Ultra high energy cosmic rays observed in Cherenkov detectors of the Pierre Auger Observatory in coincidence with ASC-II detectors

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Abstract

Knowing characteristics of a shower is currently possible but only with uncertainty. Statistics are used to sort out showers. However using the Universality, can predict very accurately a shower thanks to five parameters of the shower. Using five parameters for the Universality is not enough to know perfectly the shower. In spite of relationships between these five parameters, namely the depth of the maximum of muons (X^{μ}_{max}), the depth of maximum of electrons (X^{e}_{max}), the energy of primary particle, the geometry, the number of muons at one thousand meters from the axis of the shower (N^{μ}_{1000m}), there is still an uncertainty between X^{μ}_{max} and X^{e}_{max}. New parameters like the maximum number of muons and the number of muons for a given angle have to be used to improve correlation between X^{μ}_{max}, X^{e}_{max}. Following is an analysis of numerous simulations to extract relationship between X^{μ}_{max}, X^{e}_{max} and N^{μ}_{1000m}. Then characterization of sensors was done to know if the electronic currently installed on board could allow us to collect data to validate the Universality. Moreover efficient experimentation is needed to validate the Universality. ASC-II detectors, a proposal board of plastic scintillators as a complementary detector, could be the key to solve it. However an important work has to be done to create efficient and linear electronic.

Summary

1 Introduction **2**

2 The Universality **2**

2.1 Simulation and data processing 2

2.2 Additional parameters 4

3 The ASC-II detectors **6**

3.1 Amplifier linearity 6

3.2 Linearity of detectors 6

3.3 Installation in the Pierre Auger observatory 7

4 Conclusion **8**

1 Introduction

Currently stats are used to study ultra high energy cosmic rays. The Universality is a way to change it. According to this theory, cosmic ray can be analyzed without statistics. A shower could be characterized by just five parameters: the energy of primary particle, the geometry, the depth of maximum of muons (X^{μ}_{max}), the depth of maximum of electrons (X^{e}_{max}) and the number of muons at thousand meters (N^{μ}_{1000m}). After several tests succeeded the Universality has to be upgraded. Relations between parameters are not perfectly known. The uncertainty between X^{e}_{max} and X^{μ}_{max} is an example. The non-dependence of hadronic interaction model is one of the main strength of the Universality. It is based on characteristics of showers, the topic of study is the parameters of the shower, not a model. The aim is not to create and to test theory but it is to find relationship between the parameters of showers.

Describing perfectly showers could allow to go beyond known physic. Because the energy of ultra high energy cosmic rays is 10^6 times higher than the energy of particles in the Large Hadron Collider. Reaching such energies seems to be impossible for now. Moreover it could be an important source of information from black holes or active galaxy nuclei and allowing us to know more about them. Experimental devices have to be able to validate or not predictions of the Universality. The Pierre Auger Observatory spans over 3000 km^2 in Malargüe. Its surface consists of 1600 Water-Cherenkov Detectors. These surface detectors are efficient but not enough for the Universality. That is why ASC-II detectors were created. ASC-II detectors are more sensitive to electrons than surface detectors which are very sensitive to muons. Differences between the number of electrons and muons collected between ASC-II detector and surface detector gives us more information on the fractions of muons and electrons in showers than just surface detector. Making a difference between this two components of the shower is essential because an iron nuclei creates more muons than a proton which creates more electrons. This improvement of detectors could allow to identify the type of particle. Because of the non-linear output of ASC-II detectors every components has to be studied. Our first analysis will be about amplifier of current but all the board will be tested.

2 The Universality

2.1 Simulation and data processing

According to the Universality, it would be possible to characterize each shower thanks to few parameters. As explained previously the Universality actually needs five parameters. But there is still an uncertainty about the link between X^{e}_{max} and X^{μ}_{max}. In order to find an equation which links X^{μ}_{max} and X^{e}_{max}, two hundred showers were simulated with Aires. The software Air-shower Extended Simulations [1](Aires) is an hadronic interaction algorithm which simulate the shower of particles by using few input parameters like the energy, the angles of arrival and the type of primary particle.

There are three hadronic interaction models, Sybil, QGSJET and a lighter QGSJET II. As the Universality does not depend on the model used, AiresQ which use QGSJET II was chosen to simulate showers. Using a lighter version allowed us to save time, because simulate two hundred showers spends around four weeks of calculus and data analysis.

Input parameters [2] of Aires were almost the same for every showers.

- Particle : Proton and Iron
- Energy = 1.10^{19} eV
- Thinning = 1.0E-8 Relative
- ThinningWF = 25
- Injection = 100 km
- Observing levels 21 50 g/cm^2 850 g/cm^2
- Ground altitude = 870 g/cm^2
- Geomagnetic field of ElNihuil
- Zenith angle = 0 deg

- Azimuth angle = 0 deg
- Radius limit from 1.10^{-10} m to 15 km
- Energy = 1.10^{19} eV
- GammaCutEnergy = 200 keV
- ElectronCutEnergy = 200 keV
- MuonCutEnergy = 1 MeV
- MesonCutEnergy = 1.5 MeV
- NuclCutEnergy = 125 MeV

Moreover geometrical and energetic parameters were set to simplify the problem.To understand better phenomena studied, other energies were simulated 5.10^{18} eV and 1.10^{18} eV. Just three parameters of the Universality were non-constant, namely X^{μ}_{max}, X^{e}_{max} and N^{μ}_{1000m}. Study will be about links between these three parameters.

The first idea to simulate showers was to cut the simulation in two parts. Indeed, at such energies physics is not precisely known. So to avoid problems due to model used, the first one was from 100 km to 100 g/cm^2 (4 km). Then the second part was from 100 g/cm^2 to the ground (870 g/cm^2). The output of the first simulation was treated by algorithms. This algorithms simulated showers by using characteristics of particles from the output as input. Unfortunately even if thinning was low 10^{-8}, particles had weights different from 1. Whereas particles simulated which had a weight of 1 in the second shower. As we wanted all the particles at 100 g/cm^2 and the density of particles is more important close to the axis of the shower, using a radius limit of 1.10^{-10} m was very important for the cut simulations. And the geomagnetic field ElNihuil is the one from the Pierre Auger observatory. So the second shower had weird and no physic characteristics. For next studies, using a lower thinning and being sure that the weight of every particle is 1 could solve this problem. However, such a thinning triggers a very important time of calculus.

The Gaisser-Hillas function was used to fit outputs from Aires.

$$N(X) = N_{max} \exp\left(\frac{X_{max} - X_0}{\lambda}\right) \left(\frac{X - X_0}{X_{max} - X_0}\right)^{\frac{X_{max}-X_0}{\lambda}}$$

Parameters collected from fits and studied were X^{μ}_{max}, X^{e}_{max}, the energy of primary particle, the zeniths angle of primary particle, the azimuths angle of primary particle, N^{μ}_{1000m}, the depth of first interaction (X_0), the attenuation length for electron part (λ_e), the attenuation length for muon part (λ_μ), the number maximum of electrons (N^{e}_{max}) and the number maximum of muons (N^{μ}_{max}), the number of muons for a given angle (N^{μ}_{angle}).

Data processing - Some parameters described previously are useless for our study. Others have to be treated like X^{μ}_{max} or X^{e}_{max}. They are expressed in g/cm^2 but it is more useful in km. So algorithms read lines from the outputs of Aires and adapted values for calculus.

Methodology adopted - First links between parameters have to be found. The idea is to plot X^{μ}_{max} in function of X^{e}_{max} with a third parameters. The third one represents colors on the graph. When a gradient of colors which seems to have a signification appears, a relationship between the three parameters exists. The more the gradient is homogeneous better is the correlation. Starting with the best gradient allows a better convergence to the result. When parameter is identified this parameter is plotted in function of $X^{\mu}_{max} - X^{e}_{max}$. So the correlation between this parameter and the uncertainty of X^{μ}_{max} and X^{e}_{max} is plotted. Then the same process is done for the second best parameter. This is done until all the parameters previously identified are analyzed.

2.2 Additional parameters

As we mentioned, the number of muons at thousand meters (N^{μ}_{1000m}) are usually considered as a relevant parameter. It is a historical reason, physicists chose this value to count the number of muons. But analysis called into question its use to describe showers. That is why another parameter was considered, the number of muons for a given angle (N^{μ}_{angle}). The angle was arbitrarily set at 25 deg more or less 1 deg. iThe angle is between the axis of the shower and a straight line at the depth of X^{μ}_{max}. The projection on the floor of the difference between 26 deg and 24 deg makes a ring where all the muons which touch the floor are counted. It triggers a problem, muons which come from another depth with another angle are counted too.

As expected there is a link between N^{μ}_{1000m} and N^{μ}_{angle}. The figure 1 shows an uncertainty of 9% means that two parameters are not perfectly correlated. That is why using N^{μ}_{angle} could be an improvement to describe showers and has to be tried.

Analysis of data showed that N^{μ}_{angle} is very correlated with X^{μ}_{max}. Indeed it is even more correlated with X^{μ}_{max} than N^{μ}_{1000m}. The graph 2 shows that point. So N^{μ}_{angle} is a better choice to describe showers than N^{μ}_{1000m}.

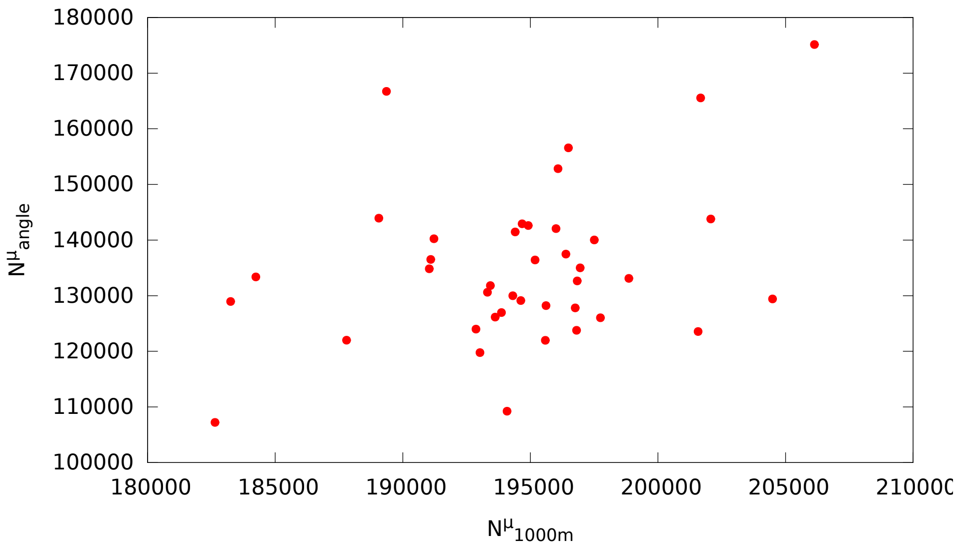

Figure 1: Correlation between N^{μ}_{angle} and N^{μ}_{1000m} for iron nuclei of 10^{18} eV

Another main parameter to describe showers is the number maximum of muons (N^{μ}_{max}). This parameters is linked with X^{μ}_{max} and X^{e}_{max} too but it is less related to both X_{max} than N^{μ}_{angle}. The figure 3 shows the relationship.

As we can see on the graph 4, using this 3 parameters implies an uncertainty of 1.4% (10.7 g/cm^2) for an energy of primary iron nucleus of 10^{18} eV which is better than the 7% of uncertainty between X^{μ}_{max} and X^{e}_{max}. It means shower can be predicted 5 times better by using this new parameters. For this energy, geometry and particle the equation is

$$X^{\mu}_{max} = -12.5N^{\mu}_{max} + 0.395X^{e}_{max} + 8.969110^{-4}N^{\mu}_{angle} + 493.3974$$

Extreme values of the model are the worst ones. The reason could be the methodology of analyzing which is more relevant with values close to the average. Indeed, values are subtracted then added from values of references. So extreme values are further from the values of reference and from the model. Values of coefficients are not significant because these values will change with energy, data samples, type of particle etc. But their existence proves the link between parameters Such results are also obtained at 10^{19} eV and 5.10^{18} eV. Using energy to characterize showers could be a way to improve precision. Others parameters as first interaction point or attenuation lengths do not have impact on the link between X^{μ}_{max} and X^{e}_{max}. The flux of muons depends on radial density. Correlation could be better with an angle different from 25 deg.

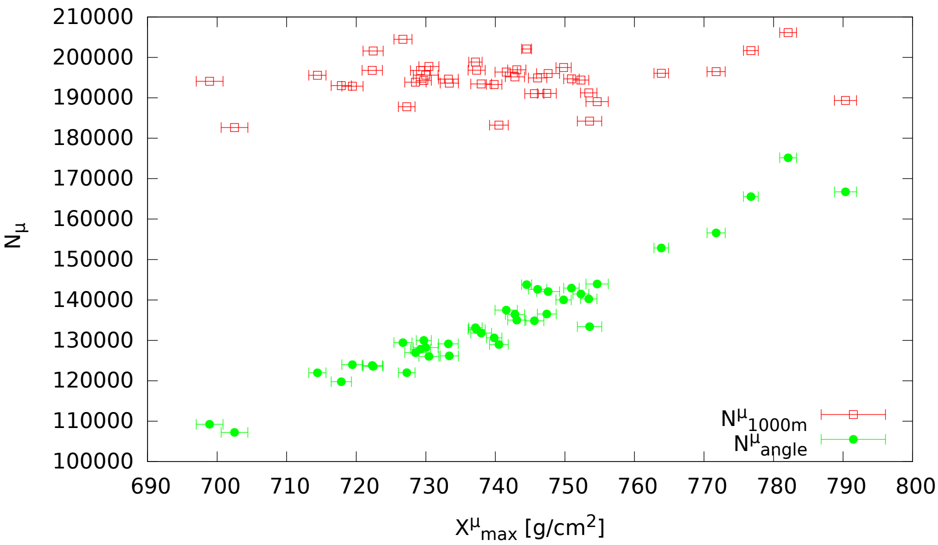

Figure 2: Graphs of N^{μ} in function of X^{μ}_{max} for iron nuclei of 10^{18} eV

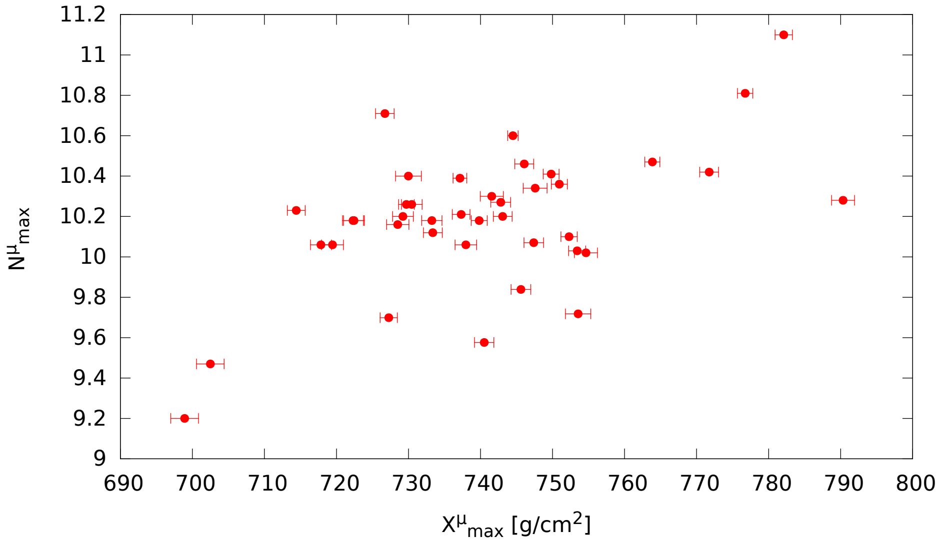

Figure 3: Correlation between N^{μ}_{max} and X^{μ}_{max} for iron nuclei of 10^{18} eV

Another study was about the number of muons at 25 deg like previously but only the particles created between X^{μ}_{max}+10 g/cm^2 and X^{μ}_{max}-10 g/cm^2 were counted. Correlation between this new parameter and X^{μ}_{max} was bad. This result is not very surprising because this new parameter only gives information about the number of muons created at the depth of X^{μ}_{max}. Whereas N^{μ}_{angle} which is an information about all the shape of the shower and how it behaves. Another way to improve correlation would be using N^{μ}_{angle} as information about the shape of the shower and another one better than N^{μ}_{max} to describe the maximum of muons.

As this new parameters can not be directly measured, they have to be fitted. Data from simulations were used to know if it is possible to fit parameters from experimental data. The values of X^{μ}_{max}, N^{μ}_{max} and λ_{μ} were fitted from the output of Aires as if it was experimental data. And at the same time another fit of X^{μ}_{max} and λ_{μ}. The aim of this attempt was to obtain the same values of X^{μ}_{max}, N^{μ}_{max} and λ_{μ}. Values were not

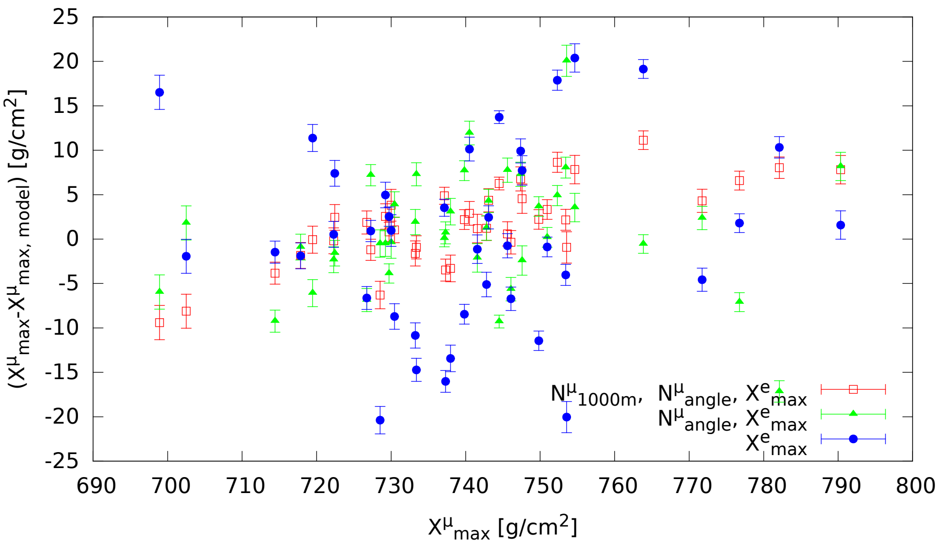

Figure 4: Gap in percentage between the model and the real values of X^{μ}_{max}

the same at all, and some values were negatives. As this new parameters can not be fitted directly another way to find them has to be found.

3 The ASC-II detectors

3.1 Amplifier linearity

Protocol - A diode receives tension from a low frequency generator. Then a photo-diode collects light and change it into current. This current is amplified by amplifier. And finally a system to acquire data (FPGA NEXYS-II) collects and measures current in the output of amplifier. Values of the input tension in diodes was changed from 0.4 V to 5.2 V. The value of 0.9 V was the minimum value to make diodes working and 5.2 V was the tension of the saturation of amplifier. As frequency does not have impact on the experimentation it was arbitrarily set at 20 kHz. The scheme of the experimentation is in the annex A.

Results - figure 5 shows that response of amplifier can be considered as linear. Amplifier of current are not the cause of the non-linearity of sensors and can be used in new boards.

3.2 Linearity of detectors

Protocol - In ASC-II, light produced by particles crossing the plastic scintillator is collected by a photo multiplier tube R7111. In a linear detector doubled input means doubled output. To check if ASC-II detectors respect it two diodes were used. The signal of both diodes should be the same signal than if each diode is switched on individually and summed. The aim of the experimentation is to measure current delivered by the sensor when each diode is switched on and when they are both. Then we compare the sum of the two values and value of both. Two diodes are linked with a low frequency generator which sends the same tension but different frequencies to diodes. Frequencies had to be multiples of the other to get a pic sum. Choices were 20 kHz and 30 kHz. So the pic sum had a frequency of 10 kHz. Then a system to acquire data measures current and an treatment by computer gives us the value of each diode and the value of both. The scheme of the experimentation is the annex B.

Results - New electronic has a similar output of the old one. But as we can see on the graph 6 linearity is better. However there is still a lack of linearity from 2000 μA. As a particle creates a current of 20 μA, just 100 particles could be analyzed which is far from the 2000 particles expected. Non linearity response of

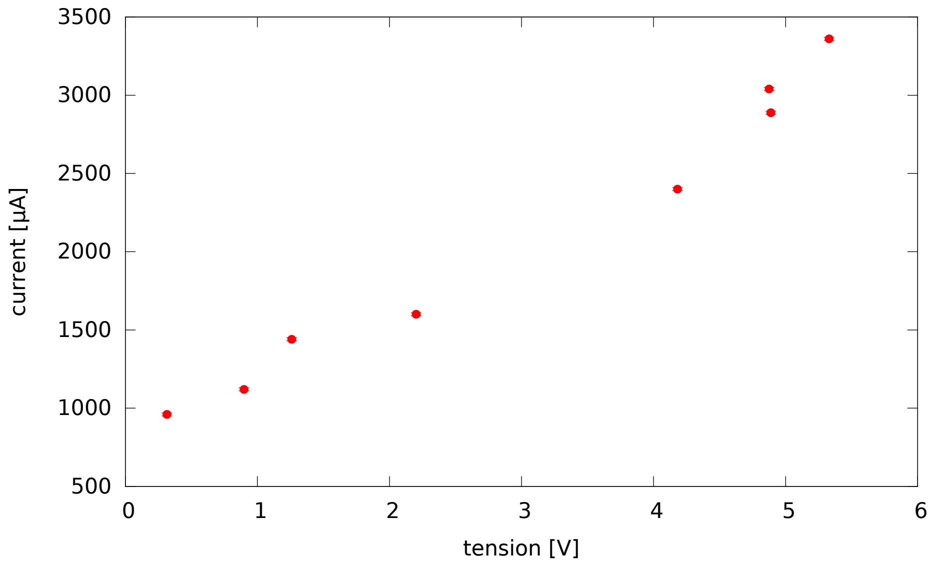

Figure 5: Output current (μA) in function of input tension (V) for amplifier of current

detectors could come from PMT used. Linearity could be improved in the future by using new components by having an effect on the non linearity of PMT.

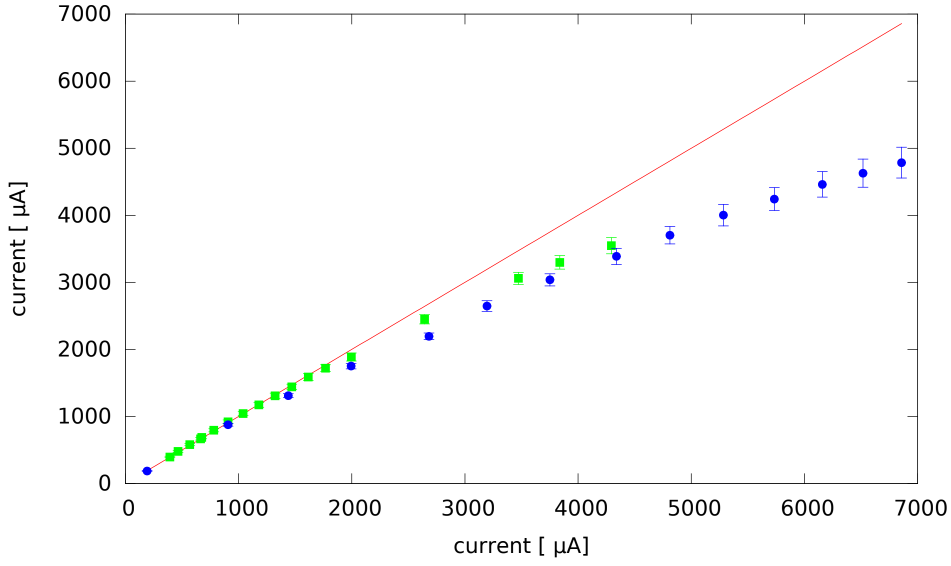

Figure 6: Output of ASC-II detectors, using old board (blue), and new board (green)

3.3 Installation in the Pierre Auger observatory

After we made sure we had an efficient electronic, seven electronic boards were made to replace old ones in the Pierre Auger Observatory. Six with the same PMT and another with a bigger one.

As the cause of non linearity could be PMT. Another one bigger was installed on the tank called "Phil Collins". The work in the field was composed of three tasks :

- replacing board

- connecting board with scintillator
- doing adjustments of supply and acquiring system to get pulses

Now this detectors have to be calibrated. This calibration has to be done on the field, because it depends on the temperature, the pressure and other climatic effects. So for now, data gave by ASC-II detectors can not be considered as usable. In the future, maybe a month it depends on problems during calibration, data collected by them will be considered as usable.

4 Conclusion

Step by step relationships between parameters of the Universality are known better, uncertainty decreases. Some results are a little bit astonishing, X^{μ}_{max} depending on X^{e}_{max}, N^{μ}_{angle} and N^{μ}_{max} for example. This study showed that using N^{μ}_{angle} and N^{μ}_{max} increases precision by a factor five and changed uncertainty from 7% to 1.4%. But there is still an important work to do to finalize the Universality and reach an uncertainty of 0%. As we explained previously the energy of primary particle and geometry were set. So simulate shower with free energies and geometry could allow us to find a better correlation and description of showers. One of the most sticking point was that all the relationships between parameters found are linear. There is not quadratic or exponential link. Maybe this fact comes from difficulty to identify the non-linear correlations.

Now ways to identify new parameters are needed. ASC-II detectors are good solutions to reach an relevant precision and identify new parameters.The linearity of ASC-II sensors is better thanks to few improvements. But ASC-II detectors have to be upgraded to be more precise and more efficient.

References

[1] N.N. Kalmykov & S.S. Ostapchenko, A.I. Pavlov Phys; B (Proc. Suppl.) 52B (1997) 17n(figure)

[2] S.I. Sciutto, User's guide and reference manual (2002)

List of Figures

1 Correlation between N^{μ}_{angle} and N^{μ}_{1000m} for iron nuclei of 10^{18} eV 4
2 Graphs of N^{μ} in function of X^{μ}_{max} for iron nuclei of 10^{18} eV 5
3 Correlation between N^{μ}_{max} and X^{μ}_{max} for iron nuclei of 10^{18} eV 5
4 Gap in percentage between the model and the real values of X^{μ}_{max} 6
5 Output current (μA) in function of input tension (V) for amplifier of current 7
6 Output of ASC-II detectors, using old board (blue), and new board (green) 7
7 scheme of the experimentation about amplifier 9
8 scheme of the second experimentation about all the sensor 9

ANNEX A

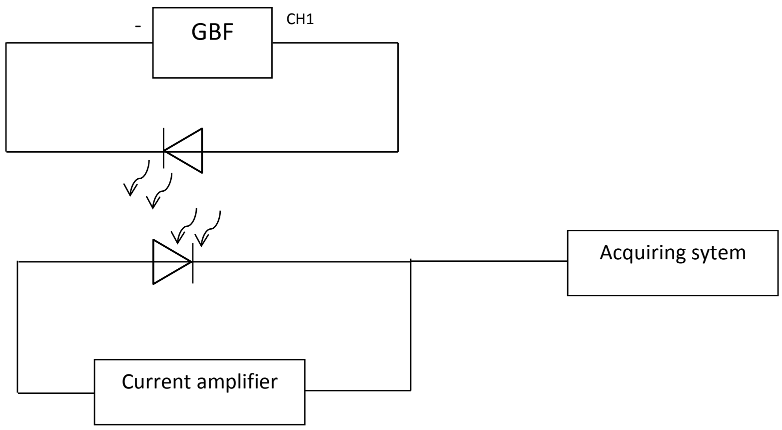

Figure 7: scheme of the experimentation about amplifier

ANNEX B

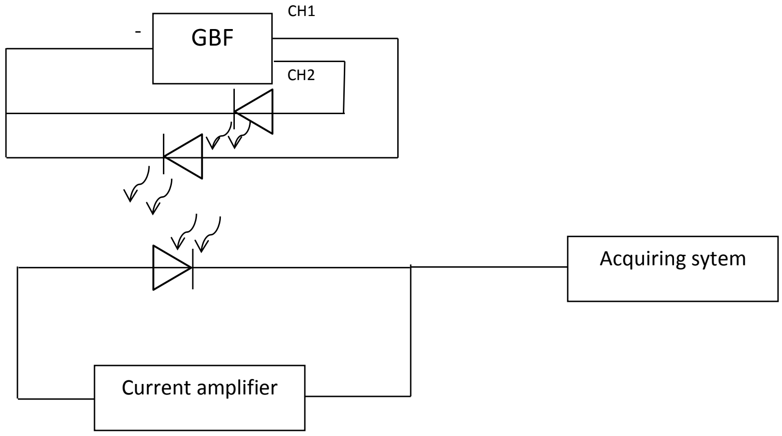

Figure 8: scheme of the second experimentation about all the sensor