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Development and test of a DRS4-based DAQ system for the PADME experiment at the DAΦNE BTF

E Leonardi[1], **M Raggi**[1,2] **and P Valente**[1]

[1] INFN Sezione di Roma, Piazzale Aldo Moro 5, 00185 Rome, Italy
[2] “Sapienza” University of Rome, Piazzale Aldo Moro 5, 00185 Rome, Italy

Abstract. A possible Dark Matter model postulates that it interacts with Standard Model particles only through a massive photon-like vector particle, called dark photon or A'. The PADME experiment at the DAΦNE Beam-Test Facility (BTF) in Frascati is designed to detect dark photons produced in positron on fixed target annihilations decaying to dark matter ($e^+e^- \rightarrow \gamma A'$) by measuring the final state missing mass. The DAQ system of the PADME experiment will handle a total of 921 channels, with a DAQ rate of 50 Hz. All channels will be acquired using the CAEN V1742 board, a 32 channels 5 GS/s digitizer based on the DRS4 chip. Two such boards were successfully used during the 2015 and 2016 tests at the BTF, where a complete DAQ system, prototypal to the one which will be used for the final experiment, was set up. In this paper we will report on the details of the DAQ system, with specific reference to our experience with the V1742 board.

1. Introduction

The long standing problem of reconciling the cosmological evidence of the existence of dark matter with the lack of any clear experimental observation of it, has recently revived the idea that the interaction of the new particles with the Standard Model (SM) gauge fields is not direct but occurs through “portals”, connecting our world with new “secluded” or “hidden” sectors. One of the simplest models introduces a single U(1) symmetry, with its corresponding vector boson, called Dark Photon or A'. In the most general scenario, the existence of dark sector particles with a mass below that of A' is not excluded: in this case, so-called “invisible” decays of the A' are allowed. Moreover, given the small coupling of the A' to visible SM particles, which makes the visible rates suppressed by ε^2 (ε being the reduction factor of the coupling of the dark photon with respect to the electromagnetic one), it is not hard to realize a situation where the invisible decays dominate. There are several studies on the searches of A' decaying into dark sector particles, recently summarized in [1][2].

At the end of 2015 INFN formally approved a new experiment, PADME (Positron Annihilation into Dark Matter Experiment) [3][4], to search for invisible decays of the A'. Aim of the experiment is to detect the non-SM process $e^+e^- \rightarrow \gamma A'$, with A' undetected, by measuring the final state missing mass, using a 550 MeV positron beam from the improved Beam-Test Facility (BTF) of the DAΦNE Linac at the INFN Frascati National Laboratories [5]. The collaboration will complete the design and construction of the experiment by the end of 2017 and will collect $O(10^{13})$ positrons on target in two years starting in 2018, with the goal of reaching a $\varepsilon \sim 10^{-3}$ sensitivity for dark photon masses up to a maximum of $M_{A'} \sim 24$ MeV/c^2, limited by the available c.o.m. energy.

The experiment, shown in figure 1, is composed of a thin active diamond target, to measure the average position and the intensity of the positrons during a single beam pulse; a set of charged particle veto detectors immersed in the field of a 0.5 Tesla dipole magnet to detect positrons losing their energy due to Bremsstrahlung radiation; and a calorimeter made of BGO crystals, to measure/veto final state photons. As the rate of Bremsstrahlung photons in its central region is too high, the calorimeter has a hole covered by a faster photon detector, the small angle calorimeter (SAC). The apparatus is inserted into a vacuum chamber, to minimize unwanted interactions of primary and secondary particles that might generate extra photons. The maximum repetition rate of the beam pulses is 50 Hz.

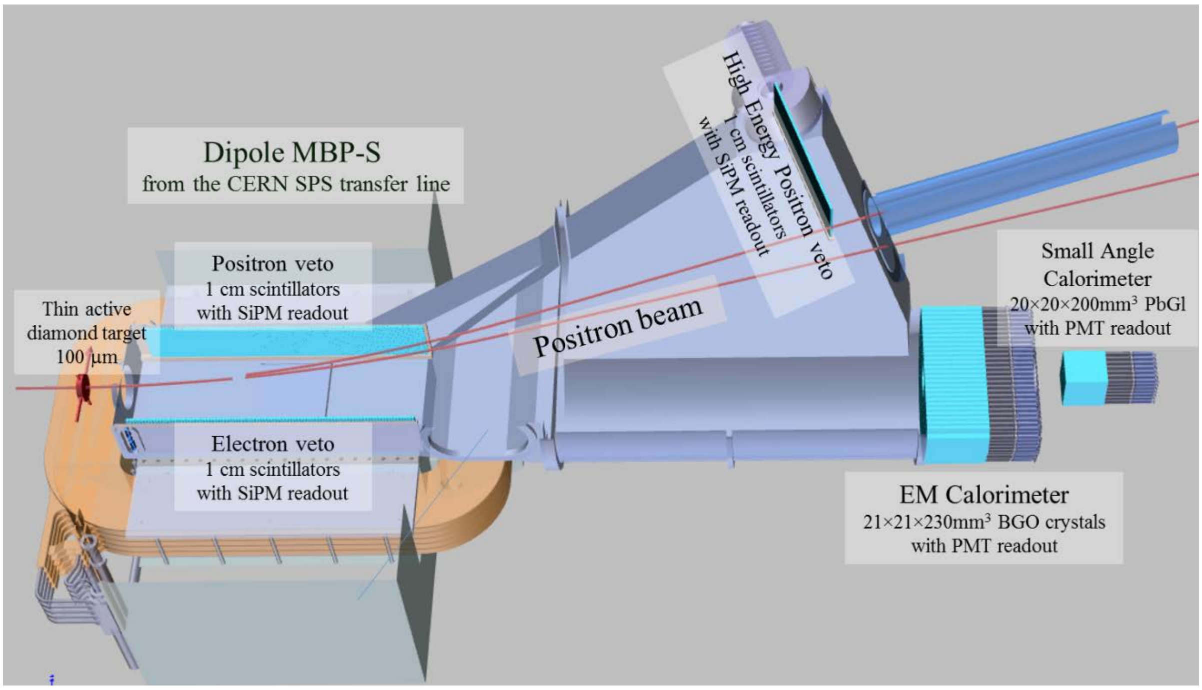

Figure 1. The PADME experiment as seen from above. The positron beam travels from left to right.

The 921 channels of the experiment will be read by DRS4-based FADC boards and the resulting data will be written to ROOT files to be used for analysis. This paper describes the DAQ system that will be used for the PADME experiment, with special attention to the DRS4 characteristics, and reports on the first results obtained with a DAQ system prototype used during several testbeams at the BTF in 2015 and 2016.

2. The PADME Detector

2.1. The diamond target

The incoming e^+ beam impinges on an active diamond target. The reason to choose this material is that, due to its low Z, diamond is the rigid material with the best ratio between the annihilation and the Bremsstrahlung processes.

The target consists of a 20×20 mm^2 polycrystalline diamond with a thickness of 100 μm. Two orthogonal sets of 19 readout strips with a pitch of 1 mm are graphitized with laser on the two sides of the diamond and used to read the X and Y coordinates of the impinging particles [6].

The final target will measure the position of the beam with an expected spatial resolution < 1 mm and its total charge with a precision better than 10%.

The first prototypes of the target were successfully tested at the BTF in 2015 and 2016 [7].

2.2. The electromagnetic calorimeter

The recoil photon from the $e^+e^-\rightarrow\gamma A'$ process will be detected by an electromagnetic calorimeter positioned 3 m downstream from the target (figure 2). It consists of 616 BGO crystals recovered from one of the electromagnetic end-caps of the L3 experiment at CERN [8]. The crystals are cut to a $21\times21\times230$ mm^3 shape and arranged in a roughly cylindrical shape with ~60 cm diameter. To avoid the pile-up of low-angle Bremsstrahlung photons, a squared hole of 5×5 crystals is left in the central region of the calorimeter. Light coming from the crystals is read by 19 mm diameter PMTs.

The expected energy and angular resolutions of the calorimeter are $\sigma(E)/E < 2\%/\sqrt{E}$ and $\sigma(\theta) < 2$ mrad, respectively.

A prototype of the calorimeter, composed by a 5×5 array of BGO crystals, was successfully tested at the BTF in 2016 [9].

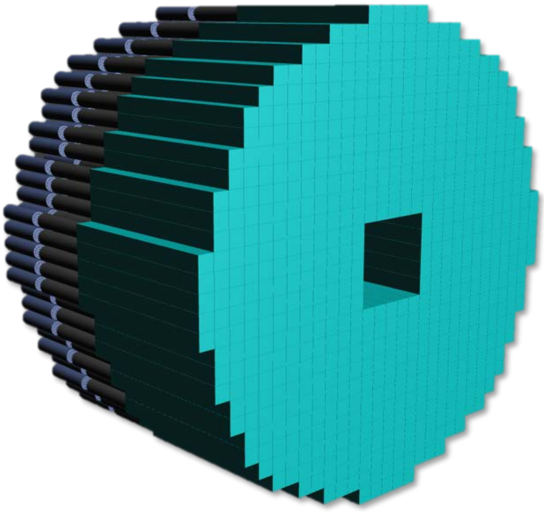

Figure 2. The BGO electromagnetic calorimeter. Front view.

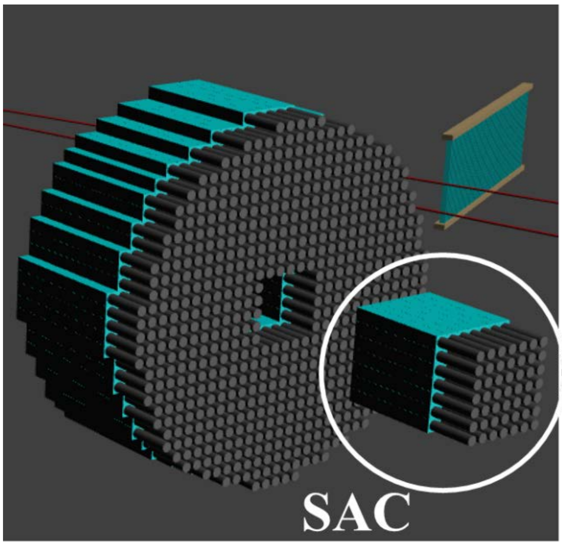

Figure 3. The Small Angle Calorimeter (SAC). Rear view.

2.3. *The small angle calorimeter*

In the region immediately around the axis of the incoming beam the rate of photons emitted by Bremsstrahlung process in the target is too high to be resolved by the BGO crystals, which have a relatively slow 300 ns signal decay time. The central hole of 5×5 crystals left in the electromagnetic calorimeter is therefore covered by a much faster small angle calorimeter (SAC) positioned immediately behind it (figure 3).

The SAC is composed by an array of 7×7 SF57 lead-glass blocks with a $20\times20\times200$ mm^3 shape coupled with a fast PMT readout system and can resolve the foreseen rate of O(10) photons with $E > 50$ MeV in a single 40 ns beam spill.

2.4. *The charged particles veto system*

Charged particles coming from Bremsstrahlung and Bhabha scattering events, two relevant background processes, will be detected by a charged particles veto system. This is composed by three independent detectors: one for electrons, one for positrons with energy below that of the incoming beam, and one for positrons with energy close to that of the beam.

Each of the three detectors will be composed by a linear array of $10\times10\times184$ mm^3 plastic scintillator fingers with a SiPM readout system. The low energy electron and positron veto arrays will be positioned along the internal walls of the bending magnet, a 0.5 Tesla dipole on loan from the CERN PS, while the high energy positron veto will be positioned perpendicular to the outgoing beam direction in proximity of the beam exit duct.

The expected time resolution of the veto system is < 1 ns with a MIP detection efficiency > 99%. By measuring the impact point along the axis parallel to the direction of the incoming beam, it will also measure the charged particle momentum with a resolution of a few percent.

3. The PADME DAQ system

The PADME DAQ system will read data from 921 channels, detailed in table 1, with an expected acquisition rate of 50 Hz, defined by the DAΦNE Linac duty cycle.[1]

Table 1. Number of DAQ channels for each PADME detector

Detector	Channels
Diamond target	32
Electromagnetic calorimeter	616
Small angle calorimeter	49
Charged particles veto system	224
Total	921

All channels will be connected to a set of FADC boards based on the DRS4 chip (described later) which will acquire the data with a sampling rate varying from 1 to 5 GHz, depending on the detector characteristics: the relatively slow signal (τ_{decay} ~ 300 ns) produced by the BGO crystals will be sampled at 1 GHz while the faster signal from the other detectors will be sampled at 5 GHz.

A Trigger Distribution System will generate a configurable common trigger signal, based on the main BTF trigger, on a cosmic trigger for calibration, and on a software/random trigger, which will be distributed to all DAQ boards.

At the level 0 (L0) of the DAQ system, data from each FADC board will be read by individual DAQ processes running on a farm of front-end servers, connected to the boards via optical link, and will be written to independent output files on a temporary disk buffer after applying a zero suppression algorithm tuned to the specific detector.

At the level 1 (L1) of the DAQ an Event Builder process will collect data from all boards and merge them in the so-called RAW data structure which will then be written to ROOT-based [10] output files. Within the event building process, a set of filter algorithms will tag each event according to its characteristics and add this information to the RAW event structure. After the RAW file is created, a garbage collection system will eliminate the individual board files from the temporary disk buffer.

The resulting RAW files will finally be copied to the Central Data Recording Facility at the experiment's Tier1 site, where the reconstruction and analysis of the data will be performed.

Figure 4 shows the PADME DAQ system logical schema, including an example of two possible filter algorithms to be used at L1.

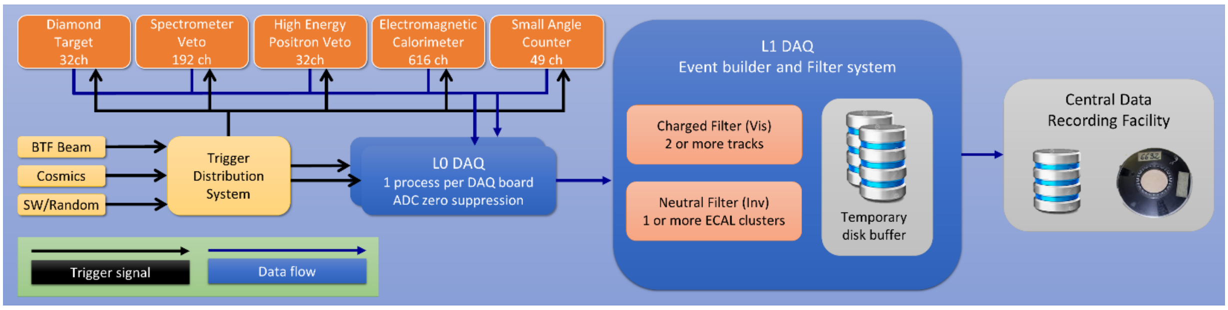

Figure 4. Logical schema of the PADME DAQ system.

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[1] One bunch per second is used by the Linac for beam energy measurements and is not sent to BTF, so that the effective rate is of 49 bunches per second.

4. The DRS4 chip and the CAEN V1742 board

The DRS4 chip[2] was developed at the PSI (CH) by Stefan Ritt and Roberto Dinapoli for the MEG experiment [11]. It consists of a 1024 cells switched capacitor array (SCA) with a tuneable 12bit sampling rate going from 0.7 to 5 GS/s on 8+1 channels (1 channel is dedicated to the sampling of the trigger signal). The incoming analog waveform is continuously stored in the 1024 sampling cells; a trigger signal stops this process and starts the digitization process of the cells' content.

Using 4 of these chips, CAEN produced a commercial VME module, the CAEN V1742 board [12], shown in figure 5. This board has 32+2 input channels (2 channels are dedicated to the trigger signals) organized into 2 groups of 16+1 channels with a 1 Vpp input dynamics. Sampling rate can be selected at 5, 2.5, and 1 GS/s. The board also includes a 128 events memory buffer and offers both a VME64X-compliant interface and an optical link compatible with the CAEN A3818 PCI Express board which can control up to 32 boards over 4 independent links with a maximum transfer rate of 80 MB/s per link. Due to the digitization process used by the DRS4 chip, the complete readout of an event introduces a 110 μs (181 μs if trigger signals are also digitized) dead time, which is comfortably compatible with the 50 Hz trigger rate of the PADME experiment.

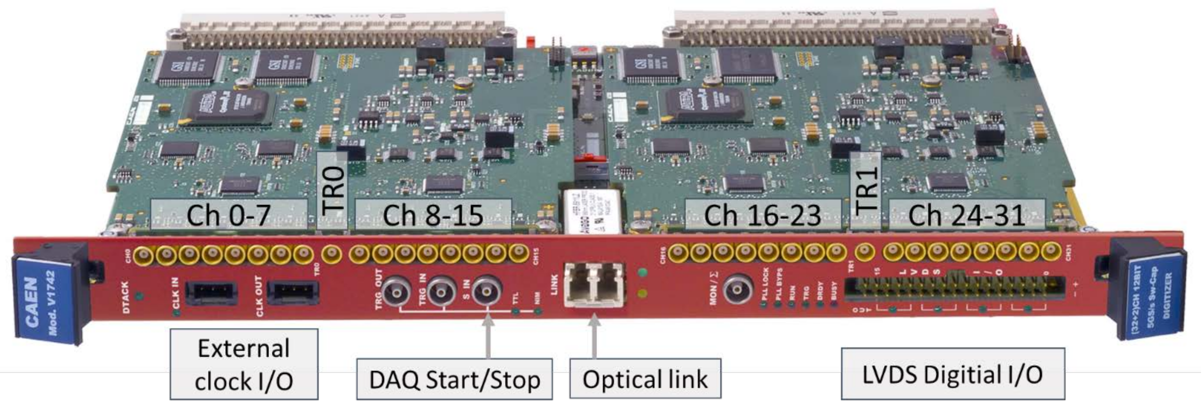

Figure 5. The CAEN V1742 board.

In a version of the board specifically modified for PADME, the input dynamics was increased to 2 Vpp and the 700 MS/s sampling rate of the DRS4 chip was enabled and made selectable via the board firmware: this was aimed at optimizing the digitization of the relatively long signals coming from the electromagnetic calorimeter.

5. The DAQ system prototype

A prototype of the full DAQ system was tested during the 2015 and 2016 testbeams at the BTF. Two V1742 boards were used in parallel to acquire data from the 5×5 crystals prototype of the electromagnetic calorimeter, from the first implementation of the diamond target, and from a small version of the charged particles veto system.

The full DAQ chain (L0+L1) of the experiment was active: L0 produced two independent streams of output files, one stream per board, which were then merged by the Event Builder into a single ROOT file, subsequently used for analysis.

The system also included a fully functional Run Control module to handle the configuration and execution of the data acquisition runs. Interaction with the Run Control was possible via a text-based

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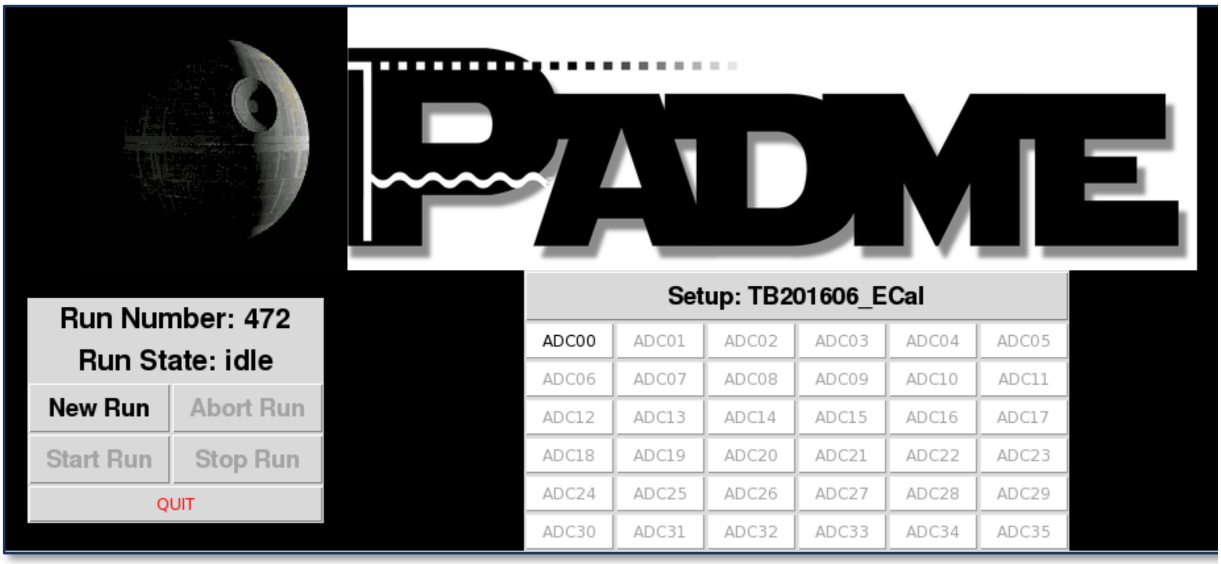
[2] `https://www.psi.ch/drs/DocumentationEN/DRS4_rev09.pdf`

interface over which a graphical user interface, based on the Tk library [13] and shown in figure 6, was built. The current version of the software is available from GitHub.[3]

This prototype allowed the verification of the correct functioning of the conceptual design of the PADME DAQ system. Specific care was dedicated to the precise matching of event parts, based on the relative timing of the two boards. This study showed a slow drift of O(1ppm) of the boards internal clocks. Taking this into account, the final DAQ system was modified to include a common clock source to be distributed to all V1742 boards via the External clock I/O connection.

The tests also confirmed the expected total throughput from a fully populated board: the size of each event is ~54 KiB, including the sampling of the trigger signals, corresponding to a total data rate of ~2.6 MiB/s for the 49 triggers per second produced by the BTF line. Extrapolating these numbers to the full experiment, where the 921 total channels will be read by 30 V1742 boards, we expect a total data rate of the order of 80 MiB/s. This data rate will be acquired by a set of four A3818 boards, for a total of 16 optical links, mounted on two server nodes: given the maximum transfer rate of 80 MB/s per link, this configuration should amply support the experimental throughput. The real amount of RAW data written to disk will depend on the effectiveness of the zero suppression algorithm: some preliminary (conservatives) estimates give a final RAW data rate below 10 MB/s.



Run Number: 472
Run State: idle

Setup: TB201606_ECal

Figure 6. The PADME Run Control graphical user interface is based on the Tk library.

6. Conclusions

The PADME experiment will search for the dark photon A' with mass up to 24 MeV/c^2 in the annihilation process $e^+e^-\rightarrow\gamma A'$, with A' undetected, using the Beam-Test Facility of the DAΦNE Linac at the INFN Frascati National Laboratories. Data taking will start in 2018 and will collect $O(10^{13})$ e^+ on target in 2 years.

The DAQ system will handle the data coming from the 921 channels of the experiment using a set of DRS4-based FADC boards. The system will include a L0, where data are read from the boards and written to file after applying a zero-suppression algorithm, and a L1, which will merge the collected events, tag them according to their characteristics, and write them to ROOT-based output files.

A prototype of the full DAQ system, based on the CAEN V1742 board, was successfully used during several teastbeams at the BTF in 2015 and 2016.

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