Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

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Journal of Physics: Conference Series **2374** (2022) 012189 doi:10.1088/1742-6596/2374/1/012189

A novel cylindrical detector for borehole muon radiography.

Luigi Cimmino*[1,2], Fabio Ambrosino[1,2], Mariaelena D'Errico[1,2], Vincenzo Masone[2], Lorenzo Roscilli[2] Giulio Saracino[1,2]

[1]University of Naples Federico II.
[2]INFN sezione di Napoli.

E-mail: cimmino@na.infn.it

Abstract. Muography (or muon radiography) is a recent imaging methodology that uses cosmic muons to investigate the mass distribution in large objects, such as volcanoes or mines, or to detect the presence of cavities in the subsoil or within buildings such as the pyramids. In recent years detectors with different geometries, sizes and technologies have been developed. In particular detectors with reduced size, that can be inserted in a borehole, are of particular interest in geophysical applications. We have developed, and patented, an innovative detector for well applications consisting of plastic scintillators with arc shape and rectangular section bars. Good spatial resolution was achieved with a reasonable number of channels. Detailed simulations based on Monte Carlo methods have shown excellent performance in cavity detection. Preliminary results of a prototype show good performance in terms of the number of photoelectrons produced by cosmic muons and track reconstruction.

1. Introduction

Direct imaging of the interior of a large body can be done with radiographic imaging exploiting muons. This methodology is called Muography and in muographic applications one measures the absorption of muon flux inside matter. The density of the material passed by muons is extrapolated by means of two-dimensional maps. Detectors with planar geometry and active surface of order of square meters is usually used in muographic application. Muon radiography is nowadays used in the field of archeology [1, 2, 3, 4], geophysics and other [5].
Borehole cylindrical detector are suitable to some archaeological application. Detector with planar geometry is usually used in Muography, but this is not the optimal choice for the use in boreholes, where a cylindrical geometry optimize the geometrical acceptance.

2. The Cylindrical Detector

The detector has been designed to have a diameter of 24 cm, in order to fit into a well with a diameter greater than 25 cm drilled with ordinary drilling machines at a standard cost. The detector is equipped with plastic scintillators (DETECT-Europe UPS-932A) in the shape of an arcs and bars, both with rectangular section (see fig. 1). Scintillators are read by Silicon photomultipliers (SiPMs) S13360-3050PE manufactured by Hamamatsu; the bars are coupled to SiPMs at both ends and the arcs are coupled only to one end. The photosensor is soldered onto a dedicated printed circuit board (PCB) and connected to a two-pin connector mounted

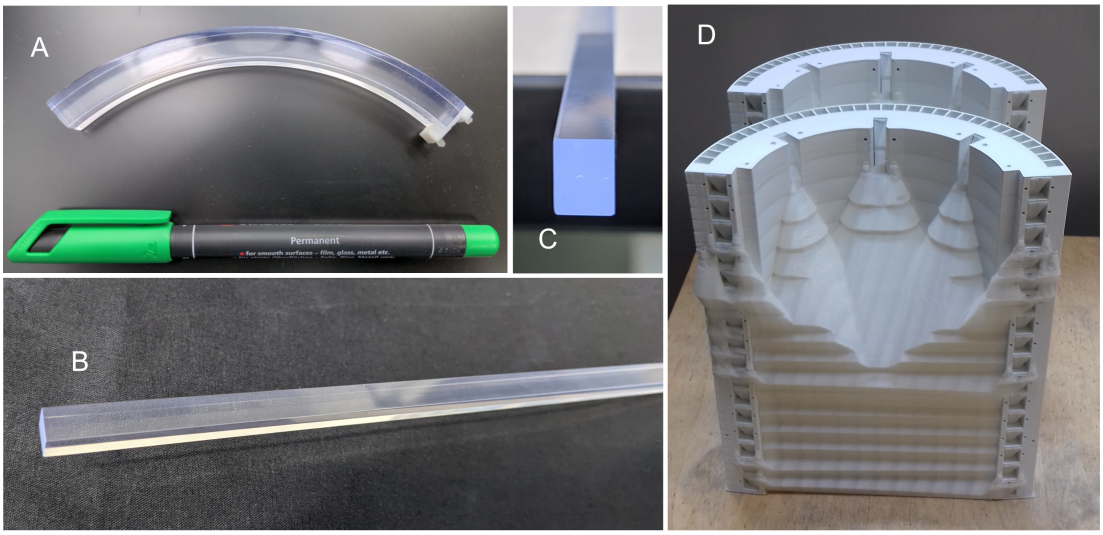

Figure 1: Details of the detector components. **A** - arc-shaped scintillator. **B** - 1 m long plastic scintillator bar. **C** - magnification of the rectangular section of a bar. **D** - two printed rack elements in ABS for housing the scintillators, before removing the dissolvable support materials.

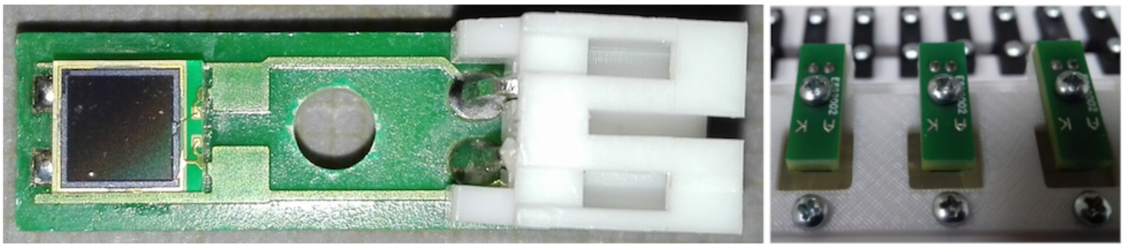

Figure 2: On the left, the SiPM mounted on the PCB together with the connector. On the right, three SiPMs mounted on the detector.

on the same PCB (see fig. 2).
The detector is constituted by two identical semicylinders with the electronics inserted in the concavity as in figure 3. The arcs (A_1 and A_2) and the bars (B_1 and B_2) form two layers that provide the angular coordinates of the incoming muon. Each semicylinder is composed by 128 arcs and 32 bars and have an acrylonitrile butadiene styrene (ABS) structure that houses the scintillators. To take advantage of the full reflection of the light inside the scintillators, tiny spacers in the scintillator housing ensure there is a layer of air between the scintillators and the housing itself.
The low power consumption front-end and data acquisition electronics is based on the electronics of detectors [2, 6] and is described in [7]. A programmable trigger logic is set to $(A_1 * B_1) + (A_2 * B_2)$, thus the tracks recorded by the detector corresponds to those that crosses both semicylinders or only one semicylinder in two distinct points.

3. Detector Characterization and Open Sky Test

An optimal working point (WP) of the detector is set by applying the SiPMs bias voltage V_{bias} and the discriminator threshold levels set by a programmable 10-bit register (DAC10). Figure 4 shows the typical counts rate, measured by one board, as a function of the DAC10. The

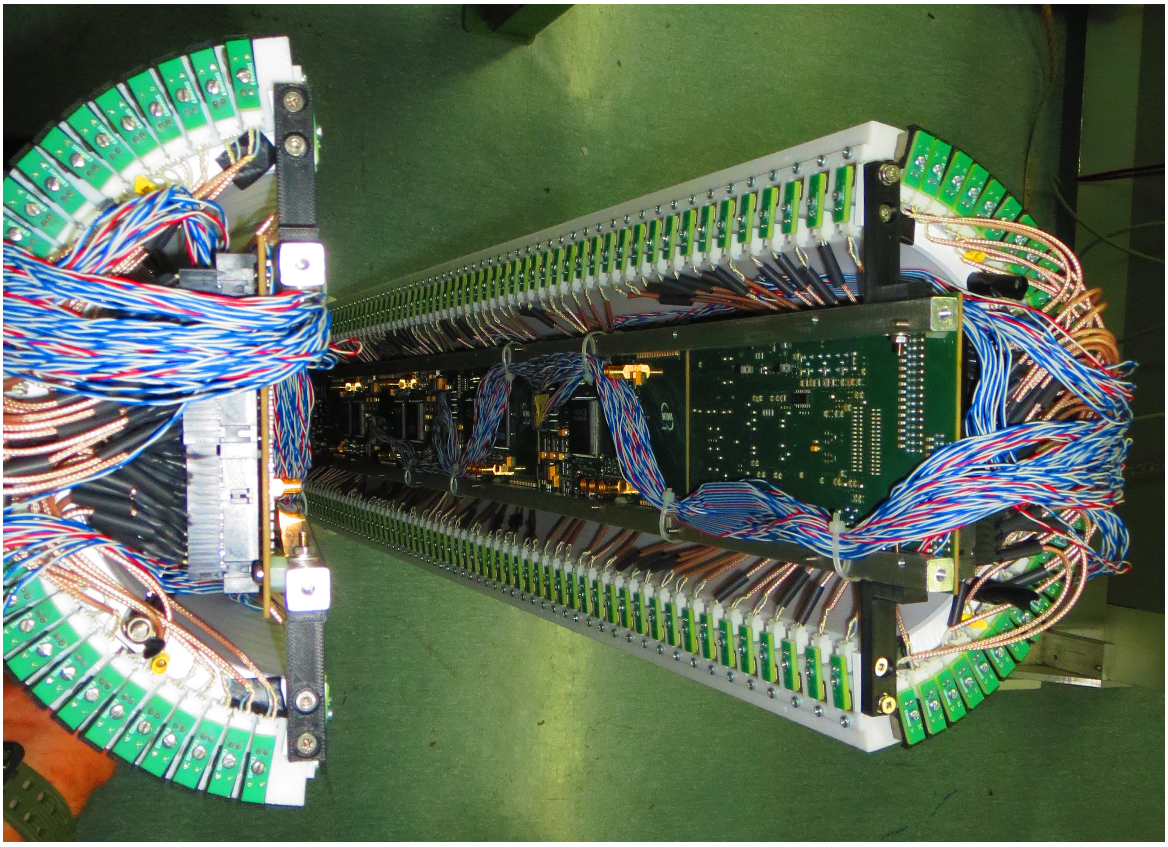

Figure 3: Semicylinders assembled with all the scintillators inserted and the silicon photomultipliers wired to the electronics front end boards.

dark noise counts dominate at low threshold levels; at higher threshold levels, cosmic counts dominate. Furthermore, the dark counts rate increases as a result of the increase in temperature due to electronics overheating. Then the acquisition system changes the WP to compensate the temperature variations, but this produces an increase in the breakdown voltage V_{bd} of the SiPMs so the system also increases the V_{bias} to maintain, as much as possible, a constant overvoltage level V_{ov} between different WPs ($V_{bias} = V_{bd} + V_{ov}$). Humidity sensors are used to detect water infiltrations inside the stainless steel container. In this case, the acquisition system switches off the detector to avoid damage to the electronics and SiPMs.
A *GEANT4* [8] toolkit was used to produce synthetic data with the aim to study the expected performance of the detector. The use of synthetic data allows us to plot the expected muon flux in open sky, in order to compere it to the one measured in the same condition. As it can be seen in figure 5 (top), the comparison between the expected and the measured muon flux shows a good agreement. Many measurements have been conducted in order to test the detector performance, in particular the trigger rate stability (see figure 5).

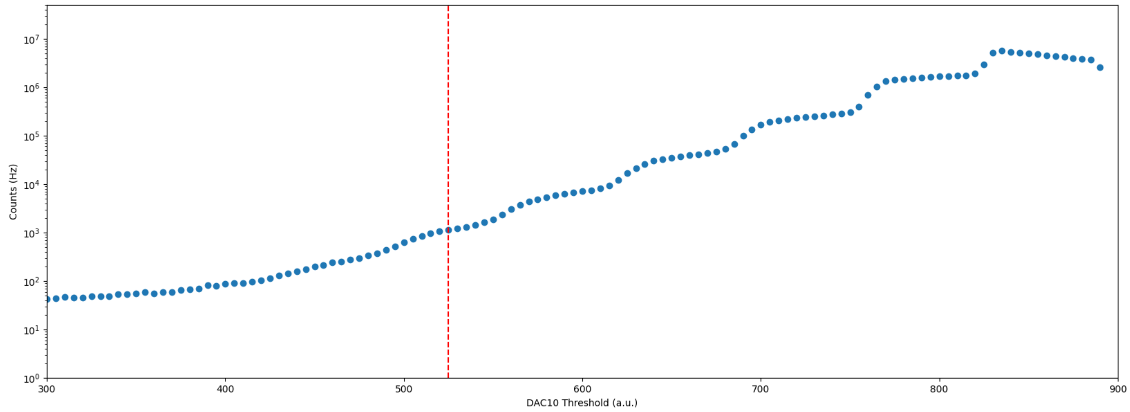

Figure 4: Counts rate of 32 SiPMs as a function of the discriminator threshold level. A higher value of the DAC10 corresponds to a lower threshold level. The dashed red line indicates the threshold level at which the board is operated.

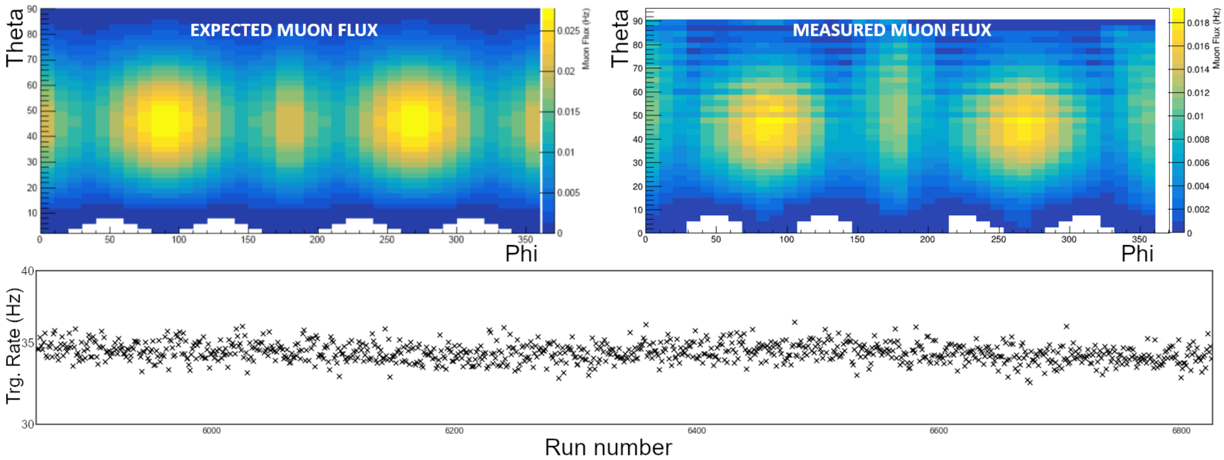

Figure 5: **Top** - The expected muon flux and the measured muon flux in open sky, detector in vertical position. **bottom** - The trigger rate measured by the detector in vertical position approximately every 8 minutes over one week.

4. Conclusions

We designed and build a cylindrical muon detector made of arc-shaped plastic scintillators. The simple design lowers production costs and make the detector assembly suitable for industrial production. The cylindrical geometry and the optimized trigger allows to obtain 360° muographic imaging. First tests show good performance and the detector is now in use for a first measurement campaign inside the Mt. Echia in the city of Naples (Italy).

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