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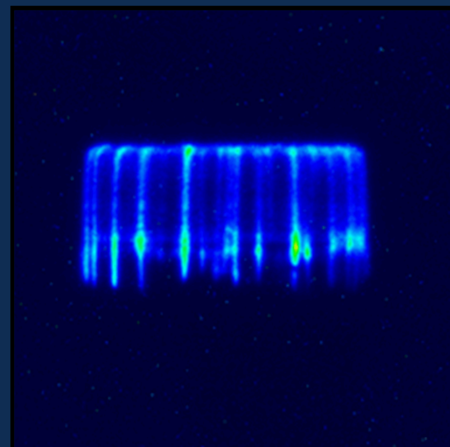

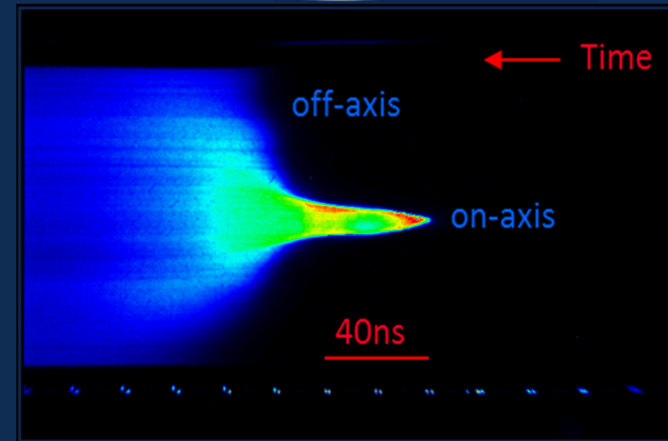

MEASUREMENTS OF MAGNETIC AND ELECTRIC FIELDS IN HIGH ENERGY ELECTRON BEAM DIODES*

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Abstract

The RITS accelerator (5-11MV, 100-200kA) at Sandia National Laboratories is being used to evaluate the Self-Magnetic Pinch (SMP) diode as a potential flash x-ray radiography source[1]. This diode consists of a small, hollowed metal cathode and a planar, high atomic mass anode, with a small vacuum gap of approximately one centimeter. The electron beam is focused, due to its self-field, to a few millimeters at the target, generating bremsstrahlung x-rays. During this process, plasmas form on the electrode surfaces and propagate into the vacuum gap, with a velocity of a 1-10 cm's/microseconds. These plasmas are measured spectroscopically using a Czerny-Turner spectrometer with a gated, ICCD detector, and input optical fiber array. Local magnetic and electric fields of several Tesla and several MV/cm were measured through Zeeman splitting and Stark shifting of spectral lines. Specific transitions, the shape of which are susceptible to magnetic and electric field effects, were utilized through the application of dopants. Data was analyzed using detailed, time-dependent, collisional-radiative (CR) and line-shape calculations. In addition to spectral line analyses, determinations of plasma properties were obtained from continua and line spectra as well. Recent results are presented.

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

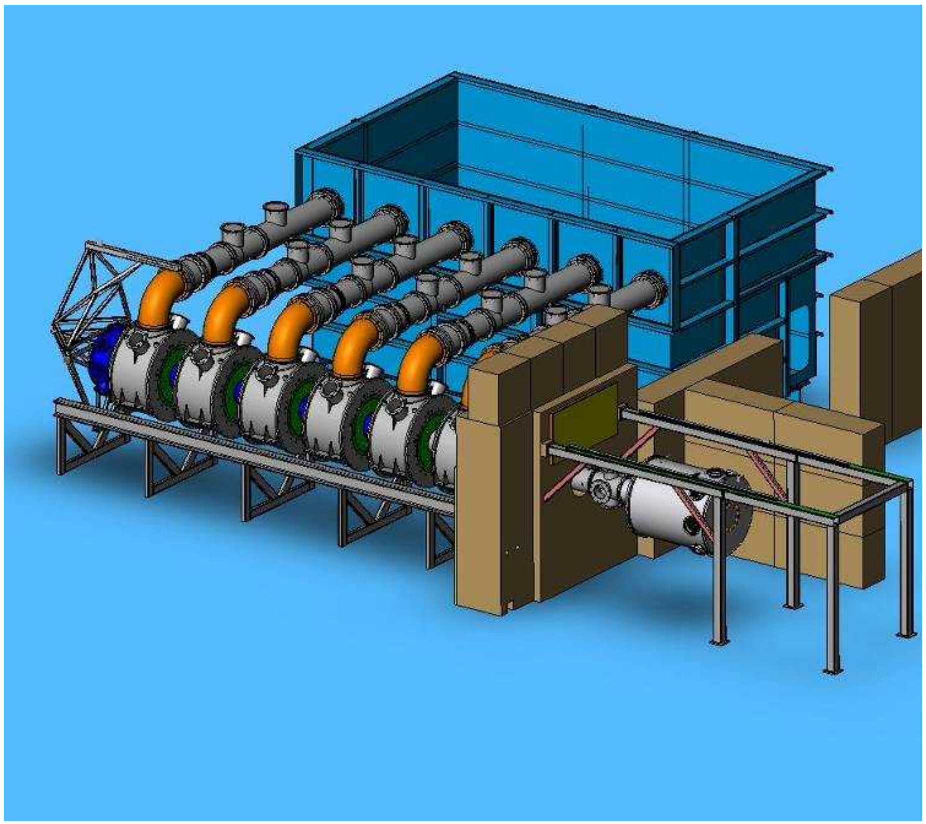
Purpose of Plasma Measurements in High-Powered Diodes

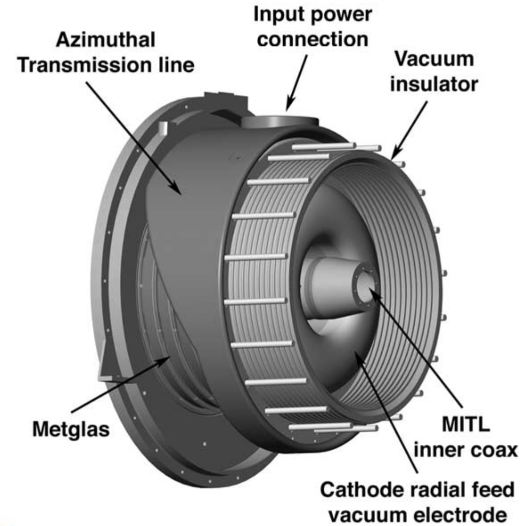
- Provide quantitative measurements of plasmas and fields generated in high-powered (TW), pulsed-power diodes.
- Gain a physics understanding of plasma formation in high power devices.
- Input experimental data into particle in cell (PIC) codes to better predict plasmas and fields within these type of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

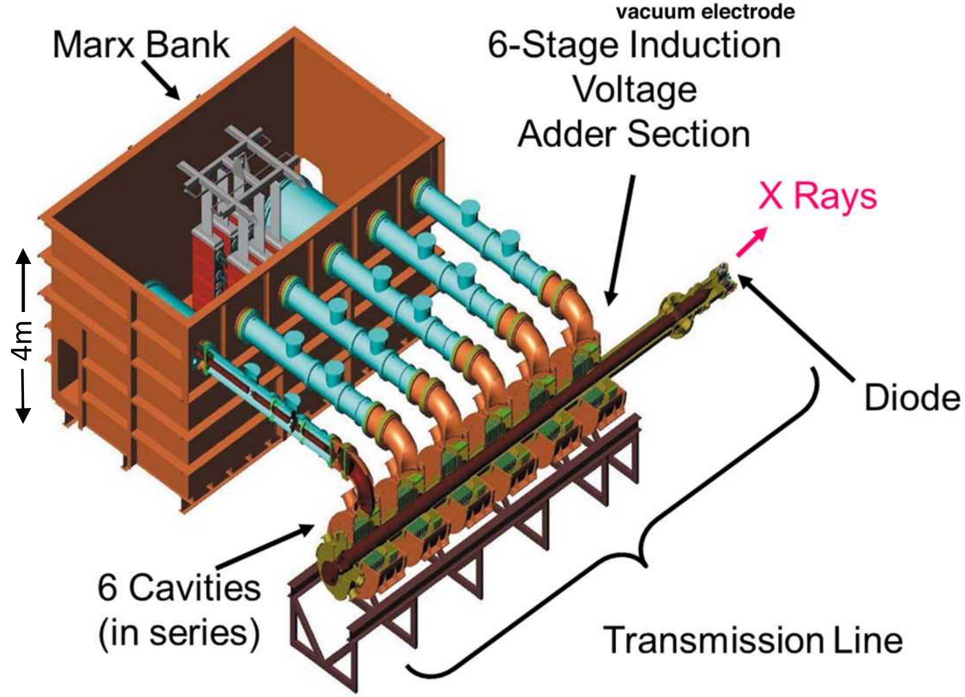
RITS-6 Pulsed-Power Accelerator at Sandia National Laboratories

Sandia National Laboratories

RITS-6 is a 8-11 MeV Marx driven six-stage Inductive Voltage Adder (IVA) capable of driving a variety of electron beam diodes.[2]

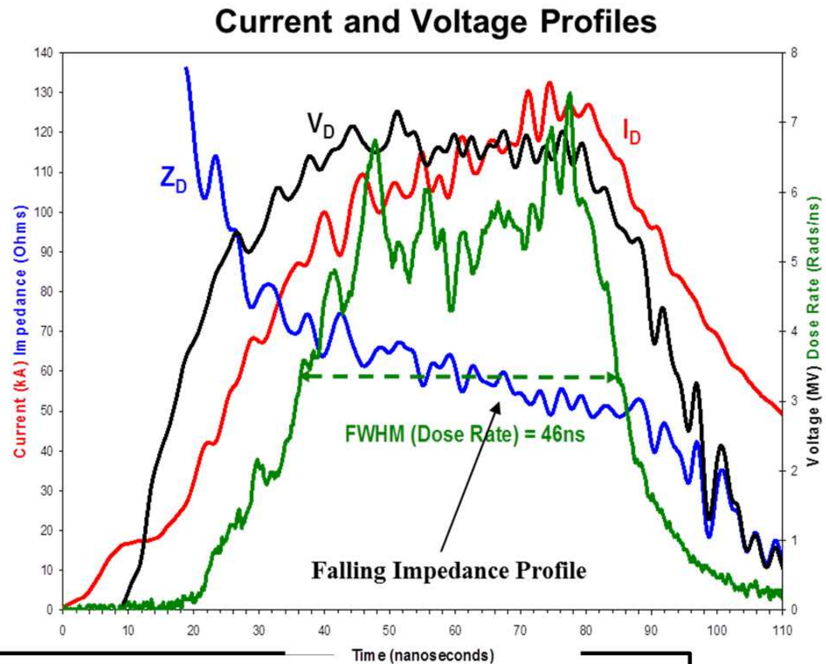






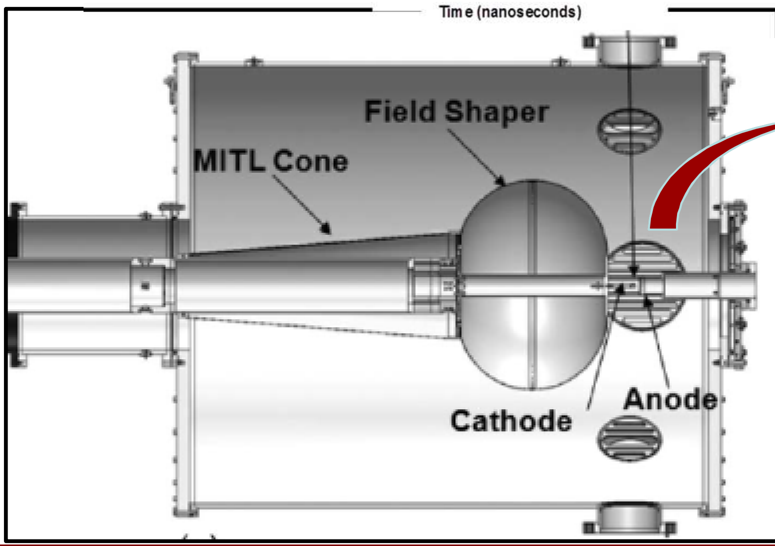
[2] D. Johnson, et al., *Proc. 15th IEEE Int. Pulsed Power Conf.* (IEEE, Jun. 13-17, 2005) p. 314–317.

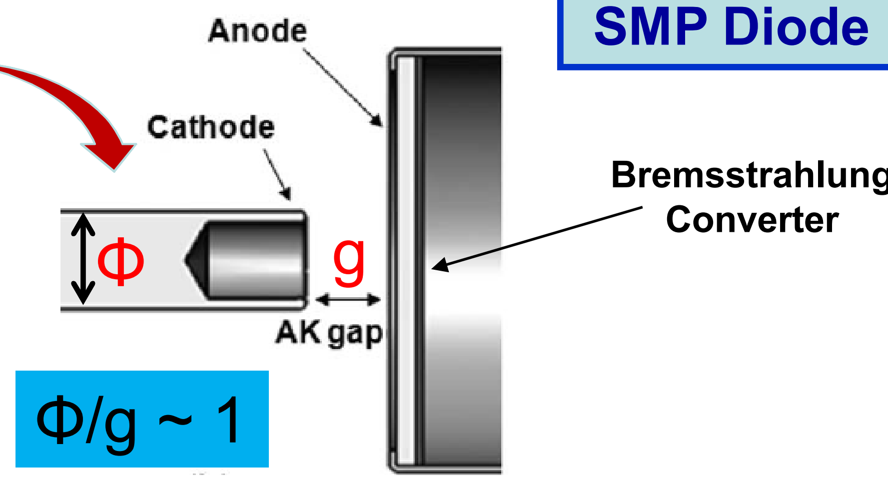
We are Evaluating the SMP Diode at the RITS-6 Pulsed-Power Accelerator



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





Plasma Dynamics in the SMP E-Beam Diode

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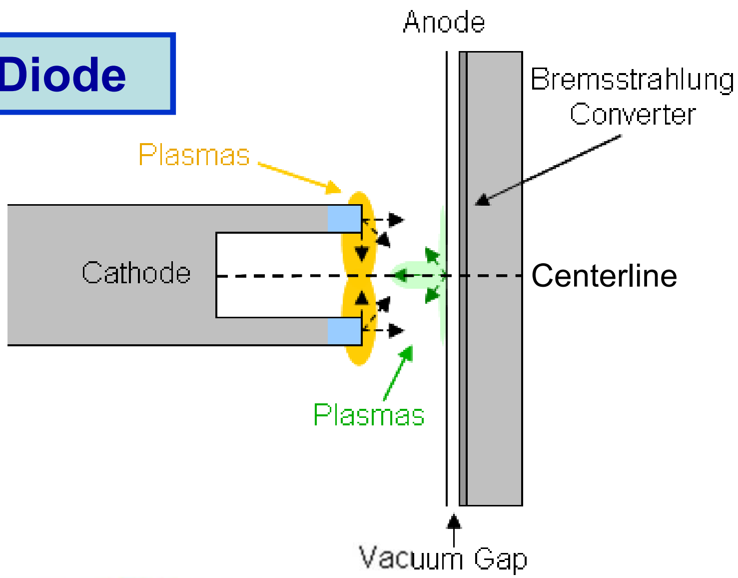
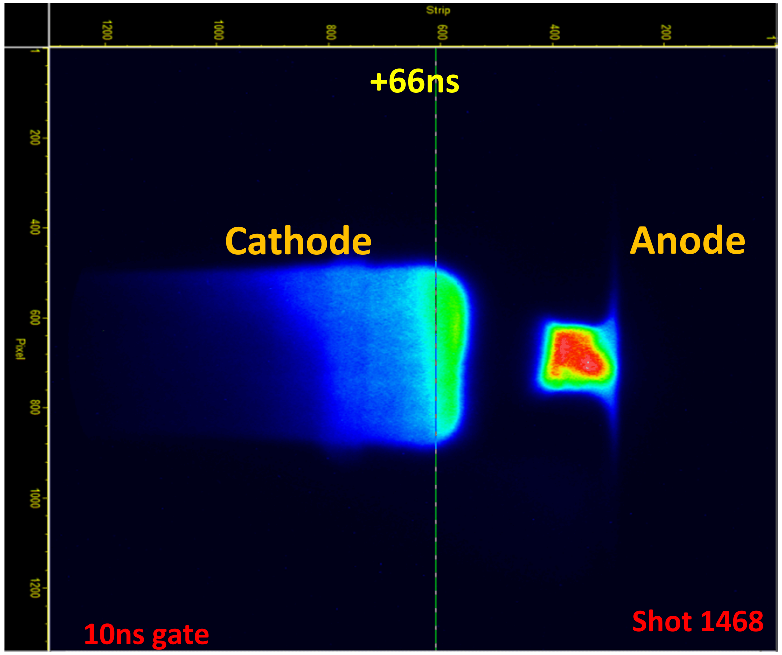
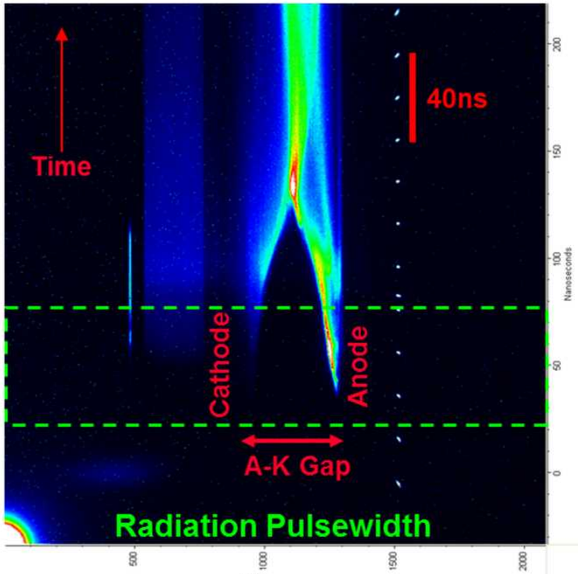
SMP Diode

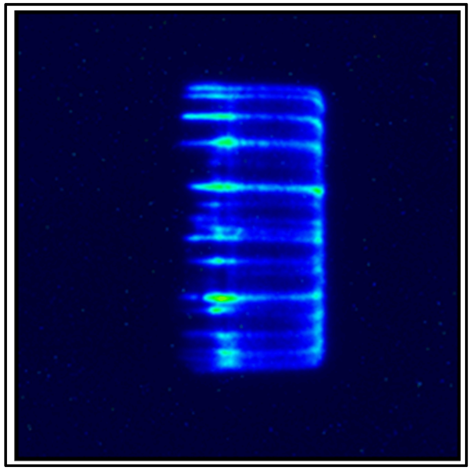




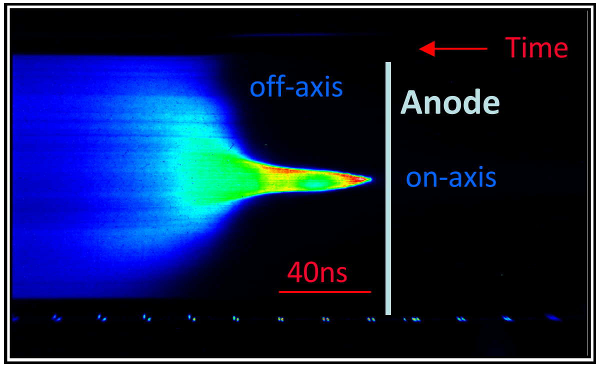
Optical Framing Camera Image



Axial Plasma Expansion at Centerline



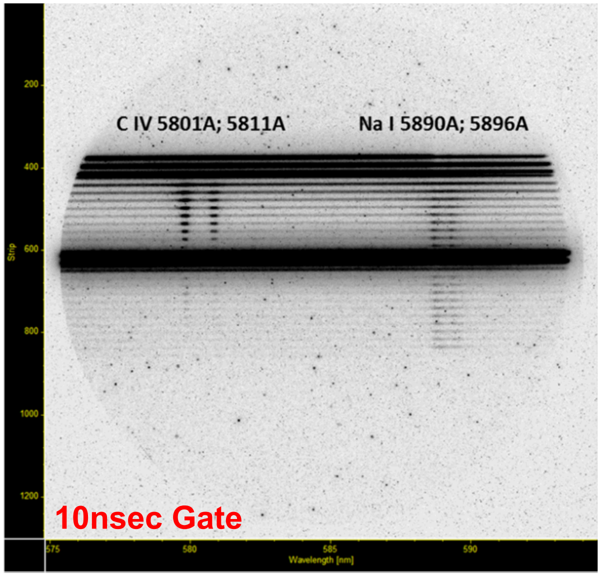
Cathode Filamentation



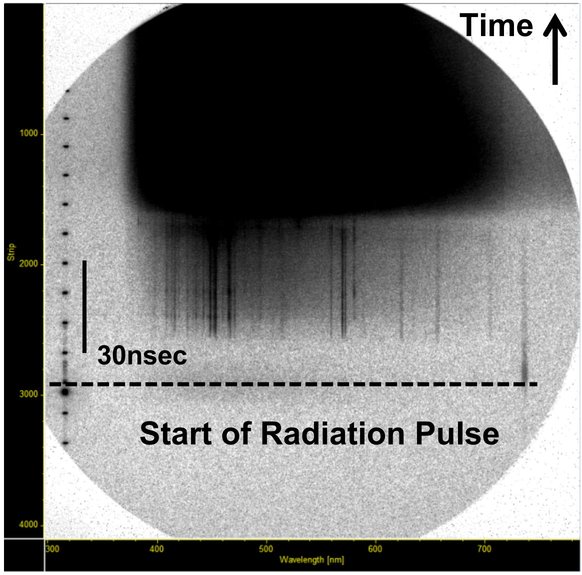
Radial Plasma Expansion near Anode

Plasma Measurements taken on the SMP Diode

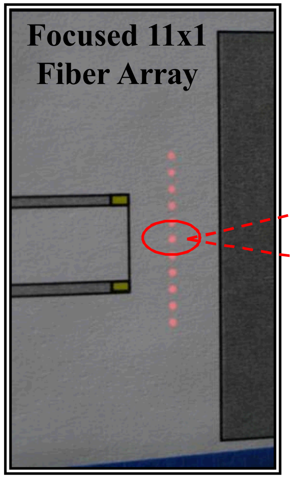
- Multi-Fiber Gated spectra
- Streaked spectra
- Avalanche Photodiodes

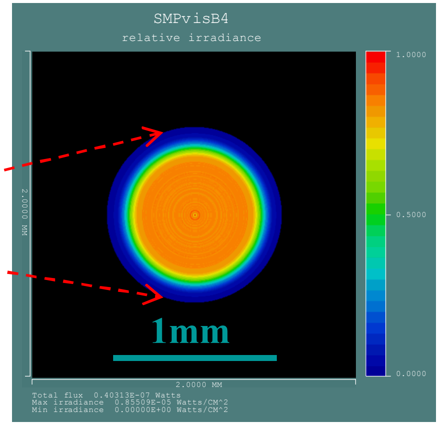


High Spectral Resolution (0.5A)

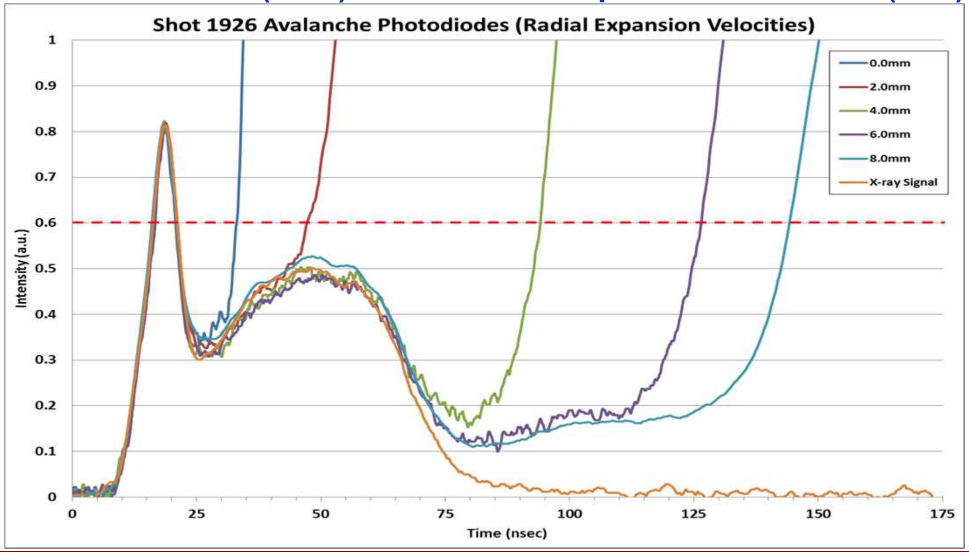


Lower Spectral Resolution (10A)



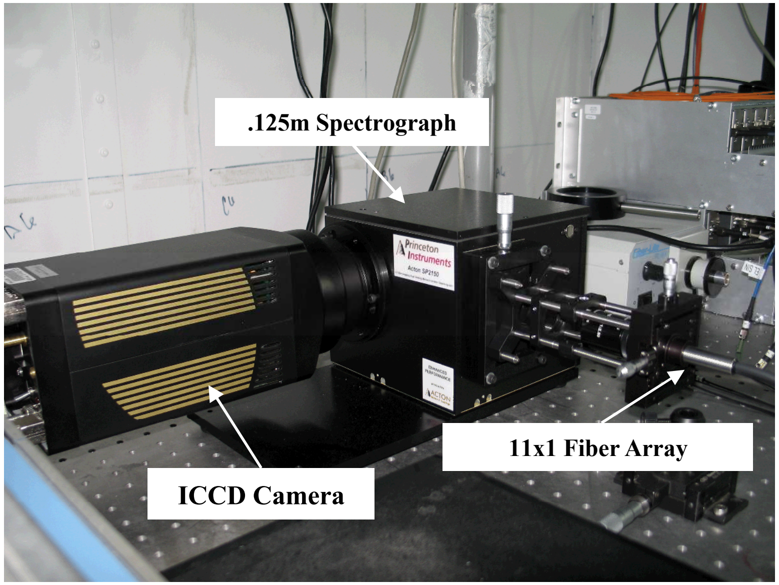


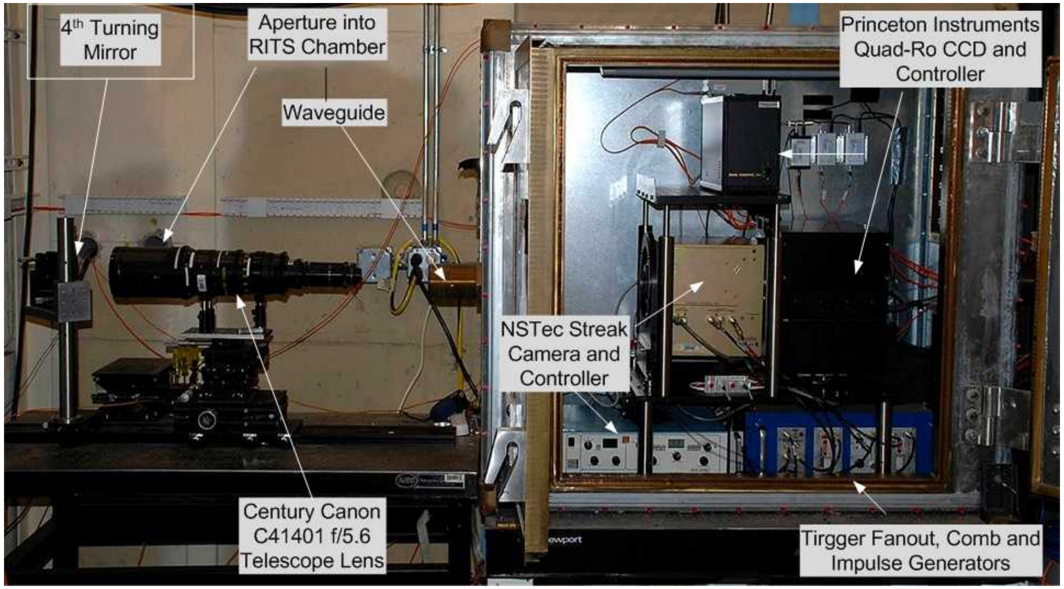
Fiber Focal Spot Size

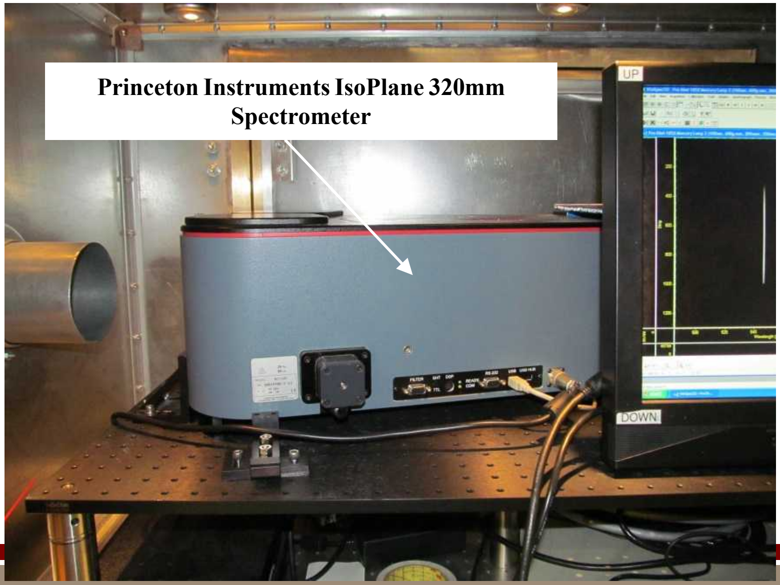


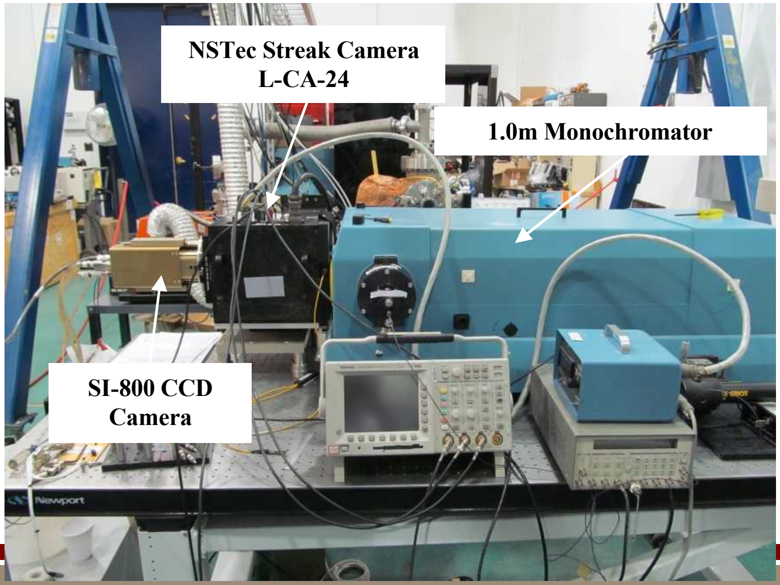
Imaging and Spectral Diagnostics on RITS-6

Spectrographs and ICCD/Streak Cameras

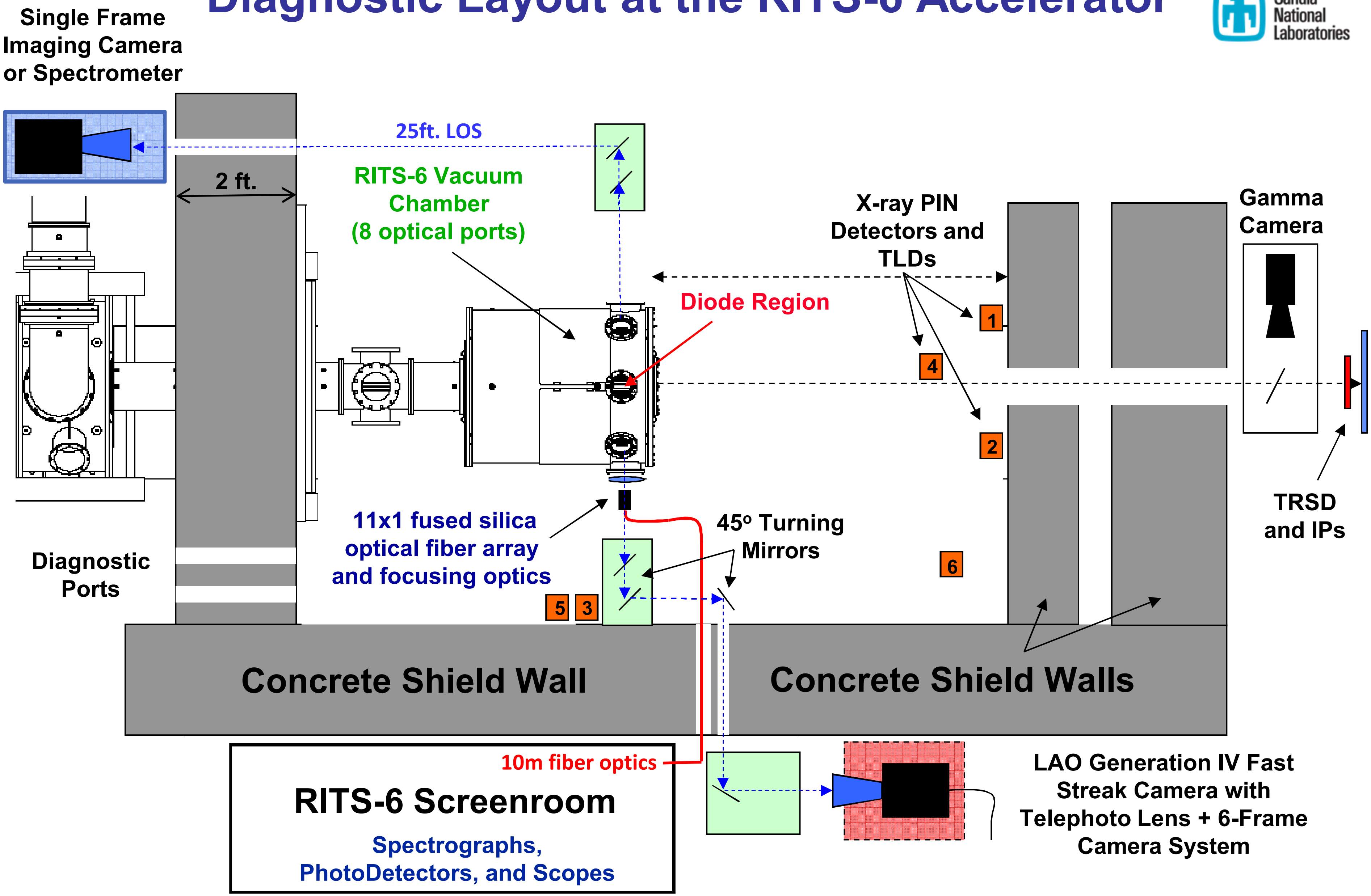








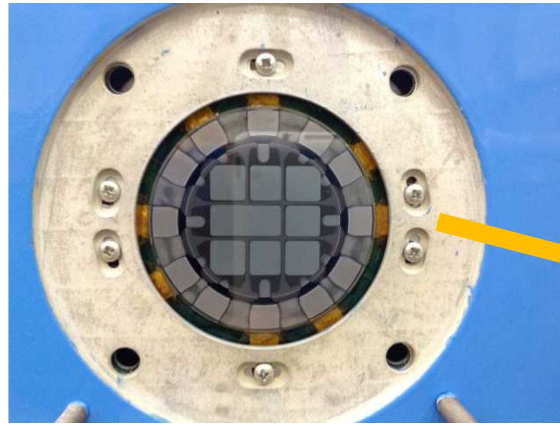
Diagnostic Layout at the RITS-6 Accelerator

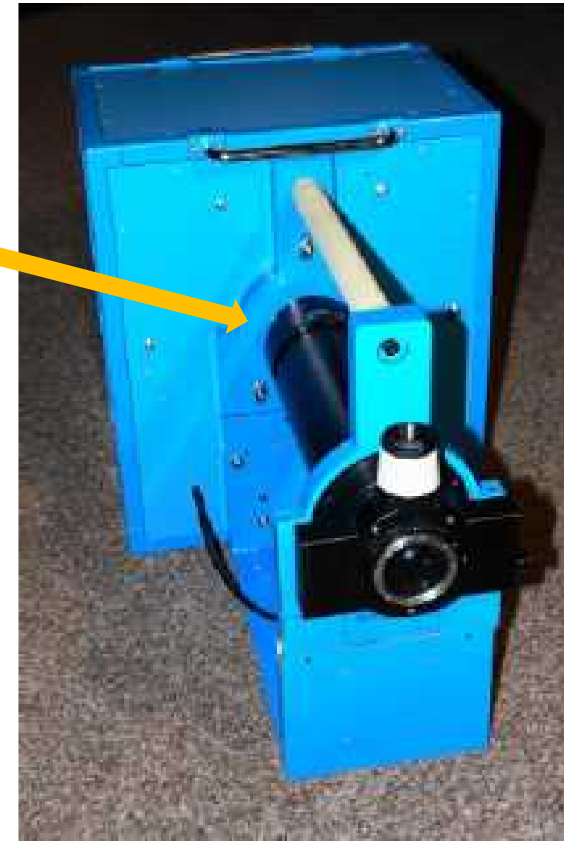


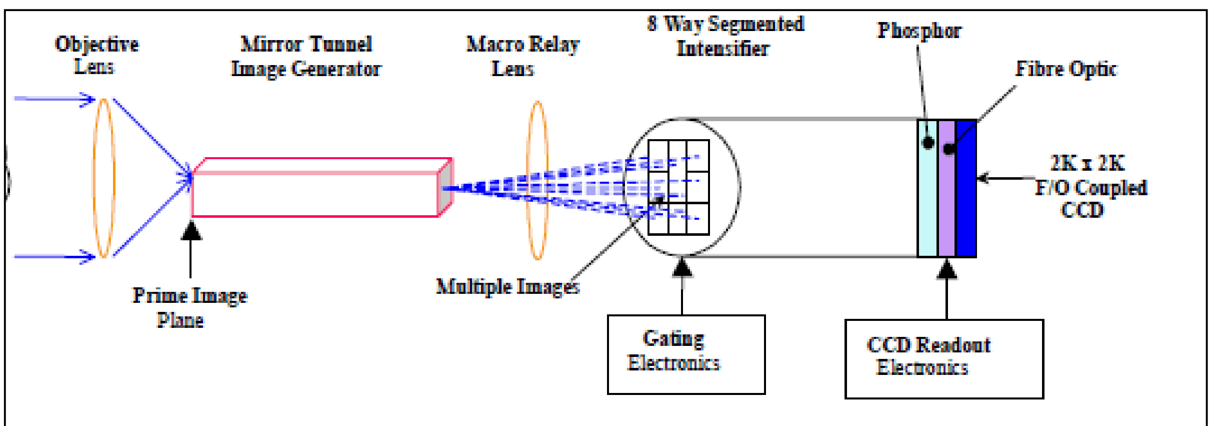
Photek Ultra8 Multi-Frame Camera System

Photek Ultra8 Multiframe Camera*

- 40mm 8-way Image Intensifier
- Gen II Intensifier
- S20 Photocathode
- P43 Phosphor Screen
- Fiber Optic Input Window
- 2K x 2K CCD array
- 650 x 650 Individual Frames
- Factor of 1000 gain
- 12 bit imaging
- 2ns minimum exposure
- 9% Peak Quantum Efficiency

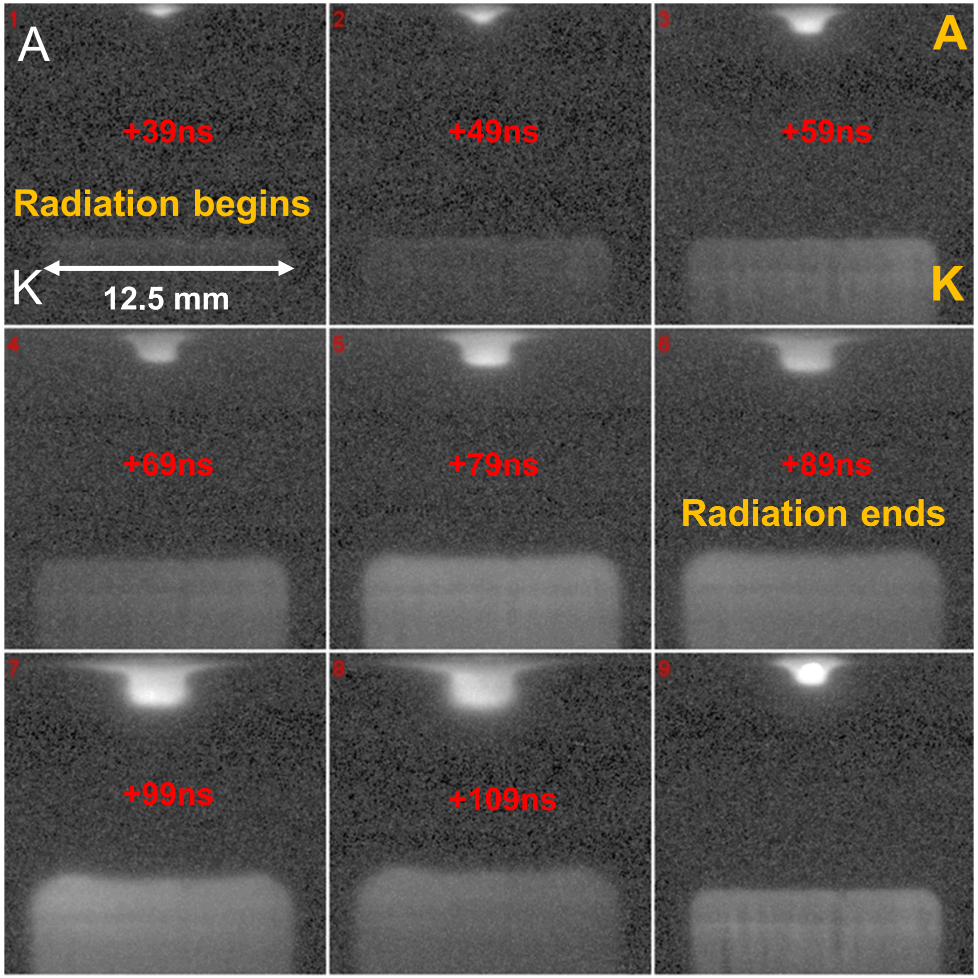




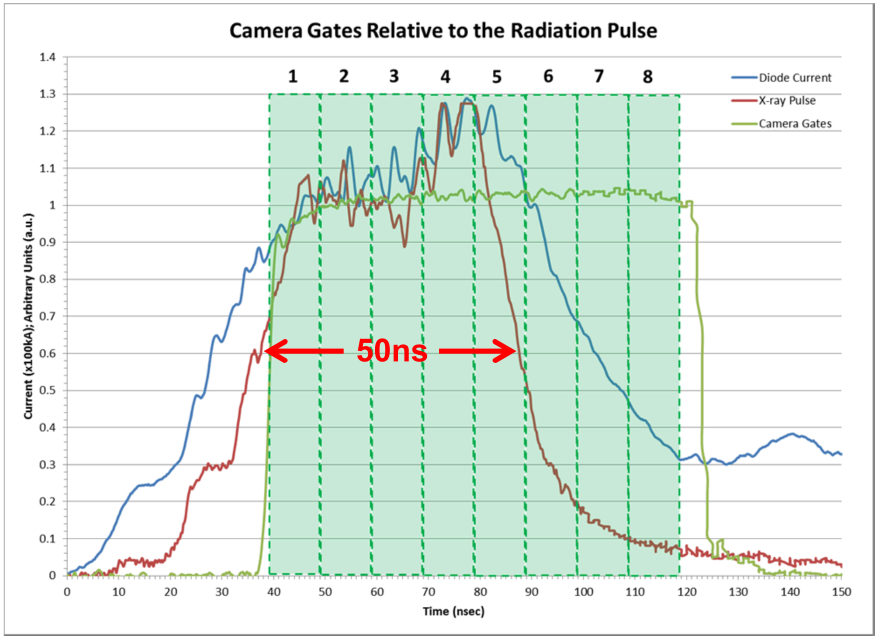


*G.W. Smith, et al., *Proc. of SPIE,* Vol. 7126, p. 712603-1.

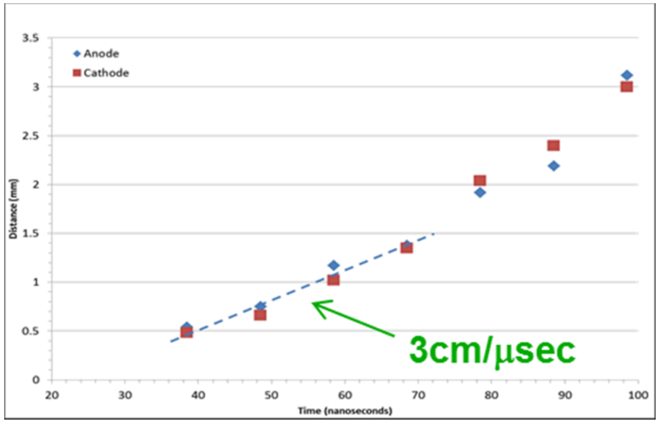
Optical emission and spectroscopy on RITS reveals plasma structure, apparent closure velocities



*10ns gates



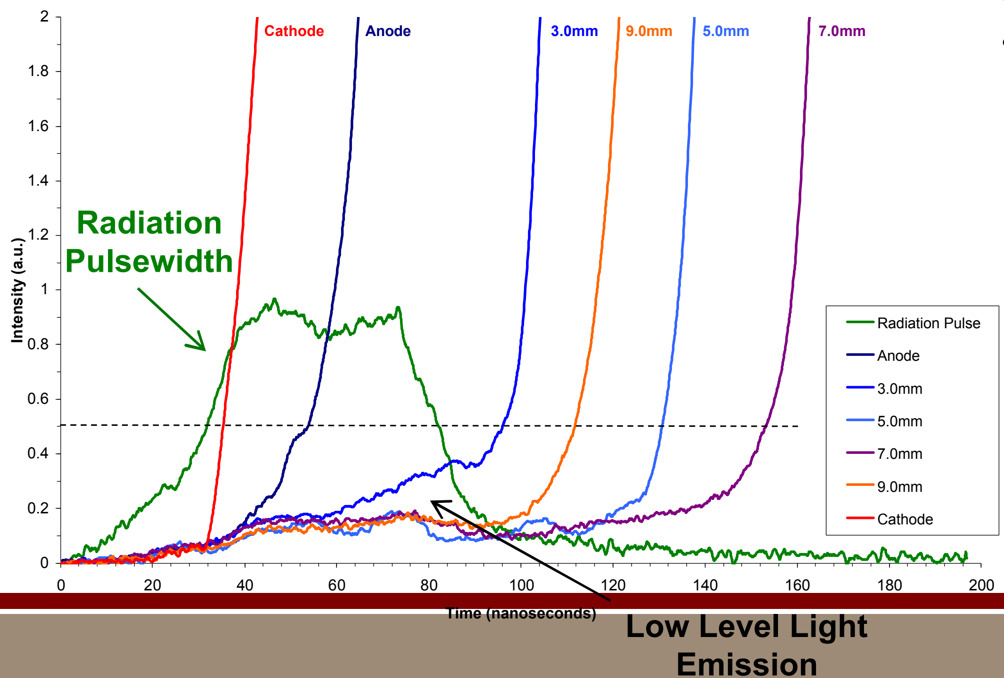
FWHM of Radiation Pulse: 50ns



Plasma Measurements using Silicon Avalanche Photodetectors

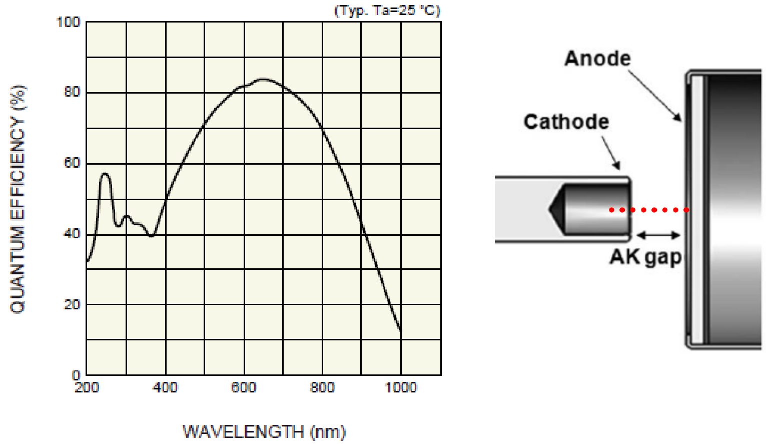
Anode Expansion Velocity: 4.8-8.7cm/μsec

Cathode Expansion Velocity: 2.6-4.8cm/μsec



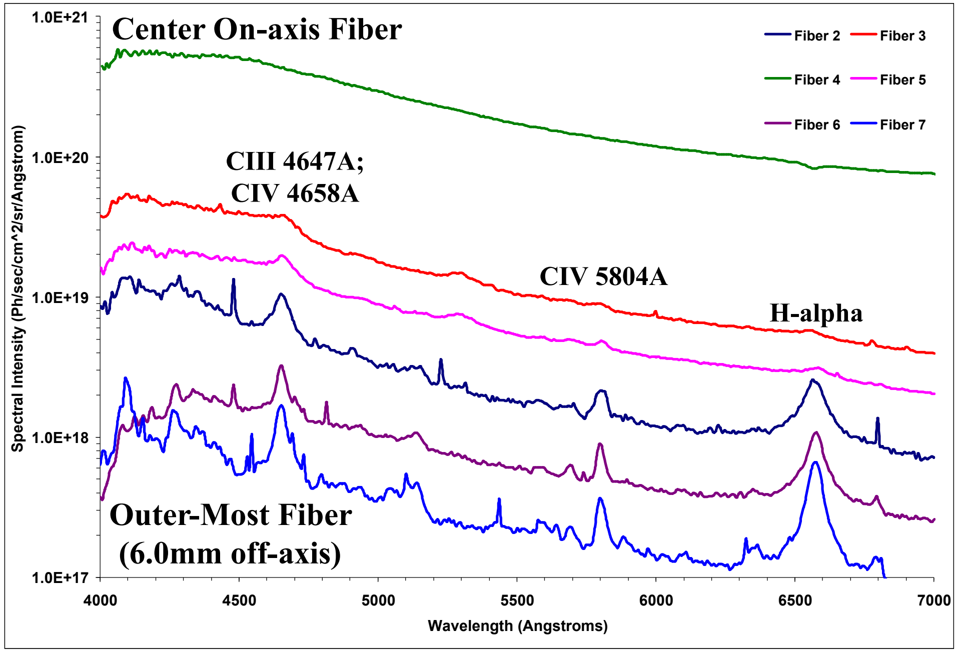
NSTec Model H-EO-53 Avalanche Photodiode

- 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)

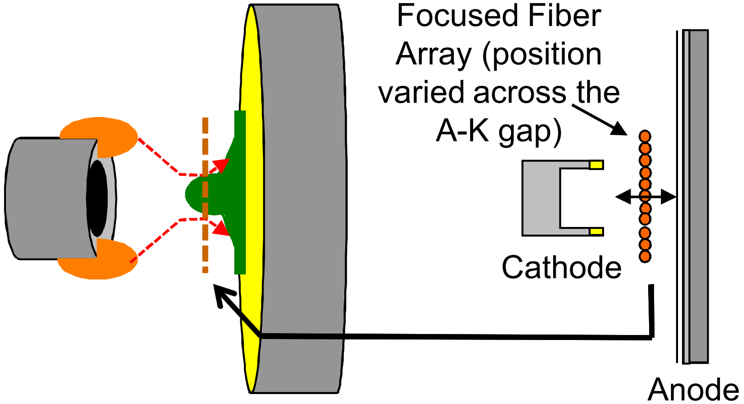


Detailed Visible Emission Spectroscopy and Analysis Reveals the Density, Composition, Evolution, and Structure of the Anode Plasma

- 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?



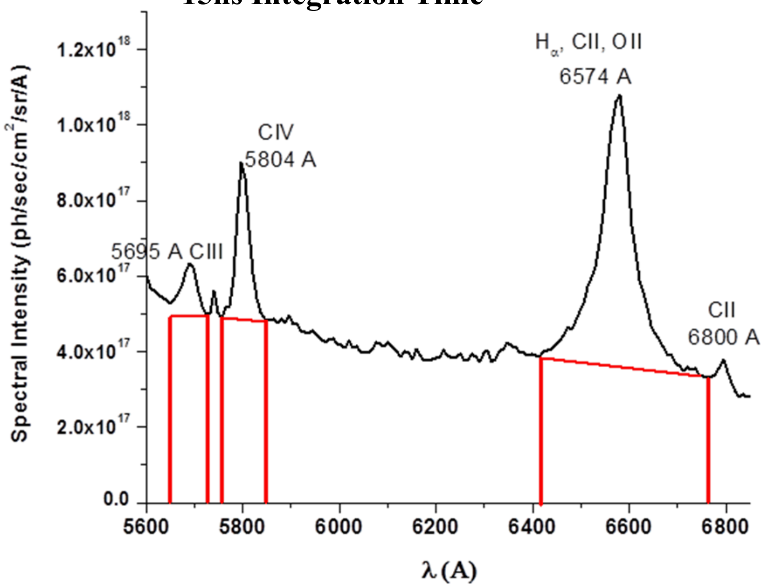
15ns Integration Time

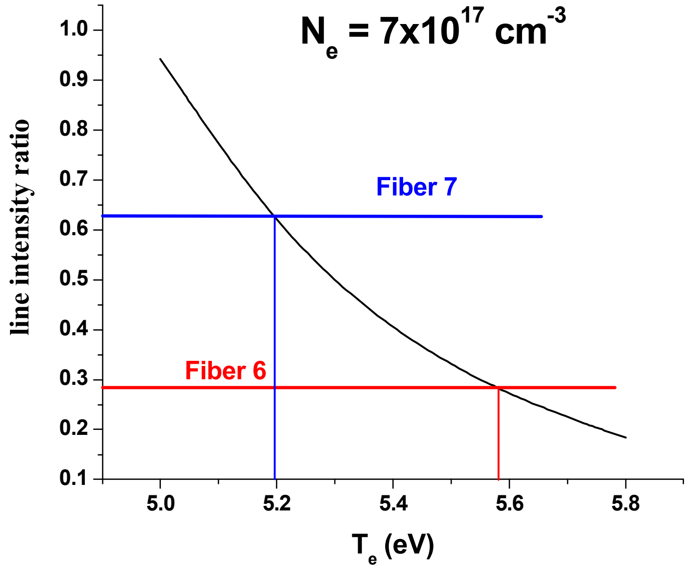


Carbon Ion Lines Observed

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

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



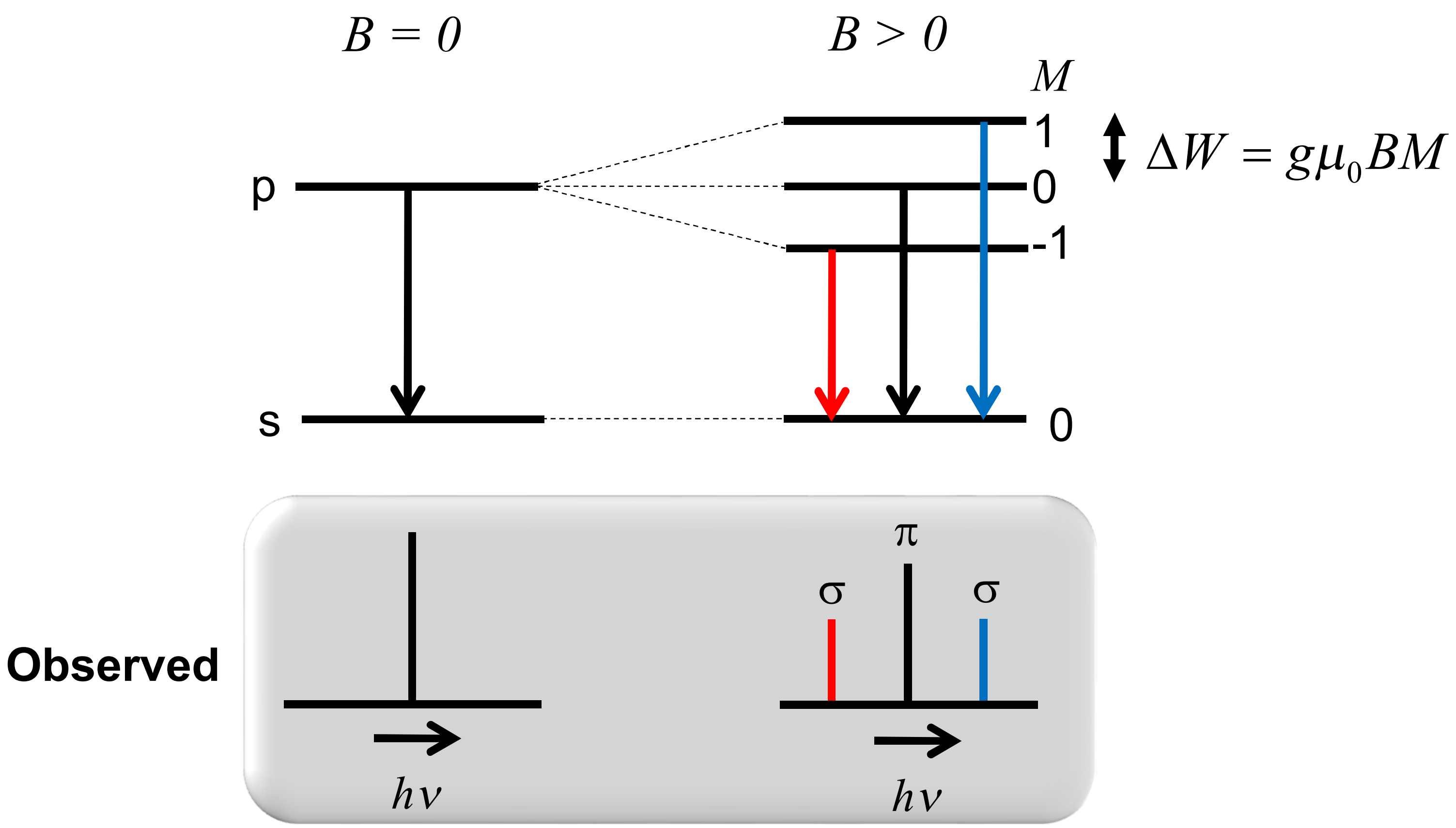


Fiber 6 (4.0mm off-axis on the anode surface)

N_e from H-alpha:	$1.1x10^{18}$ cm^{-3}	
N_e from Continuum:	$6.1x10^{17}$ cm^{-3}	
Electron Temp. (T_e):	5.6eV	
$N_{hydrogen}$ (Z = 1):	$3.2x10^{17}$ cm^{-3}	**(28%)**
N_{carbon} (Z = 2.9):	$4.0x10^{16}$ cm^{-3}	**(10%)**
$N_{e(oxygen\ and\ Al)}$:	$7.0x10^{17}$ cm^{-3}	**(62%)**

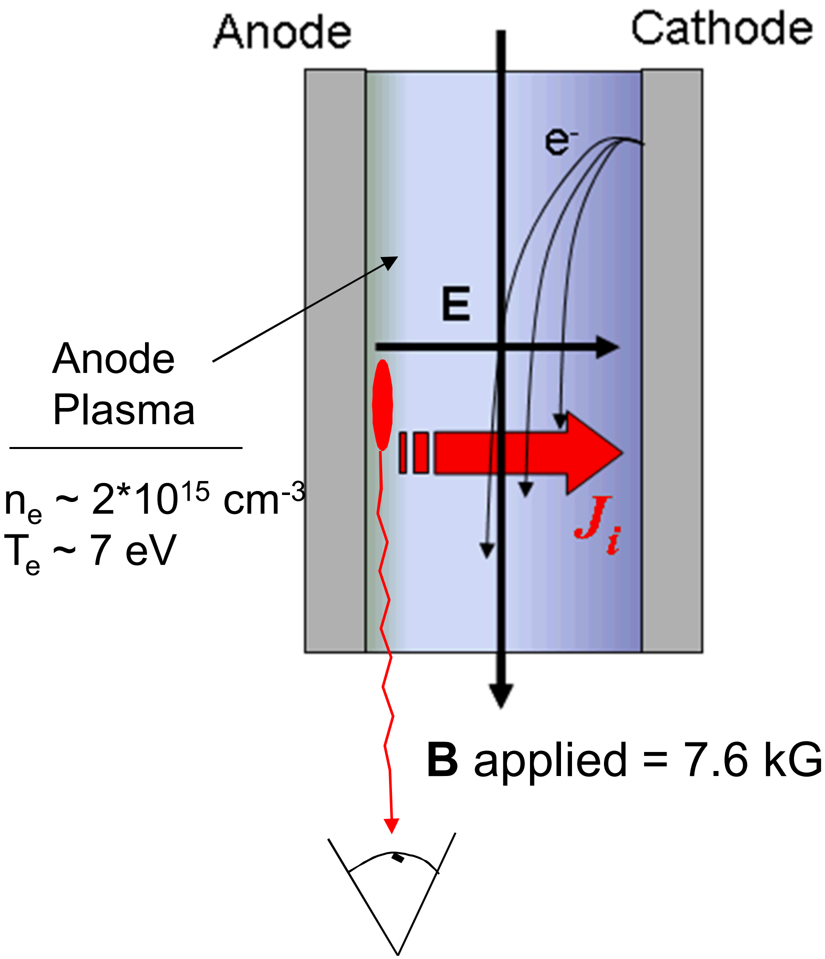
Plasma parameters are determined through comparisons of line ratios, line broadenings, and absolute continuum intensity measurements.

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



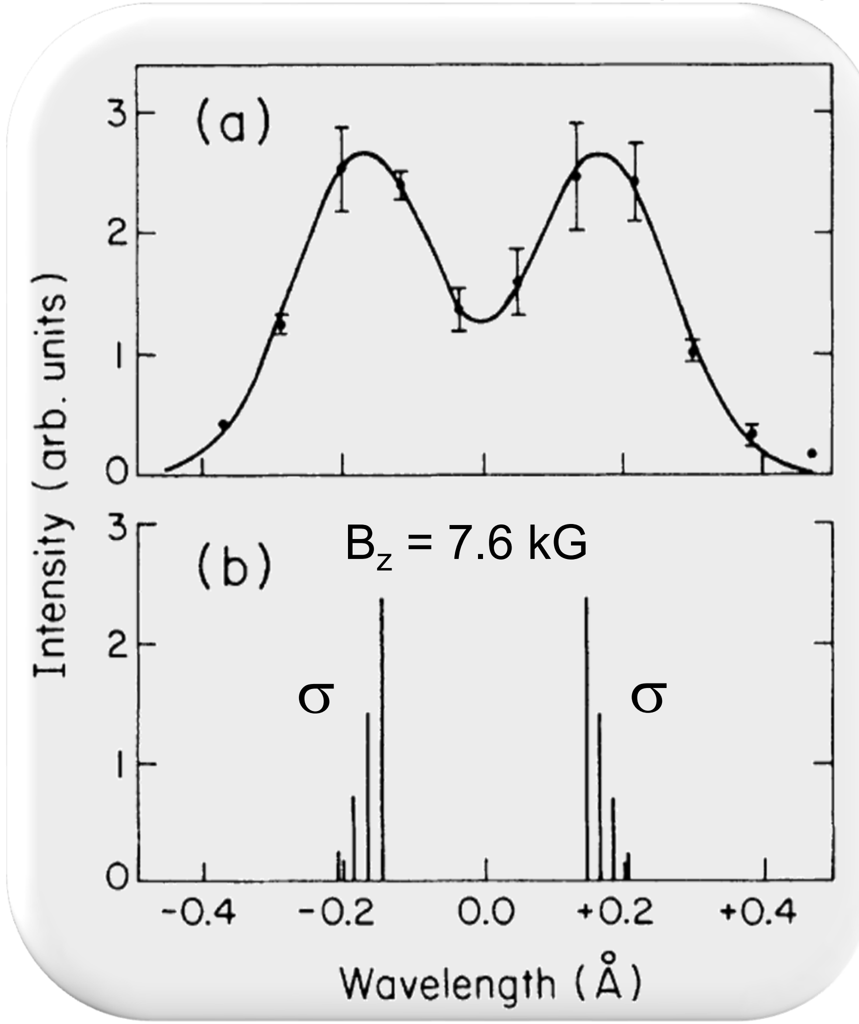
$$h\Delta\nu = \mu_0 B\left(g_u M_u - g_l M_l\right), \begin{bmatrix} \Delta M = 0, & \pi \\ \Delta M = \pm 1, & \sigma \end{bmatrix}$$

Zeeman Splitting was Used to Measure the B-field Penetration in an Ion Acceleration Gap[3]



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

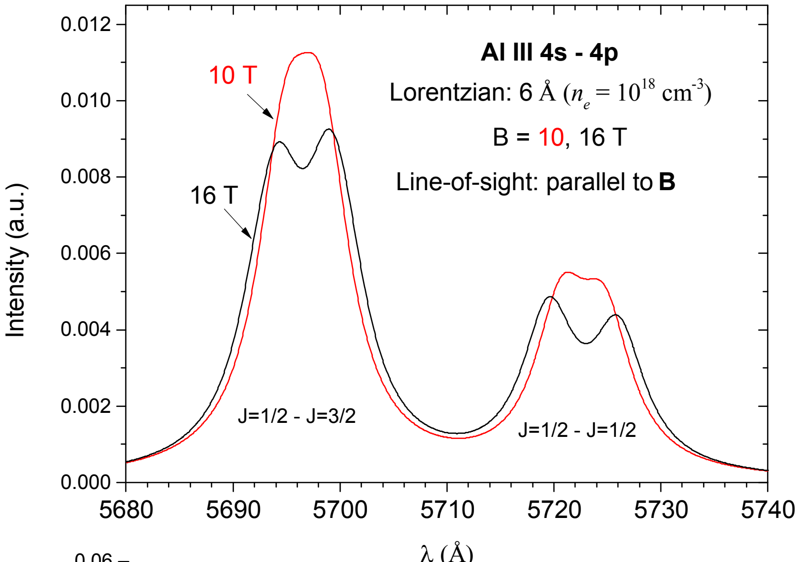
Zeeman split Ba^{1+} 5d – 6p (6142 Å)



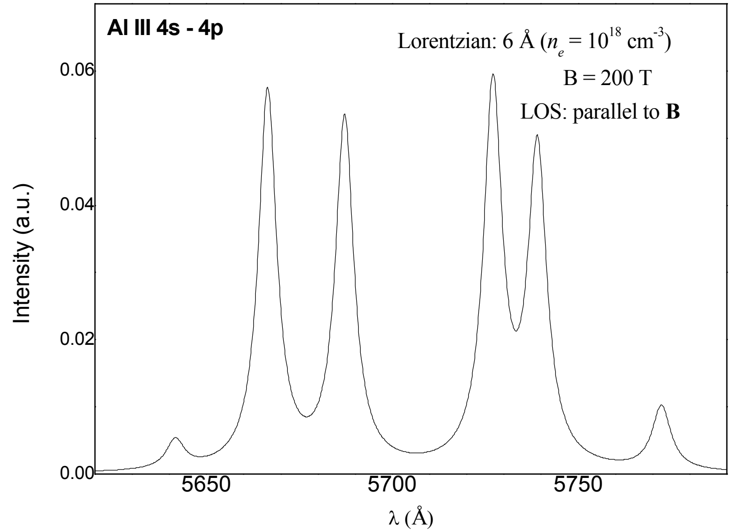
[3] Y. Maron et. al., Physical Review A, <u>39</u>, p. 5856-5862 (1989).

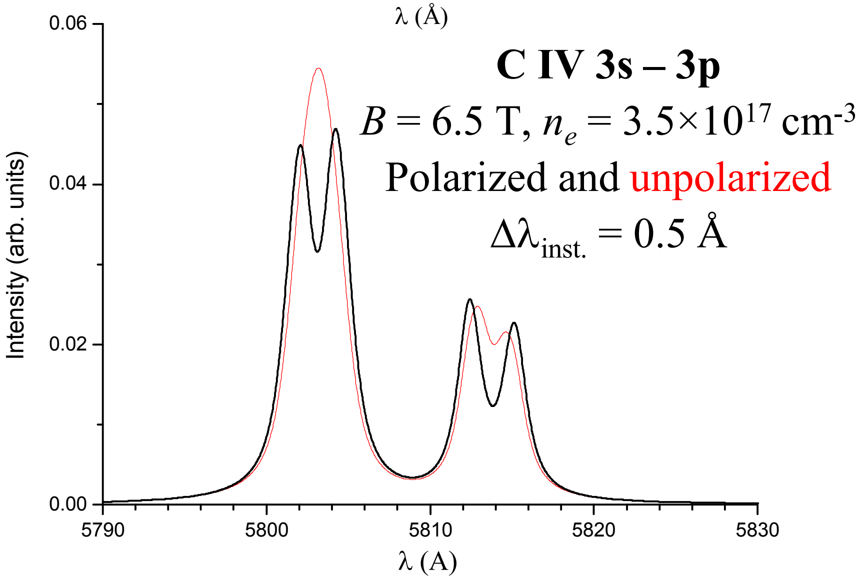
Aluminum and Carbon are Good Candidates for Measuring B-fields in the SMP Diode

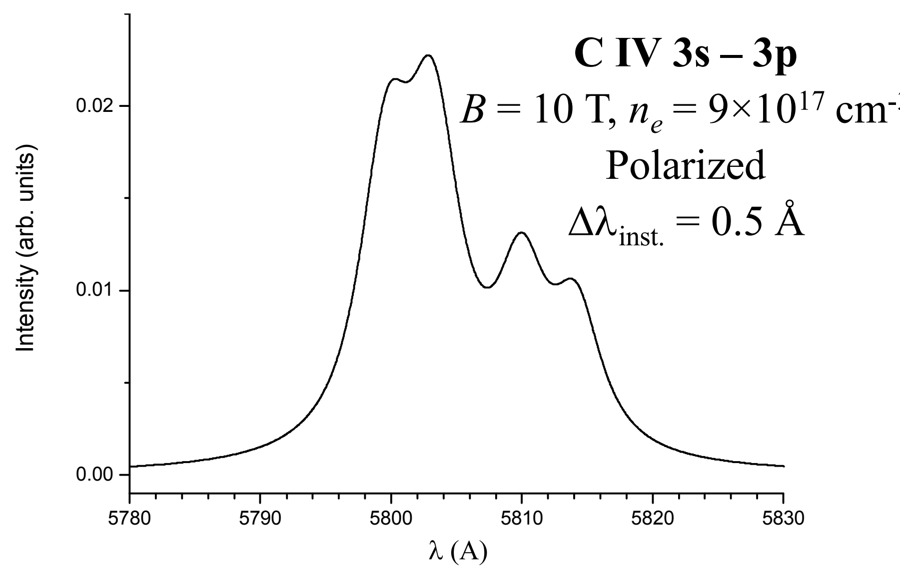
N_e 10^{18} cm^{-3}; B_Φ = 10-16 Tesla



N_e 10^{18} cm^{-3}; B_Φ = 200 Tesla







Aluminum and Carbon Line Analysis

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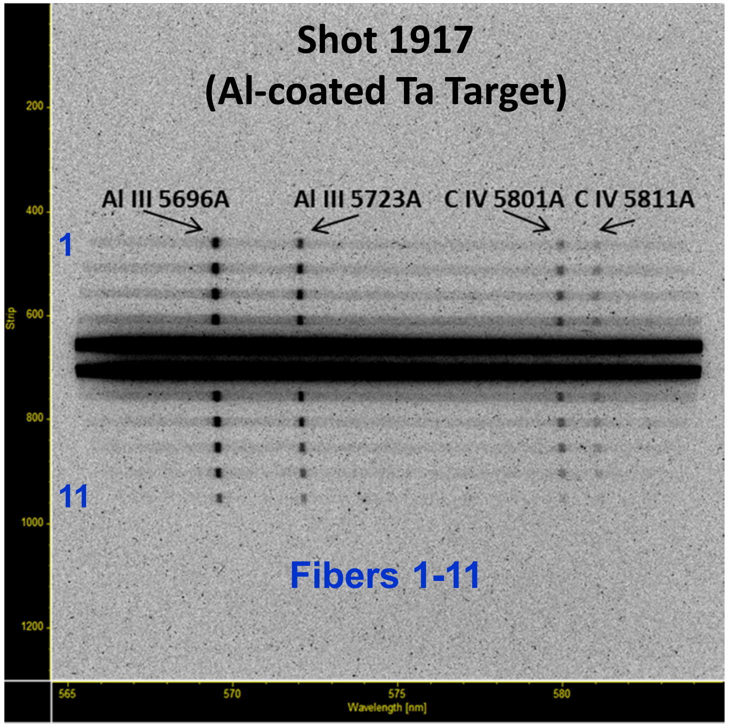

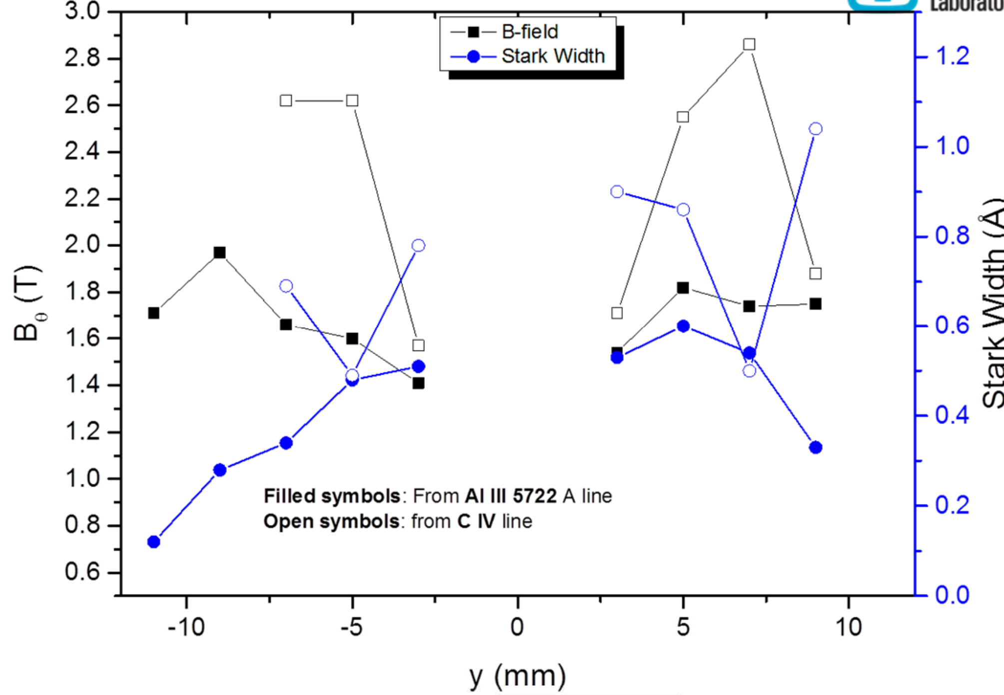

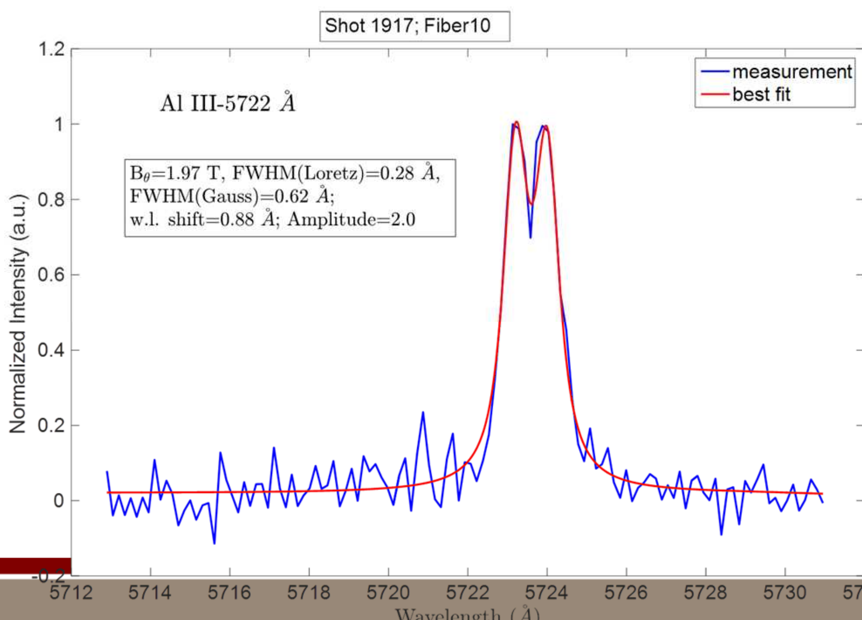

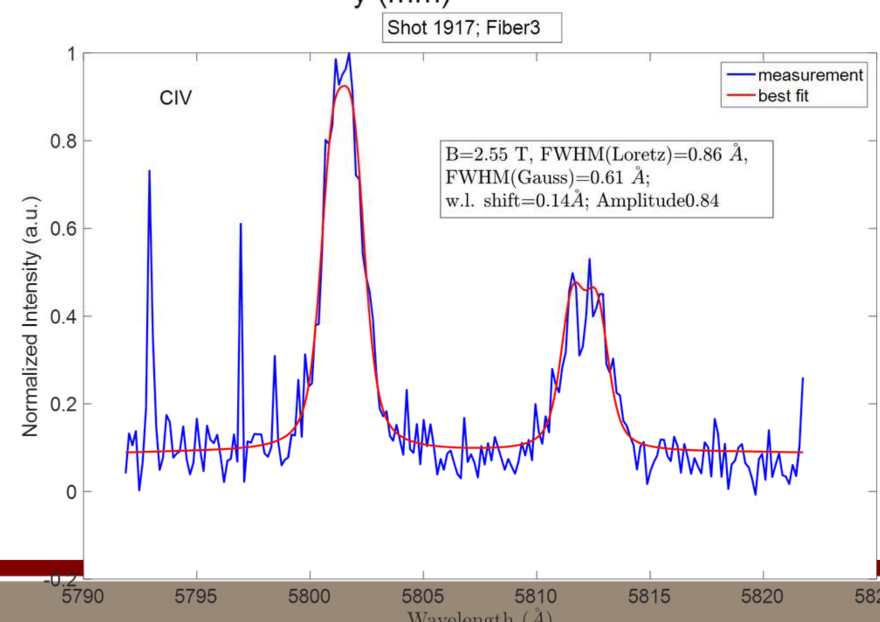

Aluminum and Carbon Line Analysis using Double Fiber Array

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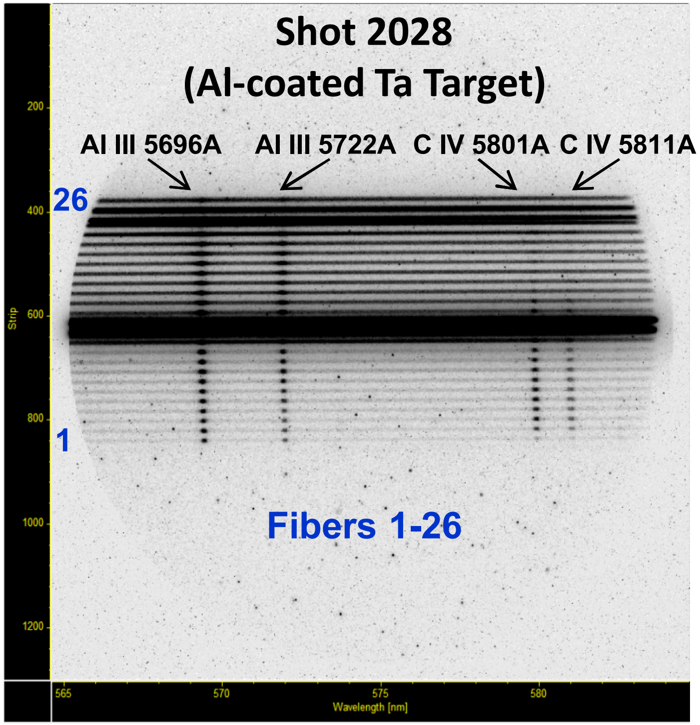
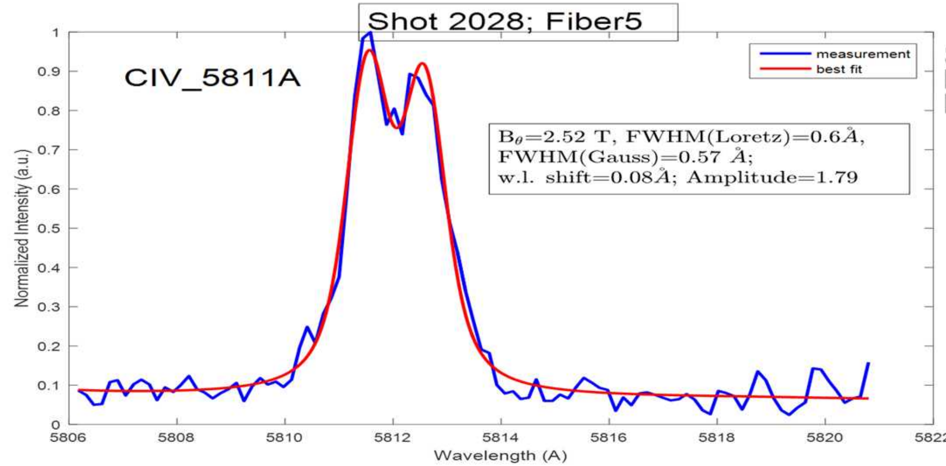
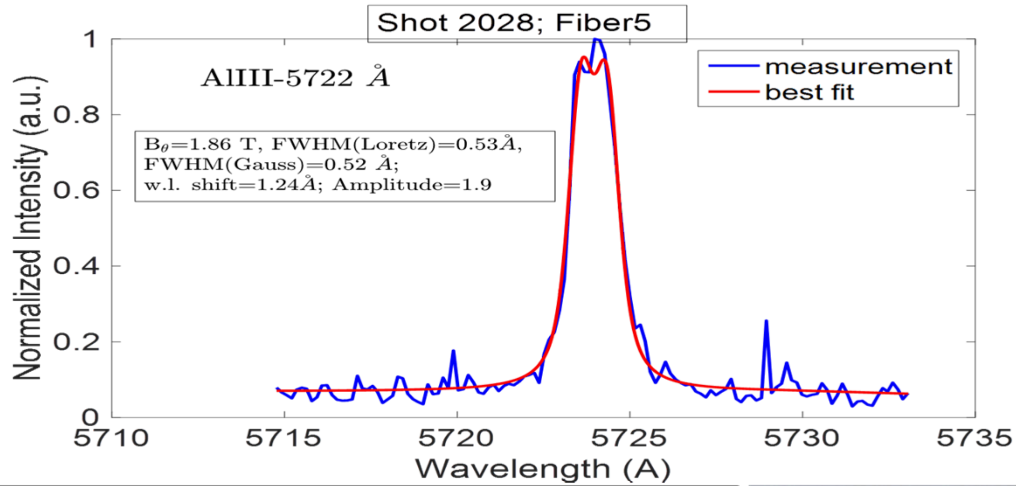
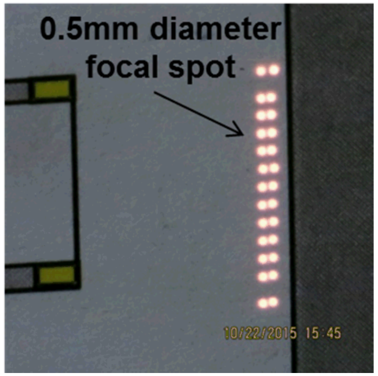
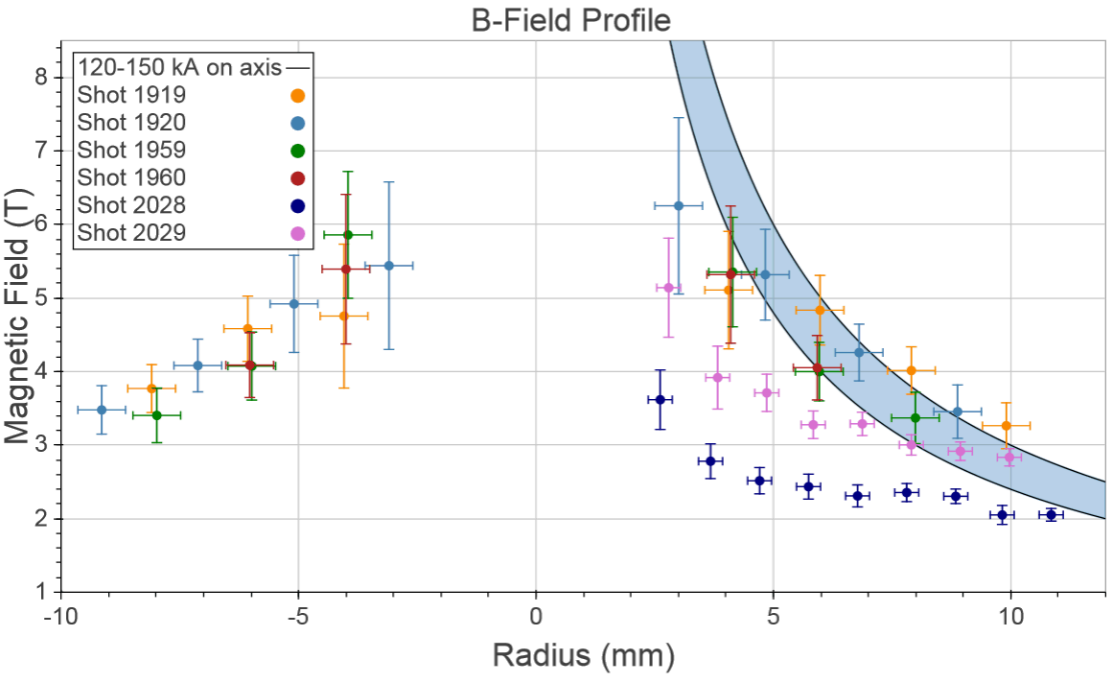






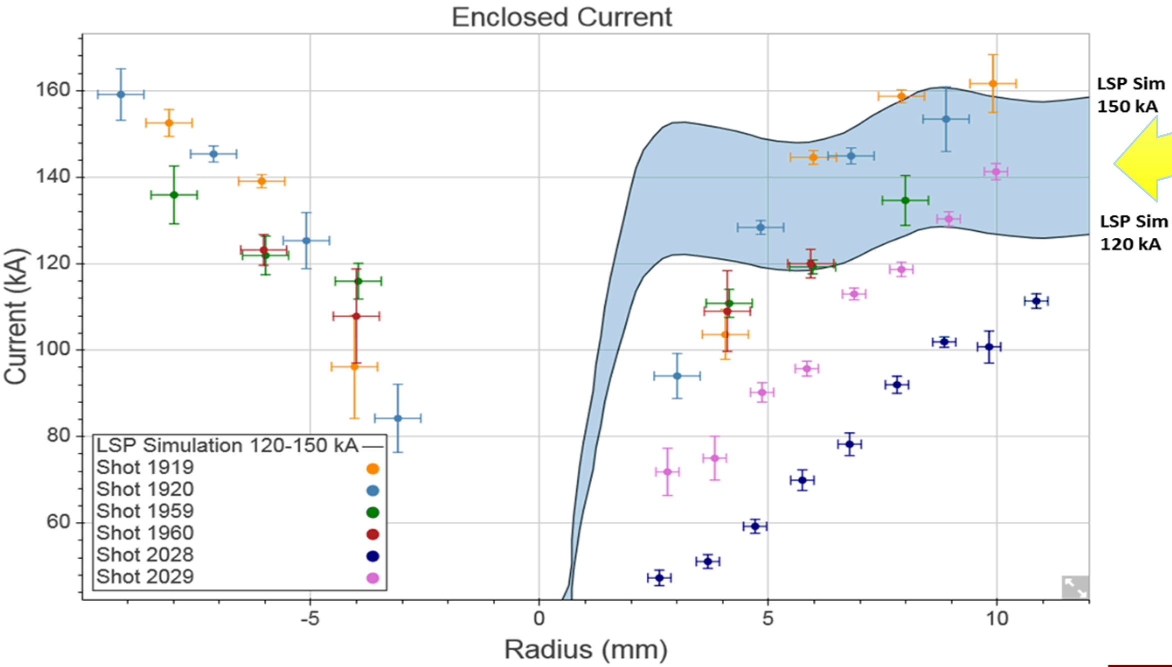
Fiber No	B_θ (T) from			N_e ($\times 10^{17}$ cm^{-3}) from		
	Al III 5722A	C IV 5801 A	C IV 5811 A	Al III 5722A	C IV 5801 A	C IV 5811 A
Fiber 5	1.86	2.2	2.5	0.9	1.4	1.5
Fiber 18	<1.5	-	-	2.4	-	-

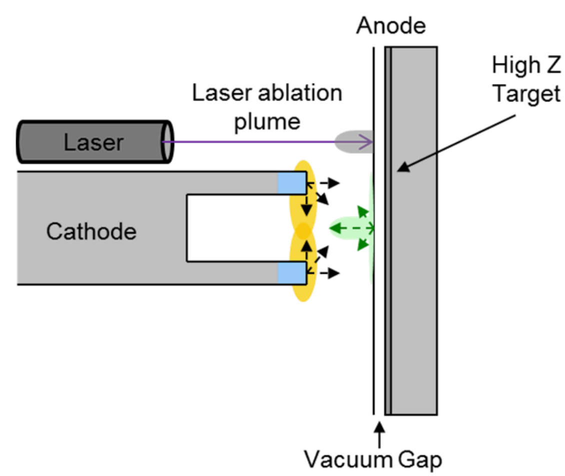




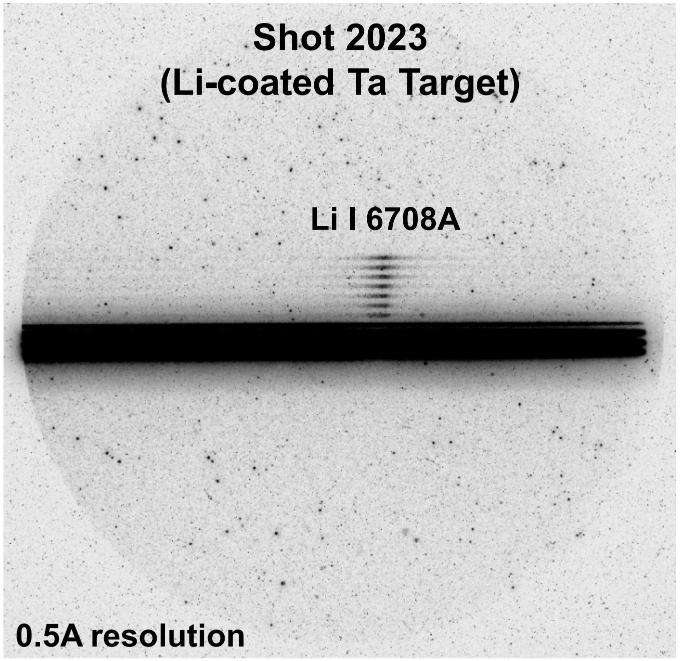
- Enclosed current increases roughly linearly with radius
- Symmetric measurements.
- LSP simulation for a standard foil SMP diode (scaled to match shot current of 120-150 kA)
  - Suggests more of the current is enclosed within a few mm region than the splitting measurements would suggest.

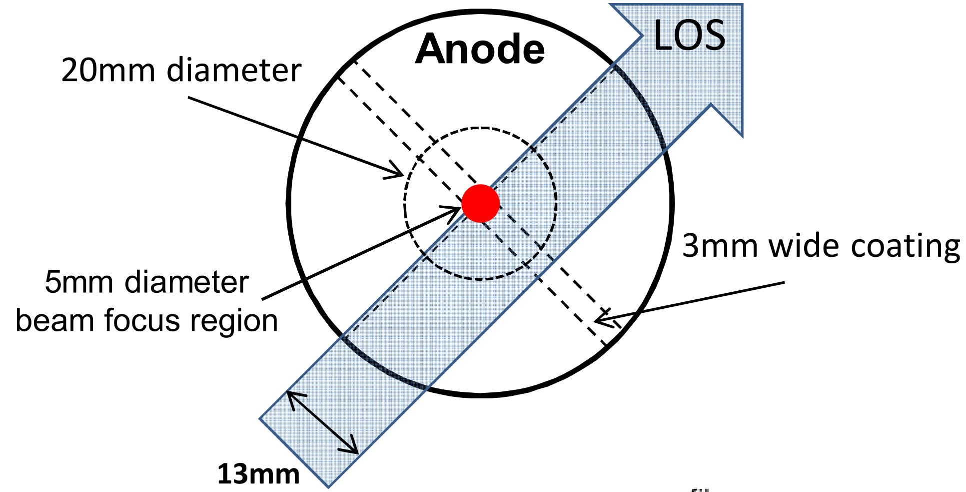
$$B = \frac{\mu_o I}{2\pi r}$$

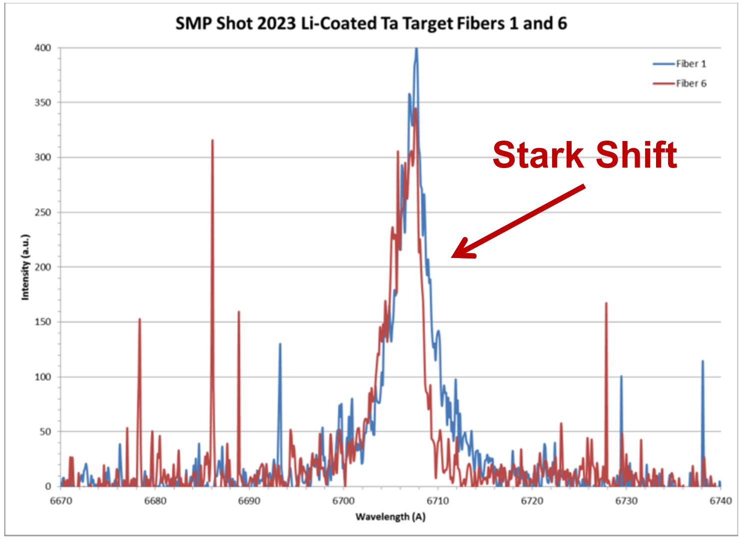




Electric Field Measurements







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.

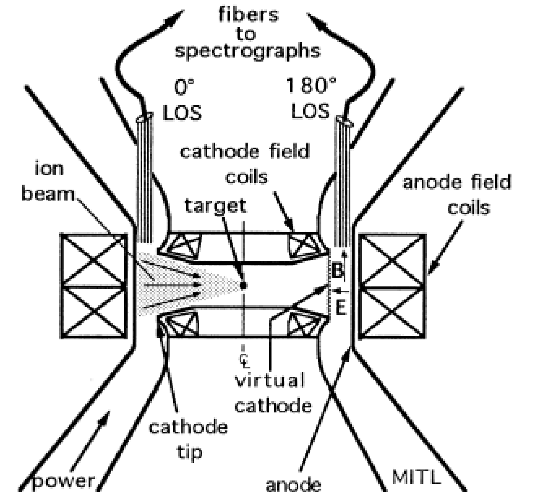


FIG. 1. Schematic of the PBFA II ion diode. The diode is cylindrically symmetric about the center line C_L and spectroscopic lines of sight (LOS) are located in two azimuths at 0° and 180°.

J. Bailey et al., Phys. Rev. Lett., 74, 1771 (1995).

Summary and Conclusions

- Measurements of local magnetic fields in the SMP diode have been performed. Changes in the magnetic fields have been determined over very small (0.5mm) spatial extents. These measurements yield current distributions in the diode and the return current flow in the plasma.
- A new technique[4], 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.
- Measurements of the magnetic field provide needed information regarding local current distributions in the diode.
- 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.

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

Future Work

- Continue developing techniques to analyze spectral data, which take into account opacities, impurities, signal to noise, line emission, absorption, and continua effects.

- Want to map magnetic fields and currents further into the A-K gap. This will require greater signal to noise.

- Want to implement streaked spectra at high resolution to be able to record the time evolution of the B-fields in a single shot.

- Further explore Stark shifts to measure E-fields in the diode as a function of time and space with high spectral resolution.

- Use these techniques on other pulsed-power platforms such as Ursa Minor, Mykonos, and Z.