Development of a telescope for cosmic muon flux and density measurements

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Abstract

As a student in Particle Physics, I want to build a compact telescope based on small and gas-tight Glass Resistive Gas Chambers ("mini-gRPC") in order to make a feasibility study of possible research of Mars geology. The first part of the project will be a simulation to optimize parameters for the detector conception. The second part will be the construction of a miniRPC prototype with the ideal parameters taken from simulation and some tests will be performed. As a matter of fact, first and second part will take place at Université Catholique de Louvain in Belgium during the semester. The third part will be the data collection and analysis by bringing the telescope to the Mars Desert Research Station (MDRS) in the Utah desert. The goal is then to make a study of the muon flux generated by interactions of primary cosmic rays and, if time allows,to proceed to a radiography or tomography (3D) of the landscape (mountains, hills, etc.) of the Utah desert with "muography", an imaging technique that relies on the measurement of the absorption of muons freely and abundantly produced by the interactions of cosmic rays with the atmosphere. This technique is very interesting for planets exploration because for example we could radiograph Mars and characterize its interior and tell about the planets evolutionary state and history and even find some places geologically well-adapted for future colonies implantation.

The compact detector size and the stability of its response make mini-gRPC an attractive choice with respect to other detectors previously employed for imaging on similar scales. An important innovation of our design is gas tightness: this will make the detector more "portable" and solve the usual safety and logistic issues for gas detectors.

1 Introduction

Next year is supposed to be my last year in physical science and I chose the development of detectors for muography as form of my master's thesis. It gave me an idea of experiment to perform "on Mars" and by discussing with some professors, I found what I could do. The experiment would consist of studying the flux of muons by means of a "mini-gRPC" that I would have previously built and developed in a laboratory at Université Catholique de Louvain (UCLouvain, Belgium) with the help of my supervisors, Andrea Giammanco and Eduardo Cortina. The muon is a an unstable particle from the lepton family like the electron but with a mass around 200 times greater. Muons generally come from the cosmic radiation reaching the earth's surface.

The reasons to use muography on Mars are multiple (Figure 1). Firstly, the fact that muons (which trigger the RPCs) are present in any atmosphere. Secondly, some research [11] shows that the muography technique is suitable for application on planetary bodies other than the Earth. Thirdly, by their nature, high energy muons can go through very thick rocks (Figure 2). Fourth, RPCs are passive detectors because they have lower power requirements, they naturally work with the energy deposit of the muons (radiation) contrary to active imagers (X-ray, radar, etc.). Finally a fifth reason would be that if this technique is applied to Mars bodies, it would be a big step for future space exploration missions in the Solar System. Indeed we could automatically radiograph the new planet and characterize its interior and tell about the planet's evolutionary state and history.[10]

2 Resistive plate chambers

2.1 Basic principle of operation

Developed in 1981 by R. Santonico and R. Cardarelli [9], resistive plate chambers (RPCs) [1] [13] are gaseous detectors that consist of two parallel plates of high

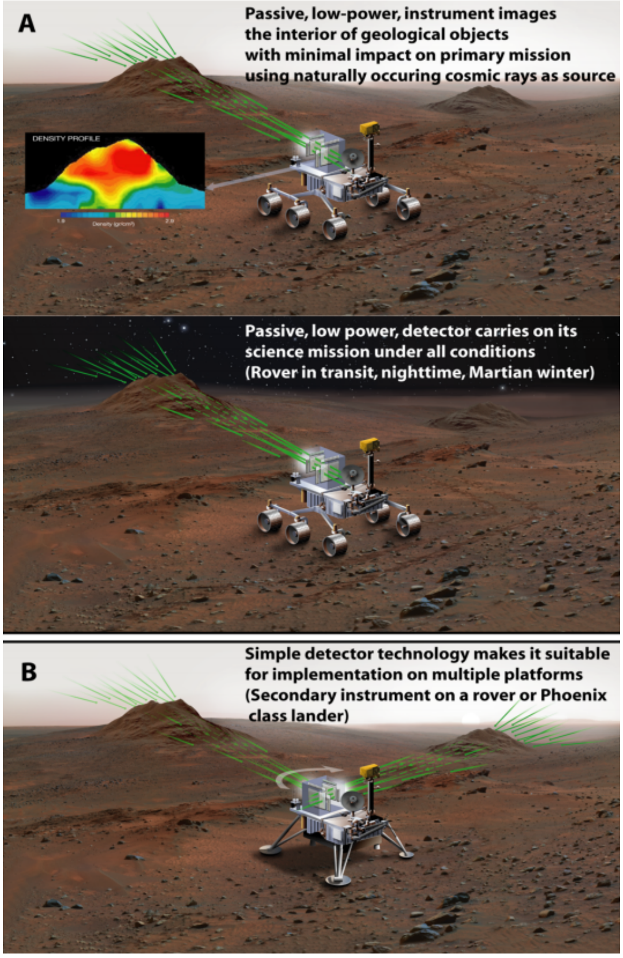


Figure 1: Operational concept of muography.[10]

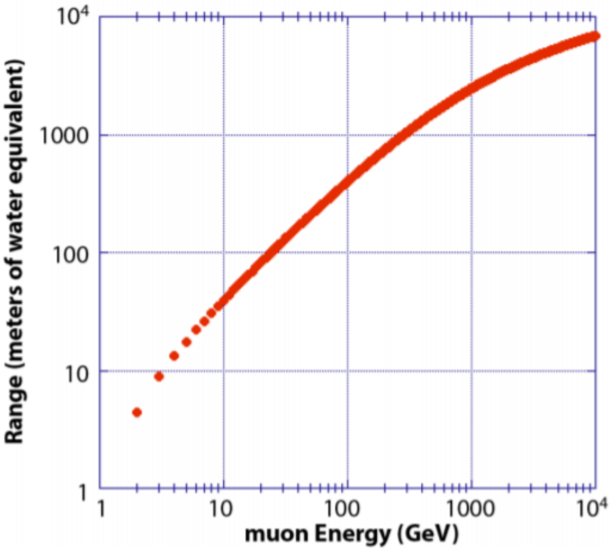


Figure 2: Muon range in standard rock underground on Earth as a function of muon, expressed in meters of water equivalent [8].

resistivity that act as a capacitor. Figure 3 gives a schematic view of an RPC. On the outside of these resistive plates a conductive coating is applied. By connecting one of these coatings to a negative high voltage (HV) source and grounding the other coating, the resistive plates become a cathode and an anode respectively. This results in an electric field across the gas gap. When an energetic charged particle, e.g. a muon, passes through the gas volume it ionizes the gas molecules and generates an ionising track according to the Bethe-Bloch formula for the working gas. This liberates free electrons and ions which are accelerated by the strong electric field towards the anode and the cathode respectively. On the way to the electrodes the ions and electrons can collide with other gas molecules and free other ion pairs if they have a sufficient kinetic energy. This threshold energy is the first ionization potential of the gas (depending on gas type and detector geometry). These newly formed ion pairs get accelerated and by hitting other gas molecules they can also form new ion pairs, making the effect stronger. This cascade of secondary ionizations results in an avalanche, which can be interpreted as an amplification of the original electron ion pair. It is called Townsend multiplication, i.e. on average every colliding electron liberates more electrons and an exponential growth of the number of free electrons occurs. This avalanche will induce a charge on the read-out strips and the charge constitutes the signal. When the electron avalanche reaches the anode this preludes the end of the useful signal. Because the electrodes are made out of resistive material the induced charge will not spread over the entire electrode and the position information of the events is not lost. The spot where the avalanche hits the RPC electrode is slowly recharged by a small current flowing through the electrode. The read-out strips in an RPC are put on the anode side and are separated from the resistive coating by an insulating material so that they are not electrically connected.

3 Project Plan : Things that should be done at UCL before the trip

3.1 Simulation

At the time of writing (Aug. 2017), my primary goal is simulation because I want to know which parameters are the best to optimise my detector (nature of the mixing gas, gap width, distance between consecutive detectors, etc.). Therefore I will write a program in *ROOT* [2] which is a modular scientific software framework. It provides all the functionalities needed to deal with big data processing, statistical analysis,

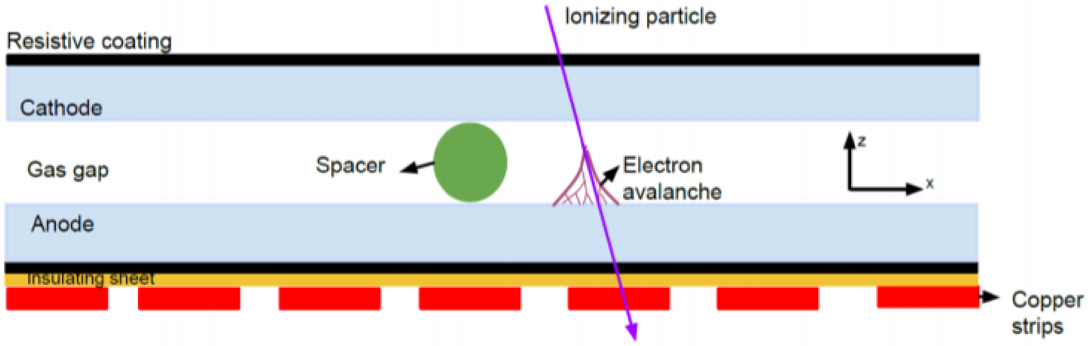


Figure 3: Schematic view of an RPC. An ionizing particle passes through the gas gap and an electron avalanche is initiated towards the anode.[3]

visualiation and storage. It is mainly written in C++ but integrated with other languages such as Python and R. With a program I will simulate my detector and I determine all its characteristics for its future construction.

The mechanism of signal formation in RPC is very simple and is applied in most gas-filled ion chambers, proportional counters and even in semi conductor detectors. Actually signals from detectors arise because of the motion of charge carriers after they are formed by the incident radiation.

Usually, to calculate the signal, we look at induced charge/current on electrodes due to the motion of charge carriers in a detector and we can calculate the signal thanks to the Shockley-Ramo Theorem [6] and the concepts of the weighting field and weighting potential. This theorem states that the instantaneous current induced on a given electrode is equal to

$$i(t) = q\overrightarrow{v} \cdot \overrightarrow{E_w} \tag{1}$$

where q is the charge of the carrier (electron/ion), $\overrightarrow{v}$ is its velocity, and $\overrightarrow{E_w}$ is called the weighting field which is the electrical field in the case of all the electrodes are connected to the ground except one which is connected to a delta potential. Here the velocity equals to $\overrightarrow{v} = \mu\overrightarrow{E}$ where μ is the mobility and $\overrightarrow{E}$ is the actual field of the detector ($= \frac{V}{d}$). However the weighting field equals to $\overrightarrow{E_w} = \frac{1}{d}$. We can calculate the weighting potential/field if we solved the Laplace equation :

$$\nabla^2\phi_w = 0 \tag{2}$$

$$E_w = -grad\phi_w \tag{3}$$

In fact a simulation program already exists but for silicon and diamond detectors, called $Weightfield2$. The program uses $GEANT4$ [12] libraries to simulate the energy released by an incoming particle in silicon or diamond, and Ramo's theorem to generate the induced signal current. There is also a graphical interface which allows to modify the parameters of the experiment.

For now, I simulated a simple ionizing chamber with charge particle which passed through the detector and created ions pairs that drift toward the electrodes and produce a current that we can measure. Fig. 4 illustrates my first simulation. My next goal is to simulate the muon passing through four RPCs consecutive by taking into account the angular distribution of cosmic muons coming in the acceptance of the detector.

Now the challenge is to improve this program to be able to face real situations. We could then make a study of time and space resolution, efficiency, acceptance, etc.

Figure 5 is a simple program that illustrates the configuration of the future detector. There will be four RPCs; two X & Y RPCs up and two X & Y RPCs down.By this way we obtain a real telescope and in terms of the distance between these RPCs planes, we will optimize the parameters to find the best trade-off between acceptance, efficiency and resolution.

3.2 Construction

I've already learnt to build a prototype of a single detector in Ghent (Belgium) during an internship in July 2017 . I write the procedure below [7]. My future miniRPCs built at UCL will be very similar except that we will start from a simple prototype composed of four planes of mini-gRPCs.

3.2.1 Glass cutting

Cutting of the glass was already done. In case we need to build more, we would have to cut glass plates in a square shape of 20x20 cm2 with a glass cutter. Of course, cleaning the glass is necessary and then we

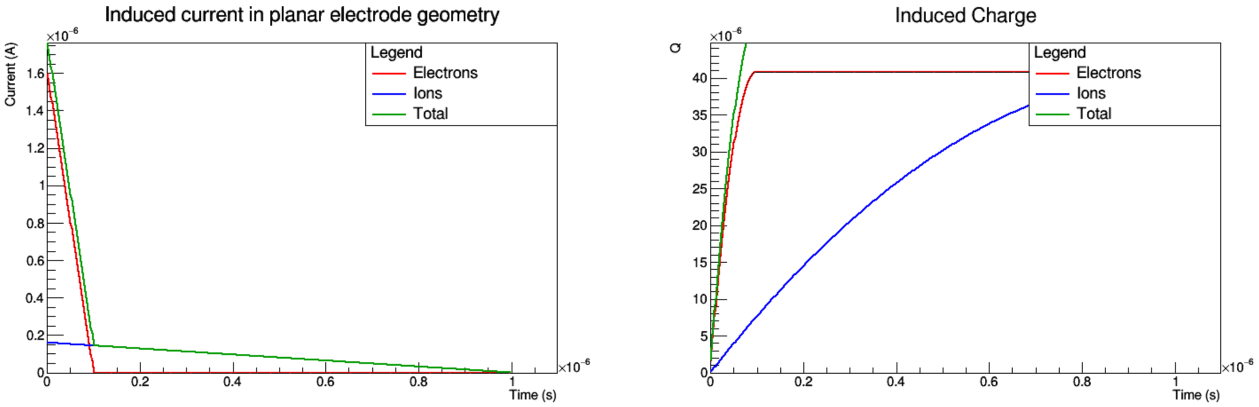


Figure 4: On the left : Induced current versus time (Shockley-Ramo's therorem). On the right : Accumulated charge on electrodes versus time.

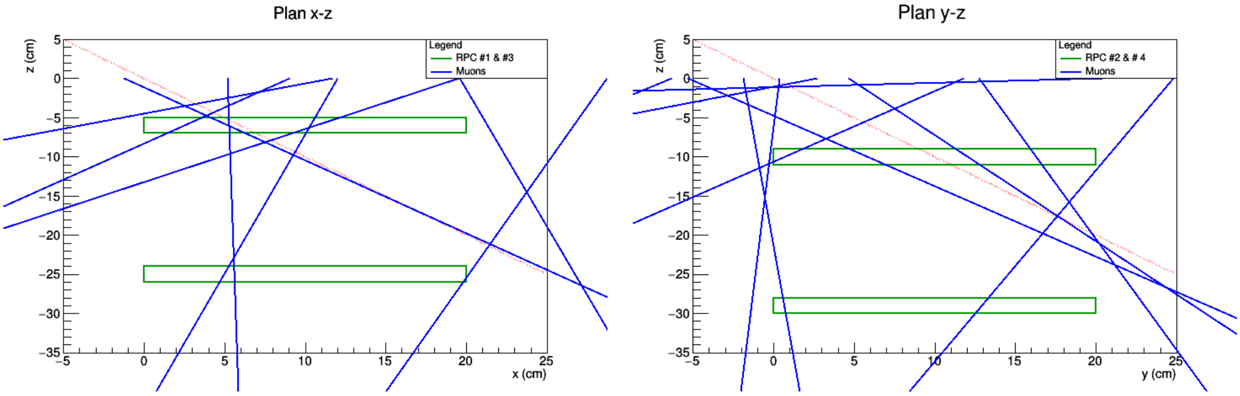


Figure 5: Simulation of muons passing through 4 RPCs in two different views.

can mark it to make the cutting more easy. The glass breaks along the marks by applying some pressure.

3.2.2 Resistive coating & resistivity measurement

Initially, the glass is a perfect insulator. We apply some paint to lower its resistivity, to uniformly spread the applied high voltage and to give to the electrodes a "capacitance" such that the gap can easily recharge after an ionizing event.

Before starting to paint, we have to clean the glasses with cleaning products and to paste them on a carton (like a mask) under a hood to prevent certain areas from being coated (areas for the edge spacers and gas connectors).

The mixture (half and half) is made of 3cc paint and methanol (which evaporates when it is painted). The paint consists out of *CPM10C Colloidal Dispersion* which comprises a colloidal dispersion of antimony-doped tin oxide in water - proportions of 20 of powder for 80 of water. A roller was used to apply a uniform coating to the plates. We can paint several glasses to make a comparison between them with regards to resistivity in order to choose the best resistive coating for our detector.

Measuring a sheet resistance has to be more elaborate than other measurements like measuring the resistance between two points. Indeed it not a one-dimensional path anymore, as the electrons have all possible paths to go accross a surface. The concentric ring probe (CRP - Figure 6) gives a solution to this problem. This probe consists of two concentric conductive ring-shaped pads between which the resistance is measured. Moreover it is loaded with a certain mass in order to give a better contact with the surface. We use a digital multimeter to read the measure in units of Ω (Ohm) and we multiply by 10 (correction factor given by the manufacturer).

We divide the glass plates in 9 spots like in figure 7 and take a measurement at each spot.

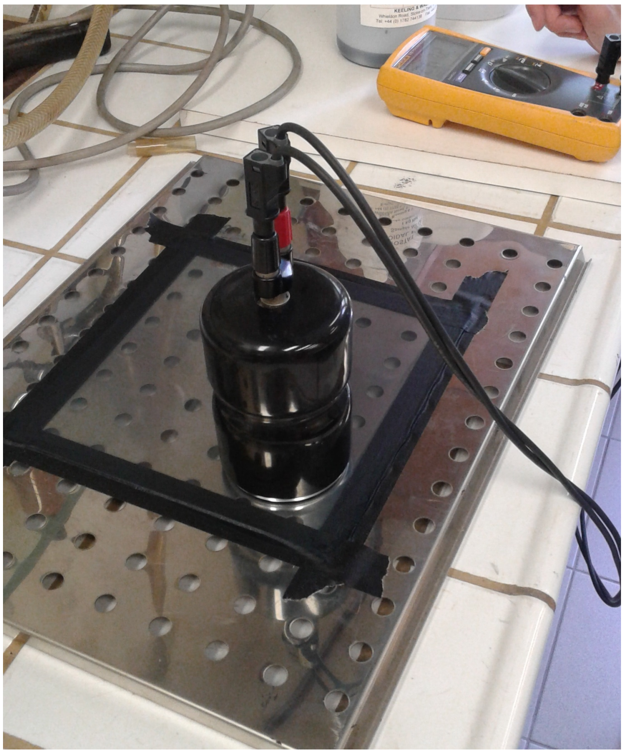


Figure 6: The CRP used to measure the sheet resistances.

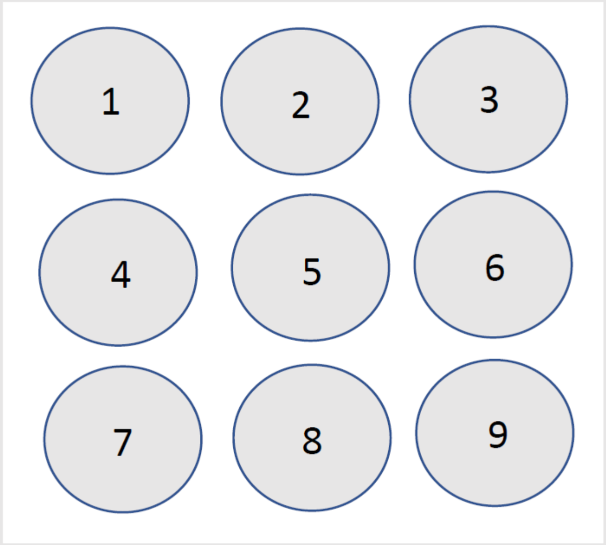


Figure 7: Example of sheet resistance measurement using the CRP.

3.2.3 Gas gap construction

To ensure a uniform width gap, we use edge spacers between the glass sheets as shown in figure 8.

3.2.4 High voltage connection

In order to make the high voltage connection, we solder (by using tin) the electrodes on the strips (in copper) which are connected to the resistive coating where the high voltage is distributed across the plates (figure 9). We use the same procedure for the electrode grounded. To insulate the inactive part of the glass plates, we use dielectric tape (Kapton tape).

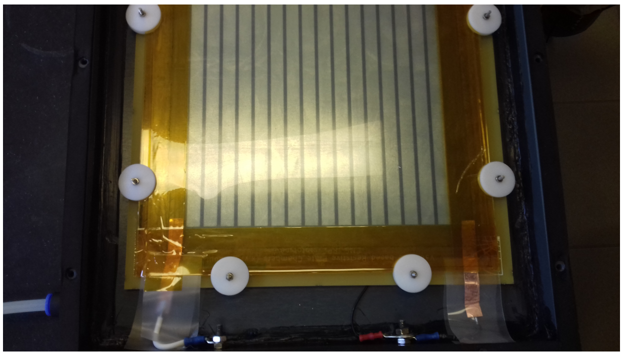


Figure 8: Gas gap construction with spacers (in white).

3.2.5 Readout strips

In Ghent, I used a printed circuit board (PCB), whose readout is very easy. The readout wires are connected to an adapter board for connection with a front-end board CMS equal to those used in the CMS experiment[4]. If I do not have a PCB, I will have to make my own strips made of copper.

3.2.6 Detector casing

We take a metal casing with holes that are used to connect the high voltage connection, the gas inlets and the readout strips. The assembled detector is shown in figure 10.

3.3 Looking further

If the project is well advanced before going to Mars Desert Research Station in Mars 2018, we will use the RPC to be able to make muography, an imaging technique that relies on the measurement of the absorption of muons freely and abundantly produced by the interactions of cosmic rays with the atmosphere.

Muography was first applied for practical purposes in 1955 to measure the overburden over a tunnel, and in the late 1960s in a search for hidden chambers in the Second Pyramid of Chephren in Giza. But it took a few more decades before advances in detector R&D and data processing made this technology a competitive tool for subsurface imaging of large structures. Since 2006 this technique has been used successfully to map the interior of mountains in Japan, allowing a finer spatial resolution than achievable with conventional geophysics techniques such as gravimetry or seismic tomography. Since then the technique has been applied to active and dormant volcanoes in other countries, for example Stromboli, Vesuvius and Etna in Italy, Puy de Dôme and La Soufrière de Guadeloupe in France.

Table 1: Example of output

Number of the muon	Number of signals	
	Channel	Time (ns)
0	5	
	10	449.600000
	8	468.000000
	9	433.400000
	11	433.600000
	0	202.100000
1	1	
	11	465.900000
2	4	
	6	464.600000
	5	606.900000
	5	448.000000
	4	464.400000
...	...	...

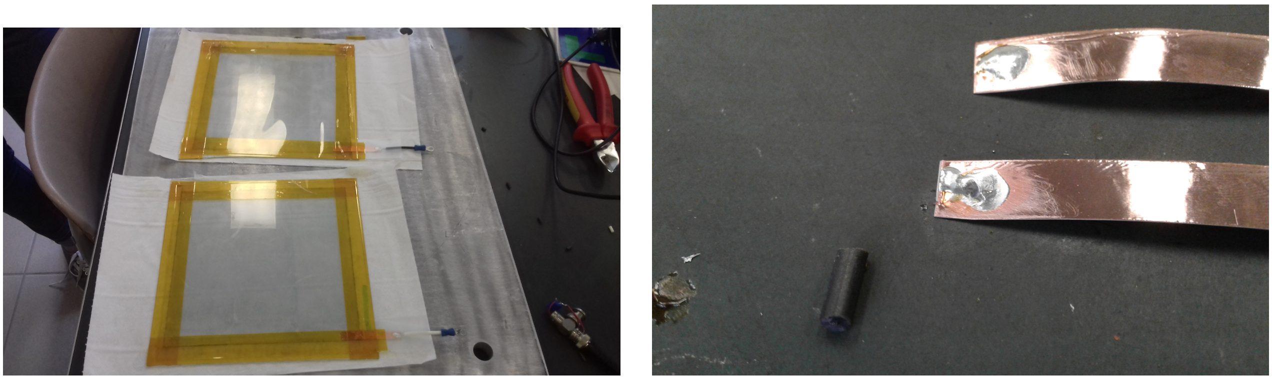
If this technique is applied to Mars geology, we could study the interior structure of several interesting targets on the surface of Mars, which could give new answers to questions about geologic history, climate, biologic potential, and the nature of current activity. Six potential target geological features are shown in figure 11.

4 Project Plan : Things that will be done in the USA

4.1 Data Analysis

For the moment the data structure is obtained with CMS Front End Electronics (FEE). At each trigger (muon = coincidence of the two PMTs), a window of 1μs around the signal of the trigger is opened to see what contained the buffer of the TDC (Time to digital converter). Table 1 gives an example of output obtained in Ghent during my internship (July 2017).

The data obtained will be formatted to lead some specific studies and make some interesting plot and histograms with *ROOT*. I will benefit of my Professors' experience as well as that of Cristina Carloganu (CNRS, France) and collaborators in Clermont-Ferrand and Giulio Saracino (INFN, Italy) and collaborators in Naples and Florence to reuse the codes and programs already created.



Insulation of glass plates with kapton tape (in yellow)

Soldering of a copper sheet

Figure 9:

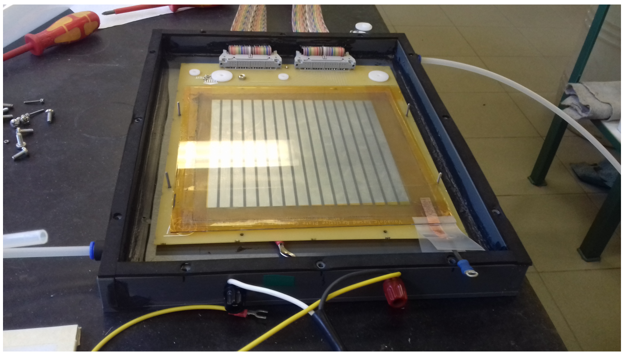


Figure 10: Assembled miniRPC with one gap

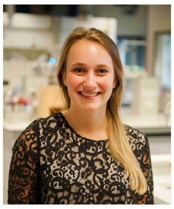
4.2 Measurement of the cosmic muon flux

Cosmic rays are high-energy radiation, mainly originating outside the Solar System. In fact when these radiations pass through the Earth's atmosphere, they produce showers of secondary particles that sometimes reach the surface. Their origin is mysterious and is primarily composed of high-energy protons and atomic nuclei.

As a proof of principle, we want to measure the cosmic muon flux with our telescope made of four mini-gRPCs in order to reproduce the theoretical vertical flux of muons and the muon energy spectrum shown in figure 12. Figure 13 shows the vertical fluxes of the major cosmic ray components in the atmosphere in the energy region where there is the largest number of particles. Muons, produced in interactions of the primary cosmic rays in the air (decay chain of charged mesons), are the most important number of charged particles at sea level. They are produced high in the atmosphere and by ionization lose approximately 2 GeV before they reach the ground. An important characteristic is the angular distribution of muons. Indeed for muons of $E_\mu \approx 3$ Gev, it is $\propto cos^2(\theta)$.

If the mini-gRPC is not operational by February we will consider our plan B : Use already available scintillators. We could make some of the measurements that we had planned but in another range of precision.

About the author



Sophie Wuyckens will assume the role of Physicist and Astronomer of the MDRS crew. In 2013, she started physics studies at Université de Mons, Belgium. She spent her third year of Bachelor at Université Laval, Québec, Canada. In 2016, she decided to continue her cursus at Université catholique de Louvain (Belgium), where she chose the field of particle physics and cosmology field. She is now in her last year of the Masters degree and has chosen muography as her memoire topic.

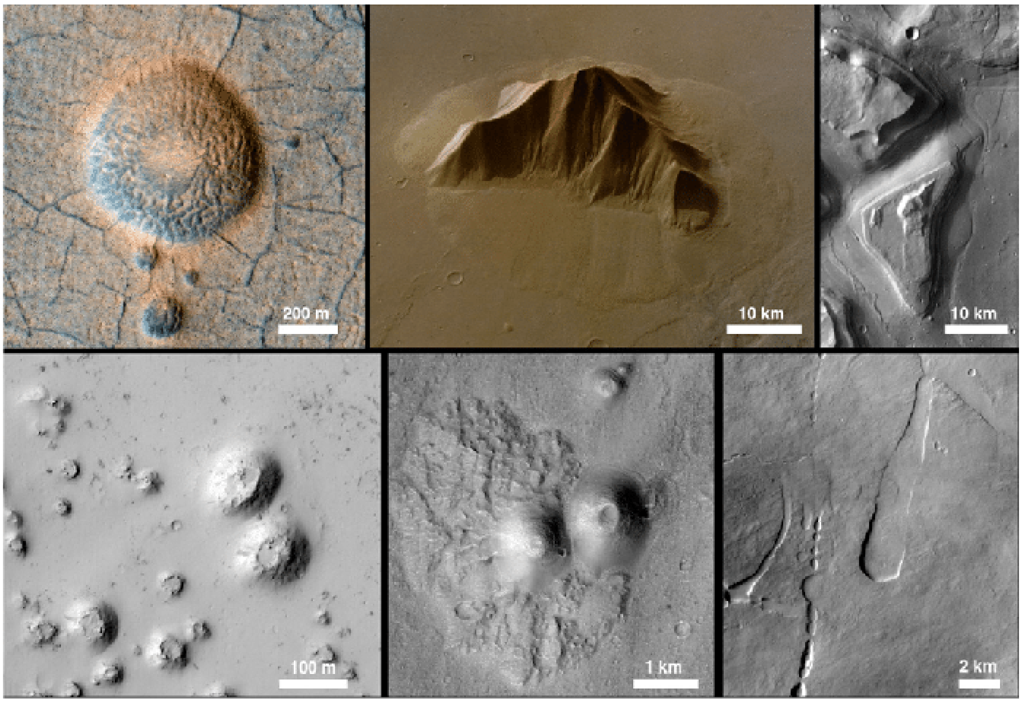


Figure 11: Orbital images of examples of classes of potential targets for muon radiography on Mars. Top left: perennial ice-cored (but non-glacial) hill (pingo). Top middle: perspective view of a massif in the Eastern Hellas region with surrounding ice-rich lobate aprons. Top right: mesas in Hydraotes Chaos, once a source of outflow flood waters, and potentially a host of remnant aquifers. Lower left: rootless cones on platy lava flows in Elysium Planitia. Lower middle: Enigmatic edifices in Hydraotes region that may be rootless, or connected to a vent system. Lower right: chains of collapse pit on Ascraeus Mons. Areas between pit chains may contain lava tubes or caves in the subsurface. [10]

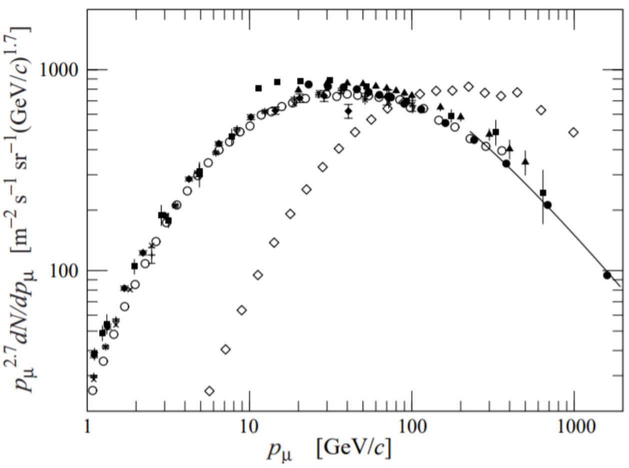


Figure 12: Spectrum of muons at sea level at two different angles $\theta = 0°$ & $\theta = 75°$ [5]

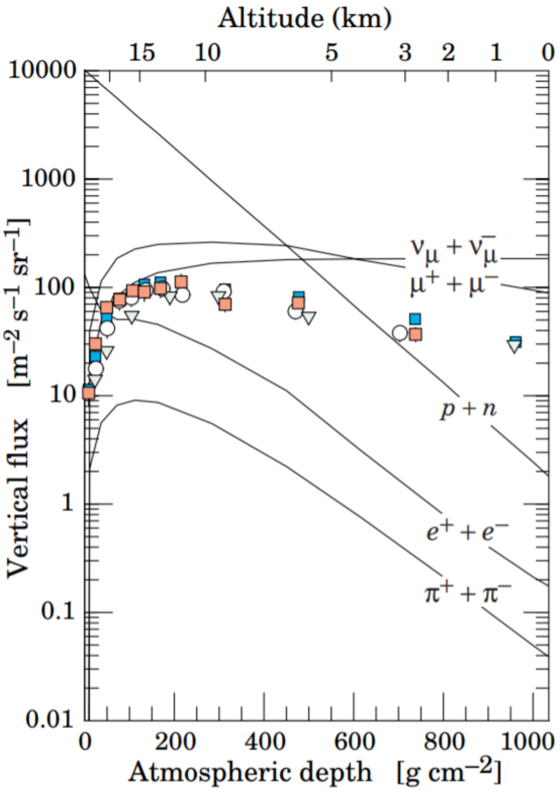


Figure 13: Vertical fluxes of cosmic rays in the atmosphere with E > 1 GeV [5]

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