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Search for hidden high-Z materials inside containers with the Muon Portal Project

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ABSTRACT: The Muon Portal is a recently born project that plans to build a large area muon detector for a noninvasive inspection of shipping containers in the ports, searching for the presence of potential fissile (U, Pu) threats. The technique employed by the project is the well-known muon tomography, based on cosmic muon scattering from high-Z materials. The design and operational parameters of the muon portal under construction will be described in this paper, together with preliminary simulation and test results.

KEYWORDS: Search for radioactive and fissile materials; Particle tracking detectors; Computerized Tomography (CT) and Computed Radiography (CR)

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1 Introduction

The detection of nuclear weapons and special nuclear material is crucial to thwart nuclear proliferation and terrorism and to secure weapons and materials worldwide. The future international regulations [1], which will enter into force by 2014, will require the inspection of all cargo containers traveling to U.S. ports. However, the inspection protocols currently in force in the major international borders and ports usually provide for the control of only 1% of the traveling cargo containers. To avoid manual inspection of the containers, many radiation detection techniques have been developed in order to identify the presence of nuclear material emitting radiation. The most common technique is the X-ray radiography, based on the absorption of X-rays from an intense source. Other possibilities are the directional imaging with gamma rays and neutron radiography. However, as a drawback, all these techniques are not very sensitive in case of heavily shielded nuclear materials.

In contrast, advanced non-intrusive inspection equipments have been developed in recent years to detect dense materials that may be consistent with the presence of certain fissile materials. In this paper we describe a possible application of muon tomography as alternative to the standard radiation portal monitors for the inspection of cargo containers.

2 Muon tomography for container inspection

Muon tomography is the technique of using naturally occurring cosmic muons to detect and image dense materials. It is known that, as muons pass through matter, they undergo many small angle deviations due to multiple Coulomb scattering and the outgoing muon track may be characterized by a scattering angle $\Delta\theta$ and a displacement Δl, taken relative to the orientation and position of the incident muon. It is the spread in overall scattering angles over many muons that is significant, as the distribution is dependent on the radiation length, X_0, which is material dependent and a function of atomic number (Z) and density [2]. As a result, by the determination of the scattering angles, it is possible to reconstruct a three-dimensional map of the scattering points, highlighting in this way the presence of high-Z fissile materials (U, Pu) or their shielding (i.e. Pb).

With respect to the traditional inspection methods, muon tomography can offer several advantages since it is completely passive, highly penetrating, and provides a three dimensional density profile of the inspection volume. Thanks to these characteristics, muon tomography complements the standard radiation detection portals in use, allowing to scan a container in a short acquisition time, without opening it and damaging its content.

For its implementation, muon tomography requires tracking the cosmic ray muons before they enter and after they exit the probed volume so that the scattering angles of muons traversing the volume can be measured precisely. In recent years several projects have been proposed with the aim of building prototype detectors for muon tomography [3–7]. Of course, the performance of each detection system, in terms of spatial and angular resolution, depends on the technical solutions implemented. As an example, the Los Alamos and the IHEP-Protvino groups have published promising results from scanners using drift tubes [8, 9]; also the INFN group in Padua has built a fully operative, muon-based scanning prototype based on drift chambers, that is able to perform a fully passive tomographic scan since 2010 [10]. Finally the Chalk River group has already published data from a scanner using scintillator bars [11].

Within this context, the Muon Portal Project [12] was recently started by the collaboration of some research centers (University of Catania and INAF — Astrophysical Observatory of Catania) and industrial partners (STMicroelectronics, Insirio and Meridionale Impianti Welding Technology), with the aim of building a full-scale prototype for the scanning of traveling containers. A technical description of the detector is given in section 3, whereas the results of preliminary experimental tests for the construction of the first detection modules are described in section 4. Finally, the algorithms implemented for a fast and reliable image reconstruction are discussed in section 5.

3 Design of the detection system

The acquisition of a tomographic image of a container requires the use of a large tracking detector, able to reconstruct the incoming and outgoing muon directions. After more than one year of R&D activity, the Muon Portal Collaboration has finally defined the detector design, which consists of four XY tracking planes of plastic scintillator bars with embedded WLS fibers and SiPM readout, two placed above and two below the investigated volume [13, 14]. The detector covers an overall area of $18\,\mathrm{m}^2$ ($3\,\mathrm{m} \times 6\,\mathrm{m}$) and is suitable for a full inspection of a 20’ container ($244 \times 259 \times 610\,\mathrm{cm}^3$).

The detector has a modular structure since each plane consists of six identical modules ($1 \times 3\,\mathrm{m}^2$ each), suitably placed in order to minimize the dead area as shown in figure 1. A total of 48 modules are planned for the overall detector.

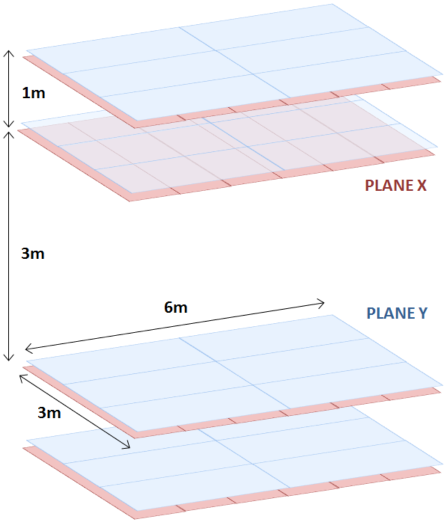

Figure 1. Scheme of the apparatus design for the Muon Portal (the distances between the planes are not to scale).

Such geometry implies a slight drop of the detection efficiency at the container borders. To carefully inspect these inefficient regions, a higher statistics — that corresponds to a longer inspection time — would be required. As an alternative, a possible upgrade of the apparatus would be to increase its acceptance by adding detection modules to each plane. However simulations are in progress to evaluate the benefit/cost ratio of such a modification.

Each module is made of 100 extruded plastic scintillator strips ($1 \times 1 \times 300\,\mathrm{cm}^3$). The spatial resolution, in the order of a 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 3 mrad. Details about each detector component will be given in the next sections.

3.1 Scintillator strips and WLS fibers

The choice of extruded plastic scintillator strips for the detection of cosmic muons is due to a reasonable compromise in terms of efficiency, light yield, emission and absorption spectra, aging properties, maintenance, cost and availability on the market.

A series of strip samples with different composition, size and fiber configuration have been tested by measuring their light response to the passage of cosmic muons. The description of the experimental apparatus and some results are discussed in section 4.

As an example, figure 2 shows a picture of two strip prototypes tested in our laboratories: on the left it is shown a strip (1 cm × 1 cm section) provided by the Fermi National Accelerator Laboratory with a centered hole able to accommodate two 1 mm WLS fibres; on the right a strip (0.7 cm × 1 cm section) provided by Uniplast (Vladimir, Russia) with two 1 mm grooves along the same side. Other prototypes manufactured by Amcrys (Kharkov, Ukraine) were tested as well.

Since the collection of the light also depends on the emission and absorption spectra of the WLS fibers used, the strips were tested with multi-cladding fibers both from Kuraray (Y11(200)M) [15] and Saint-Gobain (Bicron BCF-91A) [16].

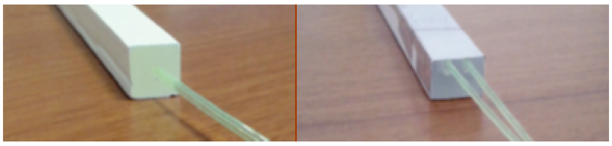

Figure 2. Pictures of two among the various designs of extruded scintillator strips tested for the Muon Portal Project. Picture on the left refers to the Fermilab design, picture on the right to the Uniplast design.

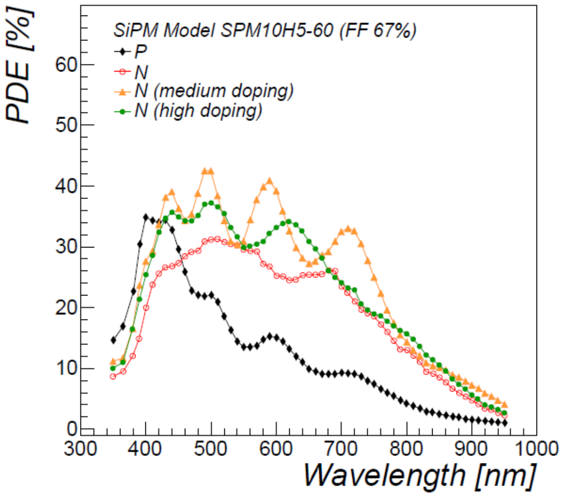

Figure 3. Photon Detection Efficiency for different silicon photomultipliers technologies currently under test for the Muon Portal application.

The results of the tests suggested to choose, for the final design, 3 meters long strips, with 1 cm × 1 cm section, read out by Kuraray WLS fibers. A design of the individual detection module has been already prepared and an assembly tool is already built, to pack the strips, insert the WLS fibres, prepare their surface with a diamond tool for an optimal optical coupling to the photosensors and arrange the connection to the front-end electronics at one end of the module.

3.2 Photosensors

It was chosen to use custom designed SiPMs to convert the scintillating light collected by WLS fibers into charge signal. The SiPM prototype designed for the Muon Portal project has to maximize the photon detection efficiency (PDE) and the cell fill factor, as well as to ensure a low cross-talk and dark count rate. Different SiPM prototypes, both with the p-on-n and n-on-p technologies, have been produced by STMicroelectronics. The devices have been fully characterized (both from the electrical and optical point of view) at different temperatures and working conditions.

Figure 3 shows a summary of PDE measurements as a function of the light wavelength λ, carried out on several devices with different SiPM technologies, at 5 V of overvoltage. In the range $\Delta\lambda = 500$–550 nm (which corresponds to the main emission region of the Kuraray WLS fiber) the best device shows a PDE of the order of 35%. The layout of the final chip is based on such technology (*N — medium doping*) and embeds 4 independent round shaped SiPMs with 60 μm × 60 μm cells. Actually the chip contains two types of SiPMs, which differ for their cell

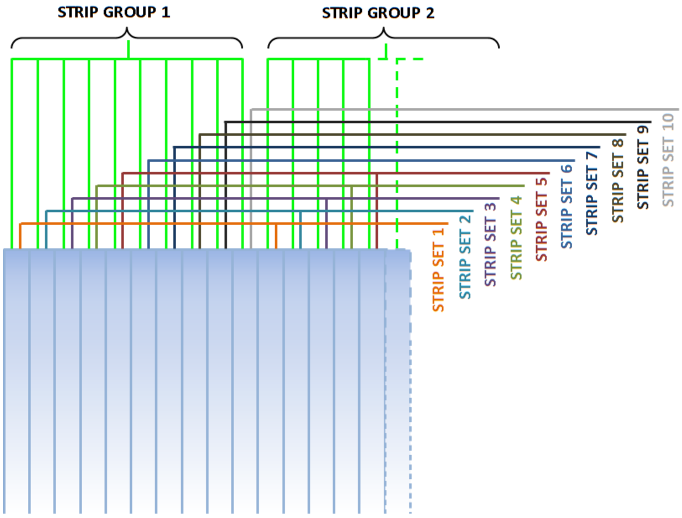

Figure 4. Channel reduction system implemented in the Muon Portal readout electronics.

pitch: the MUON60 type has 548 cells, a cell fill factor of about 67% and a photon detection efficiency of $\sim$35% for the green light; the MUON75 type has 320 cells, a cell fill factor of about 74% and a photon detection efficiency of $\sim$38%. As soon as the chip will be available, we will choose the best SiPM layout. The SiPM batch is currently under production and will be available at the beginning of 2014.

In the final design the SiPMs will be optically coupled to the polished fibers and will be enclosed inside a hermetic box, in order to be operated in dark conditions at a controlled temperature.

3.3 Readout electronics and data acquisition

As it is designed, the overall number of channels of the portal (fibers and photosensors) is 9600 in total. However a smart readout strategy allows to reduce the number of electronic channels by a factor of 10. This is achieved by the use of two WLS fibres running along the same strip and going to an equal number of SiPMs. For each strip one of the two fibers is read together with fibers of 10 contiguous strips (*Strip Group SG*), while the remaining fibers are combined in proper *Strip Set SS* of 10 strips (the i-th Strip Set includes the i-th strip of each SG). The strategy is explained by the sketch shown in figure 4.

A particle crossing one strip generates two signals (one for each fiber). Their combination is able to identify the interested strips inside each module by the following formula:

$$\text{Strip}_{\text{hit}} = i + 10 * (j - 1) \tag{3.1}$$

where i and j are respectively the *Strip Set* and the *Strip Group* that gave a signal.

From each module the 20 output analog signals are sent to the readout boards with MAROC3 chips on board [17], where the signal is amplified, shaped and converted to digital by a comparison to a threshold. Real-time boards based on National Instrument FPGA FlexRIO [18] are being used to decode the hit strip and produce a label frame for the event. For the purpose of correlating the arrival of muons in the Muon Portal detector to additional detectors located around it, a GPS time-stamping unit has also been incorporated in the acquisition architecture. This will allow off-line correlation of the events measured in independent detectors placed close to the portal, with a time precision of about 40 ns. For such purpose, we plan to use an array of 3 large area scintillator detectors, placed 5 meters apart in a triangular geometry. Preliminary tests have confirmed the possibility to detect cosmic ray air showers, reducing the spurious coincidence with the muon portal to a negligible level.

3.4 Mechanical structure

A customized mechanical support has been designed to place and align the detection modules. The envisaged distances between the detection planes is 100 cm, whereas the inner part of the detector will be about 300 cm high, to allow the insertion of a standard container (figure 1).

The structure itself has been designed in order to minimize the material budget traversed by the muons, thus avoiding undesired scattering. Sensors for alignment and alarms will be installed in the structure to monitor the temperature variations and the mechanical stress due to the weight of the various components.

4 Preliminary results from experimental tests

As discussed in section 3.1, a series of experimental tests have been carried out on several prototypes of scintillator strips and WLS fibers from different suppliers, to choose the best configuration for the final design of the detector and optimize the light collection at one end of the strip.

The strips to be tested, equipped with two WLS fibers, were placed inside a dark box. The length of the strip samples was 60 cm and the light was collected by 3 meters long WLS fibers accommodated — but not glued — in the grooves. By sliding the fibers into the grooves, it was possible to change the distance between the muon impact point and the photosensors (section 3.2) 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.

As an example we report in figure 5 some typical results obtained on a sample of the Uniplast design strip. The muon rate detected on a small region of the strip (approximately 60 cm) is reported as a function of the distance from the photosensor. The strip was equipped with Kuraray WLS fibers. The light was detected with one of the STMicroelectronics prototype described in section 3.2. It is evident that the choice of the threshold (reported in photoelectrons) has influence on the uniformity of the detection efficiency along the length of the strip. It is important to note that, even if each individual SiPM is quite noisy at low thresholds, the 8-fold coincidence between the detection planes allows to drastically reduce the spurious coincidence rate. The result in figure 5, together with detailed GEANT4 simulation studies of the transport of the light inside the strip, suggested the use of thicker strips (at least 1 cm thick, instead of 0.7 cm) in order to preserve the detection efficiency along the strip above 90%. Additional experimental tests carried out on Amcrys scintillator strips (1 cm thick, 3 m long) with Kurary WLS fibers, confirmed such an hypothesis.

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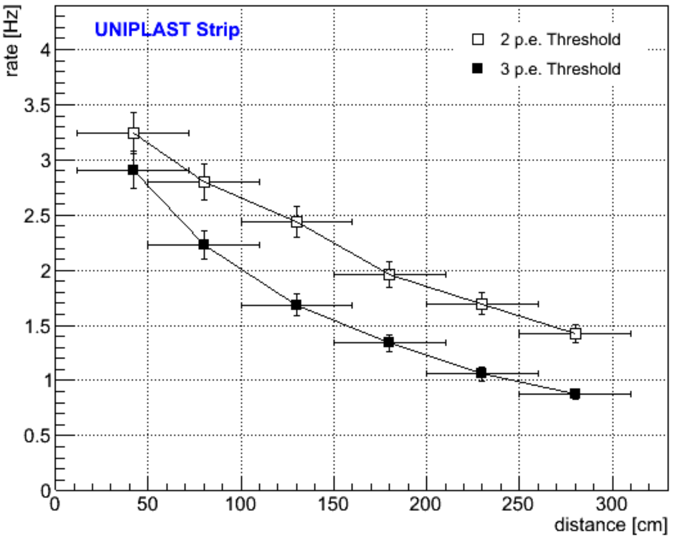

Figure 5. Detection rate of cosmic muons versus the distance from the SiPMs, for an Uniplast strip sample with Kuraray Y11(200) fibres embedded. The data are reported for two different acquisition thresholds (given in terms on number of photoelectrons).

5 Simulations and image reconstruction

Detailed GEANT4 simulations have been carried out in order to understand the performance of our detector and to optimize the algorithm for the reconstruction of the tomographic image. The main ingredients of the simulations include the implementation of a full replica of the complete detector, of the structure 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.

The output of the GEANT4 simulations has been used to implement several algorithms for the reconstruction of the tomographic image. In this paper we focus on the two most commonly used algorithms, the POCA (*Point Of Closest Approach*) and EM-ML (*Expectation Maximization-Maximum Likelihood*) methods. Further algorithms and results can be found in ref. [19].

The simplest method to reconstruct the tomographic image is the POCA 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.

A more sophisticated algorithm is the Maximum Likelihood method. It is an iterative algorithm 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 a log-likelihood function, 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.

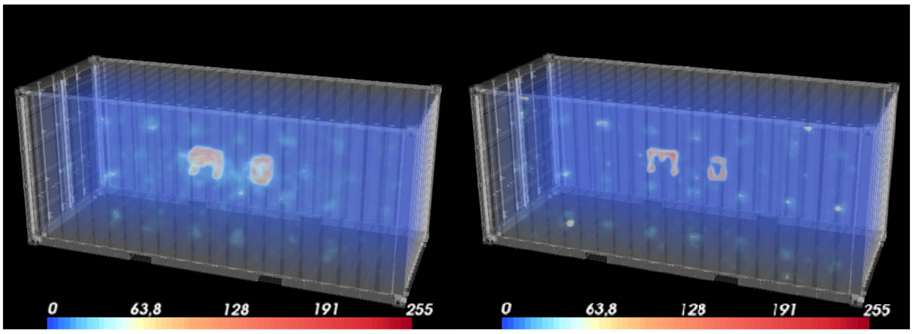

Figure 6. Tomographic imaging of the simulated scenario obtained with the POCA (left) and EM-ML (right) method.

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 $10\,\text{cm} \times 10\,\text{cm} \times 10\,\text{cm}$, 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 with an iron engine inside, with relative support bars and a concrete block. Figure 6 shows the tomographic image reconstructed with the two algorithms, POCA (left) and EM-ML (right), supposing a statistics of 1 million of events (corresponding to 10 minutes of data taking).

In both cases it is possible to clearly distinguish the M and O letters, made by elements with higher atomic numbers (Uranium and Lead). However, in the POCA reconstruction, 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. On the contrary, 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 [19].

6 Conclusions

For the overall completion of this Project, a preliminary research and development phase has been undertaken on several aspects. Prototypes of SiPM sensors have been already produced by the STMicroelectronics and will be customized for this specific application. The geometry and segmentation of the strip detectors is already finalized, with most of the preliminary tests already carried out. The architecture of the front-end electronics and of the data acquisition has been designed and the first modules are under construction. All the simulation and reconstruction tools have been tested, and only minor improvements and optimization required. Moreover, in view of the full operation of the portal, we have foreseen the development of an image elaboration system and a control and monitoring system, the former being responsible for the processing of tomographic analysis and image visualization, the latter being designed for control of the data acquisition procedures. Such R&D phase will soon be followed by the construction of the overall apparatus (48 modules, for a total of 4800 detectors), in order to arrive at the completion of the entire setup within mid 2015.

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