The CTH experiment

CTH* is a five field-period torsatron investigating the avoidance of disruptions over a wide range of plasma parameters.

Plasmas are created by launching an ECRH pulse to ionize Hydrogen gas, after which a plasma current is ohmically driven in this pre-established plasma resulting in a higher temperature and density.

CTH has the unique feature of operating with different ratios of vacuum to plasma transform. This allows CTH to control the magnetic topology from tokamak-like to stellarator-like.

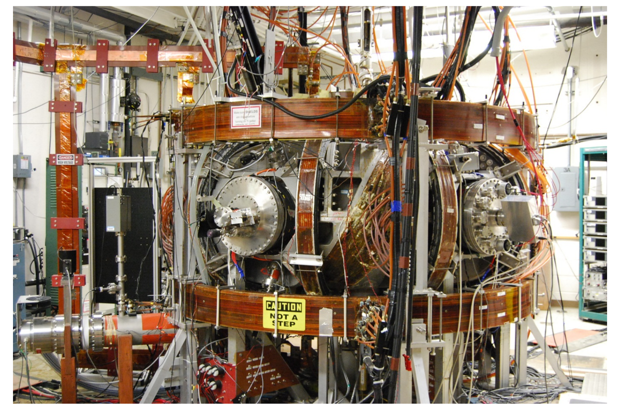
*Supported by US DOE Grant DE-FG-02-00ER54610

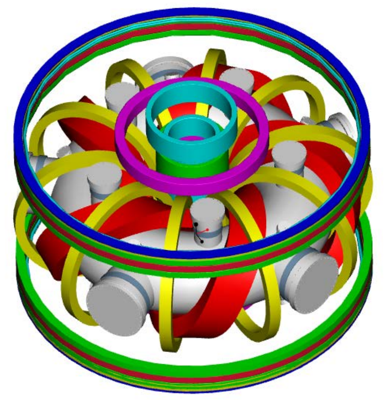
CTH parameters:

- Aspect ratio $A \approx 3-4$
- $R = 0.75\,m$, $<a> = 0.2\,m$
- $|B| \leq 0.7\,T$ on axis
- $0.02 \leq \iota_{vac} \leq 0.32$
- $I_{plasma} \leq 80\,kA$
- $n_e \leq\ 5\times10^{19}\ m^{-3}$
- $T_e \leq\ 200\,eV$
- $P_{input}\ \leq 30\,kW$ of ECRH
- $P_{input}\ \approx 200\,kW$ of Ohmic drive
- Vacuum pressure $\approx 1\times10^{-8}\,Torr$

Motivation for Thomson Scattering:

- Internal, local measurement of electron density and temperature
- Improved Equilibrium Reconstructions with V3FIT especially for pressure profiles
- Better characterize CTH plasmas to understand disruptions and MHD activity



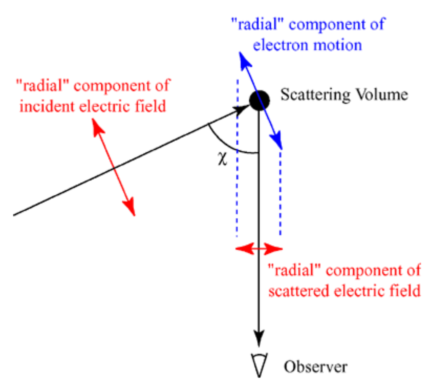


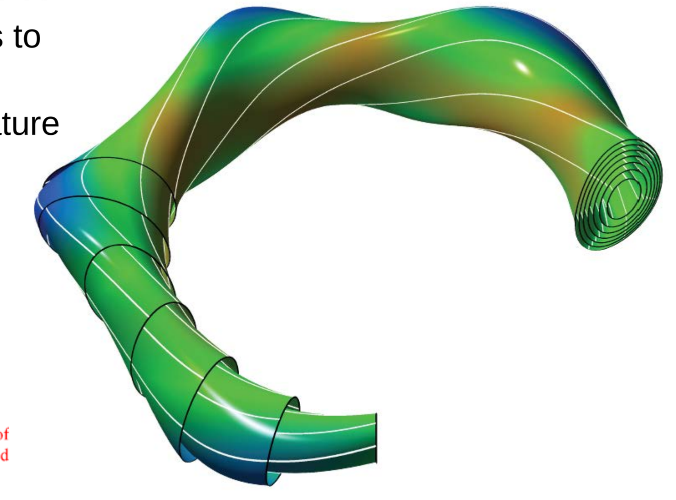
Thomson Scattering as a Plasma Diagnostic

Thomson Scattering Basics

- Elastic scattering of electromagnetic radiation from free charged particles
- Electrons accelerate the radiation's electric field causing the electrons to reradiate.
- Scattered Intensity is proportional to the electron density and temperature

$$I_{scattered} \propto \sqrt{\frac{m_e}{2\pi T_e}}\, n_e \exp\left(\frac{m_e\omega^2}{2k^2T_e}\right)$$





Advantages of Thomson Scattering

- Non-invasive
- Non-perturbing
- Internal and local measurement

$$\frac{P_{scattered}}{P_{input}} \approx r_e^{\,2}\, n_e\, L\, d\Omega$$

$$\frac{P_{scattered}}{P_{input}} \approx 2.94\times10^{-14}$$

$$P_{scattered} \approx \frac{1.7\,J}{7\times10^{-9}s}(2.94\times10^{-14})$$

$$P_{scattered}\ \approx 7\,\mu W$$

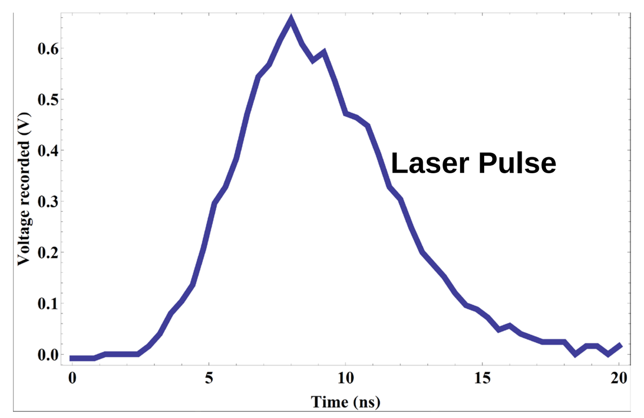
Addressing the Challenges of Thomson Scattering

- Low number of scattered photons
  - High Power laser
  - Large Viewing solid angle
- Necessary stray light mitigation
  - Geometrically confine stray light
  - Actively filter and spectrally isolate desired wavelengths
- Complex system components
  - High throughput spectrometer, PMT, and laser are all commercially available

System Components

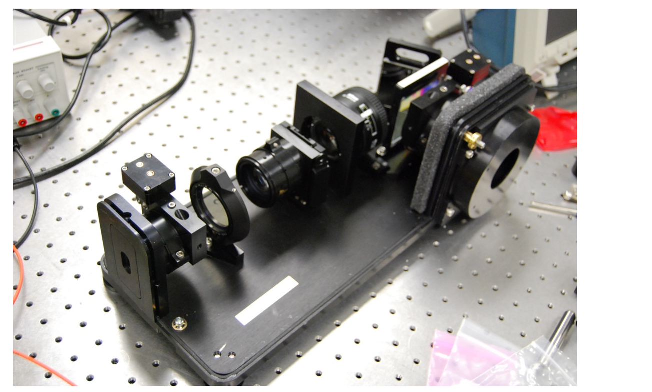
High Energy Nd:YAG Laser

- 3.5 J at 1064 nm and 2 J at 532 nm
- Pulse width of 6-10 ns
- Rep rate of 10 Hz
- $M^2 \approx 7$
- Gaussian beam with beam waste of 12 mm



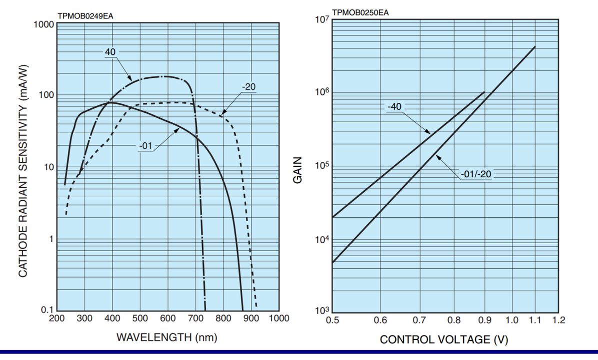
HoloSpec Imaging Spectrograph

- f/1.8 allows for large throughput of light
- Option of Interference filter that rejects laser line
  - 532 nm laser light not focused onto imaging device
- Kaiser volume-phase holographic transmission grating
  - Spectral coverage: 533.1 to 563.3 nm over 26.6 nm



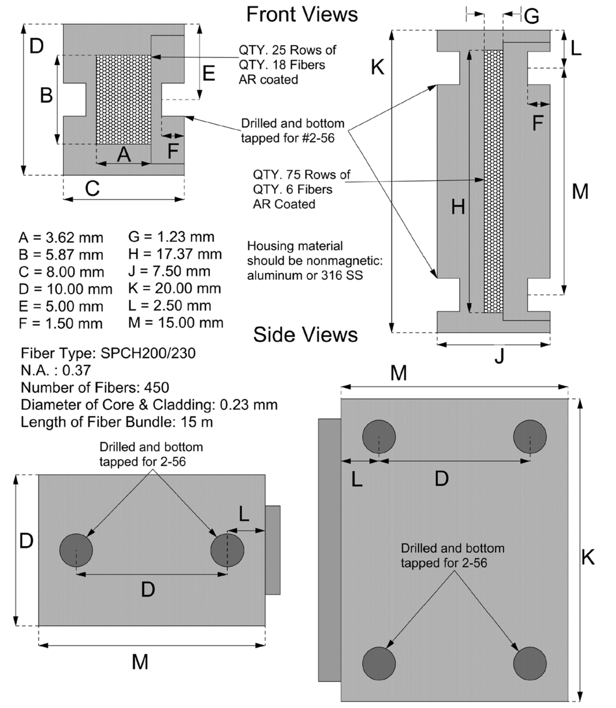
Hamamatsu H11706-40 PMT Module

- 5 mm diameter effective active area
- Fast gating FWHM of 1 μs
- Quantum Efficiency ~40% at 550 nm



Spectrometer input Custom Fiber Bundle

- 17.37 mm by 1.23 mm for spectrometer input
- 450 fused silica fibers
  - 230 μm diameter including cladding
  - N.A. 0.37

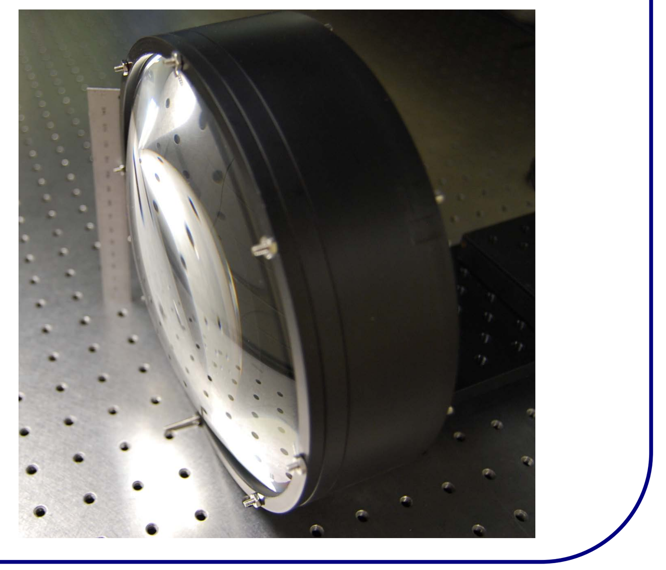


PMT input Custom Fiber Bundles

- Curved bundle to match curvature of spectrometer output plane
- Fibers need N.A. > 0.42
- Every spectral channel needs an individual bundle

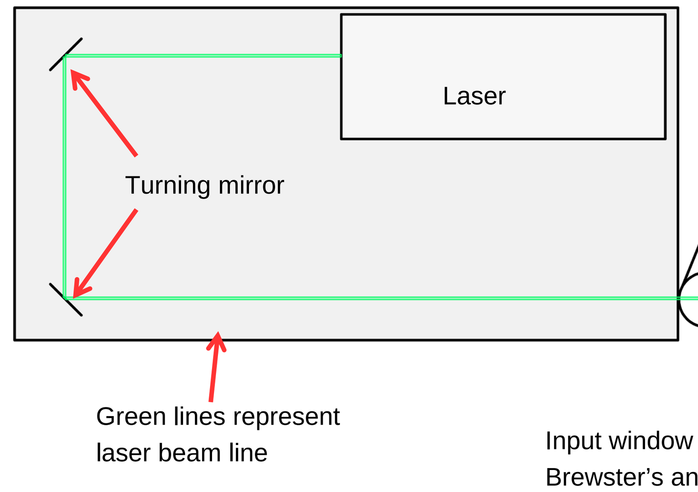
Large PCX Condenser Lenses

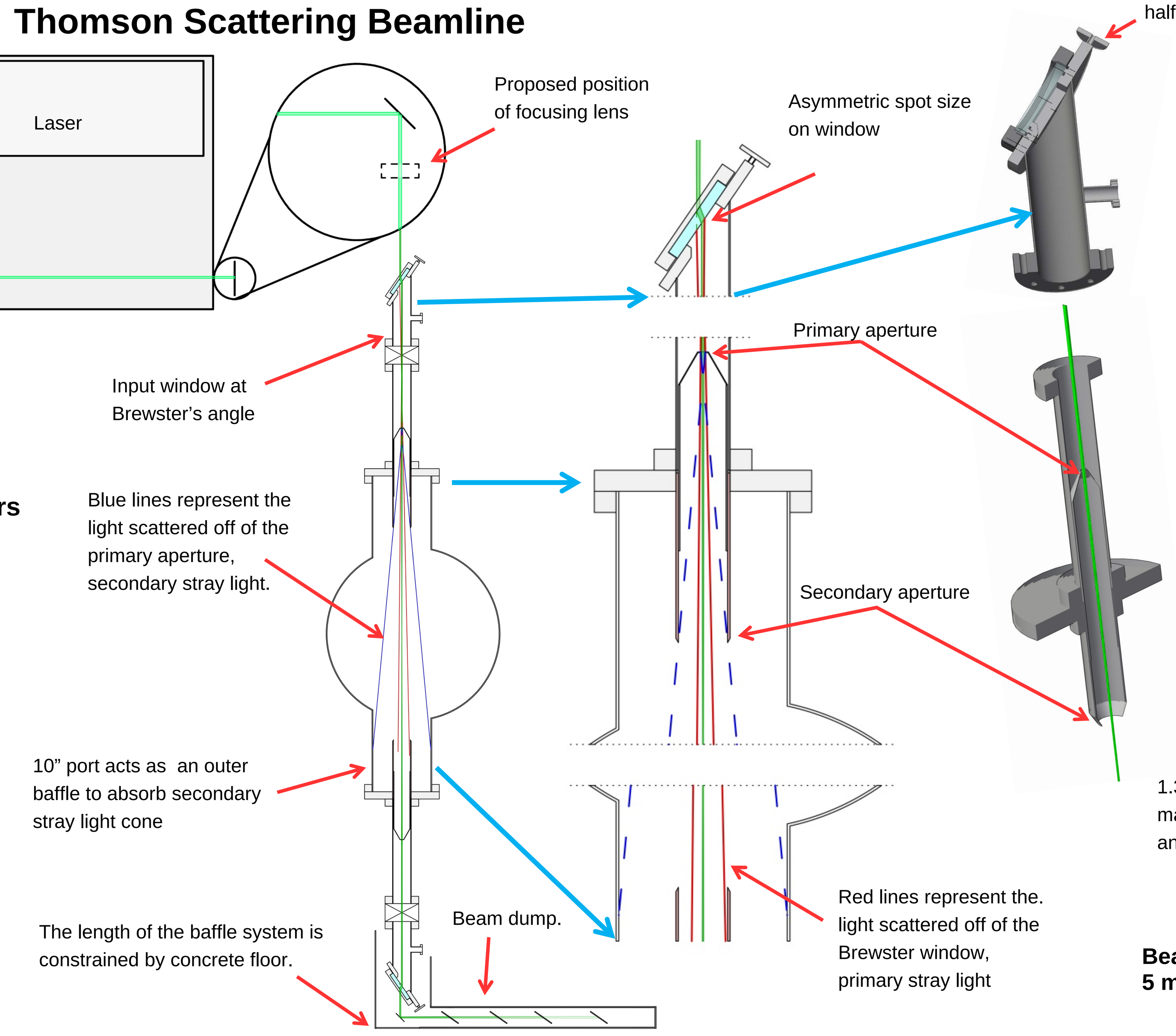
- Two adjacent plano-convex f/2 lenses
- 150 mm clear aperture
- Effective f-number of optics: ~ f/1.5
- AR coated for increased transmission



Proposed Beamline Geometry

Thomson Scattering Beamline

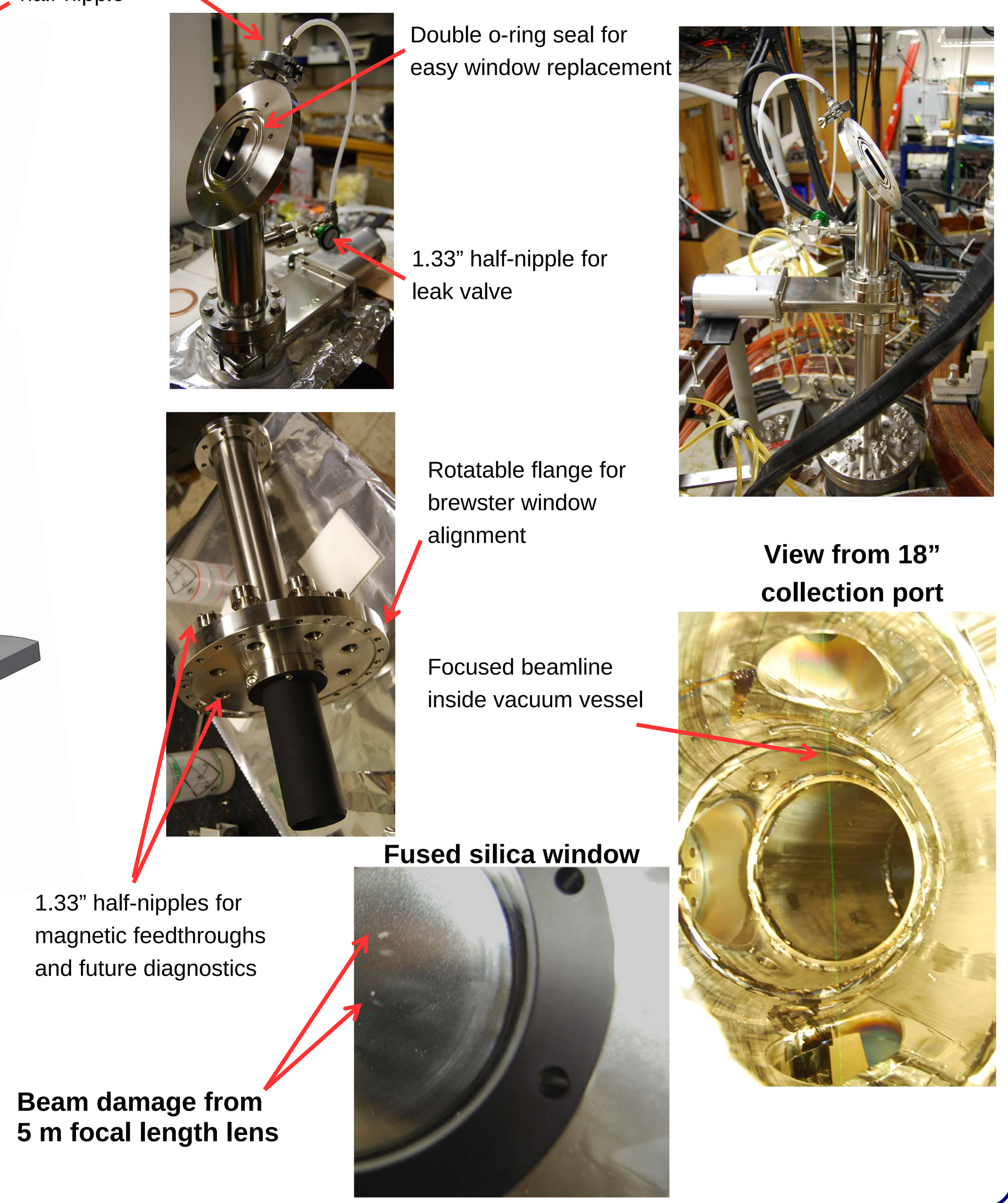




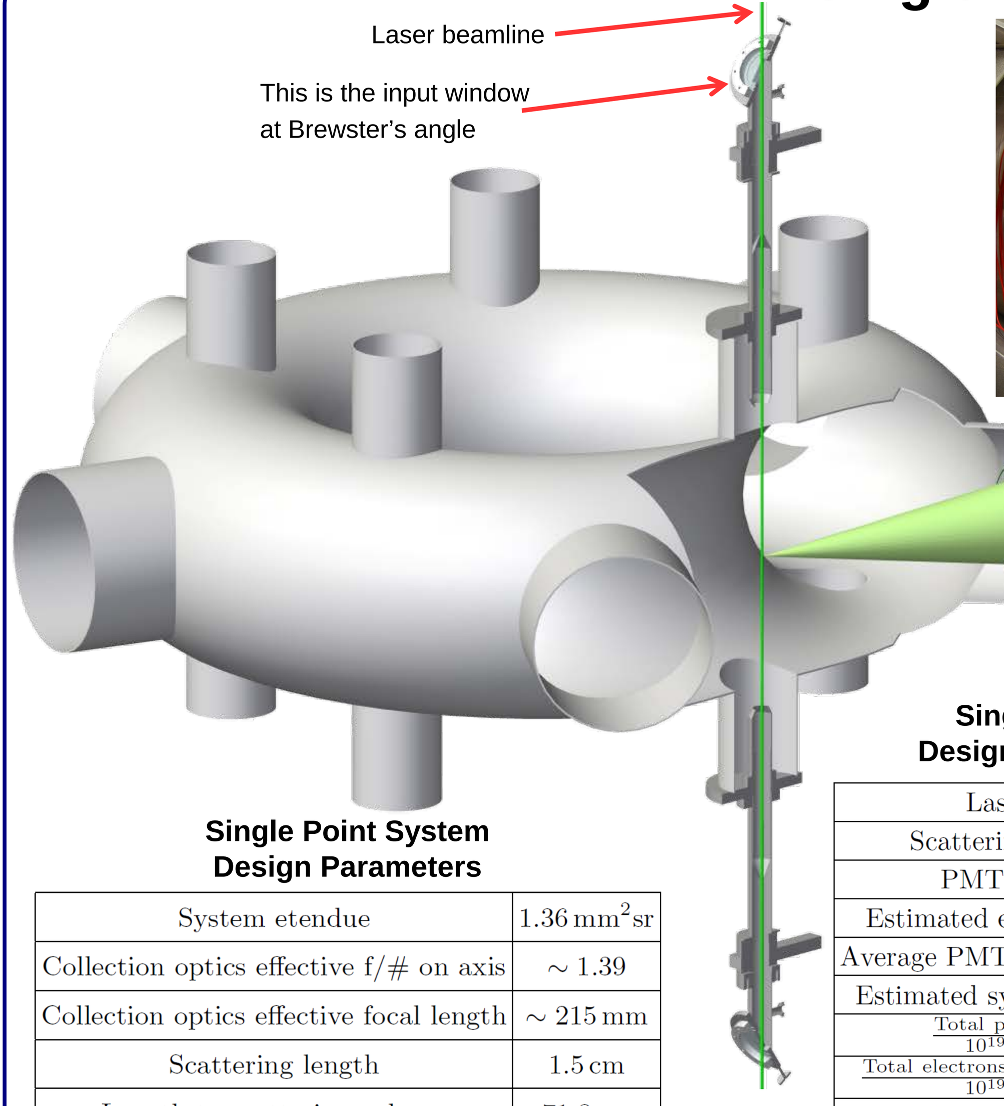
Beam line design parameters

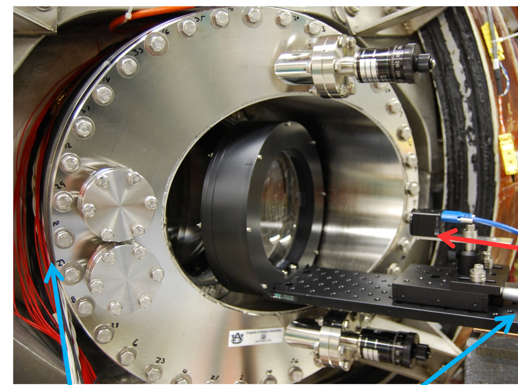
Focal length	$< 5.0\,m$
Primary aperture diameter	$6.35\,mm$
Secondary aperture diameter	$57.404\,mm$
Distance between lens and window	$< 3.78\,m$
Distance between window and primary aperture	$0.4\,m$
Distance between primary and secondary aperture	$0.4\,m$
Distance between input and output baffles	$0.720\,m$
Distance from bottom port to concrete floor	$0.780\,m$

Installation of Beamline



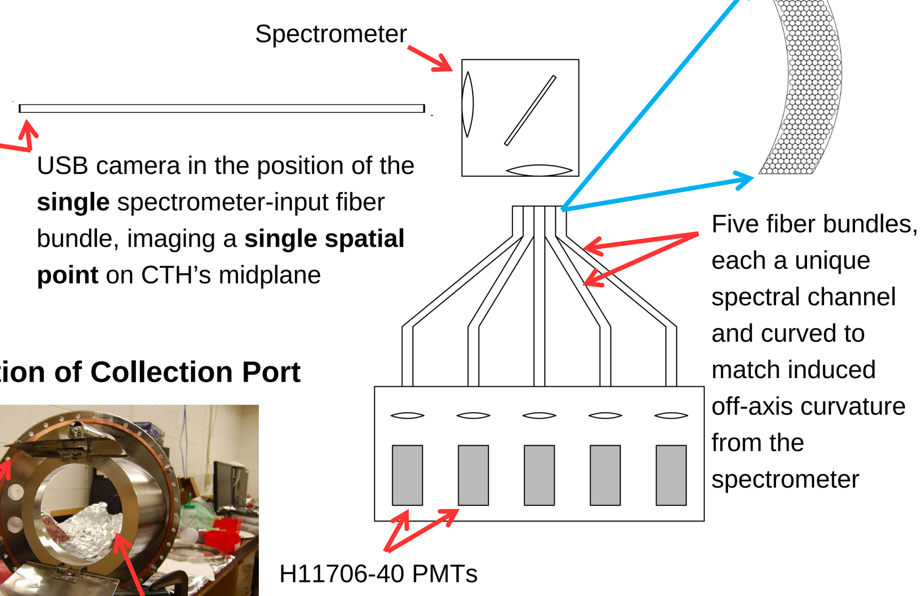
Single Point Collection Geometry and Signal estimates



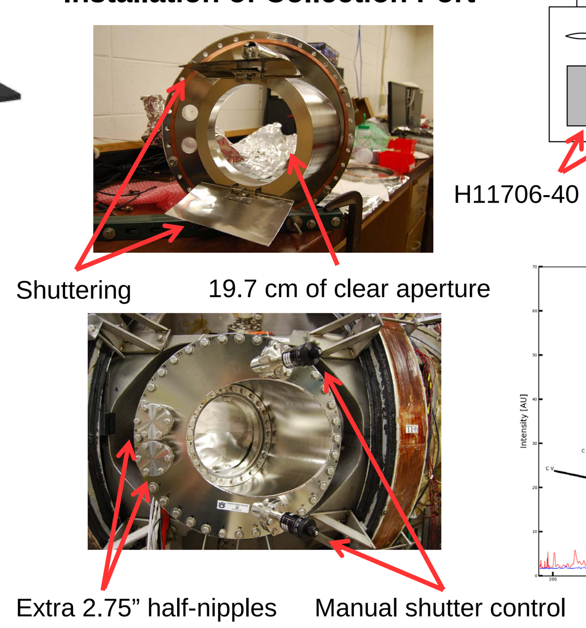


USB camera in the position of the **single** spectrometer-input fiber bundle, imaging a **single spatial point** on CTH's midplane

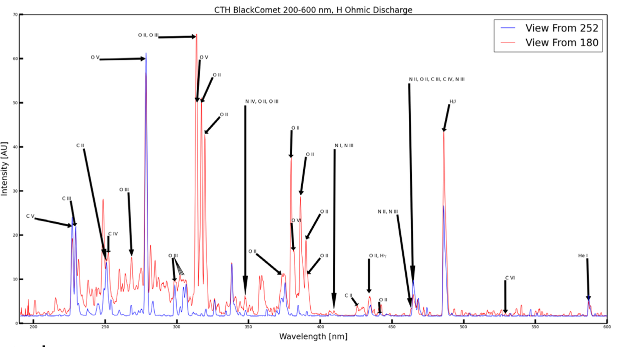
Spectrometer and detector diagram



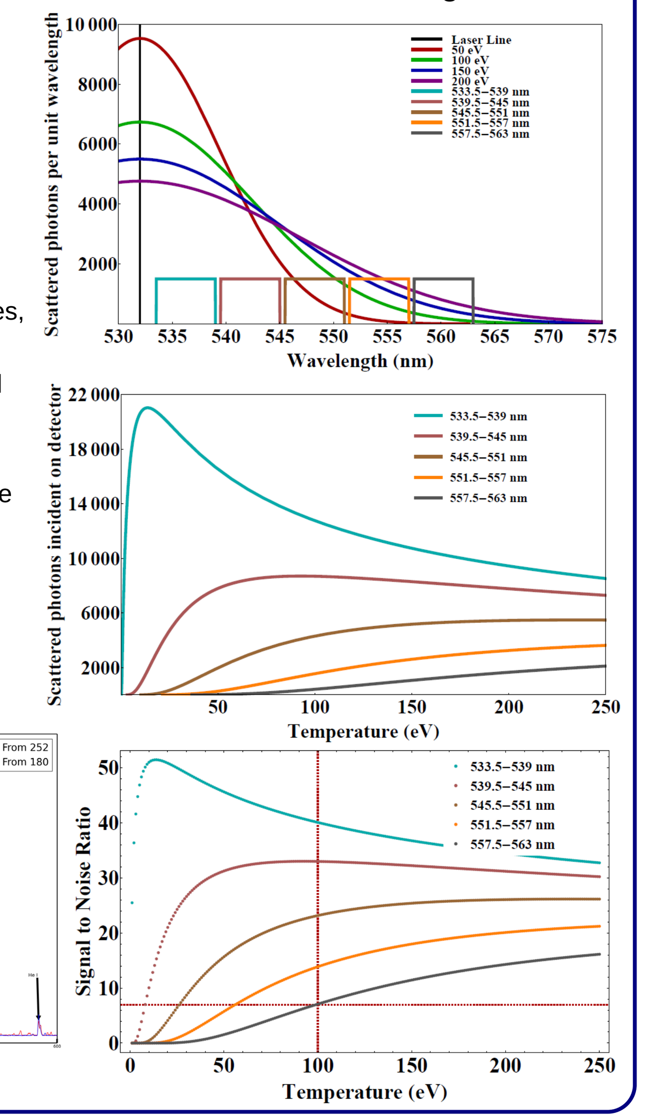
Installation of Collection Port



CTH Visible Spectra



Simulated Thomson signals



Single Point System Design Parameters

System etendue	$1.36\,\mathrm{mm}^2\mathrm{sr}$
Collection optics effective f/# on axis	~ 1.39
Collection optics effective focal length	$\sim 215\,\mathrm{mm}$
Scattering length	$1.5\,\mathrm{cm}$
Length to scattering volume	$71.8\,\mathrm{cm}$

Single Point System Design Parameters (cont)

Laser energy	$1.7\,\mathrm{J}$
Scattering wavelength	532 nm
PMT active area	$19.63\,\mathrm{mm}^2$
Estimated excess noise factor	~ 1.6
Average PMT quantum efficiency	~ 0.39
Estimated system transmission	~ 0.37
$\frac{\text{Total photo-electrons}}{10^{19}\ \text{plasma e-}}$	$\sim 10^4$
$\frac{\text{Total electrons collected per channel}}{10^{19}\ \text{plasma e-}}$	$\sim 10^3$
S/N ratio per channel	~ 8 to 40

Future work

- Finish installation of beamline components and determine the correct focal length beamline optic
- Bench test collection optics with custom diffraction grating to determine output plane fiber bundles curvature
- Implement full design and calibrate the system including data comparisons to soft x-ray and interferometer measurements
- Use Thomson scattering data as internal conditions for the V3FIT code for improved equilibrium reconstructions

References

[1]Schlossberg et al., Rev. Sci. Instrum 83, 10E335 (2012).

[2]Schoenbeck et al., Rev. Sci. Instrum 83, 10E330 (2012).

[3] Sheffield, John. "Noncollective Scattering." *Plasma Scattering of Electromagnetic Radiation: Theory and Measurement Techniques*. Amsterdam: Elsevier, 2011. 69-90. Print.