Implementation of the Pegasus Multi-Point Thomson Scattering System

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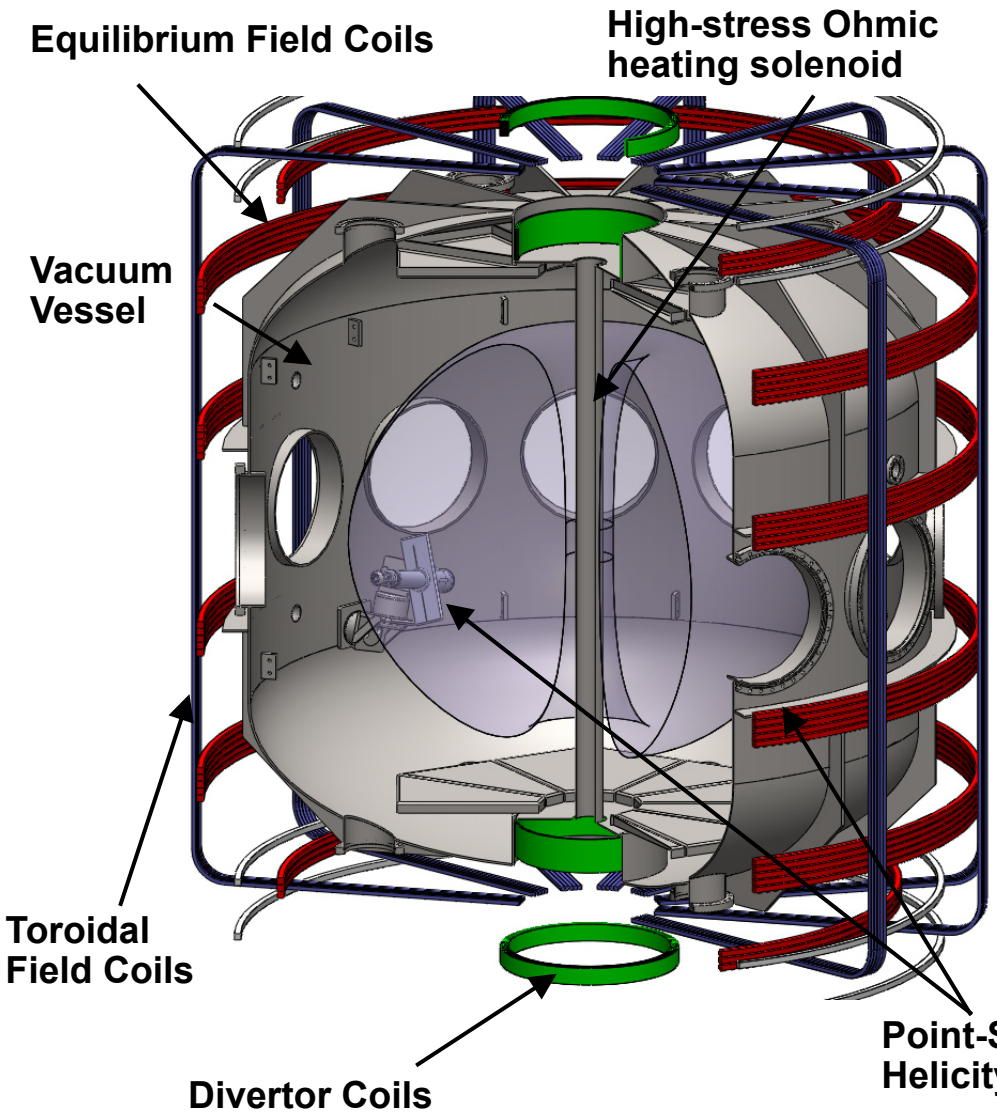
PEGASUS Toroidal Experiment

Diagnostic and Control 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 provide 16 additional spatial channels
- Laser triggering, alignment improvements increase scattered signal
- Synchronized and automated system operation
- Developed intra-shot beam alignment capability

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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

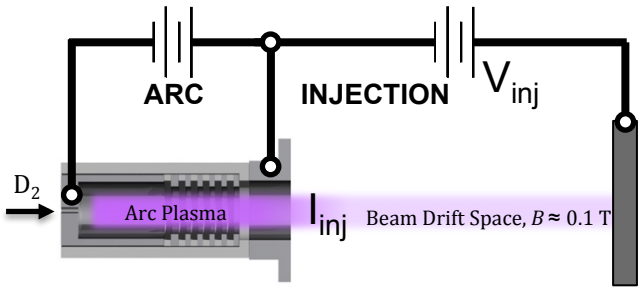
Major research thrusts include:

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

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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

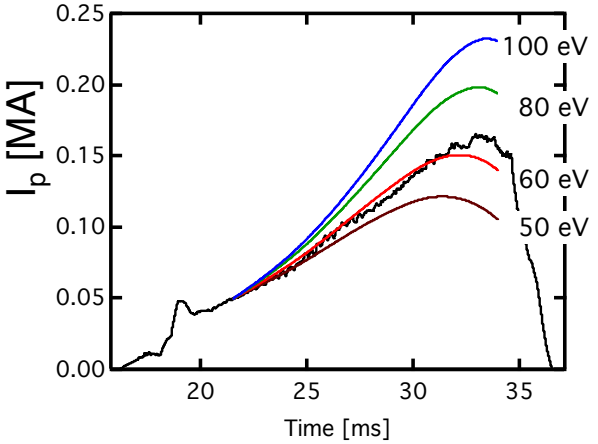
$$I_p \le \frac{A_p}{2\pi R_0 \langle \eta \rangle} \left(\frac{A_{inj} B_{\phi,inj}}{\Psi} V_{inj} + V_{IND} \right)$$

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)

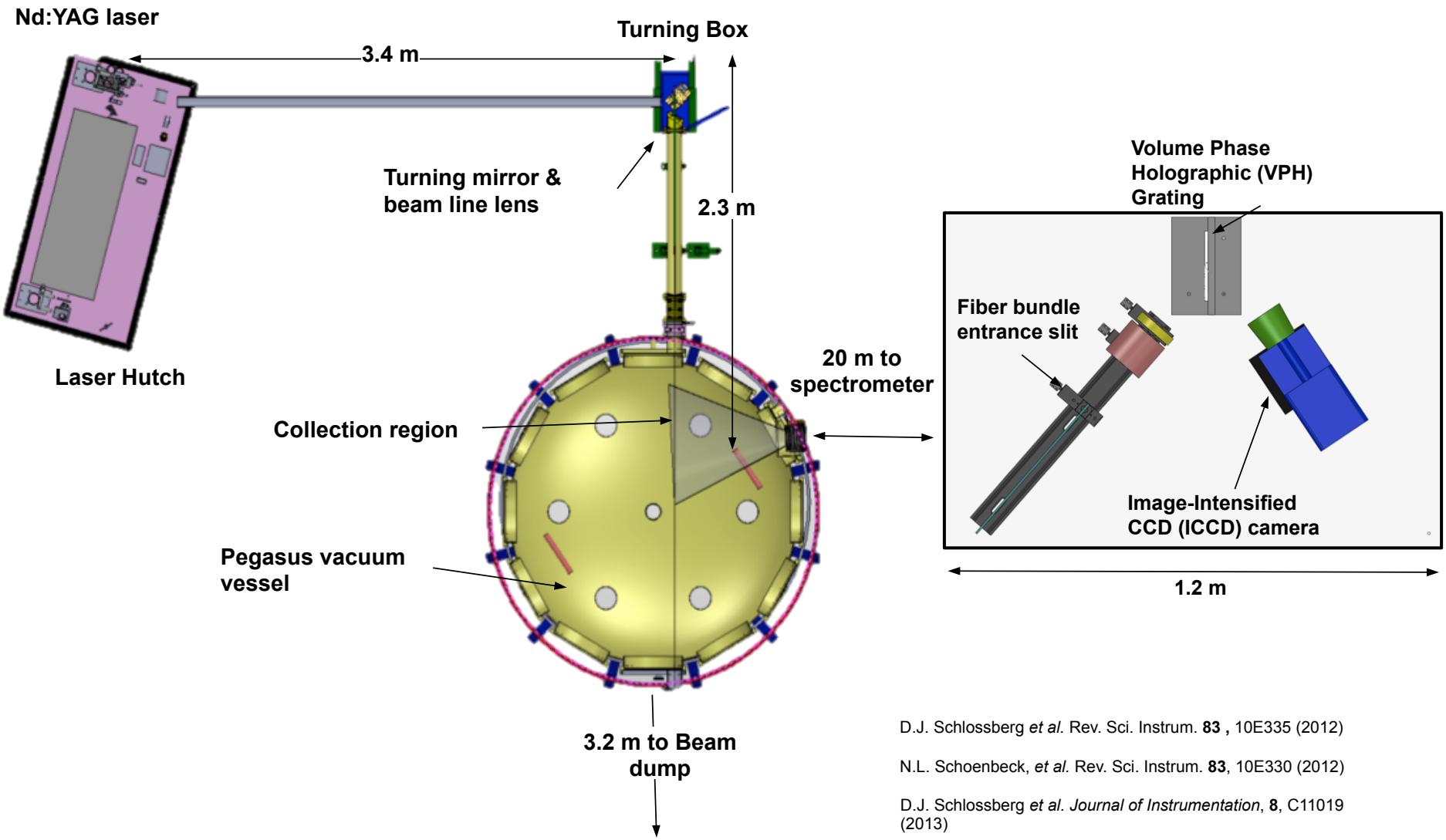
T_e dependent terms



[(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)

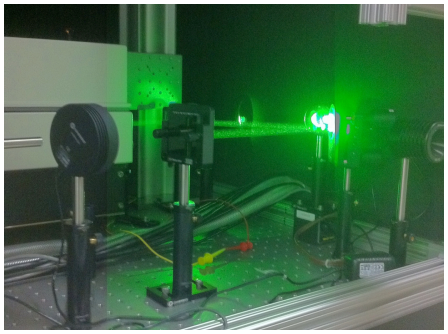
N.L. Schoenbeck, *et al.* Rev. Sci. Instrum. **83**, 10E330 (2012)

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

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

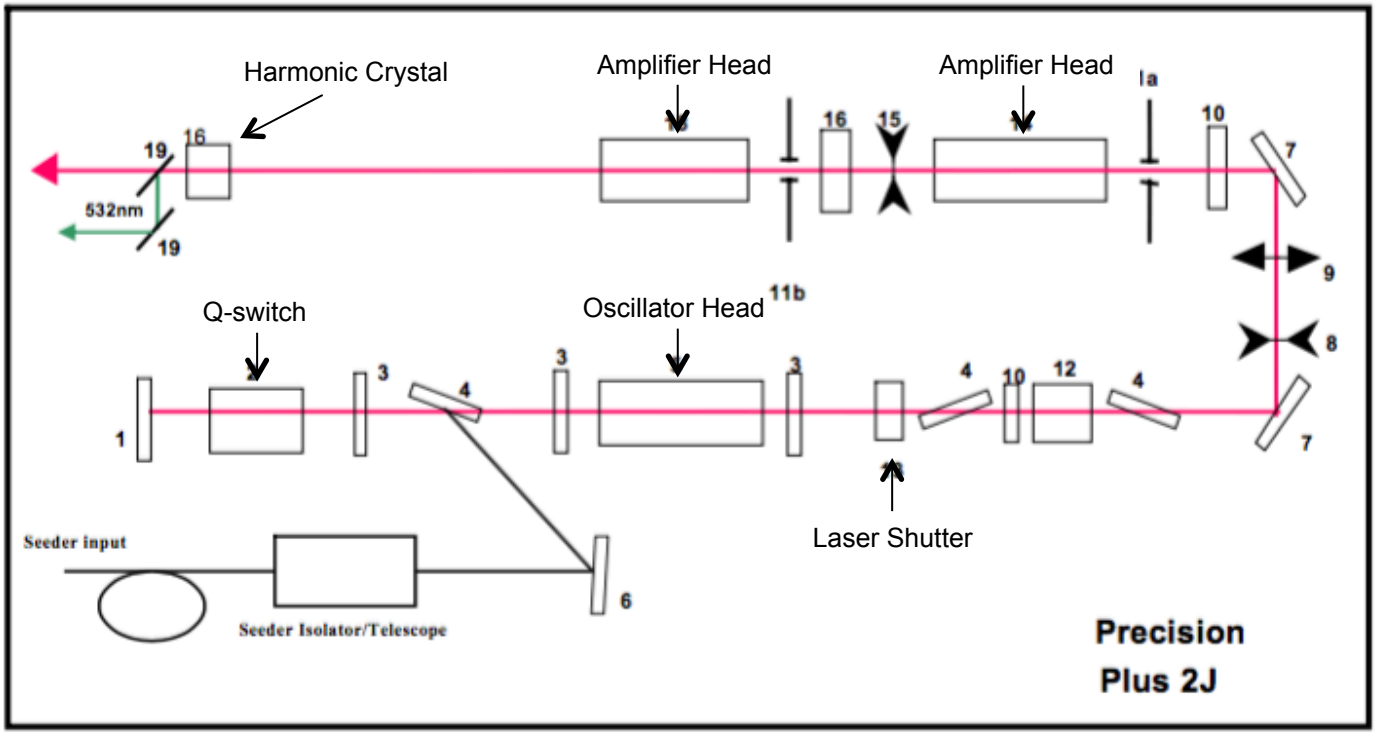
- Continuum Powerlite DLS Plus 2J Nd:YAG laser
- Frequency doubled to provide 2J at 532 nm



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

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Laser features Q-switch Control for Pulsed Operation



*Continuum Powerlite DLS Laser System Manual

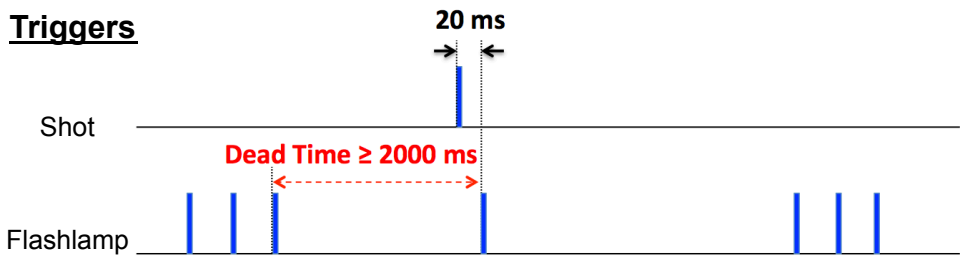
- One oscillator head and two amplifier heads provide 3J @ 1064 nm or 2J @ 532 nm per pulse

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Improved Triggering Configuration Maintains Optimal Pumping Rate

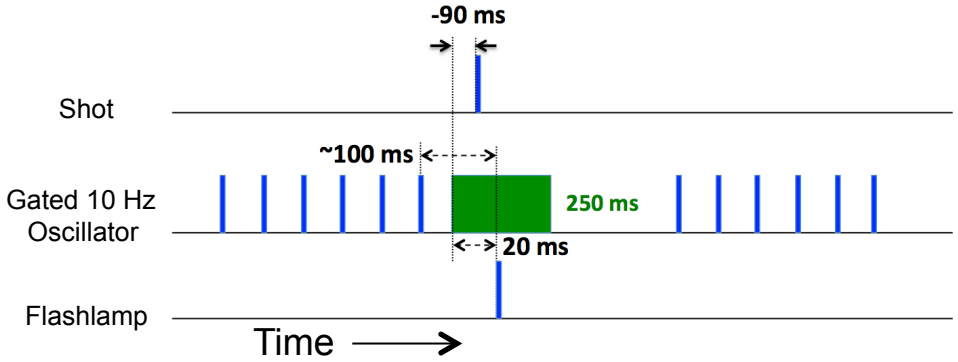
- Original triggering configuration could have ≥ 2s delay between final priming pulse
  - Degrades laser energy, beam quality

Original Configuration



- Improved configuration uses a gated 10 Hz oscillator to constantly pump the laser
  - Oscillator is gated for 250 ms
  - Delay generator triggers flashlamps and Q-switch during gated period

Improved Configuration

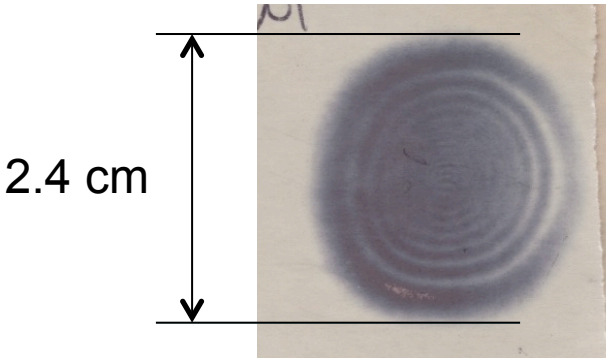


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Laser Timing Modifications Improve Beam Quality and Energy Density

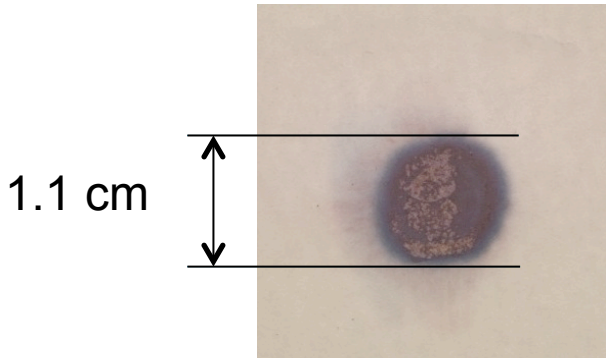
- Significant improvement in measured laser power
  - Original configuration: ~ 1.3 J
  - Modified configuration: ~ 1.8 J

Original Configuration



- Back burns taken 1m from laser indicate a large improvement in beam quality

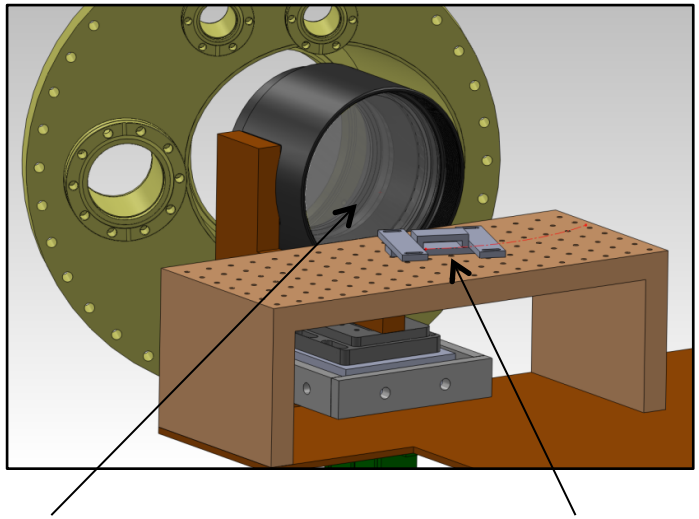
Improved Configuration

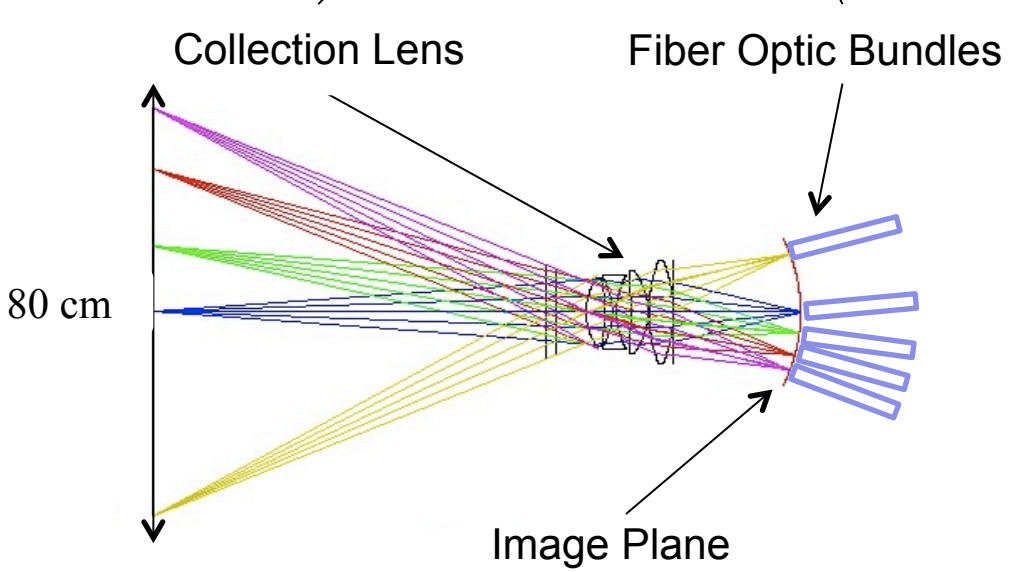


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Multi-Element Collection Lens Supports High Throughput Field of View

- 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

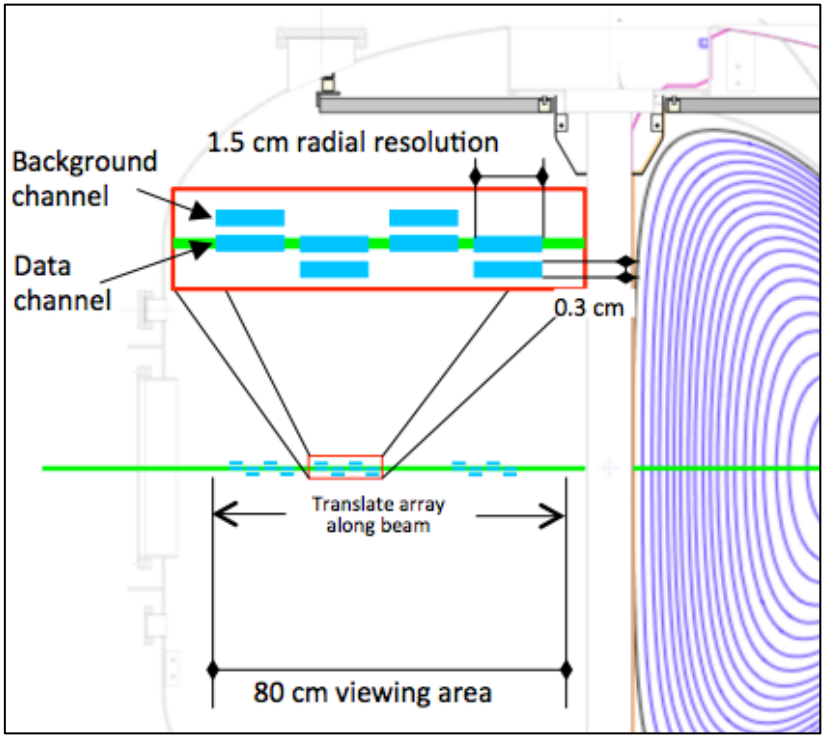


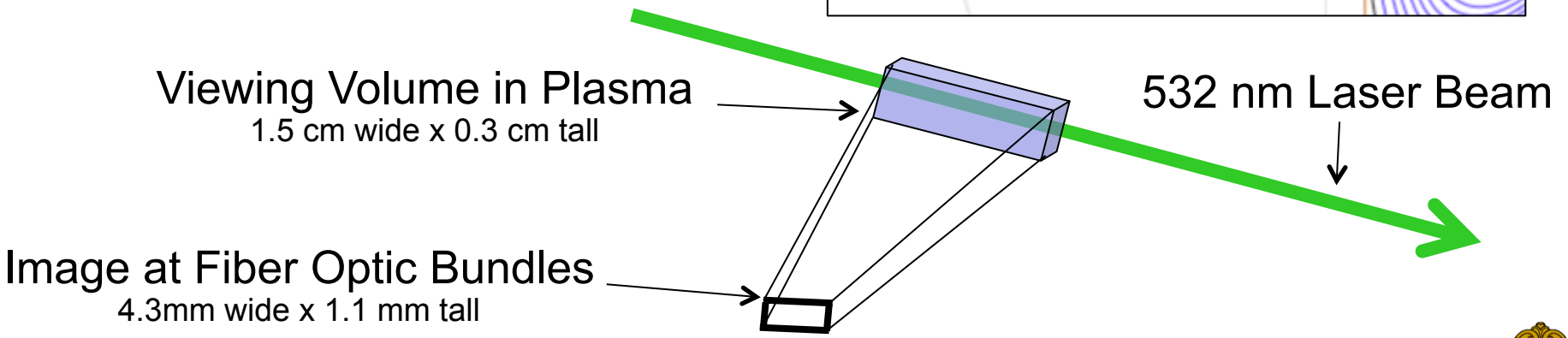


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Fiber Bundles Image 80 cm Radially Along the Midplane

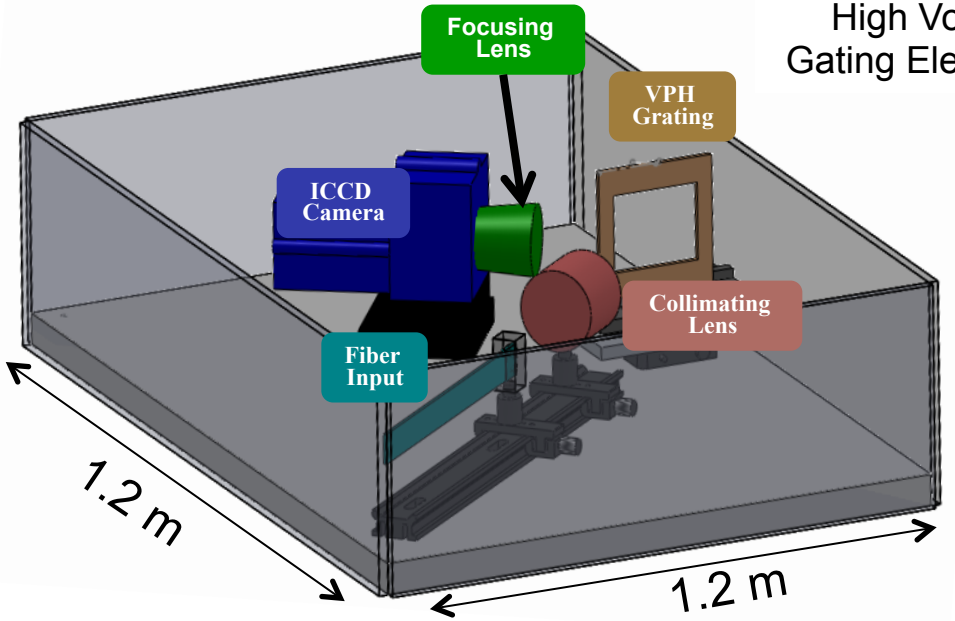
- 8 spatial channels per spectrometer
  - 4 data, 4 background channels
  - High and low background channels assist beam alignment
- Fibers can be translated to 4 calibrated spatial locations on the beam line



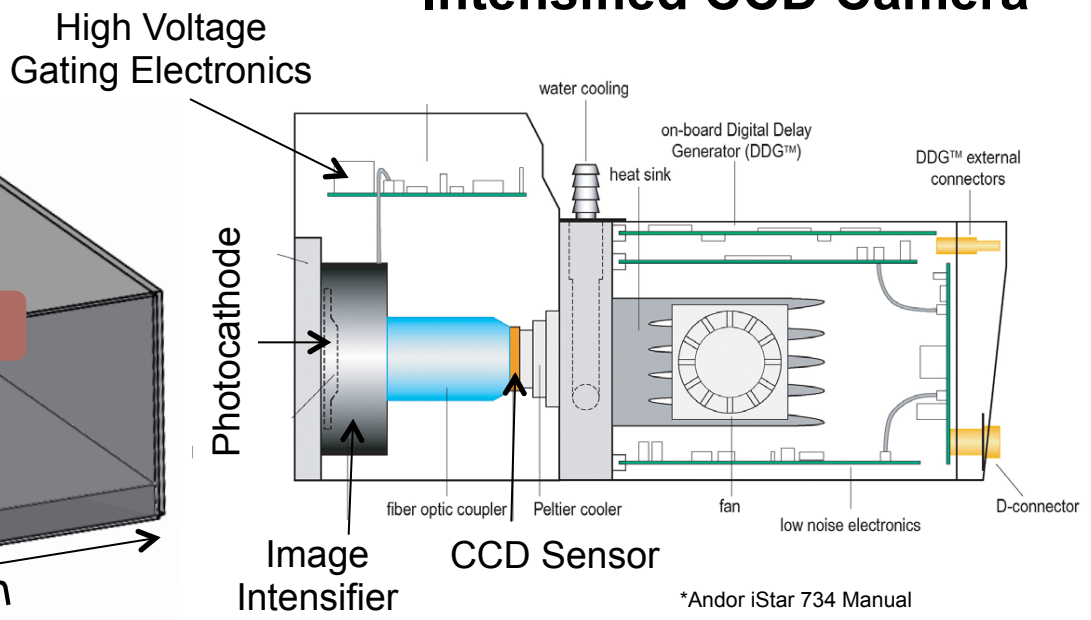


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Compact Spectrometer Uses Andor iStar 734 ICCD Cameras



Intensified CCD Camera



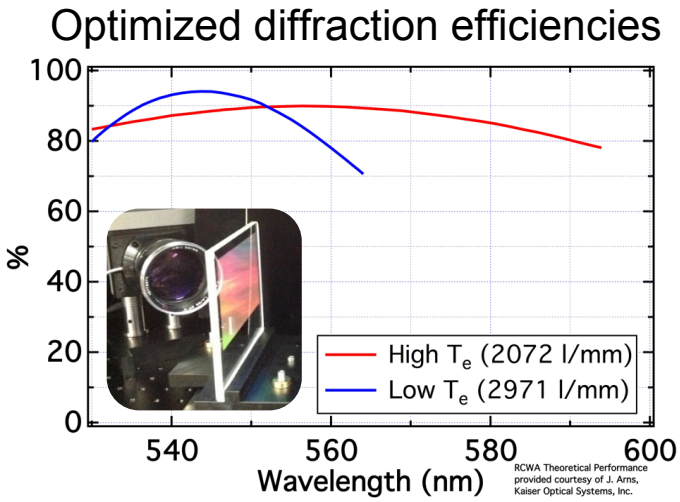
ICCD Manufacturer Specifications: Andor iStar 734

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

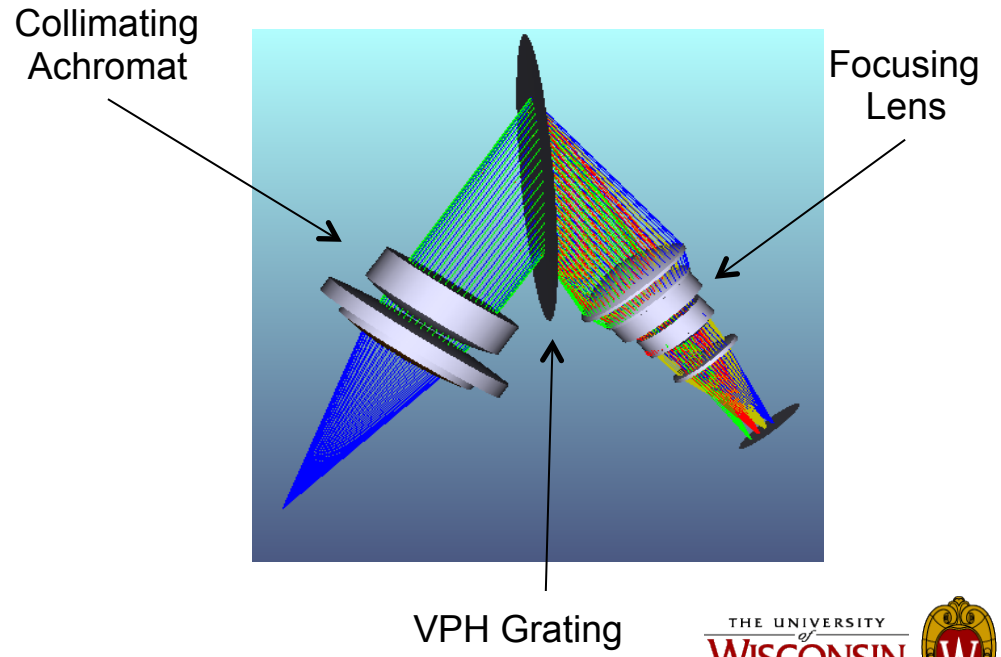
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Spectrometer Design Features Interchangeable VPH Gratings for Multiple Temperature Regimes

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



- 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)

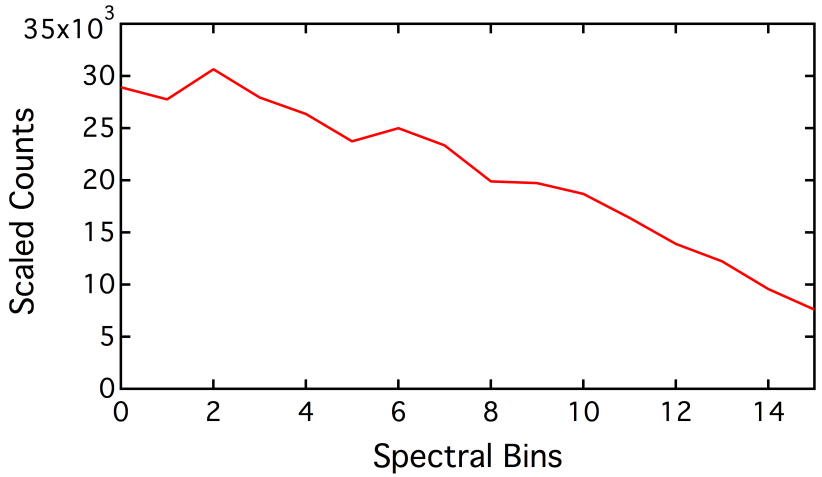


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High Speed Shutter Needed to Prevent Light Leakage through ICCD Photocathode

- Leakage tests conducted
  - Image Intensifier disabled and exposed to intense flat-field
  - Detector still observes significant counts, confirms leakage through the photocathode
- High speed shutter blocks background light after collection time
  - TS Collection Window ~ 16 ns
  - Pegasus shot duration ~ 10-20 ms
- Implemented hard disk drive shutter with open-close time ≤ 2 ms[1]

ICCD Spatial Channel from Leakage Test



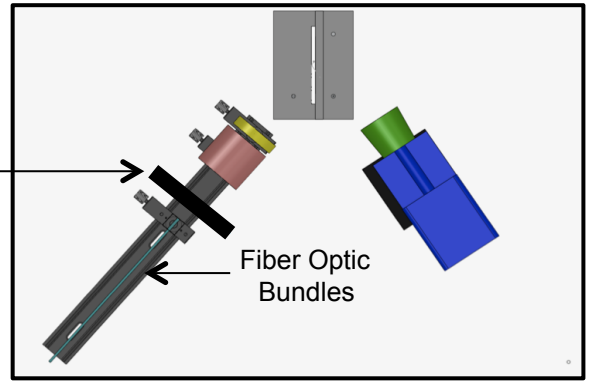
Shutter Type	Open-Close Time	Extinction	Cost
LCD Shutter	500 us	~99%	$$$
Photo-elastic Modulator	50 us	~90%	$$
Hard Disk Drive Shutter	2 ms	100%	$

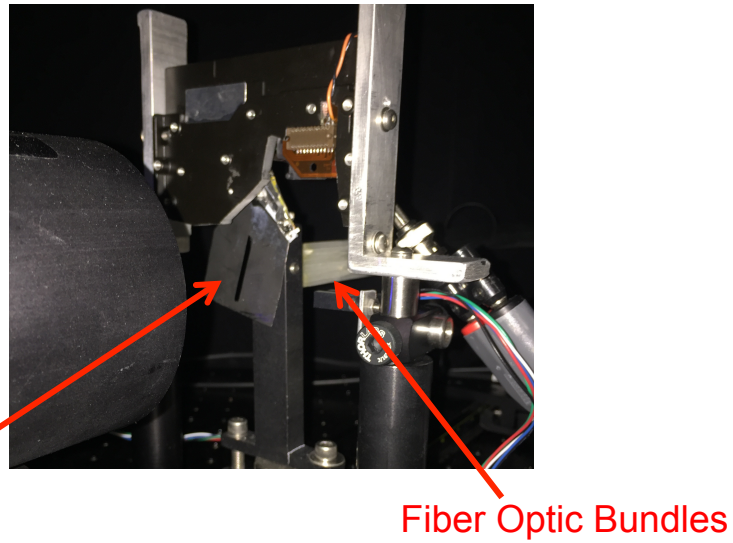
[1]Scholten, Rev. Sci. Instrum **78**, 026101 (2007)

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High Speed Shutter Features a Unique Cost-Effective Design

- High speed shutter constructed from used hard disk drive
  - Voice-coil motor used as the actuator
- Mounted at fiber output, prevents image intensifier light leakage
- Shutter performance dependent upon temporal alignment and driving voltage

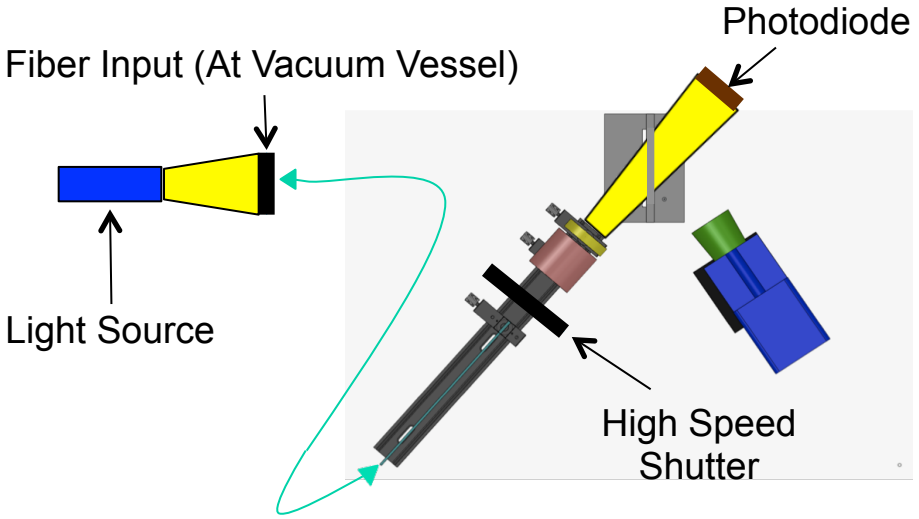


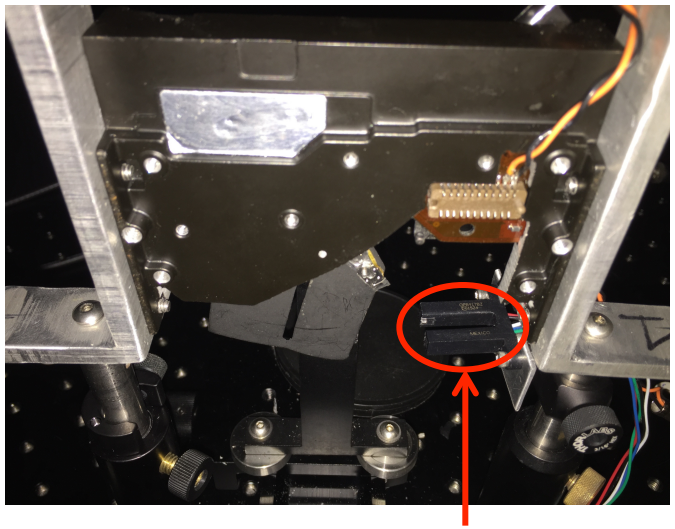


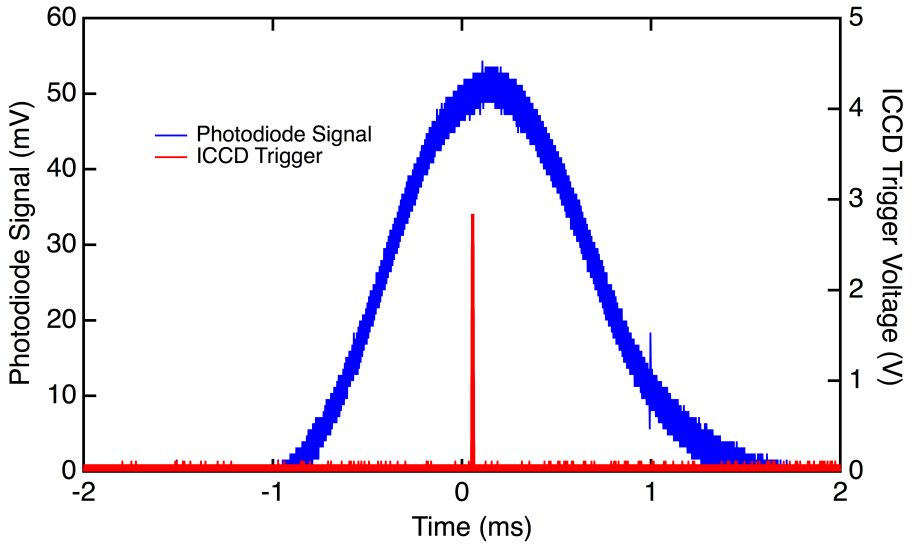
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High Speed Shutters Minimize Detector Exposure to Intense Plasma Background

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





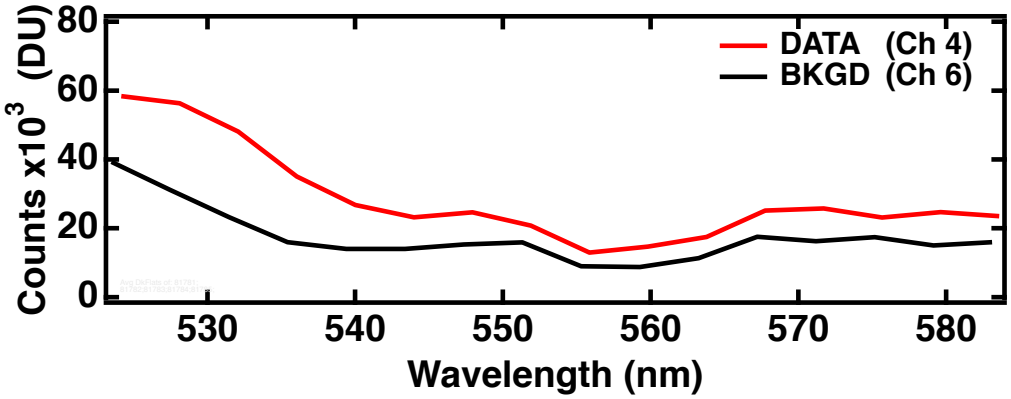


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High Speed Shutters Decrease Leakage Through the Image Intensifier

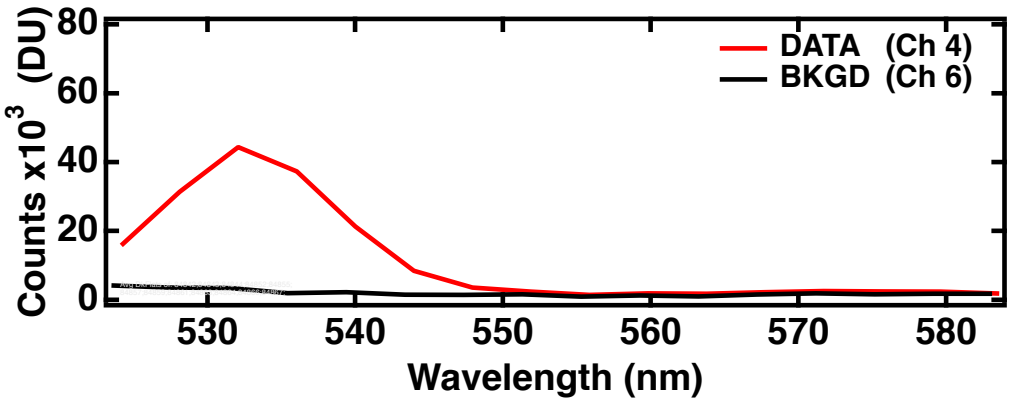
- Improved SNR
  - Lower background without impacting scattered signal

No fast shutter



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

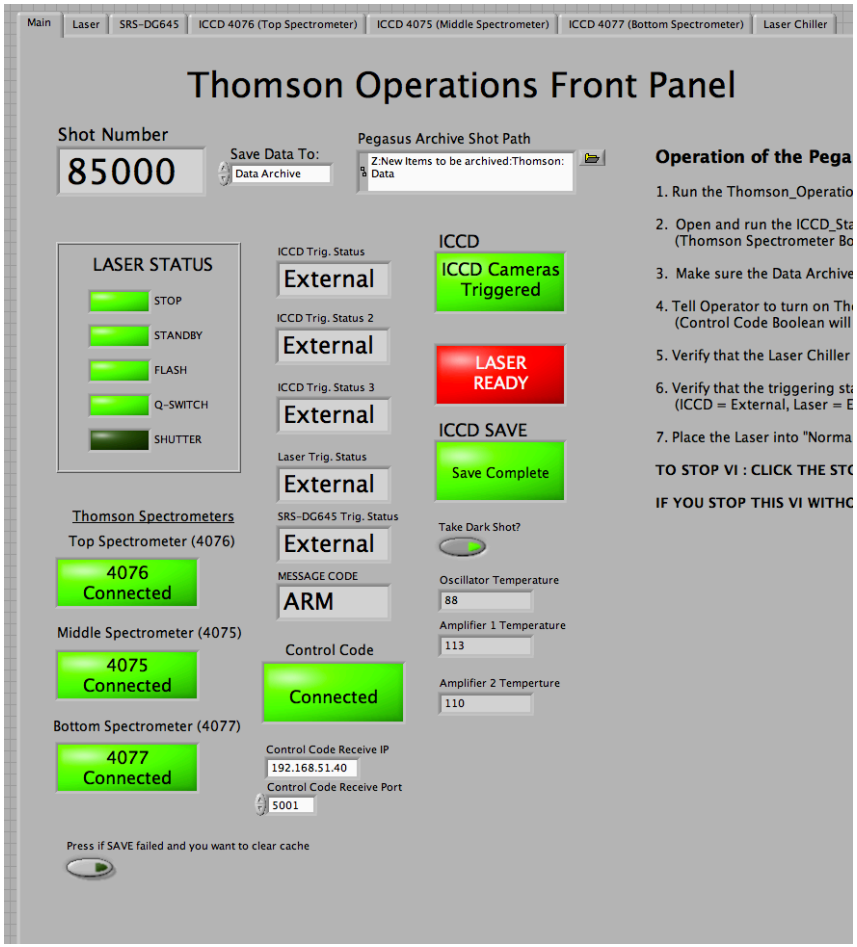
With fast shutter



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A Unified Thomson Control Interface has Automated and Streamlined Thomson Operation

- Integrated Thomson interface allows for safe and reliable operation of a complex diagnostic
- Real-time feedback of laser state and head temperatures identify and prevent system damage
- Automation allows diagnostician to pursue other venues during operation, such as real-time data analysis

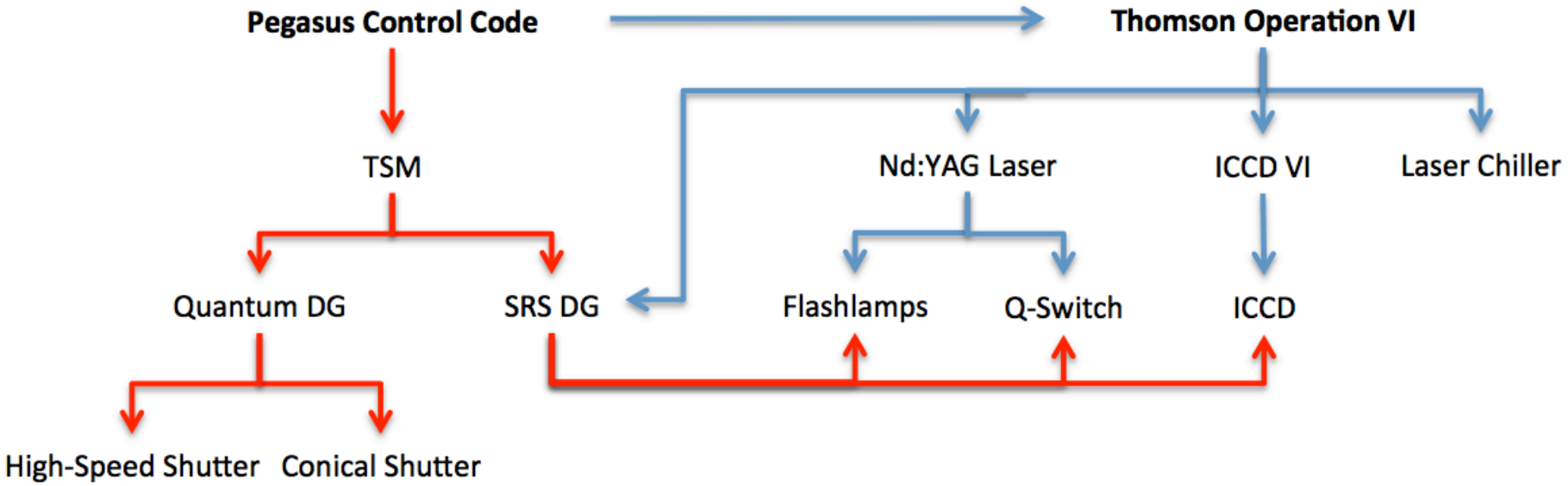


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LabVIEW Programming Allows for Synchronized and Automated Data Collection

- 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 Stanford Research System-Delay Generator 645
  - SRS-DG 645 interfaces with Pegasus shot cycle via Timing Sequence Modules (TSMs)

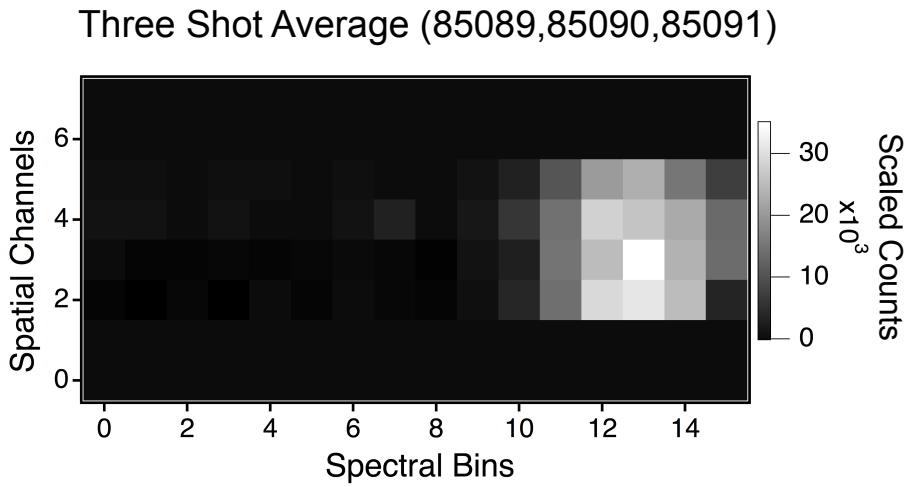


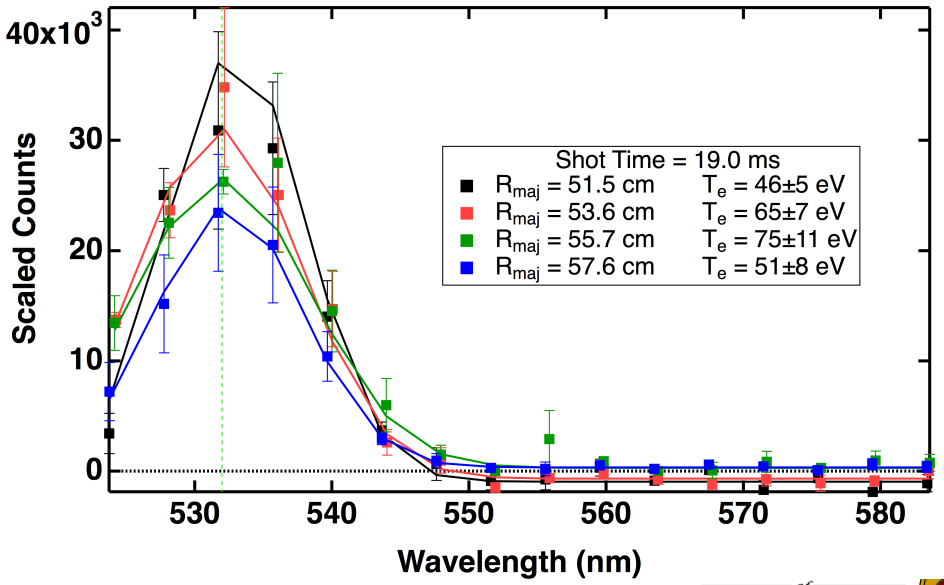
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Modifications to Triggering Configuration and System Automation Have Improved Data Collection

- Triggering modifications have increased laser power and scattered signal

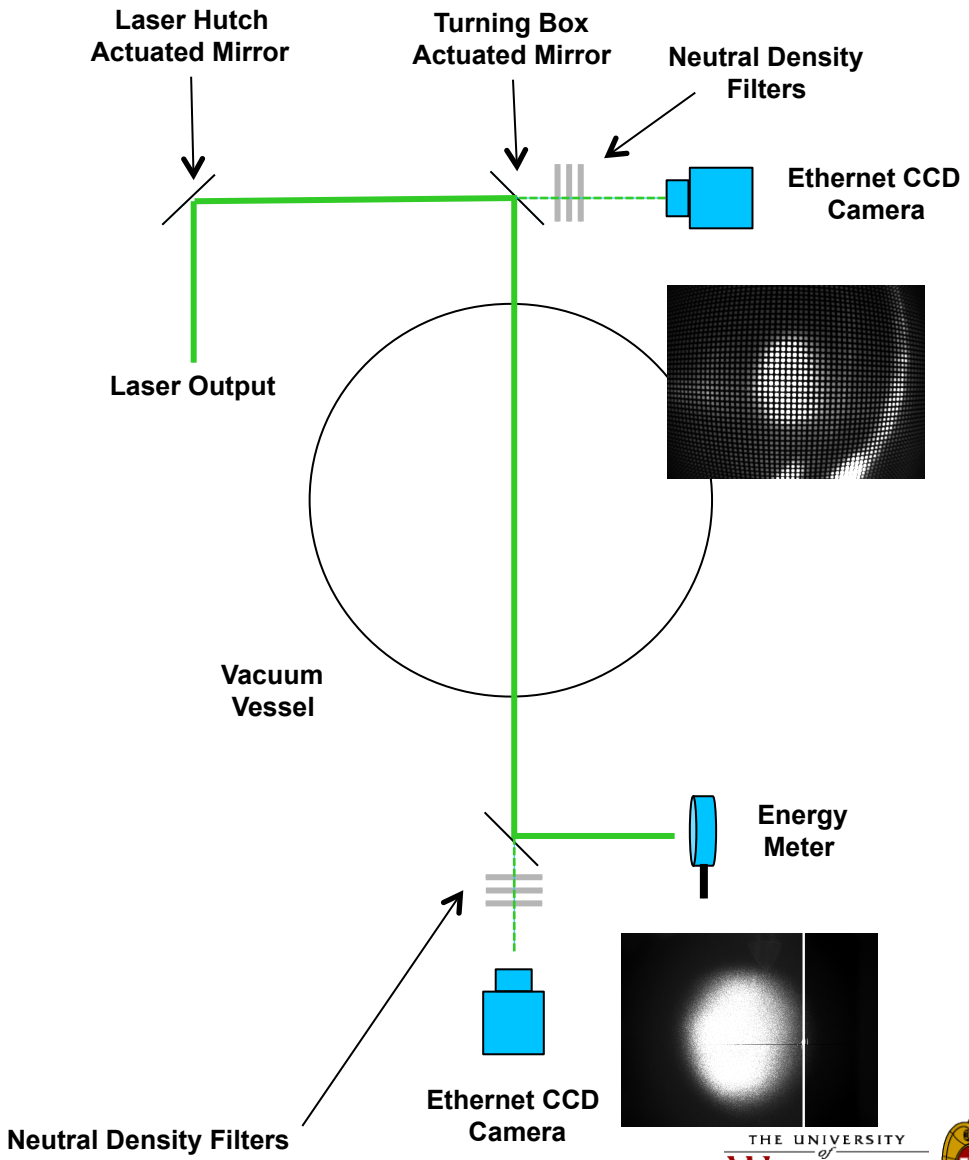
- Increase in observed signal improves photon statistics and data quality





Laser Alignment Maintained with Remotely Actuated Mirrors and Networked Cameras

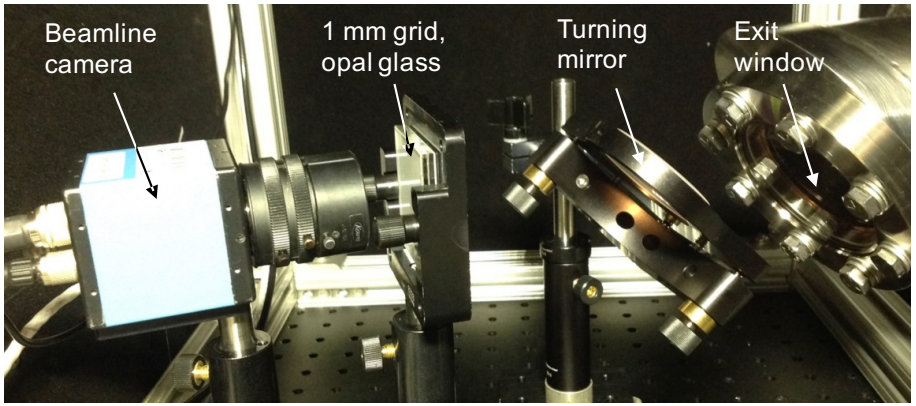
- Thermal variations, vibrations detune beam alignment
- Two actuated mirrors control laser alignment
  - Position monitored with cameras
- Energy meter measures exit power at end of beam line
  - Acts as beam dump



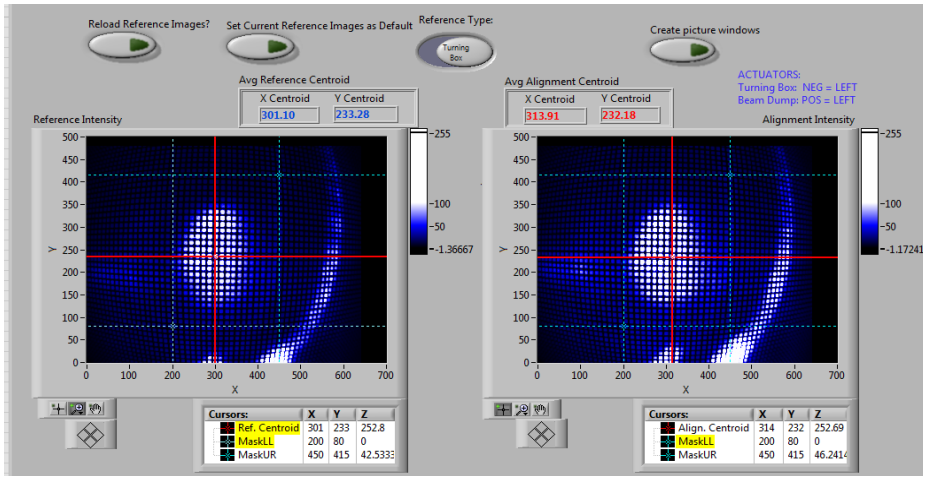
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LabVIEW Image Processing Tools Characterize Beam Alignment

- Two networked ImagingSource CCD cameras capture beam positions through vessel



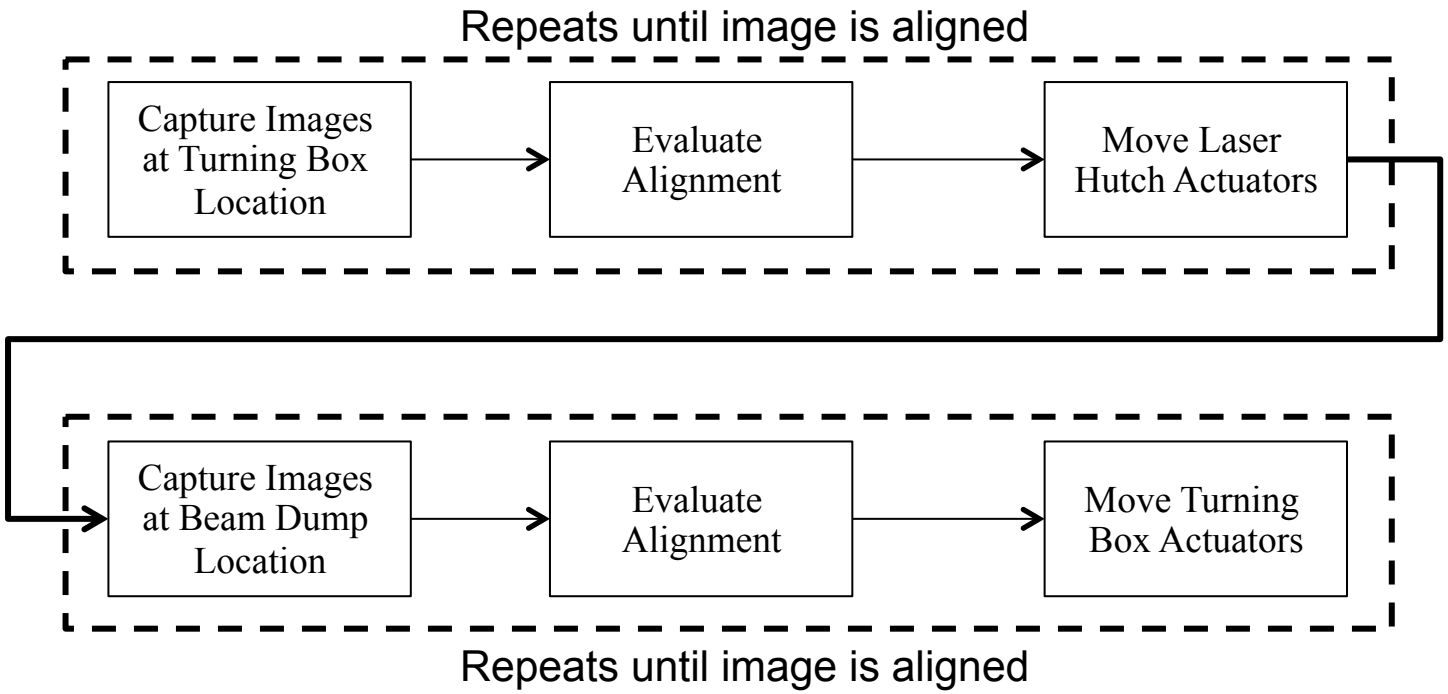
- Beam spots analyzed to evaluate laser alignment
  - Centroid values compared to fiducial values from Rayleigh calibrations
  - Auto alignment corrects misalignment to within a two pixel difference (~ 0.29 mm)



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Alignment VI Created to Provide Intra-Shot Beam Alignment

Flow Diagram used by Alignment VI



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Upgrades to Pegasus Thomson System Significantly Improve Reliability

- Modifications to laser timing and addition of high speed shutters improved scattered signal to noise ratio
- Recalibrated detector set and system automation improved diagnostic efficiency and reliability
- Improved Thomson system in use characterizing local helicity injection plasmas
- Future Work:
  - Investigate sources of background signal in Pegasus discharges
  - Integrate laser energy measurements, data analysis into automation process



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