A thin large size active diamond target for a dark photon search experiment

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The Lecce group is responsible for the design, construction and operation of the diamond active target of PADME, a new experiment proposed to search for a dark photon in the annihilation of e^+e^- at INFN Laboratori Nazionali di Frascati.

The compelling cosmological evidence for dark matter is still missing an experimental observation at microscopic level of non-ordinary particles representing elementary constituents of the dark matter. This might be the natural consequence of scenarios where the new particles do not interact directly with ordinary matter but manifest themselves only through "portal" fields connecting our world with new "hidden" sectors.

A theoretically simple and well motivated model assumes the existence of an abelian gauge symmetry U(1), in addition to the Standard Model gauge symmetry group, whose gauge boson, the dark photon U, couples directly to the matter fields of the hidden sectors and mixes to the Standard Model (SM) photon thus providing a connection with the visible sector.

Dark photons were searched in accelerator experiments by looking for resonant fermion pair production in meson decays from beam dumps, or in e^+e^- collisions, but no evidence was found so far [1].

At Laboratori Nazionali di Frascati an alternative approach is proposed for the new experiment PADME. At the Beam Test Facility (BTF), the invisible decay of a dark photon will be searched in positron-electron annihilations by triggering on single photon final states and reconstructing the missing mass of the event [2].

The PADME detector should be built in 2017. The dark photon mass range accessible with PADME extends from 1 MeV to 23.7 MeV, given the present maximum positron energy of 550 MeV of the LNF linac. The beam of BTF has a bunched structure. At present 10.000 e^+ are delivered in a bunch 20 ns long at the rate of 50 Hz.

A data taking campaign of about six months in 2018 should ensure exclusion limits for the dark photon coupling ϵ of about 0.001, for a bunch length of 40 ns (corresponding to 10^{13} e^+ on target), or about 0.0005, for a bunch length of 480 ns (corresponding to 10^{14} e^+ on target).

The sensitivity of the experiment is sufficient to confirm or reject the hypothesis that the discrepancy between the expected and measured value of the muon anomalous magnetic moment (more than a 3 sigma effect) is due to virtual corrections related to a dark photon of mass in the MeV range. In the Standard Model, the leading QED correction to the g-2 is about $\frac{\alpha_e}{4\pi} \approx 10^{-3}$ for both the electron and muon magnetic anomaly. A dark photon with a mass much smaller than the muon mass and much higher than electron mass, would contribute to the muon g-2, but not the electron g-2. The size of teh correction to the muon g-2 would be $\Delta(g-2)_\mu \approx 10^{-9} \approx \frac{\alpha_e}{4\pi}\epsilon^2 \approx 10^{-3}\epsilon^2$, which means $\epsilon \approx 10^{-3}$, a value in the reach of the PADME experiment.

Events from e^+e^- annihilation producing a dark photon (see the diagram in fig. 1) manifest themselves as a final state with only one photon. The U boson is unobserved, but its mass can be computed from the kinematics of the well known initial state (the beam) and the final state photon. Therefore, a signal for dark photon in PADME would be a peak, at the value of the U boson mass, in the distribution of the missing mass computed in single-photon events. In order to improve the resolution on the missing mass, the PADME experiment will measure bunch-by-bunch the beam position and profile on the carbon nuclear target. The adopted solution is to build a thin diamond active target providing a spatial resolution better than 1 mm in the two directions X and Y transverse to the beam.

Our group in Lecce proposed to build a full carbon active target of PADME with a polycrystalline diamond sensor where the electrodes on both side are graphitic strips produced on the diamond surface by a controlled irradiation process by an excimer laser [3]. The advantages of this technique developed in Lecce, compared to the use of traditional metallic electrodes, are

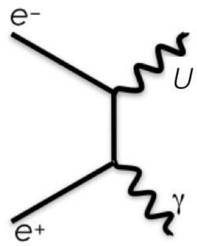

Figure 1. Feynman diagram for U boson (dark photon) production in annihilation of a positron with an eletron of the target.

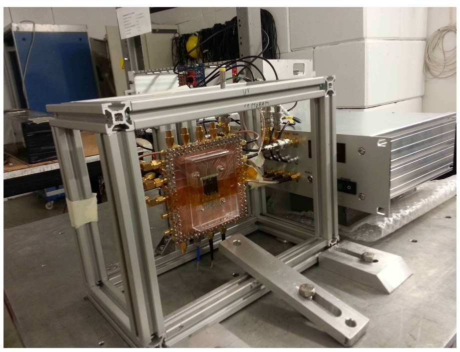

Figure 2. First full carbon PADME active target prototype realized in Lecce.

twofolds: first of all, the target is entirely made of an homogeneous light Z material, thus limiting the rate of the most abundant background process which is QED bremsstrahlung, in addition the damage probability, due to manipolation, is reduced. The target will have a thickness between 50 and 100 μm, to minimize the photon re-interaction, and a cross section of about 2x2cm^2, to intercept the whole positron beam profile. Diamond wafers such thin and large were never used so far and they are expected to be quite fragile to work with.

The active target is segmented on both sides with 1 mm pitch orthogonal strips. The strip geometry has been preferred to a pixel segmentation to allow all materials related to front-end electronics to sit outside of the beam cross section area. As a consequence, the active target can reconstruct only X and Y profile of the beam independently, but it cannot provide bunch by bunch a two dimensional beam mapping.

With respect to diamond detector "state of the art", the most challenging aspect of an active diamond target for the PADME experiment is related to the small thickness and large area. On the other hand, the quite low signal (CCD $<$ thickness/2) for a MIP particle is not a problem for PADME, because the bunch of electrons is composed of few thousand particles. Nevertheless, response uniformity, gain fluctuations and linearity are important for the overall performance of the active target and must be carefully measured.

In October 2015, a full size active target diamond prototype was build in Lecce with strips on the two surfaces oriented in orthogonal direction and having a pitch of 1 mm, using an UV ArF excimer laser (see Fig. 2). The prototype was tested in November 2015 at the Beam Test Facility (BTF) at INFN Laboratori Nazionali di Frascati using e^+e^- beams of about 450 MeV energy. The preliminary results show a very good spatial resolution of about 0.2 mm on the average X and Y beam position for bunch multiplicity of about 10,000 particles (see Fig. 2).

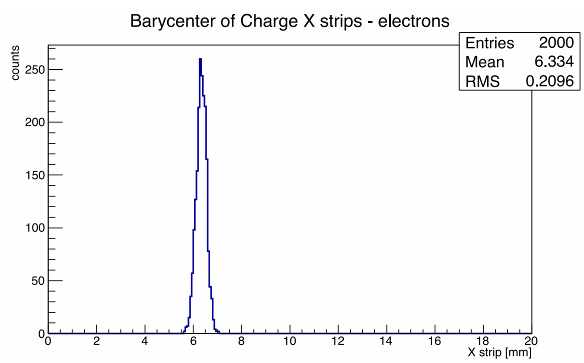

Figure 3. Distribution of the BTF beam X position estimated by the charge weighting method applied to the PADME diamond active target prototype realized in Lecce.

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