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Single layer Compton camera based on Timepix3 technology

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Abstract: The Compton camera concept is based on reconstruction of recorded Compton scattering events for incoming gamma rays. The camera usually consist of two or more position (2D) and energy sensitive detectors. The Compton scattering of the incoming gamma ray recoiling an electron occurs in the first detector. The position and energy of recoiled electron is recorded. The scattered gamma ray continues to the next detector where it is absorbed and its energy and position is recorded too. Knowing both positions and energies the scattering angle can be calculated using the Compton equation. By detecting multiple events the position and image of the gamma source can be reconstructed. The Compton scattering and absorption of the scattered gamma can occur within a single detector too. Such events can be used for reconstruction only if the detector provides information on 3D positions of both events along with their energies. The Timepix3, a hybrid single photon counting pixel detector, is perfect device for such measurements. It can record time-of-arrival (ToA) and energy of incident gamma rays simultaneously in each pixel. In this article we present a concept of miniaturized single layer Compton camera consisting of a single Timepix3 detector with a thick 2 mm CdTe sensor. Thanks to Timepix3 high resolution ToA measurement (1.6 ns), it is possible to measure the drift time of charge transport within the sensor and thus determine the vertical position (depth) of both interactions. By knowing both energy and position of the events in the sensor, we can reconstruct the image of the gamma source. The angular resolution of the presented Compton camera depends on the detected energy and reaches the order of a few degrees.

Keywords: Compton imaging; Gamma camera, SPECT, PET PET/CT, coronary CT angiography (CTA); Particle detectors

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Contents

1 Introduction

The Compton camera is an alternative approach to collimator based Gamma camera for imaging of the distribution of sources of gamma radiation in space. Gamma cameras are nowadays used for many applications from localization of radioactive sources in an environment to functional medical imaging applications such as scintigraphy or single-photon emission tomography (SPECT). The Gamma (Anger) camera consists of a thick collimator and sensitive detector, usually scintillator combined with photo multiplier tubes (PMT). This arrangement has however many disadvantages: large and heavy collimator, narrow field of view, limited detection efficiency, etc.

The concept of Compton camera, does not require any collimator and therefore can offer better detection sensitivity and broader field of view. Especially in application such as SPECT, this could improve the quality of images and help reducing the radiation exposure of the patients.

The Timepix3 Compton camera consisting of two Timepix3 [1] detectors was already presented [2]. In this contribution we present a novel approach to Compton camera: a miniaturized device using only one single Timepix3 detector.

1.1 Hybrid pixel detector Timepix3

Timepix3 is a hybrid single photon counting pixel detector. It is an event based readout chip (every hit pixel is immediately sent to a readout) and can record time-of-arrival (ToA) and Time-over-threshold (energy) of the incident gamma simultaneously in each pixel. The chip has a pixel matrix of 256×256 pixels with 55 um pitch and offers high energy resolution (σ = 1 keV at 60 keV, 7 keV at 356 keV) as well as time resolution (1.6 ns). In the event by event mode, it can record and transfer to readout 80 Mhit/s/cm^2. The Timepix3 readout chip can be combined with different sensor materials such as Si, CdTe or CZT.

1.2 MiniPIX TPX3 — miniaturized Timepix3 readout device

MiniPIX TPX3 is a miniaturized, portable and flexible readout system for Timepix3 detectors with USB 2.0 connectivity (see figure 1). It has dimensions of a USB thumb drive and can be powered from the USB port. The maximal hit rate is 2.3 million hits/s/cm^2 in event by event mode. It can be equipped with different sensors such as Si, CdTe, CZT and can supply bias voltage from −500 to +300 V. Thanks to its small dimension, low weight and advanced features of Timepix3 chip, it in can be used in many new applications such as spectral X-ray imaging, XRD, Gamma or Compton camera.

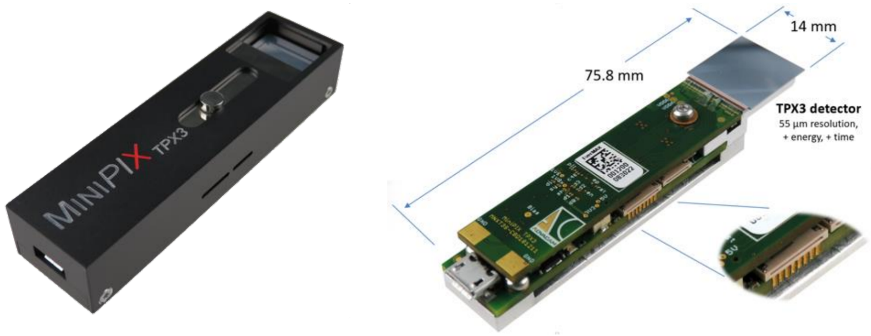

Figure 1. Photo of the MiniPIX TPX3 (left) and photo of the PCB inside the MiniPIX TPX3 with dimensions.

2 Principle and method

2.1 Compton camera

The Compton camera concept is based on reconstruction of recorded Compton scattering events of incoming gamma rays. Usually, two or more detectors (layers) are used for construction of the Compton camera. The scattering of primary gamma ray occurs in the first detector (called scattering detector — usually thin) recording position and energy of the recoiled electron. The scattered gamma quantum continues towards the second detector (called absorption detector — usually thick and high Z) where it is absorbed and its energy and position recorded. Then, using Compton scattering equation it is possible to determine the scattering angle and estimate possible directions of the original gamma ray as a surface of a cone. When the Compton camera records number of such events the location and shape of the gamma source can be reconstructed.

The Compton scattering of primary gamma and the absorption of both recoiled electron and scattered gamma can often occur only within a single detector. By knowing the position and energy of both events, the same reconstruction principles as in the case of the two detectors can be applied and the location of the gamma source determined.

2.2 Depth determination

The lateral 2D position of the event can be obtained directly from the Timepix3 chip (hit pixels location), but the vertical position (depth) has to be determined different way. The Timepix3 can measure ToA very precisely with a resolution of 1.6 ns. This ability can be used to measure the

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difference in charge collection time of different events (or different parts of the same event) in the CdTe sensor. Since the CdTe sensor is semi-insulating with homogenous electric field inside, the drift speed during charge collection is constant. The charge collection time is proportional to the depth of the interaction. Then the difference between times of charge collection for two coincident events can be directly translated to their depth distance.

In order to calibrate the charge collection time to depth, a measurement with many cosmic muons was performed. The cosmic muons have straight paths penetrating the whole thickness of the sensor slantwise. The time recorded by pixels along the muon track show nice linear dependency proving constant drift speed of charge being collected. By measuring the time difference between the pixels at both ends of the measured muon track the charge collection time for whole sensor thickness can be determined (see figure 2). For 2 mm thick CdTe sensor the charge collection time is about 86 ns. From this knowledge the time difference between two coincidence events can be than converted to their relative vertical distance.

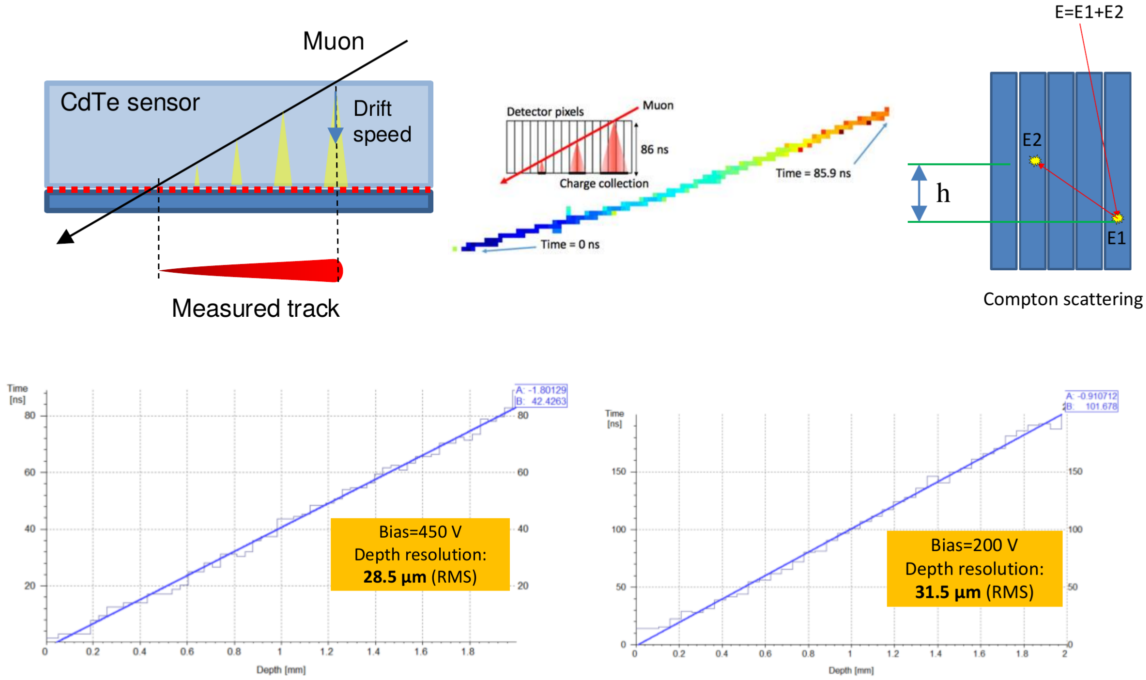

Figure 2. Illustration of a cosmic muon interaction in the CdTe sensor. Muon penetrates whole thickness of the sensor from top to bottom, each hit pixel has different charge collection time depending on the depth of interaction (left). Example of a measured cosmic muon (middle). Scheme of the Compton scattering in the sensor (right). The two recorded time profiles recorded along the tracks of the two muons are shown in the charts at bottom for two different bias voltages of 450 V (left) and 200 V right showing about the same depth resolution of about 30 µm.

2.3 Energy measurement

The Timepix3 measures charge collected in each pixel as Time-over-threshold (ToT) values. These values needs to be converted to energy by using the energy calibration method described in [3]. From the measured energy of the incident particles, an energy spectrum can be obtained. The

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figure 2 shows an example of energy spectrum for ^{152}Eu and ^{133}Ba gamma sources. The photo peaks for both sources can be clearly seen. However, the spectrum also contain signals from internal X-ray fluorescence of CdTe sensor, created by the excitation of the Cd and Te atoms in the sensor by the incident gamma resulting in the emission of the XRF photon. The emitted XRF photon is detected in another pixel of the detector as separate event and the energy of the original event is decreased. This effect can be corrected by looking for such coincidence events and reconstructing them into the original primary event as described in [4] and [5].

The energy spectrum also contains signals from the internal Compton scattering — the incident gamma scatters in the sensor, recoils an electron and changes direction. Both recoiled electron and the scattered gamma are recorded by the detector. By looking for coincidence events that fulfills the Compton and Klein-Nishina formula, these Compton scattering events can be found. If these events are combined into one and assigned to the correct position chosen by the more likely scattering scenario, the effect in the energy spectrum is that the photo peak is improved and the Compton signal reduced (see figure 3 right). This shows that the internal Compton scattering events are correctly detected.

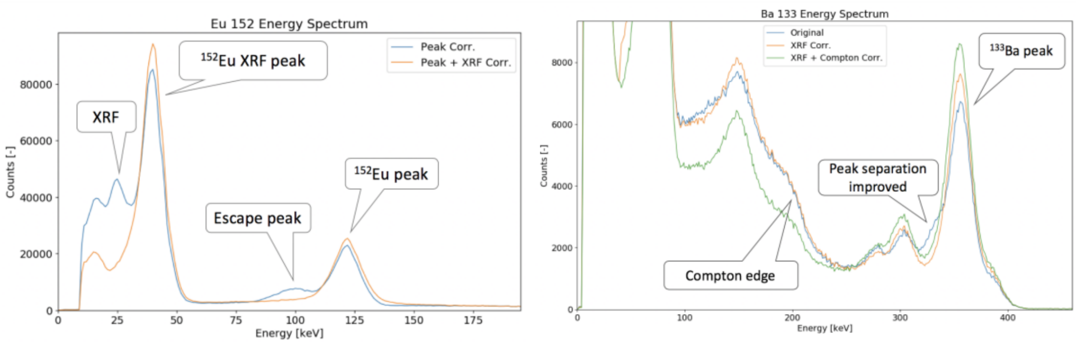

Figure 3. Energy spectrum of Eu-152 with XRF correction (left). Energy spectrum of Ba-133 with XRF and internal Compton scattering effects corrected (right).

2.4 Reconstruction method

The measured Timepix3 pixel data are calibrated with the energy calibration [3] and corrected for time-walk effect [6]. The pixels are analyzed and pixels close to each other belonging to a single events grouped into clusters. Then, the clusters having a small difference in timestamp (falling into a time coincidence window) are grouped together into coincidence groups. The groups are analyzed for internal CdTe XRF events and the primary events reconstructed. Furthermore, for simplicity, only the groups containing two clusters are selected for next processing steps.

The energies of two events in each coincidence groups are entered into the Compton equation (see figure 4) to calculate the scattering angle and the charge collection time difference of the two events is converted to depth difference. From the scattering angle and position of the events in the detector a cone can be constructed (see figure 4). The possible position of the gamma source lies on the surface of this cone. Multiple coincidence events are processed and their cones constructed. The intersection of these cones represents the location of the gamma source. For visualization, a projection plane is placed on top of the detector showing conic curves created by intersections of

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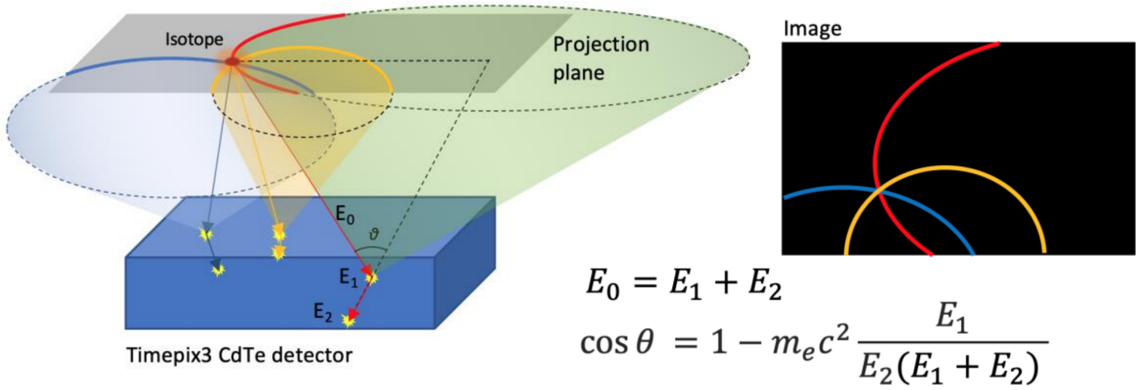

Figure 4. Scheme of the reconstruction of the position of the gamma source (left). Reconstructed image schema (right). Calculation of the scattering angle from Compton equation (bottom).

cones with this plane. By plotting higher number of these curves a back-projected image of the source can be obtained (see figure 4).

3 Measurement and results

The functionality and evaluate the performance of the Compton camera, several measurements were performed with different gamma sources (^{133}Ba, ^{131}I, ^{137}Cs, ^{22}Na) positioned at different distances. The goal of these tests was to verify the principle of the single layer Timepix3 Compton camera. Therefore only a simple back projection was used for reconstruction of the gamma sources. In the future investigations different filtering techniques can be used to improve the image quality.

3.1 Measurement with ^{133}Ba sources

The first measurement was performed with ^{133}Ba gamma source dissolved in silicone. Four small pieces of about 3×3 mm were cut from the ^{133}Ba and placed on top of the detector in the distance of 2 cm. The pieces were placed in the corners of a square with side length of about 2 cm. Figure 5 shows the schema of the setup. The measured data were processed and the image reconstructed from a projection plane placed 2 cm above the detector (see figure 5). All four sources can be clearly distinguished. Because the pieces were not cut precisely and were differing in size and volume, the intensity of each piece was also different. That explains the different intensity of the pieces in the reconstructed image.

3.2 Measurement with different gamma sources — Na, I, Cs

The aim of the second measurement was to evaluate the performance of the Compton camera for different gamma sources with different energies measured at the same time. Three gamma sources (see figure 6 middle) were chosen and placed above the detector in the distance of about 7 cm: ^{22}Na (511 keV), ^{131}I (364 keV) and ^{137}Cs (662 keV). From the measured data, an energy spectrum was created that clearly shows contributions of all three sources (see figure 6 left). The data were processed and the image reconstructed (see figure 6 right). All three sources were again clearly recognized.

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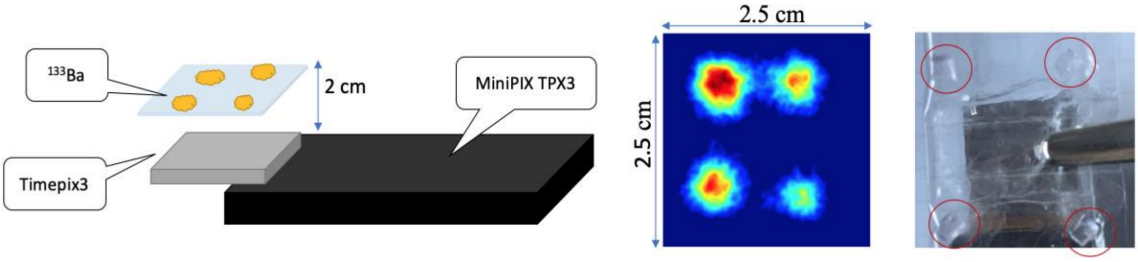

Figure 5. Schema of the measurement setup with ^{133}Ba source (left). Reconstructed image (middle). Photo of the sources above the detector (right).

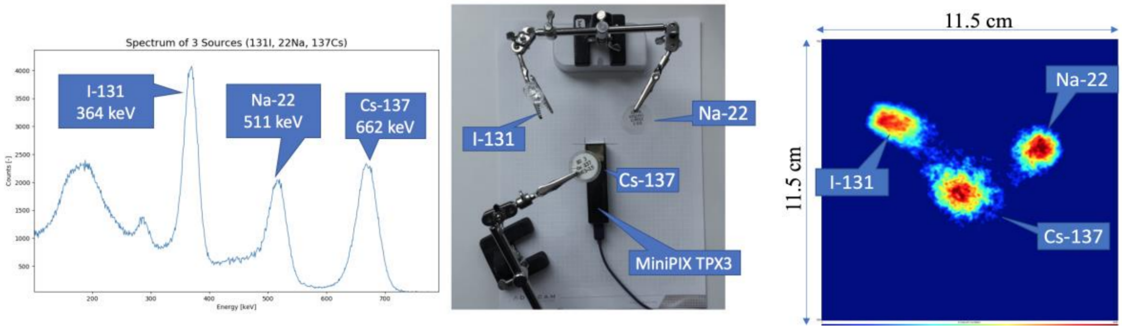

Figure 6. Energy spectrum of the measurement with 3 different gamma sources (left). Photo of the measurement setup (middle). Reconstructed image (right).

Since Timepix3 can measure precisely energy and in the energy spectrum the 3 sources are clearly distinguishable, it should be possible to recognize different gamma sources by its energy. Therefore, multiple energy windows with width of 50 keV covering energies from 0 to 750 keV (see figure 7 right) were applied on the measured data to filter out events with energies outside of the window. For each such window an image was reconstructed (see figure 7 left). The images shows that the 3 gamma sources were located correctly in the corresponding energy windows and that in each such window only a single source is visible. The energy window 250–300 keV also shows a weak signal — this corresponds to the second peak of ^{131}I (284 keV) that has only 7% probability. These results demonstrates that the single layer Compton camera is not only capable of locating gamma sources but also distinguishing different isotopes based on their energy.

3.3 Measurement with ^{131}I in an environment

All the previous measurements were performed with the gamma sources placed in close distance of the detector. The goal of the last measurement was to evaluate the performance of the camera for more distant sources placed in an environment. In the experiment, 3 small flasks with ^{131}I gamma source solution were placed in a room at different location in the distance of 3 m from the detector (see figure 8). The measured data were reconstructed and image generated. The sources were localized at correct positions in the room. For the visualization, a photo was taken from the position of the detector and the reconstructed image was combined with the photo keeping the correct proportions (see figure 8).

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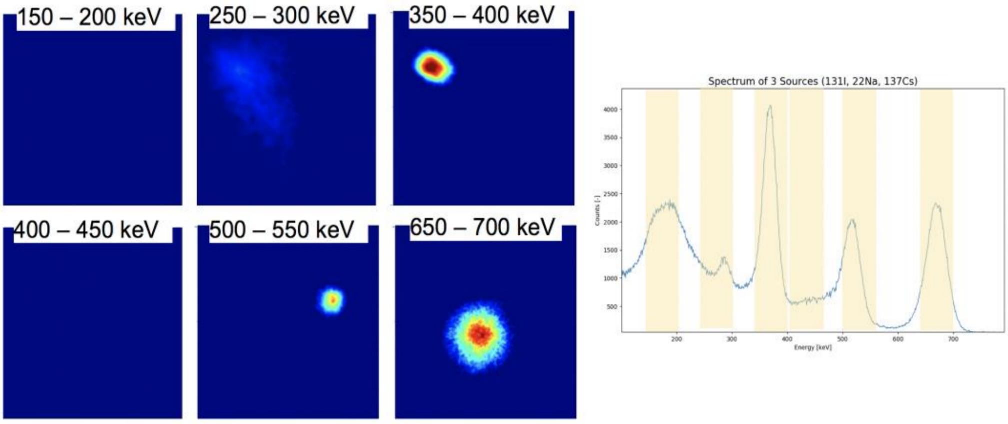

Figure 7. Reconstructed images for different energy windows (left). Energy spectrum with highlighted energy windows (right).

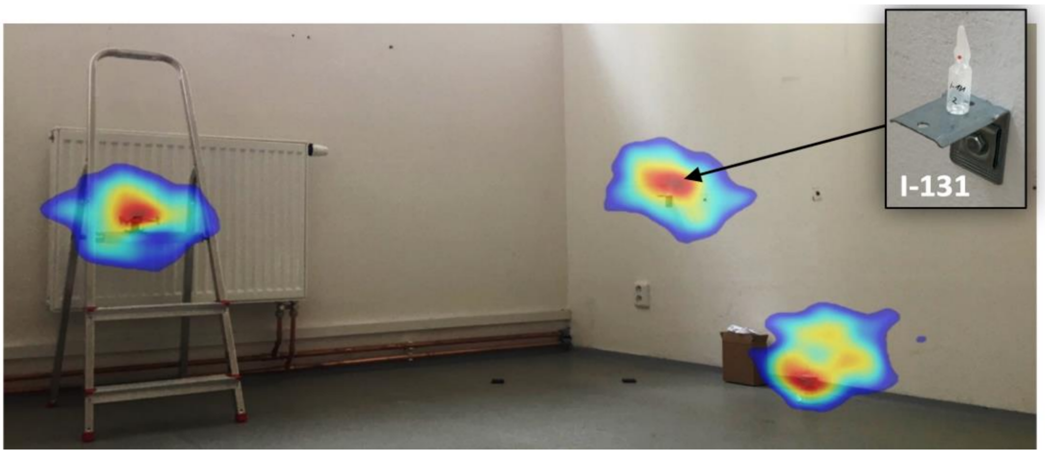

Figure 8. Photo of a room from the position of the detector combined with the reconstructed image. Photo of the flask with a solution of ^{131}I gamma source (inset).

4 Conclusion and future works

In the previous work [2] we have shown that Timepix3 can be used for designing a multilayer Compton camera. In this work we have explored a possibility to improve on the previous design by using the precise Timepix3 time measurement to measure the time of charge collection in the sensors. Thanks to the measured charge collection time it is possible to obtain the position of the interacting event within the sensor. Therefore it is possible to construct a single layer Compton camera consisting of single Timepix3 detector with CdTe sensor. Combining the Timepix3 detector with a miniaturized MiniPIX TPX3 readout system it is possible to construct a very compact and light Compton camera.

The performance of our Compton camera was demonstrated on several measurements with different gamma sources. The measurements have shown that it is possible to distinguish gamma sources at different locations in close and further distance from the detector. The Timepix3 Compton camera can not only localize the sources but also differentiate their type by their energy.

The goal of this preliminary study was to explore the feasibility of using single Timepix3 detector for Compton camera. Therefore all the reconstructed image were created by simple back projection. The image quality can be improved by further image processing techniques such as filtering and deconvolution and will be explored in future works

Acknowledgments

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