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Muon tomography with Resistive Plate Chambers for geological characterization

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ABSTRACT

Muon tomography is one of several fields of applied physics that have witnessed the successful use of particle detection based on Resistive Plate Chambers (RPC). In this work, we report on an innovative project concerning transmission muography for geological characterization. For this purpose, a muon telescope built of four RPC planes was mounted on an adjustable structure and the telescope's response to atmospheric muons was studied. Data acquisition campaigns took place at different locations for producing muographic images of the building of the Physics Department of the University of Coimbra, in Portugal. More recently, the detector was moved to an underground gallery of an old mine, where it is taking data that is being assessed in combination with the results from conventional geophysics techniques.

1. Introduction

1.1. Muon tomography

Muon tomography is a technique that explores the flux of muons that reach the Earth's surface to produce images of objects typically of large dimensions [1–3]. High-energy muons are produced in the atmosphere during the development of particle cascades initiated by interactions of cosmic rays. The fact that the muon flux at sea level is abundant, that muons travel through matter in almost linear trajectories and with small rate of energy loss, being able to reach hundreds of meters underground, makes atmospheric muons an excellent probe for imaging.

The two techniques used in muon tomography are transmission muography and scattering muography. In transmission muography, a detector is placed below an object that partially attenuates the muon flux and characteristics of the object such as slant mass, size, shape are inferred from the directional dependence of the attenuation. In scattering muography, detectors are placed before and after an object with high atomic number, enabling a reconstruction of the properties of the object from the measurement of the muon scattering angles.

The field of muon tomography has witnessed a rapid development, with applications to several fields, such as archeology, vulcanology, civil engineering and industrial safety, each with specific requirements on the detection technique used, including telescopes based on Resistive Plate Chambers (RPC) [4].

1.2. LouMu project

The LouMu project is a collaborative effort, started in 2018, involving Portuguese physics, geology and science outreach institutions, with

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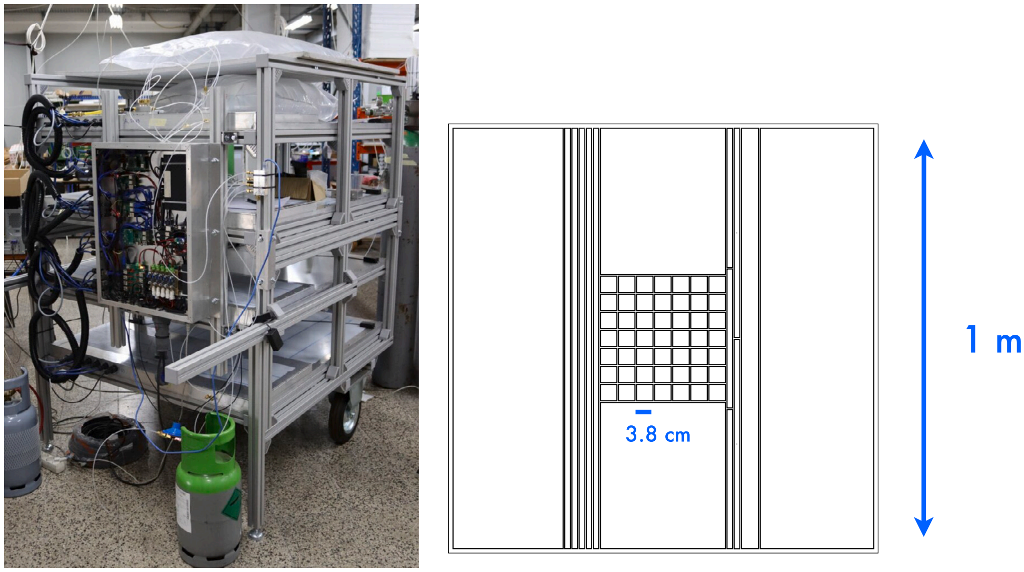

Fig. 1. The RPC muon telescope (left) and a scheme of the three lower readout planes, segmented in pads of variable size and shape (right).

the goal of performing muography in a mine located at Lousal, in the south of Portugal [5,6]. The mine, which was used for the extraction of pyrite, has been converted into a science center and museum. It is placed in a site of geological interest, crossed by a geological fault. The goal of this project is to apply transmission muography for the purpose of geological characterization, combining it with data taken from conventional geophysics measurements and assessing what knowledge is gained from the inclusion of the muon data.

A prototype RPC telescope was initially installed in the mine in order to prepare the operational conditions and take monitoring data in the underground environment, and remains in exposition for the science center visitors. The telescope used for the muography measurements was built at LIP-Coimbra and started taking data in the first quarter of 2020. The first data was taken in the laboratory for the characterization of the detector response. Later, the detector was placed in a few locations of the Physics Department of the University of Coimbra for producing muographs of the building. By the end of April 2022, the telescope was moved to the Lousal mine.

2. RPC muon telescope

2.1. Description

The muon telescope is made of four $1\,\text{m}^2$ RPC planes that are separated vertically by 33.5 cm, as shown in Fig. 1 (left).

The 1 mm double-gap RPC are filled with Tetrafluoroethane, the gas volumes being separated through the placement of nylon filaments (fishing line) from glass plates with 2 mm thickness. The high-voltage, applied through a graphite paint outside the glass, sets a working point of about 3 kV per gap for operation in avalanche mode. The assembly is enclosed by an acrylic box and electric signals induced in an external readout plane are read by MAROC boards with measurement of charge.

All readout planes are segmented into 64 channels by the inclusion of 1 mm thick guard rings. The upper plane is made of strips, was built to assess the response of the readout strip configuration and is used mainly for background veto. The three lower readout planes have the same configuration, having a central region (the *corepix*) with 7×7 squared pads of 3.8 cm side and bigger outer pads with varying sizes and shapes, as shown in Fig. 1 (right). The corepix region allows the reconstruction of muon trajectories with a positional resolution better than 2 cm and an angular resolution in the muon zenith angle $\theta \approx 3°$ ($tg\,(\theta) \approx 0.05$). If needed, these values may be varied by adjusting the vertical distance between the planes. The outer region allows for a bigger angular aperture and higher statistics at the expense of a lower resolution.

The telescope triggers events from atmospheric muons by demanding that, from the three lower planes, at least two planes have signal inside the corepix within a time window of 30 ns. The muon trajectory is reconstructed as a straight line going through the position of the pads that have the highest signal in each of the corepix planes.

2.2. Response studies

The study and characterization of the telescope response was performed in the controlled environment of the laboratory. The studies were focused on the aspects that mostly affect the performance on the muography application, namely the detector time stability, the background contamination, the spatial uniformity and the efficiency for detecting muons.

With a few exceptions due mostly to power cuts or software crashes, the setup is stable through time, as observed from the constant trigger rates and event rates in each plane. The time stability is achieved by monitoring the values of environmental parameters (temperature, pressure), measured by sensors attached to the detectors, and by adjusting the applied voltage for compensating variations in such parameters in order to maintain a constant reduced electric field in the gas [7].

Dark rates have been measured with average values in the corepix pads of $\approx 0.5\,\text{Hz/cm}^2$, used as reference to estimate the expected background from random coincidences that yield either spurious triggers or higher multiplicity of signals. The aforementioned trigger condition, together with demanding a signal in the upper plane, are effective in removing these sources of background, as estimates of signal-to-background ratios above 10 thousand, both in the laboratory and in the mine, indicate.

Spatial uniformity in the detector response is particularly important for muography, so that any non-uniformity in the data arises solely from the object being imaged. Therefore, the pad electronic gains have been calibrated by normalizing the charge distributions from vertical muons to the same median value. The number of events on threefold corepix vertical pixels are shown in Fig. 2 (left), where the effect of the reduced active gas volume due to presence of the nylon filaments is visible in four lines of pads. This effect is corrected for in the simulated detector response. Not so striking, but also visible, is a lower number of counts in the central column. Investigations point the cause to be cross-talk at the readout level.

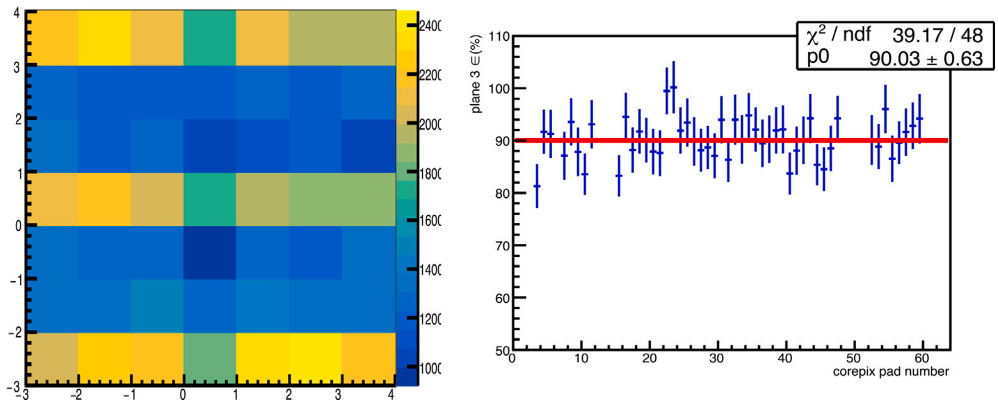

Fig. 2. The spatial uniformity is evaluated from counting vertical muons that cross the same corepix pad in the three lower planes (left) and determining the intrinsic efficiency for their detection (right).

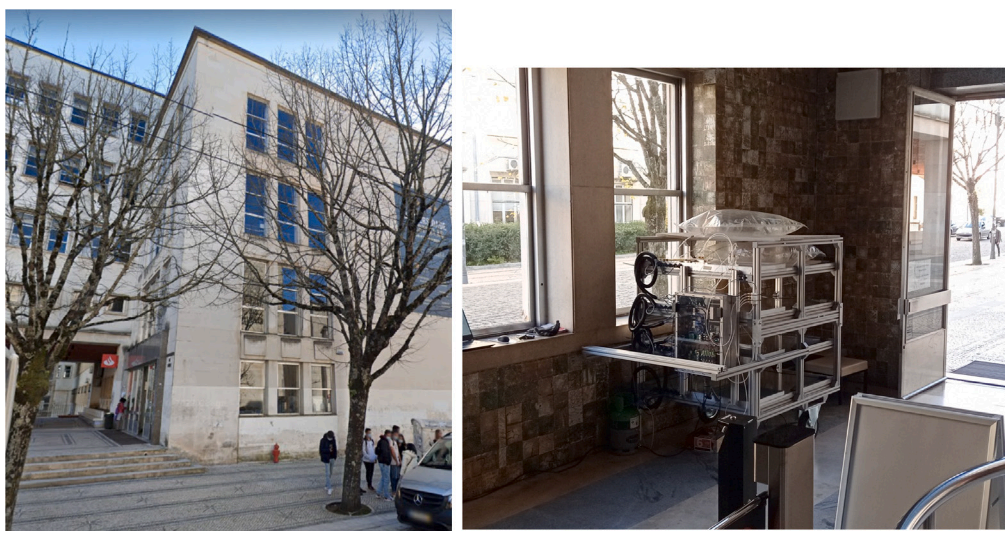

Fig. 3. Outside view of the Physics Department of the University of Coimbra (left), and a picture of the muon telescope positioned inside at the entrance hall (right).

The intrinsic efficiency for detecting vertical muons has been determined for all the pads of the three corepixes, revealing high efficiency and uniformity, as shown in Fig. 2 (right) for the case of one data acquisition run and the bottom plane.

3. Muographs

3.1. Coimbra building

The first muographs produced with this experimental setup were taken from the several locations where the detector was placed at the Physics Department of the University of Coimbra, exemplified in Fig. 3.

The expected muon transmission to the detector at each location was simulated, departing from a $cos^2(\theta)$ muon zenith-angle distribution and considering an exponential attenuation through the building roofs and walls. As input, we used the structural information from the building and the attenuation constant determined by considering the vertical muon rates from two measurements with different number of roofs above the detector [8].

Fig. 4 (top) shows a high-resolution simulation of the muon transmission expected at the entrance of the building. It makes evident the salient features expected in the transmission mapped for different muon directions within the corepix aperture. High transmission corresponds to small amount of material crossed (windows and doors near the telescope, visible in Fig. 3) and low transmission corresponds to trajectories going through long distances inside the walls and roofs.

A simulation with the detector resolution was also performed by including the detector response, as shown in Fig. 4 (left). The central region has higher resolution and corresponds to muons crossing the three corepixes, while the outer region, which extends the telescope aperture with lower angular resolution, concerns muons that go through only two consecutive RPC planes.

The data, shown in Fig. 4 (right), contains the features expected from the simulation, being particularly clear the wall and windows right next to the detector. While a qualitative agreement has been found between simulations and data, on-going work is being pursued for refining the detector response in what concerns the efficiency dependencies (e.g. direction, impact point) and cross-talk effects, to be implemented in an optimized detector model. Additional developments include also the production of muographs with the combination of data taken at different locations and telescope inclinations that see the same parts of the building.

3.2. Lousal mine

The mine environment presents additional challenges for the muography application. The muon telescope was placed at a mine storehouse about 17 m underground, where the muon flux is reduced by a factor ≈8 from the sea-level value, requiring longer periods of data taking. The higher amount of traversed matter implies higher muon scattering with the corresponding degradation of resolution. Whereas at the building sharp features are expected in the transmission maps, at the mine

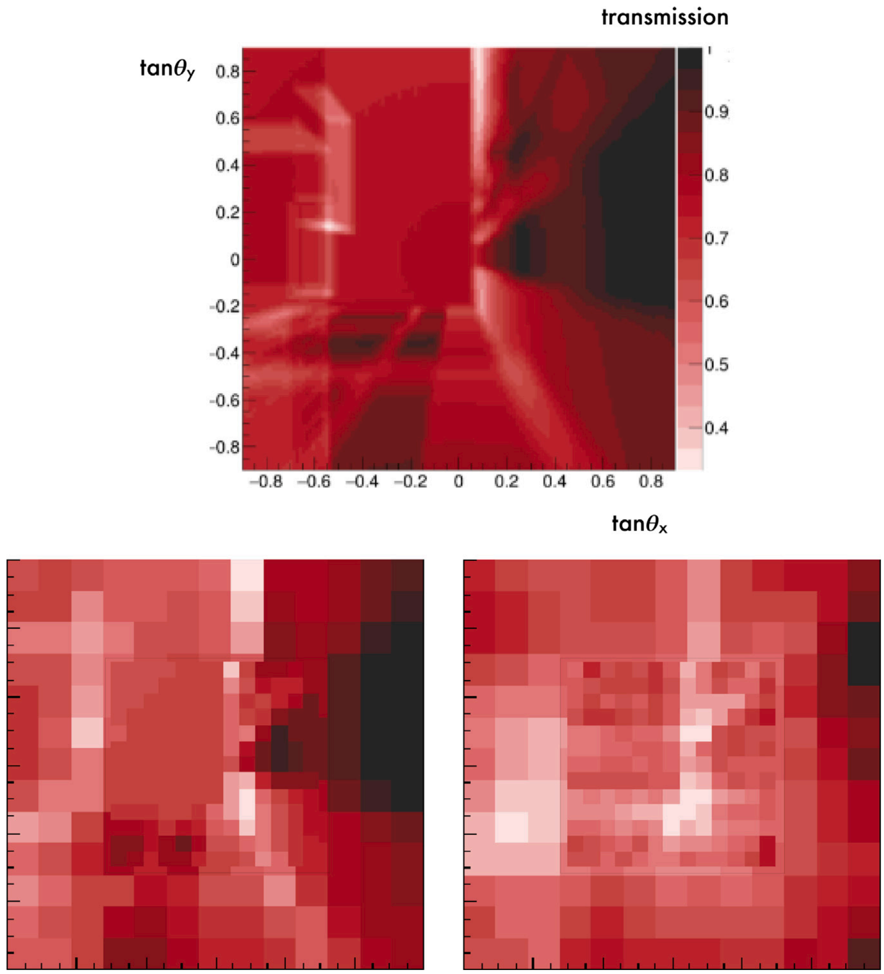

Fig. 4. High-resolution simulation of the muon transmission to the RPC telescope placed at the entrance hall of the building (top), together with the simulation convoluted with the detector response (left) and the muon transmission data (right).

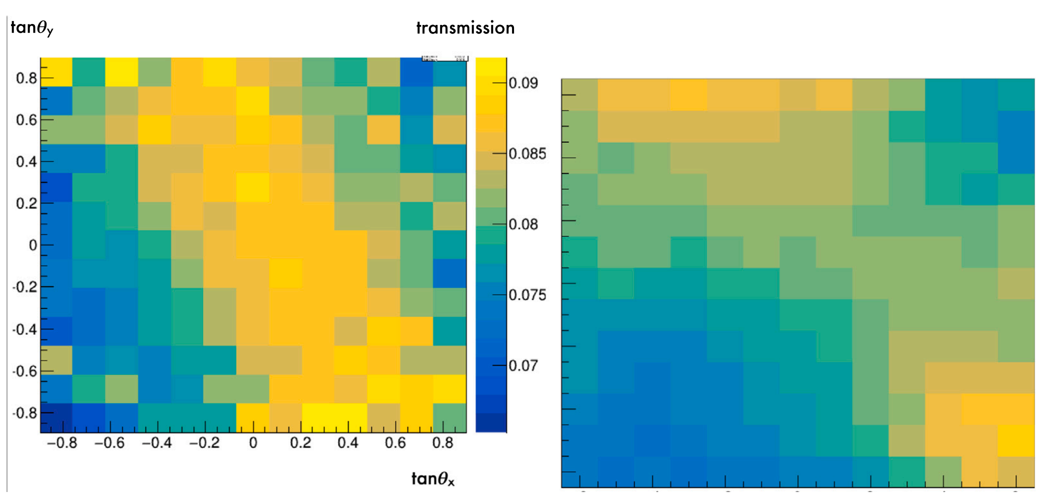

Fig. 5. Preliminary: the simulated muon transmission map (left) compared with the transmission map obtained from the data taken from a mine storehouse, 17 m underground (right).

smooth and small variations are expected, arising from slow changes in the average soil density. On the other hand, there is the advantage of a more stable environment, with negligible daily variations of temperature or humidity.

The simulation of the muon transmission expected inside the mine was divided in two steps: a Geant4 simulation of the muon flux at surface transported through the soil down to the mine at detector depth, whose output is fed to a fast simulation of the detector geometry and response. A preliminary reference model of the soil, comprising altitude, rocks and density profiles, was produced according to the data acquired in geophysics campaigns. These included conventional geophysics measurements, namely the extraction and analysis of geological samples, laser scans, seismic refraction, ground penetrating radar and drone photogrammetry.

Fig. 5 shows the preliminary simulation of the low resolution transmission map (left), obtained with only two consecutive RPC planes, compared with the data taken at the mine (right). Geophysics data indicates that there is a geological fault above the telescope position, corresponding to an average rock density 10% lower than that of the surrounding soil. The projected orientation of the fault is diagonal to that of the storehouse and detector, creating a pattern of higher transmission across the map. A similar trend is visible in a preliminary assessment of the data that is yet to include the full detector response, opening encouraging prospects for the next steps of the analysis.

4. Conclusion

Muon telescopes based on RPC have been proven useful in muography applications. The potential of extending the range of applications to the detailed geophysical characterization of sites with geological interest is being explored by the LouMu project. A muon telescope based on RPC was built and has taken data in the laboratory, leading to the production of muographs of a building. The data are being further explored to refine the detector model, to reduce the systematic uncertainties and for developing algorithms for transmission maps with improved resolution. The findings are to be applied to the muon measurements performed at the Lousal mine, that are being combined with a geological model of the underground environment, based on the geophysics data. Preliminary muographic results indicate the presence of a known geological fault in the site. A joint inversion of muographic and geophysical data is expected to allow a quantitative assessment of the usefulness of this technique for geological characterization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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