3D muography with a gaseous TPC equipped with 2D multiplexed Micromegas

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Abstract. Potential applications of muon tomography, or muography, as non-invasive scanning method have increased in the last years together with the performance of the particle detectors used for muon detection, known as muon telescopes. A new concept muon telescope is presented, which could enlarge even more the range of application of this technique. It is based on a compact TPC equipped with a 2D pixelized Micromegas detector with multiplexed readout. This detector will overcome some of the constraints of the instruments currently used, as they limited acceptance, while keeping other features required for muography as stability, robustness or portability. Moreover, it will be capable to reconstruct the 3D direction of the incident muons with a single instrument.

With its design and features, this kind of detectors can be fitted at boreholes from where they can scan the surroundings, being an interesting technique for mining exploration, geotechsics or monitoring of dykes or bridges which has arouse the interest of industry. In a further phase it is expected to develop a network of these detectors which will allow the 3D reconstruction of the studied object by the combination of the images registered by each of the telescopes. Main features and first tests and results of this new instrument will be presented together with some studies, performed by Monte Carlo simulations, of the capabilities of this muon telescope and the analysis principle.

1. Introduction

Muon tomography, or muography, is the technique based on the use of the atmospheric muons produced at Earth’s atmosphere by cosmic rays to scan the structures of big objects [1]. It relies on the capability of these particles to pass through hundred of metres or even kilometres of matter. During this path, muons are attenuated, or their trajectory deviated, mainly depending on the opacity of the traversed material, defined as the product of the crossed length by its mean density ($\varsigma [g/cm^2] = L [cm] \times \rho [g/cm^3]$) [2]. Focused on the muon attenuation or their deviation, two complementary techniques are commonly used to perform muography measurements, usually known as transmission [3, 4] and deviation [5, 6] methods respectively. Among them, transmission method is more suitable for bigger objects since it is only required to place one detector behind the studied structure. On the other hand, this technique has lower sensitivity to opacity variations so longer measurement times are usually required. However both techniques provide a non-invasive scanning method suitable for big objects. Currently as well
as in the last years, muography has been widely used in such a different fields like vulcanology \cite{7, 8}, archaeology \cite{9, 10}, engineering \cite{11}, homeland security or nuclear safety. The wide range of applications is directly related with the improvement of the detectors used for the muons track reconstruction, integrated in the commonly known as muon telescopes. Nowadays different types of detectors provide good enough angular resolution keeping the required robustness, autonomy and portability to perform long measurements in varying environmental conditions. Nonetheless there exist new potential applications which require new detector concepts trying to overcome the limitations that current telescopes have. In this direction, the Commissariat à l’Energie Atomique et aux Énergies Alternatives (CEA) group has conceived a new telescope concept based on a compact Time Projection Chamber (TPC) equipped with a 2D pixelized Micromegas with multiplexed readout. With this configuration it will be possible to reconstruct 3D muon tracks with a single detector covering an acceptance of 2π in solid angle, overcoming two of the main limitations of current telescopes. Moreover, the reduced size of the detectors allows to fit them in boreholes or small spaces, having the possibility to use them in potential muography applications as mining, civil engineering or prospecting using boreholes.

2. The Instrument

The main goal of the instrument design is to have a full detection system in the most compact volume possible. A sketch of this design is showed in figure 1. The whole set-up is contained in a gas tight cylinder of \(\sim 18\) cm diameter and \(\sim 60\) cm height. It is equipped with different feedthroughs for services like gas or optical fibre for data transfer. Inside it, \(\sim 20\) cm correspond to a buffer volume to install ancillary systems as the DAQ or the HV modules. The TPC itself is composed of a cylindrical field cage of 40 cm length and 15 cm diameter with the readout electrode and the cathode at both sides. The field cage is made by copper strips shaped in a kapton-copper foil. The foil is glued to a cylinder and copper strips are connected by resistors to obtain the required electric field degradation. A copper disk supported by a 3 mm thick PCB makes the cathode. The main component of the TPC and the overall telescope is the 2D pixelized bulk Micromegas detector. It covers a circular active surface of 12 cm diameter by 1344 hexagonal pads of 3 mm side. 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 a photograph of the Micromegas as well as the routing for the pads multiplexing. This routing has been designed using in 2D a similar technique as the presented in \cite{12}. It respects different vicinity restrictions to avoid ambiguities in the muon track reconstruction process.

With this configuration the three dimensions of the incident muon tracks can be reconstructed. Two of the dimensions are obtained from the triggered pads while the third one is reconstructed from the time information of registered signals. However with the current design is not possible to discriminate between parallel tracks since there is no \(t_0\) measurement. Even if this effect does not prevent the use of the detector for several applications, some changes are being considered to be able to measure \(t_0\), which will improve the resolution of the instrument and will make it capable to identify smaller anomalies.

3. First prototype and results

A first prototype has been built to perform fast tests of the Micromegas detectors performance using atmospheric muons. This test bench has 3 cm drift length without any field cage and can operates at atmospheric pressure with a continuous gas flushing. Voltages to generate the drift electric field are supplied to the cathode (with the same design that for the final instrument) and the Micromegas mesh using a HV DC module, while pads remain grounded. Signals induced
in these pads are registered by a self-triggering electronics based on the DREAM ASIC. Two pictures of the set-up are shown in figure 2. Different tests for the first manufactured Micromegas have been carried out in an Ar-iC₄H₁₀-CF₄ (95-2-3) gas mixture and a drift field of ∼200 V/cm, while the voltage applied to the mesh varied between 380 and 400 V. Different data sets were taken placing the set-up both in vertical and horizontal position. Figure 3 presents an example of a registered event. It shows raw signals after the subtraction of the pedestal and the common noise. Pulses over an arbitrary threshold are considered. Even if several pads are triggered because of the multiplexing, 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 as mentioned in section 2. Even with a preliminary analysis, these tests already demonstrated the capabilities of multiplexed Micromegas to reconstruct muon tracks. Other parameters like the total integrated charge or the event time distribution have also been studied to confirm the efficient detection of muons. Moreover the evolution of the detection rate has revealed quite constant during the data taking, demonstrating the stability
of the tested systems.

**Figure 3.** Photographs of the first prototype devoted to the test of the Micromegas detectors performance. Gas chamber, DAQ system and HV DC module are identifiable (see text for details).

**Figure 4.** Example of a muon event registered in the Micromegas test bench. Plot on the left shows the pads corresponding to the signals over threshold. Due to the multiplexing the triggered pads are 7 times the registered pulses. However a single longer track is identifiable (circled in orange) corresponding to the muon track projection on the Micromegas plane. The three plots on the right 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 and length in the coordinate perpendicular to the Micromegas plane. In this case, and taking into account the drift length and velocity of the used gas, the sampling rate was set to register one pulse sample every 48 ns.

4. Monte Carlo simulations

In parallel to all the instrumentation activities, different Monte Carlo simulations have been performed with two main purposes. First, to make a feasibility study to evaluate the potential sensitivity of the instrument. Second, to evaluate the differences induced by potential anomalies in the expected registered data in order to develop the analysis routines. To carry out these studies a simulation framework devoted to muography simulations has been used. The framework, based on Geant4 [14] and C++/ROOT [15] routines, has been conceived at CEA in a modular and versatile way. It can be adapted to any muography application as well as to any muon telescope optimizing the computing time. 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. This structure can be imported from 3D-CAD models so the geometry of the studied object is precisely implemented. 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 [16]. For all the presented simulations the muon parametrization at Earth’s surface proposed in [17] has been used. It is also worth mentioning that for all the simulations no detector effects have been taken into account while an ideal detection efficiency has been considered. Further tests with experimental set-ups would allow to update the obtained results.

4.1. Sensitivity studies

The sensitivity studies have been done for one of the potential applications of the TPC. For these simulations the instrument has been defined at the bottom of a borehole of 30 m depth to scan all the surroundings in an elevation angle range from 30° to 90° (i.e. vertical direction). In a global environment of standard soil (with a mean density of 2.2 g/cm³) a set of cylindrical cavities have been defined at different positions varying their size and density. A drawing of one of the simulated cases is showed in figure 5. These cavities induce a variation on the traversed opacity (Δς) by muons with respect to the case where there are no cavities, leading to a difference in the number of registered muons for a given direction. By means of the statistical significance of this difference it is possible to determine the smallest opacity difference detectable depending on the measurement time. Figure 6 shows two plots summarizing the results of the study. Due to the position of the simulated cylinders, an overall comparison of all the simulations can be done for elevation angles between 30° and 60°. In this range the sensitivity to detect opacity variations increases for bigger elevation angles, in agreement with the angular distribution of muons at Earth’s surface. For a one month measurement the TPC would be able to detect opacity differences down to about 6% with 3σ significance (figure 6a). This means that at 30 m depth it could be possible to identify a cavity of 3.8 m diameter if filled with water or 2.1 m diameter if filled with air. As expected, the sensitivity improves with the squared root of measurement time (figure 6b). As an example in the most favourable case, the sensitivity to detect opacity differences passes from 6% to 4% when doubling the measurement time from 1 to 2 months.

Figure 5. Schema of the simulated case to perform the sensitivity study. A TPC is placed at the bottom of 30 m depth borehole in a soil environment and the presence of cylindrical cavities with different sizes and densities (see text for details).
Figure 6. (a) Minimum opacity difference ($\Delta \varsigma$) detectable depending on the elevation angle at different significance levels for a 1 month simulated measurement (see text for details). (b) Evolution with time of the minimum detectable significance of two particular cases of elevation angle and significance level.

4.2. Analysis principle
Considering that the TPC instrument will provide information about the 3D muon track, a simulated measurement can also be used to evaluate the expected registered signals to develop the associated analysis to identify possible anomalies. A particular case has been simulated to illustrate this. A TPC instrument has been placed at the bottom of a 30 m depth borehole inside a standard soil environment. Four cavities from 18 to 90 m$^3$ where defined and filled with air or water. In this configuration a 30 days measurement has been simulated. Figure 7a summarizes the 2D distribution of the detected muons. If two symmetric angular regions are projected to one dimension (figure 7b) it is observed that, while for one of the regions the projection follows the expected trend (which is a convolution of the angular distribution of muons at Earth’s surface, the opacity associated to each incident direction and the acceptance of the detector), the other region reveals an excess standing out from the trend which points to the identification of a cavity.

5. Outlook and conclusions
Muography stands out nowadays as a method for the scanning of big structures, being possible to perform measurements far away from the studied object in a non-invasive, versatile and safe way. It is mainly due to the improvements on muon detectors that the number of potential applications of muography have increased. Reciprocally, new possible applications would need the conception of new instruments. With this aim the CEA group has conceived a new muon telescope based on a gaseous TPC readout by a 2D pixelized multiplexed Micromegas. As main advantages, these instruments provide a bigger acceptance with a single set-up, being more compact than current versions of telescopes. These features make these detectors specially interesting for mining or civil engineering applications. One of the most important components of this instrument is the Micromegas readout. Consequently, first test-bench has been designed to check their performance and to collect information about the best parameters for their operation in terms of gain or drift field for example. Further laboratory prototypes will be focused in the proper integration of the whole instrument components as well as in the first measurements as proof of concept. All these previous tests will lead to the construction of a fully autonomous instrument capable to carry out on-site measurements.

In parallel to all the instrumentation activities different studies have been carried out by Monte Carlo simulations. They have been mainly focused in the estimation of the potential
Figure 7. (a) 2D distribution of the registered muons from the simulation of the TPC at the bottom of a 30 m depth borehole and the presence of different cavities (see text for details). Two regions are indicated with orange rectangles corresponding to Region 1 (left) and Region 2 (right). (b) 1D projection of the angular distribution of the 2 regions indicated in (a). The projection of Region 1 follows the expected trend (dotted line) which is a convolution of the muon angular distribution, the opacity associated to each incident direction and the detector acceptance. For Region 2 a muon excess due to the presence of a cavity is identifiable.

sensitivity of this instrument as well as in the development of the required tools for further experimental data analysis. As next steps, simulations will be used to evaluate the capabilities to perform 3D muography using a network of these TPCs. Furthermore simulations will also be focused in the muon track identification and reconstruction algorithms. The accuracy of all these simulations will be improved thanks to the detector information taken from prototypes operation.

References
[1] George E P 1955 Commonwealth Engineer 455
[2] Nagamine K 2003 Cambridge University Press, Cambridge
[3] Lesparre N et al 2010 Geophysical Journal International 183 1348
[4] Marteau J et al 2012 Nucl. Instrum. Meth. A 695 23
[5] Borozdin K N et al 2003 Nature 422 277
[6] Procureur S 2018 Nucl. Instrum. Meth. A 878 169
[7] Oláh L 2018 Scientific Reports 8 3207
[8] Ambrosino F et al 2015 J. Geophys. Res. Solid Earth 120 7290
[9] Morishima K et al 2017 Nature 552 386
[10] Saracino G et al 2017 Scientific Reports 7 1181
[11] Guardincirri E et al 2017 Pure and Applied Geophysics 174 2133
[12] Procureur S et al 2013 Nucl. Instrum. Meth. A 729 888
[13] Flouzat C et al 2014 Dream: a 64-channel Front-end Chip with Analogue Trigger Latency Buffer for the Micromegas Tracker of the Clas12 Experiment TWEPP conference
[14] Agostinelli S et al (GEANT4 collaboration) 2003 Nucl. Instrum. Meth. A 506 250,
Agostinelli S et al (GEANT4 collaboration) 2006 IEEE Trans. Nucl. Sci. 53 270,
Allison J et al 2016 Nucl. Instrum. Meth. A 835 186
[15] Brun R and Rademakers F 1997 *Nucl. Instrum. Meth. A* **389** 81
Antcheva I et al 2009 *Comp. Phys. Comm.* **12** 1499

[16] Gómez H 2019 *Nucl. Instrum. Meth. A* **936** 14

[17] Shukla P and Sankrith S 2016 Energy and angular distributions of atmospheric muons at the Earth Preprint hep-ph/1606.06907