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Operation and performance of the active target of PADME

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ABSTRACT

The PADME experiment at the Laboratori Nazionali di Frascati of the INFN searches for a hypothetical dark photon A', produced in the annihilation between a positron of a beam with an electron of a target. The target is an active component of the experiment; it consists of a thin and large size diamond detector with a pattern of graphitic strips on both sides acting as ohmic electrodes for detector polarization and signal readout. In this paper the operation and performance of the active diamond target, as observed in the first PADME physics run, are reported.

1. Introduction

Despite the strong experimental effort pursued by direct searches and searches at high energy colliders, the nature of the dark matter pervading our universe is still puzzling. This motivated the proposal of a new, hidden gauge sector under which dark matter particles are charged. One of the simplest models introduces one massive vector, called Dark Photon A', corresponding to a broken extra U (1) gauge symmetry [1], which could mix with the ordinary photon and decay, if kinematically allowed, in pairs of dark particles or ordinary fermions. Several experiments around the world are looking for A' in the visible and invisible decay modes.

PADME[2] (Positron Annihilation into Dark Matter Experiment) is searching for A' production through the process $e^+e^- \rightarrow \gamma A'$. The positron beam is produced in bunches of 50 Hz by the LINAC of Laboratori Nazionali di Frascati at an energy of 545 MeV. PADME is the only experiment using an active target and the missing mass method, which is independent from the A' decay mode. The missing mass is evaluated for events with only one photon in the final state and it is defined by the invariant mass of the 4-momentum difference between the initial state particles, positron and electron, and the final photon:

$$M^2_{miss} = (P_{e^+} + P_{e^-} - P_\gamma)^2,$$

which corresponds to the A' mass for signal events. PADME is sensitive to the values of A' mass up to $E_{cm} = \sqrt{2m_e E_{beam}}$= 23.7 MeV/c^2 and mixing parameter $\epsilon^2 > 10^{-6}$ for 4× 10^{13} Positrons On Target (POT). The main sources of background are represented by bremsstrahlung photons and e^+e^- annihilation into 2 (or 3) photons.

The PADME detector consists of an active diamond target, a magnetic dipole, a veto system for charged particles made of scintillating fingers readout by silicon photomultipliers and two electromagnetic calorimeters readout by photomultipliers. The first one is designed to optimize the energy resolution and is made of 616 BGO crystals arranged in a disk with a central hole. The second one is located at small angle is made of 5×5 lead-fluoride crystals. In the invisible decay channel, signal event candidates are selected requiring a single cluster of deposited energy in the BGO calorimeter, not in time with other clusters of deposited energy in the calorimeters and charged particles in the veto systems. Instead, for the visible decay channel, the selection requires the time coincidence of the single cluster with a positron and an electron in the veto systems.

In PADME the active target accomplishes several tasks such as monitoring the beam during data taking, providing a measurement of the number of positrons per bunch, constraining the dark photon production point to reduce the missing mass resolution. A diamond detector is suitable as active target thanks to its low atomic number (Z=6). This allows to limit the bremsstrahlung interactions (cross-section proportional to Z^2), which is the main background, with respect to the signal which scales as the annihilation (cross-section proportional to Z), keeping the pile-up in a 300 ns long bunch at a manageable level.

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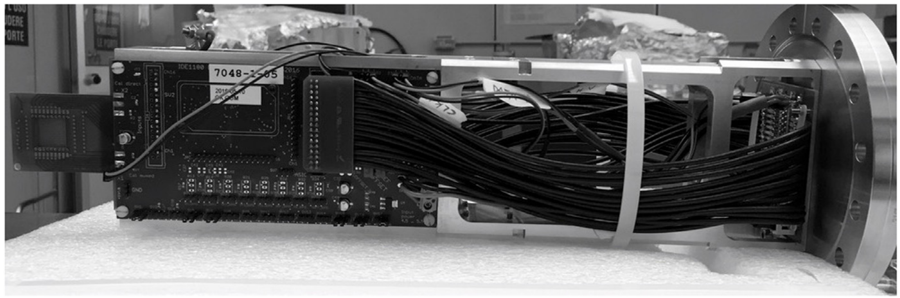

Fig. 1. A photographic picture of the PADME active diamond target before installation.

2. The PADME active diamond target

The sensor of the PADME active target is made of an "as grown" polycrystalline diamond film 100 μm thick grown by Chemical Vapor Deposition (CVD) and cut, using a laser, to an area of 2×2 cm^2 by Applied Diamond Inc. (USA) [3]. In order to have a full carbon active area the strip electrodes were fabricated on the CVD diamond surface by focusing an ArF excimer laser (λ=193 nm) moved by an automated two axis micro-metric scan system at University of Salento and INFN Lecce. This laser-writing technique is capable to produce intrinsic ohmic and radiation-hard electric contacts [4] of any shape on the fragile diamond film without lithography or other risky handling processes [5]. Nineteen graphitic strips 1.9 cm long and 0.85 mm wide were built with a 1 mm pitch on the two sides, oriented in orthogonal directions to reconstruct the horizontal (X view) and the vertical (Y view) beam profile. The graphitic strips exhibit an electric resistance of about 2.5 kΩ.

The doubled-side diamond strip sensor was precisely and symmetrically positioned by a micrometric handling system above the 1.5×1.5 cm^2 hole of a printed circuit board (the inner board) with the X measuring view facing down. The sensor was mechanically connected to the inner board by spots of Araldite glue previously deposited using a dispensing system equipped with a syringe. The electrical contacts between each X graphite strip and the corresponding line on the printed circuit board (PCB), were made by manually filling with a 2-component conductive adhesive glue EPOXY E-solder 3025 passing through holes in the printed circuit with a diameter of 0.75 mm and copper plated. The glue was deposited by a syringe and, during the process, the resistance of the electric connection of the graphitic strip to the inner board was monitored. The Y graphitic strips were interconnected to the inner board by four 25 μm diameter aluminum wires each at INFN Perugia using an automatic wire bonding machine. Several pull tests on the wires made on dummy structure showed a good strength of the bonding aluminum–graphite.

The inner board distributes the high voltage to each strip and it is electrically and mechanically connected by two connectors and four plastic screws to two identical front-end boards outside the beam region. The front-end boards consist of two evaluation boards of the AMADEUS chip made by IDEAS (Oslo) [6]. The integrated circuit AMADEUS contains 16 charge sensitive pre-amplifiers, with 20–40 ns adjustable shaping time and an equivalent-input-charge noise of about 1100 e^-+68 e^-/pF, providing all 16 analog outputs. This allows sixteen graphitic strips per view, out of nineteen, to be AC coupled to charge sensitive pre-amplifiers and the analog signal to be fully digitized and recorded for offline analysis. A picture of the diamond target mounted on the PCB connected to the front-end electronics before installation in the experiment is shown in Fig. 1.

In September 2018 the active target was placed under vacuum in the positron beam line of the Beam Test Facility (BTF) at INFN Laboratori Nazionali di Frascati (LNF) in front of PADME vacuum vessel hosting the PADME magnet and veto detectors. The target is kept in position inside a 10 cm diameter vacuum tight cross by a precisely machined aluminum frame connected to a vacuum flange which can move horizontally by a motorized system and a vacuum bellow. The electrical services, the control signals and the output signals are routed outside the vacuum through a 50-pins vacuum feedthrough connector placed on the movable flange. All PADME detector signals are digitized by CAEN V1742 modules with 12 bit ADC reading 1024 samples of the signal at a rate changing from 1 to 5 GS/s, according to the detector type. The active diamond target signals are sampled at 1GS/s. Fig. 2 shows an example of an analog signal as measured in running condition from a strip centered on the beam spot. The single channel gain of the front-end boards were measured in-situ using a pulse generator and the internal injection charge circuit of the AMADEUS chip. This allows to convert the charge obtained by the waveform integration in the input charge collected by the graphitic strips and, hence, in the multiplicity of particles in the beam bunch.

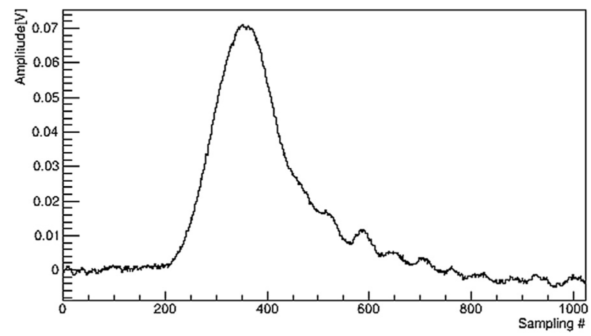

Fig. 2. An example of a representative digitized waveform of the active diamond target. The channel corresponds to x = -1 mm in Fig. 3, the detector bias voltage is 250 V and the positron bunch multiplicity is about 20000 with an energy of 545 MeV.

3. Operations and performance

During the whole run I from September 2018 until February 2019 the active diamond target worked in stable conditions with a constant bias voltage of 250 V, without suffering any discharge and without detectable changes in the leakage current. The target provided the X and Y beam profiles and multiplicity for both the online LINAC and PADME shifters. This allowed the commissioning of the new BTF beam line and the beam parameter optimization for the experiment. In addition, during the data taking periods the beam conditions were also carefully controlled and monitored in time making use of the active diamond target and the online monitor software.

Fig. 3 shows the X and Y profiles of a single bunch of about 20000 positrons. Only one strip out of 32 was found to be unresponsive probably due to a failing electric contact between the strip and the PCB; its signal was emulated interpolating linearly the adjacent strips, as shown in Fig. 3. From the profiles the beam width is estimated as the root mean square of the distribution (~2.4 mm in the horizontal direction and ~2.9 mm in the vertical direction). The mean values

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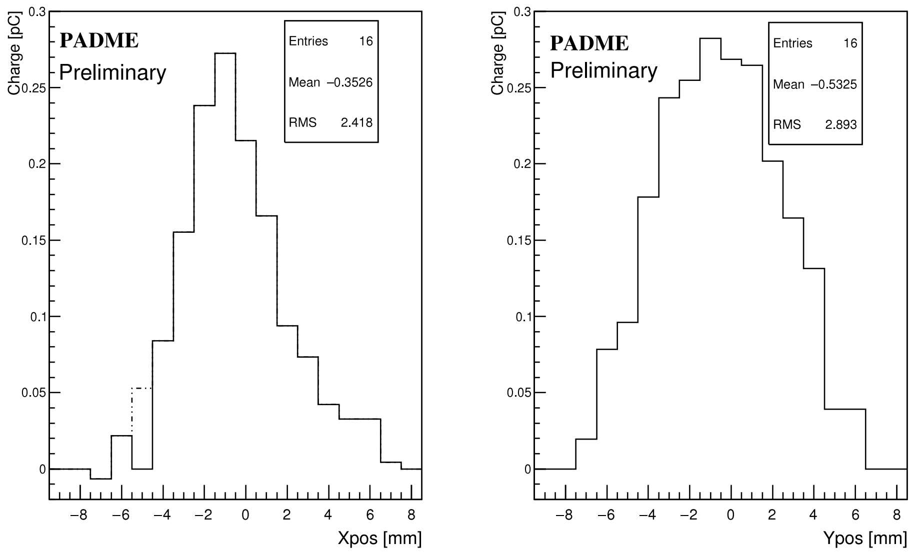

Fig. 3. An example of a single positron bunch profile along X (left) and along Y (right). The dotted line corresponds to an unconnected strip; its signal is calculated interpolating linearly the adjacent strips. The detector bias voltage is 250 V and the positron bunch multiplicity is about 20000 with an energy of 545 MeV.

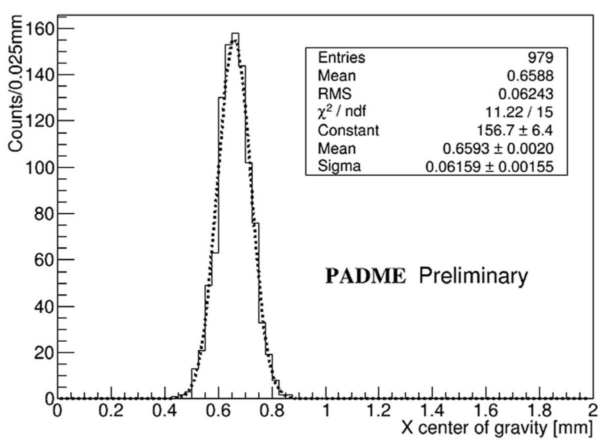

Fig. 4. Distribution of the average positron bunch position as obtained by the charge center of gravity method in the x measuring view. A gaussian fit is superimposed. The detector bias voltage is 250 V and the positron bunch multiplicity is about 20000 with an energy of 545 MeV.

of the beam profiles give an estimation of the average beam position corresponding to the charge of gravity (Fig. 4). Fig. 5 shows the trends of the bunch multiplicity and the average beam position as measured by the active diamond target in a typical run.

The benchmark performance of the detector is the capability to provide precise information of the average beam position in a suitable range of values event by event and accurate measurements of the bunch multiplicity to extract the number of positron on target for each run. In Fig. 4 the spatial resolution of the detector is evaluated to be about 0.06 mm from the distribution of the charge center of gravity for about 1000 events for a bunch multiplicity of about 20000 positrons and an energy of 545 MeV. In Fig. 6 the linearity of the charge center of gravity is estimated by moving the active target along the X axis. The beam was centered on the target at about x=-4 mm and the target was displaced along X in 10 steps of 1 mm each. The method gives a linear response with a slope value of about 0.9 which can be used to correct for the exact position. We can conclude that the statistical and systematic errors on the average bunch position are well inside the experiment requirement of less than 1 mm.

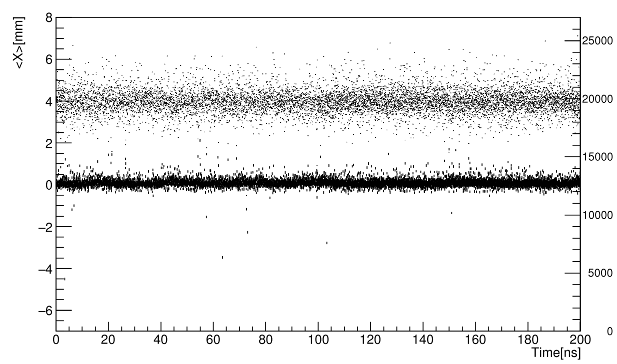

Fig. 5. Trends in time of the average beam position (Y axis on the left) and the positron bunch multiplicity (Y axis on the right) as measured by the diamond target in a typical run.

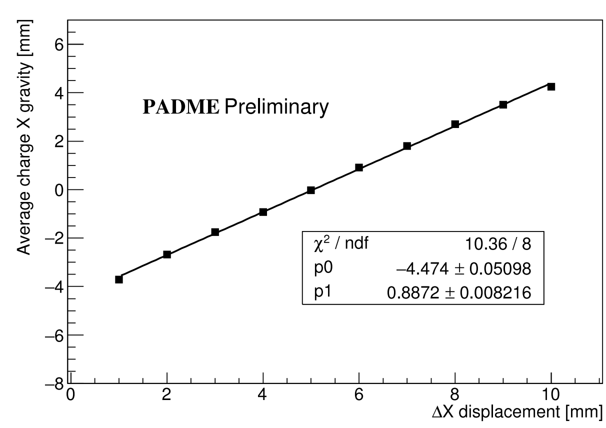

Fig. 6. The average positron bunch position as obtained by the charge center of gravity method along the x direction as a function of detector horizontal displacement. The detector bias voltage is 250 V and the positron bunch multiplicity is about 20000 with an energy of 545 MeV.

The active diamond target was calibrated in term of positron bunch multiplicity by a lead-glass Cherenkov calorimeter working in full containment mode for 545 MeV positrons. The calorimeter was previously calibrated by the BTF experts and used as bunch multiplicity monitor

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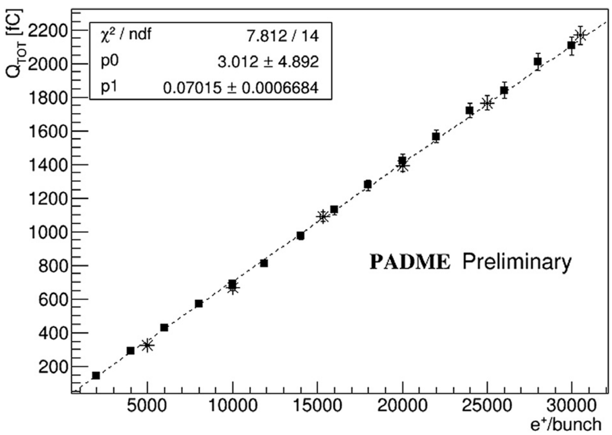

Fig. 7. Total average charge of the x measuring view as a function of the positron bunch multiplicity. The square and star data points correspond to measurements collected in different days. The detector bias voltage is 250 V.

from one single particle to few tens of thousand particles. The cross calibration could not be performed online because the active target is in vacuum. Than at each step of the calibration the beam was extracted in air from a beryllium window by switching-off the last bending magnet and absorbed by the calorimeter without hitting the active target. The calibration was done in an interval of positron multiplicity from 2000 to 30000 in steps of 2000 for a total of 15 data points. The procedure was repeated a week later for 5 data points to verify the reproducibility of the cross-calibration and to exclude drift in time of the active detector response. The results of the target cross-calibration are reported in Fig. 7 and a good linearity and reproducibility is seen.

From this calibration is possible to extract the charge collected for a minimum ionizing particles crossing the detector, which it results to be about $q_c = 0.07$ fC/MIP = 437.5 e − h/MIP, and to extract the charge collection distance (CCD), an important figure of merit for detector-grade diamond.

The CCD is defined as the sensor thickness d multiplied by the ratio of the collected charge q_c and the generated charge q_g by a minimum ionizing particle ($q_g = 36\ \frac{\text{e-h}}{\mu m}\ d$):

$$CCD = d\ \frac{q_c}{q_g} \sim 12\ \mu m.$$

This is only about 10% higher of the CCD value measured with a similar beam with a 50 μm thick CVD sensor from the same supplier [7].

4. Conclusions

A thin and large size CVD diamond detector with graphitic readout strips on both sides has been steadily and successfully operated during the first data taking campaign of the PADME experiment.

The diamond detector performance measured in-situ shows excellent beam monitor capability:

- single bunch X and Y beam profile reconstruction;
- good spatial resolution and linearity observed with a charge weighting algorithm;
- linear response to the multiplicity of the beam bunch of particles.

The PADME active target reached its design aims to provide a measurement of the beam impact point with better than 1 mm precision and to measure the integrated luminosity at the percent level.

It is the first full carbon detector used in a high energy physics experiment.

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