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Beam diagnostics with silicon pixel detector array at PADME experiment

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Abstract: During 2022 data taking (Run III) PADME searched for a resonant production and a visible decay of the X17 particle into e^+e^-. A precise knowledge within 1% uncertainty of the number of positrons was required for the observation. To that purpose, an array of 2×6 Timepix3 (total of 512×1536 pixels) hybrid pixel detectors operated in data-streaming mode with ToA resolution of 1.56 ns for every pixel was employed. Two methods for data acquisition were developed. A frame-based method, integrating the number of hits for each individual pixel for a predefined period of time served for monitoring the beam conditions and to provide a rough estimation of the beam distribution and number of positrons. A data streaming mode exploiting the nanosecond time resolution of Timepix3 detector was used for precise characterization of the transverse beam profile and the distribution of the incident positrons within each bunch of $\sim$ 200 ns duration.

Keywords: Beam-line instrumentation (beam position and profile monitors, beam-intensity monitors, bunch length monitors); Particle tracking detectors; Analysis and statistical methods; Data processing methods

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Contents

1 Introduction: the PADME Run III searching for X17

For the first and the second run of data collection, PADME was searching for signals of a dark photon [1] in positron on target collisions at the DAΦNE Beam Test Facility (BTF) by reconstructing the missing mass of the final state in the process $e^+e^- \to \gamma A'$ (A' indicates the dark photon). For the third run, PADME extended its physics program, looking for evidence of the hypothetical X17 particle (its predicted mass is ~ 17 MeV), related to the reported anomaly in the angular correlation spectra of e^+e^- emitted in ^{8}Be decay [2].

PADME was searching for the new particle via a resonant production, which was directly accessible with PADME's setup, by exploiting the precise beam parameters manipulation of the BTF beam line, capable to fine vary the positron energy (270 to 290 MeV range, corresponding to the 17 MeV mass of X17) and the existing detector setup of PADME, sensitive to the energies of the final states particles, produced following the annihilation in the resonant search [3].

The process of resonant energy scanning works as follows: varying the energy of the incident positrons, PADME is looking for a peak of the secondary produced particles from the decay of X17. The position of the peak on the energy scale corresponds to the energy of X17 ($\sim \sqrt{s}$ of the e^+ beam).

The hypothetical X17 particle is created when the incident positron beam collides with one electron of the thin diamond target of PADME. Then the particle decays into e^+e^- and their energies are measured by the Electromagnetic Calorimeter (ECal), consisting of 616 BGO scintillators, forming a cylindrical array around the projection of the beam line (figure 1). The ETag detector, comprising 18 vertically segmented 5 mm thick plastic scintillators, discriminates charged from neutral particles registered by the ECal, and serves as an anti-veto detector for the background processes ($e^+e^- \to \gamma\gamma$).

A positive signal for X17 production is the increase of the $\sigma(e^+e^- \to e^+e^-)$ cross-section for a given beam energy. The cross-section is estimated by normalizing the number of the secondary produced e^+e^- pairs, compared to the number of the incident positrons:

$$\sigma(e^+e^-)_{\text{Ebeam}} \simeq \frac{Ne^+e^-(E_{\text{beam}})}{N_{\text{positrons}}(E_{\text{beam}})} \tag{1.1}$$

For Run III, a new more precise silicon pixel detector, Timepix, was mounted at the end of the beam line, to overcome the limitation of the rough estimation of the number of the e^+ given by PADME's lead glass detector, whose resolution is not sufficient to allow the measurement of X17.

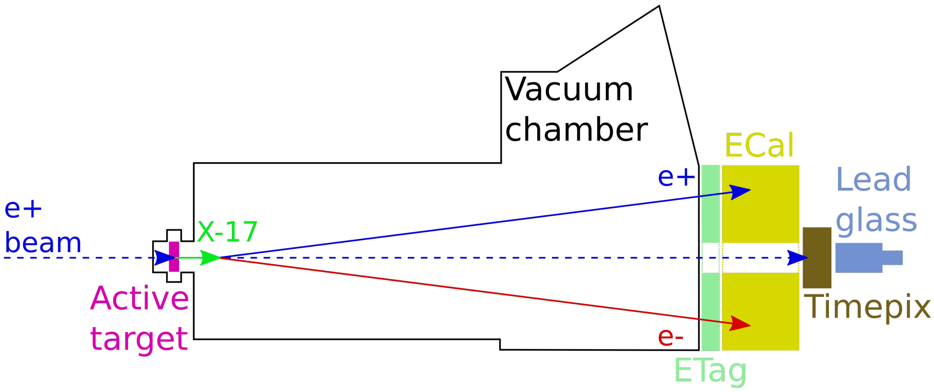

Figure 1. The detector setup during PADME Run III.

2 PADME's Timepix

A single Timepix3 chip consists of 256 × 256 pixels (pixel size of 55 µm × 55 µm). It can provide ToA (Time-of-Arrival) and ToT (Time-over-Threshold) for each individual pixel (px). It has two modes of operation: a frame mode, in which, for each pixel, ToA/ToT measurements of the particle interaction are provided for a predefined interval of time; and data-streaming (DS) mode, providing continuous information for ToA/ToT for each event in a pixel with sampling rate corresponding to 1.56 ns [4].

PADME's Timepix detector setup (figure 2) consists of an array of 2 × 6 Timepix3 sensors from ADVACAM [5], read out by high-speed ZEM4310 interface module boards [6], sequentially grouped in pairs of two and transferring data/commands to 6 NUC PC units [7]. The setup also includes two power boards, a water cooling system for the sensors and an external module, providing 40 MHz clock signal, needed for the proper operation and synchronization of the chips. The whole system is managed by a more powerful main PC unit.

Figure 2. PADME's Timepix detector without the front cover.

The Timepix detector was placed at the end of the PADME setup, registering the beam particles which do not interact with the diamond target. For an independent measurement of the beam intensity, a lead glass detector is positioned behind the Timepix.

3 OP/DAQ application framework

The developed data aggregation and management framework (OP/DAQ) for PADME's Timepix detector is a bidirectional client-server system. It consists of three distinct components: a web-based application that provides graphical user interface for beam monitoring and control of the data repetition parameters; a communication and operational module for configuration and management of the sensors and of the PC units chain; and a data storing module of the acquired data, serving both readout modes of operation (figure 3).

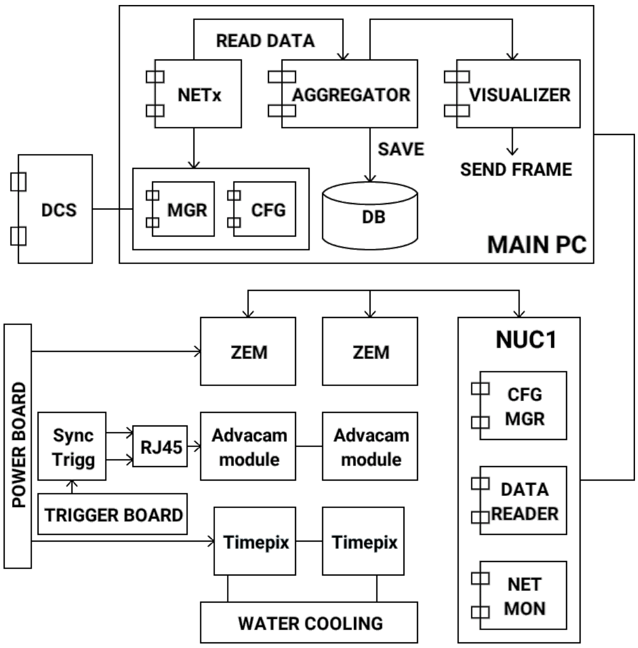

Figure 3. Architecture of the Timepix detector and OP/DAQ Framework.

The monitoring component is based on bottlepy application server [8] and chiby [9], a javascript micro-library for the user interface, running on the main PC unit. It provides visual information for the beam spread to the user, a picture based on the data gathered in frame mode, and provides functionality for manipulating the acquisition time, threshold, bias and repeatability interval of the aggregated data frames.

The component that manages hardware and PC units is based on a finite-state machine model, communicating between the units with high-performance ZeroMQ messaging library [10]. It operates the hardware units from a configuration files and/or the input from the monitoring application provided by the user.

The data storage is based on SQLite3 and stores the row data of ToA/ToT output and the meta information of the operational parameters for every chip: bias, threshold, operational voltages and currents, temperature.

Since, this was the prototype of the OP/DAQ framework, the web-server and the database were running on the main PC unit. This allowed for rapid development and upgrades of the system during the Run III data taking.

The 12 Timepix chips operated in frame mode for the majority of PADME Run III. Data were aggregated every few minutes for a period of 1 s, providing measurements of the number of fired pixels for both ToA and ToT. The overall collected data in frame mode are ~ 50 k frames corresponding to about 2 months of continuous data taking. The software module, acquiring data from the data-streaming mode of operation, was completed close to the end of Run III, due to the complexity of the operation with high rate of data flow and hardware issues, related to the heat dissipation of the chips, to the stability of operation of all 12 Timepix3 chips together, and to problems related to the operation of the hardware trigger module of the detector. The collected data in DS mode amount to a total of ~ 3 h, for three different values of the beam energy.

4 Data analysis

Since the majority of collected data is from the frame mode of operation (over the time period of the whole Run III), the analysis framework is mostly focused on processing the data from this operation mode. However, its functionality and the application programming interface (API) is directly applicable to analyze the data from the data-streaming mode for the evaluation of X and Y spread, total number of events, beam profile characteristics.

4.1 Frame mode

A single run (run id: 50444) of data collected during PADME Run III is used to validate the analysis framework and the results are presented below. The energy of the positrons for this run was ~ 289.5 MeV. The duration of the run was ~ 6 h and a total number of 342 frames were collected with the Timepix detector. The summary of the collected data and a map of the chips position are reported in table 1.

Table 1. Map (row, column) of the array of 2×6 Timepix3 chips and a percentage of collected frames during Run 50444 for each individual chip.

D03-W0039 chip(1, 1) 0% frames	B05-W0050 chip(1, 2) 0% frames	G06-W0050 chip(1, 3) 100% frames	D09-W0050 chip(1, 4) 100% frames	E08-W0050 chip(1, 5) 100% frames	I04-W0039 chip(1, 6) 100% frames
D09-W0039 chip(2, 1) 100% frames	E10-W0039 chip(2, 2) 100% frames	F01-W0039 chip(2, 3) 51% frames	F11-W0039 chip(2, 4) 100% frames	E02-W0039 chip(2, 5) 100% frames	G02-W0039 chip(2, 6) 100% frames

During the data collection in frame mode of operation, some of the chips reported partial or no data. More frequently, these chips are the leftmost on the upper row chip(1, 1) and the third on the bottom row chip(2, 3) (figure 4). This introduces a challenge for the proper estimation of the beam characteristics.

To overcome these limitations, data from different chips were combined and analyzed. Since the beam was impinging in the center of the Timepix array, the investigated sets include: all the chips; all the chips from the first row; the chips from the second and fourth column, thus eliminating the problematic chip(2, 3); the second row; all chips, except the not working ones; only the chip(1,3), which

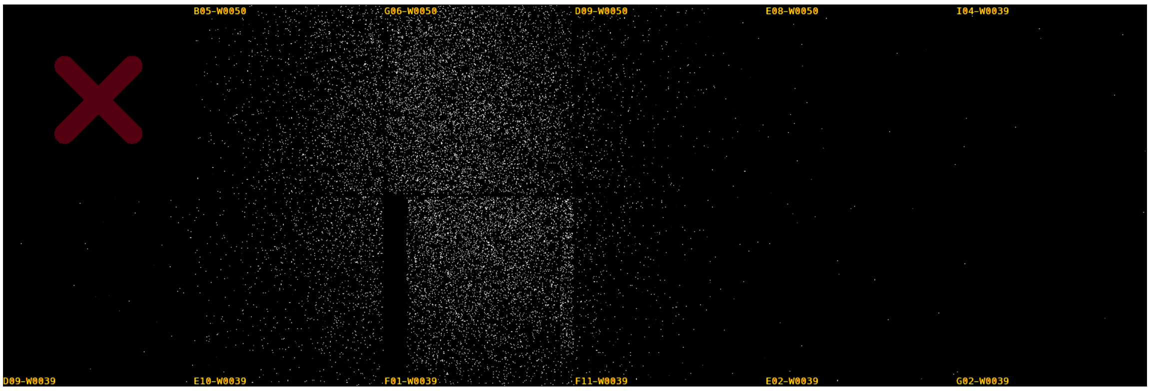

Figure 4. Example of a reconstructed image from the data obtained in a frame mode with corrupted chip(2, 3) or missing readings, chip(1, 1) with an X mark.

had the most stable readings and the highest number of events. For each of them, a Center-of-Gravity (CoG) and a Gaussian fit (Gauss) were performed. The criteria for choosing this method are: the lowest difference between CoG and Gauss; the highest correlation parameters; the higher statistics; and stability over time. The results for some of the sets of data are summarized in table 2.

Table 2. Comparison of the results, measuring the center of the beam and its spread for different sets of data from Run 50444. The position of the beam is given in units of the pixel size (px = 55 µm).

Method	all chips	1^{st} row	4^{th} column	chip(1, 3) only
CoG(X), [px]	754.9	751.8	848.5	672.5
RMS(X), [mm]	6.5	6.3	3.2	3.5
Gauss(X), [px]	755.4	746.0	780.8	746.3
Sigma(X), [mm]	6.1	6.4	5.5	6.2
CoG(Y), [px]	314.6	382.9	307.3	382.6
RMS(Y), [mm]	6.8	3.9	6.9	3.9
Gauss(Y), [px]	382.8	383.1	369.0	380.4
Sigma(Y), [mm]	15.6	10.5	10.0	10.5

The method which was finally adopted to monitor beam parameters relies on the data, collected from the chips from the first row of the Timepix array. This set provides stable measurements of the center of the beam both in the X and Y directions (figure 5).

There is a systematic difference between the two methods in the evaluation of the X direction while in the Y direction, the spread of the CoG is lower than that provided by the Gaussian estimation. Even during a run with a constant beam energy, any small shifts in the position of the beam can be detected, e.g. for run 50444 the position of the center in X was shifting at the end of the run while in Y it remained stable during the whole run.

The correlation between the Center-of-Gravity and the Gaussian fit results for the first row is linear and shows that the bias, that usually arises when eliminating data from some chips, is minimal (figure 6).

The size of the beam spot at the exit of the PADME setup, estimated by the sigma value of the Gaussian fit is shown in figure 7. Its average value for the whole run 50444 is 6.4 mm in X and 10.5 mm in Y (115.5 and 190.5 respectively in pixel size units).

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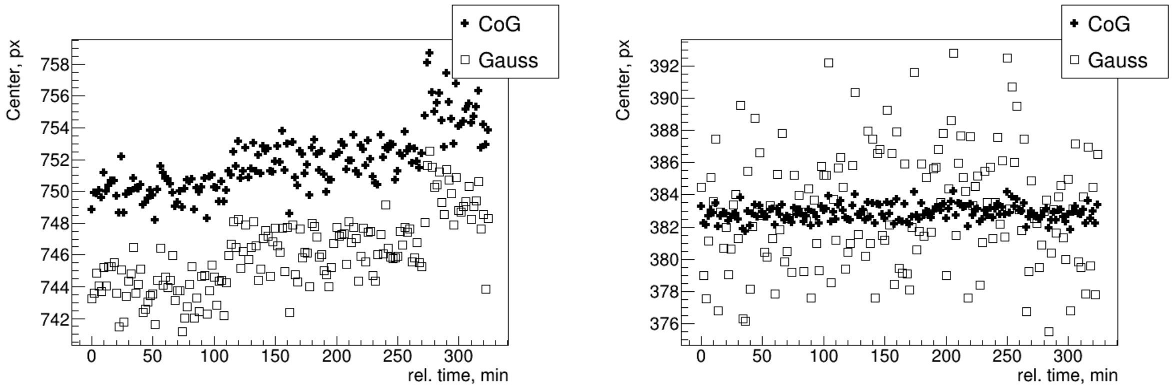

Figure 5. Estimation of the center of the beam using CoG (plus mark) and Gaussian fit (square mark). Left: X direction, right: Y direction.

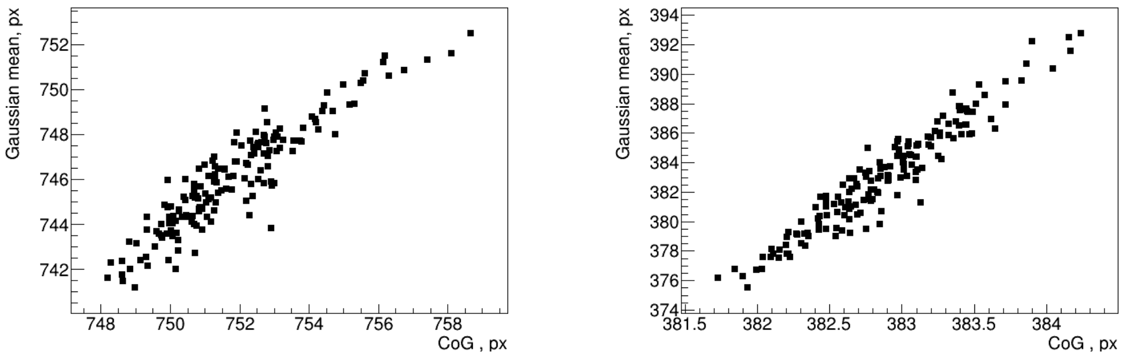

Figure 6. Correlation between CoG and Gauss methods, estimating the center of the beam Left: X direction, right: Y direction.

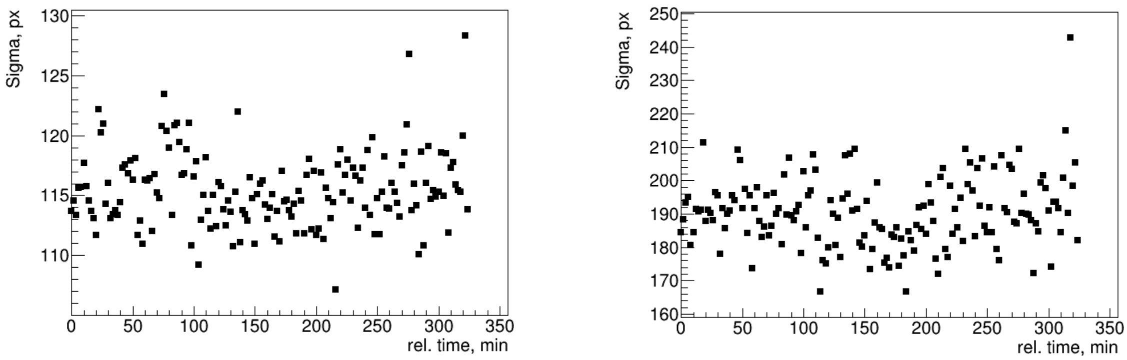

Figure 7. Variation of the spread of the beam, during run 50444. Left: X direction, right: Y direction.

4.2 Data streaming mode

PADME collected data in data-streaming mode for a few test runs at the end of Run III. These measurements prove that a more precise knowledge of the beam parameters can be obtained for the future runs. The streaming mode provides knowledge about the beam profile distribution over X and Y axes dynamically (figure 8), without the limiting factor of the frame mode, in which it is not possible to identify two or more events occurring in a single pixel for the duration of the frame.

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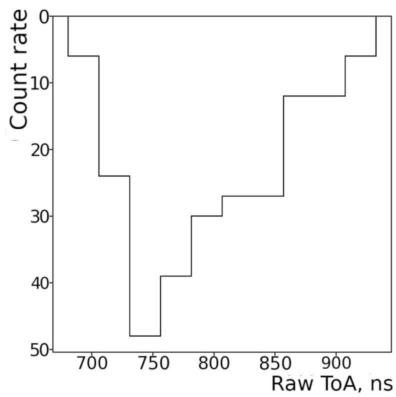

Figure 8. Single bunch profile, captured in the data-streaming mode of operation. Provides information for the time distribution of the incident particles within the length of a single positron bunch (~ 200 ns).

The DAΦNE LINAC accelerates 50 bunches per second. 49 of these are directed towards the PADME setup while one is deflected by a pulsed magnet to the LINAC beam monitoring equipment. This is reflected in a characteristic structure in the spacing between the different bunches, with 49×20 ms and a long 20 ms beam gap indicated by the red arrows in figure 9.

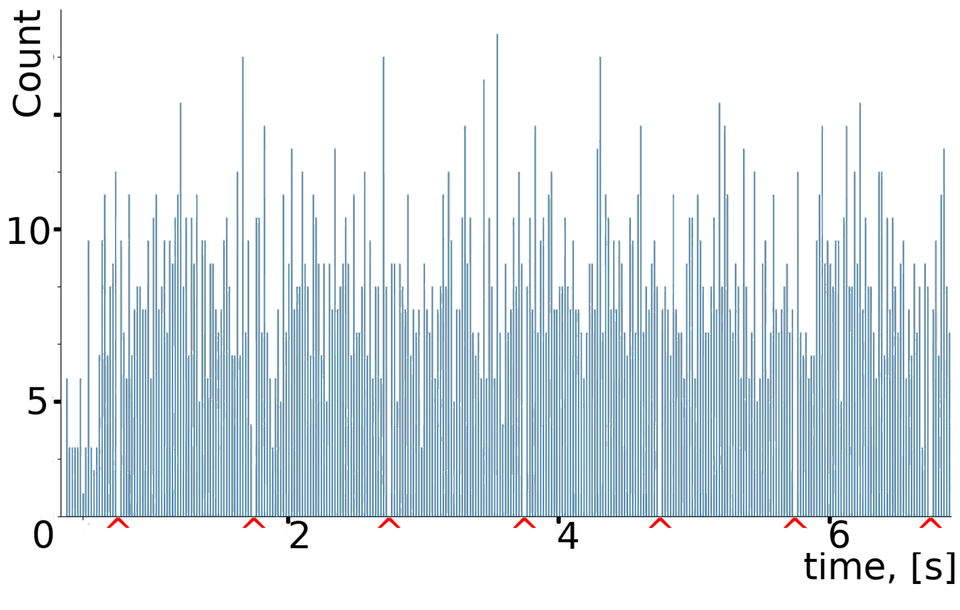

Figure 9. Number of particles per bunch, registered by the Timepix detector. The arrows mark the DAΦNE LINAC beam gap every second.

Time synchronization of the Timepix with the rest of the detectors was achieved by exploiting the beam gap occurring every second. This feature of the beam line helped with resynchronizing the data from one of the chips, which reported false and progressively higher ToA over the time of acquisition. This problem was identified to be related to the time walk of the internal clock of the chip.

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5 Conclusion

The precise knowledge of beam characteristics in terms of number of particles and their spatial distribution is a key element not only for dark photon studies (performed in PADME Runs I and II) but also for the investigation of the existence of new dark sector particles produced by means of a resonant production mechanism (as the search for a hypothetical X17 state, performed during PADME Run III).

An array of 12 Timepix3 detectors measuring the outgoing beam of the PADME experiment was installed and operated during the dedicated run for X17 search. The presented OP/DAQ and Analysis Framework for synchronous operation of 2×6 Timepix3 array enabled PADME to improve its beam monitor capability and to perform at best its physics program.

Exploiting the sophisticated streaming mode readout of the Timepix sensors, providing pixel time resolution of 1.56 ns, a comprehensive real time information for the beam flux and spread is available.

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