# Design and noise model for CCD-based, time-resolved PHA measurements

R. Schooff, S. Diem, R. Fonck, M. Reinke, and K. Tritz
*University of Wisconsin-Madison, Madison, Wisconsin 53706*

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A CCD pulse height analysis system is considered for the measurement of electron temperature on the Pegasus Toroidal Experiment. The first-generation CCD/PHA system will have one spatial point and obtain seven time points with a time resolution of 2.4 ms. Time resolution is achieved by shifting the exposed rows of the CCD behind a masked off portion of the chip during the plasma discharge. Criteria for valid photon detection are developed to account for pulse pileup effects and maximize count rate. Error analysis and Monte Carlo calculations indicate that the CCD/PHA system should achieve typical uncertainties to <5% of the deduced temperature. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1535246]

## I. INTRODUCTION

We examine the use of a spatially sampling CCD detector as a time-resolved soft x-ray pulse-height-analysis (PHA) spectrometer system. The emphasis here is on developing criteria for maximizing count rates for determining the local electron temperature with good statistical accuracy while minimizing the influence of pulse-pileup. As a particular example, the requirements for practical $T_e$ measurements on the Pegasus spherical torus experiment[1] are considered. Typical parameters for these plasmas are $n_e \approx 1-6\times 10^{19}\,\mathrm{m}^{-3}$ and $kT_e \approx 100-500\,\mathrm{eV}$.

As is well known, the soft x-ray (SXR) emission from hot plasmas contains contributions from line emission, bremsstrahlung, and recombination radiation.[2] The bremsstrahlung and recombination radiation give a continuum spectrum with the functional form,

$$\frac{dN}{dE_\nu} = 3\times 10^{-21} n_e^2 \frac{\zeta e^{-E_\nu/T_e}}{E_\nu \sqrt{T_e}}, \qquad (1)$$

where $N$ is the number of quanta of radiation of energy $E_\nu$, $n_e$ is the electron density, $\zeta$ is the x-ray anomaly factor, and $T_e$ is the electron temperature in keV. The impurity line radiation is superposed on this continuum at discrete energies. For plasmas with thermal electron energy distributions, the measurement of the exponential decay of the spectrum gives an accurate measurement of the electron temperature.

PHA (Refs. 3–5) is routinely used to measure the soft x-ray (SXR) continuum for deducing the electron temperature. It has recently been shown that a low-noise CCD camera can be used as a pulse height detector for the soft x-ray spectral range.[6,7] A single photon detected by the CCD will create a net charge proportional to the photon's energy. When a sufficient number of discrete photons are collected, a spectrum is formed that is representative of the plasma emissivity described in Eq. (1). In contrast to conventional PHA systems, this CCD approach provides a compact, relatively simple detector system. The use of a large number of pixels as detectors in parallel provides the capability for a very high effective count rate.

This CCD/PHA method has been demonstrated and proven to be an accurate measure of $T_e$ on CHS and LHD.[6,7] However, the original application used the entire CCD chip for a single exposure and did not provide time resolution for the $T_e(t)$ measurements.

We consider here the use of a CCD camera in a multi-exposure, frame-transfer mode to allow time-resolved measurements of the SXR spectrum. This work addresses two issues critical to a practical realization of these measurements: (1) criteria for identifying individual photon detection events and the allowed count rate imposed by these criteria; and (2) the accuracy in $T_e$ measurements which can be obtained with accessible CCD technology.

## II. EVENT SELECTION CRITERION AND ALLOWED COUNT RATE

A critical requirement for determining the SXR spectrum is that individual photons can be reliably detected and their energies determined. At a low level of detected counts, the statistical noise is high and the uncertainty in the derived $T_e$ values is unacceptably high. At high count levels, significant spectral distortion due to pulse pileup and/or multi-pixel exposure of single photons arises and degrades the temperature measurement. In effect, the desired statistical accuracy in the measured spectrum determines the number of pixels required in the camera active area for a given measurement.

An x-ray modeling code is used to create sample SXR spectra which can reasonably be expected from the experiment. The resulting emission and intensity spectra are used to randomly fill a model CCD camera system, which in turn allows examination of statistical properties of the measurement. This code calculates the SXR emission spectrum, including impurity line emission and continuum radiation,[8] as a function of radius in the plasma cross section. The density and temperature profiles are assumed to have the same shape as the pressure profile determined from magnetic equilibrium analysis of plasmas in the Pegasus experiment.[9] The total intensity spectra are then obtained by integrating along the

 

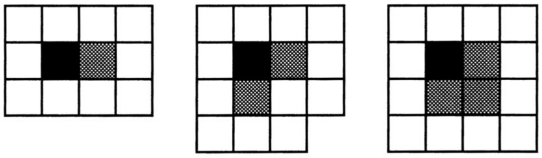


FIG. 1. The four possible event geometries physically allowed by the impact of one photon.

camera lines of sight through the plasma. We assume a midplane tangential view of the plasma.

Be foil filters are employed to avoid strong oxygen line emissions in the ≤1 keV photon range. The remaining line emission from small amounts of Ti arises in the 4–5 keV range, leaving at least the 1.5–4 keV range available for continuum measurements.

In reconstructing the SXR spectrum, there is an uncertainty in the energy of individual photons detected on the CCD chip, which in turn can give rise to increased uncertainty in the $T_e$ measurement through spectral distortion. With a low-noise scientific grade CCD camera, the largest contribution to the total noise is due to the shot noise, or the statistical variation in the total number of electrons created by an incident photon. For the total energy resolution and spectrum modeling herein, detector noise contributions have been found to not significantly alter the measured spectrum.

The measurement of electron temperature by pulse height analysis with a multipixel area detector depends on two factors. First is the determination of the energy of each x ray. This requires that only one photon be collected in a given pixel area so that it is the only identifiable source of signal electrons in that area of the CCD chip. Second, enough photons must be collected to give a pulse height distribution with sufficiently low statistical noise to give a useful $T_e$ measurement.

Consideration of these competing requirements gives rise to an event selection rule that is used to determine how many photons can be collected to get the maximum amount of energy information for a given number of active pixels. Pulse pile-up occurs when an incident photon impacts a pixel, or adjacent to it, that already contains charge from a previous event.

The effect of pile-up is exacerbated by the fact that when a photon is absorbed in silicon, it will release electrons in a finite sized cloud. This electron cloud (less than about 1 $\mu$m diameter[10]) expands by diffusion as it is moved into the potential well of the CCD pixel for collection. If the photon is absorbed close to a pixel boundary the cloud will diffuse into the surrounding pixels, creating a multipixel or split-event. The most common of these events is the two-pixel event where the charge is shared between adjacent pixels. If the event occurs near a pixel corner, a three- or four-pixel event can result.

These geometries[11] are shown in Fig. 1. The black pixel is the main photon impact location and the gray pixels are those that register electron counts above a detection threshold. The white pixels surrounding the event make up the "exclusion zone" for pile-up.[11] If another event is detected in any of the white pixels, some of that event's electrons may spill into the center pixel and effectively degrade the energy information. If the incident photons are monoenergetic, it is trivial to sum the signal electrons in the gray squares to get the proper energy. For photons in a continuous spectrum, however, it becomes difficult to determine which events are split events and should be summed and which events are adjacent monopixel events and should not be summed.

A strict selection criterion is therefore used to determine acceptable events for use in the pulse height distribution. Specifically, an incident photon must be detected as a monopixel event. This provides optimal background discrimination and overall accuracy in detecting the photon energies. Events that contain signal electrons in the exclusion zone will be rejected due to uncertainties in event identification. This criterion somewhat reduces the overall number of pixels that can be used for valid photon detection, but gives a more reliable representation of the energy of each photon in the spectrum.

We estimate the total number of photons which can be detected as monopixel events for a given number of incident photons and given detector array size. A simple model describing the number of monopixel events is readily derived from consideration of the active chip area and fractional active pixel areas.

Each photon that is randomly incident on the chip has a certain probability that its electron cloud will split into adjacent pixels. A typical split fraction considered in the model for the CCD detector are {0.778-monopixel, 0.195-bipixel, 0.014-tripixel, 0.013-quadrapixel}.[11] The average effective area covered by a single photon event, in pixel units, is then

$$A_{\text{phot}}=9(0.778)+12(0.195)+15(0.014)+16(0.013)$$
$$=9.76 \text{ pixels.} \tag{2}$$

For photons randomly incident on the open area of the CCD array, the total effective area filled after the *n*th photon is given by

$$A_n=A_{n-1}+A_{\text{phot}}\left(1-\frac{A_{n-1}}{N_{\text{pix}}}\right), \tag{3}$$

where $N_{\text{pix}}$ is the total area of the CCD in pixels. The second term in the above relation is just the effective area of a single photon event times the probability of that photon hitting an open area on the chip. The total number of monopixels, out of *n* incident photons, that will be detectable to contain valid energy information can be shown to be given by

$$G(n)=S_1 n\left(1-\frac{A(n)}{N_{\text{pix}}}\right)=S_1 n\left(1-\frac{A_{\text{edge}}}{N_{\text{pix}}}\right)\alpha^n,$$
$$\text{where } \alpha=\left(1-\frac{A_{\text{phot}}}{N_{\text{pix}}}\right), \tag{4}$$

where $S_1$ is the monopixel split fraction and $A_{\text{edge}}$ is the number of unusable edge pixels. These edge pixels are declared unusable for monopixel events because they are not completely surrounded by a valid exclusion zone.

A Monte Carlo calculation of the distribution of randomly placed photons incident on the CCD array confirms

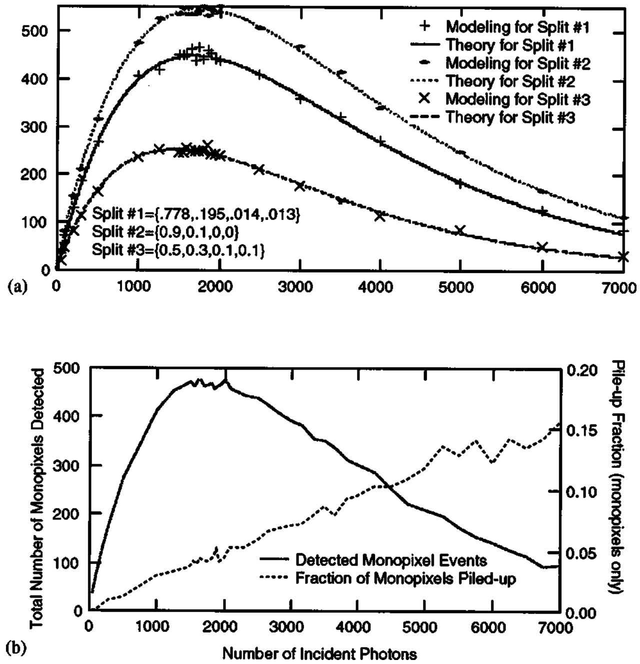


FIG. 2. (a) The number of monopixel photons collected versus number of incident photons for a 200 eV plasma spectrum with 16384 pixels exposed. (b) Total number of monopixel events detected and monopixel pile-up fraction versus number of incident photons.

the validity of the analytic model summarized above. Figure 2(a) shows the number of valid monopixel events as a function of total incident photons for several model split fractions (for a sample 16384 array size). The agreement between the analytic model of Eq. (4) and the Monte Carlo simulations is very good. The Monte Carlo model gives the added information of how many of the detected monopixel events are actually occupied by more than one photon, representing the monopixel pileup fraction. This fraction is indicated in Fig. 2(b).

The maximum of $G(n)$ gives the maximum number of monopixel photons which can be collected for a total number of pixels in the detector array. This value is given by

$$n_{\mathrm{opt}}(N_{\mathrm{pix}}) = -\left[\ln\left(1-\frac{A_{\mathrm{phot}}}{N_{\mathrm{pix}}}\right)\right]^{-1} \tag{5}$$

and is shown in Fig. 3 for different split fractions.

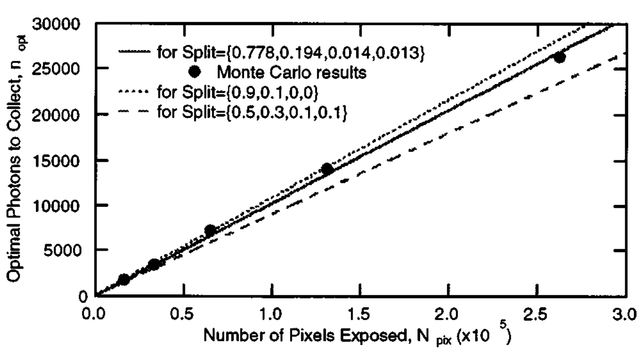


FIG. 3. Optimal number of photons to collect as a function of the number of exposed pixels for different split ratios. The dots represent the results from the Monte Carlo analysis for exposed areas of 512 pixels by 32, 64, 128, 256, and 512 pixels.

If the exposed area of the chip and the total intensity from the plasma is known, then the camera aperture and filter can be designed to maximize the useful number of photons and hence obtain the best pulse height spectrum statistics. For instance, for an exposed area of the chip with 30 rows by 512 columns, the optimal number of photons to collect is ~1600 photons. Optimally, the camera throughput and filtering would be designed to achieve this photon count.

We note that this estimate of the allowed number of photons to be collected in a given number of active pixels contrasts with the earlier criteria of Liang *et al.*[6] They suggest the value $\sqrt{N_{\mathrm{pix}}}$ as the limiting number of detected photons to avoid pileup. This appears to be unnecessarily restrictive. Using the spatial characteristics of the photon events, and limiting valid counts to monopixel events only, allows a significantly higher usage of the available pixels, with a correspondingly higher accuracy or improved time resolution for a fixed detector size.

## III. TIME-RESOLVED CCD/PHA POINT DESIGN AND SNR ESTIMATES

A CCD-based time-resolved PHA spectrometer consists of a back-illuminated, thinned CCD chip with quantum efficiencies $\geqslant 0.5$ in the SXR range. A typical chip array contains 512×512, 24 mm square pixels. Illumination of the CCD chip is achieved by mounting the camera in vacuum with a direct line of sight to the plasma and imaging through a pinhole aperture. The system noise is low enough so that, in the energy range of interest, photon noise will dominate to give an energy resolution of $dE/E \sim 5\%$. A pinhole imaging aperture is adjusted to allow variation of exposure for optimizing photon count in accordance with the previous discussion.

Time resolution is achieved by shifting the rows of the CCD behind a masked off area on the chip while the plasma discharge is evolving. The exposed rows remain behind the mask until the plasma is extinguished, and are then read out. This essentially acts as a frame-transfer CCD imager with user-defined frame sizes. The number of time points in the data is set by the open area in the mask and by the parallel (row) shift time of the chip. As an example, a row can be moved down the chip in 80 $\mu$s. With 30 rows exposed, this results in 2.4 ms over which any one row is exposed. A first-generation mask is shown in Fig. 4. The mask is made of gold to block all of the x rays that come from the plasma during the discharge.

A simulation of this diagnostic system demonstrates the range of applicability to plasmas typical of the Pegasus Toroidal Experiment. These calculations use sample emissivities from the x-ray modeling code to randomly fill a model CCD array with photons. The measured monopixel photons are used to get a sample emissivity spectrum and thus give a temperature measurement.

The lower bound of the temperature fits has been set at 1.4 keV for the 5 mil beryllium filter cases since transmission of the filter is $<0.03\%$ for photon energies below this value. A common upper bound for the temperature fit cannot be universally specified because its value changes with tem-

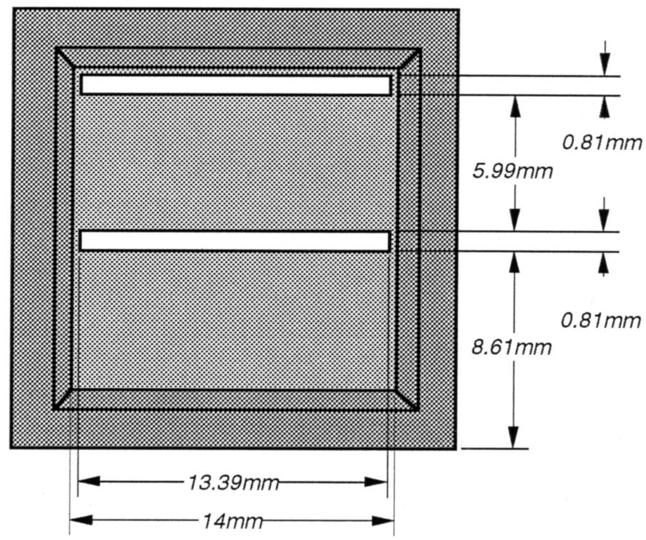


FIG. 4. An example gold mask that allows two exposure windows on a standard 512×512 CCD detector.

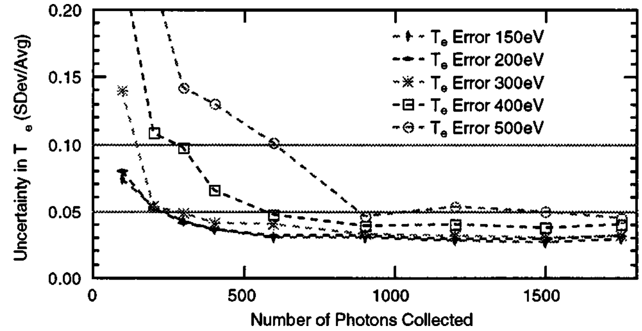


FIG. 5. Error in the temperature fit measurements as a function of number of incident photons for several plasma temperatures, for $N_{\text{pix}}=512\times 32$.

perature and number of photons collected. The upper limit for the fitted photon energy range is chosen by requiring that the spectrum is monotonically decreasing and/or that the intensity is at least 5% of the maximum. Practically, this results in upper fit limits of ~3 keV. This upper fit boundary effectively minimizes or excludes all monopixel pile-up events, with no detectable effect on the temperature fit.

Figure 5 shows the relative uncertainty in the electron temperature fits for five different plasma temperatures as a function of number of photons collected. These calculations assumed an active CCD area of 512×32 pixels. Good agreement between the fitted and real $T_e$ is obtained for this measurement of Pegasus plasmas, indicating that $T_e$ can be found accurately over a large range of temperatures and photon fluxes, proving the versatility of this diagnostic.

This camera system shows acceptable accuracy over a large range (100–7500) of photons collected. An accurate fit will be able to be made equally well for a 300 eV plasma in one discharge and a 200 eV plasma in the next, without requiring a change in the aperture size even though the total photon flux varies by a factor of 7 in this range. Thus, measurements over the plasma discharge from initiation through the plasma heating stage to the termination are feasible with the same aperture size. This relatively simple diagnostic approach is readily applicable to a wide range of magnetically confined plasmas.

## ACKNOWLEDGMENTS

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