Characterization of the Dosepix detector with XRF and analog testpulses

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ABSTRACT: Dosepix is a hybrid pixel detector based on the technology of the Medipix and Timepix detectors. The Dosepix detector has a matrix of $16 \times 16$ square pixels, with the sensor segmented into rows of small ($55 \mu m$) and big ($220 \mu m$) pixels. In addition to photon counting, the Dosepix detector has a time over threshold mode which permits energy resolved measurements.

In this contribution, we present results of the characterization of the Dosepix detector regarding energy calibration and energy resolution. We calibrated the detectors with X-ray fluorescence (XRF) and analog testpulses. We determined a conversion factor from testpulse amplitude to energy. This work aims to develop a calibration method of the Dosepix detector without the need for radiation. In addition, Monte Carlo simulations with ROSI were carried out to compare energy deposition spectra reconstructed with the radiation-based calibration and with testpulse-based calibration.

KEYWORDS: X-ray detectors; Radiation monitoring

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1 Introduction

Dosepix [1, 2] is an energy resolving photon counting pixel detector, based on the Medipix technology [3]. In addition to the photon counting mode, Dosepix is able to perform energy resolved measurements in the Time-over-Threshold mode like the Timepix detectors [4]. Additionally, it is possible to set 16 unique energy thresholds in each pixel [2] in order to sample the spectrum with 16 energy channels for each pixel. A reliable calibration procedure for each pixel is needed. The most accurate method of energy calibration is to use monochromatic radiation. This way of calibration needs a special setup. The calibration with analog testpulses needs only a dark environment and no changes in the experimental setup. The design of Dosepix offers the possibility to inject a controlled quantum of charge using a fixed capacitance and a voltage pulse which we call analog testpulse [2] and which could be used for energy calibration. In this work, a calibration method with analog testpulses will be described and the energy calibration with x-rays and analog testpulses will be compared. Furthermore, the detector response to x-rays and the energy resolution will be investigated.

2 Material and methods

2.1 Dosepix detector

Dosepix [1] is a hybrid pixel detector with 16 \times 16 pixels which is combined with a 300 \mu m thick p-in-n silicon sensor layer in this study. Its intended use lies in the field of dosimetry and radiation protection with the use of the concept presented in [5]. These applications ask for a small detector size and a big dynamic range for low and high flux environments. Therefore, the sensor layer is segmented into 4 rows of small pixels (55 \mu m) and 12 rows of big pixels (220 \mu m). The Dosepix detector offers analog testpulses [2] for energy calibration and chip testing. For this purpose, the
Dosepix electronics can be programmed to operate in a mode whereby the input signal from the silicon sensor is ignored. Instead, the frontend electronics in the pixel processes a controlled quantum of charge generated by a calibration capacitance and a voltage pulse of programmable amplitude, which we call the analog testpulse. According to Wong [6], the charge $Q_{\text{test}}$ can be calculated by

$$Q_{\text{test}} = V_{\text{test}} \cdot C_{\text{test}}$$

(2.1)

where $C_{\text{test}} \approx 7.3 \text{ fF}$ and $V_{\text{test}} = q \cdot 2.5 \text{ mV}$ with the number of DAC steps $q$ of the register in $[0;511]$ controlling the testpulse amplitude. Thus, the injected charge per DAC step corresponds to $114 \text{ e}^{-}$ and the dynamical range of the analog testpulse extends to a charge of $58 \text{ ke}^{-}$ which is equivalent to an energy deposition of $209 \text{ keV}$ in silicon.

The deposition of energy in a pixel leads to a charge signal coming from the sensor via the bump bonds to the pixel electronics. In the analog part, the current signal is amplified, and then compared with the discriminator threshold of the pixel. In the digital part, the user can choose between two modes [1]. In the counting mode, 1 clock pulse is registered in the counter for each event with energy deposition above threshold. In the Time-over-Threshold (ToT) mode, the number of clock cycles (100 MHz) arriving during the time in which the input of the discriminator is above the threshold is registered. ToT is a measure of the collected charge, and according to that a measure of the deposited energy in the pixel.

2.2 Measurement setup and simulation

For the XRF measurements, the setup consisted of an X-ray tube (Siemens Megalix) and different target materials (Fe, Cu, Pb, Sn, Gd) for the production of fluorescence photons. In the measurements, the K-diagram lines ($K_\alpha$, $K_\beta$) of Fe, Cu, Sn and Gd were used, as well as the L-diagram lines of Pb. Energetically close lines can not be resolved, and thus a mixture of these close lines is measured. An additional measurement was performed with $\gamma$-emission from the decay of $^{241}\text{Am}$ in order to avoid this drawback and in addition to obtain a calibration point at a higher energy. The well defined spectrum from $^{241}\text{Am}$ with its narrow line at about $59.5 \text{ keV}$ is a good option for the comparison between measured and simulated detector response. For each target material and a $^{241}\text{Am}$ source, approximately 5,000 events were accumulated per pixel in ToT mode. The evaluation was carried out without the use of single cluster analysis.

A Monte Carlo simulation with ROSI [7], which is based on GISMO and EGS4-code with the LSCAT extension, was carried out to compare the energy deposition spectra reconstructed with XRF and testpulse calibrations. The simulation was performed for an energy of $59.5 \text{ keV}$.

3 Results

3.1 Energy calibration

The relationship between ToT and collected energy can be approximated by $ToT(E) = a + b \cdot E + c/(E - t)$ which has been shown to be an appropriate description of the ToT response of Timepix by Jakubek et al. [8]. In figure 1, the relationship between ToT and energy deposited in the silicon pixel is shown for measurements with XRF and the $59.5 \text{ keV}$ line of $^{241}\text{Am}$ as well as a measurement with analog testpulses.
Figure 1. Energy calibration of an exemplary big pixel with analog testpulses (red solid line) and radiation measurements (blue dashed line).

For the conversion from the injected charge in DAC register steps $q$ which is a measure of the charge in the analog testpulse to the energy $E$, the formula $E = r \cdot q + o$ is inserted in the equation above which gives

$$f(q) = \left( a + b \cdot (r \cdot q + o) + \frac{c}{(r \cdot q + o) - t} \right).$$ (3.1)

The factor $r$ is representing the ratio of keV per DAC step and the offset $o$ is an additional free parameter. For the determination of $r$ and $o$, the parameters $a$, $b$, $c$, and $t$ from the calibration with XRF and Am-241 are used, and only $r$ and $o$ are free parameters in the least-square fit. For silicon as sensor material, an average conversion factor $r$ of $\bar{r} = (0.4341 \pm 0.0003)$ keV per analog testpulse unit and an offset of $\bar{o} = (1.81 \pm 0.02)$ keV was obtained for a tested detector. For another detector assembly, we obtained $\bar{r} = (0.4395 \pm 0.0005)$ keV per analog testpulse unit and $\bar{o} = (-2.86 \pm 0.05)$ keV. The factor $r$ seems to be in the same range for different detector assemblies whereas the offset $o$ might vary. After selecting a common conversion factor $r$ for all devices, it can be used for the calibration with analog testpulses only and the parameters $a$, $b$, $c$, and $t$ can be determined from the analog testpulse measurement. To overcome the variation of $o$, this parameter could also be gained from the fit to the analog testpulse measurement.

The calibration curves in figure 1 are in good agreement for the radiation measurement and the analog testpulses. Some deviations in the region of the threshold can be found where the ToT values of the analog testpulse measurement exceed the ToT values of the fitted functions and the radiation measurement. This could be explained by the fact that the analog testpulse signal is quite noisy for small energies. Furthermore, the gained parameter $t$ has a strong influence on the calibration for low energies as it describes the position of the threshold. Thus, deviations from the fitting process have a big impact on the energy calibration especially in the low energy range.
Figure 2. Ratio $R$ of average ToT values from energy calibration with analog testpulses to XRF measurements.

Table 1. Maximum and minimum deviation of the ToT value after energy calibration with analog testpulses within the whole matrix.

| Energy E [keV] | 10  | 15  | 20  | 30  | 40  |
|---------------|-----|-----|-----|-----|-----|
| maximum deviation [%] | 3.9 | 5.9 | 6.2 | 5.9 | 5.5 |
| maximum minimum [%]    | -9.3| -7.3| -6.2| -5.0| -4.3|

The reliability of the energy calibration with analog testpulses can be evaluated by the ratio

$$R = \frac{\text{ToT}_{TP}(E)}{\text{ToT}_{rad}(E)}$$  \hspace{1cm} (3.2)

of the average ToT values over all pixels respectively at a certain energy $E$ from energy calibration with analog testpulses $\text{ToT}_{TP}(E)$ and with radiation measurements $\text{ToT}_{rad}(E)$. In figure 2, the ratio $R$ shows a small energy dependence with an average deviation of less than 4% from unity. The agreement between the two calibration methods is better for energies in the linear part of the calibration function.

For single pixels, the maximum and minimum deviation of ToT values after calibration with analog testpulses in table 1 depends on the energy but for all considered energies in the range of 10 keV to 40 keV is less than 10%.

### 3.2 Energy response

The detector response to $E_\gamma = 59.5$ keV is given by the energy deposition spectra in figures 3 and 4 in which the number of detected photons $N$ per energy bin is normalized to the maximum number of photons per bin in the peak $N_{peak}$. The figures show energy deposition spectra of a big pixel and accordingly small pixel obtained from an exposure with photons of 59.5 keV, from an analog
Figure 3. Energy deposition spectra at 59.5 keV of an exemplary big pixel (220 µm) reconstructed with XRF energy calibration (red) and with testpulse calibration (blue). The expected energy deposition spectrum obtained with the simulation is shown in black.

For the big pixel in figure 3, the radiation measurement and the simulation are in very good agreement for energies above 28 keV. In the low energy range, differences due to scattered radiation from objects in the vicinity of the measurement setup, like shielding and laboratory equipment, and charge sharing effects can be seen. Furthermore, the 26.3 keV line of $^{241}$Am as well as the 17.5 keV testpulse measurement with a length of 133 DAC steps of the analog testpulse, corresponding to approximately 59.6 keV or approximately 332.5 mV as input voltage to the analog input, and from a Monte Carlo Simulation with ROSI at an energy of 59.5 keV.

Figure 4. Energy deposition spectra at 59.5 keV of an exemplary small pixel (55 µm) reconstructed with XRF energy calibration (red) and with testpulse calibration (blue). The expected energy deposition spectrum obtained with the simulation is shown in black.
and 21.0 keV lines of its decay product $^{237}$Np can be observed. The energy for analog testpulses might vary slightly from 59.5 keV due to the fact that the parameters $r$ and $o$ for the conversion from testpulse units to energy are average values for the whole matrix. They vary from pixel to pixel by a standard deviation of 0.005 keV per DAC step for the parameter $r$ and 0.4 keV for the parameter $o$ which could explain the shift to lower energies. For the small pixels in figure 4, the simulation and the analog testpulse measurement are in good agreement but not with the radiation measurement. Assuming, the radiation measurement shows the true energy response, we find that the peak in the simulation and the analog testpulse measurement is shifted to lower energies. For the analog testpulse measurement, this could be explained again by the uncertainties of the conversion from DAC steps to energy. Reasons for the differences between simulation and radiation measurement might be found in differences of the implementation of the big and the small pixels which are realized in a less detailed manner concerning the exact pixel shape and thereby the sensitive volume defined by the electric field lines in the sensor.

### 3.3 Energy resolution

In figure 5, the energy resolution in the Time-over-Threshold mode was determined by a Gaussian fit to the full energy peak in the energy deposition spectra for illumination with fluorescences. This method gives an upper limit for the energy resolution $\sigma(E)/E$ because close fluorescence lines cannot be resolved and their mixture is not taken into account. In comparison, the big pixels have a slightly better energy resolution than the small pixels due to fewer charge sharing effects. The energy resolution for the lead L-fluorescence XRF measurements at about 11.7 keV seams to be worse than for the other target materials, but this can be explained by the mixture of the $L_\alpha$, $L_\beta$ and $L_\gamma$ which could not be resolved individually by the detector. The difference between small and big pixels is larger for the 8.13 keV and 11.7 keV measurements with copper and lead as target material than for the other target materials. This is due to the fact that the charge sharing effect...
already plays a notable role for the small pixels. The photon is absorbed on average closer to the surface of the sensor in this energy range than for higher energies. Therefore, the contribution of charge carrier diffusion is bigger. This increases the relative energy resolution especially of the small pixels. For higher energies, the charge sharing effect gains in importance also for the big pixels and the difference between small and big pixels decreases in terms of energy resolution.

4 Conclusions and future work

The energy calibration is very reliable with the use of XRF, but requires changes in the setup which is not necessary for the energy calibration with analog testpulses. For analog testpulses, the calibration deviates in average about 4% from the calibration with XRF and 59.5 keV measurements but might vary for single pixels up to 10%. However, the calibration with analog testpulses can be obtained without special calibration facilities and could be sufficient for certain applications. In the future, more chips need to be calibrated with XRF and analog testpulses in order to verify the method with respect to differences of detector assemblies and their impact on the calibration with analog testpulses. Moreover, the possible change of the energy calibration due to the amount of total ionizing dose accumulated over the time of use needs to be tracked and the influence on the conversion factor from analog testpulse to energy needs to be evaluated. Furthermore, the detector response to 59.5 keV photons from measurements, analog testpulse measurement and Monte Carlo simulation are in reasonable agreement above 10 keV for the big pixels. For the small pixels, future investigations of the detector response are needed, especially concerning the effective pixel size. The energy resolution can be estimated from XRF peaks and reasonable values were determined which show a better energy resolution for big pixels than small pixels due to charge sharing effect.

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