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Design of a muonic tomographic detector to scan travelling containers

The Muon Portal Collaboration

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ABSTRACT: The Muon Portal Project aims at the construction of a large volume detector to inspect the content of travelling containers for the identification of high-Z hidden materials (U, Pu or other fissile samples), exploiting the secondary cosmic-ray muon radiation. An image of these materials is achieved reconstructing the deviations of the muons from their original trajectories inside the detector volume, by means of two particle trackers, placed one below and one above the container. The scan is performed without adding any external radiation, in a few minutes and with a high spatial and angular resolution. The detector consists of 4800 scintillating strips with two wavelength shifting (WLS) fibers inside each strip, coupled to Silicon photomultipliers (SiPMs). A smart strategy for the read out system allows a considerable reduction of the number of the read-out channels. Actually, an intense measurement campaign is in progress to carefully characterize any single component of the detector. A prototype of one of the 48 detection modules (1×3 m^2) is actually under construction. This paper presents the detector architecture and the preliminary results.

KEYWORDS: Muon spectrometers; Search for radioactive and fissile materials; Particle tracking detectors

Contents

1 Introduction

A container is a reusable steel box used worldwide for the safe storage and movement of materials. Each year, hundreds millions of containers transported by cargo ships (the most widespread sizes are 20ft and 40ft long) transported by cargo ships are in transit through ports around the world. The total yearly traffic is estimated in 200 Millions containers, but only 1% of them is actually inspected. However, the future international security regulations will require the inspection of all containers destined to U.S. ports.

The most common technique to verify their content is the X-ray radiography. It is based on the absorption of the X-rays from an intense source, but it requires high fluxes to cross dense objects.

Other possibilities are directional gamma imaging and neutron radiography. The application of these techniques, however, is complex and expensive, and the performances can be seriously degraded in presence of shielding materials.

Another solution, which uses the natural cosmic radiation to obtain a muon tomography, has been proposed in the recent years.

Several Projects have been proposed in recent years worldwide with the aim of building prototype detectors for muon tomography [1–4]. They differ in few aspects, like their sensitive area and the details of the used detector technique.

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2 The Muon Portal project

2.1 Motivations

The Muon Portal project [5] is an Industrial research activity funded by a PON (National Operative Programme) Project in the field of transport and advanced logistics (2011–2014).

The aim of the project is to design and implement a prototype of a portal, which employs the muon tomography technique, principally for the identification and localization of materials with high atomic number Z hidden inside containers.

Muons are mainly produced by air showers induced by primary cosmic rays, such as protons. They are the most abundant energetic particles arriving at sea level, with a flux of about one muon per square centimeter per minute.

Advantages of the inspection based on muon radiography techniques are:

- Scan without opening the container;
- Radiation already present in nature;
- Short acquisition time (few minutes);
- No damage on the contents (Minimum Ionizing Particles).

The detection technique is based on the determination of the scattering angle of cosmic muons crossing the particle trackers induced by heavy materials. Consequently a system for muon tomography requires two tracking detectors, above and below the volume to be inspected. Indeed, the scattering angle is particularly sensitive to the atomic number Z of the crossed material.

2.2 Apparatus design

Figure 1 shows a sketch of the apparatus layout. The detector consists of 8 detection planes corresponding to four logic X-Y planes with 3×6 m^2.

Each plane consists of six identical modules (1×3 m^2 each), suitably placed in order to cover both the X and Y coordinates with a modular structure, minimizing the dead area, which is negligible, in the order of 0.1% of the total sensitive area.Each module is made of 100 extruded plastic scintillator strips ($1 \times 1 \times 300$ cm^3). Two WLS (Wave-Length Shifting) fibers are optically and mechanically coupled to each strip, in order to transport the light, produced in the strip by the crossing particles, to the photo-sensor placed at one of the fiber ends.

The envisaged distance between the detection planes of each tracker is 100–140 cm, while the inner part is about 300 cm high, to allow the insertion of a standard container. In this way, the spatial resolution, in the order of few mm, will be suitable to provide a good tracking capability for each muon, allowing the reconstruction of the incoming and outgoing tracks and, consequently, the scattering angle with a geometrical angular resolution of about 0.2 degrees [5].

A suitable mechanical support has been designed for the detection planes, minimizing the material budget traversed by the charged particles.

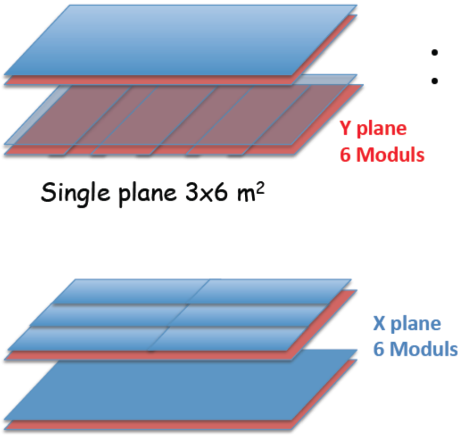

Figure 1. Sketch of the detector layout. Two trackers consisting of eight X or Y planes in total, with 6 modules for each are visible.

2.3 Collection of the scintillation light

In order to reduce the problem of light absorption along the strip and to adapt the wavelength of the light emitted at more appropriate values in the region of the photo-sensors maximal sensitivity, we decided to use WLS fibers to transport the light produced in the scintillating bars. A series of experimental tests have been carried out on several prototypes of scintillator strips and WLS fibers from different suppliers, in order to choose the best configuration for the final design of the detector, and optimize the light collection at one end of the strip. Among the strip prototypes with 1 cm^2 cross-section, we tested various samples with a centered hole able to accommodate two 1 mm WLS, as well as strips with two 1 mm grooves put on the same side. The Kuraray fibers showed the best performances in terms of number of photoelectrons detected by a suitable photomultiplier (PMT), varying the distance from the photo-sensor (details in ref. [6]). In figure 2 the rate of cosmic muons detected by a SiPM (produced by ST Microelectronics, which is one of the industrial partners of the project) placed at one end of a Uniplast strip (Vladimir, Russia), in function of the distance crossed by photons into the fiber, is shown, setting two different SiPM thresholds. The strip has 1 cm^2 cross-section with two 1 mm grooves along the same side. The power supply voltage for the SiPMs is around 30V.

With both the thresholds in figure 2 the detection efficiency is above 90%.

Test performances have shown that a SiPM threshold of 2 photoelectrons gives a good uniformity in the response along the strip. These results were confirmed by additional experimental tests carried out on Amcrys scintillator strips (1 cm thick, 3 m long) with Kuraray WLS fibers.

2.4 Detection of the scintillation light

It was chosen to use custom designed SiPMs to convert the scintillating light into an electric signal. Different SiPM prototypes, both with the p on n and n on p technologies were produced and tested by ST Microelectronics in order to maximize the photon detection efficiency (PDE), the fill factor with a low cross-talk and dark count rate.

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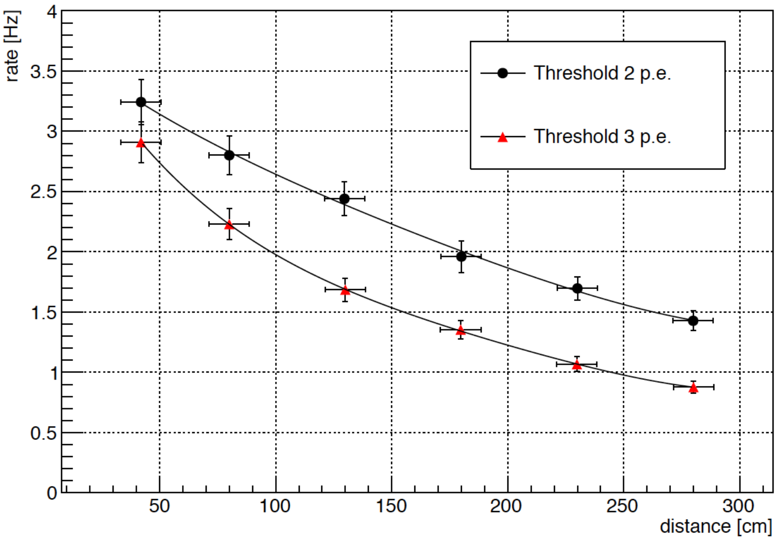

Figure 2. Rate of cosmic muons versus the distance from the SiPMs, detected employing Uniplast strip sample with Kuraray Y11 (200) fibers embedded. The data are reported for two different acquisition thresholds (given in terms on number of photoelectrons).

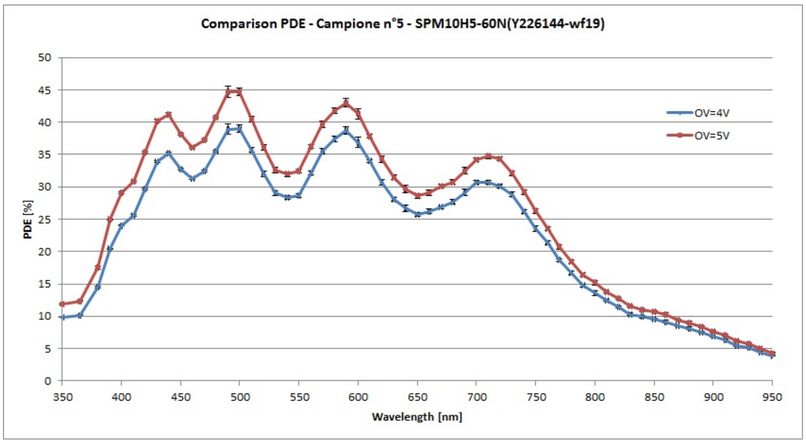

Figure 3. PDE measurement comparison at OV=4V and OV=5V and T=28 ° C.

Figure 3 shows the comparison between PDE measurements carried out at two values of Over Voltage (OV) on a SiPM device similar to the one that will be used for the Project.

The layout of the test chip is shown in figure 4. It is a *n* on *p* chip, with 4 SiPMs: two couples respectively with pixel size 60 um and 75 um. The PDE is about 40% and the fill factor 67%.

The main characteristics of the package are reported in table 1.

2.5 Front-end and read-out electronics

It is possible to summarize the read-out system working principle as follows: for each detector module, 200 channels are read by as many SIPMs. Thanks to a smart read-out strategy [7, 8], the output channels are reduced by a factor 10. The 20 analog signals from the front-end modules are sent to the read-out boards where the conversion of the analog signal to digital signal takes

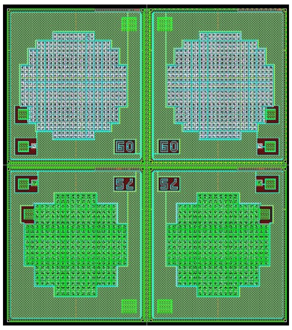

Figure 4. Layout of the test chip, made of 4 SiPMs, produced and tested by STMicroelectronics.

Table 1. Main characteristics of the SiPMs package used for the Muon Portal project.

SMD package	**Unit**	**Value**
Package size	mm^2	5.1 × 5.1
Silicon die size	mm^2	4.18 × 4.68
Edge width (wire side)	Mm	0.5
Edge width (no wire side)	Mm	0.3
Total package thickness	Mm	0.7 ± 0.1
Resin		Transparent

place, by a comparison to a user-defined threshold. The data are pre-analyzed and stored into a data acquisition PC.

A front-end box for each module of the detector planes is provided (figure 5).

It accommodates the SiPMs, the control system of power supply and temperature, the front-end electronics, one or more connectors for the control of the functional parameters of the front-end and for interfacing to the acquisition electronics. The SiPMs are read using a suitable front-end electronics consisting of amplifiers and line drivers.

The use of SiPM sensors as collectors of the signals coming from the fibers, requires a remote adjustable power supply, able to compensate the variations of the intrinsic characteristics (gain, PDE, dark) caused by the environment.

The power supply section and the temperature controller able to stabilize the working point of the SiPM, which will be suitably selected to have almost identical characteristics, are currently in the design phase.

The temperature conditioning (sensors and actuators), power, control and communication (Gbs Ethernet) systems will be managed by a unique chip Semi-Custom Front-end (FPGA Front-end).

The analog signals from the six boxes of a detection layer are sent to an adapter module.

The read out electronics consists of two MAROC3 (Multi Anode Read Out Chip) [8, 9] chips manufactured by OMEGA (figure 6) per layer, with 64 channels each and individually adjustable gain, 8 bit resolution, housed into the adapter module. The chips are interfaced to a read-out

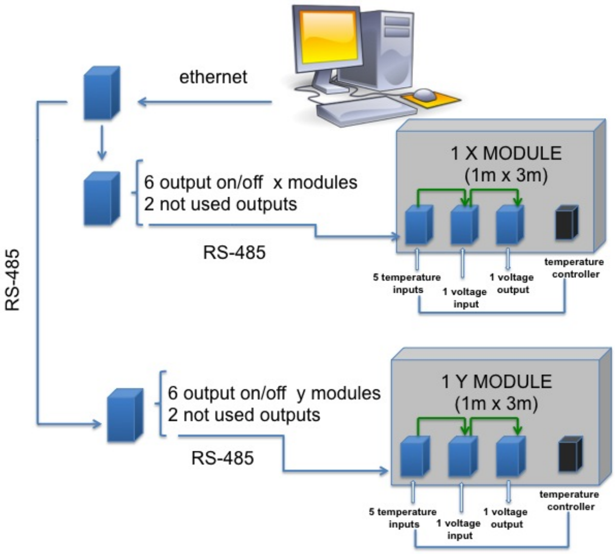

Figure 5. Front-end modules, communicating with the RS-458 serial protocol, designed for the Muon Portal prototype. One representative Muon Portal module-plane per direction is depicted.

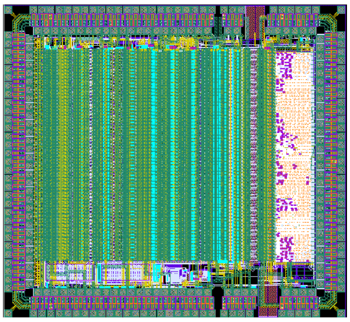

Figure 6. Layout of the MAROC3 chip by OMEGA.

board, based on programmable logic VIRTEX5 FPGA, produced by National Instrument (NI). The MAROC3 chip amplifies, shapes at 15 ns and compares each signal coming from the front-end to a suitable threshold. The FPGA board samples the outputs from the two MAROC3 chips, decodes the hit strip and produces a label frame for the event.

We have acquired a MAROC3 evaluation board that was tested in a preliminary phase by using a signal generator, in order to find the optimal configurations in terms of gain of the individual channels and threshold of the discriminators, such as to equalize the responses of the channels being equal input signals.

The characterization of the chip has also requested the implementation of suitable software in LabVIEW code, in order to optimize the performances of the board for our purposes, making the graphical interface easily understandable and of immediate use.

In total, for the read-out of the overall detector, 8 flex-RIO boards [10], a real-time module to correlate the signals from all the detection planes, a GPS module for the synchronization are needed, housed into a suitable crate. At present, it was decided to purchase the CRATE NI PXI

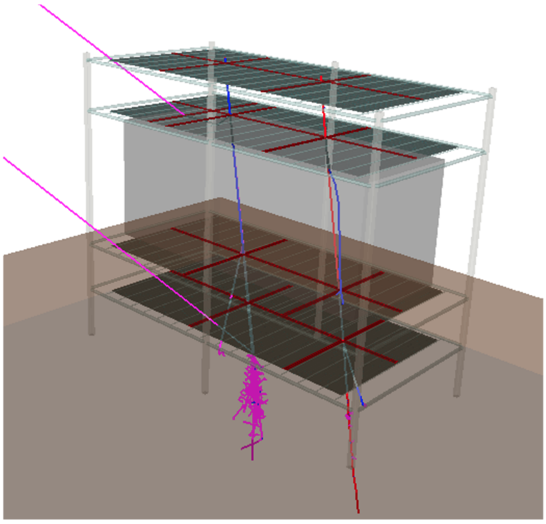

Figure 7. GEANT4 simulation of scattering events induced by primary muons, as revealed by a full replica of the detector. A simulated container is visible between the inner detector planes.

Express 1062Q chassis which houses the controller in addition to the PXIe-8135 NI flex-RIO with 132 digital I/O sampled up to 300MHz for the acquisition and pre-analysis of the signals from the front-end and the real time modules. Next step will be the test of the full electronic chain in response to the signal produced by muons in a scintillating strip employing the custom designed SiPM.

3 Simulation software support

3.1 GEANT4 simulations

Appropriate GEANT4 simulations on the transport of scintillation photons inside the scintillator strips and the WLS fibers have been carried out for each geometrical configuration [11]. A full replica of the complete detector, incorporating the individual scintillator strips, the mechanical structure, and the walls of the container, together with the soil below the detector has been implemented as shown in figure 7 [12].

Many simulations have been performed in order to reproduce, event by event, scattering of single muons as revealed by the detector, inserting materials with different Z within the volume of the container.

Muons and electrons from showers induced by primary protons were modeled with realistic energy and angular distributions by means of CORSIKA simulations. Identifying the hit in each plane, it is possible to reconstruct the tracks of the incoming and outgoing tracks of the particle after passing through the container volume, and then estimate the deflection angle. Multi-hit events induced by electromagnetic showers of high-energy electrons into the environment surrounding the detector were also considered.

3.2 Algorithms for image reconstruction

We implemented three different methods to reconstruct the tomographic image (details in ref. [5]).

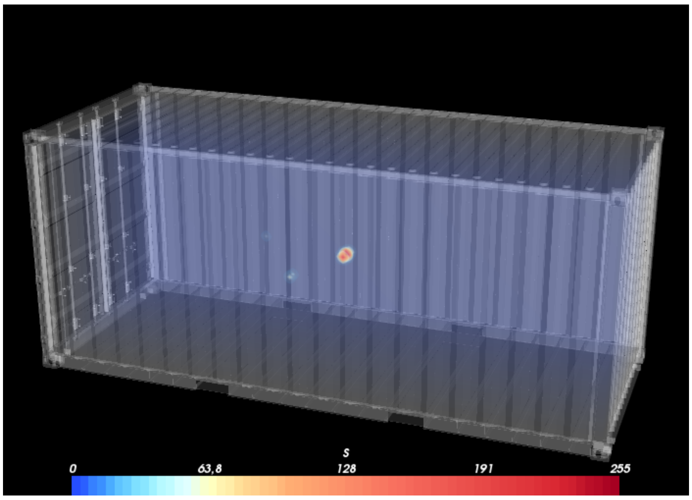

Figure 8. Tomographic imaging of the scenario C obtained with the clustering method. A lead box of size 10 cm × 10 cm × 10 cm is placed at the center of a container, which is filled with layers of washing machine-like elements. The number of muons considered for the simulation is 5×10^5.

The POCA (Point of Closest Approach) algorithm is the simpler one, but with the lower spatial and angular resolution. Considering only single scattering events, it evaluates the point of closest approach between the incoming and outgoing tracks, by simple geometrical calculations.

The clustering algorithm is a density-based algorithm. It is an improvement of the POCA method, based on a two points correlation analysis.

Finally the EM-ML (maximum likelihood) methods are iterative algorithms based on the subdivision of the entire volume to be inspected in k voxels (characterized by a density of scattering λ_k). Thanks to iterative procedures to maximize log-likelihood, it is possible to find the best set of the parameters λ_k.

We validated the mentioned algorithms using GEANT4 simulations with different tomographic scenarios:

- Scenario A: four threat boxes of different materials (**W**, **U**, **Pb**, **Sn**) of size 10 cm × 10 cm × 10 cm inserted at the center of an empty container.

- Scenario B: a "MUON " shape built with voxels of size 10 cm × 10 cm × 10 cm inserted at the center of an empty container. Each letter is made of a different material:
  M = Uranium, U = Iron, O = Lead, N = Aluminium.

- Scenario C: same scenario of B. A denser environment is assumed inside the container volume, filled with layers of washing machine-like elements. These are made of an aluminium casing with an iron engine inside with relative support bars and a concrete block. An example obtained with the clustering algorithm is shown in figure 8.

In conclusion, the target objects are reconstructed with a considerably better resolution by the EM-ML method.

4 Conclusions

In conclusion, the Muon Portal Project aims at the design and construction of a portal prototype based on muon tomography for the identification and localization of materials with high Z, hidden inside containers

The design of the detector architecture, a simulation campaign on the detector response, the preliminary tests on individual components (strips, WLS fibers, SiPM) were carried out in order to obtain the best performances in the reconstruction capabilities. As a final result of such tests, the final detector components were chosen. In details, as photo-sensor, the SiPM MUON60 (60 micron is the single cell size) by ST Microelectronics will be employed and after the production of thousands of devices, the SiPMs are currently being tested, individually, for the determination of Breakdown Voltage.

As regards the choice of the fibers, the Kuraray Y11 have shown the best compromise in terms of light yield and costs, and they will be coupled to the extruded AMCRYS (Kharkov, Ukraine) strips (10×10 mm^2 cross-section, 3 m long with 2 grooves).

In order to improve the collection of the scintillation light, suitable optical glue will be applied between fibers and strips. Moreover, each module will be covered with a reflective layer of Mylar. The front-end and read-out electronics architectures have been defined and described in the text.

Image reconstruction algorithms employing different methods are almost ready. Assembly of the modules is in progress.

The complete prototype will be ready at the beginning of 2015, and it will be used to inspect containers transiting in ports. Other future applications of the muon detector are under study (such us in landfills and airports).

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- INAF – Astrophysical Observatory, Catania
- STMicroelectronics S.r.l. Catania
- Meridionale Impianti Welding Technology
- Insirio SPA

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