Muons tomography with Micromegas: Archaeology, nuclear safety and new developments for Geotechnics.

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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. 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 muography measurements in-situ, next to the studied objects. At present, a new muon telescope concept is being developed at CEA, combining a Time Projection Chamber (TPC) readout by a 2D multiplexed bulk Micromegas. This new generation of detectors will enlarge the possible application fields of muography, being specially interesting for geotechnics.

1. Introduction
Muon tomography, or muography, was proposed as scanning method of big structures [1] soon after the discovery of muons produced at the Earth’s atmosphere by cosmic rays [2, 3, 4]. Muons have the capability to pass through hundreds of metres or even kilometres suffering an attenuation or a trajectory deviation mainly related to the opacity of the traversed material, defined as the product of the crossed length by its mean density [5]. Two main methods arise for muography. First is the so-called transmission method [6, 7]. It relies on the well-known radiography concept, as it is used with X-rays in medicine. The attenuation of muons crossing the studied object depends on the opacity of the materials traversed by muons along their path before their detection. Based on this principle, a 2D mean density image can be obtained studying the directions of all detected muons after crossing the studied object. Furthermore, the combination of measurements done at different points would provide information to obtain a 3D image. The second one is the deviation method [8, 9]. It studies the muon direction changes when they traverse the scanned object, which are driven by the Coulomb multiple scattering. The deviation angle, as described by Moliere’s theory [10], mainly depends on the opacity of the traversed object. Assuming that the direction change has been produced by a main diffusion process, the diffusion point can be deduced from the intersection of muon trajectories before and
after crossing the object, obtaining this diffusion point and its associated deviation angle hence the local opacity. Therefore a 3D density map can be obtained from all reconstructed events.

Being complementary, both muography techniques provide a non-invasive scanning method utilisable for big objects, with an application range from few metres to hundreds of meters depending on the used technique. While the deviation method is more sensitive to opacity variations, it can only be used for smaller objects with limited opacity, since it is necessary to place muon detectors upstream and downstream the studied object. On the other hand, transmission method requires longer measurement times, but it is capable to scan bigger objects.

During the last years the application fields of muon tomography have increased significantly. Nowadays there exist projects related to vulcanology [11, 12], archaeology [13], engineering [14], homeland security or nuclear safety applications. One of the main reasons for this enlargement is the improvement of the detectors used for the muon tracks reconstruction. At present several techniques provide instruments with good enough angular resolution, while keeping the required robustness, autonomy and portability to perform long measurements in varying environmental conditions. Among these techniques, the Commissariat à l’Énergie Atomique et aux Énergies Alternatives (CEA) group conceived a muon telescope based on the operation of bulk Micromegas detectors, which has allowed the group to perform different muography measurements and to work in several projects at present.

2. Micromegas-based muon telescopes

The main requirement for muography measurements is the precise reconstruction of the incident muons direction. The detectors used with this purpose must provide excellent angular and spatial resolution. Moreover, these detectors should be integrated in a detection system, commonly referred to as muon telescopes, which also have some requisites. Because of the type and location of the structures commonly scanned by muon tomography, measurements take place outdoors, exposed to environmental conditions and during long periods of time, often several months. This requires a telescope based on a robust technology besides its performance. Furthermore, the telescope should be preferably portable, autonomous and with a stable operation despite measurement conditions. The CEA group took Micromegas detectors [15] as basis to develop a muon telescope.

These telescopes mainly consist of several planes of Micromegas (usually 3 or 4) placed in parallel. When a muon crosses the telescope, the induced signals in the Micromegas are used to determine the muon interaction point in each of them. From these points the incoming muon trajectory can be reconstructed. Thus, the most important part of the telescope is the Micromegas readouts themselves. Nowadays, these gaseous detectors are largely used in nuclear and particle physics, representing a stable and robust technology offering an excellent performance. For these telescopes, bulk Micromegas [15] with an active surface of \(50 \times 50 \text{ cm}^2\) are used in an Argon-\(\text{C}_4\text{H}_{10}\)-\(\text{CF}_4\) (95-2-3) gas mixture at atmospheric pressure. The active surface is readout by 1037 strips (with 482 micrometres pitch) both in X and Y coordinates, \textit{i.e.} 2074 channels must be registered to readout a single Micromegas. In order to simplify the signal acquisition system, adapting it to the telescope requirements, readout strips have been multiplexed following a genetic algorithm [17] which reduces the readout channels of each coordinate from 1037 to 61. Besides the multiplexing, the Micromegas are also equipped with a screen-printing resistive layer on top of the readout strips [18]. This allows a more stable operation since this layer protects from possible sparks. Moreover it also diffuses the charge distribution, which can improve the position of the muon interaction point and, consequently, the resolution of the telescope.

As mentioned, the rest of the telescope components have been conceived and made to optimize the portability and autonomy of the instrument. Light materials as aluminium have been used for the telescope structure while the DAQ components, including the high-voltage module,
have been miniaturized reducing their power consumption. The whole instrument is controlled and monitored by a Hummingboard nano-PC running GNU/Linux, which also performs the events online reconstruction and manages the data transfer via a 3G connection. With all these features, the overall consumption of a telescope composed by 4 planes of $50 \times 50 \, \text{cm}^2$ active surface is around 35 W, being possible to supply them by batteries or solar panels. With this configuration, a position resolution of 400 micrometers can be achieved, leading to an angular resolution between 0.8 to 4 mrad depending on the distance between the Micromegas planes.

2.1. Applications and results
The CEA group has already performed different muography measurements using these instruments. Mainly using transmission methods, they have covered some of the potential applications of muon tomography. Among them, three projects could be highlighted because of their interest and their importance on the development of muography activities at CEA.

First of them is the WatTo experiment [19]. It scanned by muography a water-tower deposit located at CEA-Saclay campus. It entailed the proof-of-concept of Micromegas-based telescopes built at CEA since it was the first muography measurement done outdoors, next to the scanned object. The good behaviour of the telescope and all the ancillary systems during the measurement period allowed the obtention of an image of the water deposit structure. Moreover it was also possible to determine a clear anti-correlation between the water level in the deposit and the detected muon flux. This showed the capabilities of muography as a continuous monitoring technique.

Most relevant results obtained by CEA Micromegas-based telescopes come from the ScanPyramids project [20], which scanned the Khufu’s pyramid in Egypt by muography using three different detection techniques. Different telescopes were installed inside and outside the pyramid looking for its internal structure. Micromegas telescopes were installed at different positions outside the pyramid to complement the measurements of other detectors placed inside. These measurements, carried out over several months in different data taking campaigns, confirmed the good behaviour of the instruments in terms of autonomy, robustness and stability. Moreover, the combination of all the measurements, including those made with Micromegas telescopes, pointed out to the existence of an unexplored cavity over the Grand Gallery of the pyramid [21]. New measurements are currently ongoing with the Micromegas telescopes inside the pyramid, optimizing the detectors position with respect to the void, in order to better determine its size, position and orientation.

The third project is the so-called G2G3. In an internal collaboration between CEA groups, it aims to scan by muography two nuclear reactors (G2 and G3) dated from the 60s and located at the CEA site of Marcoule (south of France). Two goals are pursued in this project: first, to cross-check the reactors structure with the corresponding plans, and second, to explore the reactors internal structure and their parts, specially those made of concrete. If measurements sensitivity is good enough, fissures in the concrete as well as other damages in different parts could be identified. The project is divided in two main phases. The first one is devoted to the performance of feasibility studies by Monte Carlo simulations to explore muography capabilities for this application. In a further phase, on-site measurements will be carried out to compare with previous simulations. A first phase of this project revealed the necessity to perform a simulation framework devoted for muography studies and represented the first application of a simulation framework performed at CEA with this purpose.

Based on Geant4 [22] and C++/ROOT [23] routines, this simulation framework has been conceived in a modular and versatile way. It optimizes the computing time but also makes the framework adaptable to any muography application as well as to any muon telescope. Mainly, the first module is devoted to the simulations of the propagation of muons through the studied object while the second generates muons events at the telescope corresponding to those which
have traversed the studied structure. Finally, the third module generates the corresponding signal from the events registered in the previous module. A more detailed description of the framework and its main features can be found at [24]. For the case of G2G3 project one of the most important aspect is that the whole geometry of the nuclear reactor have been transformed from the 3D CAD model into GDML format for its further implementation on the first module of the framework. This accurate definition of the studied object geometry will provide a more precise comparison between experimental data and simulations. Results of preliminary simulations of this project can be found at [24].

3. 3D tomography using TPCs

Going further about other muography applications would require the development of new muon telescope concepts. They should keep the features of the current designs trying to overcome some of their limitations. With this aim a new muon telescope concept has been conceived at CEA. It is based on the operation of a gaseous Time Projection Chamber (TPC) with a small-diameter cylindrical shape. As TPC readout, a 2D pixelized Micromegas will be used. The main improvement of this detector with respect to current telescopes is its acceptance, being possible to cover almost $2\pi$ sr solid angle with a smaller single detector. The reduced diameter of the TPC, of around 15 cm, makes possible to fit these detectors at the bottom of conventional boreholes to scan the surroundings by muography or in any other reduced-space location. Furthermore, installing a network of TPCs at several measurement points would provide enough information to obtain a 3D image. Thus this TPC-based telescope has potential applications in mining exploration or geothermal sounding when installed in a borehole as well as in civil engineering or even monitoring structures as buildings, dykes or bridges when operating a detector network.

The principle of a muography measurement using this detector is equivalent to that performed with the telescopes described in Section 2. In this case the track direction is fully determined from the information provided by the TPC. From the registered directions the angular distribution of the detected muons can be obtained trying to identify any anomaly (excess or deficiency of muons) for a given direction, pointing to the identification of an internal structure. A preliminary simulation to illustrate this principle has been done using the dedicated framework developed by CEA and presented in Section 2.1. Figure 1(a) shows the simulated case. A TPC of 15 cm diameter and 40 cm height is defined at the bottom of 30 m depth borehole dug in standard rock. Some cavities with volumes from 18 to 90 m$^3$ where defined and filled with air or water. 20 millions of muons where simulated following the parametrization proposed by Shukla [25]. As result the angular distribution of the detected muons can be obtained as showed in figure 1(b). If this distribution is projected to 1 dimension, it should follow the distribution given by the muon parametrization. Any anomaly identified is associated to the presence of internal structures as showed in figure 1(c).

The main component of this telescope is the 2D pixelized bulk Micromegas detector. It covers a circular active surface of 12 cm diameter by 1344 hexagonal pads. These pads are multiplexed grouping 7 of them in a single channel. To carry out this multiplexing, a 12 layers PCB with an overall thickness of 3.2 mm has been designed. This leads to 192 channels which are divided into 3 symmetric sectors of 64 channels each, being possible to readout them by a single ASIC. Figure 2 shows the layout of the hexagonal pads divided in 3 sectors, as well as the routing for the pads multiplexing. This routing has been designed using in 2D a similar technique as the presented in [17]. It respects different contiguity restrictions to avoid ambiguities in the muon track reconstruction process.

First tests of Micromegas detectors have been performed in a test bench. Detectors have been operated at atmospheric pressure with Ar-gon-iC$_4$H$_{10}$-CF$_4$ (95-2-3) gas mixture with 3 cm drift length but without any field cage. A photograph of the experimental set-up is presented in figure 3. Voltage at the cathode has been fixed to -1000 V, while the voltage at the mesh varied from...
Figure 1. Picture of the simulated case of the tomography using a TPC (a). The detector is located at the bottom of a borehole dug in standard rock with the presence of some cavities filled of air or water. Simulations results are presented in the plots at the bottom. (b) shows the angular distributions of the detected muons from a 20 millions simulated muons following the parametrization proposed by Shukla [25]. (c) presents the 1D projection of the angular distribution in the range $0.24 < \Delta X/\Delta Z < 0.36$ and $\Delta Y/\Delta Z > 0.2$, marked in orange in plot (b). An excess of muons with respect to the overall trend is identifiable at $\Delta Y/\Delta Z \sim 0.4$, corresponding to one of the cavities defined.

-380 V to -400 V, keeping the Micromegas pads grounded. Pads signals have been registered using the same DAQ as for Micromegas telescopes described in Section 2. Figure 4 presents some examples of events registered with this test bench. For these examples raw signals are showed (i.e. any treatment as pedestal subtraction have been applied). Pulses over an arbitrary threshold are considered. Even if several pixels are triggered because of the multiplexing, in both presented cases a single long track is identifiable. The third component of the track, this corresponding to the drift field direction, can be reconstructed analysing the time difference of the registered pulses. Even with a preliminary analysis, these tests already demonstrated the capabilities of multiplexed Micromegas to reconstruct muon tracks.
4. Outlook and conclusions
Nowadays muon tomography, or muography, stands out as a method for the scanning of the internal structure of big objects. Some of its main advantages are that it is non-invasive, versatile and safe, being possible to perform measurements far from the studied objects. The increase of the number of its potential applications is related to the improvement of the detectors used, specially in terms of spatial and angular resolution, stability and robustness. Among them, Micromegas-based telescopes, as those conceived and developed at CEA, have revealed their capabilities and have been successfully used in several projects. However, new potential applications of muography requires the development of new instruments capable to overcome some of the limitations of the current ones. CEA group proposes a new muon telescope concept based on a gaseous TPC readout by a 2D multiplexed Micromegas. As main advantages, these instruments provide a bigger acceptance with a single telescope, smaller than current versions. Furthermore the installation of a network of these TPCs would provide information to make a 3D reconstruction of the scanned object. These features make these detectors specially interesting for mining or civil engineering.
Figure 4. Two examples of muons registered in the Micromegas test bench. The three plots on the left shows the registered signals in each ASIC, corresponding to each sector of the Micromegas. Signals in orange are those over an arbitrary threshold. Time difference between pulses provides information about the track direction in the coordinate perpendicular to the Micromegas plane. Plots on the right show the pads corresponding to the signals over threshold. Due to the multiplexing the triggered pads are 7 times the triggered pulses. However a single continue track is identifiable (circled in orange) corresponding to the muon track projection on the Micromegas plane.

One of the most important components of these telescopes is the 2D multiplexed Micromegas. As first step, a preliminary checking of the performance of these detectors in a devoted test bench has been done. At this stage, next steps will consist on the construction of a first prototype to be operated at the laboratory. It will include all the remaining detector components, mainly the whole drift length (~40 cm) with the corresponding field cage, as well as all the ancillary systems as DAQ or gas system. Future measurements carried out with this prototype will represent the proof of concept of this new telescope. In a further step, and based on the outcome of the first prototype, a final design and construction of a TPC capable to perform on-site measurements will be carried out.

In parallel, feasibility studies by Monte Carlo simulations will continue to evaluate the capabilities of these detectors depending on the size of the structures to scan, the depth where the TPCs will be installed or the measurement time. They will be performed using the framework developed for muon tomography studies mentioned in Section 2.1. These studies will consider measurements with a single TPC as well as with a detector network. The latter case will provide enough information to perform 3D tomography measurements. Moreover, simulations will also be used to develop the analysis tools, mainly focused on track identification and reconstruction algorithms.

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