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Energy calibration of the GEMPix in the energy range of 6 keV to 2 MeV

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ABSTRACT: The GEMPix is a small gaseous detector with a highly pixelated readout, consisting of a drift region, three Gas Electron Multipliers (GEMs) for signal amplification, and four Timepix ASICs with 55 µm pixel pitch and a total of 262,144 pixels (512 × 512 pixels). A continuous flow of a gas mixture (here propane-based tissue equivalent gas) is supplied externally at a rate of 5 L/h. By placing a sealed ^{241}Am source outside of the detector and varying the source-detector distance, the residual energy of alpha particles entering the sensitive volume of the GEMPix through a thin Mylar window is varied. An alpha spectrometry measurement was performed to determine the emission spectrum of the source, and this spectrum was then used as an input to a FLUKA Monte Carlo simulation to obtain the residual energy of the alpha particles. Thus, a calibration curve from 5.9 keV (from an ^{55}Fe source) up to more than 2 MeV was obtained, which is needed for future applications of the detector, in particular for microdosimetry.

KEYWORDS: Detector alignment and calibration methods (lasers, sources, particle-beams); Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEGAS, InGrid, etc); Particle tracking detectors (Gaseous detectors)

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Contents

1 Introduction

Energy calibrations of gaseous detectors with radioactive sources are a standard procedure. While gamma sources can be placed outside the detector, alpha sources are usually placed inside the detector, because the alpha particles are easily stopped by the walls or window of the detector. In this work, we present a technique to calibrate a thin-window gaseous detector — the GEMPix — using an ^{241}Am source placed outside the detector.

The GEMPix [1] is a small gaseous detector developed at CERN a few years ago, consisting of Gas Electron Multipliers (GEMs) [2] coupled to a 55 µm pitch pixelated readout, the Timepix [3]. The entrance window is a 12 µm thin aluminized Mylar foil (thickness of the aluminum: 100 nm), through which alpha particles from a source placed outside the detector can enter the sensitive volume. By varying the distance between the window and the source, the residual energy of the alpha particles deposited inside the detector is varied. Thus, a calibration curve with a single source but several different alpha energies can be obtained. To complete the calibration at low X-ray energies, an ^{55}Fe source was used. In this way, a calibration valid from 5.9 keV to more than 2 MeV was obtained, which is needed for future application of the GEMPix in microdosimetry.

2 Materials and Methods

2.1 The GEMPix

The GEMPix (figure 1) is a small gaseous detector obtained by coupling two technologies developed at CERN, namely Gas Electron Multipliers (GEMs) to four naked Timepix application specific integrated circuits (ASICs) with 262,144 (512 × 512) pixels of 55 × 55 µm^2 area for readout. The drift gap is 1.1 cm wide and the area instrumented with the Timepix ASICs is 2.8 × 2.8 cm^2. Electrons produced by ionization in the drift gap are guided by an electric field (drift field) towards a series of three GEMs. Each standard GEM consists of a Kapton foil (50 µm thick) that is copper-cladded (5 µm thick) on both sides and shows a regular pattern of holes of 70 µm diameter and 140 µm distance between holes. Gas amplification takes place in the holes due to the large electric field strength inside them. In total, seven electric fields (drift, three GEMs, two transfer and the induction field between the last GEM and the Timepix) are supplied by a module specifically designed for this purpose (HVGEM [4]). Figure 2 shows a scheme of the detector. The applied voltages (field strengths) are: 880 V (0.8 kV/cm) for the drift field, 300 V (3 kV/cm) for the transfer field between the first and the second GEM, 600 V (3 kV/cm) for the transfer field between the second and the third GEM and 500 V (5 kV/cm) for the induction field. Each GEM is operated at 460 V. A continuous flow of a gas mixture (propane-based tissue equivalent gas, short: TE gas) is supplied externally at a rate of 5 L/h.

The electrons produced by ionization and amplified by the triple GEM are then detected by four Timepix ASICs, which are usually coupled to a semiconductor sensor, but here measure directly the total charge. The Timepix ASICs are read out by the FITPix interface [5] using the Pixelman software [6]. The obtained quantity is the Time over Threshold (TOT) that is a measure for the deposited charge and therefore energy.

By applying a correction for changes of ambient conditions (temperature, pressure, humidity), the GEMPix was operated over nine days with a stable response within ±3% [7]. A more detailed description of the GEMPix and some of its applications can be found in references [1] and [8].

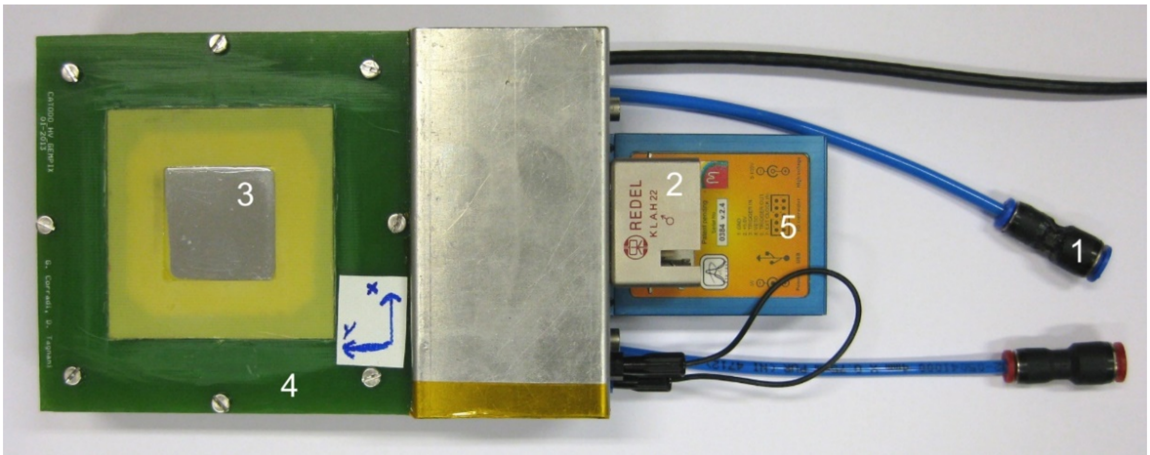

Figure 1. The GEMPix detector: (1) external gas supply, (2) external HV connector, (3) Mylar entrance window, (4) frame to hold the GEM foils, (5) FITPix readout.

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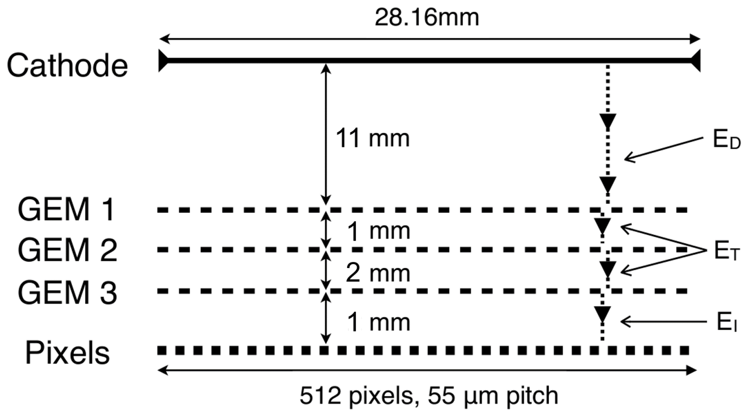

Figure 2. Scheme of the GEMPix: radiation enters the drift gap through the Mylar foil also serving as the cathode. The electrons produced in the drift gap are then guided and amplified by a series of electric fields and finally detected by the Timepix readout.

2.2 Alpha spectrometry of the ^{241}Am source

The alpha source consists of a thin ^{241}Am foil of 18 mm diameter, placed on a metal support and encapsulated by a 1.8 µm thin Palladium foil. Its activity was 39.2 kBq in November 2020. Its energy spectrum needs to be well known as a basis of this calibration method. A theoretical emission spectrum of ^{241}Am would be insufficient as it would not consider shielding effects by the source encapsulation. Therefore, an alpha spectrometry measurement was performed with a Canberra Alpha Spectrometer Model 7401.

2.3 Measurements with the GEMPix

For the measurements with alpha particles, the GEMPix was fixed on an aluminium rod on which a positioning system holding the ^{241}Am source was also placed (figure 3). The distance (in air) between the GEMPix window and the source was adjusted by a micrometre screw between 6 mm and 17.25 mm. In total, 14 measurements were performed with a step size of 1 mm between 6 mm and 16 mm and then three additional measurements at 16.75 mm, 17.00 mm and 17.25 mm, in order to describe better the non-linear part of the calibration curve. The zero distance was calibrated by moving the source without collimator in contact to the Mylar window. A collimator consisting of a thin Poly Methyl Methacrylate (PMMA) sheet (2 mm thickness) with a 1 mm diameter hole was placed between GEMPix and source. The GEMPix measured the TOT counts in each pixel in a frame-based mode with a fixed duration of 50 ms. 1,000 frames were acquired per position, except for the three largest distances (16.75 mm, 17.00 mm and 17.25 mm), where 2,000 frames were acquired. Particle tracks in the GEMPix leave clusters of pixels yielding a signal (figure 4). The 2D images were analysed using the ROOT [9] based Mafalda framework [10], which includes a cluster analysis: the TOT counts of all pixels in a cluster were summed up, resulting in a single value of TOT counts per particle track. By choosing a 50 ms frame duration, superposition of alpha particle tracks was improbable and the effect of superposition on the results became negligible. Thanks to the pixelated readout, tracks from alpha particles and from gamma-rays emitted by the ^{241}Am source can be distinguished (figure 4). For the analysis presented here, clusters with an

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Figure 3. The ^{241}Am source is placed on a holder such that its distance from the GEMPix can be adjusted by a micrometer screw.

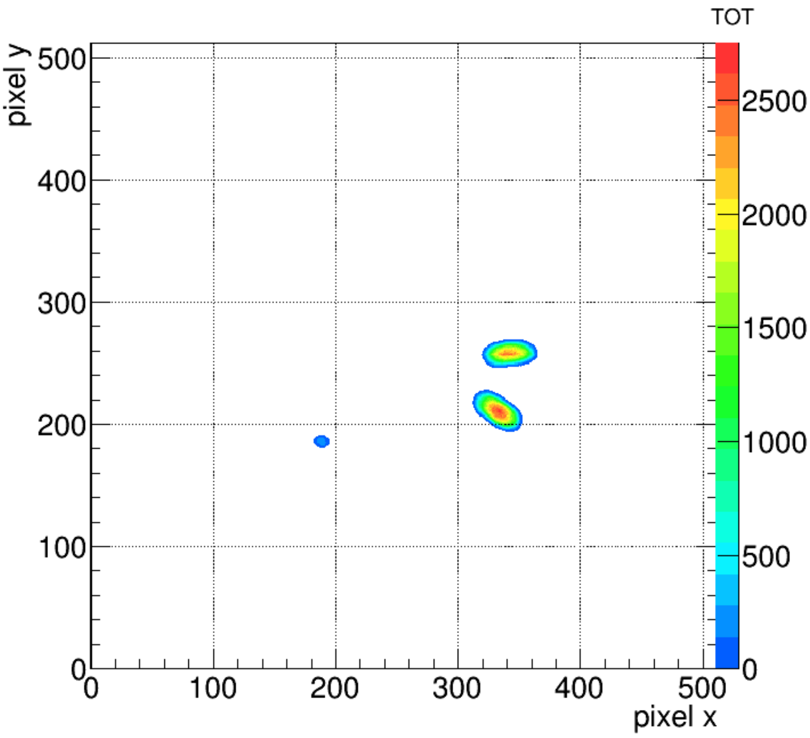

Figure 4. A 2D image (frame) acquired with the GEMPix for 10 cm source-detector distance. X- and y-axes denote the spatial coordinates in pixel numbers. The TOT counts are color-coded. This image contains two alpha tracks (right side) and one low-energy event (left side, probably a secondary electron produced by a gamma-ray from the ^{241}Am source). Most of the images contain maximum one alpha track, as the frame duration was chosen short enough to avoid superposition of tracks.

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energy lower than the maximum gamma-ray energy deposition (50,000 TOT counts) were excluded. This threshold value was obtained by a measurement with a 2 mm PMMA sheet placed between source and detector: in this way, alpha particles can no longer enter the drift gap of the GEMPix and the maximum of the gamma-ray spectrum was determined.

The measurement with the ^{55}Fe source was carried out by placing the source in front of the Mylar entrance window, without the collimator and the positioning system. 1000 frames with a frame duration of 5 ms were acquired — the shorter duration was adapted to the higher count rate induced by the ^{55}Fe source compared to the ^{241}Am source. The same cluster analysis as for the ^{241}Am measurements was used, yielding the TOT counts per ^{55}Fe X-ray.

2.4 FLUKA simulation

In order to know the residual energy of the alpha particles in the drift gap of the GEMPix for each distance in air between the detector and the source, a Monte Carlo simulation was performed using FLUKA [11, 12] version 2020.0.8 with the FLAIR user interface [13] version 2.3-0. The GEMPix, the source, the collimator and the surrounding air were implemented in the simulation. The source was designed as a disk emitting the spectrum acquired by the alpha spectrometer. The density of the air was adjusted to be 1.15×10^{-3} g/cm^3, corresponding to the pressure and temperature values (and therefore the density) during the measurements. 500,000 primary alpha particles per source position were transported using the PRECISIO card [11] and 10 keV transport threshold. The residual energy of the alpha particles in the gas volume was scored using a USRBDX card [11].

2.5 Crystal Ball fit function

The energy spectra simulated in FLUKA and measured with the GEMPix were fitted with the following function developed by the Crystal Ball collaboration for processes with losses such as energy measurements in a calorimeter [14, 15]:

$$f(x) = N \times \begin{cases} \exp(-\frac{(x-\overline{x})^2}{2\sigma^2}), for \frac{(x-\overline{x})}{\sigma} > -\alpha \\ A \times (B - \frac{(x-\overline{x})}{\sigma})^{-n}, for \frac{(x-\overline{x})}{\sigma} \leq -\alpha \end{cases}$$

with a normalization constant N, mean $\overline{x}$ and sigma σ describing a Gaussian function, and $A = (\frac{n}{|\alpha|})^n \times \exp(-\frac{|\alpha|^2}{2})$ and $B = \frac{n}{|\alpha|} - |\alpha|$ with the fit parameters n and α describing the left exponential tail of the Gaussian in the energy spectrum. The use of this function in case of the ^{241}Am source is motivated by the emission of alpha particles from the source that then undergo several energy losses in the encapsulation of the source, the air and the Mylar window, with the exact amount of energy loss depending on the angle of emission. This results in a distribution with a main Gaussian peak and a tail to lower energies, which is fitted satisfactorily by the Crystal Ball function. In case of the ^{55}Fe source, the use of this fit function is motivated by a tail towards low energies most likely due to X-rays undergoing a photoelectric effect on the surface of or close to the cathode. The resulting number of electrons will then be only partially drifted towards the GEMs resulting in a low energy detected by the GEMPix.

2.6 Fit function for the energy calibration

The actual calibration was performed by plotting the measured TOT counts per cluster against the residual energy of the alpha particles in the GEMPix simulated by FLUKA (in case of the ^{241}Am source) or the known energy of 5.9 keV (in case of ^{55}Fe X-rays). Experimental and simulated values were obtained as the mean value of the Crystal Ball fit function.

In order to describe the final calibration data, the usual surrogate function for Timepix energy calibrations [16] was used:

$$f(x) = ax + b - \frac{c}{x - d}$$

3 Results

3.1 Alpha spectrometry measurements of the ^{241}Am source

Figure 5 shows the resulting spectrum acquired in vacuum. The peak position of 4.7 MeV is lower than the emitted energy of 5.5 MeV [17], demonstrating the effect of the encapsulation and the need of this measurement in order to use it as an input for the FLUKA simulation. The spectrum also shows a tail towards lower energies due to other, less frequent emission lines at lower energies and to different path lengths in the source encapsulation.

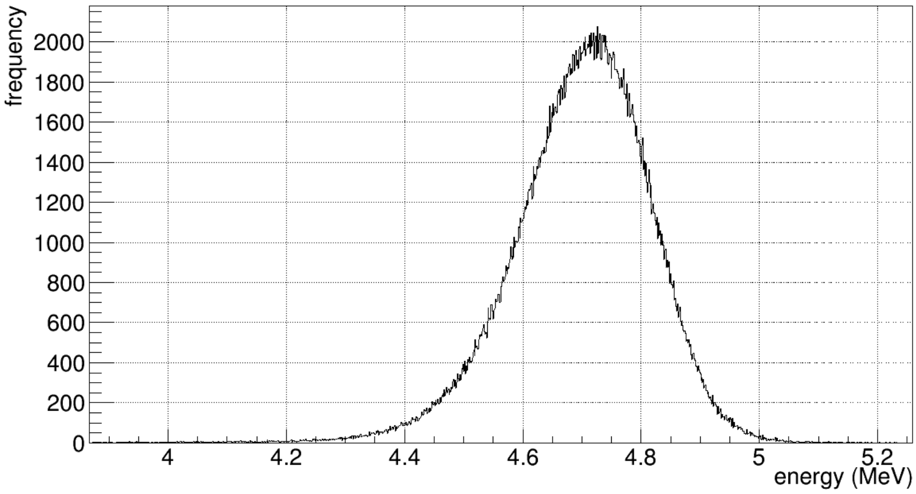

Figure 5. The energy spectrum of the alpha source acquired by the Canberra Alpha Spectrometer. The shape is asymmetric because more than one energy line contributes to the spectrum and because of losses in the source encapsulation.

3.2 FLUKA simulation of the residual energy

Figure 6 shows the simulated energy spectrum of the alpha particles entering the drift gap of the GEMPix for a distance in air between source and detector of 9 mm. The curve is fitted by a Crystal Ball function, whose parameters are shown in the figure. The simulation is able to reproduce the general shape of the spectrum, with a main Gaussian peak and a tail towards lower energies.

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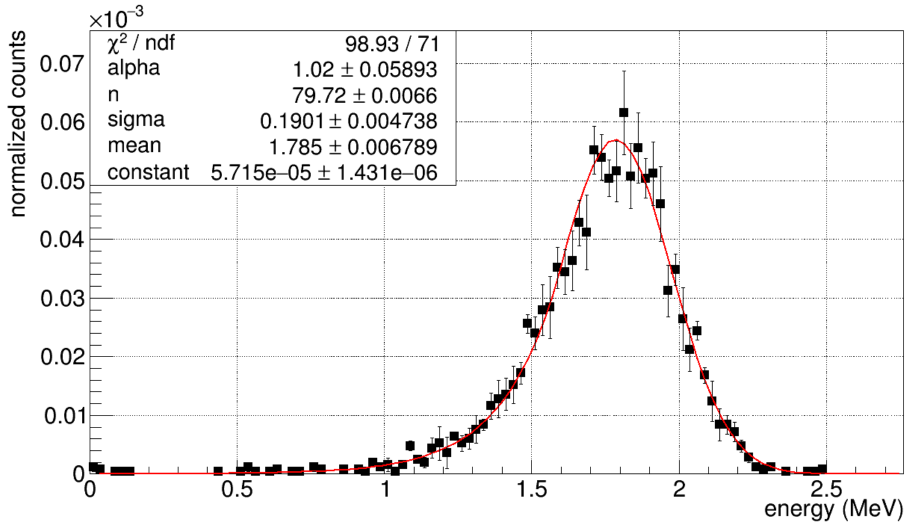

Figure 6. The spectrum of the residual energy of the alpha particles in the drift gap of the GEMPix as simulated with FLUKA, for 9 mm distance in air between source and detector. The counts are normalized to the area (per cm^2) and to the number of primaries. The bin width is 25 keV. The red line is the Crystal Ball fit.

3.3 Measured energy spectra

Figure 7 shows the measured spectrum of the TOT counts per cluster for a 9 mm source-detector distance in air for irradiation with the ^{241}Am source. Also in this case, the fit function is able to describe well the shape of the spectrum.

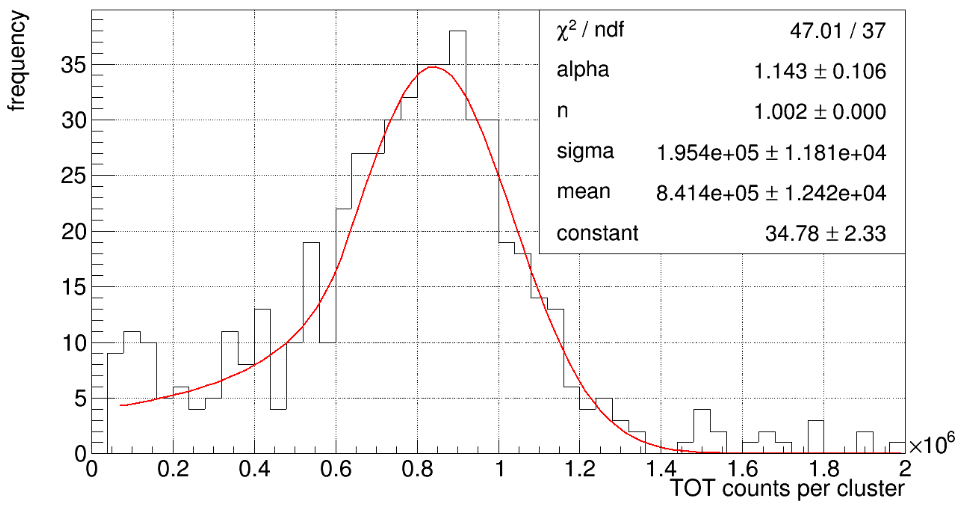

Figure 7. The frequency distribution of the TOT counts per cluster as measured by the GEMPix for a 9 mm distance in air between detector and ^{241}Am source. The red line is the Crystal Ball fit.

Figure 8 shows the TOT spectrum measured with the ^{55}Fe source. Again, the Crystal Ball function fits the spectrum well.

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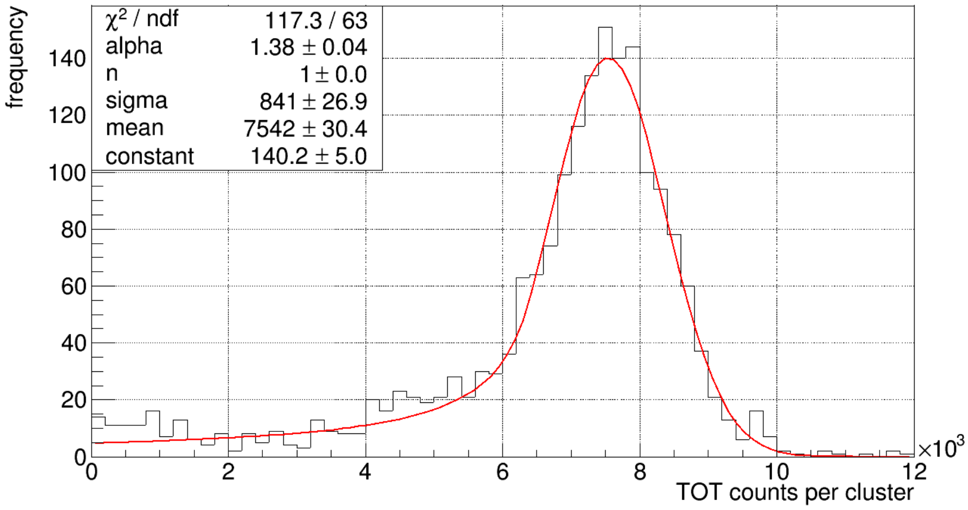

Figure 8. The frequency distribution of the TOT counts per cluster as measured by the GEMPix with the ^{55}Fe source. The red line is the Crystal Ball fit.

3.4 Energy calibration

Figure 9 shows the final energy calibration curve. The surrogate function usually used for energy calibrations of Timepix detectors describes the data satisfactorily. The shape — especially the non-linear part at lower energies — is typical for an energy calibration with Timepix and has been observed also when coupling Timepix readouts to silicon sensors [16].

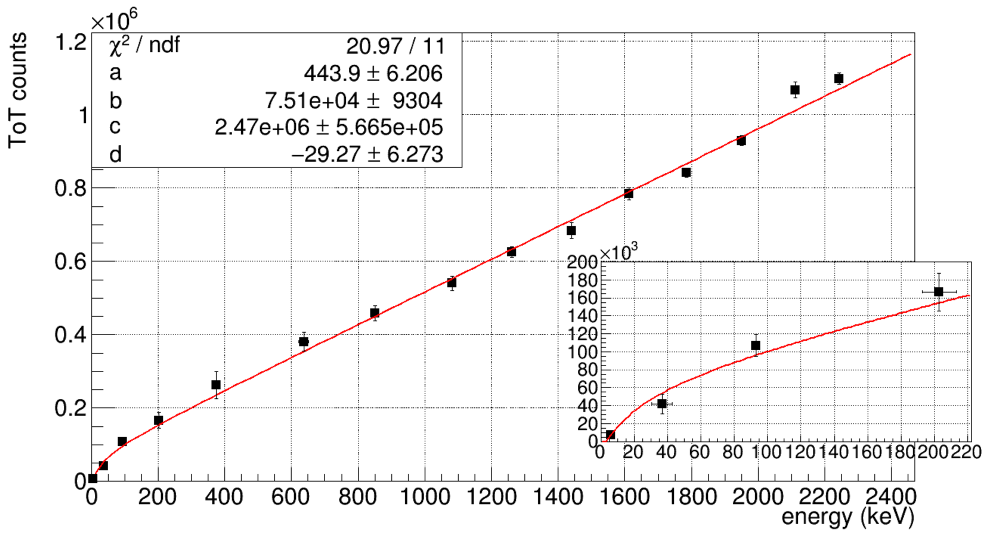

Figure 9. The calibration curve of the GEMPix: measured data are plotted against the simulated residual energy for 14 different distances in air with an ^{241}Am source. The small plot shows a zoom to the low energy region, its axes having the same units as those of the main plot. The point at the lowest energy is the data point for ^{55}Fe with an energy of 5.9 keV.

4 Discussion and conclusions

This paper has discussed a novel energy calibration method of the GEMPix, a gaseous detector with a highly pixelated readout. Usually, alpha sources are placed inside gaseous detectors for energy calibration (for example in case of the gold standard detector in microdosimetry, the Tissue Equivalent Proportional Counter). Thanks to the thin Mylar window of the GEMPix, alpha particles from an external ^{241}Am source can enter the drift gap, though. The source-detector distance was varied to obtain different residual energies of the alpha particles interacting with the sensitive volume. Simulated and measured energy depositions of the alpha particles were fitted with a Crystal Ball function. While the parameters mean, sigma and constant depend on the Gaussian part of the spectrum, the parameters alpha and n describe the exponential tail at lower energies. When comparing measured and simulated spectra (figures 6 and 7), n differs significantly: the simulated spectrum drops to almost no counts at energies below 0.5 MeV (yielding $n = 80$), while in the measured spectrum there are counts even at the lowest energies (yielding $n = 1$). Furthermore, the energy resolution in the simulation (FWHM/mean) is better by a factor of 2. This indicates that there are processes of energy straggling, which are not included in the simulation. However, in this analysis only the mean value of the distributions was used. The resulting calibration curve was fitted with a surrogate function. In contrast to measurements with Timepix detectors, the analysis presented here takes into account the energy per cluster (i.e., per particle track) and not per pixel: the electron diffusion in the GEMPix requires a cluster-based analysis as almost any energy deposition will result in an electron cloud on the readout larger than the pixel size and therefore, will result in a cluster of pixels yielding a signal. The surrogate function describes well the data for all measurements, i.e., from 5.9 keV to about 2.2 MeV. This procedure will be used in the future for applications of the GEMPix to microdosimetry.

Acknowledgments

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