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The performance of the diamond active target of the PADME experiment

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ABSTRACT: A large size, thin, high-quality polycrystalline diamond slab was used to build the full carbon active target of the PADME experiment. PADME is searching for a dark photon of mass up to 23.7 MeV, with a 550 MeV pulsed positron beam provided by the Beam Test Facility of the Laboratori Nazionali di Frascati. The target was built in the laboratories of INFN Lecce and University of Salento by realizing graphitic strips on both sides of a commercial CVD diamond sensor of $2 \times 2\,\mathrm{cm}^2$ cross section and 100 microns thickness, by means of a UV excimer laser. The strips, with 1 mm pitch and oriented in orthogonal directions on the two surfaces, allow to reconstruct two views of the beam profile and to evaluate the particle multiplicity of each bunch. The detector was operated from September 2018 to end of February 2019. Here a review of the status, the operation experience, and the performance of the device in the PADME experiment is presented.

KEYWORDS: Dark Matter detectors (WIMPs, axions, etc.); Detector alignment and calibration methods (lasers, sources, particle-beams); Diamond Detectors

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2020 JINST 15 C04045

Contents

1 Searching for a dark photon with PADME

Elementary particle physics aims to discover and understand the most basic constituents of Nature. Our current knowledge is encompassed in the Standard Model (SM) of particle physics which is remarkably successful in describing the physics of familiar matter to high precision, but it is also known to be incomplete. In particular, the introduction of new physics can describes the dark matter anomaly, can be responsible for neutrino masses and for the matter-antimatter asymmetry in nature. To justify the physics beyond the SM several theories have been proposed. One of these assumes the existence of a dark sector, in which a collection of new particles do not exhibit any charge directly under the SM strong, weak, or electromagnetic forces. Such particles may interact only indirectly with familiar matter through several “portal” interactions that are constrained by the symmetries of the SM. One of the simplest theory suggests the presence of a new abelian Gauge symmetry $U(1)$ added to the SM. The consequence of this field is the creation of a new massive Gauge boson A' called “dark photon”. The A' boson can interact with the standard photon γ through the kinetics mixing:

$$L_{\text{mix}} = -\frac{\epsilon}{2} F^{\text{QED}}_{\mu\nu} F^{\mu\nu}_{\text{dark}} \tag{1.1}$$

where ϵ is the strength of the interaction and it can be as small ($< 10^{-3}$) as to preclude the discovery of the dark photon in most of the experiments.

1.1 The PADME experiment

PADME [1] is seeking for the A' in the invisible decay mode, using the missing mass method. The 550 MeV positron beam of the Frascati Beam Test Facility (BTF) interacting with the electrons of the diamond target can generate a dark photon through the reaction:

$$e^+e^- \to \gamma A' \tag{1.2}$$

up to values of the A' mass of 23.7 MeV. A schematic drawing of the experiment is shown in figure 1.

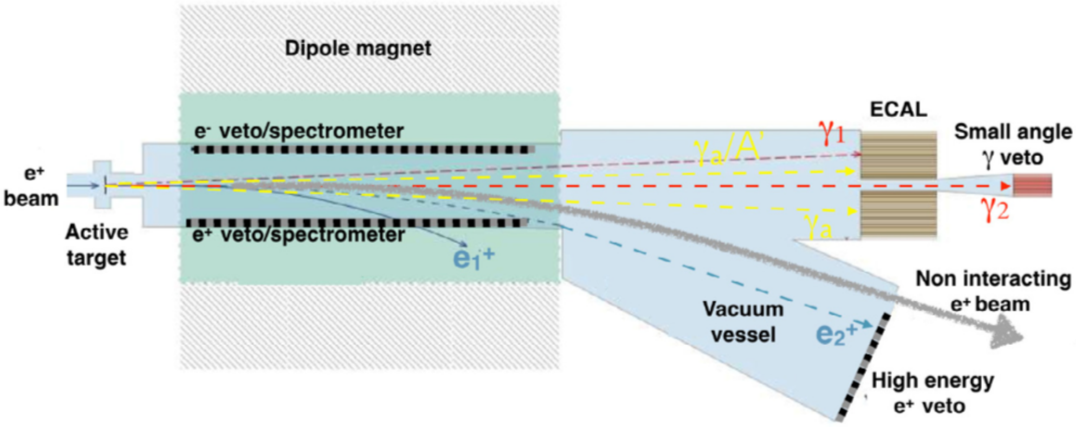

Figure 1. A schematic drawing of the PADME experiment.

The positron beam impinges on the diamond target and those that do not interact are bent by a magnetic field of 0.5 T outside the acceptance of the PADME calorimeters. A veto systems for charged particles, made of two arrays of plastic scintillator bars, is installed inside the magnet in order to veto Bremsstrahlung events and other backgrounds induced by charged particles. To measure energy and direction of the ordinary photons, a cylindrical BGO calorimeter (ECAL) is used, with a central squared hole ($100 \times 100\,\mathrm{mm}^2$) to allow the passage of Bremsstrahlung photons. The central squared hole is covered by the Small Angle Calorimeter (SAC) placed just behind ECAL and made of a 5×5 PbF_2 crystal matrix with a readout based on fast photomultipliers.

2 The diamond target

To allow high resolution on the missing mass evaluation and to measure the beam flux, PADME uses an active target able to reconstruct the beam spot position and the bunch multiplicity.The choice of the target material has been dictated by the need to have the best ratio between annihilation cross-section ($\propto Z$) and background Bremsstrahlung reaction ($\propto Z^2$). In addition, the target should be thin enough (about 100 µm if made of carbon) to reduce the number of pile-up events to a level manageable by the electromagnetic calorimeter of PADME, that is meant to detect the photon coupled with the dark photon, with high energy resolution.

2.1 Design and construction

The PADME target is a full carbon detector made of a polycrystalline diamond film 100 µm thick with a full active area of $2 \times 2\,\mathrm{cm}^2$. It has been realized in the L3 laboratory at the Università del Salento, in collaboration with INFN (DIAPIX experiment), where a system for the manufacturing of nano-graphitic electric contacts on diamond material is available. This system uses a 193 nm UV ArF excimer laser ($\lambda = 193$ nm) [2].

On both detector surfaces there are 19 graphitic strips 1.9 cm long and 0.85 mm wide with a 1 mm pitch, 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 [3]. The

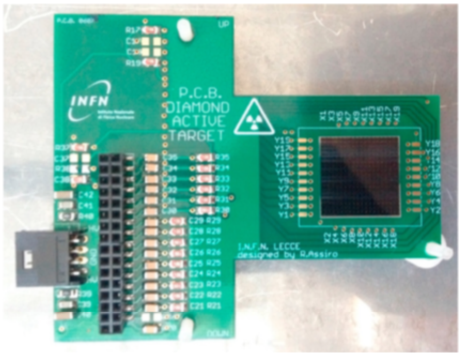

Figure 2. The PADME diamond sensor with graphitic strip mounted on the inner board.

sensor was mounted on a readout board. Figure 2 shows the side of the board with the X view of the target. The electrical contacts between each X graphite strip and the corresponding line on the printed circuit board (PCB), were made manually with a 2-components conductive glue (EPOXY E-solder 3025) filling passing-through copper-plated holes in the printed circuit (diameter 0.75 mm). The glue was deposited with a syringe and during the process the resistance of the electric connection of the strip was monitored. Each Y strip was connected to the inner board by four 25 µm diameter aluminium wires using an automatic wire bonding machine at INFN Perugia. Several pull tests on the wires made on dummy structures showed a good strength of the bonding aluminium-graphite.

The main figure of merit of the detector-grade diamond sensor is the charge collection distance (CCD) defined as $CCD = L \cdot Q_c/Q_g$, where L is the sensor thickness, $Q_g = 36\frac{e^-}{\mu m}L$ [µm] is the charge generated by a relativistic charged particle in the given thickness and Q_c is the charge collected at the electrodes, not trapped in the material bulk. The CCD of the diamond used for the PADME target was measured to be $\simeq 12\,\mu m$ [4].

3 Active Target Performance

During the first data taking (from October 2018 to the end of February 2019) and the beam test made in July 2019, the target provided online the X and Y beam profiles and multiplicity for both the accelerator and PADME shifters. Figure 3 shows the X and Y profiles of a single bunch of about 2×10^4 positrons with an energy of 545 MeV. 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 the figure 3.

The mean value of the beam profiles gives measurement of the position of the beam core which corresponds to the charge center of gravity (figure 4).

The main tasks of the detector are to provide a precise measurement of the average beam position (less than 1 mm) event by event and to measure the bunch multiplicity to extract the number of positrons impinging on the target. In figure 4 the spatial resolution of the detector is

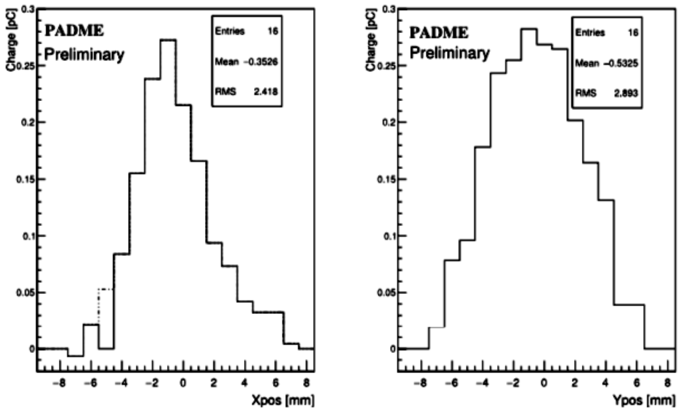

Figure 3. Single bunch beam profile along X (left) and along Y (right). The dotted line corresponds to an unconnected strip; its signal is calculated interpolating linearly the charge measured in the adjacent strips. The detector bias voltage is 250 V, the multiplicity of positrons in a single bunch was 2×10^4 PositronOnTarget and the beam energy was 545 MeV.

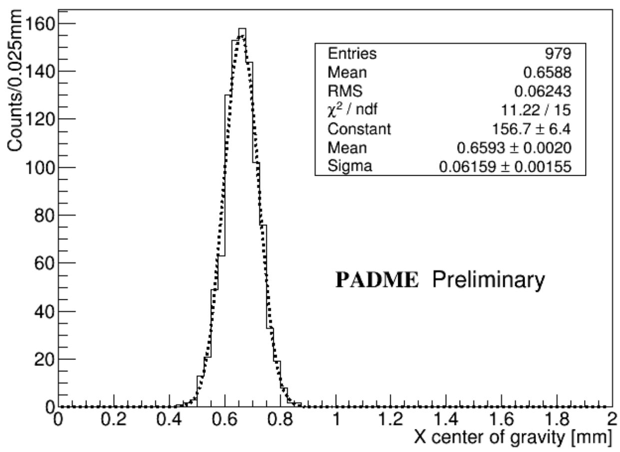

Figure 4. Distribution of the average positron bunch position as obtained by the charge center of gravity method in the X measuring view. A Gaussian fit is superimposed. The multiplicity of positrons in a single bunch was 2×10^4 POT and the beam energy was 545 MeV [4].

evaluated to be about 0.06 mm analyzing the distribution of the charge center of gravity for about 10^3 events with a bunch multiplicity of about 2×10^4 positrons and a beam energy of 545 MeV.

The linearity of the charge center of gravity measurement is estimated by moving the active target along the X axis, see figure 5. 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. This results shows that the statistical and systematic errors on the average bunch position are less than 1 mm, well below the experimental requirement.

The absolute response of the active diamond target was calibrated by a lead-glass Cherenkov calorimeter working in full containment mode for 545 MeV positrons. The calorimeter was used

2020 JINST 15 C04045

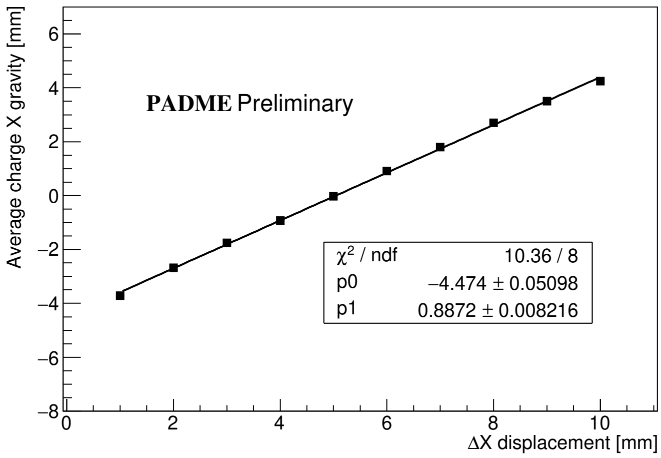

Figure 5. The average beam position as obtained by the charge center of gravity method along the X direction as a function of detector horizontal displacement. The detector bias voltage is 250 V and the positron bunch multiplicity is about 20000 with an energy of 545 MeV [4].

as bunch multiplicity monitor in a dedicated data taking where the beam current was varied. The calibration was done in an interval of positron multiplicity from 2×10^3 to 3×10^4 in steps of 2×10^3 for a total of 15 data points. The procedure was repeated a week later for 5 data points to verify the reproducibility and to exclude a drift in time of the diamond detector response. The results of the target cross-calibration show a good linearity and reproducibility, see figure 6.

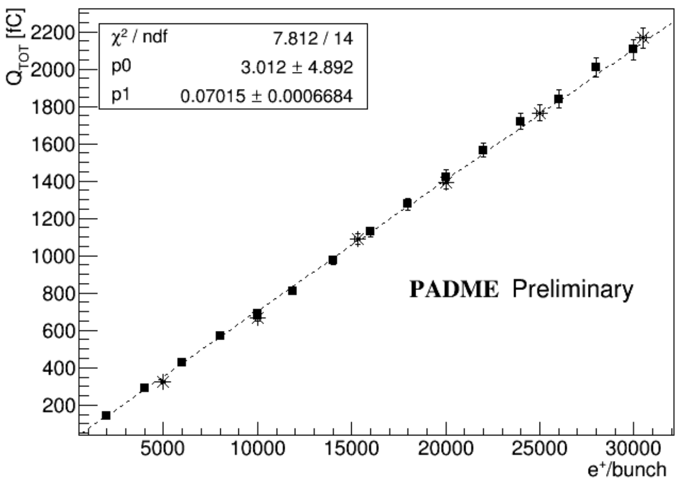

Figure 6. Total average charge of the X measuring view as a function of the positron multiplicity in a bunch. The square and star data points correspond to measurements collected in different days. The detector bias voltage is 250 V [4].

2020 JINST 15 C04045

4 Electromagnetic interactions of the beam in the target

The most abundant processes occurring when the beam hits the target are annihilation and Bremsstrahlung. The former

$$e^+e^- \to \gamma\gamma \tag{4.1}$$

has a close kinematics. Therefore an annihilation event can be recognised from the time coincidence and the ϕ symmetry of the energy clusters in the electromagnetic calorimeter.

The latter

$$e^+N \to e^+N\gamma \tag{4.2}$$

with a photon and a positron with energy lower than the beam energy, are identified in PADME by means of the scintillator bars inside the dipole magnet as a positron detector and spectrometer.

The comparison between the data collected in a standard run ($2 \times 10^4 e^+$/bunch) and those of a special run with the same beam configuration but the target off the beam line (next section) allows to establish a clear evidence for both processes.

4.1 Annihilation events

The annihilation process is identified in PADME by detecting two photons using either ECAL and SAC. It is very difficult to detect the photons when one or both are inside the acceptance of the SAC, because of the huge number of photons coming from Bremsstrahlung and leaving a signal there. In ECAL, the Bremsstrahlung background is less abundant and therefore it is possible to discriminate the annihilation photons. For this study, only events with both photons detected inside ECAL are used. The first selection request is the time coincidence $\Delta t = | t_{Cl_1} - t_{Cl_2} | < 3$ ns between two reconstructed clusters in the detector. Energy and momentum conservation imply that the two clusters have coordinates and energy correlated, such that:

$$CoG_x = \left| \frac{x_{cl_1} \cdot E_{cl_1} - x_{cl_2} \cdot E_{cl_2}}{E_{cl_1} + E_{cl_2}} \right| < 1.\,\text{cm} \tag{4.3}$$

$$CoG_y = \left| \frac{y_{cl_1} \cdot E_{cl_1} - y_{cl_2} \cdot E_{cl_2}}{E_{cl_1} + E_{cl_2}} \right| < 1.\,\text{cm} \tag{4.4}$$

where the $x(y)_{cl_{1(2)}}$ is the $x(y)$ position of the selected cluster and $E_{cl_{1(2)}}$ is its energy. Through this cut based analysis we can study the two photons that came from the annihilation. These events show a peak at $E \simeq E_{\text{beam}}$ in the distribution of:

$$E_{Cl_1} + E_{Cl_2} = E_{\gamma_1} + E_{\gamma_2} \tag{4.5}$$

where $E_{Cl_{1(2)}}$ is the energy of the photons that passed the selection.

If the target is removed from the beam line, no annihilation occurs and the $E_{Cl_1} + E_{Cl_2}$ spectrum exhibits only a shoulder at low energy from pairs of background energy deposits accidentally satisfying the selection cuts.

This is clearly shown in figure 7 where the red histogram corresponds to a standard data-taking run and the blue one corresponds to a data taking with the target off the beam line.

2020 JINST 15 C04045

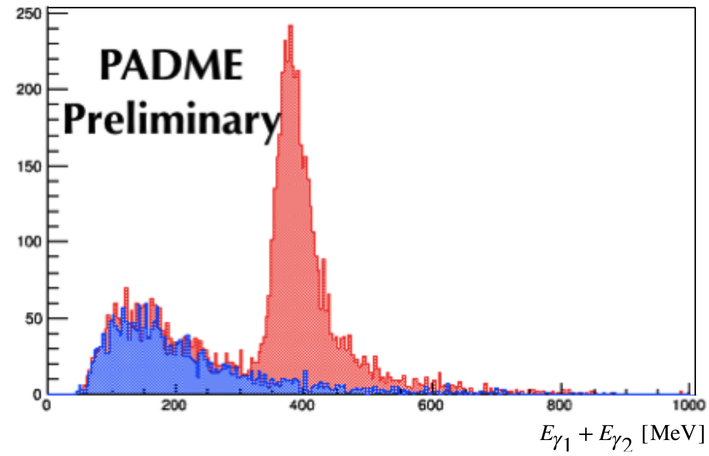

Figure 7. Sum of the energy of the two candidate photons originating from an annihilation process. In red the events selected in the standard run, in blue the same variable in a special run without the target.

4.2 Bremsstrahlung events

To detect Bremsstrahlung events the positron veto (PVeto) [5] is used along with the SAC. The lower energy positron after Bremsstrahlung gives a hit in the PVeto in coincidence with a cluster in the SAC due to the photon. Therefore, after requiring $\Delta t = | t_{cl_{\text{SAC}}} - t_{cl_{\text{pveto}}} | < 1$ ns the correlation between the energy of the cluster in the SAC and the curvature of the positron trajectory, measured by the position of the hit in the PVeto, provides evidence for Bremsstrahlung interactions.

In figure 8 (right) such correlation is shown. The PVeto channel identifier Ch_{id} is proportional to the z coordinate of the impact point of the positron on the detector and hence is indicative of the kinetic energy of the charged particle. A clear evidence of this correlation is observed in a standard run (plot on the right), which disappears as soon as the target is removed from the beam line (plot on the left).

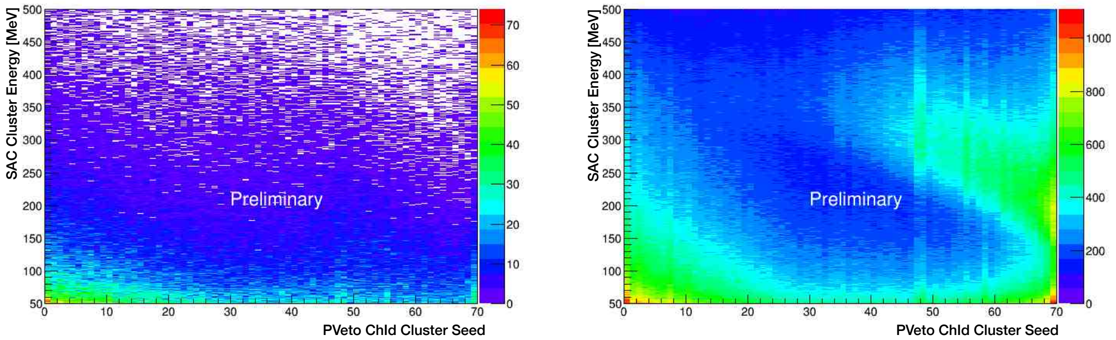

Figure 8. Energy of the photon in the SAC as a function of channel identifier of the scintillator bars hit by the positron after Bremsstrahlung. On the left the data correspond to the special run without the target, on the right data collected in standard data-taking conditions are shown.

5 Conclusions

The PADME experiment is designed to test the dark photon hypothesis, for values of the mass below 23.7 MeV using the missing mass technique in e^+e^- annihilations. The 100 μm thick diamond active target has the essential role of proving a measurement of the profile and flux of the positron beam. The response of the target, observed with early PADME data, shows the capability to follow the displacement of the beam with a spatial resolution on the centroid well below the design requirements. The detector exhibits also a linear response to the multiplicity of positrons in each bunch of the beam.

Acknowledgments

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