Development of a Multichannel Spectrometer for the Thomson Scattering Diagnostic on Pegasus

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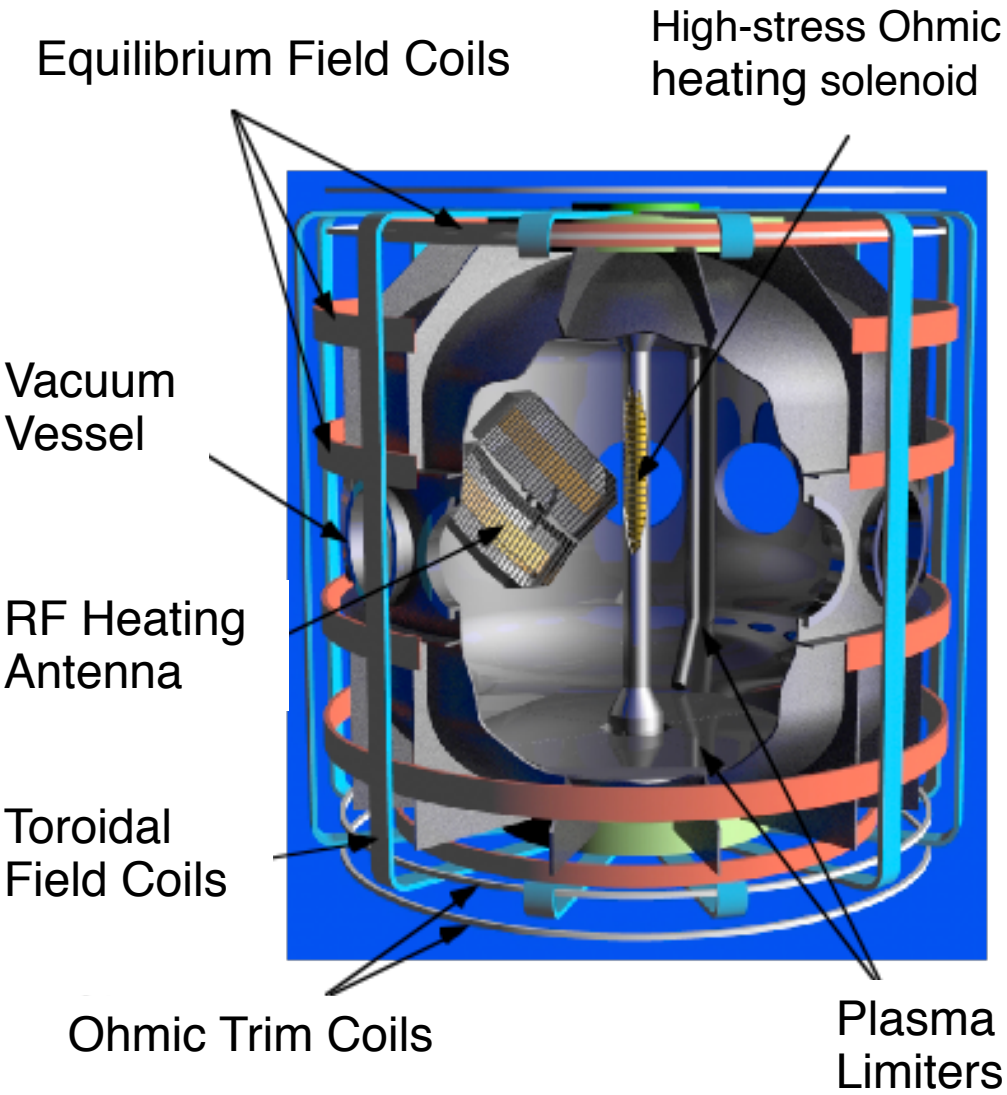


PEGASUS Toroidal Experiment

Abstract

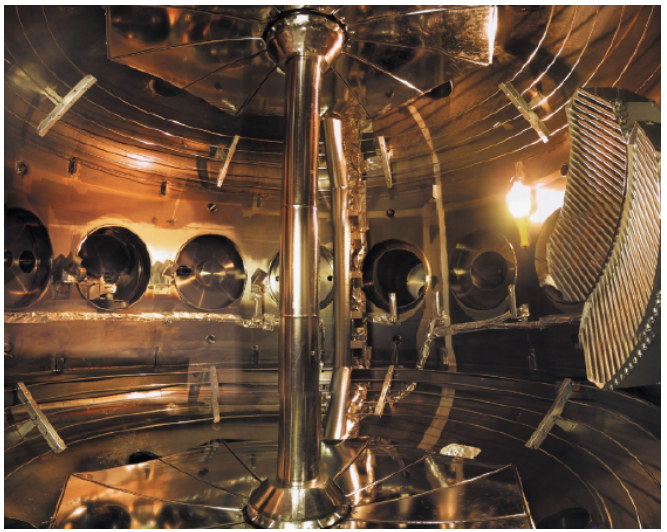
- **Motivation:** Explore electron transport in helicity-driven discharges and investigate edge stability
- **Source:** Red-shifted scattered light from frequency doubled Nd:YAG laser (532-632 nm)
- **Spectrometer Components:**
  - New high throughput volume phase holographic (VPH) grating technology
  - New high quantum efficiency image intensified CCD cameras (ICCD)
- **Design:**
  - 2 temperature ranges: 10eV-100eV and 100eV-500eV
  - Up to 8 spatial channels per spectrometer
- **Result:** A compact, simplified system

Pegasus Toroidal Experiment



Experimental Parameters

Parameter	To Date
A	1.15 – 1.3
R(m)	0.2 – 0.45
I_p (MA)	≤ .21
I_N (MA/m-T)	6 – 12
l_i	0.2 – 0.5
κ	1.4 – 3.7
τ_{shot} (s)	≤ 0.025
β_t (%)	≤ 25
P_{HHFW} (MW)	0.2



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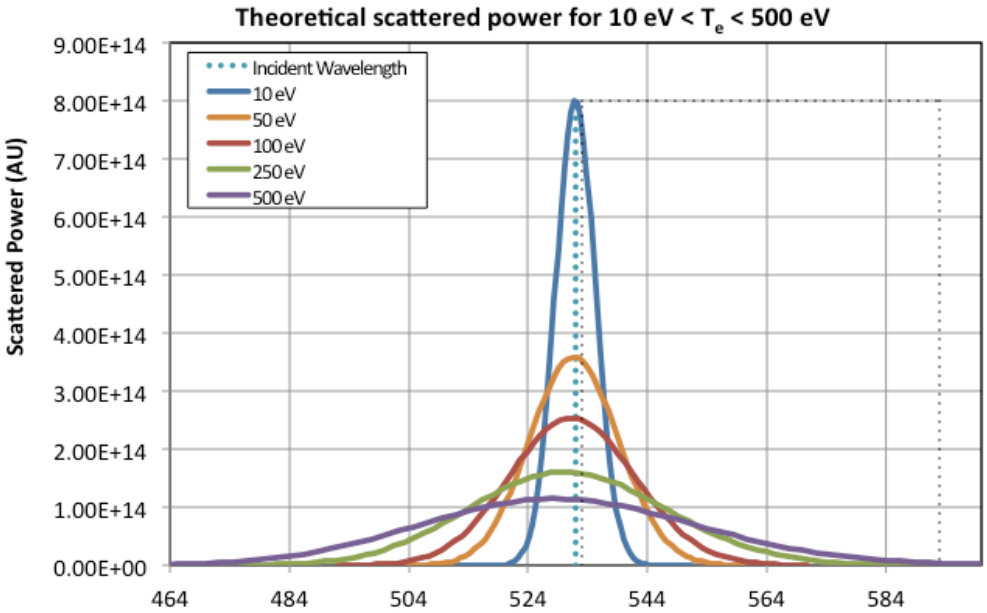
Thomson Scattering Background info

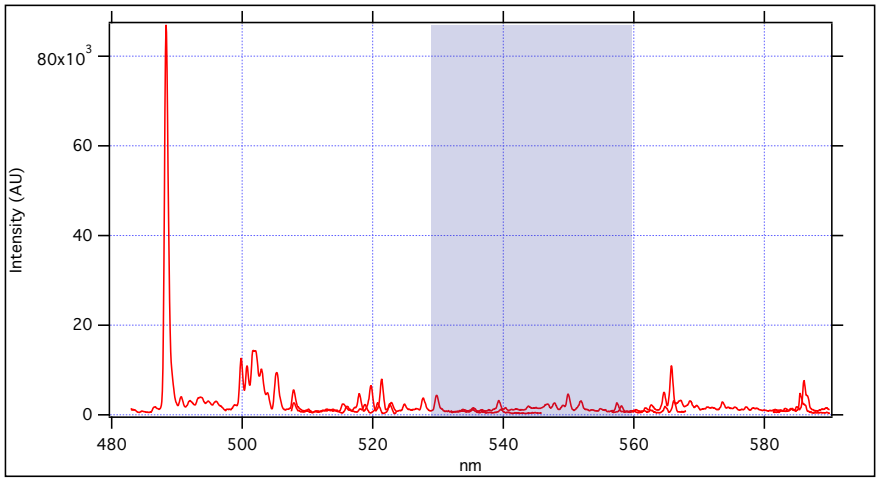
- Elastic scattering of EM radiation off free electrons in the plasma
- Low energy limit of Compton scattering
- Results in temperature dependent spectrum of Gaussian shape about the laser wavelength
  - At high temperatures there is a slight relativistic blue shift

$$
\begin{aligned}
I_{det} &= \frac{E_{laser}}{E_{photon}} \sigma n_e l \frac{\xi}{4\pi} \\
&= E_{laser} \left(\frac{\lambda_{laser}}{hc} \right) \sigma n_e l \frac{\xi}{4\pi} \\
&\approx 2.66 \times 10^{11} \mathrm{s}^2/\mathrm{kg} \left(E_{laser} \cdot \lambda_{laser} \cdot n_e \cdot l \cdot \xi \right)
\end{aligned}
$$

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Thomson Scattering On Pegasus





- Preliminary calculations of scattering light on Pegasus yields an average of ~3600 scattered photons per laser pulse in the direction of our viewing optics
  - For more info see Dave Schlossberg PP9.00008
- To improve data analysis at various temperatures, the spectrometer has been designed for low (10-100eV) and high (100eV-500eV) ranges

N.L. Schoenbeck, APS Division of Plasma Physics 11/16/2011

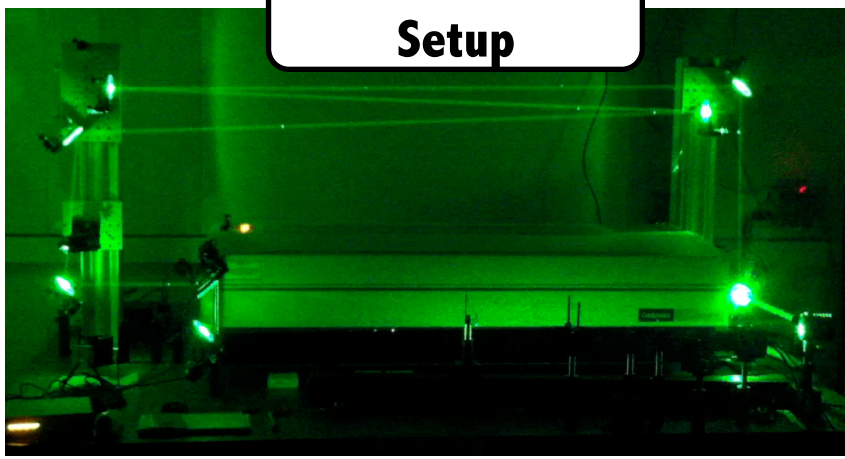
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Implementation of a Thomson Scattering Diagnostic

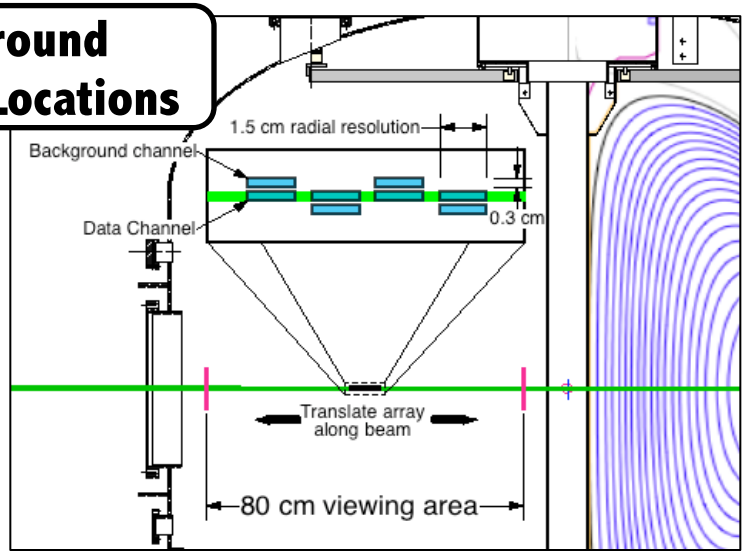
See Dave Schlossberg PP9.00008

- Selection and testing laser
  - 2J 532 nm Nd:YAG laser with ~10ns pulse length
- Scattering calculations and reduction of stray light within Pegasus Tokamak
  - Beam line baffles
  - Beam dump
- Viewing port and background channels

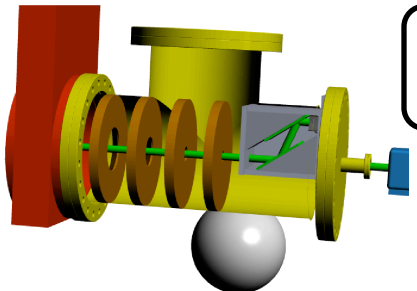
Laser Test Setup



Background Channel Locations



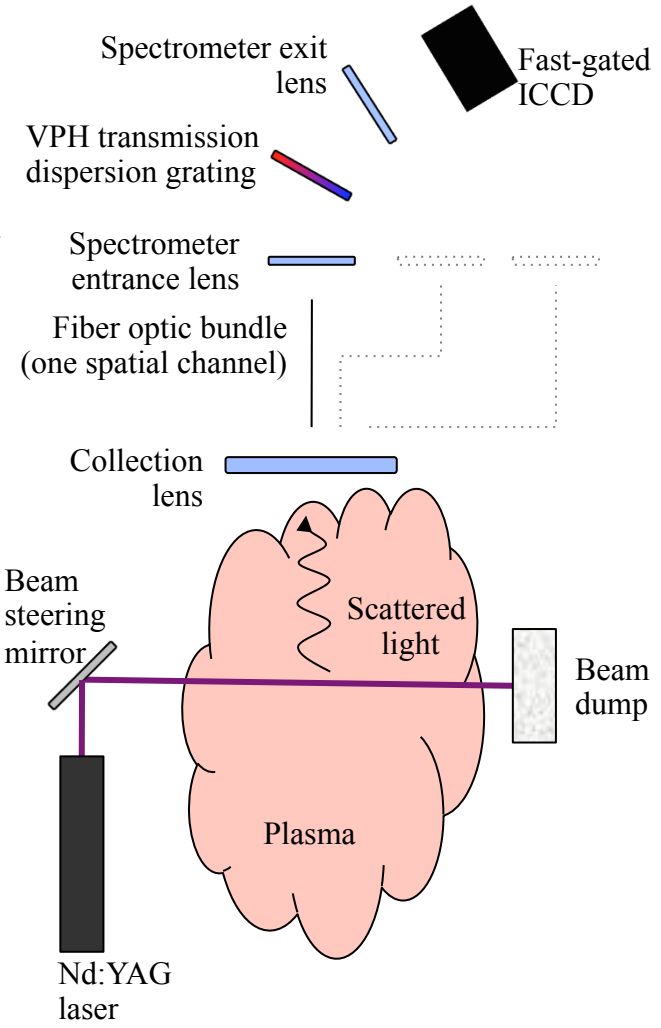
Beam Dump Design



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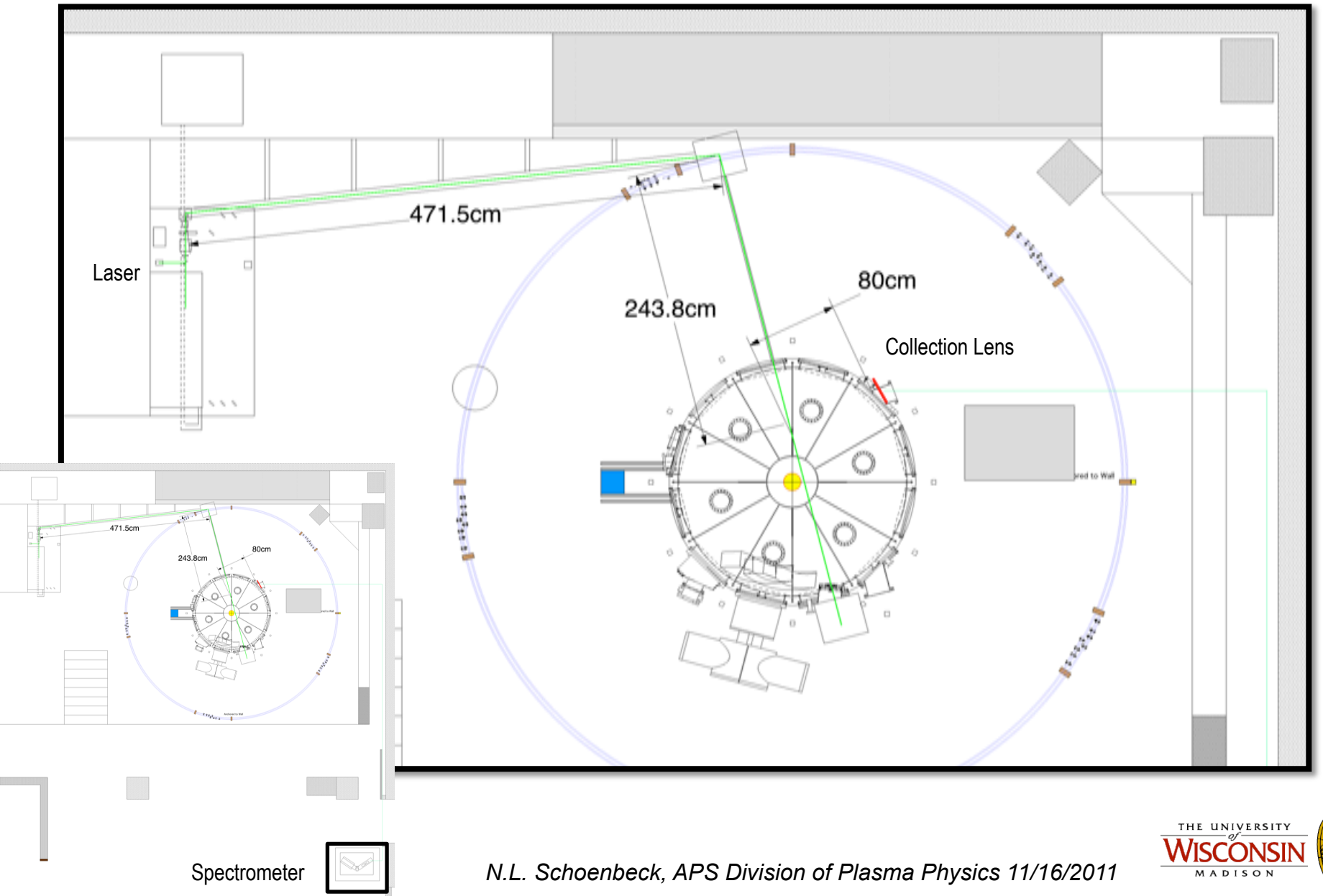
Pegasus Thomson Scattering System Key Components

- Frequency doubled Nd:YAG laser @ 532 nm
- Beam Dump
- Collection Lens & Fiber Optics:
  - 136mm clear aperture with an 80 cm field of view along the laser
  - Fiber optic bundles to image plasma location to spectrometer
- Spectrometer
  - Achromatic lens at spectrometer input
  - Cut-on filter to block laser wavelength
  - Volume phase holographic (VPH) grating
    - New high efficiency, >70%, transmission gratings
    - Simplifies spectrometer design and reduces stray light from reflections
  - Camera lens at spectrometer output
  - Image intensified CCD (ICCD) cameras
    - High quantum efficiency (QE ~45%)
    - Low Noise



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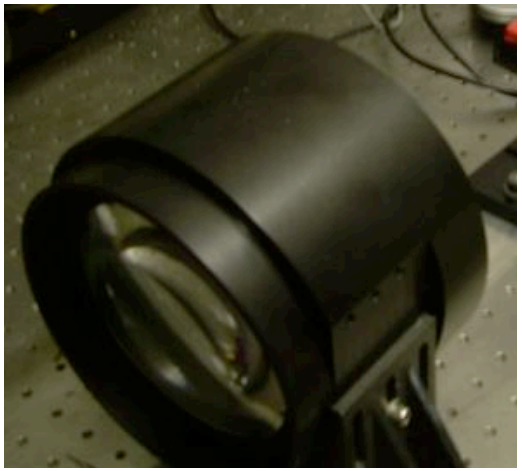
Thomson System Location on Pegasus

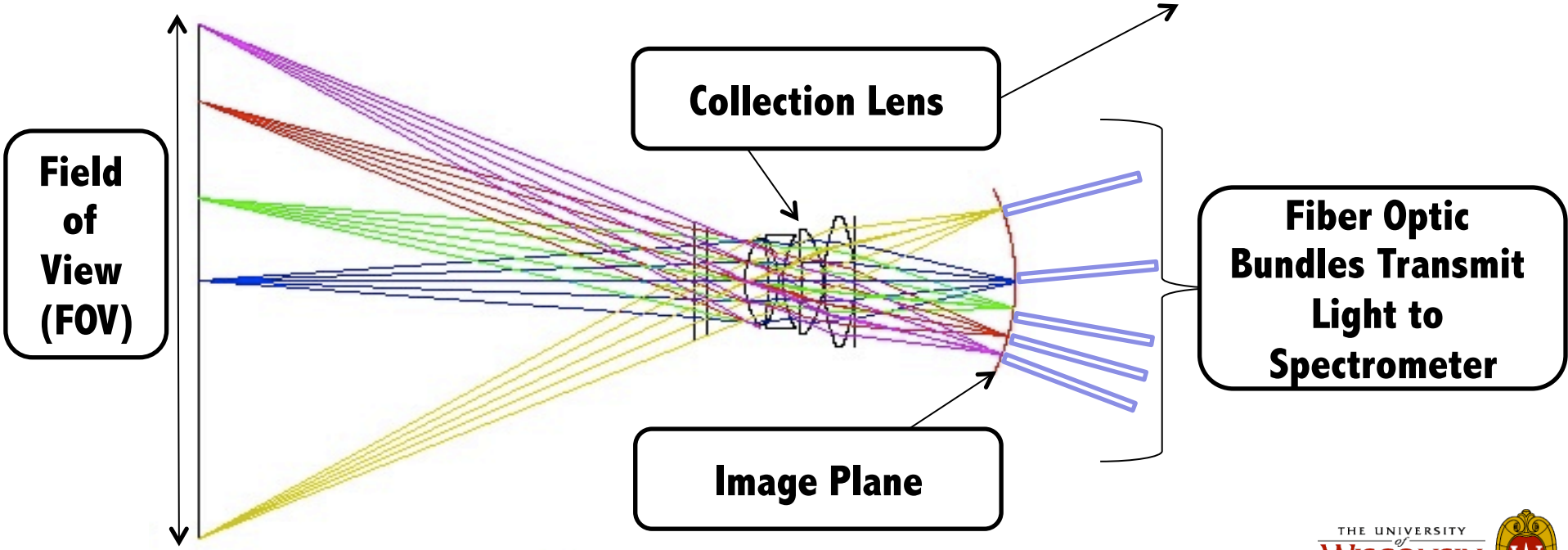


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Collection Lens Designed to Collect Full Field of View

- Design Criteria:
  - Collect 80 cm flat field of view 72cm from lens
  - Resolution sufficient to collect a scattering area ~1.3cm x 0.3 cm
- Curved image plane with open locations for fiber placement
- Image Plane: F# 2.1 with a focal length of 20.2cm
- Resolution: 100um
- Magnification ~1/3

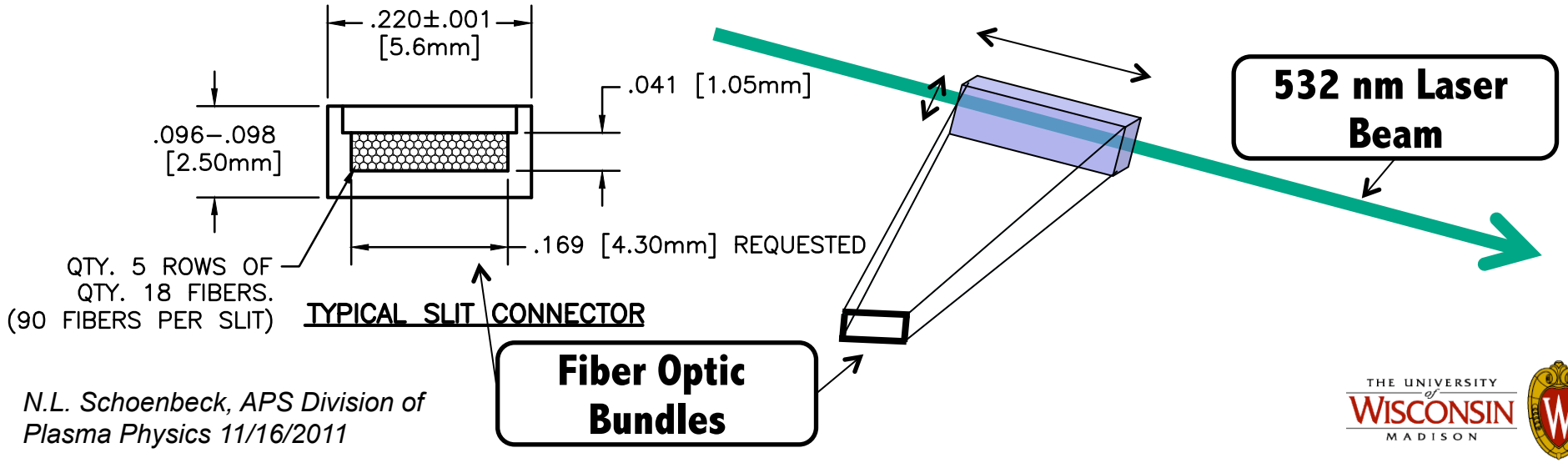




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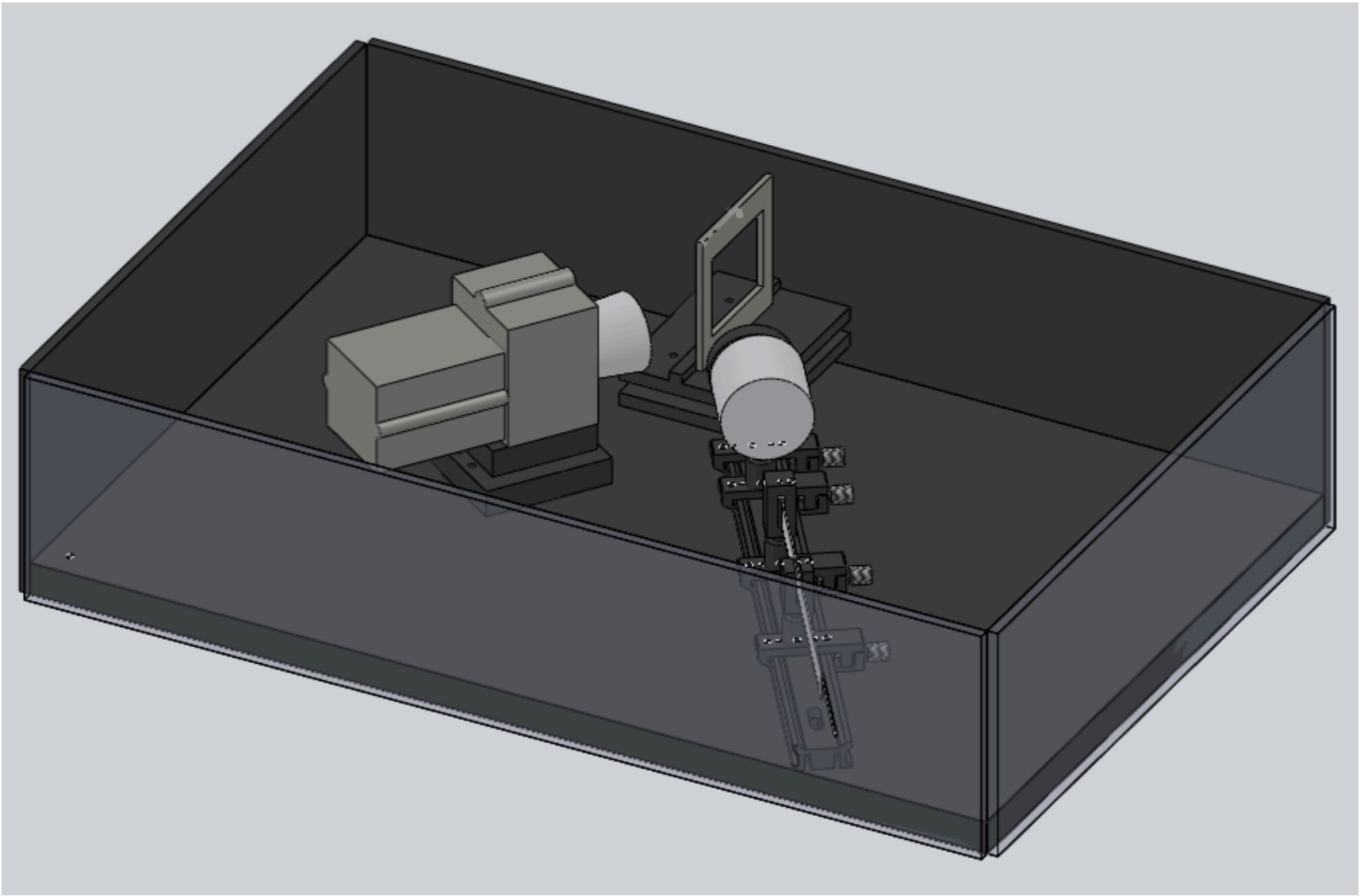
Fiber Optic Bundles Map to1.4cm of Light Along Laser Beam

- Each spatial channel:
  - 0.3 cm tall (across the laser) by 1.4 cm along the laser in the plasma
  - With demagnification this gives .98mm x 4.50mm fiber dimensions
- Fibers will be stationary with plans to populate more plasma locations in the future
  - Repositioning fibers for different data points done manually as needed
  - Initial measurement will be done with 8 spatial channels: 4 data points with corresponding background channels
  - Plans to expand to 24 spatial channels



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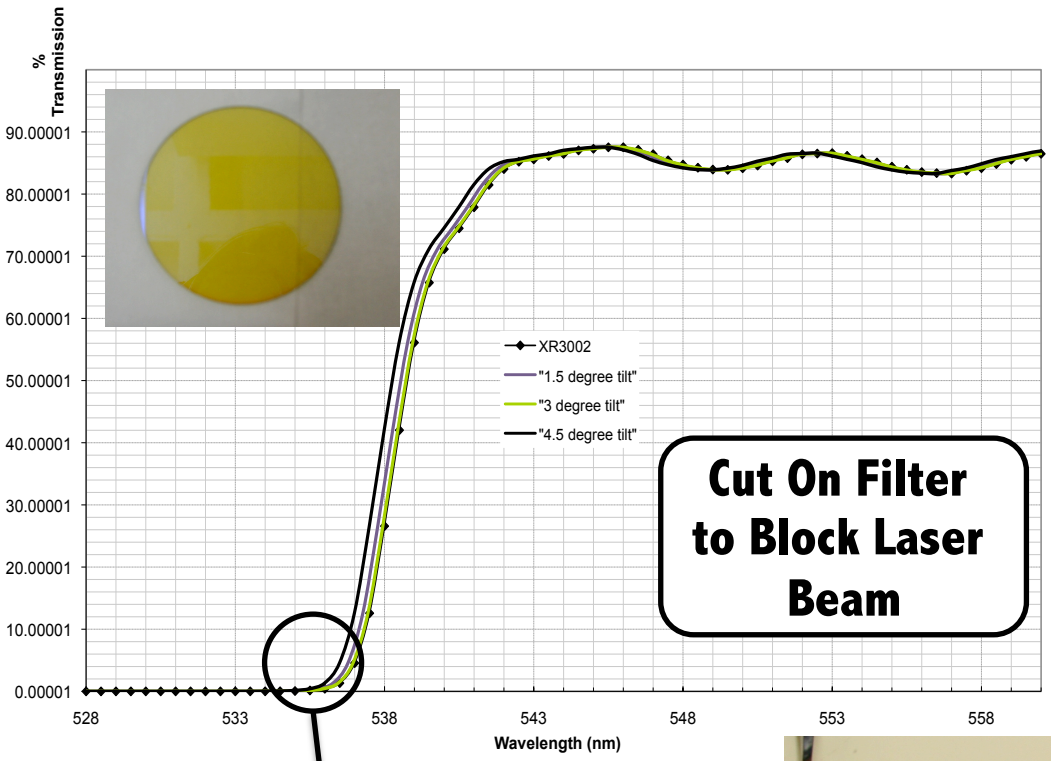
Thomson Spectrometer Layout

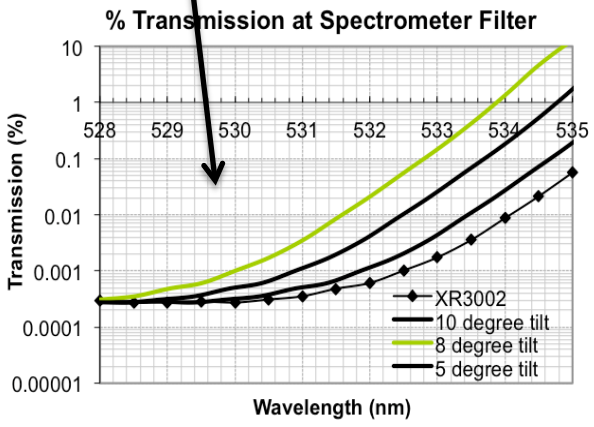


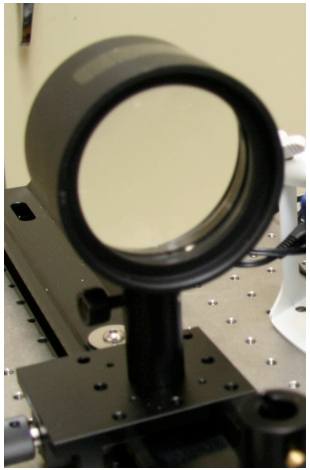
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Large diameter Input Lens & Filter to Reduce Walk-off

- Input Lens: Achromat from Wright Scientific
  - F# 1.8 with 124mm focal length
- Images collimated light onto 3” cut-on filter
  - Block wavelengths <535 to about 0.001% transmission
  - Light enters filter at different angles, depending on spatial channel. Maximum angle is 4.5 degrees
- Small portion of light lost at grating from off-axis fiber bundles

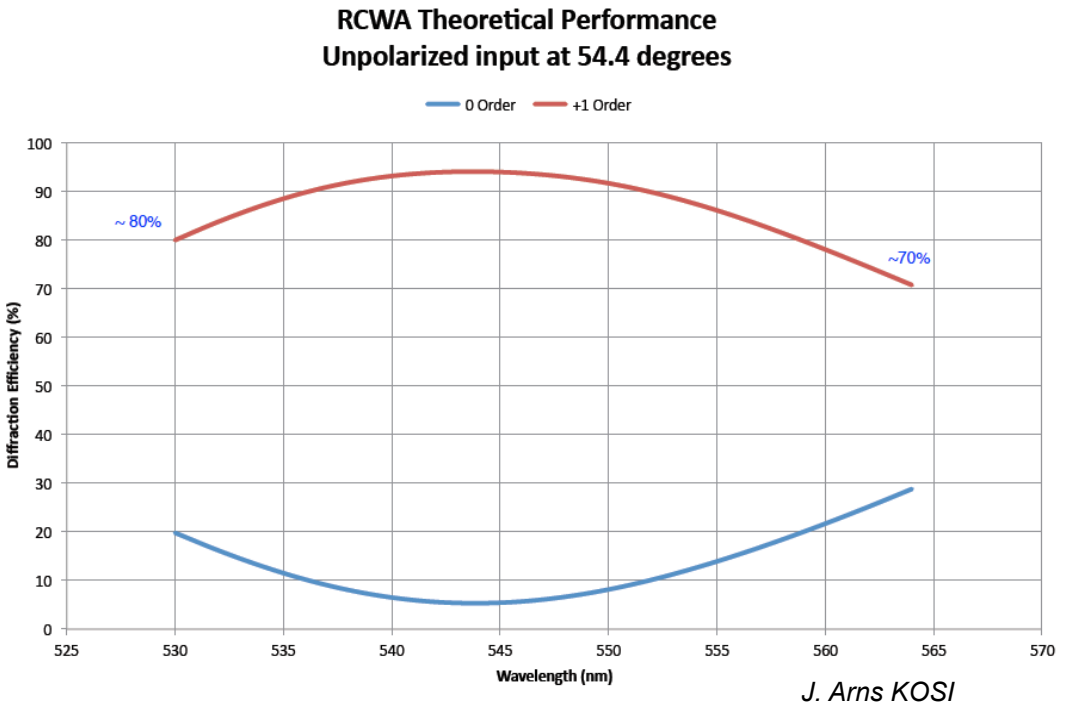




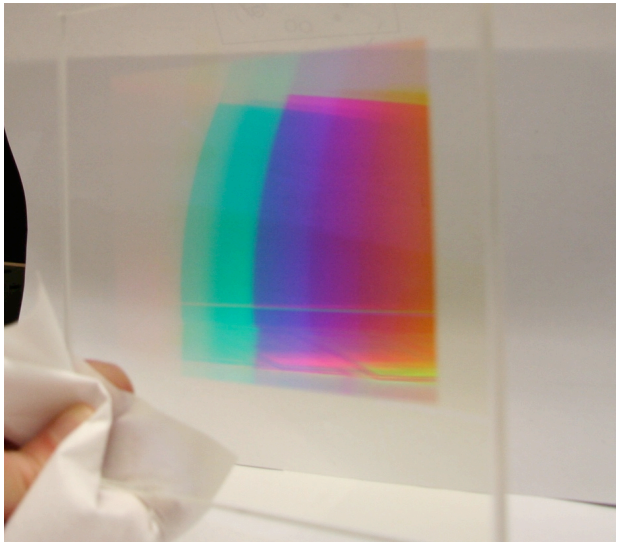


VPH Grating Designed for High Throughput in 2 Temperature Regimes

- Two gratings
  - 2971 lines/mm for low temperatures (~10eV-100eV)
  - 2072 lines/mm for high temperatures (~100eV-500eV)
- 3” gratings to minimize walk-off
- Dispersion selected such that camera width is limiting the etendu
- Spectrometers will be built at two input angles
  - 54 degrees
  - 36 degrees



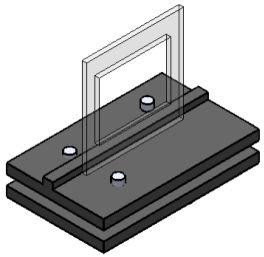
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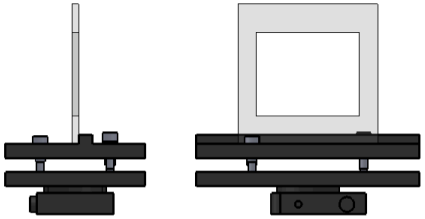


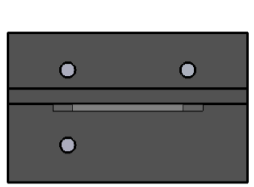
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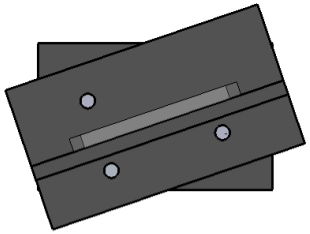
VPH Grating Mount Designed for Flexibility with 2 Blaze Angles

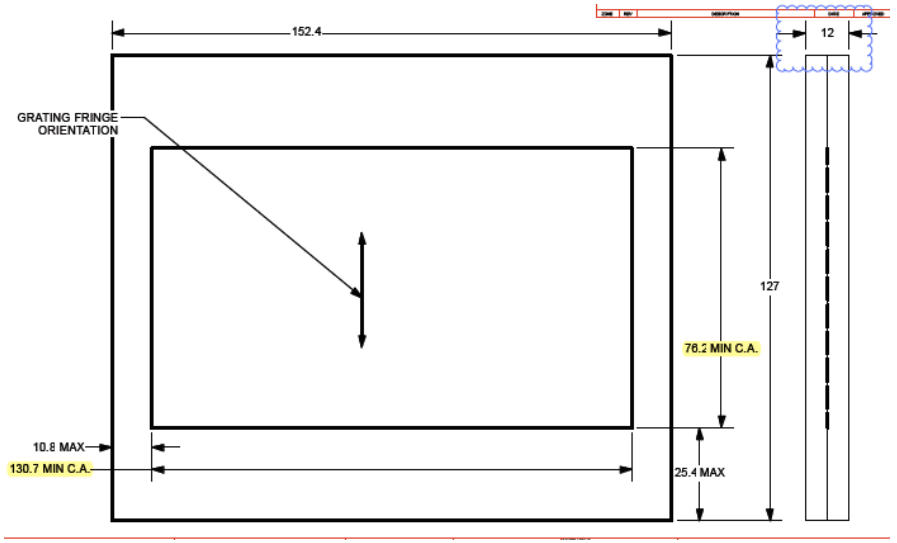
- Kinematic mount designed to clip in appropriate grating for a given temperature range
- 3 degrees of freedom (roll, tilt, & yaw) built in for fine adjustments







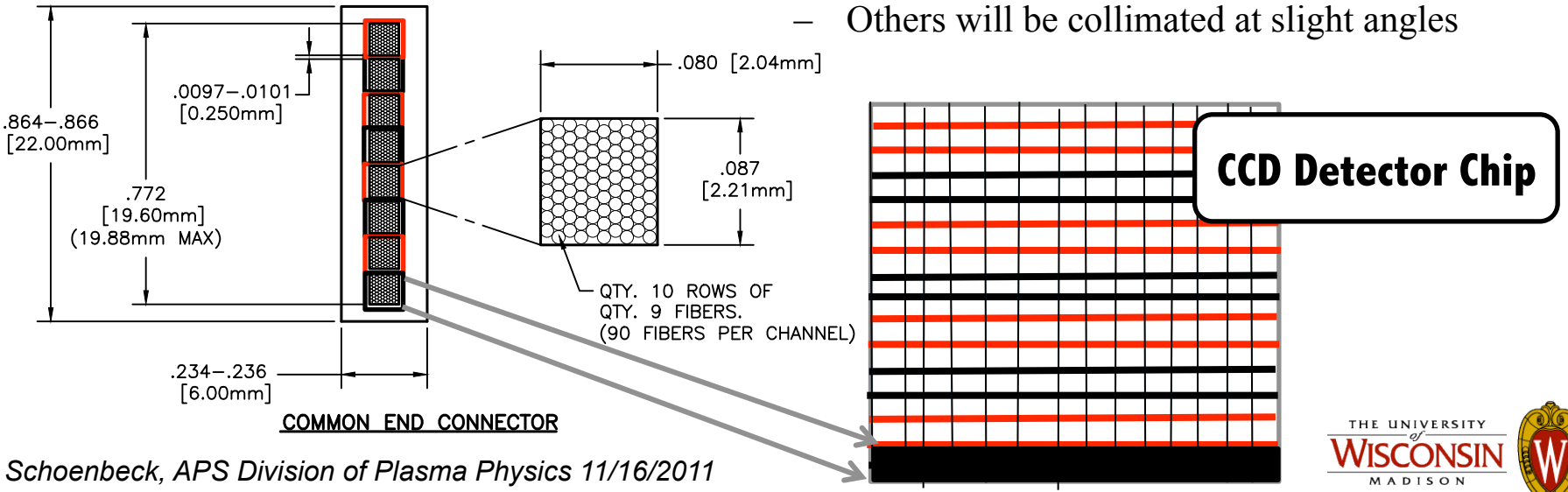




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Detector Area Sets System Etendu & Size of Fiber Optic Bundles

- Design Criteria:
  - Eight spatial channels vertically
    - Depends on camera detector height and magnification of spectrometer
  - 10 spectral bins horizontally
    - Based on camera detector width and dispersion of grating
  - Total area must be conserved
- 8 legs are bundled together
  - Bundled length ~1' (30cm) to simplify strain relief at spectrometer
- Minimum spacing to maximize use of detector area
  - ~0.25mm gaps between fiber channels
- Light from fiber channels collimated by entrance lens
  - Central 2 channels nearly parallel
  - Others will be collimated at slight angles



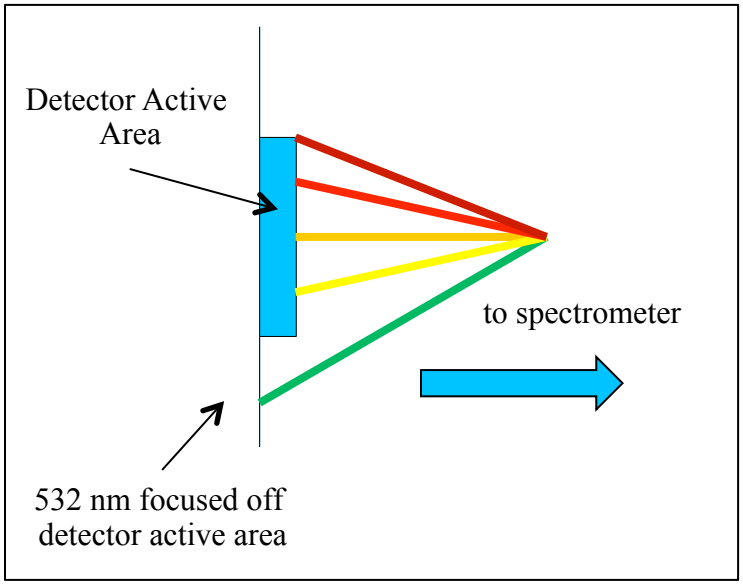
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Exit Lens & Camera Aligned such that 532nm Light Misses Detector

- Camera aligned such that laser light is not detected
- Photography lens used as the exit lens
  - High resolution
  - Small demagnification given input lens
- Camera stage designed for 2 input angles.



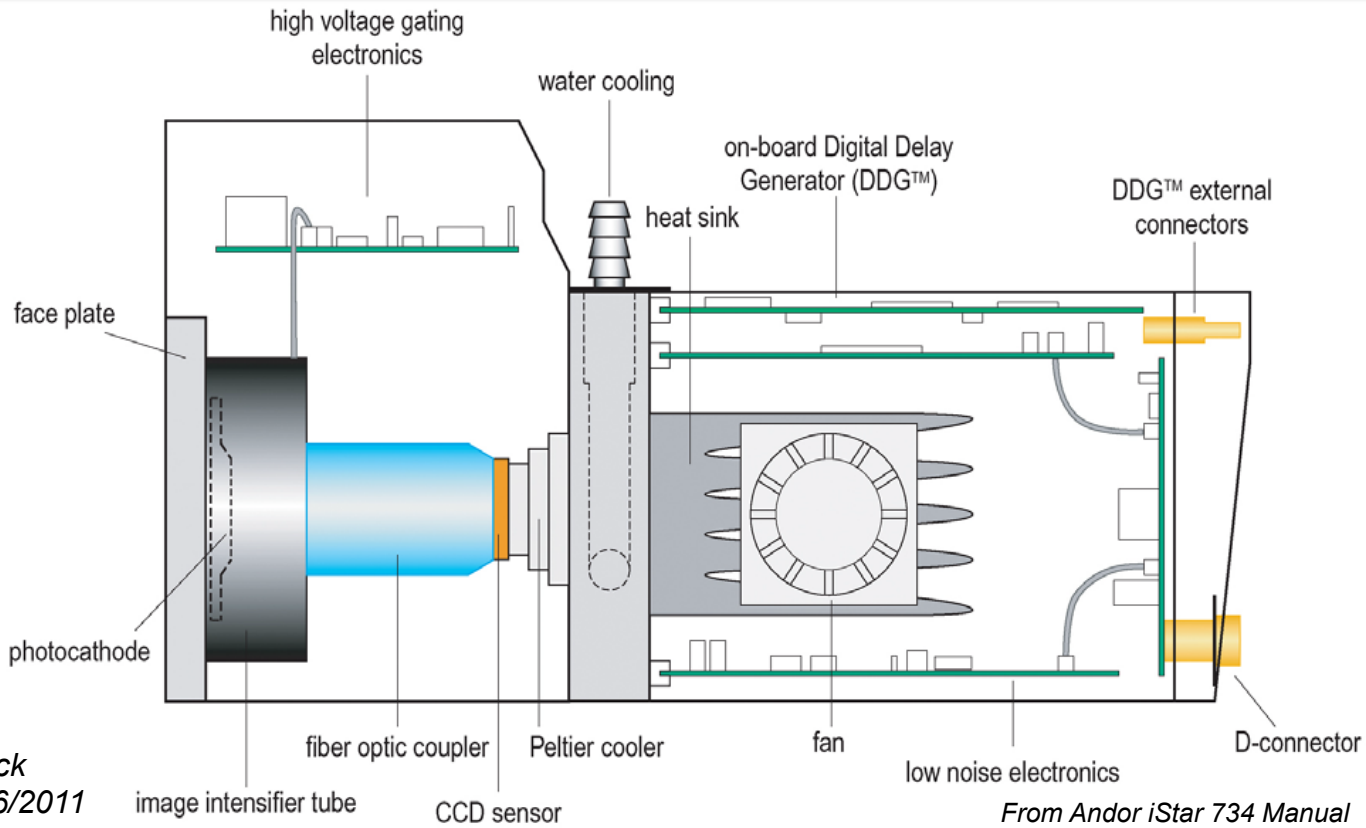




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ICCD Detectors Chosen for High Gain & Low Noise Qualities

Manufacturer's Specifications: Andor iStar 734			
Effective Active Area (mm)	13.3 x 13.3	Effective Pixel Size (um)	19.5 x 19.5
Read Noise	As low as 2.9 e-	Active Pixels	1024 x 1024
Spectral Range (nm)	120 - 1090	Photocathode QE (max)	Up to 45%
Minimum Optical Gate Width	As low as 1.2ns	Image Intensifier Gain	>200

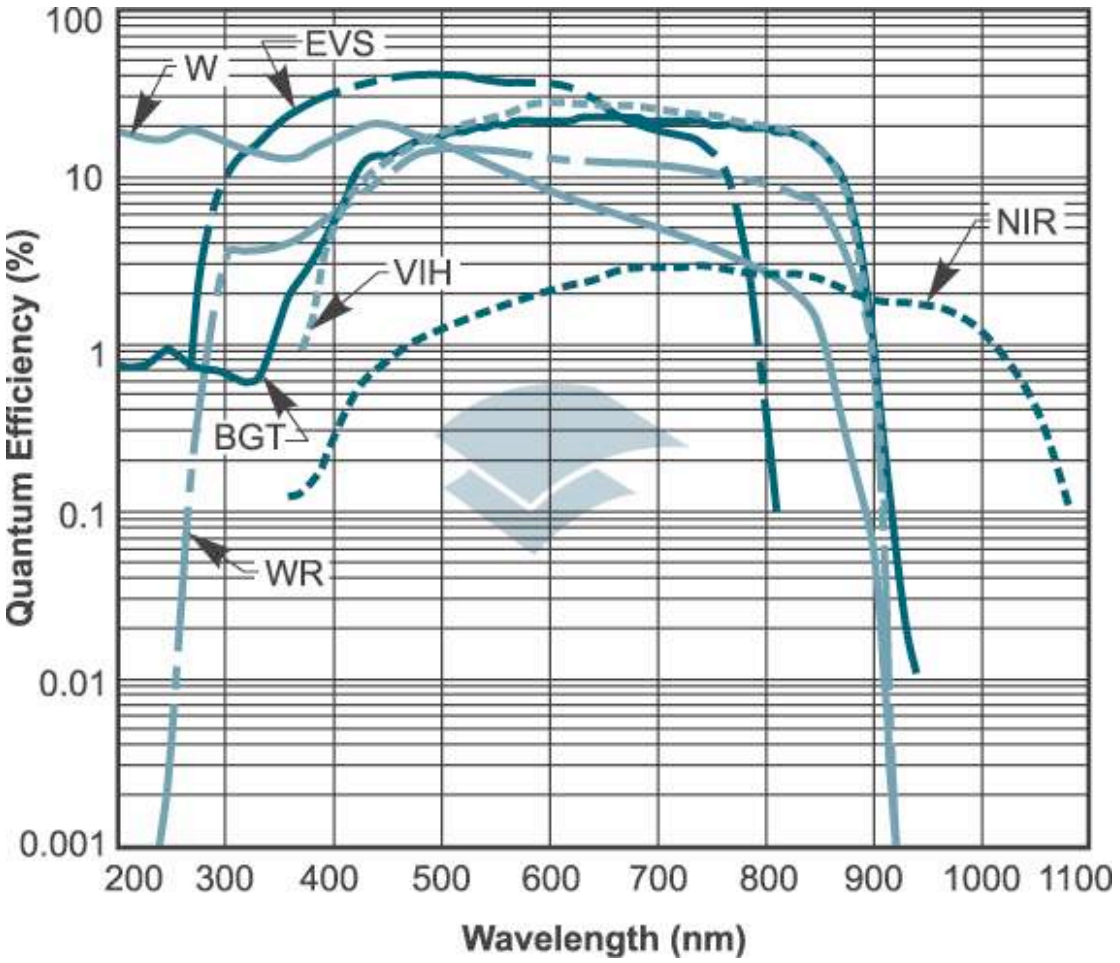


From Andor iStar 734 Manual

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New Gen 3 Image Intensifiers Have Improved Quantum Efficiency

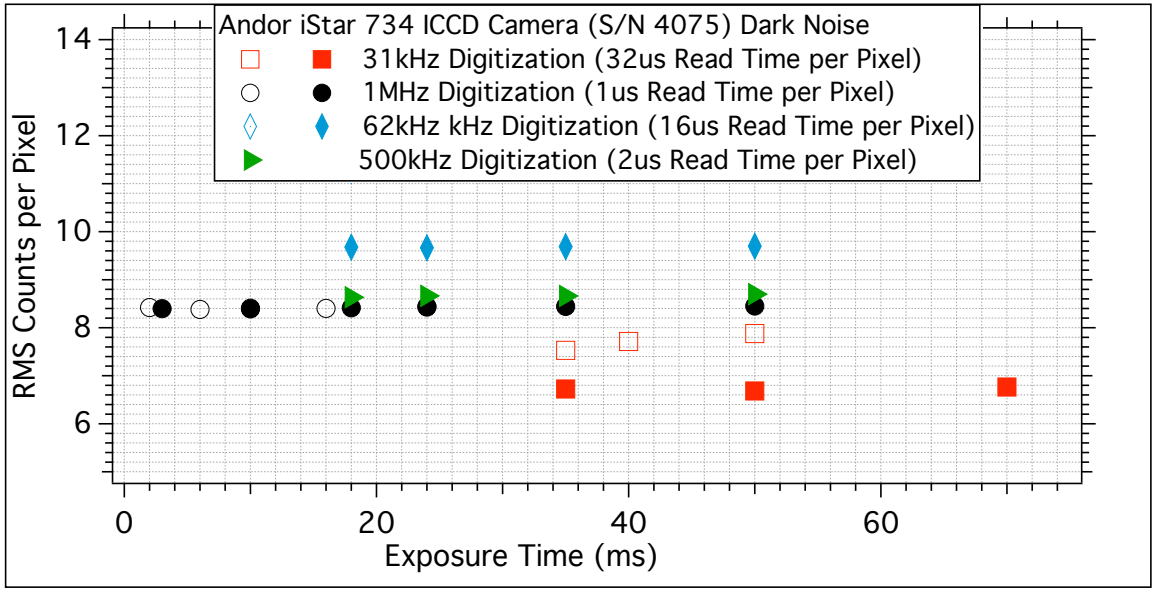
- New technology has made it possible to make a simplified detector system
- Gen 3 ICCD cameras have ~45% QE across visible region
- Motivated switch to 532 frequency doubled Nd:YAG laser to take advantage of this technology



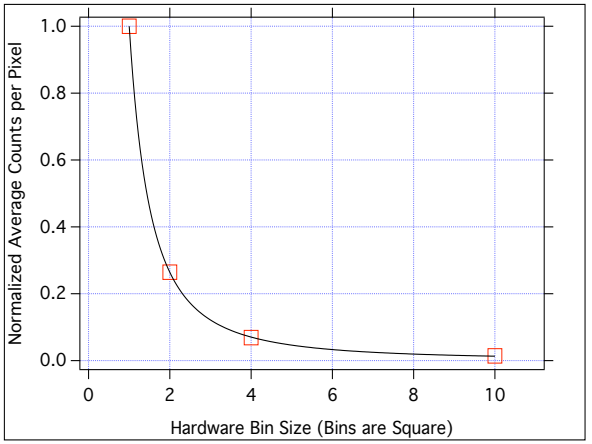
From Andor iStar 734 Manual

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Dark Noise Testing Indicates Low Read and Low Dark Current Noise



Digitization Rate	Measured Read Noise (RMS per Pixel)
31 kHz	6.65 ± 0.10
62 kHz	9.66 ± 0.02
500 kHz	8.61 ± 0.02
1 MHz	8.39 ± 0.01



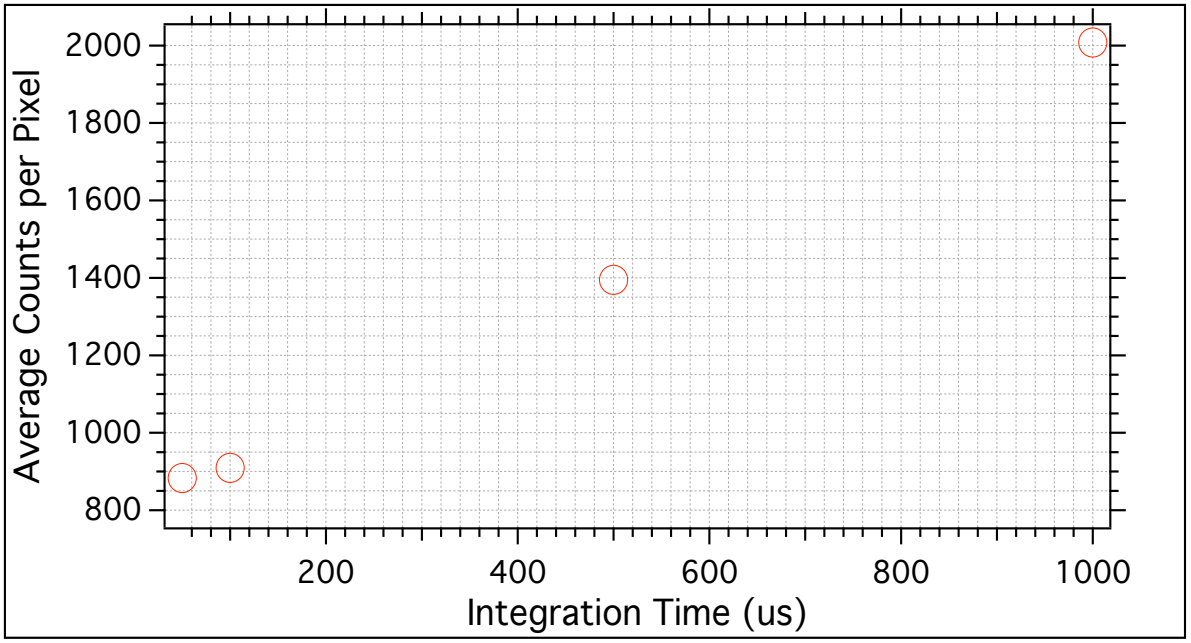
- CCD dark noise ~ $\sqrt{N_{Read}^2 + N_{Dark\ Current}^2}$
- Read noise dominates dark signal
  - Can be reduced by hardware binning
- Additional noise sources include electron background illuminescence (EBI)
  - Expected at < .2 electrons/pixel/sec

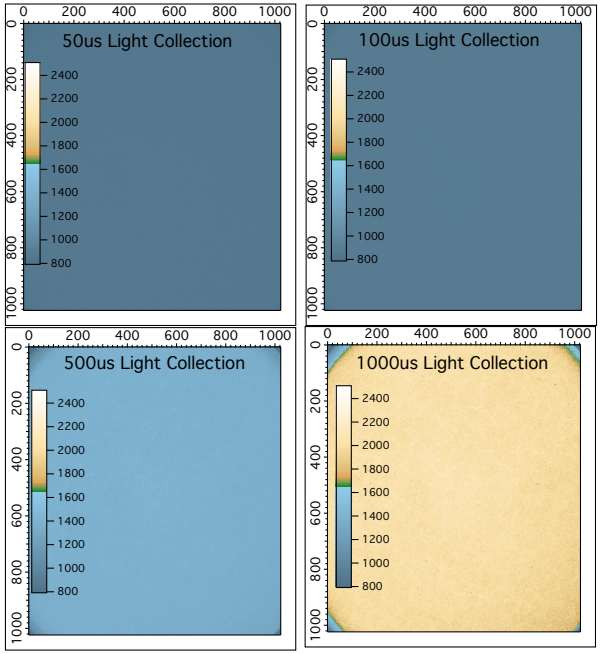
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Camera Sensitivity Appears Linear with Intensity

- Preliminary test of the camera response with a steady white light source
- Variable gating collects light
- Background signals level ~800 (programmed by Andor)

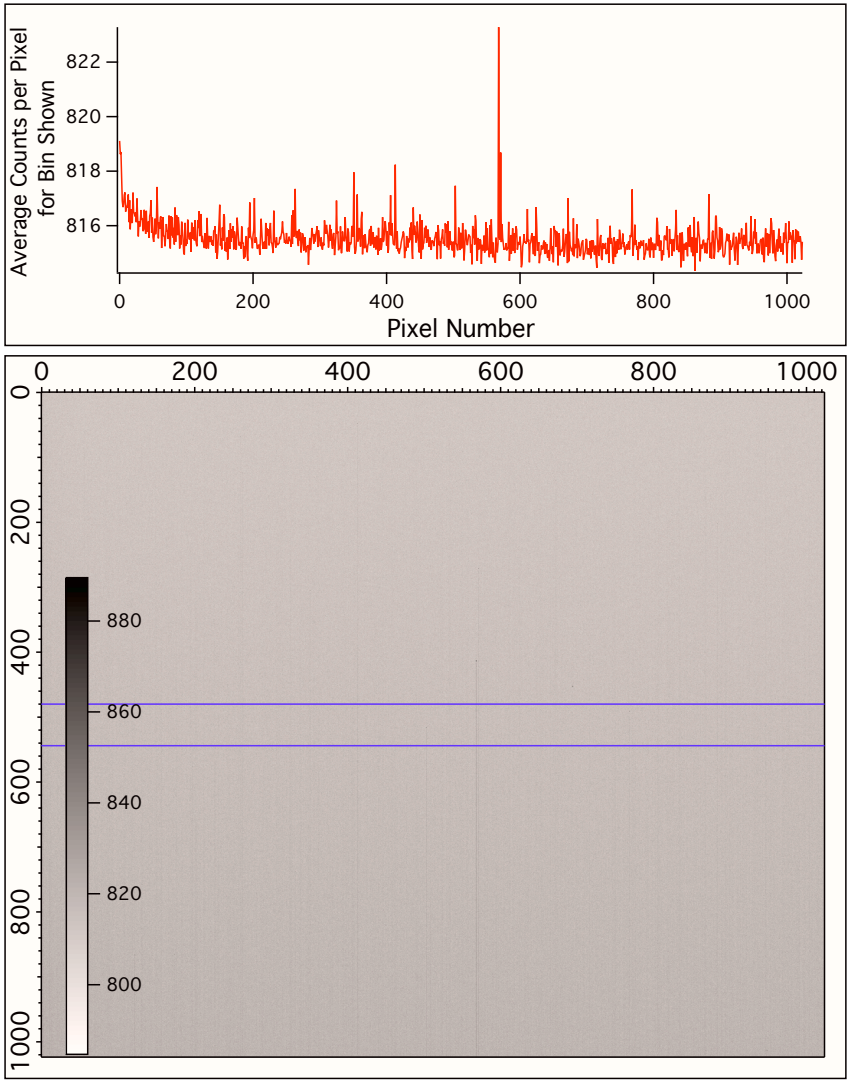




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Thomson Data Analysis Using ICCD Camera

- Image data: All 8 spatial channels into a single file
- Background fluctuations subtracted for each shot
- Spatial & spectral bins are created in software
  - 3nm spectral bins for 10-100eV
  - 6nm spectral bins for 100eV-500eV
- Individual bins searched for cosmic rays
- Fitting routines will determine plasma temperature and density



Dark Noise Image from S/N 4075

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Summary

- A new Thomson Scattering system has been designed for the Pegasus Toroidal Experiment
  - Novel spectrometer components include:
    - Transmission VPH grating
      - High efficiency (>70%)
    - ICCD camera as detector
      - High gain
      - Fast gating
      - Low Noise
- Testing of individual components is underway
- Preliminary data expected early next year

Acknowledgements & Website

Work supported by US DOE Grant DE_FG02_96ER54375

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