DEAR Technical Note IR-26

X-ray rate restriction in charge-coupled devices

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1 Introduction

The best present-day detector for the detection of soft X rays (in the energy range between 1 keV and 20 keV) in the presence of a high-radiation background, for instance in the experimental area of an electron-positron collider such as DAΦNE in Frascati (Italy), or the experimental areas at the Paul Scherrer Institute (Switzerland), are Charge-Coupled Devices (CCDs) [1]. This was successfully demonstrated recently by detection of X rays originating from cascade transitions in exotic atoms [2].

The CCDs used in the present investigation - English Electric Valve CCD-05-20 - are MOS-type silicon devices with a 770 columns $\times$ 1152 rows pixel structure; each pixel being square-shaped with 22.5 μm in sidelength and approximately 30 μm depletion depth. The CCD detector system has been developed by the group of J.-P. Egger at the University of Neuchâtel [1, 3, 4].

This pixel structure is the basis for the unique background rejection capability of CCDs by pattern recognition. Due to the size of the active detection area soft X rays mainly give rise to a signal in a single pixel, which is defined as a hit pixel having eight neighbour pixels with charge content below a set threshold. Charged particles create multi-pixel events (clusters) as they almost always create charges in the field-free region of the chip from where the charges can be spread out on more than one pixel. Selecting only single-pixel hits is therefore a very efficient way to reject non-x-ray, i.e. background events [5].

To read out the signal of an individual pixel, which is done at the beginning of a column, the collected charges must be shifted pixel by pixel to the beginning of the column. To guarantee a good charge transfer efficiency and therefore a good energy resolution ($\sim$ 170 eV at 5.9 keV), the read-out time for a single pixel must be quite long (64 μs). This adds up to 28 s for the whole chip (the chip is read out in two electronically split halves). This readout time defines the minimum exposure time of a CCD detector, which in principle, can be exposed much longer. As the CCD chip is cooled down to 160 K, thermal noise is not posing a problem for exposure times even as long as 30 minutes. CCDs are time integrating, hence all the events occuring during one exposure are on a single image (data file).

Due to this time integrating feature, CCDs can also be overexposed. The more hits are recorded in a single exposure, due to high count rates or/and long exposure times, the more pixels are filled with charges and the probability rises that two single-pixel hits are, by accident, in neighbouring pixels and therefore rejected by the analysis algorithm. This saturation effect decreases the x-ray detection efficiency dramatically at higher CCD occupancies[1]. The investigation of this saturation effect is the scope of the present paper.

2 Measurements

For the discussed measurements one of the CCD detectors used in the DEAR[2] experiment [6] for the observation of kaonic nitrogen X rays was employed. Two CCD-05-20 chips were irradiated with X rays originating from a ^{55}Fe source (^{55}Fe $\rightarrow$ K capture $\rightarrow$ ^{55}Mn + Mn X rays at 5.9 keV and 6.5 keV).

The CCDs were exposed for various time periods ranging from 30 seconds up to 40 minutes. The data were analyzed using the single-pixel analysis as described in [5] with statistical cuts on the neighbour-pixel distributions (2σ-cuts and 5σ-cuts).

The CCD raw data, an example of which is given in Figure 1a, show a large noise peak due to electronic read-out noise, statistical and thermal fluctuations. This noise peak defines the zero value for the application of the

[1]The occupancy of a CCD is defined as the number of hit pixels divided by the total number of pixels.

[2]DEAR = **DA**Φ**NE** **E**xotic **A**tom **R**esearch

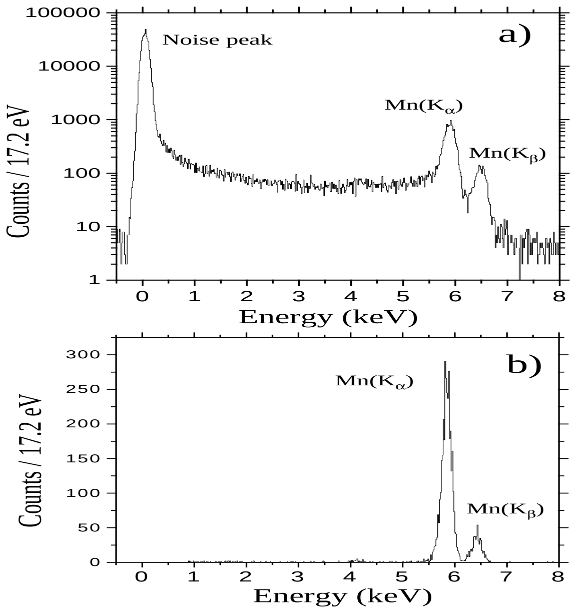

Figure 1: X-ray energy spectrum measured with a CCD detector irradiated with X rays originating from a ^{55}Fe source. a) CCD raw data (note the logarithmic scale), b) spectrum obtained with single-pixel analysis (2σ-cuts).

analysis cuts. $2\sigma(5\sigma)$-cuts mean that the distributions of the eight neighbour pixels of a hit pixel are within 2 (5) standard deviations of the corresponding noise peak distributions for the three following quantities related to the eight neighbour pixels [5]: the maximum charge content (energy), the mean charge content and the standard deviation of the charge content.

The single-pixel criterium guarantees a very good energy resolution. Figure 1b) shows an energy spectrum obtained using single-pixel analysis. The Mn 2$\rightarrow$1 (K_α) and 3$\rightarrow$1 (K_β) transitions are apparent. Comparing Figure 1a) and 1b) shows the large background reduction due to single-pixel analysis.

All hit pixels were counted to calculate the CCD occupancy corresponding to a given exposure time.

At very low occupancy the probabilities of individual cluster sizes orig-

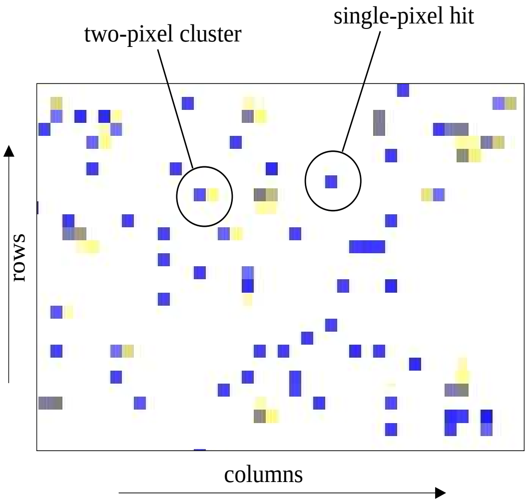

Figure 2: Enlarged section of a CCD exposure. Single-pixel hits and differently-sized multi-pixel hits are clearly visible. Dark pixels have a higher charge content (energy) than gray pixels.

inating from Mn X rays (mainly K_α at $\sim$5.9 keV) were determined to be about 45% for single-pixel hits, 43% for double-pixel hits, 6% for three-pixel hits and 6% for four-pixel hits. The probabilities for higher cluster sizes are negligible.

In Figure 2, a small enlarged area of a CCD exposure (raw data) shows single-pixel hits and differently sized multi-pixel hits (clusters) at an occupancy of about 10%.

The number of X rays per half-CCD per exposure extracted from the measurements and their dependence on CCD occupancy are shown in figure 3 for 2σ-cuts (full squares) and 5σ-cuts (open triangles). With less stringent cuts (5σ) more hits are accepted as single pixels and hence the observed number of X rays per half-CCD per exposure is about 50% higher. At low occupancies a linear increase of the number of X rays is observed, but at an occupancy of about 5% this linearity is lost and saturation of the CCDs is reducing the x-ray recognition probability. The maximum number of counts per half-CCD per exposure is reached at an occupancy of about 14%. In the linear range the occupancy is also linearly related to the measurement time.

For occupancies higher than 60% the effective x-ray detection probability is equal to zero because only a few very big clusters are left to cover the whole pixel area and no space for single-pixel hits with unhit neighbour pixels is available.

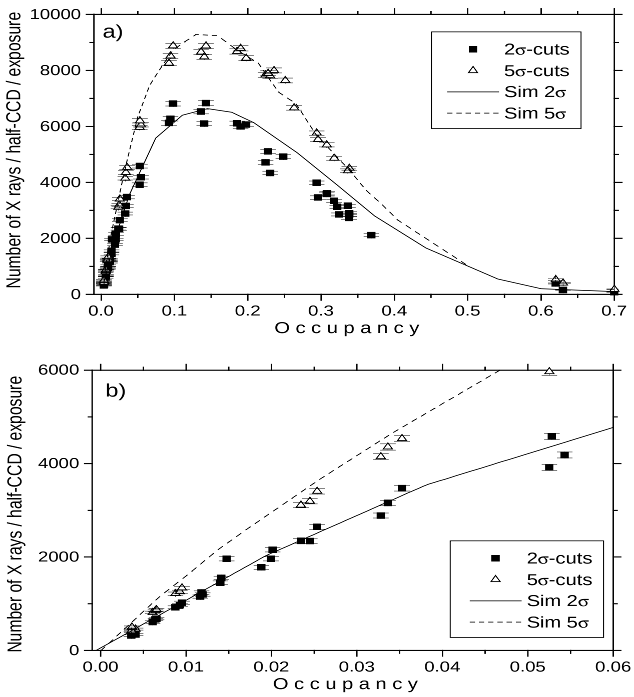

Figure 3: a) Occupancy dependence of the measured number of X rays per half-CCD per exposure for 2σ-cuts (full squares) and 5σ-cuts (open triangles) together with the results from the simulation (full line and dashed line). b) Enlarged view of the low-occupancy region.

3 Simulation

To investigate the saturation behaviour a simple program was written which simulated x-ray data, e.g. randomly distributed x-ray hits on a 770×576 matrix. Different cluster-size distributions for single-pixel hits and two-, three- and four-pixel clusters were used, starting from 100% to only 20% of single pixel hits, including also the measured one for ^{55}Fe given above. It has to be noted that different percentages of single-pixel hits correspond to different incident x-ray energies; e.g. 100% to energies around 1.5 keV (K lines of aluminum) and 45% to $\sim$ 5.9 keV. The generated random data were analysed using a pattern recognition program to select single-pixel hits similarly as it is done for real data.

Using the measured cluster-size distributions the observed x-ray counts per half-CCD per exposure could be reproduced well for the analyses with 2σ-cuts (Figure 3, full line) and 5σ-cuts (Figure 3, dashed line). For higher occupancies the simulation slightly overestimates the x-ray counts for the 2σ-cuts analysis. This can be explained by the fact that for higher occupancies the noise peak becomes broader and its position raises. As the analysis algorithm normalizes to the noise peak width, the effective thresholds on energy cuts and neighbour pixel distributions change slightly with increasing occupancy. This preserves a good energy resolution but changes the discrimination between single-pixel and double-pixel hits for a constant cut threshold.

To investigate the general behaviour of the occupancy dependence of the number of X rays per half-CCD per exposure, different distributions of single-, two-, three- and four-pixel hits were simulated. The calculated results are displayed in Figure 4 for the following simulated distributions (the four given numbers are the probabilities for single-, two-, three- and four-pixel hits): a) 100% - 0% - 0% - 0%, b) 75% - 17% - 4% - 4%, c) 59% - 33% - 4% - 4%, d) 45% - 43% - 6% - 6%, e) 43% - 43% - 8% - 6%, f) 20% - 72% - 4% - 4%.

The maximum number of recognized X rays trivially depends on the percentage of single-pixel hits. The more single-pixel hits in one exposure, the higher count rates can be achieved. But also the dependence on occupancy is very similar for the different simulated distributions. The maximum of the distributions shows a small drift from an occupancy of approximately 11% for only single-pixel hits to $\sim$ 14% for 20% single-pixel hits. For ideally distributed single-pixel hits the largest achievable count rate per half-CCD per

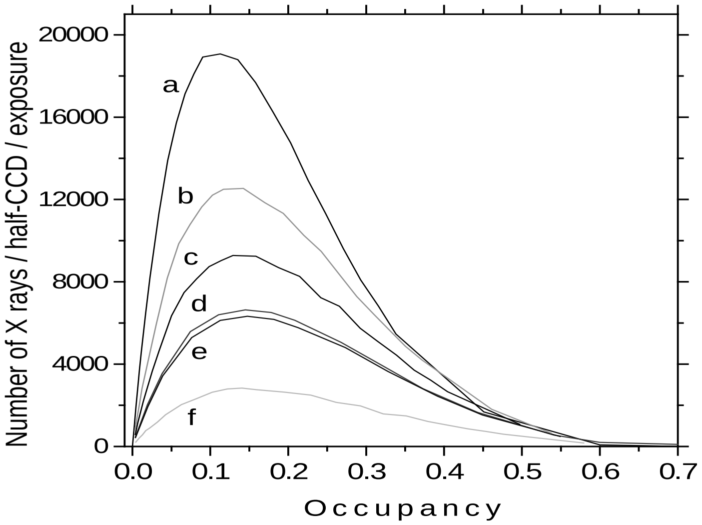

Figure 4: Occupancy dependence of the number of detected single-pixel hits (X rays) per half-CCD per exposure resulting from the simulation for different distributions of single-pixel hits, two-, three- and four-pixel clusters: a) 100% - 0% - 0% - 0%, b) 75% - 17% - 4% - 4%, c) 59% - 33% - 4% - 4%, d) 45% - 43% - 6% - 6%, e) 43% - 43% - 8% - 6%, f) 20% - 72% - 4% - 4%. d) corresponds to the 2σ-cuts and c) to the 5σ-cuts of Fig.3.

exposure would be 110880 at an occupancy of 25%. The ideal distribution shows a hit in every pixel with odd column and row number. Of course, the ideal distribution cannot be achieved at all. Randomly distributed hits result in a large reduction of the counting rate because with increasing number of hits, i.e. increasing occupancy, the probability that a new hit is within the eight neighbour pixel of another hit increases fast.

From the simulation the x-ray recognition efficiency, i.e. the probability to recognize a simulated single-pixel hit as single-pixel hit can be extracted. The obtained results are shown in Figure 5 for the simulation of only single-pixel hits (full line) and for the various distributions b)-f) given in Figure 4 (dotted lines).

Additionally the x-ray recognition efficiency was calculated for a cluster-size distribution which was measured in the DEAR interaction region [7] during electron and positron beams ciculating in the DAΦNE collider (Figure 5, dashed line). This measured distribution peaks at four-pixel hits (21% probability), has about 6% single-pixel hits and has a significant probability ($\sim$10%) for hits with size larger than 10 (Figure 12 of Ref.[7]).

Two results can be extracted from Figure 5.

1) The x-ray recognition efficiency drops very fast with increasing occupancy; at 5% occupancy it is at 0.7, at 10% occupancy already at 0.5. Therefore the shortest possible read-out time should be used for CCD data taking in order to not decrease the x-ray detection efficiency by a simple saturation effect.

2) The occupancy dependence of the x-ray recognition efficiency depends only very weakly on the distribution of the various cluster sizes. The strong efficiency reduction exists for all investigated cluster-size distributions.

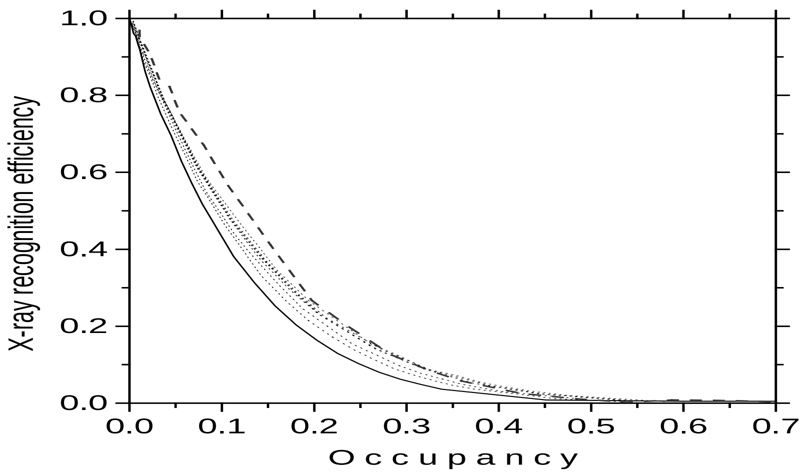

Figure 5: Occupancy dependence of the x-ray recognition efficiency for the simulated cluster-size distributions as given in Fig.4, a (full line), b-f (dotted lines), and (dashed line) for the cluster-size distribution measured in the DEAR interaction region of the DAΦNE collider [7].

4 Summary

A simple simulation was performed to understand the maximum number of X rays per exposure which can be counted in a CCD detector and its dependence on occupancy. The simulation can well reproduce the results measured with a ^{55}Fe x-ray source. The highest x-ray rates were found at occupancies between 11% and 14% for the different simulated cluster-size distributions. A dramatic reduction of x-ray recognition efficiency was found with increasing occupancy which recommends a read-out time as short as possible for any measurements using CCDs in order to not decrease the x-ray detection efficiency by a simple saturation effect.

Note:

This DEAR Technical Note was submitted for publication to Nuclear Instruments and Methods in Physics Research A.

References

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