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Timepix4 calibration and energy resolution evaluation with fluorescence photons

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Summary. — The Timepix4 is a pixelated and hybrid detection system developed by the Medipix4 Collaboration at CERN. It consist of a 448×512 pixel reading matrix which can be bump-bonded to a semiconductor sensor with square pixels at a pitch of 55 μm. The Timepix4's ability to isolate individual particles and measure the energy they release in the sensor makes it a valuable tool for spectral imaging, capable of acquiring continuous energy spectrum images even in the presence of a high rate of incident events. This article presents a calibration method for the Timepix4 and evaluates the device's energy resolution using fluorescence photons produced with a micro-focus X-ray tube as a radiation source.

1. – Introduction

The Timepix4 [1] is a pixelated and hybrid detection system developed at CERN by the Medipix4 Collaboration. It features a 448×512 pixels reading matrix connected, via bump-bonding, to a semiconductor sensor with square pixels of 55 μm pitch. The device can be optimized for various applications by using different sensor materials and thicknesses. When radiation interacts with the sensor, it releases energy, causing ionization of the material and generating electron-hole pairs. An electric field then directs the resulting charge to the collection electrodes, where the signal is finally transmitted to the readout matrix. The charge-sharing effect is possible and leads to the charge distribution among a cluster of adjacent pixels. The pixels of the readout matrix are composed of an analog front-end [2] and a digital part. The analog front end comprises a charge amplifier with three gain levels and a discriminator. The discriminator has a threshold that can be adjusted at the pixel level via a local DAC, and allows to equalize the thresholds of all the pixels. When the discriminator output is above the threshold, the signal is digitized and several pieces of information, related to timing, spatial and charge quantities, are stored. The Timepix4 offers two operating modes: frame-based and data-driven. In the data-driven mode, output packet are generated only when a piel is hit, providing information on the Time of Arrival (ToA) of the events, acquired with a time bin of 195 ps [3], and on the Time Over Threshold (ToT) of the signal. After the calibration of the detection system, ToT can be used to measure the energy deposition of incident radiation in each pixel. Information from each recorded hit is encoded in 64-bit packets. The matrix readout can be achieved through up to 16 fast links, each operating at a maximum speed of 10 Gbps. In data-driven mode, the Timepix4 can process up to $3.6 \cdot 10^6$ events mm^{-2} s^{-1}. By using ToT and ToA information, events can be clustered, allowing for the isolation of individual particles incident on the sensor and precise measurement of their energy. The capability to acquire images with a continuous energy spectrum, even in the presence of a high rate of incident particles, places Timepix4 as an excellent tool for spectral imaging [4]. A comprehensive device characterization under various usage conditions is essential to assess its applicability range. This article introduces a calibration method for the Timepix4 and assesses its energy resolution using fluorescence photons produced with a micro-focus X-ray tube as a radiation source [5].

2. – Measurement set-up

2˙1. *The detector*. – The measurements were carried out using a Timepix4 assembly bonded to a 300 μm thick Si sensor, as depicted in fig. 1 (left). The discriminator threshold was set at 1000 electrons (corresponding to 3.63 eV), and the acquisitions were performed in data-driven mode. A fan was employed to maintain a stable temperature of the detection system. The connection between the detector and the computer utilized the SPIDR4 readout peripheral produced by Nikhef. Timepix4 configuration was made through slow control with a 1 Gbps Ethernet cable. For the data readout, 2 of the 16 fast links, each operating at 2.56 Gbps, were employed. A custom developed C++ software managed both set-up configuration and data acquisition.

2˙2. *The source*. – To calibrate the Timepix4, a high number of events at various energies was generated. This was accomplished by employing a micro-focus X-ray tube from Hamamatsu to produce fluorescence photons on different metal foils. The foils were placed at about a 40-degree angle to the direction of radiation propagation. The detector was situated outside the primary beamline to capture fluorescence photons exclusively. By varying the material of the samples, an energy range between 6.40 and 25.19 keV was explored. The used materials and the corresponding energies of the $K\alpha$ emissions are detailed in table I. To ensure an ample dataset, the acquisition time and X-ray tube voltage were adjusted to acquire at least 1000 events for each pixel at every energy. The experimental setup is shown in fig. 1 (right).

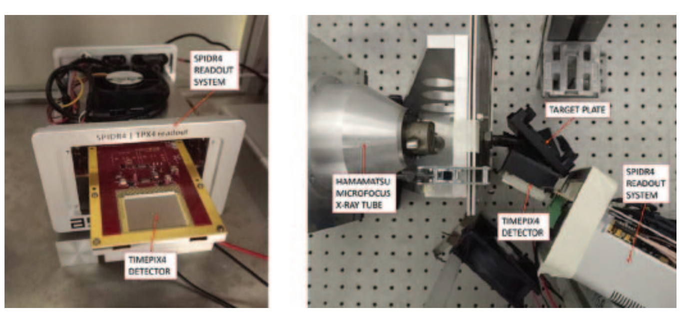

Fig. 1. – Timepix4 connected to SPIDR4 (left); measurements set-up: the plate is placed along the beam line, the detector, protected by a black case, is placed close to the sample (right).

TABLE I. – *Materials and energies of the $K\alpha$ emissions* [6].

Material	$K\alpha$ energy [keV]	Material	$K\alpha$ energy [keV]	Material	$K\alpha$ energy [keV]
Fe	6.40	Cu	8.04	Pd	21.12
Co	6.92	Zr	15.72	Sn	25.19
Ni	7.47	Mo	17.44		

3. – Data analysis

To calibrate the Timepix4, a cluster analysis on the acquired hits was performed, selecting only events with a cluster size of 1. For each pixel and for every sampled energy, the histograms of the ToT of the acquired events were generated. As illustrated in fig. 2, Gaussian fits were performed on the resulting spectra to extract the average ToT values. Finally, a ToT *vs.* energy plot was created for each pixel, and a non linear calibration function

$$ToT = a \cdot E + b - \frac{c}{E - t} \qquad (1)$$

was fitted on the obtained points, as shown in fig. 2 (left). The calibration procedure provides, for each detector pixel, the parameters a, b, c, and t, enabling the conversion of the acquired ToT values into energies. Further acquisitions with the Timepix4 were made to evaluate the calibration results. In particular a dataset of about $3{\cdot}10^5$ events was obtained for various materials (Cu, Rb, Mo, Ag, Ba).

4. – Results: Timepix4 energy response

A cluster analysis was performed on the dataset acquired to evaluate the energy response of the calibrated detector, selecting only the events with a cluster size of 1. The ToT of these events was converted into energy using the calibration parameters. Gaussian fits were performed on the energy spectra to reconstruct the photopeak's position and width and to evaluate the detector's energy resolution. The comprehensive results are summarized in table II. Figure 3 shows some examples of the analyzed spectra.

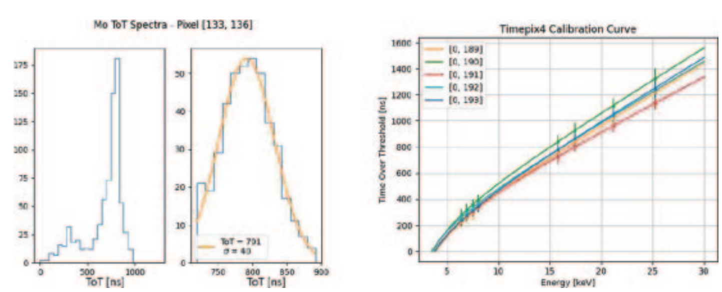

Fig. 2. – Mo ToT spectra acquired by one of the Timepix4 pixels, with a Gaussian fit on the photopeak (left); calibration curves for some Timepix4 pixels (right).

TABLE II. – *Calibration results and energy resolution evaluation.*

Materials	Kα energies [keV]	$E_{measured}$ [keV]	$\sigma_{measured}$ [keV]	FWHM/E
Cu	8.04	8.02	0.74	0.22
Rb	13.37	13.59	0.66	0.15
Mo	17.44	17.55	0.94	0.13
Ag	22.10	22.33	1.01	0.11
Ba	32.06	32.28	1.18	0.09

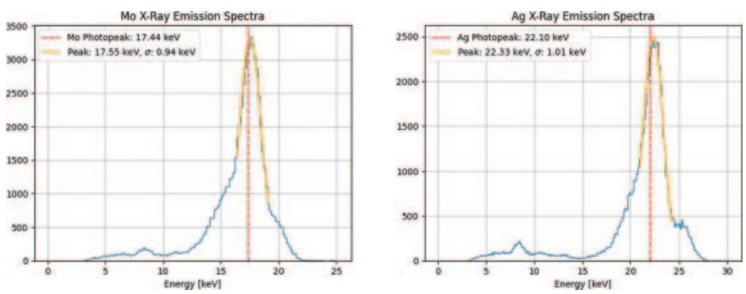

Fig. 3. – Energy spectra of different sources acquired with the Timepix4: Mo (left) and Ag (right). Lower amplitude peaks due to the Kβ emissions of the materials are observed.

5. – Conclusions

The reconstructed photopeaks positions match the nominal energies of the fluorescence photons. The energy resolution, calculated as Full Width at Half Maximum divided by the peak position, results in 9% at 32.28 keV. An improvement in the calibration procedure can be achieved by increasing the density of the calibration curve sampling or by expanding the explored energy range, especially in the low-energy nonlinear region. This can be done by increasing the variety of materials used or by implementing a mixed calibration procedure that exploits the test pulses internally generated by the device.

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