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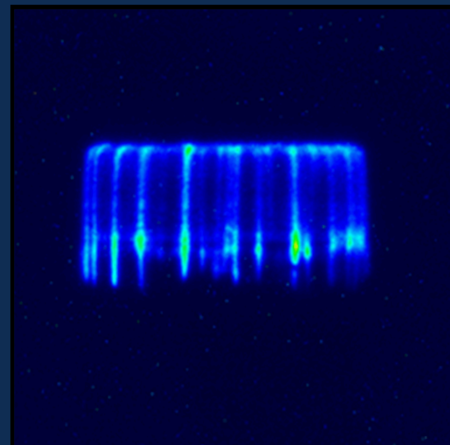

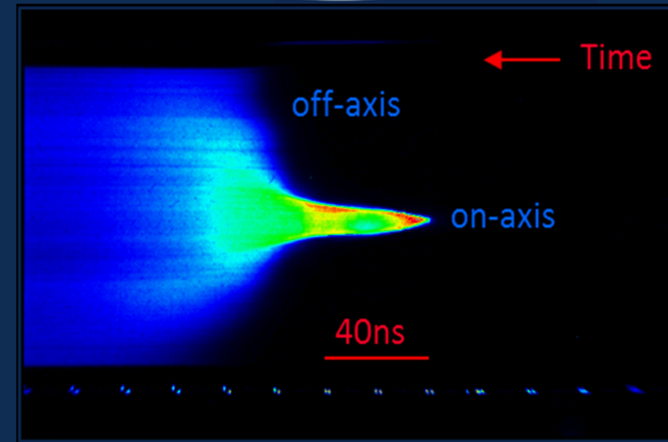

SPECTROSCOPIC METHOD FOR DETERMINING MAGNETIC FIELDS IN HIGH ENERGY ELECTRON BEAM DIODES*

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Abstract

The RITS-6 accelerator (5-11MeV, 100-200kA) at SNL is being used to evaluate the Self-Magnetic Pinch (SMP) diode as a flash x-ray radiography source[1]. This diode utilizes a small, hollowed, metal cathode and a planar high atomic number anode to produce a focused electron beam (< 3mm), which generates high energy Bremsstrahlung x-rays. During this process, electrode plasmas form and propagate in an approximately 1cm A-K vacuum gap. These plasmas are measured spectroscopically using high resolution (<1 Angstrom) Czerny-Turner spectrometers with ICCD and/or streak camera outputs[2]. This paper explores using a novel plasma spectroscopy method to measure the magnetic fields (1-25 Tesla) within the SMP diode. With this technique, the magnetic field effects on line shapes and fine structure features can be measured even when the line shapes are dominated by Stark or Doppler broadening. This provides a great advantage over other techniques such as Faraday rotation or polarization spectroscopy. Several suitable line species have been identified and experimentally measured. Recent results with inferred B-fields will be presented.

[1] K. Hahn, N. Bruner, M. D. Johnston, B.V. Oliver, et. al., *IEEE Trans. Plasma Sci*. 38 (2010) 2652-62.

[2] M.D. Johnston, B.V. Oliver, D.W. Droemer, B. Frogget, et al., *Review of Sci. Instruments,* Vol. 83, No. 8, p. 083108-1.

Purpose of Plasma Measurements in High-Powered Diodes

- Provide quantitative measurements of plasmas and fields generated in high-powered (TW), pulsed-power diodes.
- Gain a physics understanding of plasma formation in high power devices.
- Input experimental data into particle in cell (PIC) codes to better predict plasmas and fields within these type of devices.
- Use this information to improve present diode designs and use as a predictive capability for future, next generation capabilities.

RITS-6 Pulsed-Power Accelerator at Sandia National Laboratories

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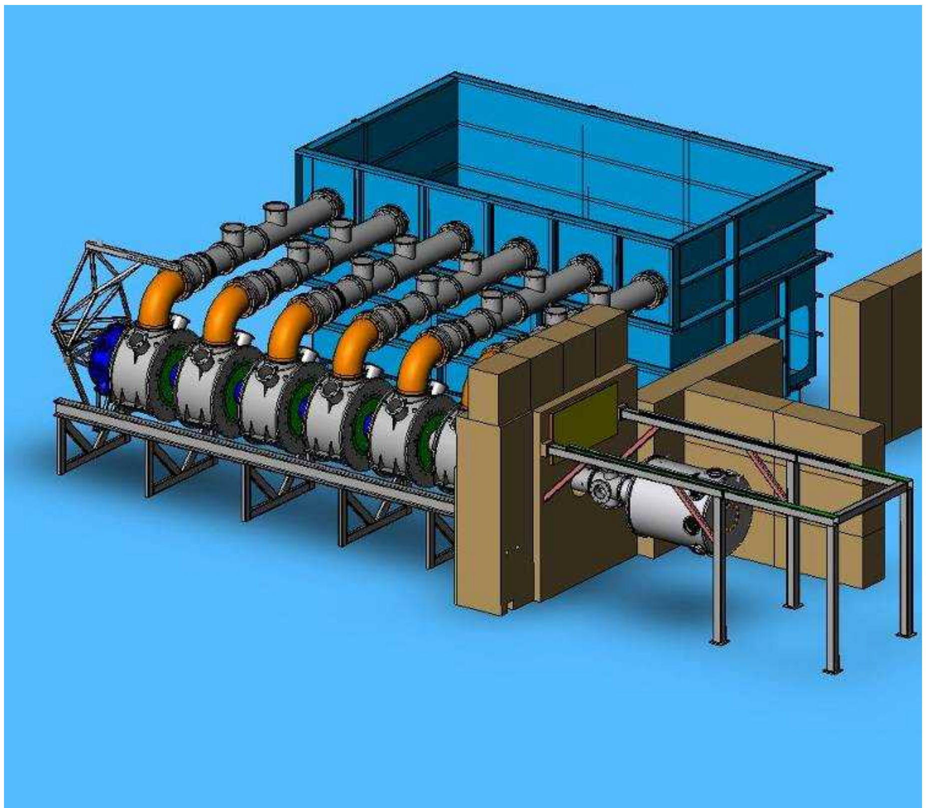
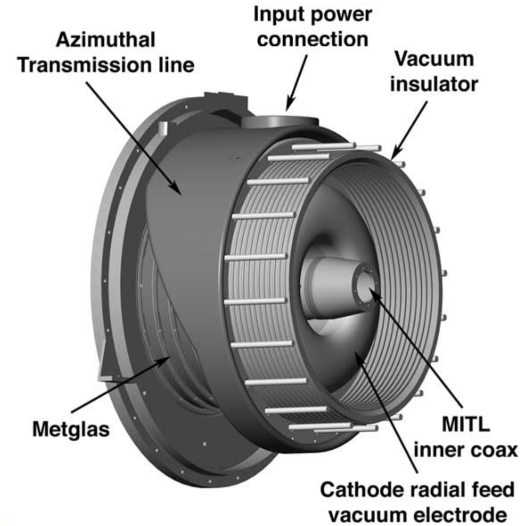
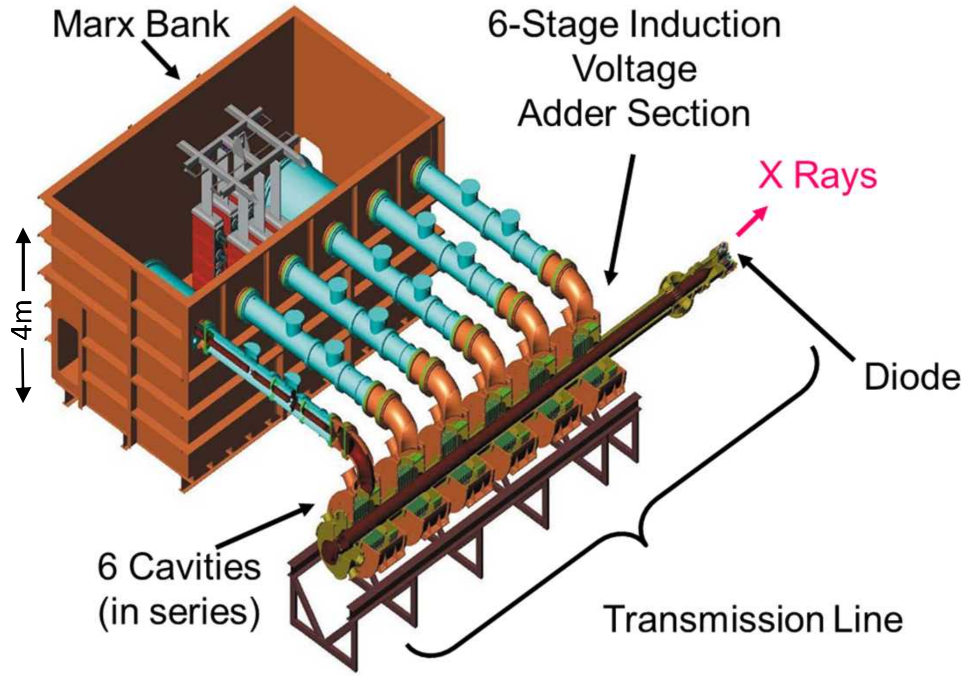
RITS-6 is a 8-11 MeV Marx driven six-stage Inductive Voltage Adder (IVA) capable of driving a variety of electron beam diodes.[3]

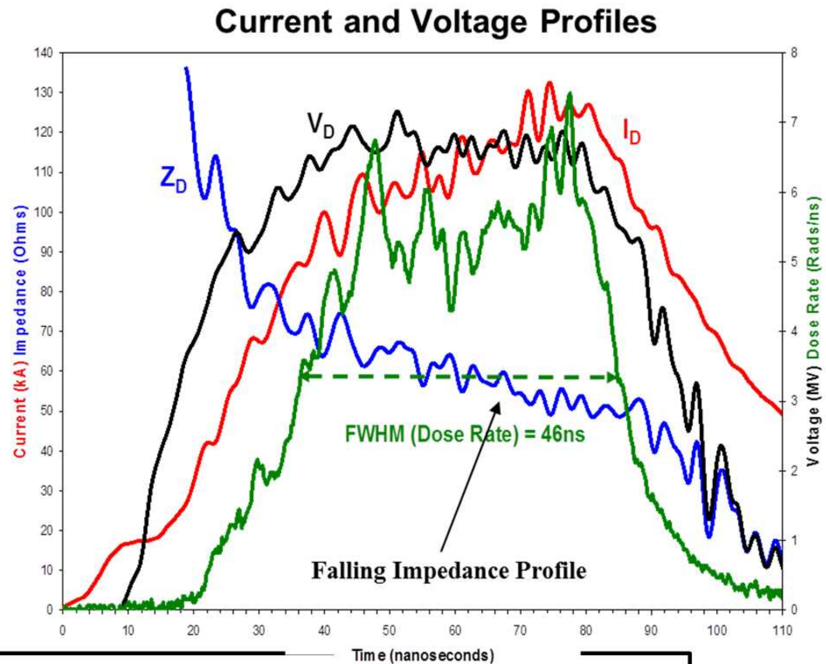






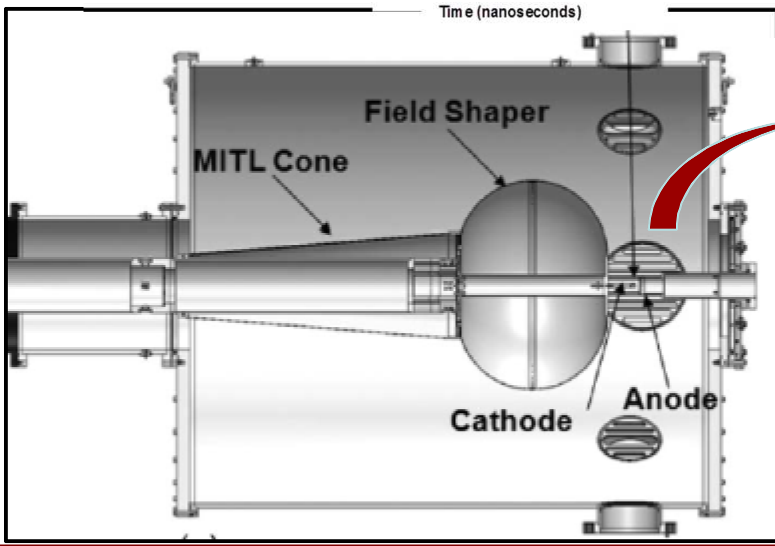
[3] D. Johnson, et al., *Proc. 15th IEEE Int. Pulsed Power Conf.* (IEEE, Jun. 13-17, 2005) pp. 314–317.

We are Evaluating the SMP Diode at the RITS-6 Pulsed-Power Accelerator

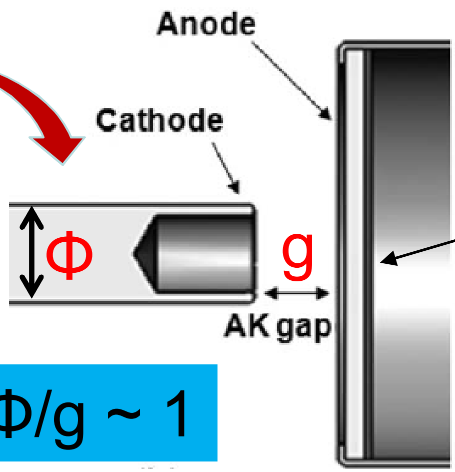


SMP Diode Parameters

- 6-8.5 MV
- 150 kA (~15% ions)
- 50 Ω Impedance
- 70ns Electrical Pulse
- 45ns Radiation Pulse
- > 350 Rads @ 1 meter
- < 3 mm focal spot size

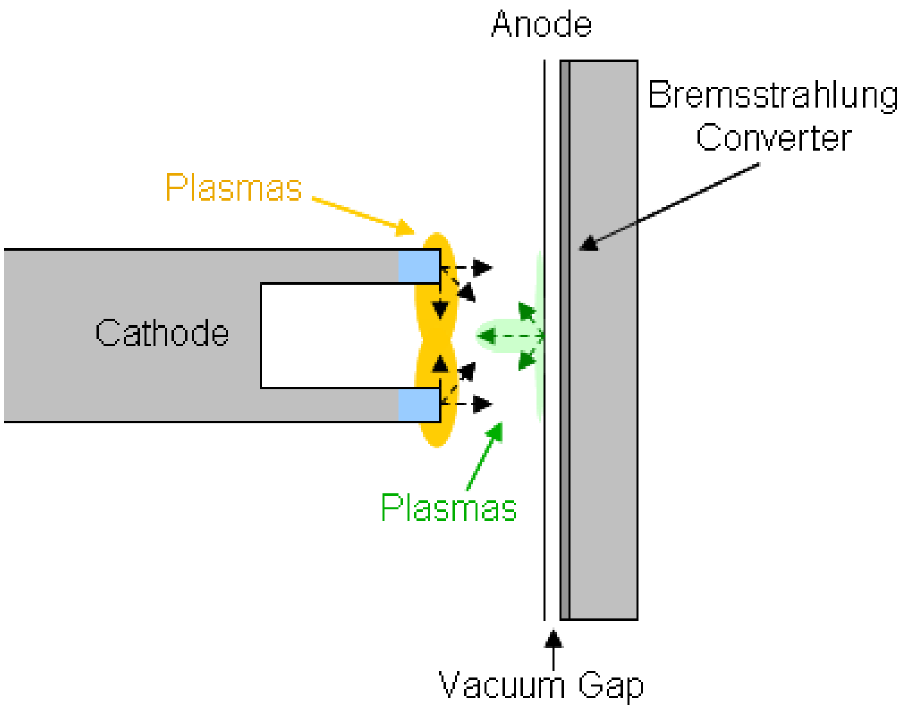


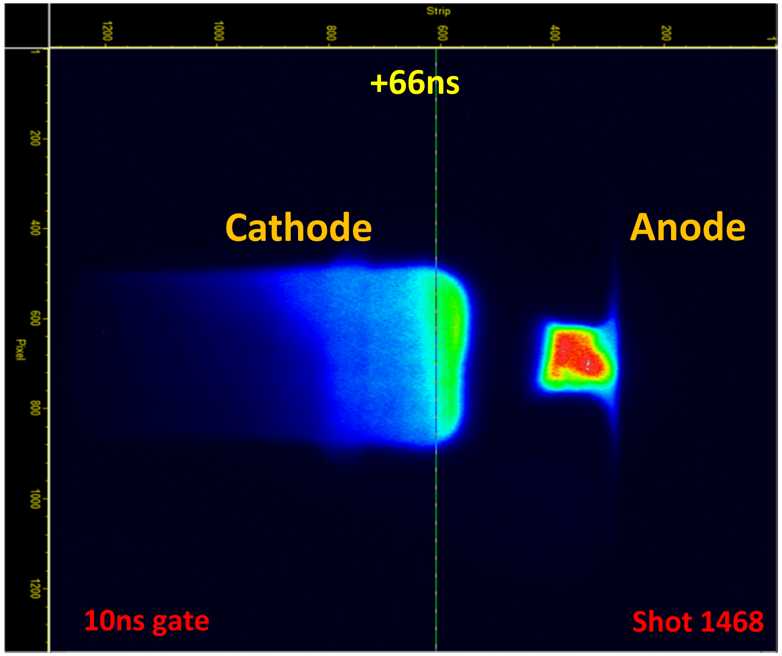
SMP Diode



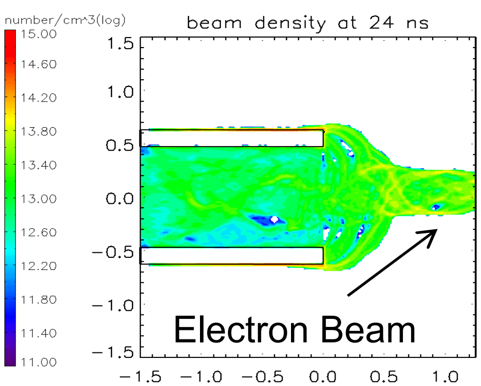
Φ/g ~ 1

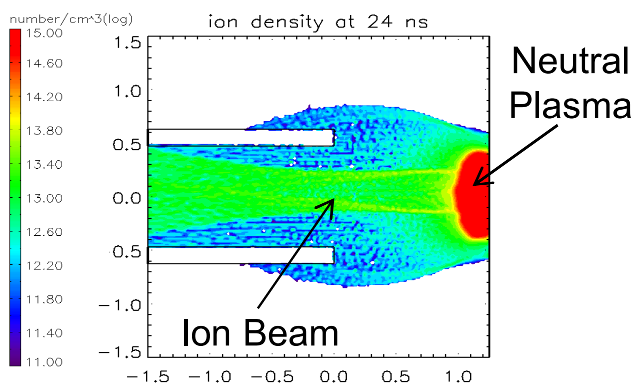
Plasma Dynamics Within the SMP E-Beam Diode

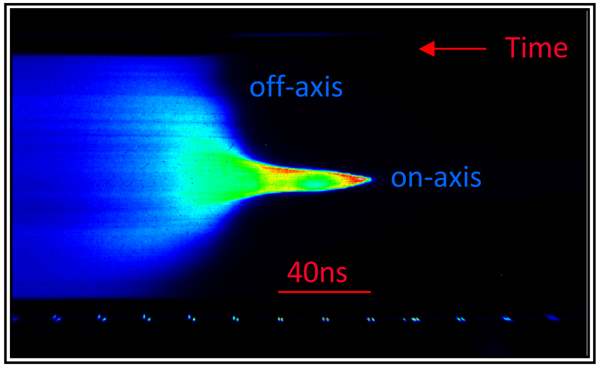




Optical Framing Camera Image

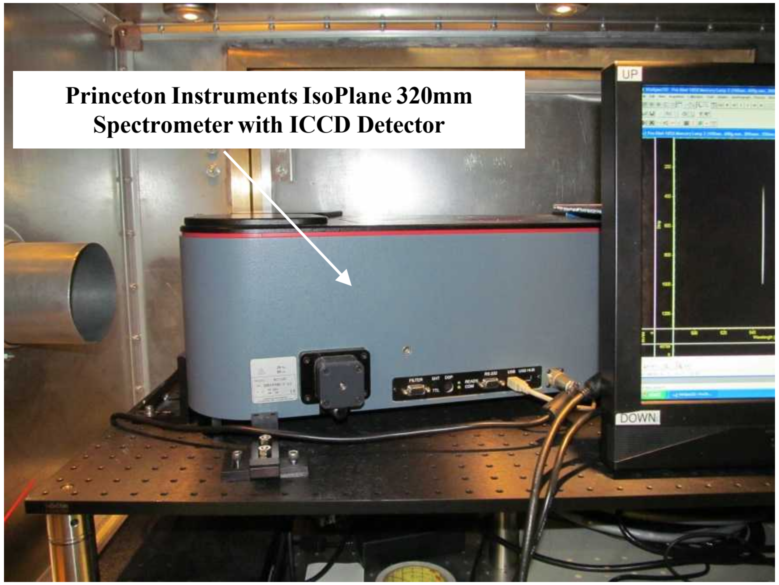


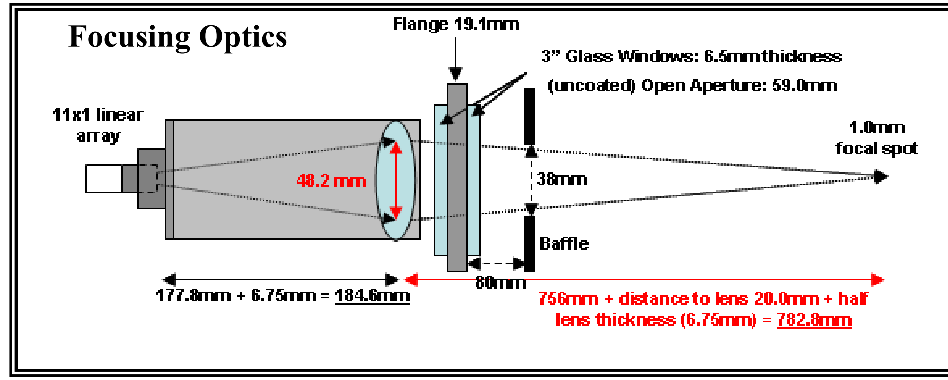


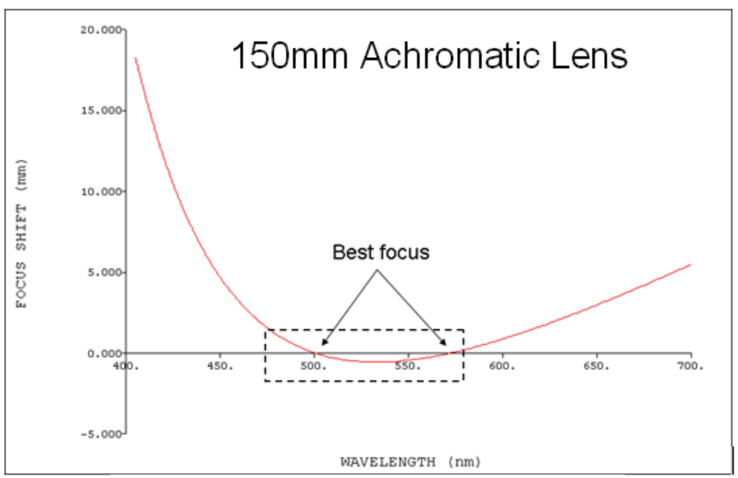


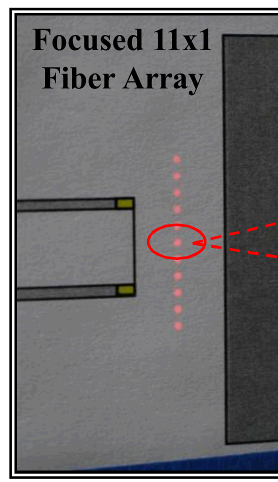
Optical Streak Image

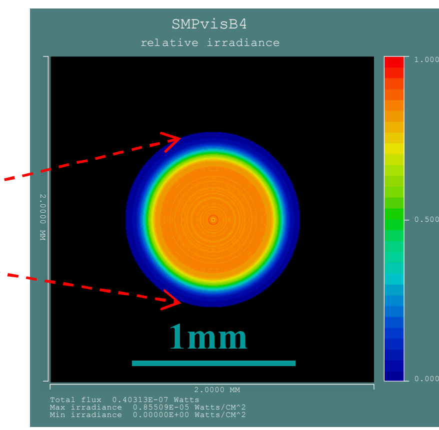
Plasma Spectroscopy Diagnostic











Fiber Focal Spot Size

Detailed Visible Emission Spectroscopy and Analysis Reveals the Density, Composition, Evolution, and Structure of the Anode Plasma

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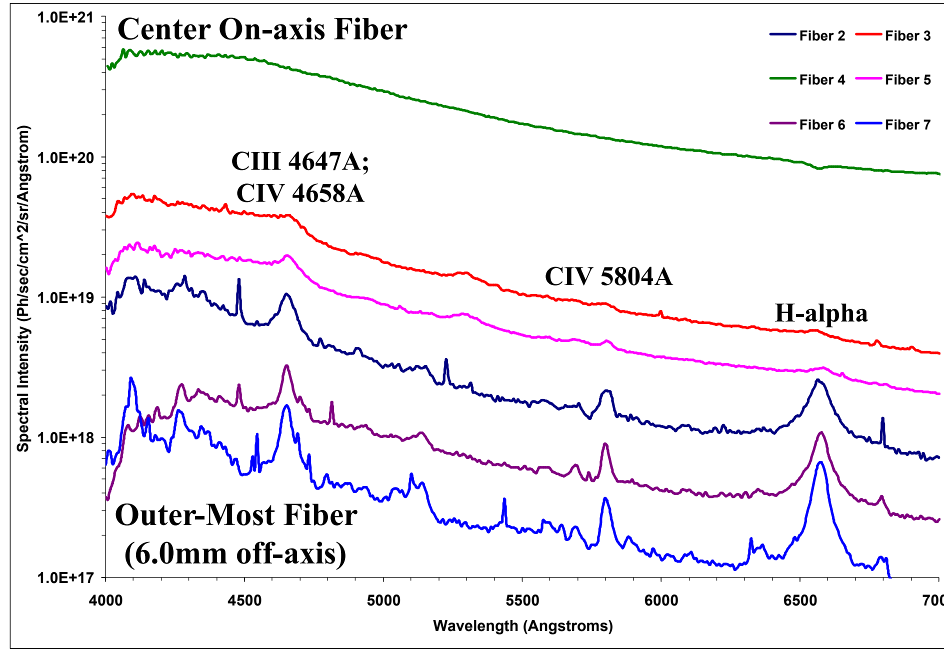
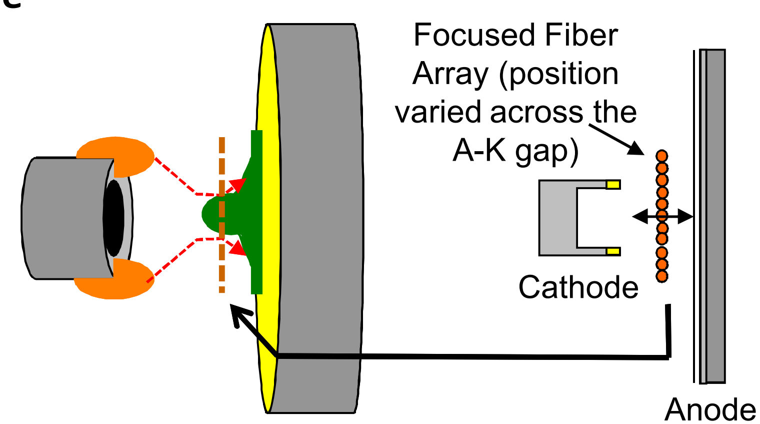
- **Spectra collected along the anode surface during the radiation pulse consist of carbon ion lines, hydrogen neutrals, and continua.**
- **Line of sight traverses plasmas with different properties.**
- **Plasma density decreases by a factor of ~35x from the center outward to 6mm.**
- **Asymmetries in plasma composition and density can be observed across the surface.**
- **Can these be correlated with electron beam focus and x-ray spot profile?**



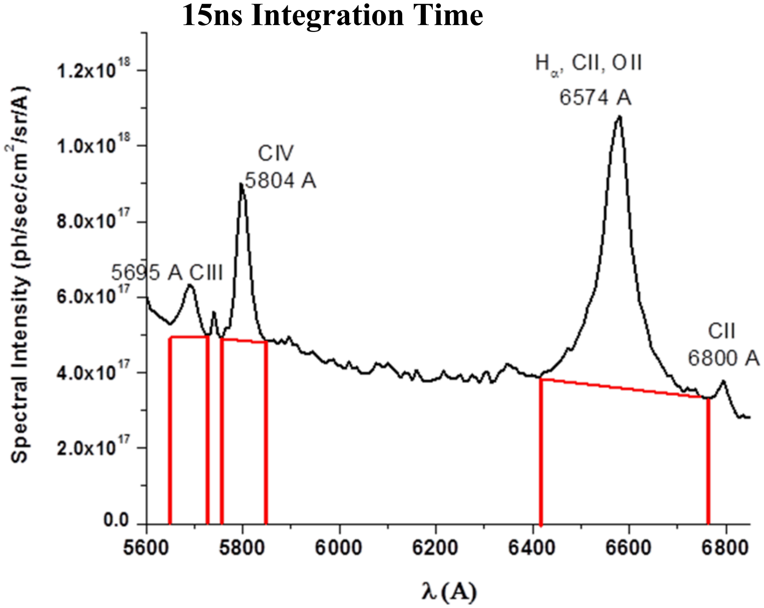
15ns Integration Time

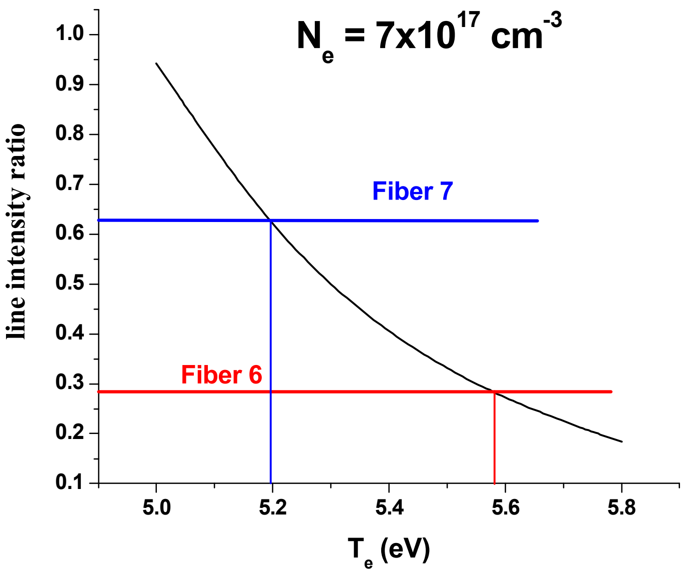


Carbon Ion Lines Observed

- **CIII 4647A**
- **CIV 4658A**
- **CIV 5804A**

Spectral Data is Evaluated Using Time-dependent, Collisional-Radiative (CR), and Radiative Transport Calculations



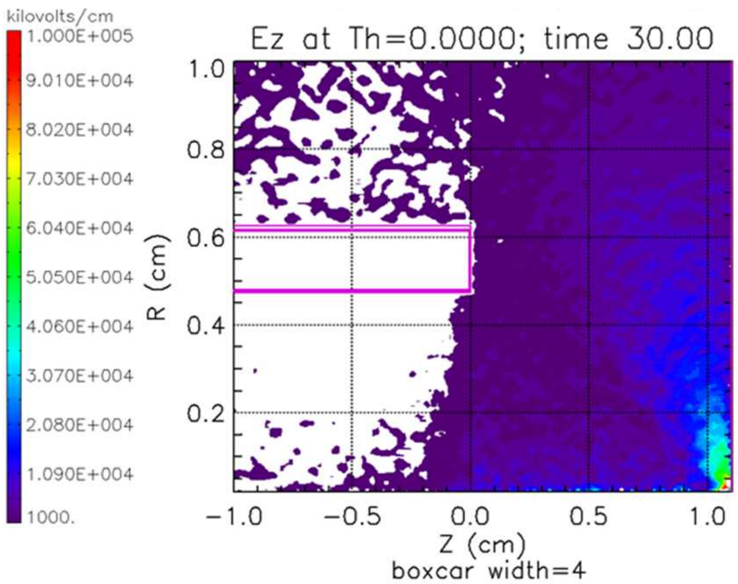


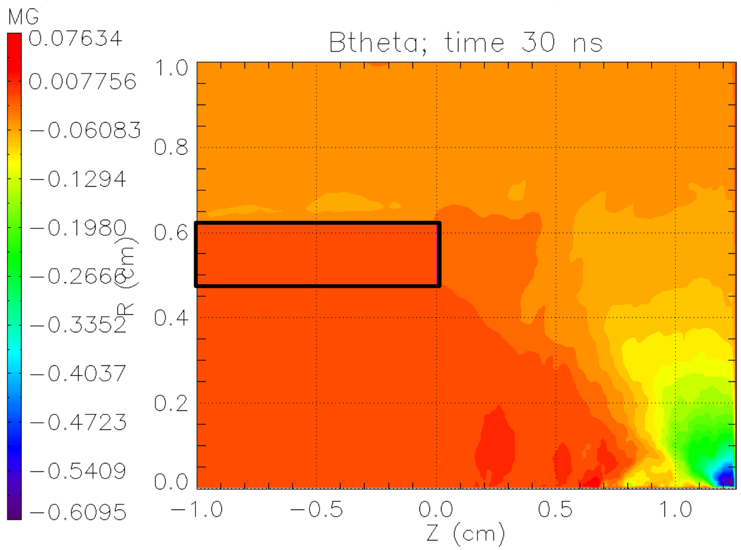
Fiber 6 (4.0mm off-axis on the anode surface)

N_e from H-alpha:	1.1×10^{18} cm^{-3}	
N_e from Continuum:	6.1×10^{17} cm^{-3}	
Electron Temp. (T_e):	5.6eV	
$N_{hydrogen}$ (Z = 1):	3.2×10^{17} cm^{-3}	(28%)
N_{carbon} (Z = 2.9):	4.0×10^{16} cm^{-3}	(10%)
$N_{e(oxygen\ and\ Al)}$:	7.0×10^{17} cm^{-3}	(62%)

Plasma parameters are determined through comparisons of line ratios, line broadenings, and absolute continuum intensity measurements.

Simulations Indicate the SMP Diode has Electric Fields of 5-15 MV/cm and Magnetic Fields of 5-15 Tesla.

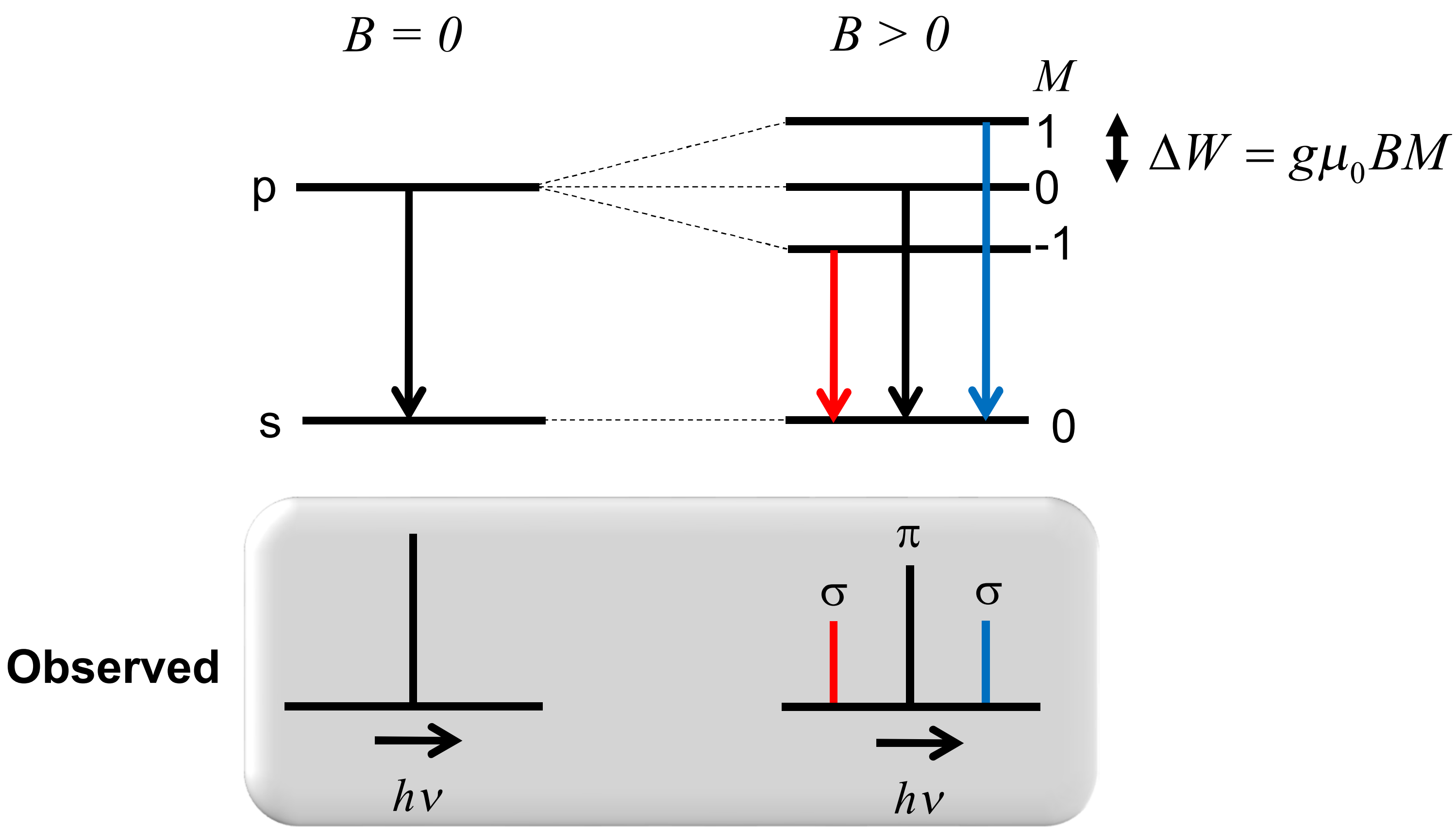




- **Average E_z fields of 5-15 MV/cm**
- **E_z fields up to 50 MV/cm near axis**

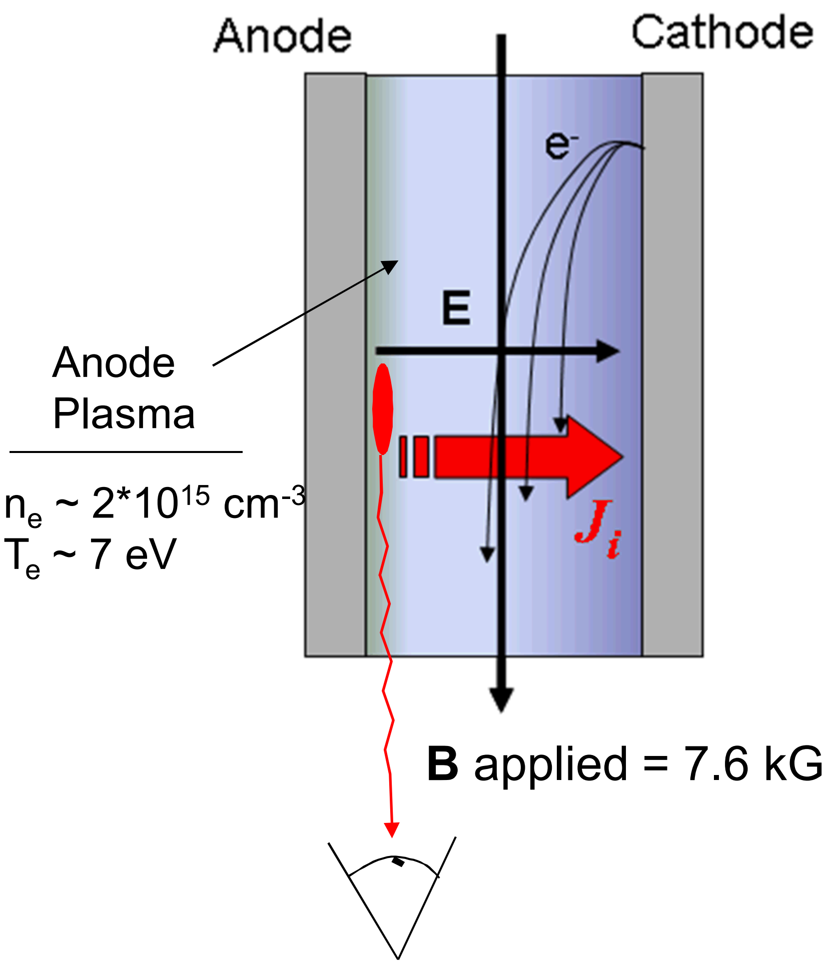
- **Average B_Φ fields of 5-15 Tesla**
- **B_Φ fields up to 60 Tesla near axis**

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



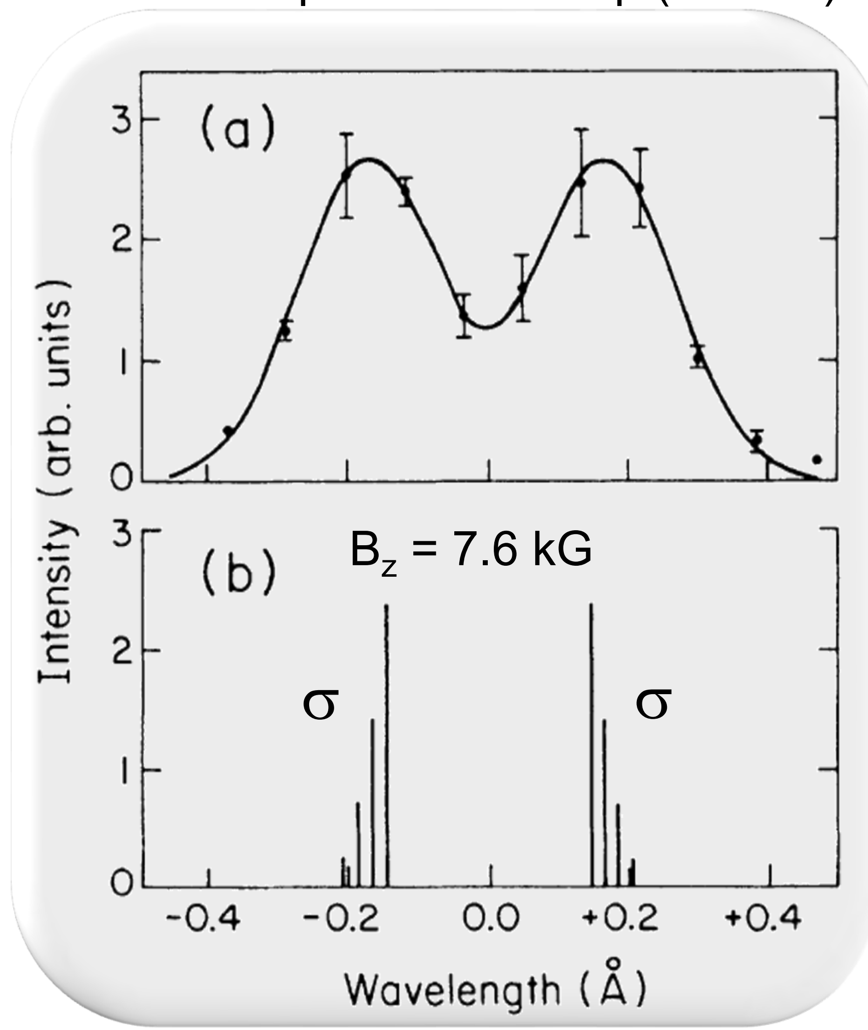
$$h\Delta\nu = \mu_0 B\left(g_u M_u - g_l M_l\right), \begin{bmatrix} \Delta M = 0, \ \pi \\ \Delta M = \pm 1, \ \sigma \end{bmatrix}$$

Zeeman Splitting was Used to Measure the B-field Penetration in an Ion Acceleration Gap



$$h\Delta\nu = \mu_0 B\left[g_u M_u - g_l (M_u \pm 1)\right]$$

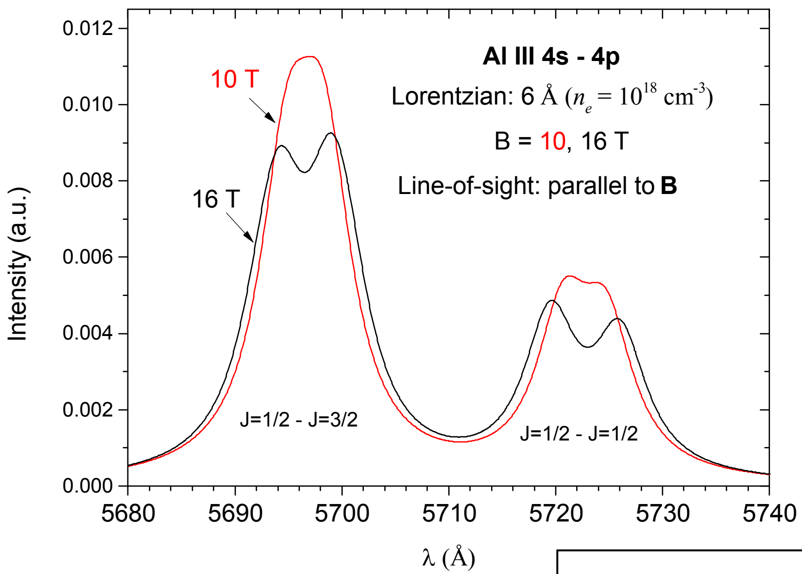
Zeeman split Ba^{1+} 5d – 6p (6142 Å)



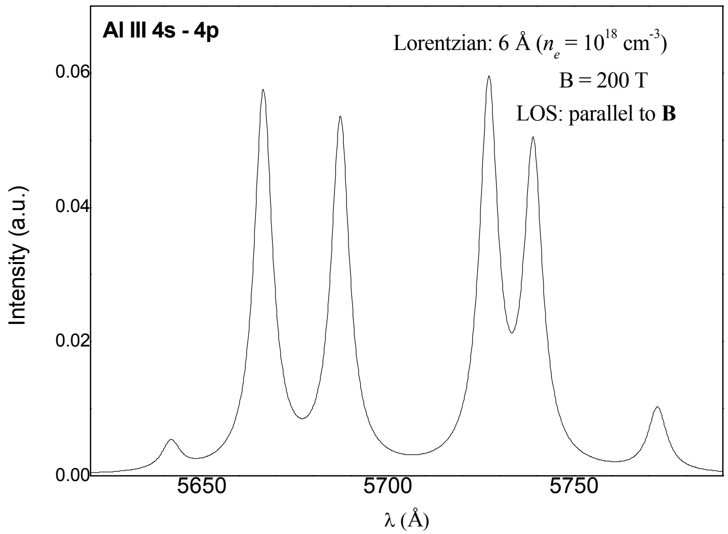
Maron et al., PRA 39 (1989)

Aluminum is a Good Candidate for Measuring B-fields in the SMP Diode

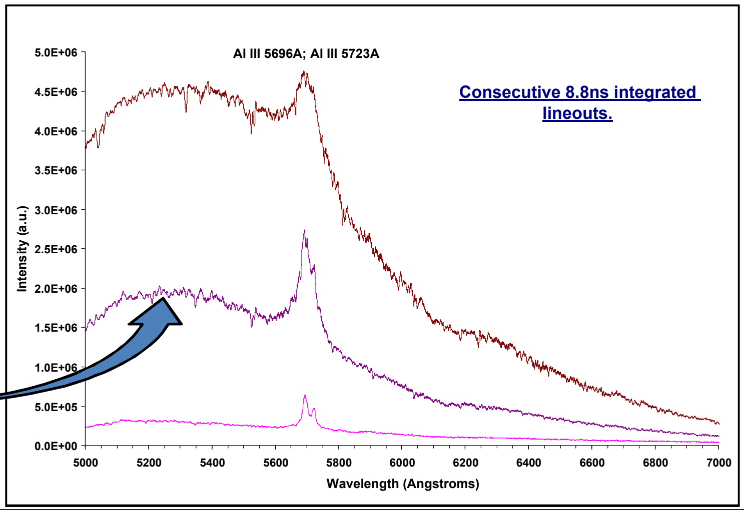
N_e 10^{18} cm^{-3}; B_Φ = 10-16 Tesla



N_e 10^{18} cm^{-3}; B_Φ = 200 Tesla



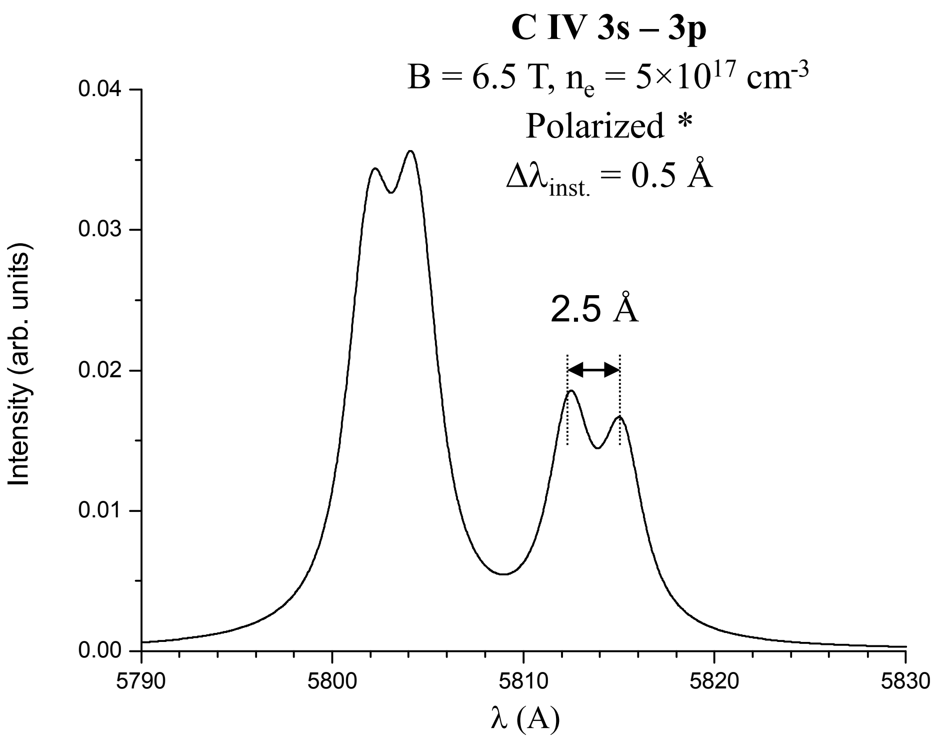
RITS Data:
Al III 4s-4p Transition

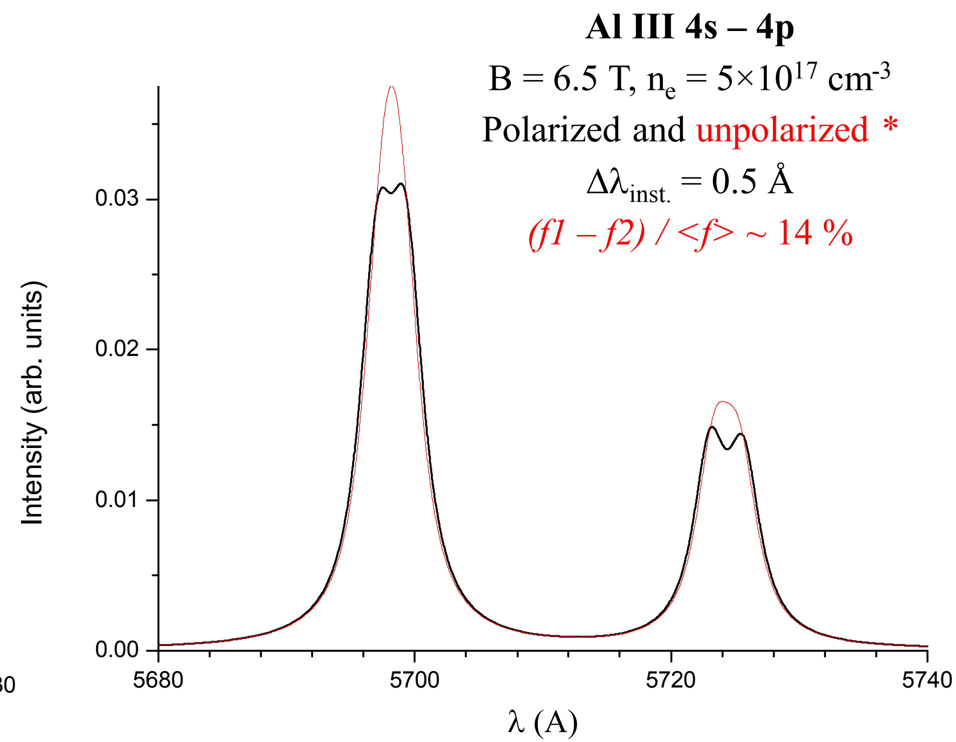


Other Lines Calculated:

Li I 2s-2p
Na I 3s-3p
CIV 3s-3p
Si IV 4s-4p

Zeeman splitting of C IV and Al III Lines at Relevant SMP Plasma Densities





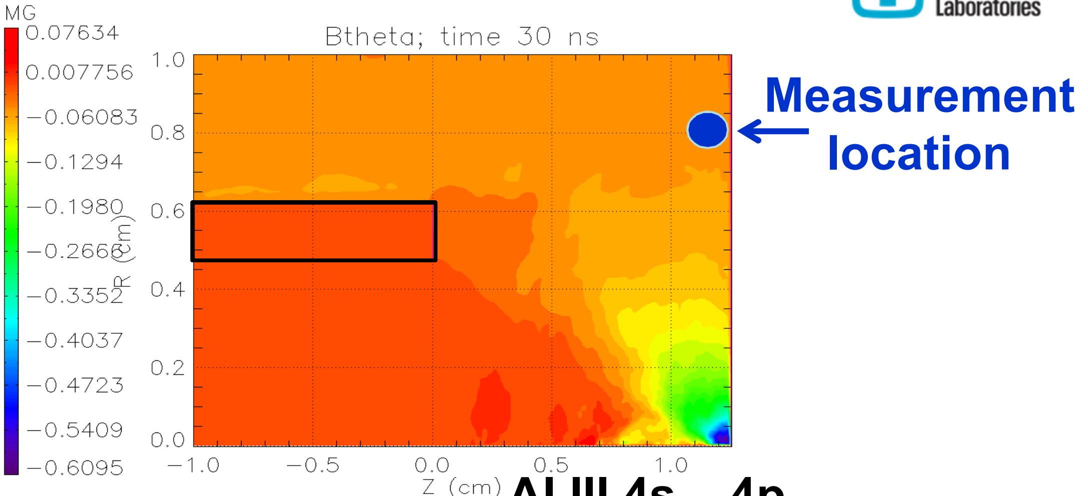
- A magnetic field of 6.5 T at $n_e = 5\times10^{17}$ cm^{-3} can be determined by Zeeman splitting in C IV, if polarization techniques are used.
- A 6.5-T field should also be detected even if the emission is unpolarized, if the new diagnostic method is used.[4]

* Polarized – the magnetic field is assumed to be in the direction parallel to the line-of sight
Unpolarized – The magnetic field is assumed to lie in a plane perpendicular to the line-of-sight

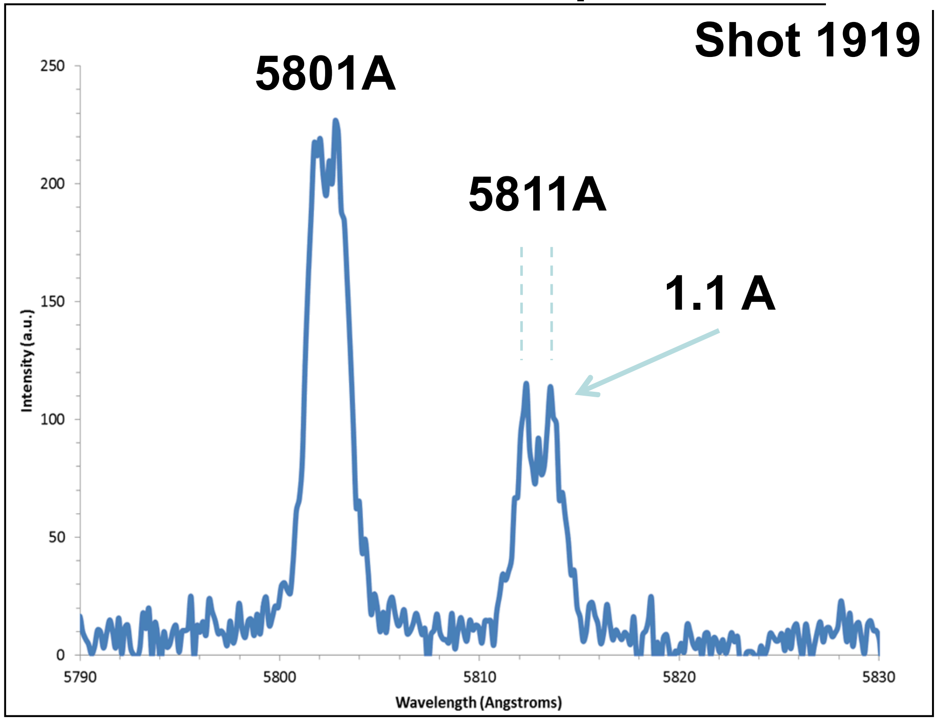
[4] R. Doron, et al., *High Energy Density Phys.*, 10, 56-60 (2014).

Zeeman Splitting of Carbon and Aluminum Ion Lines in the SMP Diode on RITS

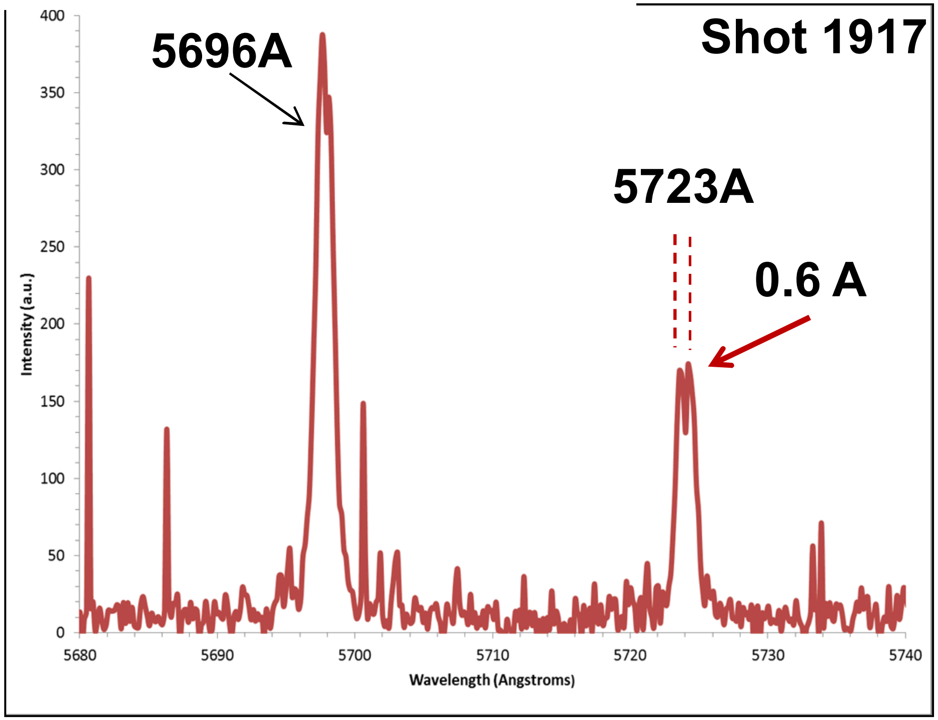
Experimental measurements are in good agreement with predicted B-fields using LSP modeling.



C IV 3s – 3p

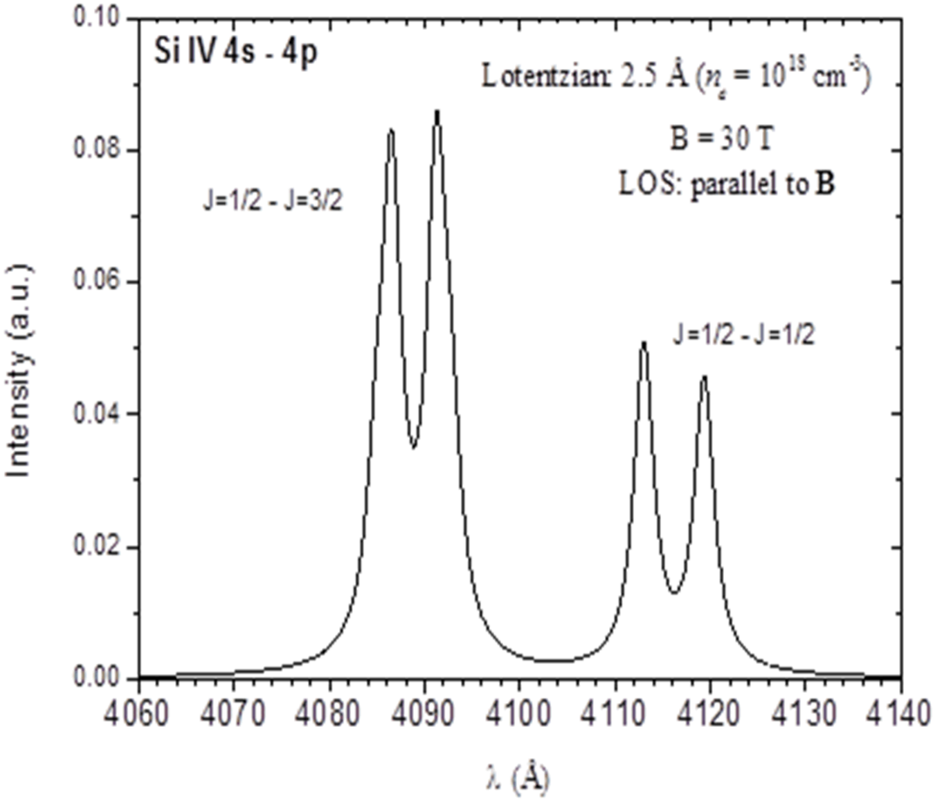


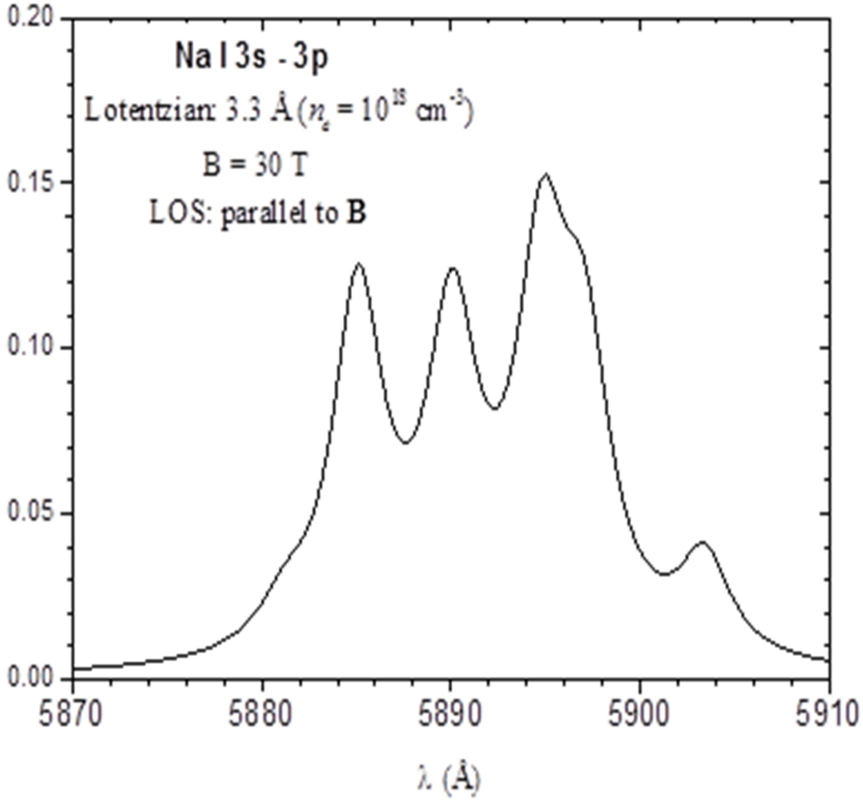
Al III 4s – 4p



Zeeman splitting measurements give consistent 4 Tesla B-fields at large radii.

Other Options for Zeeman Splitting Measurements Also Exist





Candidate lines should exhibit small broadening due to Stark and Doppler effects. Based on expected plasma temperatures and densities, suitable lines can be chosen.

Summary and Conclusions

- The first successful measurements of local magnetic fields in the SMP diode have been completed.

- A new technique, developed at the Weizmann Institute, to measure Zeeman splitting of spectral lines has been employed on the SMP diode at SNL.

- Measurements like these 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. Experimental measurements, such as these, are necessary to validate the models.

- Measurements of the magnetic field provide needed information regarding local current distributions in the diode.