A Compact Multichannel Spectrometer for Thomson Scattering

N. L. Schoenbeck, A.S. Dowd, R.J. Fonck, D.J. Schlossberg, K.E. Thome and G.R. Winz

University of Wisconsin-Madison

HTPD
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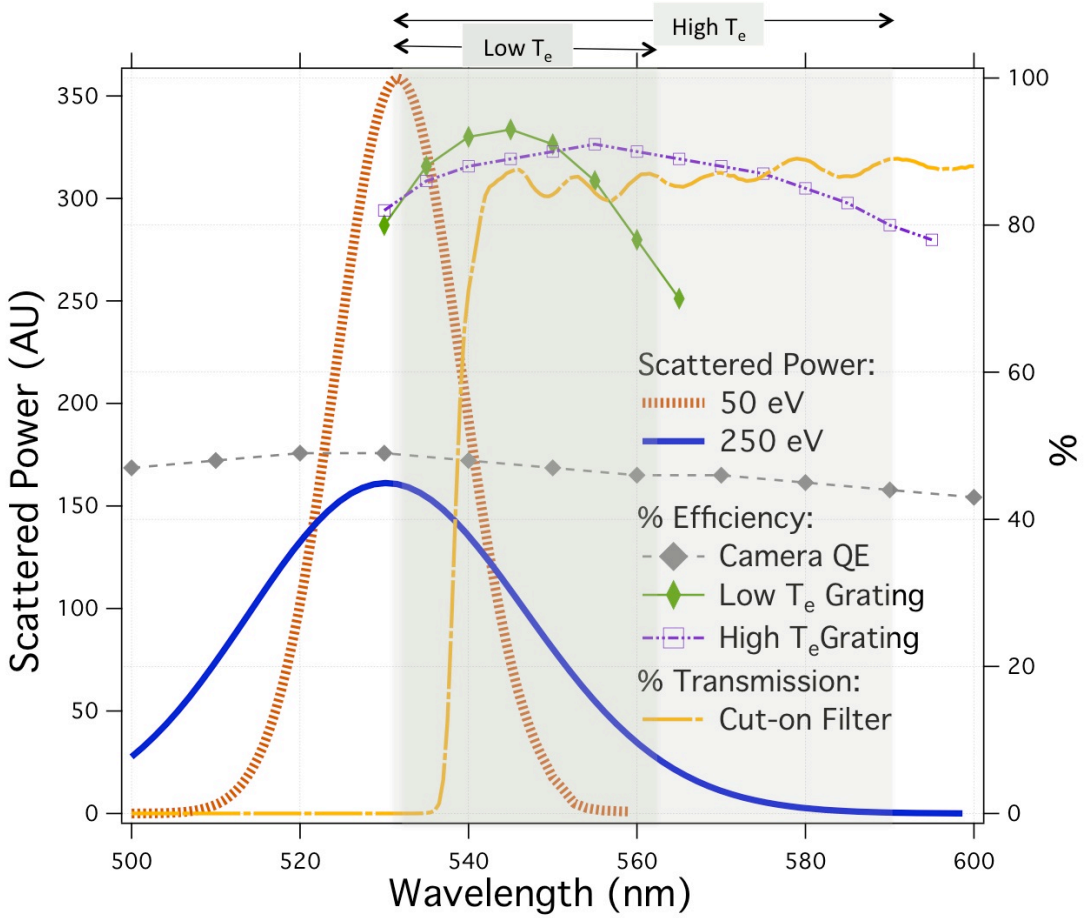
PEGASUS Toroidal Experiment

Abstract

- **Motivation:** Recent improvements in volume phase holographic (VPH) gratings and image intensified CCD (ICCD) cameras.
- **High efficiency visible wavelength system**: F/2 optics, optical fiber bundles with packing fractions of ~0.70 couple to the spectrometer, VPH gratings with >70% efficiency
  - Measurements of $T_e < 100$ eV are achieved by a 2971 l/mm grating
  - Measurements $T_e > 100$ eV are achieved by a 2072 l/mm grating
- **Detector**: Fast-gated (~2ns) ICCD camera
  - Fast Gate captures 9ns laser pulse
  - Gen III image intensifier provides >40% quantum efficiency in the visible region
  - P43 phosphor screen requires a minimum integration time of 2 ms.
  - Dark noise, dominated by read noise, can be reduced to ~7 counts/pixel by digitizing at 31 kHz and can be further reduced by on-chip binning of the CCD.

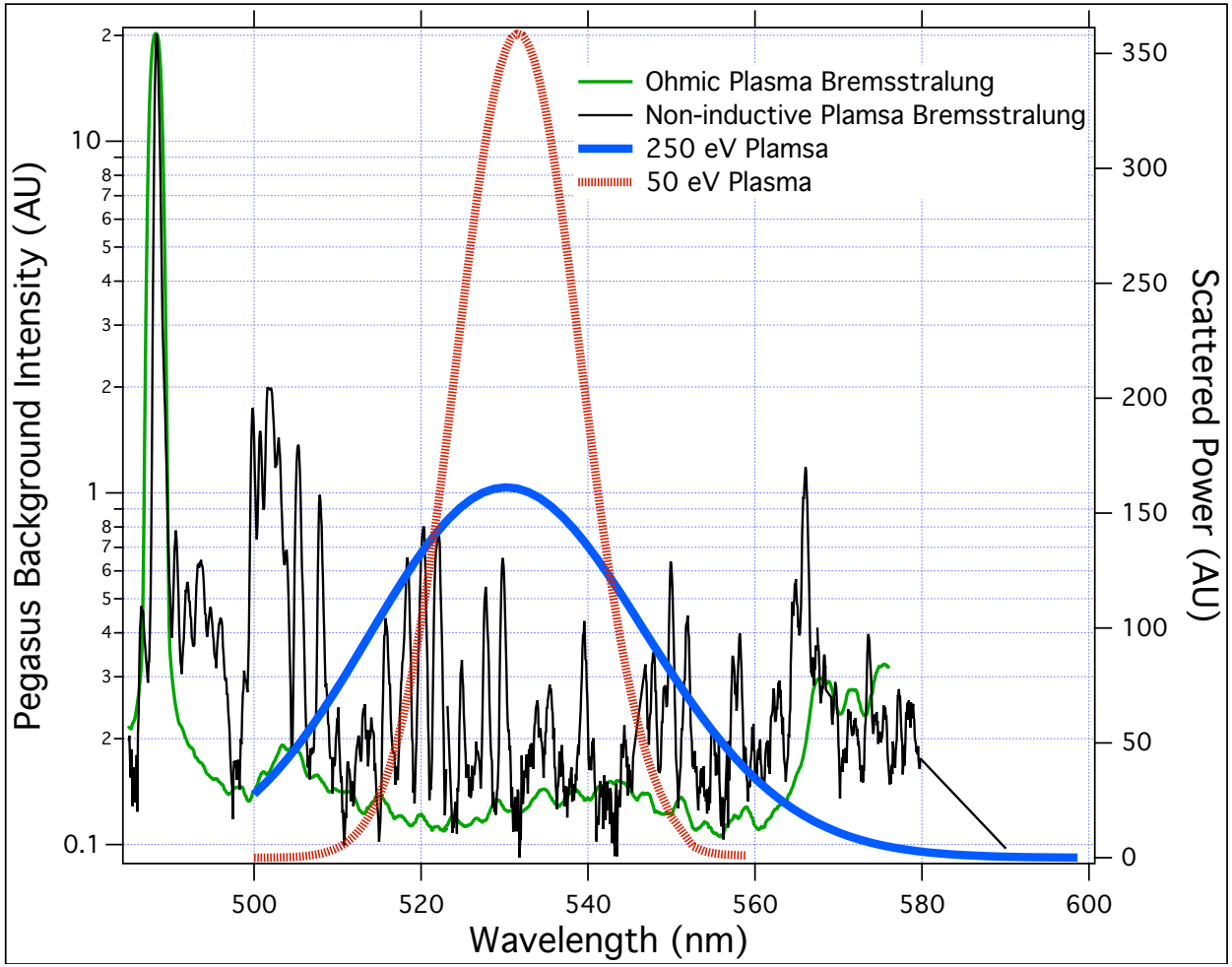
Thomson Scattering On Pegasus

- Elastic scattering of EM radiation off free electrons in the plasma
- Temperature dependent Gaussian shape about the laser wavelength
- Calculations on Pegasus yields an average of 50,000 scattered photons per laser pulse
  - For more info see
    Dave Schlossberg
    P.4.12 – Tues May 8 3pm

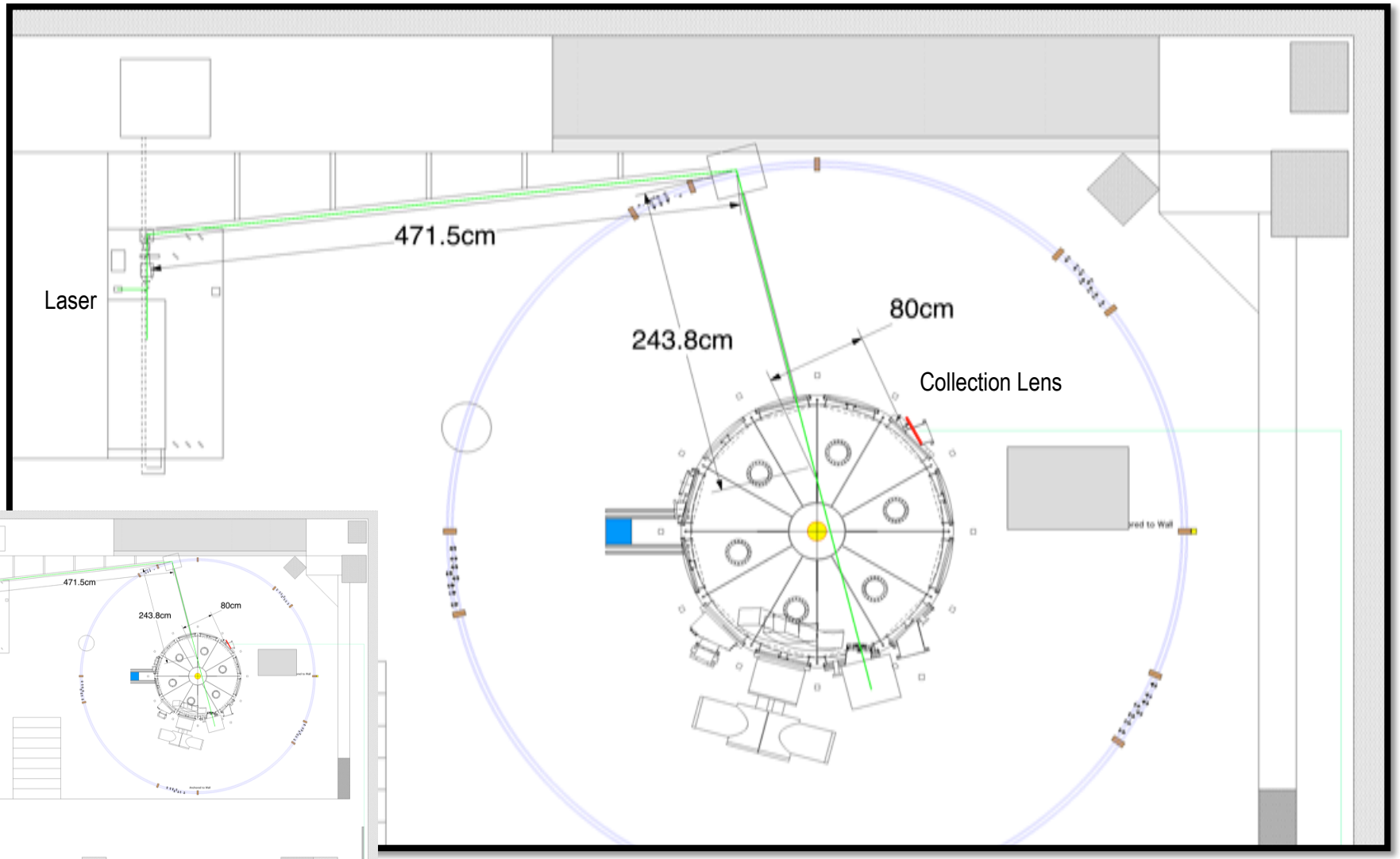


532-592 nm Range Corresponds to Low Background Impurity Region on Pegasus

- Ohmic plasmas are low impurity and dominated by Bremsstralung radiation
  - May be able to eliminate or reduce background channels
- Non-Inductive plasmas will need background subtraction



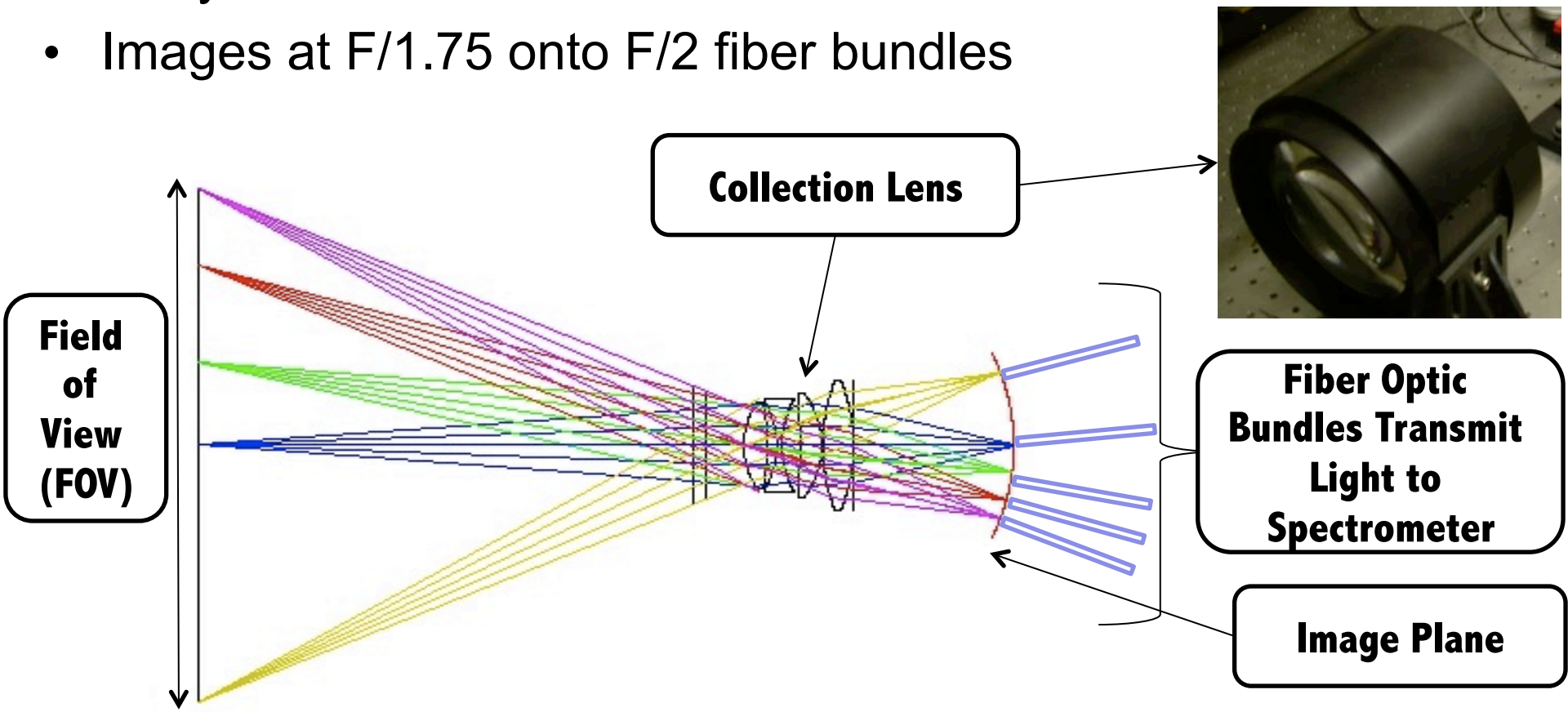
Thomson System Location on Pegasus



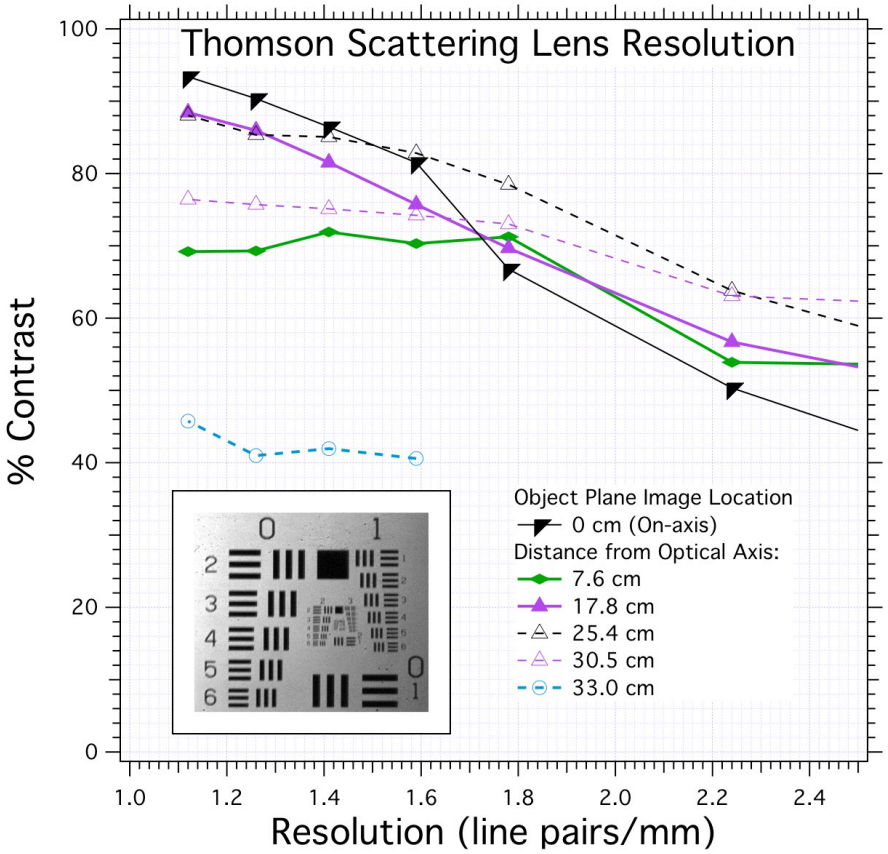
Spectrometer

Custom Collection Lens Designed for 80 cm Field of View with F/2 Optics

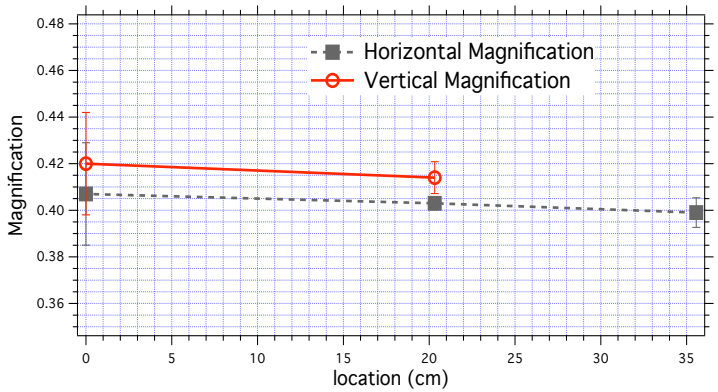
- Collects at F/8 over 80 cm FOV from 75 cm away
- Images at F/1.75 onto F/2 fiber bundles



Custom Lens Maintains High Resolution Over 70 cm Viewing Area

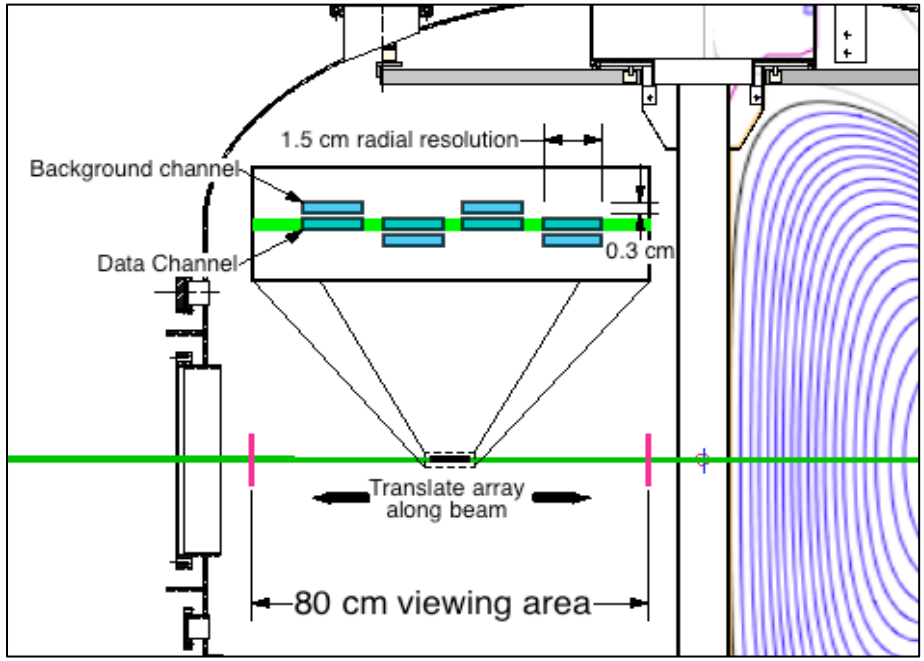


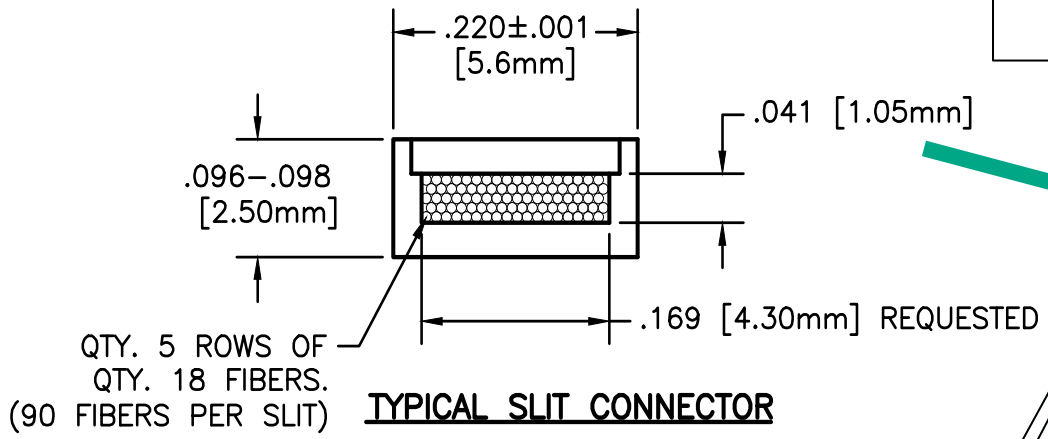
- The modulation transfer function defines the contrast of an image at a given resolution
- The custom collection lens maintain >50% contrast to a resolution of 2.5 lp/mm
- The magnification is ~0.41

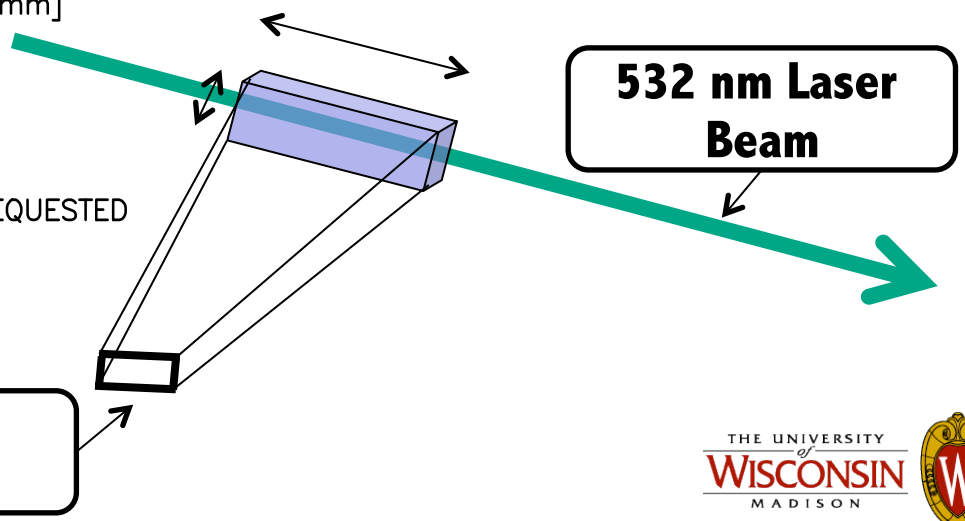


Fiber Optic Bundles Map to1.4cm of Light Along Laser Beam

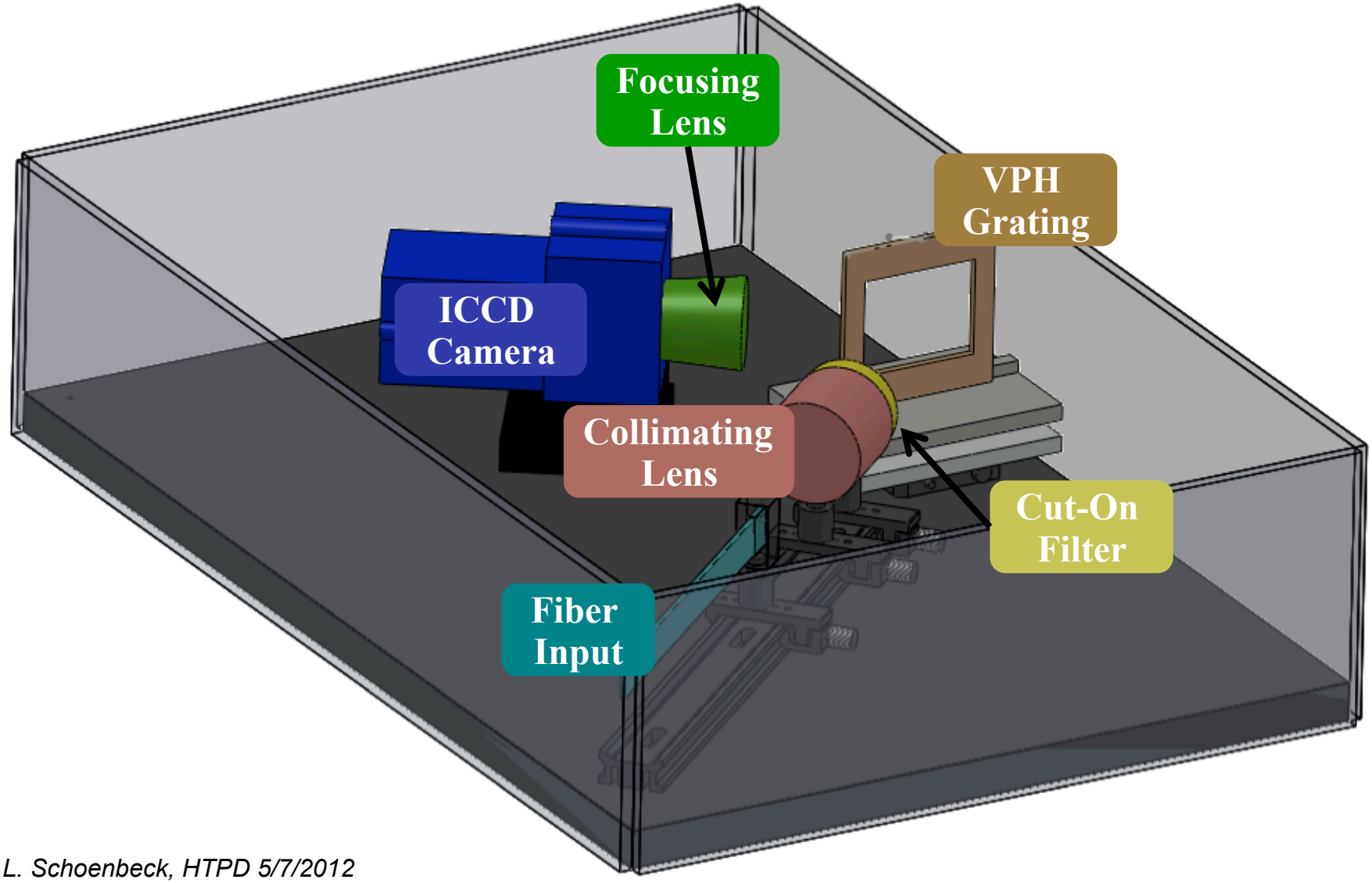
- Each spatial channel: 0.3 cm tall (across the laser) by 1.4 cm along the laser in the plasma
- Fibers will be moved shot-to-shot
  - Each spectrometer allows for 8 fiber bundles, 3 spectrometers will be deployed





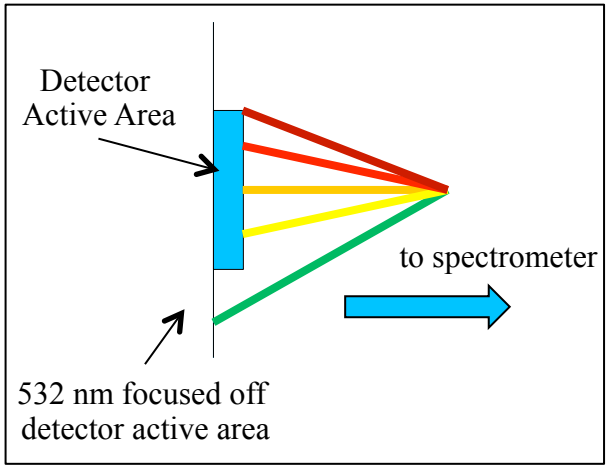


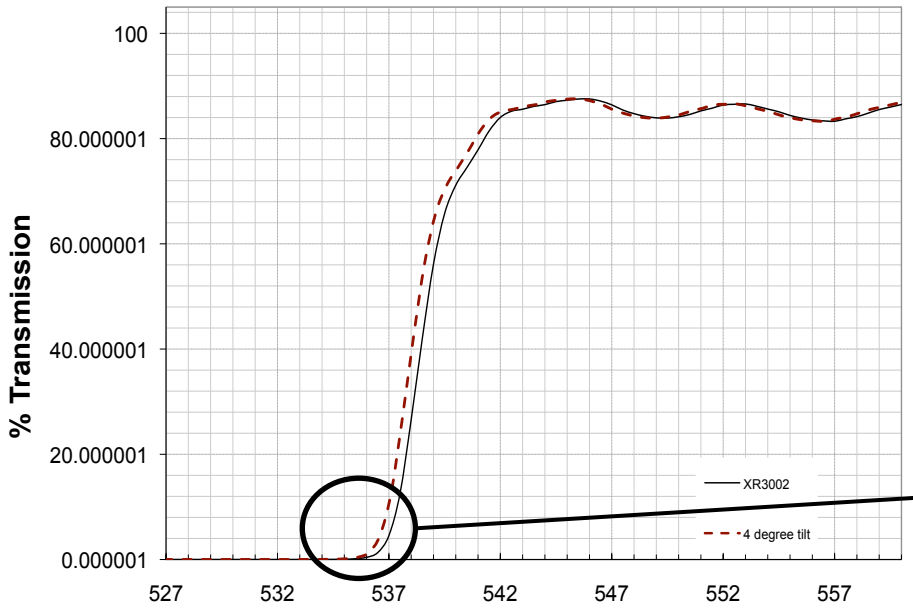
Thomson Spectrometer Layout

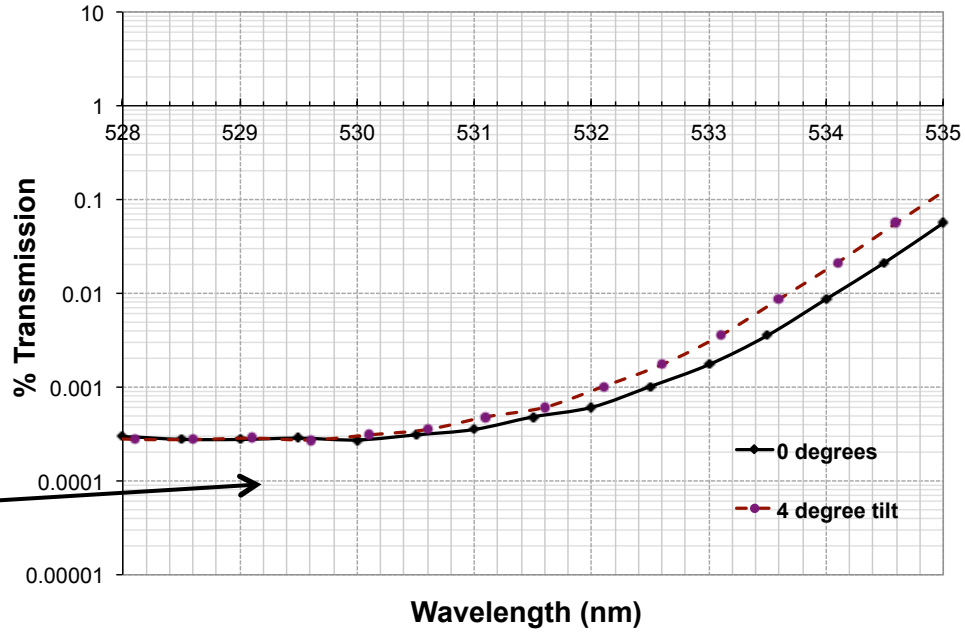


Cut-on Filter to Prevent Laser Light at Camera

- Off-axis fiber channels at up to 4° vertically
- Different cut-on wavelength and transmission for different channels
- Detector is aligned to prevent transmitted 532nm light that from hitting camera







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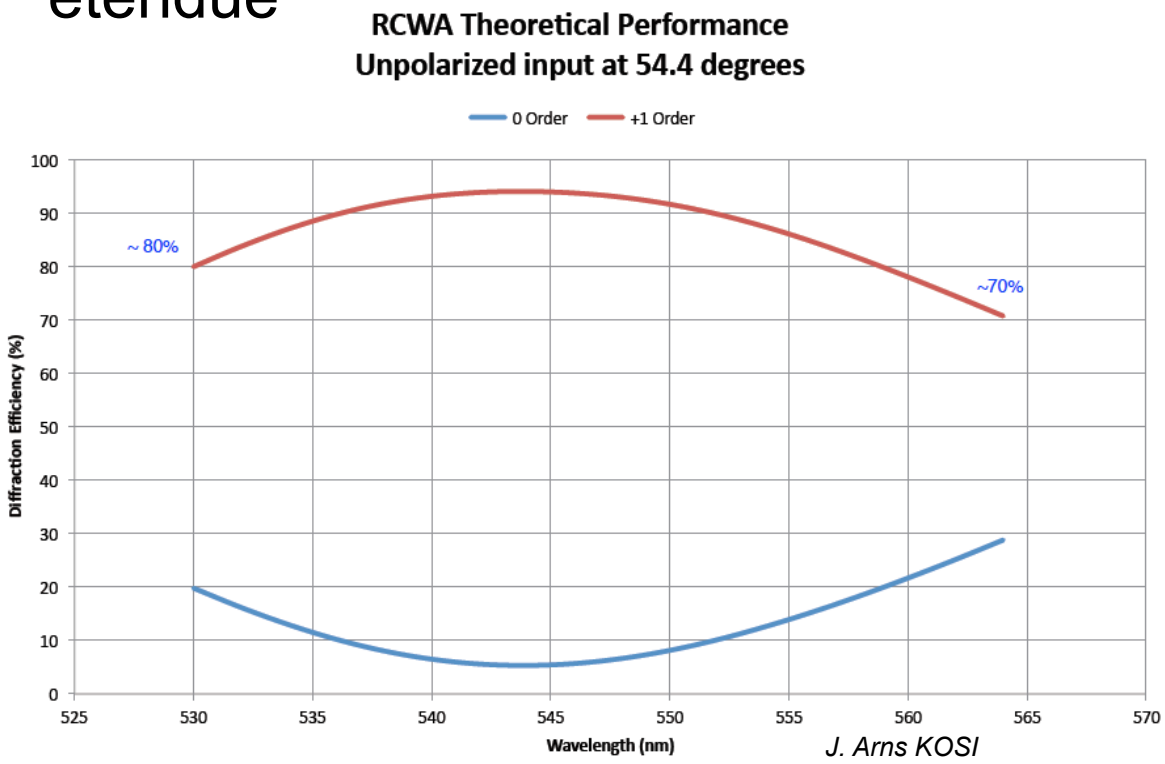
VPH Grating Designed for High Throughput in 2 Temperature Regimes

- Two gratings
  - 2971 lines/mm for low temperatures (~10eV-100eV)
  - 2072 lines/mm for high temperatures (~100eV-500eV)
- Dispersion selected such that camera width is limiting the etendue



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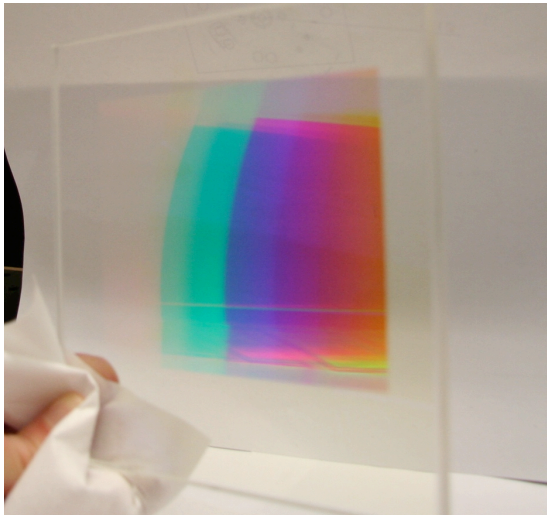

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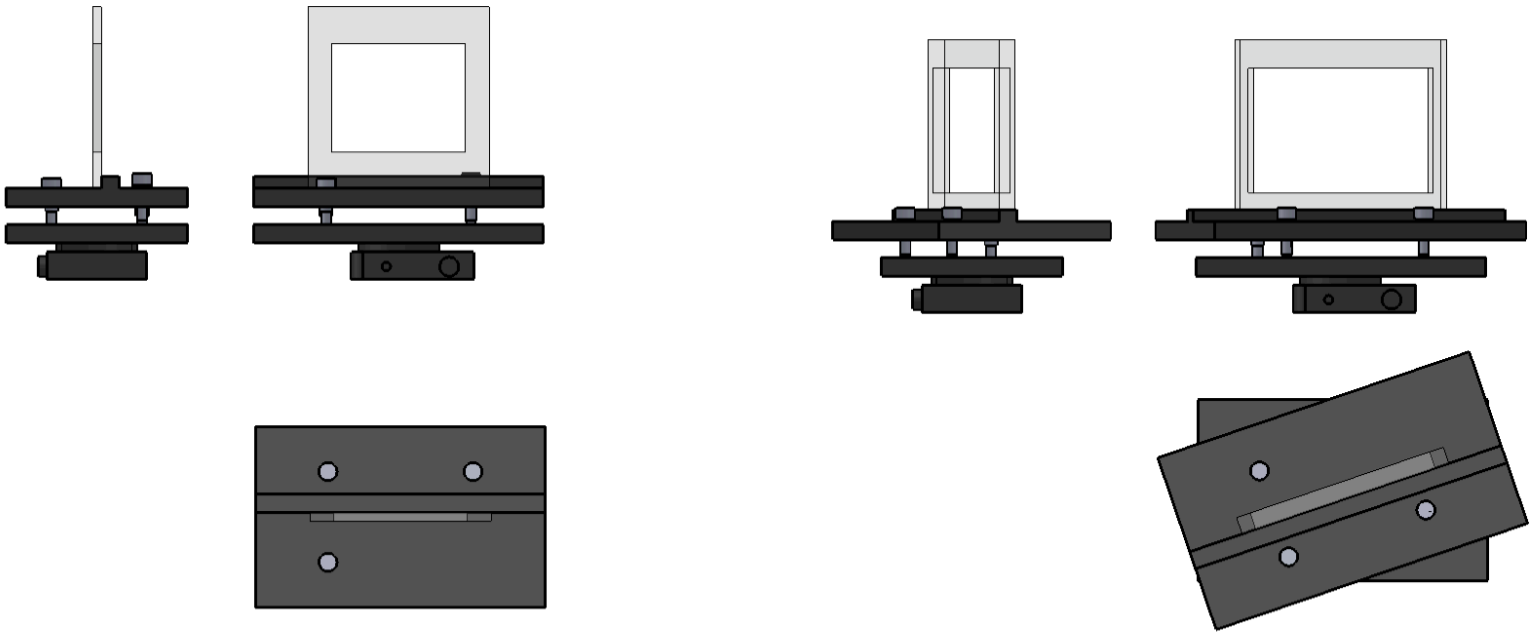
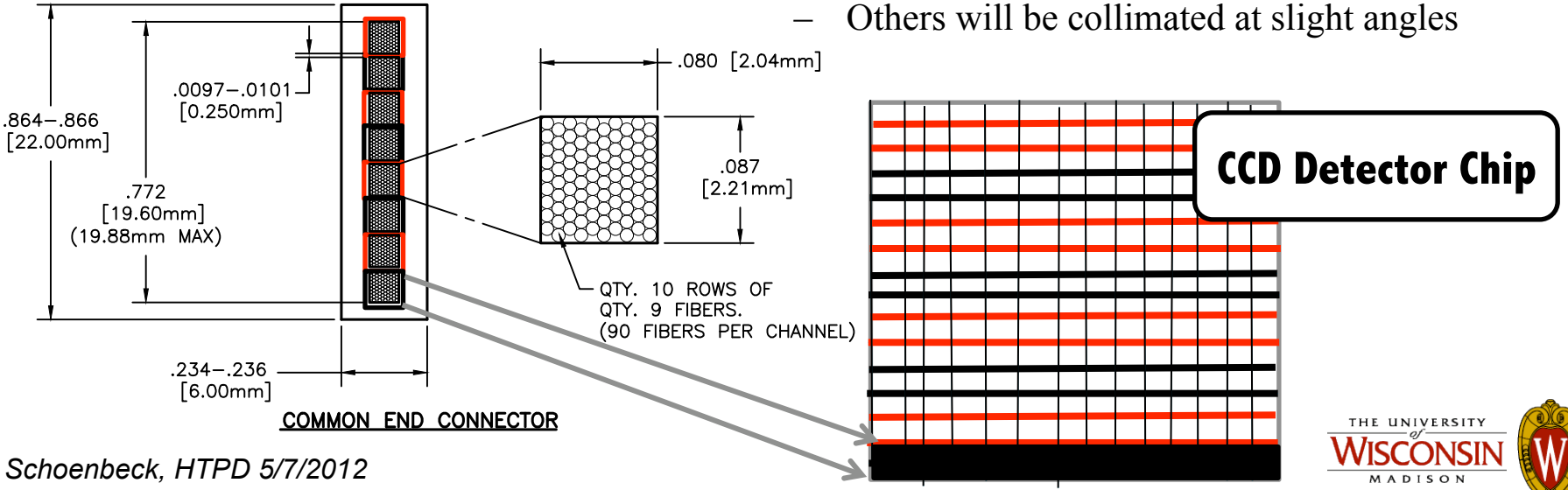
Spectrometers Designed for Easy Exchange of Gratings

- Gratings require spectrometers to be built at two input angles:
  - 54 degrees
  - 36 degrees
- Fine tune grating position with rotation stage and precison adjustment screws



Detector Area Sets System Etendue & Size of Fiber Optic Bundles

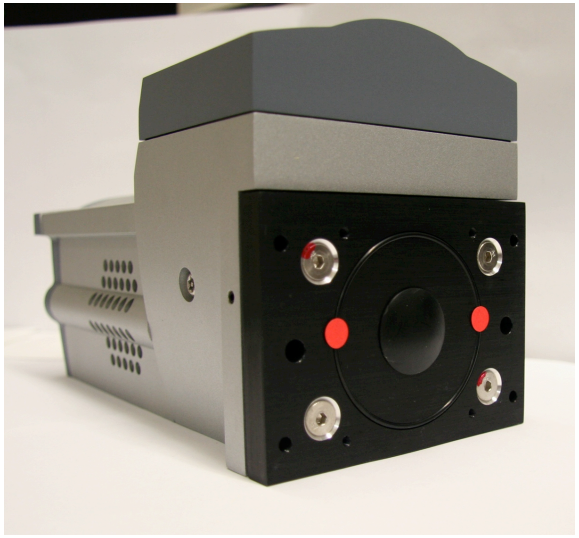
- Design Criteria:
  - Eight spatial channels vertically
    - Depends on camera detector height and magnification of spectrometer
  - 10 spectral bins horizontally
    - Based on camera detector width and dispersion of grating
  - Total area must be conserved
- 8 legs are bundled together
  - Bundled length ~75 mm 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

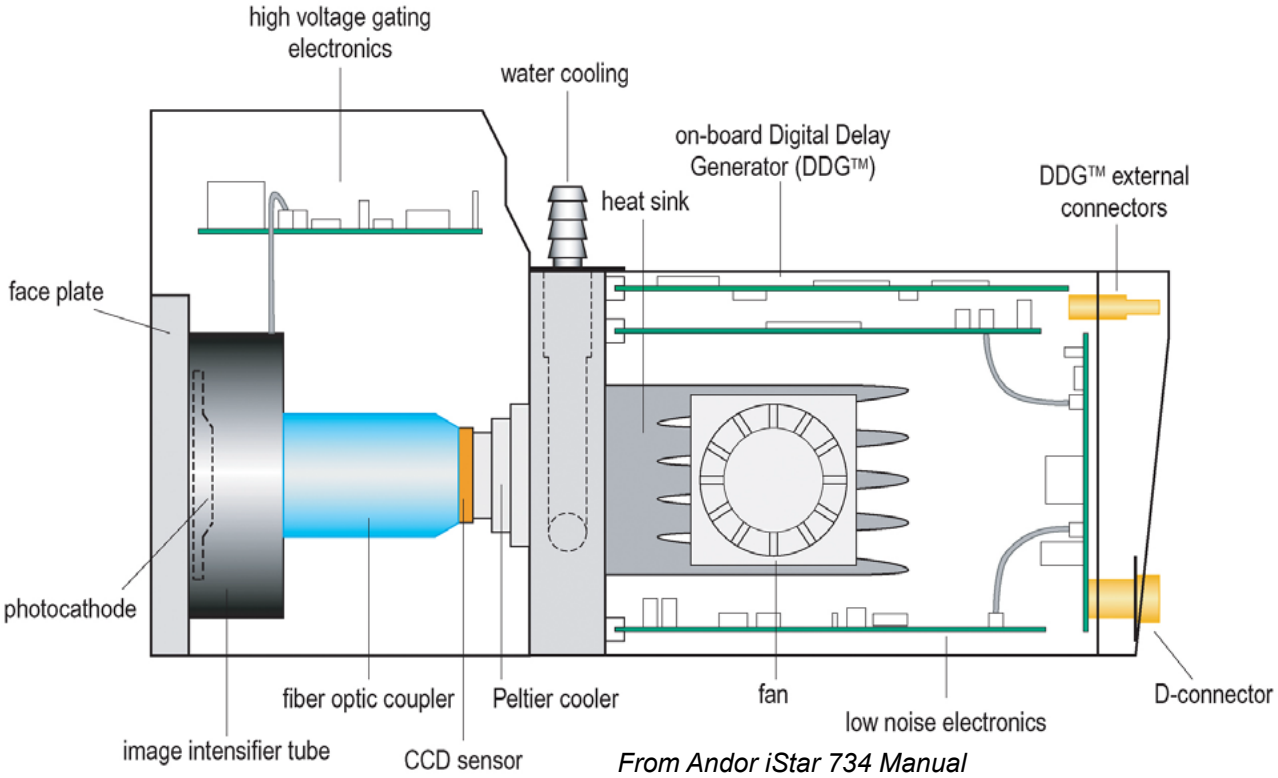


ICCD Detectors Chosen for High Gain & Low Noise Qualities

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

APD and ICCD Camera SNR are Comparable

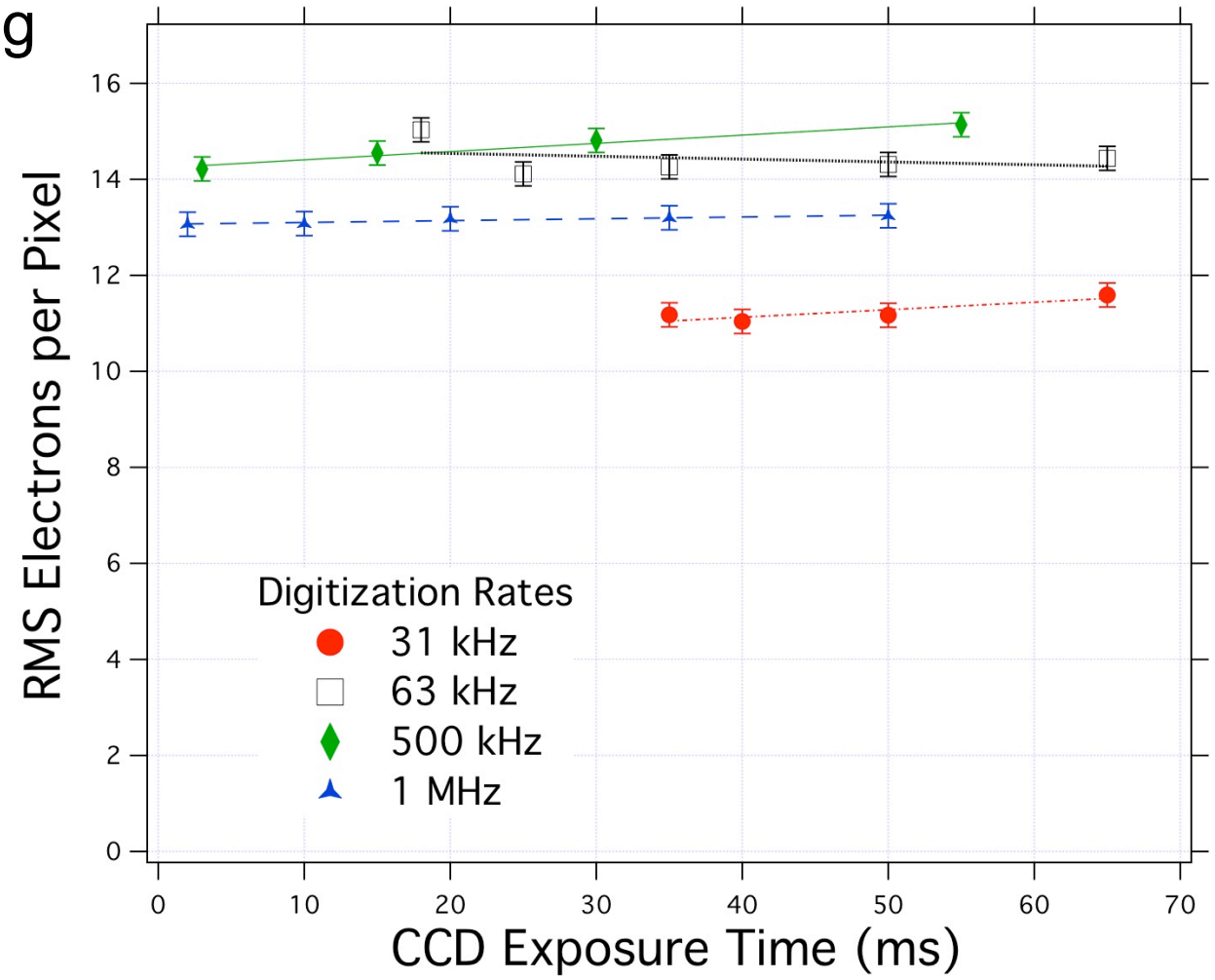
	InGaAs APD	Si APD	ICCD Camera
Laser Wavelength	1064 nm	1064 nm	532 nm
Laser Power	3 J	3 J	2 J
Scattered Photons	140,000	140,000	50,000
QE	0.9	0.4	0.5
Collected Electrons	126,000	56,000	25,000
Excess noise	3	2	1
Read Noise	n/a	n/a	10 e-/bin
SNR	205	167	153

Given similar noise characteristics, ICCD cameras were chosen as the detector to simplify the design and reduce the overall cost

- Photon noise in both systems ~$\sqrt{N}$
- Excess noise in only present in APDs
- Read noise is per bin on CCD
  - The 1024 x 1024 chip will be read as 160 bins

Dark Noise Testing Indicates Camera's are Read Noise Dominated

- CCD dark noise ~ $\sqrt{N_{Read}^2 + N_{Dark\ Current}^2}$
- Read noise can be reduced by hardware binning



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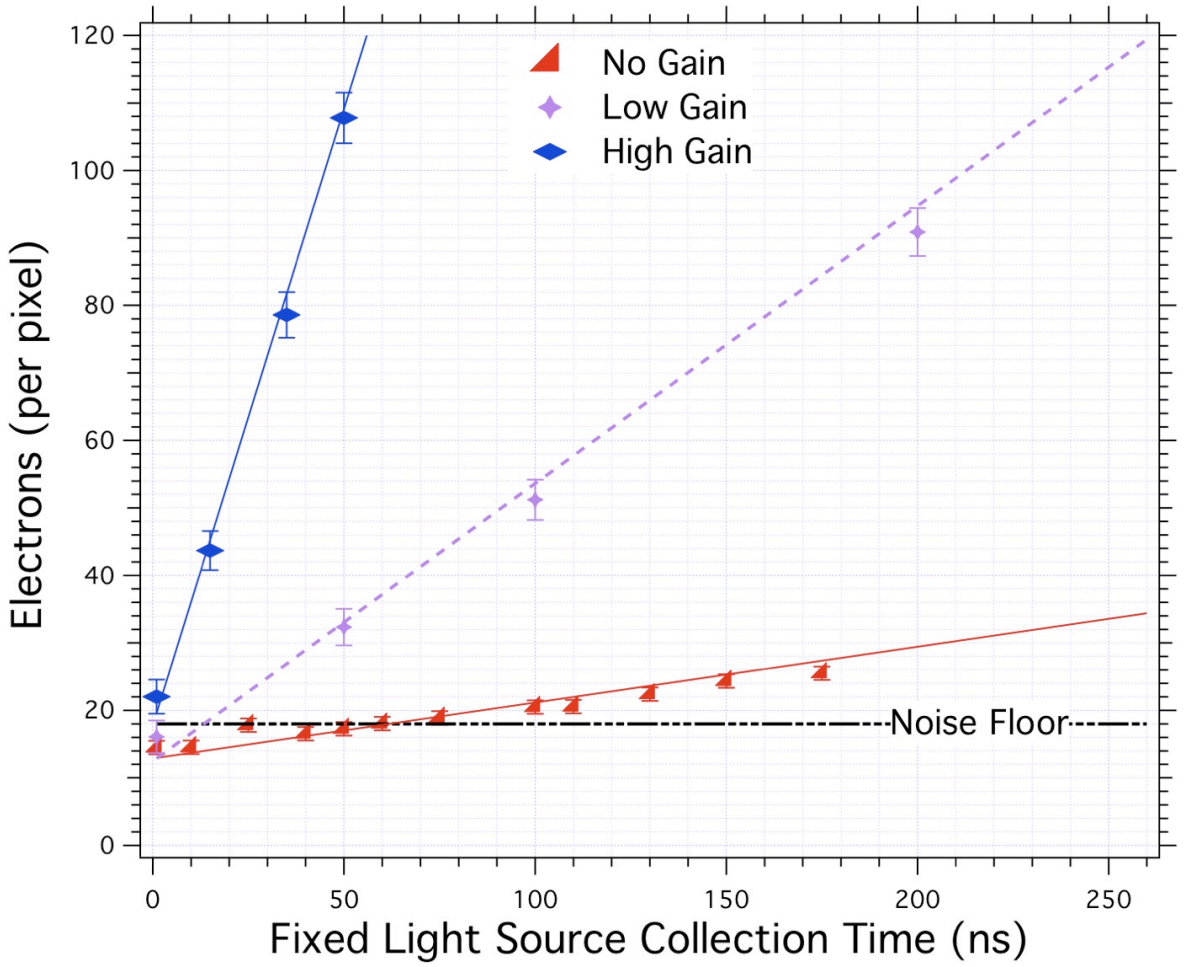
CCD Response is Linear for Expected Photoelectron Levels

- Camera collected light from a fixed light source over different exposure times
- I.I. gain was varied
- Each setting gave near linear trends
- Signals found when extrapolating to zero photons match the detector dark noise



Summary

- A new Thomson Scattering system has been designed for the Pegasus Toroidal Experiment
  - Novel spectrometer components include:
    - Transmission VPH grating
      - High transmission (>70%)
    - ICCD camera as detector
      - High gain
      - Fast gating (<2 ns)
      - SNR within a factor of 2 of APD detectors
- System Currently being Installed
- On-vessel calibration measurements expected in June

Acknowledgements & Website

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