Commissioning of Thomson Scattering on the Pegasus Toroidal Experiment

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PEGASUS Toroidal Experiment

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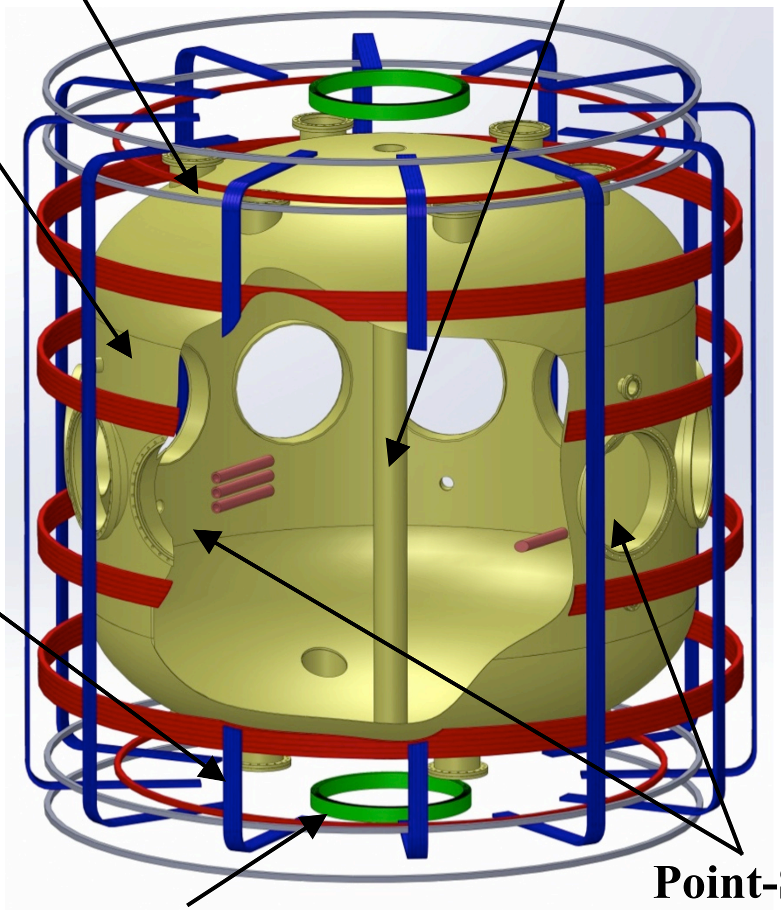
Abstract

- Multipoint Thomson scattering is implemented on the Pegasus Toroidal Experiment
  - Nd:YAG laser — *532 nm, 2 J, 7 ns FWHM, <3 mm dia.*
  - Volume Phase Holographic (VPH) diffraction gratings — *> 80% efficiency, 532-592nm, 2971 l/mm & 2072 l/mm*
  - Image-Intensified CCD (ICCD) cameras — *Gen III image intensifier, high Q.E., gate width > 2 ns*
- Diagnostic calibrations conducted and laser beam line optimized
  - Spectrometer calibrated (λ, intensity), system-wide alignment and timing calibration completed
  - Laser beam line alignment cameras installed
- Stray light mitigation systems installed and enable Rayleigh and Thomson scattering data
  - 4 apertures, 2 louver-type baffles installed in-vessel
  - Beam exit moved farther from collection region
- First measurements made for H-mode plasmas on Pegasus

Pegasus is a compact ultralow-A ST



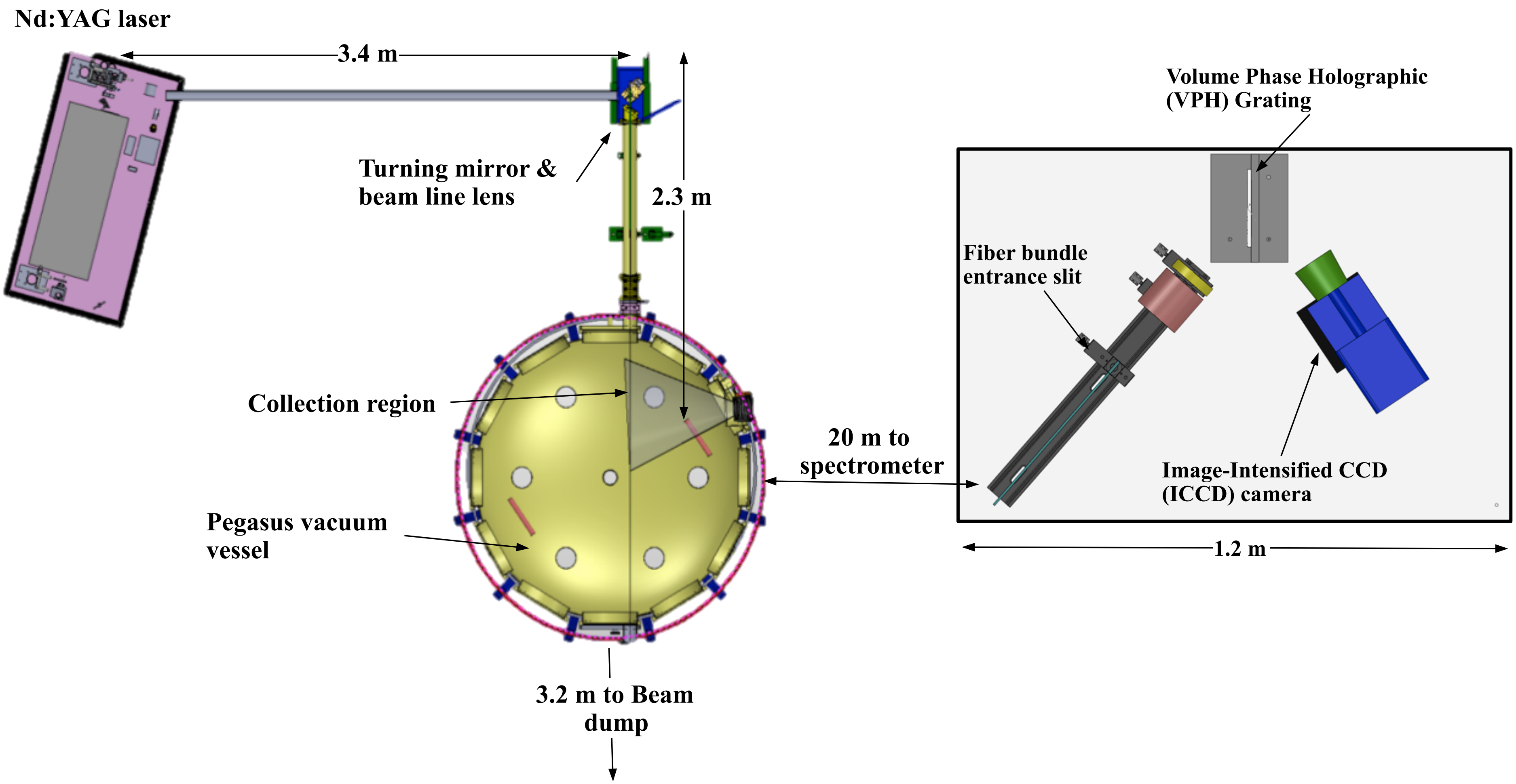
Experimental Parameters

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)	$\leq$ .21	$\leq$ 0.30
I_N (MA/m-T)	6 – 12	6 – 20
RB_t (T-m)	$\leq$ 0.06	$\leq$ 0.1
κ	1.4 – 3.7	1.4 – 3.7
τ_{shot} (s)	$\leq$ 0.025	$\leq$ 0.05
β_t (%)	$\leq$ 25	> 40
P_{HHFW} (MW)	0.2	1.0

Major research thrusts include:

- *Non-inductive startup and sustainment*
- *Tokamak physics in small aspect ratio:*
  - *High-I_N, high-β operating regimes*
  - *ELM-like edge MHD activity*

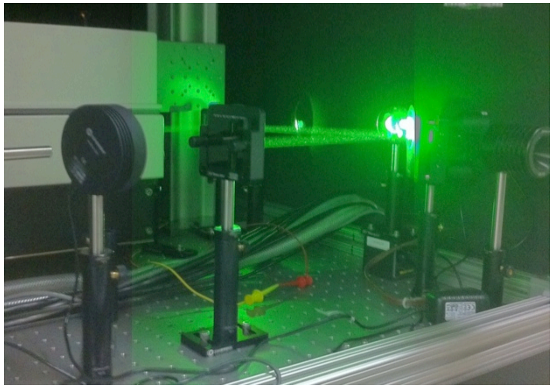
Pegasus Thomson scattering uses Nd:YAG laser, VPH gratings, and ICCD



Laser specifications balanced between commercial availability and physics needs

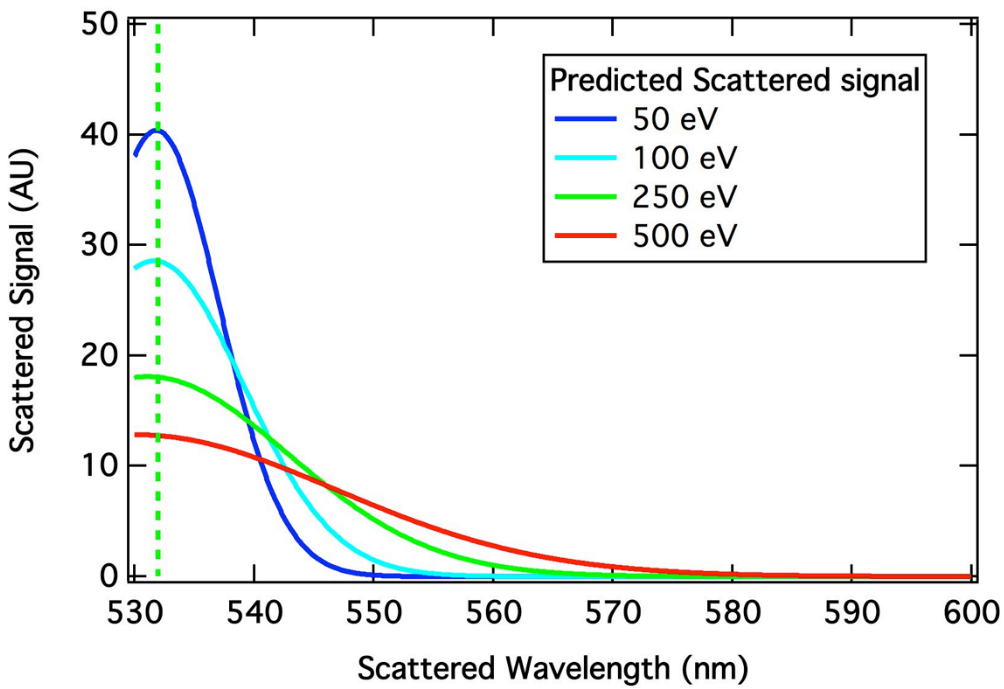
Specification	Value	Determining factors
Output Energy	≥ 2000 mJ	Scattered intensity fraction
Divergence	≤ 0.5 mrad	Desired spatial resolution, component damage thresholds
Pointing stability	≤ 50 μrad	Beam line
Pulse length	≥ 10 ns	Availability at desired power
Repetition Rate	≥ 10 Hz	Shot duration; availability
Jitter	≤ 500 ps	Time resolution
Beam diameter	8 – 15 mm	Availability
Polarization ratio	≥ 90%	Scattering dependence
Energy stability	± 2 %	Availability; repeatability; Intensity resolution

- Identify tolerable limits due to physics needs and layout constraints
- Reliable, "turn-key" operation of laser required
  - Nd:YAG used extensively for MPTS in plasmas
  - Operate flash lamps at steady 10 Hz to obtain maximum stability
- Operation in the visible eases alignment and safety issues



Spectral range 532 – 592 nm for Pegasus operating scenarios

- 10 eV < T_e < 500 eV for Pegasus plasmas
- Use high dispersion VPH grating for low temperatures:
  - 532 nm < $\lambda_{scatter}$ < 562 nm
- Use low dispersion VPH grating for high temperatures:
  - 532 nm < $\lambda_{scatter}$ < 592 nm

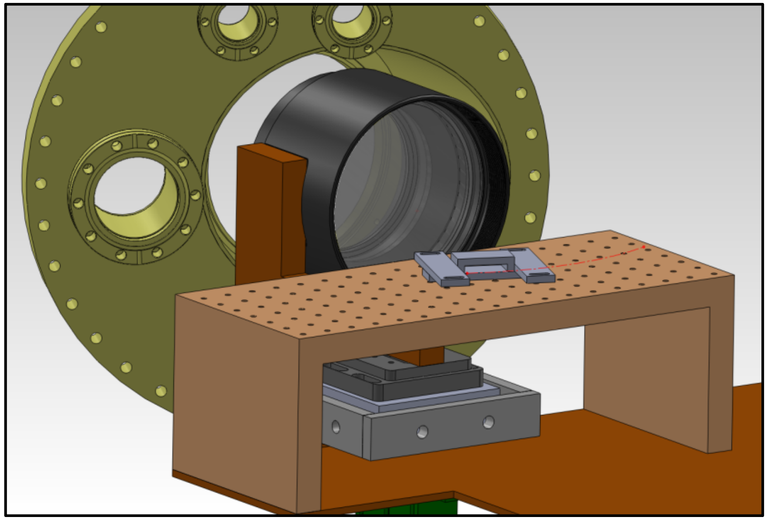


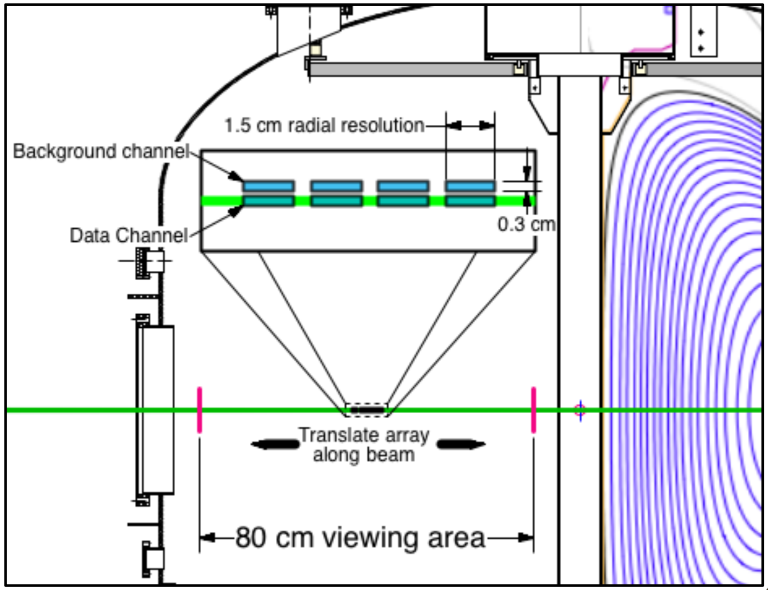
Based on: A.C. Selden, *"Simple Analytic Form of the Relativistic Thomson Scattering Spectrum,"* Phys. Lett. **79A**, 5,6 1980.

- Signal levels dictate λ bin sizes of 4 nm and 8 nm in the low and high temperature cases, respectively

Custom collection optics allow flexible channel configurations

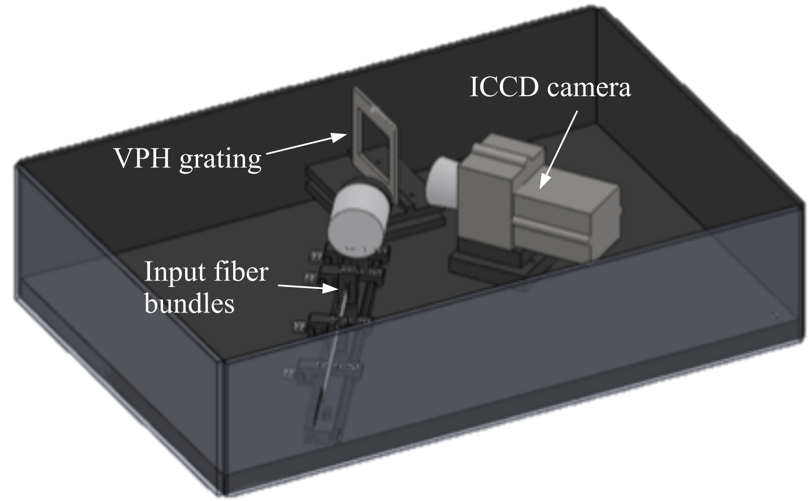
- Individual channels correspond to close-packed fiber bundles
  - Viewing volumes 1.5 cm x 0.3 cm
  - Roughly 194, 210 μm dia. fibers per bundle
- Initially, 4 data channels and 4 background monitors
  - Evaluate performance & plasma conditions and reconfigure as needed
- Scan array radially from shot-to-shot
  - Smoothly variable positioning along major radius
  - Channels can be positioned as single array or separately along viewing region

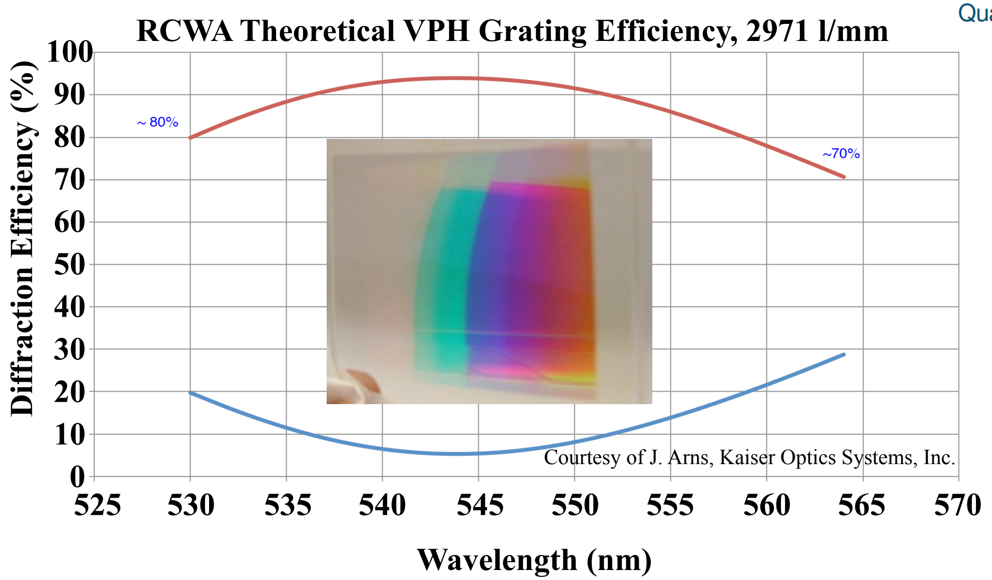




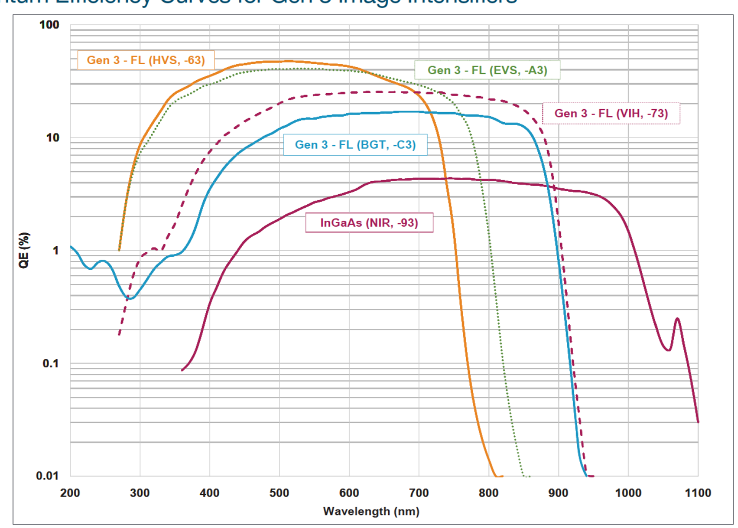
Spectrometers employ VPH gratings and ICCD cameras

- Custom achromatic entrance lens
- Kinematic mount provides easy interchange of gratings with different dispersions
- Image Intensified CCD (ICCD) detector
  - High quantum efficiency Gen 3 Intensifier
  - Fast gating capability down to 1.2 ns





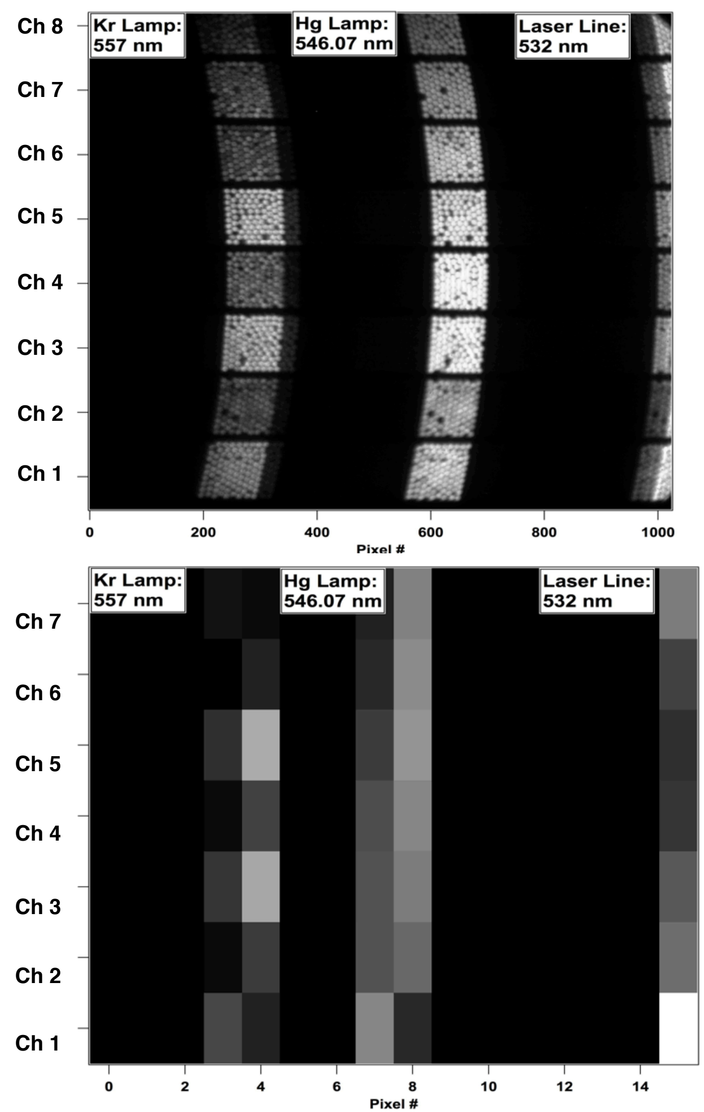
Quantum Efficiency Curves for Gen 3 Image Intensifiers



On-CCD binning used to increase signal-to-readout-noise ratio

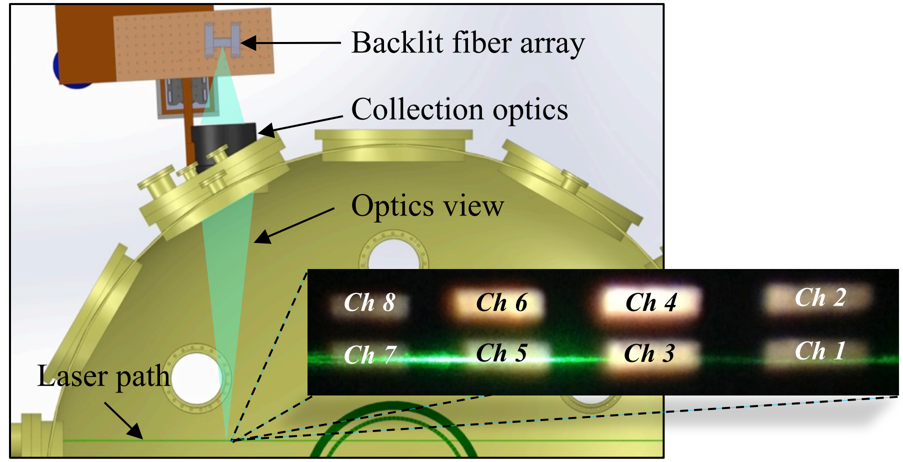
- Binning is customized to match image positions of 8 spatial channels
  - Spatial location maps vertically on detector
  - Wavelength increases right-to-left on detector
  - Provides 16 spectral bins

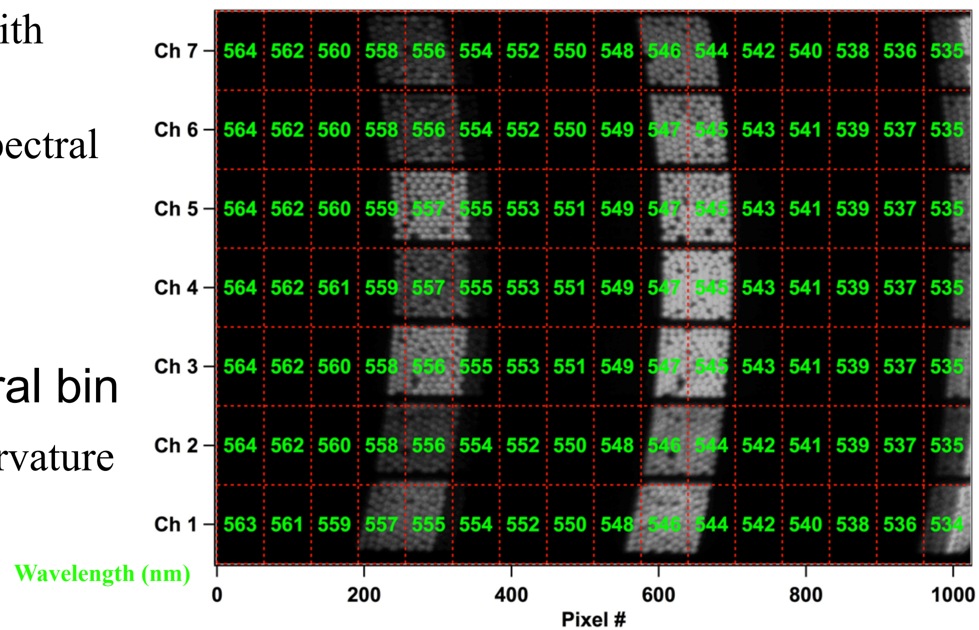
- Binning prior to readout boosts SNR
  - CCDs are 1024 x 1024 pixels
  - Read noise ~ 8 e- / read event
  - Bin 133 pix V x 64 pix H to obtain photon noise dominated statistics for typical plasma densities



Spatial and spectral calibrations of collection system conducted

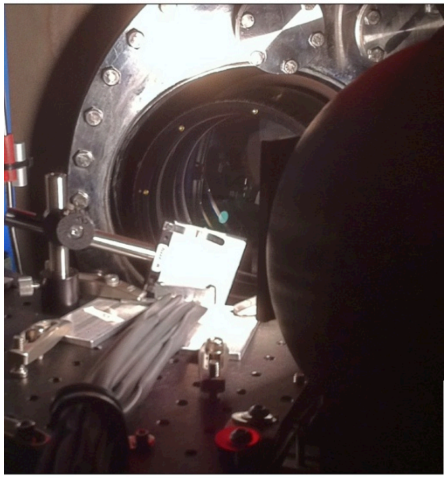
- Spatial calibration maps fiber array location to major radius
  - Backlight fibers at collection optics
  - Measure image location in-vessel
- Spectral calibration maps wavelength location across detector
  - Use emission-line calibration lamps with known wavelengths
  - Use full-frame readout to maximize spectral resolution
- Software-bin to calculate central wavelength for each on-chip spectral bin
  - Slight variation due to entrance slit curvature

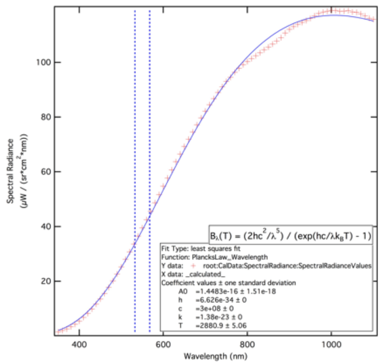


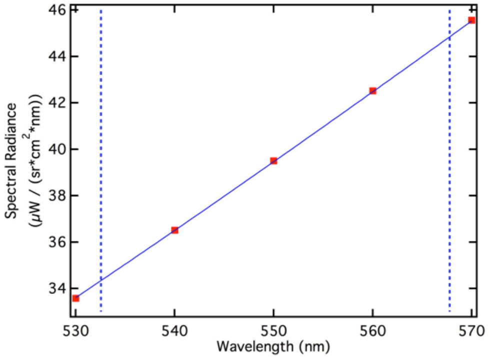


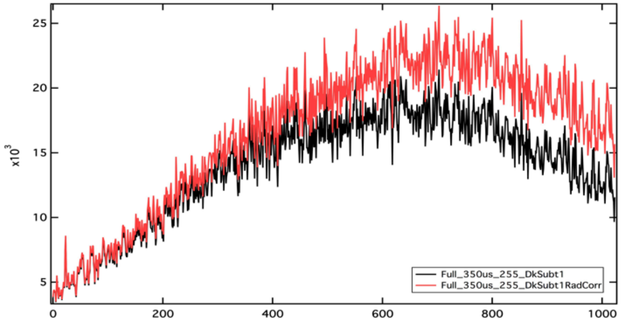
Relative intensity calibration conducted

- Calibrated source used
  - Black-body curve fit to calibrated intensity values
- Wavelength range of interest fit
- Calibration intensity >> Thomson signal
  - Increase signal-to-noise ratio
  - Necessitates full-frame, lower gain settings to avoid detector saturation



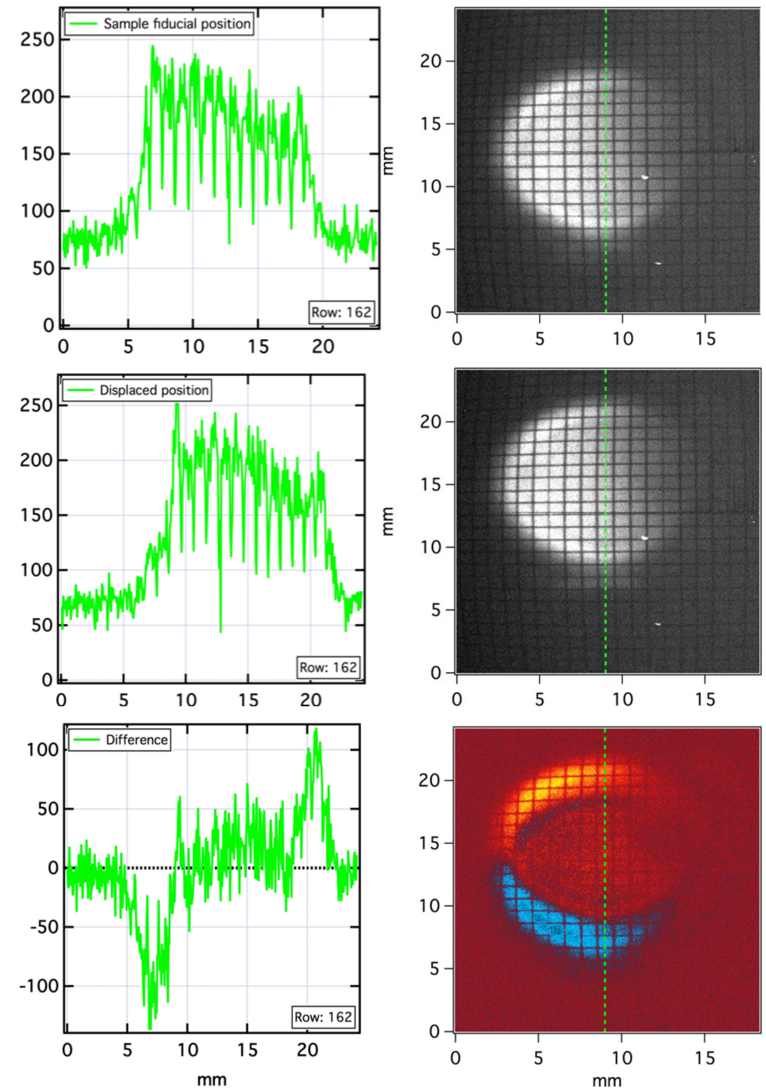


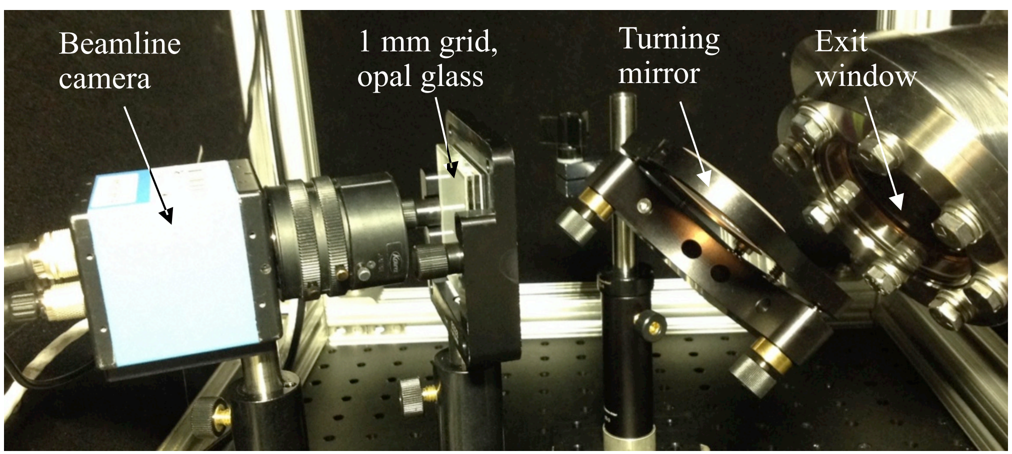




Beamline cameras provide inter-shot alignment

- Externally-triggered CCD cameras placed behind turning mirrors at Brewster windows
- Small laser percentage transmitted through mirror onto 1 mm transparent grid
- Diffused spot captured by camera
  - Lensing provides ~55 um spatial resolution (18 pix / mm)
- Difference between “fiducial” image and shot image provides alignment correction



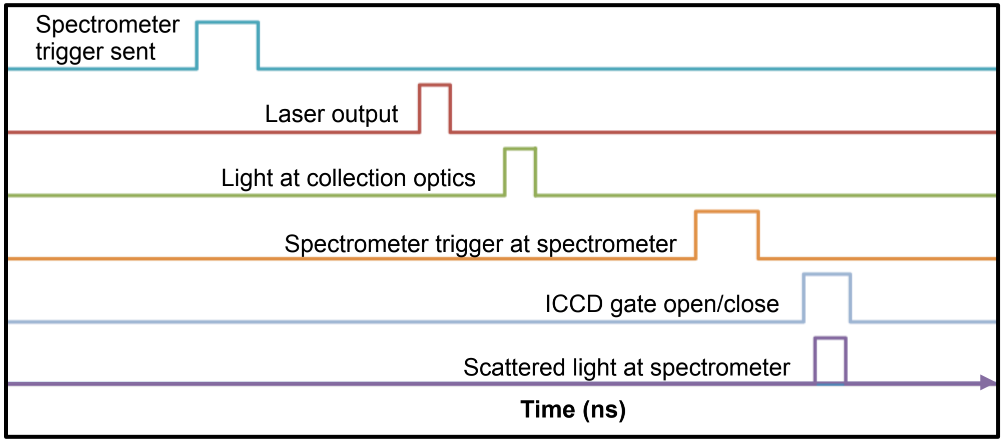


System timing fine-tuned to ensure optimal signal collection

- ICCD provides single time point per plasma
  - Not a continuous time record like GHz digitizers
  - Careful accounting of system delays necessary

- Electronics and optical delays measured when possible
  - Coaxial cable = 161 ns
  - Fiber optics = 100 ns
  - Internal electronics delays as specified

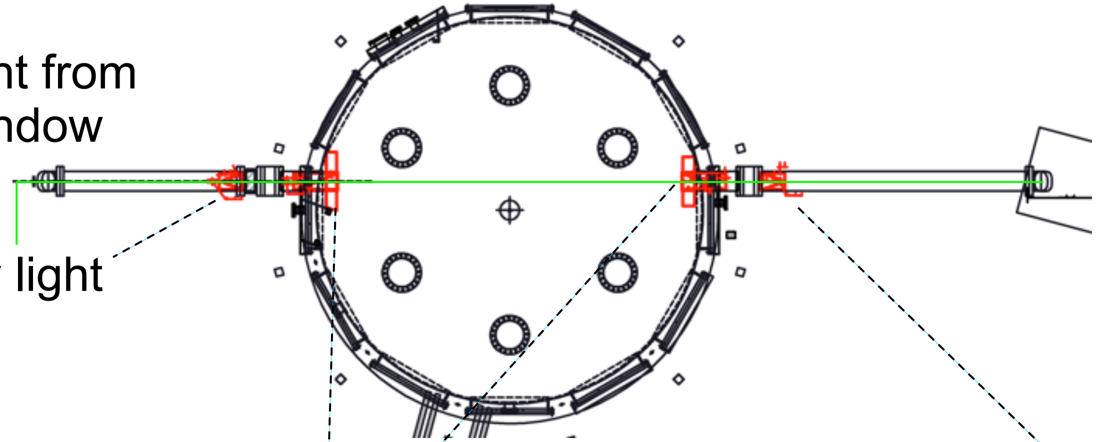
- ICCD gate width a balance
  - Minimum set by scattered signal width
  - Maximum set by reducing background plasma light collected

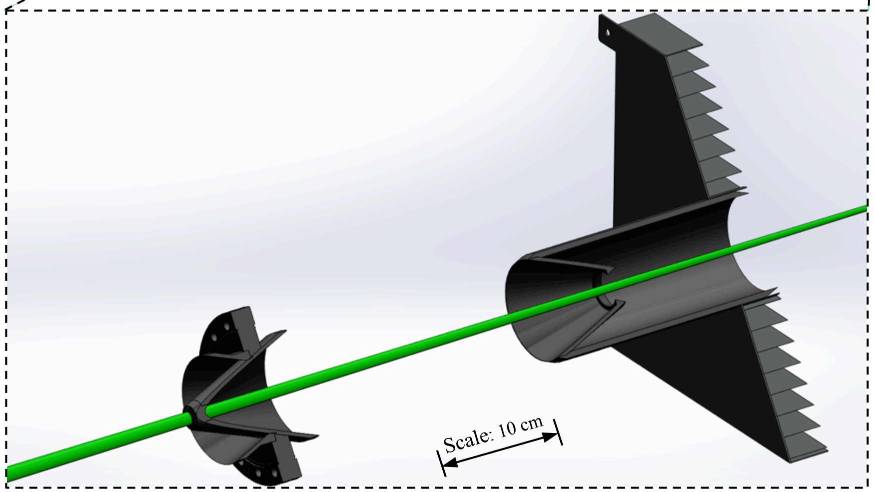


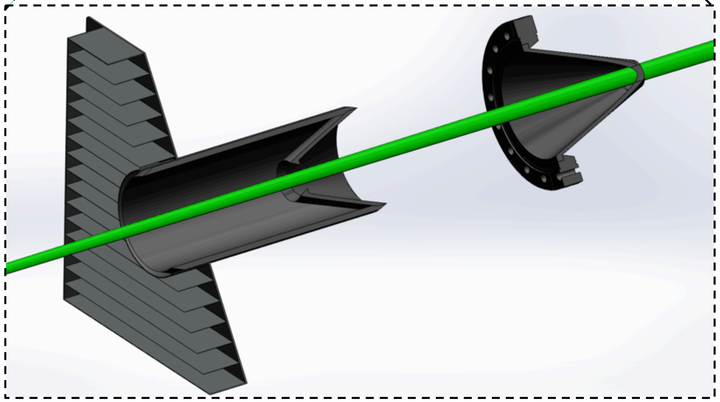
Signal Name	Delay		Start Time (ns)
	Value (ns)	Description	
Pegasus master trigger			0
Delay generator	85	Internal electronics	85
Flash lamps	0		85
Q-switch	240762	Lamp output	240847
Laser output	590	Internal laser	241437
Scattered light at coll. optics	27.35	Light speed (air)	241464.35
Scattered light at spectrometer	100	Light speed (quartz)	**241564.35**
Spectrometer trigger sent	518	Manually set	241365
Trigger at spectrometer	161	Coax. cable	241526
ICCD Gate Open	35	Internal electronics	**241561**
ICCD Gate Close	15	Manually set	**241576**

Beam line apertures designed for stray light mitigation

- "Critical" apertures block stray light from laser passing through vacuum window
- "Subcritical" apertures block stray light scattered from critical apertures
- Baffles block stray light scattered from subcritical apertures

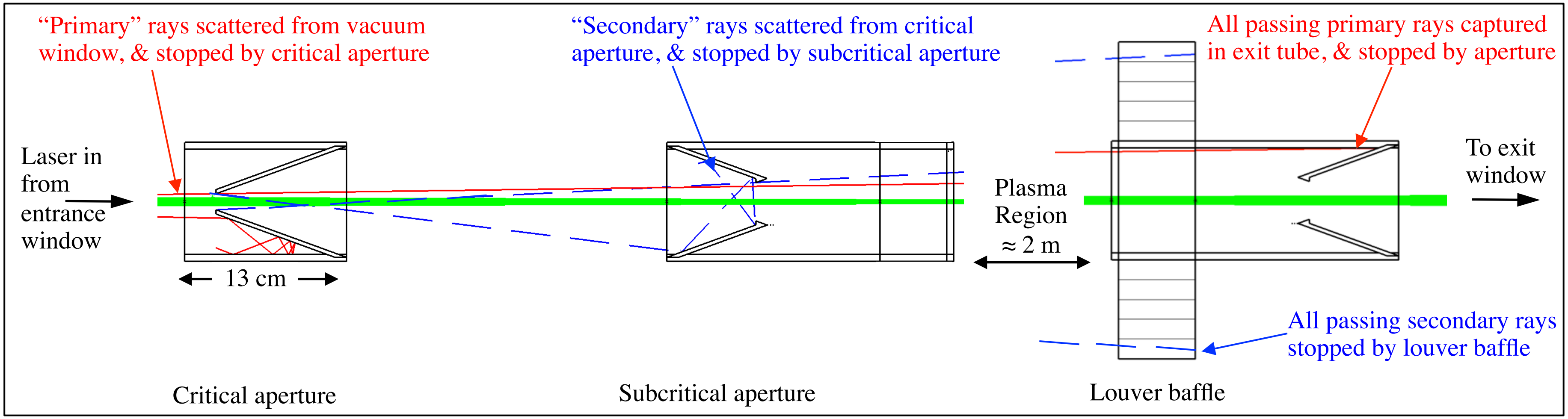






***Based on implementations by:*
C.J. Barth, et al. Rev. Sci. Instrum. ***82****, 3380 (1997)*
J.P. Levesque, et al., Rev Sci. Instrum. ***82****, 033501 (2011)*

Ray tracing provides optimum location and diameters for aperture systems



- Given:
  1. 3 mm radial clearance between focused laser beam and critical aperture knife edge
  2. 3 mm radial clearance between primary light cone and subcritical aperture knife edge
- Optimize:
  1. Locate critical aperture such that primary light cone falls within exit tube
  2. Locate subcritical aperture to minimize diameter of secondary light cone on opposite wall
- Design louver baffle large enough to capture secondary light cone

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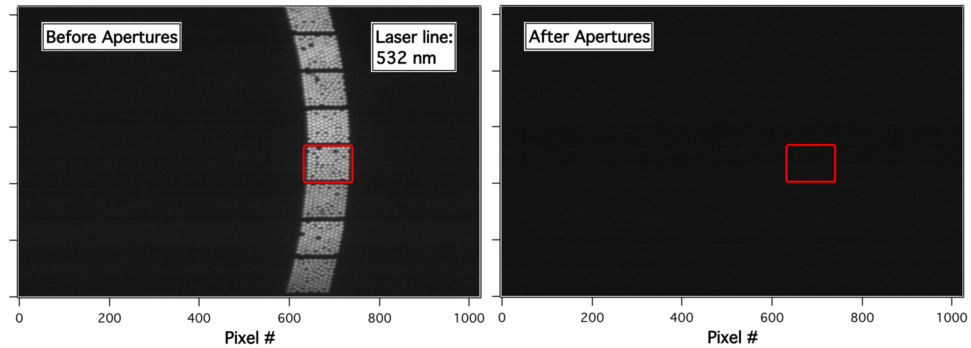
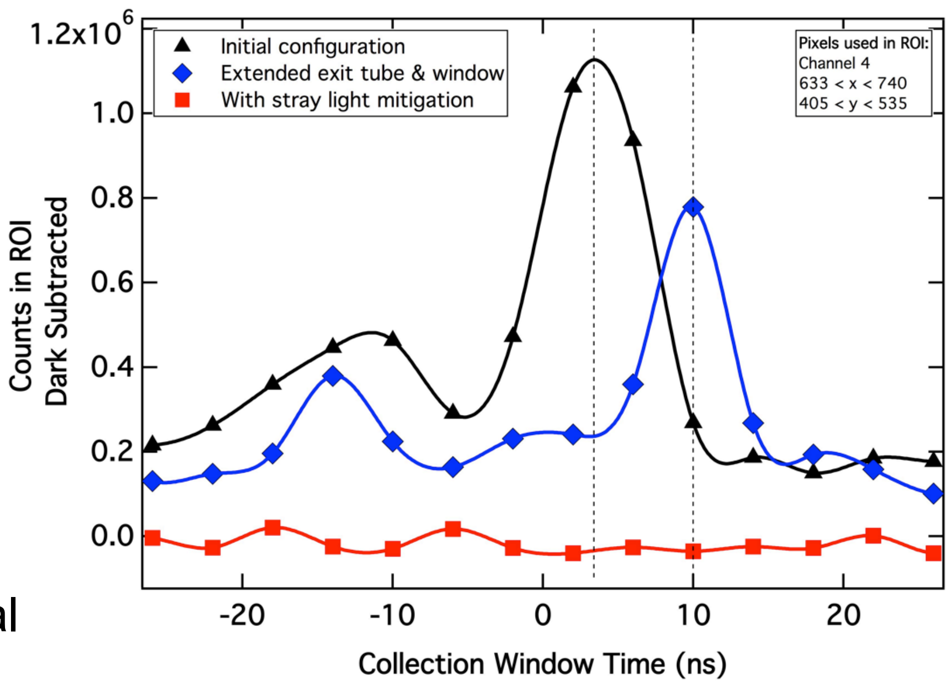
Mitigation system effectively reduces stray light

- Spectrometer tuned to measure stray light
  - Initial stray light readily measured using non-binned readout
  - Intensity quantified by summing counts within region of interest *(boxed in red)*
  - After mitigation system installed, no significant signal in non-binned readout



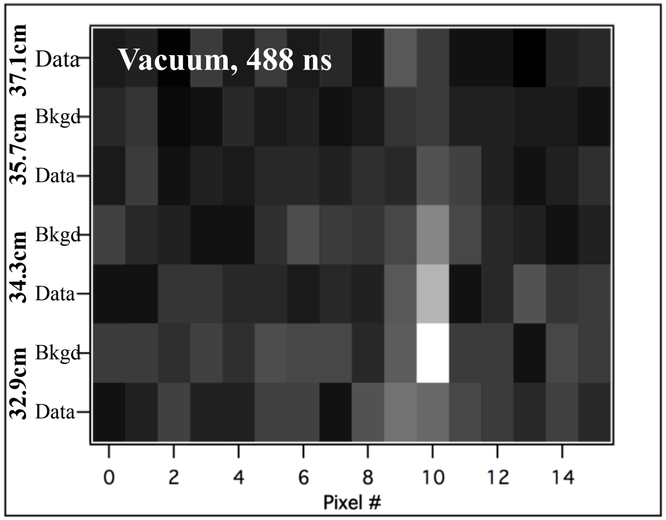
- Collection time window scanned for each step in mitigation process
  - Sources of stray light identified by change in times of peak stray signal
  - 1.5 m extension on exit window = 7 ns delay in peak time

- Stray light levels reduced below noise threshold for Thomson scattered signal

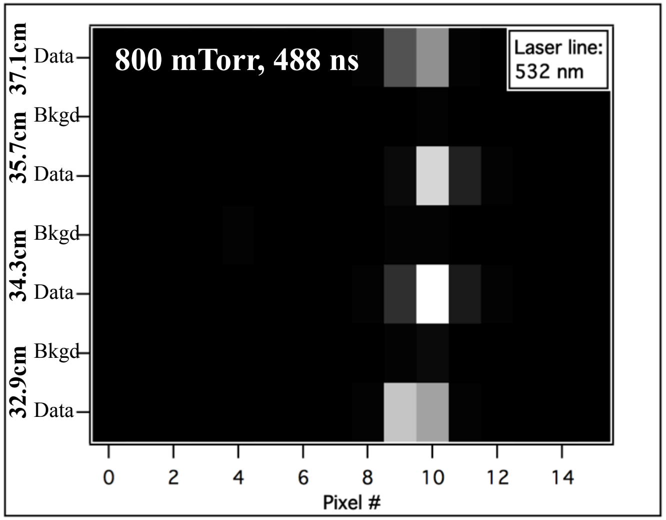


Rayleigh scattering used for system calibration

- First, stray light characterized in vacuum
  - Data used for background subtraction of scattering data
  - With detector settings used for plasma ops (binned readout, high gain) stray signal still negligible
  - No clear distinction between data and background channels



- Then, N_2 introduced for Rayleigh scattering
  - For scattering conditions, clear distinction between data and background channels



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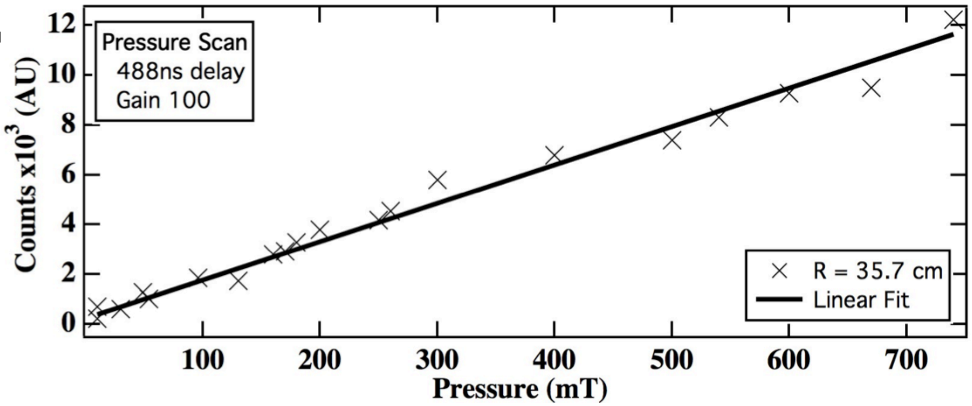

Optimum collection time verified using Rayleigh scattered signal

- ICCD provides single collection time window
  - Variable window start time, picosecond accuracy
  - Variable window width, 2 ns minimum
- During Rayleigh calibration, window start time scanned
- Once time of scattering found, window width reduced and fine time scan conducted.
- Time scan repeated at several pressures of N_2
- Optimum time 488 ns after Q-switch
  - This is the delay time between Q-switch trigger and *sending* the spectrometer trigger

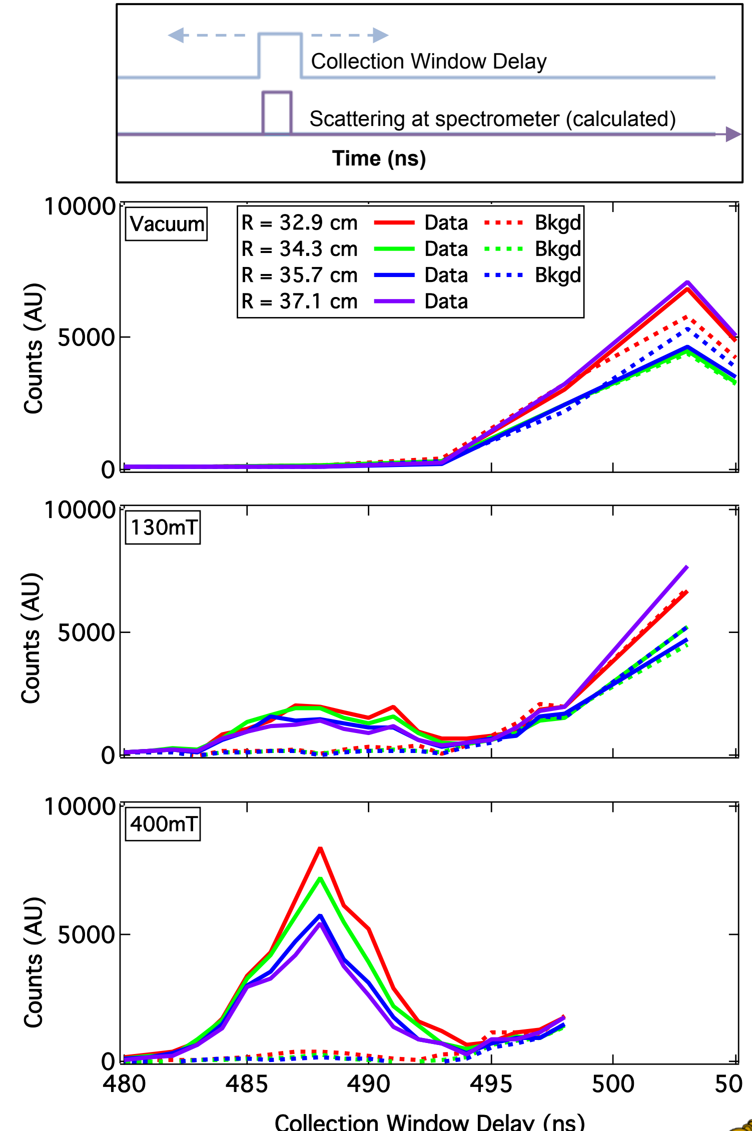

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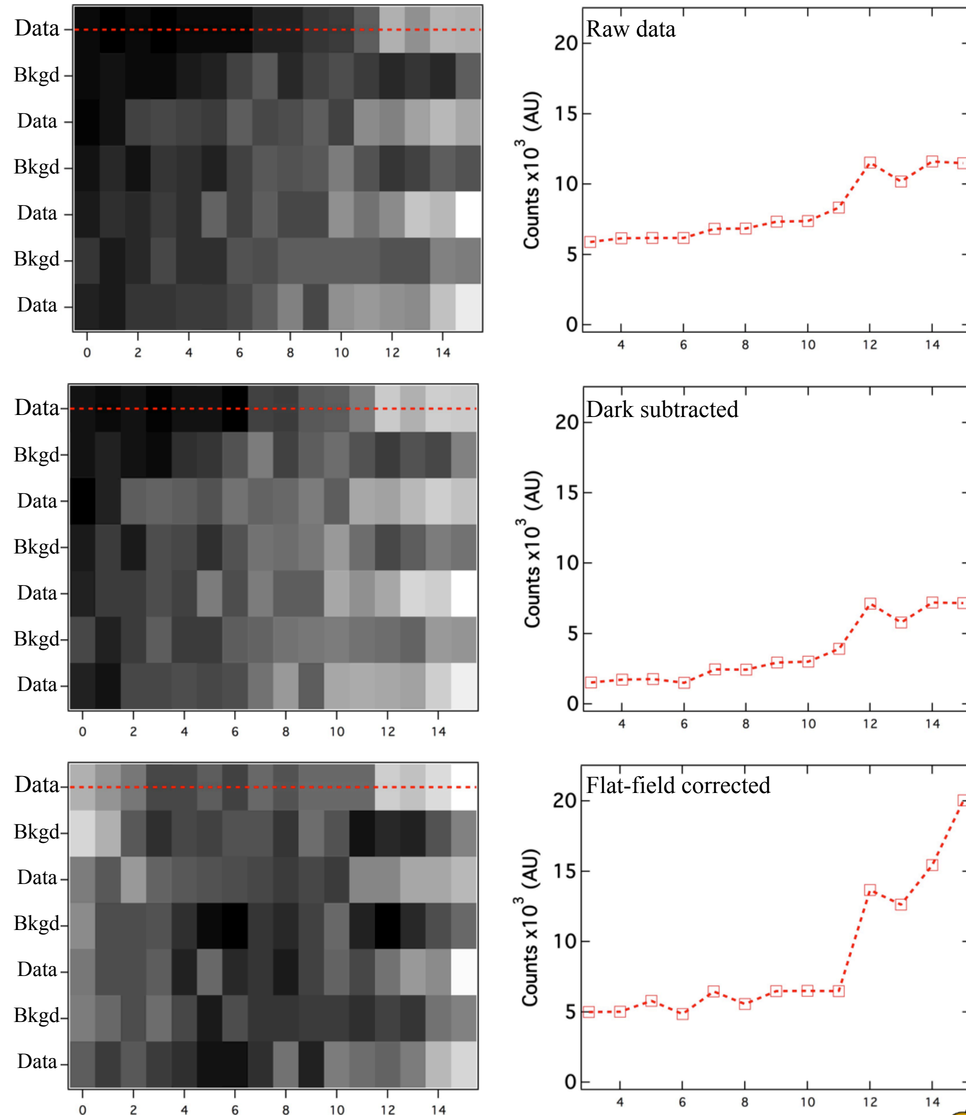
Image processing for plasma data in development

- Single image for each plasma shot
  - Each image contains 8 spatial channels (4 on-laser, 4 background)
- Subtract a dark image from plasma image to remove fixed pattern noise & offsets
  - Hot pixels
  - Camera background count offset
- Correct for flat field effects
  - Differing efficiencies vs. wavelength
  - Optical vignetting



D.J. Schlossberg, 55th Meeting of the APS Division of Plasma Physics, Denver, CO, Nov.11-15, 2013

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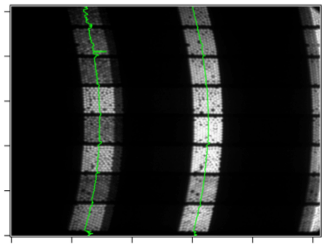
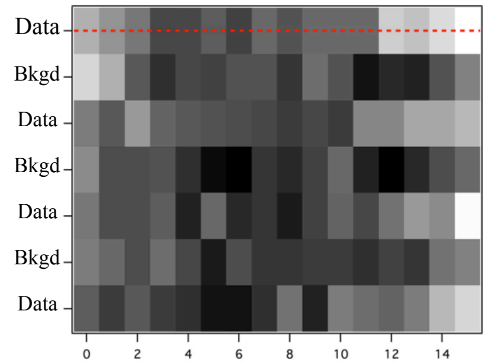
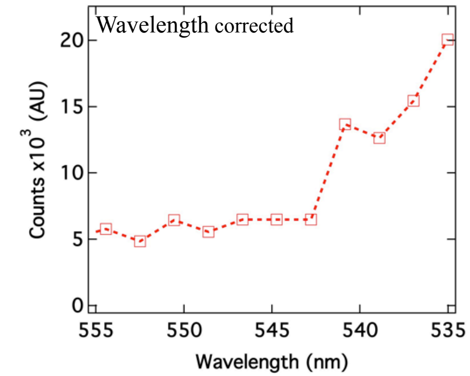
Initial analysis applies Gaussian fits

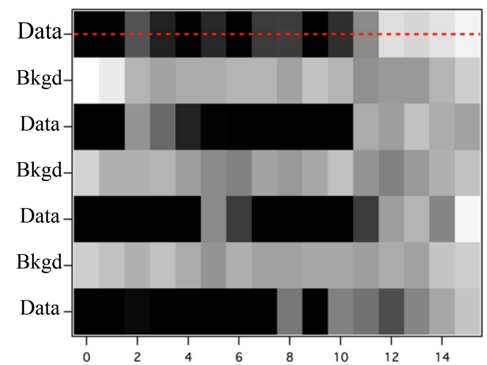
- Correct λ mapping for slit curvature
  - Use previous calibration with emission line lamps

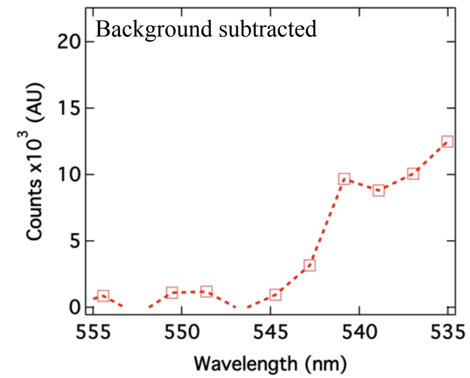




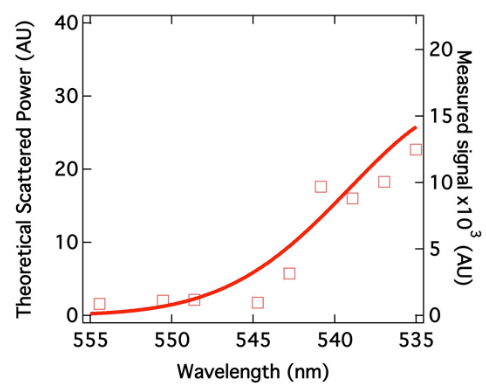


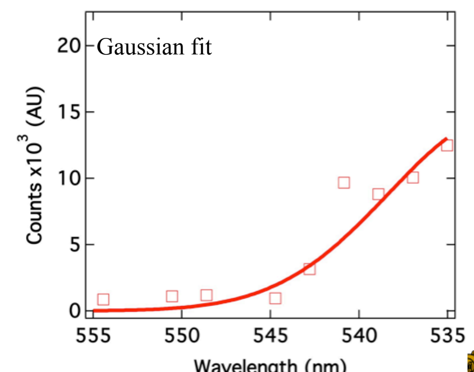
- Subtract background channels from data channels





- Non-relativistic fit to Gaussian
- Relativistic fit using Selden's formulation
- More refined fitting in development



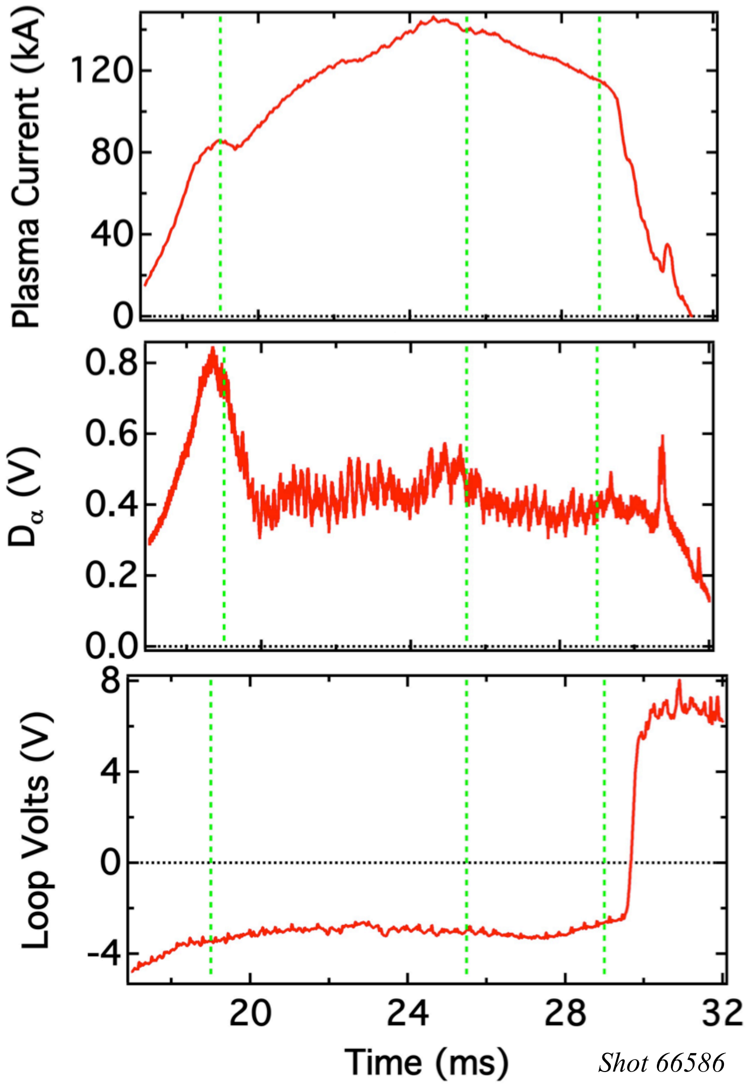


First results obtained for 130 kA OH discharges

- First Thomson data on Pegasus collected for several OH plasmas
  - Typically I_p = 130 kA, B_T = 0.1 T, τ_{shot} ~ 20 ms

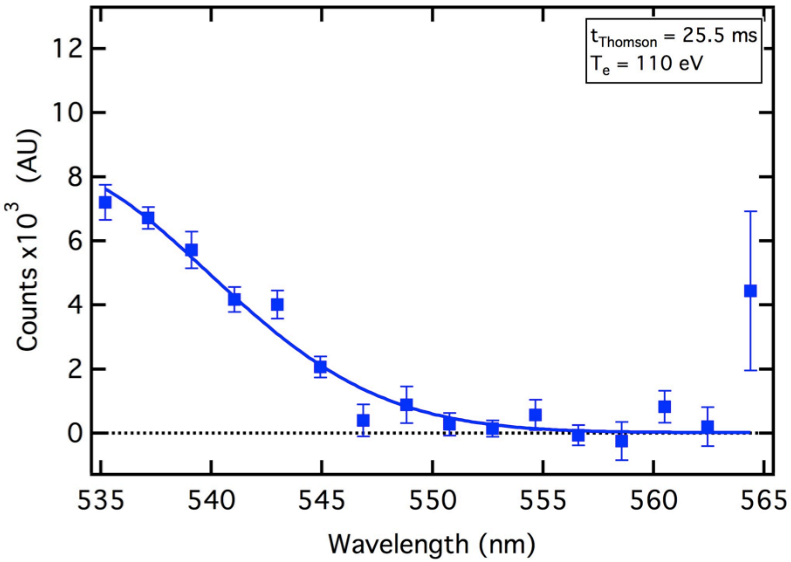
- Time of Thomson collection window scanned from shot-to-shot
  - Early phase
  - Mid-phase *(dashed green line)*
  - Late phase

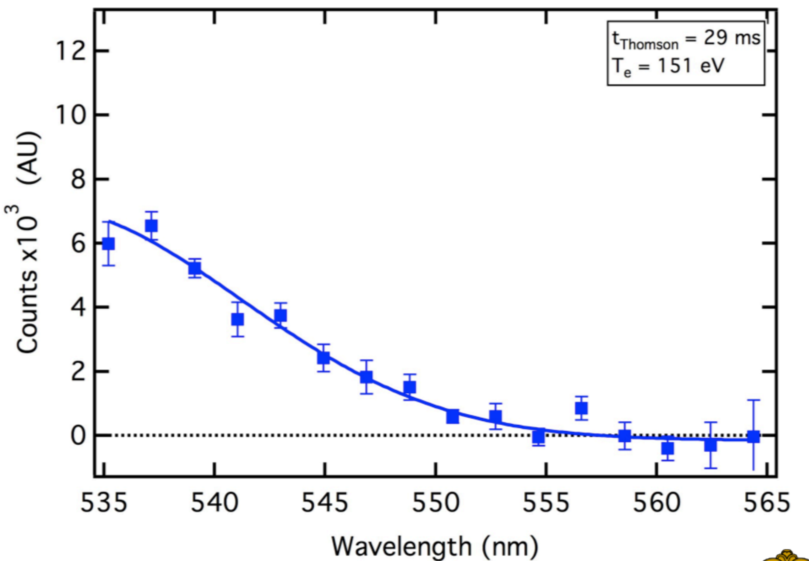
- Future directions:
  - Temperatures will be compared at these three times
  - Compare signal magnitudes with microwave interferometry densities



Preliminary data analysis conducted for several plasmas

- Position of 8-channel array spanned 32.9 cm < R_{maj} < 37.1 cm
  - 4 data channels
  - 4 background channels
- For initial analysis:
  - $t_{Thomson}$ = 25.5 ms, 29 ms
  - Spectral resolution $\Delta\lambda \approx 3$ nm
  - Due to ICCD camera software, binning restricted data collection to 7 spatial locations
- Data averaged over spatial points and multiple shots, then Gaussian fits applied
  - $T_e \approx 110\text{-}150$ eV
  - More refinement of analysis planned





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Summary

- A novel Thomson scattering diagnostic was implemented on the Pegasus Toroidal Experiment
- Stray light was successfully mitigated by beam line apertures and baffles, and by increasing exit tube length
- Overall system timing has been verified and optimized
- Relative Rayleigh scattering calibration completed
- First plasma signal measured
- Future directions include more refined analysis, installation of additional spatial channels, and investigation of non-solenoidal startup discharges

Reprints available at: http://pegasus.ep.wisc.edu/Technical_Reports/APS_DPP.html#APS13