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Muon tomography using micromegas detectors: From Archaeology to nuclear safety applications

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Abstract

Muon tomography, or muography, stands out as a non-invasive technique for the scanning of big objects internal structure. It relies on the measurement of the direction changes or absorption of atmospheric muons when crossing the studied object. For the first case, the trajectory reconstruction of muons upstream and downstream the object, provides information to generate its 3D density map. For bigger objects, a 2D map can be obtained by measuring the absorption for different incident directions. Proposed several decades ago, the performance achieved in particle detectors in the last years, specially in terms of stability, robustness and precision, has enlarged the possible applications of this technique.

Bulk Micromegas represent a well-known technology suitable for the construction of muon telescopes based on these detectors. Thus autonomous and portable instruments have been conceived and constructed at *Commissariat à l'Énergie Atomique et aux Énergies Alternatives* (CEA), being able to perform measurements *in-situ*, next to the studied objects. Furthermore, a Geant4-based simulation framework, capable to handle 3D models of the studied objects, is also being implemented to be used as support tool during the feasibility studies and for data analysis and results interpretation.

Keywords:
Muography, Muon, Tomography, Imaging, Simulations, Micromegas

1. Introduction

Soon after the discovery of muons produced at the Earth's atmosphere by cosmic rays [1, 2, 3], the idea to use them as scanning method of big structures, the so-called muon tomography or muography, was proposed [4]. This technique leverages the capability of cosmic muons to pass through hundred meters or even kilometres with an attenuation or trajectory deviation mainly related to the length of matter traversed along their path and its corresponding density [5]. The so-called transmission muography relies on the well-known radiography concept (widely used, for example, in medicine with X-rays). In principle, the attenuation of the muon flux crossing the studied object is related to the opacity of material (average density × path-length) encountered by muons before their detection. Studying all the directions for which muons go through this object, it is possible to obtain its 2D mean density image based on this principle. A 3D image could also be obtained from the combination of multi-directional images. A more detailed description of the absorption muon imaging approach can be found in Refs. [6] and [7].

Alternatively, muon imaging can be based on the study of the muon direction changes when they traverse the object (driven by the Coulomb multiple scattering). This deviation angle is described by the Moliere theory [8] and it mainly depends on the opacity of the traversed object. Thus, registering the upstream and downstream muon trajectories, the deviation angle can be measured. Assuming that the direction change has been produced by a main diffusion process, the muon deviation point can be reconstructed as the intersection of both muon trajectories inside the volume. Thus, this deviation point and its corresponding deviation angle, which is related with the material density, can be associated. Doing this for all reconstructed events, a 3D density map can be obtained. Further information of this method can be found in Refs. [9] and [10]. Based on these techniques, muon imaging provides a non-invasive scanning method utilisable for big objects (from few metres to hundreds of metres depending on the used technique). While the deviation method is more sensitive, the range of application is

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limited to relatively small objects with limited opacity, since it requires the installation of muon detectors at both sides of the scanned structure. Transmission approach requires longer measurement times but is more suitable for the scanning of big objects.

Last years have witnessed a significant increase in the number of applications and studies based on muography. They go from such a diverse subjects as vulcanology [11, 12] or archaeology [13] to homeland security, engineering [14] or nuclear safety applications. This can be possible thanks to the improvement of the detectors used for the muons track reconstruction, increasing their angular resolution, keeeping the required robustness, auntonomy and portability. Among the different detectors used for muography, the *Commissariat à l'Énergie Atomique et aux Énergies Alternatives* (CEA) group conceived a muon telescope based on the operation of Micromesh gaseous structure (micromegas) detectors. This has allowed our group to perform different muography measurements and keep working in several projects at present.

In this work, a brief description of the Micromegas-based muon telescope is given in section 2. Some of the activities are summarized in section 3, while the description and first results of the simulation framework performed devoted to these projects are presented in section 4. Finally, section 5 gathers main conclusions and future prospects of the projects.

2. A micromegas-based muon telescope

Considering the muon tomography principles and the characteristics of the required measurements, muon telescopes used for this application should fulfil some features. Most important is to have excellent spatial and angular resolution, which will allow the precise reconstruction of the incident muons direction. Furthermore, these instruments are expected to operate over several months and next to the studied object, often located outdoors and exposed to varying environmental conditions. This requires a telescope based on a performing and robust technology and preferably portable, autonomous, protected from the environment and with a stable operation. The CEA group chose micromegas detectors [15] as basis of its muon telescope.

The operation principle is the following. Micromegas readouts are placed in parallel. When a muon reaches the telescope the induced signals in the detectors are used to determine the muon interaction point in each of them, consequently the incoming muon trajectory can be reconstructed. Most important part of the instrument are micromegas detectors themselves. Largely used in particle physics, these gaseous detectors provide a stable and robust readout with excellent performance. In this case 50×50 cm^2 bulk-micromegas detectors [16], operating in an Argon-iC_4H_{10}-CF_4 (95-2-3) gas mixture, are used. With 1037 readout strips (with 482 micrometres pitch) both in X and Y coordinates, they have two peculiarities: first, the presence of a screen-printing resistive layer on top of the readout strips [17] allowing a more stable operation, avoiding sparks, and providing a more diffused charge distribution for a better position reconstruction. The second is the multiplexing of the readout strips [18] reducing the readout channels from 1037 to 61, which simplifies the signal acquisition process. Rest of the telescope components have been optimized to improve its portability and autonomy. Light materials as aluminium have been used for the detector structure while the DAQ components, as high-voltage and readout modules, have been designed with a reduced size and low power consumption. The whole instrument is controlled by a Hummingboard nano-PC running GNU/Linux which also performs the online reconstruction of the muon trajectories and the data transfer via a 3G connection. Figure 1 shows one of the micromegas-based muon telescopes operated for muon tomography. A more detailed description of this kind of telescope and its operation can be found in Refs. [19] and [20]. With these features the overall consumption of the instrument is around 35 W, which can be supplied by batteries or other autonomous method. The achieved position resolution is of the order of 400 micrometres, leading to an angular resolution between 0.8 and 4 mrad, depending on the distance between the telescope planes. Different tests and measurements carried out with these devices have demonstrated their autonomy and stable operation [19].

Figure 1: Photograph of one of the micromegas-based muon telescopes in use for muon tomography measurements. Details about their features and operation can be found in Refs. [19] and [20].

3. Applications

Several muography measurements have been already performed using micromegas-based muon telescopes, using both the transmission and the deviation methods, covering several applications. One of them is the scanning of the Khufu pyramid in Egypt inside the Scanpyramids project [21]. Three different detection techniques have been used by placing muon telescopes inside and outside the pyramid to scan it looking for internal structures as halls or corridors. Micromegas instruments are one of the used detectors, being installed at different locations outside the pyramid, to complement the data taking by the other detectors placed at the interior. Combined results of all three detectors point to the existence of an unexplored big void inside the pyramid [20]. Further measurements, optimizing the detectors position with respect to this void, are expected to be done trying to better determine its position and size.

The second project which is worth mentioning is related to the scanning of nuclear reactors. In an internal collaboration within CEA groups. Muon tomography measurements will be used for the scanning of the G2 and G3 reactors located at the CEA site of Marcoule (south of France) since the 60s. This inspection has two main objectives. Firstly to cross-check the validity of the existing plans. Secondly, to check the reactor internal structure and its components, specially the concrete parts. If the measurements are sensitive enough, possible damages in the reactor components, as for example fissures inside the concrete, could be identified. Thus, the G2G3 project aims to provide information about the structure and status of the nuclear reactors allowing their safer dismantling. Furthermore, this project will represent a proof of concept on the utilisation of muon tomography for the scanning and surveillance of nuclear reactors. The G2G3 project is currently at its first phase, devoted to the performance of feasibility studies by Monte Carlo simulations to explore the muography capabilities. In a further phase, and based on the conclusions extracted from the feasibility studies, corresponding on-site measurements will be carried-out. Thus, the first phase of the project put in evidence the necessity to have a reliable simulation framework.

4. A muon tomography simulation framework

As for any other particle physics experiments, Monte Carlo simulations represent a useful tool for muon tomography. They allow the performance of feasibility studies previous to the experimental measurement, giving information about the best detector location or the required measurement time. After the data taking, they also can be used for the data analysis and results interpretation, providing a better understanding of the detector behaviour. All this will improve the measurement sensitivity. To achieve that, the simulation framework requires the precise implementation of the detailed geometry of the studied object as well as of the muon parametrization at the measurement location. Furthermore, the accurate definition of the main features and performance of the used detector will grant a more efficient comparison between simulations and experimental data. With this aim, a modular simulation framework has been conceived trying to optimize the computation time as well as its versatility. Thus, the full simulation process is divided into three main steps.

The first one is devoted to the simulation of muons through the studied object. It is based on the Geant4 simulation framework [22]. It requires as input information the muon parametrization to be used as event generator, the implementation of a detailed model of the studied object and the position where the detector will be placed. In this phase the detector is defined as a generic sphere, so detector features are not taken into account. Most challenging part of this module is the handling of the studied object geometry. Precise descriptions are usually available in 3D CAD models. In order to implement them in Geant4, it is necessary a previous conversion into GDML format.

Output of the first module (muons reaching the generic sphere defined as detector) are directly used as input of the second module, which generates the muon events at the muon telescope. Based on Geant4 as well, in this step detector main features are required as information, specially regarding the overall geometry and active volumes. Other detector details as the supporting structure or cables are not necessary to implement since they do not affect sensibly the muon path. The outcome of this module is a set of energy deposits for each of the events reaching the active volumes of the detector.

Last module of the framework generates the corresponding signal from the events registered in the previous step. This process is carried out using C++ routines. Thus, this final output can be directly compared with the experimental data. In this case all the features which have influence in the signal generation must be implemented. In the case of micromegas telescopes, it comprises the type and main properties of the used gas in the drift region, which will determine different parameters as the diffusion coefficients. Furthermore, intrinsic micromegas properties as the resistivity or the readout path are also required.

This modular framework optimizes the whole simulation process, allowing the parallelization of the computation. Simulation of muons through matter usually takes a lot of time, so it is better to optimize this step. In this case, an unique simulation performed with the first module can be used to test different detector configurations in the further steps, which are faster. Thus the overall computation time is reduced. It is also worth mentioning that, even if the framework has been conceived thinking on micromegas-based telescopes, the second and third modules allow the definition of any kind of detector, so this is a versatile tool where different types of instruments can be directly compared using the same simulation input. A preliminary example of the performance of simulations is presented in Figure 2.

Following the muon parametrization at Earth's surface proposed in [23], 5×10^6 muons have been generated. A simplified model of the nuclear reactor studied in the G2G3 project has been implemented to perform the simulation. It includes the concrete body, the iron pre-stressing cables and the graphite core. For these first simulations 264 hours of computing time were required, although the processes were parallelized in 100 simultaneous simulations, obtaining the simulation output in $\sim$3 hours. Figure 2 summarizes the result of the offline analysis done for the simulations. Angular distribution of muons reaching the detector placed at one of the sides of the reactor is shown. When the final angular distribution is normalized by the initial muon parametrization the external shape of the reactor, as well as the graphite core or the cables heads, are identifiable.

5. Prospects and conclusions

Muon tomography reveals as a performing non-invasive technique for the scanning of the internal structure of big objects. Mainly related with the improvement of the muon detectors capabilities, specially in terms of angular resolution, robustness and autonomy, the applications of this technique have increased in the last years. Based on the operation of an instrument built with micromegas detectors, the CEA group has performed different muography measurements and is currently involved in

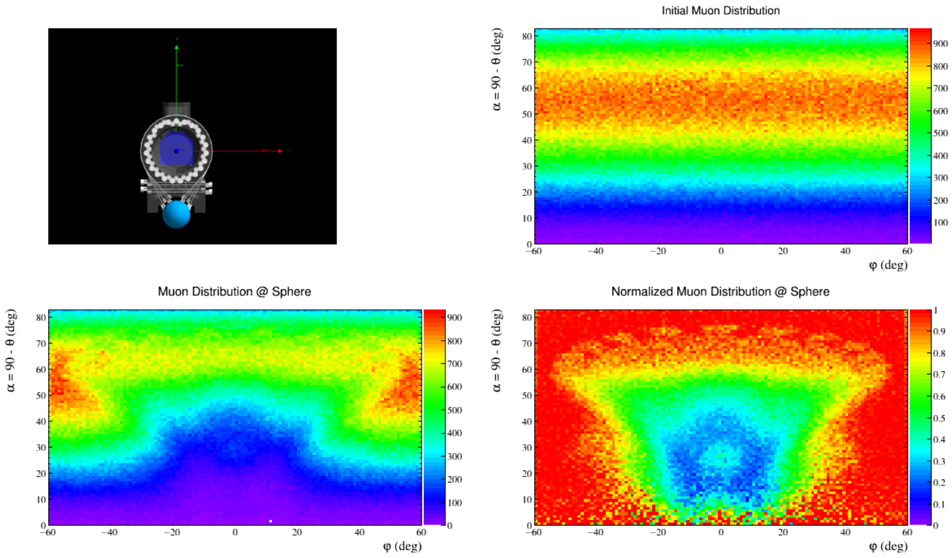

Figure 2: Results from simulations of muons through the nuclear reactor studied in the G2G3 project. Top Left: Simulated geometry of the reactor (see text for details) with the defined detector (blue sphere besides the reactor). Top Right: Zenith - azimuth (θ - φ) angular distribution of the simulated muons corresponding to the muon parametrization at Earth's surface proposed in [23]. Bottom Left: θ - φ angular distribution of muons reaching the detector after crossing the reactor. Bottom Right: θ - φ angular distribution of muons reaching the detector normalized by the initial angular distribution of simulated muons. Contour of the reactor as well as some components are identifiable.

other projects going from archaeology to nuclear safety applications. In parallel to the experimental measurements, a simulation framework is also being developed, representing a useful tool to perform feasibility studies as well as to complement the data analysis and interpretation. For the near future, besides continuing taking data for the ongoing projects, two main work-lines are planned. Regarding the detectors, the development of new resistive micromegas is planned, trying to improve their performance as well as the manufacturing process. Considering the whole instrument, the construction of a telescope with 1 m^2 active surface (i.e. four times bigger than current telescopes), making each telescope plane combining four 50 × 50 cm^2 bulk-micromegas detectors, is also expected. Regarding simulations, efforts will be focused on the fully implementation of the simulation framework, paying special attention to the last step, devoted to the detector response. With these tools it will be possible to keep working in the current projects. Furthermore, the exploration of new applications, related for example with civil engineering, mining or boreholes, is also planned.

References

[1] S.H. Neddermeyer, C.D.Anderson. Note on the nature of cosmic-ray particles, *Phys. Rev.* 51 (1937) 884

[2] S.H. Neddermeyer, C.D.Anderson. Cosmic-ray particles of intermediate mass, *Phys. Rev.* 54 (1938) 88

[3] P. Auger. Rayons Cosmiques, *PUF, Paris* (1941) 136

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

[5] K. Nagamine. Introductory Muon Science, *Cambridge University Press, Cambridge* (2003)

[6] N. Lesparre et al. Geophysical muon imaging: feasibility and limits, *Geophysical Journal International* 183 (2010) 1348

[7] J. Marteau et al. Muons tomography applied to geosciences, volcanology, *Nucl. Instrum. Meth. A* 695 (2012) 23

[8] H.A. Bethe. Molière's Theory of Multiple Scattering, *Physical Review* 89 (1953) 1256

[9] K.N. Borozdin et al. Radiographic imaging with cosmic-ray muons, *Nature* 422 (203) 277

[10] S. Procureur. Muon imaging: Principles, technologies and applications, *Nucl. Instrum. Meth. A* 878 (2018) 169

[11] L. Oláh et al. High-definition and low-noise muography of the Sakurajima volcano with gaseous tracking detectors, *Scientific Reports* 8 (2018) 3207

[12] F. Ambrosino et al. Joint measurement of the atmospheric muon flux through the Puy de Dôme volcano with plastic scintillators and Resistive Plate Chambers detectors, *J. Geophys. Res. Solid Earth* 120 (2015) 7290

[13] G. Saracino et al. Imaging of underground cavities with cosmic-rays muons from observations at Mt. Echia (Naples), *Scientific Reports* 7 (2017) 1181

[14] E. Guardincerri et al. 3D Cosmic Ray Muon Tomography from an Underground Tunnel, *Pure and Applied Geophysics* 174 (2017) 2133

[15] Y. Giomataris et al. MICROMEGAS: a high-granularity position-sensitive gaseous detector for high particle-flux environments, *Nucl. Instrum. Meth. A* 376 (1996) 29

[16] Y. Giomataris et al. Micromegas in a bulk, *Nucl. Instrum. Meth. A* 506 (2006) 405

[17] T. Alexopoulos et al. A spark-resistant bulk-micromegas chamber for high-rate applications, *Nucl. Instrum. Meth. A* 640 (2011) 110

[18] S. Procureur et al. Genetic multiplexing and first results with a 50 × 50 cm^2 Micromegas, *Nucl. Instrum. Meth. A* 729 (2013) 888

[19] S. Bouteille et al. A Micromegas-based telescope for muon tomography: The WatTo experiment, *Nucl. Instrum. Meth. A* 834 (2016) 223

[20] K. Morishima et al. Discovery of a big void in Khufus Pyramid by observation of cosmic-ray muons, *Nature* 552 (2017) 386

[21] ScanPyramids project, www.scanpyramids.org

[22] S. Agostinelli et al. (GEANT4 collaboration), GEANT4: A Simulation toolkit, *Nucl. Instrum. Meth. A* 506 (2003) 250, *IEEE Trans. Nucl. Sci.* 53 (2006) 270
J. Allison et al. Recent developments in GEANT4, *Nucl. Instrum. Meth. A* 835 (2016) 186

[23] P. Shukla. Energy and angular distributions of atmospheric muons at the Earth, arXiv:1606.06907 [hep-ph]