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## The Dosepix detector — an energy-resolving photon-counting pixel detector for spectrometric measurements

A. Zang,<sup>a,1</sup> G. Anton,<sup>a</sup> R. Ballabriga,<sup>b</sup> F. Bisello,<sup>a,c</sup> M. Campbell,<sup>b</sup> J.C. Celi,<sup>c</sup>  
A. Fauler,<sup>d</sup> M. Fiederle,<sup>d</sup> M. Jensch,<sup>c</sup> N. Kochanski,<sup>c</sup> X. Llopert,<sup>b</sup> N. Michel,<sup>e</sup>  
U. Mollenhauer,<sup>c</sup> I. Ritter,<sup>a</sup> F. Tennert,<sup>a</sup> S. Wölfel,<sup>2</sup> W. Wong<sup>b</sup> and T. Michel<sup>a</sup>

<sup>a</sup>Erlangen Centre for Astroparticle Physics,  
Friedrich-Alexander-Universität Erlangen-Nürnberg,  
Erwin-Rommel-Str. 1, 91058 Erlangen, Germany

<sup>b</sup>Medipix Team, Microelectronics section, CERN,  
1211 Geneva, Switzerland

<sup>c</sup>IBA Dosimetry GmbH,  
Bahnhofstr. 5, 90592 Schwarzenbruck, Germany

<sup>d</sup>Freiburger Materialforschungszentrum, Albert-Ludwigs-Universität Freiburg,  
Stefan-Meier-Str. 21, 79104 Freiburg, Germany

<sup>e</sup>Customized Microelectronic Solutions,  
Bruckwiesenstr. 3, 91220 Schnaittach, Germany

E-mail: [andrea.zang@physik.fau.de](mailto:andrea.zang@physik.fau.de)

ABSTRACT: The Dosepix detector is a hybrid photon-counting pixel detector based on ideas of the Medipix and Timepix detector family. 1 mm thick cadmium telluride and 300  $\mu\text{m}$  thick silicon were used as sensor material. The pixel matrix of the Dosepix consists of 16 x 16 square pixels with 12 rows of  $(200 \mu\text{m})^2$  and 4 rows of  $(55 \mu\text{m})^2$  sensitive area for the silicon sensor layer and 16 rows of pixels with 220  $\mu\text{m}$  pixel pitch for CdTe. Besides digital energy integration and photon-counting mode, a novel concept of energy binning is included in the pixel electronics, allowing energy-resolved measurements in 16 energy bins within one acquisition.

The possibilities of this detector concept range from applications in personal dosimetry and energy-resolved imaging to quality assurance of medical X-ray sources by analysis of the emitted

<sup>1</sup>Corresponding author.

<sup>2</sup>Formerly at: IBA Dosimetry GmbH, Bahnhofstr. 5, 90592 Schwarzenbruck, Germany.

photon spectrum. In this contribution the Dosepix detector, its response to X-rays as well as spectrum measurements with Si and CdTe sensor layer are presented. Furthermore, a first evaluation was carried out to use the Dosepix detector as a kVp-meter, that means to determine the applied acceleration voltage from measured X-ray tubes spectra.

**KEYWORDS:** X-ray detectors; Radiation monitoring; Hybrid detectors

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## 1 Introduction

The Dosepix detector [1, 2] allows energy-resolving acquisitions based on Time-over-Threshold measurement (TOT) [3]. Furthermore, the detector concept provides 16 digital thresholds in each pixel corresponding to 16 energy channels. Each event is sorted instantly into these bins according to the measured TOT, resulting in an energetic sampling of the incident photon spectrum even in short exposure times. The detector can be applied in personal dosimetry and energy-resolved imaging [4]. Furthermore, it is possible to characterize an X-ray tube spectrum, for example, in relation to the applied acceleration voltage of the X-ray tube. This so called kVp-value is an important indicator in quality assurance of medical X-ray devices. An alteration of the kVp-value has direct impact on the patient dose applied and the image quality obtained [5]. The detector's design allows using different sensor materials, whereas silicon is commonly used. This is due to its availability and the wide experience, already gathered with this material and its application with pixelated photon-counting detectors. However, the disadvantage of silicon is the low detection efficiency for photon energies above 40 keV. Using the Dosepix as a kVp-meter implies photon energies up to 150 keV, which corresponds to the tube acceleration voltages used in radiology [5]. Therefore, the evaluation of high-Z sensor materials, as for example CdTe, is important as well, since these provide a higher detection efficiency in the photon energy range of interest. The dose rates applied range from 1 mGy/s to at least 200 mGy/s.

In the following, measurements are presented regarding energy resolution of detector assemblies with silicon sensor layer as well as CdTe sensor layer. Count-rate linearity was evaluated, especially focusing on an application as a kVp-meter in radiology. Furthermore, first results in the reconstruction of applied kVp from measured X-ray tube spectra are shown.

## 2 Materials and methods

### 2.1 The Dosepix detector

The Dosepix detector [2] is based on the architecture of the Medipix and Timepix detectors [3, 6]. The ASIC of this hybrid photon-counting detector consists of 16 x 16 square pixels with 220  $\mu\text{m}$  pixel pitch. Due to the hybrid setup, different sensor layers can be used with the same ASIC design. Most measurements described in this publication were carried out with a 300  $\mu\text{m}$  thick p-in-n silicon sensor which is connected pixel wise to the readout ASIC via tin coated copper pillars. The silicon sensor has 12 rows of  $(220 \mu\text{m})^2$  pixels and four rows of pixels with a sensitive area of  $(55 \mu\text{m})^2$ . In order to be compatible with bonding to the readout chip, the small area pixels have the same pitch as the large ones; a common guard region — with the same surface doping — surrounds the small pixels. This guard electrode is connected to a reference voltage (approximately electrical ground) but is separated from the pixel electrodes. Therefore, charge carriers released in this region are collected by the guard electrode, and do not contribute to the signal of the pixels. In addition to the silicon sensor, a 1 mm thick cadmium telluride sensor with 16 x 16 pixels at 220  $\mu\text{m}$  pitch has also been coupled to the readout chip, and measurements have been performed. The CdTe detector was assembled at the Freiburger Materialforschungszentrum (FMF), using indium bump bonds instead of copper pillars.

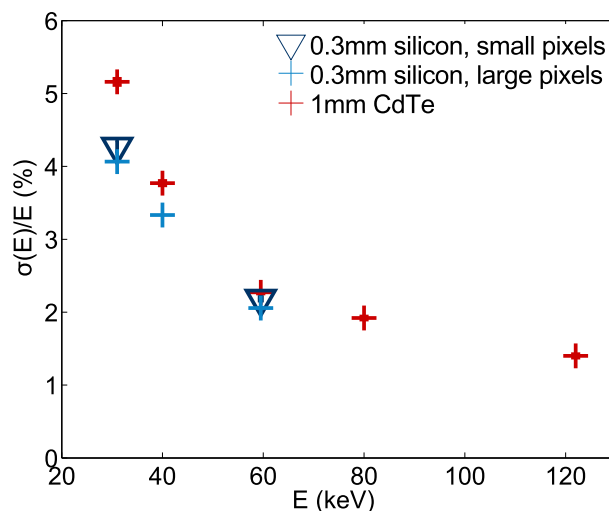
An incident photon deposits energy in the sensor layer leading to a generation of charge carriers, which are separated by a bias voltage applied to the sensor layer. The drifting charge induces a current signal, which is amplified and shaped by the pixel electronics. The time during which the preamplifier output pulse exceeds an analog threshold (TOT: Time Over Threshold) is correlated to the amount of charge generated in the sensor layer. Therefore the TOT-value is a measure of deposited energy. It is measured by counting clock cycles of a 100 MHz reference clock.

The Dosepix provides two modes for energy-resolving acquisitions. On the one hand, it is possible to read out the TOT-value corresponding to the latest photon interaction in each pixel (called TOT-mode below). On the other hand, the energy-binning mode is provided. Here, each TOT-measurement of an impinging photon in each pixel is directly compared to 16 digital thresholds. These digital thresholds can be set pixelwise and define 16 energy channels equipped with 16 bit deep counters. The 16th channel counts all events above the highest threshold. In energy-binning mode, it is therefore possible to sample energetically the incident photon spectrum in each pixel in 16 energy channels in a single acquisition.

### 2.2 Measurement setup

The relative energy resolution  $\sigma(E)/E$  of the detector was measured with the emission lines from decays of  $^{133}\text{Ba}$ ,  $^{152}\text{Eu}$  and  $^{241}\text{Am}$  in TOT-mode. The values for relative energy resolution are the results of Gaussian fits to peaks at energy  $E$  and with the standard deviation  $\sigma$  in the measured energy deposition spectra in each pixel.

The count rate linearity was measured with a conventional medical X-ray tube, with increasing tube current at 60 kV, 80 kV and 100 kV tube voltage in energy binning mode. The first digital threshold was set for all pixels right above noise level at 6 keV deposited photon energy for the silicon assembly and at 7 keV for the CdTe assembly. To enlarge the range of dose rates to be



**Figure 1.** Relative energy resolution for both detector assemblies with silicon and CdTe sensor layer and the pixel sizes provided by the detectors.

measured without exceeding a critical power limit of the X-ray tube, the distance between the focal spot of the tube and the detector position was altered between 25 cm and 200 cm.

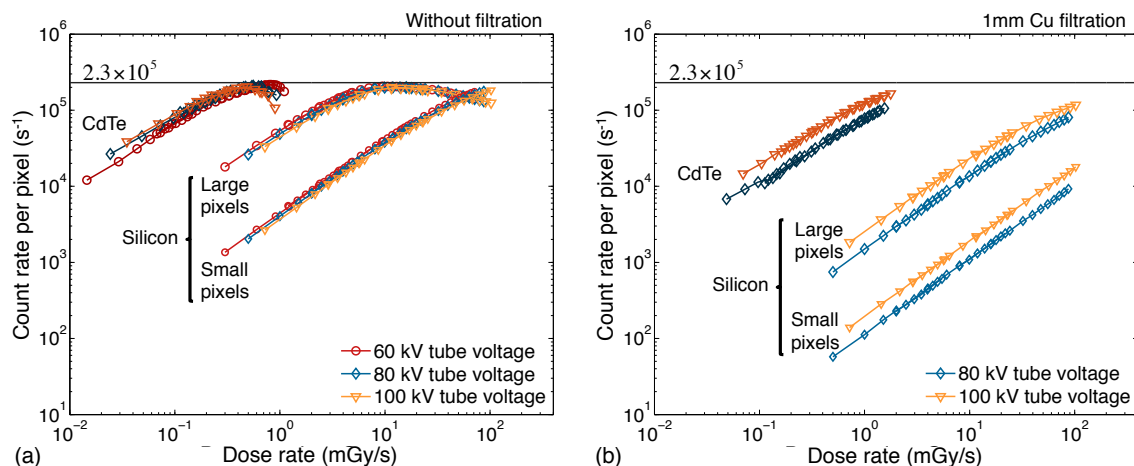
The X-ray tube spectra shown in section 3.3 were derived with the same X-ray tube as mentioned above at various acceleration voltages in energy-binning mode. The 16 digital thresholds were chosen from 12 keV to 72 keV in 4 keV steps for all pixels in the first pixel column of the detector. In each further column, thresholds were shifted by 0.25 keV compared to the prior one. This way, an even finer sampling of the incident spectrum can be achieved using the whole pixel matrix. The tube current was set to 20 mA for the silicon assemblies and to 2 mA for CdTe. 3 mm of aluminum was inserted between tube and detectors and the acquisition time amounted to 3 s for each spectrum.

In the measurements related to the kVp determination from measured X-ray tube spectra presented in section 3.4 the tube current at each acceleration voltage was chosen to provide constant photon flux emitted by the tube when changing the tube voltage. The flux impinging on the detector was then increased or decreased by varying the distance between the focal spot of the X-ray tube and the detector. 1 mm copper was used as filtration in front of the detector to reduce impact of analog pile up. The 16 digital thresholds ranged from 12 keV to 132 keV in 8 keV steps for the first pixel column and were shifted by 0.5 keV in each further column.

### 3 Results

#### 3.1 Energy resolution

Relative energy resolution  $\sigma(E)/E$  for both sensor layer types at energies  $E$  between 30 keV and 122 keV is shown in figure 1. For silicon, values for both small (55  $\mu\text{m}$ ) and large pixels (220  $\mu\text{m}$ ) are presented, whereas for CdTe only large pixels are available. The assembly with silicon sensor layer shows better results than with CdTe. This can be explained by the larger thickness of the CdTe sensor layer and a higher contribution of charge carrier diffusion in the 1 mm thick CdTe

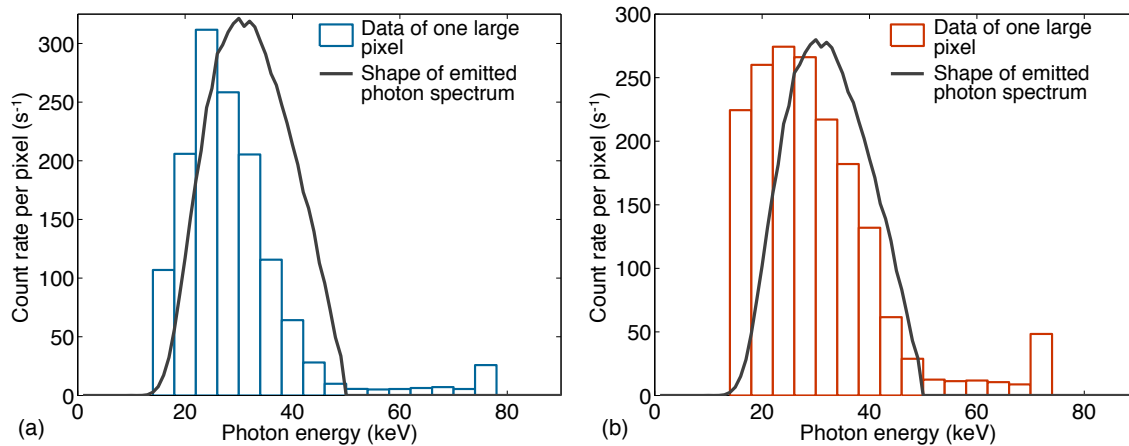


**Figure 2.** Count rate linearity with increasing dose rate for both detector assemblies and pixel sizes when irradiated with X-ray tube spectra. a) Measured counts per pixel and second without filtration. b) Measured count rate with 1 mm of copper inserted in front of the detectors.

sensor compared to the 300  $\mu\text{m}$  thick silicon sensor. Hence, number of events suffering from charge sharing is increased where deposited energy is only partly assigned to one pixel electrode. This results in wrong energy information measured. Differences between the pixel sizes can also be ascribed to increasing impact of charge sharing with decreasing pixel size. At 40 keV, the low activity of the  $^{152}\text{Eu}$  source prevented a correct determination of relative energy resolution for the small pixels. Results for energies between 7 keV and 42 keV and a Dosepix with silicon sensor layer are presented by Ritter et al. [7], obtained with X-ray fluorescence measurements.

### 3.2 Count rate linearity

The count rate linearity of the detector assemblies was measured when irradiated with a conventional X-ray tube for both sensor types. To use X-ray tube spectra and not mono-energetic radiation corresponds to the application of the Dosepix as a kVp-meter, but also in the fields of dosimetry and imaging. The results for the X-ray spectra with 60 kV, 80 kV and 100 kV acceleration voltage with increasing dose rate are shown in figure 2 on the left hand side for both detector assemblies and pixel sizes. At  $7.5 \cdot 10^4$  counts per pixel per second a deviation of approximately 5% between the measured count rate and expected linearity is reached for a 60 kV tube voltage. This value results by calculating the difference between the measured count rate and a linear fit to the data points at low dose rates. Here, a linear response is still sufficiently provided. The deviation is due to increasing impact of analog pile up, when two following events cannot be separated in time. These events are counted as one photon with higher energy. When exceeding a critical dose rate, analog pile up dominates and measured count rate decreases even with rising dose rate. For the given experimental setup this behavior occurs at about  $2.3 \cdot 10^5$  measured counts per pixel and second, corresponding to the black line in figure 2. It is obvious that the CdTe sensor layer provides only a small dynamic range concerning dose rate up to about 0.6 mGy/s until this critical limit is reached without filtration. This is the result of the high detection efficiency of the sensor layer. The large pixels of the silicon sensor layer reach the highest count rate possible at 7 mGy/s. Using the small



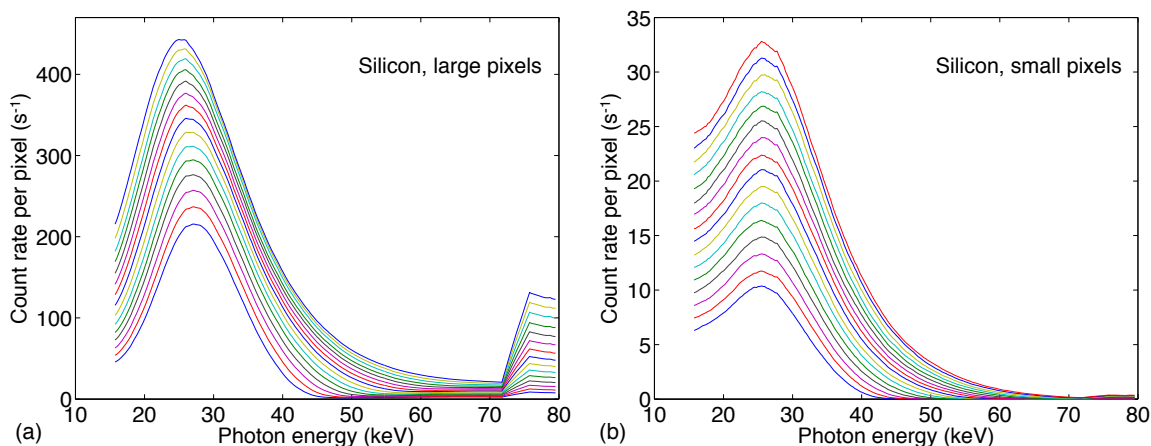
**Figure 3.** Measured data of one single large pixel for a) a silicon and b) CdTe detector assembly. Additionally the expected shape of the emitted photon spectrum is shown, obtained by simulation. The value of the last bin plotted includes all events measured above the last digital threshold.

pixels of the silicon assembly an approximately 16 times higher photon flux can be reached than with large pixels, due to the approximately 16 times smaller sensitive area. Variation of the tube acceleration voltage leads to slightly different results. This may be explained by the unequal impact of analog pile up and charge sharing effects at different photon energies. To apply the Dosepix as a kVp-meter, dose rates up to at least 200 mGy/s have to be reached [5]. To cope with high photon flux additional filtration has to be inserted in front of the detectors to reduce the number of photons impinging on the sensor. Count rate linearity with 1mm copper filtration is shown in figure 2 on the right hand side for both detector assemblies. Here only 80 kV and 100 kV are plotted for clarity. Inserting filtration results in a further energy dependent deformation of the incident spectrum. Therefore differences between measured flux at different acceleration voltages increase with filtration.

### 3.3 X-ray tube spectra

Data of one single large pixel and both sensor layers is shown in figure 3 when irradiated with a 50 kV tube spectrum. In case of the silicon assembly the dose rate at the position of the detector amounted to 2 mGy/s, in case of CdTe to 0.03 mGy/s. Furthermore, the expected shape of the emitted photon spectrum is shown, obtained by simulation. Comparing the shape of the emitted spectrum and the measured data, CdTe seems to be more suitable for determination of the kVp-value due to the higher efficiency at high photon energies. However, the disadvantage of the CdTe sensor layer is the small dynamic range concerning the photon flux the detector is exposed to, as already stated in section 3.2. To prevent domination of analog pile up, massive filtration has to be inserted even at relatively low flux. This worsens kVp-determination at low acceleration voltages drastically, as only few photons can pass the filtration. Therefore, the procedure of kVp-determination presented in section 3.4 focuses only on silicon assemblies. In figure 4 measured spectra with increasing tube voltage from 40 to 70 kV are shown for big as well as small pixels of a silicon sensor. It is not simply possible to obtain the kVp-value by using the end point of the



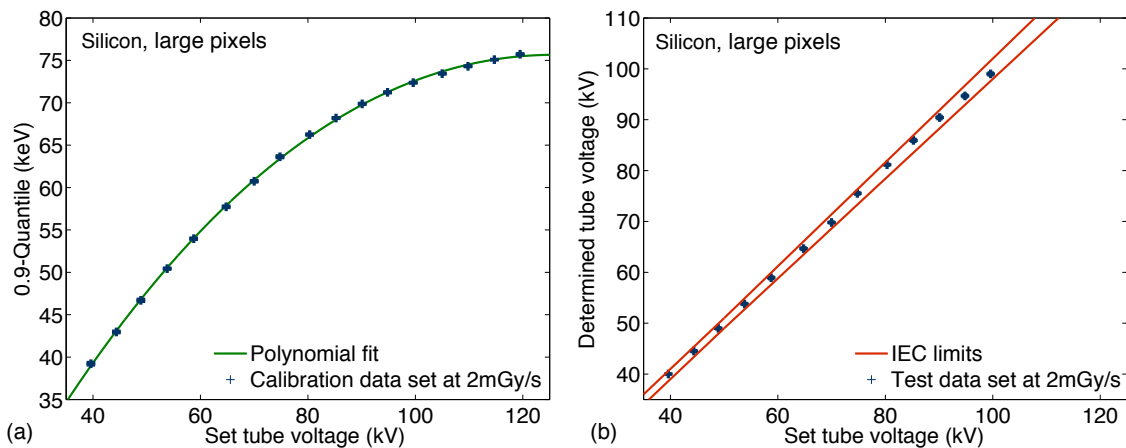


**Figure 4.** Measured X-ray tube spectra with increasing acceleration voltage from 40 kV to 70 kV using shifted energy bins for subsequent detector columns for a) large pixels and b) small pixels of a silicon detector assembly. The sudden rise of the curves above 70 kV results from pile-up events with a measured energy above the last digital threshold. This is an artifact of the illustration, as they are assigned to an energy bin of a certain width in the measured spectra of each pixel. These events are excluded in further analysis.

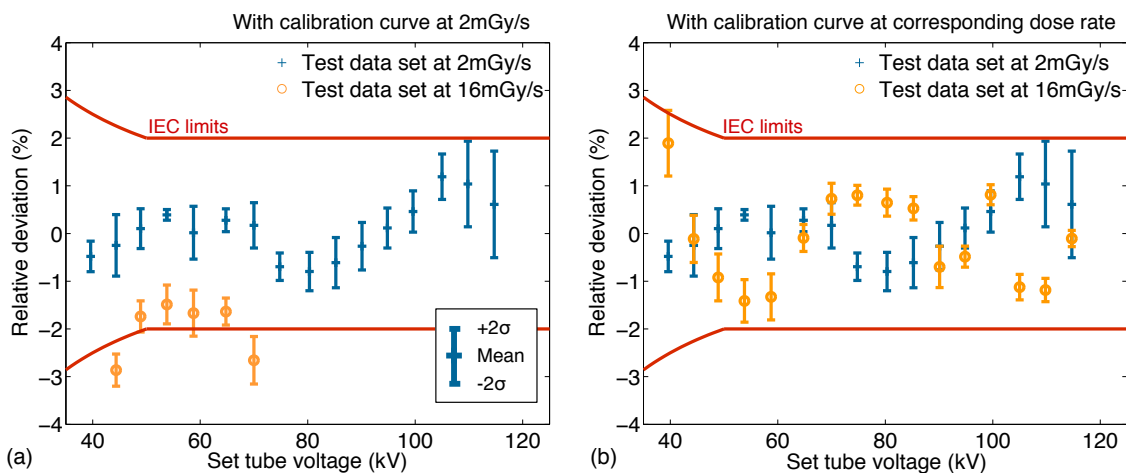
spectrum, as the measured spectra are corrupted by analog pile-up and the low efficiency of silicon above 40 keV. The result of these two effects is a smeared out tail of the spectra. The higher the energy of the photons the more difficult it is to differentiate between the measured spectra.

### 3.4 kVp-determination

To determine the kVp, certain characteristics of the measured spectra have to be evaluated and a calibration curve with increasing tube voltage is needed to extract the desired information. In first evaluations quantiles of the measured energy distributions turned out to be suitable for this procedure. In figure 5 (a) measured values for the 0.9-quantile with increasing tube voltage, obtained with a large-pixel silicon sensor, is shown. The thereby obtained calibration curve can then be used to determine the applied tube voltage of test data. To reduce effects of analog pile up 1 mm of copper was inserted in front of the detector. In figure 5 (b) the mean of reconstructed kVp-values of 10 measurements at different tube voltages are presented. All data points lie within the limits, plotted in red, of  $\pm 1$  keV or  $\pm 2\%$  above 50 keV, which correspond to the limits given in IEC 61676 [5]. In principle, it is possible to determine the kVp-value using the Dosepix detector and quantiles of the measured energy distribution. One problem of this procedure is the dependence of the measured spectra on the photon flux, due to analog pile up. It is necessary to use flux dependent calibration curves to find correct kVp-values, as shown in figure 6. Here, on the left hand side, relative deviation between set and determined kVp of test data sets at 2 mGy/s and 16 mGy/s are presented using a single calibration curve obtained at 2 mGy/s. The determined kVp-value and set kVp-value do not agree within the limits for the 16 mGy/s example. On the right hand side, a flux dependent calibration curve is used, whereupon all data points remain within the given limits. The same results can be shown for the small pixels.



**Figure 5.** a) Obtained calibration data for 0.9-quantiles of the measured energy distribution with increasing acceleration voltage. b) Determined acceleration voltage (kVp) of a test data set. The mean of 10 measurements at each voltage setting is shown. The error bars corresponding to  $\pm 2\sigma$  are too small to be clearly visible in this illustration. Additionally the IEC limits [5] are plotted in red.



**Figure 6.** a) Relative deviation between set and reconstructed tube voltage for 2 mGy/s and 16 mGy/s using a calibration curve obtained at 2 mGy/s. The mean of 10 measurements at each tube voltage is shown with error bars corresponding to  $\pm 2\sigma$ . b) Relative deviation when using flux dependent calibration data.

#### 4 Conclusion and outlook

The Dosepix detector provides energy-resolved measurements. It is possible to quickly sample an incident photon spectrum in 16 energy bins in each pixel. Furthermore different sensor layers can be applied, thanks to the hybrid detector design. This allows a wide range of applications in personal dosimetry or energy-resolved imaging. Focus of this contribution is on using the Dosepix as a non-invasive kVp-meter, that is to determine the acceleration voltage applied to an X-ray tube by direct measurement of the photon spectrum. One major problem, besides decreasing detection efficiency with photon energy, is analog pile-up. To cope with dose rates in case of application as a

kVp-meter, additional filtration has to be inserted in front of the detectors. 1 mm of copper extends the possible dose rates for the silicon sensor layer and 220  $\mu\text{m}$  wide pixels from 7 mGy/s to above 100 mGy/s and for 55  $\mu\text{m}$  wide pixels from about 100 mGy/s to above 400 mGy/s. Exceeding this limit, dominance of pile up events results in a decreasing measured count rate even with an increase in dose rate applied. Still it is not simply possible to extract used kVp from measured photon spectra. Flux dependent calibration curves of certain characteristics, as for example 0.9-quantiles, are needed even at low dose rates to determine the kVp from measured spectra. Currently we are working on the implementation of an iterative method to determine kVp as well as flux. An iterative method is necessary as measured flux depends as well on kVp due to analog pile-up, to charge sharing events and to the energy dependent attenuation in the necessarily used filter material. First tests imply that this iterative algorithm is able to cope with photon fluxes up to at least 200 mGy/s but detailed evaluations still have to prove the method's capability and robustness. The application of CdTe as sensor material seems to be difficult, as problems due to analog pile-up increase massively, although CdTe provides higher sensitivity at high photon energies.

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