SAND2015-10428C

Magnetic Field Measurements Using Zeeman Splitting on the SMP Diode At Sandia National Laboratories

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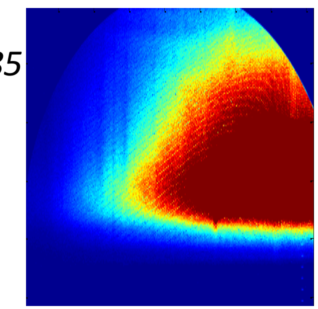

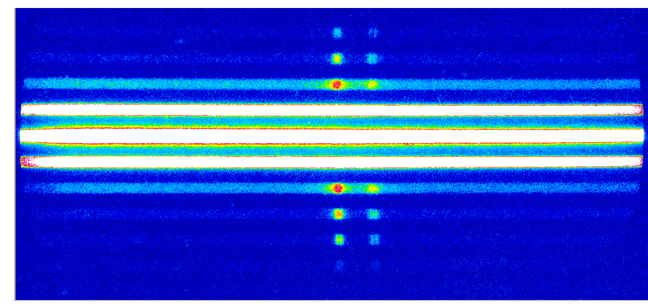

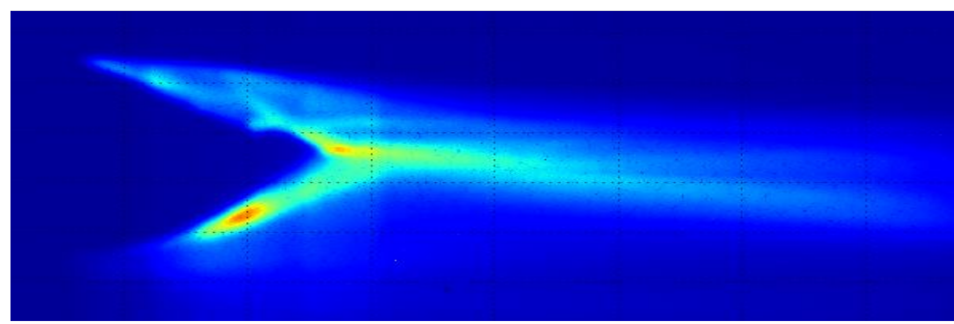

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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SAND No. 2011–XXXXP.

Motivation

- Determine the current distribution in the Self Magnetic Pinch (SMP) Diode using Zeeman splitting to measure local magnetic fields.

- Compare experimental data with LSP[1] simulations

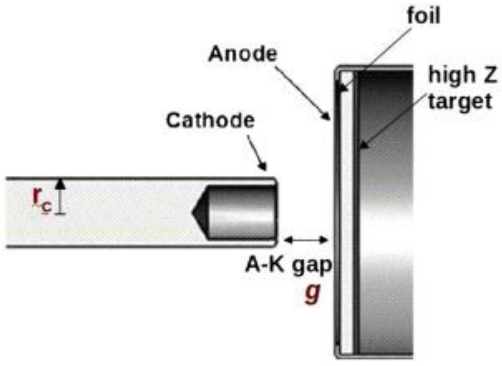
- Improve diode designs

- Provide a proof of principle measurement on RITS for future Z convolute B-field measurements

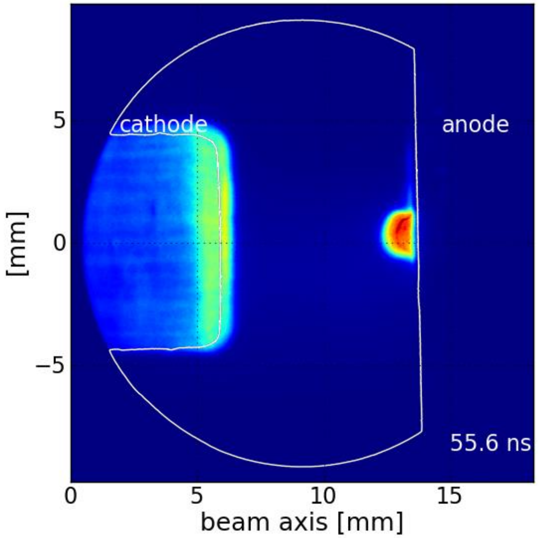
1. LSP Suite: Particle-in-Cell (PIC) code, http://www.mrcwdc.com/LSP/index.html

RITS-6 Accelerator

- RITS uses a 6 stage induction voltage adder to deliver power to the load
- The SMP diode produces an electron beam for x-ray radiography.
- The beam pinches from its self B-field as it crosses the A-K gap
- Plasmas form on the electrode surfaces and expand into the AK gap, decreasing the diode impedance over time[2]
- Diode Parameters
  - ~8.0 MV
  - 130-160 kA
  - Few mm spot size
  - 40-50ns Radiation Pulse with Foil
  - 30-40ns Radiation pulse with bare converter



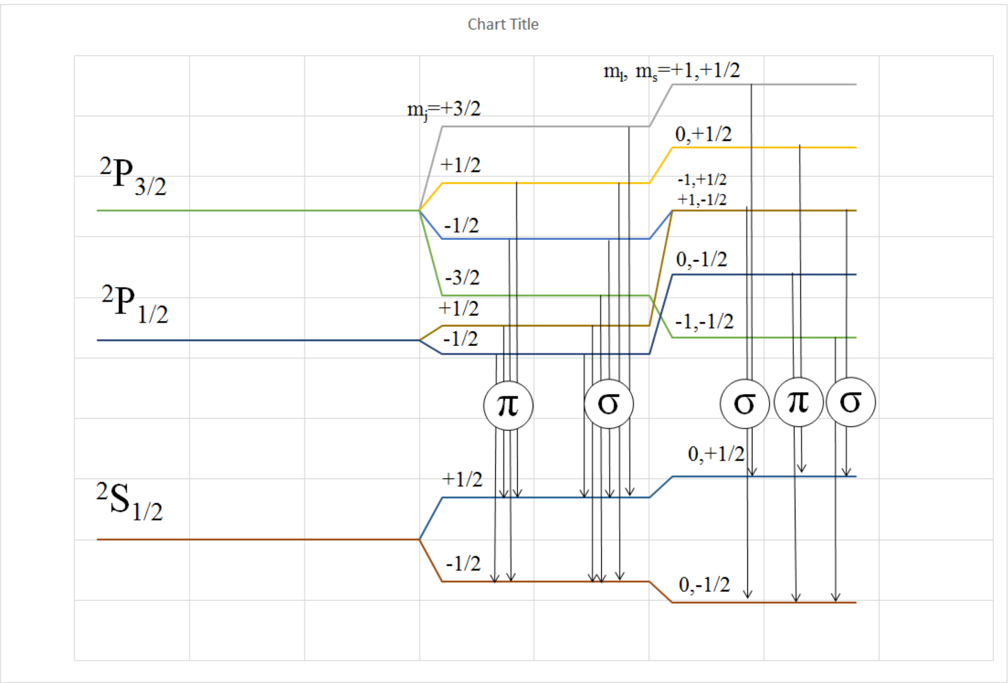
Diode Configuration[1]



1. N. Bruner et al. 2011
2. N. Bennet et al. 2014

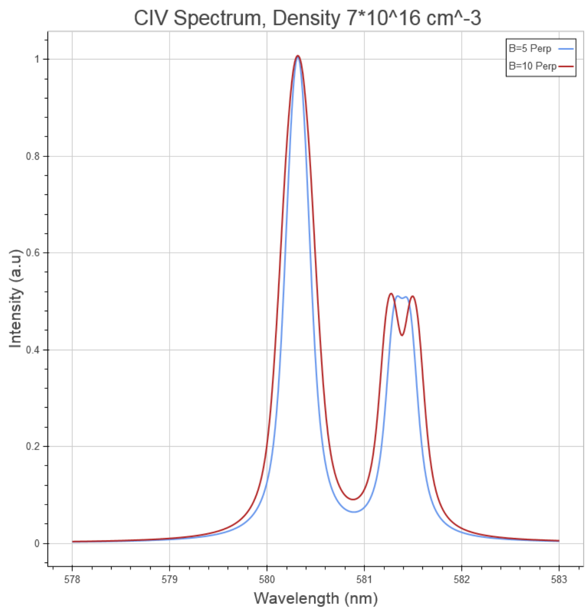
Zeeman Splitting

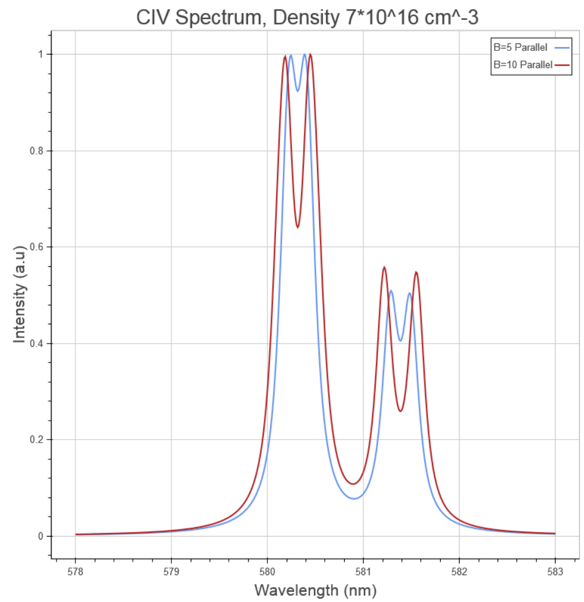
Energy Diagram



- Weak field:
  - $\Delta E = g m_j \mu_B B$
- Strong Field:
  - $\Delta E = (m_l + 2m_s)\mu_B B$
- For small B-fields it is advantageous to look parallel to the field lines, as pi components are not visible.
- Zeeman splitting can be used to infer local B-fields at the plasma location.
- B-dots are limited to measuring fields outside the plasma region and Faraday rotation requires a specific B-field direction and an external polarized light source.

Zeeman Effect Simulated Spectra



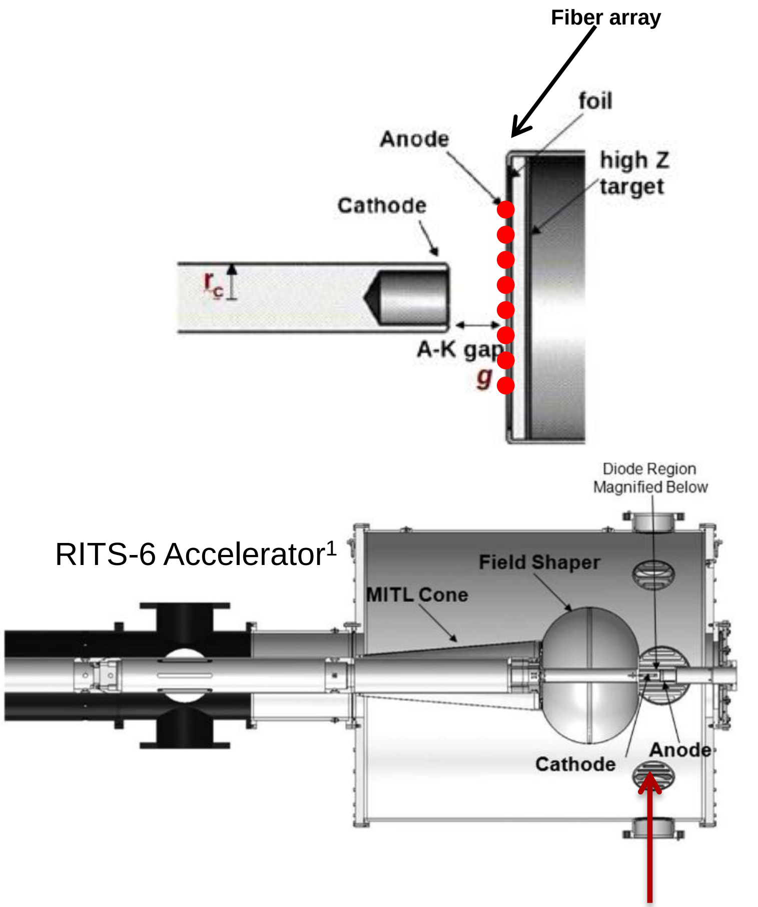


- Perpendicular and parallel lines of sight plotted using a resolution of 0.06 nm for the CIV doublet.
- The ^2S-^2P doublet is particularly useful for this effect because the $P_{1/2}$-$S_{1/2}$ transition is always slightly more broadened than the $P_{3/2}$->$S_{1/2}$ transition[4,5,6].

4. E. Stambulchik et al. 2007
5. S. Tessarin et al. 2011
6. Cowan, 1981

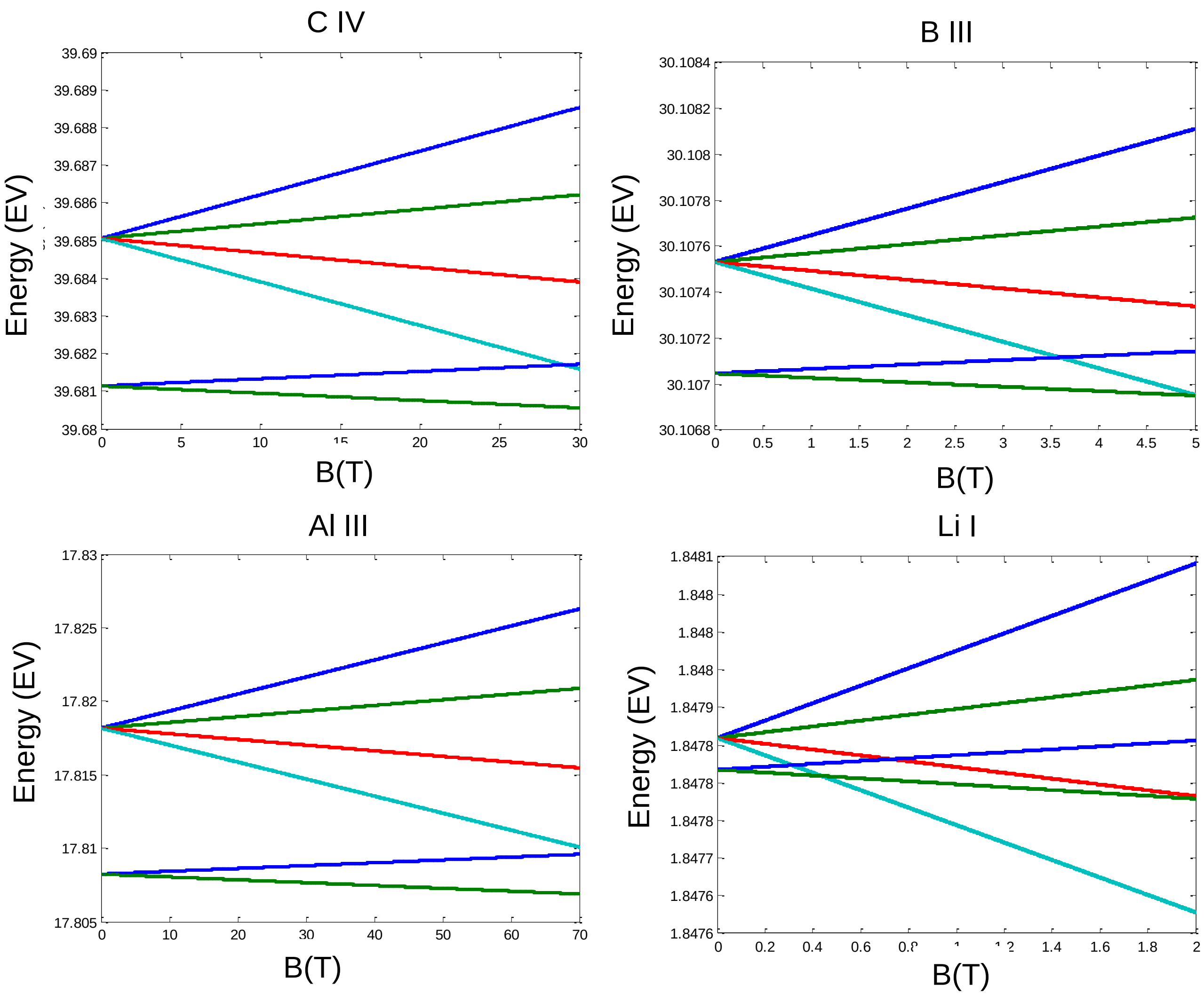
Experimental Setup

- Fibers are focused to a 1mm spot across the surface of the foil or converter where the B-fields are the largest.
- A 0.35m lens coupled spectrometer is used with a 2400 g/mm grating. (~0.6 A resolution)
- Spectra are collected toward the end of the radiation pulse, just before impedance collapse to maximize light.



Lens coupled fiber array
Focused at the anode

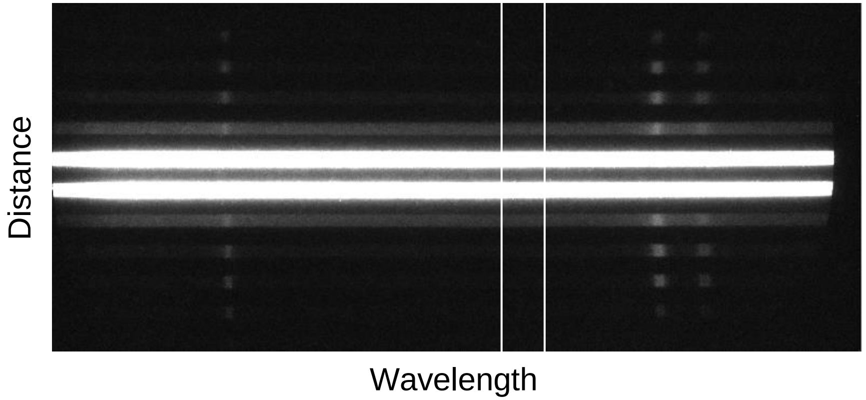
Potential Emission Lines

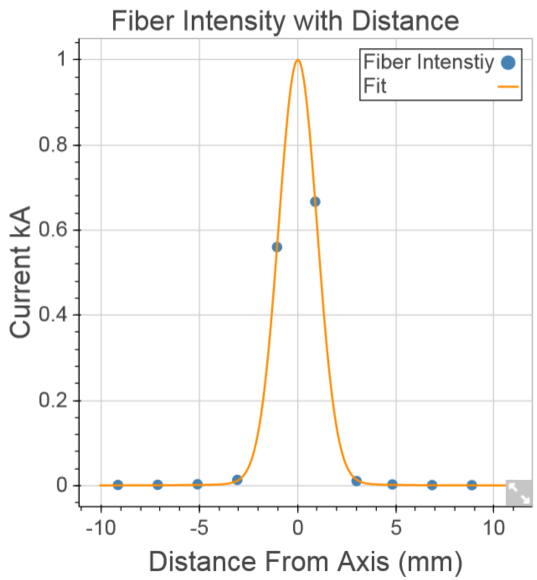


- Lines that transition to the Paschen-Back regime at low fields may be useful.
- Potential dopants include B III, Si IV, Li I, Na I
- C is a contaminant possibly from the oil used on the knob to prevent emission
- Dopants would help isolate the fiber position.

Distance from Axis

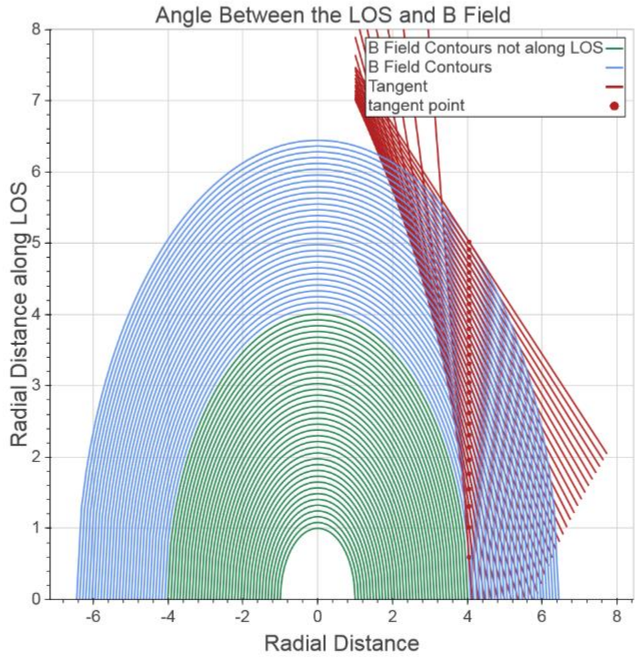
- It is difficult to align the fibers so that the center fiber of the array is on the axis of the beam.
- A Gaussian profile is fit to a vertical lineout of the spectra.
- The peak is considered to be the axis for this analysis.





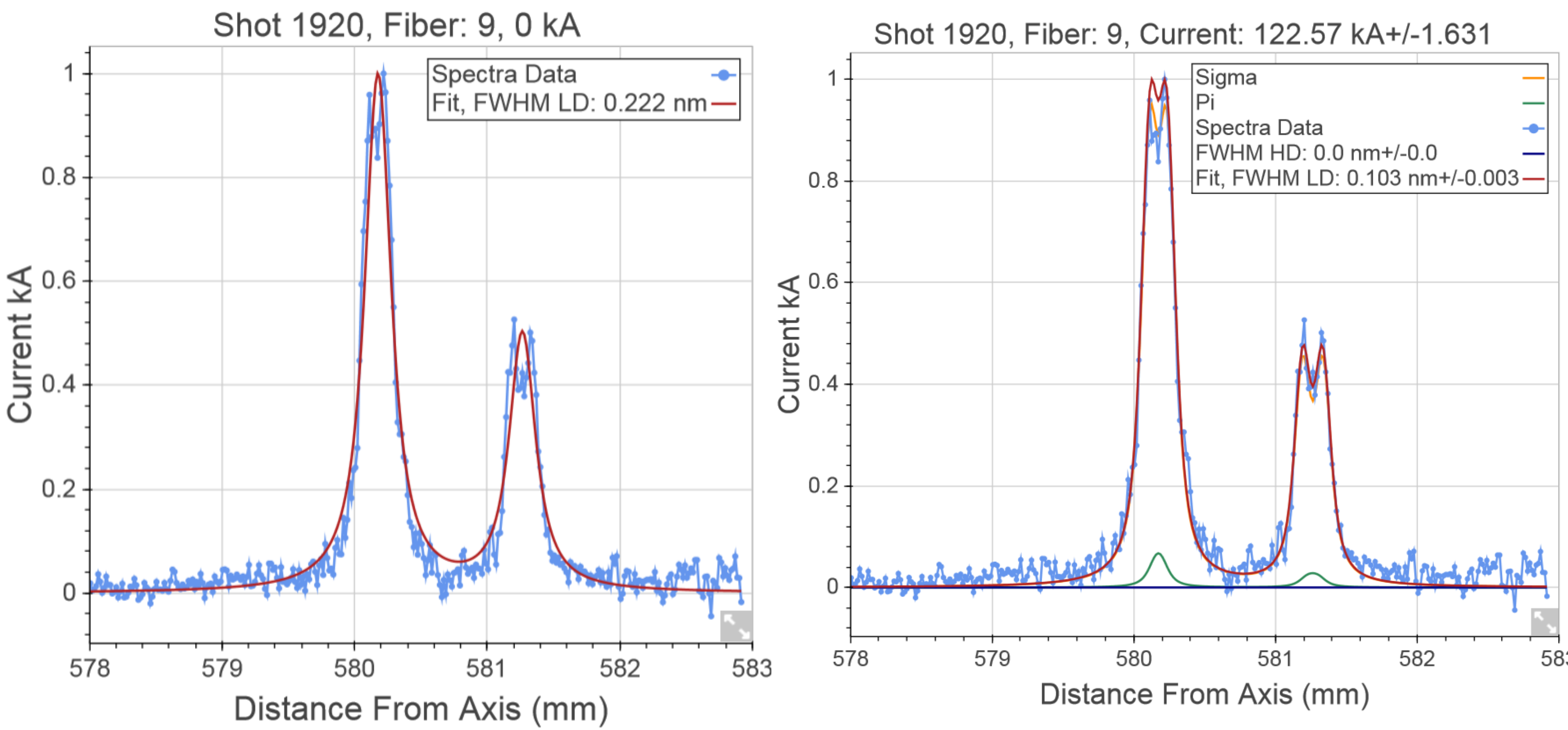
Zeeman Splitting Fits

- Each component of the Zeeman splitting is broadened by density and the instrument
- The spectral profile is fit with the parameters: Lorentzian FWHM (high and low density), and current, using the instrument resolution from the Hg spectra.
- Zeeman splitting is fit assuming:
  - Gaussian spot intensity
  - Fiber is well focused for a 1cm chord
    - Sigma and pi line components are factored into the fit
  - Cylindrical symmetry of e-beam
  - Optically thin plasma, p3/2->s1/2 and p1/2->s1/2 ratio is 2



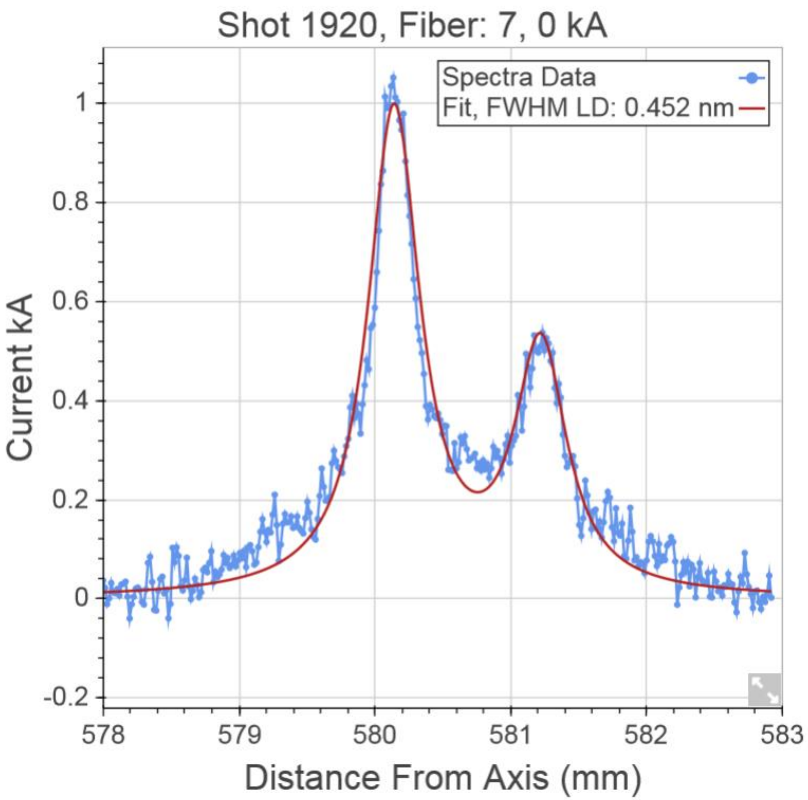
Parallel and perpendicular components change the line profiles. Line of sights closer to the center contain more pi components than lines further from the axis.

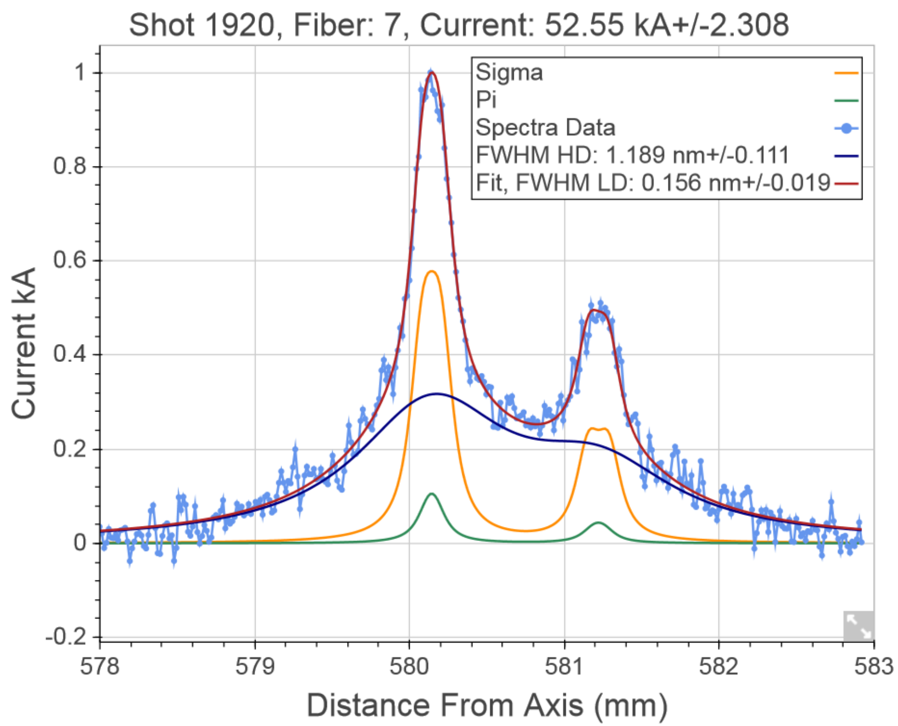
Comparison between fits



- Outer fiber fit with and without a magnetic field.

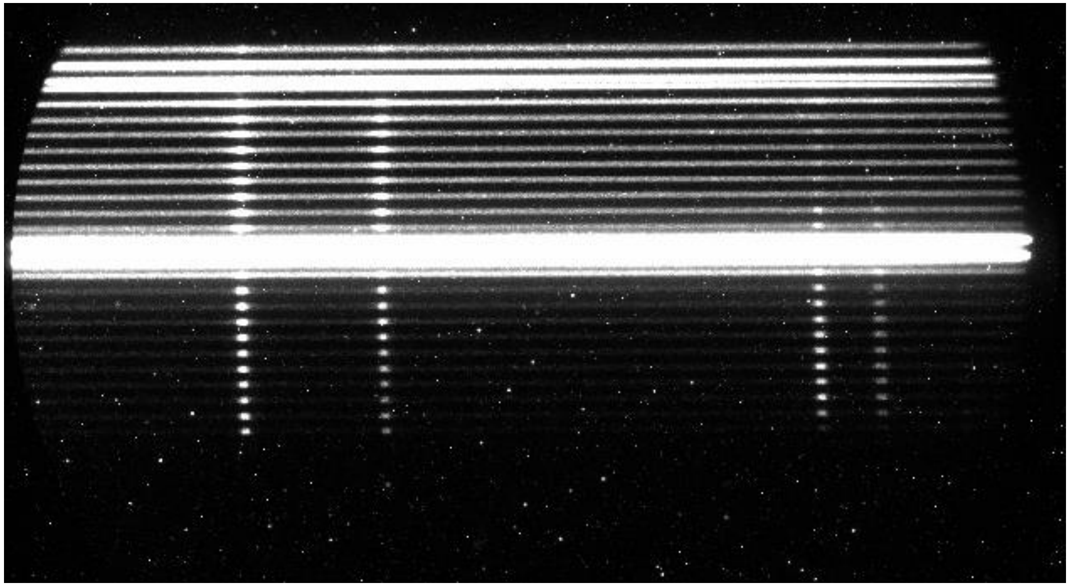
Comparison between fits





- A fit of a spectrum taken close to the axis with and without the magnetic field.
- Doublet broadening and the wings are more accurately fit.

Density Gradients

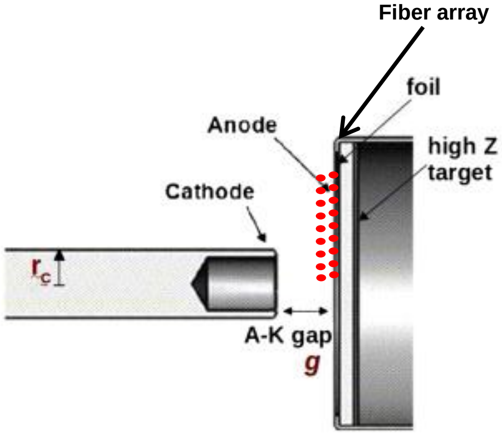


On the anode surface

~.5mm off the surface

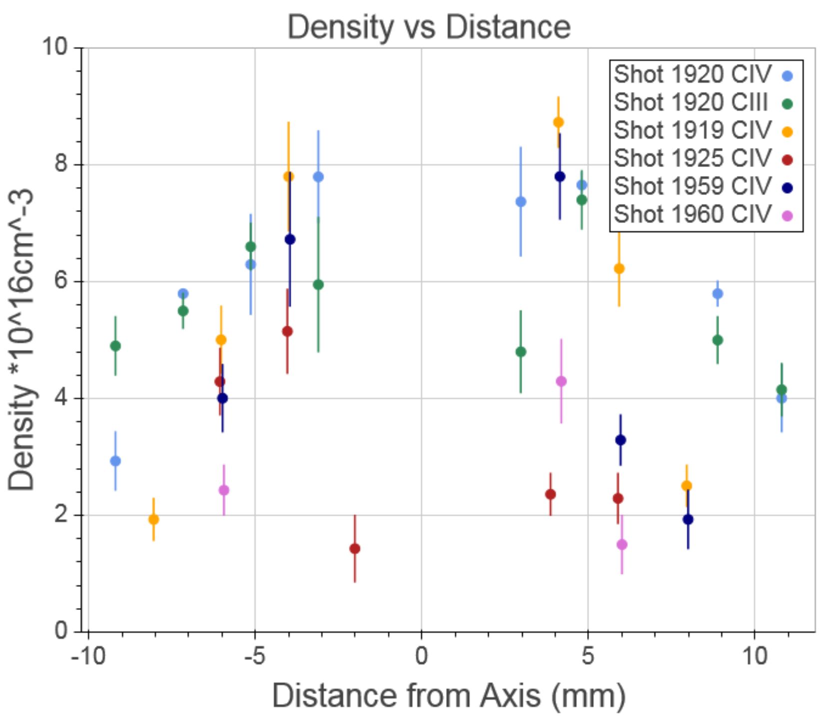
Fiber array consists of 26 fibers, focused to a .5 mm spot parallel to the anode surface.

The array is designed to separate the high density surface plasma from the lower density plasma that is used to fit Zeeman splitting.



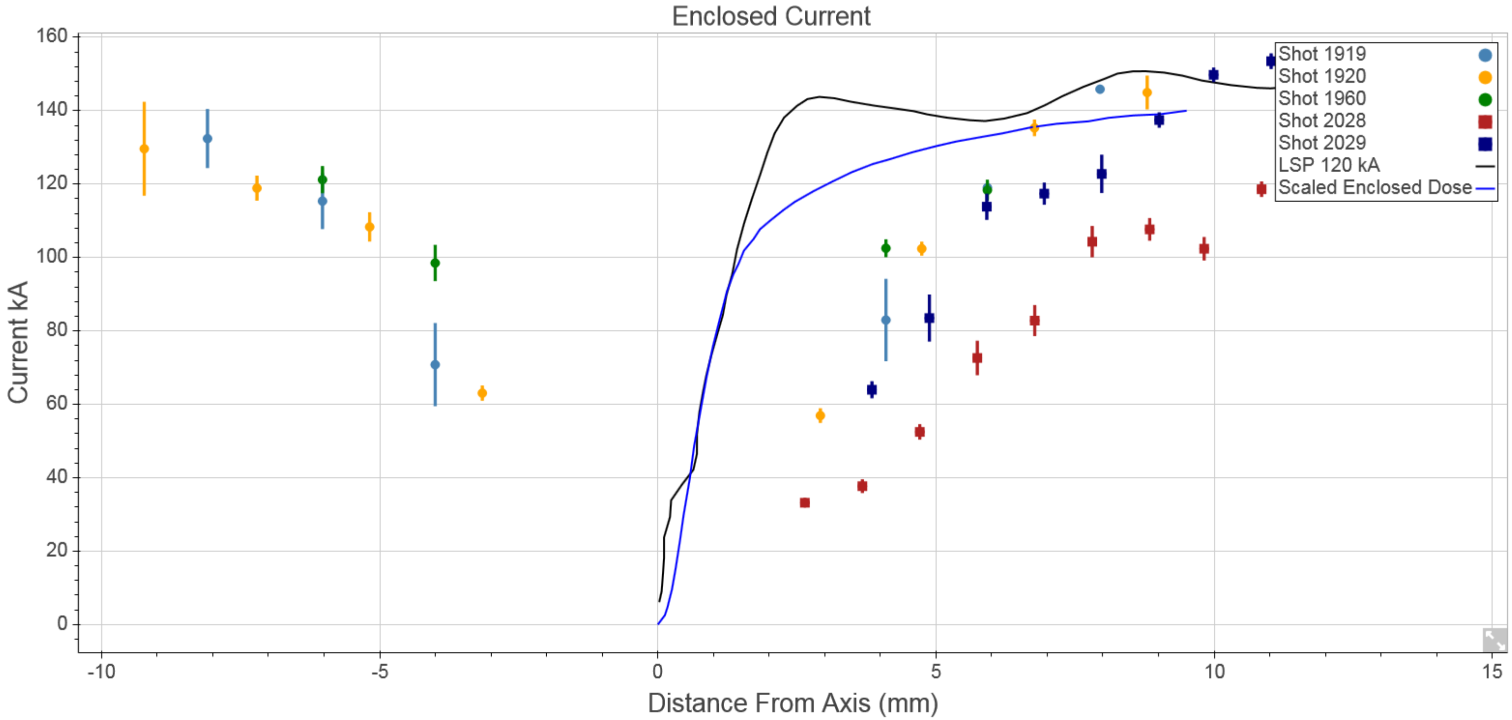
Density Measurements

- Low density components shown after fitting Zeeman splitting. Errors shown are approximated from the fit uncertainty.
- Temperatures from CIII/CIV are 5-6 eV across the anode. Densities are ~mid $10^{16} cm^{-3}$ and drop with distance from the axis.
- Densities are approximated using PrismSpect[1]
- Good agreement with LSP simulations



1. PrismSPECT Spectral Analysis Code, http://www.prism-cs.com

Enclosed Current and B Fields



Simulation From N. Bennett

- Enclosed current increases with radial distance and may begin to flatten at ~8-10mm.
- LSP simulation for a standard foil SMP diode
  - Just after the end of the radiation pulse.
  - Suggests most of the current is enclosed within a few mm region than the splitting measurements suggests.

Future Work

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- Increase signal to noise to better resolve Zeeman splitting
- Use isolated dopants to more accurately spatially resolve the field distribution and increase SNR
- Further compare experimental data with LSP simulations
- Map magnetic fields and currents further into the gap
- Resolve the discrepancy between the expected B-field profiles and the data

Conclusions

- Proof of principle B-field profile measurements have been made on RITS-6
  - Yields current distribution on the anode
- C IV and Al III line splitting has been measured.
- Densities has been estimated using PrismSpect to fit Stark broadened lines
- These data suggests a large fraction of the total current may be outside a few mm radius

References

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2. N. Bennett, M. Crain, D. Droemer, et al. Phys. Rev. ST Accel. Beams 17, (2014)

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4. E. Stambulchik, K. Tsigutkin, and Y. Maron, PRL 98, (2007)

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6. R.D. Cowan, *The theory of atomic structure and spectra* (1981)

7. H.R. Griem *Plasma Spectroscopy*, (1964)

8. K. Hahn, N. Bruner, S. Cordova, R. Gignac, M. Johnston, IEEE Trans. Plasma Sci, 38, (2010)