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Ethernet Embedded Readout Interface for Timepix2 — Katherine readout for Timepix2

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Abstract: This paper introduces a readout system for the Timepix2. Firstly, this chip is described and the readout modes are discussed in detail. The new readout system presented is based on the Gigabit Ethernet interface and implements pre-processing, i.e. decoding of the raw pixel data, directly in the hardware. The device suppresses zero pixels, so that only useful data are sent to the computer/server. In a special independent mode, the readout can send completed data files to a remote server via SSH and does not need to use a control software. In island mode, the device stores measured data to a local storage (SD card). The process of calibration and its results are also discussed. An energy resolution of approximately 1.5 keV was achieved for 60 keV gamma-rays from an ^{241}Am source. We present enhanced features of the readout system facilitating measurements and data evaluation, such as the *HW support of clustering* and *Matrix Occupation Control*. The former implements the pixel clustering directly in the hardware and sends energy calibrated results of the cluster finding algorithm to the computer. The latter automatically controls acquisition time of detector in order to reduce cluster overlapping. Measurements with Timepix2 are presented in iron and electron test beams. Results show that pixels of Timepix2 saturate at a per-pixel energy deposition of 1.9 MeV.

Keywords: Detector control systems (detector and experiment monitoring and slow-control systems, architecture, hardware, algorithms, databases); Data acquisition circuits; Data acquisition concepts; Particle tracking detectors

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Contents

1 Introduction

The hybrid pixel detector Timepix [1], introduced in 2006 and developed by CERN in the Medipix Collaboration, has proved valuable for a broad range of applications in physics and life science [2]. It is used e.g. as a radiation monitor in environments with harsh radiation fields, in space projects (SATRAM [3] and REM [4]) or in the ATLAS experiment (the ATLAS-TPX network [5] uses 16 detector units based on Timepix). An overview of current applications can be found in [2]. To date, Timepix has profited from the development of easy to use, small and compact readout systems, such as the FITPix [6], the USB Lite device [7], the FITPix Lite [8], and standalone systems like the RasPIX [9]. Timepix2 was designed as an improved version of Timepix implementing additional features to solve drawbacks found when using Timepix in different applications. Timepix2 has a reduced power consumption, allows a simultaneous measurement of ToT and ToA, prevents the ToT measurements to be cut by the shutter signal closing the frame, implements adaptive gain and the possibility to monitor the matrix occupation during frame acquisition.

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2 Timepix2

Timepix2 [11] is based on the 130 nm CMOS technology of the TSMC foundry in Taiwan. The active area is arranged a matrix of 256 × 256 pixels with 55 µm pitch, so that the total active area is14 mm × 14 mm (1.98 cm^2). The chip has been designed to use TSV (Through Silicon Vias) technology and supports low voltage swing SLVS standard of the I/O ports (for serial communication). Using the 32-bit parallel gate for fast data readout e.g. at 100 MHz, a data rate of 3.2 Gbps can be achieved.

Analog front-end. In the analog front-end, Timepix2 makes it possible — only for hole collection — to use *adaptive gain*, which extends the measurable per-pixel energy range and suppresses the volcano effect. The peaking time of the amplifier is ~ 100 ns for standard gain and 200 ns in *adaptive gain*.

Analog masking allows to turn off the power supply for the pixels, resulting in reduced power consumption of the chip. This is a very important feature for applications with limited power budget, e.g. space applications, wearable sensor systems, dosimetry, etc. Each pixel implements a 5-bit discriminator fine adjustment to get a uniform distribution of the per-pixel thresholds over the entire chip. Parameters of the analog front-end are controlled by 19 internal programmable DACs.

Digital part. The digital part of Timepix2 implements several features to configure the chip for use in different applications. The ToT clock signal is fed to chip externally (by a readout system). The ToA is then generated internally from the base ToT clock by a programmable divider. This means that different clock frequencies for ToT and ToA can be used. For instance: a fast ToT clock getting good ToT/energy resolution can be combined with a slow ToA clock enabling long frame acquisition times. A *Matrix Occupation Monitor* functionality, which flags up if a predefined pixel matrix occupation is reached. This allows unsupervised measurements in radiation fields where the radiation levels are changing in time (see discussion in section 4.2).

Each pixel contains four counters — A, B (10-bit) and C, D (4-bit). These counters can be interconnected together and provide wider counters depending on the selected mode. Timepix2 allows simultaneous and continuous modes. The *simultaneous* mode enables a measurement of energy (ToT) and time (ToA) at the same time. Data are sequentially taken and read out. Therefore, the dead time of the measurement is given by time of the readout process (~ 18.5 ms at 100 MHz data clock).

In *continuous* mode, two sets of pixel counters are built (A+C and B+D). While the first set is used for measurement, the second one is used for data readout. As result, the dead time is practically eliminated. Counters switch between reading and measuring — this limits the minimal acquisition times for measurement that is determined by reading time of one counter set (min. 6.5 ms–9.2 ms at 100 MHz data clock). Table 1 shows a summary of the implemented modes.

As well as the 65,536 pixels in the matrix, Timepix2 contains 8 additional purely digital pixels with external inputs. These pixels accept discriminated signals from external sources, for example, from external single pad diodes with a preamplifier/discriminator chain. These digital pixels can also be used for synchronization with other instruments in the measurement chain. Via ToA measurement, we are able to get time-stamps of external signals with uniform timing.

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Table 1. Timepix2 modes description.

Type	Mode Name	Description	Counter Set 1	Counter Set 2
Simultaneous	ToT10/ToA18	Both ToT and ToA values are available at the same time. Only first event is relevant for ToA value. 1)	10-bit ToT	18-bit ToA
	ToT14/ToA14		14-bit ToT	14-bit ToA
Continuous	ContToT10/ Event4	ToT and counting (number of events) are available. 1)	10-bit ToT 4-bit Count	10-bit ToT 4-bit Count
	ContToT14	Only ToT available. 1)	14-bit ToT	14-bit ToT
	ContToA10	Only ToA related of the first event.	10-bit ToA	10-bit ToA
	ContToA14		14-bit ToA	14-bit ToA
	ContEvent10	Event counting only.	10-bit Count	10-bit Count
	ContEvent14		14-bit Count	14-bit Count

Note: 1) ToT can be related to the first event or can be integrated over all events — this is programmable by an user.

3 Readout system description

3.1 Katherine for Timepix2

The development of a readout system for Timepix2 was based on the already well tested Katherine readout for Timepix3 [13]. The newly designed device — *Ethernet Embedded Readout Interface for Timepix2 (Katherine readout for Timepix2)* — supports one standard chipboard with a Timepix2 assembly. The chipboard can be connected directly or via VHDCI extending cable. Gigabit Ethernet is used as the main interface for communication with the computer/server. It provides enough bandwidth for the maximally considered data rate generated by Timepix2, which is 100 Mbps/chip for a serial interface (only this interface is considered). An important advantage of this interface is the possibility to use long cabling (up to 100 m), something that is often problematic in the case of a USB interface. This allows remote access to detector. There is no need to have a measurement control computer close to the radiation field. For example, in test beams only the readout device is placed in the beam area, whereby the control computer can be placed in the counting room at a safe distance.

The readout system implements a high voltage power supply for the sensor bias providing the range from −300 V up to +300 V. It should cover the needs of most commonly used sensors (such as silicon with thickness of 300 μm or 500 μm).

3.2 HW description

The functionality of the device is based on the Intel FPGA SoC (Field-Programmable Gate Array; System-on-Chip) device. The SoC system can use 1GB DDR3 RAM memory. An interconnection between the FPGA device and the Timepix2 chipboard is done by a VHDCI male connector via the SLVS <=> CMOS signal translators. The maximal serial data rate of Timepix2, i.e. 100 Mbps, is used. The dual-channel ADC (Analogue-to-Digital Convertor) measures DAC OUT of Timepix2.

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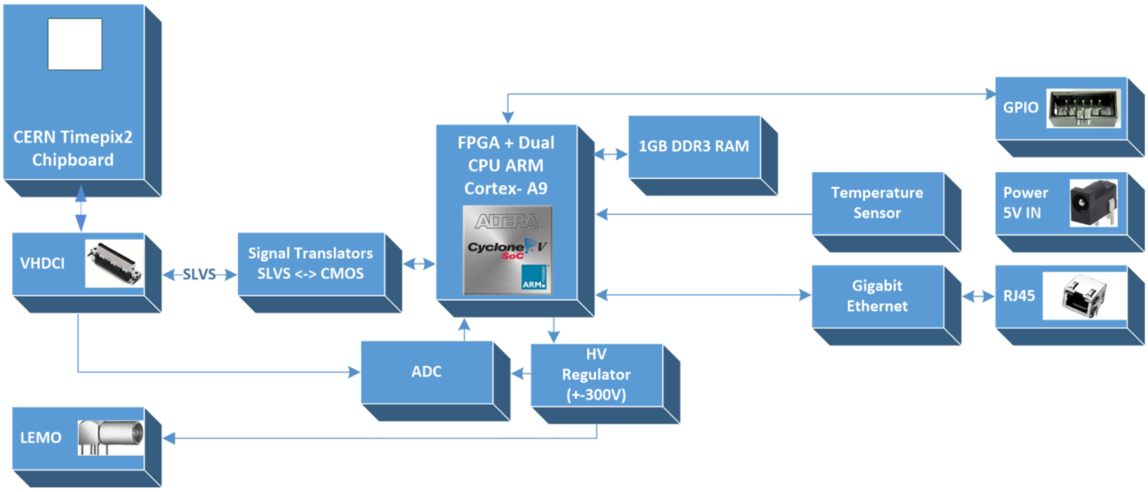

Figure 1. Readout hardware description.

The current value of the bias voltage is used for monitoring and regulation. This ADC is available via SPI (Serial Peripheral Interface). A temperature sensor measures temperature of the device (on the PCB). The user can read the current temperature in the readout system housing and the internal temperature of Timepix2, because a thermometer is implemented on the chip. The Gigabit Ethernet is implemented in the FPGA SoC device and is connected via the PHY (Physical Layer) chip to the RJ-45 connector. The GPIO signals are connected directly to the FPGA SoC device (see description of rear panel below).

Figure 2. Katherine Readout for Timepix2 — overall view and panels.

Figure 2 shows an overall view of the Katherine device and panels. The dimensions of the readout in the housing are $100 \times 80 \times 28$ mm. The front panel of the device contains a VHDC connector for the chipboard and a LEMO connector providing the bias voltage. For safety reasons, the bias voltage is not fed through the VHDCI connector of the chipboard. The vendor of the connector declares a max. limit of 100 V. Other connectors are placed on the rear panel: RJ-45 connector for Gigabit Ethernet, Power Jack for a DC 5V power supply, a GPIO connector, and three status LEDs. A General Purpose Input/Output (GPIO) connector offers up to four general-purpose

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signals. These are mainly dedicated to the integration of the device into measurement setups, where the triggering or synchronization of clocks is important (e.g. for detector stacking). The connector features a CMOS input (it can also be used as an input of external clock for the detector), a CMOS bidirectional signal, an LVDS input and an LVDS output.

The Katherine readout is not a pure interface that only translates commands between a computer and Timepix2, the device is rather an embedded computer with the interface for Timepix2. The FPGA SoC offers enough computing power and resources for user purposes: 6,500 ALMs (Adaptive Logic Modules) in the FPGA are free for on-line user calculations. The dual-core ARM Cortex-A9 processor can be used for pre-processing (an operating system can be installed), whereby 1GB DDR3 RAM are available for buffering or for onboard data processing. For that reason, Katherine is more like a platform open to users than just one final device/interface.

3.3 Communication with the computer/server

The fundamental communication with a superior (back-end) system, i.e. with a computer or a server, is based on the peer-to-peer UDP (User Datagram Protocol) communication, using two open ports: one for the detector control and another one for the measured pixel data transfer.

For detector control, a specific set of 37 commands has been established. These request-response-based commands are built by a 64-bit stream. An example of a command (*Internal DAC Scan*) is shown below.

63..48	47..8	7..0
0x000F (Cmd ID)	*unused*	Internal DAC ID

63..48	47..32	31..0
0x000F (Response Cmd ID)	*unused*	Analog Scan Value (float)

Figure 3. Command-request (on the left) and response (on the right). The most significant 16 bits stand for the Command ID and the remaining 48 bits stand for the data part of a command. The presented example shows the command for reading internal DACs with Command ID = 0x000F. The request uses 8 bits of the data part as an internal DAC ID selecting the desired DAC. In the response, the final analogue voltage value of a DAC is represented by a float number.

In figure 3 on the left, the request to read analog value of the internal DAC is shown. The most significant 16-bits stand for the *Command ID* and the remaining 48-bits stand for the data part of a command. On the right, the format of the response is shown. The device sends an output analog value of a voltage as a floating point number. It means, the readout system manages the measurement of the required value and a control software can process this value immediately. There is no need to recalculate this value. The data of the measurement are sent in 48-bit frames (see next section).

The Katherine device uses other approaches for sending measured data, they are following:

- *Automatic sending mode* sends the measured data automatically to a remote data storage via SSH (Secure Shell; Secure Copy/Secure File Transport Protocol) protocol. After the initial settings of the measurement and SSH storage server (target SSH server, target folder) the device is fully independent. The result of the measurement can be sent through the Internet or a local network to any location.

- In *Island mode*, the device is able to measure without connection with a computer or network. During the measurement, data are stored into the local memory (SD card).

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3.4 Pixel data processing

The Timepix2 serial output provides data in a specific serialized format, where data are not sent pixel-by-pixel. Thus, a "deserialization" process is needed. To get the complete counter pixel data, it is necessary to read 10 rows in case of counter A and B, or 4 rows for counter C and D.

Pixel data are available after reading all relevant counters (depending on the used detector mode). Since Timepix2 uses LFSR (Linear Feedback Shift Register) counters, it is necessary to translate counter values to binary form. This process is called *derandomization* and usually implemented by a look-up table. After these operations (*deserialization* and *derandomization*) we get the complete pixel data. In contrast to other readout systems, Katherine implements these routines directly in the HW during the readout process.

Moreover, *zero pixels suppression* is implemented in the readout system. This means that only pixel hits/events are sent to the control SW. These implemented routines simplify the use of the readout system from a software viewpoint. There is no need to process the low-level serialized and encoded raw data.

Katherine uses a "Timepix3-like" (event-by-event) format for data sending instead of the classical matrix format. Figure 4 shows the concept of the data processing inside the readout system and the data format of the output data. The data of an event (hit pixel) is capsulated to a 6-byte binary string (the figure describes the data format for the ToT10/ToT18 detector mode).

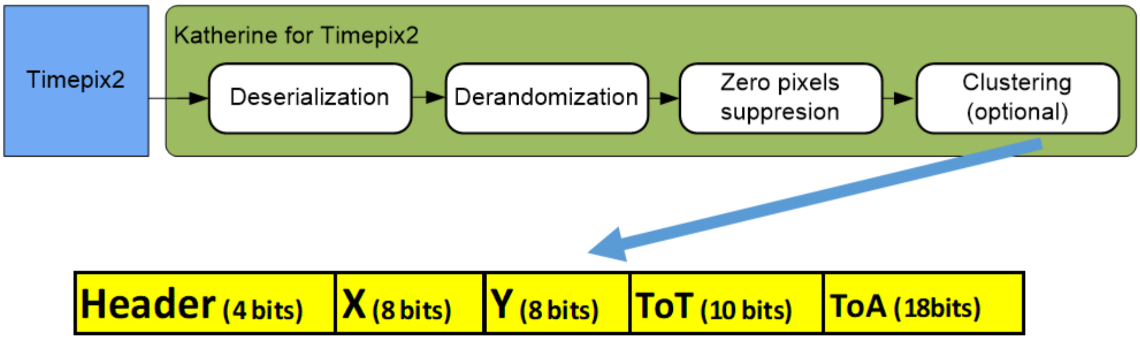

Figure 4. Pixel data processing.

The designed approaches are also valuable when integration of the readout system to a complex measurement chain is considered. The superior system only gets useful data in a decoded form. It is then very easy to plot results or to do more complex evaluations. A *HW support of clustering* (with energy calibration calculation; see section 4.1) is implemented. In this case, Katherine returns clusters corresponding to individual quanta of ionizing radiation interacting in the sensor.

3.5 SW support

A dedicated software tool, called "Burdaman for Timepix2" was designed for the purpose of using the Katherine readout. The layout of this tool is shown in figure 5. It supports control of settings and data acquisition of one or more readout devices connected to a common LAN (Local Area Network). All standard features (chip equalization, threshold scan, internal DAC scans, data acquisition, temperature monitoring, trigger settings, . . .) are available.

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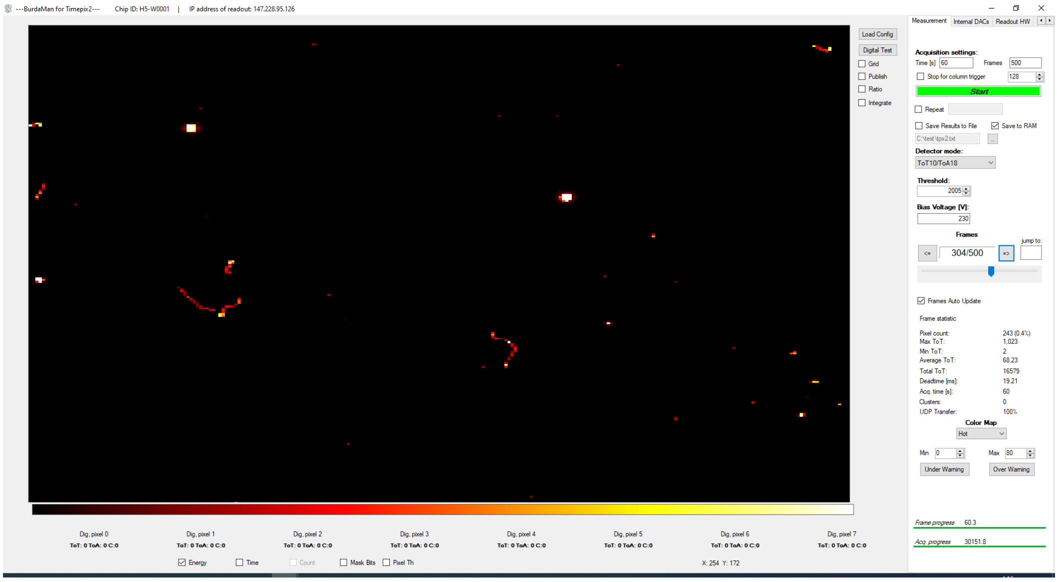

Figure 5. Control SW tool.

The software can also read data from the digital pixels (external signals) (see items below colormap scale in figure 5) and show "real-time" spectra if *HW support of clustering* is enabled.

4 Advanced features and first measurements

4.1 HW support of clustering

Clusters are sets of neighbouring pixels detected at the same moment (within a defined time window). They correspond to a particle interacting in the sensor layer. Typical clusters consists of more than one pixel. In Timepix and Timepix3, clustering is done "on-line" on the measurement PC by the control SW or off-line.

Katherine for Timepix2 implements clustering directly in the HW as an optional feature during the measurement process. The computer (superior readout system) then receives clustered data directly and can use them for high-level data evaluation. The implemented clustering algorithm processes pixel line-by-line as the Timepix2 chip is sending data to the readout device. There is no need to wait until the whole frame is read (stored in the memory). Hence a part of the clustering algorithm is running "in the background" while Timepix2 is still sending data of the current frame.

The readout device keeps and provides these cluster status values:

- *Cluster Time-stamp* — minimal ToA of pixels in the cluster
- *Pixel Size* — number of pixels in the cluster
- *Total ToT Volume* — total sum of ToT values in the cluster (this is valid when *Calibration calculation* is disabled)
- *Total Cluster Energy* — total sum of energies in the cluster (this is valid when *Calibration calculation* is enabled)
- *Centroid X/Y Coordinates* — energy/ToT weighted centroid of the cluster

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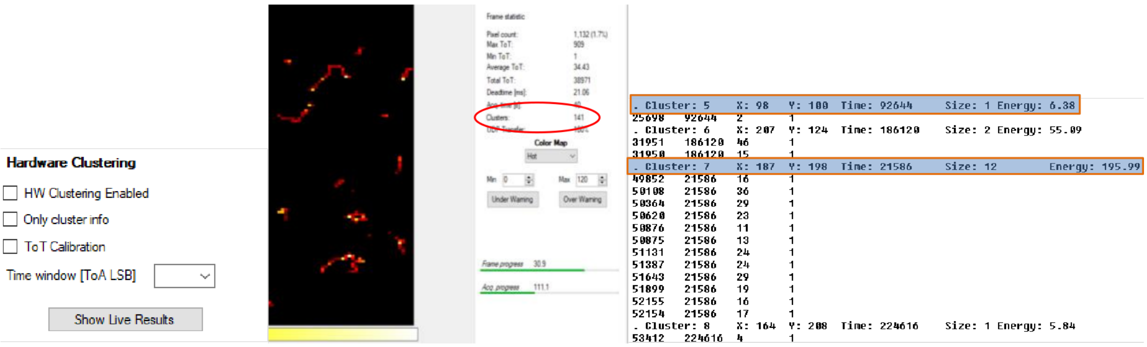
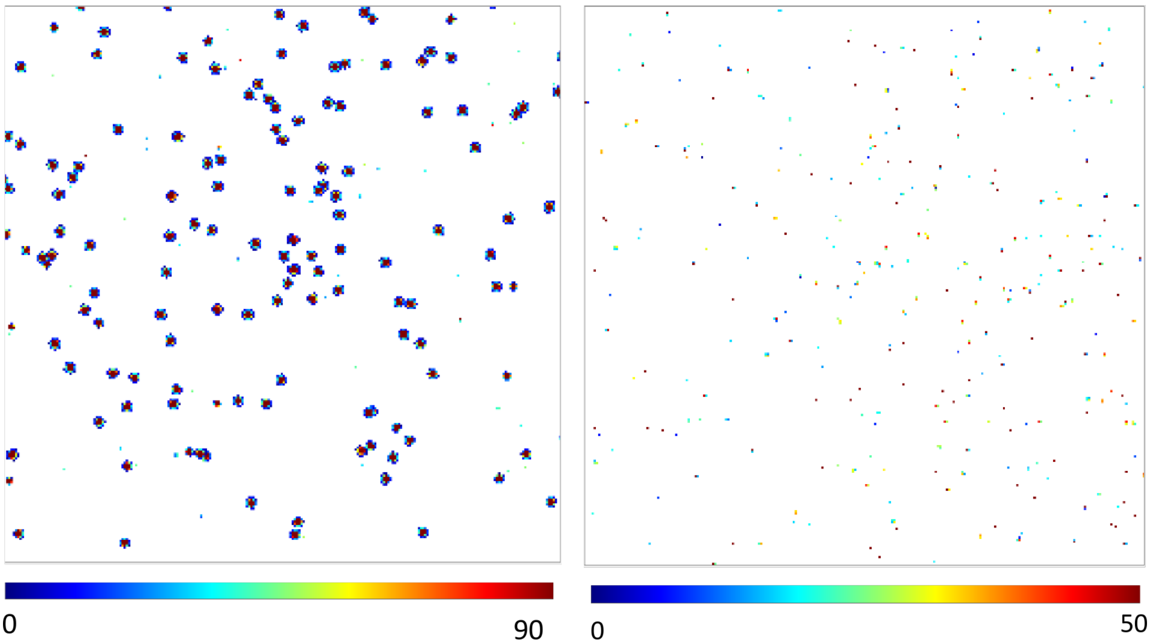


Figure 6. HW clustering settings and demonstration of output file.

HW clustering can be activated from the control SW. If calibration coefficients (parameters of calibration curve for each pixel) are provided, the ToT values can be recalculated to real energy in the readout system immediately.

Figure 7 demonstrates the clustering algorithm's performance. Figure 7-a shows a frame of Timepix2 when irradiated with alphas and gammas from a ^{241}Am source. The frame occupation in this case is $\sim$ 5.2% and 210 clusters were found there. The detector dead-times are 19.25 ms and 26.35 ms if HW clustering disabled and enabled, respectively. In figure 7-b the response is shown to a more active ^{241}Am pure gamma source. Using an acquisition time of 80 ms, the occupation is around 1% and 419 clusters were found. The readout times are 19.14 ms (with HW clustering disabled) and 23.54 ms (with HW clustering enabled).



(a) (b)

Figure 7. Response (ToT values) of Timepix2 with Si-500um to a) 241Am source b) 241Am source producing only gammas.

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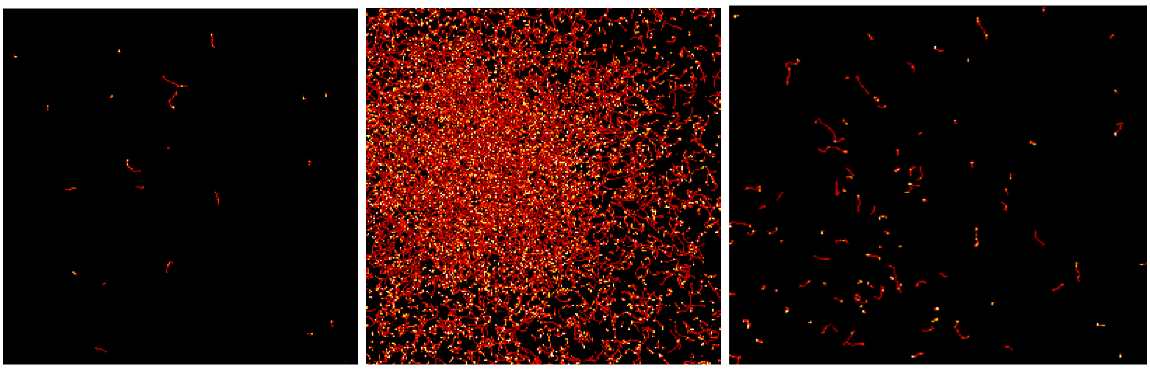
4.2 Matrix Occupation Control

The readout device allows using the *Matrix Occupation Monitor*, which is a native Timepix2 feature. It can inform (through a dedicated signal) a readout system that a defined number of columns is occupied/active and is thus linked only to columns. An active column is a column with at least one pixel hit. If the readout system can process this information from Timepix2, the functionality called *Matrix Occupation Control* can be used. The readout system can then stop the acquisition process when a defined number of columns is activated in the current acquisition. This functionality is important for measurement in environment with changing intensity of the radiation field, where it reduces overexposure and track overlap.

The feature was tested by measuring in an electron and photon field. First, a measurement was done with a ^{90}Sr source at variable distance between source and detector. The acquisition time was set to 80 ms. Figure 8-a shows the response of a detector at a distance of 50 cm. Figure 8-b shows the response at a distance of 3 cm. The distance change simulates different radiation field intensities. At 50 cm, one can see that the detector gets only few clusters. However, at a distance of 3 cm, the obtained frame is overexposed showing massive cluster overlapping. Figure 8-c shows the detector response at distance of 3 cm, but now with *Matrix Occupation Control* enabled (level of 128 columns was used). For the presented frame, the acquisition was stopped after 1.6 ms automatically. In figure 9-a, the dependency of the final acquisition time on distance between detector and source is shown (column levels of 128 and 200 were used). One can see, that shorter distance means shorter acquisition time. Figure 9-b shows the dependence of the number of clusters on distance, where the number of clusters tends to have fixed value for shorter distance. A similar experiment was set up with a ^{241}Am gamma source (see figure 10). The cluster rate (the number clusters per second) is given as a function of the distance. A column level of 200 is used. The plot shows the expected behaviour, namely that the number of clusters is decreasing according to the distance squared.



(a) (b) (c)

Figure 8. Response (ToT) of TImepix2 detector with 500um silicon sensor on ^{90}Sr radiation source. a) distance of 50 cm; fixed 80 ms acq. time. b) distance of 3 cm; fixed 80 ms acq. time. c) distance 3 cm; acq. time automatically reduced to 1.6 ms

However, it is also necessary to note the drawbacks of this approach. Because of the limited depth of the ToA counter, the range of acquisition times is limited. It is a trade-off between time precision and range. For example, when one uses the *Matrix Occupation Control* feature with a

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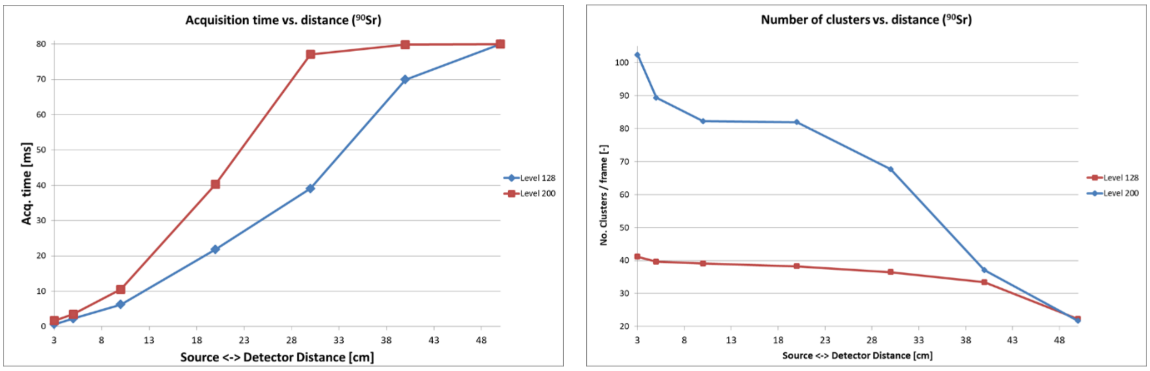

(a) **(b)**

Figure 9. a) Dependence of acquisition time on distance between detector and ^{90}Sr. b) Dependence of the number of clusters on distance between detector and ^{90}Sr.

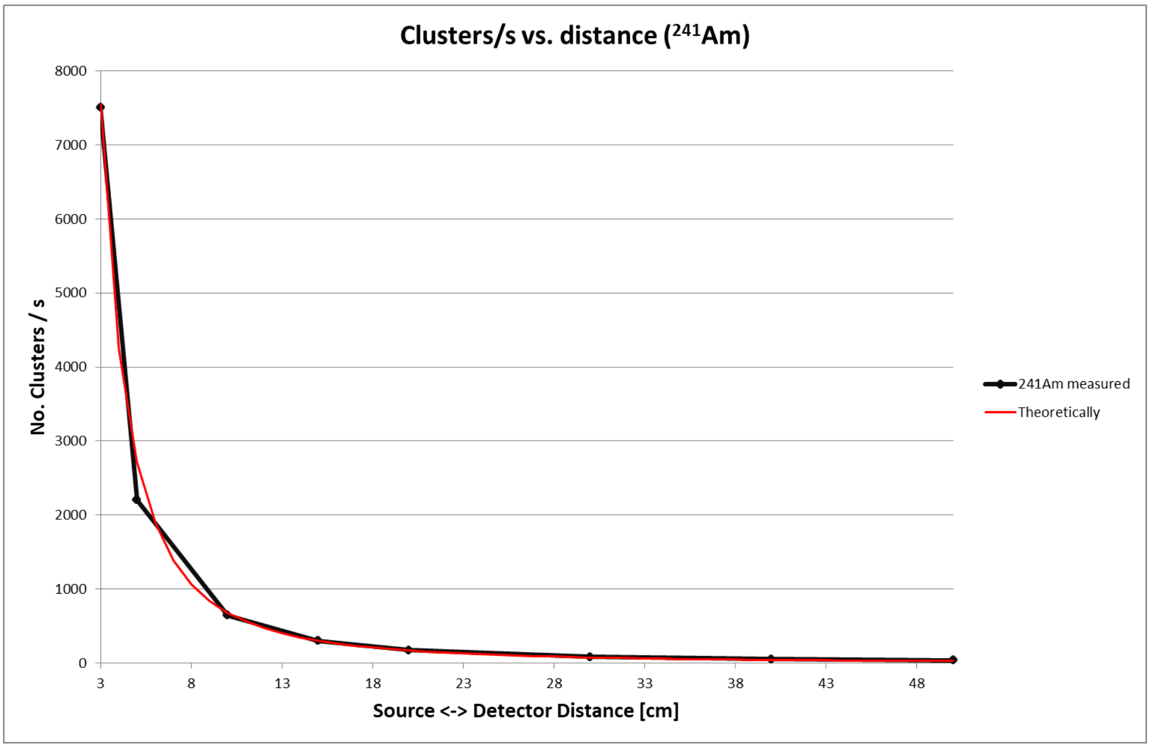

Figure 10. Demonstration of Matrix Occupation Control with ^{241}Am gamma source — dependence of the number of clusters on distance between the detector and the source.

default (time of frame when defined active columns is not achieved) acquisition time of 10 s, the ToA frequency has to be set to low frequency to avoid that the ToA counters overflow. However, when acquisition time is cut to 20 ms, the time resolution of events is still based on the ToA clock frequency set for the 10 s acquisition time. Moreover, shorter frames change the ratio of acquisition and readout time. The shorter the frames, the higher the share of dead/readout time of the detector in the total measurement time. Figure 11 shows this dependence for the measurement with the

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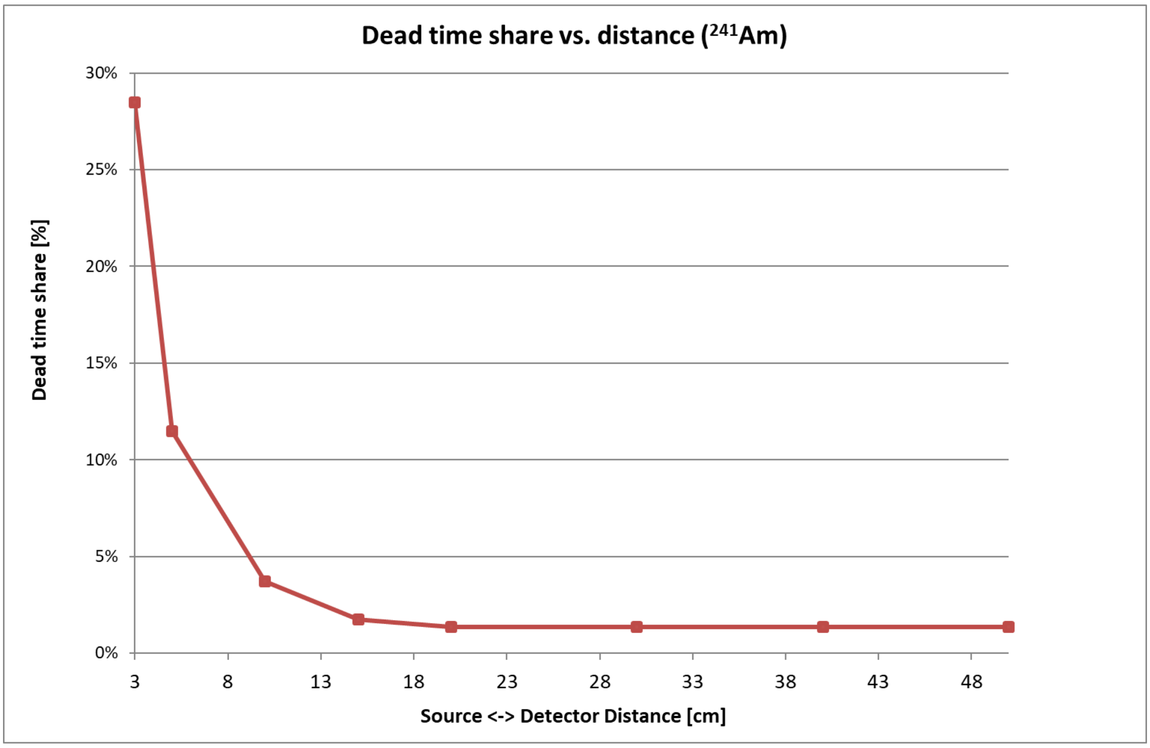

Figure 11. Measurement with ^{241}Am gamma source — dependence of deadtime share on distance.

^{241}Am gamma source. For greater distance the deadtime could be considered as marginal. When detector is closer to source, the deadtime approaches approx. 30% of total measurement time.

5 Threshold calibration and per-pixel ToT calibration

The threshold calibration is a process that makes it possible to find the relationship between the THL DAC codes and the real energy value of threshold. In the so-called THL scan procedure the sensor is irradiated with XRF (X-Ray Fluorescence) of known energy. At the beginning, the threshold is set to a value that should be safely higher than the expected fluorescence energy. Then, the THL value is gradually decreased. Once the THL value reaches the energy of the fluorescence line, the increase in the count-rate is pronounced. By determining the peak positions in the derived spectrum (dN/dTHL), the linearity of THL with energy can be demonstrated (see figure 12-a). The extrapolation of the fit curve towards the lowest possible THL value at which no noise is present gives $\mathrm{THL_{low}} = 4.8\,\mathrm{keV}$. This energy is used for energy calibration as the energy at which a ToT of 0 is measured.

In the per-pixel ToT calibration, each pixel of the matrix is irradiated by characteristic X-Ray fluorescence line photons from different elements (indium, zirconium, copper, nickel, titanium etc.) and a radioactive ^{241}Am source. This results in the energy versus ToT curve for each pixel. From this curve, the value of energy can be derived from the ToT values in each pixel [11] — see figure 12-b. The ^{241}Am spectrum after calibration is presented in figure 13-a. The dominant peak is at a mean energy of 59.78 keV and has a σ of 1.50 keV, which is consistent with the results obtained

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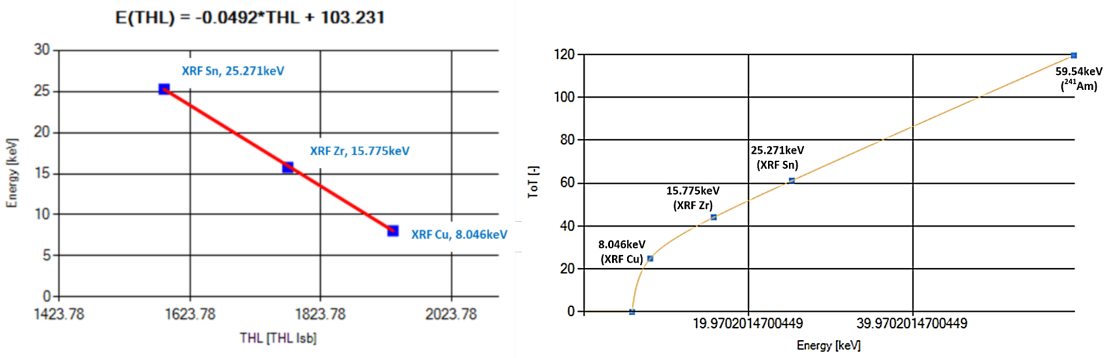

(a) **(b)**

Figure 12. a) Threshold calibration curve. b) Energy vs. ToT calibration curve for individual pixel.

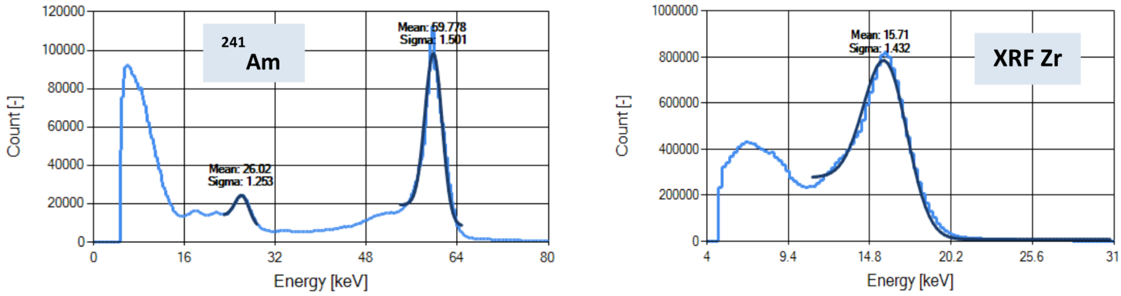

Figure 13. XRF energy spectra measured with Timepix2: the ^{241}Am spectrum and XRF Zirconium.

by Timepix3 published in [12]. Figure 13-a shows calibrated spectrum for XRF with Zirconium with peak at a mean value of 15.71 keV.

6 Test beam measurements

6.1 Iron ion beam

First measurements with the newly designed readout device were performed at the GSI beam facilities with iron ions in the energy range from 250 MeV/A up to 1 GeV/A. The aim of the measurement was to verify the functionality of the Katherine readout and Timepix2 itself. Particular attention is paid to the adaptive gain. A Timepix2 with a 500 µm thick silicon sensor was used at a bias voltage of 200 V. The lowest possible threshold was 6.5 keV. The detector was placed on a rotation stage, allowing to change the angle of impact remotely. The ToT14/ToT14 mode and adaptive gain of the analog front-end were used. Detector calibration was done as described in section 5.

Figure 14 shows response of Timepix2 to the iron ions for the impact angles 0°, 30° and 60° with respect to sensor normal. At an angle of 60° one can see elongated clusters accompanied by delta-rays. Pixels inside the cluster core are saturated.

The energy spectrum and the histogram of the cluster heights (maximal energy measured in a single pixel of the cluster) are shown in figure 15 for a beam energy of 1GeV/A irradiating the

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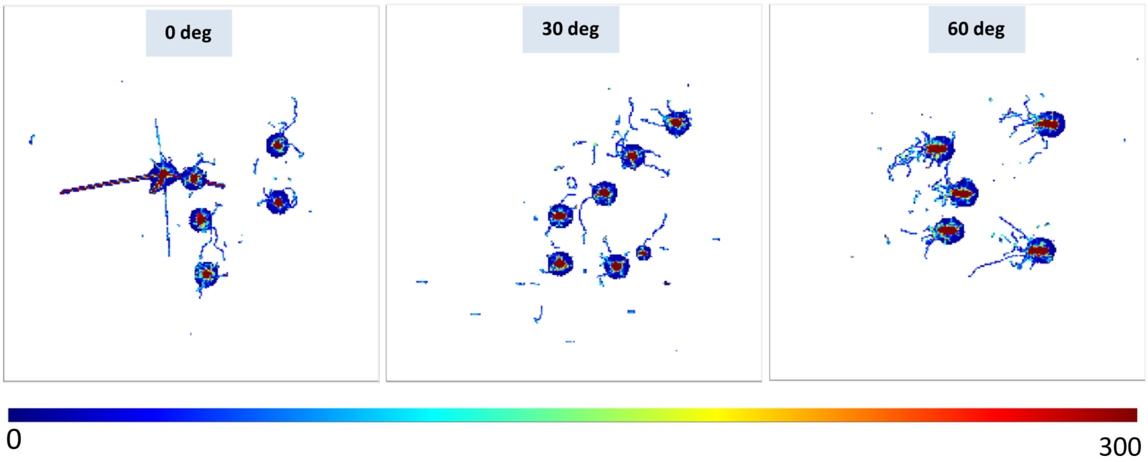

Figure 14. Energy (ToT) response of Timepix2 (with 500 µm thick silicon sensor) in an iron ion beam.

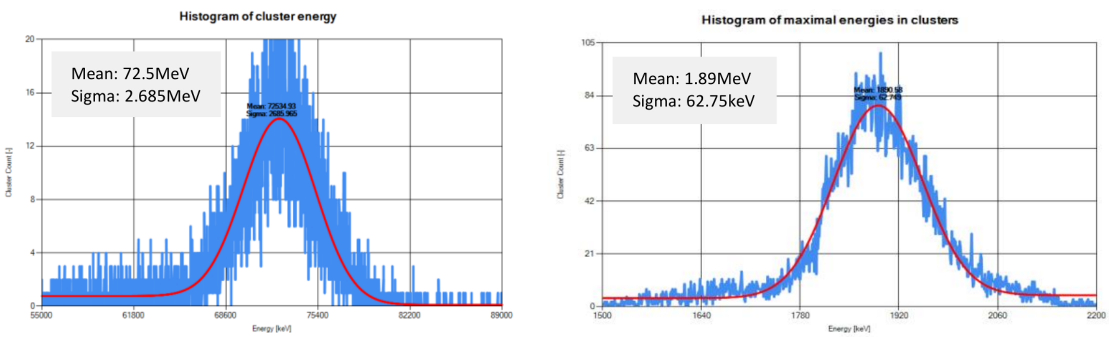

Figure 15. Evaluated data from measurement with 1GeV/c with 60° — histogram of cluster energy (energy spectrum) and histogram of maximal energies in the clustres (height values)

sensor at 60°. The deposited energy has a mean value of 72.5 MeV with a σ of 2.7 MeV. From the histogram of the heights the maximal energy a pixel can measure was found to be 1.9 MeV.

6.2 Electron beam

A second measurement was done in an electron beam with an energy of 5GeV/c at DESY. In comparison to the previous ion test beam, electrons deposit low energies in the pixels. Therefore, adaptive gain was not active, so that the lowest possible threshold level was 4.8 keV. The detector mode ToT10/ToA18 was used. The bias voltage was set at 230V. Measurements were performed for different angles. Figure 16 shows the response at 0°, 30° and 60°. One can see the increasing cluster size for higher angles (with respect to sensor normal).

The energy spectra for irradiation at angles 0° and 60° are shown in figure 17. The Landau shaped energy peaks have their most probable values at 148 keV (for 0°) and 304 keV (for 60°).

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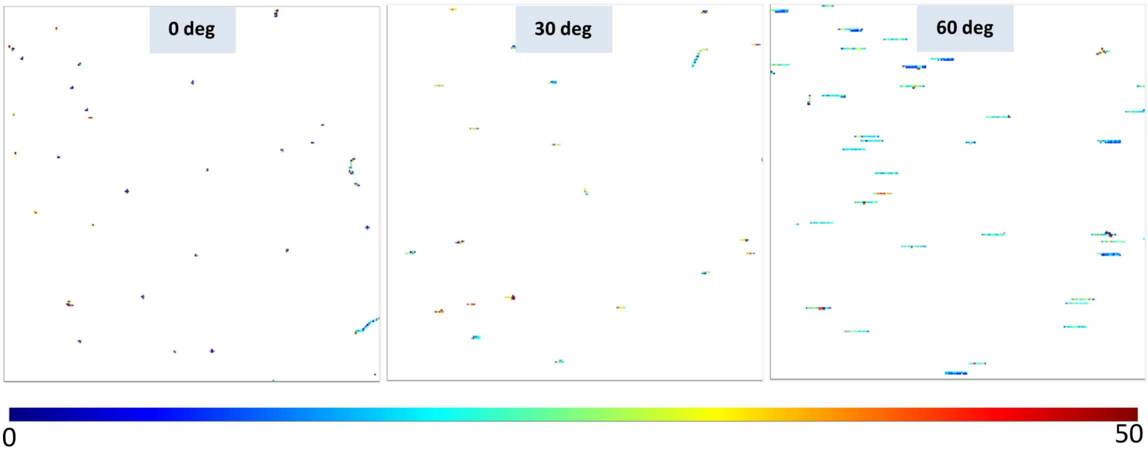

Figure 16. Energy response (ToT) of Timepix2 (with 500 µm thick silicon sensor) to electron beam with energy 5GeV/C for 0°, 30° and 60° (with respsent to sensor normal).

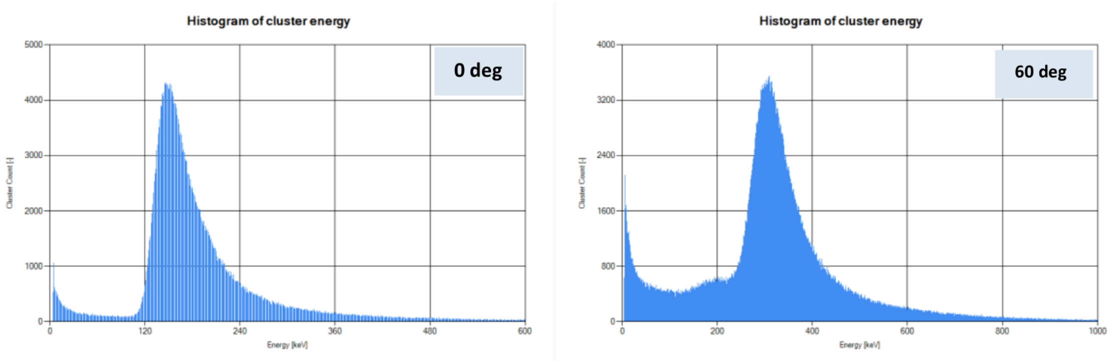

Figure 17. Energy spectra of measured data for angles 0° and 60°.

7 Conclusion

The newly designed readout system called *Ethernet Embedded Readout Interface for Timepix2 (Katherine readout for Timepix2)* using Gigabit Ethernet interface was introduced. Katherine supports all modes of Timepix2 and implements some advanced features, such as the *HW support of clustering* or a *Matrix Occupation Control*. The device can be integrated to existing measurement setups by means of GPIO ports (using, e.g. trigger input and output signals for synchronization purpose). The maximal distance between the readout and the control computer is given by the specification of the Ethernet. It is up to 100 m. Deserialization and derandomization of Timepix2 data is implemented directly in hardware to simplify control SW design.

We show the energy calibration methodology and find an energy resolution of 1.5 keV at the 60 keV gamma line of ^{241}Am. Moreover, measurements were carried out on in iron beams at the GSI in Darmstadt and in an electron beam at DESY. It was found that the maximal per-pixel energy measurement saturated at 1.9 MeV.

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