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Optical Plasma Diagnostics in High Intensity Electron Beam Diodes

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

N. Bennett 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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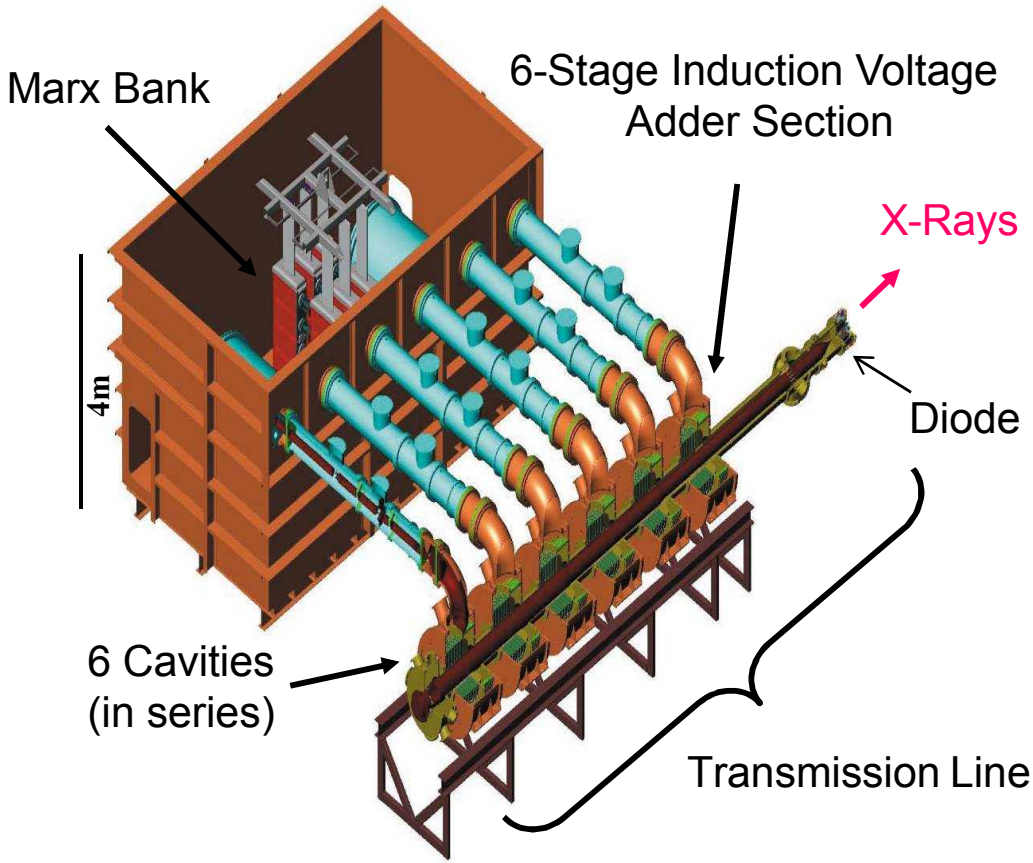
Outline

- RITS-6 Accelerator.
- Negative Polarity Rod Pinch (NPRP) Diode.
- Self-Magnetic Pinch (SMP) Diode.
- Optical Diagnostics Layout on RITS.
- PI-Max ICCD Single Frame Fast Imaging System
- Optical Streak Imaging System
- Avalanche Photodiodes
- Plasma Spectroscopy Diagnostic
- Plasma Parameters Inferred from Spectral Analyses
- Electric and Magnetic Field Measurements
- Summary

RITS-6 Accelerator at Sandia National Laboratories



RITS-6 is a multi-MeV Marx driven six-stage Inductive Voltage Adder (IVA) machine, capable of driving a variety of electron beam diodes[1].

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

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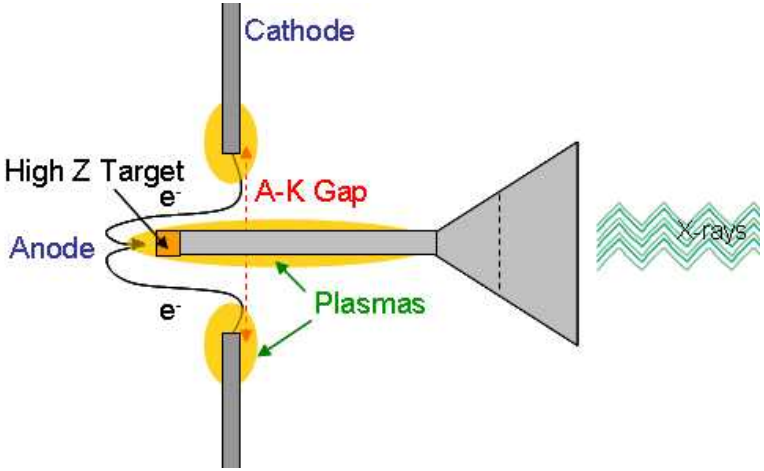
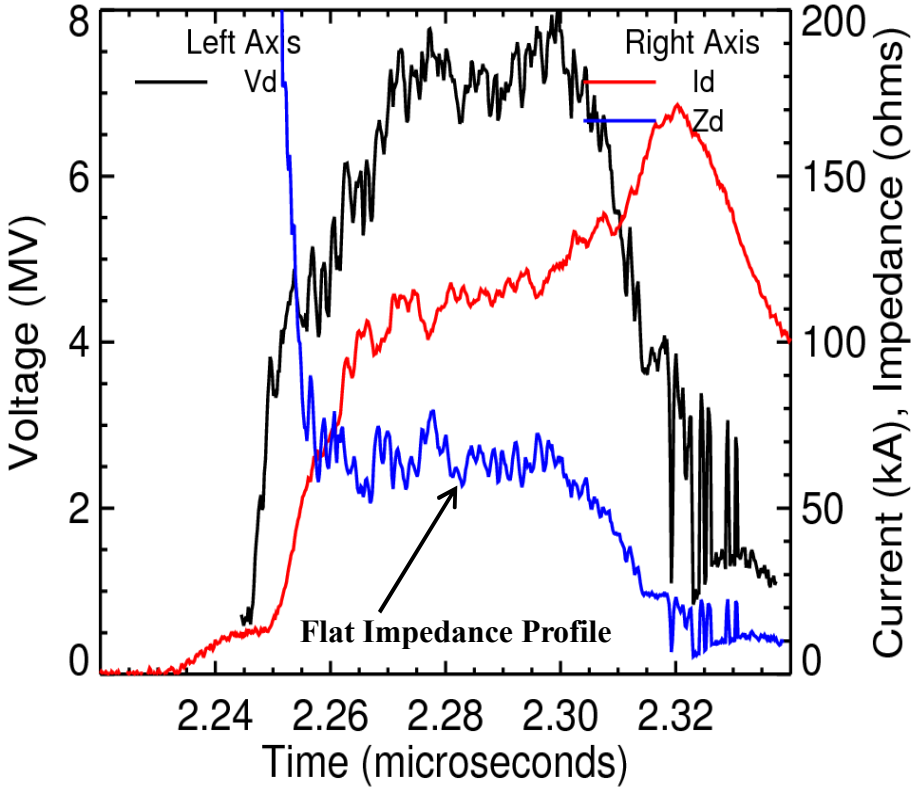
Negative Polarity Rod Pinch (NPRP) Diode Electrical Characteristics



Negative Polarity Rod Pinch

NPRP Diode Parameters

- 6-7 MV
- 120 kA
- 70ns Electrical Pulse
- 50ns Radiation Pulse
- > 120 Rads @ 1 meter
- < 2.6 mm spot size



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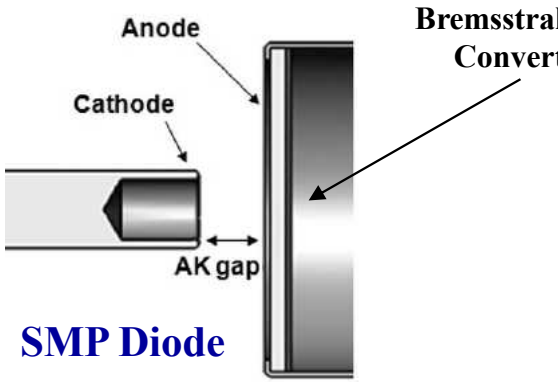
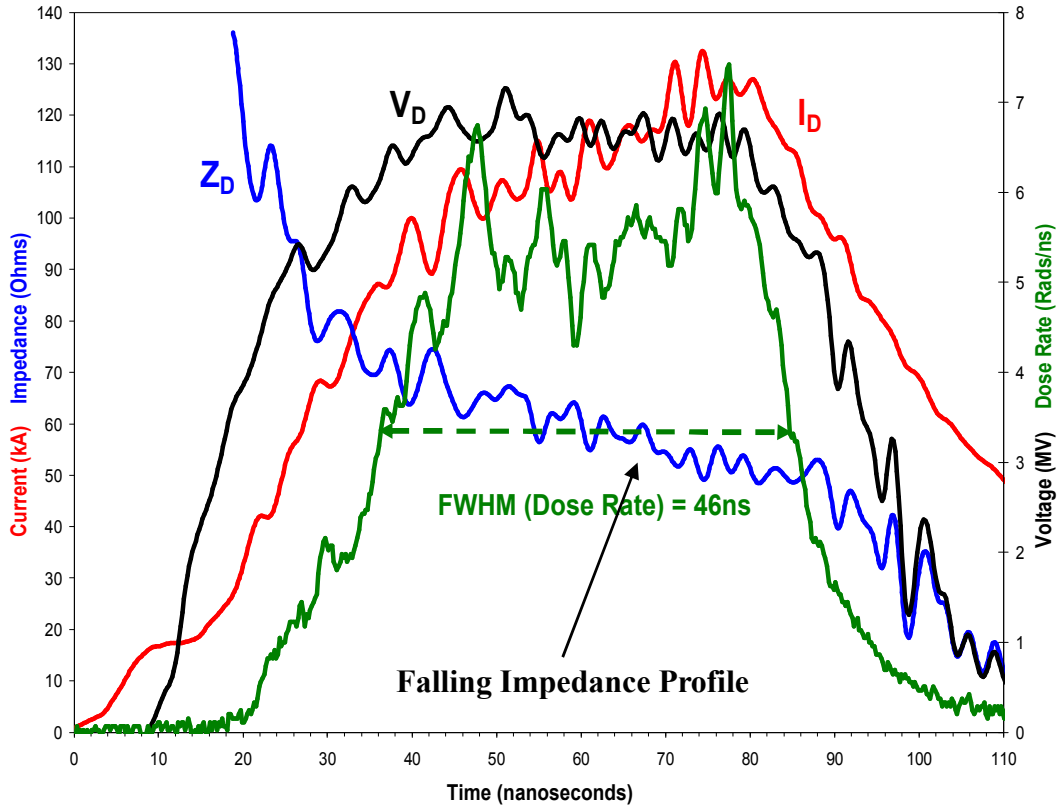
Self-Magnetic Pinch (SMP) Diode Electrical Characteristics



SMP Diode Parameters

- 4-7.5 MV
- 80-150 kA (~15% ions)
- 50 Ω Impedance
- 70ns Electrical Pulse
- 45ns Radiation Pulse
- 90-350 Rads @ 1 meter
- ≤ 2.7 mm focal spot size



MA/cm^2 current densities at the anode!

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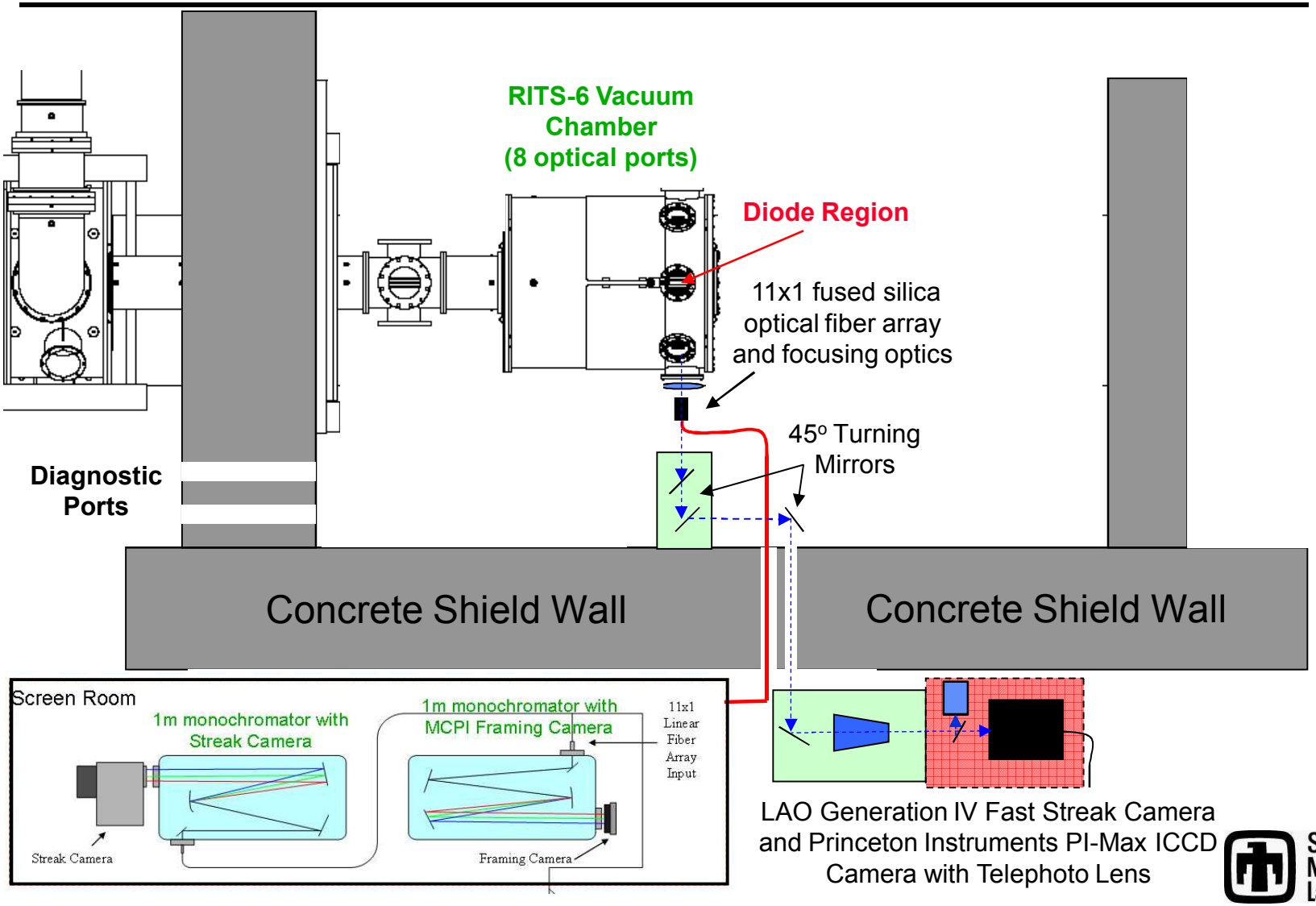
Optical Diagnostics Layout on the RITS-6 Accelerator



LAO Generation IV Fast Streak Camera and Princeton Instruments PI-Max ICCD Camera with Telephoto Lens

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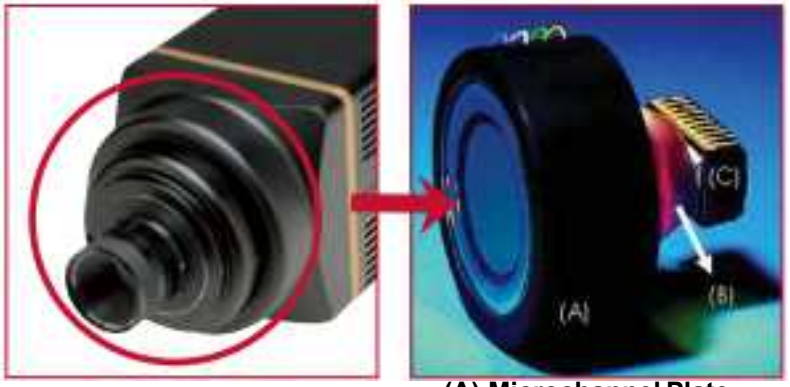
PI-Max ICCD Single Frame Imaging System

The ICCD Framing camera is a commercially available Princeton Instruments model PI-Max.

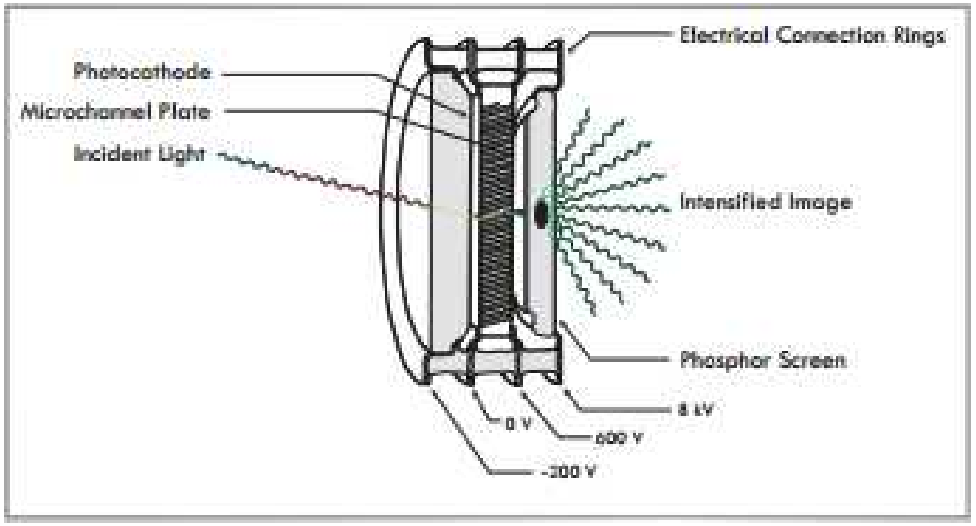
Princeton Instruments PI-Max ICCD Camera

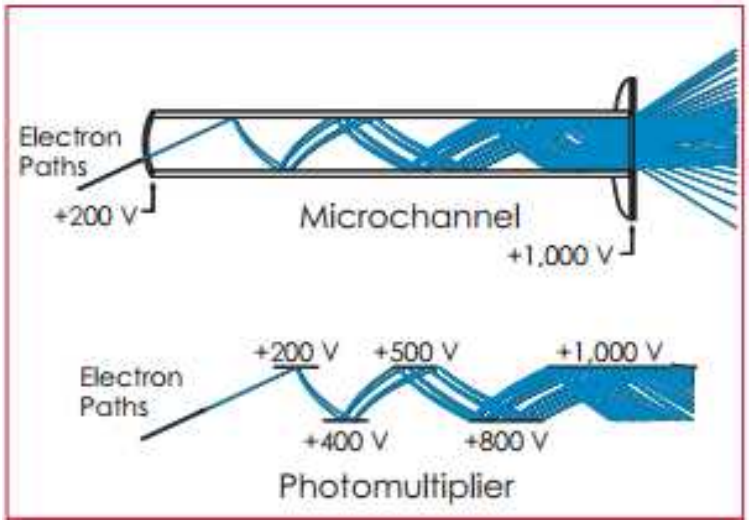
- Gen III filmless GaAsP photocathode (HBf)
- 25mm fiber-optic bonded 1:1 image intensifier
- P43 phosphor screen
- Front-Illuminated CCD
- 1340x1300 pixel array
- 20 micron pixel size
- < 7ns gating
- > 50% peak QE



Princeton Instruments PI-Max Camera

(A) Microchannel Plate, (B) Fiber–optic faceplate, and (C) CCD





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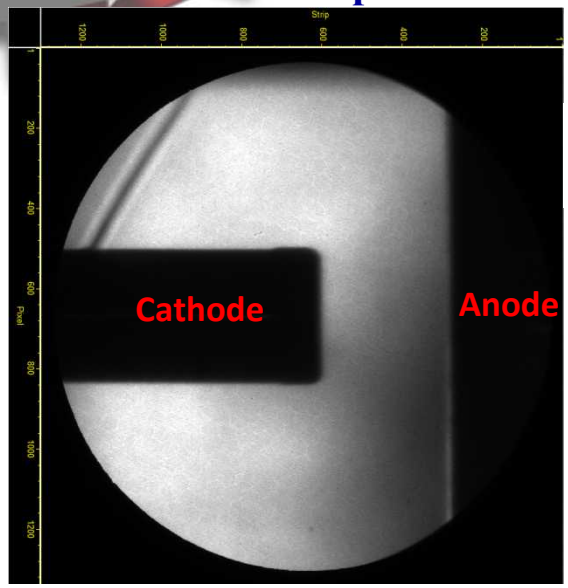
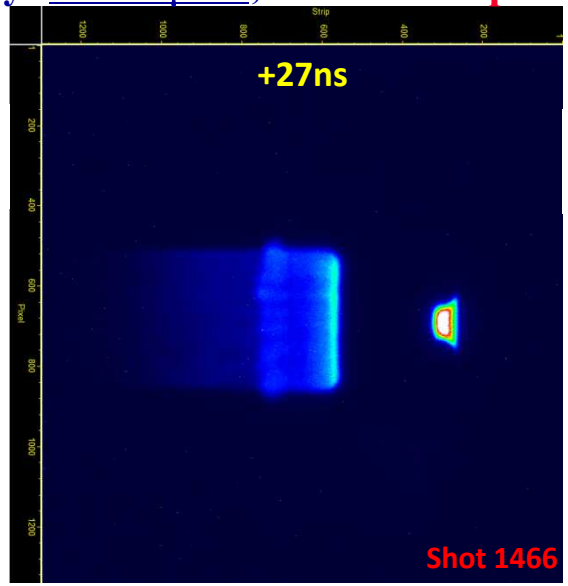
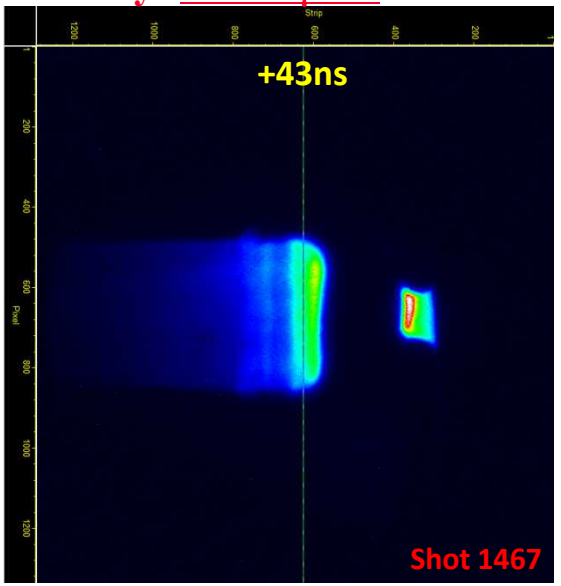
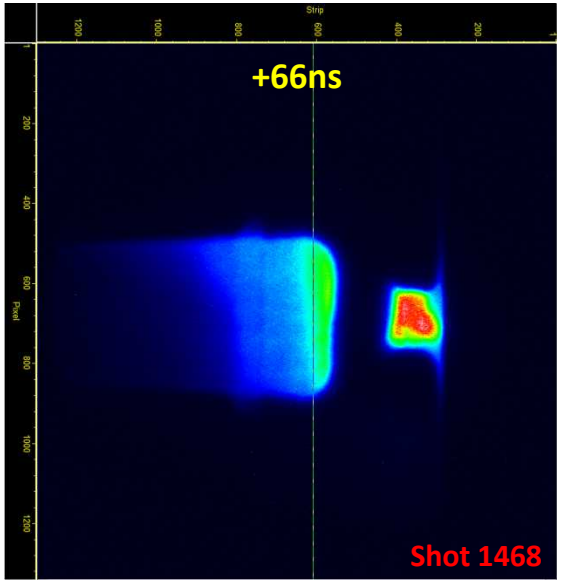
Framing Camera Images of Electrode Plasma Expansion

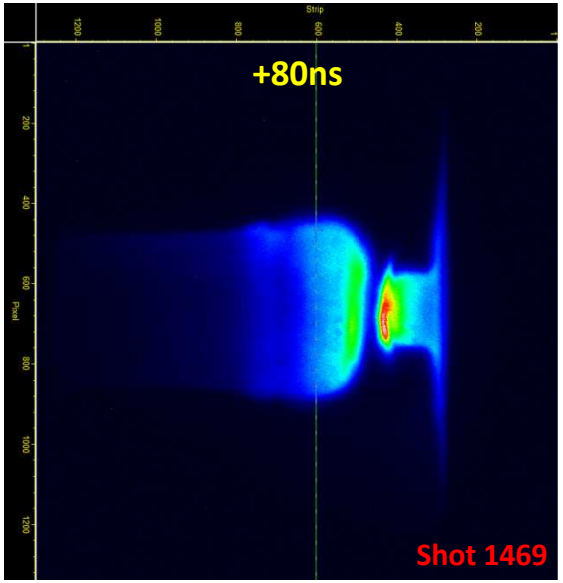
Anode Expansion Velocity: 3.5cm/μsec; Cathode Expansion Velocity: 1.7cm/μsec

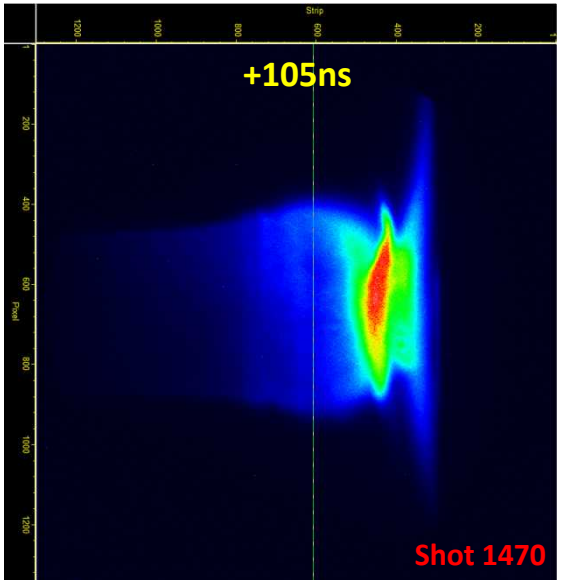












*Green line represents original cathode position

*10ns images

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Optical Streak Camera Plasma Imaging Diagnostic

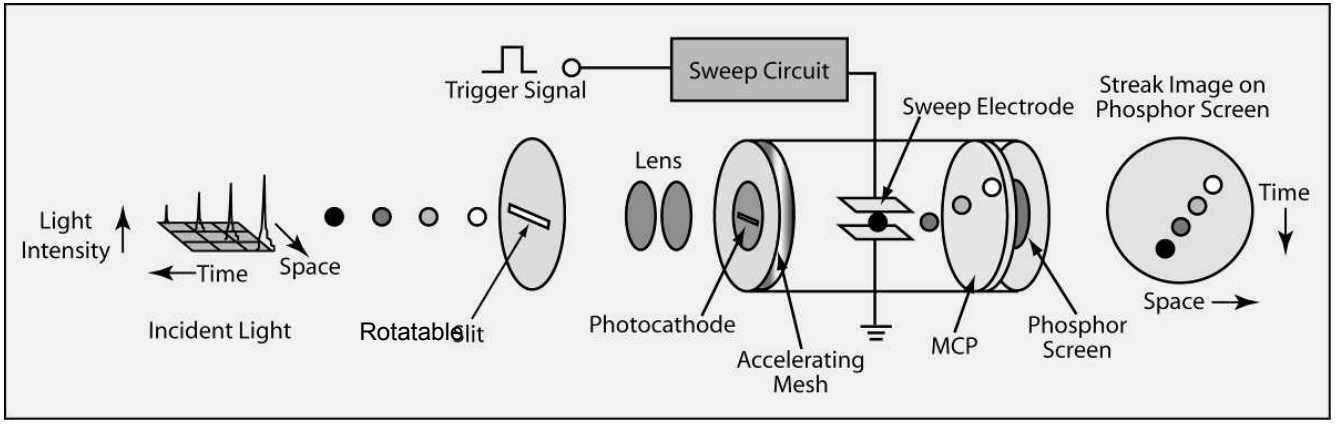
The optical streak imaging system was designed around the NSTec Gen IV Streak Camera.

NSTec Gen IV Streak Camera

- Continuously Selectable Sweep Rates from 20ns to 500µs
- Photonis P510 Streak Tube
- 6µm Fiber Faceplate (Input/Output)
- 35mm x 4mm Active Area Multi-alkali S-20 Photocathode
- 60mm Aluminized P-22 Phosphor Screen
- Selectable/rotatable input slit sizes
- Full remote control capability from external work station

Princeton Instruments Quad-Ro CCD

- 24 µm pixels
- 50mm chip



Princeton Instruments Quad-Ro CCD
(Steak camera detector)

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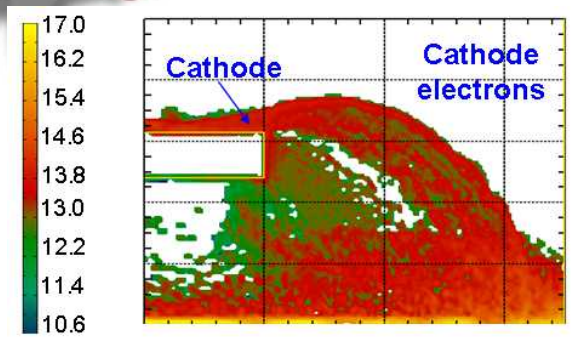
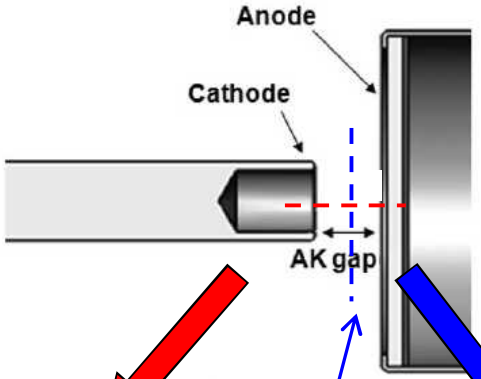
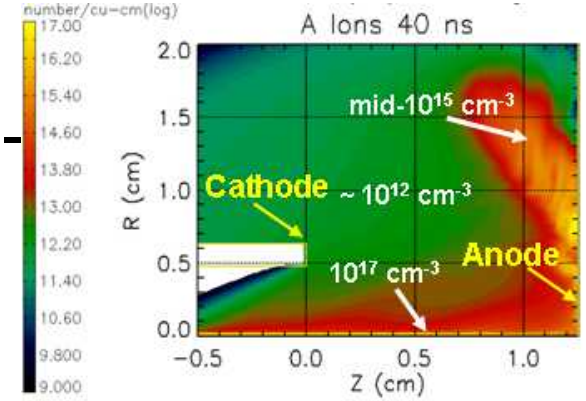
Typical Streaked Images of A-K Gap Plasmas

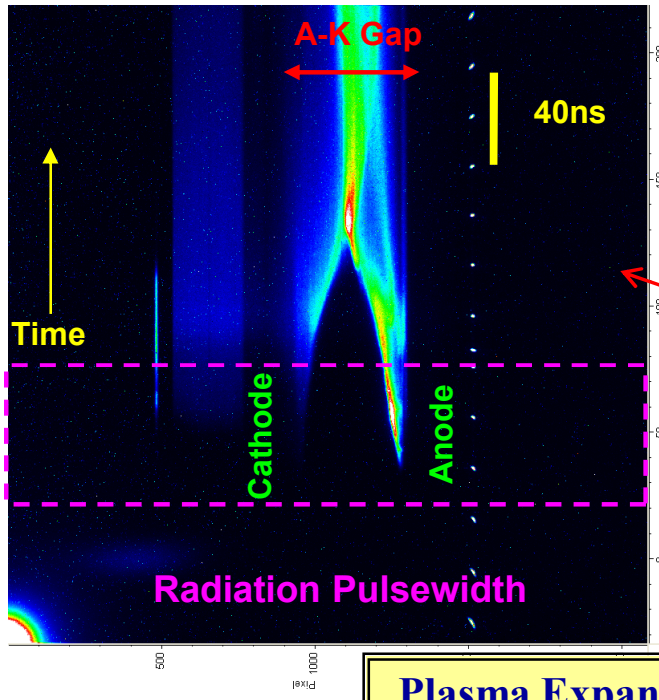


Hybrid particle-in-cell (PIC)/fluid simulations using LSP code





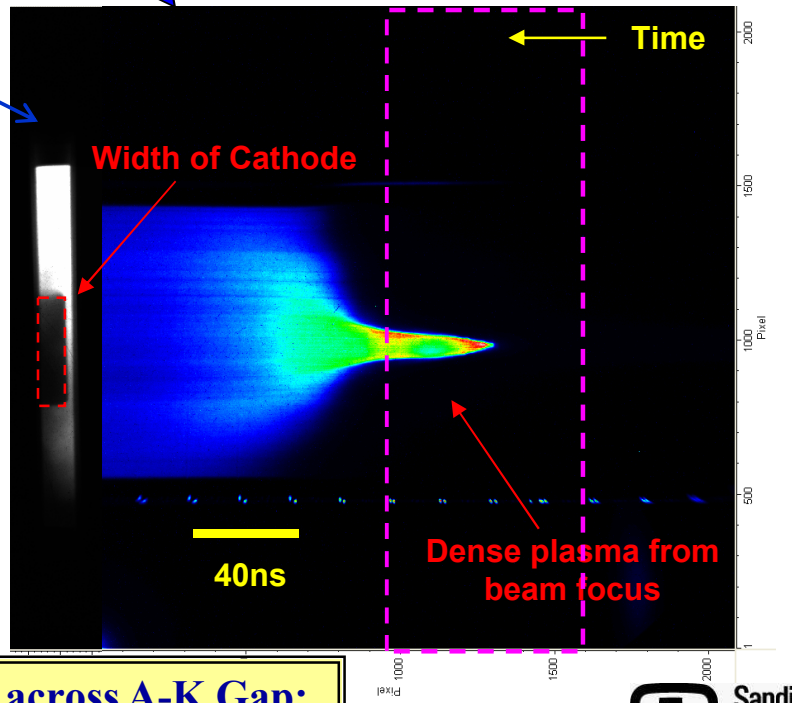
Axial Plasma Evolution



Vertical slit orientation across gap

Horizontal slit orientation spanning gap

Radial Plasma Evolution



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

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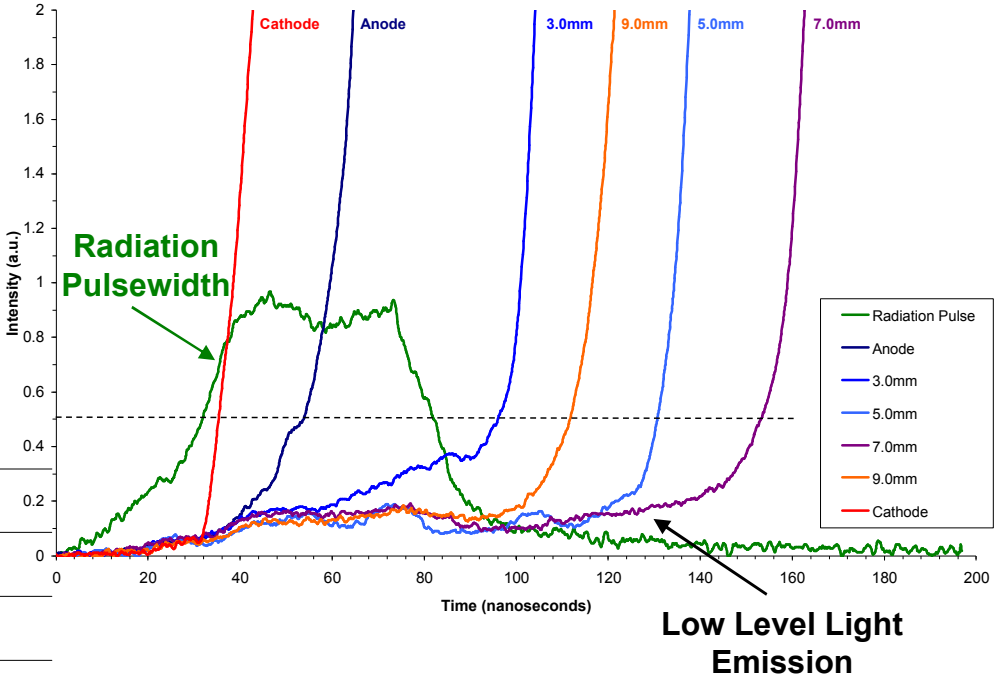
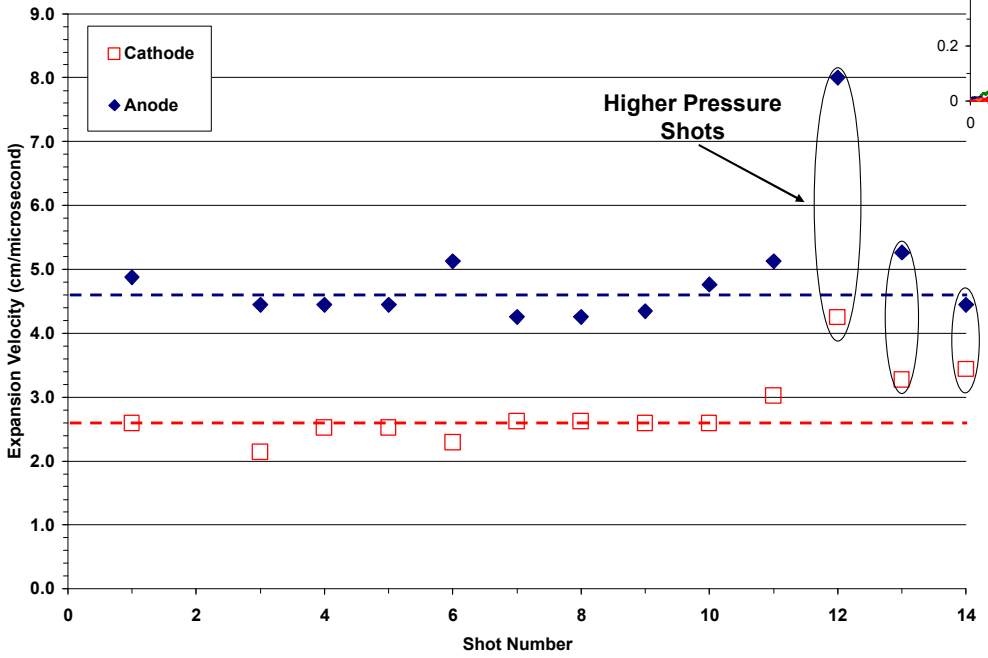
Plasma Propagation Measurements using Silicon Avalanche Photodetectors

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

Silicon Avalanche Photodetectors





*All data taken on the same shot

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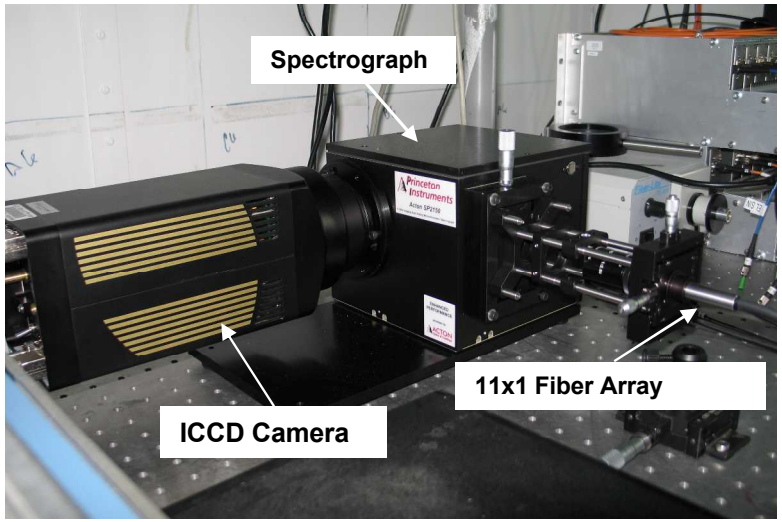
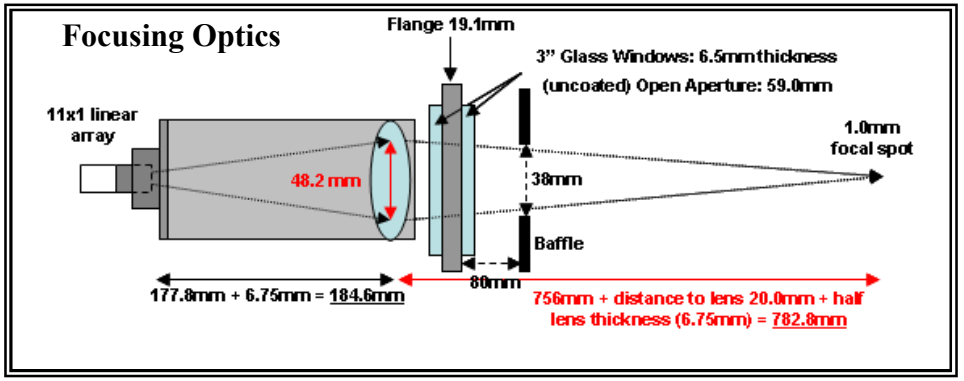
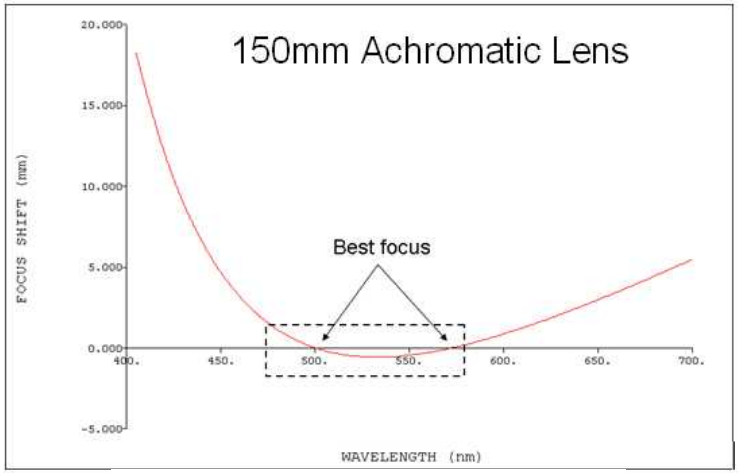
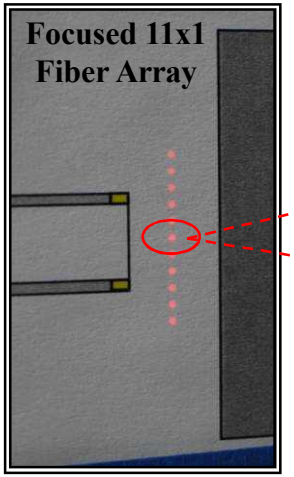
Plasma Spectroscopy Diagnostic

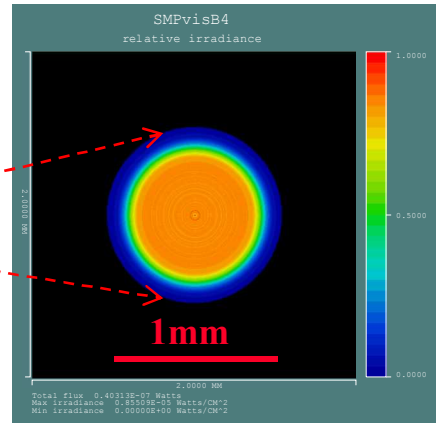
Spectrograph with ICCD camera











Fiber Focal Spot Size

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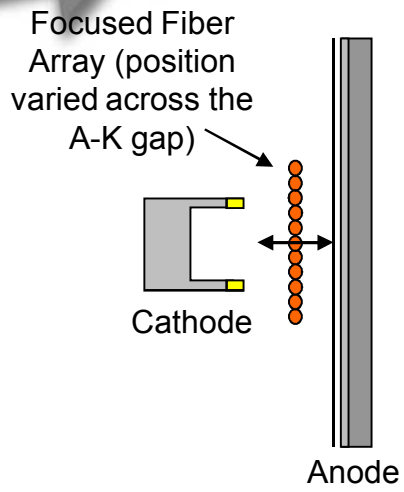
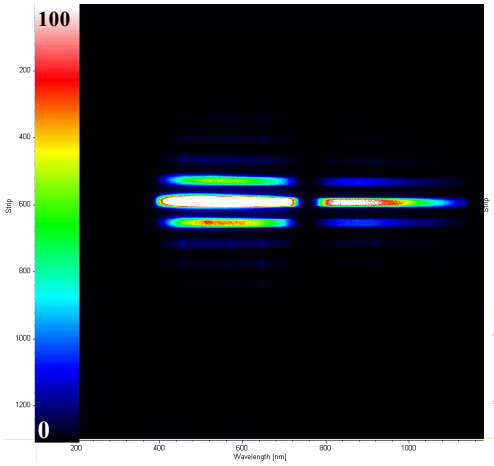
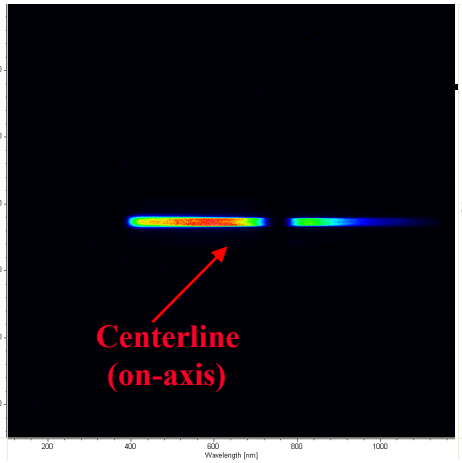
Radial Distribution of Spectra at Different Axial Locations (spectra collected on separate shots)

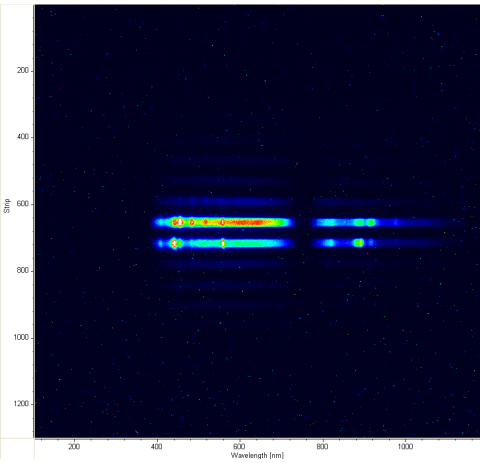




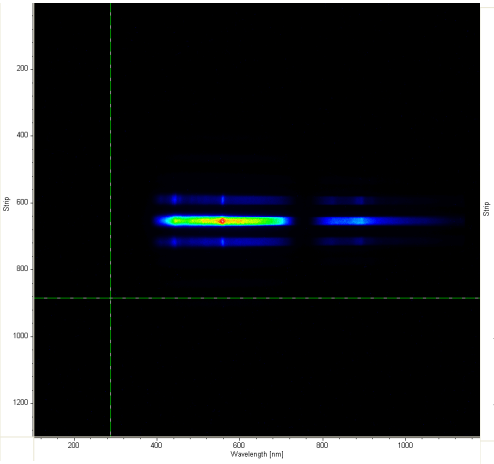
Anode



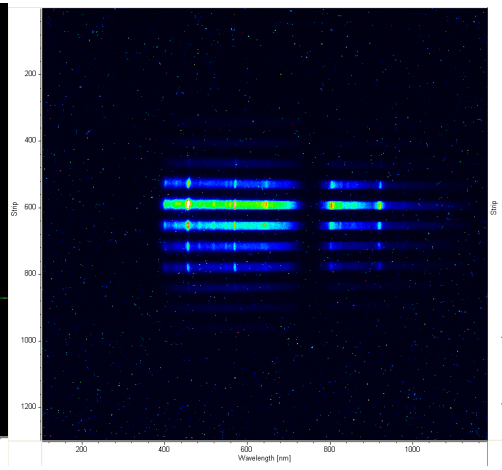
1/6 Gap



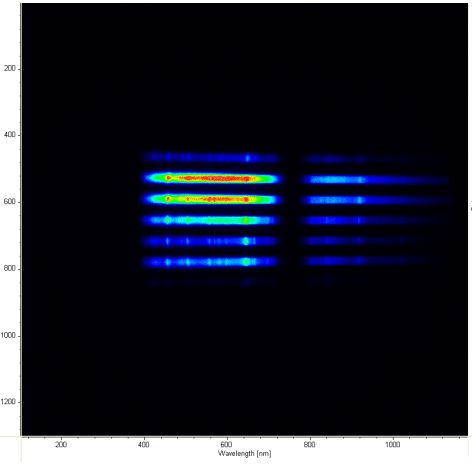
1/3 Gap



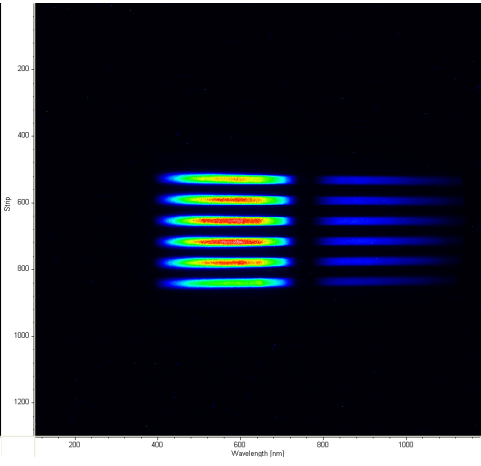
Mid-Gap



2/3 Gap



5/6 Gap



Cathode

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

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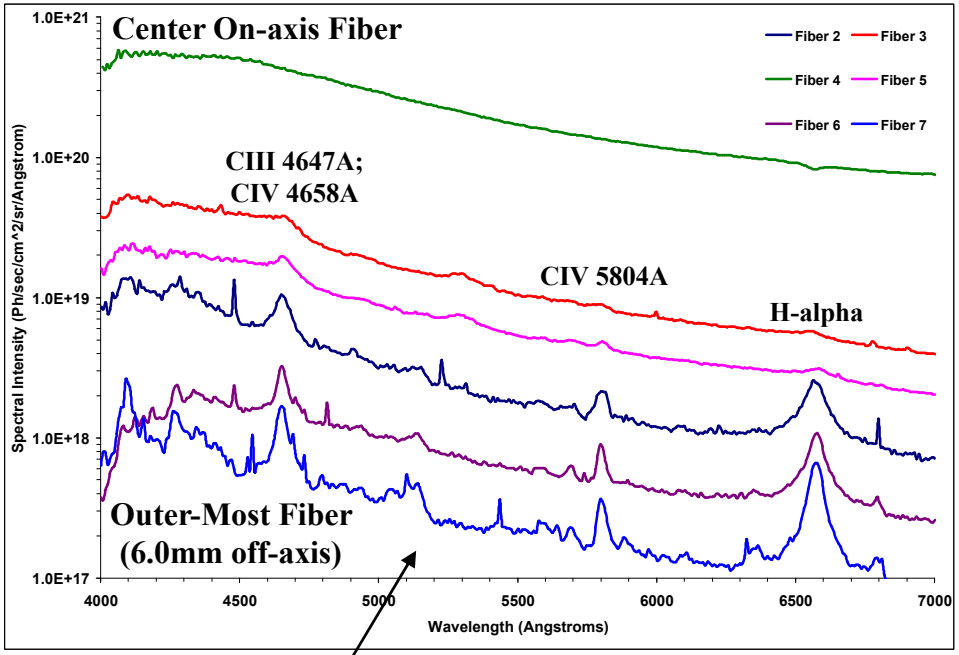
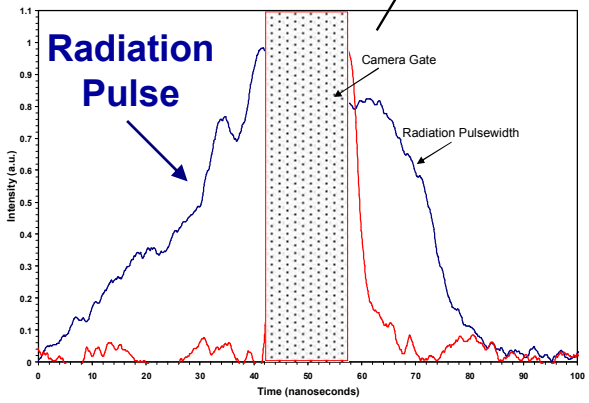
Spectral Data at Anode Surface During the Radiation Pulse

- 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 ~35x 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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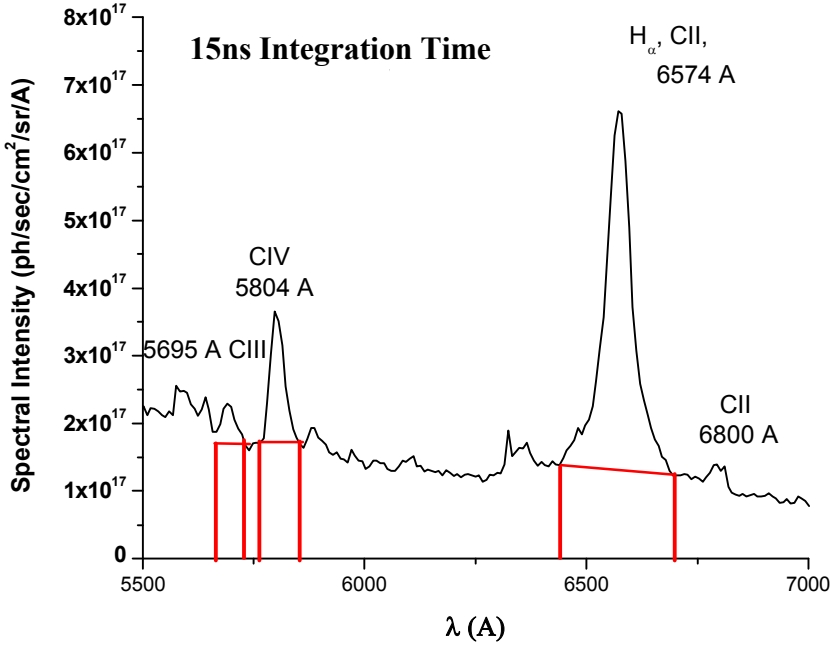
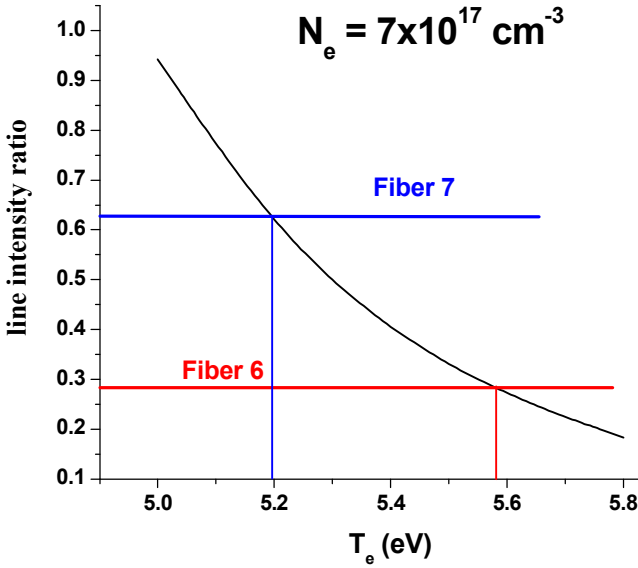
Sample Analyses of Spectral Data off the Anode Surface Following the Radiation Pulse

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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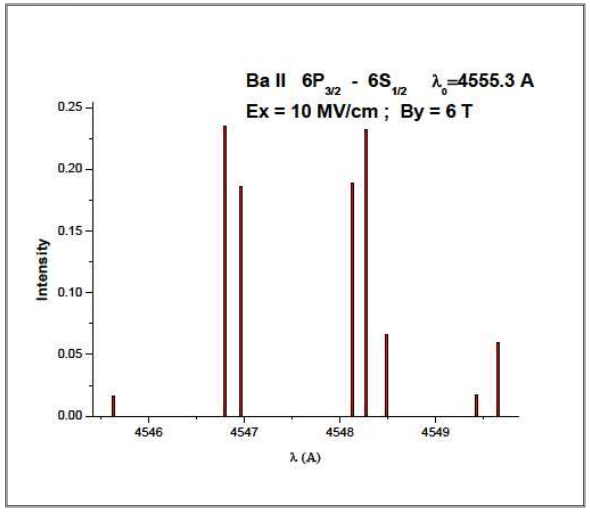
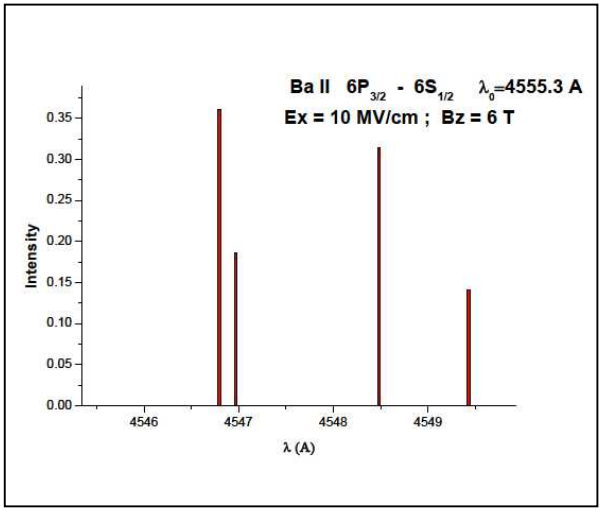
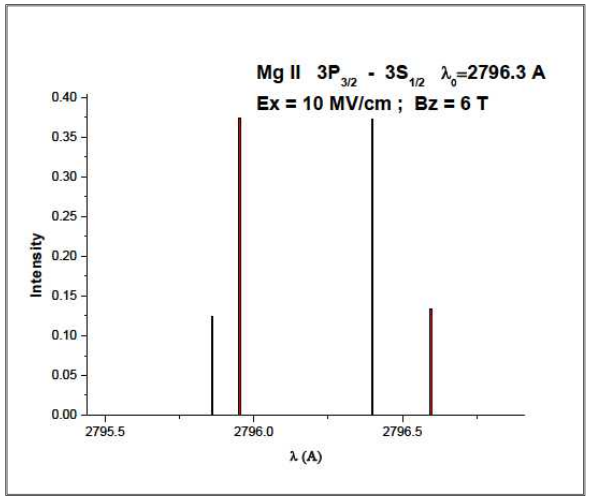
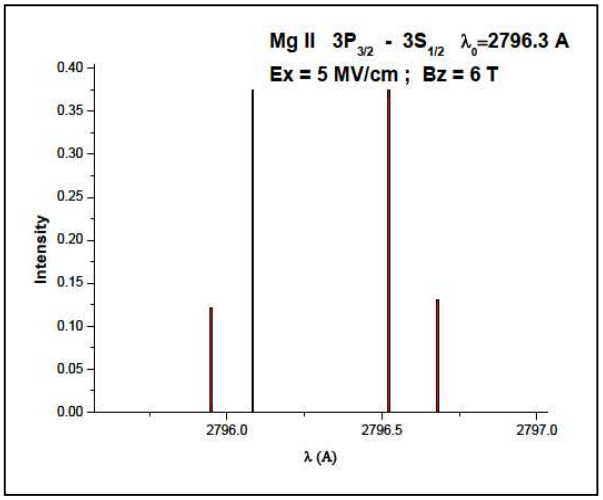
Electric and Magnetic Field Measurements in E-Beam Diodes









- Electric and magnetic fields present in e-beam diodes fielded at RITS can be measured spectroscopy.
- Very high electric fields (MV/cm) cause shifts in the transition frequencies of spectral lines (second-order Stark effect). These shifts can be calculated and measured.
- Similarly, strong magnetic fields (several Tesla), cause splitting of spectral lines (Zeeman splitting), which can be calculated and measured.
- Through a judicial choice of transition lines and species, very large E and B fields can be measured in the vacuum gap and within the dense plasma regions.

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Summary

•Dense plasmas are formed on electrode surfaces in the SMP diode during the ~45ns 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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