Spatial Expansion and Automation of the Pegasus Thomson Scattering Diagnostic System

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57th Annual APS-DPP Meeting

Savannah, GA

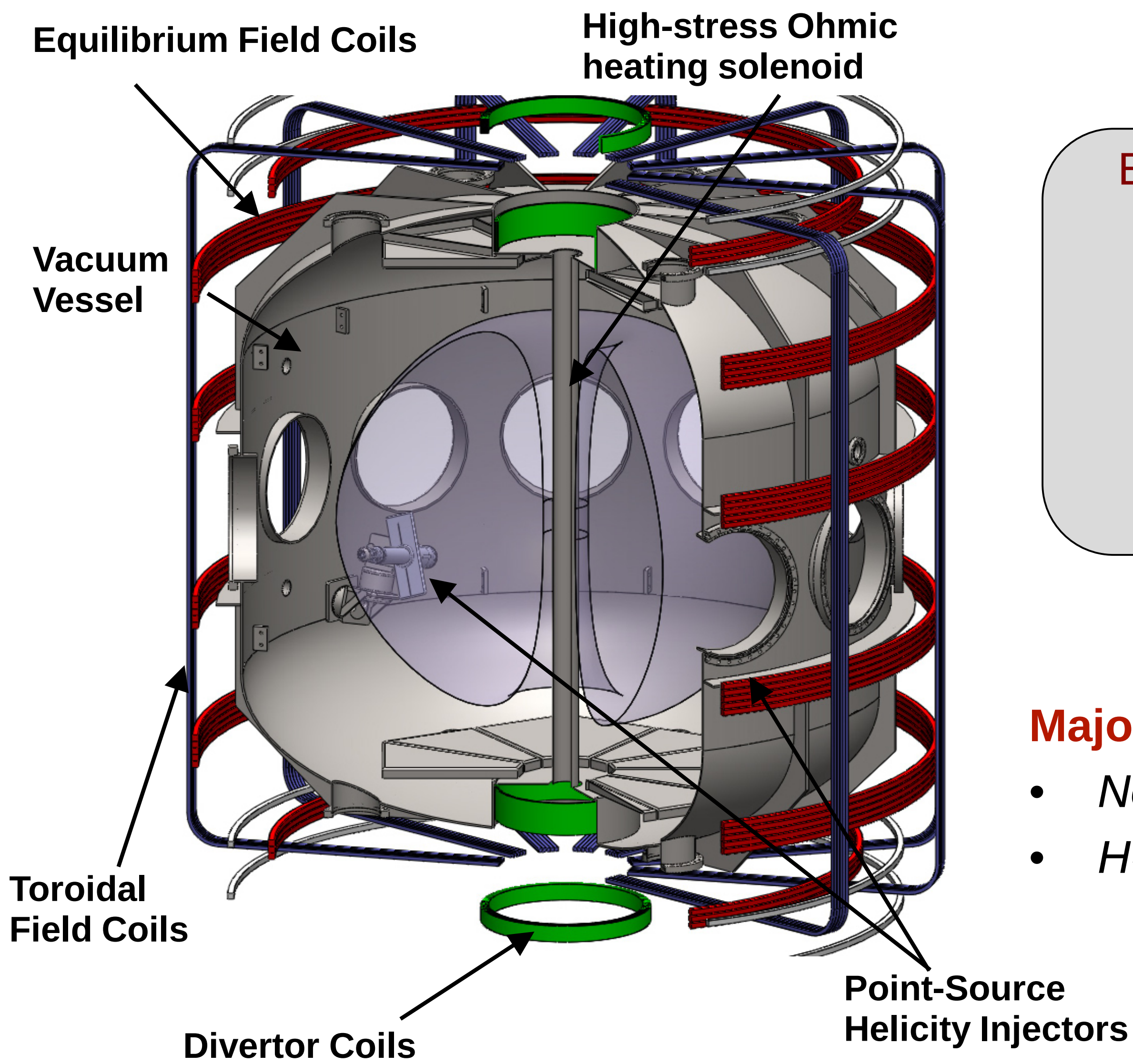
November 17, 2015

PEGASUS Toroidal Experiment

Enhancements to Pegasus Thomson Scattering System Implemented

- Collection of T_e and n_e profiles is a critical plasma measurement
  - Equilibrium/Stability
  - Transport and confinement
- Two new spectrometers deployed
  - Additional 16 data channels
- Laser triggering and alignment improved
  - Increased scattered signal
- Improved calibrations methods and analysis techniques
- Synchronized and automated system operation

Pegasus is a Compact Ultralow-A ST



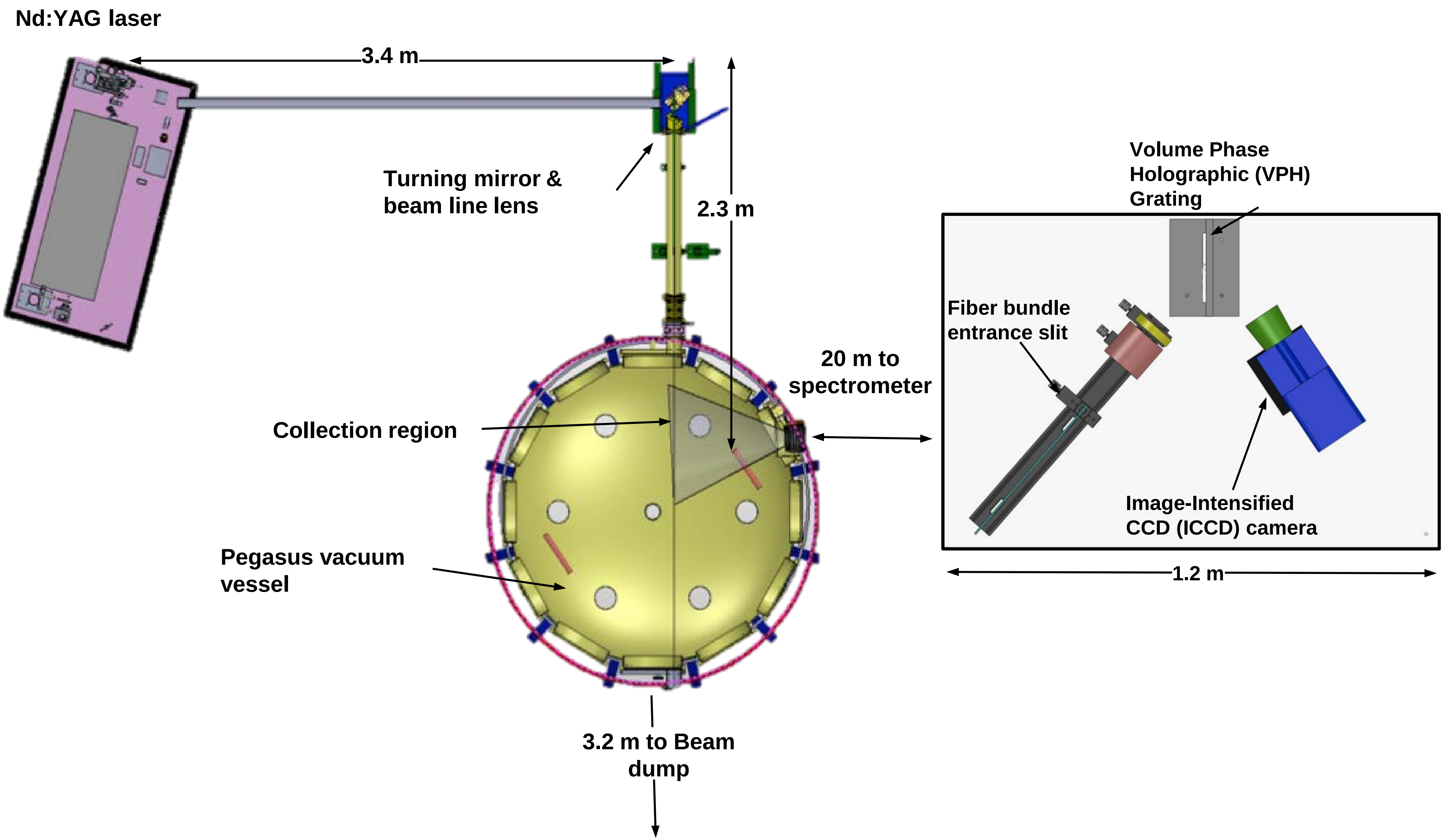
Experimental Parameters

Parameter	Achieved
A	1.15 – 1.3
R(m)	0.2 – 0.45
I_p (MA)	≤ .21
κ	1.4 – 3.7
τ_{shot} (s)	≤ 0.025
β_t (%)	≤ 25

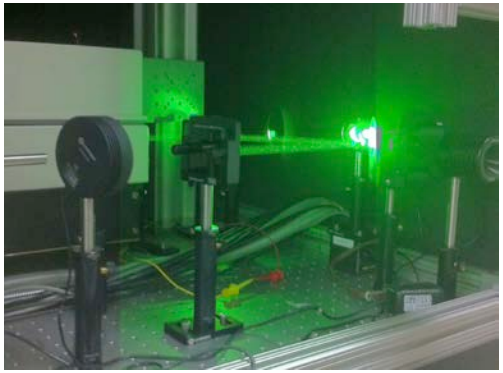
Major research thrusts include:

- *Non-inductive startup*
- *H-mode, ELMS at low A*

Layout of the Pegasus Thomson Scattering Diagnostic



“Turn-key” 2J Laser Optimized for Operation on Pegasus

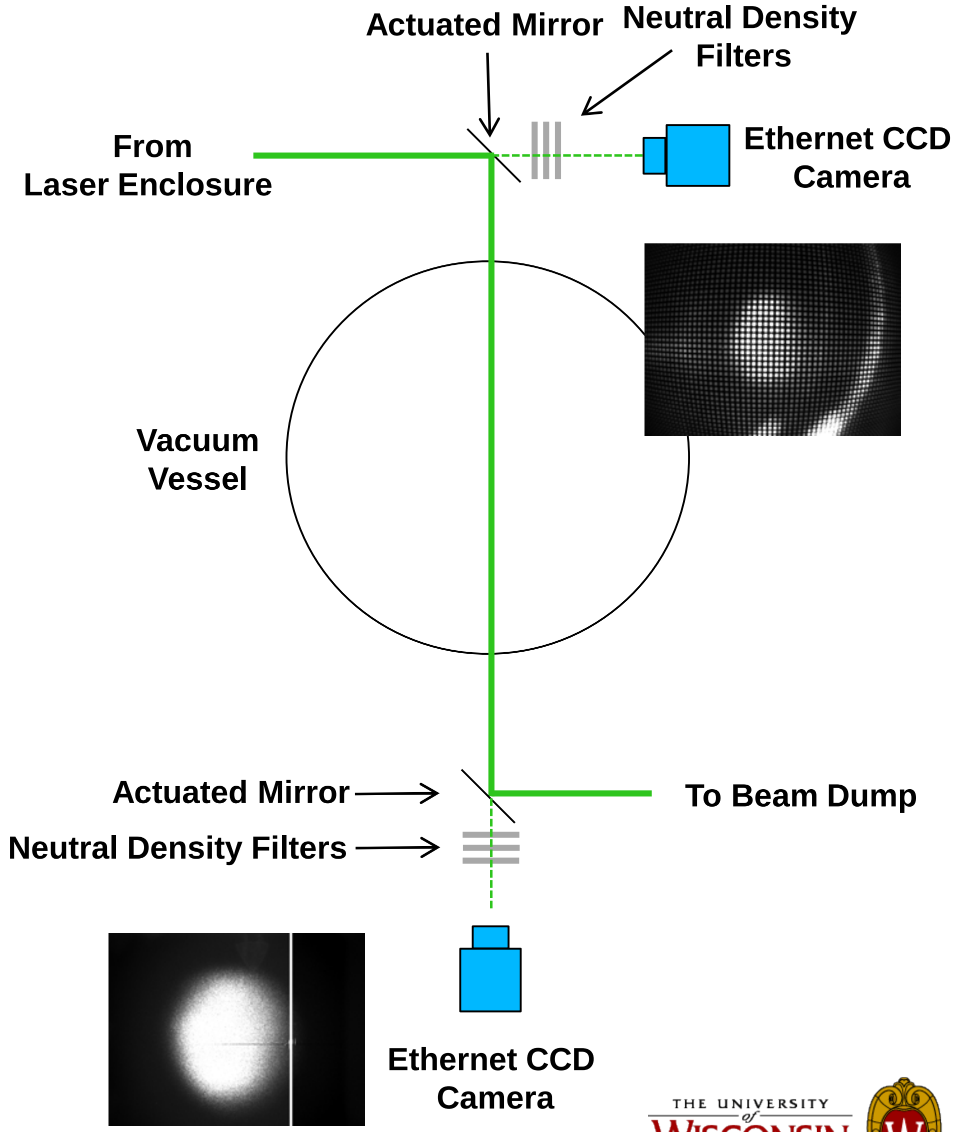


- Continuum Powerlite DLS Plus 2J Nd:YAG laser
- Frequency doubled to provide 2J at 532 nm

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

Laser Alignment Maintained with Remotely Actuated Mirrors and Networked Cameras

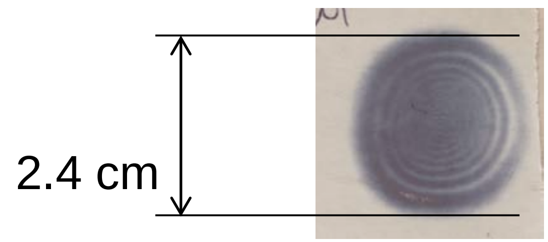
- Thermal lensing, vibrations detune beam alignment
- Two actuated mirrors control laser alignment
  - Position monitored with cameras
- Energy meter measures exit power at end of beam line
  - Acts as beam dump



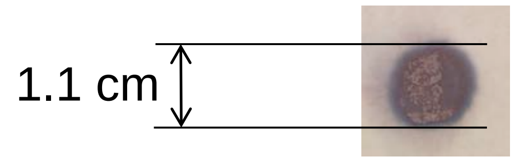
Timing Sequence Modifications Improve Beam Quality and Energy Density

- New delay generator pulses flashlamps, Q-switch at 10 Hz
  - Reduces laser idling time
- Improved beam quality and output power
  - Original configuration: ~ 1.3 J
  - Modified configuration: ~ 1.8 J

Burns taken before entrance to vacuum vessel (Images to scale)



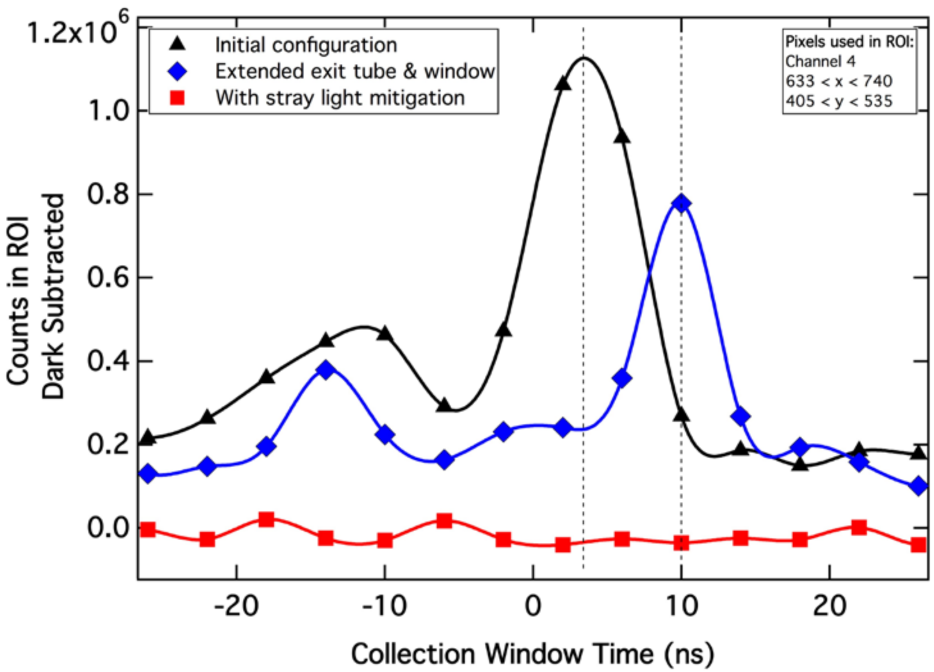
Original Configuration

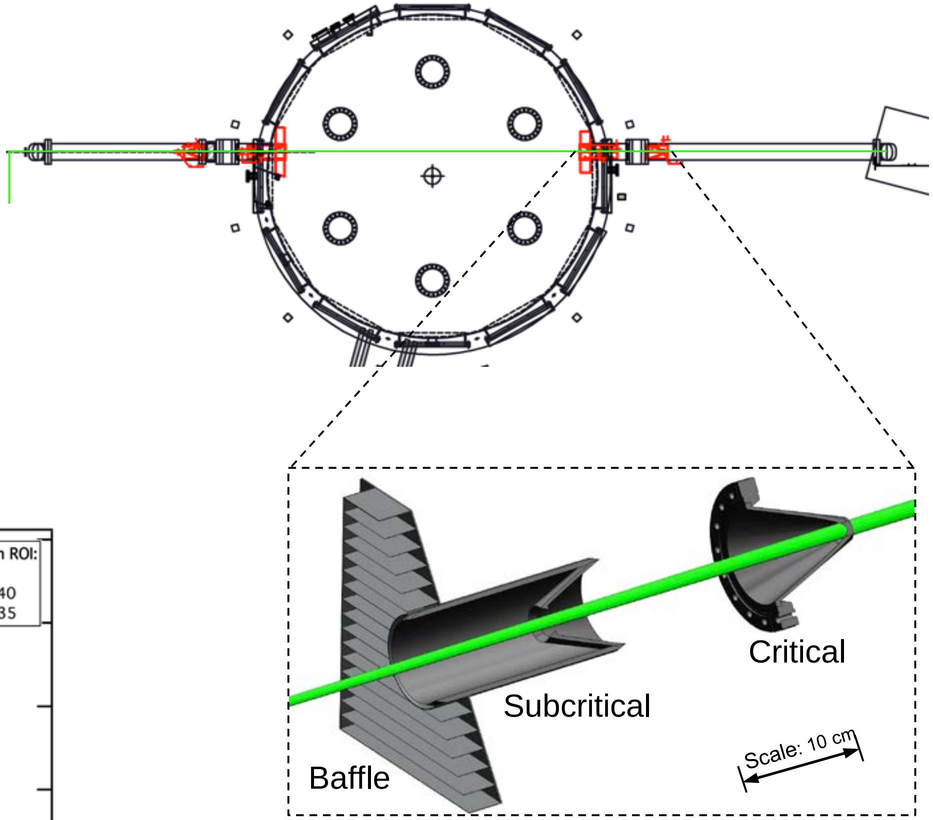


Modified Configuration

Aperture Assembly Reduces Stray Light by a Factor of 10^6

- "Critical" apertures
  - Block stray light from vacuum vessel
- "Subcritical" apertures
  - Blocks scattered light from critical apertures
- Baffles
  - Blocks light from subcritical apertures





***Based on implementations by:*
C.J. Barth, et al. Rev. Sci. Instrum. ***82****, 3380 (1997)*
J.P. Levesque, et al., Rev Sci. Instrum. ***82****, 033501 (2011)*

D.J. Schlossberg *et al*. *Journal of Instr.* **8** C11019 (2013)

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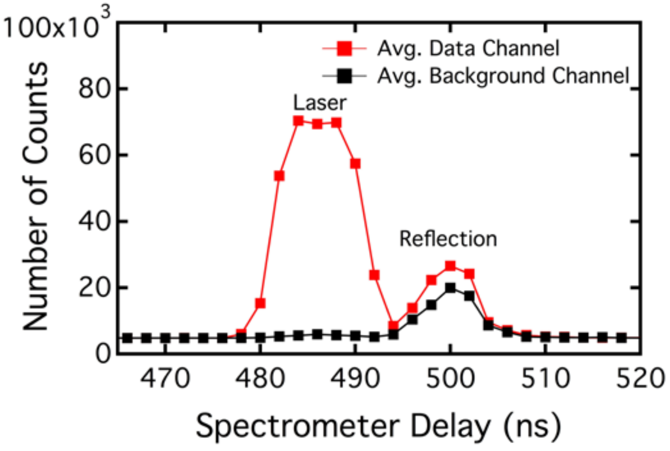
Gated Collection Window Used to Mitigate Stray Light Reflections

- Spectrometer collection time scanned with respect to laser

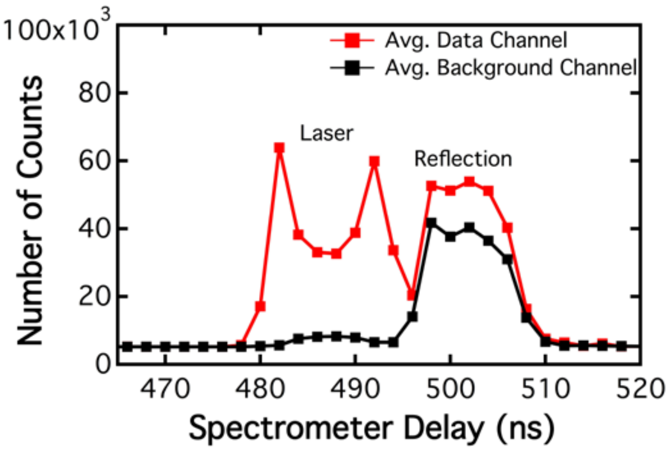
- Initial laser pulse, stray light reflections clearly identified

- Use of fast gating enables elimination of stray light
  - Optimum delay determined to be 479 ns with a 16 ns gate width

Spectrometer – SN4076

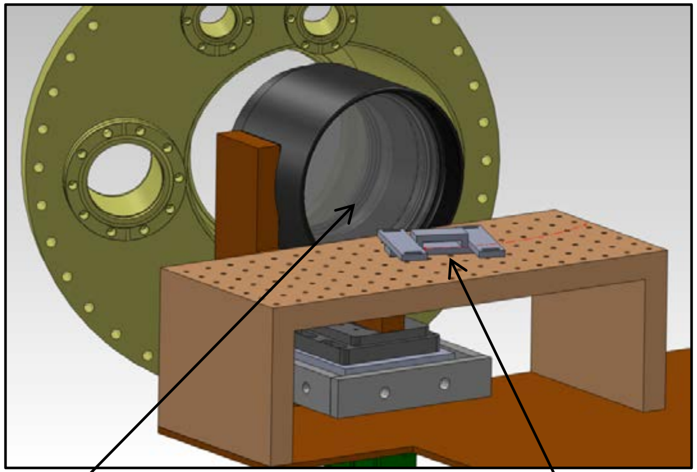


Spectrometer – SN4077

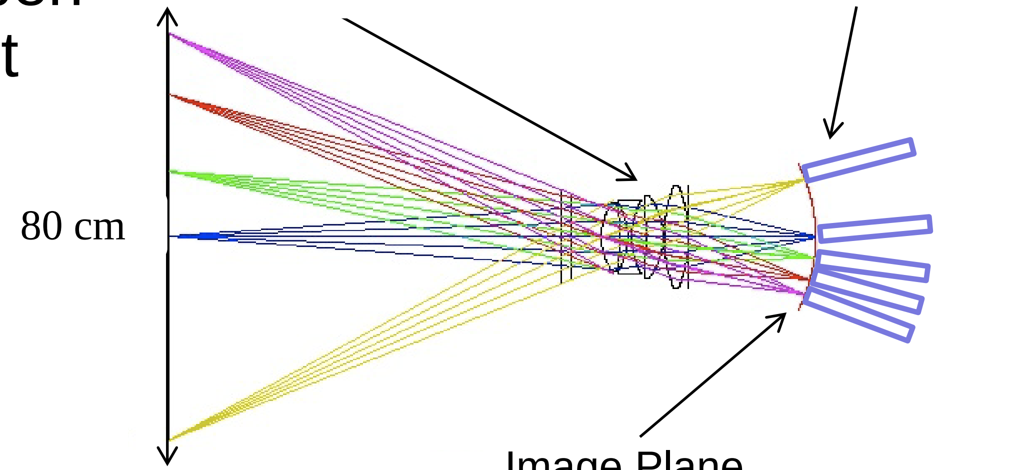


Multi-Element Collection Lens Supports High Throughput Field of View

- Design Criteria:
  - Collect 80 cm flat field of view
    - 72 cm from lens
  - Resolution sufficient to collect a scattering area ~ 1.5 cm x 0.3 cm



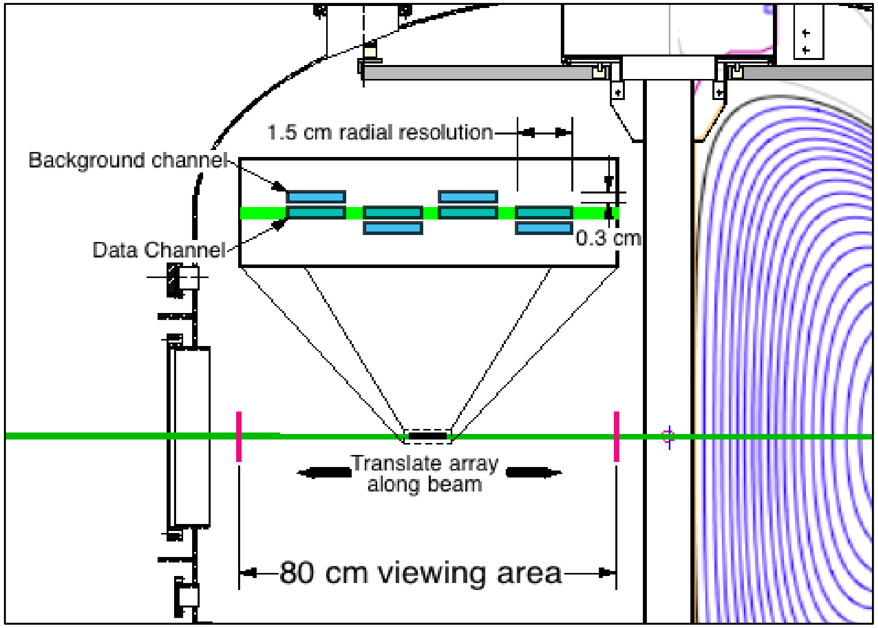
- Curved image plane with open locations for fiber placement
  - F# 2.1
  - 20.2 cm focal length



- Magnification ~1/3

Fiber Bundles Image 80 cm Radially Along the Midplane

- Each channel is 0.3 cm x 1.5 cm
- 8 spatial channels per spectrometer
  - 4 data, 4 background channels
  - High and low background channels assist beam alignment



Viewing Volume in Plasma
1.5 cm wide x 0.3 cm tall

532 nm Laser Beam

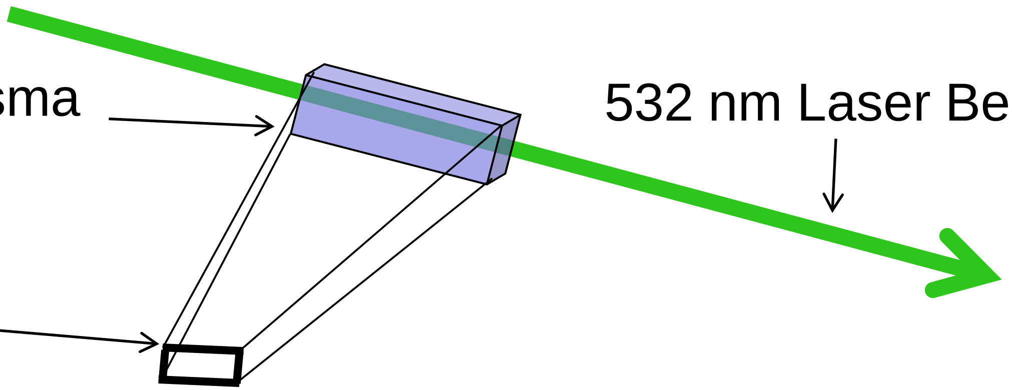


Image at Fiber Optic Bundles
4.3mm wide x 1.1 mm tall

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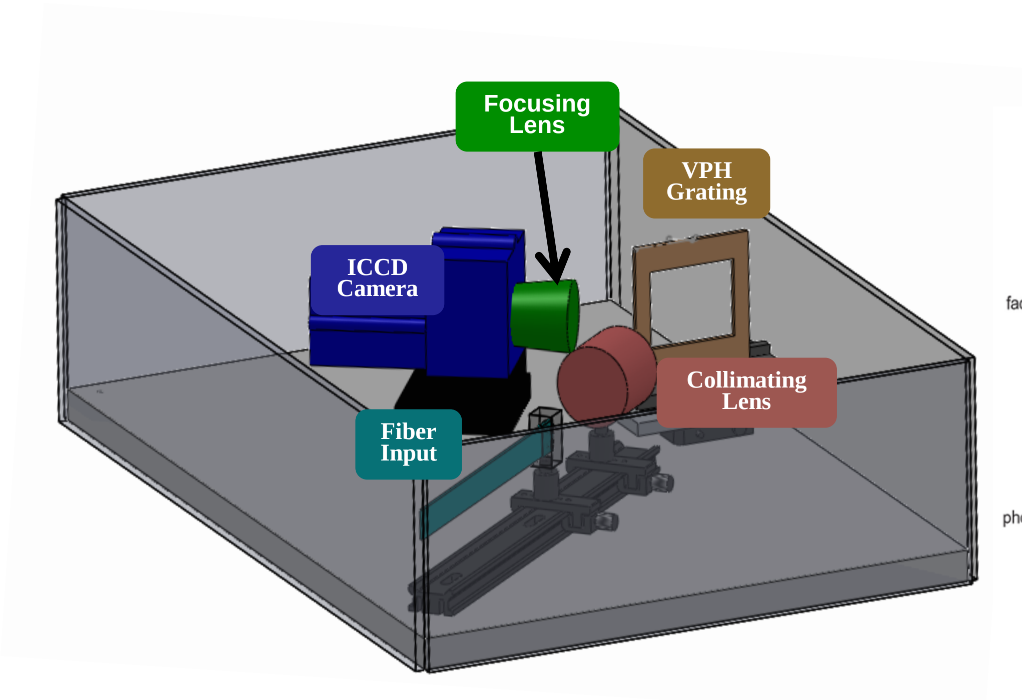
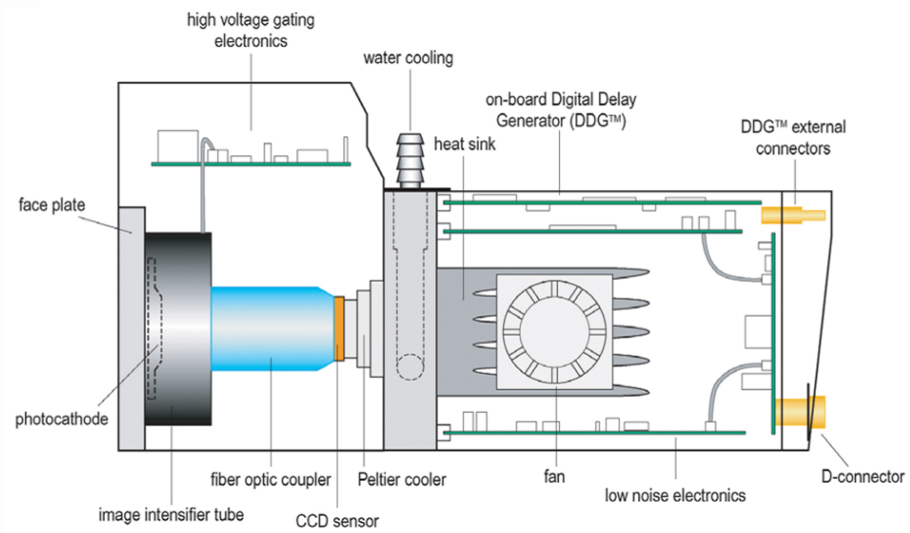
Compact Spectrometer Uses VPH Gratings and ICCD Cameras

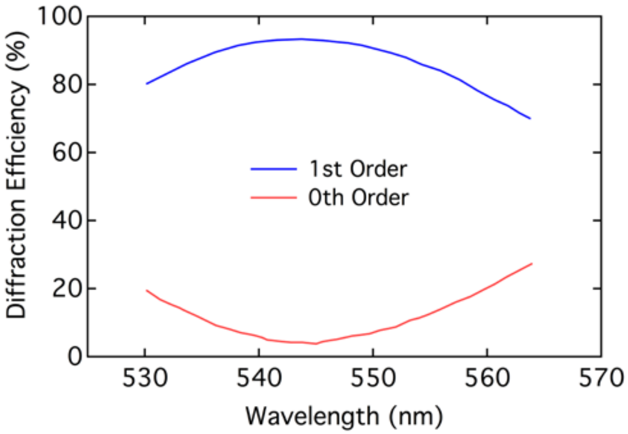




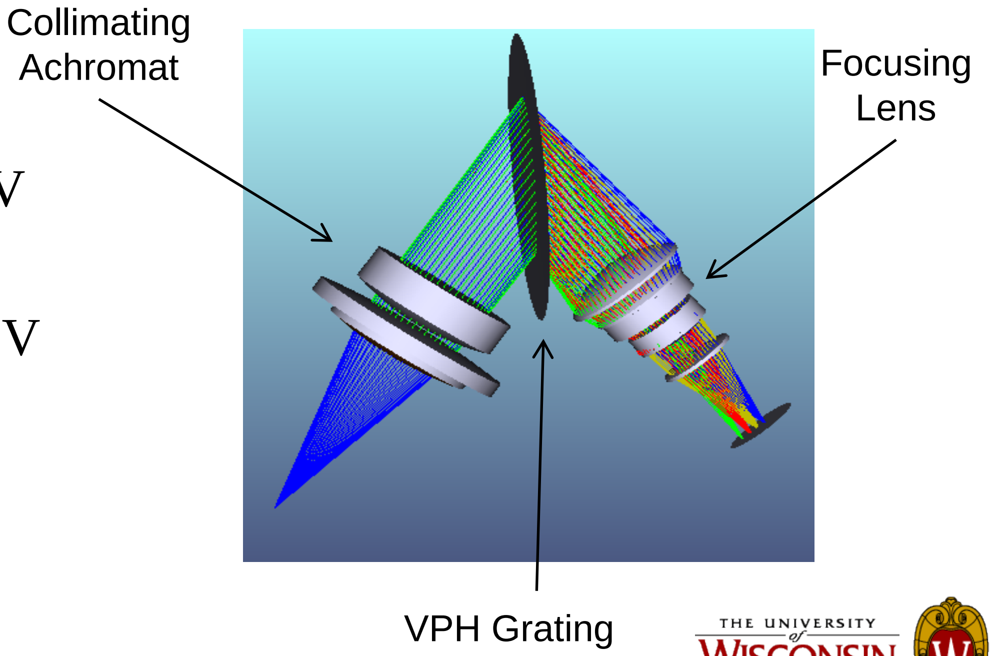
ICCD Manufacturer Specifications: Andor iStar 734			
Effective Active Area (mm)	13.3 x 13.3	Effective Pixel Size (um)	19.5 x 19.5
Read Noise	≥ 2.9 e-	Active Pixels	1024 x 1024
Spectral Range (nm)	120 - 1090	Photocathode QE (max)	≤ 45%
Minimum Optical Gate Width	≥ 1.2ns	Image Intensifier Gain	> 200

Spectrometer Design Features Interchangeable VPH Gratings for Multiple Temperature Regimes

- Volume-Phase Holographic (VPH) grating
  - Diffraction Efficiency ~ 80%

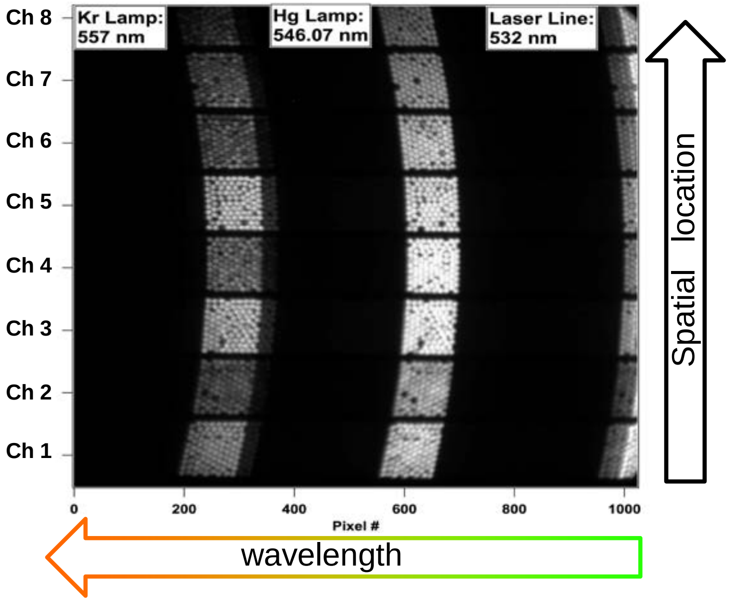


- Two temperature gratings:
  - “High T_e” grating: T_e~100eV-1keV
    - 2072 lines/mm (Core T_e)
  - “Low T_e” grating”: T_e~10eV-100eV
    - 2971 lines/mm (Edge/LHI T_e)

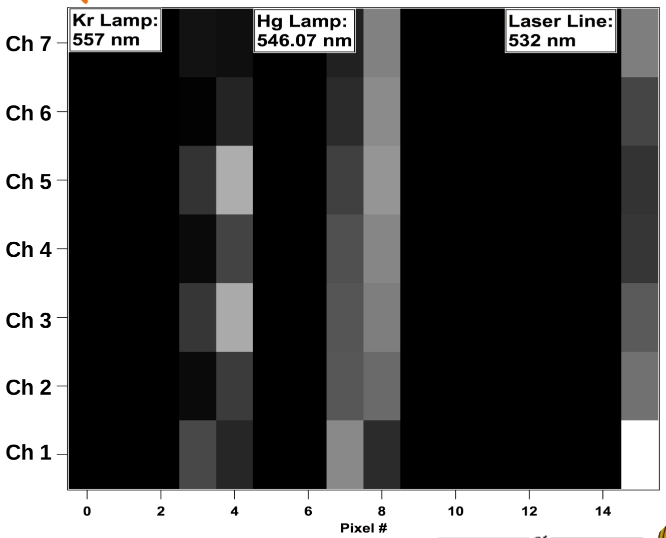


On-CCD Binning Increases Signal-to-Readout-Noise Ratio

- Binning customized to match fiber image positions of 8 spatial channels
  - Spatial locations mapped vertically
  - Wavelength increases right-to-left
  - Provides 16 spectral bins



- On-chip binning yields photon-noise dominated statistics
  - CCDs are 1024 x 1024 pixels
  - Read noise ~ 8 e- / read event
  - Bin 133 pixels V x 64 pixels H



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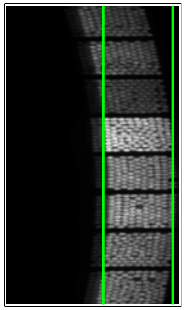
Arrangement of the Fiber Optic Bundles Altered to Combat Vignetting Effects

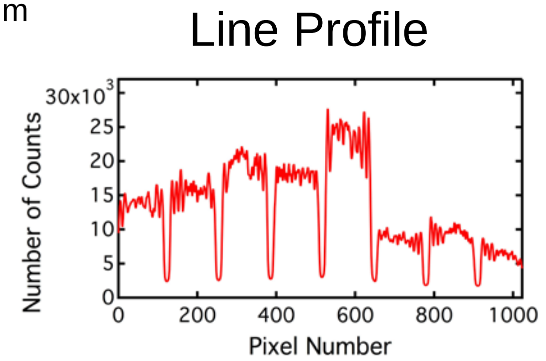
- Intrinsic vignetting due to spectrometer optics
  - Off-axis channels most sensitive to vignetting effects

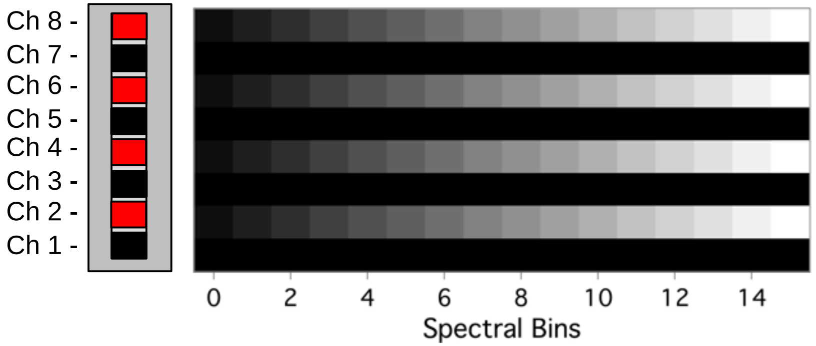
- Original configuration pairs data, background channels

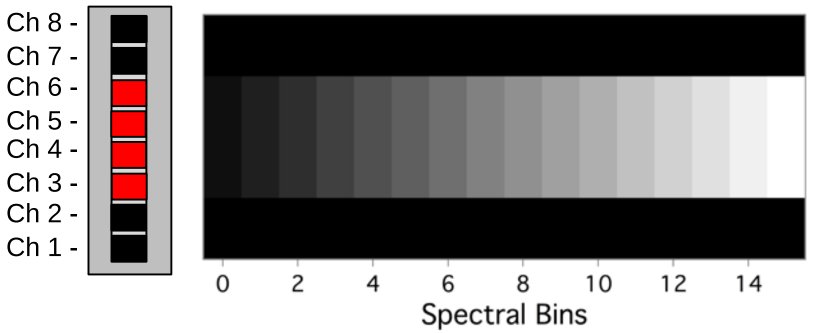
- New configuration optimizes data channel signal integrity

Laser Line: 532 nm





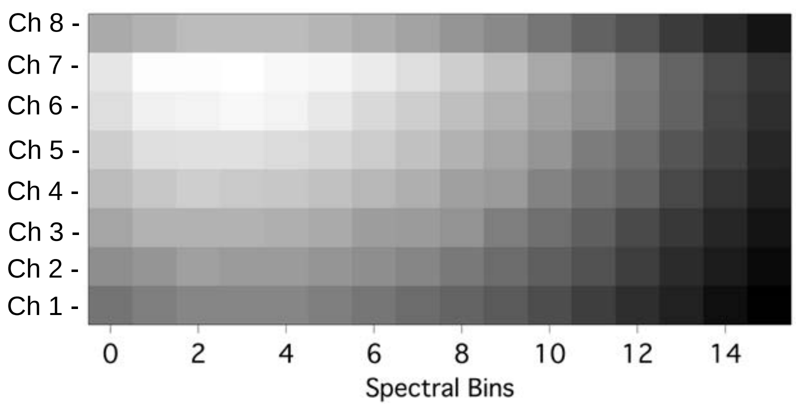




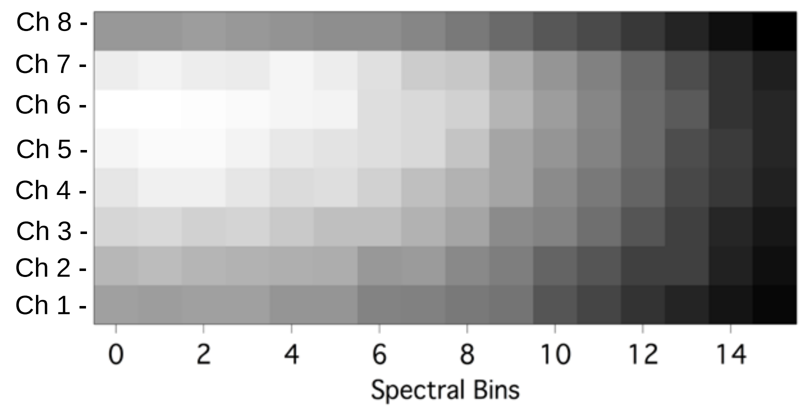
Detector Instrument Functions Obtained using Calibrated Integrating Sphere

- Thomson signal divided by instrument function
  - Accounts for detector flatness
- Previous flat field calibrations produced unreliable T_e profiles
  - Calibrations differ depending upon on-chip or software binning
  - Light leakage through ICCD Micro-Channel Plate (MCP)

Flat Field Calibration – SN4076



Flat Field Calibration – SN4077



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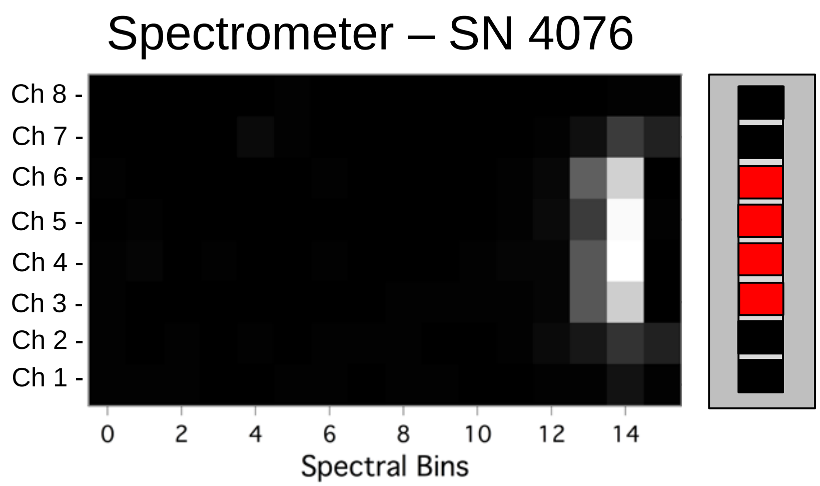
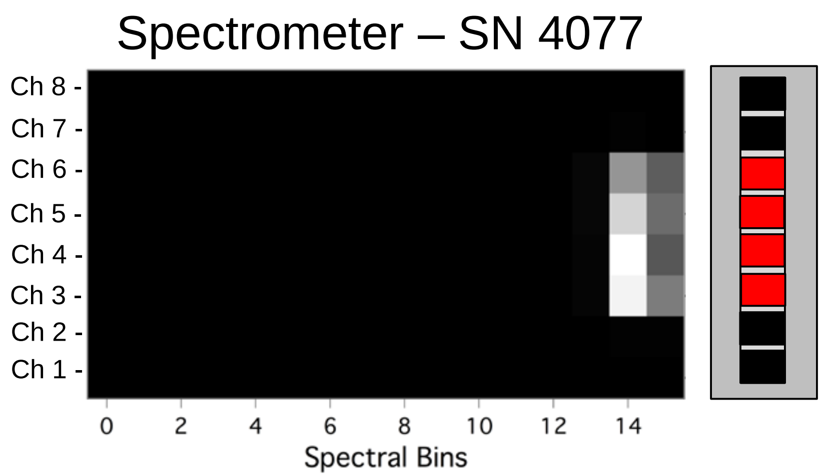
Rayleigh Scattering Confirms Beam Alignment and Spectrometer Calibrations

- Rayleigh scattering performed with ≥ 10 mTorr N_2
- Scattered signal maximized in data channels ~ 40,000 counts
- Stray light minimized in background channels ~ 5,000 counts
- ~ 2,000 counts of Johnson noise





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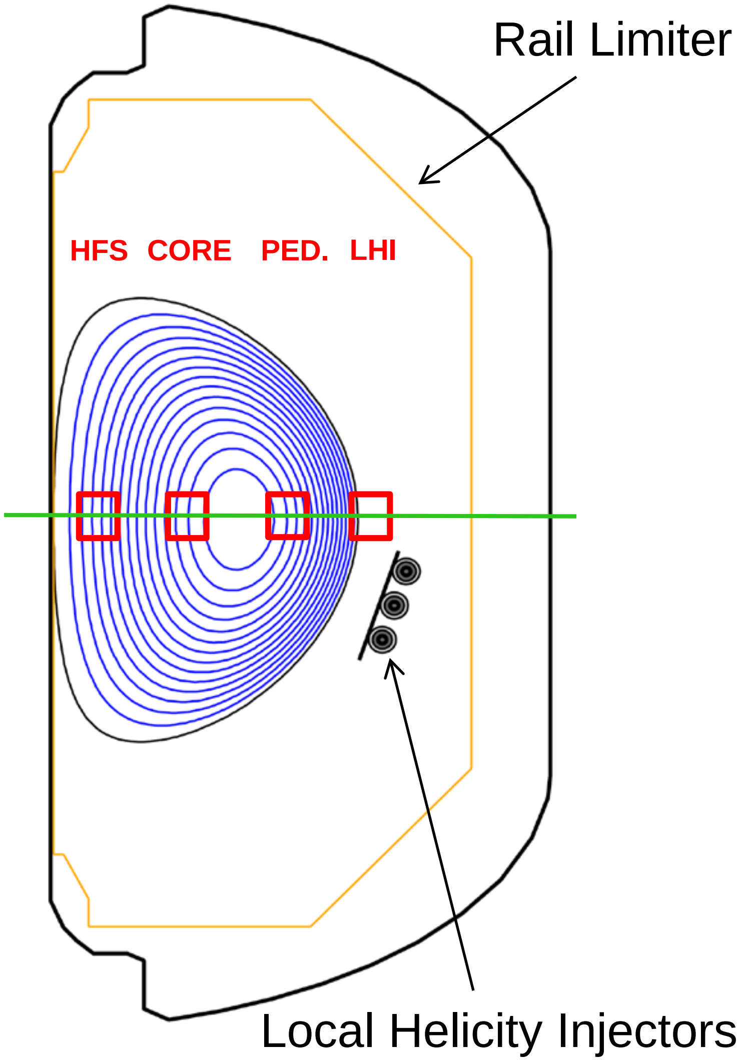
Two New Multichannel Spectrometers Allow Simultaneous Measurement of 12 Radial Positions

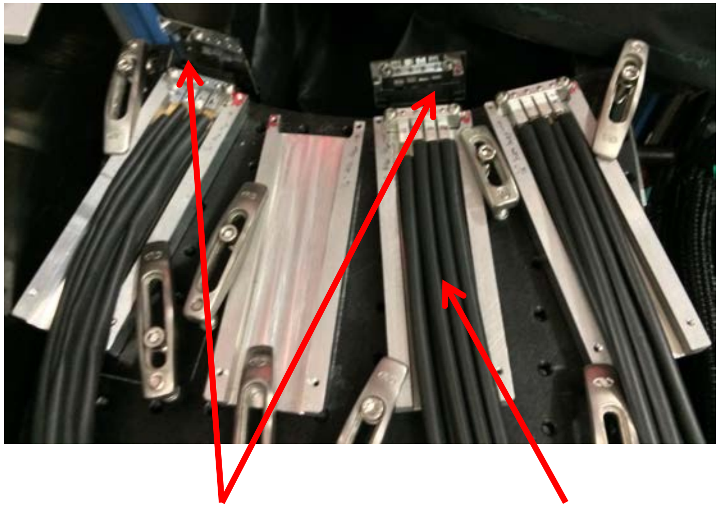
- Fiber optic mount has four sets of calibrated radial positions:
  - High Field Side (R~18.5-23.9 cm)
  - Core (R~35.0-41.1 cm)
  - "L-H Pedestal" (R~51.5-57.6 cm)
  - LHI Region (R~67.0-73.8 cm)

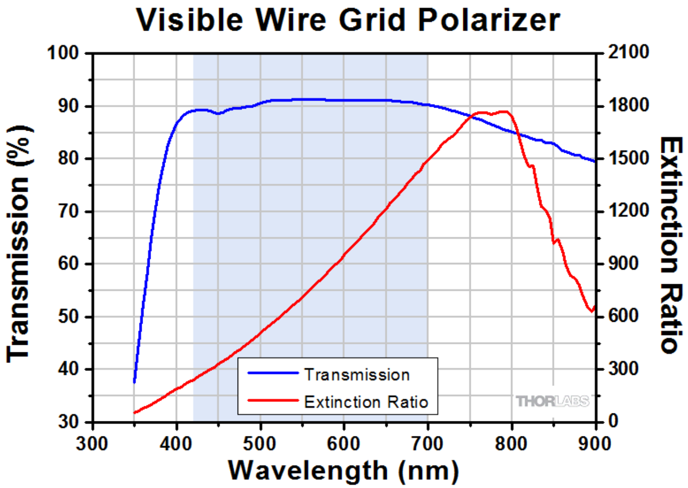
- Upgraded system provides simultaneous measurements of T_e profile $0 \leq R/a < 1.1$

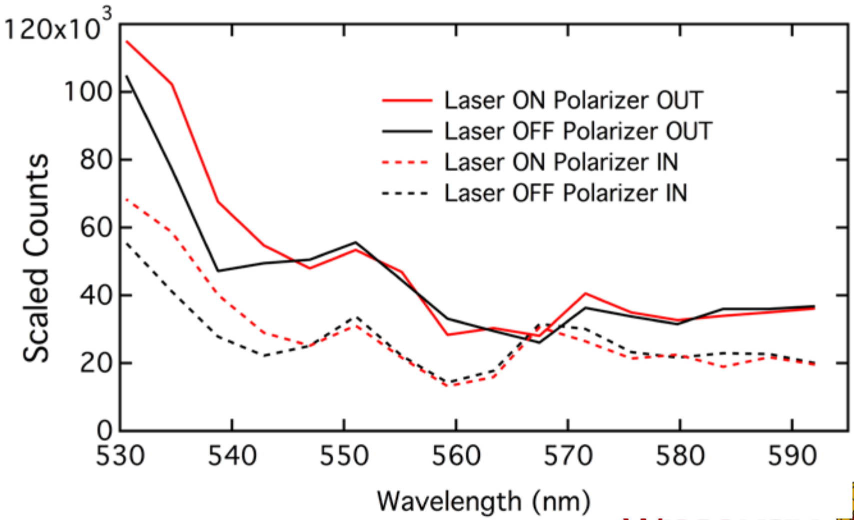


Wire Grid Polarizers Added to Collection Optics to Minimize Background Plasma Light

- Initial measurements: ~ 13,000 counts from plasma light
- Wire grid polarizers used to filter unpolarized background light
  - Scattered light maintains incident polarization
  - Polarizers have 90% transmission







https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=5510

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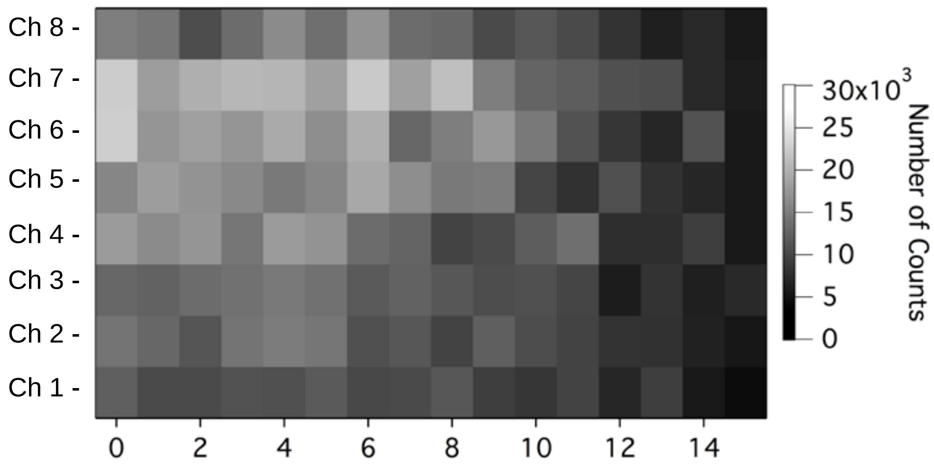
High Speed Shutter Needed to Prevent Light Leakage through ICCD Microchannel Plate

- Images taken with MCP off still observe counts



- Fast shutter will reduce background light observed after the collection window
  - TS Collection Window ~ 16 ns
  - Pegasus shot duration ~ 20-30 ms

Shutter Type	Rise Time	Transmission
LCD Shutter	500 us	~63%
Photo-elastic Modulator	50 us	~90%
Hard Disk Drive Shutter	500 ns	100%

- Implementing fast shutter with rise time ≤ 500 ns[1]

[1]Scholten, Rev. Sci. Instrum **78**, 026101 (2007)

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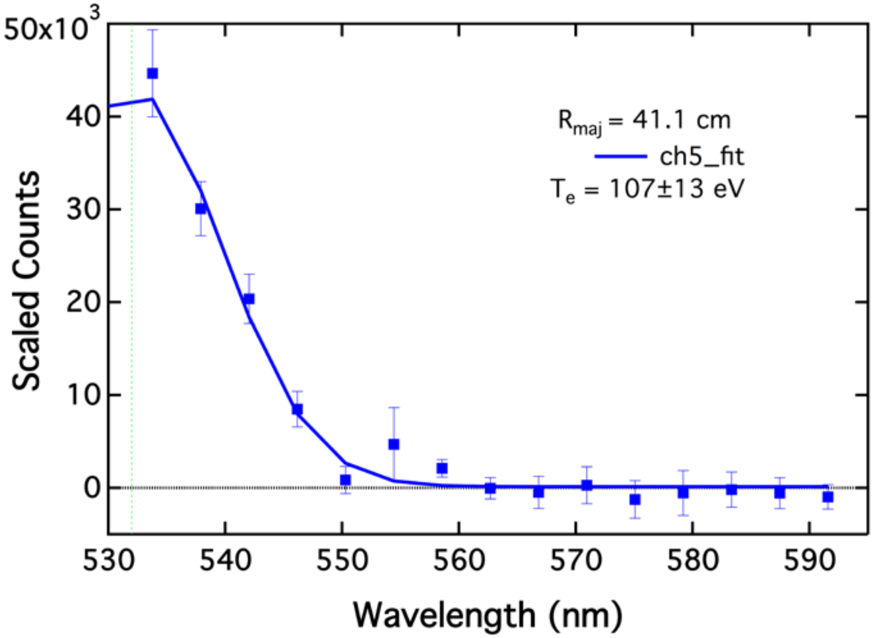
Improvements in System Calibrations have Produced Reliable T_e Measurements

- New system modifications and calibrations observe T_e (0) ~150 eV and $T_{e,\ edge}$ ~50 eV

- Data fits model Gaussian profile



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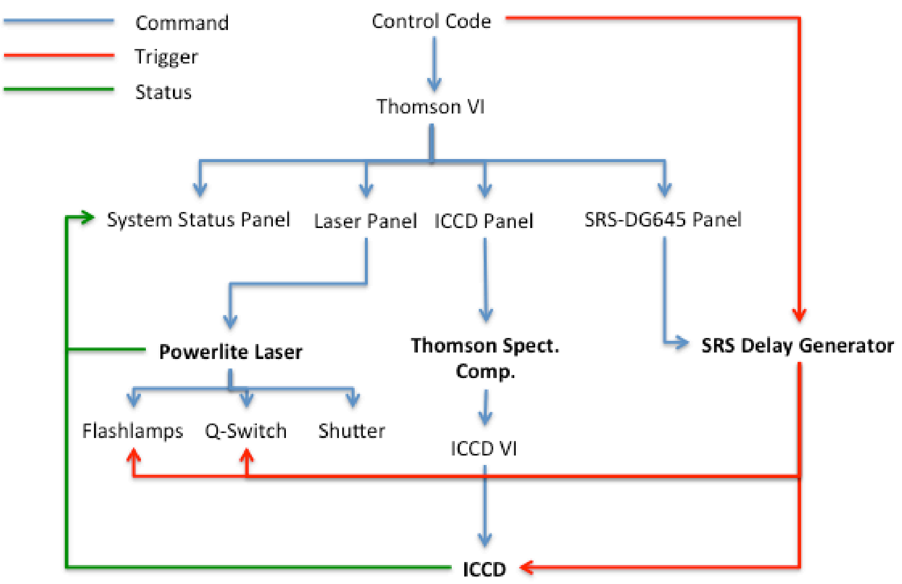
LabVIEW Programming Allows for Synchronized and Automated Data Collection

- LabVIEW used to interface Thomson components

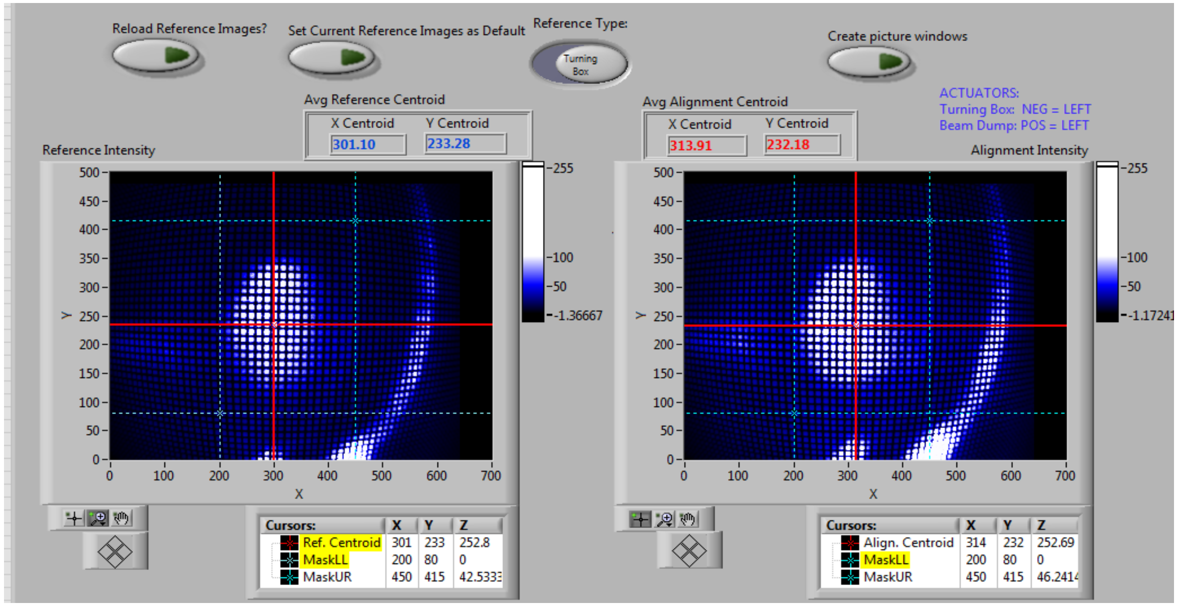
- Ethernet commands issued to arm laser and ICCD cameras
  - Operator only required to monitor state of the active laser



- Physical triggering of the laser components and the ICCD cameras via a Timing Sequence Module (TSM)
  - Delay generators store Thomson delay scheme

System Automation Extended to Intra-Shot Beam Alignment

- Networked cameras and turning mirror actuators remotely accessed using LabVIEW programming
- Image processing used to evaluate beam alignment
  - Alignment from Rayleigh scattering used as fiducial



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Modifications to Pegasus Thomson System Significantly Improve System Capability

- Addition of two multichannel spectrometer enables simultaneous measurement of 12 spatial positions
- Modifications to laser timing and addition of wire grid polarizers improves scattered signal to noise ratio
- Recalibrated detector set and system automation has improved diagnostic efficiency and reliability
- Future Work:
  - Implement fast shutter to prevent ICCD leakage
  - Integrate laser energy measurements, data analysis into automation process

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Work supported by US DOE Grant DE-FG02-96ER54375

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