Profile Characterization of the PADME Experiment's Positron Beam Using a TimePix3 Sensor Array

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Abstract. A control and data acquisition software operating a TimePix3 sensor array from Advacam is described. A method for characterizing the positron beam used in the PADME Experiment is proposed and preliminary results obtained from data taking during the Fall 2022 are presented.

1. Introduction

A large body of evidence, accumulated since the beginning of the 20th century points at the existence of a physical phenomenon that manifests itself only through its gravitational action, while otherwise invisible to existing methods of observation [1]. The nature of this phenomenon, tentatively named dark matter (DM), is one of the important unsolved problems of modern physics.

The PADME experiment is investigating the existence of a ”dark sector“ (DS), elementary particles, which while neutral to the Standard Model (SM), could interact with its gauge fields via ”portals”, low-probability and difficult to observe windows of interaction ([2], [3]).

One of the simplest DS models of such ”portal“ interaction considers a U(1) symmetry and its corresponding vector particle A' (a ”dark photon”). Under this symmetry, the SM particles are neutral and the A' is expected to couple to the SM sector with an effective charge of εe [2], where ε is a small parameter.

There are also indications that a vector boson of this kind with a mass in the range from 1 MeV to 1 GeV and a coupling constant $\varepsilon \approx 10^{-3}$ may explain the anomalous muon magnetic moment [4]. Depending on the specific assumptions of the particular model, the DM mediator may decay into SM (”visible channel”) or DS (”invisible channel”) particles [3].

The PADME experiment is the first to look for a dark photon produced by annihilation and decay into invisible channel [5]. The experiment attempts to detect the missing mass spectrum of the $e^+e^- \rightarrow \gamma A'$ annihilation process in positron-on-target collisions.

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In this experiment, the missing mass of the process can be determined in a straightforward manner:

$$M^2_{missing} = (\mathbf{P}_{e^-} + \mathbf{P}_{e^+} - \mathbf{P}_\gamma)^2$$

where the right side terms are the 4-momenta of the initial and final state [3].

2. The Role of the Multipixel Detectors in the PADME Experiment.

Understanding the initial and the final state of the positrons-on-target interactions during the course of the experiment is the key for the success of PADME [6].

To acquire relevant data for the measurement of the missing mass of the single photon final states, a highly effective veto system has been implemented ([3], [7]), however it does not provide direct measurements of the beam characteristics.

One of the limiting factors of recent measurements by PADME of the $e^+e^- \to \gamma\gamma$ cross-section has been the 5% precision on the luminosity measurement. During the PADME Run III, a requirement of lowering the experiment luminosity has been introduced and this has posed further challenges to the precision of the luminosity measurements [8].

A good understanding (within error margins of $1-2\%$) of the beam parameters, in particular of the positron count, the beam spatial distribution, and the time profile of each beam bunch is essential for the improvement of the fidelity of the analysis.

The TimePix3 Array Detector with its large area, high speed of operation and especially the unique ability to provide simultaneous temporal and spatial characteristics of the incident particles at high rates is therefore an essential component of the experiment as it will improve the luminosity measurements significantly, and its comissioning is therefore crucial for the success of the planned subsequent data acquisition runs.

3. The TimePix3 Array Detector Multipixel Detector in the PADME Experiment

A key detector of the PADME experiment is the TimePix3 Array Detector, a custom-designed, hybrid, fast array of twelve TimePix3 sensors arranged in a 2×6 matrix with total size of $\approx 85 \times 30\text{mm}^2$, which can accomodate and record a large variety of cross-section profiles of incident charged particle beams. With a total number of pixels close to 8×10^5, the PADME TimePix3 Array Detector is among the largest of its type ever used in particle physics.

Each TimePix3 sensor is a hybrid matrix, containing 256×256 channels comprising $55 \times 55\mu\text{m}^2$ detector pixels and a control and readout chip. It can record time-of-arrival (ToA) and time-over-threshold (ToT) simultaneously for each pixel. The nominal resolution of the ToA readout is 1.6 ns. A key characteristic of the chip is its ability to perform readout and data acquisition simultaneously, keeping the pixels sensitive at all times when in operation. The chip's architecture allows optimized sparse readout and can achieve a high throughput of $\approx 40\text{Mhits/s/cm}^2$ [9].

The individual sensors in the TimePix3 Array Detector can operate in two modes. The first is the so-called frame mode, which integrates the ToA and ToT data over a time interval and provides output as a 256×256 pixels picture frame. The second mode is the so-called data-driven mode, where data from individual pixels are provided as a stream, and it is up to the application to consume this data appropriately.

An image of the detector array mounted in its case is shown in Fig. 1. The system allows independent operation of individual chips and individual rows, as well as joint operation of all chips as one full sensor. Fig. 2 shows heatmap of the sensor when operating a single chip (bottom left), during a thermal stability test.

4. Acquisition and Analysis System. Preliminary Results.

Initially, the TimePix3 Array Detector was operated using a vendor-provided data acquisition application, based on version 1.5 of the Pixet SDK [10], which allowed only frame-based data, and had a rather limited performance.

Figure 1. The TimePix3 Array Detector of the PADME experiment.

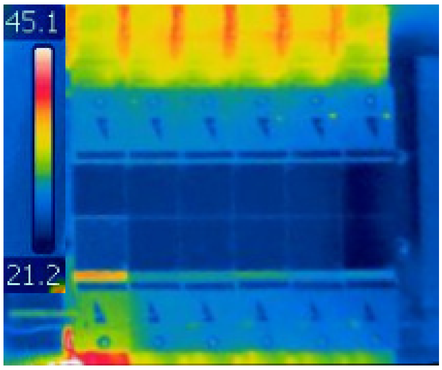

Figure 2. Heat dissipation from an operating timepix chip as measured by an IR camera.

In particular, it was prone to breakdowns caused by temporary individual chip failures, severely limiting the ability to acquire data for times longer than a few minutes. Data synchronization between individual chips was also problematic, as some of the chips return delayed measurements due to unknown hardware error conditions. A number of mitigation steps, such as extra cooling and hardware components replacement were attempted without significant improvements of performance.

To acquire and analyze the data, a dedicated control and acquisition application operating the sensors in both frame and data-driven mode has been developed, which has resolved most operational problems by implementing better sensor fault recovery algorithms and an improved communication protocol.

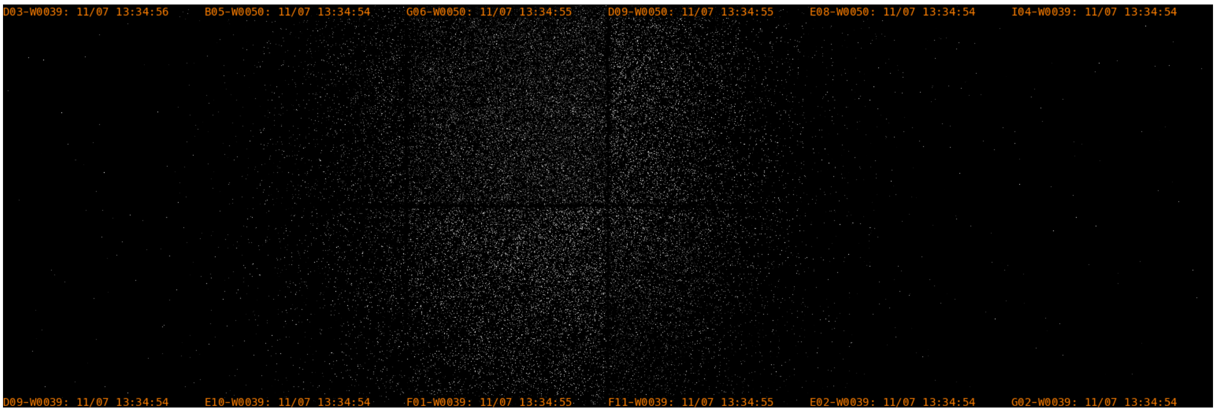

Figure 3. Beam spot picture over the full TimePix3 Array Detector, resulting from ToT measurements. Timestamps show database insertion times.

Initially, due to the data collection issues described above, beam analysis was attempted using frame data collected over short ($O(10^{-1})$ s) intervals, sufficient to avoid overlaps of multiple beam bunches. While this approach was useful for understanding the spatial distribution of the beam over time and performing the alignment of the beam with the target, it proved impossible to collect timing characteristics sufficient to link beam properties to measurements of the complete detector system.

Acquiring information about timing characteristics of individual beam bunches is only possible by leveraging the data-driven stream readout mode. Combining the acquired pixel information also makes it trivial to build the equivalent of the "frame" mode for tracking the spatial distribution from the event stream, as shown in Fig. 3. Therefore the data-driven mode is now the default acquisition mode employed in the PADME experiment. Using this approach, several important tasks, pertinent to beam

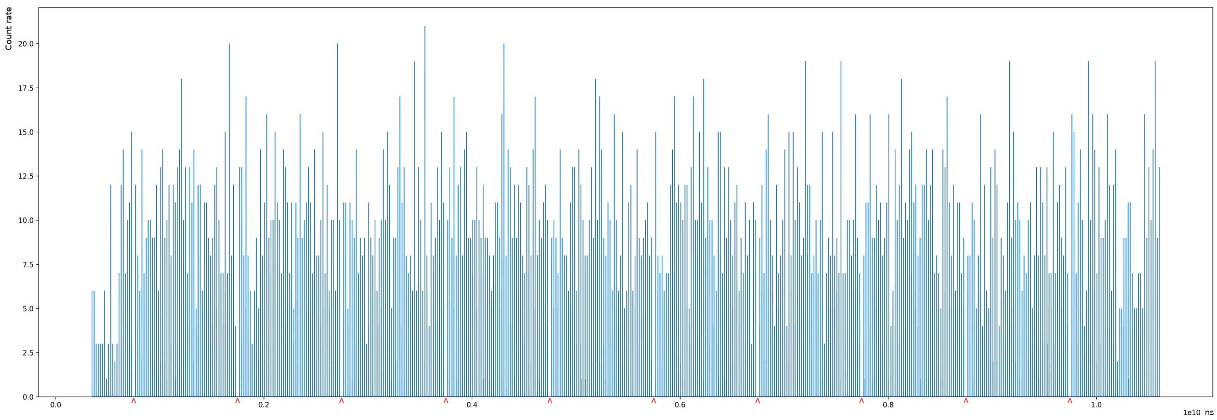

Figure 4. Chip data synchronization by beam tag and initial timestamp. Data from three chips are shown. The gaps in the graph at every 49 ticks are due to the linac sending bunches at 50Hz and skipping one bunch every second. Markers show bunch gap. Total length of the track is 10s.

characterisation have been accomplished.

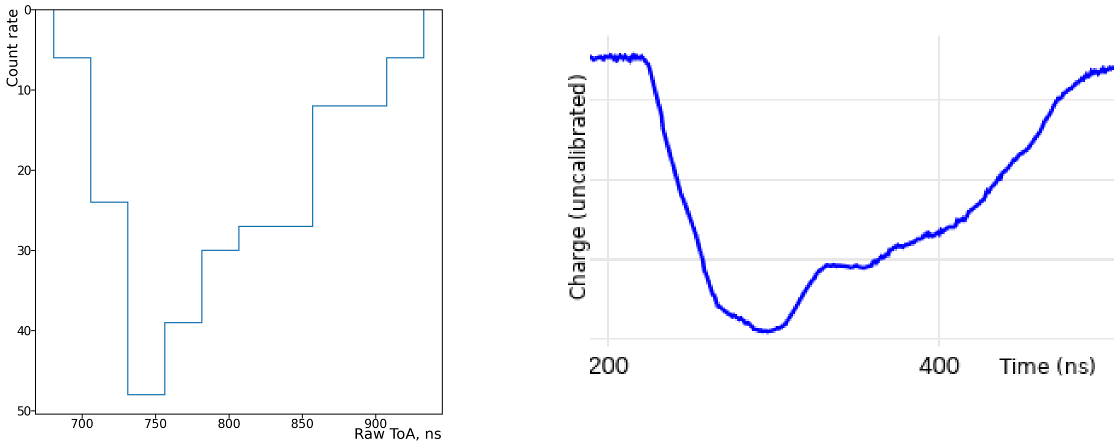

Figure 5. An example of matching individual beam bunches as seen by the TimePix3 Array Detector (left) and the lead glass calorimeter (right). Match is performed by beam batch counting and shape, as the detector system clocks of the two systems are not synchronized due to technical limitations.

First, it has been possible to see the time distribution of beam bunches and use this information, alongside acquisition start timestamp to easily align and synchronize chips even when chips report delayed measurements (Fig. 4). Second, it has been possible to record beam bunch profiles (Fig. 5) with high time resolution.

Additionally, it is now possible to match recorded bunch data to those from other detectors in the experiment (Fig. 5) and align specific bunch data across the whole detector system even though the system clocks are not explicitly synchronized. Finally, due to the ability to record and combine data offline, it is possible to iteratively improve the performance of the detectors during the data analysis phase.

5. Conclusion

The TimePix3 Array Detector of the PADME experiment has a new improved data acquisition and control software. Leveraging the data-driven mode of the array, detailed information of the positron beam used by the PADME experiment is now being collected. Both spatial and temporal individual bunch profiles are recorded, and it is possible to match bunch profiles with the rest of the detector system reliably in a preliminary analysis extension.

Immediate future work will enhance and improve data collection and include the new measurement tools in the main analysis system of the experiment.

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