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Precise energy calibration of pixel detector working in time-over-threshold mode

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ABSTRACT

The semiconductor pixel detector Timepix (256 × 256 pixels with pitch of 55 μm) is a successor of the Medipix2 device. Each Timepix pixel can be independently operated in one of three possible modes: (1) counting of the detected particles; (2) measurement of the particle energy; and (3) measurement of the time of interaction. The energy measurement in the second mode is performed via the determination of the "time-over-threshold" (TOT). The energy measurement with the Timepix detector in TOT mode requires knowledge of the energy calibration of each pixel of the matrix. Such calibration is very nonlinear in the low energy range and can be described by a surrogate function depending on four parameters. The determination of all these parameters can be performed by measurement and evaluation of the response of each pixel in at least four calibration points. The procedure is extremely demanding: it requires the analysis of at least 250 thousand spectra and the performance of 330 thousand least-squares fits. In this article, it is demonstrated that even better result can be achieved with only two or three calibration points halving the number of least-squares fits needed. The method is based on precise analysis of the shape of spectral peaks. The article also discusses the performance of energy calibrated device for spectrometry of heavy charged particles.

1. Introduction

Planar pixelated semiconductor detectors of the Medipix family are designed by Medipix consortium [1] primarily for X-ray radiography. Their ability to count ionizing particles from preselected energy range is targeted mainly at energy sensitive X-ray radiography allowing material recognition [2].

The new device Timepix [3] operating in time-over-threshold mode has the ability to measure the charge collected by each pixel, which allows substantial improvement of the quality of energy sensitive imaging [4] and opens access to many other fields [5].

2. The Timepix detector and its energy calibration

The hybrid silicon pixel device Timepix [3] consists of a pixelated semiconductor detector chip (256 × 256 square pixels with pitch of 55 μm) bump-bonded to a readout chip. Each element of the matrix (pixel) is connected to its respective preamplifier, discriminator and digital counter integrated on the readout chip. Each pixel can independently work in one of three modes: Medipix mode (the counter counts incoming particles), Timepix mode (the counter works as a timer and measures the time when the particle is detected) and time over threshold (TOT) mode (the counter is used as a Wilkinson type ADC allowing direct energy measurement in each pixel).

The Timepix detector running in TOT mode measures the charge collected in each pixel. As the device contains 65536 independent channels and as their response can be never identical it is necessary to perform an energy calibration for each of them.

The calibration procedure based on measurement of X-ray fluorescence (XRF) was already published in Ref. [6] and further improved in Ref. [4]. The device is irradiated by monoenergetic radiation recording a spectrum for each pixel using single pixel clusters[1] only. The spectral peaks are then fitted with Gaussians and four parameters of a surrogate function f describing the energy response of each pixel are computed by another fit (see Fig. 1). This procedure requires the measurement of at least 4 spectral lines and performance of at least five least-squares fits for each pixel.

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[1] A single particle can create signal in several adjacent pixels due to various reasons: hitting the border between pixels (e.g. X-rays), having longer track (e.g. electrons), being blurred by charge diffusion in the sensor (all). Thus, the charge created by the particle is shared by multiple pixels forming a cluster.

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The problem of such calibration procedure lies in the nonlinear response of pixels in the energy range close to the threshold (see Fig. 1). Fitting of spectral peaks with Gaussians in this region gives systematically shifted results as shown in Fig. 2.

3. Improved calibration procedure

The solution to the calibration problem of bad peak shape model is simple. The combination of a Gaussian $G_{\mu,\sigma,A}(e)$ with a surrogate function $f_{a,b,c,t}(e)$ has to be used for fitting instead of a plain Gaussian. Here, we use this notation: indices mark parameters, e is energy, the pixel calibration function $f_{a,b,c,t}(e)$ transforms energy to TOT signal s, Gaussian parameters are μ (mean energy), σ (energy noise) and A (spectral peak intensity or area). The new model M of the spectral peak is, therefore, a simple combination of G and inverse of f:

$$M_{a,b,c,t,\mu,\sigma,A}(s) = G_{\mu,\sigma,A}(f^{-1}_{a,b,c,t}(s)) \quad (1)$$

Although such model depends on 7 parameters, not all of them have to be searched by the fitting procedure. The parameter μ denotes the energy of the calibration peak and it is obviously known.

In principle it is possible to estimate all parameters of the calibration curve with single fit (see Fig. 3). Unfortunately, such a fit is very unstable due to the high number of free parameters requiring very good statistics. Moreover, the a and b parameters are rather correlated in the low energy range; therefore they are estimated with high uncertainty.

A much better approach combines the usage of both models: Gaussian for energies in the linear range and M in the nonlinear energy range close to the threshold. One or (better) two spectral lines (e_1 and e_2) are measured in the linear energy range and their peaks are fitted with Gaussians. From the fit we determine the mean TOT values s_1 and s_2 registered by pixel. Knowledge of these two points allows the determination of a and b for each c and t from the following equations:

$$f_{a,b,c,t}(e_1) = s_1 \quad \text{and} \quad f_{a,b,c,t}(e_2) = s_2 \quad (2)$$

Thus, the calibration function f can be now rewritten as $f_{[e_1,s_1],[e_2,s_2],c,t}(e)$ having just two free parameters c and t because both pairs $[e_1,s_1]$ and $[e_2,s_2]$ are known from Gaussian fits to high energy peaks. Now we can perform fit to one peak in the nonlinear region with the model $M_{[e_1,s_1],[e_2,s_2],c,t,\sigma,A}(e)$ searching for 4 parameters only (c, t, σ and A). The a and b parameters are then computed from Eq. (2).

The obvious effect of the described calibration technique is reliable shape restoration of spectral peaks in the nonlinear region (see Fig. 4).

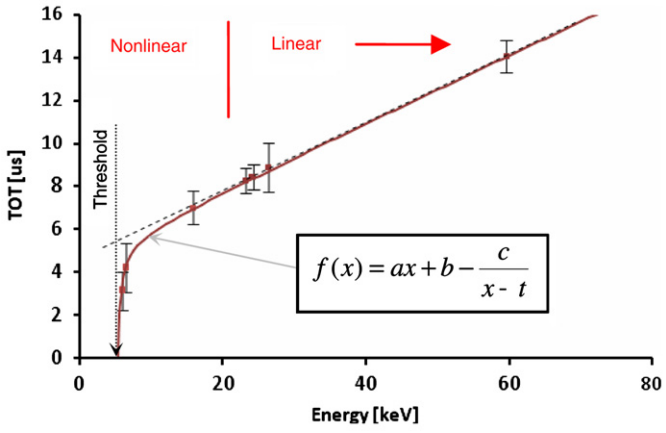

Fig. 1. Dependence on particle energy of the time-over-threshold signal measured by a single Timepix pixel. The dependence is modeled by a surrogate function f depending on four parameters.

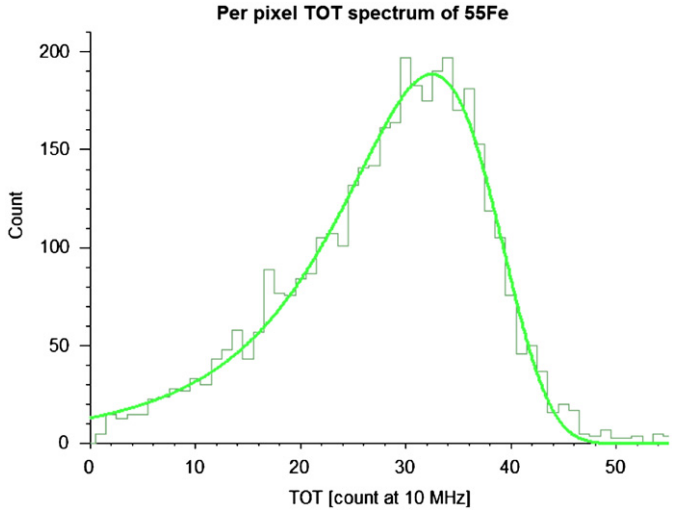

Fig. 3. The TOT spectrum of ^{55}Fe (the same spectrum as shown in Fig. 2) fitted with the model M. The model describes the data very well.

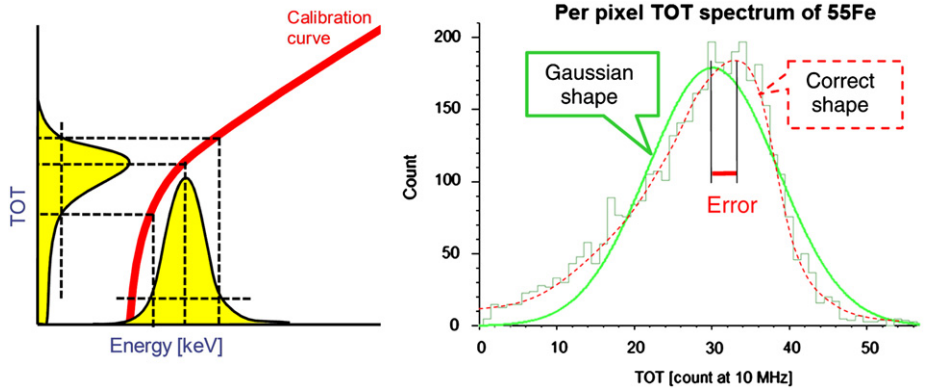

Fig. 2. The nonlinear calibration curve of a Timepix pixel device in TOT mode deforms shapes of peaks (left). Fitting of the ^{55}Fe spectrum (5.9 keV) with a Gaussian gives systematic error (right).

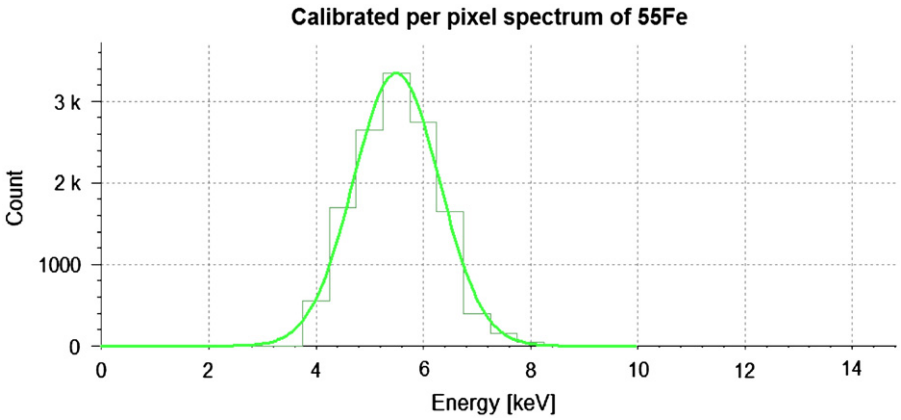

Fig. 4. The calibrated spectrum of ^{55}Fe (the same spectrum as shown in Fig. 3). The Gaussian shape is recovered by calibration.

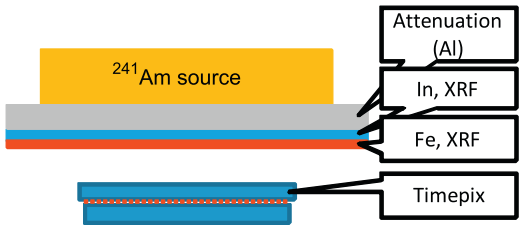

Fig. 5. Multilayer source for TOT calibration. ^{241}Am emits 59.5 keV gamma rays penetrating indium and iron plates where characteristic fluorescence X-rays are generated (24.1 keV for In and 6.4 keV for Fe). All three peaks are well separated in the per pixel spectra.

4. Calibration and quality testing

The equalized[2] Timepix chip was irradiated by a multi-energy calibration source constructed as combination of an isotopic gamma source and a set of XRF materials (see Fig. 5). Per pixel TOT spectra were recorded for all pixels taking just single pixel clusters. The measurement was performed with threshold set just above the noise level (~3.2 keV) and with a sensor bias voltage of 100 V. The clock frequency for TOT measurement was set to 10 MHz and the constant current source I_{krum} was set to its minimal value[3] of 1. The fits to the spectral peaks were performed according to the sequence described in paragraph 3 for each pixel.[4]

The quality of calibration was tested by independent measurement with the same source without Fe layer, i.e., just the ^{241}Am and In peaks remained in the spectrum. The calibrated global spectrum (summation of all per pixel spectra) is shown in Fig. 6.

The homogeneity of calibrated pixel matrix was evaluated by fit to calibrated per pixel spectra with Gaussians. All pixels are supposed to give the same mean value of measured energy. The measured dispersion was 204 eV for Indium and 516 eV for Americium peak. Such homogeneity is very good.

5. Calibration extrapolation

The quality of calibration for much higher energies was tested with 5.5 MeV alpha particles emitted by ^{241}Am source. The clusters created by such particles are 40–80 pixels large in dependence on sensor bias voltage. The particle energy was determined as a summation of the calibrated responses of all pixels in the cluster, i.e., computing a cluster volume. The resulting energy spectrum measured with a bias voltage of 7.5 V is shown in Fig. 7.

The maximum charge collected by a single pixel in the cluster (cluster height) corresponds to an energy of 500 keV at a bias of 7.5 V.

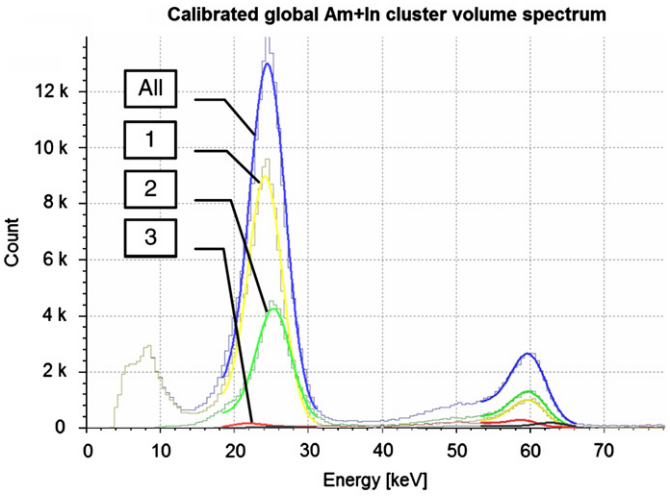

Fig. 6. Calibrated spectra of dual energy source (^{241}Am+In) for different cluster sizes (the cluster size is denoted by label). Peaks for different cluster sizes are well aligned. Peaks are fitted with Gaussians. The energy resolution (sigma of Gaussian) is 2.3 keV for both peaks.

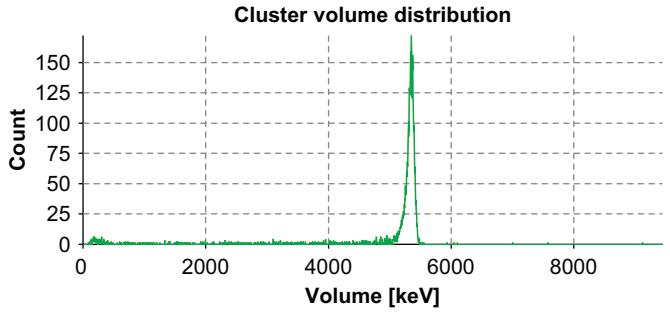

Fig. 7. Energy spectrum of ^{241}Am alpha particles (measured at a sensor bias voltage of 7.5 V). The energy resolution is 35 keV (rms).

[2] Equalization procedure sets per pixel threshold adjustment to achieve the best homogeneity [3].

[3] Also higher values of I_{krum} (up to 5) were tested without any influence on the shape of calibration curve.

[4] The calibration energies were optimized using simulations described in [4].

Increase in the bias voltage, the cluster height rises logarithmically as shown in Fig. 8. When the cluster height reaches approximately 0.9 MeV (roughly at a bias of 40 V) the response of

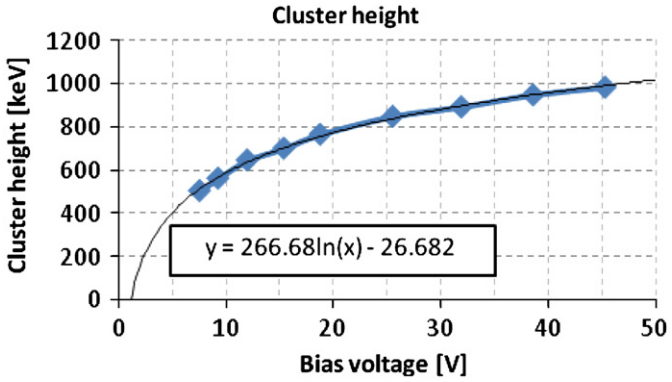

Fig. 8. Maximum signal seen by pixel in the cluster (cluster height) as a function of the bias voltage for 5.5 MeV alphas. The dependence is nicely logarithmic (parameters of logarithmic curve shown in box).

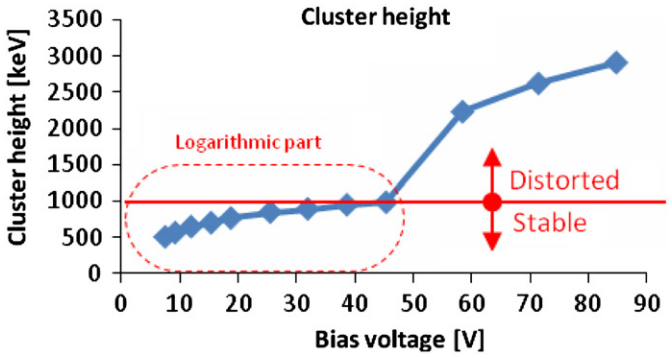

Fig. 9. Dependence of the cluster height on the bias voltage for 5.5 MeV alpha particles. When the pixel response reaches about 0.9 MeV the cluster height starts to grow unexpectedly.

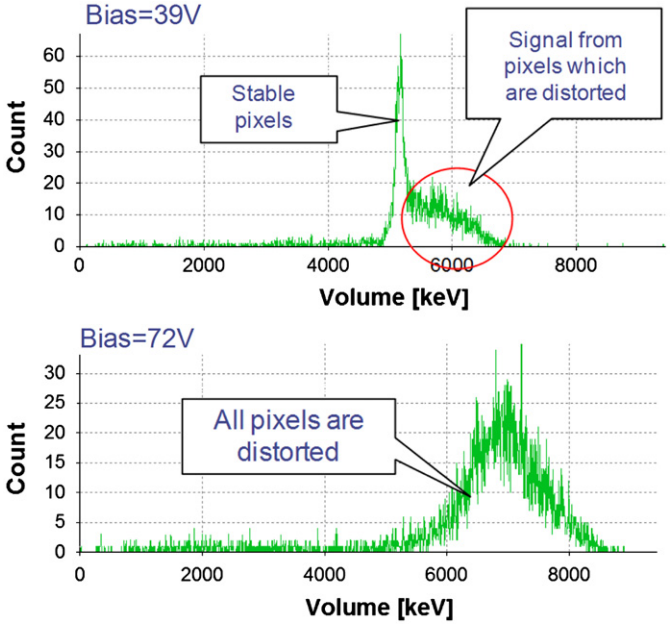

Fig. 10. Cluster volume spectra for sensor bias voltage of 39 V (top) and 72 V (bottom) showing distortion caused by the deviation of pixel response from the calibration function f (compare with Fig. 7).

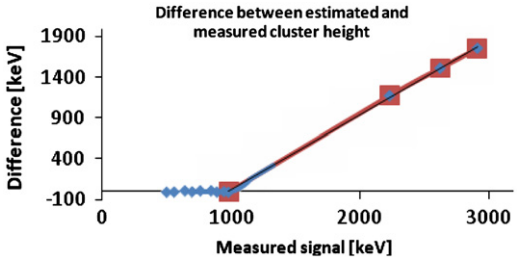

Fig. 11. The difference between estimated and measured cluster height differs from zero above 0.9 MeV.

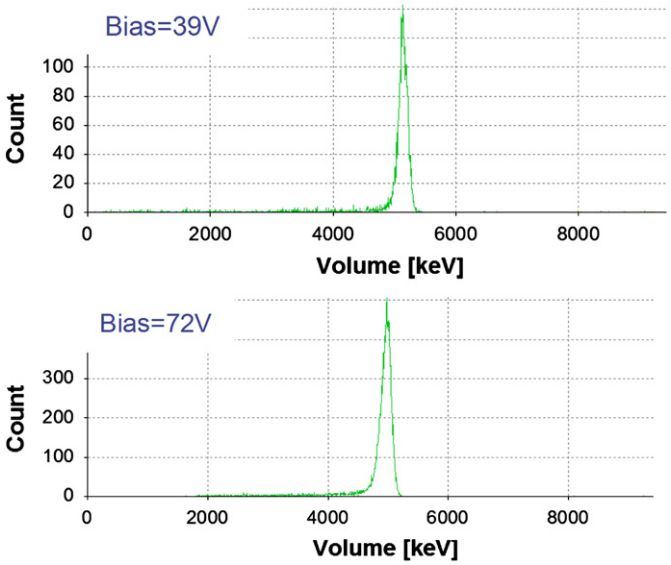

Fig. 12. Cluster volume spectra of 5.5 MeV alpha particles. The distorted response of pixels was corrected above 0.9 MeV and the spectrum shape restored (compare with Fig. 10).

pixels starts to grow dramatically (see Fig. 9). Such unexpected behavior distorts the cluster volume spectra (Fig. 10), which are supposed to be independent of the bias voltage (if all ionization charge is collected). This behavior shows that the calibration function f is not valid for very high ionization charges. The reason is probably connected with the constant current source I_{krum}, which does not work properly for so large collected charge, resulting in much longer discharging time.

As the pixel response above 0.9 MeV is still monotonous its deviation from the calibration curve can be corrected. For this purpose we can use the assumption that the dependence of cluster height on bias voltage should stay logarithmic for all bias voltages. The difference between estimated logarithmic and really measured cluster height dependence is shown in Fig. 11. We see that this difference (error) is a linear function of the measured signal, which can be directly used for correction of the calibration function in the region above 0.9 MeV.

The corrected calibration function was applied to the data set shown in Fig. 10 generating new cluster volume spectra (Fig. 12) showing a correct behavior.

6. Conclusions

It was demonstrated that the precise analysis of the shape of spectral peaks improves the quality of energy calibration of the Timepix device in TOT mode, reduces the number of calibration

points to be measured and simplifies the data processing. The surrogate calibration function describes the response of pixels very well and can be extrapolated to a large extent. Calibration done in the interval from 6 to 60 keV works well till 900 keV.

When the collected signal exceeds a level of approximately 0.9 MeV, the pixel electronics starts to show unexpected behavior, distorting the measured energy. Such a distortion can be still corrected and the range of calibration can be extended up to an energy of 1.2 MeV per pixel.

Acknowledgments

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