A large area cosmic ray detector for the inspection of hidden high-Z materials inside containers

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Abstract. Traditional inspection methods are of limited use to detect the presence of fissile (U, Pu) samples inside containers. To overcome such limitations, prototypes of detection systems based on cosmic muon scattering from high-Z materials are being tested worldwide. This technique does not introduce additional radiation levels, and each event contributes to the tomographic image, since the scattering process is sensitive to the charge of the atomic nuclei being traversed. A new Project, started by the Muon Portal Collaboration, plans to build a large area muon detector able to reconstruct muon tracks with good spatial and angular resolution. Experimental tests of the individual detection modules are already in progress. The design and operational parameters of the muon portal under construction are here described, together with the preliminary simulation and test results. Due to the large acceptance of the detector for cosmic rays, coupled to the good angular reconstruction of the muon tracks, it is also planned to employ such detector for cosmic ray studies, complementing its detection capabilities with a set of trigger detectors located some distance apart, in order to measure multiple muon events associated to extensive air showers.

1. Introduction

Hundred million vehicles pass each year through custom borders of many Countries. All are capable of transporting hidden nuclear weapons or nuclear material. Traditional inspection systems, such as those based on X-rays are of limited use, because they cannot be employed on occupied vehicles and the energy and dose are too low to penetrate many cargos. An equipment that overcomes these limitations consists of a large setup for the detection of the secondary cosmic radiation, able to signal the presence of hidden fissile high-Z elements inside a large volume, such as the containers currently employed to transport materials. The technique,
commonly named muon tomography, makes use of the multiple scattering of cosmic muons, which strongly depends on the atomic number of the traversed material, hence particularly sensitive to high-Z fissile materials (Uranium or Plutonium) or shielding materials. The secondary cosmic ray flux at sea level allows to obtain enough statistics 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. Along this line, several projects exist aiming at building prototype detectors for muon tomography [1, 2, 3]. A new Project was recently started by the Muon Portal Collaboration [4] with the goal to build a real size detector (> 100 m$^3$ volume) with all potential features to be used in a real situation. The main features of the planned setup are here described. A considerable amount of simulations has demonstrated the feasibility of the Project and the possibility of reaching enough information in a few minutes in order to reconstruct a tomographic image of a large volume.

2. The Muon Portal Detector
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 (see Fig.1), with good tracking capabilities for the charged particles (muons and electrons) traversing them, in such a way to compare their trajectories and evaluate the amount of multiple scattering for each track. According to this method, it is possible to reconstruct a 3D tomographic image, by means of appropriate reconstruction algorithms and visualization techniques.

The overall size of the detector fits that of a real TEU (Twenty-foot Equivalent Units) container, namely 6 m $\times$ 3 m $\times$ 3 m. For a suitable implementation of the detection setup, each plane is made by 6 modules (1 m $\times$ 3 m each) 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. A customized mechanical structure is being designed, to provide a suitable support for the detector planes, yet minimizing the material budget traversed by the cosmic muons, and to insert between the intermediate detection planes a structure like a real container.

2.1. Strip design
Each detection module is segmented into 100 strips of extruded plastic scintillators (1 $\times$ 1 $\times$ 300 cm$^3$), with wavelength-shifting (WLS) fibres to transport the light produced in the scintillator to the photosensors (Silicon Photomultipliers) at one of the fibre ends, in order to optimize the
amount of collected photons, still maintaining at a reasonable level the cost and the size of the detection setup. 

GEANT4 simulations of the transport of optical photons inside the scintillator strips and the WLS fibres have been carried out for several geometrical configurations. The results of the simulations have been also compared to test measurements, performed on strips of similar size (2.6 cm \( \times \) 1 cm \( \times \) 300 cm) with WLS readout. As an example, Fig. 2 shows the number of photoelectrons measured at one end as a function of the distance with respect to the muon interaction in the strip, as determined by two small trigger detectors placed above the strip. For comparison the prediction given by the GEANT4 simulations is shown with a solid line.

2.2. Electronic readout and data acquisition

To cover all the detection planes by strip detectors with the required granularity, and to limit spurious coincidences given by dark rate 9600 channels would be necessary. In order to reduce such number to a suitable level, a compression technique is being used within each module (100 detectors), which routes the information from two independent WLS fibres embedded in the same strip to two different ensembles. Their combination is able to unambiguously identify the interested strip inside each module. Only logic information will be used for each strip.

3. Simulation and reconstruction

A GEANT4 replica of the complete detector has also been implemented, which incorporates the individual strip scintillators, their mechanical supports, and the basic structure of the container roof and floor. Secondary cosmic particles are modelled with realistic energy and angular distributions of muons and electrons as derived from CORSIKA simulations for proton-induced showers, taking into account the primary energy and angular distribution. In order to save CPU time, the transport of optical photons inside the strip scintillator and WLS fibre has been simulated in detail for a particular strip and then parametrized to take into account the response of the overall detector. In any specific detector simulation, several scenarios are considered, inserting one or more “hidden” high-Z objects randomly distributed over the internal volume of the container, together with low and medium-Z materials.

For the reconstruction of tomographic images, the procedure proceeds along several steps. First the hits on each detector plane are recognized, and then combined into clusters. After checking the individual plane and the global cluster multiplicity, a tracking procedure is started, to find the possible tracks from all cluster combinations and associate the upper track (that extracted from upper planes 1-4) to the lower track (extracted from planes 5-8), in order to

Figure 3: Reconstruction of a tomographic image of a simulated Uranium structure with a “CT” shape inside a container volume, obtained with the PoCA algorithm after applying a volume rendering operation.
determine the scattering angle between upper and lower track. Several algorithms are then being tested for the reconstruction of 3D images. The simplest of them is based on the POCA (Point-of-Closest-Approach) method, from which a spatial distribution of the scattering centres is derived, with a weight proportional to some power of the scattering angle. The reconstruction of a tomographic image of a simulated uranium structure with a “CT” shape placed inside a container volume is shown in Fig. 3. Alternative, more sophisticated algorithms [5, 6], based on iterative methods, are also under investigation. They are expected to give better results especially in case of multiple scattering centres. However, their usefulness must be validated against the amount of CPU and computer resources needed. For the visualization of the 3D tomographic images, rendering procedures are applied, by the use of VisIVO software tools [7].

4. Present status of the Project

For the overall success of this Project, a preliminary research and development phase is envisaged on several aspects which will 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 scintillators and WLS fibres, the design of the software algorithms for track reconstruction and image processing. 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 prototype boards being constructed. All the simulation and reconstruction tools have been tested, and only minor improvements and optimization is required at this stage.

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 the end of 2014, and carry out all the necessary calibration measurements and data analysis, which are a particularly important and critical step towards the real use of the apparatus.

5. Conclusion and outlook

The design of the planned detector and preliminary results from simulations as well as from laboratory tests point out the feasibility of the project, aiming at the completion of a large area setup for muon tomography. Work is in progress along several lines to improve the original design and fix the operational parameters, in order to start the full construction and assembling of the detection modules. The completion and operational status of the overall apparatus is expected before the end of 2014. 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. For such applications in cosmic ray physics the muon detection capabilities could be complemented with a set of trigger detectors located some distance apart, in order to measure multiple muon events associated to extensive air showers. Preliminary studies concerning such possibility have been already undertaken.

References

[1] Borozdin K R 2003 Nature 422 277
[2] Gnanvo K et al 2011 Nucl. Instr. and Meth. A 652 16
[3] Pesente S et al 2009 Nucl. Instr. and Meth. A 604 738
[4] For further details visit our Web site: http://muons.oact.inaf.it
[5] Schulz L J et al 2007 IEEE Transactions on Image Processing 16 8
[6] Wang G et al 2009 IEEE Transactions on Image Processing 56 4
[7] Becciani U et al 2010 The Publications of the Astronomical Society of the Pacific 122 119