# Design and Operation of a Frequency Doubled Nd:YAG Thomson Scattering System with Transmission Grating ICCD Spectrometer

N. L. Schoenbeck, A.S. Dowd, R.J. Fonck,
D.J. Schlossberg, G.R. Winz



University of
Wisconsin-Madison

APS DPP
Providence, RI
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PEGASUS
Toroidal Experiment

# Novel Thomson scattering system deployed on the Pegasus Toroidal Experiment

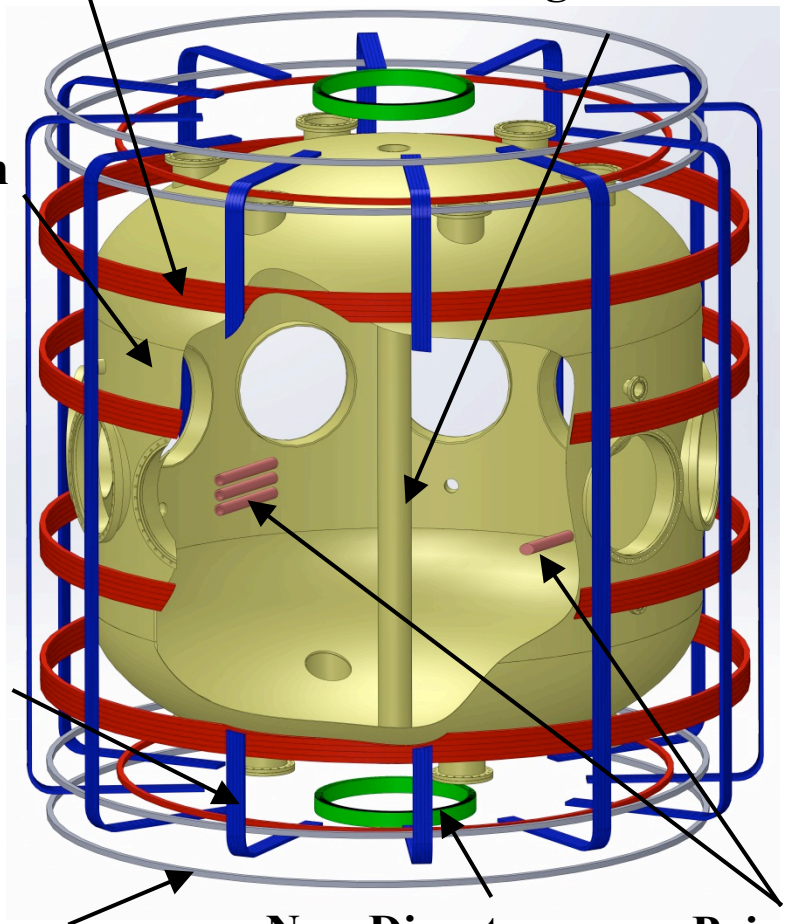
- Scattering via a 7 ns, 2 J frequency doubled Nd:YAG laser at 532 nm
  - Laser focuses to 3 mm diameter within the plasma via a 7 m beam-line.
  - Cameras and remotely adjustable mirrors allow for shot-to-shot alignment.

- A custom multi-element lens collects scattered photons from 15 cm < $R_{maj}$ < 85 cm with 1.2 cm radial resolution
  - 8 fiber optic bundles provide spatial points for sampling
  - Each set of 8 channels is measured in a single spectrometer

- The spectrometer utilizes a high efficiency (80%) volume phase holographic grating and a high quantum efficiency (> 40%) image intensified CCD (ICCD) camera
  - Two interchangeable gratings to cover 10 – 1000 eV
  - Optimized for $n_e$ from mid-$10^{18}$ to mid-$10^{19}$ $m^{-3}$

- Work supported by US DOE Grant DE-FG02-96ER54375 and the American Recovery and Reinvestment Act

# Pegasus is a compact ultralow-A ST




## Experimental Parameters

| Parameter | Achieved | Goals |
|---|---|---|
| A | 1.15 – 1.3 | 1.12 – 1.3 |
| R(m) | 0.2 – 0.45 | 0.2 – 0.45 |
| $I_p$ (MA) | ≤ .21 | ≤ 0.30 |
| $I_N$ (MA/m-T) | 6 – 12 | 6 – 20 |
| $RB_t$ (T-m) | ≤ 0.06 | ≤ 0.1 |
| $\kappa$ | 1.4 – 3.7 | 1.4 – 3.7 |
| $\tau_{shot}$ (s) | ≤ 0.025 | ≤ 0.05 |
| $\beta_t$ (%) | ≤ 25 | > 40 |
| $P_{HHFW}$ (MW) | 0.2 | 1.0 |

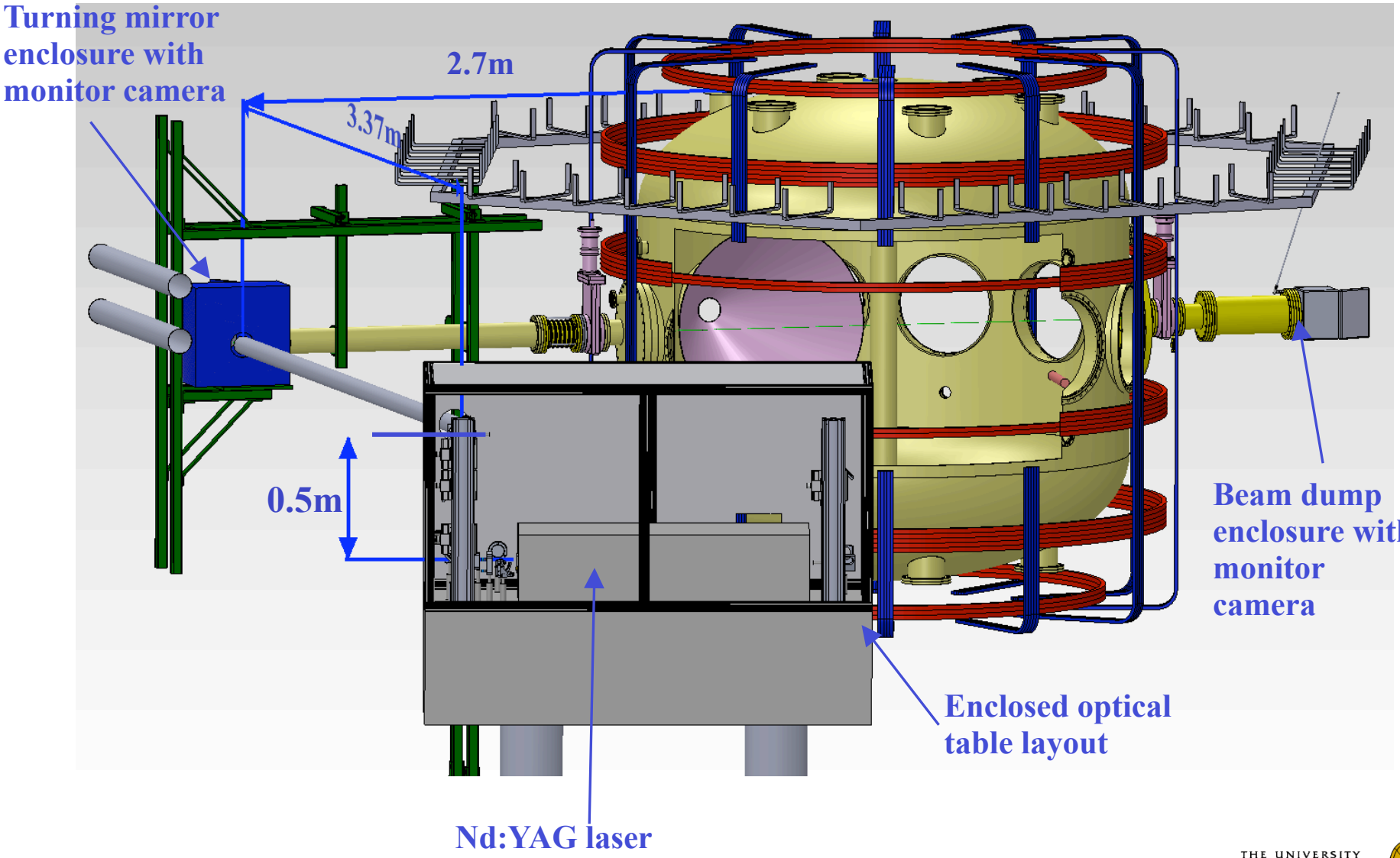
**Major research thrusts include:**

- *Non-inductive startup and growth*
- *Tokamak physics in small aspect ratio:*
  - *High-$I_N$, high-$\beta$ stability limits*
  - *ELM-relevant edge MHD activity*



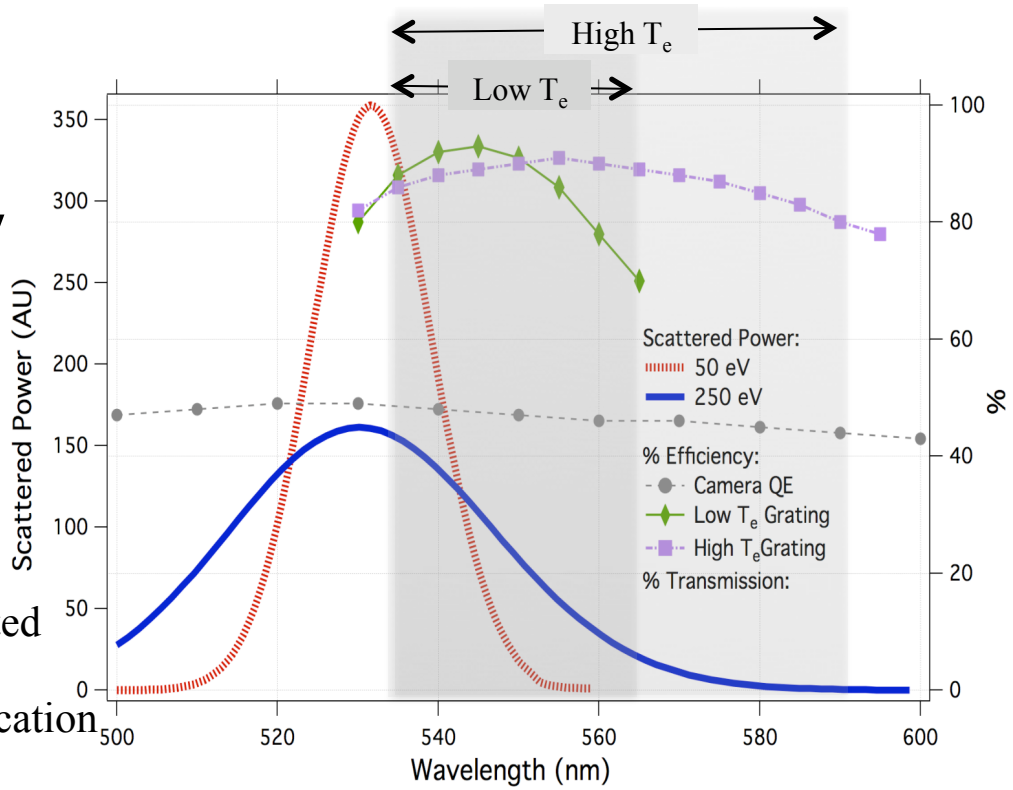
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# Laser System Integrated into Pegasus Test Cell



# New Technology Motivates Using Visible Laser for Thomson Scattering

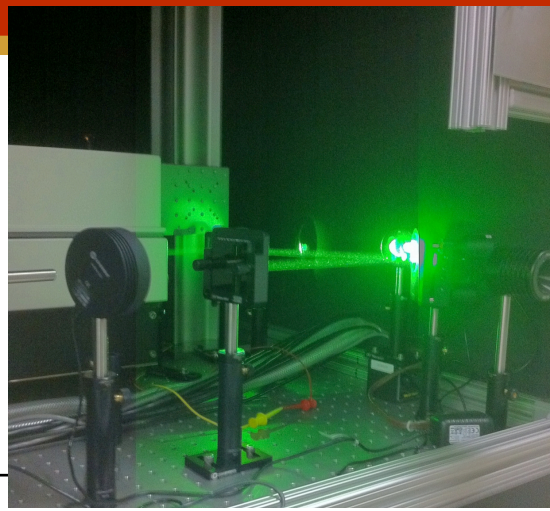
- New Gen III image intensified CCD cameras provide quantum efficiency (QE) >40% through the visible region
- Improved efficiency with VPH gratings over conventional ruled reflective gratings
- Nd:YAG laser operates in the visible (532nm) through frequency doubling
- Estimates of ~35,000 photons scattered into viewing optics per spatial point for $n_e$=1x$10^{19}$ m-$^3$
  - Given component efficiencies, an estimated 6,390 photoelectrons per spatial channel reach the micro-channel plate for multiplication
  - See Dave Schlossberg for more details



Projected TS Spectrum on Pegasus

# "Turn-key" 2J Laser Optimized for Operation on Pegasus

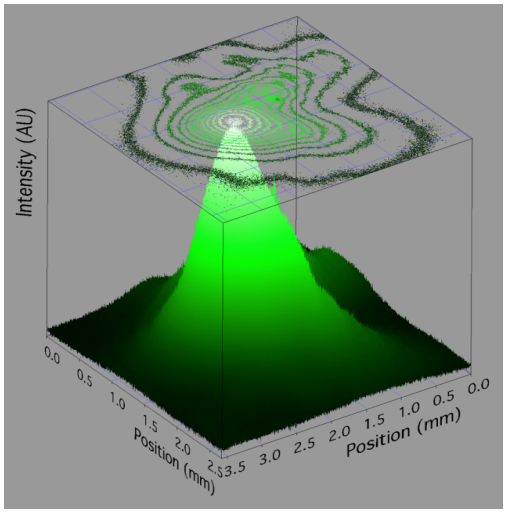
- Continuum Powerlite DLS 9000 Nd:YAG laser
- Frequency doubled to provide 2J at 532 nm

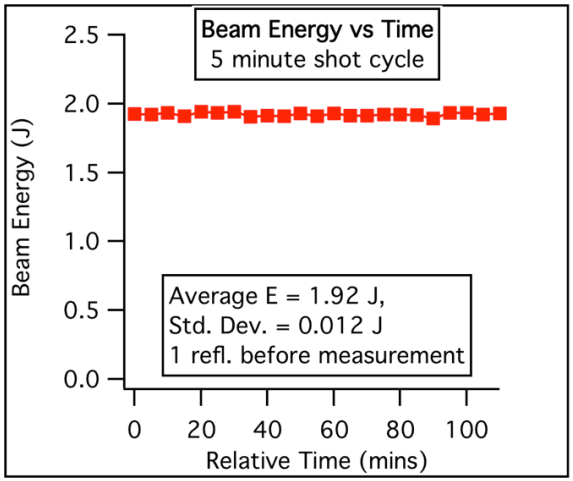


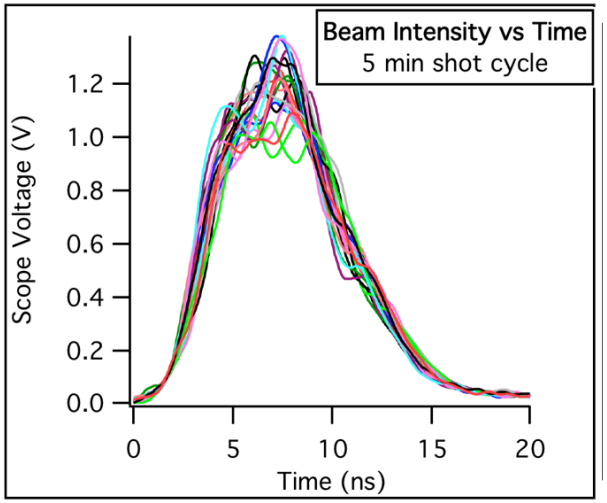
| Specification | Value | Determining factors |
|---|---|---|
| Divergence | ≤ 0.5 mrad | Desired spatial resolution, component damage thresholds |
| Pointing stability | ≤ 50 μrad | Beam line |
| Pulse length | ~7 ns FWHM | Availability at desired power |
| Repetition Rate | ≥ 10 Hz | Shot duration; availability |
| Jitter | ≤ 500 ps | Time resolution |
| Polarization ratio | ≥ 90% | Scattering dependence |

# Laser Meets Specifications and Provides Reliable Operation

- Flash lamps pulsed at 10 Hz in between shots to keep the system stable
- Delay generator triggers laser with picosecond resolution
- Verified laser stability (pointing stability, power, & pulse shape) on 5 minute shot-cycle

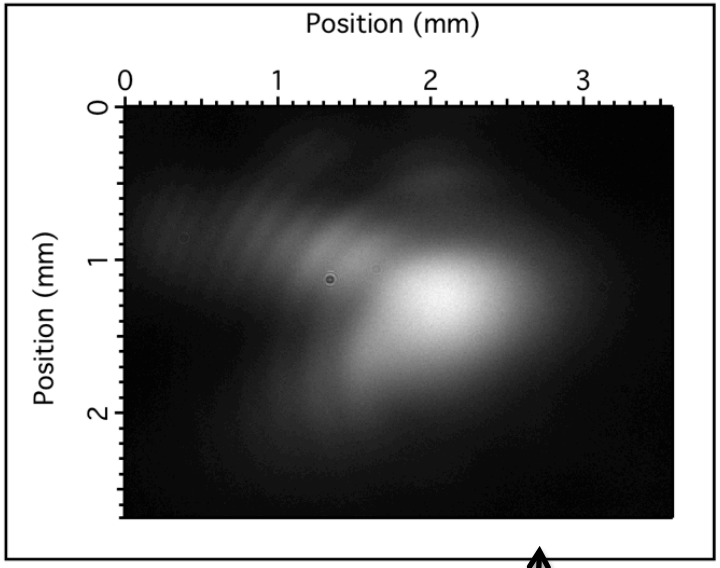


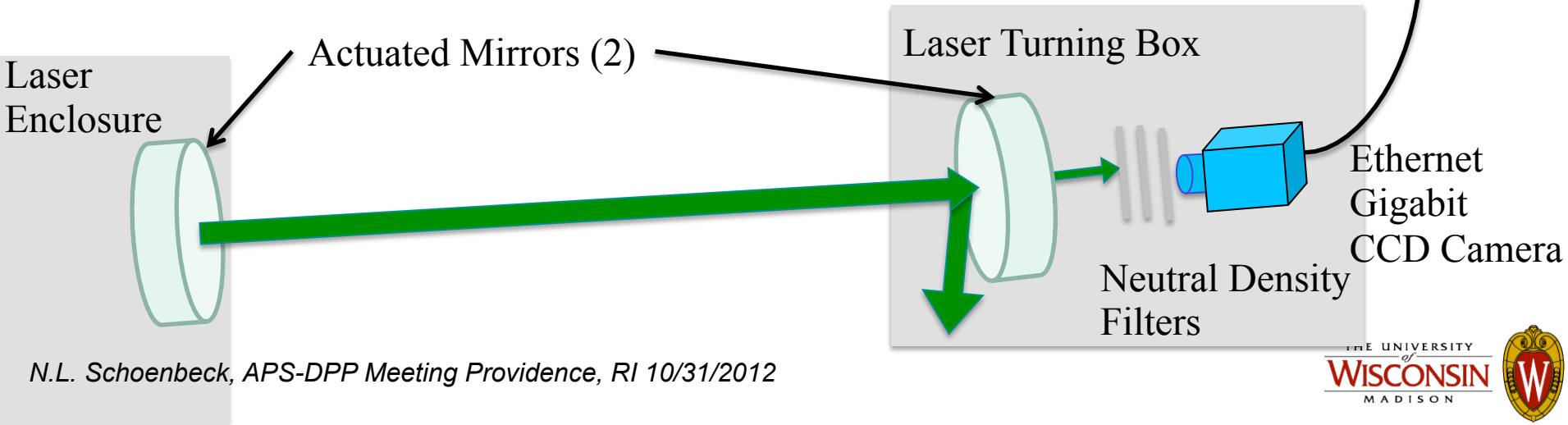



# Steering Mirrors and Cameras Enable Between Shot Alignment

- 2 actuated mirrors available for remote control of laser alignment
  - 1 mirror at exit of laser hutch
  - 1 mirror turns beam to enter vacuum vessel
- Position is monitored using a camera as beam-finder
  - Turning mirror acts as beam splitter
  - Ethernet based camera triggered to operate during Pegasus shot



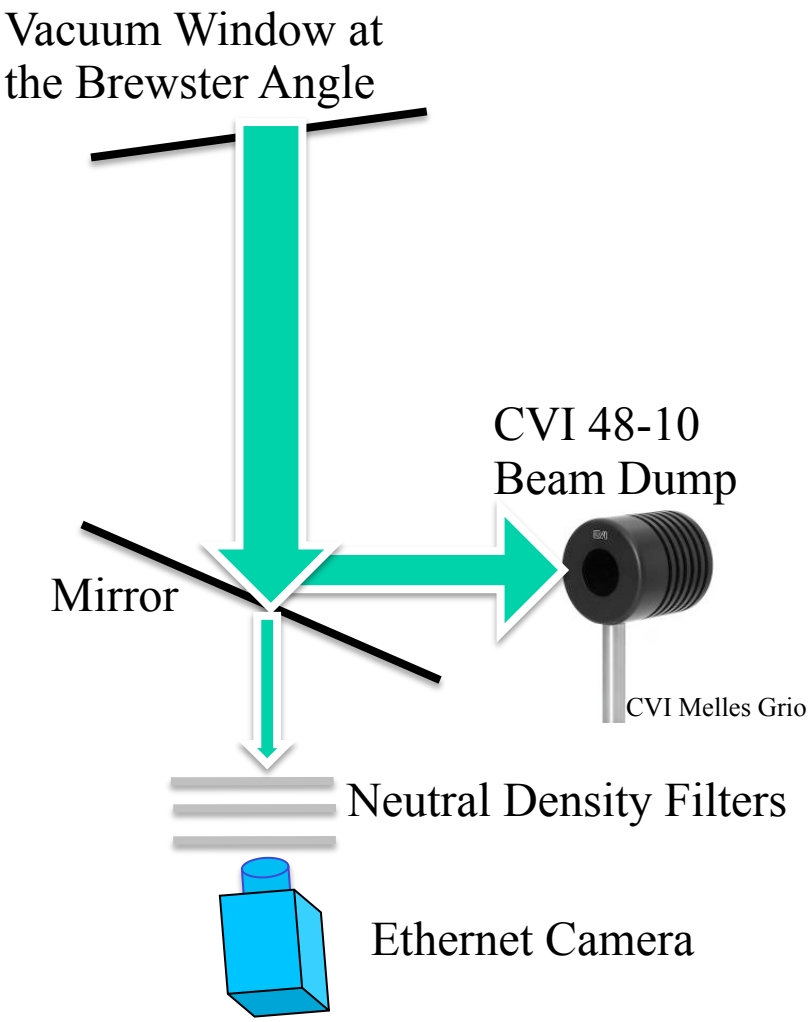






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# Beam Dump Provides 2nd Monitor for Laser Alignment though Vacuum Vessel

- Camera at beam dump acts as second beam-finder for laser alignment
  - Mirror acts as beam splitter
  - Neutral density filters reduce the signal to prevent camera saturation
- A beam dump (CVI 48-10) is used for the ~1.8J that reach the beam dump

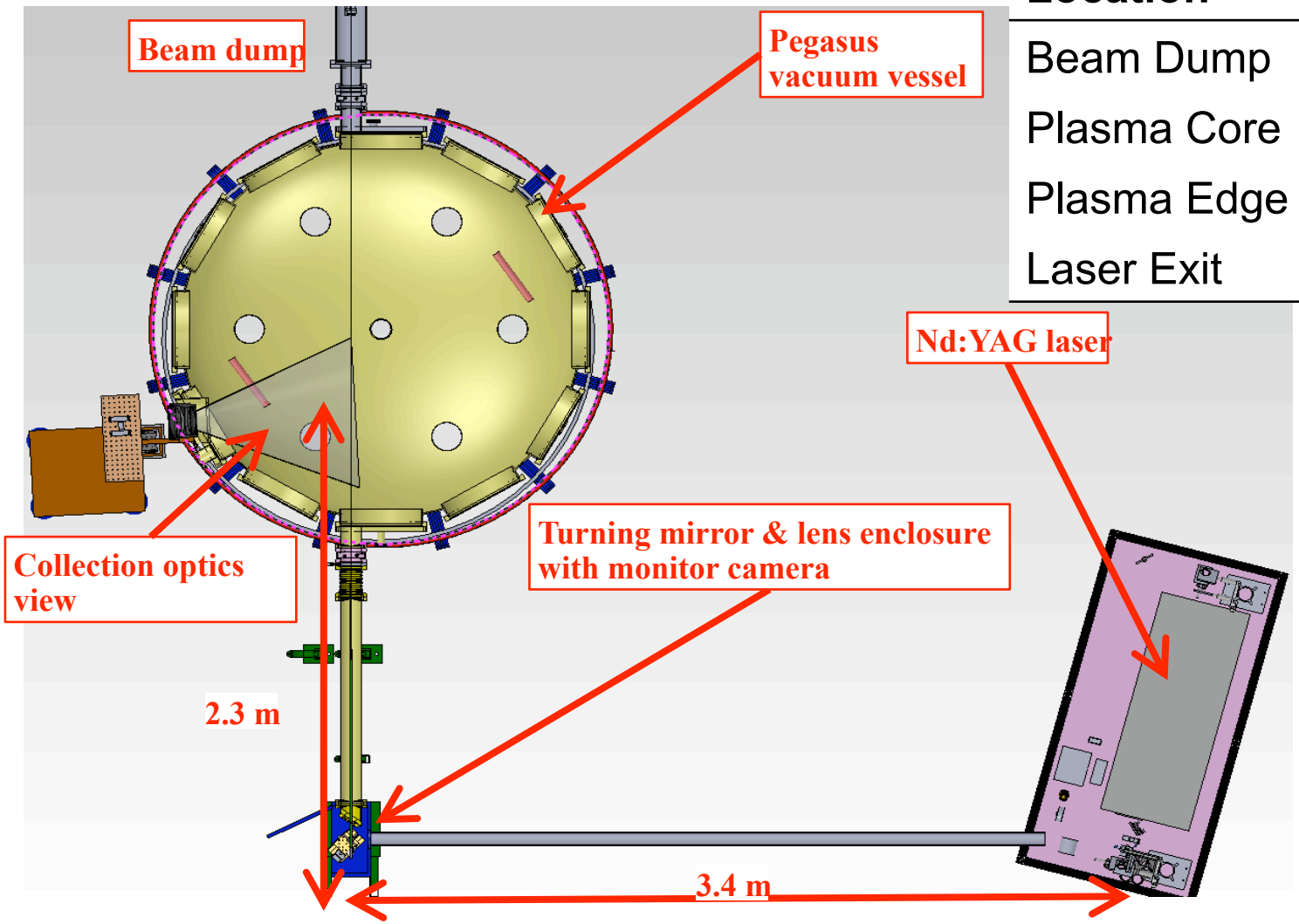





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# Laser Diameter in Viewing Area is ~1mm

| Location | Beam diameter |
|---|---|
| Beam Dump | 10.50 mm |
| Plasma Core | 2.26 mm |
| Plasma Edge | 0.04 mm |
| Laser Exit | 10.00 mm |

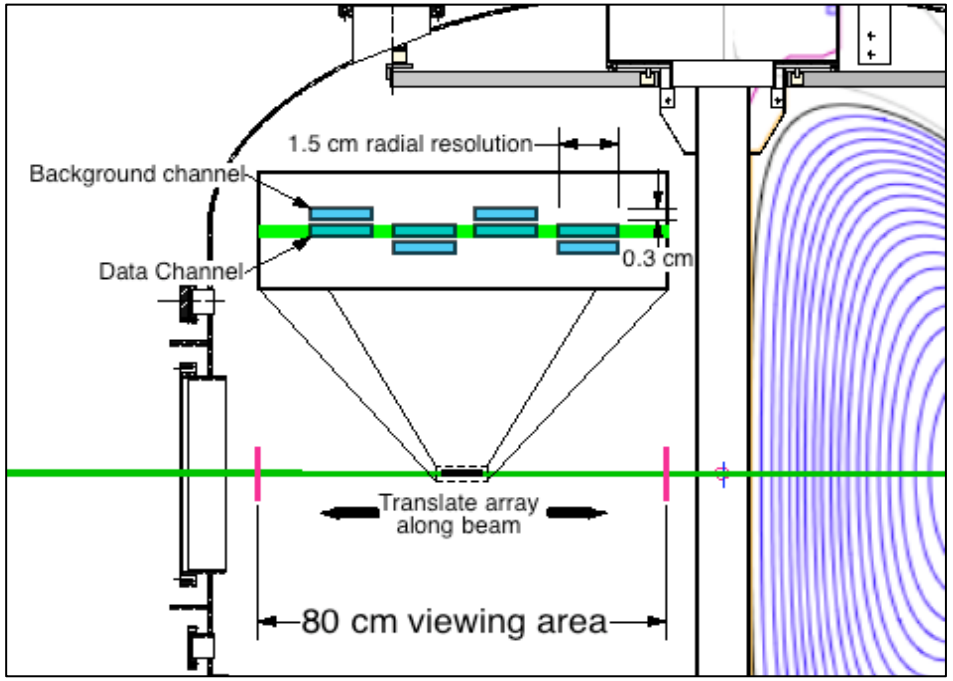


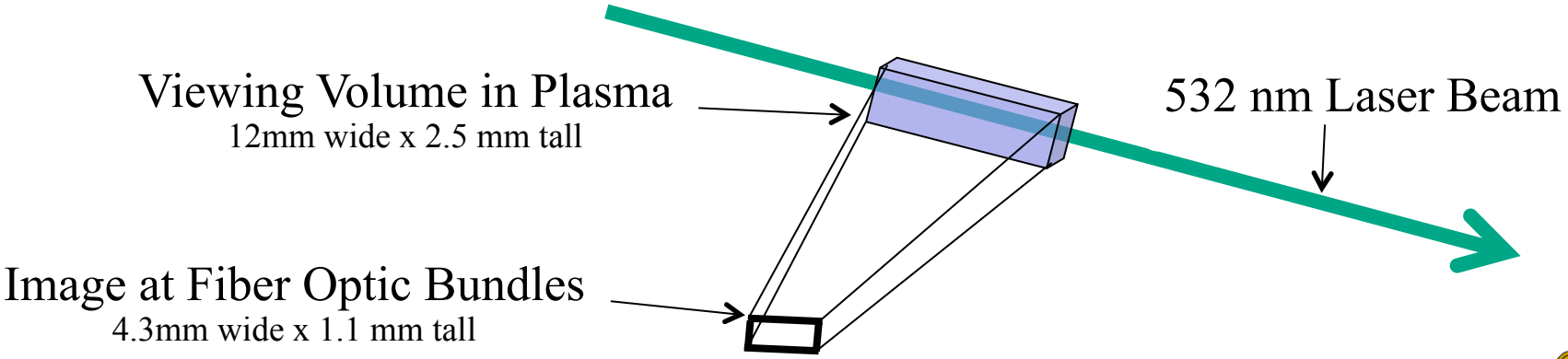



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# Fiber Bundles Image 80 cm Radially Along the Midplane

- Each spatial channel is 2.5 mm tall (across the laser) by 12 mm along the laser in the plasma
- Fibers will be moved between shots as needed
  - Initially movement is manual with plans to automate in the future
  - Each spectrometer allows for 8 fiber bundles, 3 spectrometers will be deployed



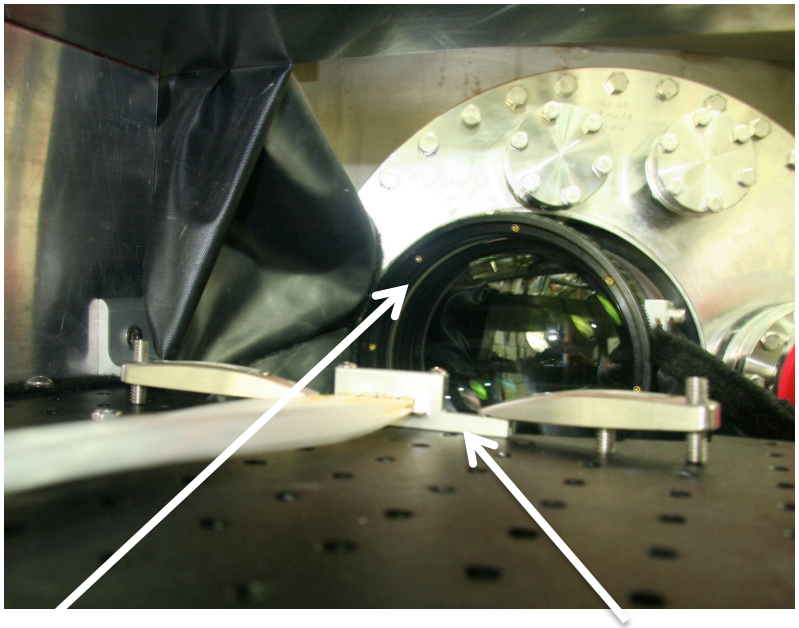



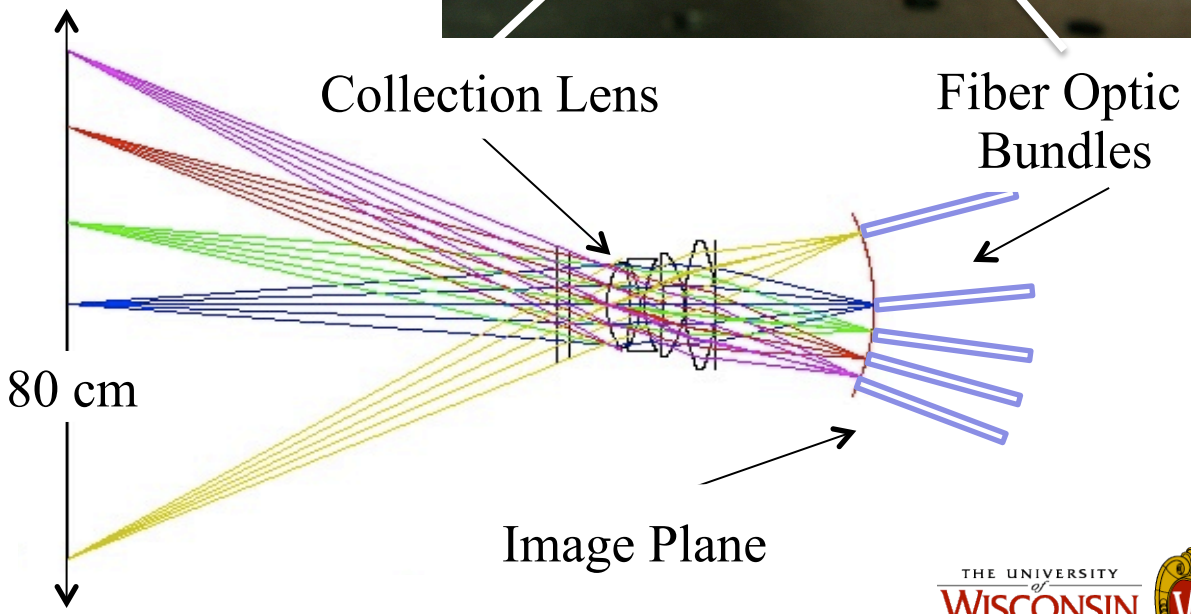



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# Collection Lens Designed to Collect Full Field of View

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



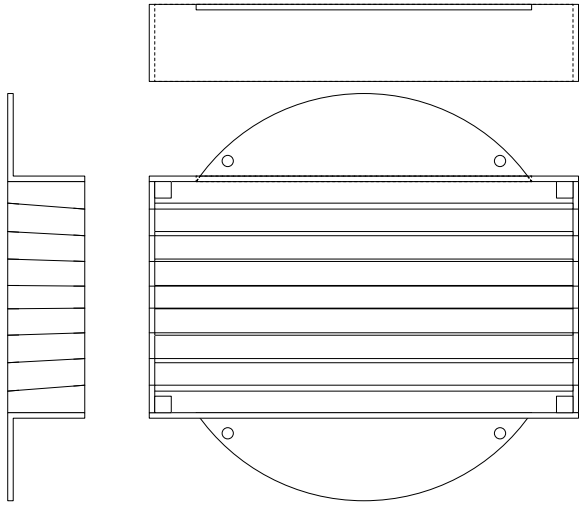


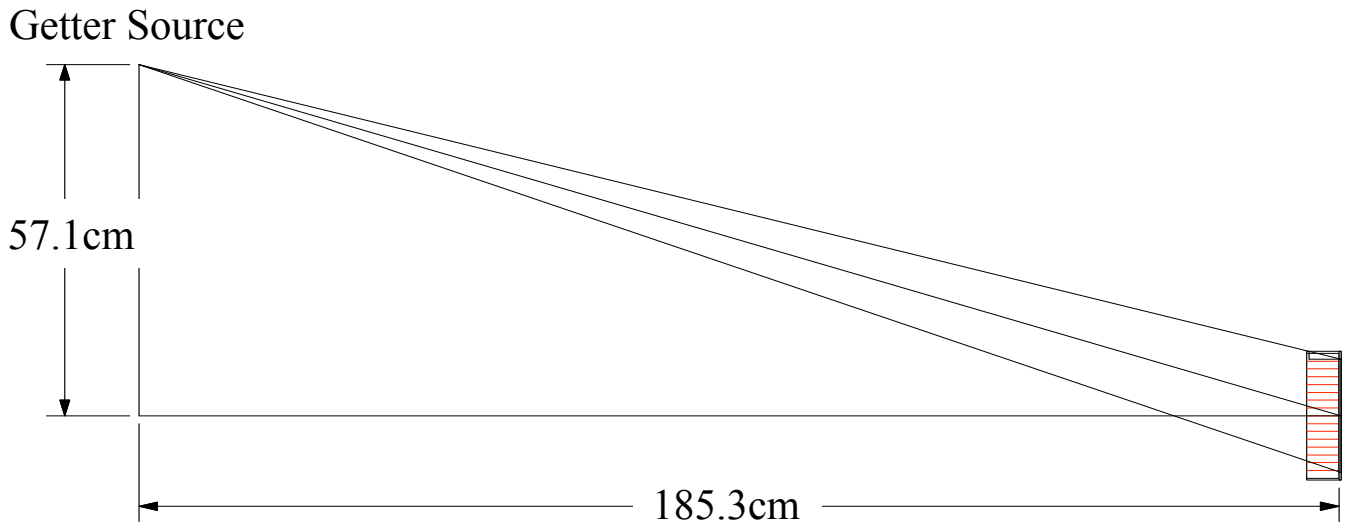



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# Custom Designed Louvers Shield Window from Getters

- Carbon painted stainless steel louvers angled to prevent rays of getter light from reaching the vacuum window
- Reduces system efficiency slightly to maintain window integrity
- Efficiency >90%

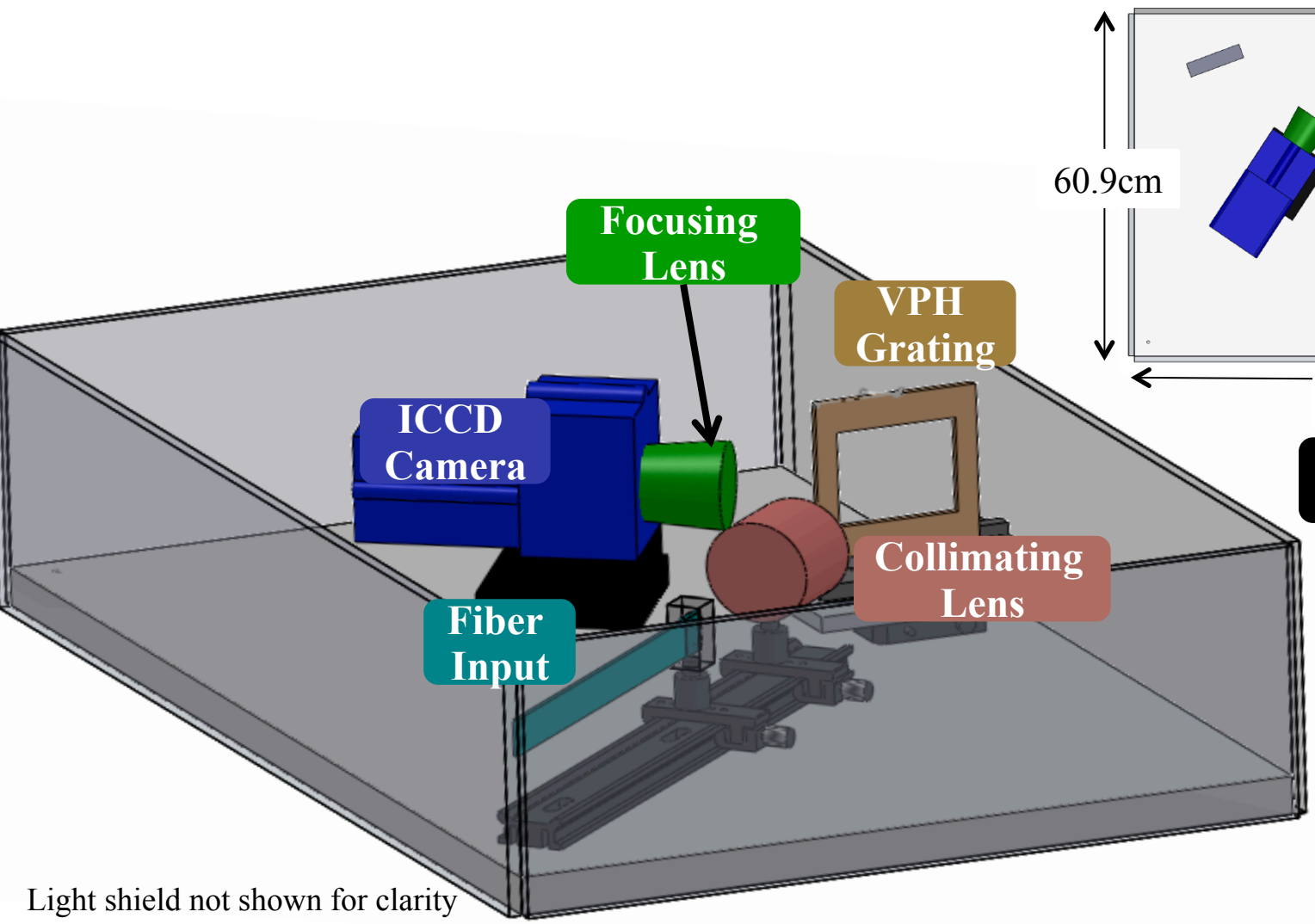


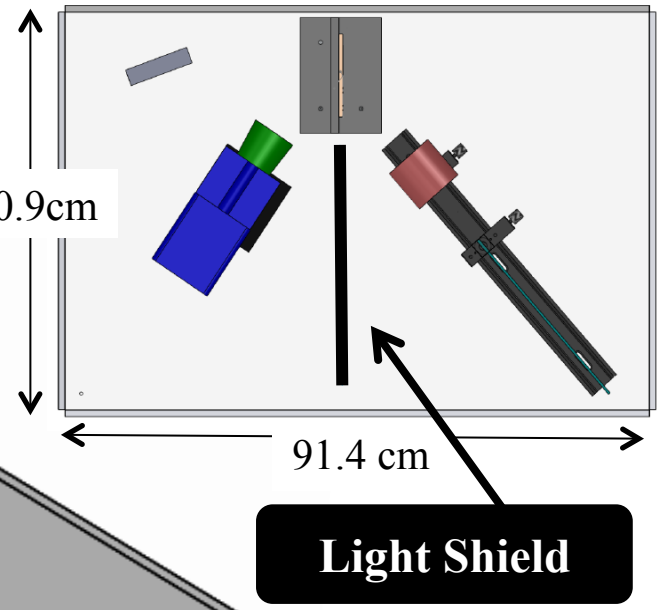





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# Compact Spectrometer Uses VPH Gratings and ICCD Cameras



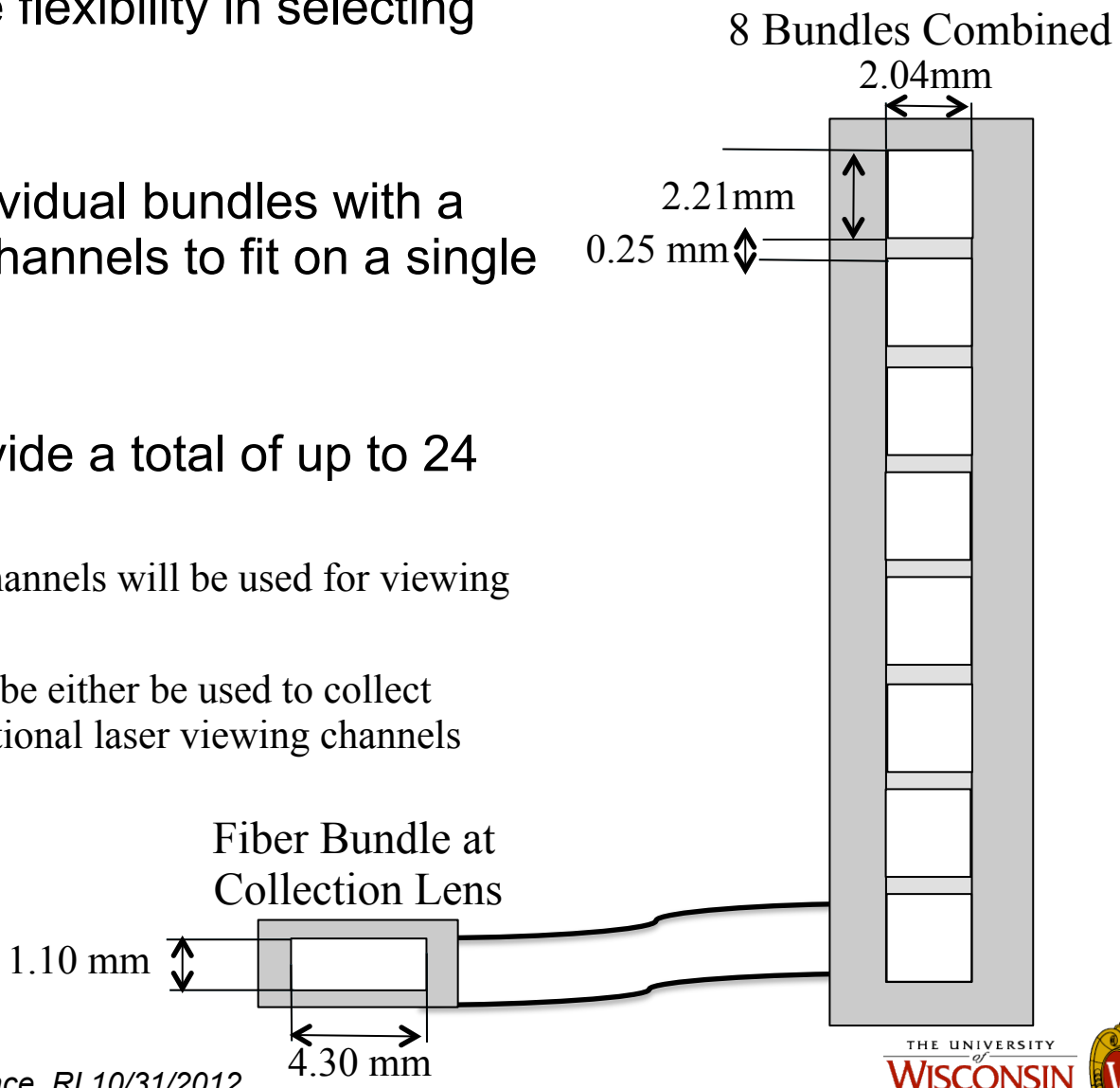

Light shield not shown for clarity



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# Fiber Optic Bundle Repackaged at Spectrometer to Fit 8 Spatial Channels through System

- 8 individual ends provide flexibility in selecting viewing locations
- A slit composed of 8 individual bundles with a 2mm width allows all 8 channels to fit on a single CCD
- 3 spectrometers will provide a total of up to 24 spatial channels
  - A minimum of 12 of these channels will be used for viewing scattered laser light
  - The remaining channels will be either be used to collect background signal or as additional laser viewing channels



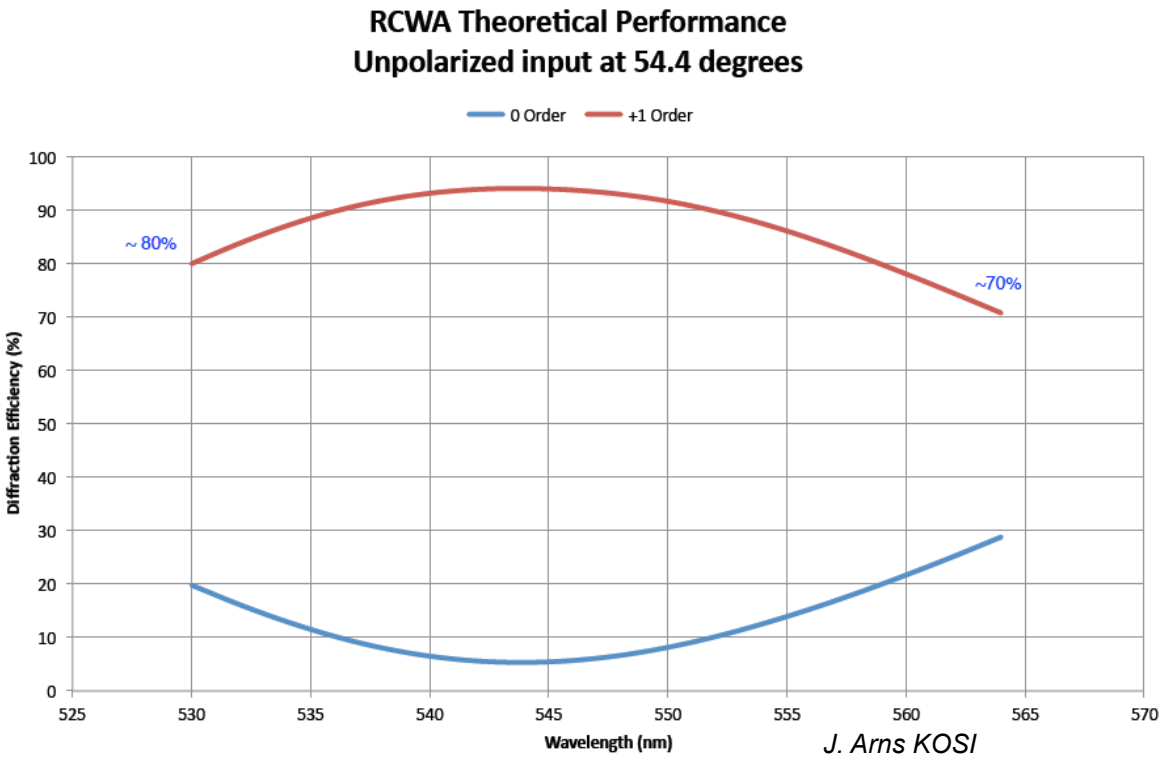



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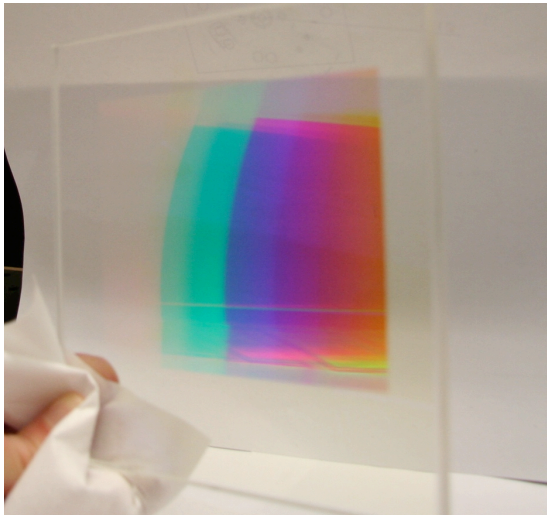
# VPH Grating Designed for High Efficiency in 2 Temperature Regimes

- Two gratings
  - 2971 lines/mm for low temperatures ($kT_e$ ~10eV-100eV)
  - 2072 lines/mm for high temperatures ($kT_e$ ~100eV-1000eV)

- Dispersion selected to utilize the full 13.3 mm width of the CCD




J. Arns KOSI





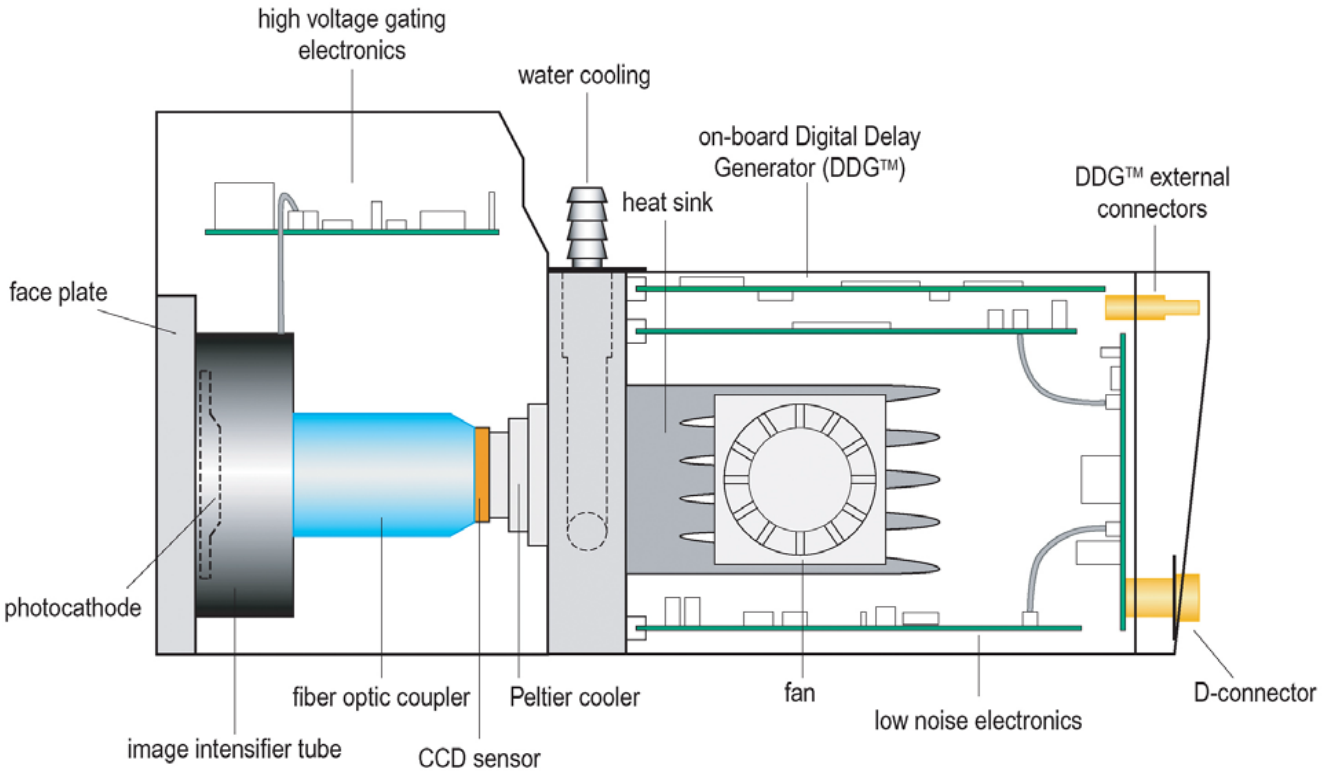
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# ICCD Detectors Chosen for High Gain & Low Noise Qualities



## 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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# Efficiencies Collection Optics and Spectrometer Predict 5000 Photons Reach the MCP

- 34 000 red-shifted photons scattered into viewing optics for plasmas with $n_e = 1x10^{19}\ m^{-3}$

- Variable gain with a maximum gain setting of 300

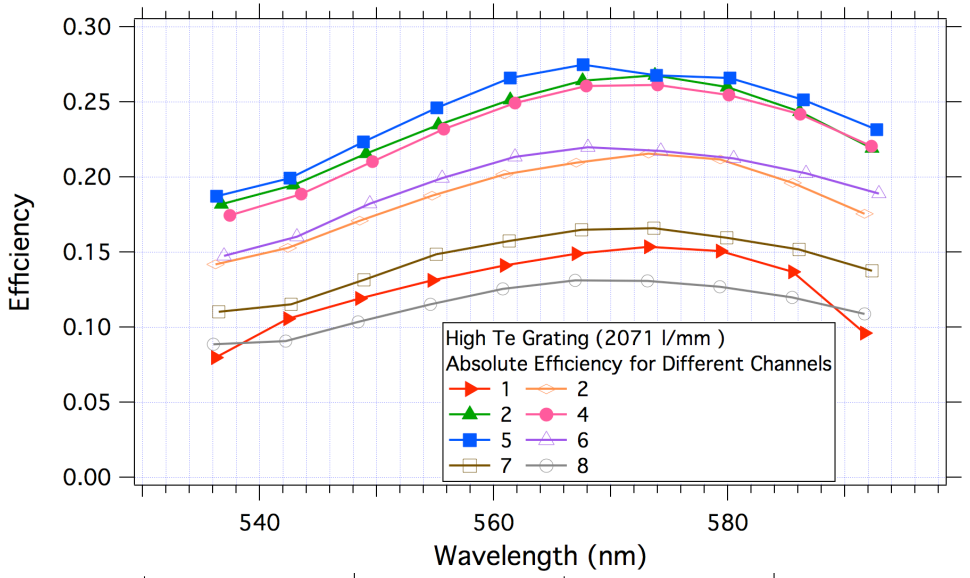
- Predicted efficiency:
  - Fiber optics, spectrometer and camera sub-system efficiency of >25% predicted
  - >19% for the full system, including the collection lens and louvers

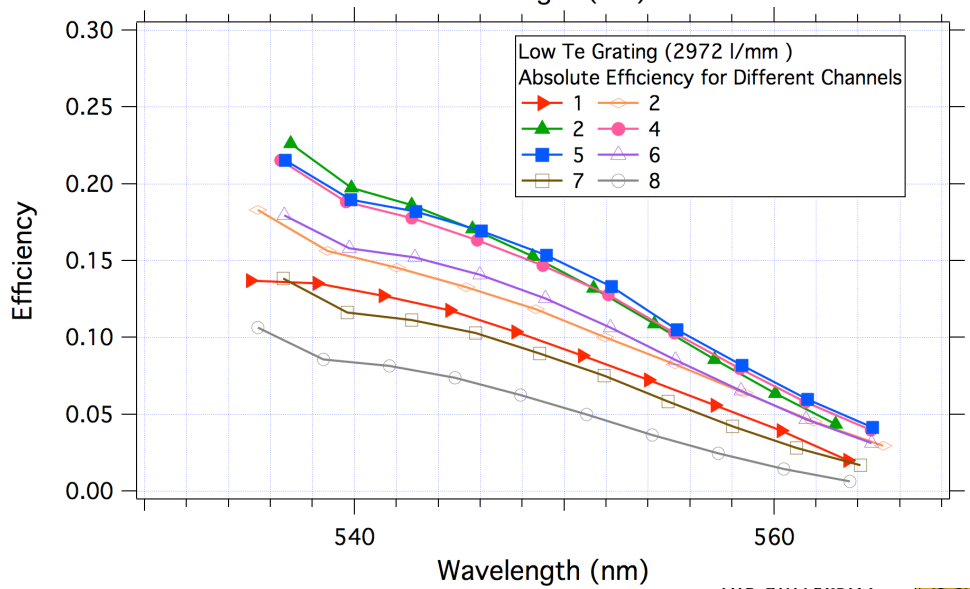
| Component | Efficiency | Photons |
|---|---|---|
| Scattered photons* | n/a | 34 000 |
| Louvers | 90% | 25 704 |
| Collection Lens | 84% | 29 376 |
| Fiber Optics | 65% | 16 708 |
| VPH Grating | >85% | 14 201 |
| Camera QE | 45% | 6 390 |
| A/D conversion | 2 photoelectrons per count | 3 195 Counts** |

*Red-shifted scattered photons into collection volume per laser viewing spatial channel
**Counts calculated is the minimum, assuming unity gain factor in the MCP

# Fiber Optics and Spectrometer Efficiency Matches Estimates Well

- Fiber optics, spectrometer and camera efficiency determined by absolutely calibrated integrating sphere.
- Low dispersion, high Te grating system approaches predicted efficiency of >25%
- High dispersion, low Te grating set up leads to high vignetting and walkoff
  - Approaches theoretical efficiency from ~532 to ~542
  - Walkoff a significant effect at upper range of interest



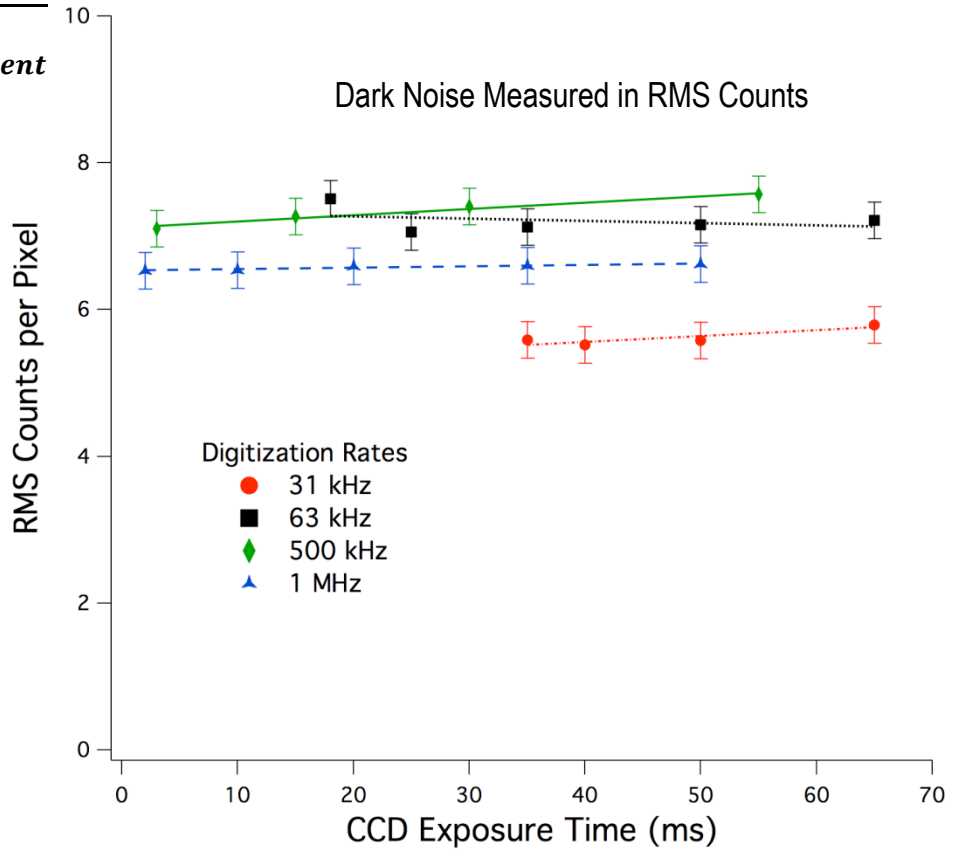






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# Dark Noise Testing Indicates Camera is Read Noise Dominated

- CCD dark noise ~ $\sqrt{N_{Read}^2 + N_{Dark\ Current}^2}$
  - Dark noise dominated by read noise without on-chip binning
  - Read noise without on-chip binning is ~7 counts per pixel
- On-chip binning
  - RMS noise in a super-pixel of 128 vertical pixels x 51 horizontal pixels is <12 counts
  - Equivalently, a 128x51 pixel super-pixel contains 0.03 RMS noise counts per single pixel






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# Pegasus Thomson Scattering System Provides Simplified Design

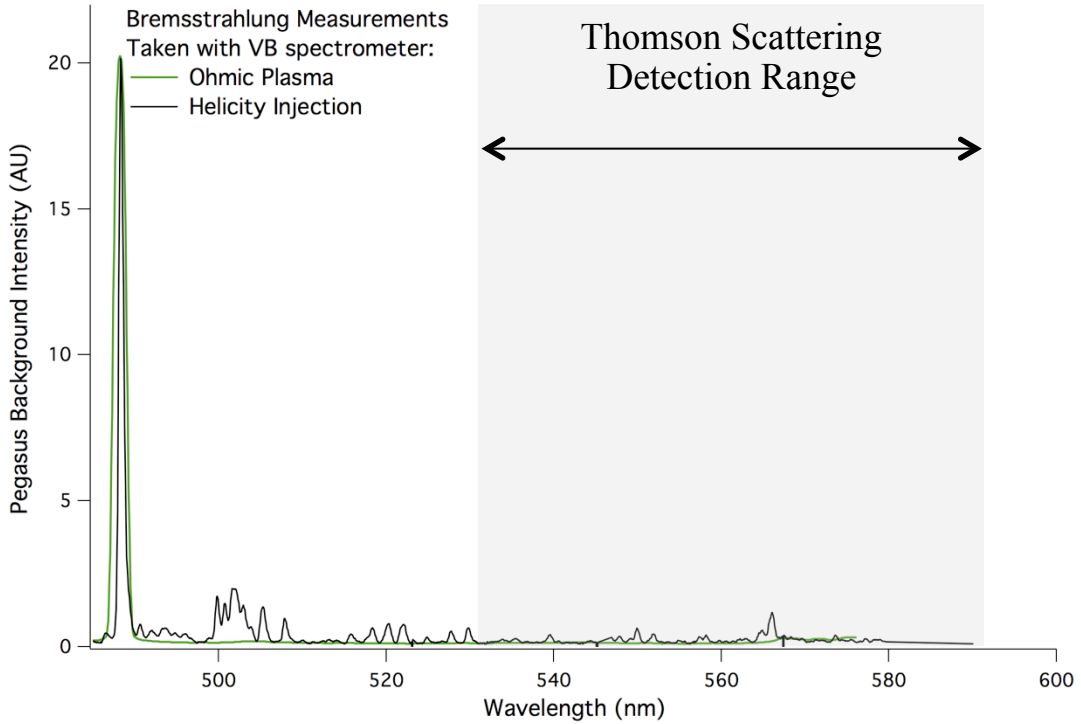
- Key components of the Pegasus Thomson scattering system include:
  - 2J Nd:YAG laser operating at 532nm
  - Remotely actuated mirrors and cameras for between shot alignment
  - Fiber bundles designed to maximize use of CCD camera
  - Volume phase holographic gratings with efficiencies >80%
  - ICCD cameras for simplified data acquisition

- A single 8-channel spectrometer currently deployed with plans to expand to 3 spectrometers (24 total channels) late 2012 and into early 2013

- Laser system and 1$^{st}$ spectrometer being fine-tuned:
  - Alignment of viewing optics and laser beam
  - Fine-tuning laser path to maximize signal

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

- Ohmic plasmas are low impurity and dominated by Bremsstrahlung radiation
  - May be able to eliminate or reduce background channels
- In helicity Injection plasmas impurity line emissions ~10 times the background
- Background signal will need to be evaluated to determine if the bremsstrahlung and impurities are a significant effect on the nanosecond timescale



# Stray Light Reduction Techniques Employed

