Thomson Scattering measurements During Local Helicity Injection in the Pegasus Toroidal Experiment

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PEGASUS Toroidal Experiment

Thomson Scattering Diagnostic System Used to Evaluate T_e and n_e During Local Helicity Injection

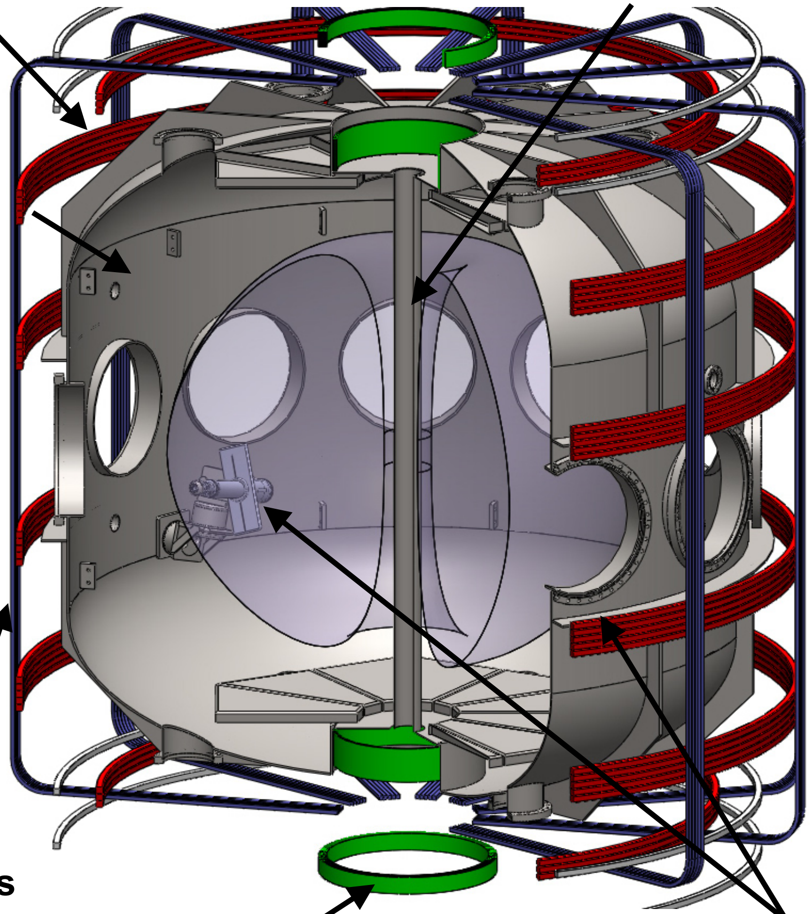
- Collection of T_e and n_e profiles is a critical plasma measurement
  - Equilibrium/Stability
  - Transport and confinement

- Three spectrometers provide 24 possible spatial locations

- Synchronized and automated system operation
  - Intra-shot beam alignment capability

- T_e and n_e profiles have been collected for multiple injector geometries

Pegasus is a Compact Ultralow-A ST



Experimental Parameters

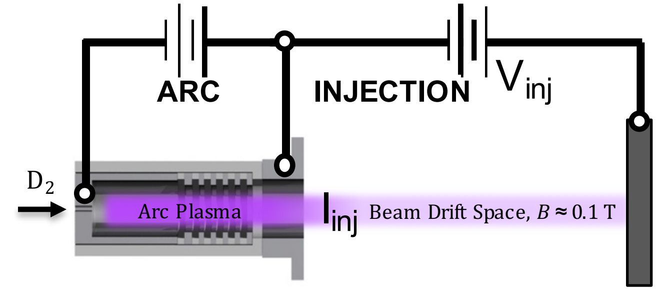
Parameter	Achieved
A	1.15 – 1.3
R(m)	0.2 – 0.45
I_p (MA)	≤ .21
κ	1.4 – 3.7
τ_{shot} (s)	≤ 0.025
β_t (%)	≤ 100

Major research thrusts include:

- *Non-inductive startup*
- *Plasma stability at A~1*

Confinement During Non-Inductive LHI Startup Critcially Depends on T_e

- Local Helicity Injection (LHI) creates tokamak plasmas with high power edge current injection
- Physics encapsulated in hierarchy of models:



E.T. Hinson *et al.* *Physics of Plasmas* **23** (2016), 052515

1. Maximum I_p Limits[(1)]:

Taylor Relaxation

$$I_p \le I_{TL} \sim \left(\frac{I_{TF} I_{inj}}{w}\right)^{1/2}$$

Helicity Conservation

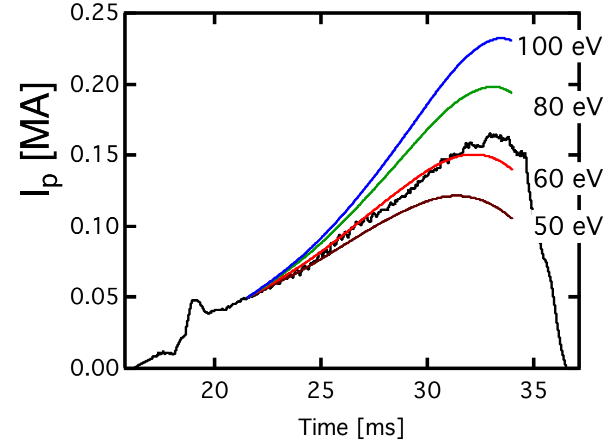
$$I_p \le \frac{A_p}{2\pi R_0 \langle \eta \rangle}\left(\frac{A_{inj} B_{\phi,inj}}{\Psi} V_{inj} + V_{IND}\right)$$

2. 0-D Power Balance Model for $I_p(t)$:

$$I_p[V_{LHI} - V_{IR} + V_{IND}] = 0 \;;\; I_p \le I_{TL}$$

3. 3D Resistive MHD (NIMROD)

T_e dependent terms



(1)D.J. Battaglia, et al. *Nucl. Fusion* **51** (2011) 073029.
N.W. Eidietis, Ph.D. Thesis, UW-Madison, 2007.

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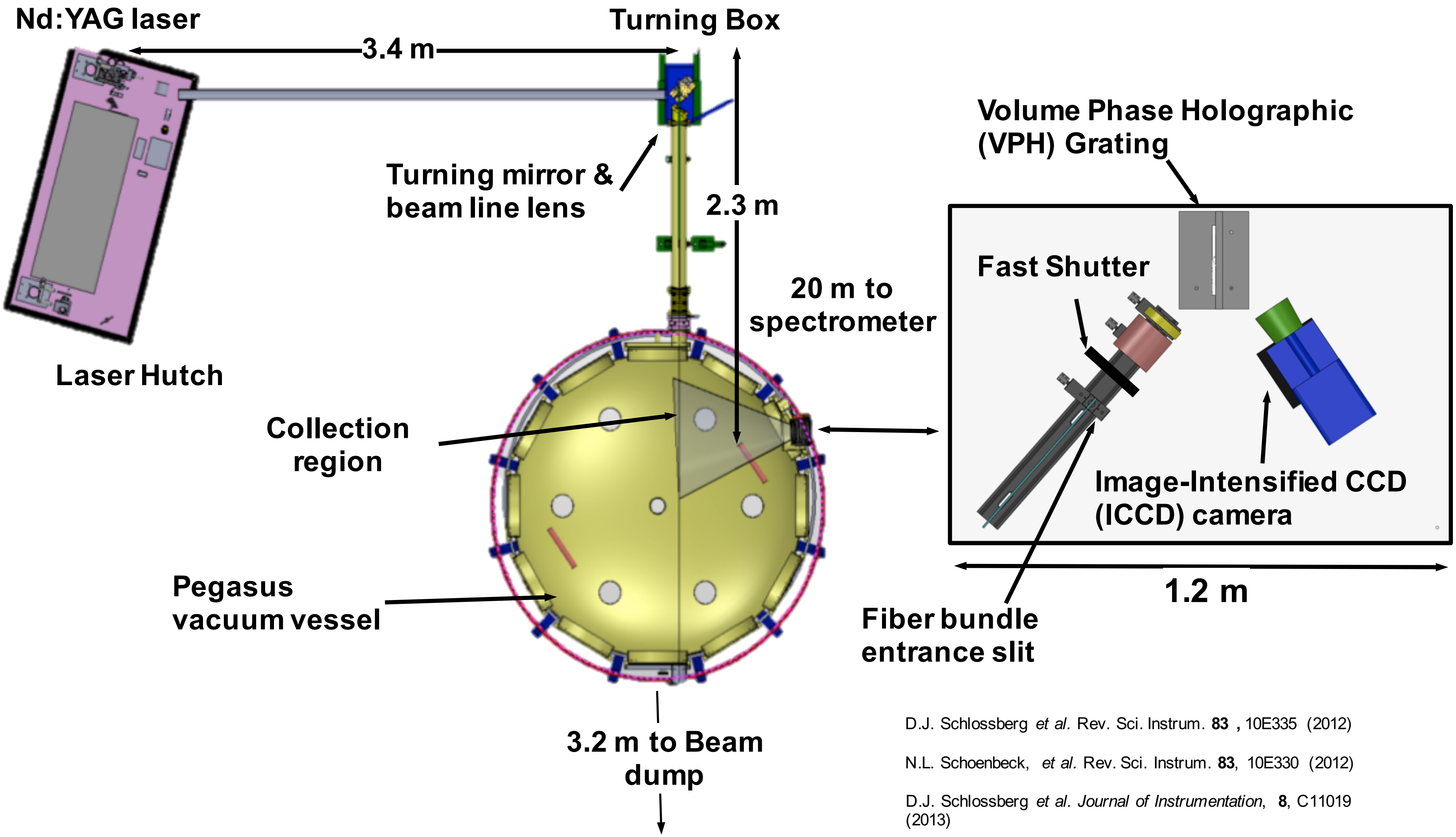
Layout of the Pegasus Thomson Scattering Diagnostic



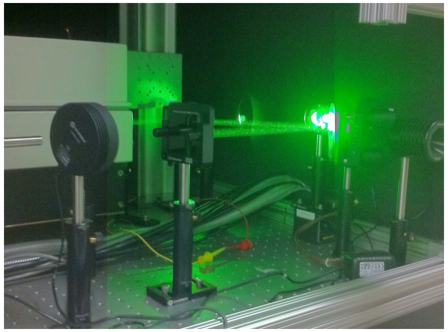
D.J. Schlossberg *et al.* Rev. Sci. Instrum. **83** , 10E335 (2012)

N.L. Schoenbeck, *et al.* Rev. Sci. Instrum. **83**, 10E330 (2012)

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

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

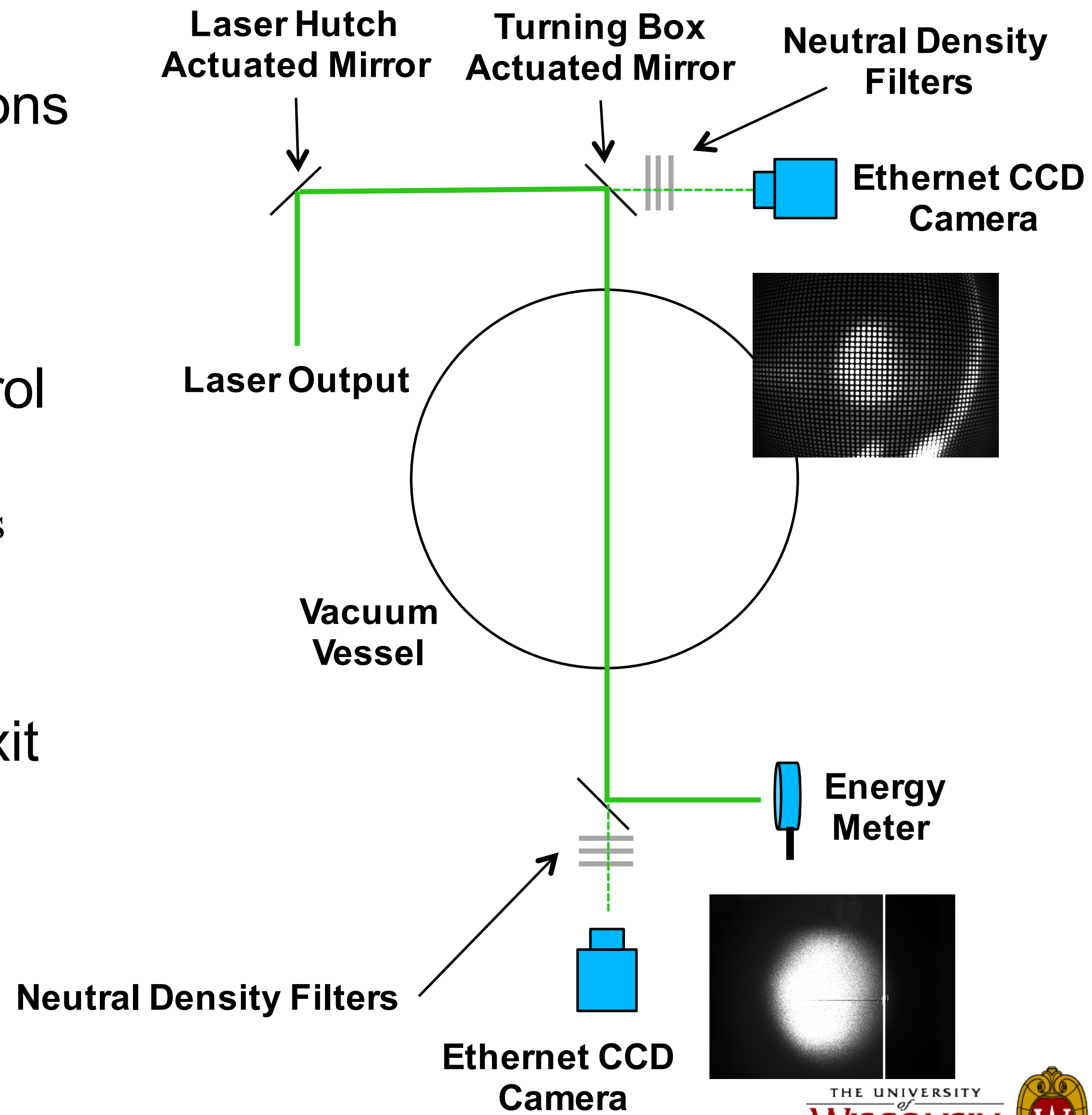
- Continuum Powerlite DLS Plus 2J Nd:YAG laser
- Frequency doubled to provide 2J at 532 nm



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

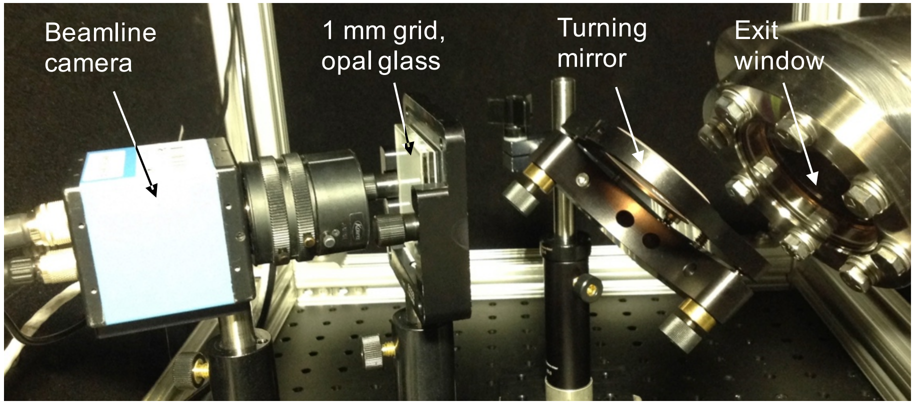
Laser Alignment Maintained with Remotely Actuated Mirrors and Networked Cameras

- Thermal variations, 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

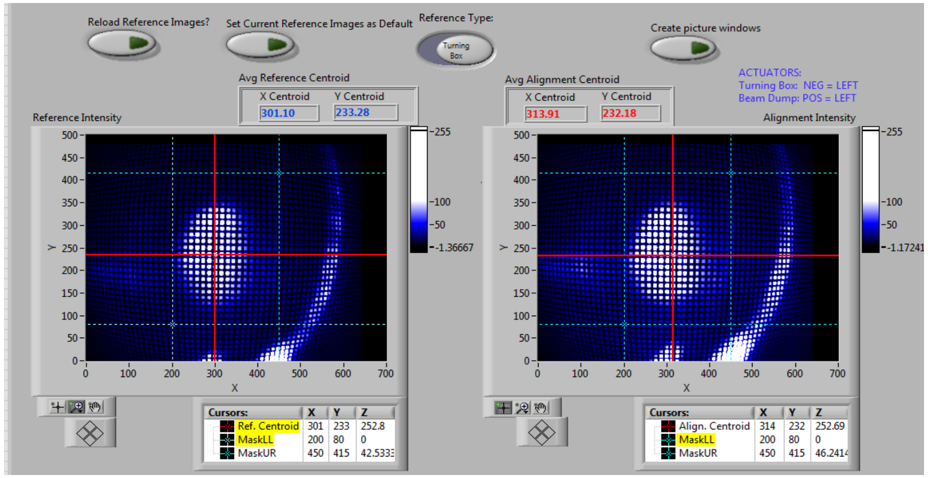


LabVIEW Image Processing Tools Characterize Beam Alignment

- Two networked ImagingSource CCD cameras capture beam positions through vessel



- Beam spots analyzed to evaluate laser alignment
  - Centroid values compared to fiducial values from Rayleigh calibrations
  - Auto alignment corrects misalignment to within a two pixel difference (~ 0.29 mm)



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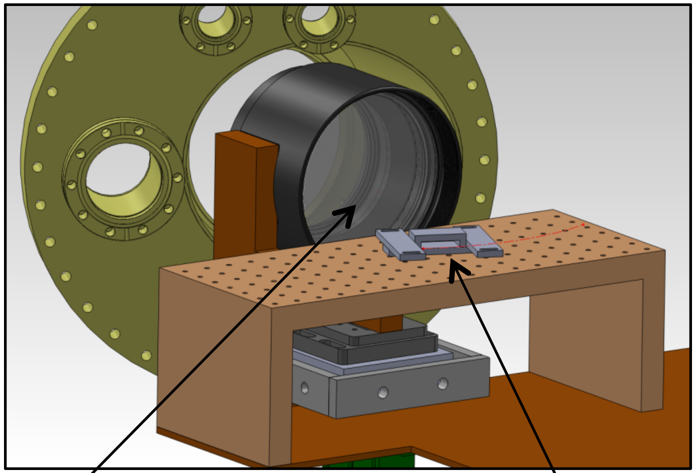
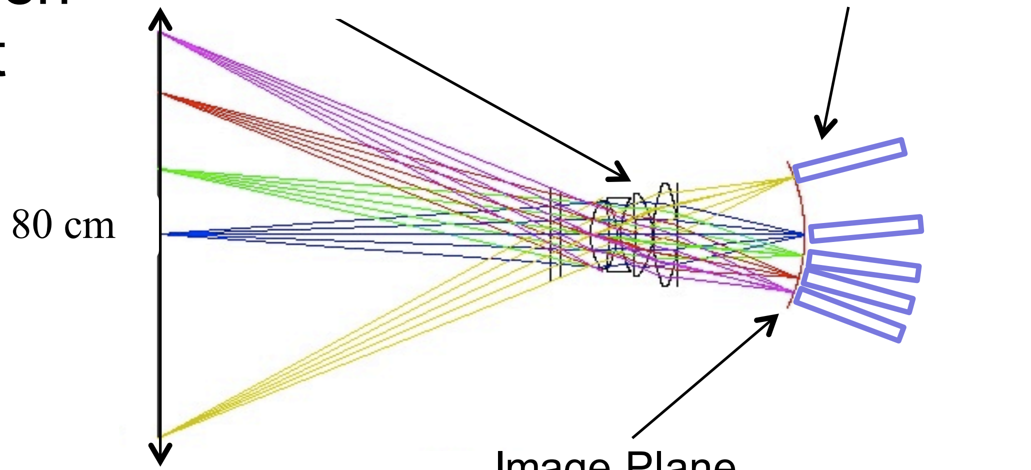
Multi-Element Collection Lens Supports High Throughput Field of View

- 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

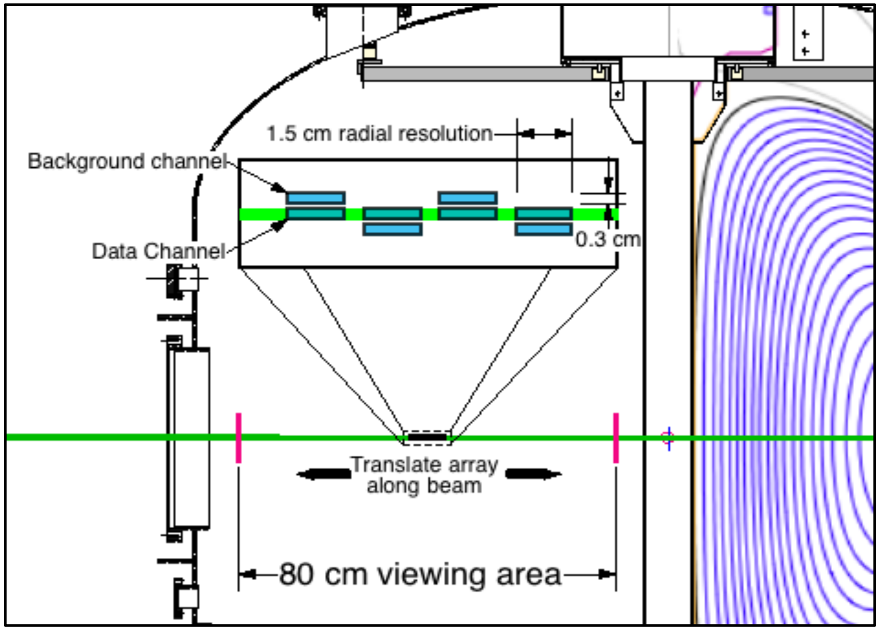
- Magnification ~1/3

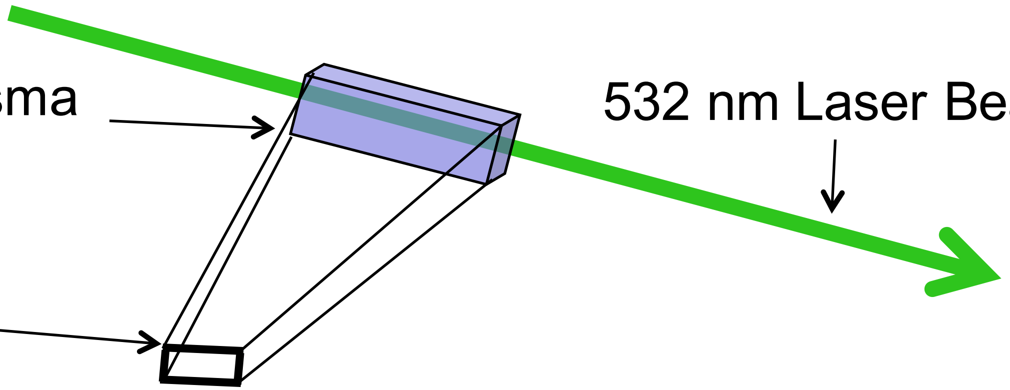




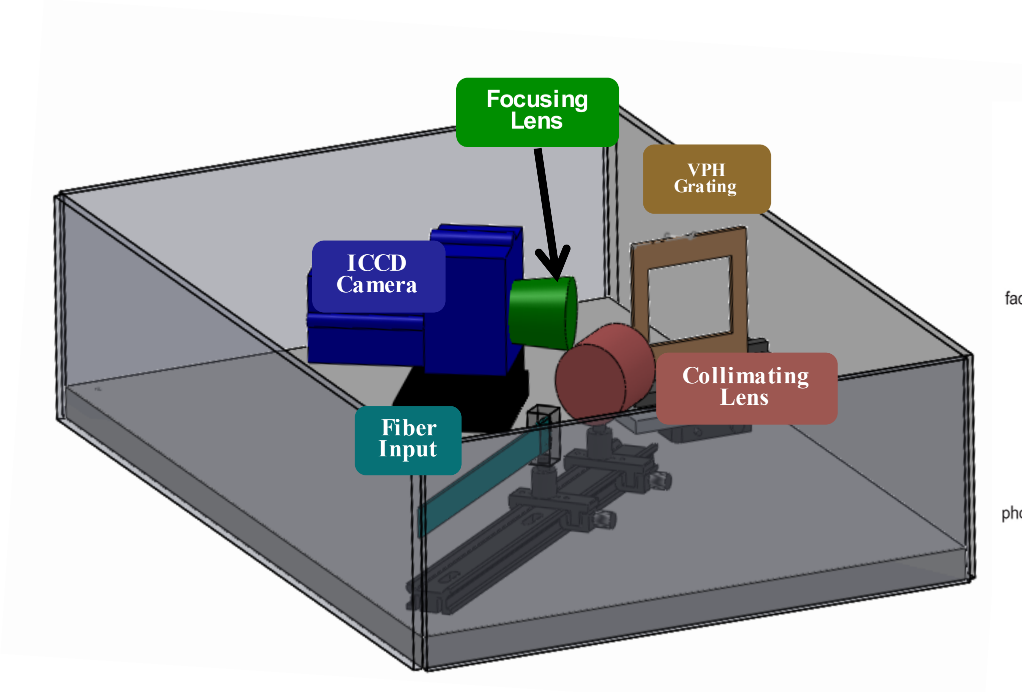
Fiber Bundles Image 80 cm Radially Along the Midplane

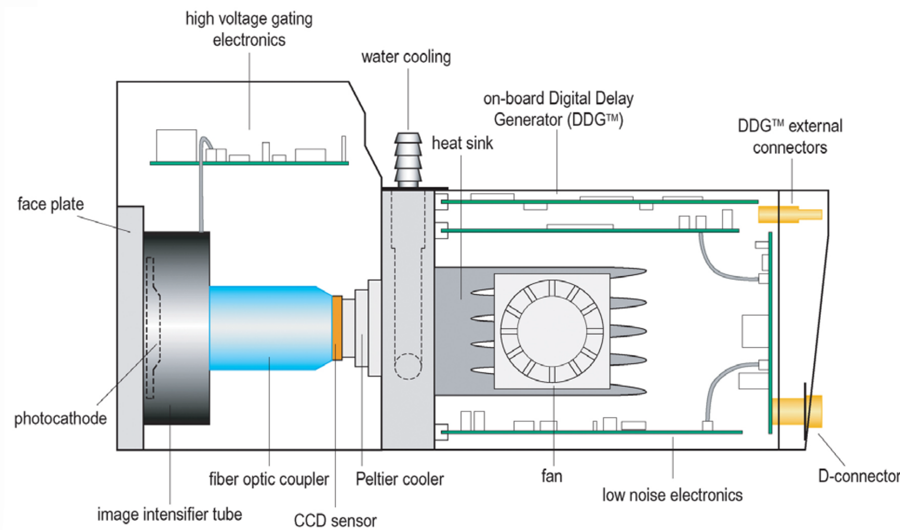
- Each channel is 0.3 cm x 1.5 cm
- 8 spatial channels per spectrometer
  - 4 data, 4 background channels
  - High and low background channels assist beam alignment





Compact Spectrometer Uses VPH Gratings and ICCD Cameras



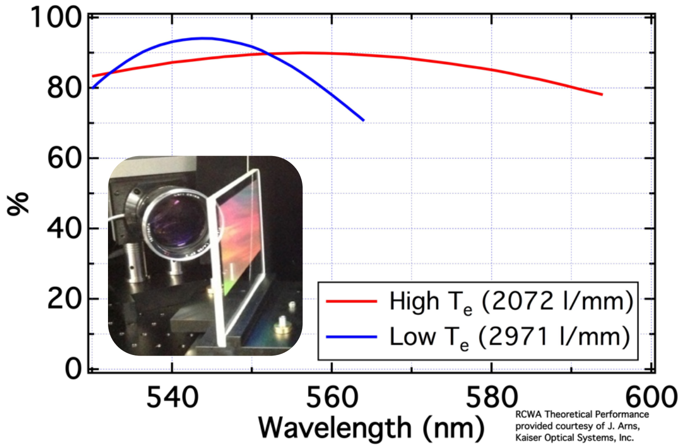


ICCD Manufacturer Specifications: Andor iStar 734			
Effective Active Area (mm)	13.3 x 13.3	Effective Pixel Size (um)	19.5 x 19.5
Read Noise	≥ 2.9 e-	Active Pixels	1024 x 1024
Spectral Range (nm)	120 - 1090	Photocathode QE (max)	≤ 45%
Minimum Optical Gate Width	≥ 1.2ns	Image Intensifier Gain	> 200

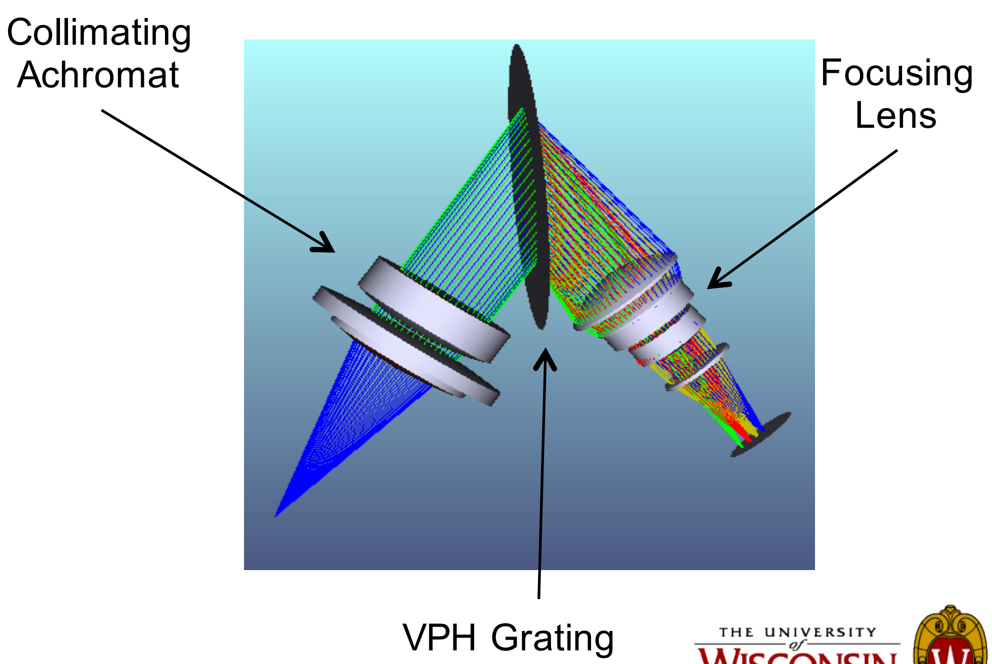
Spectrometer Design Features Interchangeable VPH Gratings for Multiple Temperature Regimes

- Volume-Phase Holographic (VPH) transmission grating
  - Custom made by Kaiser Optical Systems, Inc.
  - Unpolarized diffraction efficiency ~ 80%

Optimized diffraction efficiencies



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



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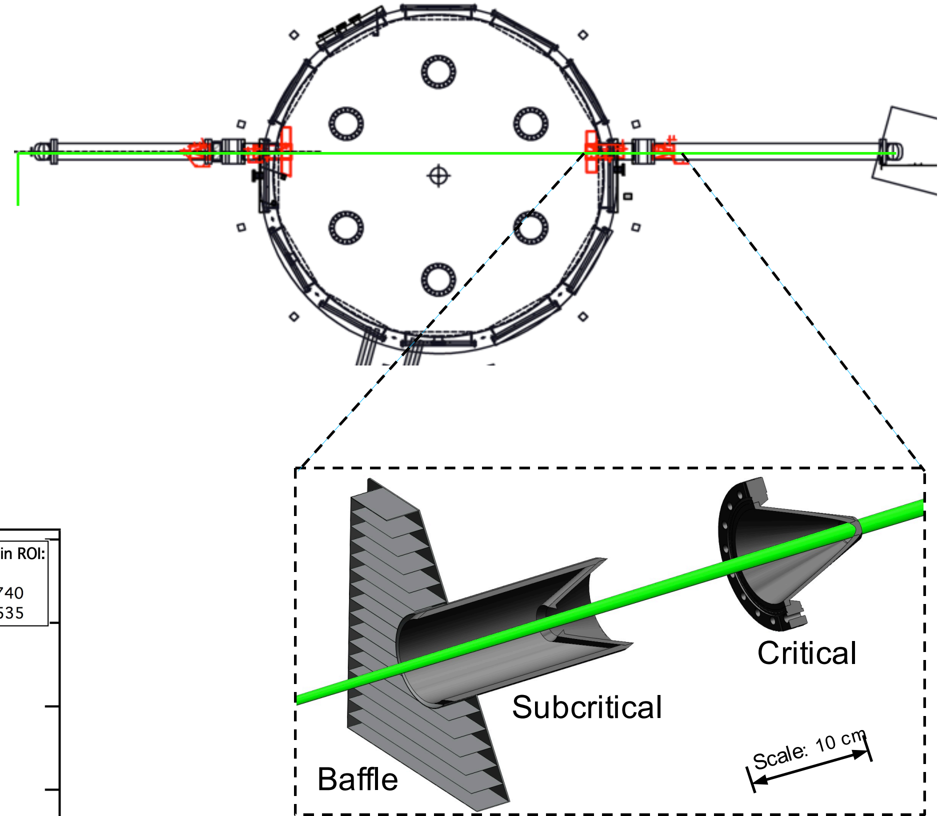
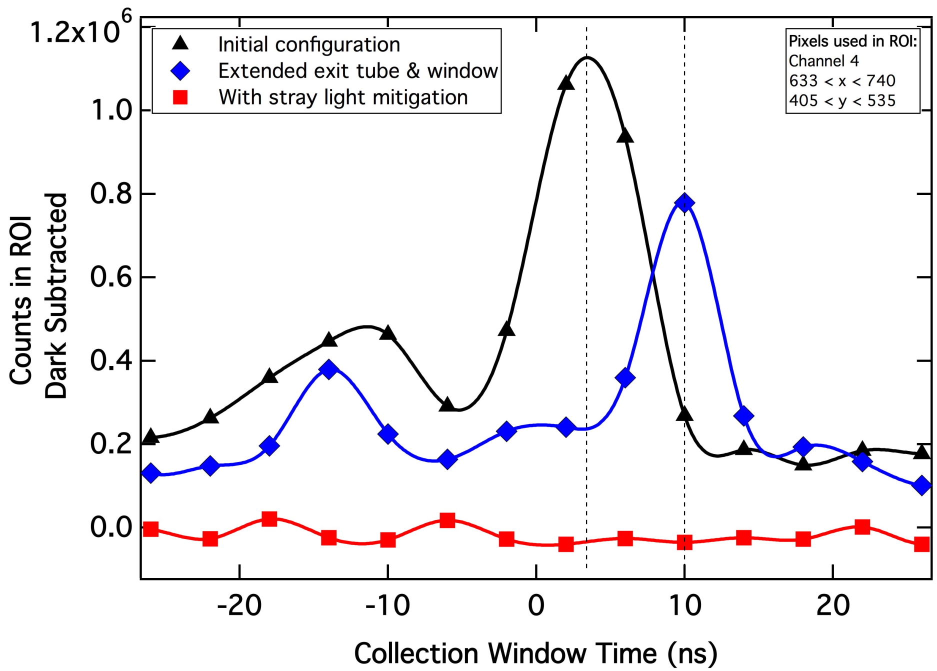
Aperture Assembly Reduces Stray Light by a Factor of 10^6

- "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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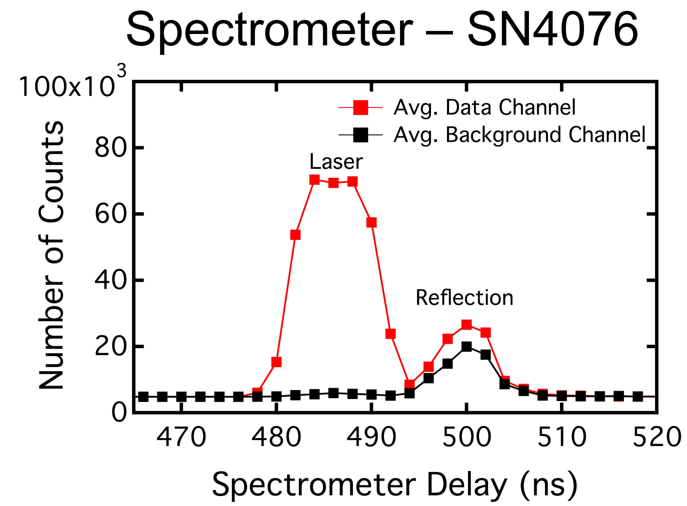
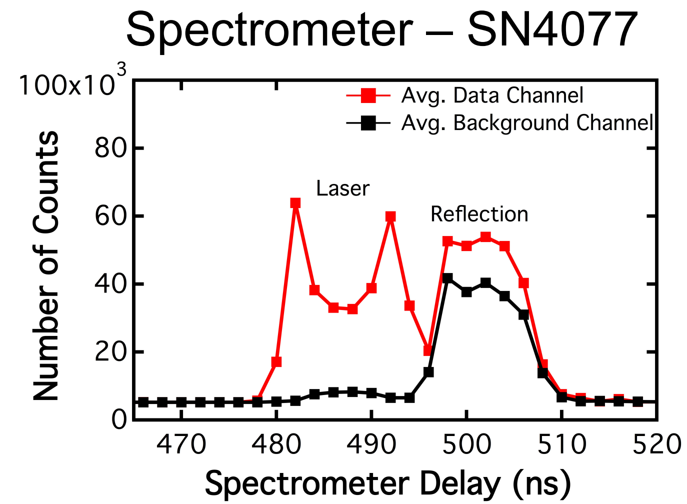
Electronically Gated Collection Window Used to Mitigate Stray Light Reflections

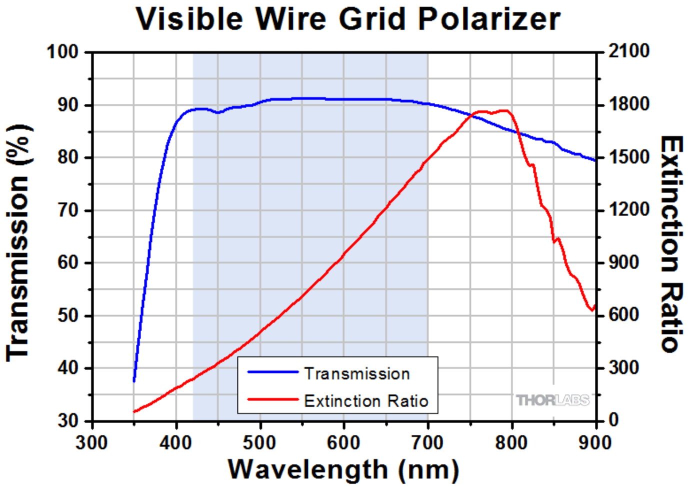
- ICCD collection time scanned with respect to laser
- Initial laser pulse, stray light reflections clearly identified
- Use of fast gating enables elimination of stray light
  - Optimum delay determined to be 479 ns with a 16 ns gate width



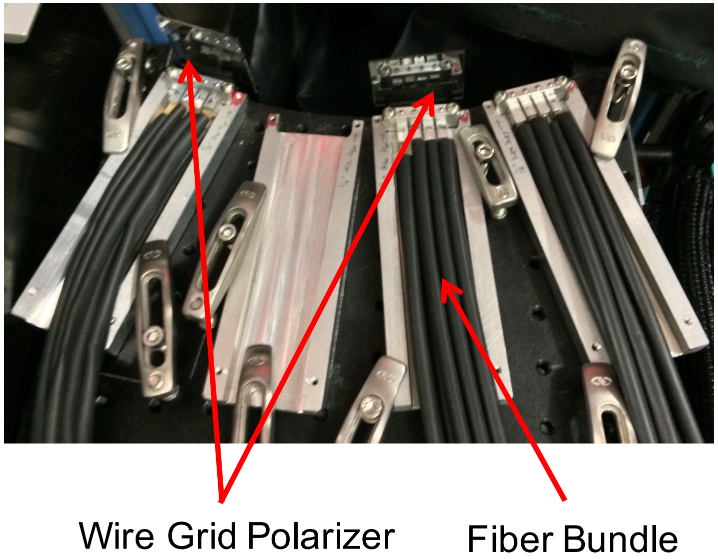


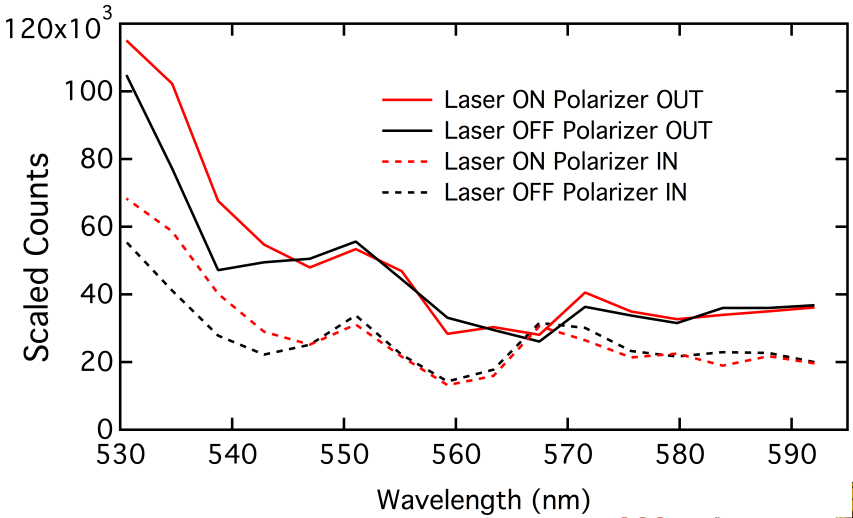
Wire Grid Polarizers Added to Collection Optics to Minimize Background Plasma Light

- 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



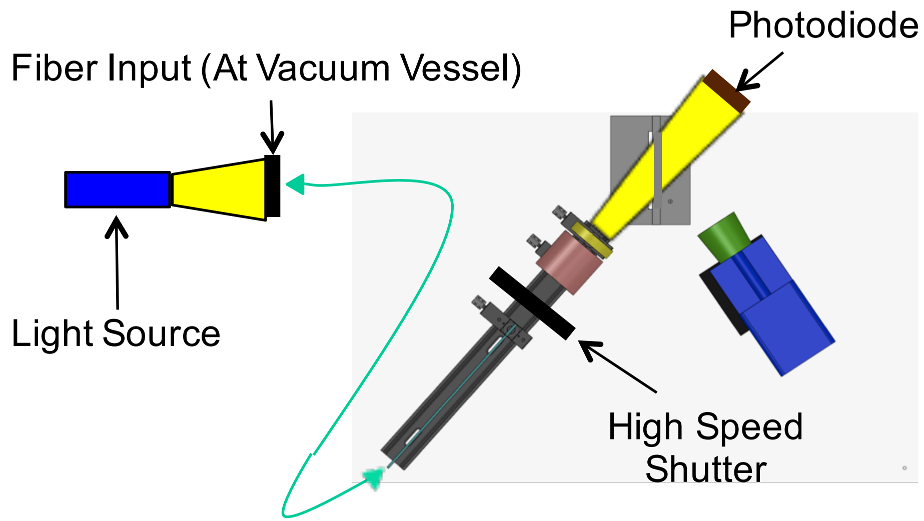
https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=5510

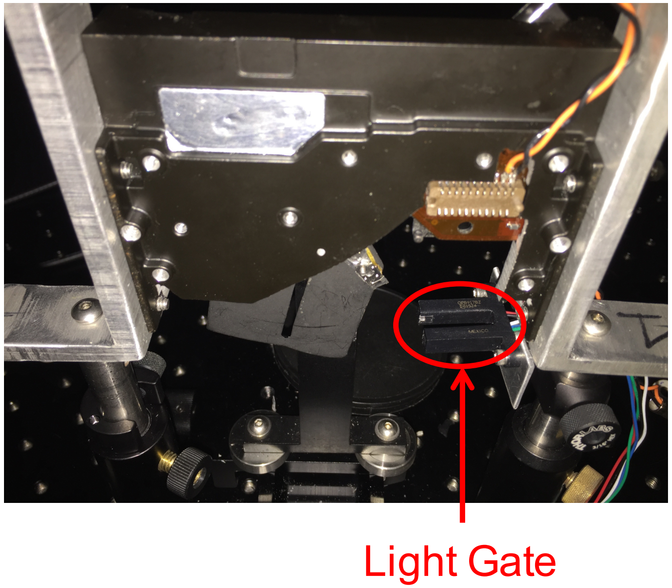


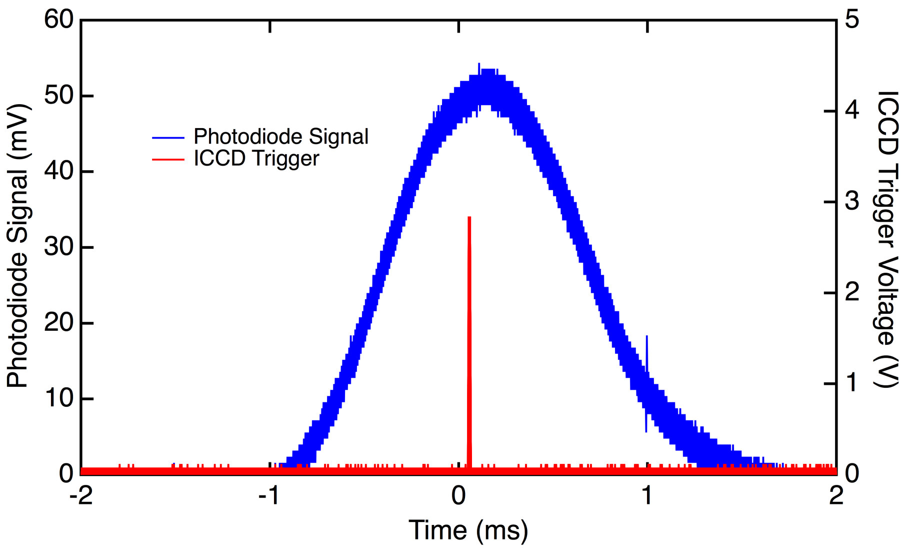


High Speed Shutters Minimize Detector Exposure to Intense Plasma Background

- Shutter temporally aligned using photodiode
- Infrared light gates monitor shutter on each shot



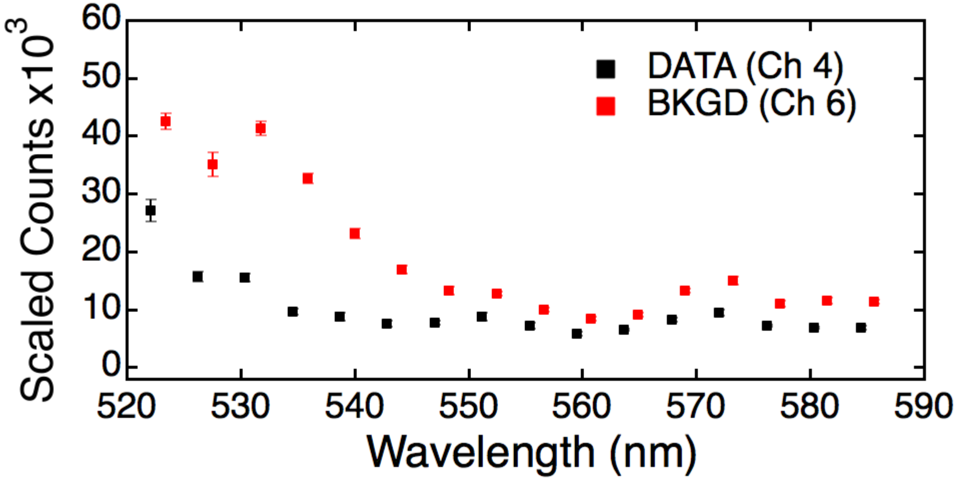




High Speed Shutters Decrease Leakage Through the Image Intensifier

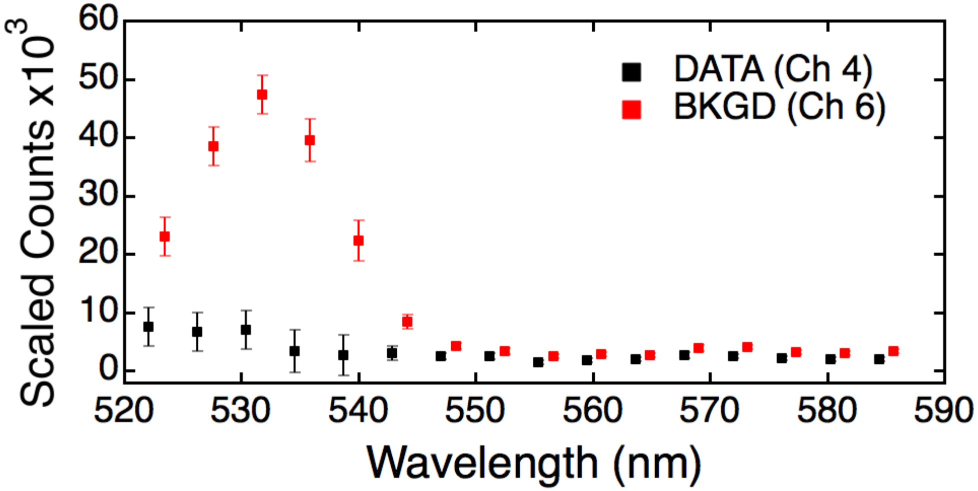
- Improved SNR
  - Lower background without impacting scattered signal

No fast shutter



- Further investigation of background signal in progress to remove small residual signal
  - Initial observations point to wall reflections

With fast shutter



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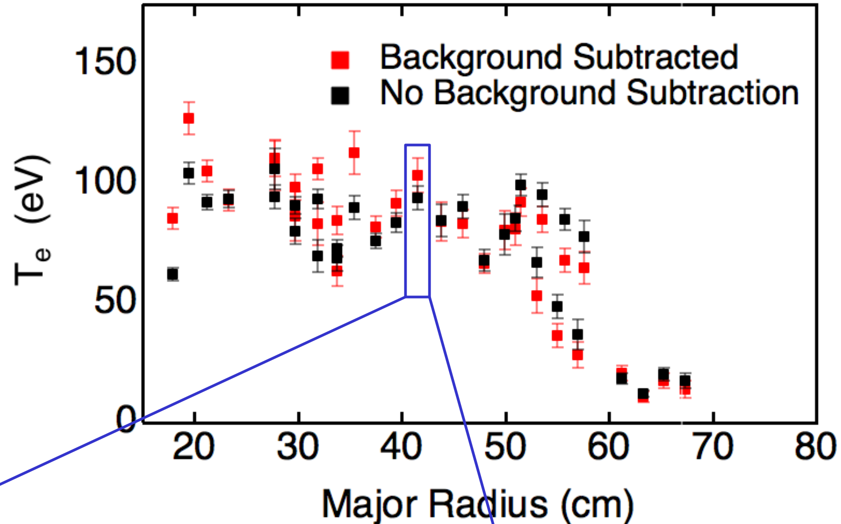
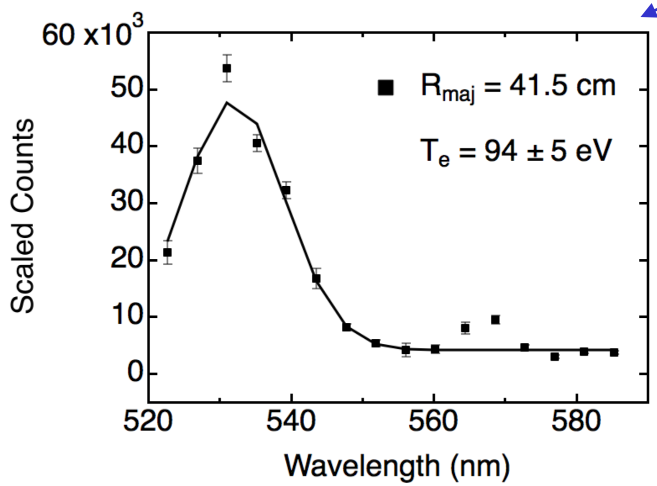
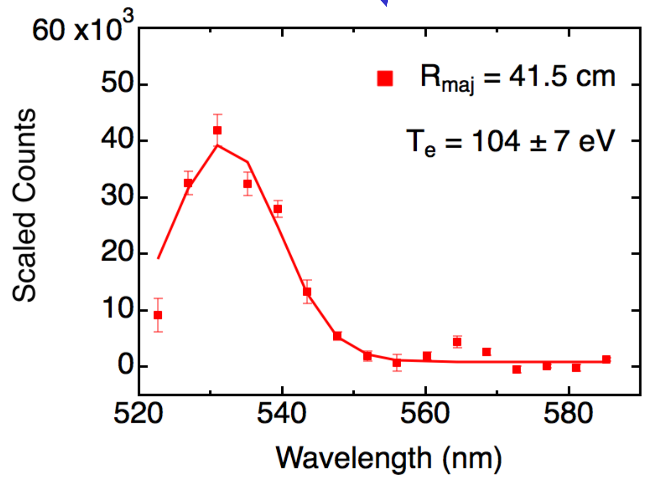
Background Signal Reduction Efforts have Eliminated the Need for Co-Located Background Subtraction

- Average relative error, σ_T/T, is ~ 10% with background subtraction analysis
- Average relative difference between background subtraction and no background subtraction cases is ~ 13.5 %
  - Data channels during laser-off shots can be used as substitutes for background channels





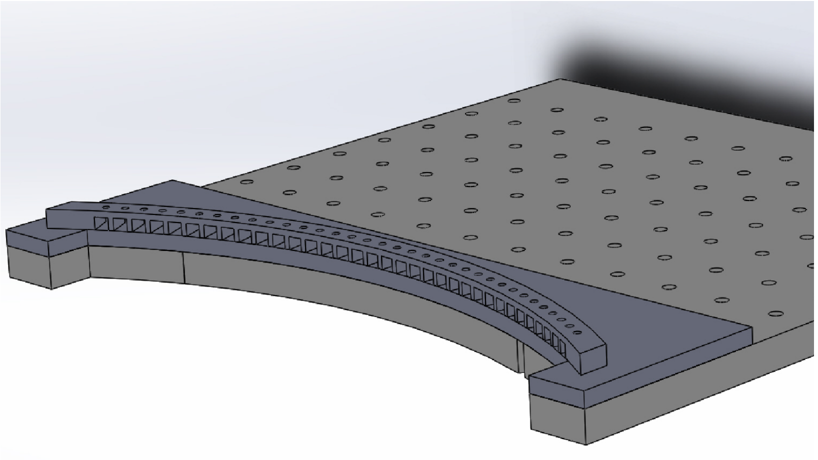
No Background Subtraction



Co-Located Background Subtraction

Fiber Mount to View Full Plasma Radius in Design Stage

- Without a demand for off laser channels, more channels can be dedicated to viewing scattered signal
- High reproducibility of Pegasus discharges allow laser-off shots to be used in background subtraction analysis
- Provides simultaneous measurement of up to 24 data channels
  - 34 possible viewing locations
- Previous fiber arrangement required moving fiducial mounts which required in-vessel calibrations.



Current Configuration*

Modified Configuration*

*Figure shows 8 of 24 total fiber channels

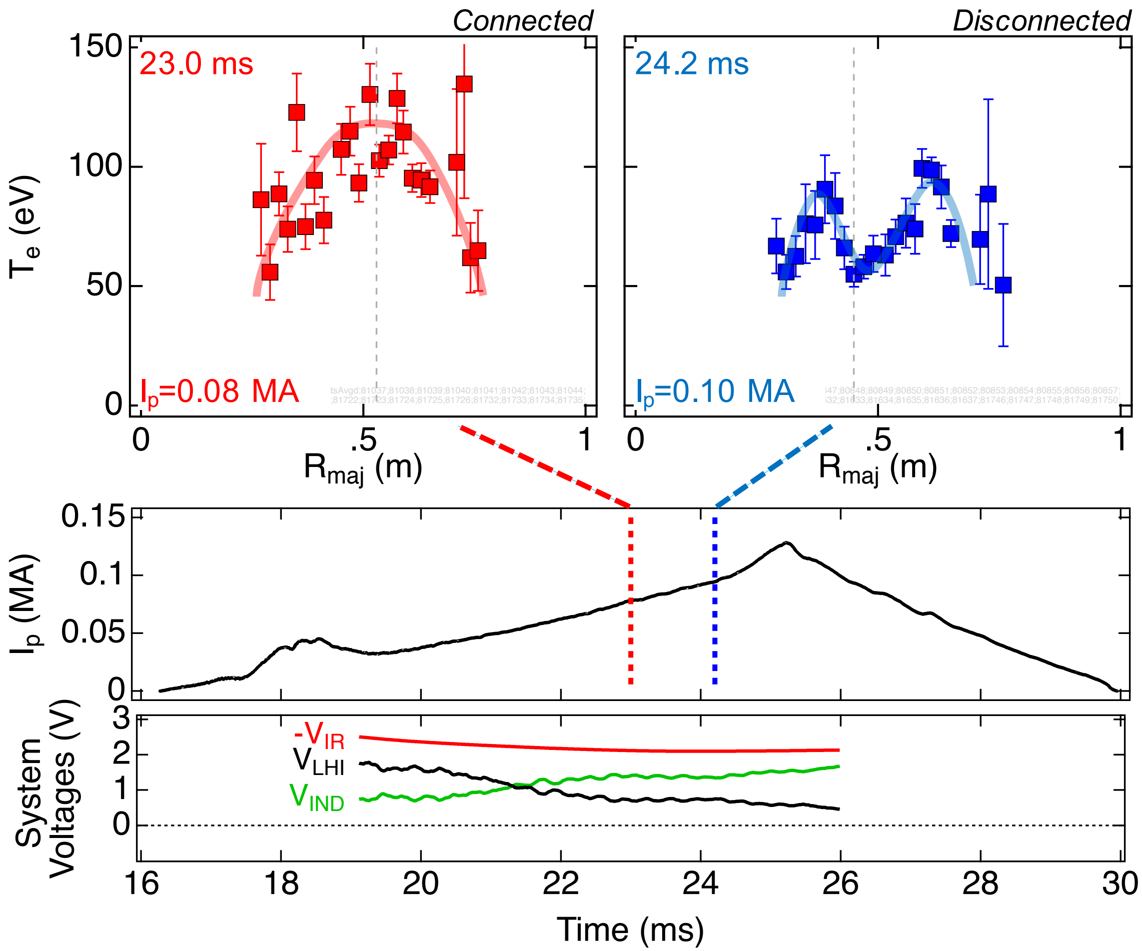
Improvements to the Pegasus Thomson System have Enabled Measurements of T_e and n_e Profiles

- Stray light and background light mitigation systems have increased SNR, yielding reliable T_e and n_e measurements
- Local Helicity Injeciton (LHI) sustains ~100 eV $T_{e,max}$, moderately high n_e
- No strong $T_e(R_{maj})$ dependence on LHI location and ratio of LHI-to-inductive drive
- Effective startup target for direct OH coupling
- Initial results motivate a transition to a full 24-data channel fiber array

LFS Local Helicity Injection Produces Core T_e > 100 eV

- Plasma position & shape evolve inward
  - Shape evolution generates V_{IND}
  - $V_{IND} > V_{LHI}$ during high-I_p phase
- Peaked $T_e(R)$ during drive phase (connected)
  - After disconnect radial compression drives skin current
- Core $n_e > 10^{19}$ m^{-3}, $T_e \geq$ 100 eV provides target for subsequent CD

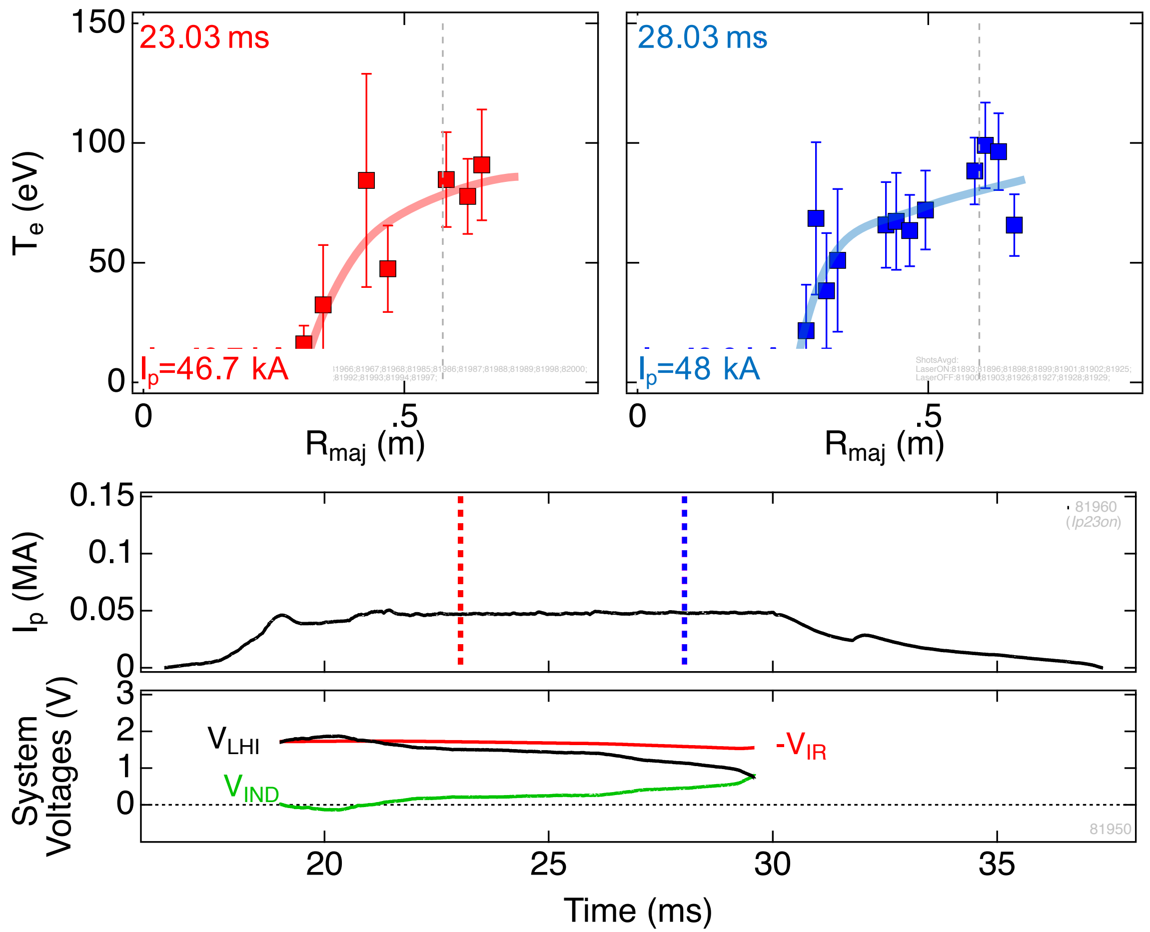
Peaked $T_e(R)$ while Connected to Injectors



T_e (R_{maj},t) Remains Peaked for LFS LHI with V_{IND} Small

- Same injection location but static, circular plasmas at large R_{maj}
  - Lower performance due to shape constraints
- V_{IND} = 0, $T_e(0)$ ~ 80 eV
- $T_e(R)$ remains peaked while driven solely by edge LHI

$T_e(R)$ > 85 eV with majority LHI-drive



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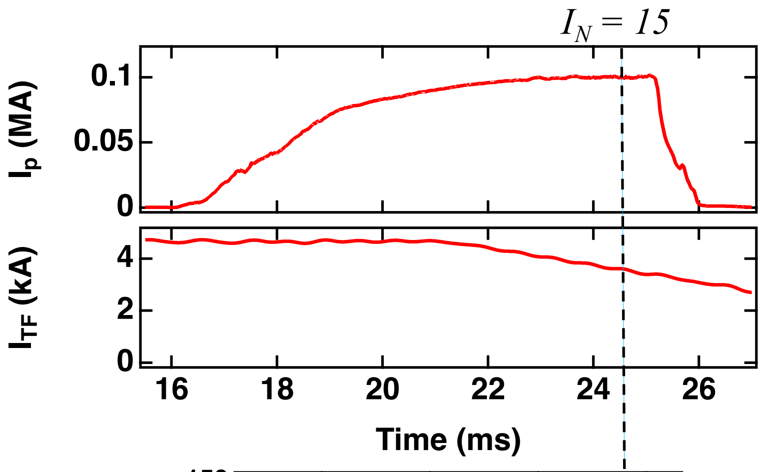
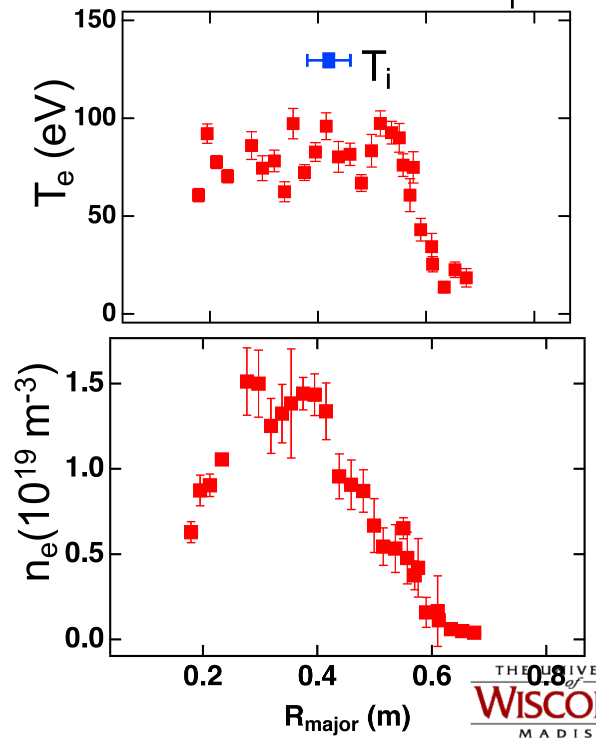
Divertor Injection at low TF Provides Non-Solenoidal Sustainment at High I_N

- HFS LHI development campaign provides unique operation space
  - dLow $I_{TF} \sim 0.6\ I_p$
  - $I_N = 5A \frac{I_p}{I_{TF}} > 10$ accessible
- Enables high β_t access
  - Aided by anomalous ion heating
- Kinetic constraints on magnetic equilibrium fits
  - $P_{tot}(0)$
  - Edge location defined by T_e profiles





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