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Optical Spectroscopy of High Intensity Electron Beam Plasmas

M.D. Johnston and B.V. Oliver
Sandia National Laboratories, PO Box 5800
Albuquerque, NM 87185-1168 USA

N. Bruner and D. Welch
Voss Scientific, LLC
Albuquerque, NM 89108, USA

V. Bernshtam, R. Doron, and Y. Maron
Weizmann Institute of Science
Rehovot, Israel 76100

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Abstract

This talk will be an overview of spectroscopic results obtained on the RITS-6 accelerator at Sandia National Laboratories on the Self-Magnetic Pinch (SMP) electron beam diode. The SMP diode produces a focused (<3mm diameter), e-beam at 7MeV and 150kA, which is used as an intense, flash x-ray source. During the ~45ns electron beam pulse, plasmas are generated on the electrode surfaces which propagate into the A-K vacuum gap, affecting the diode impedance, x-ray spectrum, and pulse-width. These plasmas are measured using a series of optical diagnostics including: streak cameras, ICCD cameras, and avalanche photodetectors. Visible spectroscopy is used to gather time and space information on these plasmas. Density and temperature calculations are made using detailed, time-dependent, collisional-radiative (CR) and radiation transport modelings. The results are then used in conjunction with hybrid PIC/fluid simulations to model the overall plasma behavior. Details regarding the data collection, system calibration, analyses, and interpretation of results will be presented.

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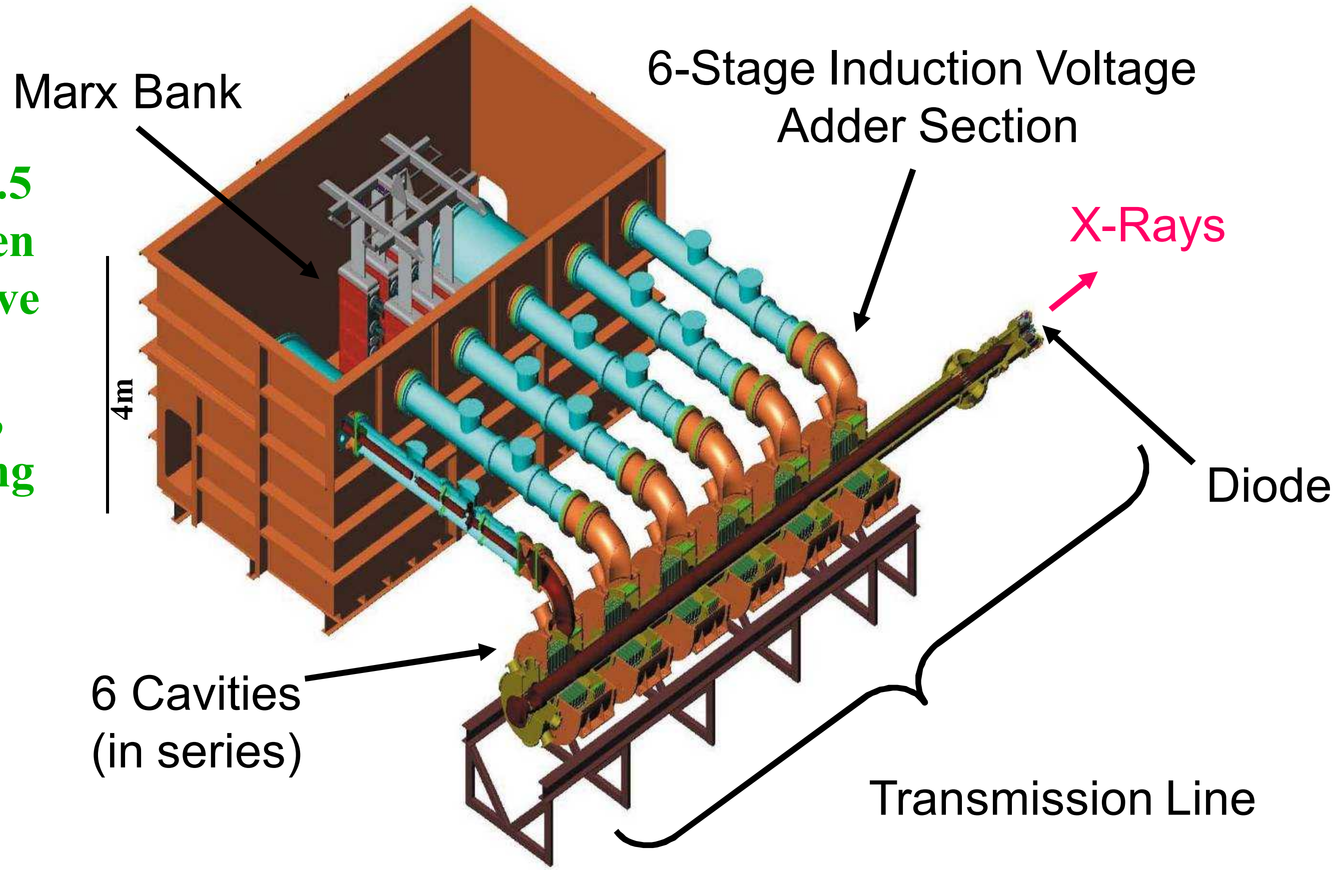
Outline

- 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

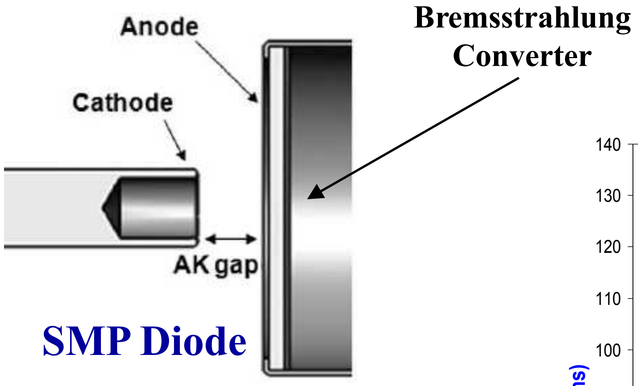
RITS-6 Accelerator at Sandia National Laboratories

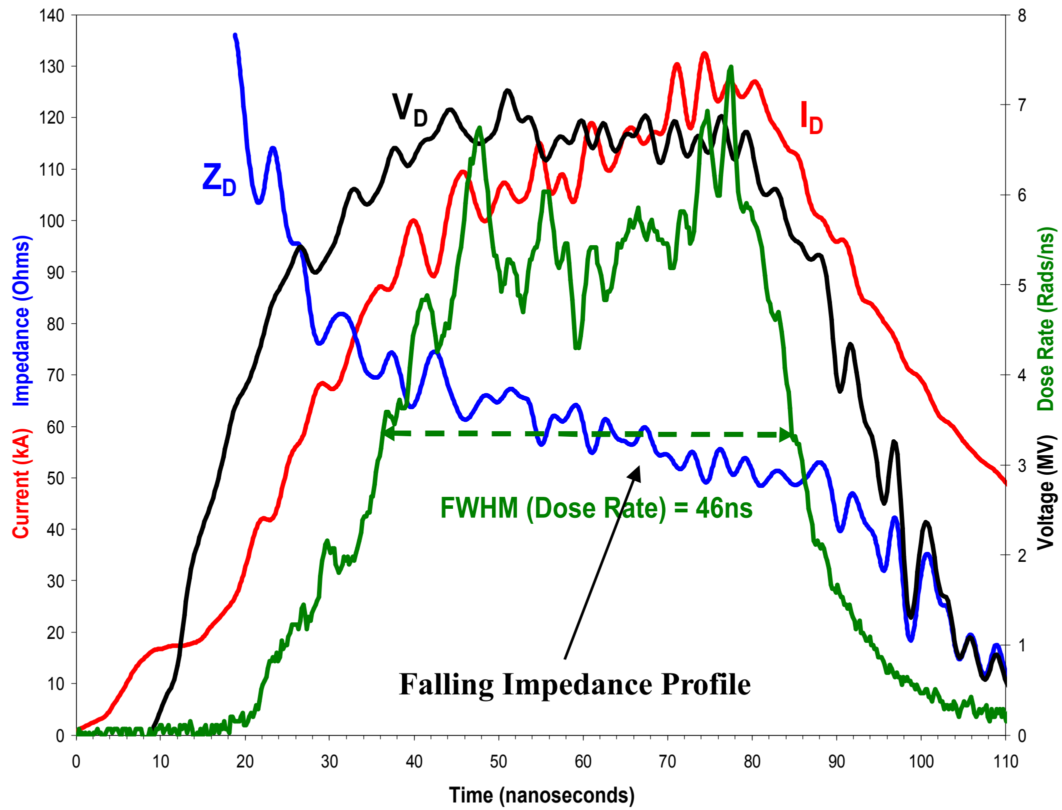
RITS-6 is a 5-11.5 MeV Marx driven six-stage Inductive Voltage Adder (IVA) machine, capable of driving a variety of electron beam diodes[2].



[1]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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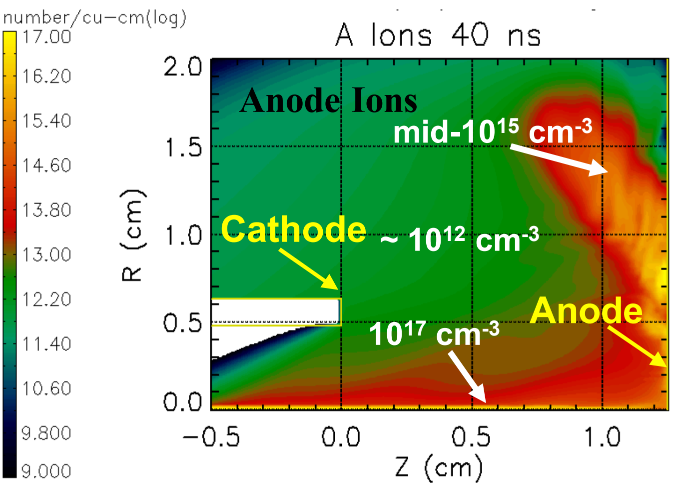
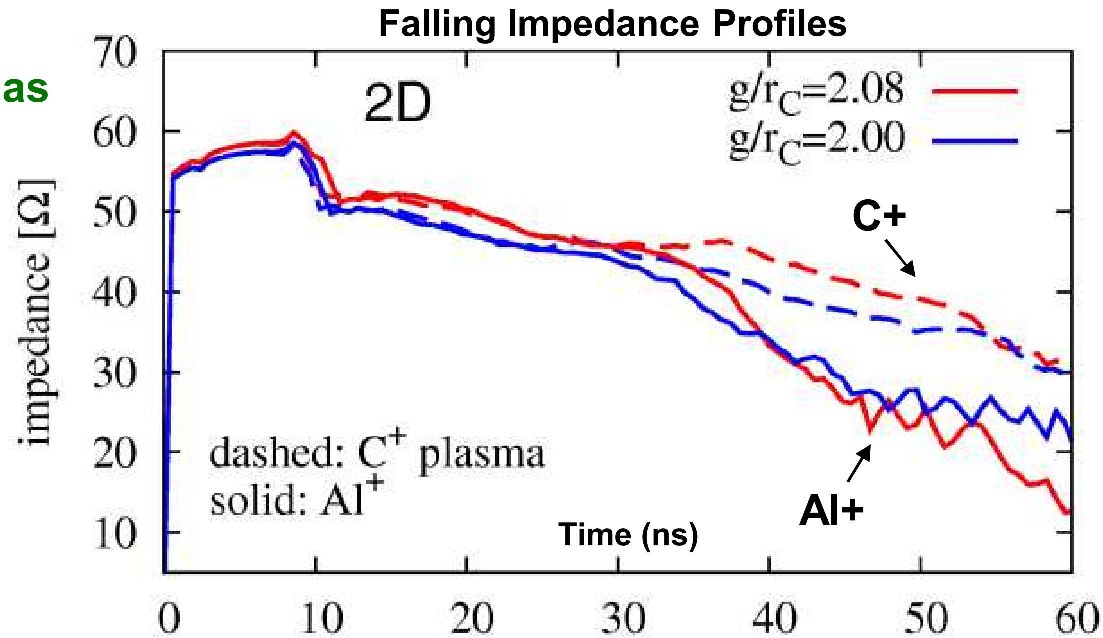
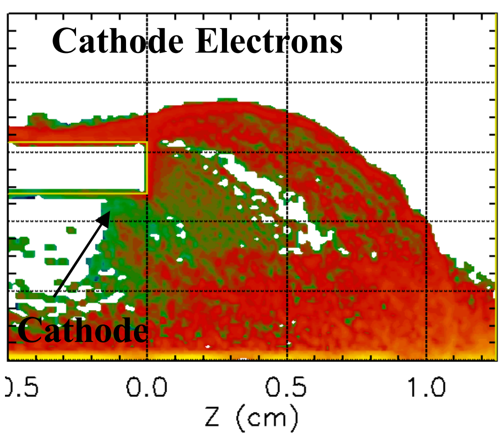
SMP Diode LSP Simulations[2]

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).

[2]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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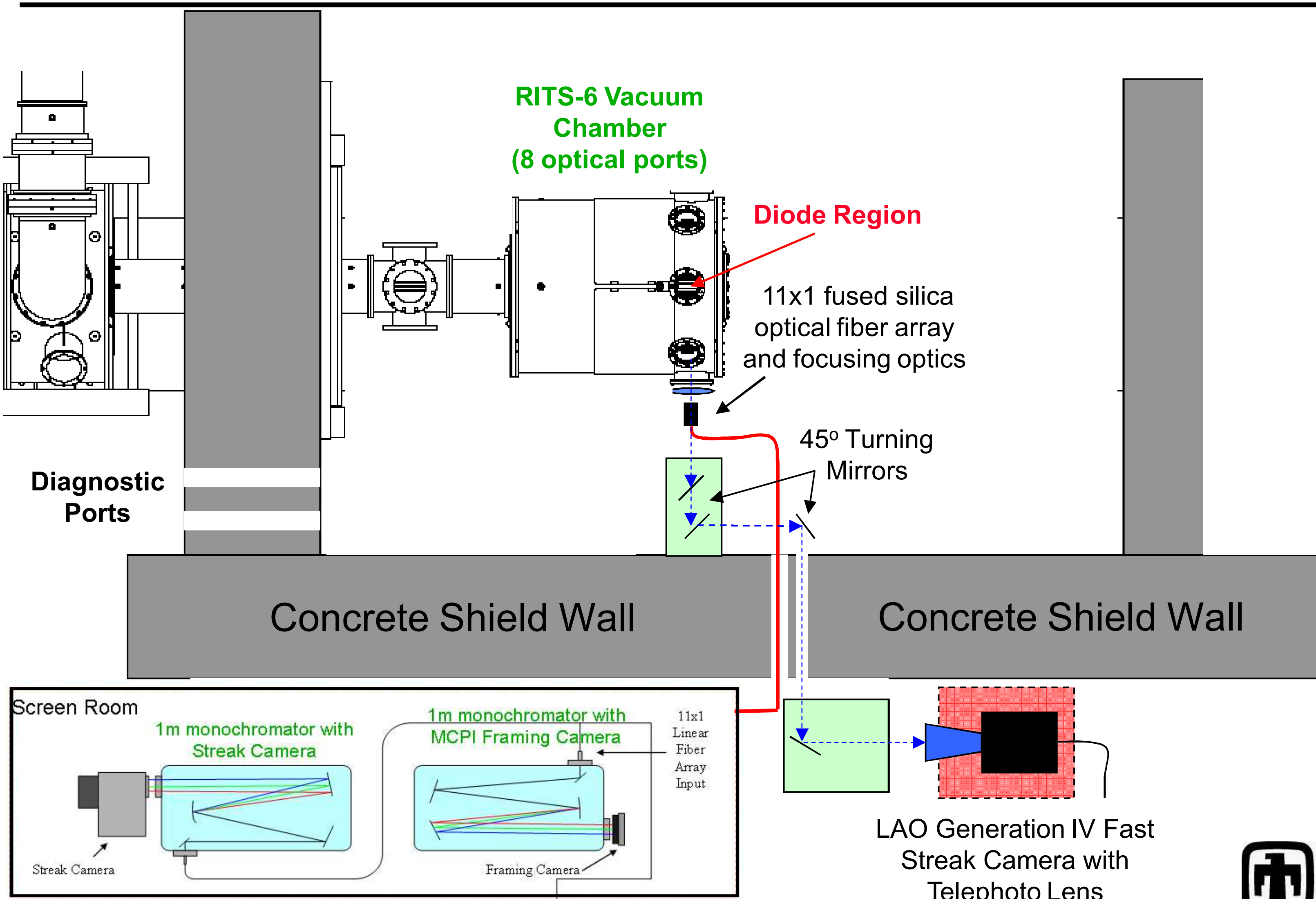
Optical Diagnostic Layout on the RITS-6 Accelerator



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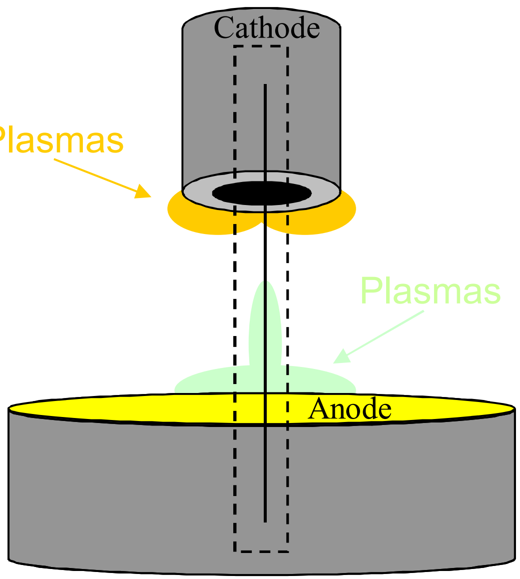
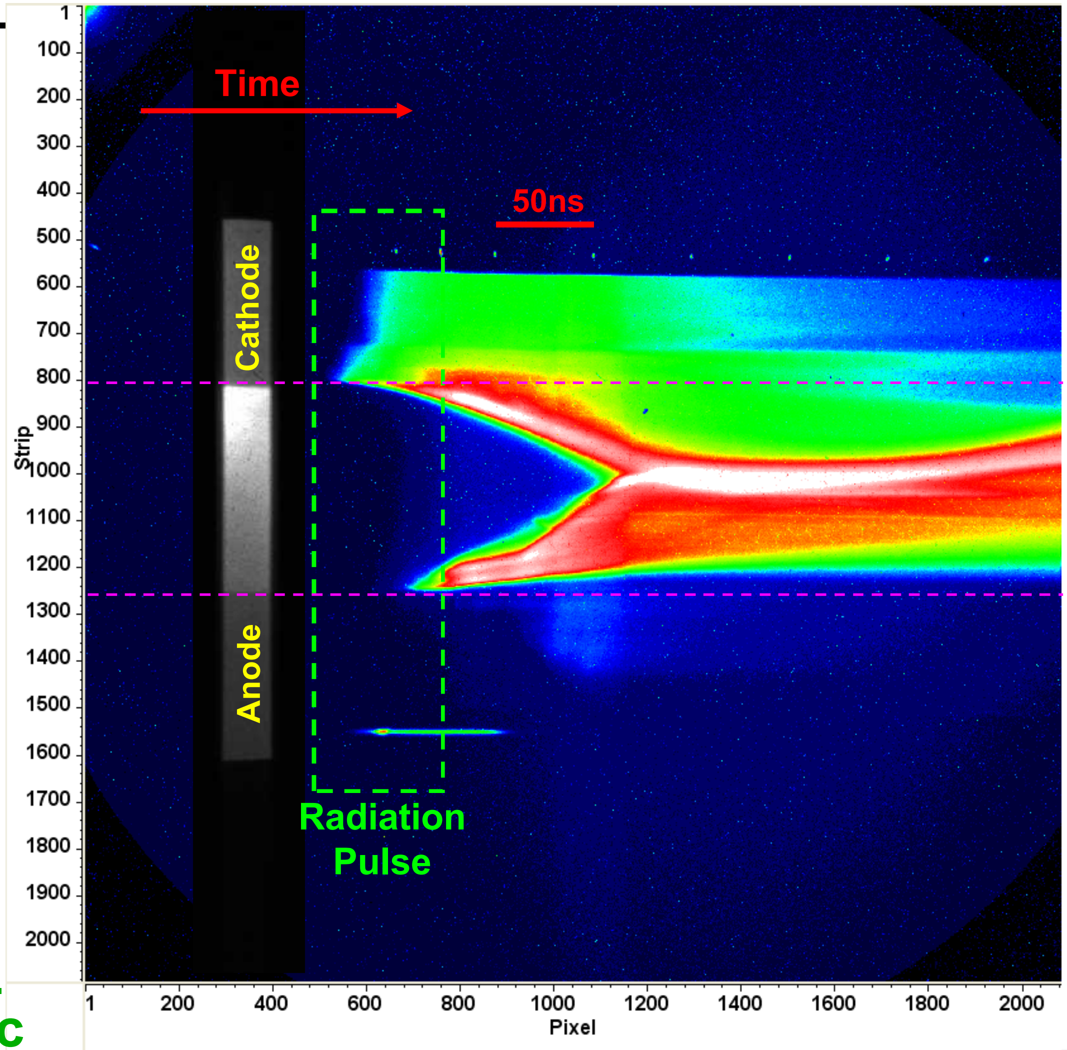
Streak Camera Image of Plasma Expansion Across the A-K Vacuum Gap

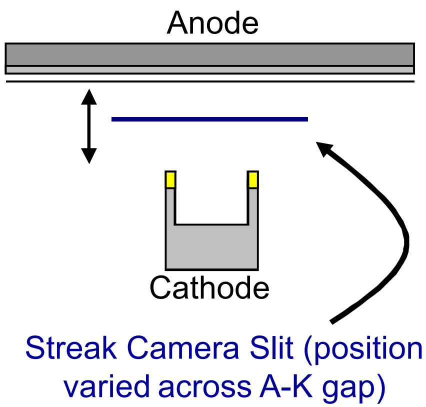
SMP Diode Configuration

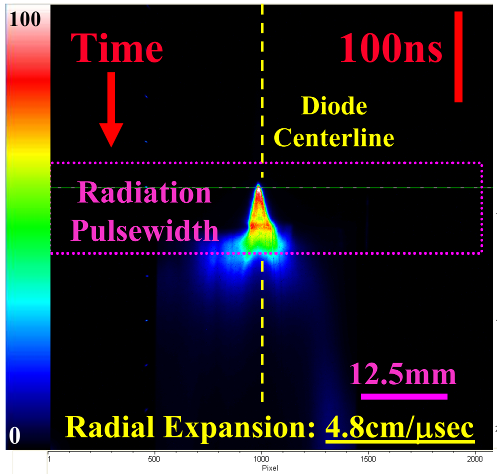




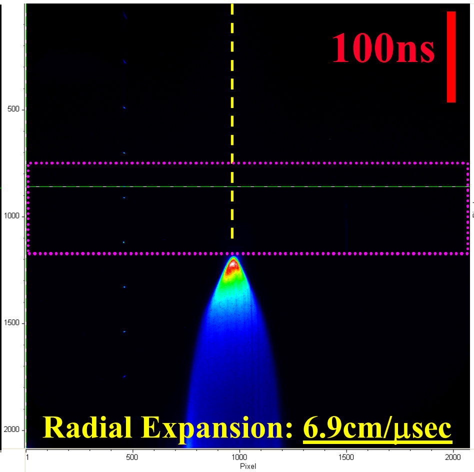
Anode velocity: 7.5cm/μsec
Cathode velocity: 2.5cm/μsec

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

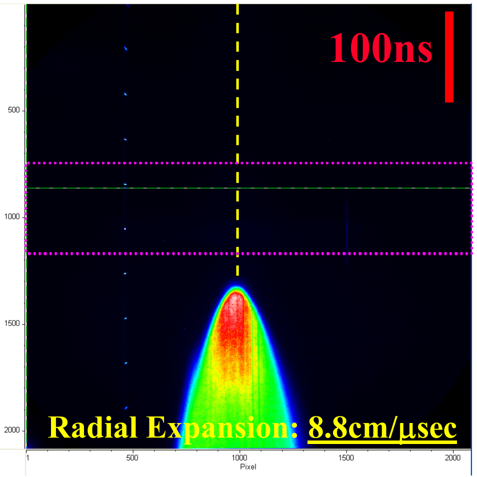




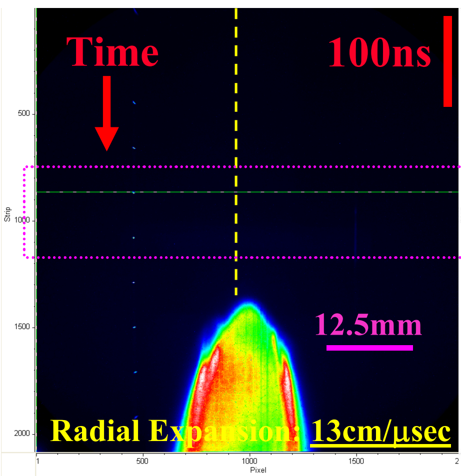
Anode Surface



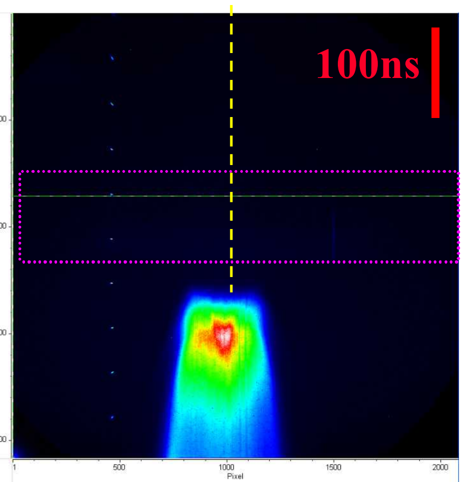
1/6 Gap



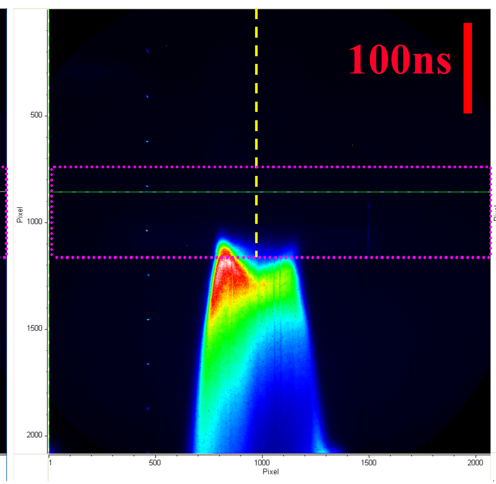
1/3 Gap



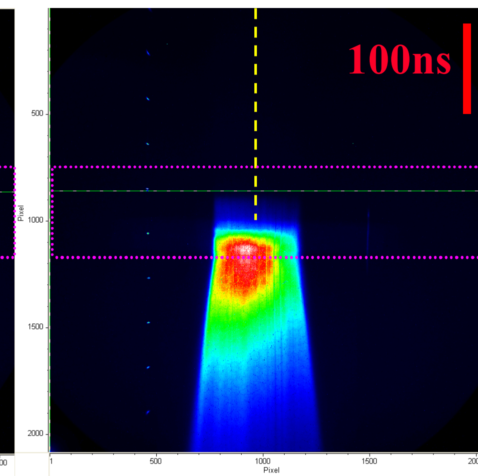
Mid-Gap



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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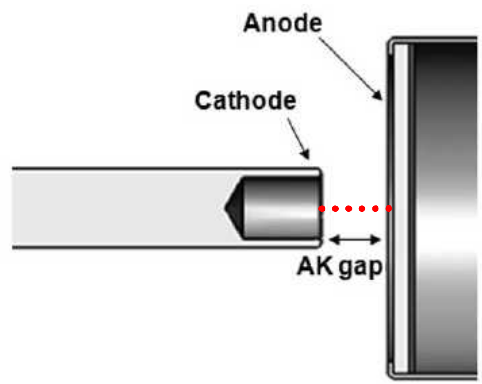
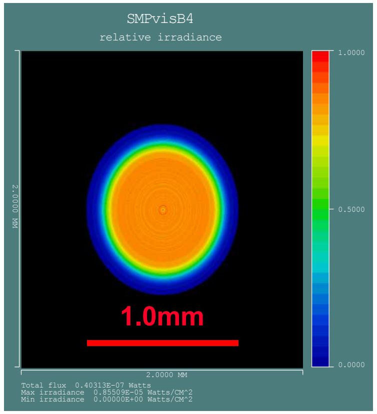
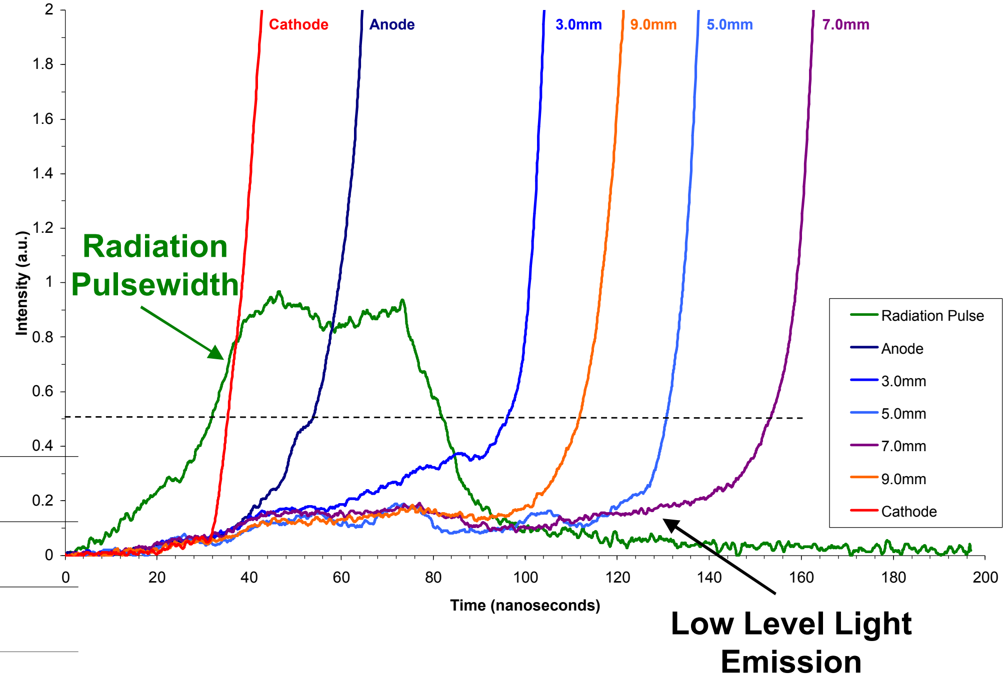
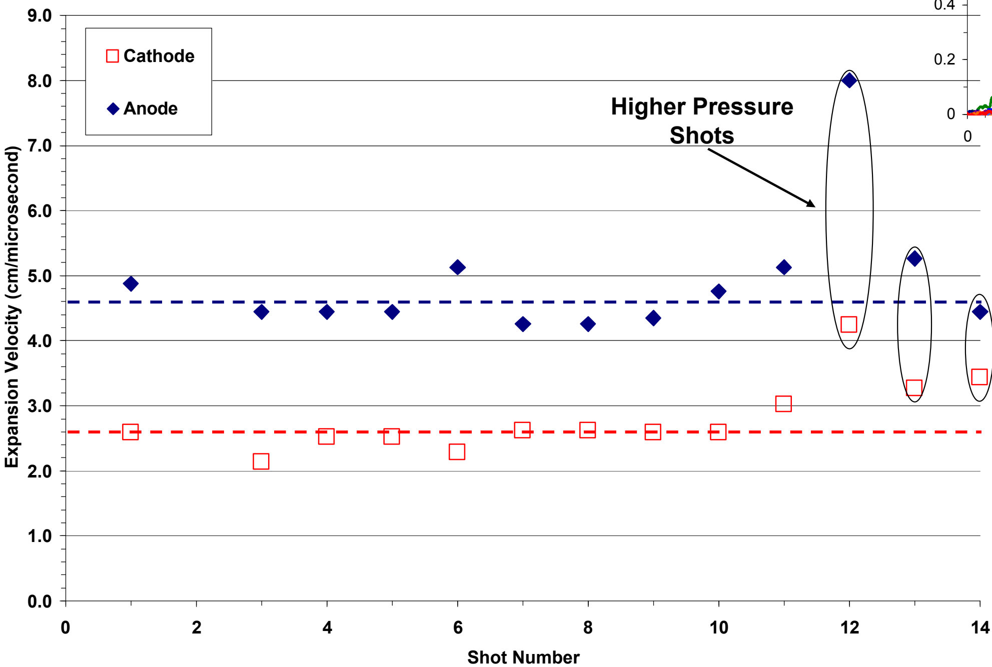
Plasma Propagation Measurements using Silicon Avalanche Photodetectors

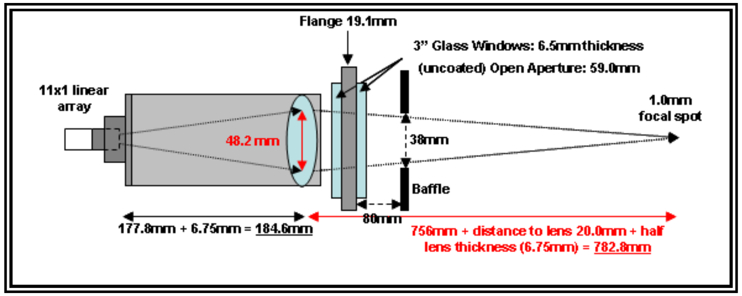
Anode Expansion Velocity: 4.6 +/- 0.3cm/μsec; Cathode Expansion Velocity: 2.6 +/- 0.2cm/μsec











*All data taken on the same shot

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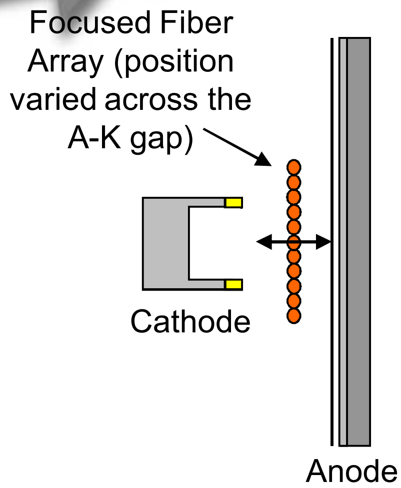
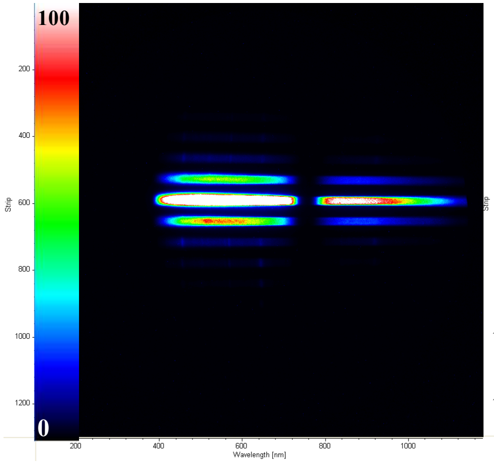
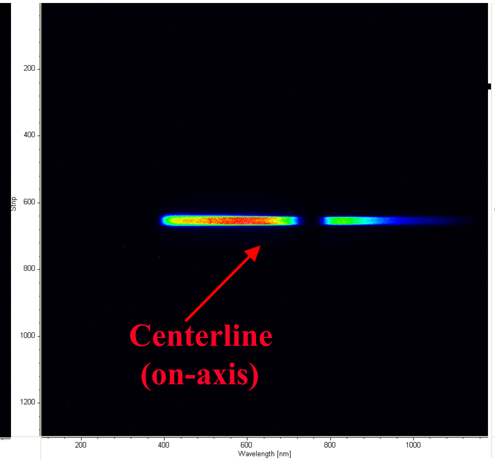
Radial Distribution of Spectra at Different Axial Locations (spectra collected on separate shots)

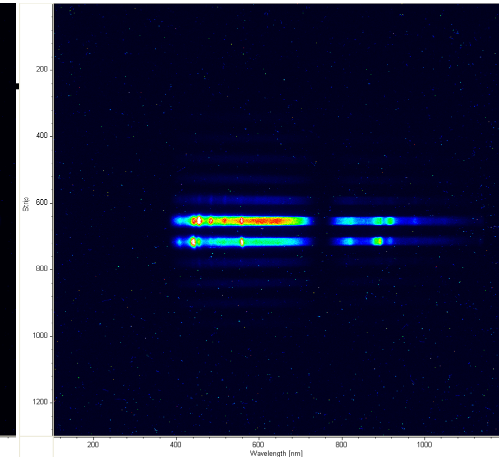




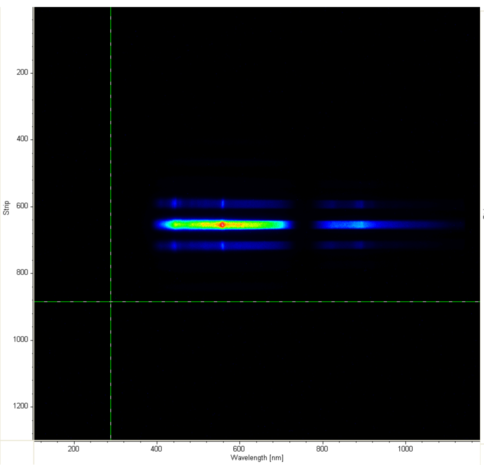
Anode



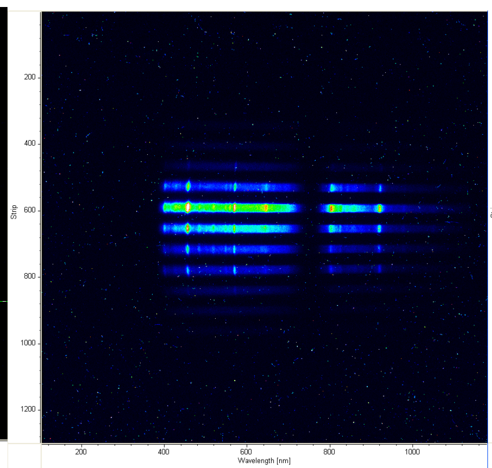
1/6 Gap



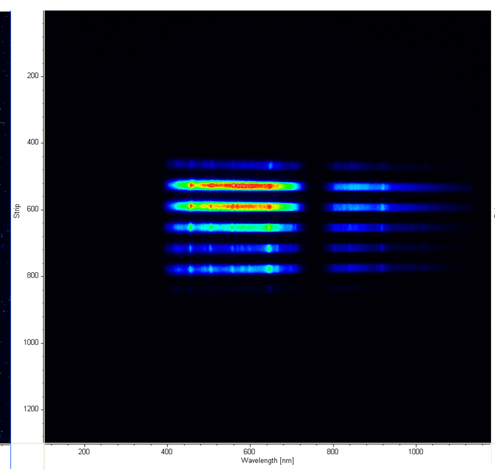
1/3 Gap



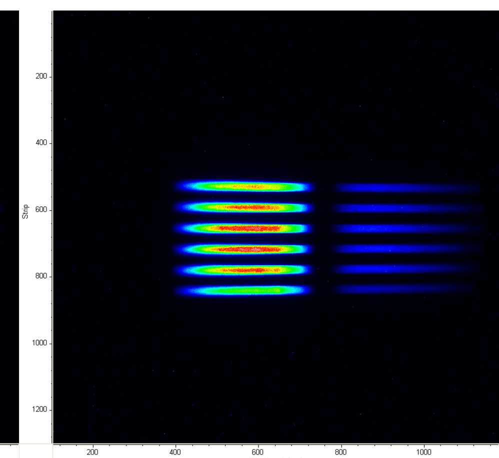
Mid-Gap



2/3 Gap



5/6 Gap



Cathode

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

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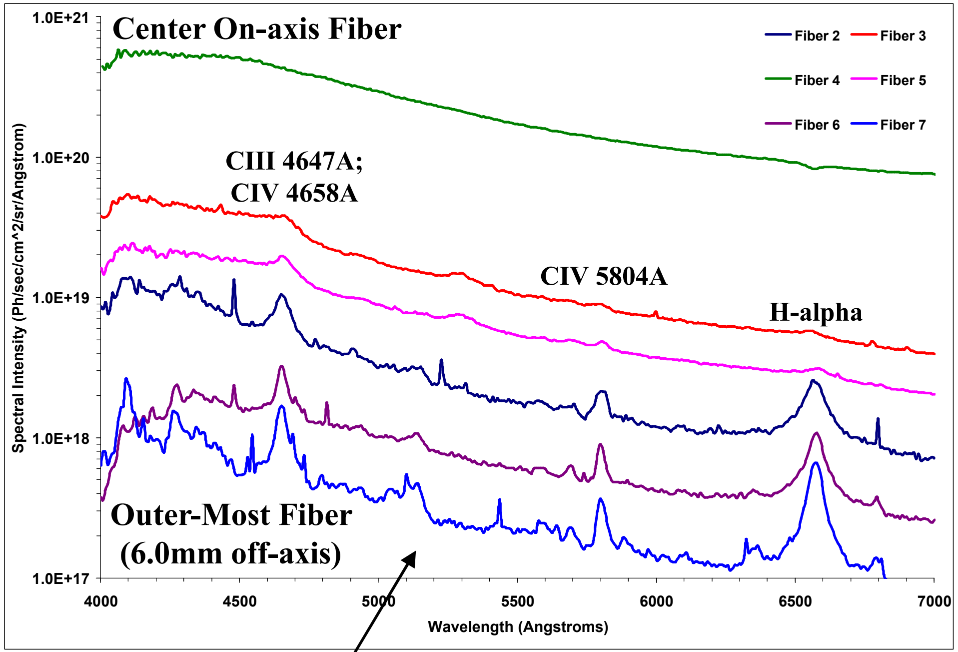
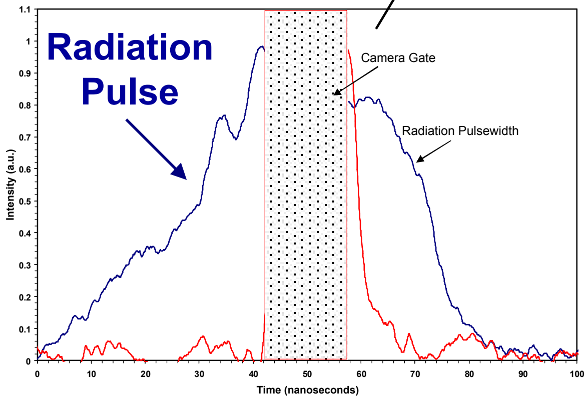
Spectral Data at Anode Surface During the Radiation Pulse

- 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[3].



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.

[3]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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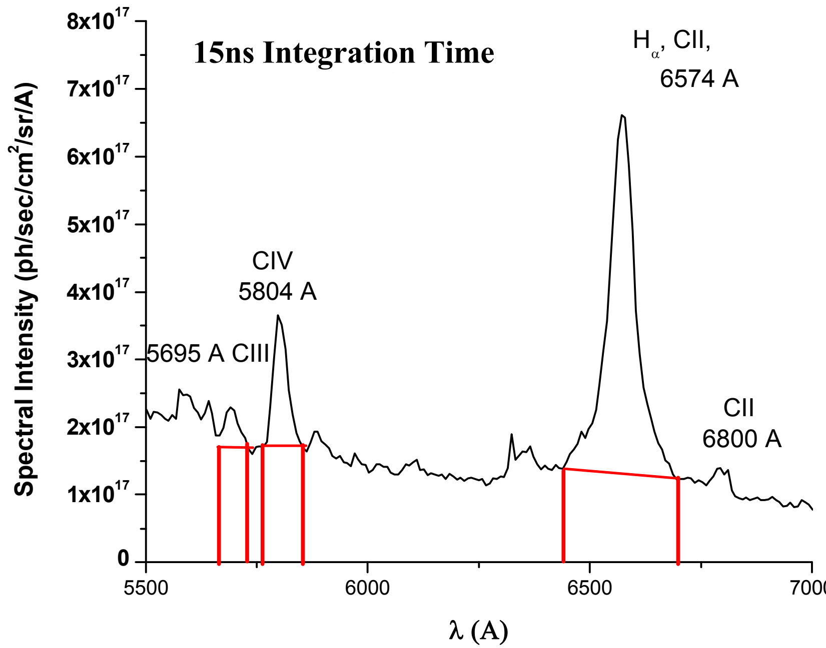
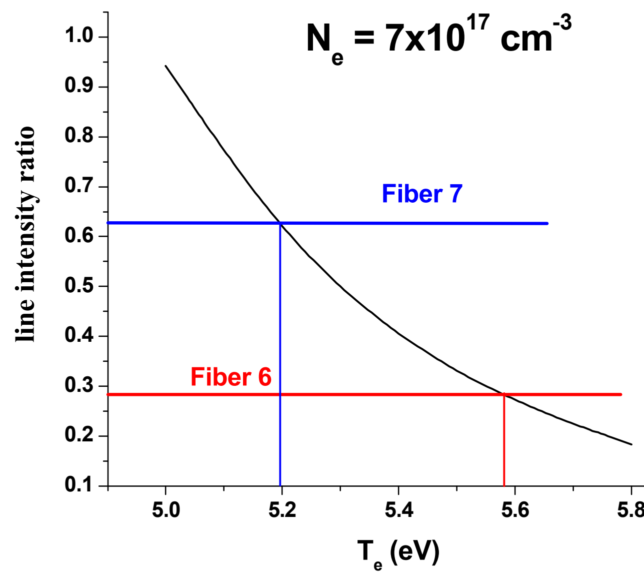
Sample Analyses of Spectral Data off the Anode Surface Following the Radiation Pulse

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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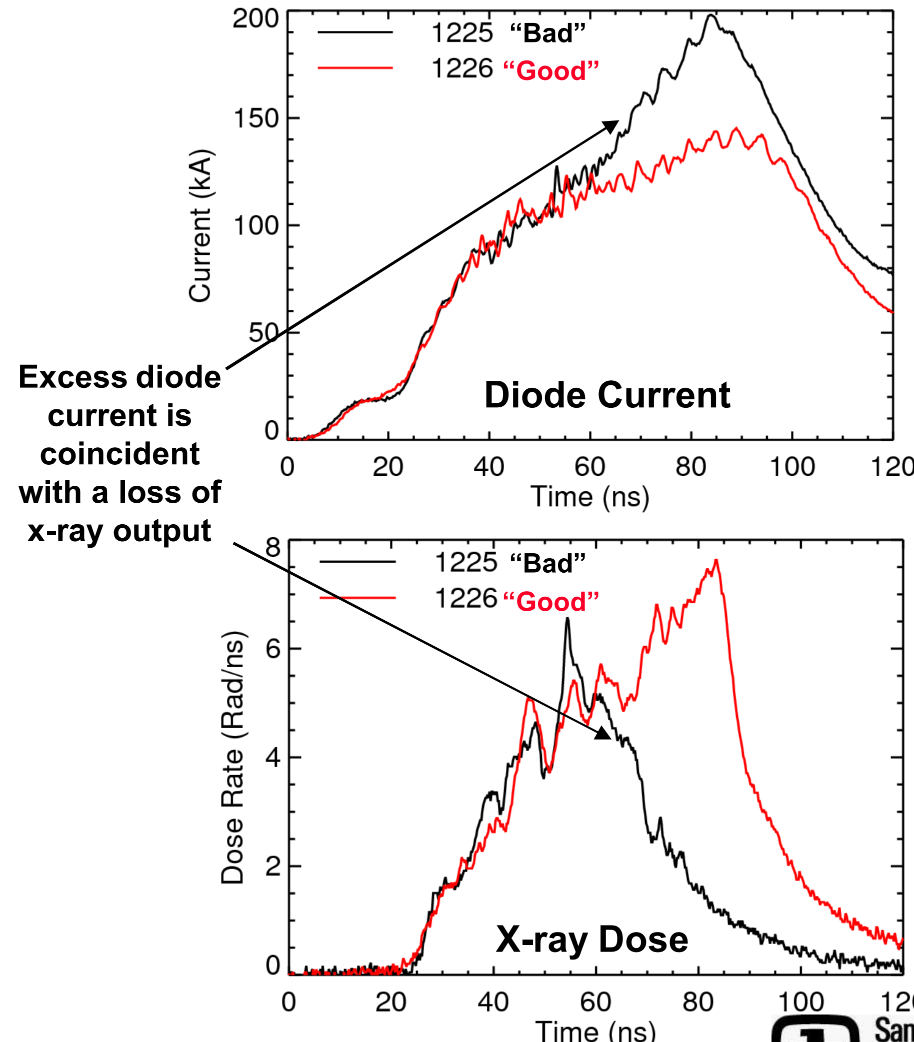
Extra Slides

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.



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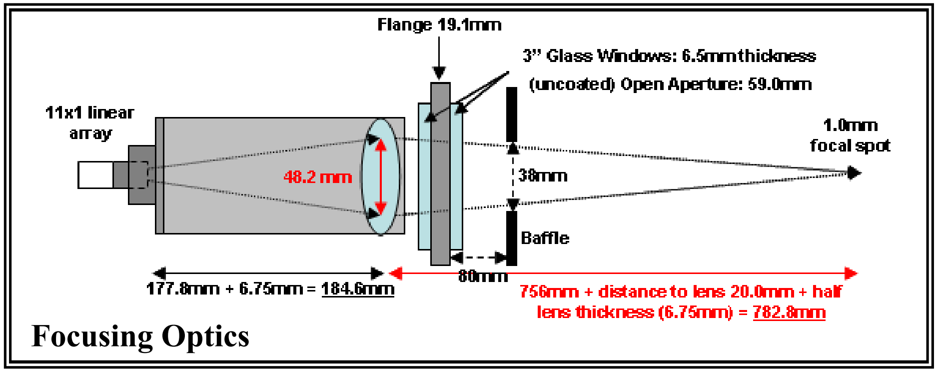
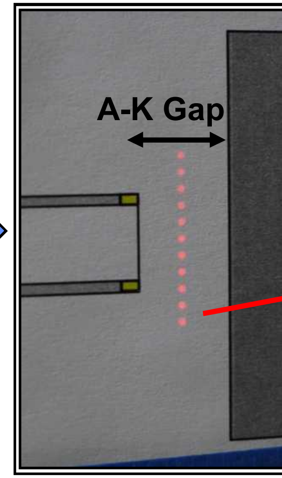
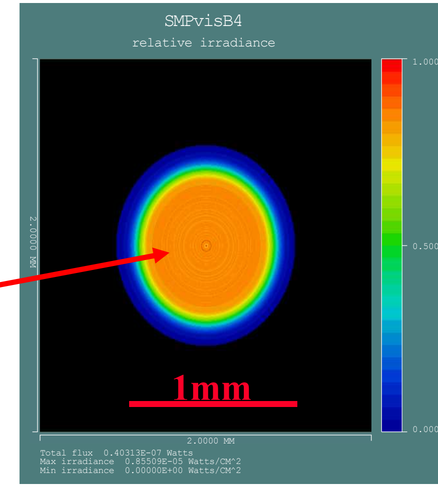
Imaging Optics on RITS-6



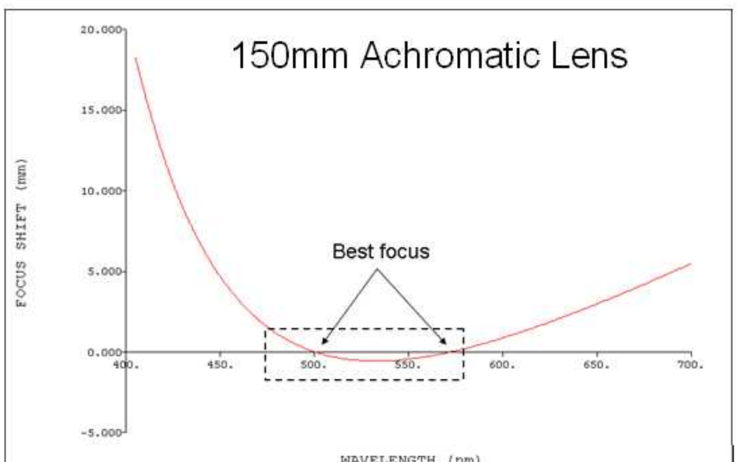
Focusing Optics



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.

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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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