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Muon Tomography for spent nuclear fuel control

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Abstract:

At present no validated methods to verify the content of Dry Storage Containers exist. The investigation profiting of cosmic muons may constitute a very effective method to detect or exclude the presence of spent fuel bundles. The layout of a possible detector and the techniques to provide the relevant information are described. A specific proposal to evaluate effects of surrounding radioactivity on detector performance is presented.

Keywords: muons tomography; spent fuel control; muon detectors

1. Introduction

Cosmic rays at sea level consist mainly of charged elementary particles called muons. Muons are produced by the decay of several types of very short-lived elementary particles, created in the upper part of the atmosphere by the interactions of primary cosmic rays, mainly protons or alpha particles, with atoms or molecules. Primary cosmic rays originate from galactic processes and thus their flux on earth is constant and isotropically distributed. At sea level the muon flux is about $10^4/m^2$/minute, with maximum intensity in the vertical direction and an approximate dependence on the zenith angle θ as $\cos\theta^2$. The cosmic muon energy spectrum is quite broad, with an average value of several GeV. Energetic muons can cross very thick layers of dense materials since they do not undergo nuclear interactions.

The use of the highly penetrative properties of cosmic-ray muons to explore inaccessible volumes has been proposed in the past [1], [2] and recently many efforts have been produced to demonstrate the potential of muon tomography in many application fields [3],[4]. A detailed review of possible applications can be found in [5].

2. Spent nuclear fuel inspection with cosmic muons

In the particular case of the dry storage containers (DSC), the approach to explore their content can profit of different physical processes occurring when muons cross the container. Firstly, since all the charged particles travelling in a medium lose energy as a function of the medium density, a fraction of muons is stopped inside the container. In addition, depending on the density and the atomic number of the crossed material, the muon trajectories undergo detectable deviations from the initial direction (multiple Coulomb scattering). These phenomena would give a threefold information on the content of the material inside the hidden volume provided a set of muon detectors could be installed around the container. In detail, cylindrical detectors can be placed around the lateral surface of the containers. They should measure the position and direction of the muons entering in the container. They should also measure position and direction of the particles that exit crossing the lateral surface of the container as shown in Figure 1.

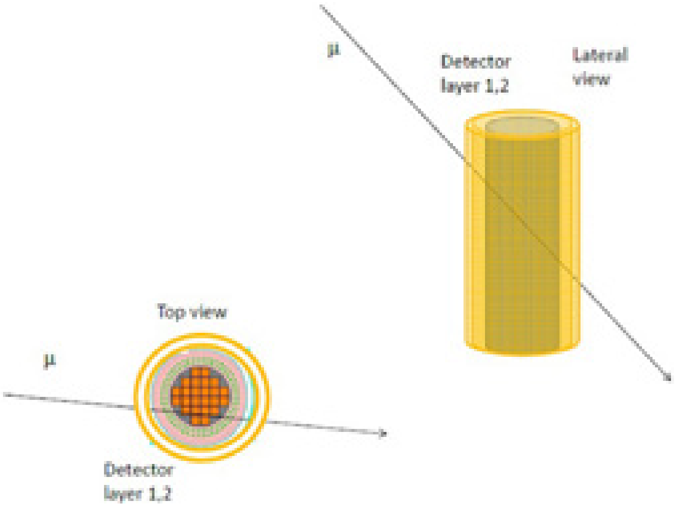

Figure 1: Sketch of a Muon Tomography station (not in scale) Top and lateral view.

With this configuration it is possible to know: i) the most probable path of muons that pass through the container; ii) most probable path of muons that should exit from the lateral surface but are absorbed; iii) the scattering angle of the passing-through muons.

The first two items contain a complementary information. Indeed, the abundance of passing-through particles is connected to spatial regions with light material (e.g. air), while the absorbed particles are located in correspondence to dense regions. In case of an inhomogeneous

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material distribution (e.g. because a fuel bundle is missing) the first set of data would show an excess of particles with a path crossing a large fraction of the light material region. At the opposite, the absorbed particles whose trajectory points to the light material region would be less copious, since they have a smaller probability to stop inside the container.

The measurement of the muon scattering angle allows to determine a two or three-dimensional image of the container. The image reproduces the spatial distribution of a quantity, the linear scattering density, that is roughly proportional to the product of the material density times its atomic number. This method requires a complex formalism and noise filtering techniques as described in [6], [7].

In more detail, to obtain a three-dimensional distribution of the material linear scattering density in the inspected volume, the space is divided into finite volume elements called voxels. The density is assumed to be uniform in the single voxel. It is important to stress that the particular geometry of the inspected volume and the well-known shape of the fuel bundles, allow the choice of voxels with vertically-elongated geometry. This results in a small size set of voxels, high statistics as regards muons per voxel, and low inspection time required.

2.1 Results with simulated data

It is possible to produce a realistic simulation of an inspection system and to obtain simulated cosmic-muon data in a situation similar to the one sketched above. The simulation software chain is based on GEANT4 package that is designed for modeling a broad range of particle processes and their interaction with matter and it is used in a variety of applications, including High Energy Physics (HEP), nuclear physics experiments, astrophysics, space science and medical physics [8]. In the present environment, the simulation includes the generation of cosmic-muon spectrum, the description of the muon detectors and the tracking of muons through a DSC. Several sets of data can be produced simulating different detectors and different containers. For each configuration, datasets with the presence of all the foreseen fuel bars and others with missing bars can be produced.

Using GEANT4, a complete CASTOR® container with and without a missing bar placed in different positions has been simulated. The simulated container is approximately a 4.9 height cylinder with a 2.3 m diameter exposed to cosmic muons with vertical axis. The main container material is steel, while the fuel bars are assumed to be bundles of zirconium cylindrical tubes filled up with Uranium Oxides. The simulation includes a cylindrical detector placed around the CASTOR, covering its entire lateral surface. The detector is composed by 8 layers of cylindrical drift tubes. Figure. 2 shows the top view sketch of the simulated CASTOR.

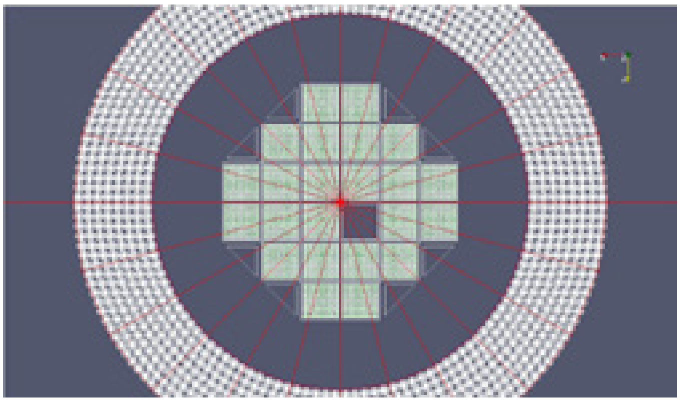

Figure 2: Top- view of a drift tube detector placed around a CASTOR® container with a missing fuel bar.

In this paper the analysis of the simulated data used a very simple algorithm based on weighted count of muons crossing each voxel Results about the detection of a missing bar in a CASTOR container, for simulated samples corresponding to three hours of cosmic-muons data taking, are shown in Figure 3. On the left there is the reconstructed CASTOR density average along vertical axis, obtained using information from absorbed muons. They are particles which are detected before entering the container with a precise trajectory reconstruction but which are not releasing any signal in correspondence to their expected position at the exit. The right image shows the result obtained with the complementary set of data when muons releasing signals on the opposite sides of the container are analyzed. The figures are the difference between the images obtained from the CASTOR under examination and reference images, obtained analysing a container without missing bars The images are obtained by averaging over the vertical axis 2 cm size voxels. This comparison with reference images is not strictly necessary but it is used to improve the contrast. The missing bar is clearly visible with both techniques and it can be seen with poorer resolution also with one hour data taking. Given the large size of CASTOR containers, comparable or even better results can be reasonably expected for other types of containers. Reconstructions based on more sophisticated algorithms or on scattering measurement are not considered in this analysis. The eventual addition of scattering-based results would improve the reliability of the technique.

These results are based on the simulation of a DSC without any nuclear activity and radioactivity emission. In real case, canisters with spent nuclear material emit gamma and neutrons that could interfere with the cosmic muons detection.

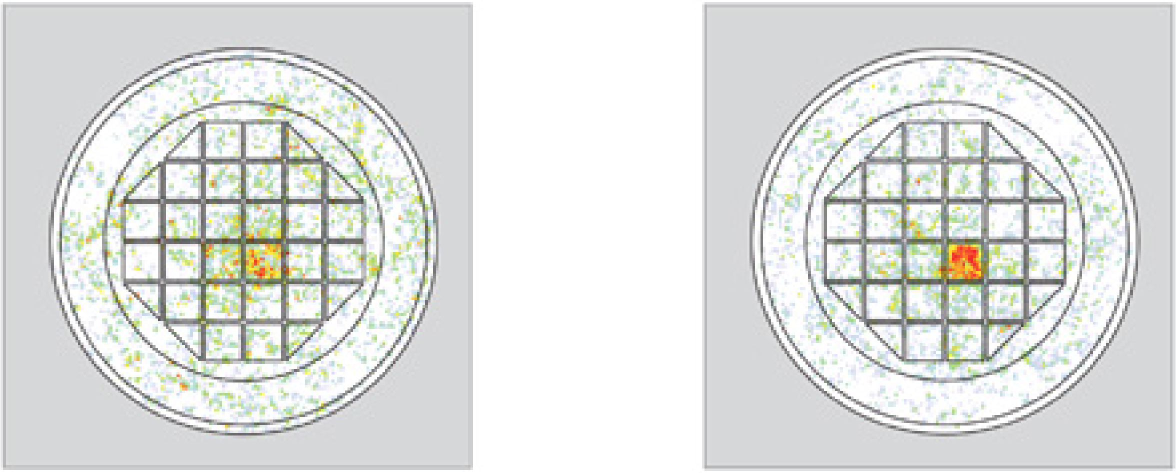

Figure 3: Top-view of the reconstructed CASTOR® density, averaged over vertical axis, obtained using absorbed muon (left) and passing-through muon information (right). The simulated container has one missing bar. Both images are the difference between the images obtained from the CASTOR under examination and reference images, obtained analysing a container without missing bars. The container structure including the bar grid is added for reference.

3. An operative proposal

While the perspectives of a system based on cosmic-muon tracking used to provide an effective control are encouraging, several concerns could arise from the environmental radioactivity in proximity of a DSC and the consequences on the muon detector response.

3.1 Detector layout for canister inspection

It has been shown that one of the cheapest way to provide muon detection with good tracking capability and large area coverage is based on drift tube technology [9],[10],[5].

As sketched in Figure 2, an ideal detector could be realised by several circular layers of drift tubes surrounding the cylindrical container. Muons crossing the tubes before entering the container and, if not absorbed, after exiting, release with large efficiency a hit in each crossed tube. It is then possible to have a good tracking of particles with a hit multiplicity that can be as large as twice the number of circular layers.

However, the presence of an intense radioactivity produced inside the container and reaching the detector can induce a number of signals with a frequency and an occupancy that could, in principle, spoil the detector performance. To quantify this effect, it is necessary to quantify the activity and the impact of its components on the detector. It is therefore not straightforward to clarify this point until several details will be available. In particular, to include the radioactivity in the GEANT4 simulation would require a precise model of the emission rate and energy, to be validated with measurements.

In any case, even if it has been demonstrated that the proposed type of detectors can be operative in presence of high radioactivity, the best way to prove their response in problematic environmental conditions is to perform a dedicated test.

3.2 A detector for a dedicated test

The proposed test consists in producing a small prototype of drift tube detector with a reasonable number of channels to measure properly a cosmic muon track and sufficiently light to be moved and transported in proximity of a DCS. The detector should be capable to self trigger the data recording in the event of a muon passage. Once positioned in proximity of a DSC, the response of the prototype in presence of the radioactivity could be easily monitored. In particular, it could be proved that the tracking capability is maintained even with the coincidence of several additional hits induced by photon conversion or nucleon interactions in some of the tubes of the detector.

The design of such a prototype is shown in Figure 4 and consists of 8 layers of 8 drift tubes each for a total of 64 channels. Each drift tube is realised with a 50 mm diameter Al tube, 1.5 mm thick and a length of 2 meters which is sufficient for the proposed test. The tubes are equipped with a 100 μm anodic wire, connected to a High Voltage supply (~3000 V), to produce a radial electric field and the necessary multiplication of the charges released by incident muons. The collected signal is then amplified and shaped by the front end (FE) electronics and then processed (time digitalization, trigger and remote transmission) by the readout block. The tubes are operated with a gas mixture (Ar85%/$CO_2$15%) that should not present any safety issue.

The total size of the prototype, including mechanical supports, would be about 0.6 m x 0.5m x 2 m, with a total mass of about 100 kg. A sufficient number of tubes have been produced so far by the Padova group in the INFN National Laboratory of Legnaro (LNL), as shown in Figure 5. To complete the prototype, it is then sufficient to assembly the cells and to equip the detector with HV and FE electronics and to complete the gas distribution system. A read-out system based on field-programmable gate array

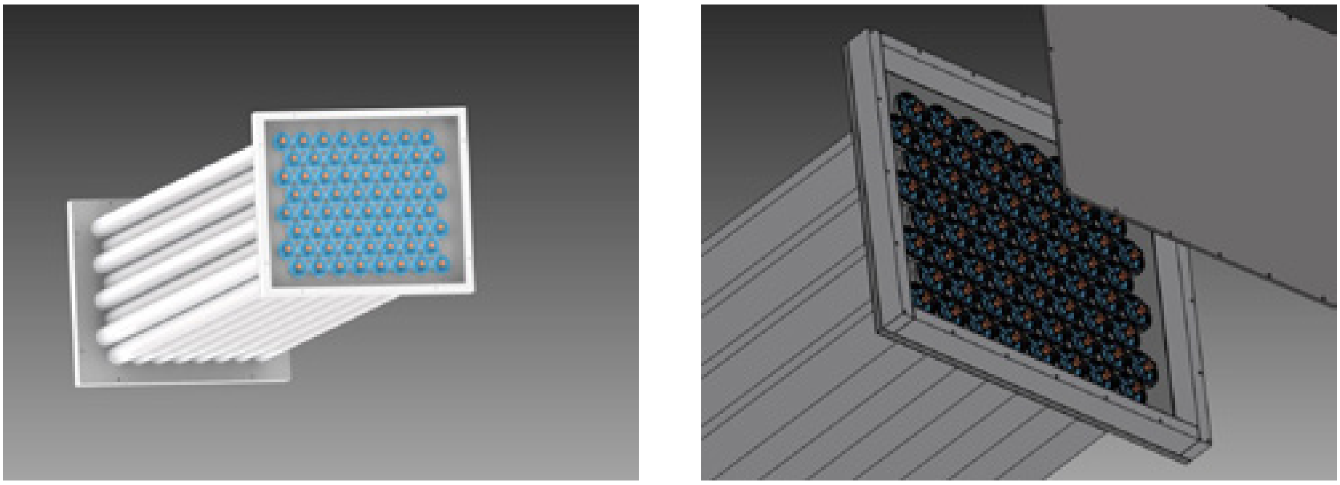

Figure 4: Schematic view of a drift tube prototype detector (left). A detail of the front-end side of the tubes (right).

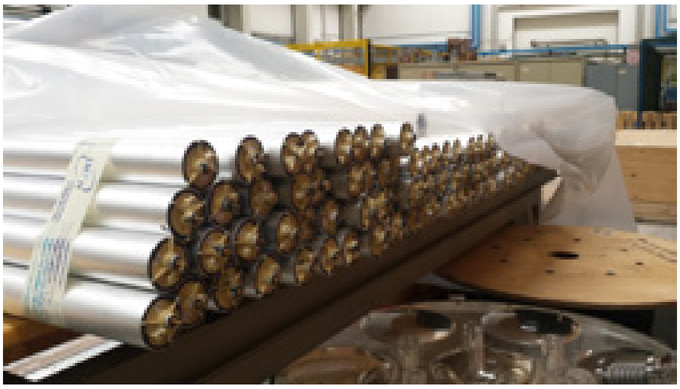

Figure 5: Set of 2m long drift tubes produced in LNL INFN laboratory.

(FPGA) circuits installed in the detector and remote data transmission to an on-line computer is foreseen. The whole electronic chain has been developed for the muon chambers produced for the CMS experiment at CERN-LHC [11] and is available to realize the prototype. Although not strictly necessary for the proposed test, the detector can be instrumented to measure also the coordinate parallel to the wire direction, as required by a complete detector devoted also to 3D imaging reconstruction.

The time needed for an “on site” test would require a couple of days for far (low radioactivity) and near DSC data taking.

4. Conclusions

The volume reconstruction using cosmic muons represents a promising technique for spent nuclear fuel control inside Dry Storage Canisters. It could ensure an effective inspection of the content of disposal canisters after closure. Remaining doubts about the detector capability to operate in presence of radioactivity can be quickly understood with a simple test in proximity of a real canister. A detector prototype for this kind of tests is proposed.

5. Acknowledgements

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6. References

[1] E.P. George, *Cosmic rays measure overburden of tunnel*, *Commonwealth Engineer* (1955) 455.

[2] L.W. Alvarez et al., *Search for Hidden Chambers in the Pyramids*, *Science* **167** (1970) 832.

[3] K.R. Borozdin et al., *Surveillance: Radiographic imaging with cosmic-ray muons*, *Nature* **422** (2003) 277.

[4] S. Pesente et al., *First results on material identification and imaging with a large-volume muon tomography prototype*, *Nucl. Instrum. Meth.* **A 604** (2009) 738.

[5] P. Checchia, *Review of possible applications of cosmic muon tomography, JINST* **11** C12072 (2017)

[6] L.J. Schultz et al., *Statistical reconstruction for cosmic ray muon tomography*, *IEEE Trans. Image Process.* **16** (2007) 1985.

[7] M. Benettoni et al., *Noise reduction in muon tomography for detecting high density objects*, 2013 *JINST* **8** P12007

[8] GEANT4 Collaboration, “*GEANT 4 – a simulation toolkit*”, *Nucl. Instrum. Meth. A* **506** (2003) 250

[9] https://www.decisionsciences.com/

[10] http://mutomweb.pd.infn.it:5210/

[11] CMS collaboration, *The CMS experiment at the CERN LHC*, 2008 *JINST* **3** S08004.