The Muon Portal Double Tracker to Inspect Travelling Containers

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***Abstract*–The Muon Portal Project goal is the design and construction of a working detector prototype in scale 1:1, to inspect the content of travelling containers by means of the secondary cosmic-ray muon radiation and recognize high-Z hidden materials (U, Pu or other fissile samples). The radiographic image is obtained by reconstructing the input and output trajectories of each muon and consequently the scattering angle, exploiting two trackers placed above and below the container. The scan is performed without adding any external radiation, in a reasonable time (a few minutes) and with a good spatial and angular resolution. The detector consists of 8 planes segmented in 6 identical modules. Each module is made of scintillating strips with two WaveLength Shifting fibers (WLS) inside, coupled to Silicon photomultipliers. The customized read-out electronics employs trading programmable boards. Thanks to a smart read-out system, the number of output channels is reduced by a factor 10. The signals from the front-end modules are sent to the read-out boards, in order to convert the analog signal to a digital signal, by a comparison to a threshold. The data are pre-analyzed and stored into a data acquisition PC. Actually, an intense measurement and simulation campaign is in progress to characterize carefully the detector components. The first detection modules (1 x 3 m^2) is now under construction. The detector architecture with a particular attention to the used electronics and the main preliminary results will be presented.**

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I. Introduction

THE yearly traffic of containers, employed in all ports around the world for the safe storage and transport of materials by ships, is constantly growing up. It is estimated in 200 Millions containers per year, but the content verification is reserved just to 1% of them, because of the time required for the inspection and the costs related to it. The most common scanning technique is the X-ray radiography. It requires an external source, which introduces radioactivity in the environment and is ineffective in crossing very dense objects, due to the absorption of the radiation.

The application of alternative techniques, such as directional gamma imaging and neutron radiography, is complex and expensive, and the performances can be seriously degraded in presence of shielding materials.

The growing demand for civilian safety regulations, however, requires scanning of all transiting containers.

The Muon Portal Project [1] (2011 - 2015) offers an alternative technique to the previous, elaborated over the last few years, based on tomography with cosmic muons.

It is aimed at building a complete tomographer prototype, principally for the identification and localization of materials with high atomic number Z hidden inside containers.

Worldwide, several Projects have been proposed with the aim of building prototype detectors for muon tomography [2]-[5].

With respect to the inspection techniques previously described, the muon tomography has some advantages. For example, the scan is non invasive (the container remains close), the use of cosmic rays doesn't require external radiations, dangerous for the environment. The acquisition time is reduced to few minutes, and the contents are not damaged because muons are Minimum Ionizing Particles (MIP).

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.

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II. Detector Architecture

The detector design includes four logic X-Y planes of dimension 3x6 m^2 corresponding to eight physical planes, one for each direction (Figure 1).

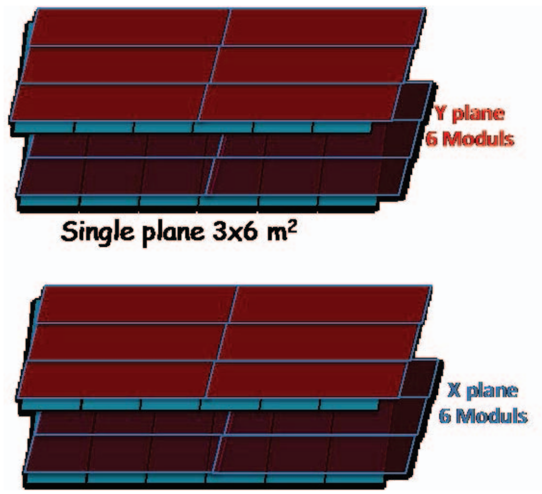

Fig. 1. Sketch of the detector layout. Two trackers consisting of eight X or Y planes in total, with 6 modules for each are visible.

In each plane six identical modules (1x3 m^2 size), are suitably placed in order to cover both the X and Y coordinates with a modular structure, minimizing the dead area, which is in the order of 0.1% of the total sensitive area. Each module consists of 100 extruded plastic scintillator strips (1x1x300 cm^3). In each one, two Wave-Length Shifting (WLS) fibers are optically and mechanically coupled, 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 detection planes of each tracker are spaced about 100-140 cm, while the inner planes are separated by about 300 cm, so that it is possible to insert 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 [6].

The detection planes are incurred by a suitable support, in order to minimize the material budget traversed by the charged particles.

III. Optimization of Light Collection

The use of WLS fibers to transport the light produced in the scintillating strips greatly reduces the light absorption along the strip and allows to adapt the wavelength of the emitted light at more appropriate values close to the region of the photo-sensors maximal sensitivity. In order to choose the best configuration for the final design of the detector and to optimize the light collection at one end of the strip a series of experimental tests have been carried out on several prototypes of scintillator strips and WLS fibers from different suppliers. 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. Following the results of the tests we decided to use for the Project the Kuraray Y11 (200) fibers, which have shown the best performances in terms of number of photoelectrons detected by a suitable photo-sensor, varying the distance from it (details in Ref. [7]).

Obviously, also the light passing through the fiber is attenuated and it's important to know how this happens. The light intensity *I(x)* of the light that reaches the SiPMs depends on the distance *x* with respect to the point where the light was produced:

$$I(x) = I_0\left(e^{-\frac{x}{\lambda_s}} + e^{-\frac{x}{\lambda_l}}\right). \qquad (1)$$

in which λ_s e λ_l are, respectively, the short and the long attenuation lengths and I_0 is the intensity at the point of emission.

For WLS fibers, λ_s is of a few tens of cm, and its effect can be neglected at distances of 50 cm. In this case, the above expression reduces to

$$I(x) = I_0 e^{-\frac{x}{\lambda_l}}. \qquad (2)$$

In Figure 2 the response of the Kuraray fibers to a blue LED light, and by using an external scintillator irradiated with a UV LED and ^{90}Sr sources, are shown. They follow the exponential trend of eq. (2).

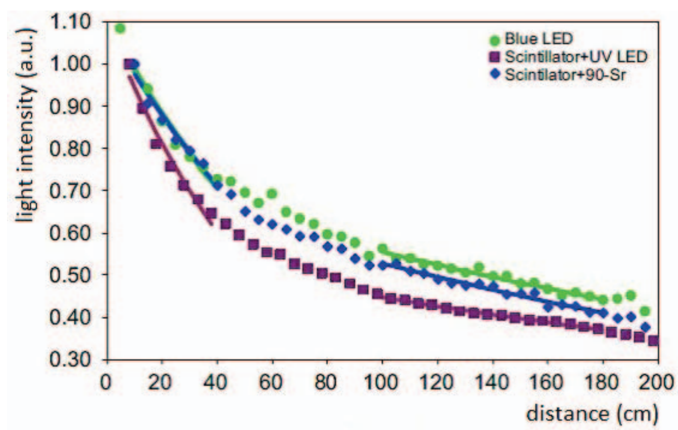

Fig. 2. Kuraray Y11(200) response to different sources, with or without the external scintillator.

IV. The Photo-sensor

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.

The layout of the final chip that will be employed for the Project is shown in Figure 3.

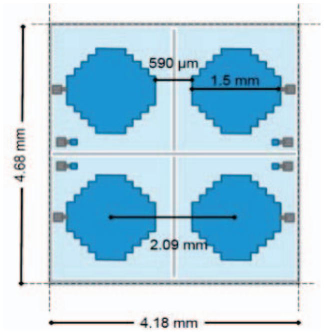

Fig. 3. Layout of the SiPM chip MUON-60 (60 µm x 60 µm is the single cell size, while the diameter of the total circular sensitive is 1.5 mm), foreseen for the Muon Portal Detector, designed by STMicroelectronics. Just 2 of the 4 SiPMs will be used for each strip.

The photo-sensor to be employed in the Muon Portal Detector requires performances more appropriate to adapt at its best both the mechanical requirements and the optical properties of the strips and the WLS fibers. Therefore the SiPMs have been planned with a higher fill-factor, smaller cells and a larger gain. The size of the SiPM will be circular with a diameter of about = 1.5 mm, with a reduction of about a factor of 2.5 in the area. The center distance of the two SiPMs is chosen to optimize the coupling with the two fibers. We expect a lower dark current and a higher PDE, but the same spectrum sensitivity. In the meantime, we have started with their characterization.

V. Read-out of the Signals

A front-end box for each module of the detector planes is provided (Figure 4). 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.

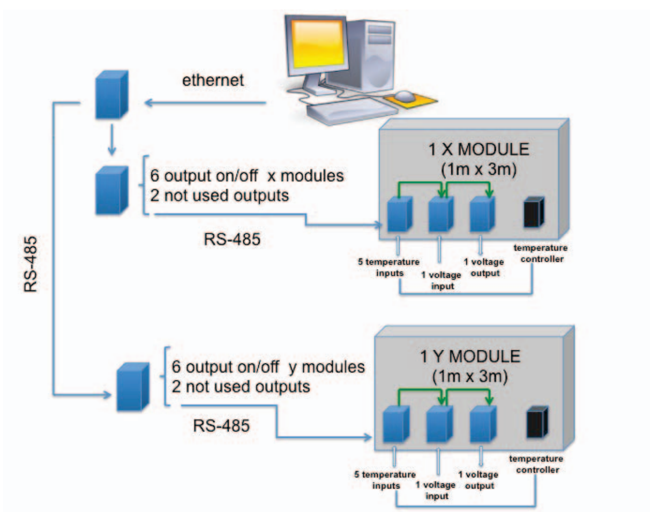

Fig. 4. Front-end modules, communicating with the RS-458 serial protocol, designed for the Muon Portal prototype. One representative Muon Portal module-plane per direction is depicted.

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 test 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). In detail, the front-end modules include also line drivers, in addition to the mechanical housings.

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 [8], the output channels are reduced by a factor 10. After the application of the reduction scheme, the 20 analog signals from the module are amplified, shaped and compared to an user-defined thresholds, then stretched by monostables. After passing the monostables, the 120 signals from a plane are sent to a NI PXI-7813R board with 160 Digital I/O. The 40 remaining lines are used to adjust the thresholds of the DAQ.

The programmable logic VIRTEX-II FPGA Module 40 MHz, housed into the board, samples the outputs from the front end module, decodes the hit strip and produces a label frame for each event. The data are pre-analyzed and stored into a data acquisition PC. In total, for the read-out of the overall detector, 8 National Instruments PXI-7813R boards, a real-time module (NI PXIe-8135) to correlate the signals from all the detection planes, a GPS module (NI PXI-6682) for the synchronization are needed, housed into a suitable crate. Until now, it was decided to purchase the CRATE NI PXI Express 1065 18-Slot Chassis, which houses the controller in addition to the FPGA boards. Next step will be the test of the full electronic chain in response to the signal produced by muons in a complete detection module, employing the custom designed SiPMs.

VI. Simulations

A. *Detector Simulation and Cosmic Rays Generation*

Detailed GEANT4 simulations have been carried out in order to understand and reproduce the performance of our detector and to optimize the algorithms for the reconstruction of the tomographic image [9]-[10]. The main ingredients of the simulations include the implementation of a full replica of the detector, of the support and container; the generation of a realistic distribution of cosmic rays (using the CORSIKA code); the transport of optical photons fully simulated and then parameterized to save CPU time; the reconstruction of hits and clusters, including those due to electromagnetic showers.

B. Reconstruction Algorithms

The output of the GEANT4 simulations has been used to implement several algorithms for the reconstruction of the tomographic image.

The simplest method to reconstruct the tomographic image is the POCA (Point Of Closest Approach) algorithm. This is a purely geometric algorithm that ignores any underlying physics of scattering and assumes a muon scattered at a single point. By projecting the incoming and outgoing tracks, it is possible to find the points where they came closest and estimate the scattering point as the midpoint of the line between the points of closest approach.

The clustering algorithm is a density-based algorithm [11]. It is an improvement of the POCA method, based on a two points correlation analysis.

Finally the EM-ML (Expectation Maximization-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**.** Even if the computation time is still prohibitive for a real application, a parallel implementation (applied both in the initialization and imaging step of the algorithm) will be soon ready to allow a real time application of the method even with a modest number of computing machines.

The algorithms have been tested and optimized over different simulation scenarios. As an example we supposed to scan a MUON shape, built with voxels of size 10 cm x 10 cm x 10 cm, inserted at the center of a 20' container. Each letter is made of a different material: M = Uranium, U = Iron, O = Lead, N = Aluminium. The shape is surrounded (thus hidden) by layers of washing machine-like elements, made of an aluminium casing and an iron engine inside, with relative support bars and a concrete block. Each tomographic reconstructed image supposes a statistics of 1 million of events (corresponding to 10 minutes of data taking).

By using the Clustering and the EM-ML methods, it is possible to clearly distinguish the M and O letters, made by elements with higher atomic numbers (Uranium and Lead). On the contrary, by applying the POCA reconstruction algorithm, a persistent halo slightly increases the size of the letters, especially along the vertical direction. It is a consequence of the basic assumptions of this algorithm. In every case, the EM-ML algorithm reconstructs the target objects with a considerably better resolution. However, the noise induced by the presence of the washing machines is present in both cases and can be reduced by implementing, for example, density-based algorithms.

VII. Experimental Tests

A. Test on the Single Strips Coupled to the Photo-sensor

Several experimental tests have been carried out on several prototypes of scintillator strips and WLS fibers from different suppliers, in order to find the best configuration for the final detector design and optimize the light collection at one end of each strip.

The strips were tested inside a dark box, equipped with two WLS fibers, no glued. The length of the strip samples was 60 cm and the light was collected by two 3 meters long WLS fibers accommodated in the grooves of each strip. Changing the distance between the muon impact point and the photosensors placed at one end of the fibers, the SiPM charge spectrum was acquired by the use of a digital oscilloscope.

In order to reduce the noise due to the SiPM dark count rate, the coincidence between the two SiPMs was imposed during the acquisition.

The rate of cosmic muons detected by the SiPM described in the section IV (made by ST Microelectronics) placed at one end of a 60 cm Uniplast strip (Vladimir, Russia), as a function of the distance crossed by photons into the fiber, was measured 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.

The choice of the threshold (reported in number of photoelectrons) influences the uniformity of the detection efficiency along the length of the strip. It is important to underline that, even if each individual SiPM is quite noisy at low thresholds, the 8-fold coincidence between the detection planes, allows to minimize the spurious coincidence rate.

B. The Mini-prototype

In order to test a working prototype within the next few months, it was decided to create a portal in a smaller size. The eight planes of the prototype will have an area of 40 cm x 1m size. For each module, the front-end support houses 10 cookies to guide the fibers to the photo-sensors, the SiPMs, arranged on 10 chips with 20 amplified SiPMs each, the control system for power supply and temperature. In addition, there are the boards for the application of the reduction channel strategy, discrimination and stretching of the signals, one or more connectors for the control of the functional parameters of the front-end and for interfacing to the acquisition electronics.

Each X-Y logic planes will have a 40 cm x 40 cm sensitive area. As soon as several tests on the mini-portal will be carried out, which will give us useful information on the final prototype performances.

VIII. Conclusions

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 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 (10x10 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 of a portal in reduced scale, in order to test a working prototype within the next few months, is in progress.

The final, large-scale prototype will be ready around mid-2015. Other future applications of the muon detector are under study (such us in landfills and airports).

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- Insirio SPA

REFERENCES

[1] The Muon Portal Project web site: *http://muoni.oact.inaf.it::8080/*

[2] K. Gnanvo et al., "*Imaging of High-Z Material for Nuclear Contraband Detection with a Minimal Prototype of a Muon Tomography Station Based on GEM Detectors*", 2011 Nucl. Instr. and Meth. A 652 16.

[3] W. Priedhorsky et al., *"Detection of high-Z objects using multiple scattering of cosmic ray muons"*, 2003 Review of Scientific Instruments 74 4294.

[4] K.R. Borozdin, *"Radiographic imaging with cosmic ray muons"*, 2003 Nature 422 277.

[5] S. Pesente et al., "First results on material identification and imaging with a large- volume muon tomography prototype", 2009 Nucl. Instr. and Meth. A 604 738.

[6] F. Riggi et al. (The Muon Portal Collaboration), *"The Muon Portal Project: Development of an Innovative Scanning Portal Based on Muon Tomography",* Proceedings of the ANIMMA 2013 Conference, Marseille, 23-27 June, 2013.

[7] OPERA experiment document: www.phy.bnl.gov/edg/reactor/daya_bay/scintillator/o_t_t.pdf

[8] D. Lo Presti et al., *"OFFSET: Optical Fiber Folded Scintillating Extended Tracker"*, 2014 Nucl. Instr. and Meth. A 737 (2014) 195-202.

[9] S. Riggi et al., (The Muon Portal Collaboration), *"Geant4 simulation of plastic scintillator strips with embedded optical fibers for a prototype of tomographic system",* Nuclear Instruments and Methods A 624 (2010) 583-590.

[10] S. Riggi et al., (The Muon Portal Collaboration), *"A Large Area Cosmic Ray Detector for the Inspection of Hidden High-Z Materials Inside Containers",* Proceeding of the ECRS 2012 Conference, Moscow, 3-7 July, 2012, J.Phys.G(Conf.Series) 409(2012)012046.

[11] S. Riggi et al., (The Muon Portal Collaboration), *"Muon* tomography imaging algorithms for nuclear threat detection inside large volume containers with the Muon Portal detector*",* Nuclear Instruments and Methods A 728 (2013) 59-68.