LIP-STUDENTS-22-27

On the effects of Slow-Control variables over the Lousal Resistive Plate Chamber Muon Telescope efficiency

André Morais[1,a] and Yanhan Zhou[2,b]

[1] *Instituto Superior Técnico, Lisboa, Portugal*
[2] *Faculdade de Ciências, Lisboa, Portugal*

Project supervisors: Sofia Andringa and Raul Sarmento *December 19, 2022*

Abstract. This study investigates the correlation between efficiency and environmental conditions, especially humidity. Previous research had already demonstrated the existence of a link between temperature changes and efficiency, we extended the results to more environmental variables and studied the specific case of the Lousal muon telescope. We used data from March to July 2022, including a time period in which the detector took data in Coimbra with large variation in environmental parameters, and a time at Lousal where the environmental variation was more gentle but the incoming muon's rate was lower. We also studied the adjustment of applied voltage according to the temperature and atmospheric pressure to minimize their impact on efficiency. The results show that the detector has experienced an increase in the working current which can only be explained by the continuous degradation of the gas used in the plates, therefore current variations must be included in the voltage adjustment algorithm.

Keywords: Resistive Plate Chamber efficiency, Environmental effects

1 Introduction

1.1 Resistive Plate Chambers

Resistive Plate Chambers (RPC) are detectors of charged particles. They consist in two layers of a gaseous mixture separated by plates of a material with high electric resistivity. In those plates are placed electrodes where a high voltage is applied, in order to induce an uniform electric field over the gas chamber. Once a charged particle passes through the detector it will ionise the gas thus enabling the occurrence of an electric discharge between the plates which can be detected by sensors placed outside the plates. The usage of several sensors each comprising a small area of the surface of the gas chamber allows a more precise characterization of the place where the particle passed through the detector. A scheme of an RPC is shown in Figure 1.

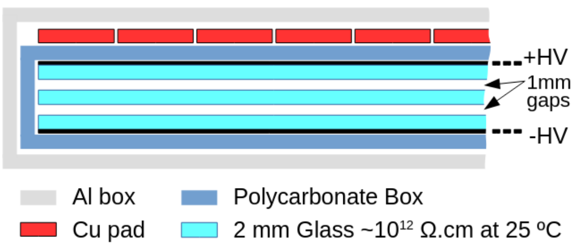

Figure 1. Schematic view of the inner components of an RPC. Adapted from [1]

1.2 RPC based Muon Tomography

Since muons are heavy particles, their trajectory remains approximately linear as they cross most materials. Moreover they are charged and thus interact with electromagnetic fields. This means they lose energy and can be stopped. Therefore, the muons from cosmic rays can be used to infer the density of materials placed above a detector. This technique is known as muon tomography or muography. Stacked RPC's are an efficient way to implement this procedure. Each RPC in a vertical stack can be used to determine a point of passage for a muon, if several signals are detected in a set of RPC in a short amount of time ($\approx$ 30ns) we can assume they were produced by the same muon, traveling between the plates and connect those point with a line deducing its trajectory, see Fig.2.

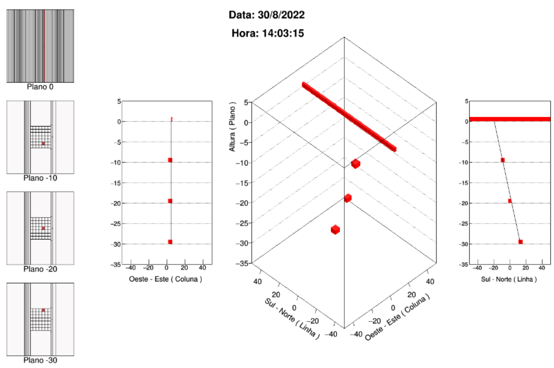

Figure 2. Determination of muon trajectories in the detector, cite from [2]

Computing the ratio of the detected muons from a certain direction over the number of muons detected on open air over a certain period of time gives a measure of the

[a] e-mail: andre.n.morais@tecnico.ulisboa.pt
[b] e-mail: fc58286@alunos.fc.ul.pt

product of the density of the material traversed by the muons with the depth of material crossed by the particle (since denser materials permit the passage of less muons). Thus, knowing the depth of the material layer we can infer its density. By performing this analysis in a large scale object such as a building or a geological formation, one can obtain a density image of the object. It is worth noting that this method is totally non invasive and requires no extra radiation to be emitted.

1.3 Applications of Muography

Several studies have used muography to obtain information on places of difficult access or where conventional techniques are too invasive to be doable. The best examples of the usage of muography are the discovery of a hidden chamber in the Khufu pyramid [3] and the monitoring of the Sakurujima volcano in Japan [4].

1.3.1 Sakurajima Volcano

Sakurajima is an active volcano in Kagoshima bay, in the island of Kyushu, southern Japan. Its last great eruption occurred in January 1911, and was the strongest eruption of the century in Japan. Another eruption of comparable strength is expected for the first half of the twenty-first century, and, nowadays hundreds of smaller short-term eruptions happen every year. Predicting such eruptions is important to protect tourists and local population alike. Using muography, the researchers have been able to detect variations of density and mass flows, thus proving these methods can be used to monitor the erosion of the volcanic structures and model the accumulation of magmatic materials inside the craters. Moreover, applying machine learning methods to muography images, these researchers are attempting to predict when eruptions may occur.

1.3.2 LouMu Project

The LouMu project uses muon tomography techniques to analyse the geological features on the rock layers above the Lousal mine, specially a geological fault that existed in this area. The Lousal mine was explored for pyrite until 1988. After the mining operations stopped, most galleries were filled up, and the area was transformed into a museum/science center. Using muography, the project researchers which to study further its properties and better understand the geological properties of the area. Furthermore, the team wishes to perfect RPC sensors for a plethora of uses including Cosmic-Ray detection and large structure 3D scanning.

2 Objectives and Methods

In this work we analysed the evolution of the efficiency of the Moun Telescope currently placed in the Lousal mine, both during its previous time in the Physics Department of the University of Coimbra and during its present stay

Figure 3. Entrance of the Lousal Mine

inside the Lousal mine. The data exhibits different behaviours along this time periods which can be divided in three main phases: the time in Coimbra (1^{st} period), the first month in the Lousal mine when the voltage adjusting software was turned off (2^{nd} period); the remaining time elapsed in the mine (3^{rd} period). Other than doing just an isolated analysis of the efficiency we compared its time-indexed evolution to the slow-control variables measured: Atmospheric pressure; Air Temperature; Air Humidity; Applied and Measured Voltages; Measured Current; Gas (R134a) Pressure and Flow (in several points of the gas circuit). By performing such analysis we expected to find non-trivial correlations between the slow-control variables and observed efficiency of the sensor in order to determine the conditions with more influence over the sensor´s data and establish the ideal functioning conditions and propose modifications to the sensor which can improve its resilience to adverse environmental conditions. During such analysis, we also tried to explain anomalies in both the efficiency and slow-control variable values.

2.1 Lousal Muon Telescope

The Muon telescope currently placed at Lousal uses 4 RPC's stacked vertically to determine the trajectory of the detected muons, as shown in Figs.2, 4]. We assigned numbers 0 to 3 to planes from top to bottom. The bottom three planes have 64 ($3.8cm \times 3.8cm$ with gaps of 0.5 cm in between) detector pads while the top plane has 64 detection lines. The RPC's use R134a gas, a tetrafluoroethane which is very stable, hard to ionise and poses no danger to humans in case of leakage (yet the gas is environmental hazardous so leakages must be avoided at all times). The gas flows in a closed circuit through the sensor and to collection bags afterwards, guaranteeing that the gas inside the detector is always in good conditions in order not to compromise the results.

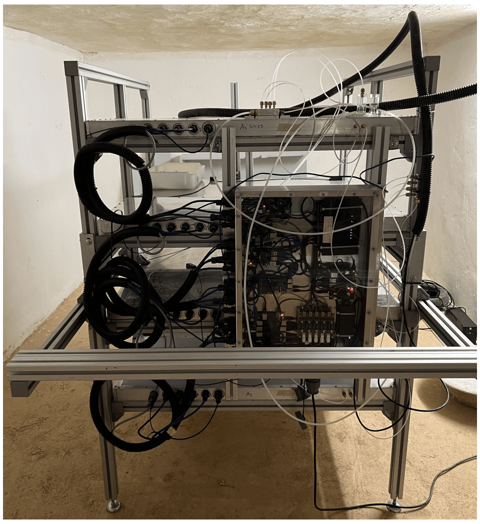

Figure 4. Front side of the detector

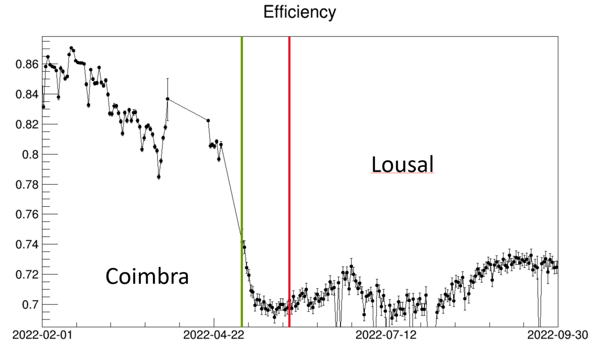

Figure 5. Variation of the efficiency along time. The detector took data in Coimbra before it was moved to Lousal in April 2022 as the green line shown. The red line represent the date we started adjust the applied voltage in Lousal, we will discuss this later.

2.2 Detector's Efficiency

The idea is if muon passes through planes 1 and 3, by structure of the detector, it must pass also the middle plane. If that signal is not seen, it means the middle plane is inefficient. The calculation of efficiency is simply a fraction between the number of events which muon was measured by planes 1, 2 and 3 at same time and the number of events that muon was only measured by planes 1 and 3 plus the number of events mentioned above:

$$\epsilon_2 = \frac{\#N_{123}}{\#N_{13} + \#N_{123}} \tag{1}$$

Notice that the plane 0 has different size and geometric shape, it is not considered on part of efficiency's calculation. Plane 2 is used as reference to study the evolution of the efficiency, shown in Fig. 5.

3 Results

3.1 Independent Analysis

On a first stage we analysed the slow control-variables and the efficiency independently. From the analysis of the efficiency alone we discovered that it had decreased significantly when the detector was moved to the Lousal mine. While in Coimbra its values were mostly on the range of 80-85% , rarely going outside of these bounds, when the detector was turned on in the mine, the efficiency plummeted to values around 70%. Along the time period whose values we studied, the efficiency did not recover significantly even when the algorithm designed to control the voltage (thus maintaining the efficiency on the desired values) was turned on. Hence, in subsequent studies we searched for some environmental condition whose change could explain this sudden decrease.

On a different perspective, the analysis of the slow-control data alone yielded some results: the main correlations between variables were due to thermodynamic laws and therefore unexpected relations between parameters did not arise; a constant difference between the measured temperature values of each sensor of the same plane showed that these were not correctly calibrated. The most important outcome of this analysis was discovering that the measured current between planes was steadily increasing in Lousal while it had remained stable in Coimbra.

3.2 Combined analysis

From further study of the available literature [5] we discovered that the environmental variables were directly correlated with a different quantity - the reduced electric field (E/N) - and that its values affected directly the efficiency as well. Hence we believed its study could provide important information about the connection between slow-control variables and the detector's efficiency. The study of this quantity gained relevance as we studied the various slow-control variables and the efficiency simultaneously.

3.2.1 E/N - the reduced electric field

As referred in the introduction, RPC's detect muons by sensing the electric discharges they induce in an inert gas. When studying electric discharges in gases the Reduced Electric Field is one of the most relevant quantities. It is defined as the ratio between the total electric field applied over the gas and the number of neutral particles present in the volume of the gas, therefore its SI units are $V \cdot m^2$ but, at the scale of the RPC discharges the Townsend (Td) defined as $1Td = 10^{-21} V \cdot m^2$ is more useful. Increasing the intensity of the electric field or decreasing the number of neutral particles in a gas has the same effect over the properties of these discharges. Hence, the analysis of this variable alone allows a more complete study of the discharge. For RPC's specifically, a complete study of the correlation of the between its values and the detector efficiency was performed in [5] and is shown in Fig. 6. An explicit formula for the E/N shows more explicitly its dependence on environmental factors.

Starting from the Ideal Gas Law, $PV = nRT$, we can easily obtain the relation $P = \rho \frac{R}{M} T$, where M denotes the molar mass of the gas and ρ its density. And, from the definition of molar mass the relation $N = \frac{N_a}{M}\rho$, where N_a represents the Avogadro number. Isolating ρ in the second equation and plugging it into the first we get: $P = \frac{NM}{N_a}\frac{RT}{M}$, which after simplifying and isolating N yields $N = \frac{N_a P}{RT}$. Finally assuming a constant electric field over the gas $E = \frac{V}{d}$, with V standing for the applied voltage and d for the distance between the points in cm where the voltage is applied. Hence, by taking the quotient of these equations we finally obtain

$$\begin{aligned}\frac{E}{N} &= \frac{RVT}{N_a P d} \\ &= K_b \times 10^{23} \times \frac{TV}{Pd} \\ &\approx 1.38068748 \times \frac{TV}{Pd}[Td] \qquad (2)\end{aligned}$$

Where K_b stands for the Boltzmann constant.

For the RPC's it is important to remark that the voltage in this equation is the effective voltage: $V_{eff} = V_{applied} - RI$ where I is the current per unit area and $R = \rho(T)tl$ stands for the resistance per unit area(cm^2) where $\rho(T)$ is the resistivity of the materials for a specific temperature, l is the glass thickness and t the ratio between the volume of gas and the plates.

For our RPC, these parametres take the followwing values: $d = 0.1cm; l = 0.2cm; t = 1.5; \rho(T) = 10.5 \times 10^{\frac{127}{24.3}} \Omega \cdot cm$.

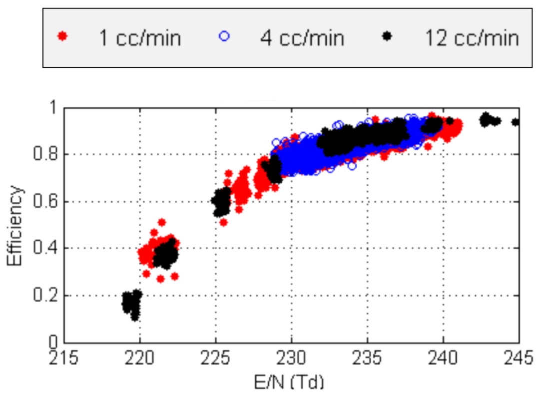

Figure 6. Correlation of efficiency with E/N, adapted from [5]

3.2.2 E/N and the efficiency

The combined analysis of both the efficiency and the E/N indicated that there was in fact a direct correlation between the two quantities as the the study mentioned earlier shows, but also that the efficiency must depend on other physical variables as well since the variations of the reduced electric field alone did not explain all the observed variations in efficiency, as shown in Fig.7.

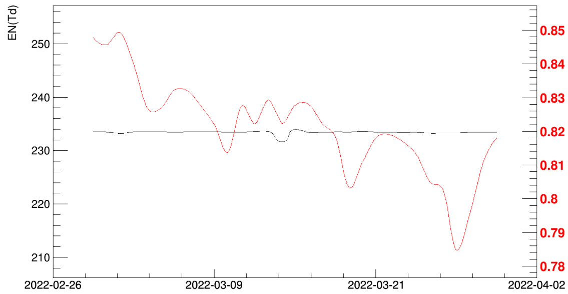

Figure 7. Variation of E/N and efficiency in March, in Coimbra - data are averaged in days, and the tendencies are smoothed.

3.2.3 E/N and the slow-control variables

As shown in the first subsections of this part, the reduced electric field must remain approximately constant and to do so the voltage must be corrected in function of the slow-control variables to account for changes the environmental conditions. This correction was already being performed automatically by an algorithm that read the temperature values and adjusted the voltage. Yet, since for small changes in temperature($\leq 10°C$) the effect of the current is insignificant it was not being accounted for in these corrections. Figure 8 shows the E/N at Coimbra and at Lousal, calculated for each hour, with the same vertical scale. In Coimbra, this effect was in fact negligible, and the E/N was maintained stable in values that guaranteed the detector's efficiency was kept as high as possible. In opposition, the aforementioned rise in current observed in Lousal creates a significant disparity which was not accounted for in the corrections. Hence, the algorithm controlled the local oscillations of the E/N but was unable to counter its global decreasing tendency. This analysis motivated a further study of the current which we shall explain subsequently.

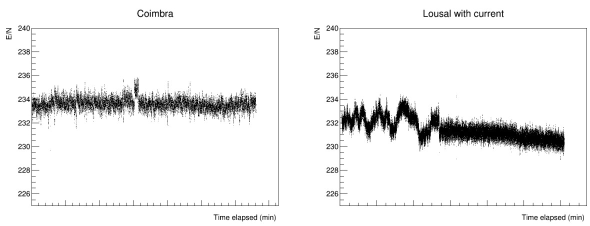

Figure 8. Comparison between the Reduced electric field variation in Coimbra and Lousal

3.3 Increase of the Current

The aforementioned increase in current was unexpected and had never been observed before while the telescope was in Coimbra. Hence, as one of the most conspicuous changes in the environmental conditions from Lousal to Coimbra we looked into it in order to determine whether it had any influence in the efficiency decrease detected earlier.

The primary approach chosen was to find any link between the behaviour of the current and the slow-control variables in an attempt to explain the causes of its change. The obvious candidate was the temperature as it has the most significant influence over the reduced electric field. Nevertheless, the comparative analysis between variables showed the direct correlation of the E/N with the gas flow rather than with the temperature. Furthermore, three distinct regimes were clearly observed, as shown in Fig.9.

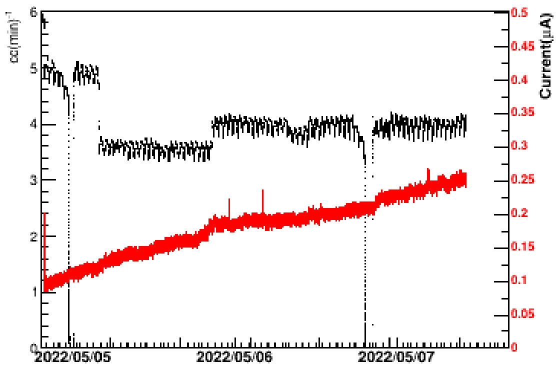

Figure 9. Superposition of the gas-flow and the current in Lousal from May 6th to until the end of July

As we can see in this figure 9, the current increases at an approximately constant rate from the moment the detector was turned on inside the mine (beginning of the x axis) up until the first days of June when the rate of change decreases significantly. This inflection point coincides with the moment when the gas flow was manually incremented. In the following weeks this diminished rate remained up until the beginning of July when see a sudden drop in the flow which caused the current to increase at a higher rate once more. This sudden reduction of the flow was caused by an error in the maintenance of the sensor, as the gas fed to the detector is kept in bottles which must be replaced before finishing entirely.

From the analysis of these two behaviours we inferred that the quality of the gas inside the sensor was deteriorating along the time it was placed inside the mine. This effect is visible in the current because the ionisation threshold and effective resistance of the gas are reduced as its quality decreases and so, for the same applied voltage, the measured current is higher. In the first days in Lousal, the current had values similar to Coimbra as the gas is still in perfect conditions, but as the time passes more contaminants accumulate in this gas and the flow of new gas is not sufficient to recover it to its original state. When the gas flow is raised the accumulation of contaminants happens at a smaller scale and that is visible in the smaller change of the current. It is important to note that this increase was still insufficient to solve the issue. In addition, after the complete breakdown of the gas, not even this augmented flow could decrease the rate of contamination of the gas. Therefore a different solution is necessary to stop the gas from deteriorating further.

3.3.1 Consequence

As the current increased, we also found that the streamer rate raised as well, as shown in the following graphs, Figs. 10,11.

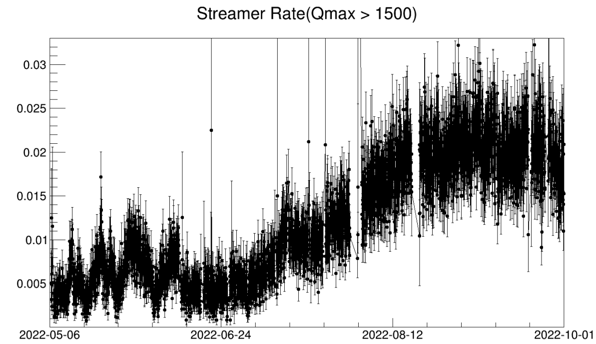

Figure 10. Fraction of events identified as Streamers as a function of time in Lousal.

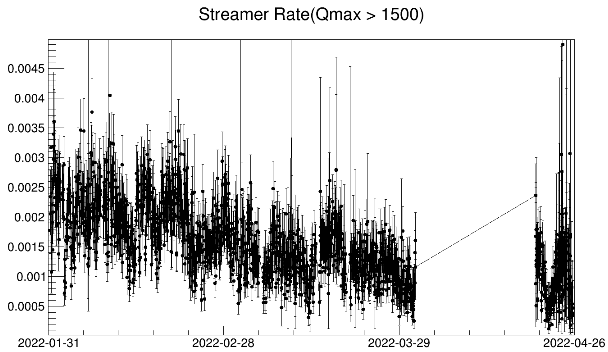

Figure 11. Fraction of events identified as Streamers as a function of time in Coimbra.

Streamer is a phenomenon which has very high maximum induced charge (Qmax). Normally, Qmax is under 200 and therefore we define 1500 as a standard for streamer. Notice that the induced charge is not the charge of muon, it is analog-to-digital converter's unit.

Higher induced charge is not a good phenomenon and can not be ignored, as it will affect RPC's efficiency, since the gas takes longer time for neutralize if Qmax is too high (higher Qmax means more particles are ionized).

While at Coimbra the fraction of streamers showed a very small variation, at Lousal it increased in time, by a total of 300%!

One of the hypothesis is that the gas is being contaminated by external humidity.

3.4 The effect of Humidity

As equation 2 shown, humidity is not a part of algorithm to adjust reduced electric field. We can control the efficiency through manipulate reduced electric field, Fig.6. In Coimbra, the efficiency did not behaved as stable as expected, even though reduced electric field was constant. So in this project we also want to study the impact of humidity to the detector.

Each point of three figures below correspond to average efficiency and humidity in a hour. The red line is simple linear regression.

Fig12 shows that the efficiency raises with humidity in Coimbra. Because we adjust applied voltage to reduce other environmental variables' influence (excluding humidity), these variables can be ignored. However, we can not exclude that in addition to humidity there may exist other independent variables causing this behaviour.

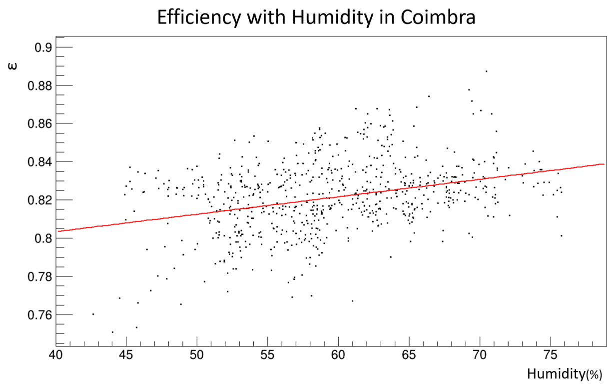

Figure 12. Correlation between efficiency and humidity in Coimbra, slope of the line: 9.1E−2 ± 1.4E−2 [%/%H]

In Lousal, this correlation had different behaviour. The figure 13 shows variation of efficiency in function with humidity, in period which we did not adjust reduced electric field. And the figure 14 is the correlation graph of these two variables after adjustment of reduced electric field. Showing a much smaller effect.

Note that we can not neglect the effect of current increase in this period. The algorithm in Lousal is same as Coimbra's, but the current was lower and stabler in Coimbra. Remember that we defined current as a constant value in the algorithm, and the real reduced electric field is shown in Figure8.

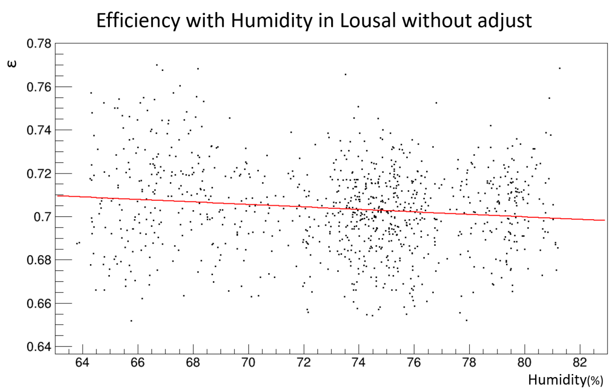

Figure 13. Correlation between efficiency and humidity in Lousal, before adjust the applied voltage, slope of the line: −5.8E−2 ± 1.5E−2 [%/%H]

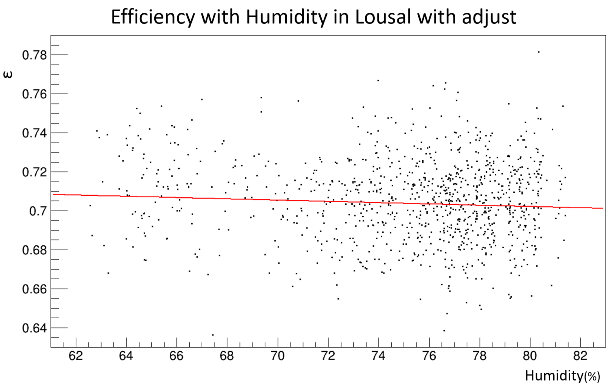

Figure 14. Correlation between efficiency and humidity in Lousal, after adjust the applied voltage, slope of the line: −3.3E−2 ± 2.6E−2 [%/%H]

4 Conclusions and next actions to take

With the present data, we can not conclude that there is an obvious correlation between the efficiency of detector and humidity.

The data of Coimbra and Lousal are not comparable due to the electric current increase. We need to change algorithm for Lousal's situation and collect data which have more stable reduced electric field.

To optimise the telescope even further and solve the aforementioned problems several corrections shall be applied in the near future.

First and foremost, the tubing which conducts the gas supply to the main body of the telescope will be tested and likely replaced if it is proven to be the cause of the gas deterioration mentioned earlier. On a first moment the gas bottle will be brought inside the mine to short-circuit this tubing. If this action causes a significant improvement of the gas quality the tubing must be replace to ensure the correct functioning of the telescope. There are two feasible alternatives to the current pipes: Teflon or steel. Steel is more durable and sturdy, it is also much more expensive and would hinder any later attempt of moving the detector, an undesirable situation. On the other hand, Teflon is more prone to suffer from the deteriorating effect of the environmental conditions outside the mine, but is cheaper, easier to replace and still allows the detector to be moved at will. Considering the pros and cons of each solution, Teflon will be probably be chosen as the best replacement material.

A completely different alternative is currently under testing as well - sealed chambers. These, by construction, would require no gas flow and therefore could not suffer from these problems. Moreover, since no continuous gas supply would be necessary these chambers are ideal for remote locations where maintenance of a detector is a arduous task. Yet these chambers need a more careful design to prevent the interior gas from deteriorating with the successive ionisation processes and ruin its results.

Hence we conclude this work with the belief RPC based muon telescopes have an enormous potential for cosmic ray observation and can still be developed to increase the quality of the data produced and decrease the amount of maintenance needed for its continuous functioning. And we hope that part of this study can be helpful for future developments.

Acknowledgements

The authors of this report would like to thank profusely to Sofia Andringa and Raul Sarmento for all their attention and patience for answering our endless questions for the whole summer.
In addition, we would like to acknowledge and express gratitude to Luís Lopes and José Nogueira for all the help and support provided during the internship.

References

[1] J.P. Saraiva et al, Journal of Instrumentation, 15(09):C09024–C09024 (2020)

[2] *Loumu project website*, https://www.lip.pt/experiments/LouMu_/tablets/index4.html

[3] K. Morishima, M. Kuno, A. Nishio, N. Kitagawa, Y. Manabe, M. Moto, F. Takasaki, H. Fujii, K. Satoh, H. Kodama et al., Nature **552**, 386 (2017)

[4] L. Oláh, H. Tanaka, T. Ohminato, G. Nyitrai, G. Hamar, D. Varga, Journal of Advanced Instrumentation in Science **1**, 285 (2022)

[5] R. Luz, PhD Thesis, IST/ULisboa (2021)