Initial Thomson Scattering Survey of Local Helicity Injection and Ohmic Plasmas at the Pegasus Toroidal Experiment

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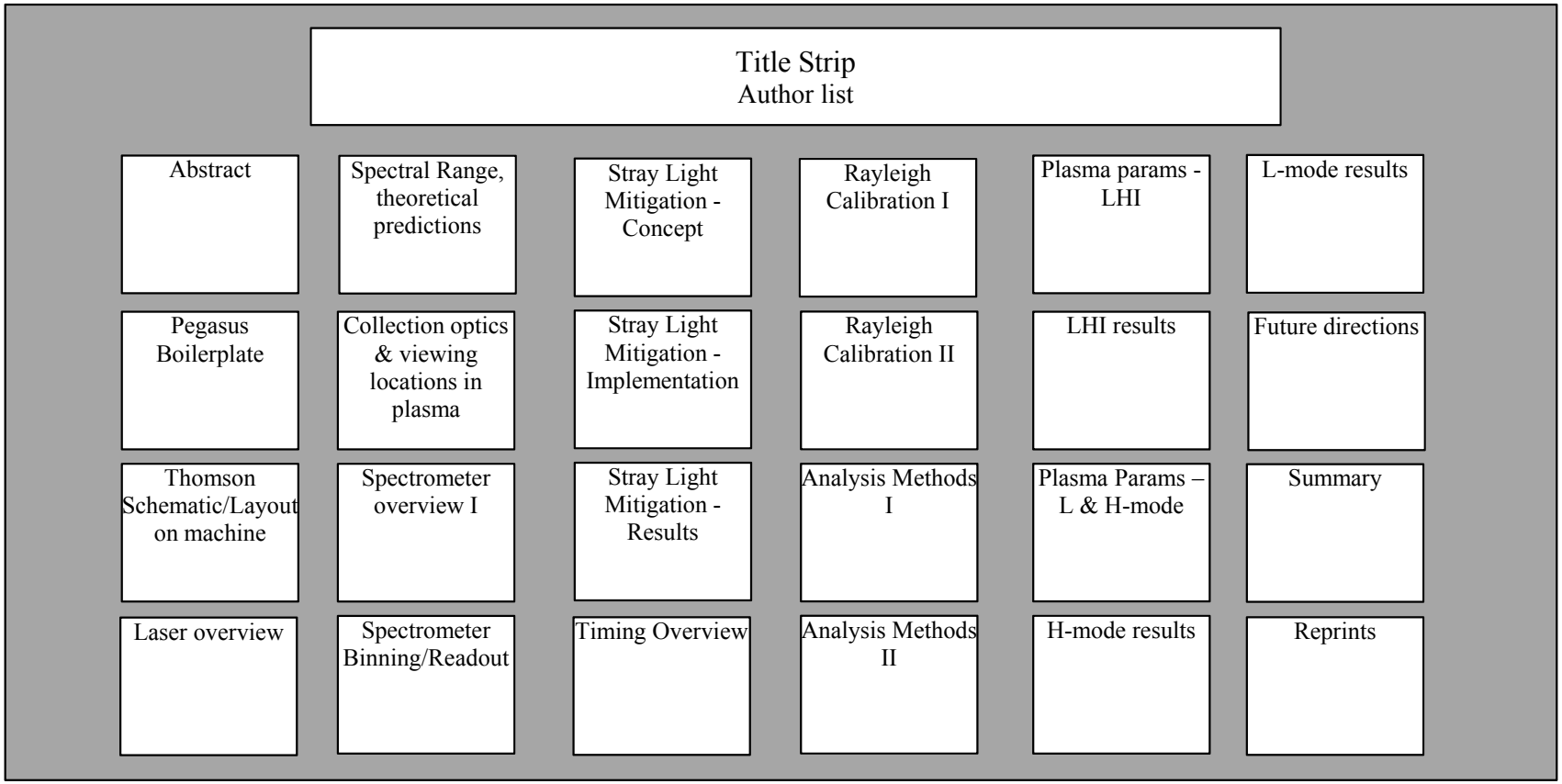
University of Wisconsin-Madison

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New Orleans, Louisiana
October 27-31, 2014



PEGASUS Toroidal Experiment

Layout

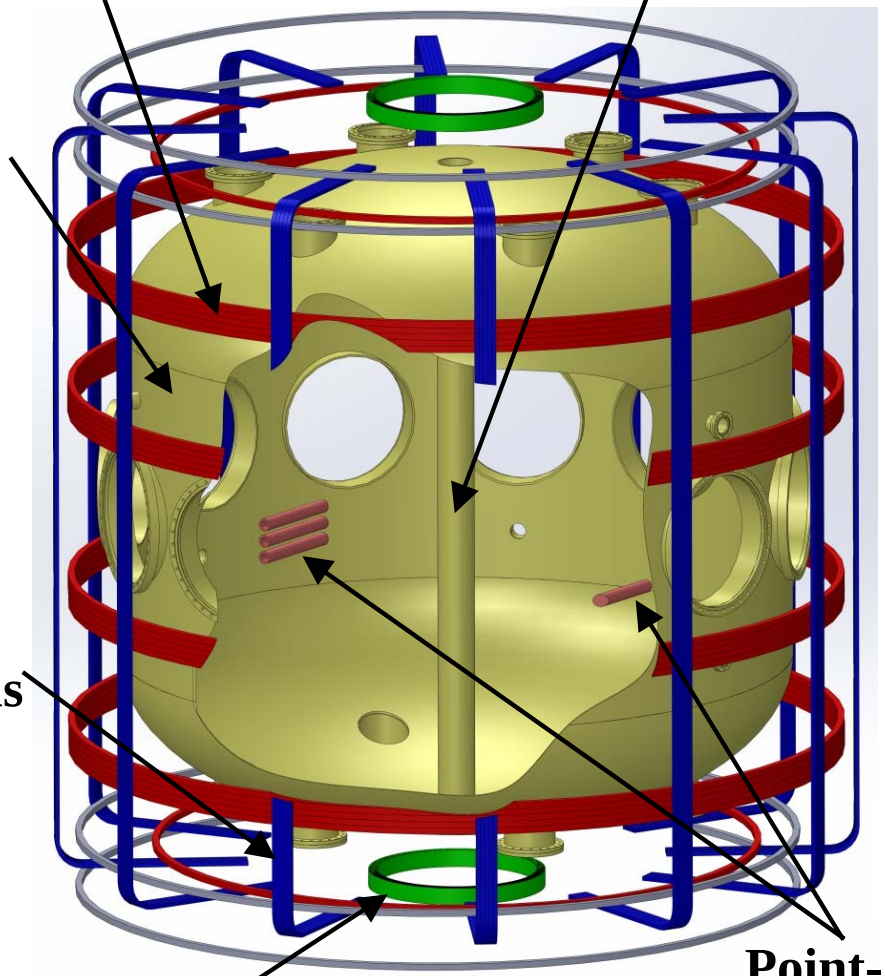


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Abstract

- Multipoint Thomson scattering on the Pegasus Toroidal Experiment
  - Nd:YAG laser — *532 nm, 2 J, 7 ns FWHM, <3 mm dia.*
  - Volume Phase Holographic (VPH) 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*
- 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
- Initial measurements obtained in plasma core for:
  - Local Helicity Injection (LHI) — $T_e \approx 75$ eV, $n_e \approx 3 \times 10^{18}$ m^{-3}, $I_p \sim 0.1$ MA
  - L-mode — $T_e \approx 150$ eV, $n_e \approx 2 \times 10^{19}$ m^{-3}, $I_p \sim 0.13$ MA
  - H-mode — $T_e > 175$ eV, $n_e \approx 2 \times 10^{19}$ m^{-3}, $I_p \sim 0.13$ MA

Pegasus is a compact ultralow-A ST



Experimental Parameters

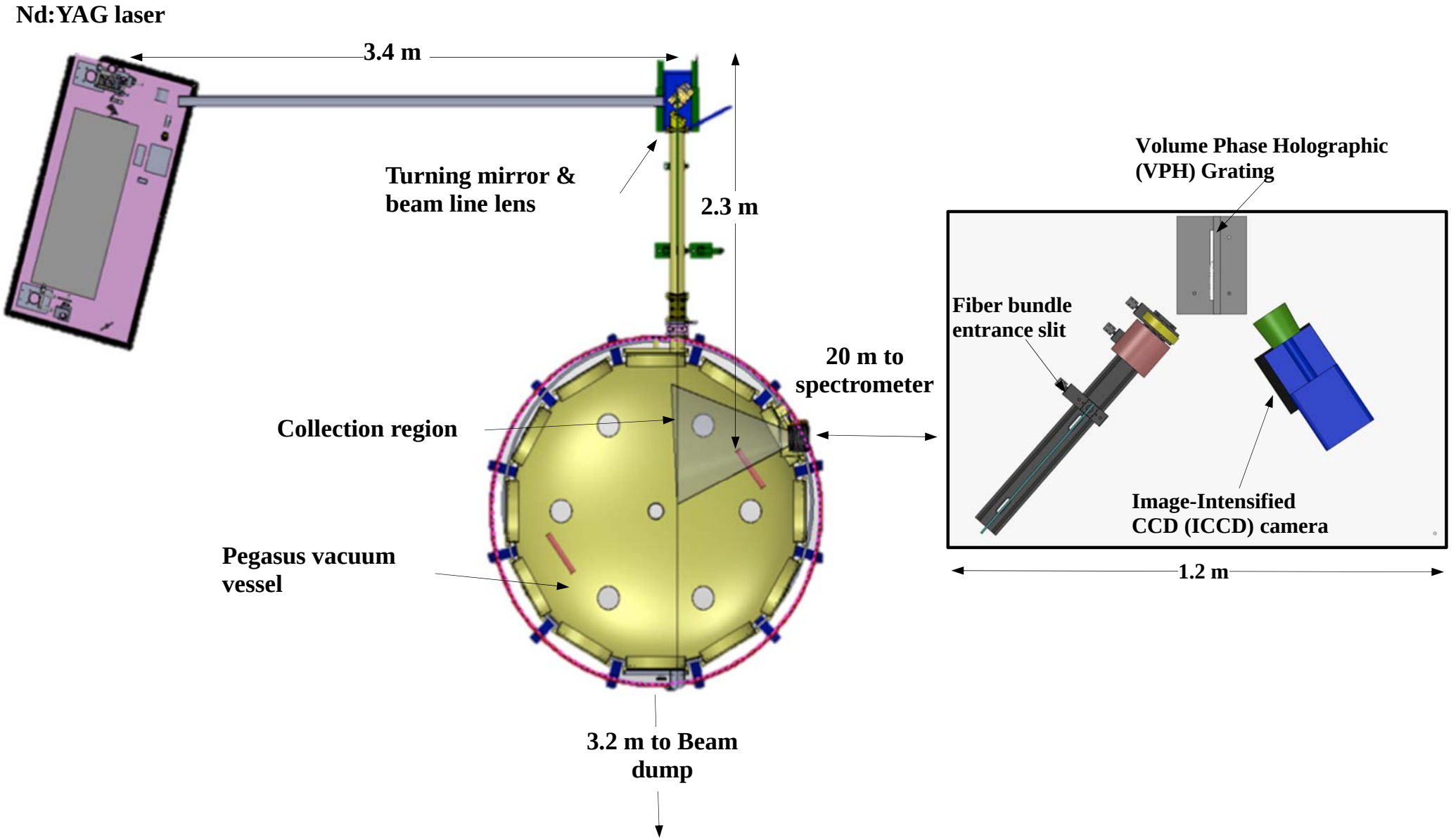
Parameter	Achieved	Goals
A	1.15 – 1.3	1.12 – 1.3
R(m)	0.2 – 0.45	0.2 – 0.45
I_p (MA)	≤ .21	≤ 0.30
I_N (MA/m-T)	6 – 12	6 – 20
RB_t (T-m)	≤ 0.06	≤ 0.1
κ	1.4 – 3.7	1.4 – 3.7
τ_{shot} (s)	≤ 0.025	≤ 0.05
β_t (%)	≤ 25	> 40
P_{HHFW} (MW)	0.2	1.0

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*

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

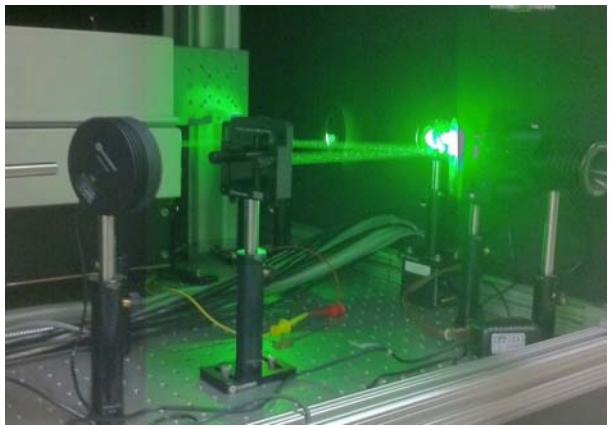


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Laser specifications balanced between commercial availability and physics needs

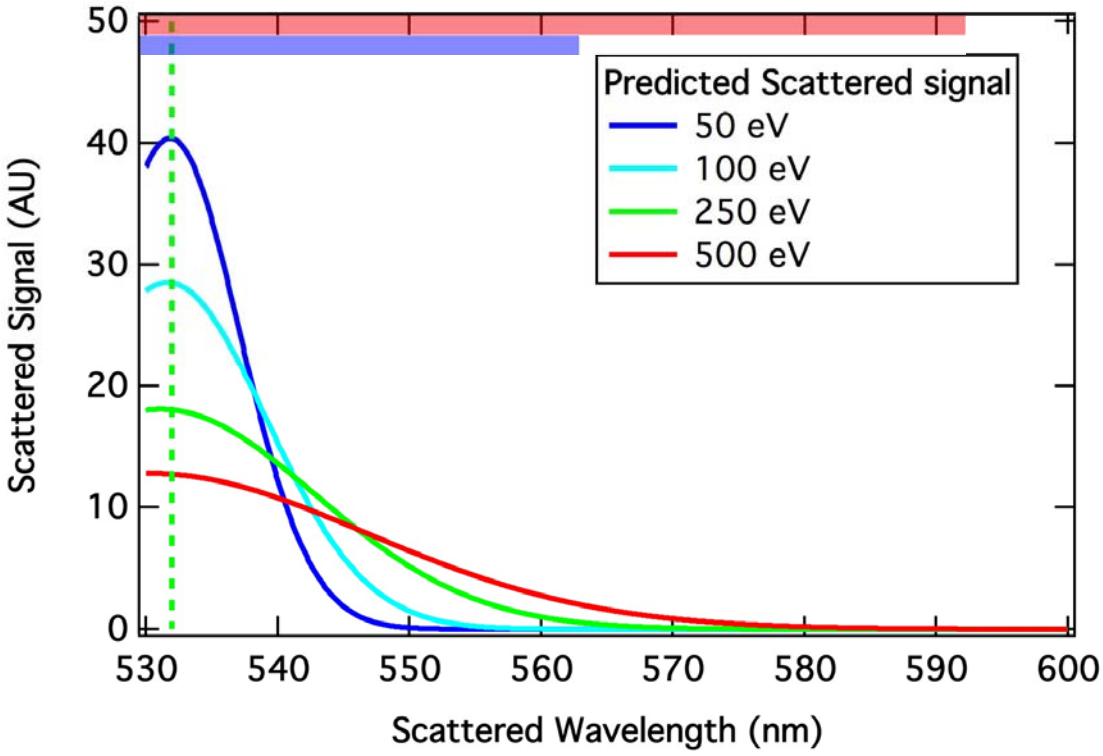
Specification	Value	Determining factors
Output Energy	≥ 2000 mJ	Scattered intensity fraction
Divergence	≤ 0.5 mrad	Desired spatial resolution, component damage thresholds
Pointing stability	≤ 50 μrad	Beam line
Pulse length	≥ 10 ns	Availability at desired power
Repetition Rate	≥ 10 Hz	Shot duration; availability
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



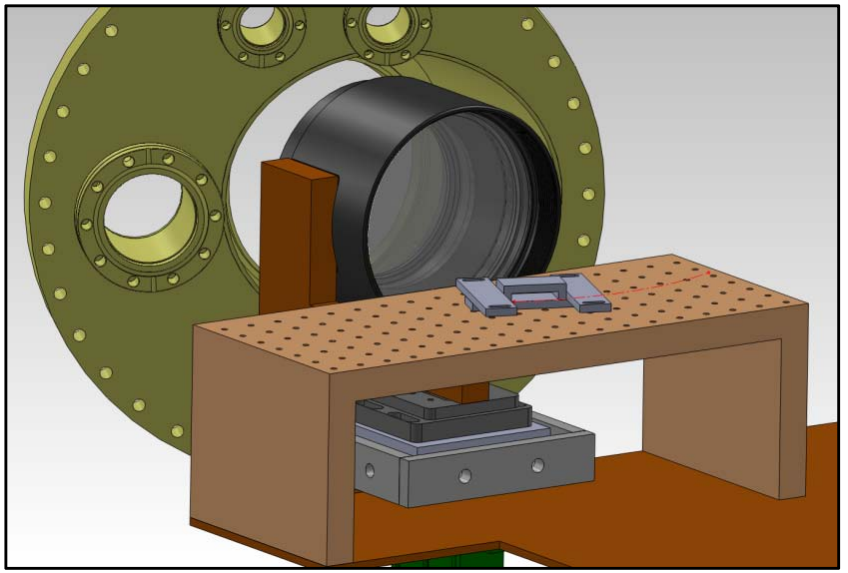
Based on: A.C. Selden, *"Simple Analytic Form of the Relativistic Thomson Scattering Spectrum,"* Phys. Lett. **79A**, 5,6 1980.

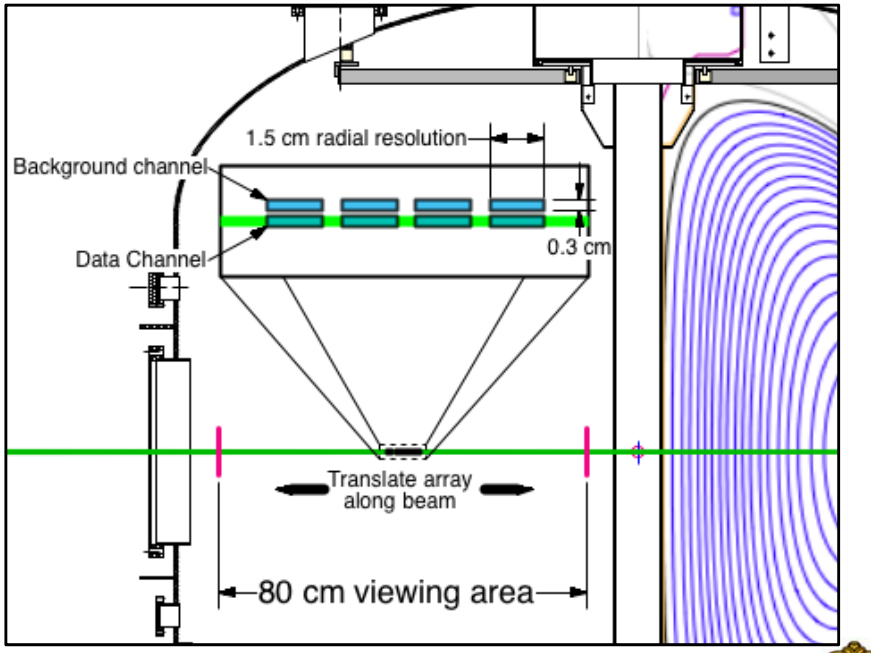
- Signal levels dictate λ bin sizes of 4 nm and 8 nm in the low and high temperature cases, respectively

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Custom collection optics allow flexible channel configurations

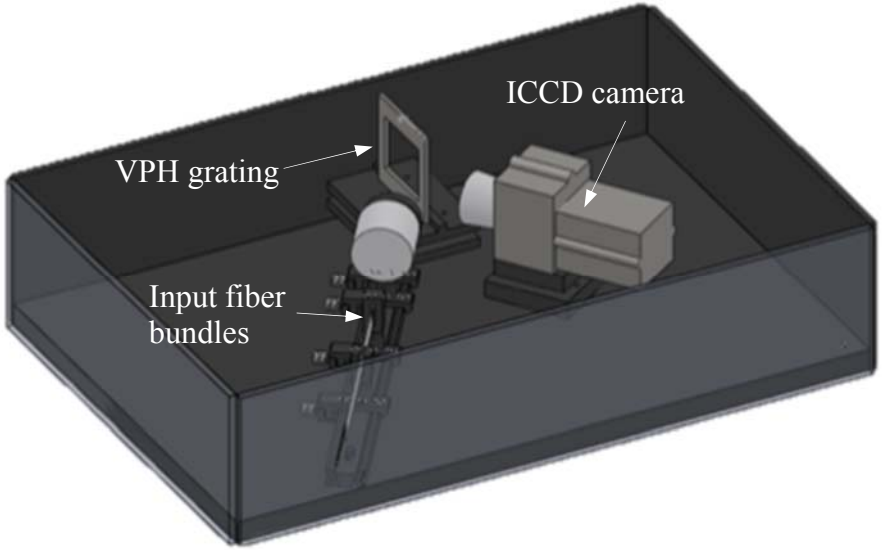
- Individual channels correspond to close-packed fiber bundles
  - Viewing volumes 1.5 cm x 0.3 cm
  - Roughly 194, 210 μm dia. fibers per bundle
- Initially, 4 data channels and 4 background monitors
  - Evaluate performance & plasma conditions and reconfigure as needed
- Scan array radially from shot-to-shot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

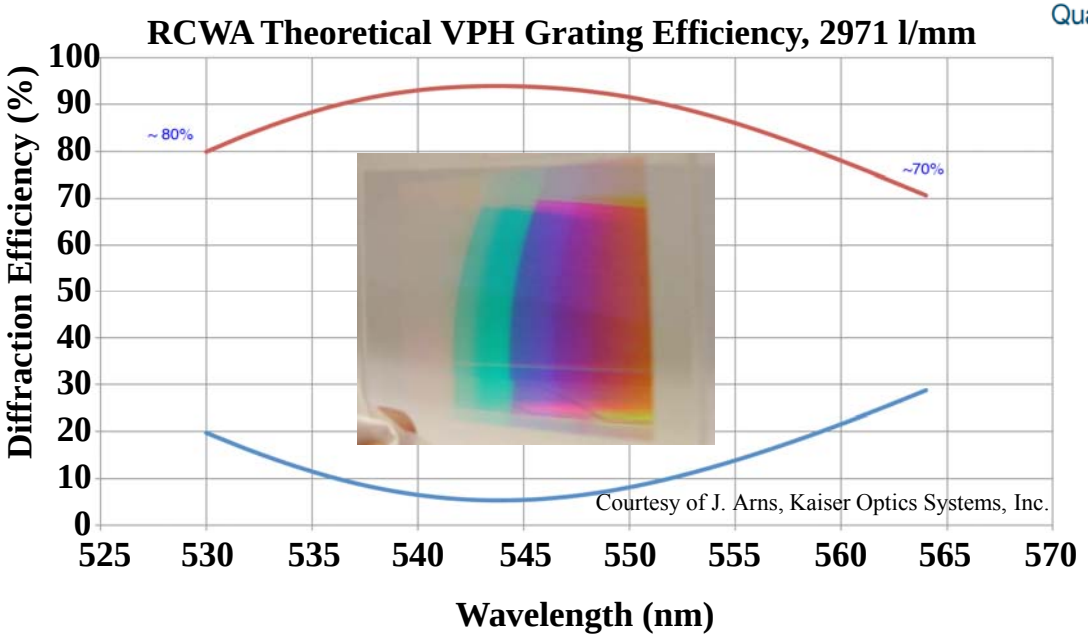


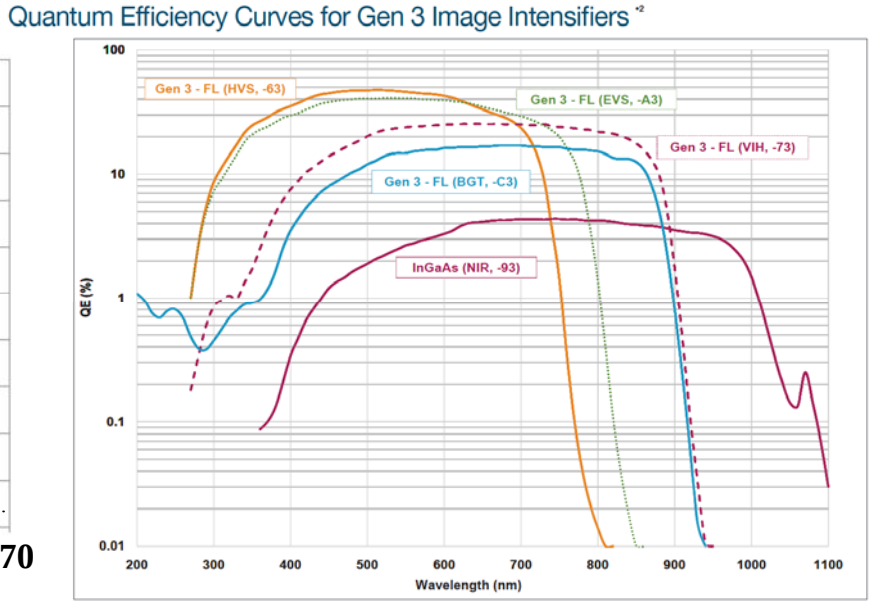


Spectrometers employ VPH gratings and ICCD cameras

- 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



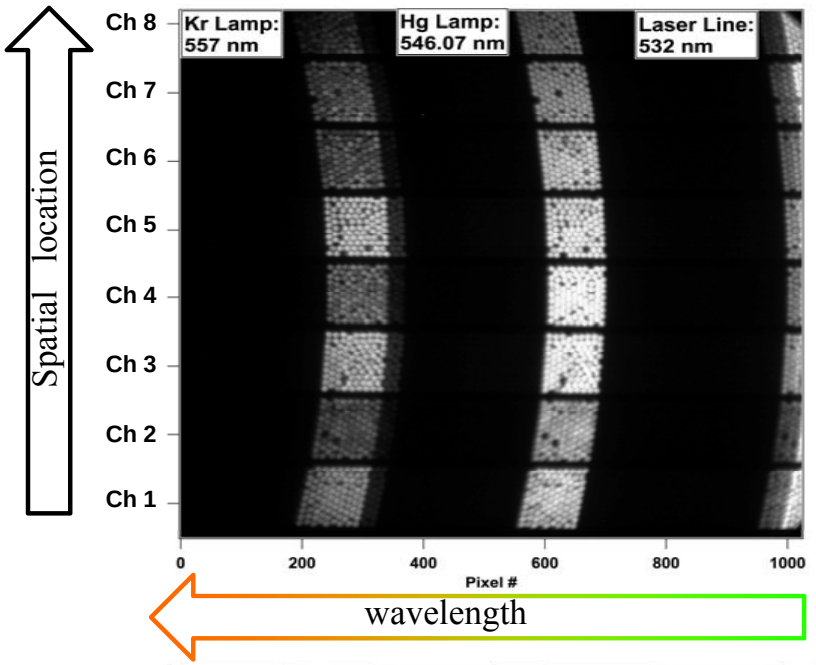




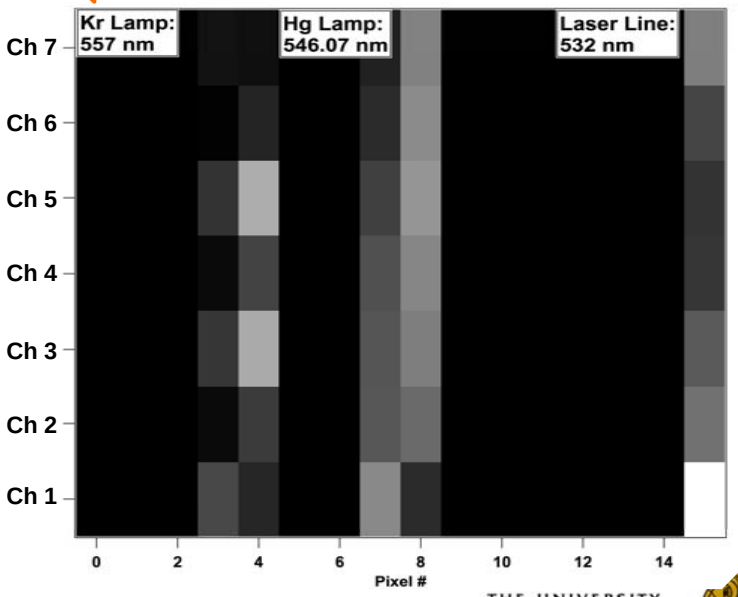
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On-CCD binning used to increase signal-to-readout-noise ratio

- 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



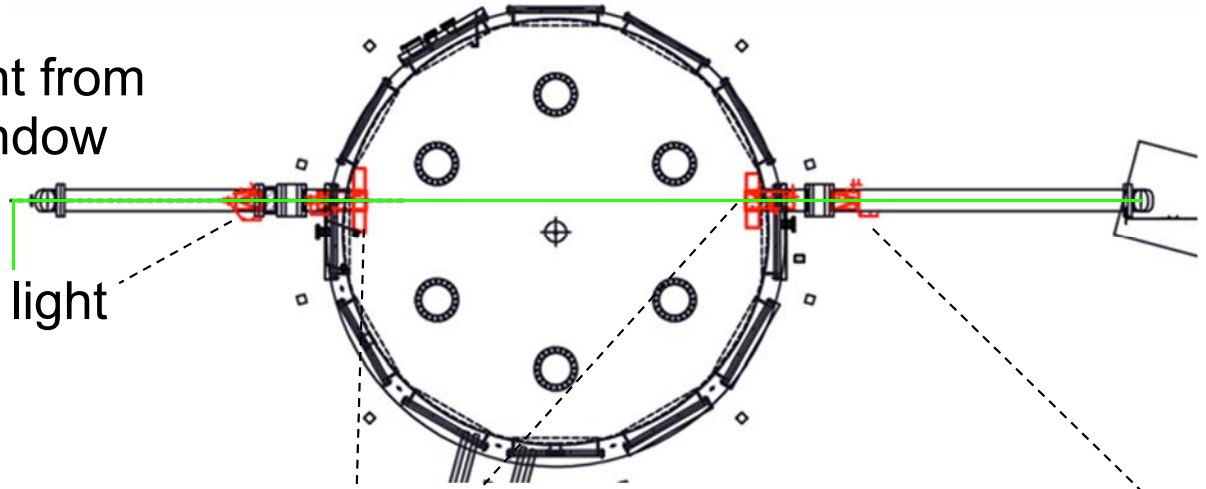
- Binning prior to readout boosts SNR
  - CCDs are 1024 x 1024 pixels
  - Read noise ~ 8 e- / read event
  - Bin 133 pix V x 64 pix H to obtain photon noise dominated statistics for typical plasma densities

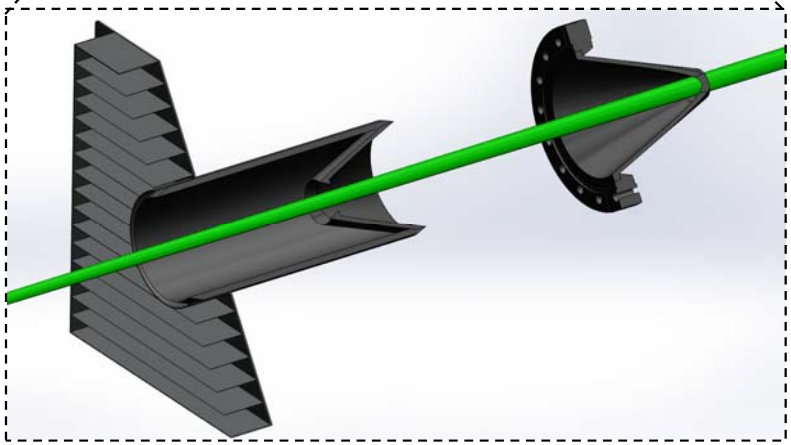


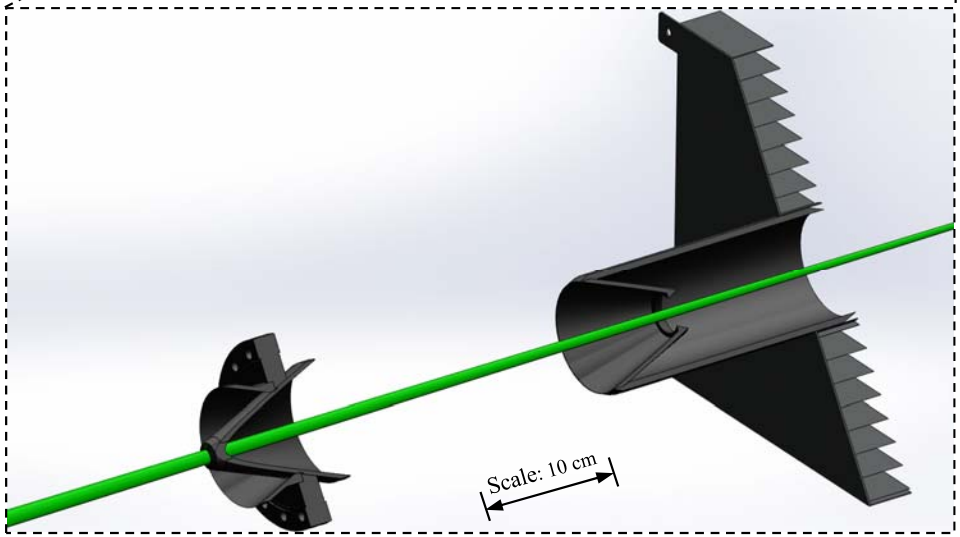
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Beam line apertures designed for stray light mitigation

- "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

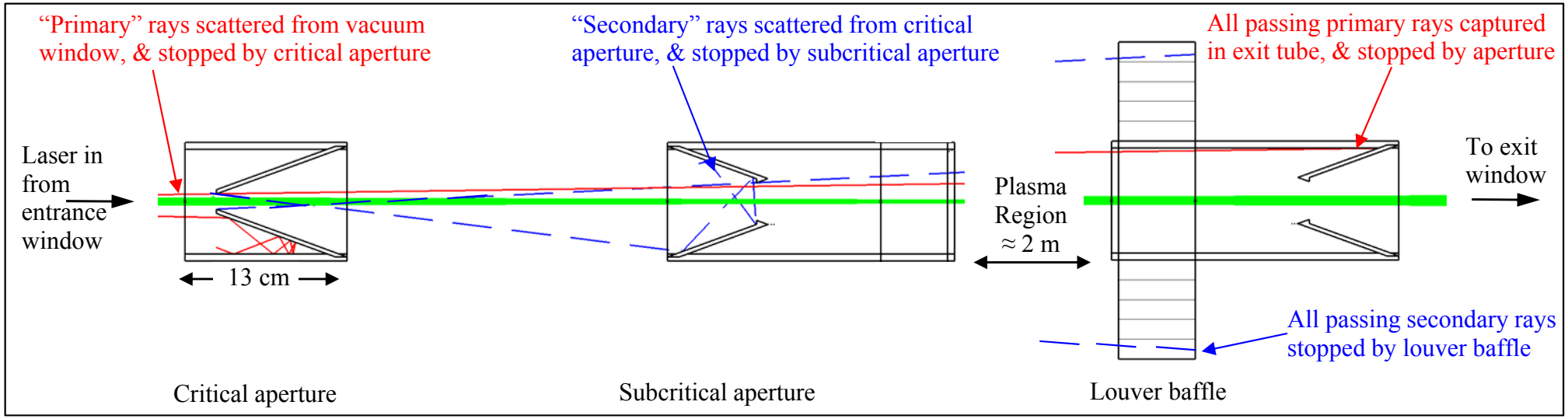






***Based on implementations by:*
C.J. Barth, et al. Rev. Sci. Instrum. ***82****, 3380 (1997)*
J.P. Levesque, et al., Rev Sci. Instrum. ***82****, 033501 (2011)*

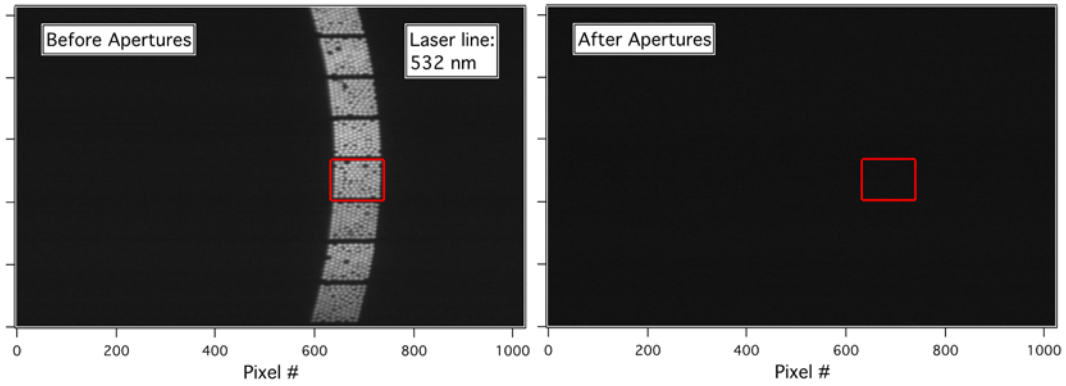
Ray tracing provides optimum location and diameters for aperture systems

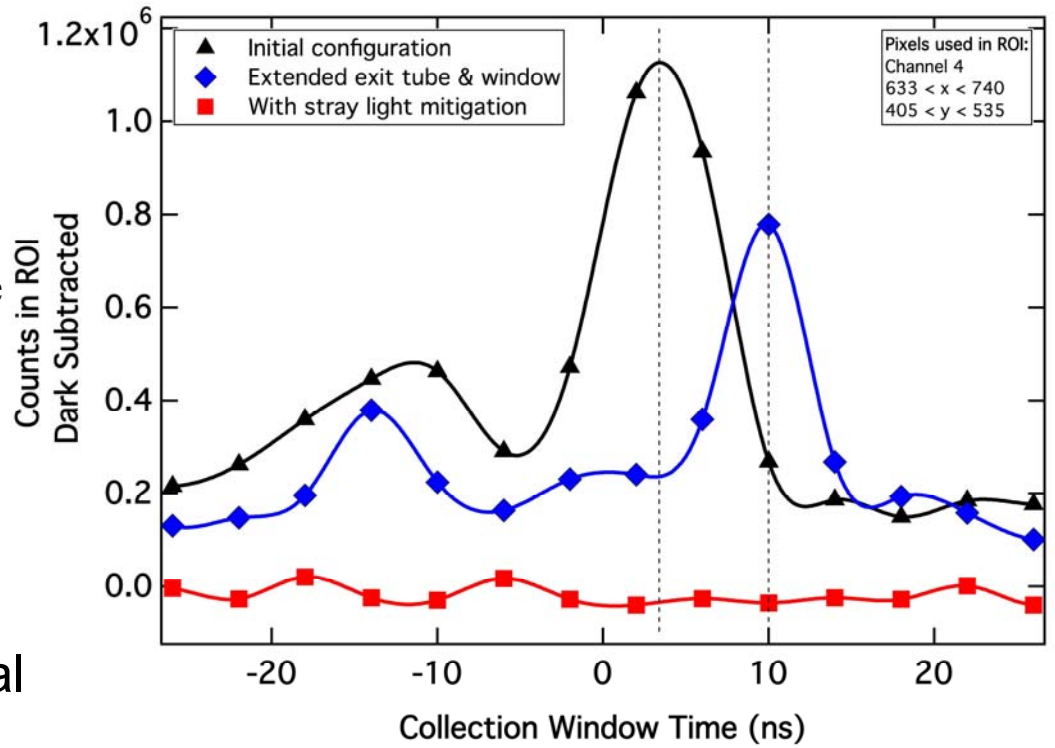


- Given:
  1. 3 mm radial clearance between focused laser beam and critical aperture knife edge
  2. 3 mm radial clearance between primary light cone and subcritical aperture knife edge
- Optimize:
  1. Locate critical aperture such that primary light cone falls within exit tube
  2. Locate subcritical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

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

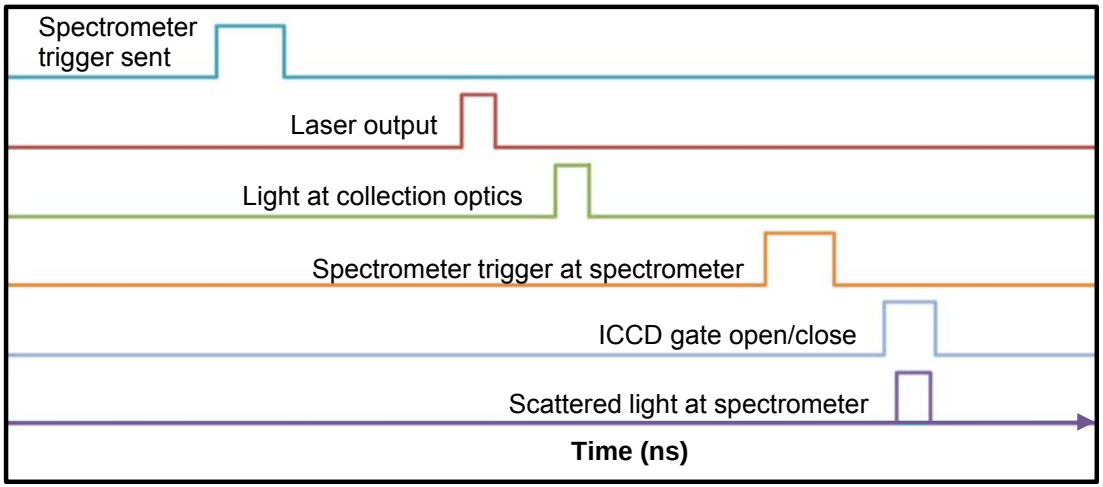




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System timing fine-tuned to ensure optimal signal collection

- 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

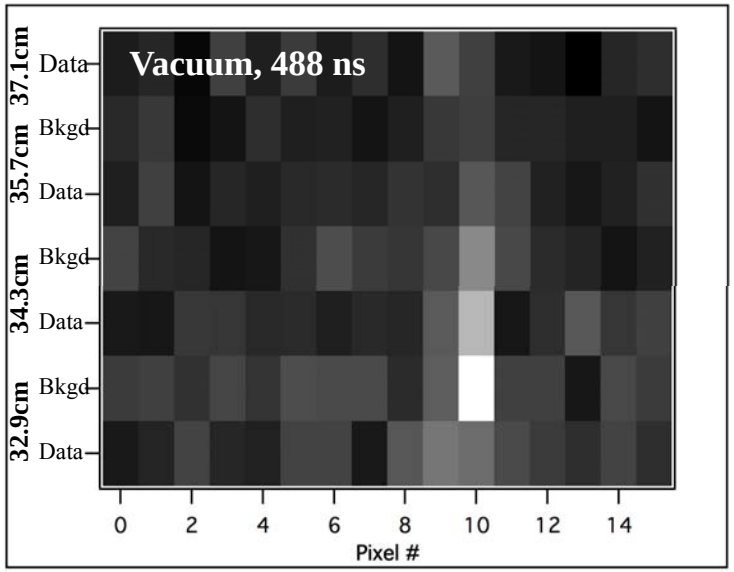


Signal Name	Delay		Start Time (ns)
	Value (ns)	Description	
Pegasus master trigger			0
Delay generator	85	Internal electronics	85
Flash lamps	0		85
Q-switch	240762	Lamp output	240847
Laser output	590	Internal laser	241437
Scattered light at coll. optics	27.35	Light speed (air)	241464.35
Scattered light 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**

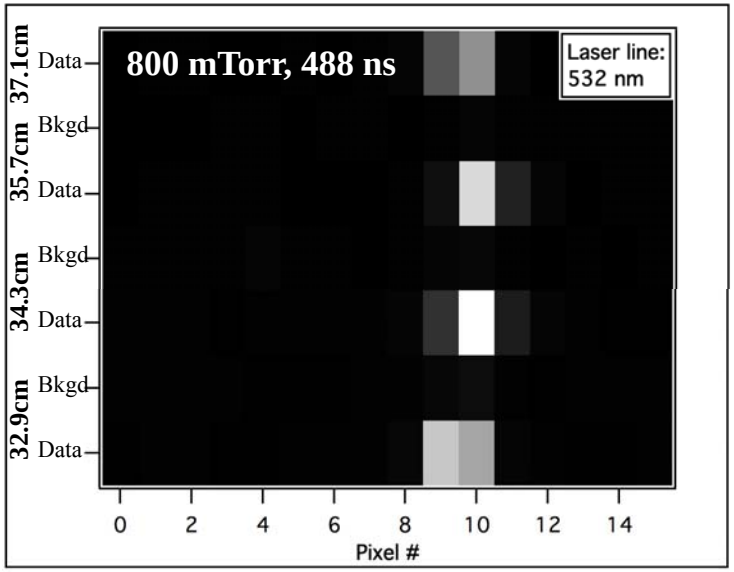
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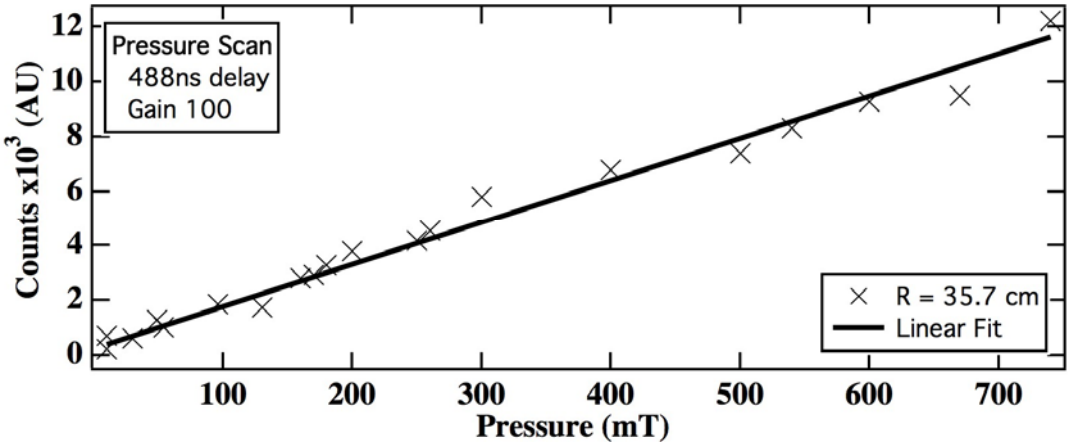
Rayleigh scattering used for system calibration

- 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

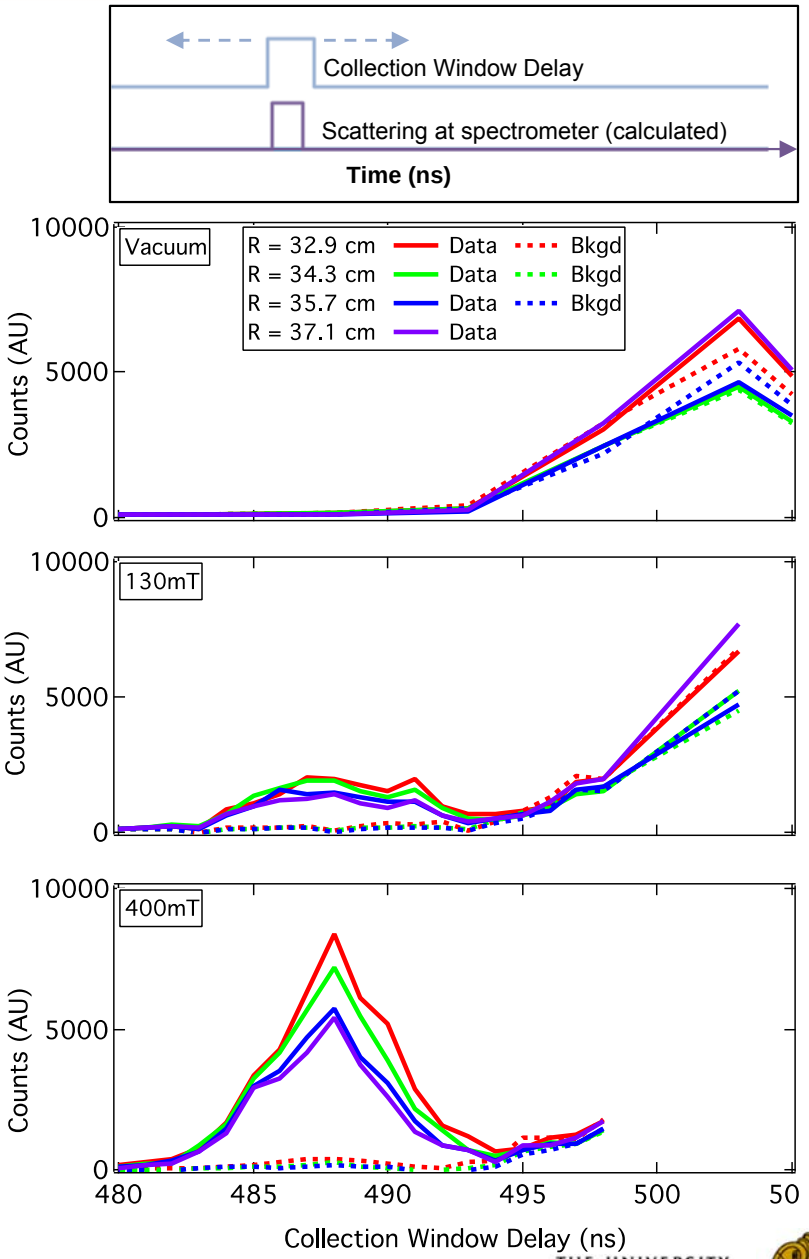




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Optimum collection time verified using Rayleigh scattered signal

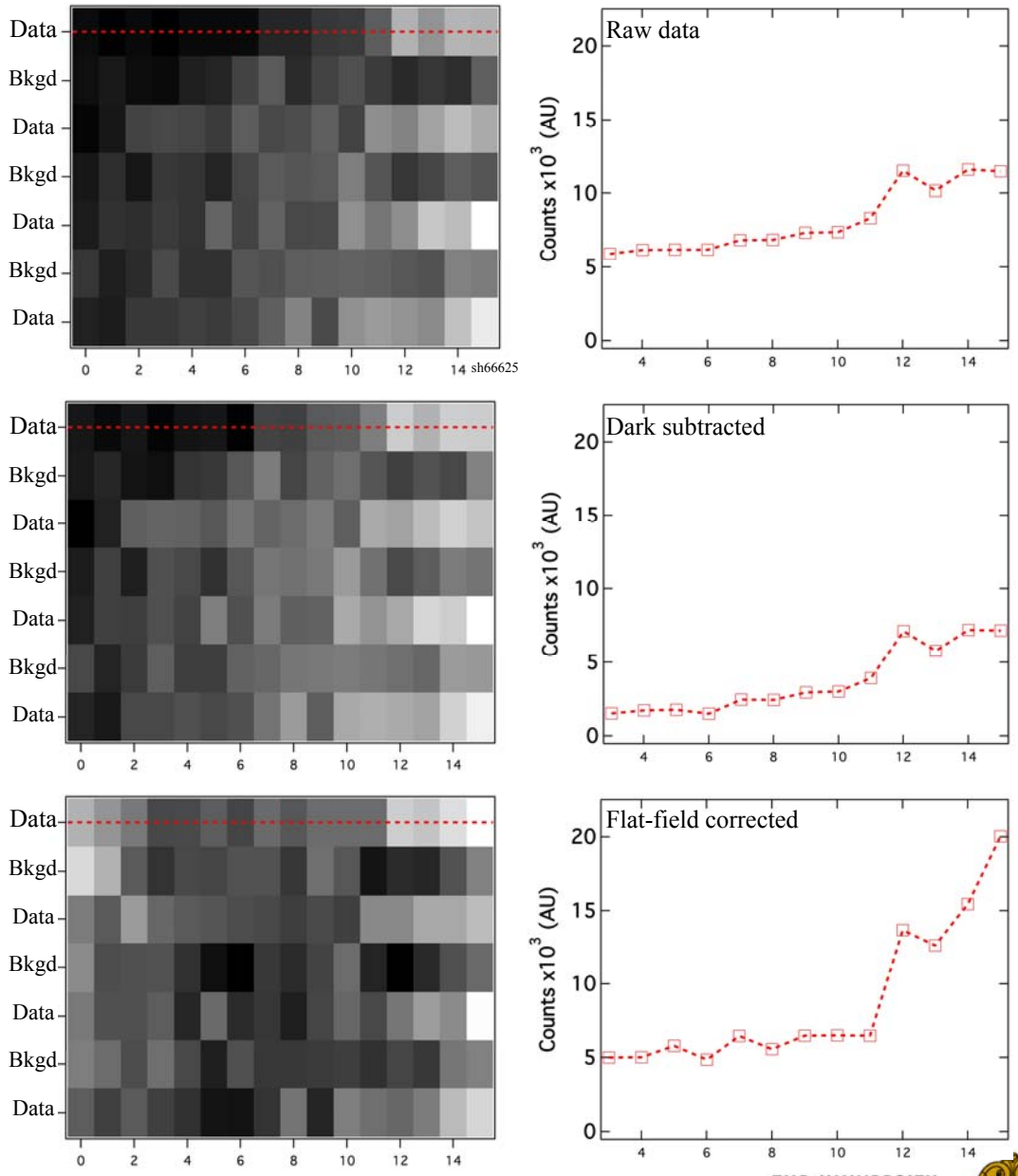
- ICCD provides single collection time window
  - Variable window start time, picosecond accuracy
  - Variable window width, 2 ns minimum
- During Rayleigh calibration, window start time scanned
- Once time of scattering found, window width reduced and fine time scan conducted.
- Time scan repeated at 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

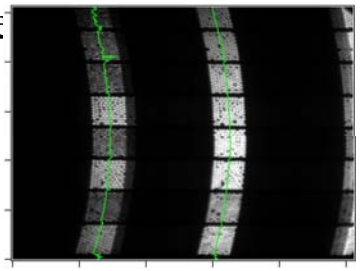
- Single image for each plasma shot
  - Each image contains 8 spatial channels (4 on-laser, 4 background)
- Subtract a dark image from plasma image to remove fixed pattern noise & offsets
  - Hot pixels
  - Camera background count offset
- Correct for flat field effects
  - Differing efficiencies vs.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



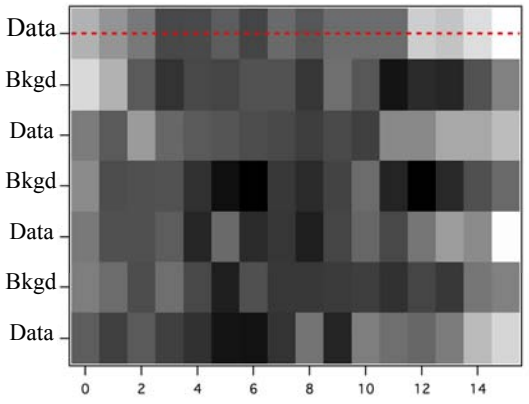
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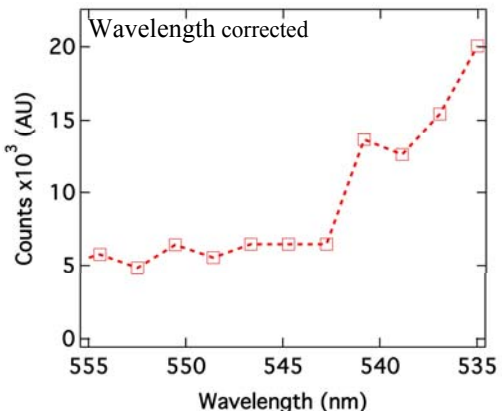
Initial analysis applies Gaussian fits

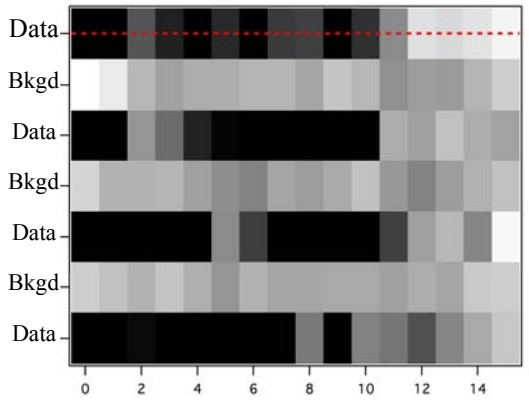
- Correct λ mapping for slit curvature
  - Use previous calibration with emission line

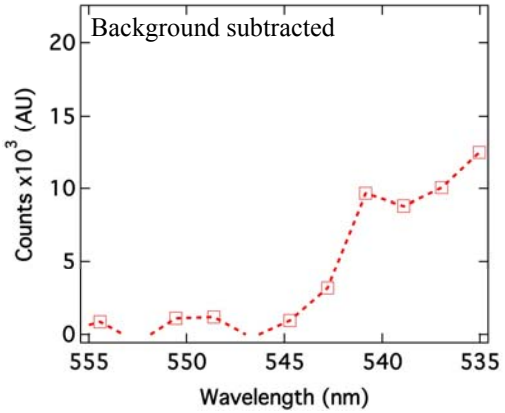


- Subtract background channels from data channels

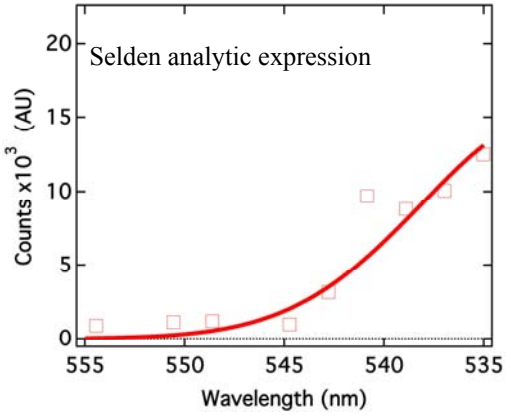


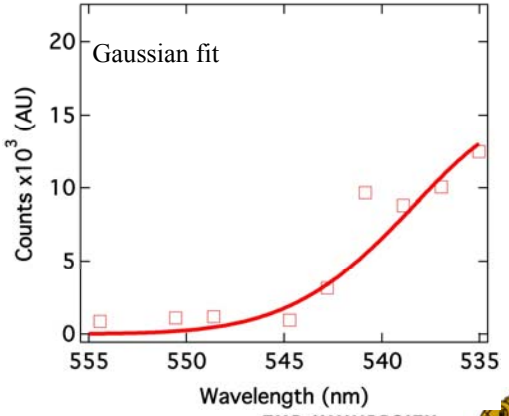






- Non-relativistic fit to Gaussian
- Comparison using Selden's relativistic formulation[1]
- More refined fitting in development



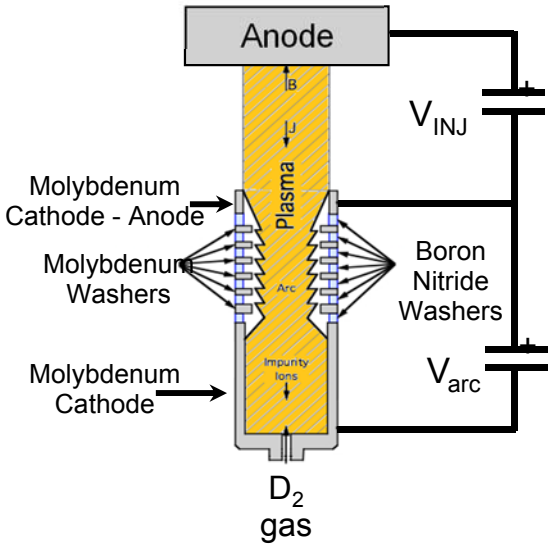


[1] A.C. Selden, Phys. Lett., **79A**, number 5, 6, Oct. 1980

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LHI provides non-solenoidal startup, and depends critically on T_e

- Local Helicity Injection (LHI) injects helicity using localized injectors at the plasma edge



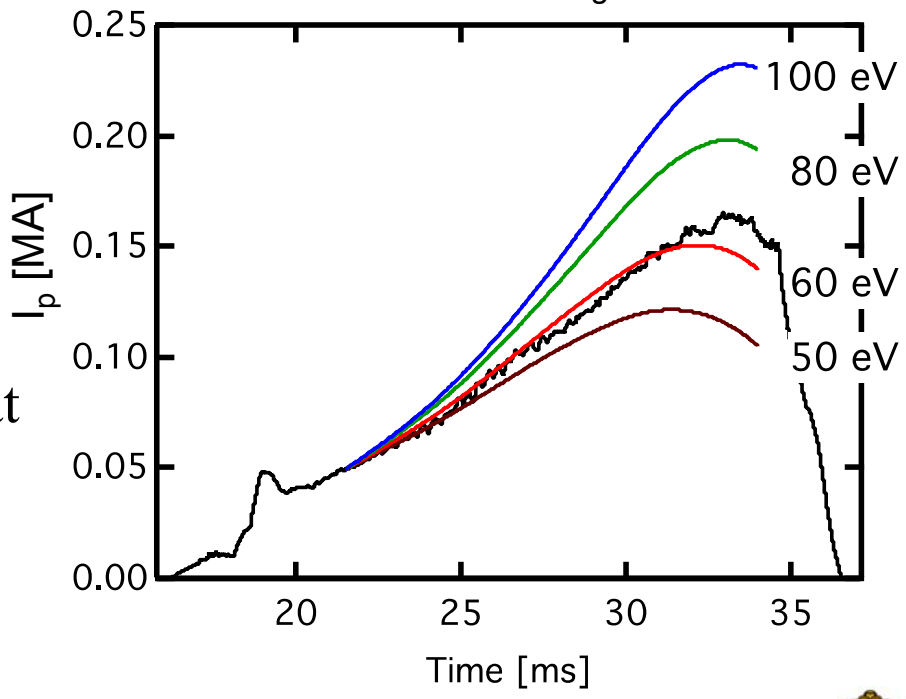
- Lumped parameter model + helicity conservation:

$$I_p\left[V_{eff}+V_{PF}+V_{Lp}+V_R\right]=0$$

See (this conference): J.L. Barr G03.00002 or M.W. Bongard PP8.00091

  - V_{eff}: From helicity conservation
  - V_{PF}: Poloidal induction voltage
  - V_{Lp}: Voltage from plasma self-inductance
  - V_R: Resistive dissipation from assumed flat Spitzer $T_e(R,t) = 70eV$

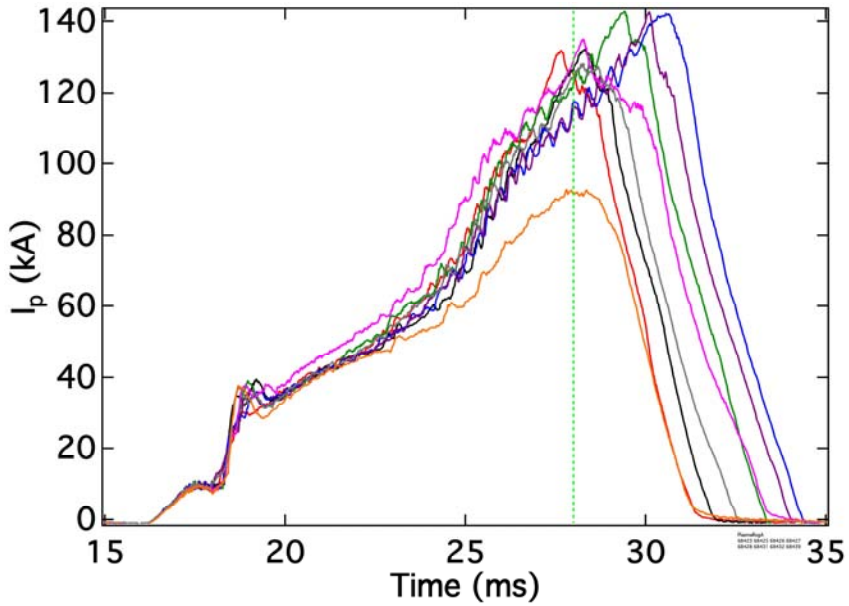
$$\eta_{Spitzer} \approx \frac{\pi e^2 m^{1/2}}{\left(4\pi\varepsilon_0\right)^2\left(kT_e\right)^{3/2}}\ln\left(12\pi n\lambda_D^3\right)$$

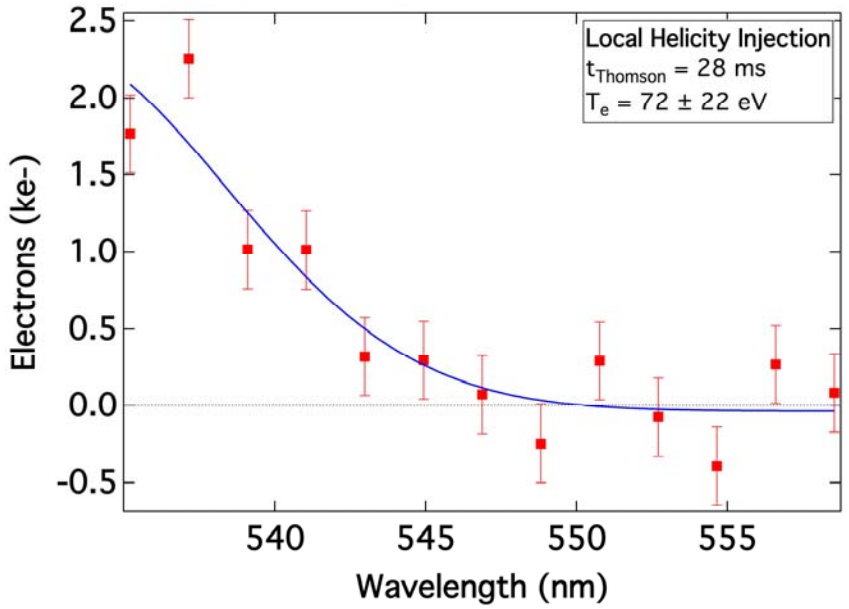


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Non-solenoidally driven plasmas exhibit warm cores at time of peak I_p

- Non-inductively driven plasmas observed with Thomson scattering
  - $I_p \sim 120$ kA, $I_{inj} \sim 4$ kA, $B_T \sim 0.1$ T
- Densities increased to maximize scattered intensity (~3×10^{18} m^{-3})
- Thomson array centered at R_{maj} = 35 cm, $t_{Thomson}$ = 28 ms
- Signal-to-noise ratio increased by averaging spatial points, and also repeated shots
- Initial results show $T_e \approx 72$ eV

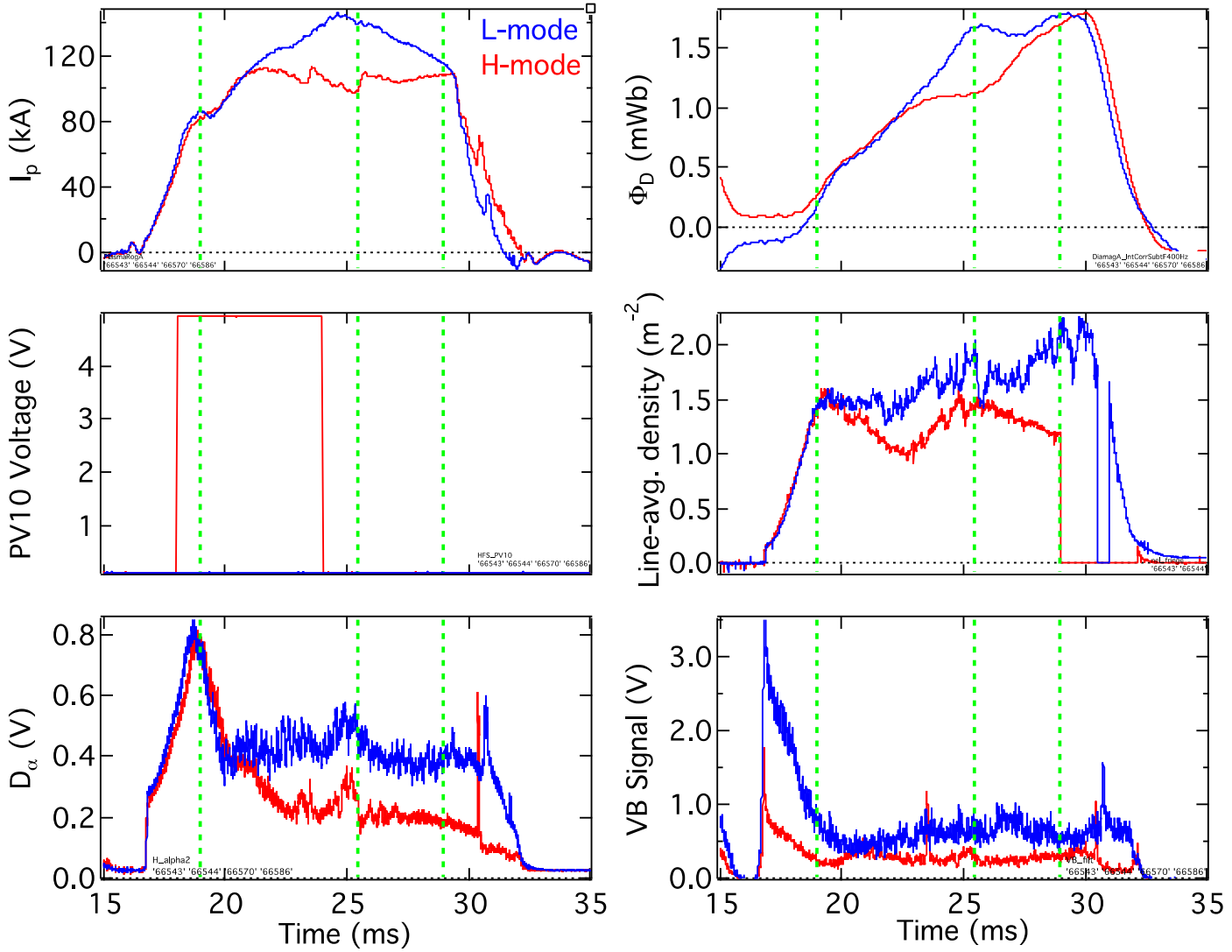




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L- and H-mode electron temperatures investigated for I_p ~ 130 kA

- Thomson data collected for L- and H-mode plasmas
  - $I_p = 130$ kA
  - $B_T = 0.1$ T
  - $\tau_{shot} \sim 20$ ms
- $R_{Thomson} = 35$ cm
- Time of Thomson collection window scanned from shot-to-shot *(dashed green line)*
  - Early phase
  - Mid-phase
  - Late phase



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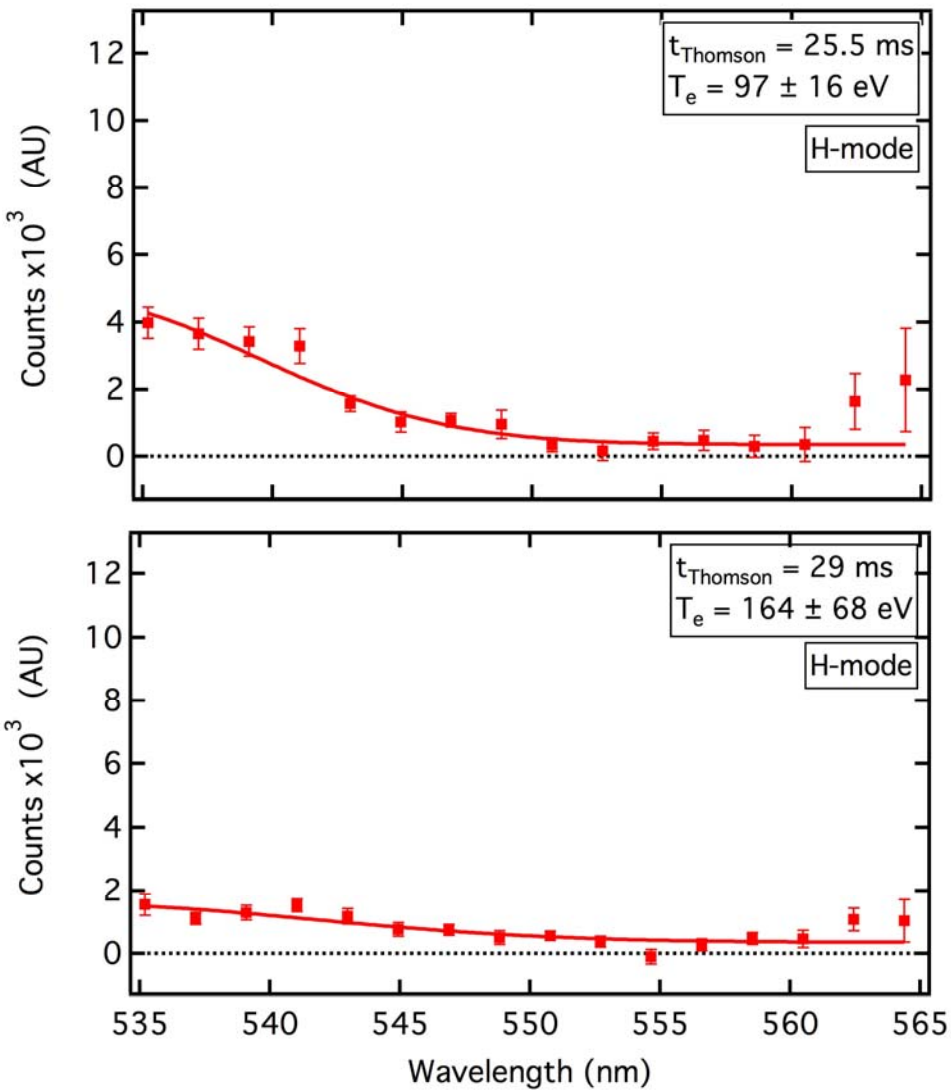
H-mode spectra indicate temperatures above spectrometer resolution

- TS spectrometer system designed with 2 interchangeable gratings:
  1. $10\ eV < T_e < 100\ eV$
  2. $100\ eV < T_e < 500\ eV$

- Initial studies used low-T_e grating

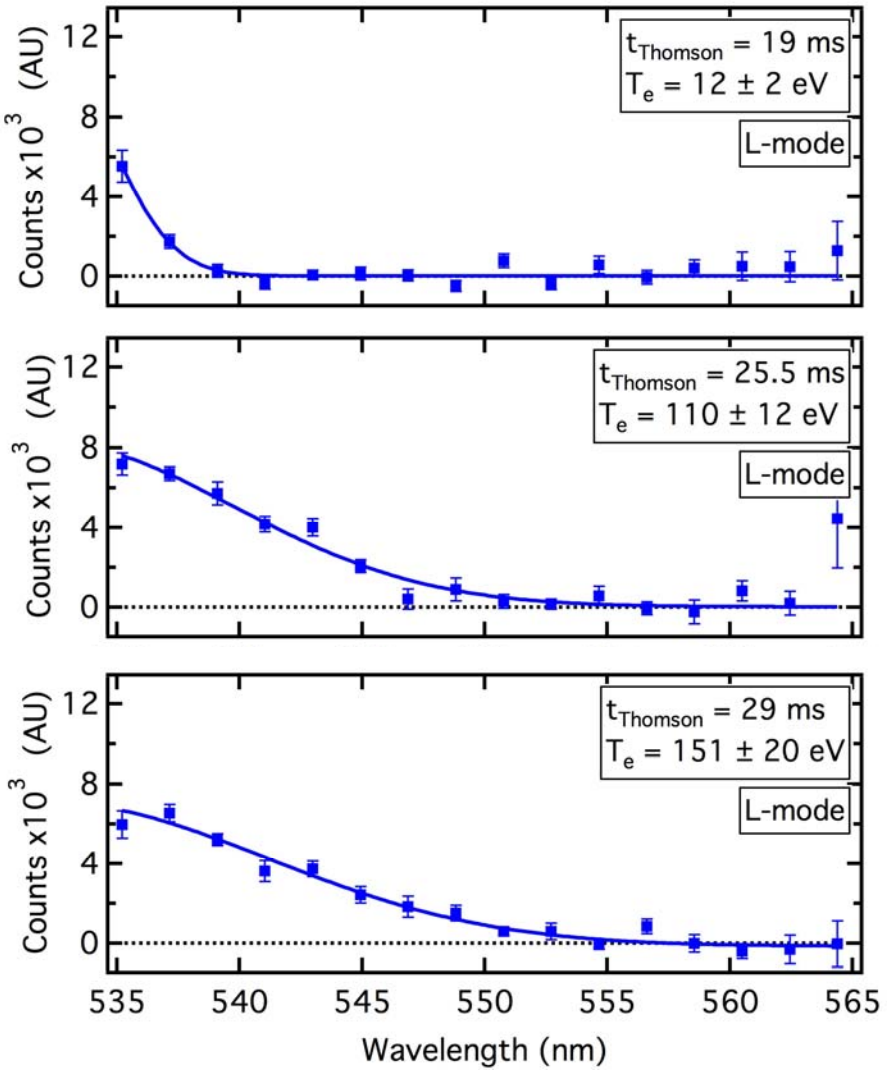
- High-T_e H-modes scatter past grating-detector wavelength limit
  - Detected signals close to noise floor, may distort calculated T_e
  - Uncertainties based on random error, while systematics at low intensities also affect δT_e

- Future studies will install high-T_e grating for H-mode operations



L-mode plasmas exhibit increasing T_e throughout discharge

- Position of 8-channel array spanned 32.9 cm < R_{maj} < 37.1 cm
  - 4 data channels
  - 4 background channels
- For initial analysis:
  - $t_{Thomson}$ = 19 ms, 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 ranges from 12 eV to 151 eV
  - More refinement of analysis planned

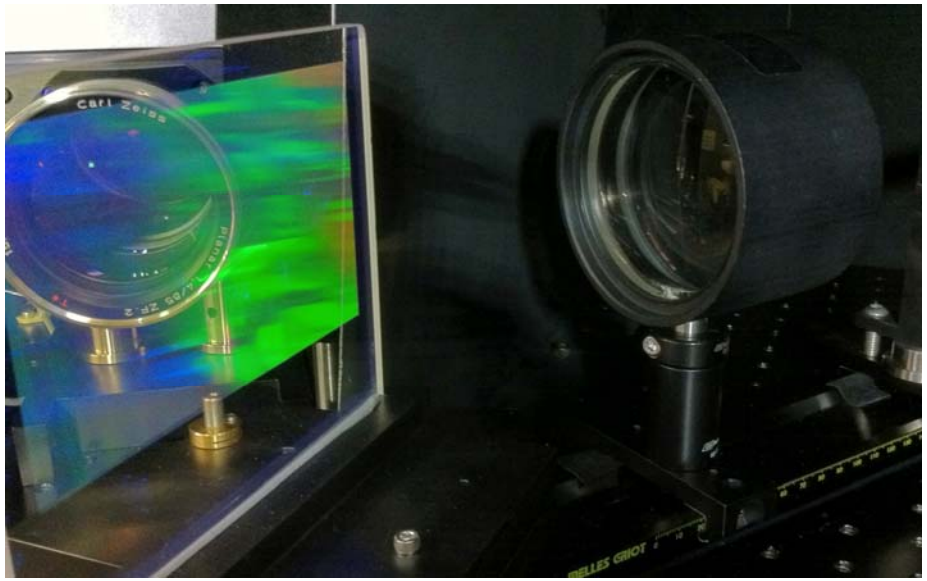


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Future Directions

- Install high-temperature grating to observe H-mode

- Conduct dedicated scan of LHI plasmas in time and space to assemble $T_e(r,t)$
  - Estimate confinement regime (ex. stochastic, L-mode, H-mode)
  - Identify regions of stochasticity
  - Determine temperature dependence on bulk parameters:
    I_{inj}, V_{inj}, λ_{edge}, I_p, B_T
  - Examine effect of intermittent, large-amplitude MHD events on $T_e(r,t)$



- Expand system to full 24 spatial channels

A novel Thomson scattering diagnostic on Pegasus yields first results

- Stray light successfully mitigated by beam line apertures, baffles, & increased exit tube length
- Overall system timing verified & optimized, and a Rayleigh scattering relative calibration was completed
- Data from L-mode indicates increasing T_e throughout discharges
- H-mode temperatures incompatible with installed grating
  - *Will install high-temperature grating in immediate future*
- LHI T_e indicates warm core in non-solenoidally-driven plasmas

Reprints

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