ABSTRACT

A CCD imaging system is currently being developed for $T_e(0,t)$ and bolometric measurements on the Pegasus Toroidal Experiment. Soft X-rays (E<10 keV) can be directly measured using a back-illuminated, thinned CCD to count individual photons and determine their energies via pulse-height analysis. Time resolution is obtained by moving exposed pixels across the CCD array behind a masked-off area on the chip. The first tests are done with a 512x512 array giving four spatial points and dt=2.5 msec. The mask is designed to optimize the tradeoff between time, energy, and spatial resolution. The presently available camera system is vacuum-coupled to the machine behind a 4 mil Be filter looking through a pinhole of diameter 0.16mm allowing measurements between R=15 and 45cm in the plasma. This same design can be extended to give a 1-D bolometric measurement by enlarging the pinhole and removing the Be filter. Initial measurements for both bolometry and electron temperature are in progress.

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Outline

- Concepts
  - CCD-based SXR PHA on CHS/LHD
  - Added capability of time evolution
  - Bolometry application

- SXR Modeling and T_e fits
  - X-ray spectrum model and measurement simulations
  - Noise Analysis
  - Simulated data results

- Hardware Implemetation
  - Camera schematic and vacuum interface
  - Lines of sight and machine view
  - Initial tests of SXR sensitive CCD

Electron Temperature and Radiated Power Will Be Measured With a CCD Camera

- Soft x-ray sensitive CCD measures individual photons in pulse-height analysis mode
  - Provides SXR spectrum in the ~2-10 keV energy range

- The CCD/PHA is accurate and cost effective
  - Assuming a thermal electron distribution
    -fair assumption for PEGASUS
  - CCD/PHA validated in CHS/LHD work

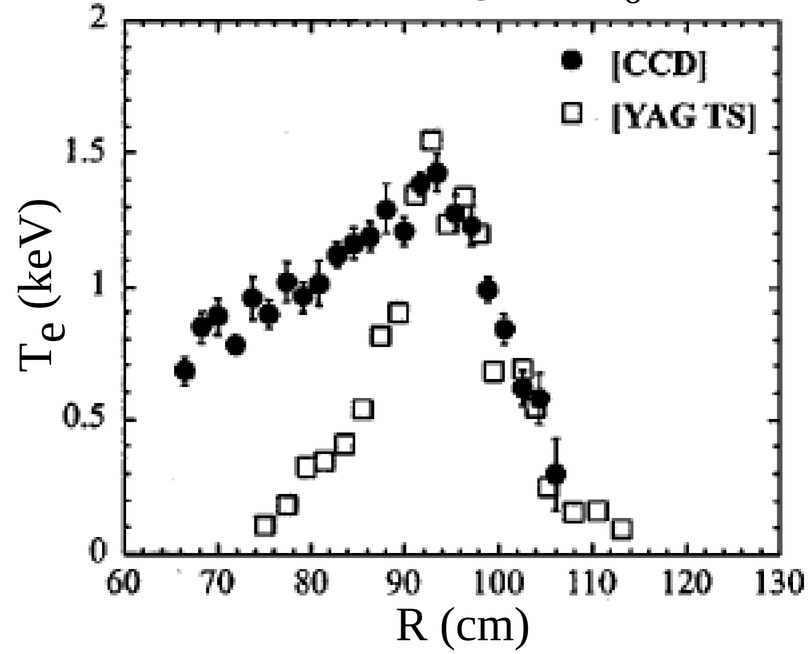
- Bolometry measurements also available
  - Measure total energy flux with no spectral resolution to give time evolving radiated power measurement

- Provide critical measurement
  - $T_e(R,t)$ needed for stored energy, confinement
  - P_{rad} monitors impurity influence on plasma behavior

CCD/PHA Measurement of T_e Demonstrated on CHS/LHD

- CCD camera system implemented by Liang[1] et al. to measure T_e
  - Back-illuminated 1024 x 1024 CCD array directly detects individual soft x-rays
  - Beryllium filters and pinholes reduced the flux of photons to allow single photon detection
    - Multiple shots averaged to get adequate statistics
  - T_e obtained by fit to SXR continuum

Measurements show excellent agreement with Thomson scattering for $R>R_o$

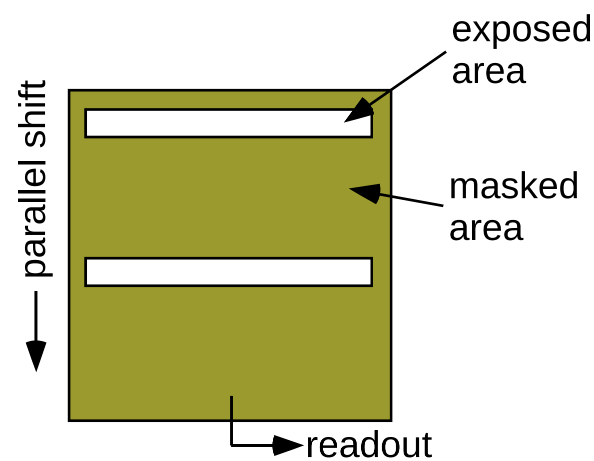


Liang, Y., et al, Review of Scientific Instruments, vol. 71 no. 10 (Oct. 2000)

1 Liang, Y., et al, Review of Scientific Instruments, vol. 72 no. 1 (Jan. 2001)

PEGASUS Will Implement A CCD/PHA System With Time Resolution Capability

- Implement partial masking to give time-resolved spectra with controlled frame transfer

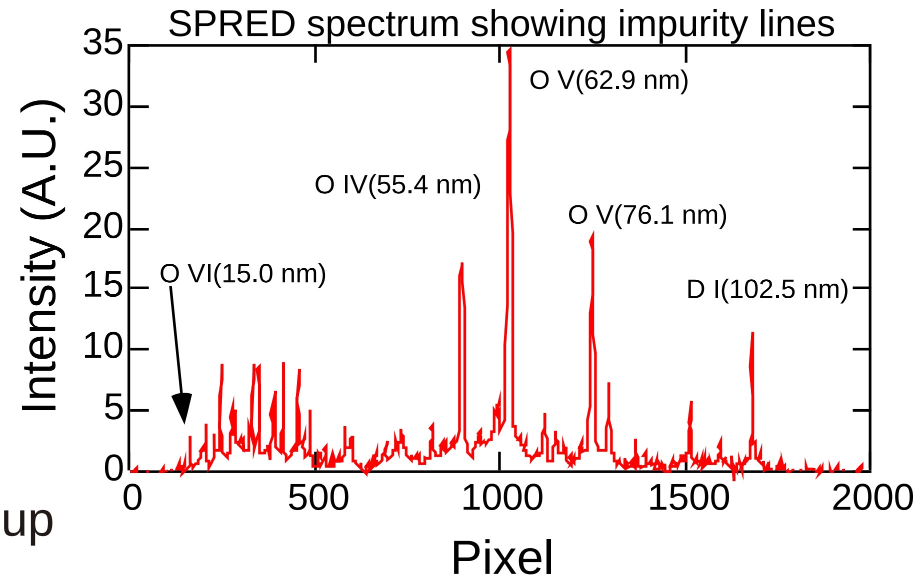


- Use fast parallel line shift to move exposed areas behind mask
  - achieve ~1-2 ms time resolution

- Requirements
  - Sufficiently large number of pixels to provide decent photon statistics while avoiding pulse pile-up
  - Maximize storage area to give large number of time intervals and spatial points
  - Very low noise readout for good energy resolution

Radiated Power Measurements Made by Direct CCD Exposure   Bolometer

- Direct exposure (i.e. no Be filter) of thinned CCD array has sensitivity equivalent to SXR diodes



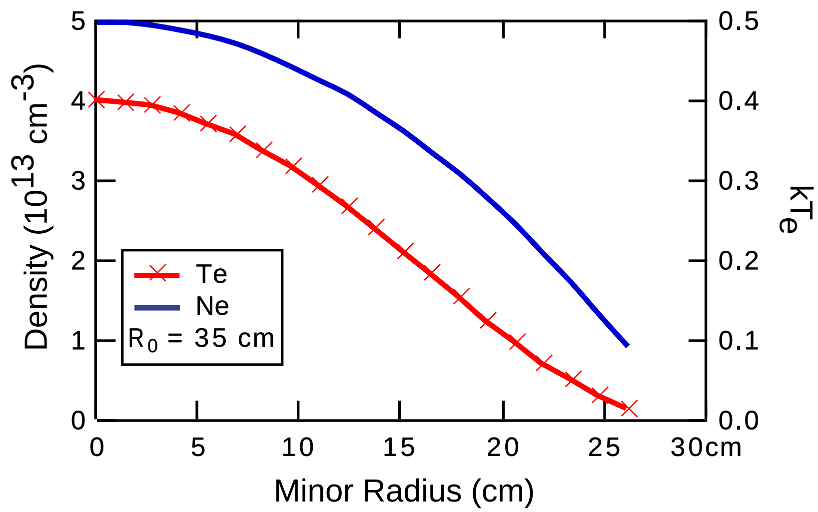
- Sensitive to bulk of the impurity radiation

- Not restricted to avoidance of pulse pile-up
  - multiple time and spatial points

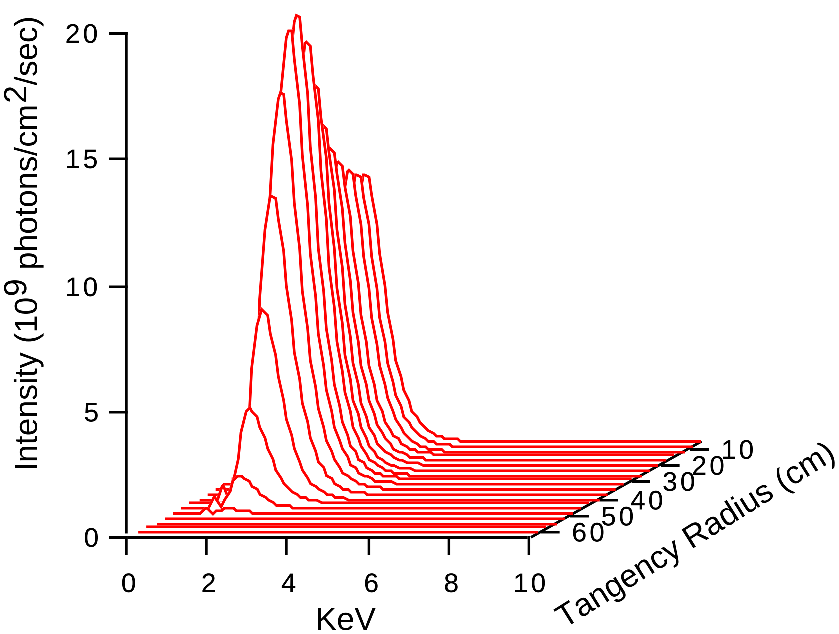
- Full spatial profile of P_{rad} with compact camera

X-Ray Code Used to Model PEGASUS Plasmas

- Initial SXR spectral simulations models the emissivity of PEGASUS plasmas



- Input model $N_e(R)$, $T_e(R)$, N_Z/N_e



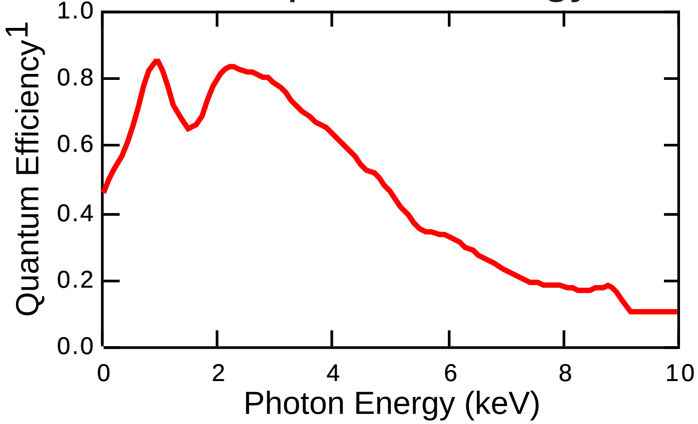
- Calculate line integrated intensity as a function of energy and tangency major radius

- Fit model spectrum to obtain T_e

$$I \sim \varepsilon \sim \frac{1}{E\sqrt{T_e}} e^{-\frac{E}{\sqrt{T_e}}}$$

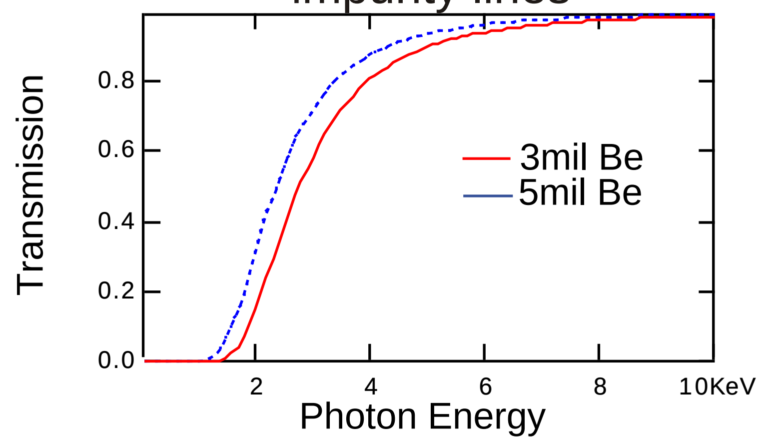
Deduction of SXR Spectrum Depends On Several Factors

Quantum Efficiency varies with photon energy



1) Andor Technology

Beryllium filters reduce impurity lines



- Photon flux reduced to appropriate level by apertures and filters
  - Be filter thickness adjusted to avoid impurity lines (<2 keV)
  - Pinhole area changed to reduce light flux and prevent pulse pileup

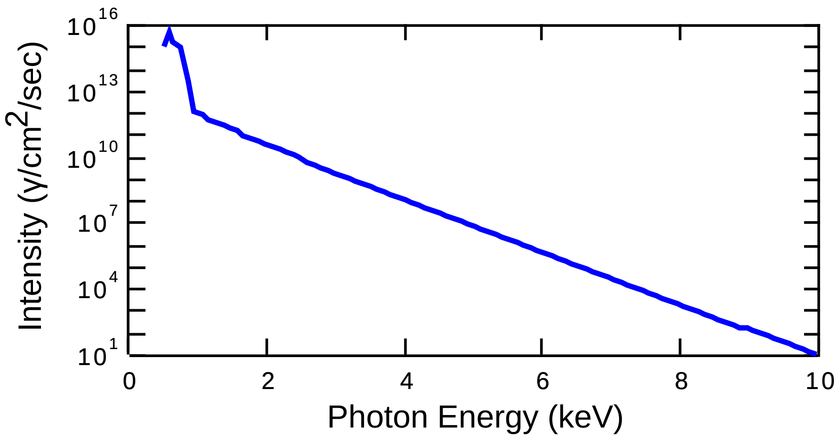
- Total number of pixels required for detection of N_γ photons set by need to minimize pulse pileup
  - $N_{pixel} > N_\gamma^2$ (Liang, et al.)

Slow-Scan CCD/PHA Decector Provides A Good Signal To Noise Ratio For Expected PEGASUS Parameters

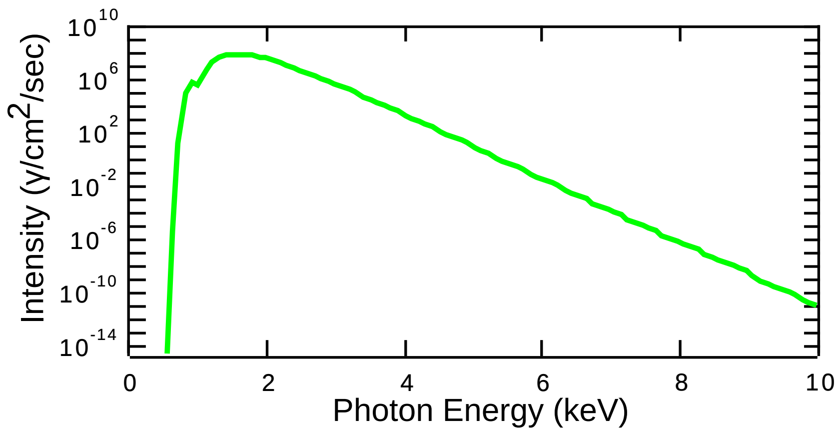
- Noise contributions
  - Dark current and noise will build up throughout the exposure to give noise ~10 electrons
  - Photon noise is $\sim\sqrt{N_\gamma}$ where N_γ is the total number of photons collected
  - Readout noise will be ~10 electrons

- Total Noise
  - Total noise (dark + readout) is ~15 electrons
  - Photons are converted to electrons at ~3.2 eV/electron
  - This results in a optimal spectral resolution of $\Delta E_\gamma \sim 50$ eV

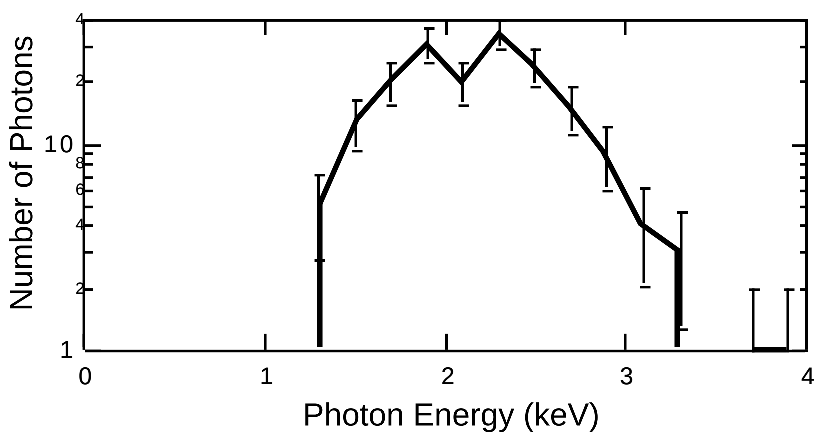
Data Handling and Error Estimates Obtained With Simulations From X-Ray Code



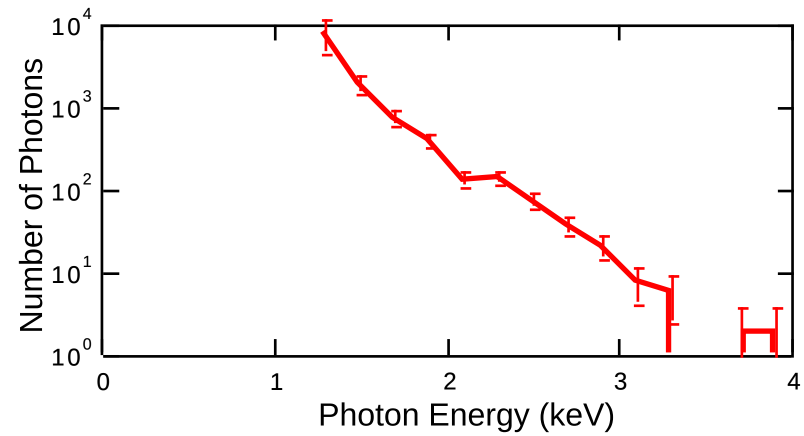
A) Raw intensity at R_{tan}=30 cm



B) Part A x QE x Filter transmission

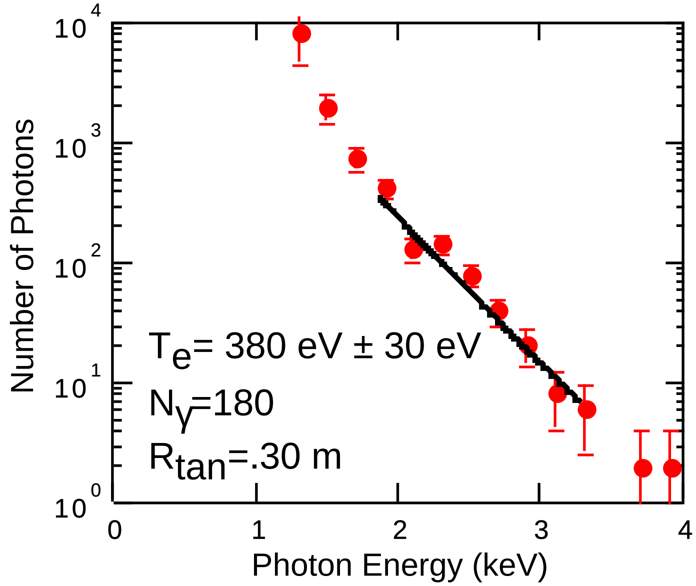


C) Random photon events distributed using part B as a probability distribution; $N_\gamma < \sqrt{N_{pixels}}$; here N_γ=180

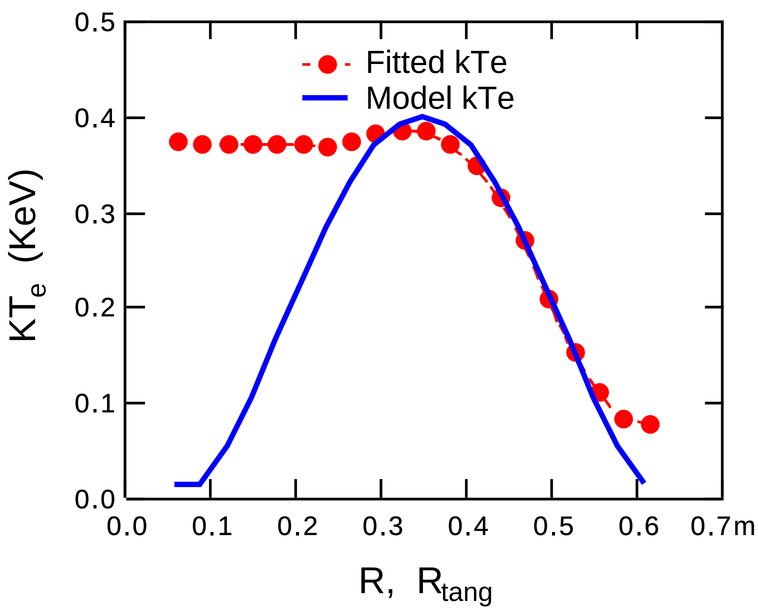


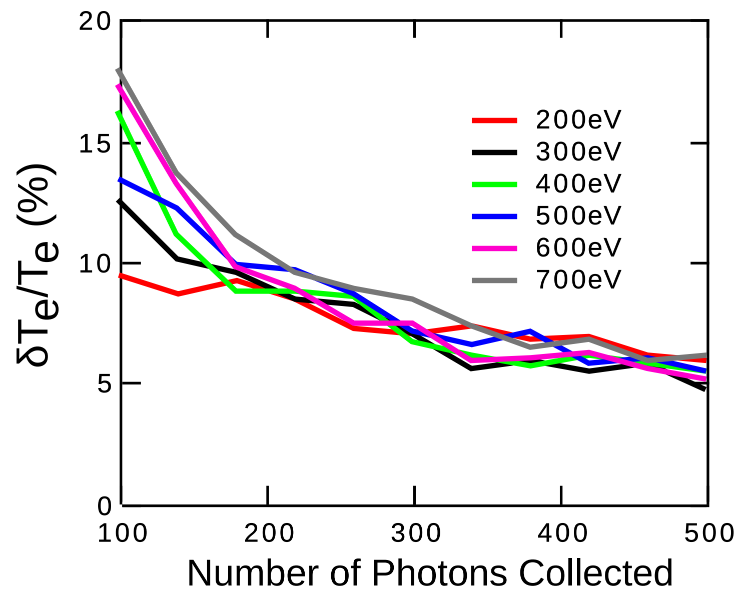
D) Simulated spectrum with QE and transmission correction; fit to get T_e

Fits Yield Good Representation of Te

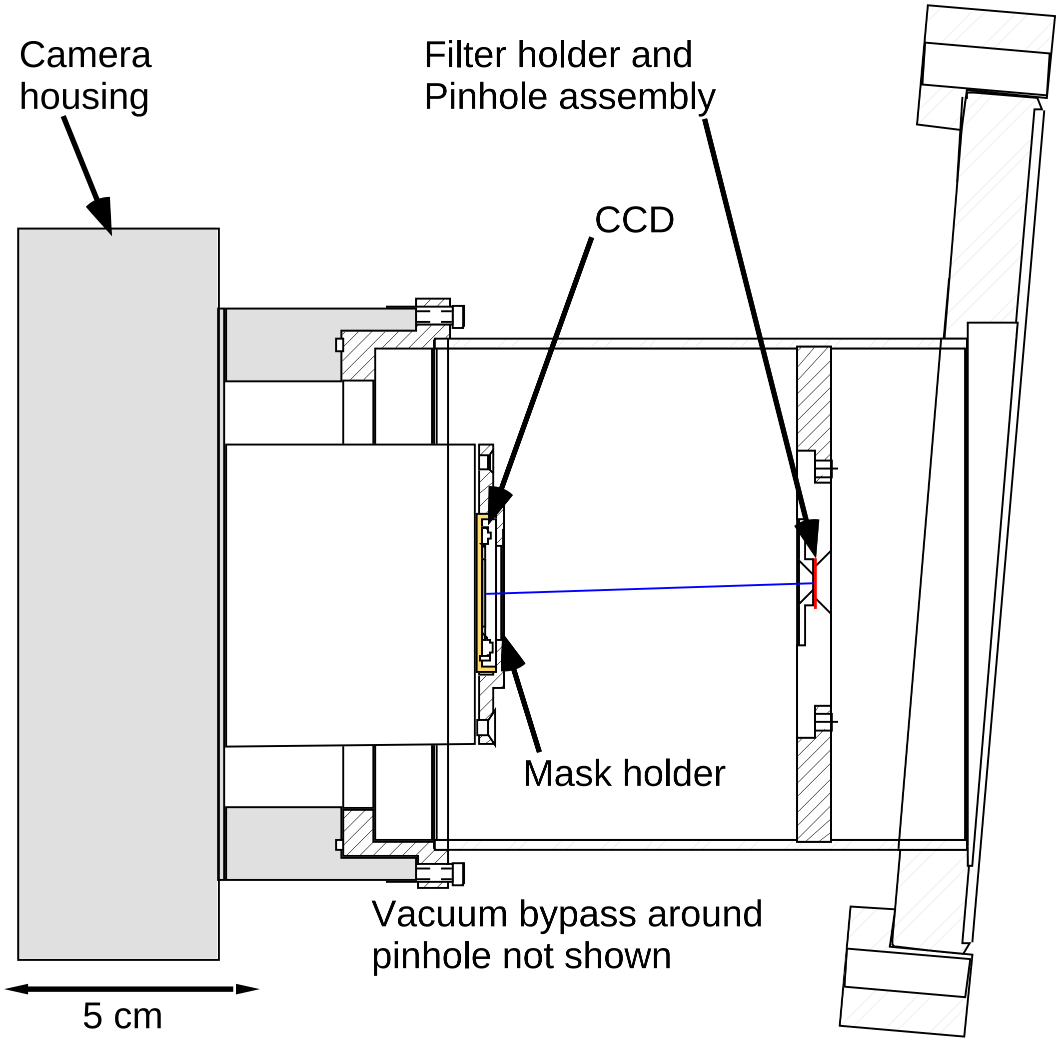


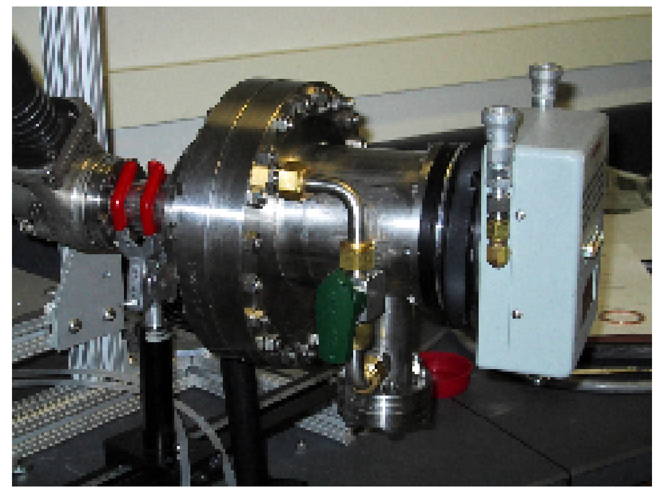
- Fitting intensity to the local emissivity model gives a good representation of T_e at R_{tan} for $R>R_o$
- Monte Carlo analysis gives $\delta T_e/T_e$ of 5-20%
  - Model determines number of photons required for a given error at a certain temperature





An Initial CCD/PHA System Has Been Assembled

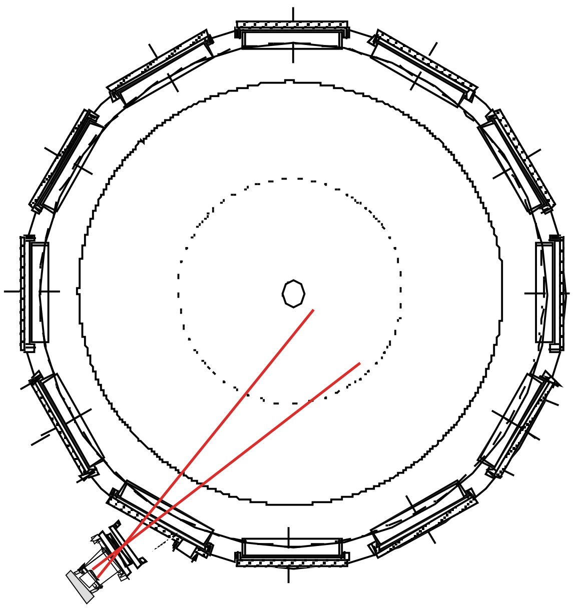




- Mounted behind gate valve on PEGASUS to allow access to filter and aperture
- First generation: Princeton Instruments 512 x 512 back-thinned CCD

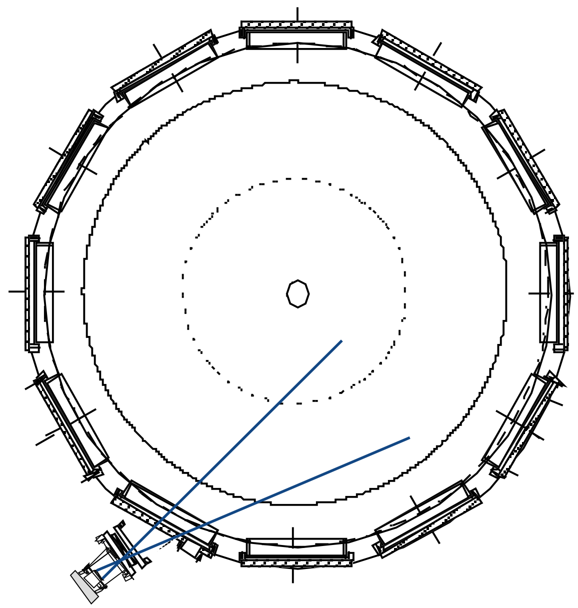
Several Different Fields of View Are Available Depending On the Application

$T_e(0)$ at multiple time points



•$R_{tan} < R_{plasma}$ $T_e(0,t)$

$T_e(R)$

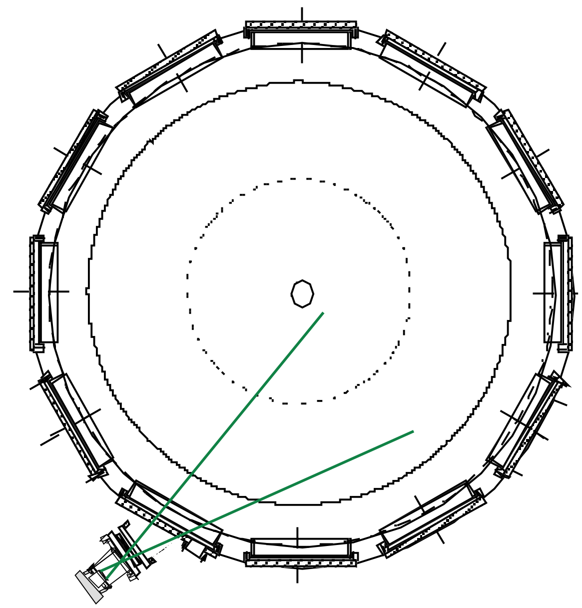


•Wider R range $T_e(R,t)$

-fewer time points

-shot averaging

Radiated Power



•Full plasma view $P_{rad}(R,t)$

Mask Design Is A Key Element In Getting Time Resolution

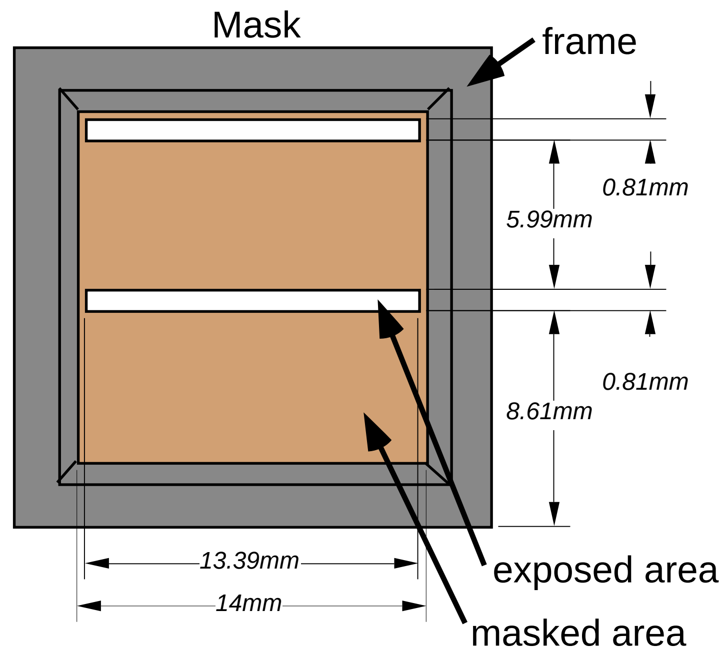
- The CCD mask was made with two slots that expose two 32 x 512 pixel areas which are added together to get more pixels for improved photon statistics

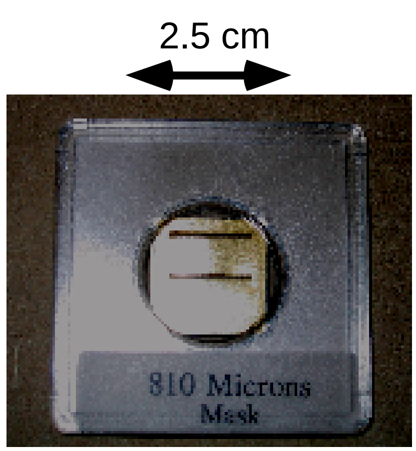
- These exposed rows are shifted down during the plasma discharge to obtain a time record of data

- The parallel shift time is ~80 μs, which results in eight time points of Δt = 2.5 ms through the discharge

- Binned in the horizontal direction for a single spatial point
  - N_{pixels} = 32768 $N_{\gamma max}$ =180 photons

- Pinhole diameters and locations are adjusted depending on the required photon flux and field of view





Summary

- T_e and radiated power measurements will improve understanding of PEGASUS plasmas
  - Time-resolved absolute measurement of T_e with CCD/PHA
  - $P_{rad}(R,t)$ to monitor impurity influence

- CCD/PHA has proven accurate
  - Current system will give $T_e(0,t)$ within ~10%
    - Δt~2.5 ms for eight time points through the discharge
  - $T_e(R,t)$ (for $R>R_o$) shows good agreement with TS on CHS/LHD

- Testing of prototype system in progress
  - Shows sensitivity to x-rays from calibration source