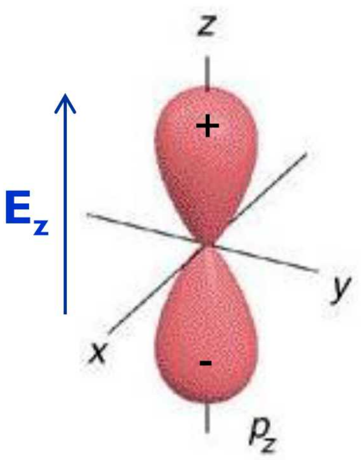
$$9.27 \times 10^{-22}\ \text{J} = 5.8 \times 10^{-3}\ eV$$

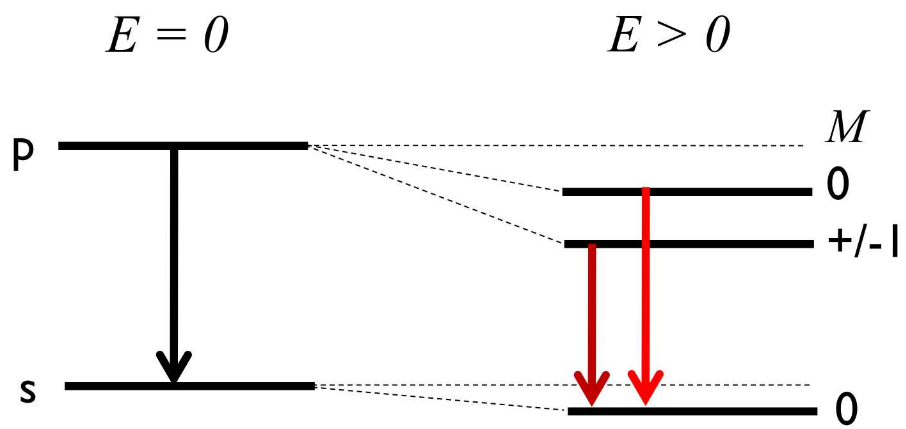
$$\Delta\lambda = \frac{\lambda^2}{hc}\Delta E = \frac{(656.1nm)^2}{1240\ eV \cdot nm} * (5.8 \times 10^{-3} eV)$$

$$\underline{\Delta\lambda = 2.0nm}$$

[10] 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



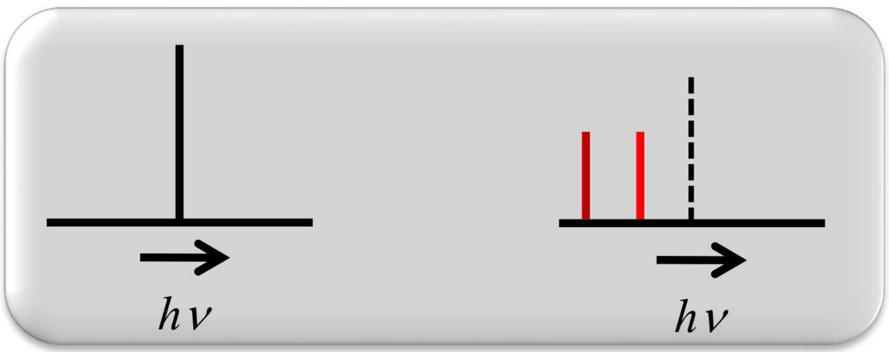


$$\Delta W = -\frac{1}{2}\alpha|E|^2$$

$$\alpha \propto M^2$$

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

Observed



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

Method for Determining Current Flow in Pulsed-Power Systems

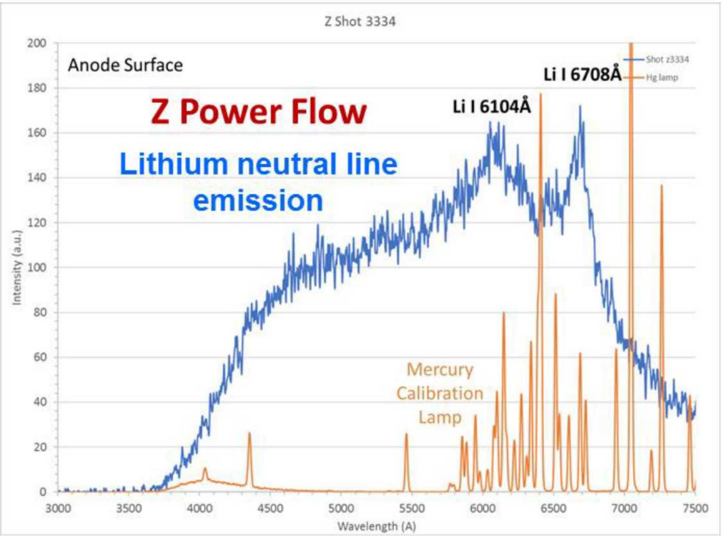
Current distribution is important in the design of new pulsed-power machines and in the understanding of existing machines like Z.

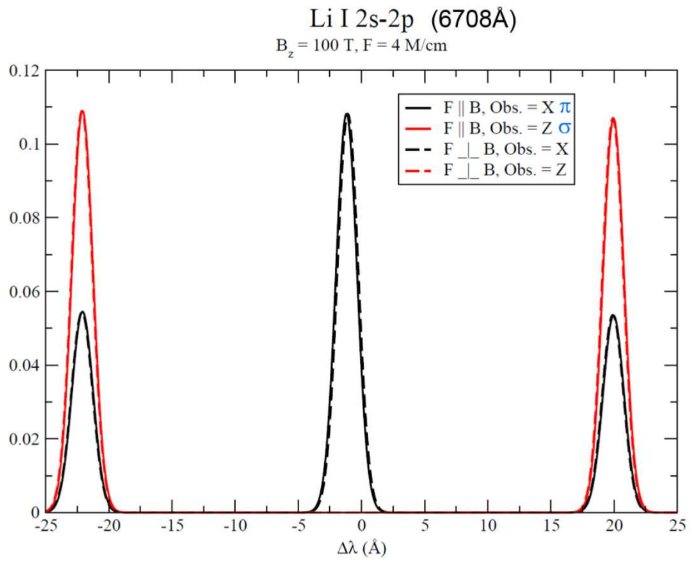
- The only way to obtain line emission from the A-K gap of a power-flow transmission line is to use neutrals, which requires:
  - Sufficient number of neutrals in the gap.
  - Using neutrals that are not field-ionized in the gap, or more precisely, the atomic level of interest (that which provides the 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 Stark shifted</u>.
- To prove the neutral atoms emitting the line(s) are in the vacuum gap (rather than in the surface electrode plasma) one also needs an emission line from the same atom that <u>is Stark shifted</u>.
- We prove, both experimentally and theoretically, that Li neutrals (6708Å and 6104Å) fulfill these requirements, namely:
  - The 2p-2s transition is <u>not Stark shifted</u> and demonstrates the Zeeman effect.
  - The 3d-2p transition <u>is Stark shifted</u> 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.

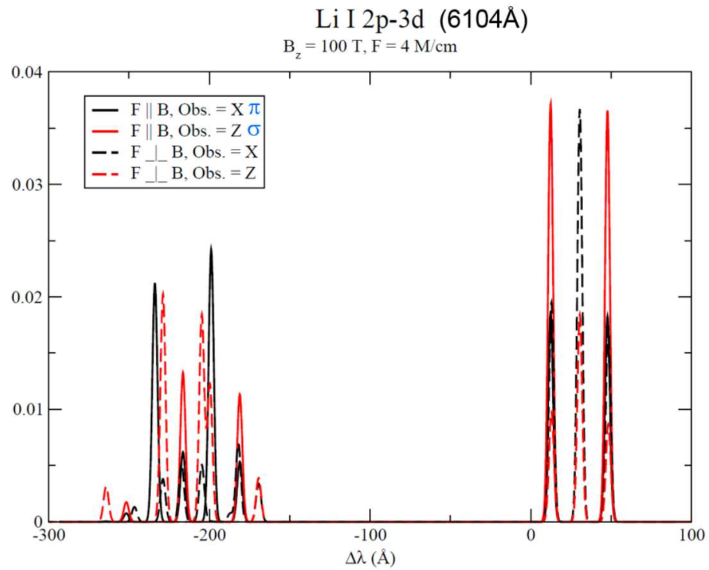
In Summary, we demonstrated a promising new method to reliably determine the current distribution in the final feed section on Z.

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 [11].

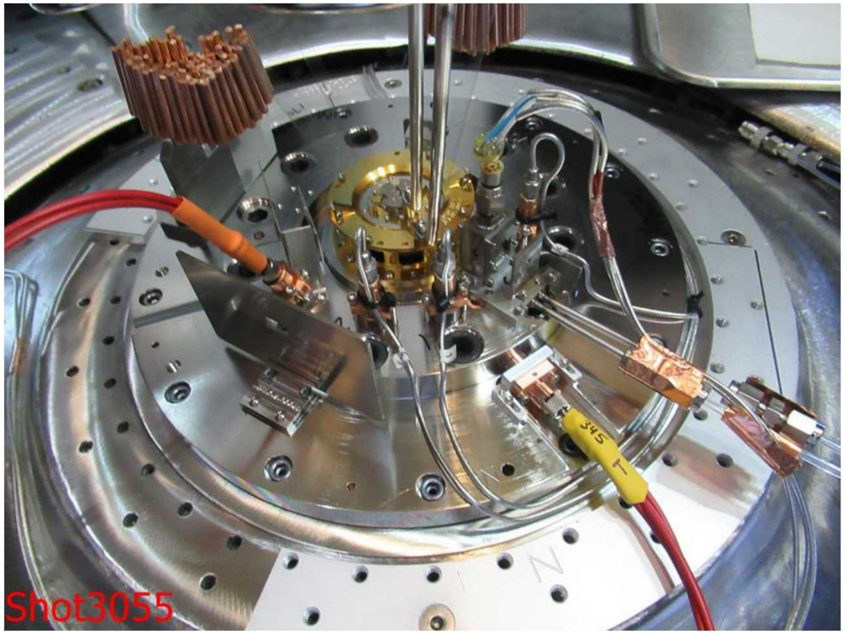




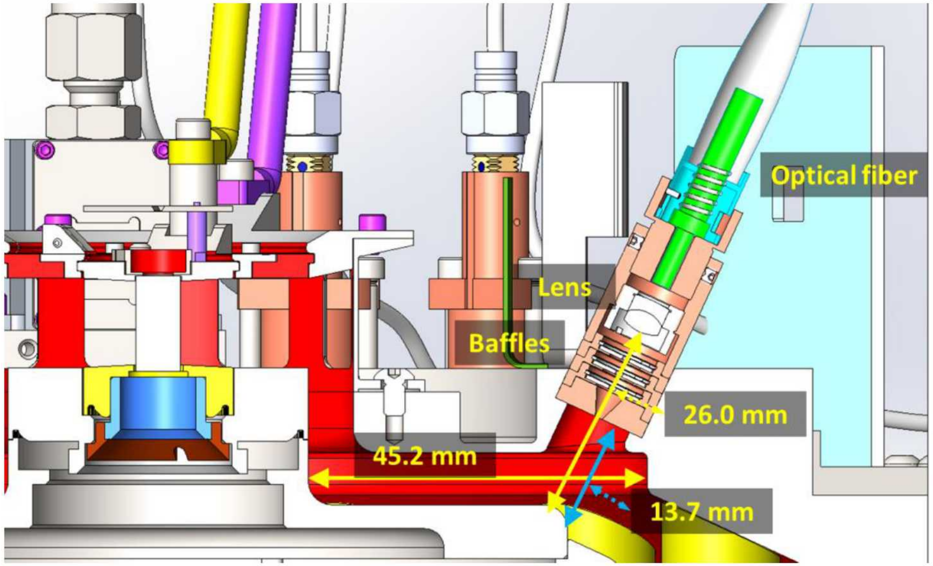


[11] S. Biswas, M.D. Johnston, *et al*., "Shielding of the Azimuthal Magnetic Field by the Anode Plasma in a Relativistic Self-Magnetic-Pinch Diode," *Physics of Plasmas, 25, 113102 (2018).*

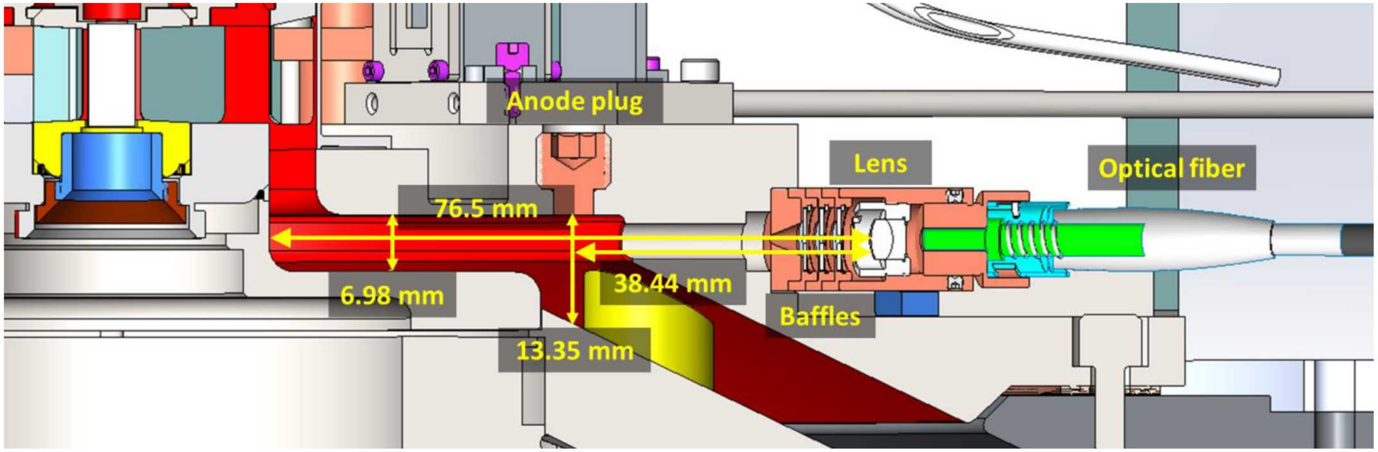
Ride-along Experiments are Fielded on Multiple Z Platforms



Wire Array Experiment

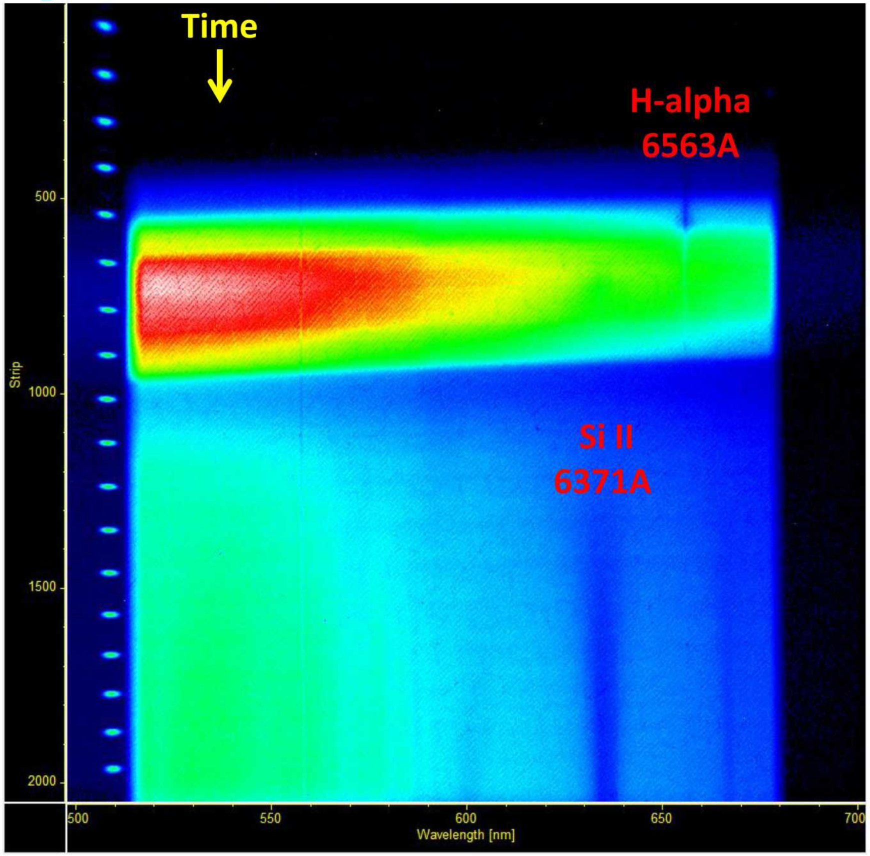


Angled LOS



Horizontal LOS

Spectra from Nested Wire Array Experiments



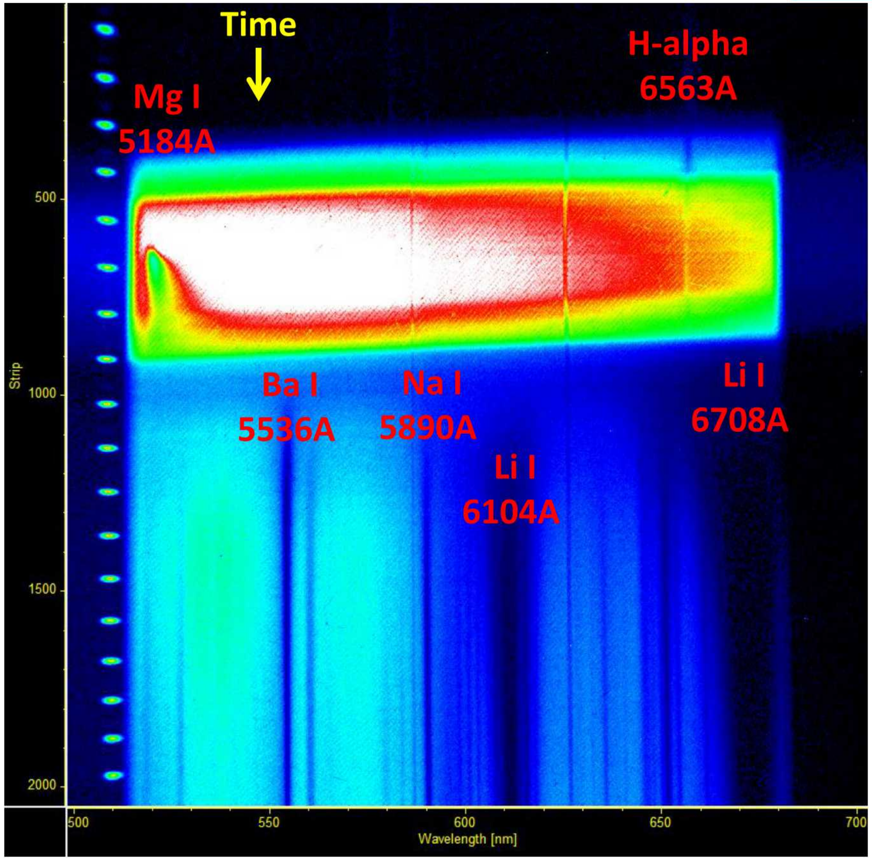
Fused Silica Window-no dopants

Grating: 150g/mm

Center Wavelength: 595nm

Sweep: 500ns

Combs: 35MHz (28ns)



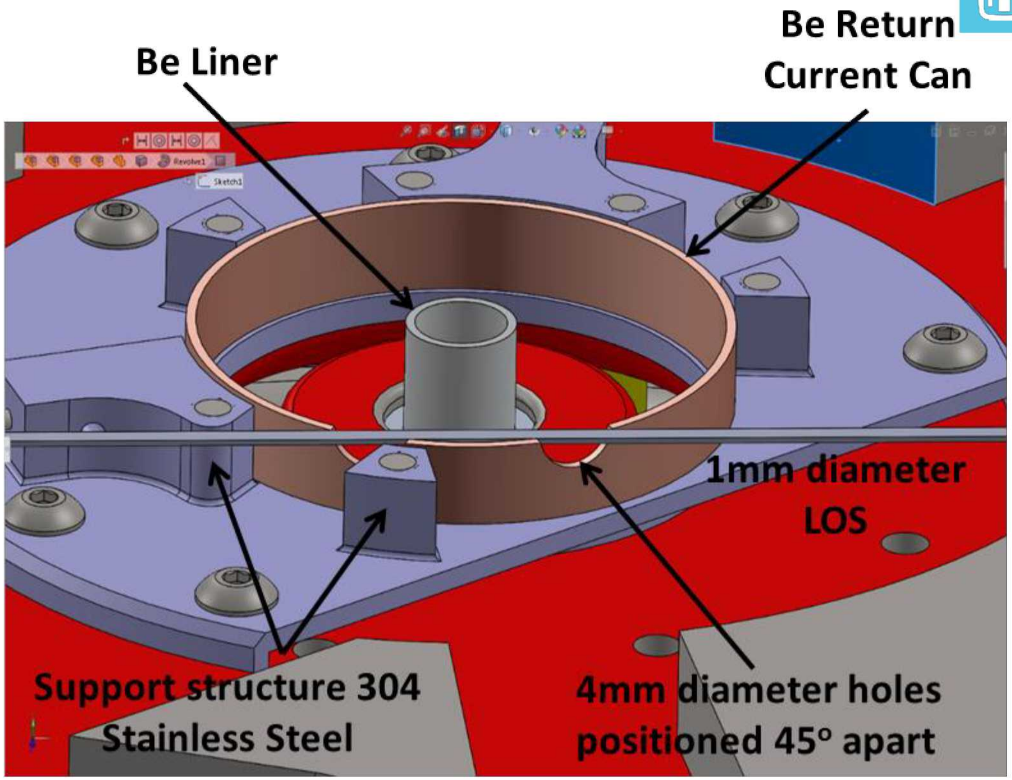
MgF_2 coated optics

Lithium and Sodium Dopants

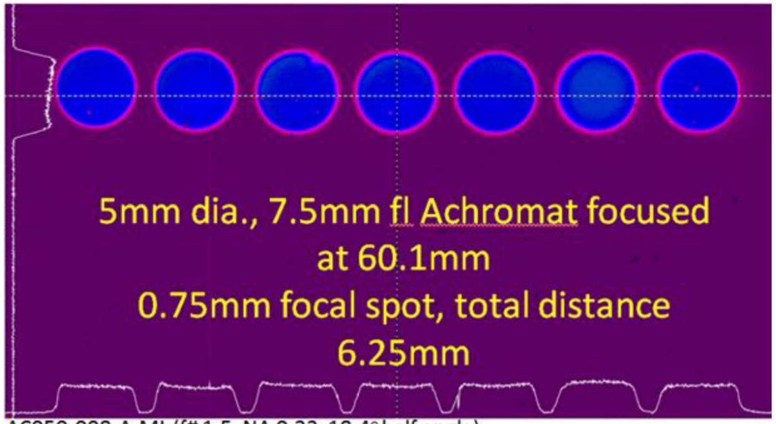
- Dopants observed from both the anode and cathode, as well as from the optics.
- Highly broadened lithium neutral lines along the anode.

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.



Be Return Current Can



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

Summary and Conclusions

- Spectroscopic measurements of plasmas in the power flow regions on Z are being conducted.
- B-fields have been measured using the Zeeman effect.
- Measurements of the magnetic field provide information regarding local current distributions, including current loss mechanisms.
- Techniques are being developed at the Weizmann Institute to further 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, CHICAGO, 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.


Thank You!