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Electrode Plasma Measurements in High Intensity Electron Beam Diodes

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Abstract

Experiments are being performed on the Self-Magnetic Pinch (SMP) electron beam diode[1] on the RITS-6 accelerator at Sandia National Laboratories. This diode produces a tightly focused electron beam (< 3mm diameter) which is incident on a high atomic number bremsstrahlung x-ray converter. Typical diode parameters are 120 kA, 7 MeV, and 70ns current pulse, giving a ~45ns x-ray pulse. Plasmas from contaminants on the electrode surfaces propagate into the A-K vacuum gap, affecting the impedance, x-ray spectrum, and pulse width. These plasmas are measured using diagnostics, which include: spectroscopy, optical imaging, and photodetection, to obtain velocity, density, and temperature information. These parameters are measured both spatially using multi-fiber arrays and temporally using streak cameras and avalanche photodiodes. Plasma densities and temperatures are determined from detailed, time-dependent, collisional-radiative and radiation transport models, which include Stark broadening of the hydrogen-alpha transition line and carbon ion line ratios. These results are combined with hybrid PIC/fluid simulations to model the plasma's overall behavior. Densities of up to 10^19 cm-3 have been measured on the electrode surfaces, decreasing by several orders of magnitude both radially and axially across the vacuum gap. Electrode plasma expansion velocities of up to 10 cm/microsecond correlate well with the decreasing impedance profile (~0.5 Ohms/ns) observed during the pulse.

[1]K. Hahn, N. Bruner, M.D. Johnston, B.V. Oliver, et. al, *IEEE TRANSACTIONS ON PLASMA SCIENCE*, VOL. 38, NO. 10, OCTOBER 2010, pp.2652-62.

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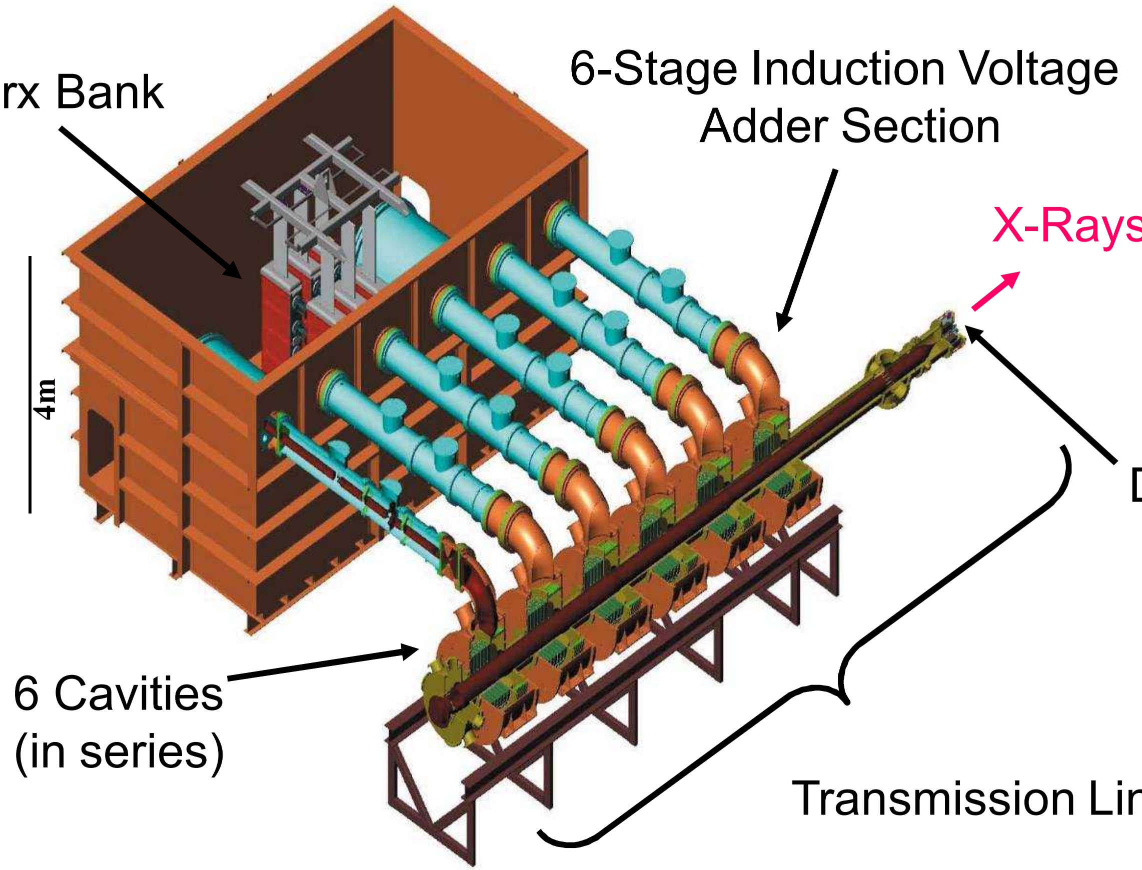
Outline

- RITS-6 Accelerator and the Self-Magnetic Pinch (SMP) Diode.
- Plasma Simulations of the Self-Magnetic Pinch Diode.
- Motivation for Plasma Spectroscopy Experiments.
- Optical Diagnostic Layout on RITS.
- Summary of Data.
    - Streak Camera
    - Avalanche Photodetectors
    - Spectroscopy
- Plasma Parameters Inferred from Spectral Analyses
- Summary

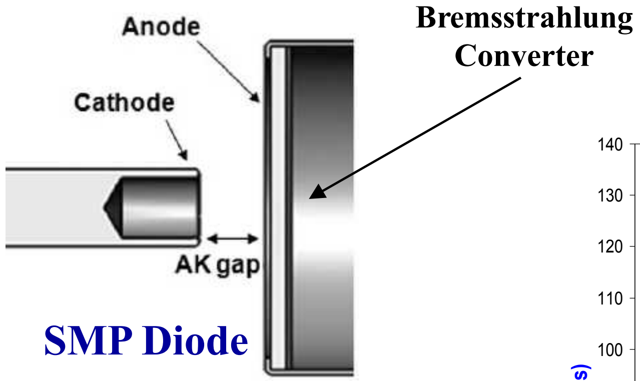
RITS-6 Accelerator at Sandia National Laboratories

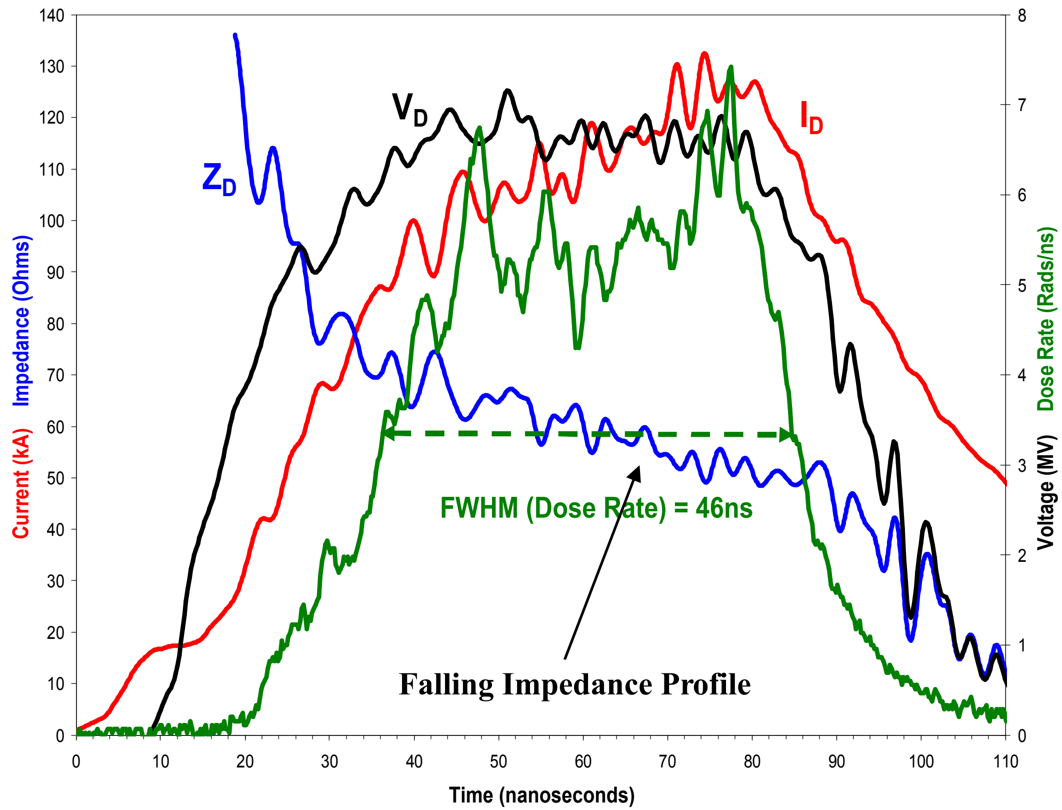
RITS-6 is a 5-11.5 MeV Marx driven six-stage Inductive Voltage Adder (IVA) machine, capable of driving a variety of electron beam diodes[2].



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

Self-Magnetic Pinch (SMP) Diode Electrical Characteristics





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

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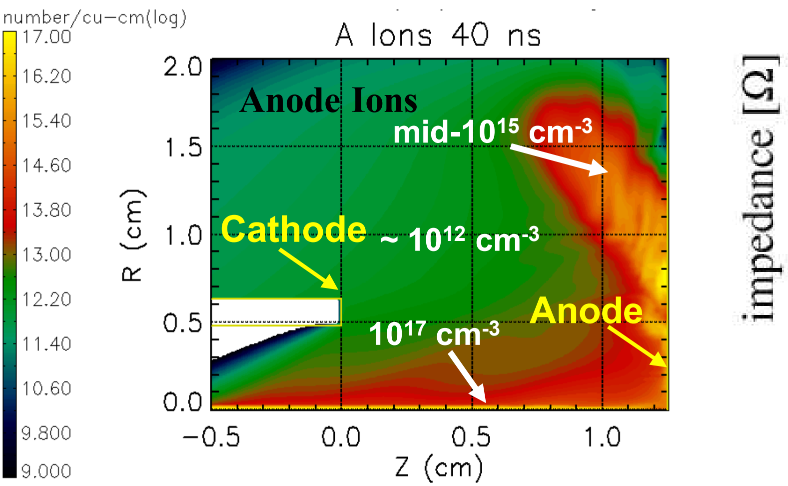
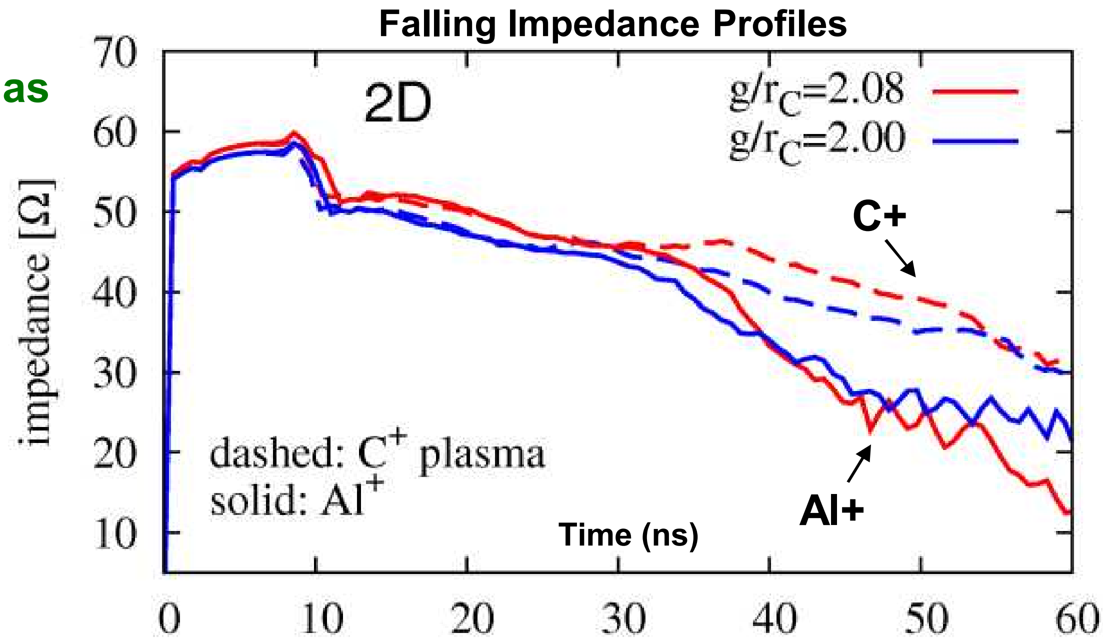
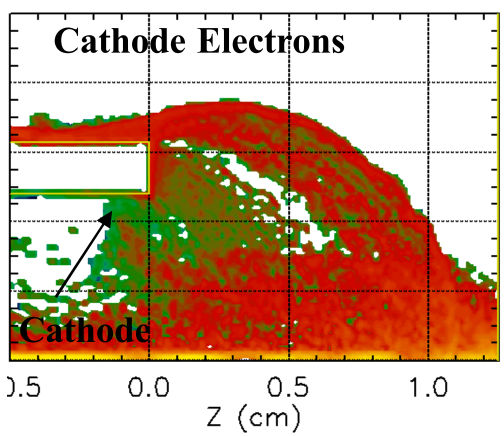
SMP Diode LSP Simulations[3]

Simulations of Evolving Plasmas







- LSP simulations predict variations in plasma density of up to 5 orders of magnitude during a ~50ns radiation pulse, and a falling impedance due to gap closure. Gap closure occurs at a rate of ~10cm/μsec, dependent on species.
- Simulations predicts a more rapid impedance collapse for Al due to excess ion charge buildup (~10^{14} cm^{-3} species) around the cathode.
- Variations in impedance behavior are affected by changes in both species and geometry (g/r_c).

[3]N. Bruner, D.R. Welch, K.D. Hahn, and B.V. Oliver, *Phys. Rev. ST Accel. Beams*, Vol. 14, 024401 (2011).

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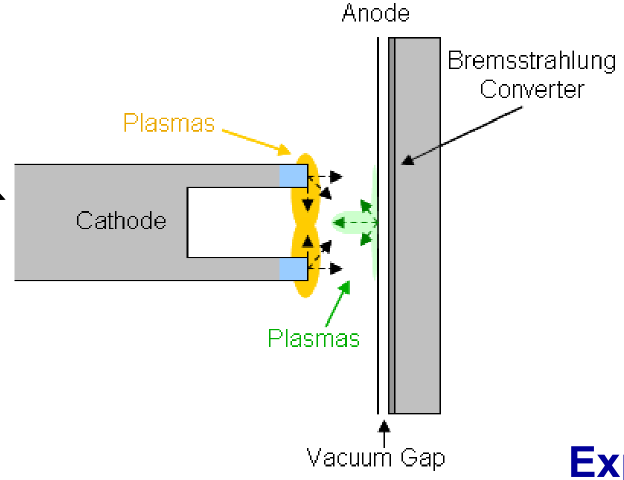
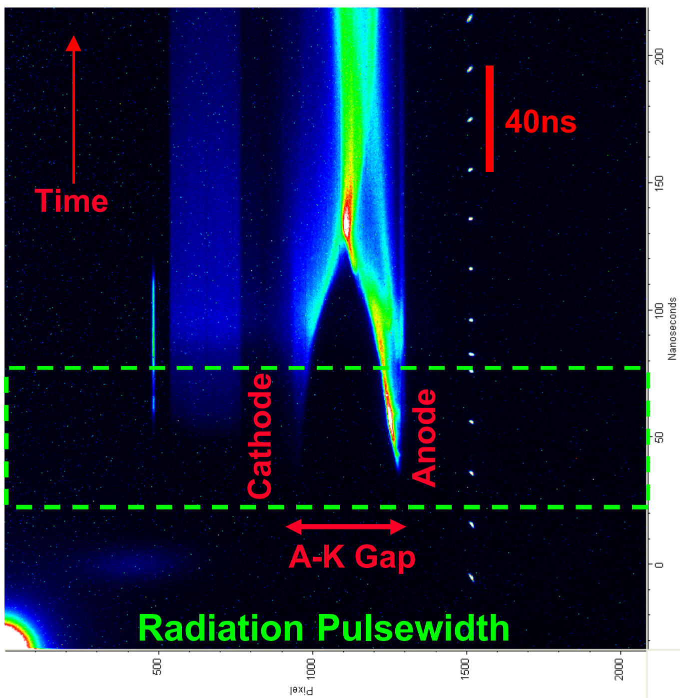
Role of Plasma Spectroscopy Experiments

Illustration of electrode plasmas in the vacuum A-K gap of the SMP diode.

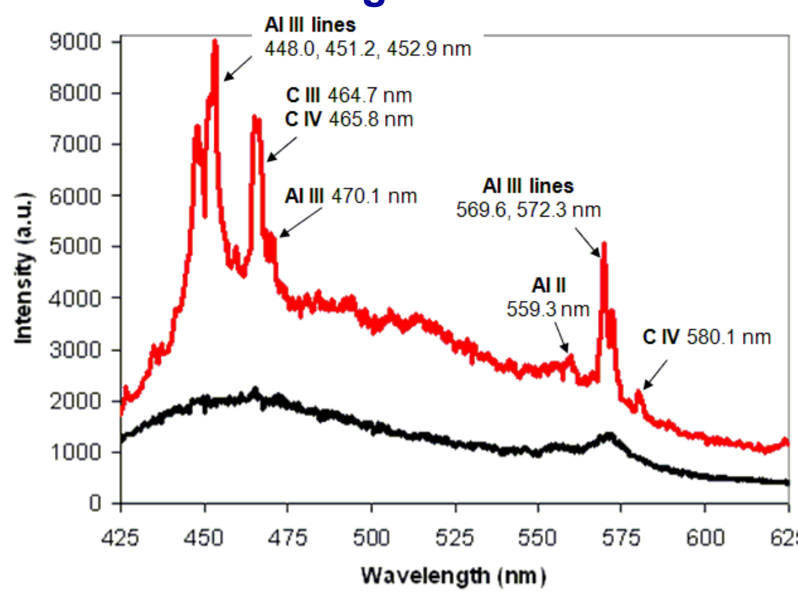


Model Predicted from Theory and Simulations

Imaging of Electrode Plasmas



Experimental Spectra of Imaged Plasmas



Plasma diagnostics provide validation for simulations!

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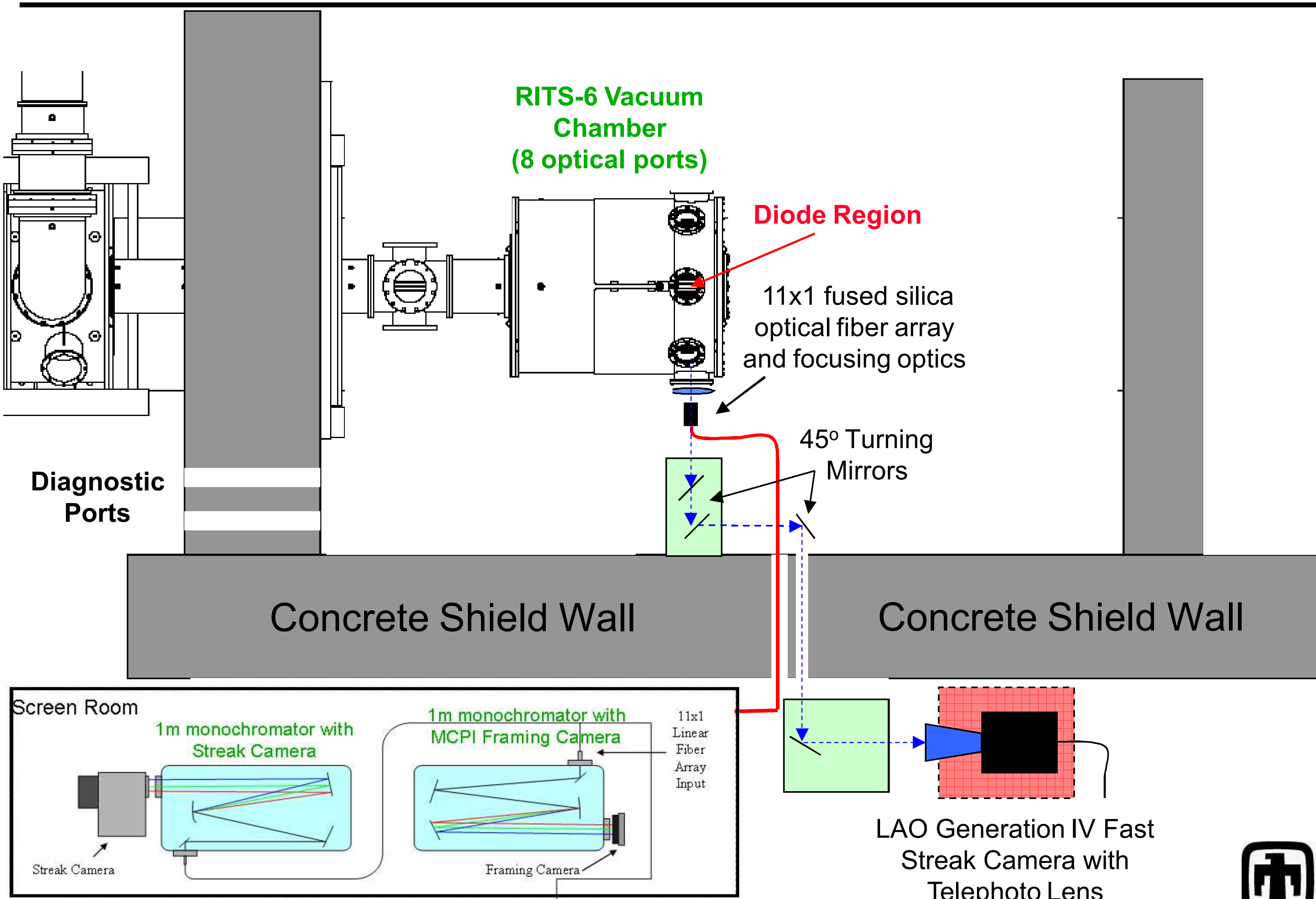
Optical Diagnostic Layout on the RITS-6 Accelerator



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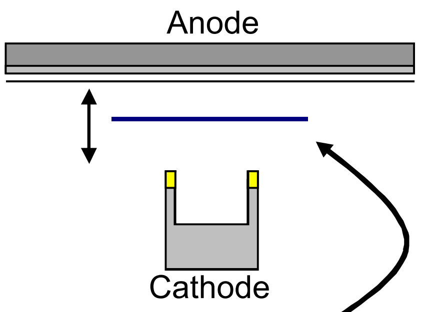
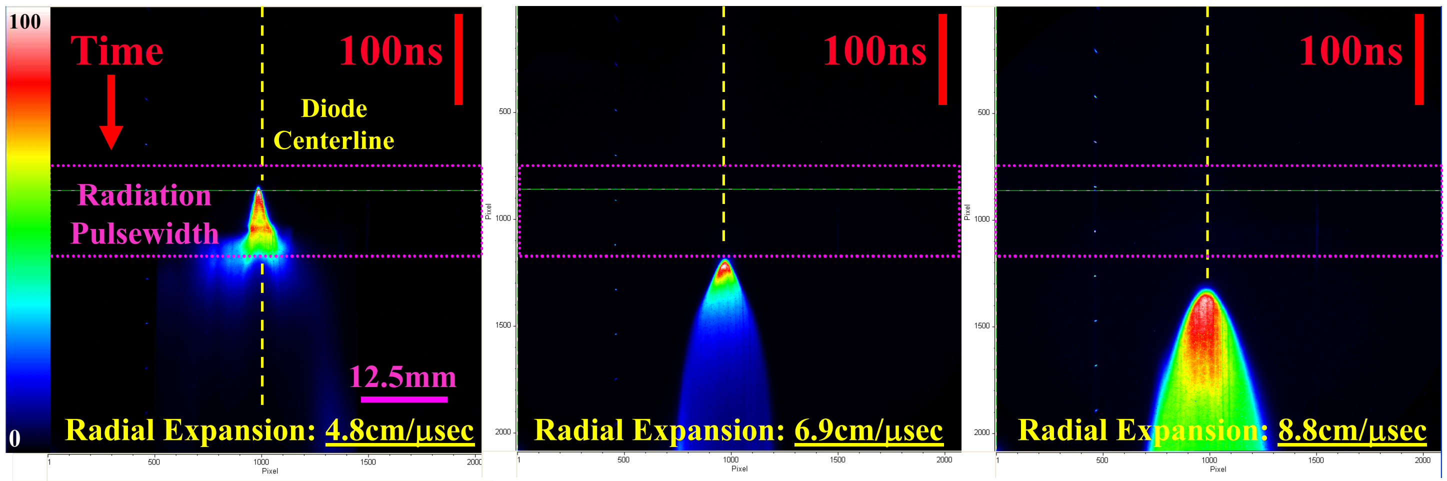
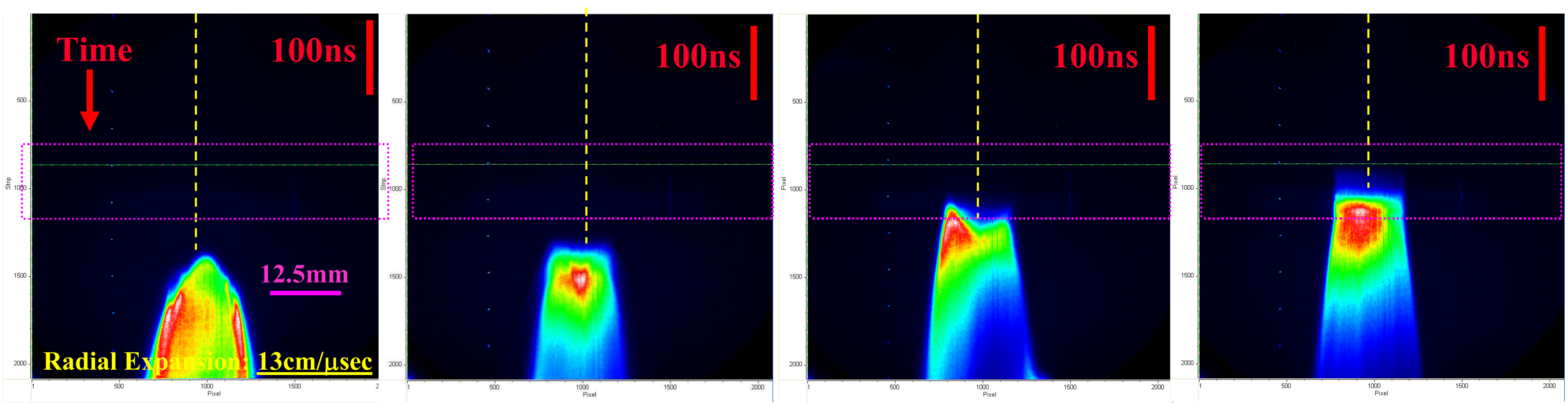
Streak Camera Images (Slit Positioned Radially at Different Axial Positions across the A-K Gap)





Anode Surface | 1/6 Gap | 1/3 Gap



Mid-Gap | 2/3 Gap | 5/6 Gap | Cathode Surface

Plasma Expansion Velocity across A-K Gap: 5-10cm/µsec

*Data taken on different shots

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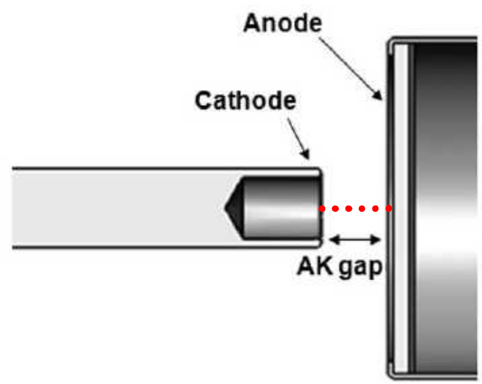
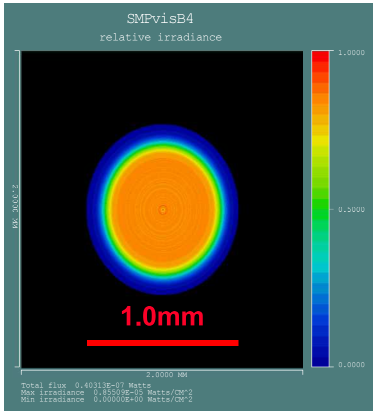
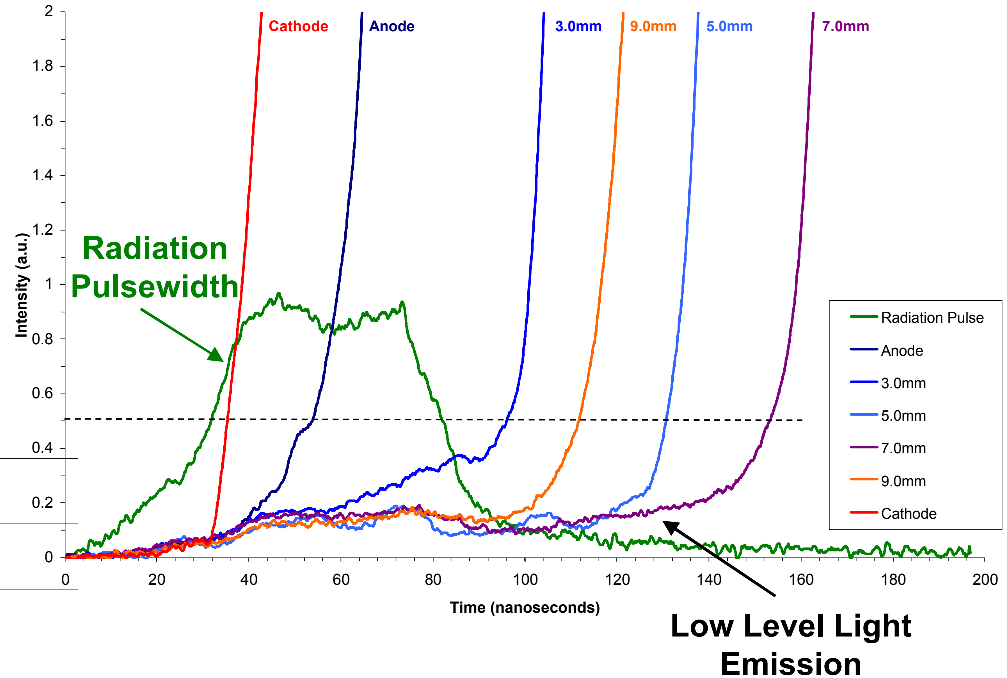
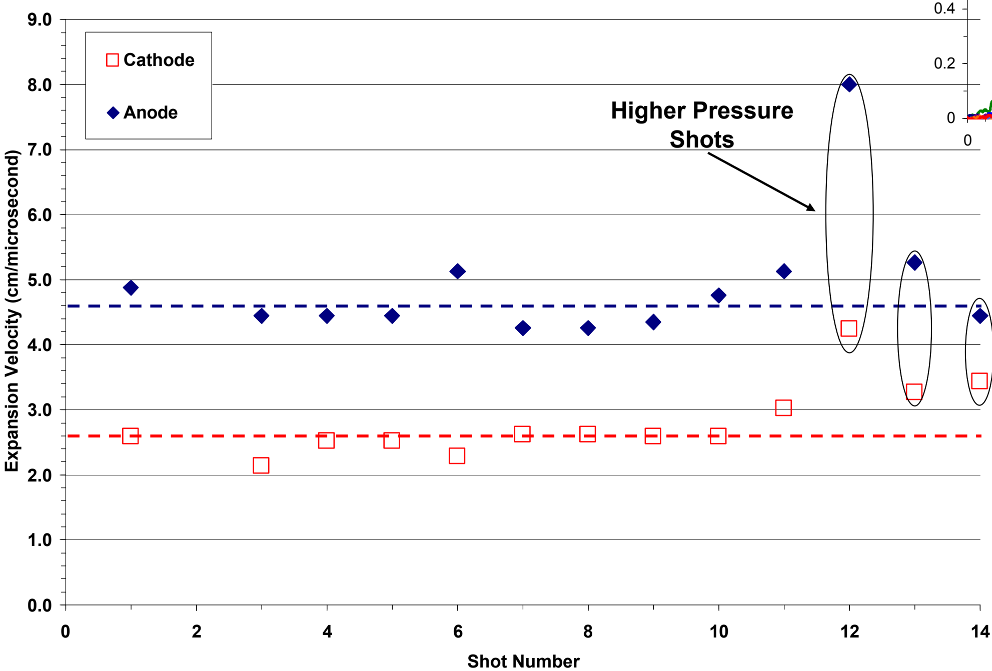
Plasma Propagation Measurements using Silicon Avalanche Photodetectors

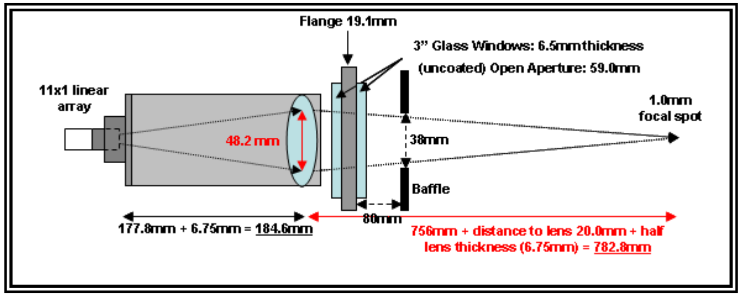
Anode Expansion Velocity: 4.6 +/- 0.3cm/μsec; Cathode Expansion Velocity: 2.6 +/- 0.2cm/μsec





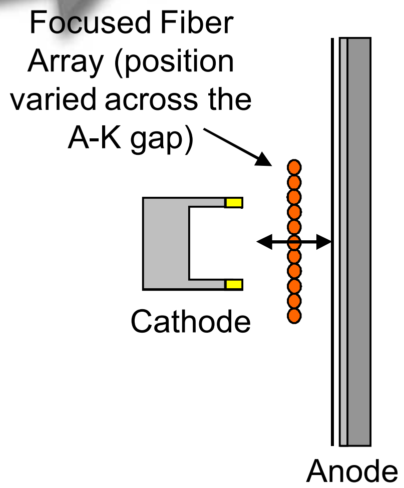


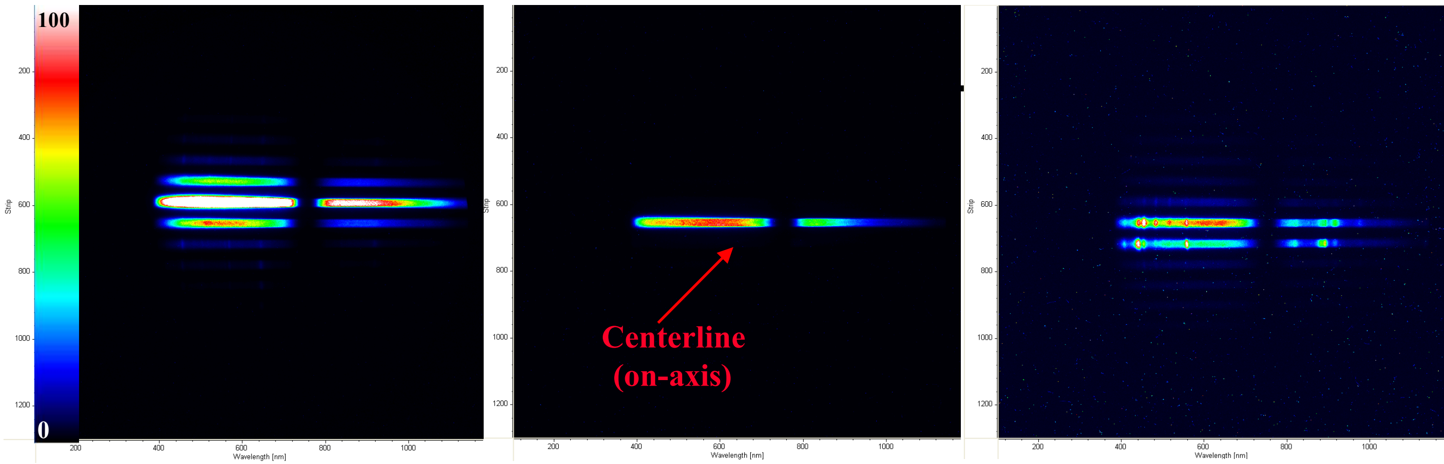




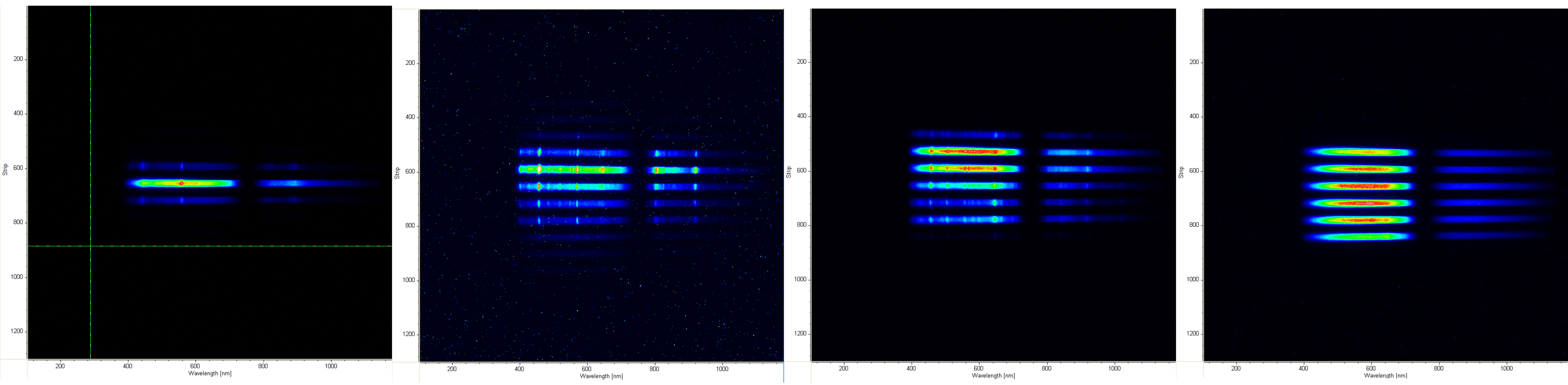
*All data taken on the same shot

Radial Distribution of Spectra at Different Axial Locations (spectra collected on separate shots)





Anode **1/6 Gap** **1/3 Gap**



Mid-Gap **2/3 Gap** **5/6 Gap** **Cathode**

*A full wavelength spectrum is recorded for each fiber in the array

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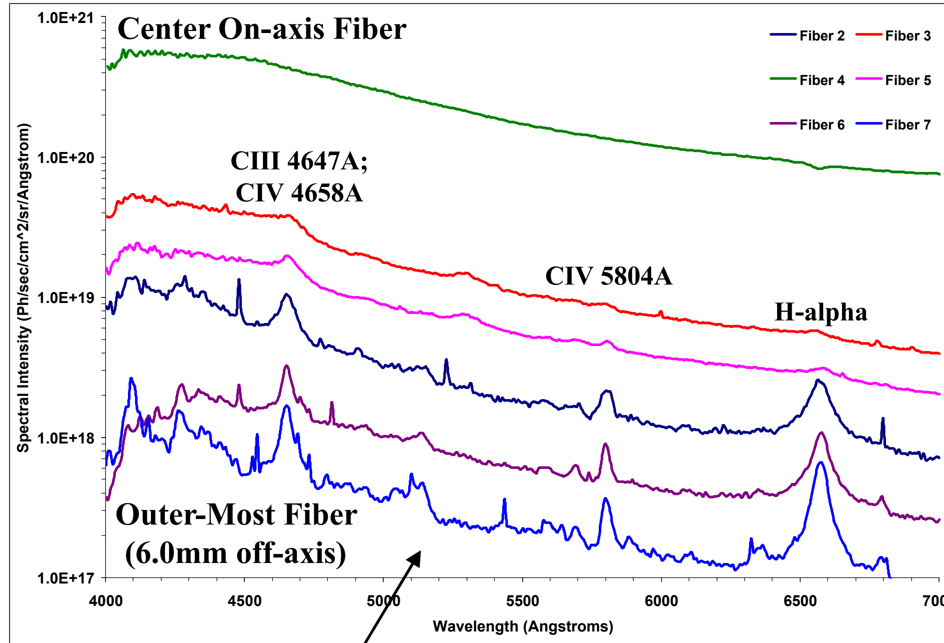
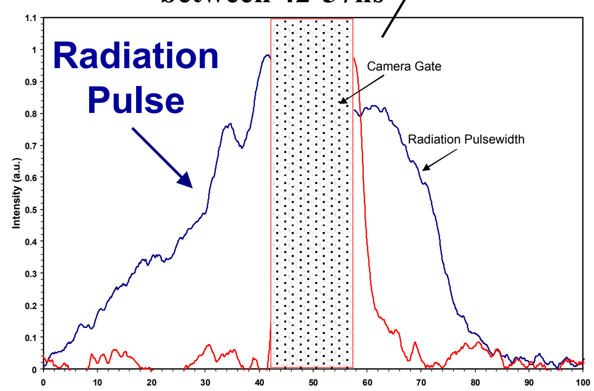
Spectral Data at Anode Surface During the Radiation Pulse

- •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 ~<u>35x</u> from the center outward to 6mm.
- •Asymmetries in plasma composition and density can be observed across the surface.
- •Intensities calibrated in absolute units[4].



15ns Integration Time

Spectra collected between 42-57ns



Carbon Ion Lines Observed

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

*Red box indicates when in the radiation pulse the spectra was collected.

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

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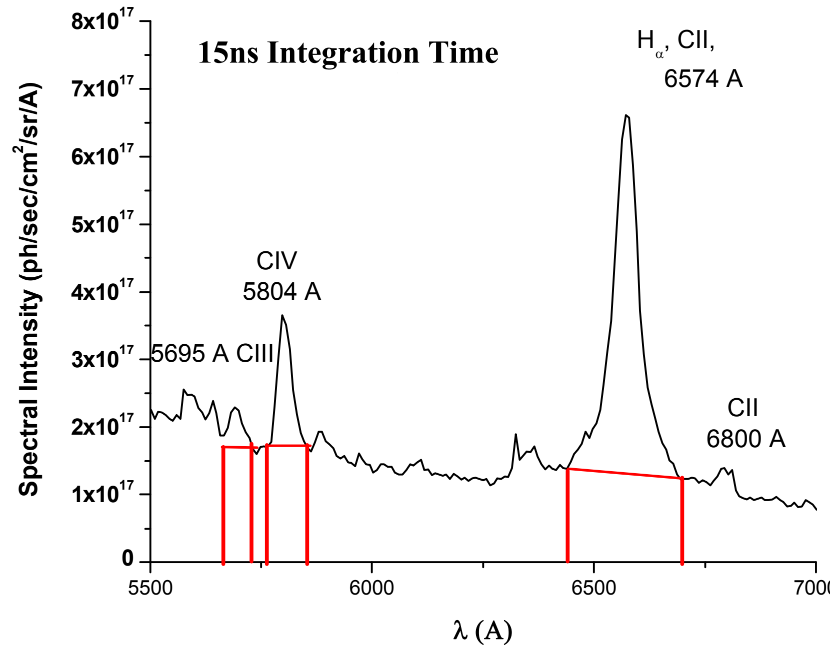
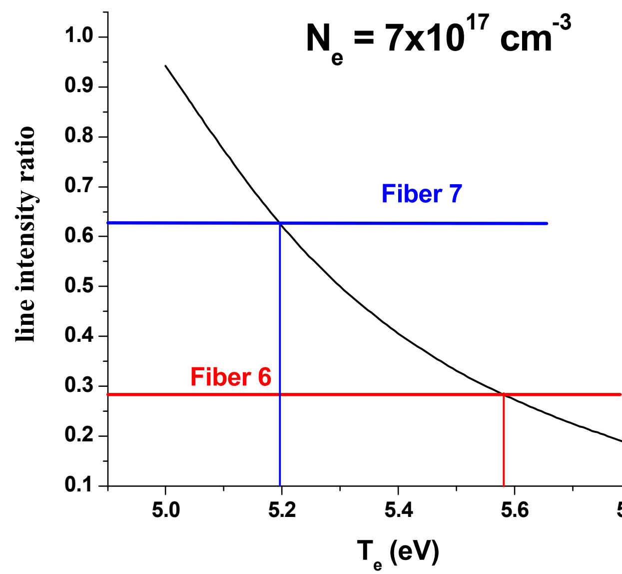
Sample Analyses of Spectral Data off the Anode Surface Following the Radiation Pulse

Electron densities are determined from Stark Broadening of the H-alpha line and from absolute continuum intensities using collisional-radiative (CR) spectral analysis. Electron temperatures are obtained from CIII/CIV line ratios.



Fiber 7 (6.0mm off-axis on the anode surface)

N_e from H-alpha:	7.4×10^{17} cm^{-3}	
N_e from Continuum:	2.9×10^{17} cm^{-3}	
Electron Temp. (T_e):	5.2eV	
$N_{hydrogen}$ (Z = 1):	3.2×10^{17} cm^{-3}	**(45%)**
N_{carbon} (Z = 2.9):	3.0×10^{16} cm^{-3}	**(12%)**
$N_{e(other)}$:	3.0×10^{17} cm^{-3}	**(43%)**



***Continuum density is averaged over the full fiber viewing area, while Stark broadening is a localized measurement.**

****Analyses use the optical streak images to determine pathlengths through the plasma volumes in time.**

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Summary

- **Dense plasmas are formed on electrode surfaces in the SMP diode during the ~50ns FWHM radiation pulse. These plasmas migrate into the A-K gap at velocities of 5-10cm/μsec.**

- **Spectroscopic data shows that these plasmas are composed primarily of hydrogen and carbon ion species. Electron densities of up to 10^{19} cm^{-3} have been measured on axis at the anode surface during the x-ray radiation pulse.**

- **It is believed that these "dense" plasma are responsible for the gradual impedance decay observed during the x-ray radiation pulse. In addition, a "rapid" impedance collapse is observed on some shots, and experiments are planned to look at this phenomena spectroscopically.**

- **Spectroscopic data is incorporated into LSP, a hybrid particle-in-cell / fluid dynamic code, to help design the next generation of enhanced radiographic sources.**

- **This type of information (density and temperature profiles in time) enhances our physics understanding of the role of plasmas in e-beam diodes.**

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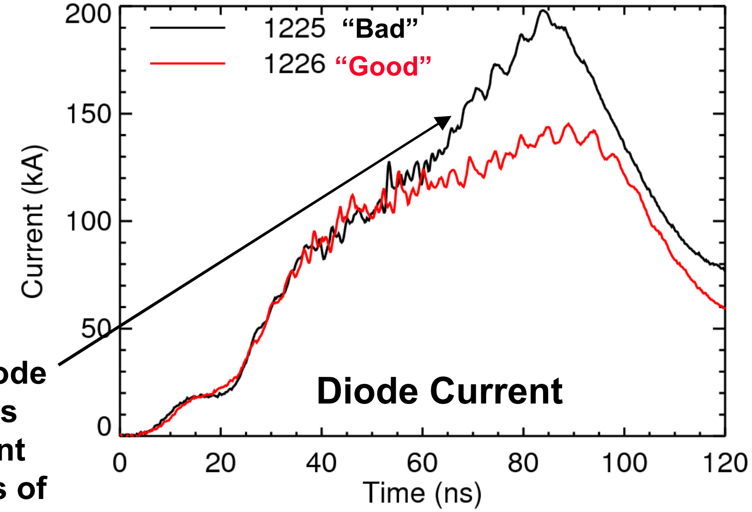
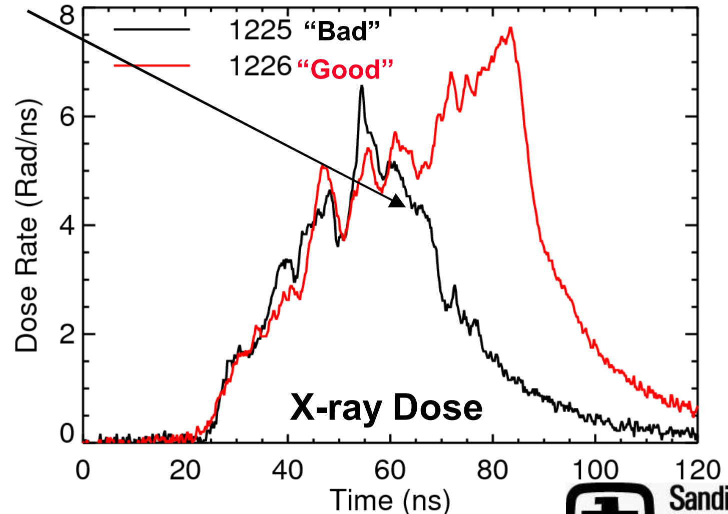
Extra Slides

Plasma Spectroscopy Experiments are Used to Try and Understand Diode Behavior.

- Help understand "good" vs. "bad" diode impedance behavior.
- Identify individual plasma species.
- Obtain plasma information including: charge states, electron and ion temperatures, and densities.
- Study the effects of plasma formation on electron beam dynamics and diagnose differing diode behavior.
- Provide experimental validation for diode physics modeling.



Excess diode current is coincident with a loss of x-ray output



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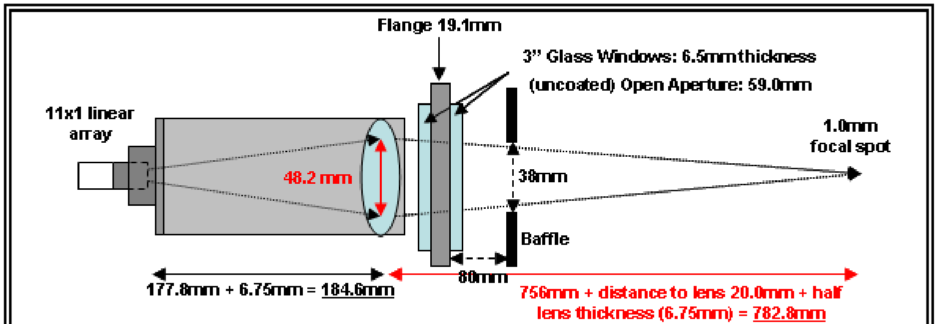
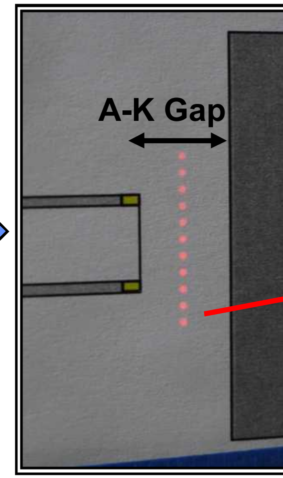
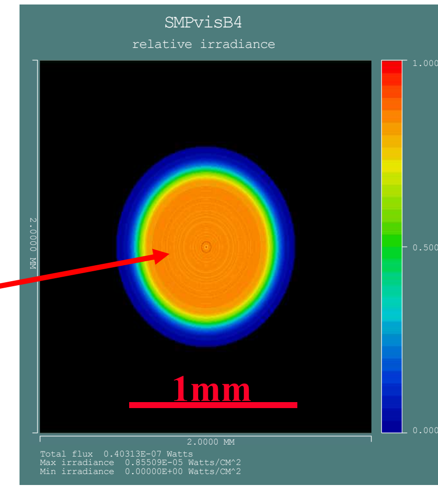
Imaging Optics on RITS-6



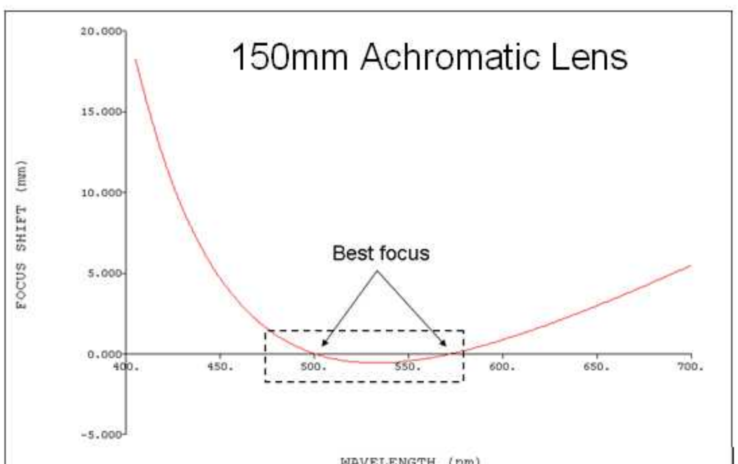
Focusing Optics



Focused 11x1 Fiber Array



Single fiber focused at 500nm



Variation in focal spot with wavelength

- Optical fiber arrays are used to collect spatial information on the plasmas in the A-K gap.
- The optics are adjusted for specific wavelengths of interest.
- Corrections are made to account for chromatic aberrations.

Determination of Stark FWHM

Assumptions:

1. **Due to the low ion temperature the line widths are determined by instrumental resolution and Stark broadening.**
2. **The instrumental response is Gaussian.**
3. **The Stark broadening of isolated lines is Lorenzian, thus the Stark FWHM[5] is:**

$$w_l = (w^2_v - w^2_g)/w_v \quad (1)$$

where w_l, w_g, *and* w_v **are the FWHM's of the Stark broadening (Lorenzian), the instrumental response (Gaussian), and the measured value (Voight), respectively.**

[5] *J. Quantitative Spectroscopy and Radiative Transfer,* Vol. 8, p. 1379 (1968)

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