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The Muon Portal Project: Design and construction of a scanning portal based on muon tomography

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ABSTRACT

Cosmic ray tomography is a technique which exploits the multiple Coulomb scattering of highly penetrating cosmic ray-produced muons to perform non-destructive inspection of high-Z materials without the use of artificial radiation. A muon tomography detection system can be used as a portal monitor at border crossing points for detecting illegal targeted objects. The Muon Portal Project is a joint initiative between Italian research and industrial partners, aimed at the construction of a real size detector prototype ($6 \times 3 \times 7\ m^3$) for the inspection of cargo containers by the muon scattering technique. The detector consists of four *XY* tracking planes, two placed above and two below the container to be inspected. After a research and development phase, which led to the choice and test of the individual components, the construction and installation of the detection modules is almost completed. In this paper the present status of the Project is reported, focusing on the design and construction phase, as well as on the preliminary results obtained with the first detection planes.

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1. Introduction

Over the last few years security issues arising at any country borders have become a serious and hot topic of discussion. Not only the security control on traveling people has become more sophisticated and complex, but also the control of goods exported and imported between countries needed to be revised. It is estimated that about 200 million containers are transported each year through the custom borders of many countries but only a small fraction of them actually pass through a complete control.

The conventional inspection systems currently used in the ports to check the contents of a cargo container are based on X-rays radiography. This technique is usually coupled with the use of external detectors to reveal the possible presence of radiations emitted by hidden nuclear fissile material. However the application of such techniques is limited since the presence of shielding materials around the radioactive source would conceal its presence.

In the last few years an alternative detection system, based on the muon tomography technique, has gained a growing interest and many research projects have been proposed aiming at building prototype detectors for muon tomography [1–4].

In the muon tomography technique the secondary cosmic radiation is used to reconstruct a 3D image of the volume to be inspected: it is known that muons suffer from multiple scattering processes, which strongly depend on the atomic number of the traversed material, hence particularly sensitive to high-Z fissile elements (U, Pu) or to their shielding (i.e. Pb); by measuring the deflection suffered by muons it is possible to discriminate between high and low-Z materials. A detection system employing such technique (muon tomograph) has to measure the deflection of muons in the volume under investigation and therefore would be made of large area tracking detectors designated to reconstruct the incoming and outgoing tracks.

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The Muon Portal Project plans to build a real size detector (18 m^2 sensitive area on each plane) with all potential features to be used in a real situation to probe the interior of a standard 20 ft container. A description of the detector used in the Muon Portal Project is reported in Section 2, while the current status of the project and the results of some preliminary tests performed on the detection modules are described in Section 3.

2. The Muon Portal Project

The detection setup is based on eight position-sensitive planes (giving X- and Y-coordinates), four placed below and four above the volume to be inspected. The first four planes provide a pair of (X,Y) points that are used to reconstruct the incoming particle track, whereas the last four planes provide a second pair of (X,Y) points used to reconstruct the outgoing track. A sketch of the apparatus is shown in Fig. 1.

The overall size of the inspection volume corresponds to that of a real 20 ft-Box container, namely $3 \times 3 \times 6$ m^3. Compared with similar devices designed for the same application by other research groups, the detector of the Muon Portal Project shows some peculiarities inherited from several research fields, making it an innovative detection setup on the whole. Preliminary descriptions of such Project have been previously reported [5–9].

The detector: The quality of the tomographic image depends on the tracking capabilities for the charged particles (muons and electrons). In our apparatus the precision in the direction reconstruction depends on the position resolution on each detection plane. In order to have a modular structure the planes are segmented into 6 independent modules (1×3 m^2 each), oriented as shown in Fig. 1. Each module is made of 100 strips of extruded plastic scintillators, with 1×1 cm^2 section and a length of 3 m. In principle the position resolution would be equal to $1\ \text{cm}/\sqrt{12} = 3$ mm, along the X- and Y-directions.

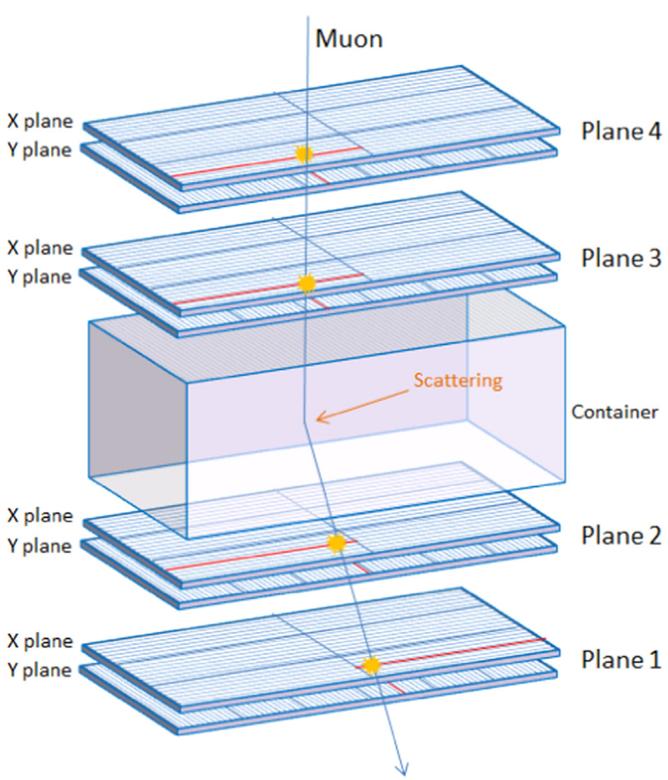

Fig. 1. Schematic representation of the Muon Portal Detector (not in scale). The eight planes provide 4 (X,Y) points that are used to reconstruct the track before and after passing through the container. The size of each plane is 3×6 m^2.

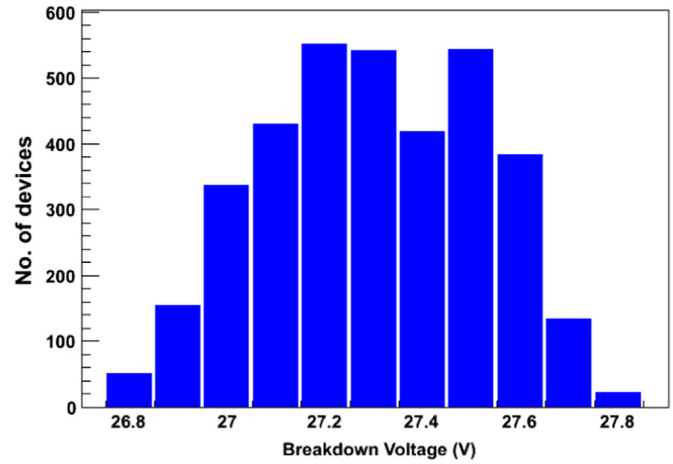

Fig. 2. Breakdown voltage distribution over a sample of about 4500 SiPMs.

The light produced in the scintillation strips is collected by two WaveLength-Shifting (WLS) fibres, that are housed (without any optical glue) into two separate grooves on the scintillator surface. The light readout is performed at one end of the fibers using a Silicon PhotoMultiplier (SiPM) specifically designed by ST Microelectronics for this application. The prototype being considered is a 1.5×1.5 mm^2 device, with 625 cells (size 60×60 μm^2), and a fill factor of about 67%. An intense work of characterization of such devices, both from the electrical and optical point of view has been made, in order to sort out the devices according to their breakdown voltage and equalize the gain of different devices installed in the same region of the detector [10]. The selection criteria chosen have led to a rejection percentage of less than 20%, that are compatible with what expected by previous tests on prototype devices. Fig. 2 shows the breakdown voltage distribution of the accepted devices.

Electronic readout and data acquisition: According to the design specification, the number of readout channels would be of the order of 10^4. A compression strategy has been implemented to reduce the overall number of channels by a factor of 10. This is achieved by the use of two WLS fibers running along the same strip (for a total of 9600 WLS fibres) and going to an equal number of SiPMs. The photosensor outputs are then properly combined in groups of ten, resulting in 20 channels per module. Their combination is able to identify the interested strips inside each module [7].

The analog output signals are sent to the front-end boards, which have a suitable gain, fast comparators and an adjustable threshold for each channel. Eight FPGA based boards PXI7813R by National Instruments are used as read-out boards to decode the hit strip and produce a label frame for the event. Finally, a GPS unit has also been incorporated in the acquisition architecture in order to correlate the arrival of muons in the Muon Portal detector to additional detectors located around it.

Image reconstruction: The reconstruction of the particle trajectories involves the identification of hits and clusters in each detection plane, the application of multi-track fitting procedures and finally the visualization of a 3D tomographic image through several reconstruction algorithms.

In order to fine tune all the software procedures listed above, a full GEANT4 [11] replica of the complete detector has been implemented, including the mechanical supports, the basic structure of the container (roof and doors) and the albedo due to the soil. A realistic distribution of secondary cosmic particles has been derived from CORSIKA simulations for proton-induced showers [12].

A detailed study of the various scenarios has been done taking into account not only single muon events, but also the presence of multi-hit events due to the development of electromagnetic showers induced by high energy electrons in the environment surrounding the detector. In each particular simulation, a set of objects of low-, medium- and high-Z material have been placed by the user inside the container volume, to understand the effect on the muon scattering and probe the capabilities of the reconstruction algorithms.

Several algorithms have been tested for the reconstruction of the muon scattering process [13,14]: in addition to the simplest method, based on the reconstruction of the Point-Of-Closest-Approach (POCA), also methods based on autocorrelation analysis, clustering and log-likelihood algorithms have been tested under different scenarios. Simulations have demonstrated the possibility to reconstruct a 3D image of the volume to be inspected in a reasonable amount of time, compatible with the requirement of a fast inspection technique.

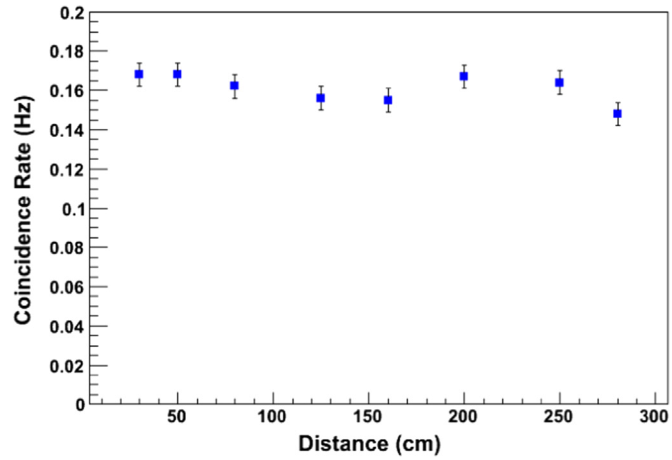

Fig. 4. Rate of coincidence events between one scintillator strip and an external trigger scintillator, as a function of its distance from the photosensor.

3. Preliminary tests of the detection modules

For the overall completion of this project, a preliminary research and development phase has been undertaken on several aspects which jointly contribute to the final design and construction of the prototype: the optimization of the individual detectors and their working conditions, the characterization of the optical photosensors and their coupling to the scintillator strips and WLS fibres, the design of the software algorithms for track reconstruction and image processing. Such R&D phase concluded last year, together with the construction of the 48 modules and the production of all the front-end electronics boards.

After the installation of the highest detection plane (Plane 4 in Fig. 1) in the mechanical structure, several tests were performed in order to check the operation of the detector and its electronic readout system. An extensively study of the threshold levels and SiPM polarization has been carried out on each readout channel in order to find the optimal compromise between the contribution of the spurious hits and the detection efficiency of the plane. Useful information has been extracted from the use a small scintillator ($15 \times 15\ cm^2$) placed at about 5 cm above the detection plane. Fig. 3 shows the hit map distribution of a portion of the detection plane in coincidence with the external trigger scintillator. Together with the scintillator shape, it is also possible to distinguish the coincidence events between the plane with the photomultiplier tube. The limited statistics of such measurement is the main cause of the poor definition of the borders of the scintillator shape.

The scintillator has also been moved in other positions of the plane, especially to check the detection efficiency in critical points, such as at the end of the modules (i.e. the farthest position to the photosensors) or at modules junctions. The result of these measurements showed that the detection efficiency is quite uniform on the whole plane. As an example Fig. 4 shows the coincidence rate between one of the scintillator strips and an external trigger scintillator, as a function of its distance with respect to the photosensor.

Further tests were performed after the installation of an additional detection plane (Plane 3). Since each plane provides, together with the hits coordinates, a time stamp of the cosmic event by means of the 25 ns electronics clock, it was possible to look for coincidences between the two planes through an off-line analysis of the data collected. The time difference between events detected by the two planes was calculated in a coincidence time window of $\pm 5\ \mu s$. As shown in Fig. 5, a peak is clearly visible against the accidental coincidences background. The width of the peak (~25 ns) is a convolution of different factors: the extension of the strip length seen by cosmic muons passing through the trigger scintillator (about 20 cm), the time emission spectrum of the WLS fibre, the propagation of the optical photons along the fibre and in the scintillator, the response of the SiPM and associated electronics.

Using the installed two planes, the angular distribution has been extracted and is reported in Fig. 6: the polar angle distribution slightly deviates from the expected $\sin\theta\cos^2\theta$ trend, probably due to shielding effects produced by the building hosting the portal.

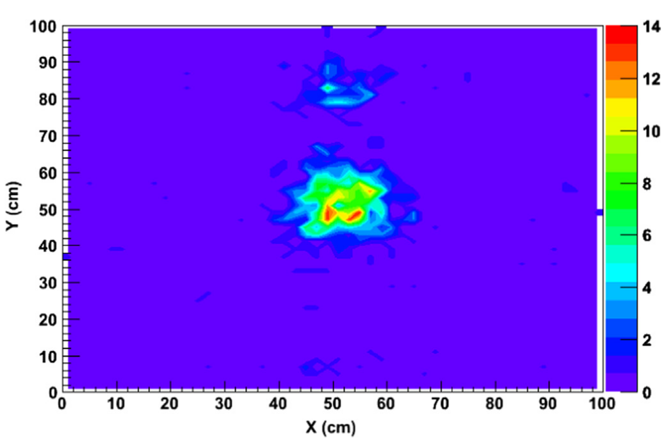

Fig. 3. 2D map of two orthogonal detection modules in coincidence with the external scintillator.

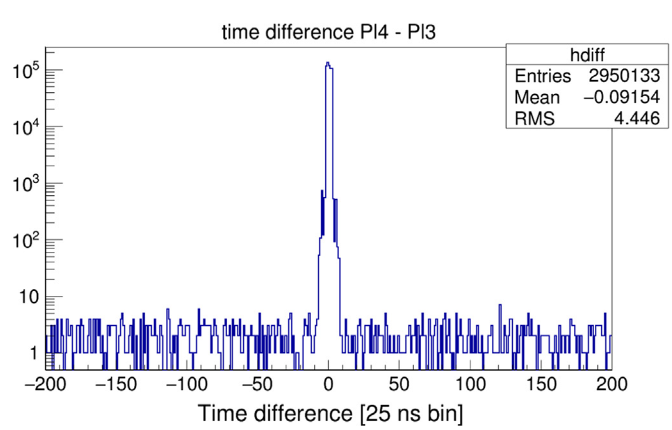

Fig. 5. Time difference spectrum for coincidence events between two detection planes, plotted with a bin size of 25 ns.

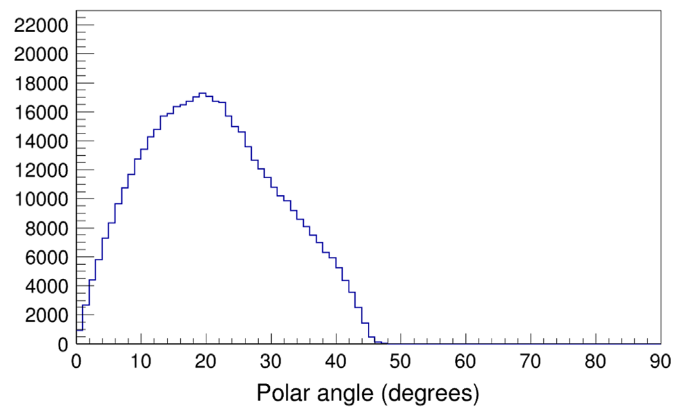

Fig. 6. Polar angle distribution of tracks measured with 2 detection planes.

The installation of the last two planes will allow us to reduce the background of accidental coincidences to a negligible level by the coincident detection of the muon passing through the eight (4*X* and 4*Y*) detection planes. Moreover the tracking procedure will further exclude spurious hits from the analysis of data.

4. Conclusions

After an initial phase of research and development and an intense construction activity, the Muon Portal Project has entered its installation phase. The first two detection planes have been successfully installed and preliminary tests have demonstrated their functionality. With the installation of the third plane, that is currently ongoing, it will be possible to perform the tracking of cosmic particles and test the detection planes without the use of external scintillators.

Due to the large acceptance of the detector for cosmic rays, complemented by a good angular reconstruction of the muon tracks and possibility to discriminate electrons from muon events, it is also planned to employ such detector for cosmic ray studies [15].

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