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The Muon Portal Project: Commissioning of the full detector and first results

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ABSTRACT

The Muon Portal Project has built a prototype of a real size detector (6 m × 3 m × 7 m) for the inspection of containers by muon tomography. This technique may provide 2D and 3D images of the interior of a container, to identify the presence of high-Z materials. In the present Project, 4800 extruded scintillator strips were arranged such as to cover four X–Y detection planes (6 m × 3 m), two placed above and two below the container to be inspected. Silicon photomultipliers were used as photosensors, to collect the light transported by Wave Length Shifter (WLS) fibres embedded in the scintillator strips. First tomographic images are here presented.

1. Introduction

More than 200 million containers are travelling each year through the custom borders of many countries. They are potential sources of small quantities of hidden nuclear material, such as fissile elements. As an alternative to traditional systems based on X-ray inspection, it has been long suggested [1] to employ the scattering process of the secondary cosmic muons, which strongly depends on the atomic number of the traversed material, hence particularly sensitive to high-Z fissile elements. To implement such technique (muon tomography), a large area muon detector is required, to reconstruct the muon tracks with good angular resolution before and after traversing the container volume (Fig. 1).

Reconstruction and visualization algorithms may then be applied to produce a tomographic image of the container volume, to signal the presence of hidden, high-Z materials against a large background originating from low- and medium-Z objects.

Different projects exploited over the past years differ in the sensitive area and in the details of the detection technique employed. A new Project was recently started by the Muon Portal Collaboration [2–8] with the goal to build a real size prototype (18 m^2 sensitive area) with all potential features to be used in a real situation to probe the interior of a standard 20' container. The main parameters of this setup, together with the instrumentation employed, are described in Section 2. Preliminary results are reported in Section 3, together with the first tomographic images of lead blocks positioned in the inner volume of the detector.

2. The Muon Portal Project

2.1. Geometrical and mechanical structure of the Muon Portal

The detection setup is based on four X–Y position-sensitive detection planes, two placed above and two below the container volume to be inspected (Fig. 1). The overall size of the detector fits that of a standard Twenty Foot Equivalent (TEU) container, namely about 6 m × 3 m × 3 m. Each physical plane (X or Y) is made by 6 modules (1 m × 3 m each)

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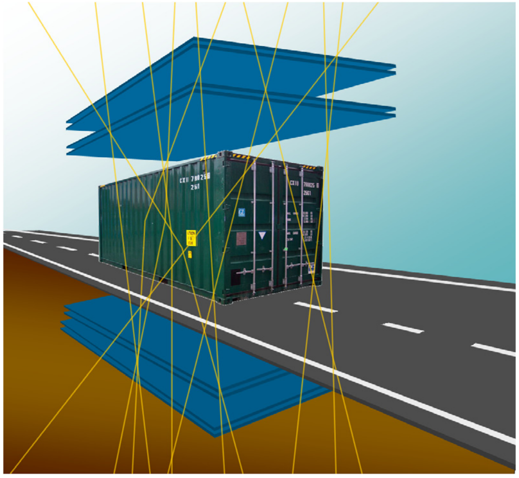

Fig. 1. A schematic view of a possible detector layout for container inspection by muon tomography.

in a proper geometry, such as to cover both the X- and the Y-coordinates by the same type of modules, without leaving any dead area between close modules. A total of 48 modules are used in this detector.

2.2. The detection modules

Each of the 48 detection modules is segmented into 100 strips of Amcrys extruded plastic scintillator ($1\times1 \times 300$ cm^3), with two Wave Length Shifter (WLS) Kuraray Y11 1 mm fibres embedded in each strip, to transport the photons to the photosensors placed at one of the fibre ends. The overall number of channels (fibres and photosensors) is 9600. Extensive tests of the individual strips and WLS fibres have been reported in a previous paper [6].

2.3. Characterization of the photosensors

The photosensors employed are Silicon Photomultipliers (SiPM), specifically designed by STMicroelectronics to maximize the photon detection efficiency and the cell fill factor, as well as to ensure a low cross-talk and dark count rate. Different SiPM prototypes (1 mm^2 area), both with the *p-on-n* and *n-on-p* technologies, have been produced by STMicroelectronics for this project before the mass production. The layout of the final chip is based on *n-on-p* technology and embeds 4 independent round shaped SiPMs: two MUON60 type with 548 cells and 60 μm pitch, and two MUON75 type with 320 cells and 75 μm pitch.

A custom procedure has been implemented for the mass characterization of all the devices, using a LabVIEW programme to measure the complete current–voltage (I-V) curve and find the Breakdown Voltage BV value for each SiPM. Detailed results on this procedure and results are reported in Ref. [7].

2.4. Electronic readout and data acquisition

Considering the number of modules and the required granularity to achieve a reasonable space and angular resolution, a large number of channels would be required for this detector. A compression technique within each module was employed to reduce such number to a suitable level. This is achieved by the use of two WLS fibres running along the same strip (for a total of 9600 WLS fibres) and going to an equal number of SiPMs, with a proper combination of the signals originating from ten channels grouped together. Additional details are given in Ref. [8].

2.5. Reconstruction and imaging algorithms

Identification of hits and clusters in each detection plane allows for the reconstruction of the tracks in the upper and lower parts of the detector and for the estimation of the scattering angle between the two tracks. Several algorithms have been tested for the reconstruction of the muon scattering process [3,9]. The simplest of them is based on the PoCA (Point-of-Closest-Approach) method, which evaluates a spatial distribution of the scattering centres, using a weight proportional to some power of the scattering angle. Such method, although of easy implementation, neglects the multiple scattering through the volume material and therefore has the drawback of providing poor-resolution images. This motivated the implementation of alternative algorithms (log-likelihood, clustering algorithms, …). The Friends-of-Friends (FoF), which is one of the most known clustering algorithms, is frequently used in astrophysics and cosmology, and was seen to produce the best results on simulated data. Basically, this method relies on two parameters, namely the linking length $r_{//}$ and the minimum number of elements in a cluster. Starting from an arbitrary initial element in the dataset it looks for all the elements contained within $r_{//}$, to define the members of a new group (friends). Clusters are defined as sets of elements that are connected by one or more of the friendly relations, so that they are friends of friends. Additional details are given in [3,9].

3. Results

Several sets of measurements were carried out with a trigger given by the coincidence between the four detection planes, varying the SiPM bias overvoltage and the individual thresholds on all channels, keeping constant the dark rate from each channel. The single hit multiplicity, the clustersize (number of close hits associated to a cluster point) and the cluster multiplicity were investigated for each individual detection plane. As an example, Fig. 2 shows the cluster multiplicity (evaluated in half detection plane), for three different values of the dark current (hence individual channel threshold) at 1, 5 and 10 kHz. Even at the lowest threshold, only 10% of the events have more than two clusters per semiplane. The clustersize for such events is relatively small, with more than 99% of the clusters having one or two hits, and less than 1% of the clusters with a clustersize larger than 2. Such clusters were removed from the tracking procedure, since they do not originate from cosmic muon tracks. In these operating conditions the cluster multiplicity is relatively low (about 1.5 per plane), resulting in an average number of cluster combinations of about 6, and the reconstruction of tracks was simply achieved selecting the track with the minimum χ^2 among all combinations.

An off-line alignment procedure was also undertaken, keeping fixed three of the four (X or Y) coordinates, and shifting the last coordinate by small amounts to minimize the χ^2. This procedure was repeated for all the detection planes, and misalignment corrections were incorporated in the tracking and image reconstruction. The results showed that misalignment corrections were very small, of the order of 5–10 mm in the worst case, compatible with the typical space resolution (about 3 mm) in each plane.

As a first test of the image reconstruction, hence of the overall capability for the detector to identify the presence of high-Z materials, we inserted a set of lead blocks with an overall volume of 4 dm^3 in between the two inner tracking planes, at $Z = 215$ cm with respect to the bottom plane. Two-dimensional tomographic images were reconstructed by evaluating the X- and Y-coordinates of the POCA between the upper and lower muon tracks, for different Z-sections along the vertical. Fig. 3 shows the results, for $Z = 185$ cm to $Z = 245$ cm in steps of 20 cm. A clear evidence of a hot spot at the expected location is observed in the two sections at $Z = 205$ and $Z = 225$ cm. These 2D images were reconstructed with a number of muon tracks of 400k. However, a still acceptable image may be obtained even with a smaller statistics (50–100k tracks), as shown in Fig. 4.

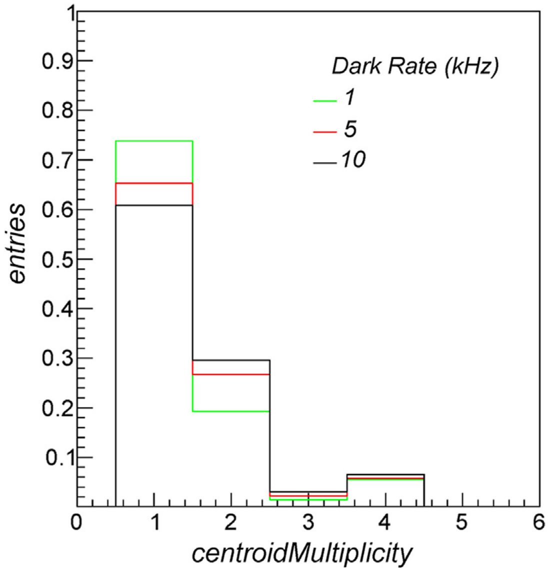

Fig. 2. Cluster multiplicity (per semi-plane) for three different values of the dark current from each SiPM.

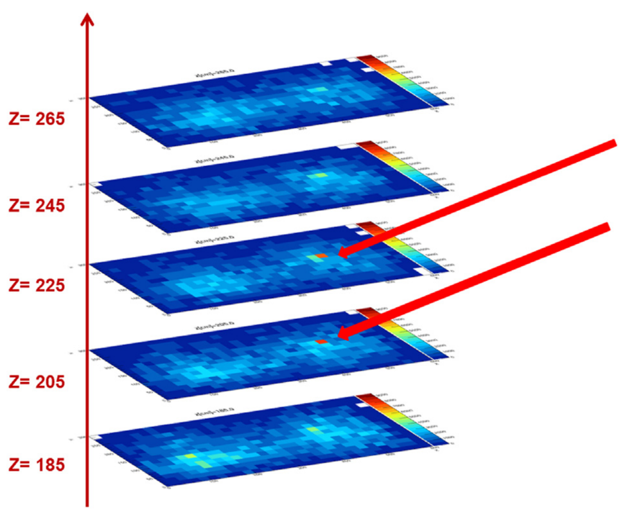

Fig. 3. Poca 2D reconstruction of the tomographic image of the inner volume, for different Z-sections, showing the presence of a lead block at $Z = 205$ cm.

4. Concluding remarks

After an R&D phase to test and choose the individual components for the construction of the detector prototype, the construction of the Muon Portal detector has been completed. A first set of commissioning measurements, with a few dm^3 lead block inserted in the inner volume of the detector, was undertaken, to align the detectors and provide a first check of the tomographic image reconstruction by the Poca algorithm. Preliminary results showed that the angular resolution and muon tracking procedures are adequate. One of the main point of concern is still related to the overall detection efficiency, which should be much higher in order to provide fast results, as those required in a real context. In the present operational conditions, still too much time (4–8 h) would be required to collect enough statistics (50–100k tracks) to provide an acceptable image of a few dm^3 lead block. However, these results are not yet indicative, since some of the 48 detection modules were not properly operating or had large dead areas, thus reducing strongly the geometrical acceptance. Moreover, due to the requirement to have a good signal from the two WLS fibres in each strip and in each of the eight individual physical planes, a 16-fold coincidence is needed to reconstruct the Poca coordinates. This means that even with a 90% light collection efficiency, the global efficiency would only be $(0.9)^{16}$=18%, whereas a moderate effort to increase the individual efficiency to 95% would increase the global efficiency to 44%, almost a factor 3 higher. There are still many points to be exploited in this respect. Improving operating temperature conditions in the lab, especially close to photosensors helps to reduce the dark current, allowing for lower thresholds and higher efficiency. Moreover, a better optical coupling between WLS fibres and photosensors is also an important aspect, to collect as much light as possible. Finally, different reconstruction software tools, which have been investigated and tested by our Project will also help in providing a better image quality – with respect to the simple Poca algorithm – even with a reduced statistics.

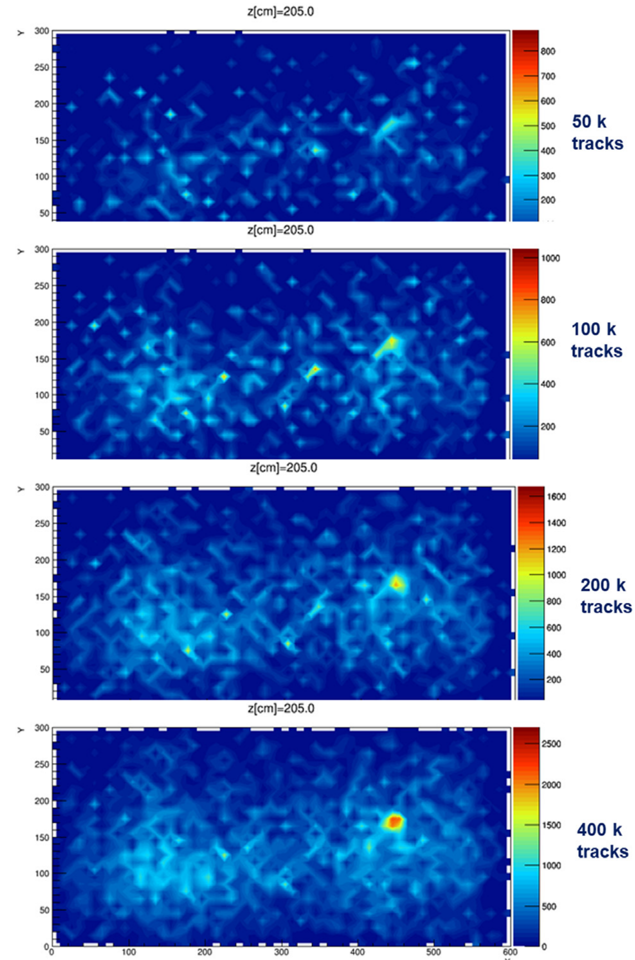

Fig. 4. Evolution of the 2D Poca tomographic image with the number of reconstructed muon tracks.

An additional important point for any realistic detector for muon tomography is also the evaluation of the performance when the high-Z material to be identified is surrounded by the typical container content, since this could increase the required scanning time or provide a poorer quality image. This problem has been addressed in our previous papers with simulated data [3] but still needs to be checked in a real situation.

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