**UNIVERSIDADE DE SÃO PAULO
INSTITUTO DE FÍSICA DE SÃO CARLOS**

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**RPCs design, development and tests for the Pierre Auger
Observatory**

São Carlos

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**RPCs design, development and tests for the Pierre Auger
Observatory**

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Supervisor: Prof. Dr. Luiz Vitor de Souza Filho

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*“I don’t pretend we have all the answers. But the questions are certainly worth thinking
about.”*

Arthur C. Clarke

ABSTRACT

MARTINS, V. B. **RPCs design, development and tests for the Pierre Auger Observatory**. 2018. 107p. Dissertation (Master in Science) - Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, 2018.

The cosmic rays are the most energetic particles in the universe. Their production, propagation, and detection are objects of studies. Surface detectors aim to identify particles from extensive air showers (EAS) which the result from the cosmic-ray interactions with the atmosphere. Resistive Plate Chambers (RPCs) have shown to be a suitable muon detector to be integrated into the Pierre Auger Observatory. An instrumentation was developed to assembly RPCs in São Carlos (BRA). Data from RPCs already built by our collaborators in Coimbra (POR) were analyzed. The detector efficiency to muons was calculated and is approximately 88%, which is in good agreement with the values quoted in the literature. Direction maps were built to investigate the muon incoming direction and the quantity of matter traversed by the muons. The dependence of the muon flux on the zenith angle was calculated and compared with results from the simulation. A square cosine dependence is expected, though it is seen that the building structure has enough matter to block some of the incident muons and alter the dependence curve. The total muon flux was estimated based on the detector efficiencies and solid angle as $1.6 \cdot 10^{-5} \text{ mm}^{-2} \cdot \text{sr}^{-1} \cdot \text{s}^{-1}$ compared with the literature value of $7.1 \cdot 10^{-5} \text{ mm}^{-2} \cdot \text{sr}^{-1} \cdot \text{s}^{-1}$, which gives an absorption by the building of approximately 77%.

Keywords: High-energy cosmic rays. Pierre Auger Observatory. Resistive plate chamber. RPCs. Muons.

RESUMO

MARTINS, V. B. **Desenvolvimento, construção e testes de RPCs para o observatório Pierre Auger**. 2018. 107p. Dissertação (Mestrado em Ciências) - Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, 2018.

Os raios cósmicos são as partículas mais energéticas do universo. Sua produção, propagação e detecção são objetos de estudos. Os detectores de superfície têm como objetivo identificar partículas dos chuviros atmosféricos extensos (EAS), o qual é o resultado das interações do raio cósmico com a atmosfera. A Câmaras de Placas Resistivas (RPCs) demonstra ser um detector de múons adequado para ser integrado ao Observatório Pierre Auger. Foi desenvolvida em São Carlos (BRA) uma instrumentação para montagem de RPCs. Dados de RPCs já construídas por nossos colaboradores em Coimbra (POR) foram analisados. A eficiência dos detectores para múons foi calculada como sendo de aproximadamente 88%, o que está de acordo com os valores citados na literatura. Mapas de direção foram construídos para investigar a direção de chegada e a quantidade de matéria atravessada pelos múons. A dependência do fluxo de múons com o ângulo zenital foi comparada com os resultados da simulação. Embora uma dependência com o quadrado do cosseno é esperada, foi constatado que a estrutura do prédio tem matéria suficiente para bloquear parte dos múons incidentes e alterar a curva da dependência. O fluxo total de múons foi estimado baseado nas eficiências do detector e no ângulo sólido é de $1.6 \cdot 10^{-5} \text{ mm}^{-2} \cdot \text{sr}^{-1} \cdot \text{s}^{-1}$. Comparado com o valor da literatura de $7.1 \cdot 10^{-5} \text{ mm}^{-2} \cdot \text{sr}^{-1} \cdot \text{s}^{-1}$ resulta em uma absorção pelo prédio de aproximadamente 77% do fluxo de múons.

Palavras-chave: Raios cósmicos de altas energias. Observatório Pierre Auger. Câmara de placas resistivas. RPCs. Múons.

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1 INTRODUCTION

Cosmic rays are energetic particles coming from outer space which penetrate and interact with Earth's atmosphere giving origin to extensive atmospheric showers (EAS).

It was probably the geologist and meteorologist Franz Linke who first observed in 1901 indications of a penetrating radiation whose intensity seemed to increase with altitude (1). In 1908, Albert Gockel and Theodor Wulf used the term "cosmic ray" for the first time but it was properly introduced by Robert Millikan 18 years later. (2). Victor Hess carefully investigated this radiation and confirmed the existence of cosmic rays in 1912 during his experiments in balloon flights with electrometers. (3) In 1913, Hess results were confirmed by Werner Kolhörster, and in 1936, Victor Hess was awarded the Nobel Prize for his discovery.

Discovered in 1938 by Pierre Auger, the EAS is the particle cascade resulting from the incoming cosmic-ray interaction with molecules in the atmosphere. The energy spectrum of cosmic rays was then extensively studied. (4) A power law distribution of cosmic rays was first described by E. Fermi in 1949, although with no predictions of the power-law index. Observations in 1959 indicated a steepening at around $3 \cdot 10^{15}$ eV ("knee") and in 1963 indicated a flatten spectrum after $3 \cdot 10^{18}$ eV ("ankle"). The observations were confirmed but the origin of the steepening is still unclear. (4) Chapter 2 elucidates the EAS and its components.

The origin of the cosmic rays is still object of studies although there is a universal agreement that the bulk of cosmic rays observed at mildly relativistic energies around 1 GeV per nucleon are exclusively of Galactic origin. The most plausible energy source for keeping the galactic cosmic-ray flux over time is the explosion of supernovae. Higher energy cosmic rays are originated in extragalactic regions but no conclusion regarding the source could be taken due to the Ultra-High Energy Cosmic Rays (UHECR) low flux and the consequent lack of statistics. (5)

Large telescope arrays are built in collaboration among scientists to detect cosmic rays more efficiently decreasing systematic errors and maximizing the detected UHECRs flux. The Pierre Auger Observatory is the world largest cosmic-ray observatory. (6) Chapter 3 introduces its objectives, characteristics, and greatest achievements so far.

The Pierre Auger Observatory will be upgraded to AugerPrime and is planned to be operational from 2018 to 2024. (7) One of the objectives of the upgrade is to improve the capability of distinguishing the EAS muonic from the electromagnetic component in order to better estimate the nature of primary cosmic-ray nuclei. (8) This estimation is important to restrict hadronic models of interaction. The Muon Array with Resistive

Plate Chambers (RPCs) for Tagging Air showers (MARTA) (9) is a complement of the AugerPrime and is described in Chapter 4.

The objectives of the present project are to design, assembly, commission and analyze the data of the RPCs in São Carlos. Unfortunately, there was a delay in the manufacturing of some parts in Portugal, namely the gaseous volume and the detector electronics. Therefore, no data was generated by the RPCs in São Carlos to be analyzed in time for this dissertation. Instead of it, data from the RPCs assembled in Coimbra was analyzed and a brief description of the assembly procedure was given in Sec. 4.6. The analyzed RPCs are located on the first floor of a six-floor building inside the Physics Department of Coimbra University.

The experimental setup in Coimbra and the results of the data analysis are presented in Chapter 5. The zenith-angle dependence on the incident muon flux and the efficiency of a MARTA prototype were calculated.

In Chapter 6 the results are summarized and the prospects for the project and the RPCs integration to the Pierre Auger Observatory are described. The conclusions for the Portuguese detectors analysis are also presented.

2 EXTENSIVE AIR SHOWERS

The phenomenon of the nearly-simultaneous arrival of many particles over a large area is called an Extensive Air Shower (EAS) and it was discovered by Pierre Auger and his collaborators at the end of the 1930s. Its discovery allowed the study of high energy cosmic particles by detecting the large air shower. Nowadays it is known that the energy spectrum extends to beyond 10^{20} eV. (4)

An air shower induced by cosmic ray has three components: electromagnetic, muonic and hadronic. (10) The electromagnetic component is composed of electrons, positrons, and photons, while the hadronic one is initiated by hadrons, in general protons or atomic nuclei, and is composed of hadrons. The muonic component as the name suggests is composed of muons. Fig. 1 shows the schema of the particle dynamics in an atmospheric shower.

Figure 1 – Schema of the shower dynamic; the fractions in percentage are given for the first interaction.

Source: Adapted from CAZON (11)

The hadronic component continually feeds the electromagnetic one by generating at each interaction an electromagnetic subshower with approximately one-third of the initial energy. (4,10)

A simple model of shower development (Toy Model) was proposed by Heitler

(1944) (10) and is shown in Fig. 2. It applies to the electromagnetic and approximately to the hadronic shower.

Figure 2 – Toy model

Source: GAISSER (10)

Each line segment in Fig. 2 represents a particle with a given energy and each vertex an interaction through which two new particles are produced with half the energy each. The interaction occurs after one collision length λ . The process continues until the energy of a single particle reaches the critical energy. After this point, the particle only loses energy by getting absorbed or decaying. As a consequence of this model, the number of shower particles initially increases until it reaches the depth X_{max} given by:

$$X_{max} = \lambda \frac{\ln(E_0/E_C)}{\ln 2}, \quad (2.1)$$

where X_{max} is the depth measured along the shower axis at which there are more particles, E_0 is the initial energy of the incoming particle and E_C is the critical energy. After the depth X_{max} the number of particles starts to decrease.

Despite both the electromagnetic and hadronic shower can be represented by the Toy Model, there are important differences in the shower development as shown in Fig. 3. Because of the larger radiation length (λ), cascades initiated by nucleons are more penetrating than the ones initiated by photons. Furthermore, the lateral spread of nuclear showers is determined by the transverse momentum of the secondaries in nuclear interactions which in turn is much larger than for an electromagnetic shower of same primary energy. (12) These features are important during the reconstruction process in order to better estimate the initial energy, type, mass and direction of the primary particle.

2.1 Hadronic shower interactions

Physical interactions describe the production of particles in the atmospheric shower. In the electromagnetic cascade the most important interactions for the shower development are the pair-production, in which a photon produces a pair electron-positron; the bremsstrahlung, in which an electron or positron loses energy releasing photons and the photoionization in which the electron or positron ionize the medium. On the other hand, the most important interactions in the hadronic shower are the hadronic interactions,

Figure 3 – Shower development generated by an incoming (a) photon, (b) proton and (c) iron with initial energy 10^{14} eV. The scale bar is 5 km in the horizontal direction and 40 km in the vertical direction.

Source: By Courtesy of LEIGUI

which produce the pions and kaons. (13) Fig. 4 shows the hadronic-shower development with first interaction given origin to pions and Table 1 shows the most important channels and their probabilities.

From Table 1 and Fig. 1 one concludes that the main source of muons is pion decays. Another decay channels may occur for a specific range of energy such as the production of muon by the decay of heavier flavor mesons.

2.2 Muon flux at earth

Muons are the byproduct of the particle-air hadronic interactions which occur from 6 to 60 km height in the atmosphere (14). The muons only undergo electromagnetic interactions with a small energy loss of about 2 GeV before reaching the ground. These particles barely lose energy during the development of the atmospheric shower due to their relatively long half-life and small hadronic cross section. (15,16) They are the "penetrating component" of cosmic rays. (10)

Figure 4 – Schema of the interactions during the hadronic-shower development

Source: PERKINS (12)

The number of muons in an air shower is an important parameter used to differentiate among interaction models. Most observational parameters such as the cosmic ray spectrum and composition are model dependent. (15) The muon flux dominates by more than one order of magnitude the flux of other particles at sea level as seen in Fig. 5.

Gaisser (10) considers the pion and kaon decay to parametrize the muon production in the atmosphere dN_μ/dE_μ as function of energy and incidence angle:

$$\frac{dN_\mu}{dE_\mu d\Omega} \approx \frac{0.14E^{-2.7}}{cm^2.s.sr.GeV} \left\{ \frac{1}{1 + \frac{1.1E_\mu \cos \theta}{115 \text{ GeV}}} + \frac{0.054}{1 + \frac{1.1E_\mu \cos \theta}{850 \text{ GeV}}} \right\}. \quad (2.8)$$

The equation is based on two assumptions: the muon kinetic energies are much larger than the muon rest energy and a flat Earth model is used. Therefore, the analytical expression is only valid for muon energy $E_\mu > 100 \text{ GeV}/\cos \theta$ and incident angle $\theta < 60^\circ$. (10, 16)

The energy distribution of primary cosmic rays follows a power law E^ν . The pion and the muon distributions also follow the same power law, which is different in the low energy region. (16)

The ratio of energy loss from inclined to the vertical direction is given by the ratio of path lengths (same as the ratio of thickness) $D(\theta)$ obtained by simple geometric calculation (16) as shown in Fig. 6 and by the equation:

Table 1 – Interactions and decays in the hadronic shower

Interaction	Branching ratio
$\pi^\pm \longrightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$ (2.2)	$\sim 100 \%$
$\pi^0 \longrightarrow 2\gamma$ (2.3)	$\sim 98.8\%$
$\pi^0 \longrightarrow \gamma e^+ e^-$ (2.4)	$\sim 1.2\%$
$K^\pm \longrightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$ (2.5)	$\sim 63.5\%$
$K_L \longrightarrow \pi^\pm e^\pm \nu_\mu(\bar{\nu}_\mu)$ (2.6)	38.7%
$\mu^\pm \longrightarrow e^\pm + \nu_e(\bar{\nu}_e) + \nu_\mu(\bar{\nu}_\mu)$ (2.7)	at low energies

Source: GAISSER (10)

$$D(\theta) = \frac{S}{d} = \sqrt{\frac{R^2 \cos^2 \theta}{d^2} + \frac{2R}{d} + 1} - \frac{R}{d} \cos \theta, \quad (2.9)$$

where S is the inclined muon path length, d is the vertical muon path length and R is the Earth's radius.

From Eq. 2.9, the energy-integrated flux of inclined muons can be described in terms of the energy-integrated vertical flux (16):

$$\Phi(\theta) = I_0 D(\theta)^{-(\nu-1)}. \quad (2.10)$$

In an approximation of a flat Earth ($\theta < 60^\circ$), $D(\theta)$ can be approximated to:

$$D(\theta) = \frac{1}{\cos \theta}. \quad (2.11)$$

Figure 5 – Vertical flux of particles (except photons) originating from cosmic rays as function of the depth in atmosphere. The points are measurements for negative muons above 1 GeV.

Source: PATRIGNANI (17); PROCUREUR (18)

Figure 6 – Geometry of an inclined and a vertical incoming muon.

Source: SHUKLA (16)

Inserting Eq. 2.11 back into Eq. 2.10 yields the widely-used expression for the

zenithal dependence on the muon flux (16):

$$\Phi(\theta) = I_0 \cos^n \theta, \quad (2.12)$$

where $n = \nu - 1$

The angular dependence of the flux is roughly proportional to $\cos^2 \theta$, where θ is the zenith incidence angle. It yields approximately 70 muons/(m².s.sr). (18–20)

The muon flux at Earth is relatively isotropic. However, some parameters alter it slightly (18):

Altitude	The muon flux increases with the altitude, as shown in Fig. 5, because at higher altitudes the low-energy muons were not yet absorbed;
Latitude	The flux near the Equator is smaller, because of the shielding effect caused by the magnetic field of Earth;
Solar activity	Solar winds increase the flux of low-energy particles;
Pressure	Short-time effect; higher pressure in the lower part of the atmosphere increases the amount of air and, consequently, the muon absorption;
Temperature	Seasonal effect; the increase of the temperature in the upper atmosphere causes an increase in the muon mean free path and, therefore, decrease the low-energy muon flux.

Considering just the angular dependence, several experiments were performed globally at different places (different altitudes and latitudes) to calculate the coefficients of the parametrized flux $I(\cos \theta) = I_0 \cos^n(\theta)$. (19) Table 2 shows the coefficient estimations of the muon flux at Earth for several experiments. (20)

2.3 Muon underground

In Section 2.2 the approximated muon flux at Earth per cm².s.sr.GeV was analytically shown in Eq. 2.8. In order to compare it with data from detectors, one must also consider the matter which the muons transverse after reaching Earth's surface, especially for underground detectors. The energy loss of muons through matter can be divided in continuous, in which the muon ionizes the medium, and discrete, in which there occurs bremsstrahlung, electromagnetic interactions with nuclei, direct production of electron-positron and hadron production. (10)

Table 2 – Muon flux coefficients estimation

Authors	Geom. Lat.(°N)	Geom. P_C (GV)	Alt. (m)	Muon Mom. (GeV/c)	n value	Integral Flux ($10^{-3}cm^{-2}s^{-1}sr^{-1}$)
Crookes and Rastin (21)	53	2.2	40	>0.35	2.16 ± 0.01	9.13 ± 0.12
Greisen (22) and (23)	54	1.5	259	>0.33	2.1	8.2 ± 0.1
Judge and Nash (24)	53	-	S.L	>0.7	1.96 ± 0.22	-
Fukui et al. (25)	24	12.6	S.L	>0.34	-	7.35 ± 0.2
Gokhale (26)	19	-	124	>0.27	-	7.55 ± 0.1
Karmakar et al. (27)	16	15.0	122	>0.353	2.22	8.99 ± 0.05
Sinha and Basu (28)	12	16.5	122	>0.27	-	7.3 ± 0.2
S.Pal (19)	10.61	16	S.L	>0.280	2.15 ± 0.01	6.217 ± 0.005
Allkofer et al. (29)	9	14.1	S.L	>0.32	-	7.25 ± 0.1
S. Pethuraj et al. (20)	1.44	17.6	160	>0.11	2.00 ± 0.2	7.00 ± 0.53

Source: PETHURAJ (20)

The muon energy loss is proportional to its energy and takes the form of

$$-\frac{dE_\mu}{dX} = a + bE_\mu, \quad (2.13)$$

where a is the ionization loss and b is the discrete energy loss.

The quantity $\epsilon = a/b$ is the muon critical energy in rock (~ 500 GeV), i.e. above this energy the discrete processes become more important than the continuous one. Table 3 shows the values of parameters a and b for standard rock and b for ice, as function of the muon energy. (30)

Eq. 2.13 can be integrated to give the relation between the energy $E_{\mu,0}$ of a muon at production in the atmosphere and its average energy E_μ after traversing a thickness

Table 3 – Parameters for the muon energy loss

E_μ	R	a	b_{brems}	b_{pair}	b_{nucl}	$\sum b_i$	$\sum b(ice)$
GeV	km.w.e.*	MeV g ⁻¹ cm ²	---	10 ⁻⁶	g ⁻¹ cm ²	---	---
10	0.05	2.17	0.70	0.70	0.50	1.90	1.66
100	0.41	2.44	1.10	1.53	0.41	3.04	2.51
1000	2.45	2.68	1.44	2.07	0.41	3.92	3.17
10000	6.09	2.93	1.62	2.27	0.46	4.35	3.78

*km.w.e.: kilometer of water equivalent (10⁻⁵ g.cm⁻²). Source: TANABASHI (30)

$X(g/cm^2)$ of rock(density 2.6g/cm³ (31)):

$$E_{\mu,0} = (E_\mu + \epsilon)e^{bX} - \epsilon. \quad (2.14)$$

Two approximations may be considered for Eq. 2.14: One for the region where $X \ll b^{-1}$ which yields Eq. 2.15, and the other for the region $X \gg b^{-1}$ which yields Eq. 2.16:

$$E_{\mu,0} \approx E_\mu(X) + aX \quad X \ll b^{-1}, \quad (2.15)$$

$$E_{\mu,0} \approx (\epsilon + E_\mu(X))e^{bX} \quad X \gg b^{-1}. \quad (2.16)$$

Based on 2.14 it is possible to calculate the minimum required energy for a muon at the surface to reach slant depth X with residual energy $E_\mu(X) = 0$, as shown in Eq. 2.17 from Gaisser (10):

$$E_{\mu,0}^{min}(X) = \epsilon(e^{bX} - 1). \quad (2.17)$$

In this approximation, using the result from Eq. 2.17 the vertical muon intensity at depth X underground (measured from the surface) can be calculated through Eq. 2.18 (10):

$$I_\mu(X) = N_\mu(> E_0^{min}(X)), \quad (2.18)$$

where $N_\mu(> (E_{\mu,0}))$ is the vertical flux of muons at the surface.

One can also show that the underground energy spectrum is given by Eq. 2.19 from Gaisser (10):

$$\frac{dN_{\mu(X)}}{dE_\mu} = \frac{dN_\mu(E_{\mu,0})}{dE_{\mu,0}} \frac{dE_{\mu,0}}{dE_\mu} = \frac{dN_\mu}{dE_{\mu,0}} e^{bX}, \quad (2.19)$$

where $E_{\mu,0}$ is obtained from Eq. 2.14.

For small depths ($X \ll \chi \approx 2.5$ km.w.e.), $E_0 = E_\mu(X) - \alpha X$. For large depths ($\chi \ll X$) the flux becomes very small and independent of depth. In this region (~ 10 km.w.e.) muons are produced by interaction of atmospheric neutrinos with rocks and different calculation out of the scope of this dissertation is needed. (10)

2.4 Experiments

Up to energies of some 10^{14} eV, cosmic rays can be measured directly with minor or none disturbing effects of cosmic-ray interactions with the atmosphere, by employing stratospheric balloons or satellite-born experiments, respectively. At higher energies, measurements of cosmic rays are only possible via observations of EAS at the ground. (32)

There are different methods for the detection of EAS including particle detectors, Cherenkov telescopes, and fluorescence telescopes. The first one focuses on the detection of electrons, positrons (surface detector) and muons (ground and underground detector) in order to infer the cosmic-ray composition. Scintillators and RPCs are examples of particle detectors.

The number of electrons at the depth of the shower maximum X_{max} , i.e. the position in the atmosphere where there is the largest number of secondary particles gives a good estimate of the primary energy independent of the composition. To be able to detect the EAS as nearby as possible from the X_{max} the observatories are usually built in high altitude places subjected to small humidity and consequently clear sky. The sum of electron and muon numbers measured at the ground relates to the primary energy, while the ratio of the muon to electron number relates to the primary mass. (32)

Cherenkov telescopes are usually water tanks with photomultipliers or scintillators which detect the Cherenkov radiation emitted by the secondary shower particles, while the fluorescence telescopes detect the light emitted by the interaction of the secondary particles with the air molecules. Both telescopes need a good clear night sky in order to efficiently detect EAS.

The experiments in high-energy astrophysics are usually developed, built and analyzed by collaborations composed of different research institutes from different countries since the experiments are very expensive and demand lot of work. The majority of the EAS observatories such as the Pierre Auger Observatory which is described in Chapter 3 integrate different but complementary detection techniques in order to better estimate the EAS variables such as primary energy and composition.

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3.1 Surface Detector (SD)

The surface detector consists of a sealed tank with 3.6 m in diameter and filled with 12,000 liters of ultra-pure water. This special water is necessary to avoid bacterial growth which could lead to reduced water clarity. Three photomultiplier tubes (PMTs) on the surface of the liner detect the Cherenkov radiation emitted by the minimum ionizing particles (MIPs) passing through the water. The detectors operate 24 hours per day and detect showers initiated by particles with energy above 3.10^{18} eV with 100% efficiency. (6) Fig. 8 shows the schematic of one SD detector.

Figure 8 – Schematic view of one SD station, including the water tank, electronics and communication equipments.

Source: THE PIERRE AUGER COLLABORATION (6)

The water-Cherenkov stations respond to both electromagnetic and muonic components of the shower. Using sophisticated analyses which explore the detector response to different shower components, it is possible to estimate the muon content. These analyses require a deep understanding of the detectors. (35)

3.2 Fluorescence Detector (FD)

There are 24 telescopes which overlook the SD array. They are distributed through four sites as represented in Fig. 7. The spherical mirror has a curvature radius of approximately 3400 mm and the spherical focal surface of ~ 1700 mm. Its field of view is $\sim 30^\circ \times 30^\circ$ and the minimum elevation is 1.5° above horizon. (6) Fig. 9 shows a photo of one telescope in Coihueco and the schema of its components.

Figure 9 – (Above) Photo of a fluorescence detector in Coihueco, (Below) Schema of the fluorescence detector including its components.

Source: THE PIERRE AUGER COLLABORATION (6)

The fluorescence detector is used to image the longitudinal development of the showers. The fluorescence light is emitted isotropically by the nitrogen molecules in the atmosphere as ultraviolet radiation and is produced predominantly by the electromagnetic component of the shower. Since the fluorescence light production is directly related to the energy deposit in the atmosphere, the primary cosmic-ray energy is determined through a nearby-calorimetric method. Moreover, the depth at which a shower reaches its maximum size, X_{max} , is observable. At primary energy of 10^{19} eV over 60% of FD showers are viewed in stereo, and at $3 \cdot 10^{19}$ eV it is 90%. (6)

The disadvantage of the FD is the duty cycle which varies from 12% to 15%. The reason for the low duty cycle is because the observations by the FD are limited to dark

nights and good weather conditions. However, high-quality data sets are collected in hybrid observations which result in higher precision in the shower direction calculation. (6)

3.3 Great achievements

The Pierre Auger Observatory has collected high-quality data over more than ten years, which has led to a measurement of flux of the UHECRs above 3×10^{17} eV with unprecedented statistics. (36) The compilation of data comprises 118,000 SD events above 3 EeV (3.10^{18} eV), 61,000 events ($E > 0.3$ EeV) from the denser infill array near the Auger Engineering Radio Array (AERA) and 9,000 hybrid events above 1 EeV. The energy spectrum of incoming cosmic rays steepens from a power law with index 3.29 ± 0.02 (stat) ± 0.05 (sys) to one of index 2.60 ± 0.02 (stat) ± 0.1 (sys), at an ankle energy of 5.08 ± 0.06 (stat) ± 0.8 (sys) EeV. Furthermore, a suppression on the cosmic ray flux beyond 10 EeV manifests at a significance of 20σ . (37) Fig. 10 shows the cosmic ray spectrum.

Figure 10 – Combined energy spectrum of incoming cosmic rays. The red line shows a fit with a change in the parameters in the region called 'the ankle' and a suppression at ultra-high energies.

Source: UNGER (38)

Strong limits have been placed on the photon and neutrino components of the flux indicating that processes such as super-heavy-particle decay do not account for a significant part of the observed particle flux. The spectrum and the X_{max} data from the Pierre Auger Collaboration indicate that the flux suppression at UHE is partly a source effect rather than the Greisen–Zatsepin–Kuzmin (GZK) process. (7)

It can be shown from data of the Pierre Auger Observatory (38) that the average mass of cosmic rays evolves towards a lighter composition between $10^{17.2}$ and $10^{18.33}$ eV,

qualitatively consistent with a transition from a heavy Galactic composition to a light extragalactic composition. In the ultra-high energies (UHE) the average mass of cosmic rays increases again.

More recently, the large-scale anisotropy in the arrival directions of cosmic rays with energies above 8×10^{18} eV was described by a dipolar distribution. Its direction indicates an extragalactic origin of UHE particles, as previously suspected, with a significance of 5.2σ . (39) The origin of the discovered dipole remains at this point a subject of speculation. (38) Fig. 11 shows the map of UHE direction origin.

Figure 11 – Map showing the fluxes of particle above 8 EeV in equatorial coordinates, using Hammer projection. A 45° top-hat function is used, the Galactic center is marked with an asterisk and the Galactic plane is shown by a dashed line.

Source: THE PIERRE AUGER COLLABORATION (39)

3.4 Auger Prime

In 2018, the Pierre Auger Observatory will be upgraded to the Auger Prime (Primary cosmic Ray Identification with Muons and Electrons). The main upgrade objectives are (7): to clarify the mass composition and the origin of the flux suppression at the highest energies; to reach a sensitivity to a contribution of protons as small as 10% in the flux suppression region and to investigate EAS and hadronic multiparticle production exploring fundamental physics.

After the upgrade, the observatory will be operated until 2024. The main upgrade will be the Surface Scintillator Detector (SSD) which will be installed on top of the water Cherenkov tanks. The SSD consists of a 4 m^2 plastic scintillator which is made of organic

materials that luminescence when interacting with ionizing radiation. (40) Fig. 12 shows the view of the scintillator mounted on top of the Cherenkov tank.

Figure 12 – Assembly of the scintillator detector on top of a Cherenkov tank.

Source: GIULIO (7)

The combined detection of the scintillator with the water-Cherenkov station detectors will provide the capability of distinguishing between the electromagnetic and muonic components of the shower. This occurs due to the fact that each detector responds in a different way to muons and electrons. Once the muonic and electromagnetic components are distinguished, more information about the primary composition is available. (7)

3.5 Combined detection: Scintillator and RPC

As an alternative of the scintillators from the Auger Prime, the construction of 40 RPCs was approved by the Pierre Auger Collaboration. The proposal was named Muon Auger RPC for the Tank Array (MARTA). Ten Cherenkov tanks are planned to be equipped with four RPCs underneath each one. (41) The RPC design is discussed in Sec. 4.6. Its objective is the muon detection in conjunction with the water-Cherenkov detectors and the scintillators. Furthermore, the RPCs will serve as a calibration for the scintillators. The Cherenkov detectors sit on top of a concrete support structure (precast) which hosts the RPCs as shown in Fig. 13.

The stations are organized in a hexagonal unitary cell with two stations at the center and a couple of co-located ones as shown in Fig. 14. (41,42)

In order to calibrate the scintillators, the detected signal must be analyzed in conjunction with the RPC signal. While the electrons-positrons and photons are easily absorbed in the water, muons pass through the tank and hit the RPC underneath it. The RPC signal is then produced mostly by muons. On the other hand, the scintillator and water-Cherenkov signal are produced by both muons and electrons. Fig. 15 shows the schema of the combined detection.

Figure 13 – The Cherenkov tank and the four RPCs form a measuring station; the assembly is shown with spaces between components (above) in order to better visualize them and without the spaces (below).

Source: By the author

Figure 14 – Hexagonal unitary cell for the measuring stations.

Source: CONCEIÇÃO (42)

Figure 15 – Combined detection showing the scintillator on top of the Cherenkov detector and the RPC underneath it.

Source: Adapted from CONCEIÇÃO (42)

4 RPCS

In this chapter the RPCs are first presented. Its composition and working principle are explained. The detector signal and characterization are described. In Sec. 4.6 the monitoring of the RPCs assembled in São Carlos is shown.

4.1 General description

Resistive Plate Chambers (RPCs) are gas detectors used especially in high-energy physics and astroparticle experiments. (43) They were first introduced in 1981 as a detector composed basically by two parallel electrode plates, with at least one of them made of a material with high bulk resistivity ($10^{10} - 10^{11} \Omega \cdot \text{cm}$) and a 2 mm gas gap in the middle. (44) In order to improve the time resolution of the detector, a new kind of RPC was introduced in 1996: the multi-gap RPC. (45) The main difference from the single-gap RPC is the presence of resistive electrically floating electrodes dividing the gas into more than one gap. The RPCs are a very good solution for muon detection because of their fast response (about 1 ns), good time resolution, flexibility in the signal readout, robustness and relatively low cost of production. (46)

4.2 Structure and materials

4.2.1 Single-gap RPC

The structure of a modern single-gap RPC, as shown schematically in Fig. 16, consists of two high resistivity plates made of glass separated by insulating spacers (nylon mono-filaments (47)), a gas gap in the middle and the pick-up pads. While the original RPC plates were made of bakelite, (44) a paper treated with a phenolic resin, the modern ones are mostly made of glass which provides the detector mechanical stiffness and surface quality. (43) The external surface of the plates is coated with a conductive material (graphite) with medium resistivity (of the order of tens of $\Omega \times \text{cm}$). (46) To protect the graphite and insulate it from external influence, it is covered with a high resistivity material (mylar layer or acrylic painting).

There are many possible combinations of gases to be used in the detector. (48,49) A good choice according to efficiency, simplicity and availability is the freon R-134a (47).

The detector plates must be gas-tight by a permanently glued acrylic box. It also assures the high-voltage insulation. (47) Gas connections and high-voltage wires are connected to the box with feedthroughs.

Figure 16 – Schematic drawing of a single-gap RPC.

Source: By the author

4.2.2 Multi-gap RPC

The multi-gap RPC came as an alternative to achieve a better time resolution. The design also increases the signal on the pick-up strips which make it possible to operate at a lower gas gain (lower voltage) with the same efficiency as the single-gap RPC. (50) Fig. 17 shows schematically a double-gap RPC. Variations on the design are also possible, for example, a double pick-up plane. (46)

Figure 17 – Schematic drawing of a double-gap RPC.

Source: By the author

4.3 Working Principle

The detector works based on the gas ionization by an incoming Minimum Ionizing Particle (MIP). A constant high voltage (5.6 kV for 1 mm double gap and pure tetrafluoroethane (51)) is applied to the plates through the medium resistivity material, as shown in Fig. 17. A cluster of n_0 electrons, produced by the ionizing particle, ignites the avalanche multiplication. The produced electronic charges $Q_e(d)$, where d is the gap height, drifts to the anode and induces on it a fast charge $q(e)$ which is the useful signal of the RPC. (52) Fig. 18 shows the working principle of an RPC.

The high resistivity of the plate assures that the discharge caused by the ionization suddenly switches off the electric field locally and in a limited area which in turn prevents

Figure 18 – RPC working principle.

Source: PARK (46)

the discharge of propagating through the whole gas. (44) The absence of violent discharges is the main property of the RPCs. (43) This feature makes them more suitable to work with than the predecessor parallel plate chambers (PPC). It is very important to find a value of the resistivity which gives the best signals. If the plates are insulated, they will accumulate charges and suffer discharges. Excessive conductivity prevents the electromagnetic induction in the cathode strips. (53) The value for the resistivity is between 10^{10} and $10^{11} \Omega \cdot \text{cm}$ as described at the beginning of this chapter.

The detector efficiency depends on the gas, the gap and the applied voltage. (47)

4.3.1 Mechanism of breakdown of gases

In a parallel plate capacitor such as a RPC, there is a dependence between the generated current and applied high voltage. This dependence was studied by Townsend and is represented by the equation below (54):

$$I = \frac{I_0 e^{\alpha d}}{1 - v e^{\alpha d} - 1}, \quad (4.1)$$

where I_0 is the initial current, α is the Townsend's first ionization coefficient defined by the number of electrons produced by an electron per unit length in the direction of the field, d is the distance between the plates and v is the Townsend's second ionization coefficient defined by the number of electrons released from cathode per incident positive ion, photons and metastable particles (excited atoms and molecules). The term $e^{\alpha d}$ is called the electron avalanche and represents the number of electrons produced by one electron traveling from cathode to anode. The first Townsend's coefficient depends on the gas gain and should be experimentally determined based on analytical formulas as in AURIEMMA (55) and AOYAMA (56). Equation 4.1 is valid if one does not consider the effect of space charge on the electric field. From Eq.4.1 three situations are derived:

$ve^{\alpha d} = 1$	This is the Townsend criterion. In this case the produced ions are able to bombard the cathode and release secondary electrons from it which start more avalanche processes resulting in a self sustained system. This condition defines the threshold for sparking.
$ve^{\alpha d} > 1$	The avalanche is cumulative and grows proportionally to $ve^{\alpha d}$. Even if the source of I_0 ceases, the process continues.
$ve^{\alpha d} < 1$	The current is not self-sustained. If the source ceases, the current stops flowing.

A cluster of electrons starts the avalanche multiplication forming an electronic charge inside the gap which is defined by the space charge. The ions and mainly the electrons align in the field direction in order to decrease it as shown in Fig. 19.

Figure 19 – Field redistribution due to the space charge.

Source: WADHWA (54)

The large increase in the number of primary electrons is called gas multiplication or gas gain and is used to characterize the gas used in the RPC. The electrons of the space charge move in the anode direction and induce in the pick-up plane a fast charge which is actually the RPC useful signal. Raether (54) observed that if the number of electrons formed in the space charge is higher than 10^6 and smaller than 10^8 , the space charge field is high enough to weaken an avalanche. If it is greater than 10^8 , the space charge field becomes almost of the same magnitude as the applied one. Then it characterizes the initiation of a streamer. (54) The streamer is a late discharge stage that develops via gas photoionization processes after the first avalanche is extinguished. (57) In this case, due to the smaller gas gap or higher applied voltage, there is an intense ionization and excitation of gas particles in front of the avalanche head. (54) The electrons recombine with the ions generating photons which in turn generate secondary electrons by ionizing the gas molecules. Then the secondary electrons generate secondary avalanches. Therefore, the process is self-sustained. Fig. 20 illustrates the streamer process.

Figure 20 – Photoionization processes responsible for the streamer generation.

Source: WADHWA (54)

4.4 RPC signal

4.4.1 Avalanche development

According to WADHWA (58), there are three time regions in the breakdown of gases with distinct characteristics:

Proportional region: It corresponds to a propagation of a Townsend avalanche, in which the electrons suffer the influence of an electric field inferior of the applied one which results in an effective gas gain smaller than the nominal one. In this region, the number of electrons increases exponentially.

Transition region: It corresponds to the beginning of the streamer. After the electrons are absorbed in the anode, they cease to compensate the ionic charge which is much slower than the electrons. In the region between the cathode and ionic charge, the electric field is increased. On the other side in the anode region, the field is decreased once the electrons were already absorbed. Therefore there is a high-gain region between the cathode and ionic charge. Photoelectrons start to be released upstream of the high gain region creating a self-sustained process. In this region, the space-charge electric field starts to be comparable to the applied field which causes the electron production to decrease.

Propagation region: The high gain region (streamer) shifts toward the cathode once the ions keep being produced upstream from the peak.

Fig. 21 illustrates the avalanche development according to its charge.

The avalanche development, i.e. the process of multiplication of electrons and the drift toward the anode is not entirely deterministic, particularly in the initial stages when the number of electrons is lower than about one hundred. After this stage, the avalanche growth proceeds deterministically. (59)

Figure 21 – Initially, the avalanche charge N_e (in blue) has a stochastic behavior until it reaches about 100 electrons when it starts a deterministic exponential growth. At some charge $N_{e,sat}$, the space-charge electric field starts to be comparable to the externally applied field and there is a departure from the exponential growth.

Source: FONTE (59)

The main processes which contribute to the avalanche fluctuations are: 1) avalanche gain fluctuations (fluctuations of the number of electrons produced by each electron); 2) cluster statistics (electron's charge density); 3) initial position (Initial position of the each cluster); and 4) variable number of clusters generated by each particle.

4.4.2 Charge Spectrum

Theoretical models for the development of the charge avalanche were developed in the literature to understand the aspects of the RPCs signals and to compare with data. (52, 59, 60) For analytical calculation, approximations should be used, though for a Monte Carlo simulation a more complex statistics must play a role.

In the following lines, a simplified model by Abbrescia (52) will be described. The model uses the Raether condition, i.e. the electric field intensity is below the streamer mode of operation.

A passing ionizing particle collides and ejects a cluster of n_j electrons distributed according to a Poisson-statistics. Each electron starts its own avalanche multiplication. Fig. 22 shows a schema of the clusters of electrons, their avalanche multiplication and their shift toward the anode.

An electronic charge $Q_c(x)$ is developed inside the gap. The drift of this charge towards the anode induces on the pick-up electrode the "fast charge" q_e . The power supply

Figure 22 – A passing particle ionizes some gas molecules. The resulted cluster of electrons begins its avalanche multiplication toward the anode.

Source: FONTE (59)

has to move the charge q_s in the circuit outside the gap in order to compensate the charge collected on the electrodes. If the cluster density λ and the average cluster size μ are known ($\lambda = 5$ clusters/mm and $\mu = 3$ for $\text{C}_2\text{H}_2\text{F}_4$ mixtures), the average fast charge induced on the pick-up electrodes for one cluster can be calculated through (52):

$$q_e \simeq \frac{k}{\eta d} \langle Q_e(d) \rangle, \quad (4.2)$$

where q_e is the fast charge visible in the circuit outside the detector; k is the reduction factor given by

$$k = \frac{\varepsilon_r \frac{d}{s}}{n \varepsilon_r \frac{d}{s} + (n + 1)}, \quad (4.3)$$

where ε_r is the glass relative dielectric constant; s is the glass thickness, and n is the number of gaps in the multigap RPC.

The electronic charge that is collected in the j th cluster of electrons $Q_e(d)$ is given by:

$$\langle Q_e(d) \rangle = q_e \mu e^{\eta x} \left(\frac{\lambda}{n + \lambda} \right)^j, \quad (4.4)$$

where q_{el} is the electron charge; μ is average cluster size in millimeters; x is the direction defined from cathode to anode, λ is the cluster density in the gas mixture.

The effective Townsend coefficient η is given by the equation below:

$$\eta = \alpha - \beta, \quad (4.5)$$

where α is the first Townsend coefficient and β is the number of attaching encounter per unit length undergone by one electron and defined as the attachment coefficient.

In order to compensate the charge collected on the electrodes q_e , the external circuit moves the charge q_s which can be calculated through (52):

$$\frac{q_e}{q_s} = k\alpha d. \quad (4.6)$$

The contributions of all clusters in the trail can be added to find the total charge collected on the respective electrodes, implying that the avalanches are considered to be developing independently from each other. From Eq. 4.4, once the gap is small, one can notice that the first avalanche contributes mostly to the total charge. Fig. 23 shows this effect by simulation. (60)

Figure 23 – Simulated contributions of the electron clusters for top a 2 mm single-gap RPC and bottom a 9 mm single-gap RPC.

Source: ABBRESCIA (60)

In order to simulate the RPC signal, it is mandatory to consider the fluctuations as explained in 4.4.1. A Monte Carlo simulation (for example as in (52) in Fig. 24) could be used to fit the best coefficients for the data.

Figure 24 – Simulated charge spectrum of an RPC compared with data for freon-based mixture.

Source: ABBRESCIA (52)

FONTE (59) developed an analytical calculation which includes the avalanche, and the fluctuations of the initial positions and also the variable number of clusters. The calculation was only possible by excluding the cluster statistics. Eq. 4.7 is the distribution of the amount of charge of all clusters. The assumptions are that all clusters contain a single primary electron and the maximum average gas gain G is large ($G \gg 1$):

$$\tilde{P}(N_e) = G^{-m} \delta(N_e) + (1 - G^{-m}) \left[\frac{e^{-\frac{N_e}{G/r}} \frac{N_e^{m-1} (G/r)^{-m}}{\Gamma(m)}}{e^{-\frac{N_e}{G/r}} \frac{N_e^{m-1} (G/r)^{-m}}{\Gamma(m)}} \right], \quad (4.7)$$

where $\tilde{P}(N_e)$ is the charge density distribution including all clusters, G is the maximum gain $G = e^{\eta g}$, $m = \frac{\lambda r}{\eta}$, $\eta = \alpha - \beta$ is the effective Townsend coefficient, $r = 1 - \frac{\beta}{\alpha}$ and Γ is the gamma function.

In Eq. 4.7, the first term on the right side represents the intrinsic inefficiency (the case in which there are no avalanches); the term in square brackets is the statistical gamma distribution with shape parameter m and scale parameter G/r . The effective Townsend

coefficient η according to Raether's formulation is given by:

$$\begin{aligned} \eta &= \alpha & N_e &\leq N_{e,sat} \\ \eta &= \alpha(1 - B \cdot \ln(\frac{N_e}{N_{e,sat}})) & N_e &> N_{e,sat} \end{aligned} \quad (4.8)$$

where B is a constant which depends on the gas. Fig 25 represents the equation 4.8 for several values of m .

Figure 25 – Representation of the total generated charge for $G = 10^4$, $r = 0.5$, $m = 0.5, 1, 2, 3$.

Source: FONTE (59)

In Fig. 25, for small N_e ($N_e \ll G/r$), $\tilde{P}(N_e)$ follows a power law $\tilde{P}(N_e) \sim N_e^{m-1}$. It means that the parameter m controls qualitatively the behavior of $\tilde{P}(N_e)$ for small N_e : if $m < 1$, the function diverges at the origin and is monotonically decreasing, if $m > 1$, it is null at the origin. (59)

4.4.3 Pick-up pads

The induced signal for each event can be obtained directly from the pick-up pads by the RPC data acquisition (DAQ) or with a bandwidth oscilloscope using a horizontal scale of 20 ns/cm and a vertical scale of 2.5 mV/cm as in (57) for 50 x 50 cm² and RPCs with 2 mm gas gap using a gas mixture composed mostly by argon. The signal depends on the applied voltage and can be analyzed in Fig. 26.

Each one of the waveforms in Fig. 26 can be time-integrated to give the total induced charge per event. If it is done for many events, the charge spectra can be obtained as in fig. 27.

Figure 26 – Voltage waveforms of an event resulted by a MIP (Minimum ionizing particle) for (a) 9.4 kV showing the avalanche signal, (b) 9.6 kV showing the streamer following the avalanche, (c) 10.2 kV where the avalanche-to-streamer delay drops, and (d) 11.4 kV where both signals merge into a single pulse. Multi-streamer signals are also observed.

Source: CARDARELLI (57)

It is notable the similarities of Fig. 24 and 27 even though the first one shows the charge spectra in a mono-log graph.

Figure 27 – Measured charge spectra showing two peaks (avalanche and streamer) for (a) 9.0 kV and (b) 9.4 kV for the experimental setup in CARDARELLI.

Source: CARDARELLI

4.5 RPC Characterization

4.5.1 Modes of operation

There are two basic modes of operation for an RPC: the avalanche mode and the streamer mode. As shown in Fig. 26, the streamer signal appears at higher applied voltages, a few nanoseconds after the avalanche signal and is up to 100 times larger than those produced by avalanches. (61) While the use in avalanche mode is mandatory in high rate environments such as ATLAS and CMS experiments at LHC, the streamer mode is preferred in low rate applications because of the high signal amplitude. (49) Many studies have been done seeking for the best design for avalanche (61) and streamer operation (49) based on the gas mixture, the gas gap width, and the applied voltage.

The most typical gases used in RPCs are Argon, Tetrafluoroethane and Isobutane, with additions of SF₆ below 1% to reduce the charge delivered in the gas. Table 4 resumes its properties. (49)

Table 4 – Typical gases and proprieties

Typical gas	Properties
Argon	Noble gas with high charge multiplication (Townsend coefficient), therefore used in streamer mode
Isobutane	UV-quencher gas which prevents avalanche; limited concentration due to flammability requirements
Tetrafluoroethane	electronegative gas with high primary ionization; baseline gas for avalanche mode
Sulfur Hexafluoride	strongly electronegative gas, used in avalanche mode to suppress the streamer fraction; improves time resolution when added to mixtures with high Tetrafluoroethane concentration

Fonte: DENNI (49)

4.5.2 Streamer Fraction

The streamer fraction is the part of the signal which comes from the streamer, i.e. originated from the secondary electrons after the first avalanche is extinguished as explained in Section 4.3.1. In the avalanche mode of operation, the streamer fraction is usually limited by requisites of construction (62) to 10% of the total signal. The determination of the exact place where the streamer signal starts is made by many authors (for (51) any signal with charge greater than 2000 ADC and for (61) "visibly separated from the avalanche tail") by visual inspection in the charge spectra graphic such as the one of Fig. 27. Once the definition is made, the streamer fraction can be calculated through (51):

$$StreamerFraction(\%) = \frac{Num. \text{ of hits } Q > 2000ADC}{Num. \text{ of hits}} 100 \quad (4.9)$$

4.5.3 Efficiency

To characterize an RPC, it is mandatory to calculate its efficiency to cosmic rays. The experimental setup to realize it is composed by at least another two working detectors. Lopes (47) uses four of them: two plastic scintillators, a small trigger RPC with 99 % efficiency to cosmic rays and the RPC under test which is placed between the bottom scintillator and the trigger RPC. A trigger is defined by the coincidence of events between the two scintillators and the trigger RPC. The signals are recorded by a digital oscilloscope and analyzed afterward via software. Whenever there is a trigger according to the definition

and the RPC under test is also triggered, a counter K increases by 1. The efficiency is then calculated as follows:

$$Efficiency(\%) = \frac{K}{Num. \text{ of trigger}} 100 \quad (4.10)$$

4.6 RPCs assembly and commissioning

As mentioned in Chapter 1, the initial project's objectives were to work and analyze data from the RPCs assembled in São Carlos. Though it was not possible because of the delay in the manufacturing of the RPCs, a brief description of the assembly and commissioning is given in this section.

Since the RPCs for the Pierre Auger Observatory are going to be installed underneath the water-Cherenkov detectors, the RPC dimensions were basically defined by the tank diameter and by some constraints related to glass sheets available in the market (51) and then adapted to the Brazilian standard measurements. Autodesk Inventor® was the software used for the drawing.

The RPCs must be robust to operate in the harsh environment of the Argentinian Pampas where there are great temperature variations. They must also operate for years without maintenance because of the difficulty to get to the many detectors once they are installed, and finally, they must be made of cheap materials available in the market.

The construction of the RPCs for the Pierre Auger Observatory is divided into parts. While the collaboration from LIP, Portugal is responsible for the sensible volume, the bubbler, and the electronics, the collaboration from USP and UNICAMP in Brazil is responsible for the construction of the aluminum box, the pick-up pads and the final assembly.

After the aluminum box manufacturing, the assembly began to take place. During this phase, two RPCs were assembled with the help of Portuguese researchers and technicians who came to São Carlos. A complete assembly manual (76 pages) was elaborated by the author to guide the technical support in the assembly of the other detectors units. An English and summarized version is available in Appendix A.

After the assembly, the induced signals in the pads were studied with a 350 MHz 2.5 GS/s digital phosphor oscilloscope. The signals in both RPC 01 and RPC 02 were investigated in order to understand the unexpected difference between them. In this experimental setup, the oscilloscope was connected to show the voltage between the ground and one of the pads when the applied voltage was 5.6 kV.

The oscilloscope was configured for 20.0 mV in the y-axis, 40.0 ns in the x-axis and the trigger for a voltage drop bigger than 40.0 mV. Fig. 28 shows a typical voltage

Figure 28 – Typical signal in one of the RPC 02 pads caused by a MIP. The biggest signal drop is the merge of the avalanche and streamer signals; the smaller delayed signal are multi-streamers.

Source: By the author

drop signal caused by a MIP (Minimum ionizing particle) in RPC 02 which is in great accordance with Fig. 26 (d).

There were no clear signals in RPC 01 whereby it may be concluded that the problem was in the sealed sensible volume.

Sensors of humidity, pressure, and temperature monitor the RPCs. The bubbles in the glycerin which are directly correlated to the gas flow in the detector are measured. Furthermore, the applied voltage between the plates and the generated leak current through the gas are monitored by the electronics.

During the period of commissioning, i.e. when the gas starts to flow, the humidity decreases as shown in Fig. 29. The low humidity is important for the good detector operation since it minimizes leak currents.

In order to keep the detector undamaged, the generated current through applied voltage must be kept under $1 \mu A$. While the humidity decreases, the leak current decreases as well. This enables one to increase the voltage. This process should be repeated until the applied voltage reaches the working voltage of 5.6 kV. Fig. 30 shows the process.

Each time the voltage is increased, the generated current increases as well. When the applied voltage is constant, the leak current decreases because of the decreasing humidity. The small current oscillation in Fig. 30 is due to daily temperature variation.

Figure 29 – Decreasing detector humidity during the commissioning period. It took about 2 months for the humidity to become stable for the mean gas flux of $90 \text{ cm}^3/\text{min}$.

Source: By the author

Figure 30 – Applied voltage and generated current during the time when the humidity is decreasing.

Source: By the author

5 RPCS DATA ANALYSIS AND RESULTS

In this chapter, the data analysis and the results of the RPCs in Coimbra are presented. Firstly, the experimental setup is described. Secondly, the data analysis procedure is shown, and finally, the results are presented.

5.1 Experimental setup

The experimental setup stays on the first floor of the building at the Coimbra University. Fig. 31 shows the detector position in the building. On the right side of the detector ($Y > 0$), there is a region with five floors while on the left side ($Y < 0$) there is a region with six floors. The building has an atrium at its center.

Figure 31 – Detector position in the building in (a) a Google Earth view, and (b) a schema of the building geometry.

Source: By the author

Muons coming from different regions have to traverse the matter of the building before reaching the detector. The amount of traversed matter is not isotropic in the azimuthal angle. Therefore, it is expected a larger muon absorption in the region with a larger amount of matter, as shown in Fig. 31 (b).

A telescope composed of four RPCs was already built and is in operation at LIP in Coimbra (POR). The RPC prototype is a box with area 2000 mm x 500 mm. Inside the sealed sensitive module, the gas gaps are between 2.85 mm thick float glasses with resistivity approximately $10^{12} \Omega \cdot \text{cm}$ at 25°C , which are separated by 30 nylon monofilaments. The signals are read by a pick-up electrode 1.5 mm thick made from FR4 Printed Circuit Board (PCB) and composed of 15 copper strips with 29 mm each separated by 1 mm. The Data Acquisition (DAQ) System, borrowed from HADES Collaboration, consists basically of a Trigger Readout Board (TRB), a 128 channels multihit Time To Digital (TDC) board, and an ARM-based dreamPlug computer. (63)

The four RPCs ($R1 - R4$) are vertically organized: R1 at 522.5 mm, R2 at 479 mm, R3 at 67.5 mm and R4 at 22.5 mm. The two upper RPCs are built from modules with two gaps, while the other two are built from modules with five gaps, all in multigap construction. The detector operates with a non-flammable gas mixture composed of 90% $\text{C}_2\text{H}_2\text{F}_4$ and 10% SF_6 , under a continuous gas flow of $15 \text{ cm}^3/\text{min}/\text{module}$ at an applied voltage of 3,100 V. Fig. 32 shows two parts of the telescope CAD drawing.

Figure 32 – CAD drawing of the RPC-telescope ate LIP, Coimbra. Top: two double-gaps RPCs, Bottom: two five-gaps RPCs.

Source: MACHADO (63)

The signal at each strip is read out at both ends by a timing Front End Electronics (FEE) with a timing accuracy of approximately 40 ps. (63) Each channel is capable of reading the time and charge information. The Y-coordinate of an event (MIP) is determined by the triggered strip (from 1 to 15) in case of a single particle event and by the mean of the triggered strips weighted by the charge in case of many-particle events. The X-coordinate is given by the difference in the arrival time of the signal in both strip ends ($X = T_2 - T_1$). A further proper coordinate normalization is also mandatory for each strip separately.

The RPC-telescope was built to test other particle detectors including a MARTA prototype also developed at LIP-Coimbra. In the same z-coordinate axis, it was placed at $z = 1430$ mm, i.e. almost 1 m above the upper telescope plane.

The trigger for an event is defined by the coincidence of all the four planes. Every half an hour a log file is generated containing the following data for each event: Date and time; X-coordinate positions for the event in each one of the planes (in TDC bins); Y-coordinate positions for each plane (an integer random number in millimeters is randomly generated within the 15 mm of the fired strip); four time instants when the MIP passes through each of the four planes; time instants when the MIP passes through each one of the 64 MARTA pads (if the pad is not triggered, the time value is 0); and deposited charges in each one of the 64 MARTA pad in bins.

5.2 Data analysis procedure

In this section, a summary of the analysis procedure is presented. Four considerations are taken before the final analysis. Firstly, the alignment of the telescope planes is tested and corrected. Secondly, the arrival direction of each event is reconstructed. After that, the relative position of the telescope and the MARTA plane is obtained. Finally, the acceptance of the detector is calculated.

The total exposure time was 87,026 s. A total of 441,111 events were triggered, which gives a mean counting rate of 5.07 events/s. First, the quality of the dataset is monitored by the event rates as shown in Fig. 33. The events rate must not vary much during data taking, because it would mean the detector has some operational problem.

The data in the four X-coordinate planes are first found in TDC bins (0 – 300). A normalization for each plane and each strip must be carried out to bring the difference from maximum and minimum value to 2,000 mm, which is the detector length in the X-direction. An analogous process is also done for the Y-coordinate, which is first found as the number of the strip which was hit (0 – 15) and from 0 to 450 mm after normalization. The spatial resolution is considered to be half of the smallest measuring unit, i.e. $\sigma_X \approx 3$ mm and $\sigma_Y \approx 15$ mm.

No data were found for the two lower planes middle strip, which means they were

Figure 33 – Data monitoring showing a relatively stable operation (events rate approximately equal 5.3 events/s.)

Source: By the author

not online. Therefore, they were not considered in the analysis.

5.2.1 Telescope alignment

A procedure was developed based on the following steps:

- 1: For each event, exclude one of the planes from the analysis;
- 2: Fit a line using the X and Y position of the three other planes;
- 3: Use the fitted line to calculate the expected position for the excluded plane;
- 4: Calculate the residuals (the difference between expected and measured position) for X and Y-coordinates;
- 5: Repeat items 1-4 for the other three planes separately ;
- 6: Fit a Gaussian distribution to all the event residuals in each plane;
- 7: Add the half of the residual mean to each plane and event position;
- 8: Repeat items 1-6 to check the new residuals. Shift position again if necessary.

The alignment algorithm above is an iterative process and demands computational time. Residuals of about one millimeter would be a good result. More alignment algorithms

Figure 34 – Planes alignment check for X-coordinate (top) and Y-coordinate (bottom).

Source: By the author

could be also implemented, for example, to align the azimuthal and zenithal angles of the surface of the planes. However this is not necessary here.

The results of the first alignment check is shown in Fig. 34. The planes are already very well aligned since no mean residual is larger than 5 mm. As the planes are already well aligned, just one correction was necessary to bring the residuals to about 1 mm, as shown in Fig. 35. The equations shown in this section were used in the alignment check and also for the event reconstruction.

5.2.2 Events arrival direction

The events are reconstructed by fitting a line through the four (X, Y) hit points in the telescope planes.

For each event, a 3D line was fitted by a χ^2 minimization joining the (X, Y) coordinates from the 4 planes together. The known Z-coordinate was used as free parameter as shown in Eq. 5.1:

$$\begin{aligned} X &= a.Z + b, \\ Y &= a.Z + b. \end{aligned} \tag{5.1}$$

A vector $\vec{d}$ is defined as the difference between a data point and its theoretical

Figure 35 – Planes alignment check for X-coordinate (top) and Y-coordinate (bottom) after first correction based on the residuals.

Source: By the author

point for each plane:

$$\begin{aligned}\vec{d} &= \vec{r}_{data} - \vec{r}_{th.}, \\ \vec{r}_{data} &= (X_{data}, Y_{data}), \\ \vec{r}_{th.} &= (X_{th.}, Y_{th.}).\end{aligned}\tag{5.2}$$

The errors of the X and Y-coordinates were then projected in the direction of $\vec{d}$ to find the total error for the points:

$$\sigma_{\vec{data}} = \frac{\vec{\sigma}_x \cdot \vec{d}}{|\vec{d}|} + \frac{\vec{\sigma}_y \cdot \vec{d}}{|\vec{d}|}.\tag{5.3}$$

A χ^2 for the line fitting was defined as:

$$\chi^2 = \sum_{n=1}^{n=4} \frac{|\vec{r}_{data,n} - \vec{r}_{th.,n}|}{|\sigma_{\vec{data},n}|}.\tag{5.4}$$

Fig. 36 shows the resulted χ^2 calculation for 441,111 number of events.

The maximum limit value for χ^2 is defined to be equal 5. The good events are then selected with $\chi^2 < 5$.

Figure 36 – Resulted χ^2 calculation for the incoming direction of 441,111 number of events.

Source: By the author

Fig. 37 shows the muon trajectory for a bad ($\chi^2 > 5$) and a good ($\chi^2 < 5$) reconstructed event.

The azimuthal angle ϕ and zenith angle θ were also derived (Eq. 5.5) from the line fitting according to the spherical coordinate system equations. The $\cos\theta$ term is used instead of θ because it is more suitable to work with:

$$\begin{aligned} \cos \theta &= \frac{|Z_2 - Z_1|}{r_{xyz}}, \\ \phi &= \arccos\left(\frac{X_2 - X_1}{r_{xy}}\right), \end{aligned} \quad (5.5)$$

where $r_{xyz} = |\vec{r}_{th,2} - \vec{r}_{th,1}|$ and $r_{xy} = |(X_{th,2}, Y_{th,2}) - (X_{th,1}, Y_{th,1})|$. The indexes 1 and 2 represent, respectively, the upper plane and the plane right underneath it. Since it is a fitted line, one can use any of the planes to calculate the angles. The ϕ angle must be then recalculated to fit to the right quadrant according to:

$$\begin{aligned} \phi' &= \phi, & \text{if } X_{th,1} - X_{th,2} > 0 \text{ and } Y_{th,1} - Y_{th,2} > 0, \\ \phi' &= \pi - \phi, & \text{if } X_{th,1} - X_{th,2} < 0 \text{ and } Y_{th,1} - Y_{th,2} > 0, \\ \phi' &= \pi + \phi, & \text{if } X_{th,1} - X_{th,2} < 0 \text{ and } Y_{th,1} - Y_{th,2} < 0, \\ \phi' &= 2\pi - \phi, & \text{if } X_{th,1} - X_{th,2} > 0 \text{ and } Y_{th,1} - Y_{th,2} < 0. \end{aligned} \quad (5.6)$$

Figure 37 – Y, X and Z positions hit in each detector plane. The full line shows the result of fitting a line to the data points.

Source: By the author

5.2.3 Telescope and MARTA relative position

As the ϕ and $\cos\theta$ angles are known for each event from Sec. 5.2.2, the hit positions on the MARTA plane ($Z = 1430$ mm) are calculated. In the MARTA plane analysis, it was considered events which triggered just a single pad at the time. Therefore, multiple events, heavier particles and triggered events with electron noise are mainly excluded.

To inspect the (X, Y) position of the pads in the same coordinate system as the telescope, the barycenter of all events was calculated for each pad. Fig. 38 shows the result.

In Fig. 38 one can especially notice the order in which the channels were assembled. Some channels are inverted with its pair, for example, the channels 17 and 19, probably due to a lack of attention during the assembly. It is also interesting how the distance between two pad centers in the vertical direction increases when it approaches a border. It happens because all the events which hit one of the border pads are inclined since the MARTA detector is larger than the telescope in this direction. The opposite happens in the other direction, i.e. the telescope is larger than the MARTA detector and this effect is not present. Furthermore, the last three channels (61-63) are turned off and recorded no data.

Fig. 38 plays a good role in determining the order of the channels, as explained before. However, it is not good for determining the relative position between the telescope

Figure 38 – Barycenter of all events in the MARTA plane for each pad.

Source: By the author

and MARTA detector because of the distance variation between the barycenters. Then, the following procedure was developed to calculate the relative position between the MARTA detector and the telescope:

- 1: Restrict the analysis in the four central pads (Ch. 27, 28, 35, 36) and for zenith angle smaller than 25 degrees to assure isotropic azimuthal incidence;
- 2: Calculate the barycenter of events in the four pads;
- 3: Verify that the differences in the X and Y-coordinate are approximately equal to the known physical dimensions of the pads (180 mm X 140 mm). If this is true, proceed to step four. If it is false, restrict the zenith angle even more;
- 4: Take the barycenter of all events in the condition established at step 1 and define it as the center of the MARTA detector;
- 5: Based on the pad dimension and on the 1 mm trail which separates one from the other, calculate the center of all pads in relation to the defined MARTA detector center.

Fig. 39 shows the result of the analysis above.

Figure 39 – Relative position between the MARTA detector and the telescope.

Source: By the author

It is seen in Fig. 39 that the MARTA plane and the telescope are not perfectly aligned in both directions, which is actually not a problem for the efficiency calculation.

5.2.4 Acceptance

One of the most important features of a particle detector is its acceptance. It depends on its geometrical format, its efficiency according to different regions and the propagation of the particle through it. (20) Fig. 40 shows a schema of the detector acceptance.

The primary cosmic ray arrive approximately isotropically at the top of Earth's atmosphere but the muon flux observed on surface, i.e. at sea level or at a certain altitude or depth from sea level has a known zenith angular dependence (see Eq. 2.12):

$$I(\cos(\theta)) = I_0 \cos^n \theta. \quad (5.7)$$

The exponent n depends on energy, latitude, and altitude. Its measured value is around two as shown in Table 2 for different experiments.

The detector signal is hence a combination of the incoming flux and the detector acceptance. For a solid angle bin Ω_i , the detector signal inside that bin is described by Eq.

Figure 40 – Schema of the detector differential acceptance, i.e. the representation of a $d\Omega = d\phi d\cos(\theta)$.

Source: Adapted from PAL (19)

5.8:

$$N_{bin,i} = \iint N_{detected}(\cos \theta, \phi) d\Omega = \iint I_0 \cos^n \theta \omega(\cos \theta, \phi) d\Omega, \quad (5.8)$$

where $N_{detected}(\cos \theta, \phi)$ is the function of number of events detected in a solid angle bin Ω_i , $N_{bin,i}$ is the number of events in that bin and $\omega(\cos \theta, \phi)$ is the differential acceptance of the detector, to be calculated.

The geometrical acceptance, i.e. the acceptance which only takes into account the detector geometry, is calculated through a Monte Carlo Simulation (MCS). Therefore, no analytical integral is needed. The MCS is developed according to the following procedure:

- 1 Generate isotropically a position (X_{top}, Y_{top}) on the upper plane. Generate also a $\cos(\theta) \in [0, 1]$ and the azimuthal angle $\phi \in [0, 2\pi]$;
- 2 Calculate the position (X_n, Y_n) for all other three planes;
- 3 Accept events which hit the detector on the lower plane;
- 4 Eliminate events which hit near the borders of all planes (100 mm for X and 30mm for Y);
- 5 The differential acceptance $d\omega$ is obtained numerically through a 2D histogram on ϕ X $\cos(\theta)$.

An exact calculation of the acceptance takes also into account the detector efficiency and the physical processes to which the particles are subjected. (20) The geometrical acceptance is through a good approximation for efficient detectors.

Once the acceptance is calculated, it should be inserted into Eq. 5.8. The muon flux depends only on $\cos\theta$, therefore, it is interesting to integrate the differential acceptance in ϕ to add up all the azimuthal angle contributions for each zenith angle $\cos\theta$ as shown in Eq. 5.9:

$$\omega_{\cos\theta}(\cos\theta) = \int \omega(\cos\theta, \phi) d\phi. \quad (5.9)$$

If the solid angle bin Ω_i is considered sufficiently small ($\Omega_i \approx d\Omega$) and the integrals from Eq. 5.8 and 5.9 may be removed:

$$N_{bin,i} = I_0 \cos^n \theta \omega_{\cos\theta}(\cos \theta). \quad (5.10)$$

The result from the Monte Carlo simulation for the acceptance must be normalized, because the number of simulated events and the area of the detector must be taken into account:

$$\lambda' = \frac{A}{N_{MC,simulated}}, \quad (5.11)$$

where A is the upper plane detector area, $N_{MC,simulated}$ is the number of events simulated in the upper plane. The normalization factor assures that, if the acceptance $\omega_{\cos\theta,0}(\cos\theta)$ is integrated (or in discrete analysis added up), the total acceptance is equal to $\frac{AN_{MC,triggered}}{N_{MC,simulated}}$, where $N_{MC,triggered}$ is the number of events that hit the bottom plane detector.

Once calculated, the normalization factor multiplies the acceptance obtained from the MC simulation to give the normalized acceptance $\omega_{\cos\theta,norm}(\cos\theta_i)$ in $\text{mm}^2.\text{sr}$. Then, the normalized acceptance is inserted in the right side of Eq. 5.10:

$$N_{bin,i}(\cos\theta_i) = I_0 \cos^n \theta_i \omega_{\cos\theta,norm}(\cos\theta_i). \quad (5.12)$$

The flux coefficients I_0 and n from Eq. 5.8 can be determined through the least square method using Eq. 5.12. The left side of Eq 5.12 is the detector signal for each $\cos\theta_i$ bin and the right side is the expected flux for the same bin ($I_0 \cos^n \theta_i$) multiplied by the normalized acceptance at that bin ($\omega_{\cos\theta,norm}(\cos\theta_i)$).

Figure 41 – Simulated XY-map of all good events in the four telescope planes with the respective number of events in each of them.

Source: By the author

After the coefficients determination, a normalization factor λ must also be defined (Eq. 5.13) to correct the integral intensity:

$$\lambda = \frac{A \cdot N_{in}}{N_{total}}, \quad (5.13)$$

where N_{total} is the number of simulated events on the upper plane from an incident flux proportional to the expected $\cos^2 \theta$; N_{in} is the number of events which hit the detector lower plane and A is the upper plane detector area.

With the calculated normalization factor, it is possible to determine the real integral muon flux (Eq. 5.14):

$$I_{0,integral} = \frac{I_0}{\varepsilon_{trigger} \cdot \varepsilon_{DAQ} \cdot \varepsilon_{selected} \cdot T_{total} \cdot \lambda} [mm^{-2}s^{-1}sr^{-1}], \quad (5.14)$$

where $\varepsilon_{trigger}$ is the trigger efficiency (not including DAQ dead time), ε_{DAQ} is the DAQ efficiency (including DAQ dead time), $\varepsilon_{selected}$ is the selected efficiency, i.e. the ratio of events from the dataset which were used in the analysis (excluding bad events which happen mainly due to multiple events together) and T_{total} is the total exposure time.

For simplicity, only the detector geometry is considered in the acceptance calculation, which is, in fact, a good approximation for efficient detectors. (20, 63)

Fig. 41 shows the resulted ϕ X $\cos \theta$ distribution.

Figure 42 – Acceptance dependence on $\cos\theta$ and the azimuthal angle ϕ . The dependence on ϕ is due to the different length in the X and Y-direction.

Source: By the author

The ϕ contribution is added up for each $\cos\theta$ bin to result in the $\cos\theta$ dependence acceptance $\omega_{\cos\theta}(\cos\theta)$. The opposite could also be done to result in the ϕ dependence acceptance $\omega_{\phi}(\phi)$.

In order to obtain a real acceptance which does not depend on the number of simulated events, Eq. 5.10 must be multiplied by a factor given by Eq. 5.11 to yield $\omega_{\cos\theta, \text{norm}}(\cos\theta)$. The resulted dependence on ϕ and $\cos\theta$ is shown in Fig. 42.

The total angular acceptance, i.e. the number of accepted events divided by the number of simulated events are 15.2%. The angular acceptance is then multiplied by the detector area ($1900 \times 420 \text{ mm}^2$) to yield the total acceptance $\Omega = 0.122 \text{ m}^2.\text{sr}$.

5.3 Results

In this section, it is shown the results of the data analysis for the MARTA prototype and the telescope at LIP-Coimbra. Directional maps are shown and the muon flux coefficients are calculated.

Figure 43 – Relative position between the MARTA detector and the telescope.

Source: By the author

5.3.1 MARTA efficiency

Fig. 43 shows the maps of all event positions in each pad. Each histogram does not represent the pad itself but the pad and its nearby region. Sometimes an event hits one pad but triggers a nearby pad due to induction or crosstalk. The safeguards shadow are seen between the pads (ground trail between pads). The events on every pad are concentrated in their respective centers as expected if one thinks about a pad acceptance.

The number of events in each pad is calculated and shown in Fig. 44. One can notice a larger number of events at the center due to the larger acceptance in this region. The relative position between the plane of pads and the telescope also plays a role.

The efficiency of the pads was calculated as shown in Sec. 4.5.3, i.e. by counting how many times the MARTA detector shows a signal whenever the telescope is triggered. In this calculation, it was considered only the good events. In a good event, the pad under analysis must be triggered and the calculated position must be within it or within one of the neighbor pads (to consider cross-talks and uncertainties in the position calculation). For the border pads, which have no neighbor pad in one direction, events with calculated position one pad length outside the detector and which triggered the nearest border pad are also considered good events. Fig. 45 shows the efficiency of the pads. The efficiencies

Figure 44 – Number of events per pad.

Source: By the author

are around 88%. This percentage is the same ratio between the sensible area and total area of the detector. The dead area is due to the presence of safeguards rings which separates one pad from another. Events which hit the safeguards may have its position calculated as a good event but do not trigger a pad, unless the muon energy is very high. In this case, even if the muon hits the safeguard region, it may have sufficient energy to induce a charge in the nearest pad.

5.3.2 Direction maps

A region of size $X = 100$ mm and $Y = 30$ mm from each side of the planes was excluded from the calculations to prevent border effects such as the stronger signal because of the larger strip area exposed to the incoming particles.

The ϕ X $\cos\theta$ distribution map is shown in Fig. 46.

Fig. 47 shows the XY-map of all good events for the four planes. Note that the central dead strip in the two lower planes.

It is also interesting to build a sky map ($\sin\theta \cos\phi$ X $\sin\theta \sin\phi$) from the data, i.e. to project the incoming particle directions on the horizontal plane. Fig. 48 shows the sky map. The most intense incoming direction is a little shifted from the vertical one.

A good and effective way to analyze the results for the XY event maps (Fig. 47) is

Figure 45 – Pad efficiencies for events with all incidence angles.

Source: By the author

Figure 46 – The $\phi \times \cos\theta$ distribution shows some regions with lack of events. Due to the different size length in the X and Y-direction (2000 mm X 450 mm), events with θ larger than a certain value do not hit all the four planes if they come from the Y-direction.

Source: By the author

Figure 47 – Data XY-map of all good events in the four telescope planes with the respective number of events in each of them.

Source: By the author

Figure 48 – Sky map for the good events in the dataset. It is the projection of the incoming direction on the horizontal plane.

Source: By the author

Figure 49 – The $\phi \times \cos\theta$ map for the $\cos^2\theta$ PDF incidence simulation.

Source: By the author

to simulate the expected detector signal and compare it with the data. An approach similar to the simulation developed for the acceptance is used. However, instead of a random incidence zenith angle, the event generator uses a $\cos^2\theta$ probability density function (PDF), which represents the expected flux. The $\phi \times \cos\theta$ map for the simulation is shown in Fig. 49. The shape of the regions with events are similar in comparison with the data $\phi \times \cos\theta$ map (Fig. 46). However, in the data map, there is a larger event concentration in the region where $\phi = 180^\circ$ while in the simulation map, the events are concentrated in the region where $\phi = 180^\circ$ and $\phi = 360^\circ$.

The sky map is also built for the simulation and it is shown in Fig. 50. A clear difference is shown in the region with the largest event concentration in comparison with Fig. 48. While the simulation shows the largest concentration area should be the vertical incidence, the data sky map shows a little shift to the left. This difference suggests there might be an influence of the site where the telescope is located on the measurement.

The XY-map for the simulated signal is also built and shown in Fig. 51 for all planes. The distribution is isotropic in each plane unlike the data XY-map (Fig. 47) which showed two brighter structures in the regions $X = 600$ mm and $X = 1000$ mm. This is another suggestion that the telescope site influences the measurements.

Motivated by the results from Fig. 47 and 48, which suggested an azimuthal influence on the incoming particle flux, the ϕ interval $[0, 2\pi]$ was divided into its four quadrants and the events from each quadrant were plotted separately. The same was done for the simulated events. Fig. 52 shows the result of the simulated events for different azimuthal regions in the upper plane.

The events in Fig. 52 are isotropically distributed with a slightly larger concentration

Figure 50 – Sky map for the good events on the $\cos^2(\theta)$ PDF incidence simulation. It is the projection of the incoming direction on the horizontal plane.

Source: By the author

Figure 51 – Simulated XY-map of all good events in the four telescope planes with the respective number of events in each of them.

Source: By the author

Figure 52 – Azimuthal dependence on the incidence muon flux on the upper plane for the $\cos^2\theta$ PDF simulation.

Source: By the author

at the center due to the detector acceptance. The number of events in each quadrant is very similar. The small differences arise due to the randomness of the event generation. The result is the same for all the planes.

Fig. 53 shows the events from the dataset according to different incidence azimuthal angle. The number of events from the quadrants is shown. The two quadrants where $\pi/2 < \phi < \pi$ and $\pi < \phi < 3\pi/2$ are the ones with the largest number of incident muons. As shown in Sec. 2.2, no muon flux dependence on the azimuthal angle is expected, which suggests an influence of the detector site on the measurements. The structures with two brighter regions in the X-axis ($X = 600$ and $X = 1000$) found in Fig. 47 are also found in the XY-maps for every azimuthal direction. It suggests the origin of these structures comes from above the detector in the vertical direction.

The same difference in the number of incoming muons is seen for the other three planes as shown in Fig. from 54 to 56.

From Fig. 54 to 56, it is seen that the brightest region shifts towards one of the plane edges as one looks to lower planes. It suggests that the most intense incidence direction is not the vertical one, as already shown in Fig. 48.

Motivated by this azimuthal difference in the muon flux, a muon tomography was calculated to try to obtain an image from inside the building. (18,64)

Figure 53 – Azimuthal dependence on the incidence muon flux on the upper plane for the reconstructed events.

Source: By the author

Figure 54 – Azimuthal dependence on the incidence muon flux on the second upper plane for the reconstructed events.

Source: By the author

Figure 55 – Azimuthal dependence on the incidence muon flux on the third upper plane for the reconstructed events.

Source: By the author

Figure 56 – Azimuthal dependence on the incidence muon flux on the fourth upper plane for the reconstructed events.

Source: By the author

Figure 57 – Muon tomography of inside the building where the telescope is located. The image is the projection of the incoming direction on the ground plane.

Source: By the author

The muon tomography is built simply by dividing the image from the data sky map (Fig. 48) by the simulation sky map (Fig. 50). Both images were previously properly normalized. The resulted image is shown in Fig. 57.

Besides the brightest region in the lower part of Fig. 57, i.e. in the horizontal direction, a bright spot is notable on the left side (second and third quadrants), pointing toward one of the exits of the building. Fig 58 shows the tomography superposed with the geometry of the building. The superposition shows that the direction of the bright regions in the tomography come from regions with less matter to be traversed.

5.3.3 Coefficients determination

The calculation developed in Sec. 5.2.4 for the coefficients determination, the results for the acceptance and the data from the telescope were used to estimate the n and $I_{0,normalized}$ coefficients. Fig. 59 shows the results of the flux estimation. The curves are both normalized to one to be compared with one another. As expected, $n = 2$ for the simulated signal. However, $n > 2$ for the data analysis. By inspection of Fig. 59, the data curve at $\cos \theta = 1$ is above the simulated one, which suggests that there is a lack of inclined events on the dataset.

It is known from Machado (63) that the DAQ resolution is of the order of 100 ps. It is also known from Fig. 33 that the counting rate is of the order of five events per second. Therefore, the DAQ efficiency should be considered 1. The selection efficiency is about 40%, and the trigger efficiency unknown, once there was no access to the raw data. It is then considered here as equal 1. The total area of the detector excludes the borders and it is equal to 798,000 mm². The total acquisition time was 87026 s. Based on Eq. 5.13, the

Figure 58 – Superposition of the schema of the building geometry and the resulted tomography.

Source: By the author

Figure 59 – Zenith angular dependence of the incident muon flux for the data (red) and for the simulation (blue). The difference between them is shown in green. The dashed lines are the fitting functions.

Source: By the author

integral muon incidence is equal to $1.6 \cdot 10^{-5} \cdot \text{mm}^{-2} \cdot \text{sr}^{-1} \cdot \text{s}^{-1}$ which is smaller but has the same order of magnitude as the other experiments of Table 2.

The lack of events is due to the muon absorption by the building. The calculated value for the integral muon flux is about 23% of the values from Table 2. An estimation was made to check if the difference could be indeed caused by the absorption. Eq. 2.8 was integrated in energy and in the solid angle to give the flux at the surface and after the passage through matter:

$$I_\mu \approx 2\pi \int_{E_{min}}^{\infty} \int_0^{70\pi/180} \frac{0.14 \sin \theta E^{-2.7}}{\text{cm}^2 \cdot \text{s} \cdot \text{sr} \cdot \text{GeV}} \left\{ \frac{1}{1 + \frac{1.1 E_\mu \cos \theta}{115 \text{ GeV}}} + \frac{0.054}{1 + \frac{1.1 E_\mu \cos \theta}{850 \text{ GeV}}} \right\} d\theta dE_\mu, \quad (5.15)$$

where the lower limit of the integral is the cutoff (minimum trigger) energy $E_{min} = E_{\mu, \text{cutoff}}$ for the surface flux and is the cutoff energy plus the energy loss in the rock $E_{min} = E_{\mu, \text{cutoff}} + E_{\mu, \text{loss}}$ for the underground flux. The upper limit of integral in θ is the limit of validity of Eq. 2.8. There is no information loss in its use because this value is also the detector acceptance limit angle.

In this estimation, two values must be given: the mean quantity of matter traversed by the muons and the cutoff energy $E_{\mu, \text{cutoff}}$. In general, inclined muons traverse less matter than vertical muons because of the absorption by the building. The muons coming from the atrium traverse almost no matter from the building. Moreover, the muons coming from the direction of the 5-floor region of the building traverse less matter than the muons coming from the direction of the 6-floor region. Despite these differences, and for simplicity, it was assumed that the muons coming from every direction traverse approximately four meters of rock (2.6 g/cm^3), which yields $X=1040 \text{ g/cm}^2$.

The energy loss $E_{\mu, \text{loss}}$ is calculated through Eq. 2.13 and the cutoff energy $E_{\mu, \text{cutoff}}$ is found to be $\sim 1.5 \text{ GeV}$ in order that the relation $I_{\mu, \text{underground}}/I_{\mu, \text{surface}} \approx 23\%$. Another values for the amount of traversed matter and the cutoff energy are shown in Fig. 60 for the same relation of absorption.

This is an estimation and there are uncertainties in the input values. The Gaisser parametrization (Eq. 2.8) for the muon spectrum is only valid for $E_\mu > 100 \text{ GeV}/\cos \theta$. However, it might be concluded that the difference in the observed flux is actually due to the muon absorption.

The muon flux coefficients (from Eq. 5.8) were also calculated separately for the four azimuthal incoming regions and shown in Fig. 61. The region which is closest to the real flux ($n = 2$) is where $90^\circ < \phi < 180^\circ$ (second quadrant). It is the same region where the brightest spot appeared in Fig. 57. The simulated flux (blue in Fig. 61) must always show the coefficient $n = 2$. Although, as the total flux was divided into four quadrants, there is not enough statistics and a simulation with more events would be demanded.

Figure 60 – Different amounts of traversed matter and cutoff energies yield the same absorption of 77%.

Source: By the author

Figure 61 – Angular dependence of the incident muon flux for the data (red) and simulation (blue). The differences between them are shown in green. The dashed lines are the fitting functions. Top: $0 < \phi < \pi/2$ and $\pi/2 < \phi < \pi$. Bottom: $\pi < \phi < 3\pi/2$ and $3\pi/2 < \phi < 2\pi$.

Source: By the author

All evidence point to the fact that the muon incidence is not isotropic in the azimuthal plane, which is definitely not a physical phenomenon. The building where the telescope is located has proven to have enough matter to block about 77% of the incidence muons.

6 CONCLUSIONS

The project covered two different areas: instrumentation and data analysis. The instrumentation includes the CAD drawing, the aluminum box production, and the RPC assembly. The data analysis includes the MARTA prototype efficiency calculation, the direction maps, and the muon flux estimation.

During the instrumentation phase of the project, there was a close collaboration with the researchers at LIP, in Portugal, which was crucial for the detector assembly. Although not all the RPCs were finished by the time of this writing, it was proven that they are robust, relatively cheap and can operate for a long time without intervention. It is planned that by the end of 2018 some RPCs assembled at USP, São Carlos will be already at the observatory site, in Argentina.

As the RPCs in São Carlos were yet not able, until the time of this writing, to detect events in coincidence, a flux and efficiency analysis was not possible. Alternatively, data from the RPCs in Portugal was used to calculate the MARTA prototype efficiency to muons, to build direction maps and to estimate the muon flux coefficients. The MARTA prototype, which is identical to the ones used in São Carlos, demonstrated a very satisfactory efficiency of approximately 88% for all pads. The inefficiency is actually mostly due to the safeguards, i.e. the trail which separates the pads rather than the detector itself. Therefore, it was demonstrated the feasibility of this kind of gaseous detectors for astroparticle physics experiments. It is expected that the use of the RPCs in other particle and astrophysics experiments grows within the next years.

Different direction maps were built for the simulation and for the data to investigate the muon incidence angle: $x \times y$, $\cos \theta \times \phi$ and $\sin \theta \cdot \cos \phi \times \sin \theta \cdot \sin \phi$. A muon tomography map was also built using both the simulation and the data maps. All of them showed some structures in the data maps that were not present in the simulation ones. The zenith angle dependence was studied for the expected flux simulation and for the data. Though the simulation showed a dependence of the zenith angle on a square of cosine, the data showed a dependence, which was also a function of the azimuthal angle.

It was concluded that the differences between simulation and data in the direction maps and in the flux estimation are due to the muon absorption by the building. An estimative of the total muon flux confirms the hypothesis. Though the expected flux is about $7.1 \cdot 10^{-5} \text{ mm}^{-2} \cdot \text{sr}^{-1} \cdot \text{s}^{-1}$ the calculated flux was $1.6 \cdot 10^{-5} \text{ mm}^{-2} \cdot \text{sr}^{-1} \cdot \text{s}^{-1}$. There are uncertainties in the estimation, for example, the trigger efficiency was assumed to be 100%, but an absorption of about 77% of the expected muon flux is found and could not be explained by the uncertainties. In order to explain this absorption, a last estimative was

made by integrating the muon spectrum given by the Gaisser parametrization (Eq. 2.8) through the whole detector solid angle. The amount of matter from the building traversed by the muons was considered to be equal to four meters of rock (density = 2.6 g/cm^3) and the detector cutoff energy was considered to be 1.5 GeV in order to the resulted integrated flux to be approximately equal $1.6 \cdot 10^{-5} \text{ mm}^{-2} \cdot \text{sr}^{-1} \cdot \text{s}^{-1}$. This estimation uses the Gaisser parametrization out of its validity ($E > 100 \text{ GeV}/\cos\theta$) and should just give an idea of the amount of matter transversed by the muons.

The telescope in Coimbra was built to be used in other detectors efficiency tests. The building where the telescope is located is not a problem for these tests since the trigger is defined by the four planes within the building. However, it was shown by this dissertation that the building has enough matter above and around the detector to influence the muon flux. If further studies of the muon flux using the telescope were demanded, a Monte Carlo simulation considering the detailed building structure would be needed. As an alternative, the telescope could be placed outside the building.

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Appendix

APPENDIX A – RPCS ASSEMBLY MANUAL

The RPCs to be installed in the Pierre Auger Observatory are a 1 mm double-gap RPC made by three 2 mm thick glass plates of an active area of 1200 X 1500 mm² each. The glass electrodes are separated by Nylon monofilaments and closed inside a permanently glued acrylic box. The high voltage is applied through the external plates acrylic painting ($1 - 10 \times 10^7 \Omega \text{sq}$). This sensible volume is placed inside an aluminum shielding box. The signal is taken from the 64 (8 x 8) pick-up electrodes of 180 X 140 mm² which are placed on the sensible volume. The box is covered by an aluminum plate and the electronics are placed in a smaller closed aluminum box. The RPC has an area of 1760 X 1285 mm², it is 25.4 mm thick in the region of the sensible volume and 60.3 mm thick in the region of the smaller box. The design is an adaptation of Lopes (51) to the Brazilian standard measurements and is shown in Fig. 62.

The freon R-134a (pure tetrafluoroethane) was chosen to be used as the ionizing gas. The reason for this choice is the low price, non-inflammability and as it is used as a refrigerator gas it can be found overall. According to Lopes,(51) this design assures efficiency above 90% and time resolution around 300 ps σ .

The MIPs signal is obtained through coaxial cables. The inner connector is welded in the center of each pad and the outer mesh is riveted in the aluminum box which works as the ground. The Data Acquisition (DAQ) is based on an Application-Specific Integrated Circuit (ASIC) of type Multi-Anode Read Out Chip (MAROC3) (65)) coupled to Field-Programmable Gate Arrays (FPGAs). The MAROC is connected to the 2-folded 32 channels readout via a mezzanine board to which the cables are welded. Fig. 63 shows the DAQ and MAROC. (9)

To be able to control the variables to which the RPC is exposed, five temperature, one temperature-humidity sensor (SHT21) and one temperature-pressure-humidity sensor were distributed through the RPC. A system of bubblers based on vaseline which is able to measure separately the gas flux in the sensible volume, in the aluminum box, and in the smaller aluminum box was developed by LIP (Coimbra) and integrated to the RPC design. The high voltage power supply used is the CAEN N471A. Small PCBs to control the bubblers and to distribute the power supply were also developed by LIP collaborators and integrated to the RPC design. A multiplexer and a Raspberry (model B+V1) controller for each RPC were used during the indoor tests.

A.1 Construction and assembly

Once the parts are ready, the assembly is basically divided into the following steps:

Figure 62 – Above: the RPC design in layers: (A) the aluminum box base, (B) the sensible volume composed by the glass plates, Nylon monofilaments and acrylic box, (C) the printed circuit board (PCB) composed by the pick-up copper electrodes, (D) the aluminum box cover, (E) delimitations of the aluminum smaller box "Puxadinho", (F) smaller box cover; Below: the closed and ready for use RPC design.

Source: By the author; LOPES (51)

1. Integration Aluminum box – sensible volume,
2. Gas and HV connections,
3. Pick-up pads preparation,
4. Integration Aluminum box – PCB,
5. Sensor positioning,
6. Electronics connections.

In the integration of the aluminum box and the sensible volume, the sensible volume is carefully placed and glued with Pufix (polyurethane polymer) inside the aluminum box.

Figure 63 – Left: The MARTA DAQ with its components. Right: MARTA DAQ Schema

Source: ABREU (9)

Figure 64 – Integration of the sensible volume with the aluminum box.

Source: By the author

The gas and the HV connectors are glued with Araldite into the aluminum bar and the gas tubes are placed in the inlet and outlet of the sensible volume as shown in Fig. 65.

The gas cylinder is connected to the pressure reducer and gas distributor. One cylinder is supposed to supply gas for four RPCs. There are three gas isolated regions in a single RPC: the sensible volume, the aluminum box which encloses the sensible volume and the smaller aluminum box ("Puxadinho") which encloses the electronics. Through the bubblers it is possible to verify the gas flux in each region. The gas circuit is made according to the schema in Fig. 66.

The pick-up pads are prepared first by welding a $100\text{ M}\Omega$ s between each pad and the trail between them. Then the inner connector of a coaxial cable is welded in each

Figure 65 – Left: Gas tube connection in the sensible volume inlet. Right: HV and gas connectors in the aluminum bar.

Source: By the author

Figure 66 – Gas circuit showing the gas separated regions (sensible volume, aluminum box and smaller box "Puxadinho"); the gas flows from the cylinder to the distributor, which distributes the gas through four RPCs; in each RPC the gas enters the sensible volume, flows to the aluminum box, then to the Puxadinho and finally leaves the RPC through the Bubbler 4; the Bubbler 1 prevents over-pressure, the Bubbler 2 gives the gas flux of the sensible volume, and the Bubbler 3 the gas flux of the aluminum box.

Source: By the author

pad center and the outer mesh is welded in the trail. The pads and the feedthrough PCB inputs are accordingly enumerated. The pad resistance must be checked with a multimeter.

The cables are organized in the Puxadinho direction and then a foam sheet is placed over the PCB. Fig. 67 shows the preparation of the pick-up pads.

Figure 67 – Preparation of the pick-up pads.

Source: By the author

The PCB is placed on the sensible volume and the cables organized to pass through the feedthrough bar according to the enumeration defined before. The outer mesh of each cable must be welded in the copper face of the small feedthrough PCB. The bar is then connected and glued delineating the aluminum box region as shown in Fig. 68.

Figure 68 – Aluminum box and PCB integration showing the cables passing through the feedthrough bar; the box lid is connected to avoid expansion of the acrylic sealing of the sensible volume.

Source: By the author

The HV filter cables are passed through their connectors and the ground welded on the bar. The other part of the filter is welded in the HV source as shown in Fig. 69.

All the bars and the gas tubes inside the box are glued with Pufix in order to roughly seal the box.

The sensors are placed on copper sheets in determined positions shown in the schema of Fig. 70, where the yellow rectangles represent the temperature sensors, the blue one represents the humidity-temperature (UT) sensor and the brown one represents the humidity-temperature-pressure (UTP) sensor.

Figure 69 – HV filter connection

Source: By the author

Figure 70 – Sensors positioning schema

Source: By the author

There are two different I2C protocol buses to transmit the data from the sensors: the first one consists of the temperature sensors numbered from 2 to 6 and the other one consists of the UT and UTP sensors. In each sensor, the I2C protocol cable is properly welded and closed with a copper sheet in a Faraday cage. A small cut on the copper sheet in the region of the sensible part of each sensor must be made to expose it as shown in Fig. 71.

Figure 71 – Sensor assembly as a Faraday cage.

Source: By the author

Once all the sensor are placed in position and the I2C protocol cables are passed through the feedthrough, the detector is covered with a foam sheet and the feedthrough is glued with Pufix in order to stanch the aluminum box region as shown in Fig. 72.

Figure 72 – The region of the feedthrough glued with Pufix.

Source: By the author

The box lid is screwed and the DAQ is fixed in a small aluminum plate. The pad cables are welded according to Fig. 73, where IN stands for Input. Fig. 74 shows the welding completed.

RJ45 connectors with a metallic shield are fixed in both sensor cables which are then connected to the multiplexer. A third bus consisting of the pressure sensor installed after the reducer and seven temperature sensors is also built and connected to the multiplexer. The electronics for an RPC to be tested indoors are composed by the main power supply, the multiplexer, the bubbler controllers, the Raspberry, the DAQ (including the MAROC) and the HV source. They are connected according to the schema of Fig. 75 (top) and are shown in Fig. 75 (bottom).

IN 12	IN 16	IN 20	IN 24	IN 32	IN 52	IN 56	IN 60
IN 0	IN 4	IN 8	IN 25	IN 33	IN 40	IN 44	IN 48
IN 13	IN 17	IN 21	IN 26	IN 34	IN 53	IN 57	IN 61
IN 1	IN 5	IN 9	IN 27	IN 35	IN 41	IN 45	IN 49
IN 14	IN 18	IN 22	IN 28	IN 36	IN 54	IN 58	IN 62
IN 2	IN 6	IN 10	IN 29	IN 37	IN 42	IN 46	IN 50
IN 15	IN 19	IN 23	IN 30	IN 38	IN 55	IN 59	IN 63
IN 3	IN 7	IN 11	IN 31	IN 39	IN 43	IN 47	IN 51

 gas
 connectors

Figure 73 – Defined correlation between the DAQ input channels and the respective pads.

Source: By the author

In order to test the communication, the multiplexer must be turned on first and then the Raspberry. The link between the Raspberry and the local PC is established through an ssh command. A C++ script is responsible for validating the communication. Once the communication is validated, the box lid and the other bars must be connected and glued with Pufix. The bubblers must also be fixed in the frontal bar.

A.2 Systems tests

The first tests consist on checking the functionality of the high-voltage source, the sensors, the bubblers and the data acquisition.

To be able to test the high voltage source, one must connect to the Raspberry and read the HV status through the command "watch -n 0.33 ./hv -b 0", where -b 0 is the source bus, 0.33 is the acquisition time interval. Fig. 76 shows the result of an RPC in a case where the HV was already applied.

Figure 74 – DAQ with 64 input cables.

Source: By the author

The gas must be already flowing for a while before turning on the HV. In order to do it, the command `./hv -b 0 -V 1.8 -I 1.0 -on` is used, where 1.8 kV is applied between the plates limited by a current of $1\ \mu\text{A}$. The system protects itself from high currents which would damage the detector using automatically a voltage increase ramp according to the limiting current. All the data are saved in a log and the user may also check them life through a "tail" command.

To turn off the HV, the command `./hv -b 0 -off` is used.

The RPC goes initially through a commissioning period, where the gas volume is renewed decreasing relative humidity. This period lasts around 20 days. (47) During this phase, the high voltage should be increased in steps of 500 V limiting the current in $1\ \mu\text{A}$. The voltage should be increased each time the current reaches the level of 500 nA until the operation voltage of 5400 V.

The bubblers and the detector temperature, humidity and pressure sensors data are saved each minute automatically in two separated log files. Two different systems count the bubbles independently: an optical system based on a LED and a photodiode which is sensitive to variations of the refraction index; and a system based on a pressure sensor. To read them, one can use the "tail command", for example, `tail -f Bub_2017-04-04.log`. The result is shown in Fig. 77.

Figure 75 – Top: Electronics connections schema discriminating the cables/connectors; a 12V external source and the local PC with an ethernet and USB connections are also shown; Bottom: Electronic connections for the first assembled RPC.

Source: By the author

The data from the third bus (gas cylinder) is read, for example, by the command "tail -f Bot_2017-04-04.log". Fig. 78 shows the result.

The bubbler optical system must be calibrated at the beginning without gas flow through the command "Calibrate.py 3", where the number three indicates the bubbler 3 (smaller box Puxadinho outlet). One must also count the bubbles for one minute and then compare with the optical system readout. If there are many bubbles per second, the optical system may fail to count bubbles. In this case, one should change the time interval in which the system counts one bubble, for example through the command "set Time.py 1".

Once the conditioning period is over, the RPC can be used as a particle detector. To take data, one should directly or via ssh command access the local computer and run the software "Marta", give the MAROC board number and the number of events the

```

hv@raspberrypi: ~/i2c-system/bin
Every 0.3s: ./hv -b 0
Tue Apr  4 17:24:58 2017

Versão 2016-09-28
-----MAC-----
:00:1E:C0:8A:C9:4D
-----ADC-----
IHVp: 0.934 uA
IHVn: 0.940 uA
VHVn: 1.828 kV
VHVp: 1.819 kV
VHVs: 1.318 nA
Vpwr: 0.832 V
Vset: 1.800 kV
Ilim: 0.998 uA
-----DAC-----
Vset: 1.800 kV
Ilim: 1.000 uA
-----IO-----
Ipos : 0
Ineg : 0
Vctr : 1
HVon  : 0
PGood: 1
HVon  : 1

```

Figure 76 – Window shown after the "HV watch command"; $IHVp$ (kV) is the positive current(μA), $IHVn$ (μA) the negative current, $VHVn$ (kV) the negative voltage, $VHVp$ (kV) the positive voltage, $VHVs$ (nA) and $Vpwr$ (V) are control variables, $Vset$ (kV) the set output voltage, $Ilim$ (μA) the maximum allowed current, $PGood$ the detector health, $HVon$ the HV status on/off

Source: By the author

```

hv@raspberrypi: ~/bottle/logs
2017-04-04T22:07:02.904060;0.084;54.0;24.5;24.5;24.0;24.1;24.0;24.0;23.7
2017-04-04T22:08:02.938261;0.079;54.0;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:09:03.052410;0.083;54.0;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:10:03.130441;0.084;53.8;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:11:03.237110;0.083;53.9;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:12:03.331495;0.084;53.8;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:13:03.320135;0.084;53.7;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:14:03.403386;0.084;53.7;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:15:02.416805;0.084;53.7;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:16:02.524828;0.082;53.6;24.4;24.5;24.0;24.0;24.0;24.0;23.7
^C
hv@raspberrypi: ~/bottle/logs $ tail -f Bot_2017-04-04.log
2017-04-04T22:07:02.904060;0.084;54.0;24.5;24.5;24.0;24.1;24.0;24.0;23.7
2017-04-04T22:08:02.938261;0.079;54.0;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:09:03.052410;0.083;54.0;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:10:03.130441;0.084;53.8;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:11:03.237110;0.083;53.9;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:12:03.331495;0.084;53.8;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:13:03.320135;0.084;53.7;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:14:03.403386;0.084;53.7;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:15:02.416805;0.084;53.7;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:16:02.524828;0.082;53.6;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:17:02.618917;0.083;53.5;24.5;24.5;24.0;24.0;24.0;23.9;23.7

```

Figure 77 – Reading the bubbler systems: Date; number of bubbles per minute in bubbler 1 (sensible volume outlet) through the pressure sensor based system, through the optical system; bubbler 1 temperature($^{\circ}C$), relative humidity; number of bubbles per minute in bubbler 2 (aluminum box outlet) through the pressure sensor based system, through the optical system; bubbler 2 temperature($^{\circ}C$), relative humidity; number of bubbles per minute in bubbler 3 (smaller aluminum box Puxadinho outlet) through the pressure sensor based system, through the optical system; bubbler 3 temperature ($^{\circ}C$) and relative humidity

Source: By the author

```

hv@raspberrypi ~/bottle/logs
2017-04-04T22:07:02.904060;0.084;54.0;24.5;24.5;24.0;24.1;24.0;24.0;23.7
2017-04-04T22:08:02.938261;0.079;54.0;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:09:03.052410;0.083;54.0;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:10:03.130441;0.084;53.8;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:11:03.237110;0.083;53.9;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:12:03.331495;0.084;53.8;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:13:03.320135;0.084;53.7;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:14:03.403386;0.084;53.7;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:15:02.416805;0.084;53.7;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:16:02.524828;0.082;53.6;24.4;24.5;24.0;24.0;24.0;24.0;23.7
^C
hv@raspberrypi ~/bottle/logs $ tail -f Bot_2017-04-04.log
2017-04-04T22:07:02.904060;0.084;54.0;24.5;24.5;24.0;24.1;24.0;24.0;23.7
2017-04-04T22:08:02.938261;0.079;54.0;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:09:03.052410;0.083;54.0;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:10:03.130441;0.084;53.8;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:11:03.237110;0.083;53.9;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:12:03.331495;0.084;53.8;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:13:03.320135;0.084;53.7;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:14:03.403386;0.084;53.7;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:15:02.416805;0.084;53.7;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:16:02.524828;0.082;53.6;24.4;24.5;24.0;24.0;24.0;24.0;23.7
2017-04-04T22:17:02.618917;0.083;53.5;24.5;24.5;24.0;24.0;24.0;23.9;23.7

```

Figure 78 – Reading the cylinder sensors: Date; reducer pressure in mbar; relative humidity and seven temperatures in $^{\circ}C$ in different positions of the cylinder

Source: By the author

software should count. After the acquisition time, a histogram for each one of the 64 pads is shown in the window. The x-axis is the energy induced in the pad (in bins) and the y-axis the number of events for each energy interval. Fig. 79 shows the first histograms obtained by the first RPC still in the conditioning time for 10000 events.

Figure 79 – First spectrum in trigger mode showing a histogram for each one of the 64 pads; in the x-axis is the energy induced in the pad in bins and in the y-axis is the number of events within an energy interval.

Source: By the author

This mode of operation is called Trigger Mode in which the RPC operates by accumulating trigger signals. In this mode, every MIP which passes through the RPC generates charge which is added up over time. It is not possible to distinguish the direction and the kind of incoming particle.