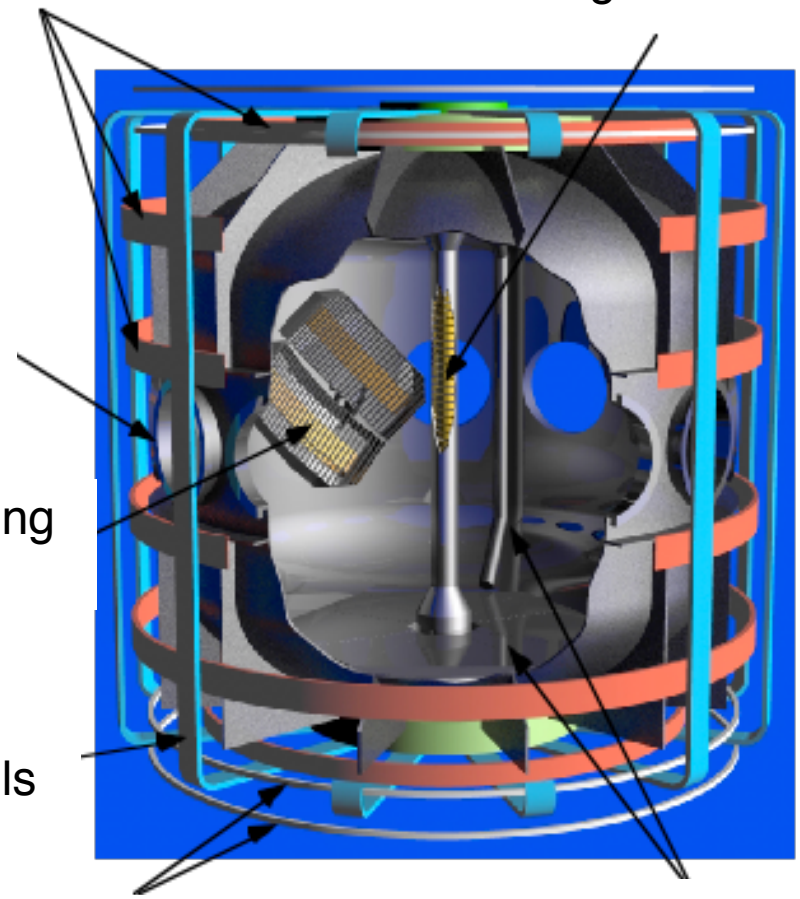
Abstract

- Use Thomson scattering to diagnose point-source helicity-driven plasmas on the PEGASUS Toroidal Experiment:
  - *Characterize dominant particle transport mechanisms*
  - *Quantify helicity dissipation sources*
  - *Expect* $\langle T_e \rangle = 50 - 500$ *eV,* $n_e > 10^{18}$ m^{-3}
- Design, test, and deploy a novel diagnostic system:
  - *2 J, 8 ns Nd:YAG laser operating in the visible, focused to* ≤ 3 *mm dia.*
  - *Custom collection optics views >70% of plasma radius, 1.4 cm resolution*
  - *High quantum efficiency, fast-gated CCD cameras detect signal*

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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Thomson scattering will aid estimation of resistive helicity dissipation

Total helicity in a tokamak geometry: $K = \int_V \left(\mathbf{A} + \mathbf{A}_{vac}\right) \cdot \left(\mathbf{B} - \mathbf{B}_{vac}\right) \mathrm{d}^3\mathrm{x}$

$$\frac{dK}{dt} = -2\int_V \eta \mathbf{J} \cdot \mathbf{B}\, \mathrm{d}^3\mathrm{x} - 2\frac{\partial \psi}{\partial t}\Psi - 2\int_A \Phi \mathbf{B} \cdot \mathrm{ds}$$

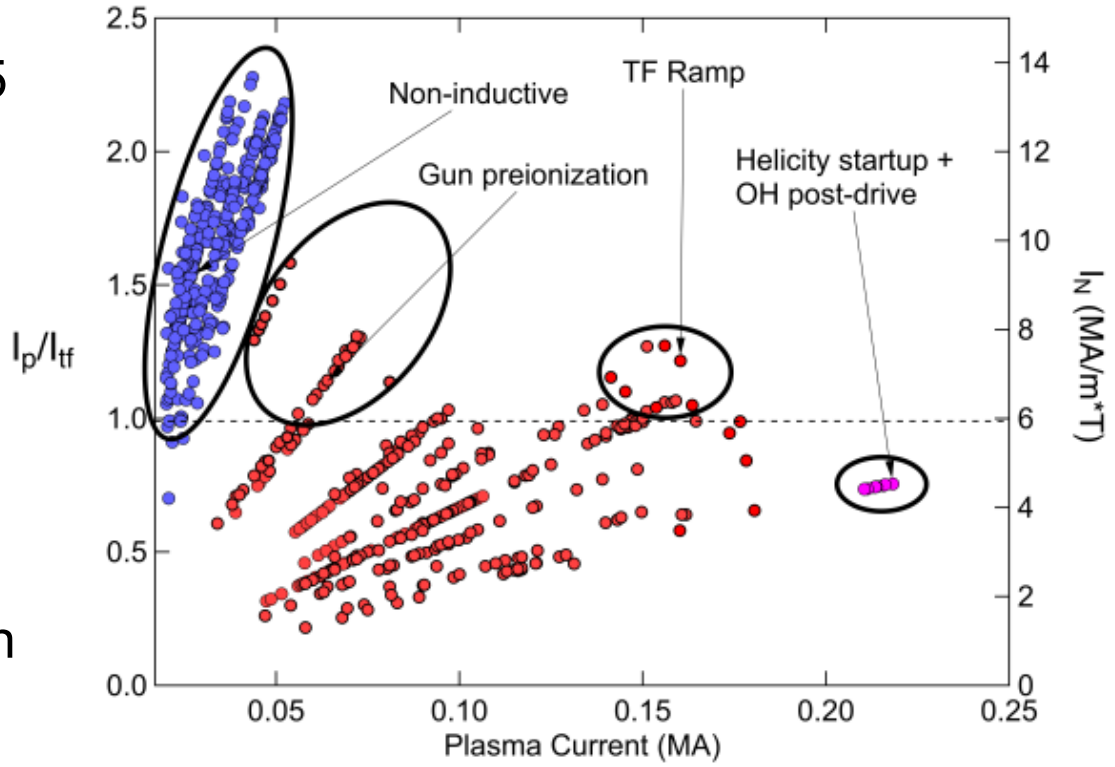
- **Resistive Helicity Dissipation**
  - **E = ηJ →** $\eta \approx \dfrac{\pi e^2 m^{1/2}}{\left(4\pi\varepsilon_0\right)^2 \left(kT_e\right)^{3/2}} \ln\left(12\pi n \lambda_D^3\right)$ **(Spitzer)**
  - **Use Thomson scattering to quantify T_e and n_e**

- **These low-density non-solenoidal plasmas present the most challenging conditions for measuring Thomson scattering**

- **AC Helicity Injection:** $\dot{K}_{AC} = -2\dfrac{\partial \psi}{\partial t}\Psi = 2V_{loop}\Psi$
- **DC Helicity Injection:** $\dot{K}_{DC} = -2\int_A \Phi \mathbf{B} \cdot \mathrm{ds} = 2V_{inj}B_{\perp}A_{inj}$

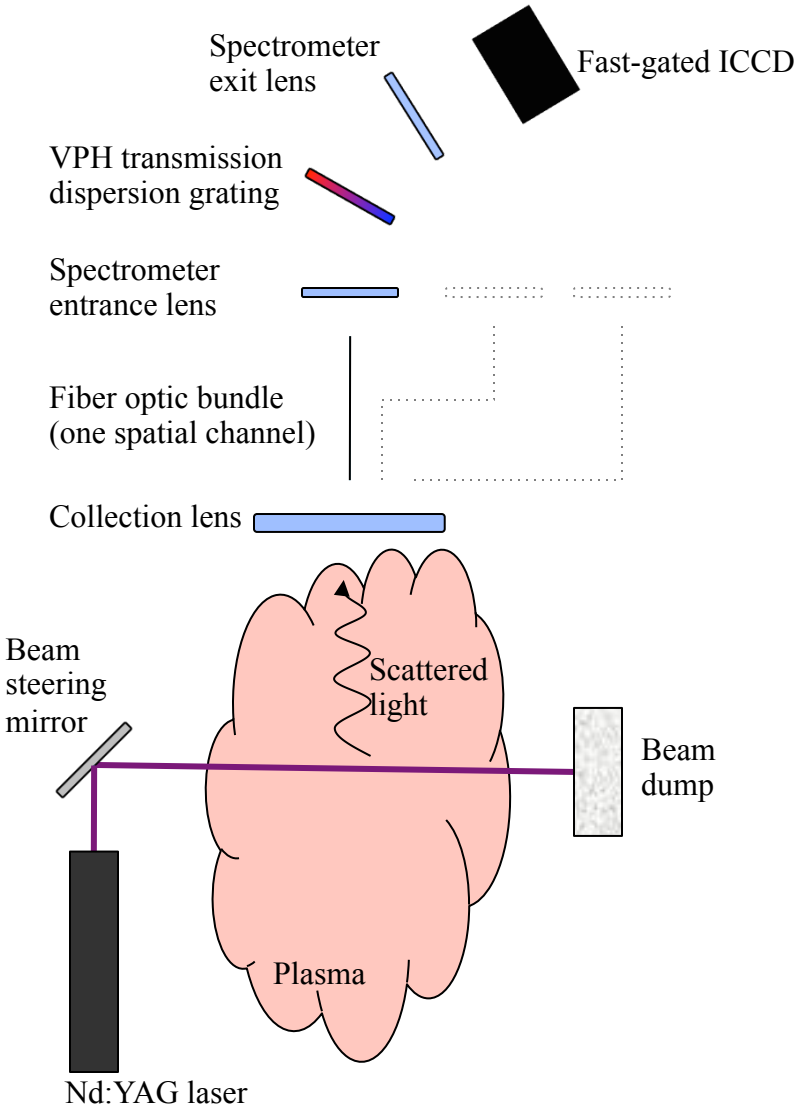
High-β, high I_p/I_{TF} scenarios will be characterized with MPTS

- Using helicity startup Pegasus can access $I_N > 5$ at $I_p \sim 0.2$ MA
- As facilities are upgraded, expect to challenge the Troyon limit
- Explore confinement and temperature distributions in these regimes unique to Pegasus



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Thomson scattering occurs when incident EM radiation excites free electrons



- "Thomson scattering" = scattering of EM radiation from free electrons
  - assumes $h\nu << mc^2$
  - here, assume incoherent scattering ($k_{inc}\lambda_D >> 1$)
- Small scattering cross-section necessitates high-energy incident light (i.e. laser)

$$\frac{dP}{d\Omega_s} = r_e^2 \sin^2\phi c\varepsilon_0 |E_i|^2$$

- Collection lens & fiber bundles provide spatially resolved measurements
- Frequency bandwidth of the scattered light is proportional to T_e
  - Dispersion grating used to measure $\Delta\nu = c/\Delta\lambda$
- Small signal levels dictate high-sensitivity, fast detection electronics (ex. fast-gated image-intensified CCD)

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Scattered intensities ~μWatt for low-density non-solenoidal plasmas

- Preliminary calculations yield scattered intensities of ~4*10^3 total photons
  - Assumes incoherent, non-relativistic scattering
  - Assumes 2J, 7 ns Nd:YAG laser pulse
  - Assumes solid angle of ~0.01 ster per channel
- Since plasma durations in PEGASUS are ~30 ms, will only be able to measure one laser pulse

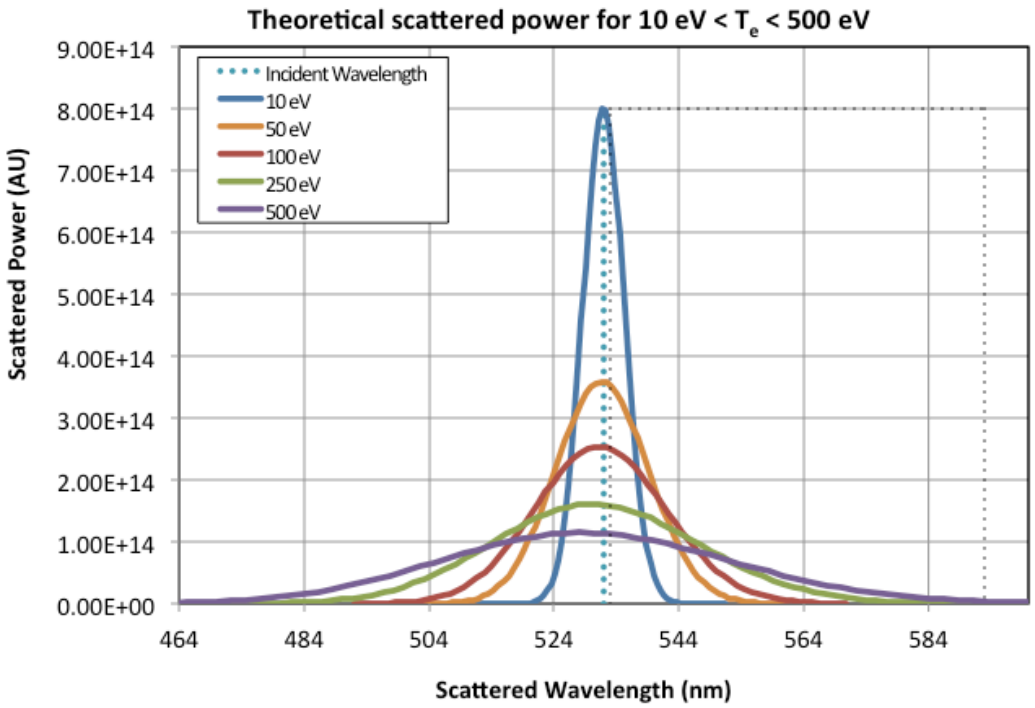
$$
\begin{aligned}
I_{det} &= \frac{E_{laser}}{E_{photon}} \sigma n_e l \frac{\xi}{4\pi} \\
&= E_{laser} \left(\frac{\lambda_{laser}}{hc} \right) \sigma n_e l \frac{\xi}{4\pi} \\
&\approx 2.66 \times 10^{11} \mathrm{s^2/kg} \left(E_{laser} \cdot \lambda_{laser} \cdot n_e \cdot l \cdot \xi \right)
\end{aligned}
$$

Symbol:	Inputs:	
E_{laser}	**Laser output energy (J)**	**2**
λ_i	**Incident laser wavelength, λ_m (m)**	**5.32E-07**
n_e	**Electron density (m^{-3})**	**1.00E+18**
l	**Length of beam for one channel (m)**	**0.014**
ξ	**Solid angle subtended by optics (ster)**	**9.225E-03**
	Pulse duration (s)	**7.00E-09**
	Output:	
I_{laser}	Number of laser photons incident/pulse	5.35E+18
I_{det}	Number of photons scattered/pulse	3658.06
	Joules incident at primary wavelength	1.367E-15
	Watts at primary wavelength	1.95E-07

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Spectral range 532 – 592 nm for PEGASUS operating scenarios

- PEGASUS plasmas typically $10\ eV < T_e < 500\ eV$
- Use high dispersion VPH grating for low temperatures:
  - $532\ nm < \lambda_{inc} < 562\ nm$
- Use low dispersion VPH grating for high temperatures:
  - $532\ nm < \lambda_{inc} < 592\ nm$
- Signal levels will likely dictate $\Delta\lambda_{inc} \approx 4$ nm and 8 nm in the low and high temperature cases, respectively



Based on: J. Sheffield, Plasma Phys., Vol 14, 783-791 (1972)

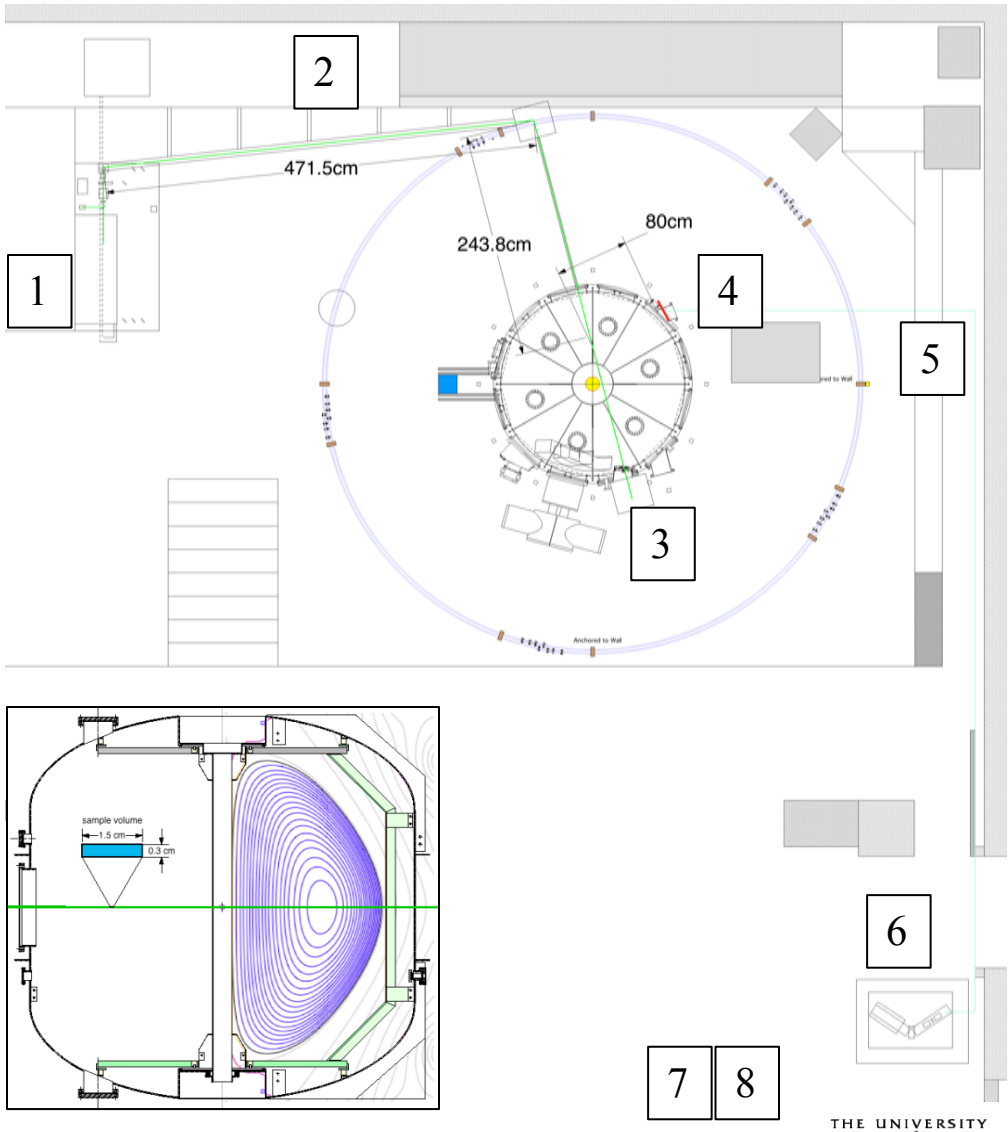
- Predictions assume 90° average scattering angle with ~10^{-2} solid angle
  - Relativistic effects evident in shift of central wavelength at $T_e = 1$ keV

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Design method divides entire system into strongly coupled subassemblies

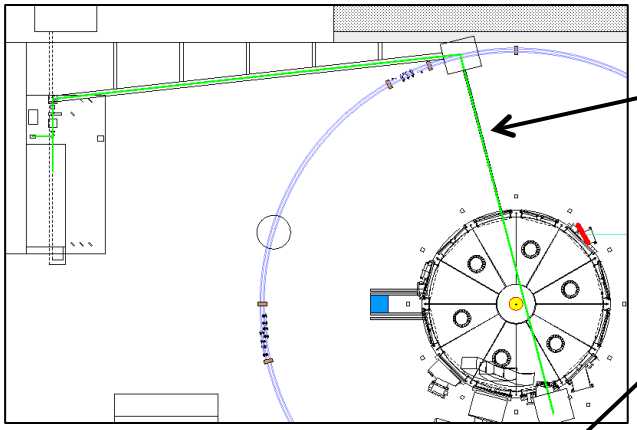
Subassemblies include:

1) Laser & enclosure
2) Beamline
3) Beam Dump
4) Collection Optics
5) Fiber Optics
6) Spectrometers
7) Control Code & SCRAM systems interface
8) Safety Overall

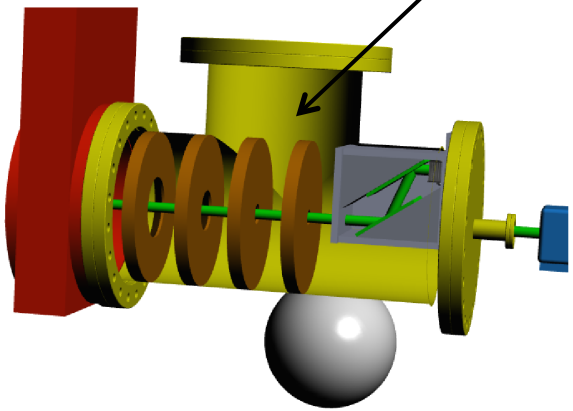


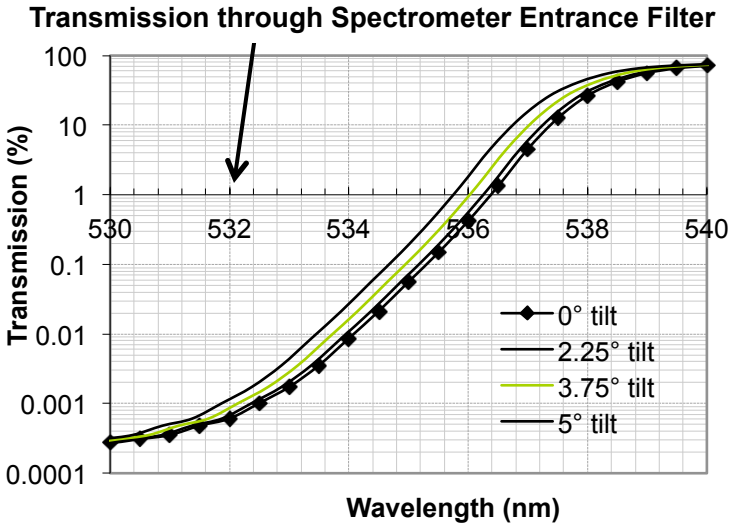
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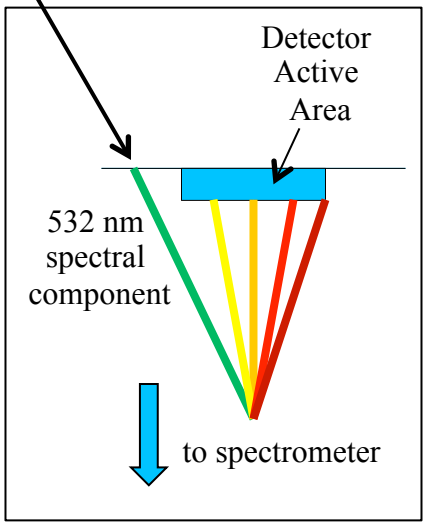
Multiple locations and methods used to reduce stray light



- Baffling along laser entrance tube
- Enclosed beam dump with baffles
- Sharp cut-on filter at spectrometer
- Grating alignment such that laser wavelength not incident on detector







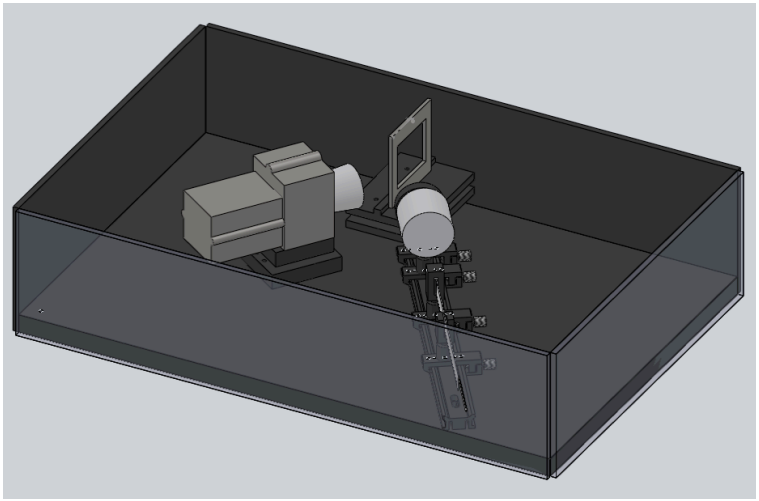
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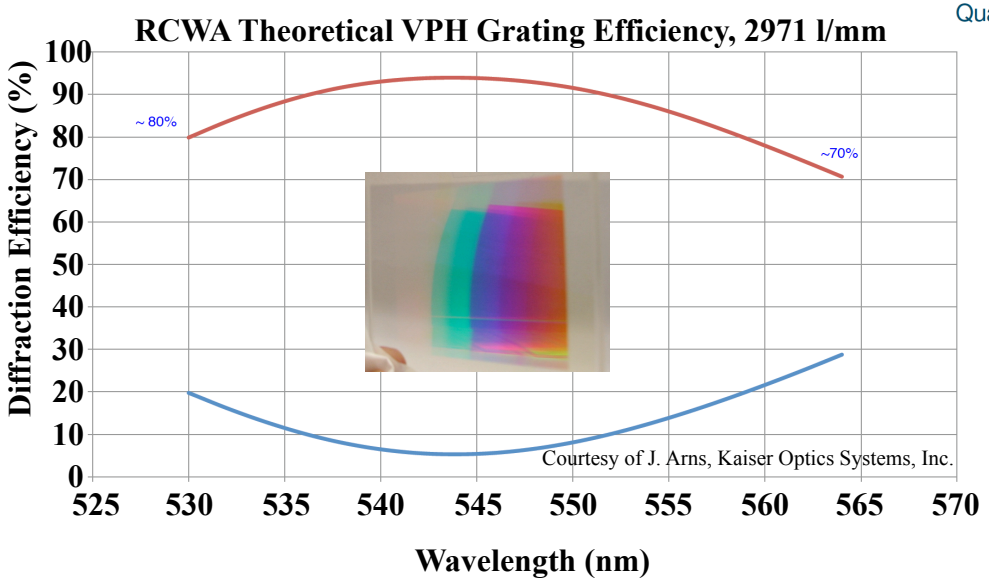
New Technology Reduces Cost & Complexity, Increases Performance

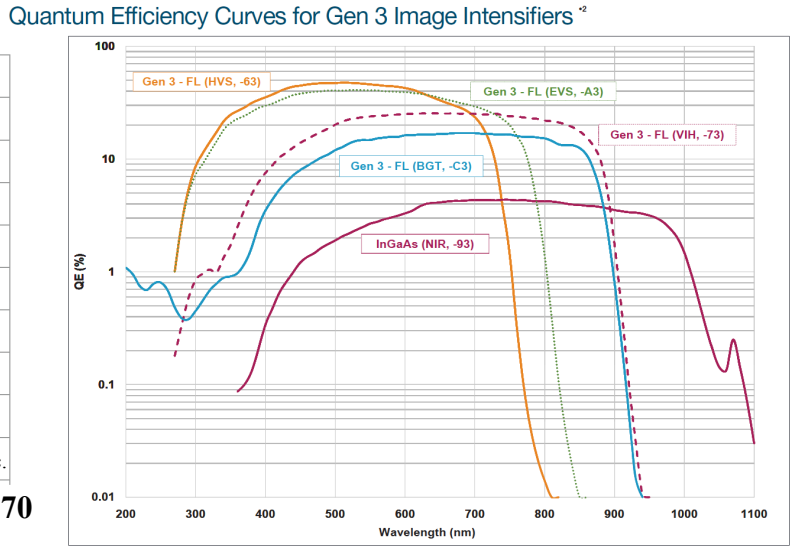
- Image-Intensified CCD chosen over APDs & fast digitizers
  - Significantly lower cost/channel
  - More compact form factor
- Volume Phase Holographic (VPH) grating chosen over bandpass filters
  - Dynamic spectral binning (with CCD)
  - Multiple channels per single grating
- Frequency-doubled ND:YAG laser chosen over Ruby laser
  - >2J at 532 nm possible
  - Visible light eases alignment
  - Excellent pointing stability allows tighter viewing volume
- Beamline optimized for simplicity and performance
  - Remotely actuated turning mirrors
  - Short beamline (<7 m)

Novel spectrometer system employed – see Schoenbeck PP9.00007

- Custom achromat entrance lens
- Custom Volume Phase Holographic (VPH) diffraction gratings
- Image Intensified CCD (ICCD) detector
  - High quantum efficiency Gen 3 Intensifier
  - Fast gating capability down to 1.2 ns



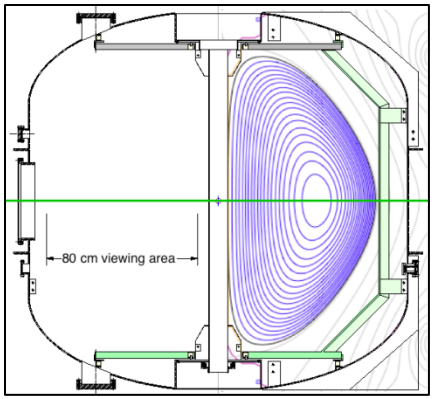


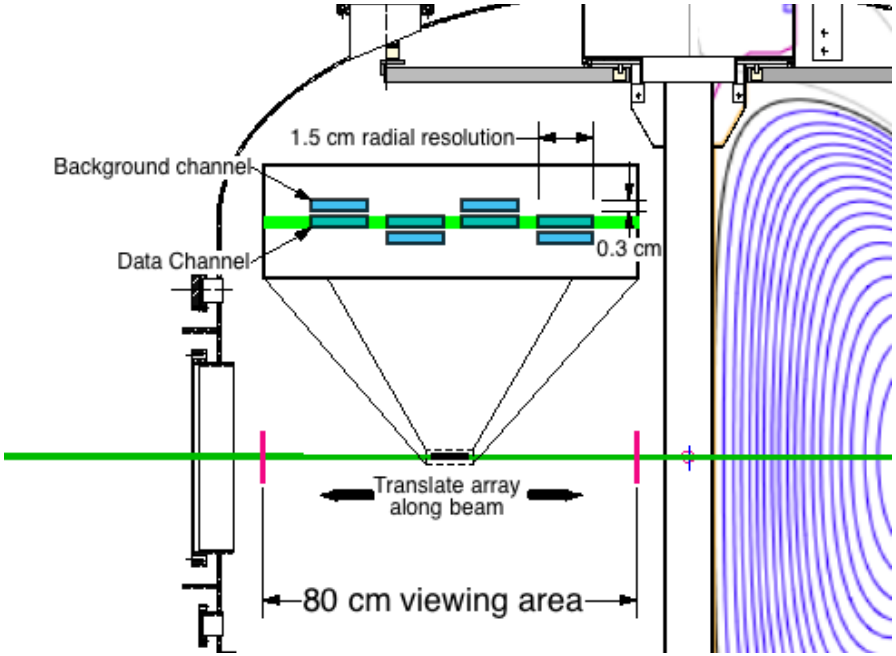


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Initial System Designed for Expandability

- Individual channels correspond to close-packed fiber bundles
  - 1.5 cm radial resolution
- Initially, 4 data channels and 4 background monitors
  - Evaluate performance & plasma conditions and reconfigure as needed
  - Upon successful implementation, immediately begin expanding to 16 additional channels
- Scan array radially from shot-to-shot
  - Initially manual positioning
  - Expand to automated positioning across curved collection optics focal plane





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Laser specifications balanced between commercial availability and physics needs

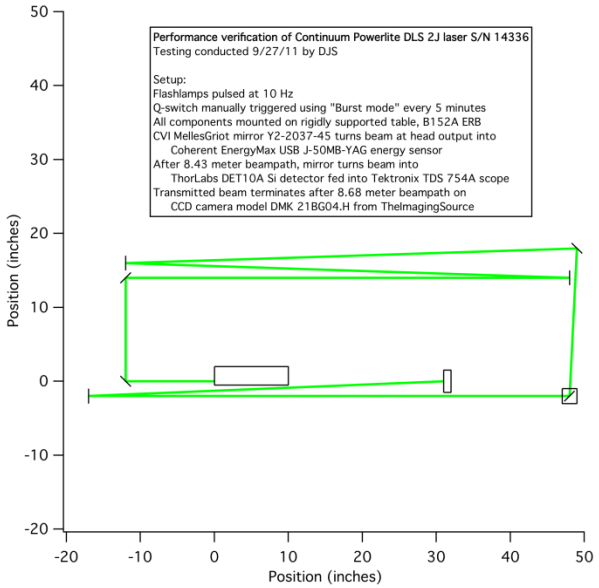
Specification	Value	Determining factors
Output Energy	≥ 2000 mJ	Scattered intensity fraction
Divergence	≤ 0.5 mrad	Desired spatial resolution, component damage thresholds
Pointing stability	≤ 50 μrad	Beam line
Pulse length	≥ 10 ns	Availability at desired power
Repetition Rate	≥ 10 Hz	Shot duration; availability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

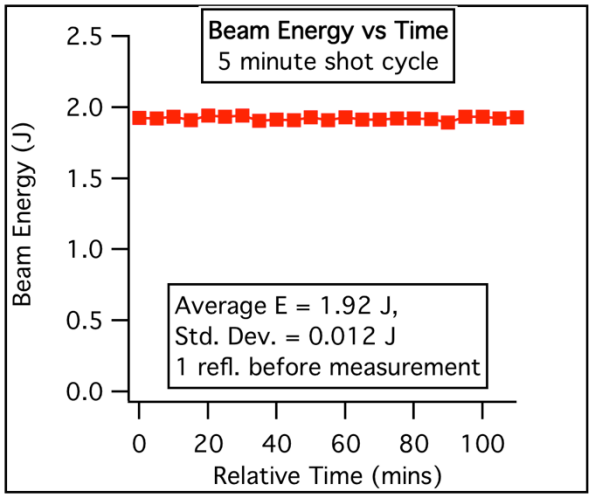
- Identify tolerable limits due to physics needs and layout constraints
- Reliable, "turn-key" operation of laser desired
  - Nd:YAG used extensively for MPTS in plasmas
  - Operate flash lamps at steady 10 Hz to obtain maximum stability
- Implement design with consideration for possible future upgrades:
  - Additional spatial points
  - Multiple laser passes
  - Multiple time points per shot

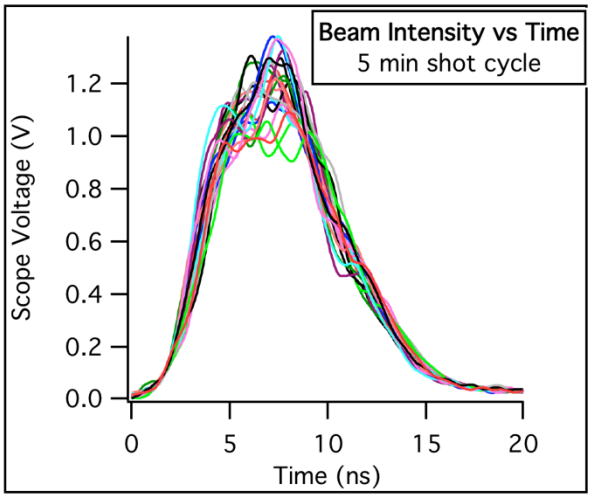
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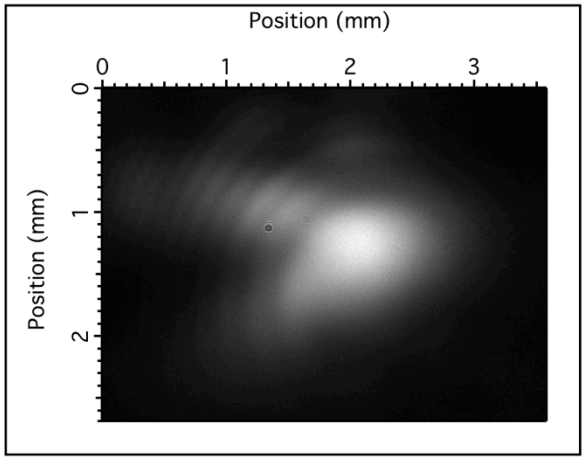
Beam energy and temporal pulse shape satisfy design requirements

- In-house calibration to ensure actual performance matches requirements
  - Test key laser properties (energy, pulse duration, pointing stability)
- Tests designed to mimic Pegasus shot cycle times and typical laser use
  - Single laser pulse every ~5 minutes





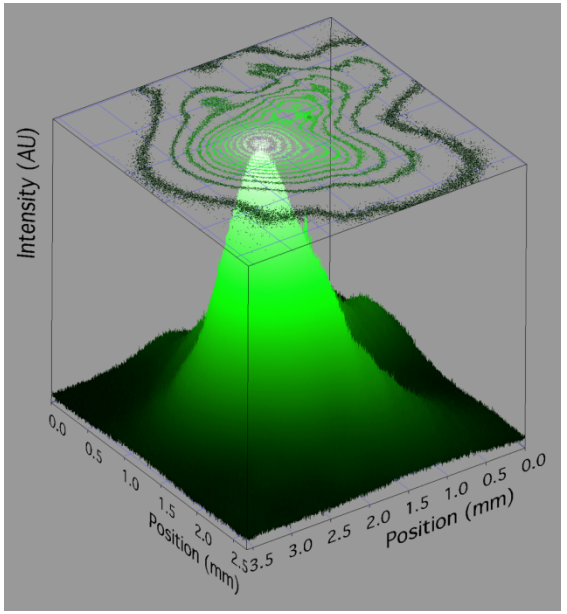


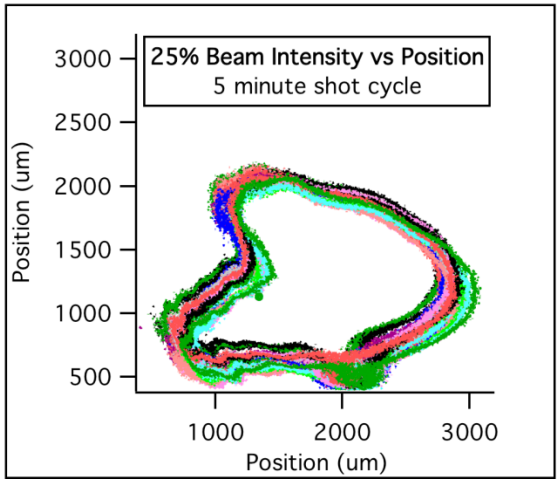


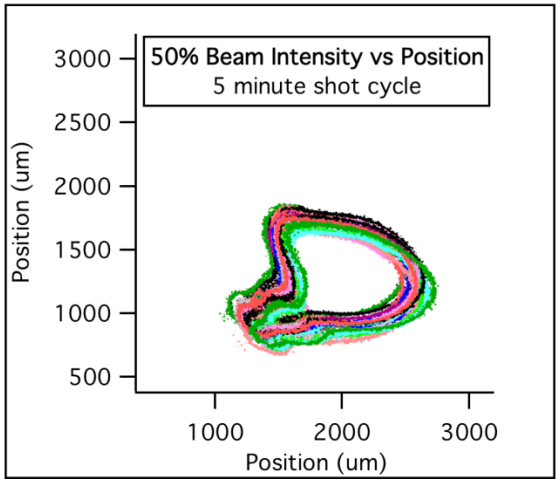
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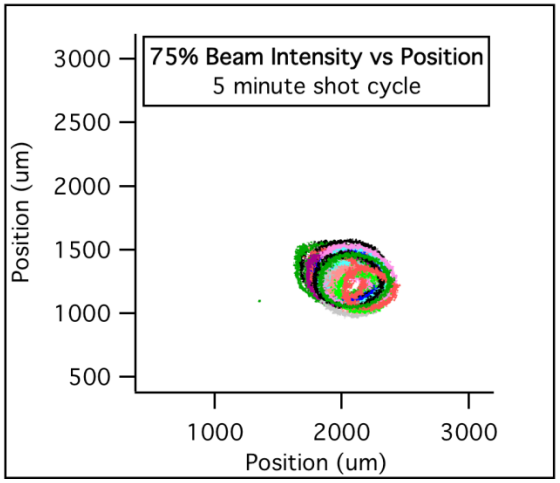
Beam pointing stability and focusing will provide well-defined viewing volume

- Beam focused over ~9m path length onto a fast-framing CCD camera
  - Single plano-convex lens
  - 5.6 µm pixel size, 640x480 pixels
  - Attenuation > 10^{-6} needed to avoid camera saturation
- Pointing stability within 3 mm viewing area defined by collection optics
- Focused beam diameter within expected range



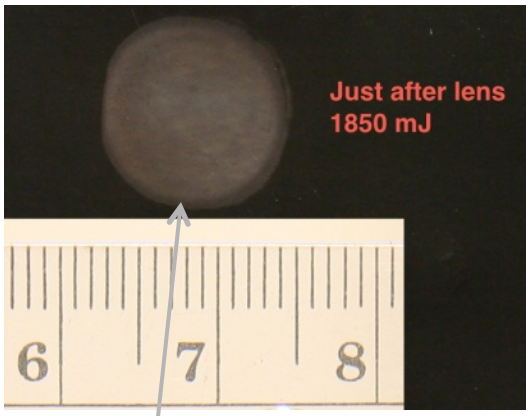




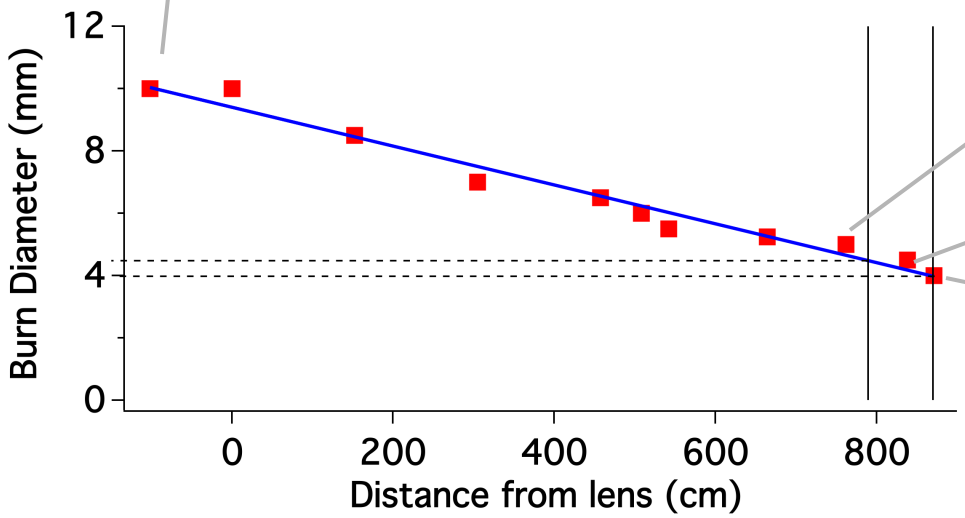


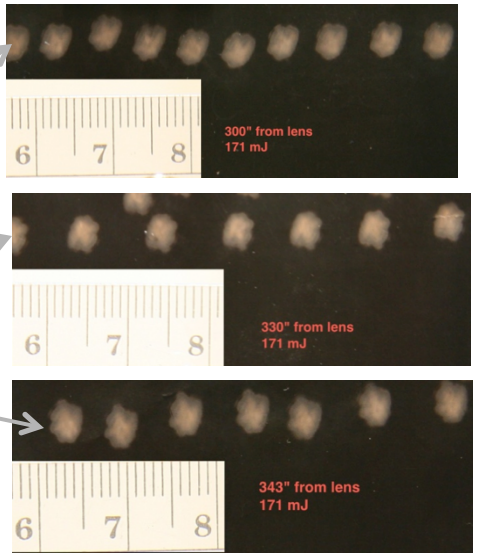
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Full-power beam diameter matches design specification



- Burn paper used to measure beam diameter at or near full-power
  - As beam is focused, unattenuated energy density becomes too large for burn paper
  - Use OD(1) high-power dielectric attenuator to reduce energy
- Unfocused beam diameter ~10 mm
- Diameter varies by <25% over expected plasma radius
- Long-focal length lens allows convenient fine-tuning on optical table

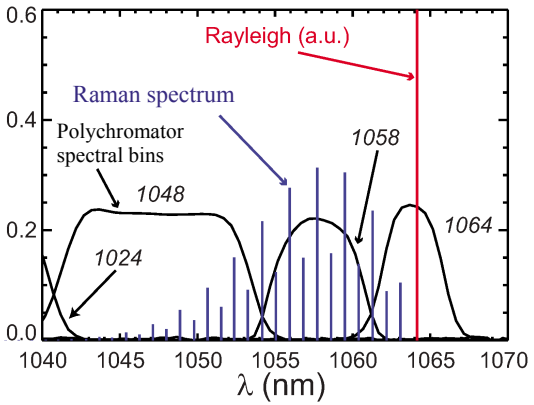




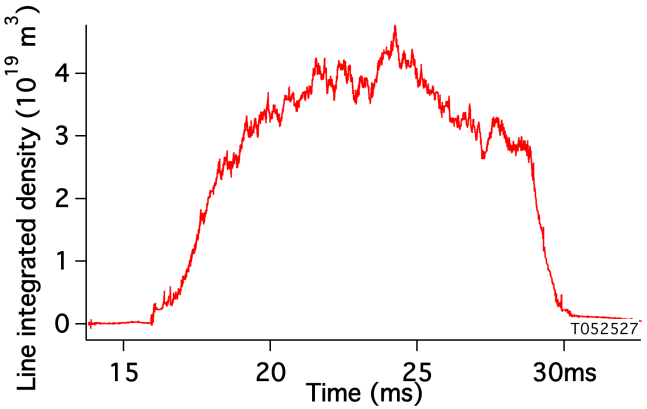
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Several calibration methods under consideration

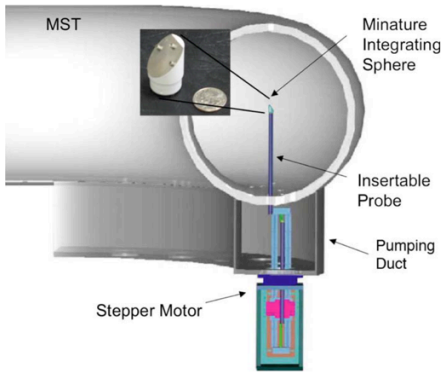
- Typical calibration methods span orders of magnitude in cross-section:
  - $\sigma_{Rayleigh} \approx 10^{-28}$ cm^2/sr
  - $\sigma_{Raman} \approx 10^{-31}$ cm^2/sr
  - $\sigma_{Thomson} \approx 10^{-33}$ cm^2/sr
- Alternate methods include:
  - Comparison with existing PEGASUS diagnostics (ex. μwave interferometer)
  - Calibration source during machine vents (requiring vessel entrance)
  - Vacuum-compatible calibrated source, actuated to move along beamline (ex. MST mini integrating sphere)



NSTX Raman Calibration
*From LeBlanc, Rev. Sci. Instr. **79**, 10E737 (2008)*



Typical PEGASUS plasma density

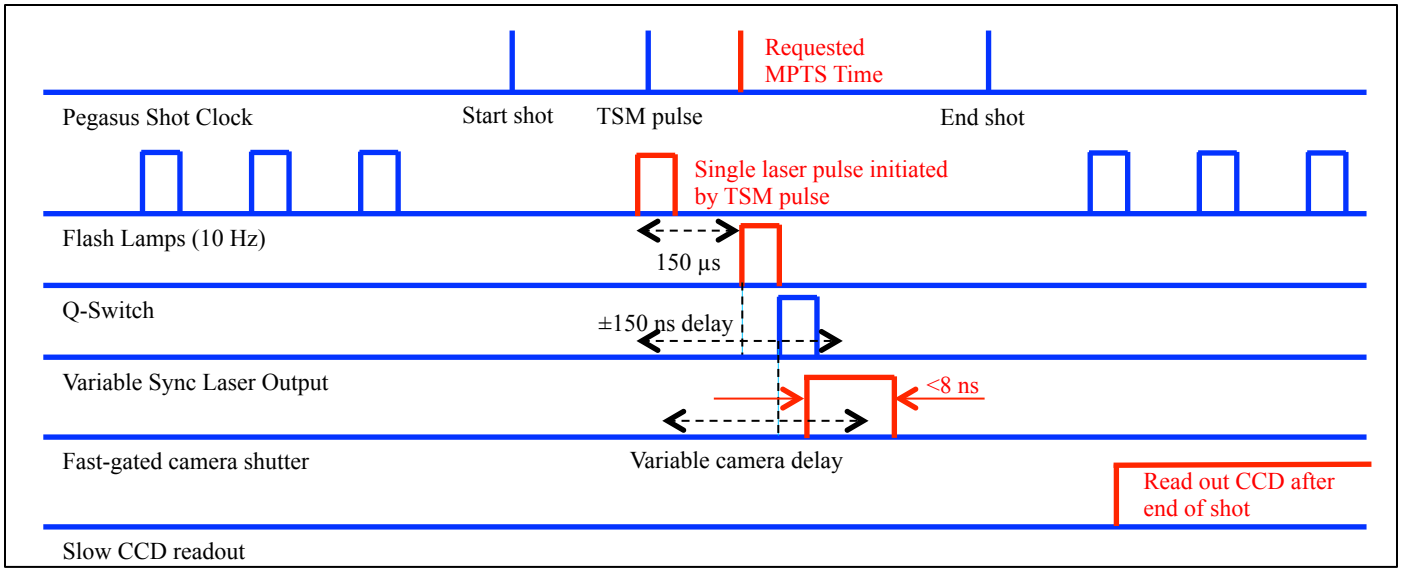


MST Insertable Integrating Sphere
*From Reusch, Rev. Sci. Instr. **79**, 10733 (2008)*

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Precision timing provided by tunable delays

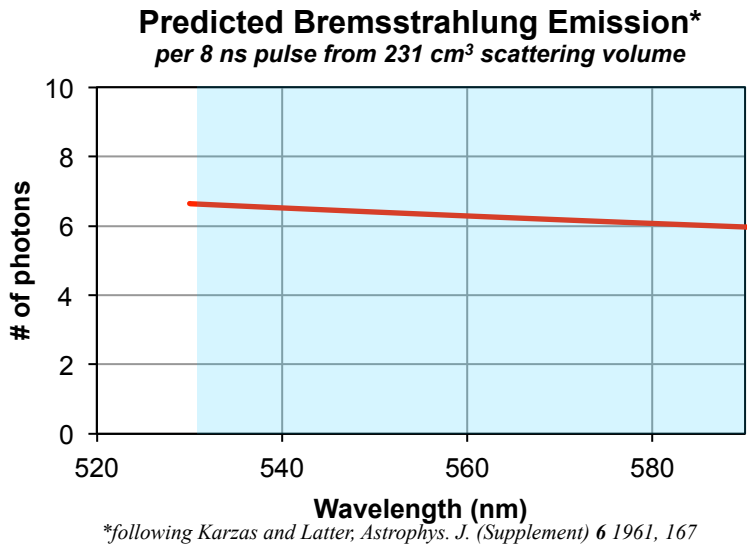
- Sub-nanosecond synchronization necessary between components
  - User requests laser pulse at given time t_0 during shot
  - PEGASUS control code issues Timing Sequence Module (TSM) pulse at ($t_0 - t_{\text{flash lamps}} - t_{\text{Q-switch}}$)
  - Variable Sync Output on laser supply triggers camera acquisition
- Tuned to account for laser propagation time through beamline and electronics calculation time internal to camera



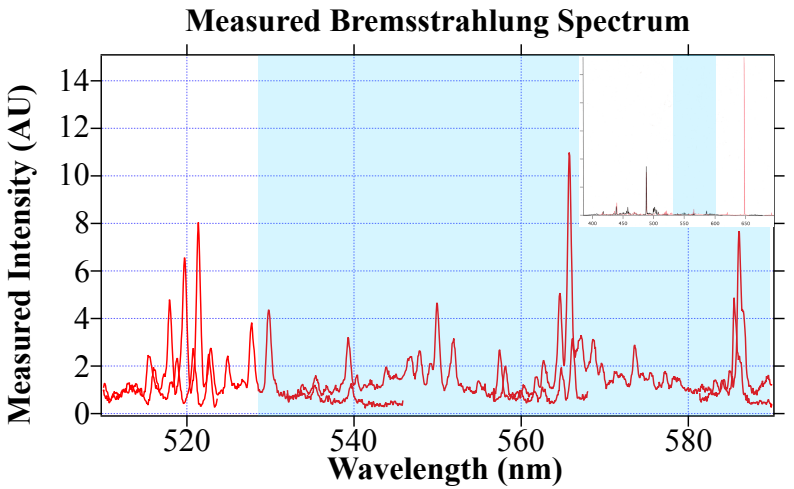
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Bremsstrahlung emission a tolerable fraction of scattered signal

- Predicted Bremsstrahlung emission shows ~photons/nm collected
  - Short collection time (8ns)
  - Moderate single channel viewing volume (231 cm^3)
- Actual Bremsstrahlung measured with scanning spectrometer
  - Small peaks within Thomson collection spectral range
- Choice of spectral collection region avoids D_α and N_2 lines



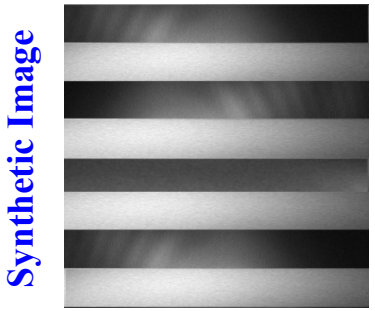
*following Karzas and Latter, Astrophys. J. (Supplement) **6** 1961, 167

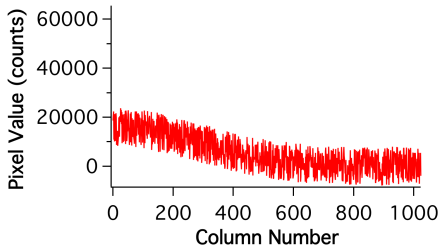


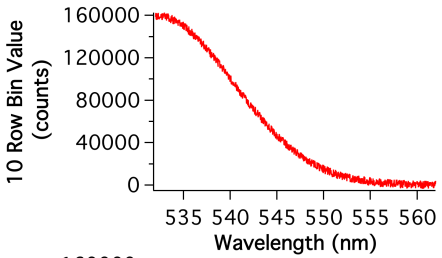
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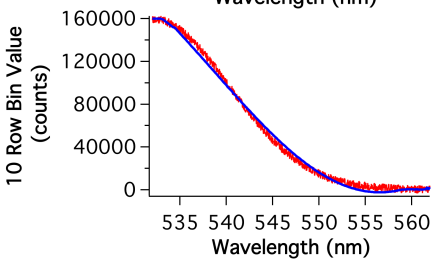
Initial data analysis routines being created and evaluated

- After system completion, data image will contain 4 scattering channels & 4 background channels
- All rows for one spatial point will be binned
- Selectable spectral binning (columns) based on plasma conditions
- Several possible fitting functions being evaluated for temperature estimation:









Selden:

$$S(\epsilon,\theta) = c(\alpha)A^{-1}(\epsilon,\theta)\exp\left[-2\alpha B(\epsilon,\theta)\right]$$

where:

$$A(\epsilon,\theta) = (1+\epsilon)^3\left[2(1-cos\theta)(1+\epsilon)+\epsilon^2\right]^{\frac{1}{2}}$$

$$B(\epsilon,\theta) = \left\{1+\frac{\epsilon^2}{\left[2(1-cos\theta)(1+\epsilon)\right]}\right\}^{\frac{1}{2}} - 1$$

$$c(\alpha) = \left(\frac{\alpha}{\pi}\right)^{\frac{1}{2}}\left(1-\frac{15}{16}\alpha^{-1}+\frac{345}{512}\alpha^{-2}+\cdots\right) when\ \alpha \gg 1$$

and:

$$2\alpha \equiv \frac{m_e c^2}{kT_e}, \theta \equiv \text{scattering angle}, c(\alpha) \equiv \text{normalizing constant}$$

$$\epsilon \equiv \left(\frac{\lambda_s}{\lambda_i}\right) - 1\ measures\ relative\ wavelength\ shift$$

$$\lambda_{i,s} = incident, scattered\ light$$

From: Selden, Phys. Lett. ***79A****, 5,6 (1980) 405.*

Sheffield:

$$P_{sc}(R,\lambda_s)d\lambda_s d\Omega = \frac{P_i r_0^2 d\Omega n_e L c}{2\pi^{\frac{1}{2}} a\lambda_i \sin\left(\frac{\theta}{2}\right)}$$

$$\cdot\left\{1-\frac{7}{2}\frac{\Delta\lambda}{\lambda_i}+\frac{c^2\Delta\lambda^3}{4a^2\lambda_i^3\sin^2(\theta/2)}\right\}$$

$$\times\exp\left(-\frac{c^2\Delta\lambda^2}{4a^2\lambda_i^2\sin^2(\theta/2)}\right)\cdot d\lambda_s$$

where:

$$incident\ power\ P_i = \frac{cE_i^2}{8\pi}A$$

$$r_0 = \frac{e^2}{mc_0^2} = 2.82\times10^{-13}cm$$

$$\lambda_s = \lambda_i + \Delta\lambda$$

From: J. Sheffield, Plasma Phys., **14** (1972) 783-791.

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Summary

- A novel Thomson scattering diagnostic is being installed on the PEGASUS Toroidal Experiment
- Laser characterization shows promising performance
- Spectrometer assembly and characterization underway
- After installation and calibration, system will be used:
  - As a routine density and temperature diagnostic
  - To investigate dominant confinement mechanisms in point-source helicity-driven plasmas
  - To quantify sources of helicity dissipation

Future directions

- Finish characterizing collection lens and detector components
- Assemble spectrometers
- Install laser, collection optics, fiber optics, and spectrometer rack in experimental area
- Perform system-wide calibration
- Finish creating and evaluating analysis routines
- Investigate physical phenomena in both higher-density (10^{19} m^{-3}) Ohmic plasmas and lower-density non-solenoidal plasmas

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