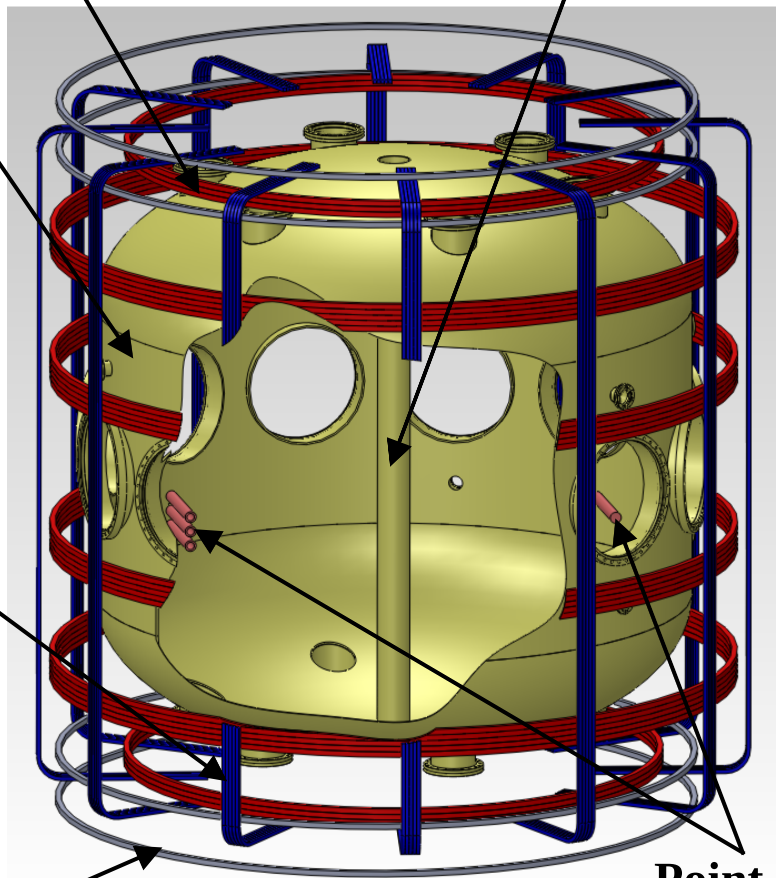
Abstract

- Technological advances are exploited by a Thomson scattering diagnostic on the Pegasus Toroidal Experiment
  - New diagnostic leverages high-energy pulsed laser, VPH diffraction gratings, ICCD cameras
  - Pegasus is a spherical tokamak ($A \approx 1.2$, $B_{T,0} \approx 0.1$, $I_{p,max} \approx 0.2$ MA)
  - Typically $n_e = 10^{18} - 5\times10^{19}$ m^{-3}; expected $T_e = 10 - 500$ eV
- Photon source is a Nd:YAG Q-switched laser
  - Operated at first harmonic, 532 nm
  - Pulse is characteristically 2 J, 7 ns FWHM, <10 Hz rep rate, $dia_{min} < 3$ mm
- Beamline and viewing geometry optimized
  - 7 m long beamline, minimal turning mirrors, high F/# PCX focusing lens
  - Collection area spans >70% of plasma radius, 1.4 cm radial resolution
- Diagnostic designed for moderate range of plasma conditions
  - Typically $>4\times10^3$ collection photons for $n_e > 0.5\times10^{19}$ m^{-3}, $T_e > 10$ eV

Pegasus is a compact ultralow-A ST



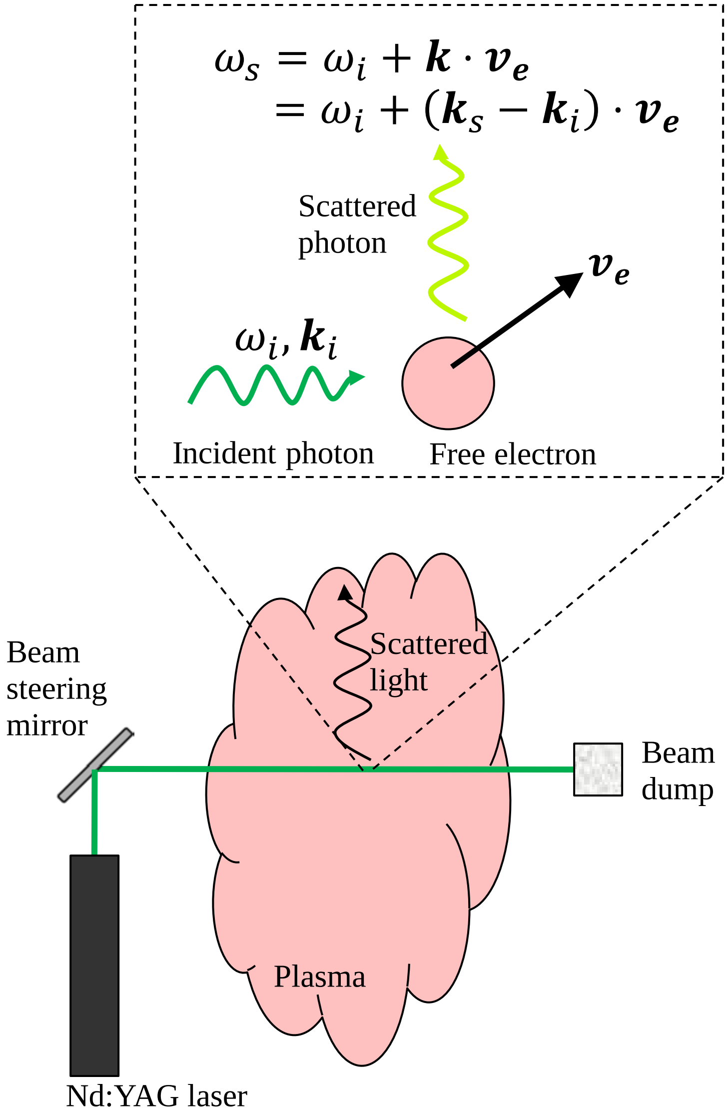
Experimental Parameters

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
$|_{shot}$ (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*

Thomson scattering occurs when incident EM radiation excites free electrons



- Thomson scattering = scattering of EM radiation from free electrons
  - Assumes $h\nu \ll mc^2$
  - Here, assume incoherent scattering ($k_{inc}\lambda_D \gg 1$)
- Small scattering cross-section requires large photon flux (ex. laser)

$\phi = \angle \widehat{E_i, \hat{s}}$

$$\frac{dP}{d\Omega_s} = r_e^2 \sin^2 \phi \, c\epsilon_0 |E_i|^2$$

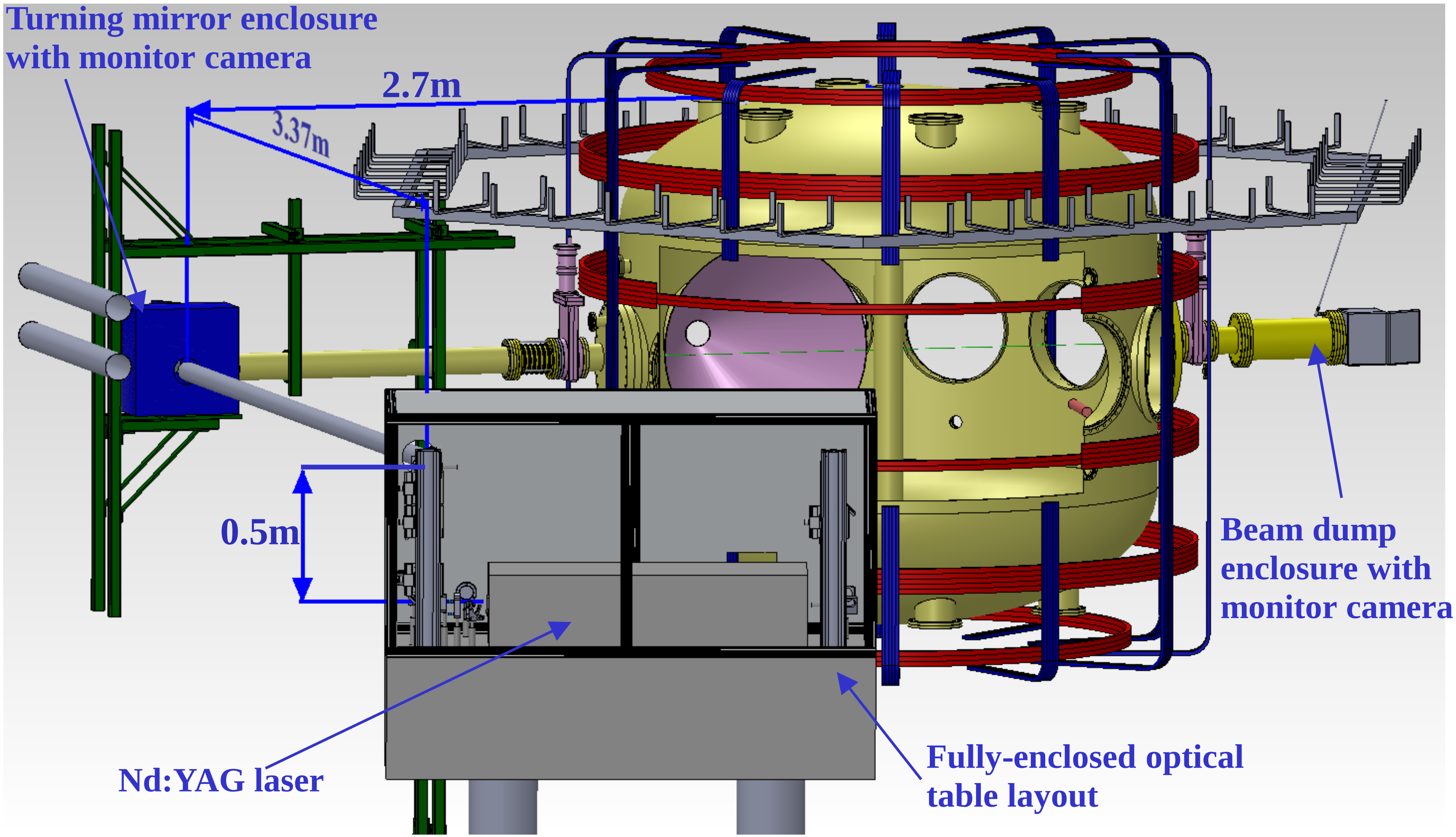
Incident electric field

Classical electron radius ≈ 2.8×10^{-15} m

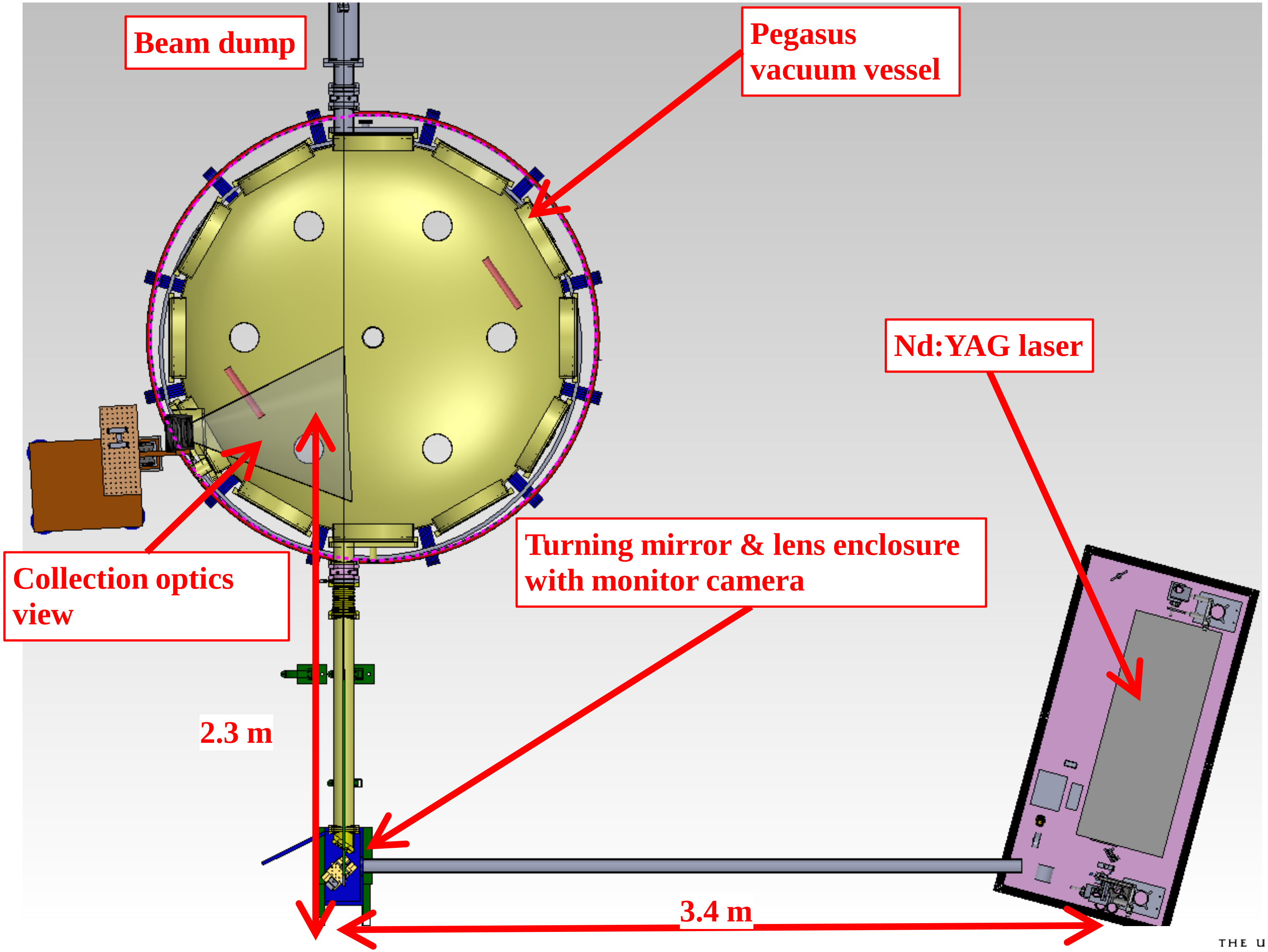
Permittivity ≈ 8.85×10^{-12} F·m^{-1}

- Scattered photon is Doppler shifted proportionally to electron's velocity, along the line of sight
- Frequency bandwidth of the scattered light is proportional to T_e
  - Dispersion grating used to measure $\Delta\nu = c/\Delta\lambda$

Pegasus Thomson Scattering Overview



Pegasus Thomson Scattering System, Cutaway Top View



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

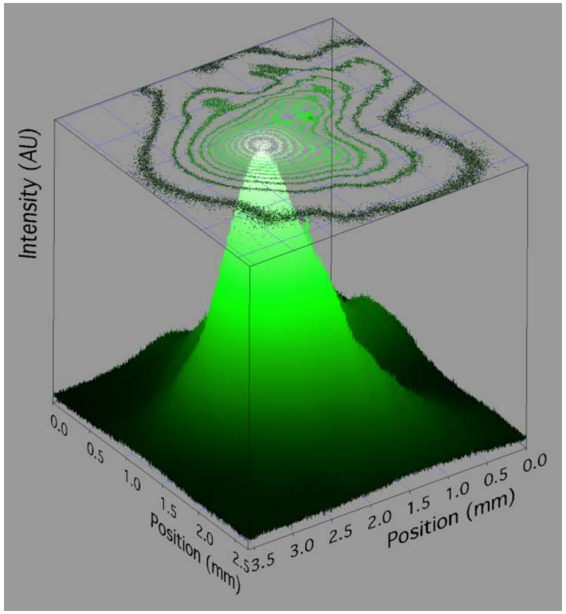
- Identify tolerable limits due to physics needs and layout constraints
- Reliable, “turn-key” operation of laser required
  - Nd:YAG used extensively for MPTS in plasmas
  - Operate flash lamps at steady 10 Hz to obtain maximum stability
- Implement design with consideration for possible future upgrades: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

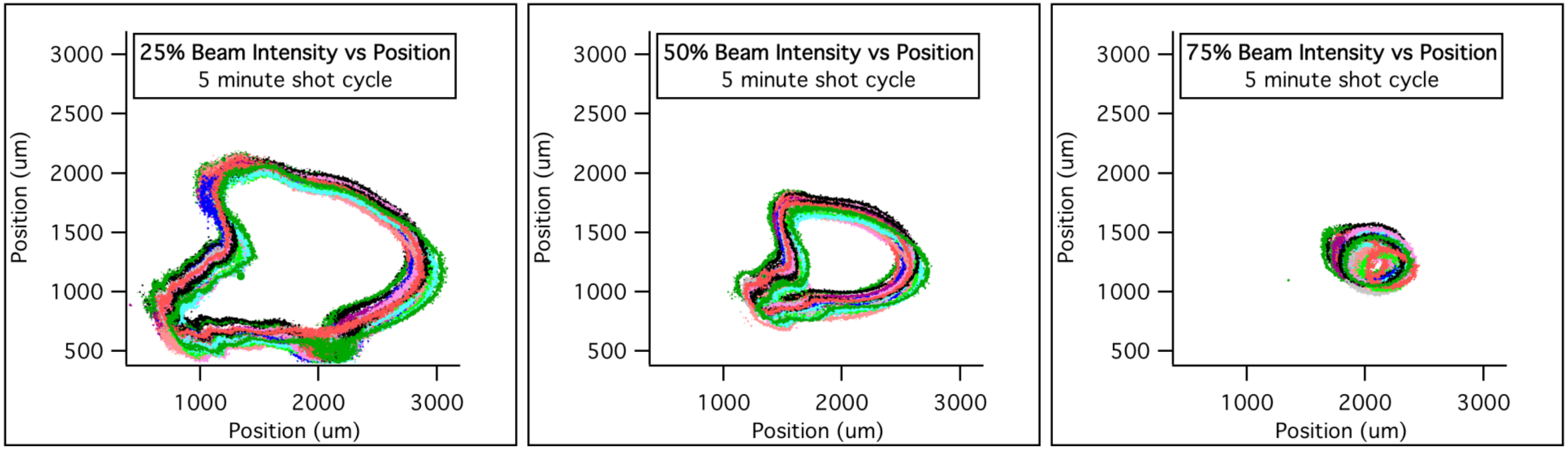
Beam pointing stability and focusing will provide well-defined viewing volume

- 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



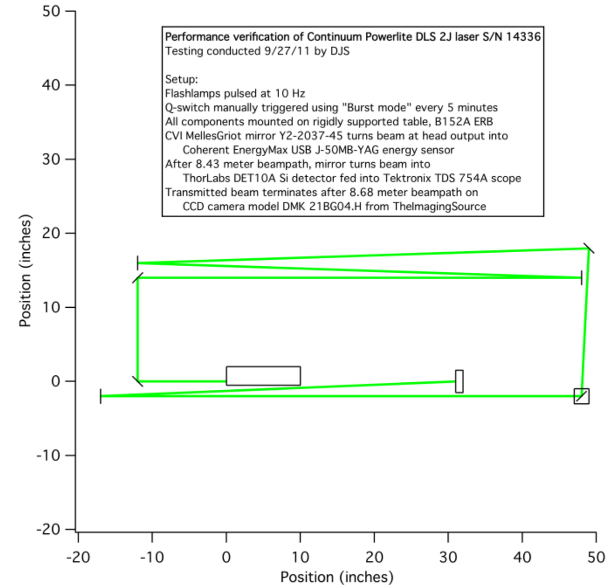


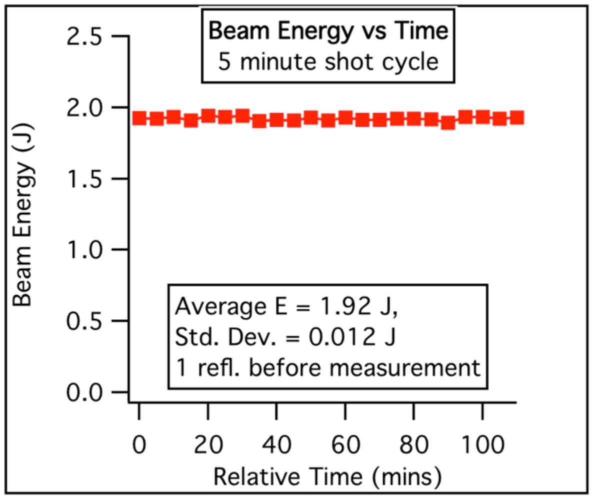
THE UNIVERSITY of WISCONSIN MADISON

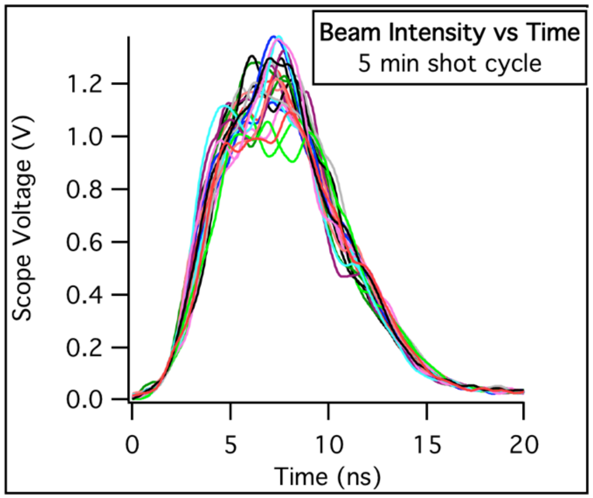
Beam energy and temporal pulse shape satisfy design requirements

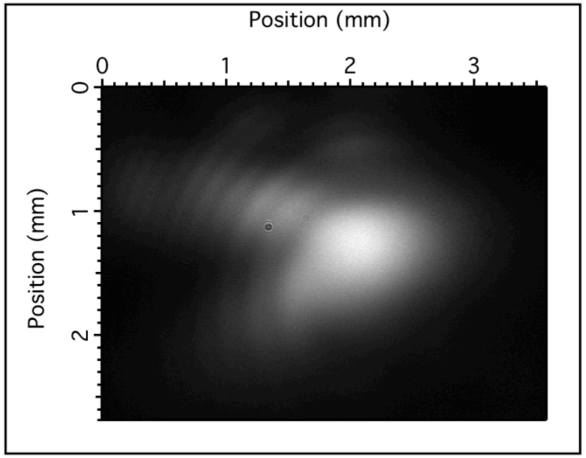
- In-house calibration to ensure actual performance matches requirements
  - Test key laser properties (energy, pulse duration, pointing stability)

- Tests designed to mimic Pegasus shot cycle times and typical laser use
  - Single laser pulse every ~5 minutes

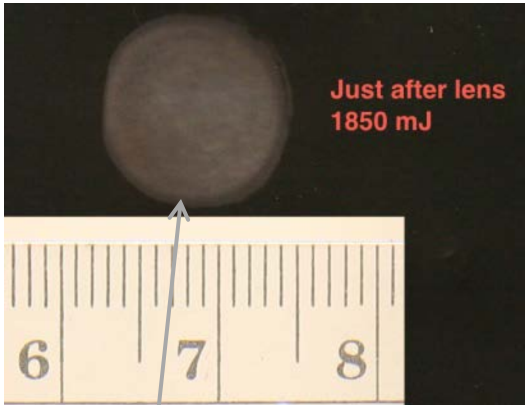




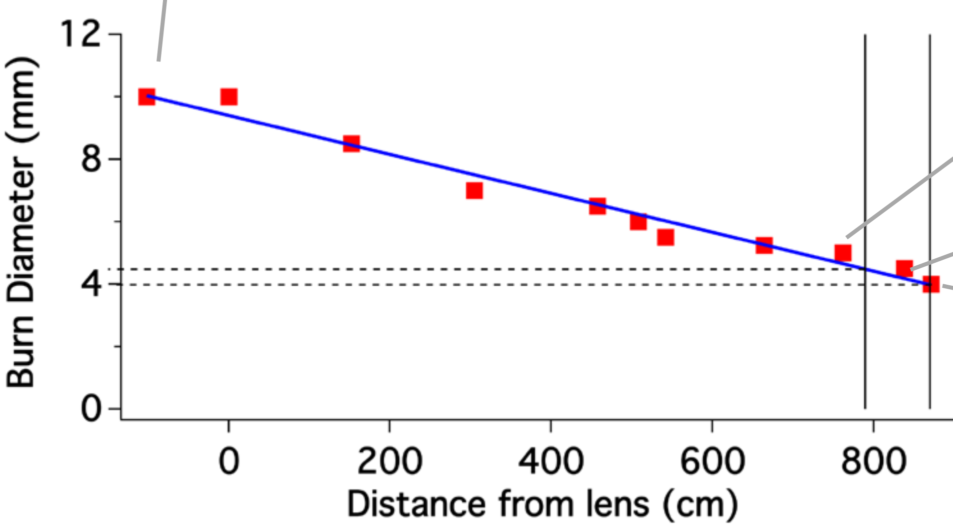


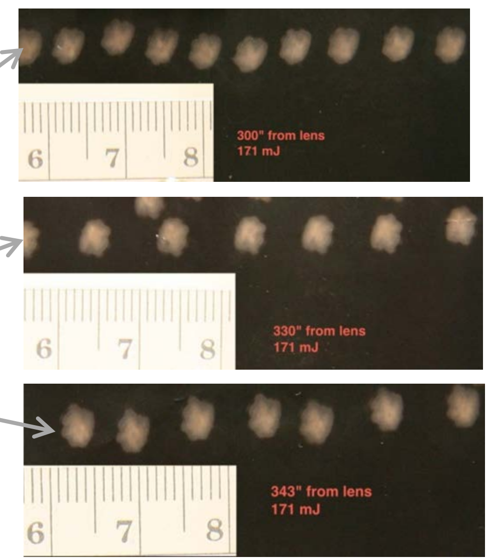


Full-power beam diameter matches design specification



- 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





THE UNIVERSITY of WISCONSIN MADISON

Scattered intensities ~μWatts for typical Pegasus plasmas

- Preliminary calculations yield scattered intensities of ~4×10^4 total photons, assuming:
  - incoherent, non-relativistic scattering
  - 2J, 7 ns Nd:YAG laser pulse
  - solid angle of ~0.01 ster/channel

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

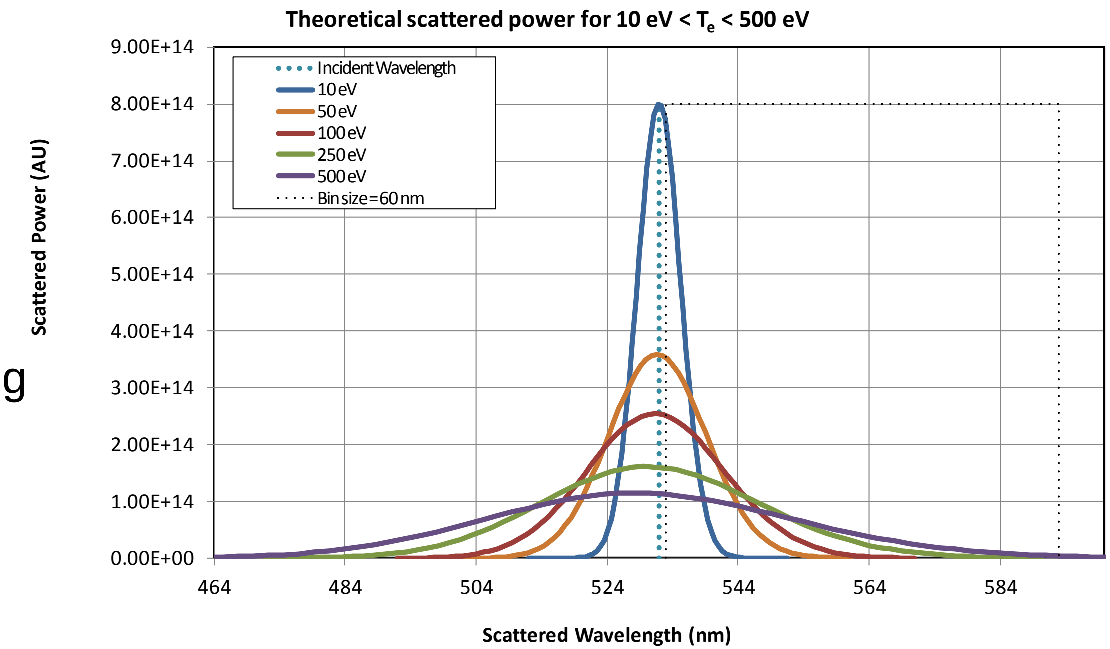
- Pegasus plasma durations are ~30 ms
  - Will only be able to measure one laser pulse per plasma shot

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+19
l	Length of beam for one channel (m)	0.014
ξ	Solid angle subtended by optics (ster)	9.23E-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	36582.10
	Joules incident at primary wavelength	1.37E-14
	Watts at primary wavelength	1.95E-06

THE UNIVERSITY of WISCONSIN MADISON

Spectral range 532 – 592 nm for Pegasus operating scenarios

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

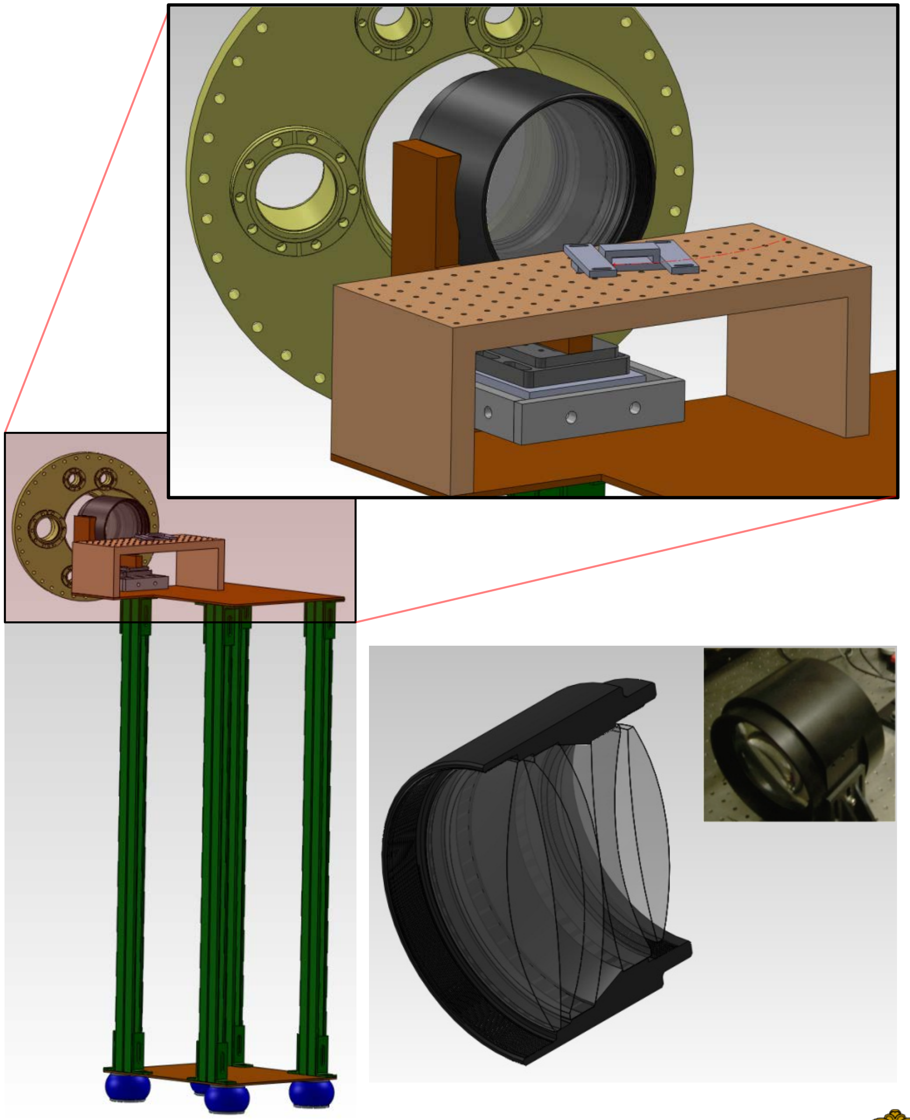


Based on: J. Sheffield, *"The Incoherent Scattering of Radiation from a High Temperature Plasma"*, Plasma Phys., **14**, 783-791, 1972.

- Predictions assume 90˚ average scattering angle with ~10^{-2} solid angle
  - Relativistic effects evident in shift of central wavelength at T_e > 500 eV

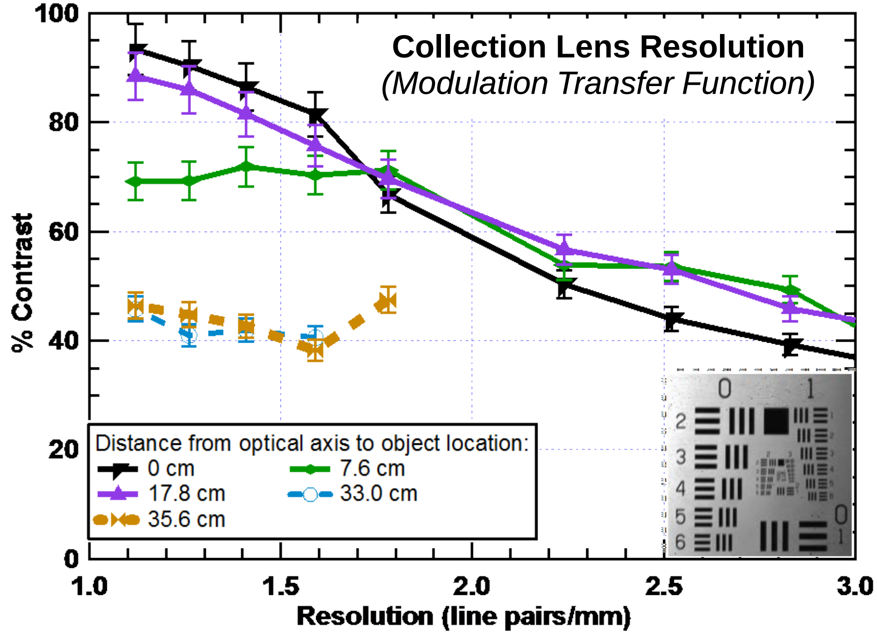
Custom Collection Optics Designed and Fabricated

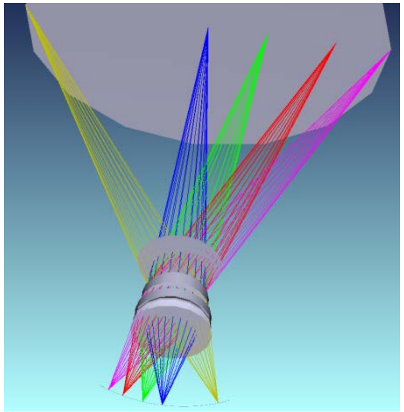
- 4 element lens system with 134 mm dia. aperture stop
- 132 cm^2 on-axis collection area with object distance ~80 cm
- Collection: ~F/6
- Imaging: ~F/1.75
- Able to view $r/R_{vessel} = 0.16\text{-}0.84$, collects over $63° < \theta_{scattering} < 110°$
- Mounted on a vibration-isolated stand, free-standing from vacuum vessel
- Fiber optic holders can be placed anywhere along lens' image plane

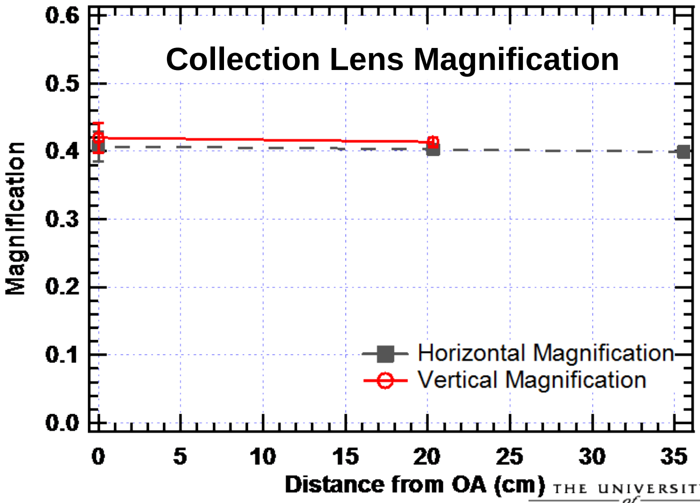


Collection Lens System Characterized

- Laboratory testing shows ~50% contrast for all spatial locations at 2.25 line pairs/mm
  - 1951 USAF resolution test chart used
  - In-vessel imaging area 3 mm x 14 mm
- Lens system is slightly anamorphic
  - Horizontal magnification ~0.40
  - Vertical magnification ~0.42
- System designed by Wright Scientific, Inc. and modeled in ZEMAX





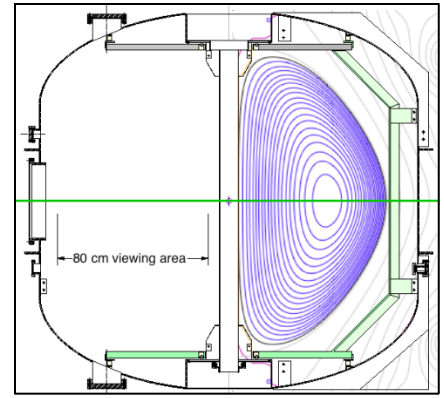


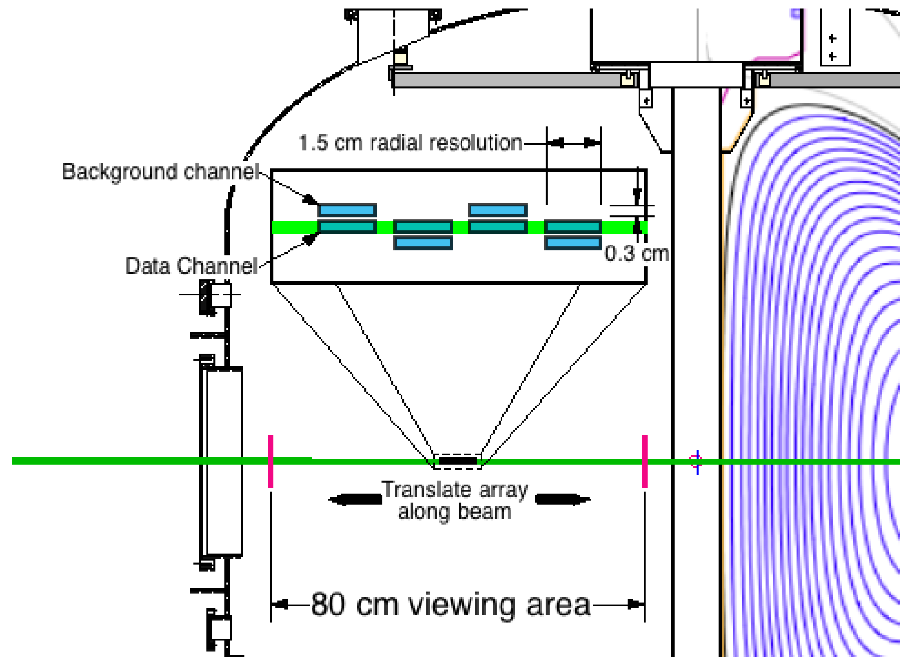
D.J. Schlossberg, 19th HTPD Conference, Monterey, CA May 2012

THE UNIVERSITY of WISCONSIN MADISON

Initial System Designed for Expandability

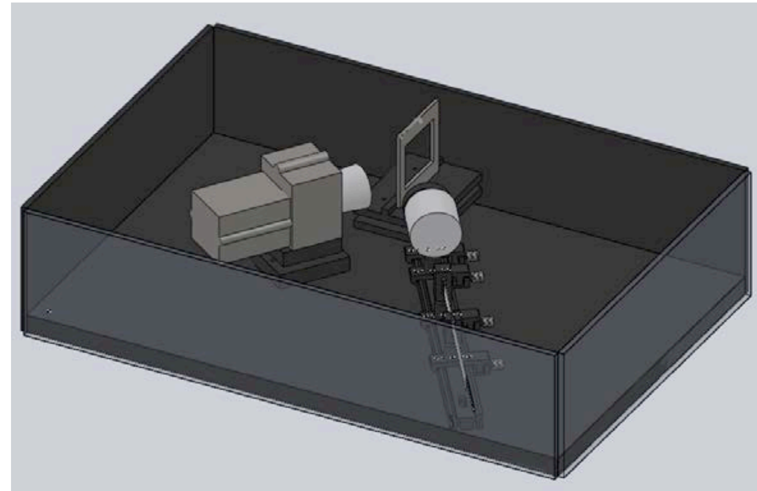
- Inidividual channels correspond to close-packed fiber bundles
  - 1.5 cm radial resolution
- Initially, 4 data channels and 4 background monitors
  - Evaluate performance & plasma conditions and reconfigure as needed
  - Upon successful implementation, immediately begin expanding to 16 additional channels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

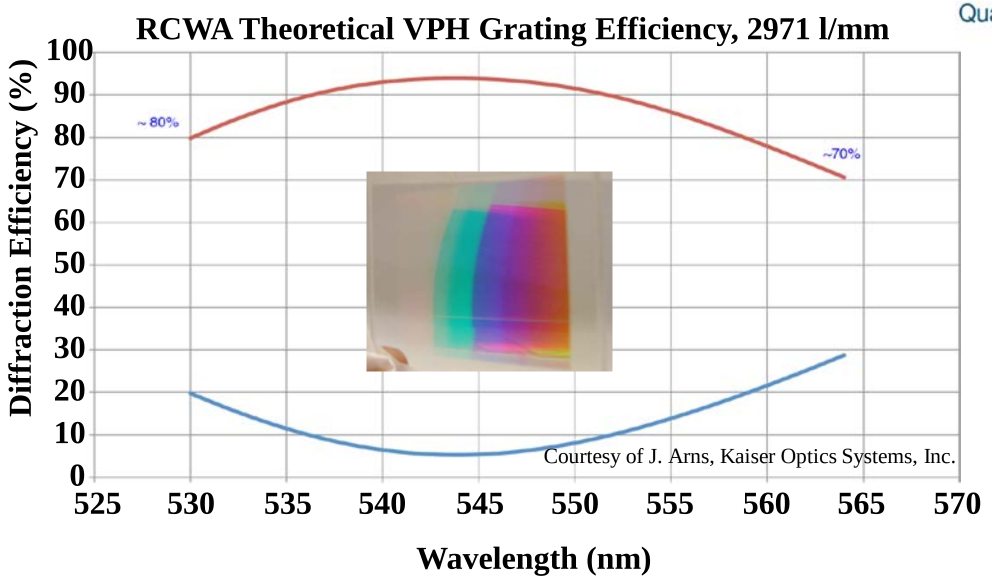




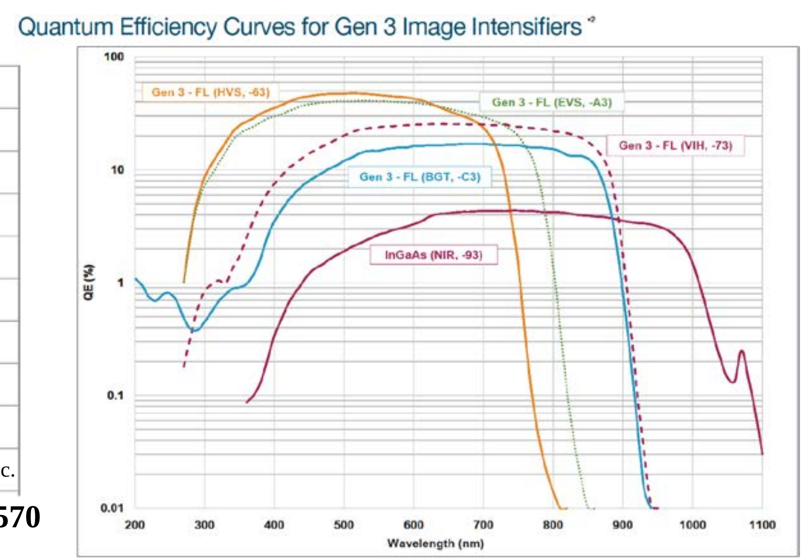
Novel spectrometer system employs VPH grating and ICCD camera

- 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





Courtesy of J. Arns, Kaiser Optics Systems, Inc.



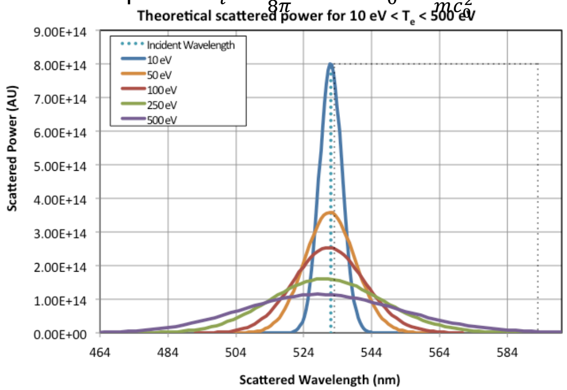
Synthetic data created in IGOR

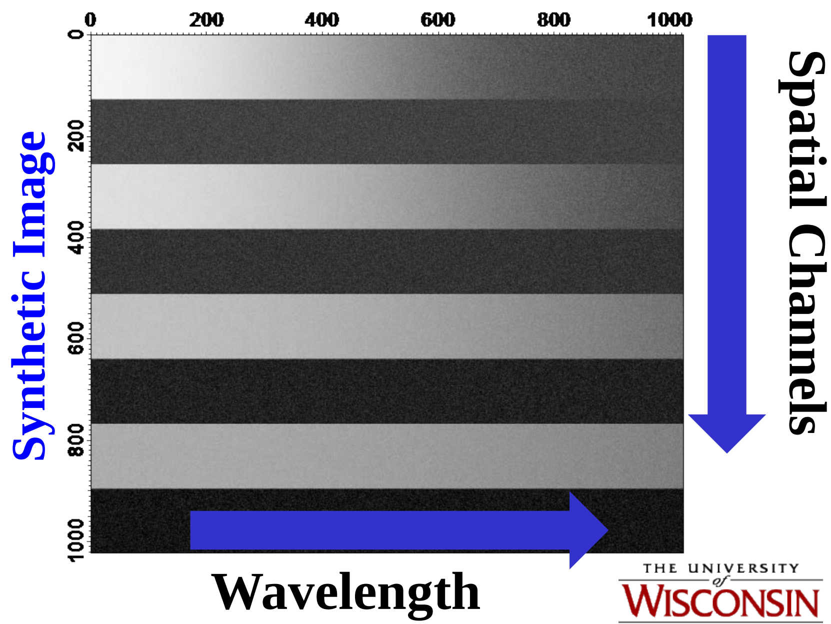
- Based on Sheffield's model/corrections for Thomson scattering:
    1. *Starts with exact results*
    2. *Duplicates for each row in given channel*
    3. *Adds photon noise from scattering*
    4. *Adds estimated background signal from plasma*
    5. *Adds detector dark current + dark current noise*
    6. *Adds camera baseline offset*
    7. *Add readout noise from detector amplifiers*
    8. *Rescales assuming data is optimized for detector's full dynamic range (16-bit)*

See: J. Sheffield, *"The Incoherent Scattering of Radiation from a High Temperature Plasma"*, Plasma Phys., **14**, 783-791, 1972.

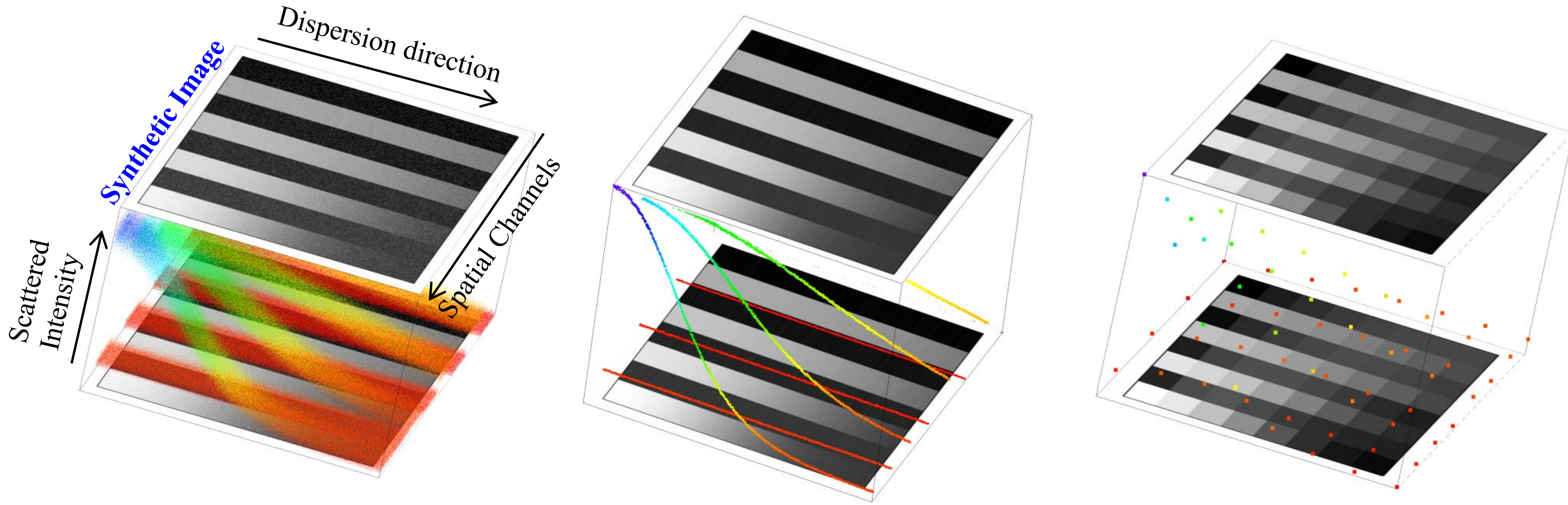
$$P_{sc}(R,\lambda_s)d\lambda_s d\Omega = \frac{P_i r_0^2 d\Omega n_e L c}{2\pi^{1/2} a \sin(\theta/2)\lambda_i}\cdot\left\{1 - \frac{7}{2}\frac{\Delta\lambda}{\lambda_i} + \frac{c^2\Delta\lambda^3}{4a^2\lambda_i^3\sin^2(\theta/2)}\right\} \times \exp\left(-\frac{c^2\Delta\lambda^2}{4a^2\lambda_i^2\sin^2(\theta/2)}\right)\cdot d\lambda_s$$

where the incident power $P_i = \frac{cE_i^2}{8\pi}A$ and $r_0 = \frac{e^2}{mc^2} = 2.82\times 10^{-13}cm$

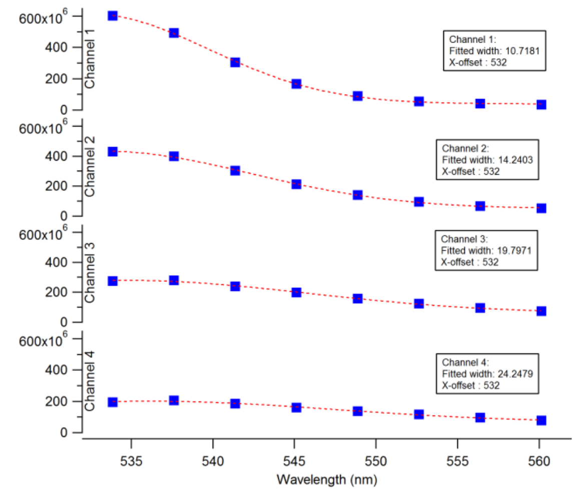




Initial data analysis routine begun

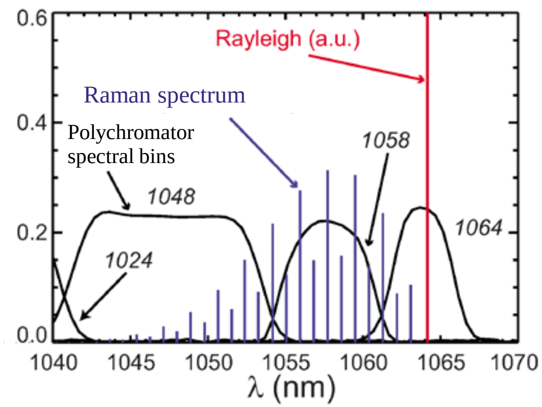


- Initial data routine coded to obtain temperatures:
  1. *Uses 1024x1024 image as input*
  2. *Bins data in "spatial direction"*
  3. *Bins data in "dispersion" direction*
  4. *Applies Gaussian curve to obtain FWHM*
  5. *Converts to temperature using exponential coefficients from Sheffield*



Several calibration methods under consideration

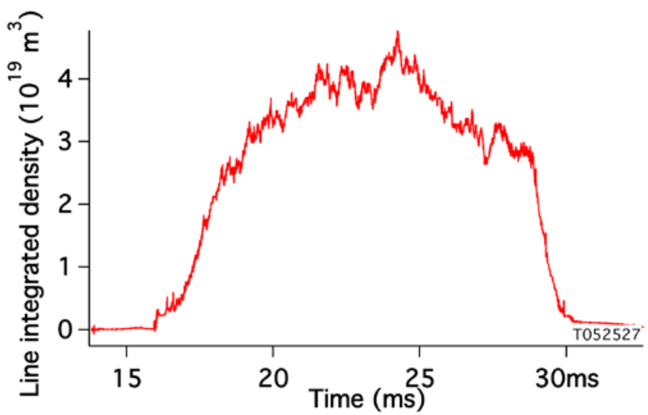
- Typical calibration methods span orders of magnitude in cross-section:
  - $\sigma_{Rayleigh} \approx 10^{-28}\ cm^2/sr$
  - $\sigma_{Raman} \approx 10^{-31}\ cm^2/sr$
  - $\sigma_{Thomson} \approx 10^{-33}\ cm^2/sr$



NSTX Raman Calibration

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

- Alternate methods include:
  - Comparison with existing Pegasus diagnostics (ex. µwave interferometer)
  - Vacuum-compatible calibrated source, actuated to move along beamline

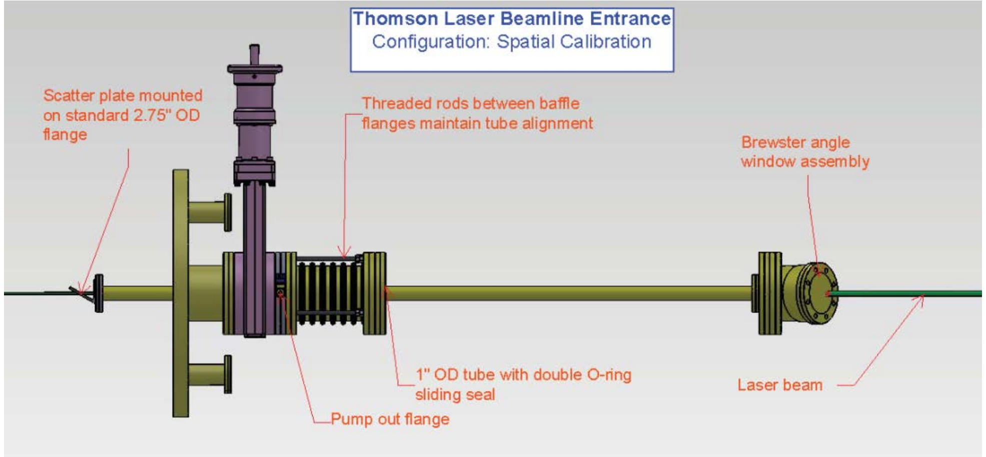


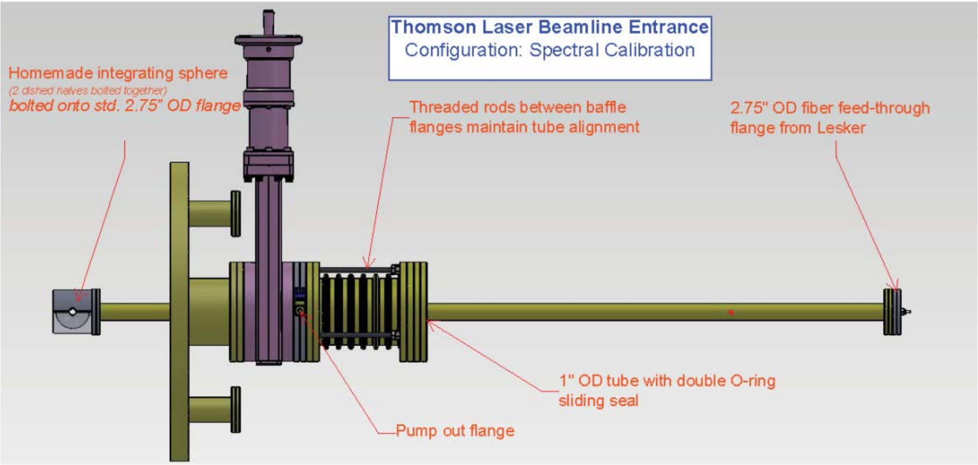
Typical PEGASUS plasma density

THE UNIVERSITY of WISCONSIN MADISON

Vacuum-compatible insertable calibration assembly designed

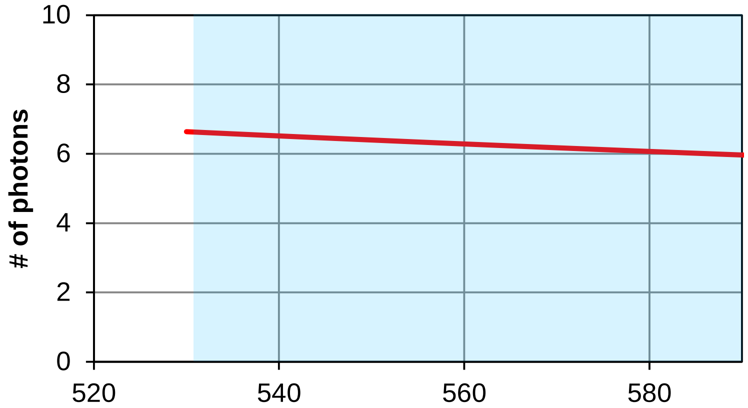
- Single assembly with 2 configurations:
  - *Spatial Calibration:* Brewster angle window, reentrant tube, scatter-plate
  - *Spectral Calibration:* Fiber optic vacuum feed-through, reentrant tube, fiber-coupled integrating sphere
- Could be use in addition to, or instead of, Raman/Rayleigh scattering



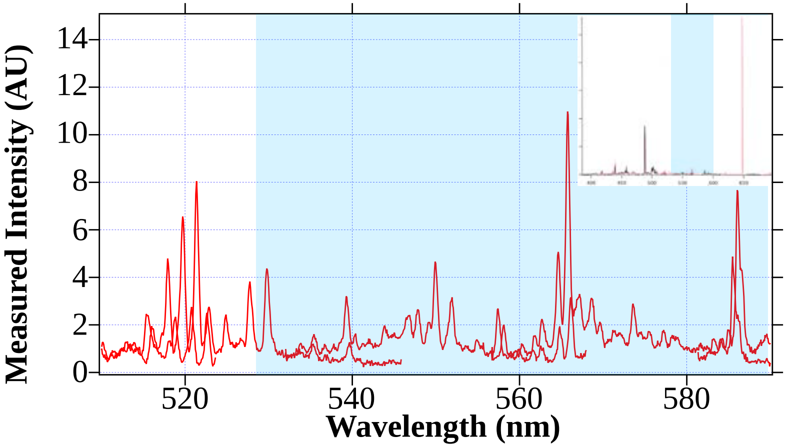


Bremsstrahlung emission a tolerable fraction of scattered signal

- 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

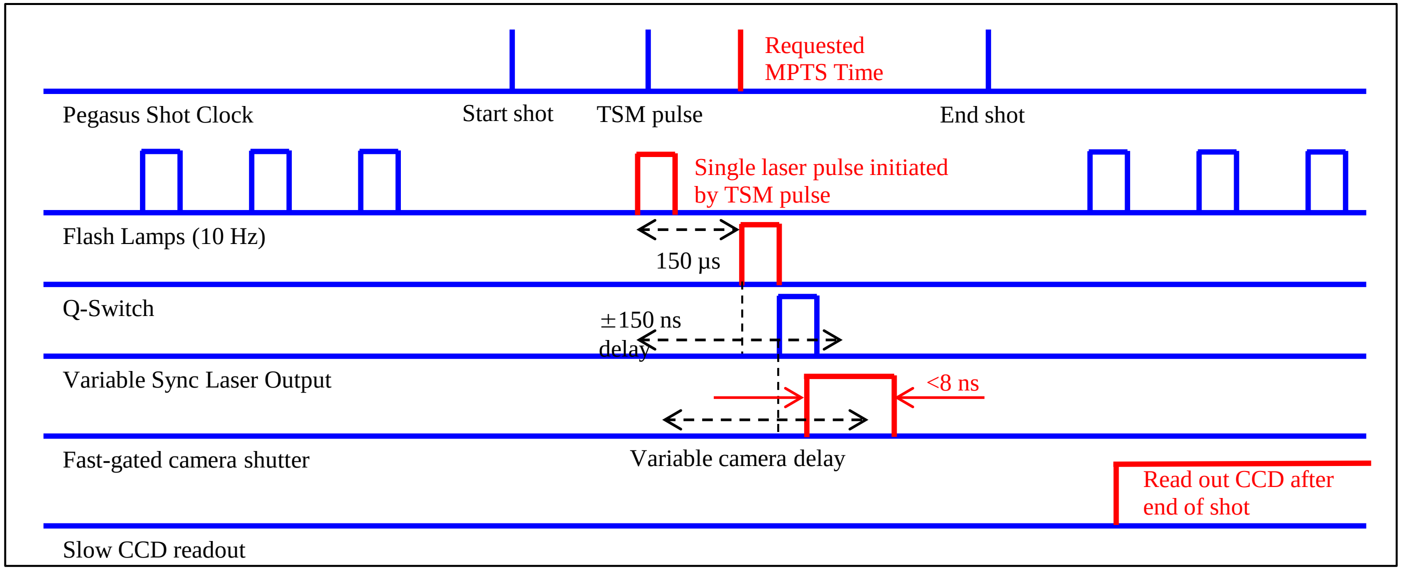


*following Karzas and Latter, Astrophys. J. (Supplement) **6** 1961, 167



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 ($t_0 - t_{flash\ lamps} - t_{Q\text{-}switch}$)
  - 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



Summary

- A new Thomson scattering diagnostic has been designed and is being implemented on the Pegasus Toroidal Experiment
  - 10 eV < T_e < 500 eV, 10^{18} m^{-3} < n_e < ~5×10^{19} m^{-3}

- Nd:YAG laser, collection optics, beam dump & beam line have been characterized and are ready for installation

- Spectrometer testing is nearly complete, and will be ready for implementation in the early summer
  - Uses Volume Phase Holographic (VPH) diffraction grating, and intensified CCD (ICCD) camera

- Calibration procedures are under development, and in-situ methods are being explored