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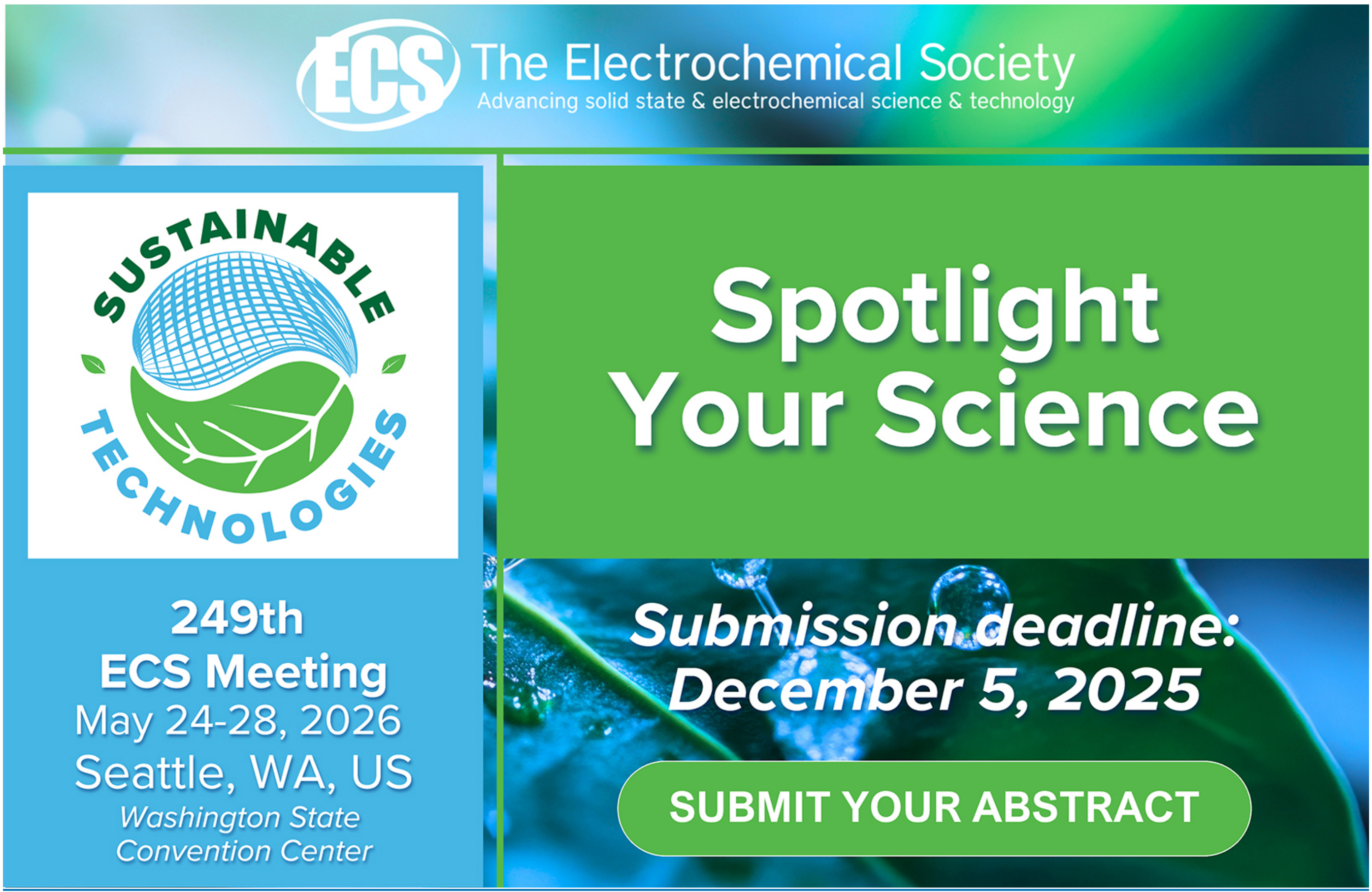

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TECHNICAL REPORT

Energy calibration of a Timepix4 detector assembly with a compact quasi-monochromatic X-ray system

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Abstract: Timepix4 is an application-specific integrated circuit (ASIC) developed by the Medipix4 international collaboration. It features a 448 × 512 pixel matrix that can be bump-bonded to pixelated sensors of various materials and thicknesses optimized for specific uses. Among its potential applications, Timepix4 can be utilized for spectral imaging, provided that an accurate energy calibration is performed to ensure precise measurements across all pixels. This calibration procedure was previously carried out using synchrotron X-ray beams, which provide a monochromatic and high-statistics source essential for pixel-by-pixel calibration. Building on this established protocol, which combines X-ray measurements with the detector internal test pulses, we introduce an alternative approach that employs a quasi-monochromatic (QM) X-ray beam generated by an X-ray tube in conjunction with a mosaic crystal. This configuration enables flexible implementation under standard laboratory conditions, minimizing the need for accelerator facilities with limited access. To validate this method, data acquired with an additional X-ray fluorescence (XRF) system were analyzed, demonstrating that the mixed calibration approach (combining QM data and test pulses) reduces discrepancy between measured and nominal energies to within 5%, compared to about 20% when relying solely on test pulses and less than 2% when using synchrotron radiation. Moreover, this improvement is accompanied by a significant decrease in the standard deviation of the measured photopeak, reflecting enhanced consistency across the pixel matrix. These findings highlight the potential of QM-based calibration as an effective and accessible alternative for achieving accurate Timepix4 energy calibration for a wide variety of spectral imaging applications.

Keywords: Hybrid detectors; X-ray detectors; X-ray radiography and digital radiography (DR); Pixelated detectors and associated VLSI electronics

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1 Introduction

Timepix4 is the latest generation of photon-counting hybrid pixel detector readout application-specific integrated circuit (ASIC) developed by the Medipix4 Collaboration at CERN. It features a 448 × 512 pixel matrix with a 55 µm pitch and an active area of approximately 7 cm^2, designed for compatibility with a wide range of semiconductor sensors. This adaptability allows for optimization in various applications, including X-ray spectroscopy, high-energy particle detection, and medical imaging [1].

Timepix4 introduces significant advancements in timing and energy measurement, operating in two distinct modes. In its frame-based mode, Timepix4 is optimized for high-speed acquisition required by intense X-ray sources, such as synchrotrons, where it can count photons at rates up to 5.0×10^9 hits/mm^2/s. This mode supports imaging at frame rates as high as 9.0×10^4 frames/s. It operates as a classic photon-counting system, where each hit above a user-defined threshold increments the pixel counter. However, this approach only provides information about the lower limit of the energy, as the system is limited, by design, to a single energy threshold setting. Alternatively, in data-driven mode, each event generates a 64-bit packet containing position and timing information, measuring both the Time-of-Arrival (ToA) and Time-Over-Threshold (ToT) of the signal. This mode enables continuous readout that can handle hit rates as high as 3.6×10^6 hits/mm^2/s. Following the calibration procedure, the ToT data provides detailed information about the energy deposited within each pixel. The combined timing and position information also allows for clustering of events, enabling the identification and energy measurement of individual particles interacting with the sensor [1]. This ability to capture images across a continuous energy spectrum, even under high particle flux, makes Timepix4 a great tool for spectral imaging.

For spectral imaging detectors, an accurate energy calibration is essential for obtaining reliable measurements of X-ray photon energies. A well-established procedure described in the literature relies on synchrotron radiation to provide stable, monochromatic X-ray beams [2, 3]. Although these methods have proven effective, they require specialized accelerator facilities, making them less accessible for routine use. Consequently, there is a clear need for an alternative calibration approach that can be readily implemented under standard laboratory conditions.

One such approach involves X-ray fluorescence (XRF) setups [4], which use different target materials and high-voltage X-ray tubes to generate characteristic emission lines for calibration purposes.

In this article, we present the results of the energy calibration performed using a quasi-monochromatic system (QM) combined with a mosaic crystal, which produces an X-ray beam with a precise and adjustable energy range, offering a practical solution for typical laboratory use. This calibration procedure is then verified using an X-ray fluorescence setup [4].

2 Materials and methods

The experimental work described in this article involves two main stages: energy calibration and validation. The first stage focuses on the use of a quasi-monochromatic X-ray system, which utilizes Bragg's diffraction to obtain energy values ranging from 8 keV to 30 keV. The second stage employs a fluorescence-based setup to validate the calibration, utilizing fluorescence photons generated by a micro-focus X-ray tube directed onto various target materials. Details of the experimental setup, calibration procedures, and data processing methods are presented in the following subsections.

2.1 Quasi-monochromatic X-ray system

The quasi-monochromatic (QM) system [5] has been commissioned in the LARIX-A laboratory of the University of Ferrara and the INFN Ferrara Division. The setup is shown in figure 1. The X-ray beam, produced by a standard X-ray tube, is diffracted by a highly oriented pyrolytic graphite mosaic crystal (Optigraph Ltd, Moscow, Russia), in a θ-2θ configuration between the beam and the crystal. The crystal has a surface area of $60 \times 28\ mm^2$, a thickness of 1 mm, and a measured mosaic spread of 0.28°. This setup allows the beam energy to be selected while maintaining a fixed direction. By varying the θ angle between 3.5° (corresponding to approximately 30 keV) and 13.6° (about 8 keV), the diffracted beam energy can be precisely tuned for the intended measurements. To prevent the primary beam from reaching the detector area and to limit the energetic spread of the diffracted beam, two lead plates forming a variable-width slit in the horizontal direction are used. These plates are aligned along the beamline and adjusted to define a horizontal aperture of approximately 1 cm. In the vertical direction, the beam exhibits a highly uniform profile. Therefore, the vertical aperture

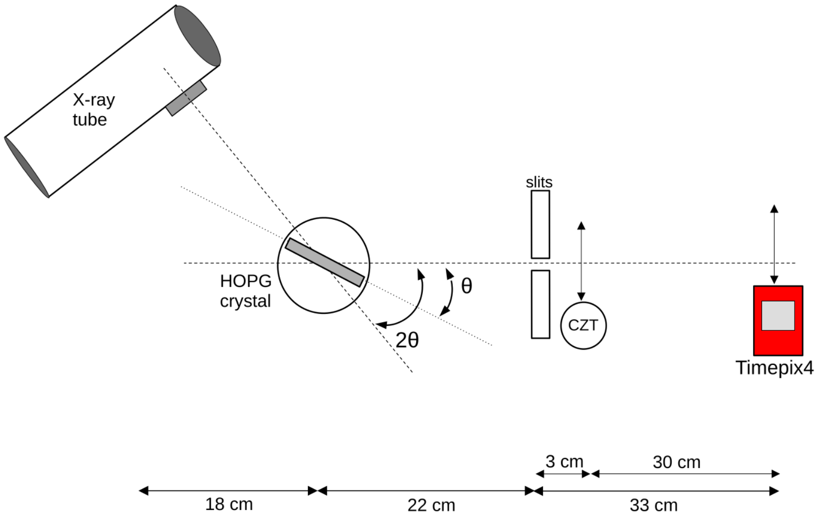

Figure 1. Schematics of the quasi-monochromatic experimental setup together with the spectroscopic detectors (CZT, Timepix4). The spectroscopic detectors are not used simultaneously. Not to scale.

was not restricted. It was only verified that it fully covered the detector height [5]. Consequently, to ensure uniform irradiation of the spectroscopic detectors, the energy spectra are acquired through a scanning process, which involves moving the detectors, along the horizontal direction, in front of the diffracted beam at constant speed by means of a motorized linear stage.

To determine the effective energy values of the QM setup, the diffracted beam is measured using the XR-100T CZT ($3 \times 3 \times 2\,\mathrm{mm}^3$) spectroscopic detector (Amptek, MA, U.S.A.). The five energy spectra obtained are shown in figure 2. A Gaussian fit is performed for each spectrum to extract the mean value of the peak and the standard deviation, which are presented in table 1. These values serve as references for the calibration procedure.

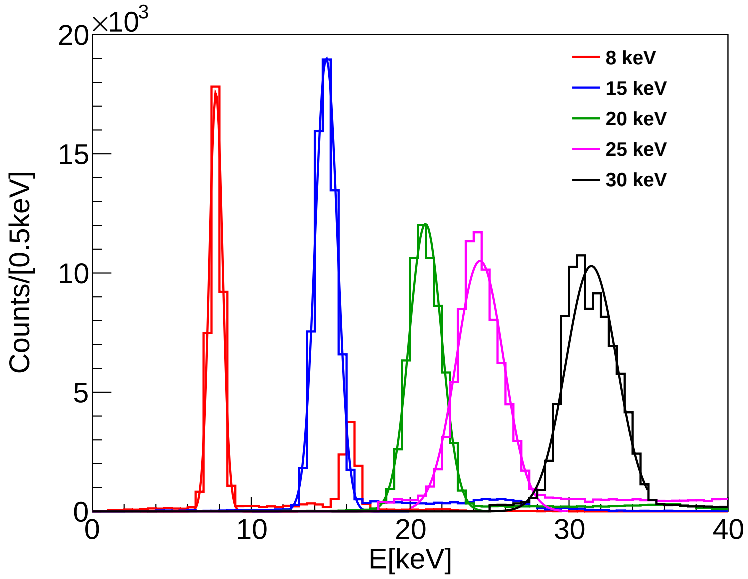

Figure 2. Energy spectra obtained from multiple scans with the CZT detector. Different colors indicate various energies, each fitted with a Gaussian curve.

Table 1. Nominal energy set in the setup by adjusting the θ angle, along with the energy values measured using the CZT detector and the corresponding standard deviation for each peak.

E_{Nom} [keV]	E_{CZT} [keV]	σ_{CZT} [keV]
8	7.8	0.4
15	14.7	0.7
20	21.0	1.0
25	24.4	1.5
30	31.4	1.6

2.1.1 Timepix4 energy calibration

Individual pixels in the detector matrix may exhibit variations in behavior due to components tolerances. To achieve a uniform and reliable detector response, a pixel-by-pixel calibration is required, which involves multiple steps. A dedicated in-house software, DataPix4 [6], is used to carry out this procedure,

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enabling system configuration, data acquisition, and real-time monitoring of detector performance. The first step is threshold equalization, ensuring that all pixels have a consistent reference level, thereby minimizing threshold dispersion across the entire detector. Once this procedure is completed, it is possible to proceed to calibrate the detector energy response. In this step, we establish the correct correlation between the ToT measurement and the charge deposited in a pixel. This calibration is performed by utilizing the internal analog test pulse of Timepix4. The test pulse provides a known, selectable electric charge injected into a capacitor at the front-end input, allowing multiple pulses with varying charges to be delivered to each pixel [7, 8]. The correlation between ToT and charge is non-linear, especially at low charge, due to the combined effects of timewalk and the preamplifier response. This non-linearity can be modeled using the following equation:

$$\mathrm{ToT} = a + b \cdot \mathrm{Q} - \frac{c}{\mathrm{Q} - d} \tag{2.1}$$

where Q is the deposited charge, ToT is the measured time-over-threshold, and (a, b, c, d) are the fit parameters that account for gain, threshold effects, and curvature corrections near the detection threshold [9]. These parameters must be calculated for each pixel, resulting in a two-dimensional distribution for each of the four parameters that ensures calibration coverage across the entire sensor matrix. Finally, the conversion from charge to energy depends on the sensor material used. In the case of silicon, the conversion factor is $3.6\,\mathrm{eV/e^-}$ [10], corresponding to the average energy required to create an electron-hole pair in the sensor. However, it has been demonstrated that due to uncertainties in the capacitor value, calibration performed solely with the test pulse is inaccurate, necessitating a mixed calibration approach [4]. The mixed calibration procedure combines two data sources: test pulses, which allows to precisely sample low charge region, and a small number of known-energy external X-ray sources [2–4]. The reference points obtained with the external X-ray sources provide an absolute energy scale, correcting any offset or slope errors arising from injection-capacitor uncertainties. Specifically, the linear part of the test pulse data ($\gtrsim 10\,\mathrm{keV}$) is shifted and tilted to align with the X-ray reference data. For the new dataset obtained, a new fit using Equation 2.1 is performed, producing an updated set of calibration parameters. This procedure has already been tested successfully using monochromatic sources such as synchrotrons and X-ray fluorescence [2–4].

In this work, we used a quasi-monochromatic system to produce an external X-ray beam with five distinct energies: 8, 15, 20, 25, and 30 keV. The energy threshold for acquisition was set to 3.6 keV. When photons interact with the detector, generating electron-hole pairs, the applied electric field drifts the electrons toward the pixel readout. The resulting charge cloud can spread across multiple pixels, causing a phenomenon known as charge sharing. To ensure accurate calibration, it is crucial to cluster the incoming hits and categorize them based on the number of pixels they occupy. For this analysis, only clusters of size 1, i.e., involving a single pixel, are considered to mitigate the influence of charge sharing, which could otherwise distort the calibration. Furthermore, the detector was irradiated according to the described setup, scanning the beam across the entire pixel matrix to collect a sufficient distribution of ToT data for each pixel. This procedure was repeated at every selected energy to accumulate at least 5×10^3 counts per pixel, thereby ensuring reliable statistics for the subsequent pixel-by-pixel calibration. Figure 3 shows the ToT distribution for the 15 keV beam impinging on the sensor. A pronounced peak at high ToT values corresponds to the photopeak of the beam, while at lower ToT values, the effects of charge sharing can be observed. Since only clusters of size 1 are considered, all detected hits at low ToT correspond to charge clouds that

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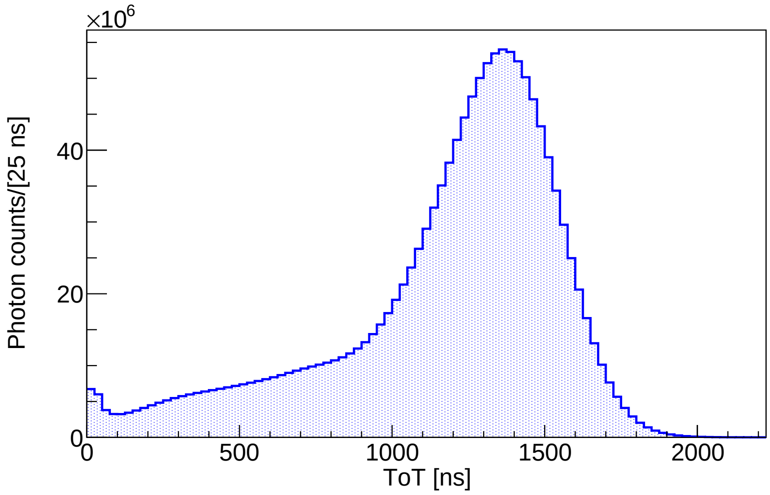

Figure 3. ToT spectrum of the 15 keV beam generated with the QM setup.

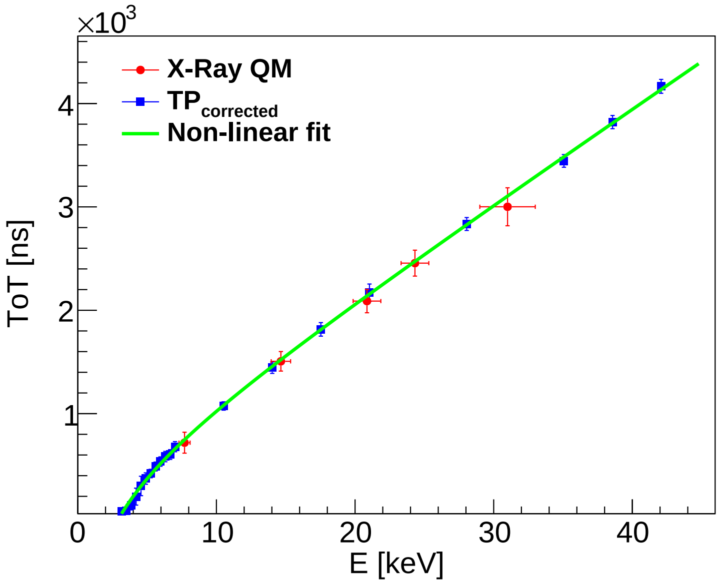

Figure 4. Example of the mixed calibration result for Pixel (440, 440), showing ToT as a function of energy. Data points from X-ray quasi-monochromatic (QM) sources (red) and corrected test pulses (blue) are displayed, with the green line representing the fit performed on the combined dataset.

spread across multiple pixels, with the energy in neighboring pixels falling below the threshold and consequently being discarded. For this reason, the fit on the photopeak is performed only on the high-ToT portion of the spectrum. From this Gaussian fit, the mean and standard deviation values are extracted for each pixel and for each energy used for the irradiation. The result of this procedure for a single pixel is shown in figure 4, where, for the X-ray QM, the energy values and their standard deviations are taken from table 1, while the ToT values and their standard deviations are obtained from the Gaussian fit in plots similar to the one shown in figure 3.

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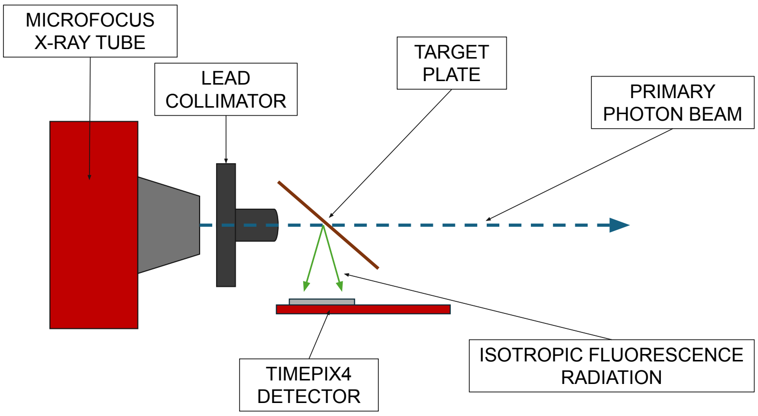

Figure 5. Fluorescence setup: target plates are positioned along the collimated X-ray beam, while the detection system is placed outside the primary photon beam to collect only the fluorescence radiation.

2.2 X-ray fluorescence system

X-ray fluorescence photons were generated using a micro-focus X-ray tube from Hamamatsu, which irradiated various metal foils positioned at an angle of approximately 40 degrees relative to the incident radiation. The detector was placed outside the primary beamline to selectively capture fluorescence photons [4]. A schematic of the measurement setup is shown in figure 5. The materials used and their corresponding emission energies are summarized in table 2. The selected materials cover a range from the non-linear region (<10 keV) to the linear region. Finally, the acquisition time and X-ray tube voltage were optimized to ensure a minimum of 10^3 recorded events per pixel for each energy level.

Table 2. Materials used to produce fluorescence photons, along with their atomic number (Z) and characteristic X-ray energy (Kα_1) [11]. The last two columns present the relative discrepancy from the Kα_1 values, calculated using the mixed and test pulse (TP) calibration techniques.

Material	Z	E_{XRF} [keV]	Mixed [%]	TP [%]
Cobalt	27	6.93	8.7	17.6
Zinc	30	8.64	6.4	21.0
Molybdenum	42	17.48	1.9	20.2
Palladium	46	21.18	1.6	20.7
Tin	50	25.27	0.8	20.5

3 Results

The energy spectra acquired with X-ray fluorescence setup were reconstructed, for comparison, applying the calibration parameters derived from only TP and from the combined dataset of TP and QM measurements, in the following referenced as Mixed. As shown in the left panel of figure 6, the energy spectrum for the XRF data for the Mo target exhibits a marked improvement in the alignment of the photopeaks. In contrast, relying solely on the Timepix4 TP calibration results in peak shifts of several keV and a broad spread. In addition, as illustrated in the right panel of figure 6, the photopeak values approach the ideal scenario, where characteristic X-ray energy and measured values coincide, when using the mixed calibration technique compared to the TP calibration. More quantitatively, table 2 shows that the relative discrepancy from the characteristic X-ray energy value, calculated as

$$\frac{|E_{\mathrm{XRF}} - E_{\mathrm{Meas}}|}{E_{\mathrm{XRF}}},$$

averages 5% with the mixed calibration, compared to a 20% deviation observed with the TP calibration. For the mixed calibration, the maximum discrepancy is observed at lower energies within the non-linear region, whereas in the linear region, the discrepancy remains below 2%. It also significantly enhances measurement precision, reducing the standard deviation of the photopeak by 50%, improving the average accuracy.

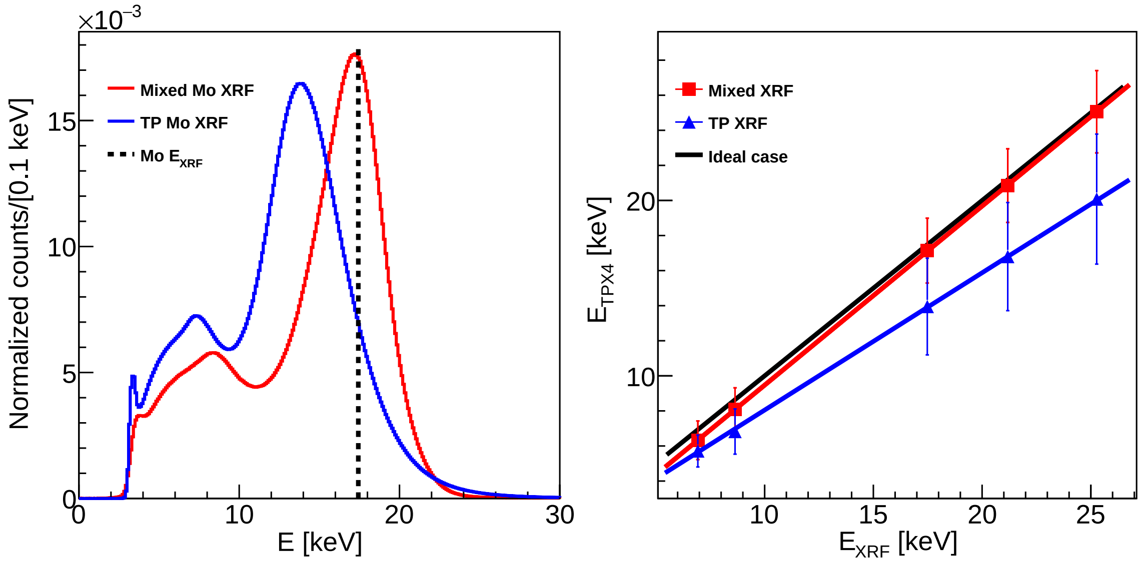

Figure 6. *Left*. Comparison of the energy spectra for the Mo target using the Mixed calibration parameters (red) and the TP calibration parameters (blue), with the black dashed line indicating the characteristic energy of the fluorescence photons produced in the target. *Right*. Energy measured by Timepix4 as a function of the characteristic X-ray energy. The results of the XRF measurements are shown in red for the mixed calibration parameters and in blue for the TP parameters, while the solid black line represents the ideal scenario.

4 Conclusions

In this work, we demonstrated that a quasi-monochromatic X-ray beam, generated by an X-ray tube combined with a mosaic crystal, can serve as an effective alternative to synchrotron-based calibration for the Timepix4 photon-counting pixel detector. By combining QM measurements with internal test pulses, we achieved for the XRF measurements an agreement with the characteristic X-ray energy values within 5% on average and better than 2% for energies above 10 keV, representing a significant improvement over the 20% deviation observed when relying solely on TP calibration, and less than 2% when compared with the use of synchrotron radiation [2]. This approach not only improves the average response but also enhances measurement precision by reducing the standard deviation of the photopeak by 50%. These findings highlight the potential of QM calibration to provide both flexibility and high accuracy under conventional laboratory conditions, minimizing the need for accelerator facilities.

Acknowledgments

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