A NEW MEASUREMENT OF THE COSMIC-RAY FLUX BELOW 5GV RIGIDITY WITH THE PERDAIX DETECTOR

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ABSTRACT

The PERDaix (Proton Electron Radiation Detector Aix-la-Chapelle) detector is designed to measure charged particles in cosmic-rays. It can distinguish particle species with a maximum detectable rigidity of 12 GV. It was designed to measure the solar modulation parameter. PERDaix was flown on the BEXUS-11 balloon on November 23rd 2010.

The detector and its readout electronics is contained inside two $60 \times 60\ \mathrm{cm}^2$ plates in $85\ \mathrm{cm}$ distance. The geometrical acceptance amounts to $32\ \mathrm{cm}^2\mathrm{sr}$. PERDaix is divided into three subdetectors: a spectrometer, a time-of-flight (TOF) system and a transition radiation detector (TRD). During its flight it recorded 177.000 charged particles at $33.4\ \mathrm{km}$ float height. The goal is to determine the proton, electron and helium flux, the solar modulation as well as to test novel particle detector technologies in stratospheric conditions.

Key words: charged cosmic-rays; particle detector; solar modulation; spectrometer; silicon photomultiplier; SiPM.

1. INTRODUCTION

The recent measurements of the PAMELA satellite experiment [1] have caused plenty of discussions in the astroparticle community. The data show an excess in the positron fraction that could for example stem from dark matter particle annihilation processes [2, 3, 4, 5] or nearby pulsars [6].

A conclusive interpretation requires further measurements. The Alpha Magnetic Spectrometer (AMS02), which docked to the International Space Station and started data taking in May 2011, will measure the cosmic-ray fluxes up to the TeV scale. It will thereby help to understand the nature of matter, antimatter and dark matter by increasing PAMELA's momentum range significantly.

Also in the low energy region up to $\sim 10\ \mathrm{GV}$ the PAMELA data mismatch the prediction made with cosmic-ray propagation models. In that region the particle spectra are influenced by the magnetic field created by the solar winds. The modulation can be described by the so-called force-field approximation [7]:

$$J(E) = \frac{E^2 - m^2}{(E + |z|\phi)^2 - m^2} \cdot J_{\mathrm{IS}}(E + |z|\phi),$$

with the solar modulation parameter ϕ, the measured flux J, the interstellar flux J_{IS}, the energy E and the mass m of the particles. $|z|$ is the absolute value of the charge in units of the elemetary charge.

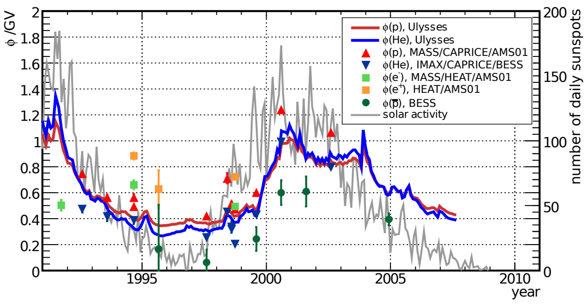

Figure 1. Solar modulation parameters $\phi^{\pm}$ as a function of the year.

The discrepancy could be explained with a charge-sign dependence of the modulation. A simple heuristic modification to the force-field approximation is the use of two modulation parameters $\phi^{\pm}$. One for positively and one for negatively charged particles. The parameters are determined from data taken by the Ulysses [8, 9], BESS [10, 11, 12] and other experiments. After correcting the positron fraction with the determined parameters $\phi^{\pm}$ the

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PAMELA data fit the prediction [13]. Since Ulysses and BESS have stopped their campaigns several years ago, PERDaix aims to measure the proton, electron and helium flux up to a rigidity of 5 GV and determine the current $\phi^{\pm}$.

2. THE PERDAIX DETECTOR

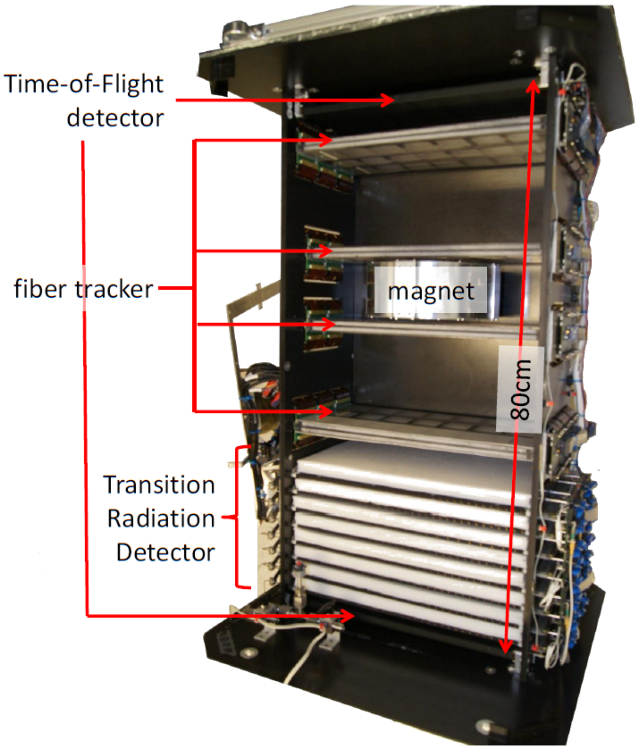

Figure 2. A photograph of the PERDaix detector.

The PERDaix detector consists of three subdetectors: a spectrometer, a time-of-flight (TOF) system and a transition radiation detector (TRD). The arrangement can be seen in Fig. 2. The actual detector has a size of $20 \times 39 \times 81$ cm^3. The overall size including electronics, batteries, cabling, etc. which are arranged around the sensitive detector components is $57 \times 59 \times 89$ cm^3. The overall weight is 40 kg and the power consumption amounts to 60 W which are provided by battery packs. PERDaix was designed to be run on batteries for about eight hours.

2.1. Spectrometer

The spectrometer measures the rigidity $R = p/q$ of particles passing through the detector. It is defined as the ratio of momentum p to charge q. The spectrometer consists of a magnet with a mean magnetic field of 0.2 T. The magnet is made up of 72 NdFeB permanent magnet cylinders arranged such that the magnet wall itself is used as the return yoke. In that so-called Hallbach arrangement the residual field outside the magnet is negligible and cannot disturb the surrounding electrical and mechanical equipment.

Four tracker double layers surround the magnet, as can be seen in Fig. 2, providing four one dimensional particle track measurements above and another four below the magnet. Each track position is measured with an accuracy better than 50 µm in the bending direction (standard deviation). Also the second dimension, the non-bending dimension, is measured with help of a 1° stereo angle inside each double layer. Each layer is made up of 5×256 400 mm long and 250 µm thin scintillating fibers that are glued together to a ribbon in the tightest arrangement. The scintillation light created by charged particles passing the fiber is conducted to the fiber's ends by total reflection. The fiber ends are read out column-wise with 32 channel SiPM arrays. Reference [15] provides a detailed description with characterization measurements and test-beam results of several fiber tracker prototypes.

The momenta of particles are determined with help of the deflection of the charged particles in the magnetic field. In that arrangement the spectrometer achieves a momentum resolution

$$\frac{\sigma_p}{p} = 0.08 \frac{p}{\text{GeV}} \oplus \frac{0.25}{\beta}$$

where $\beta = v/c$ is the quotient of particle velocity and the speed of light. With that resolution the spectrometer provides charge separation up to $R \approx 5$ GV.

2.2. Transition radiation detector

The TRD was produced similarly to the AMS02 TRD [14]. It consists of a 16 layers of radiator fleece each followed by a layer of proportional counters. The counters are made of gastight straw tubes with a diameter of 6 mm. The tubes are operated in an $\text{Xe}(80\%)/\text{CO}_2(20\%)$ gas atmosphere at 1.1 bar absolute pressure. Through the center of each straw runs a 30 µm thick gold-plated tungsten anode wire operated at 1.5 kV. When a charged particle crosses the gas volume gas molecules are ionized. The electrons from the ionization process travel towards the anode wire and are thereby multiplied in an avalanche processes up to a measurable charge.

Particles with $\gamma = (1 - \beta^2)^{-\frac{1}{2}} \gtrapprox 500$ produce transition radiation photons that can be detected by the proportional counters. In contrast to electrons, protons are well below this threshold. Thus, electrons are expected to produce a higher signal in the proportional counters. This is used to distinguish electrons/positrons from the vast majority of protons in primary cosmic-rays up to rigidities of hundreds of GV.

2.3. Time-of-flight system

The TOF provides the main trigger for the other subdetectors and measures the velocity β of the particles. This is used to distinguish upward from downward going, so-called Albedo, particles. Also the TOF improves the momentum measurement of the spectrometer below 1 GV rigidity.

The TOF consists of four modules: two at the top and two at the bottom of the detector (Fig. 2). Each module is made up of four $6 \times 50 \times 395\ \mathrm{mm}^3$ scintillator bars type Bicron BC-408. The scintillation light of each bar is detected by four Hamamatsu S10362-33-100C silicon photomultipliers, two on each side. The signals are fed into NINO discriminator chips [16]. The 64 NINO signals are processed by an FPGA on which the trigger logic is implemented. The signals are fed through to an HPTDC based time digitizing board called MTDC-64 [17]. The MTDC-64 records the time stamp, while the FPGA generates the trigger signals to start the readout of the other subdetectors.

3. PERFORMANCE DURING FLIGHT

The PERDaix detector took data continuously with little interruption time during the whole BEXUS-11 flight. In Fig. 3 the trigger rate is plotted as a function of the local time together with the height of the balloon above ground. The trigger rate increases with hight and reaches a maximum of 32 Hz at a height of 20 km (Pfotzer maximum). During the float phase, the trigger rate is constantly around 28 Hz. Every ten minutes the data taking is automatically stopped to calibrate the detector resulting in periodic dips in the trigger rate.

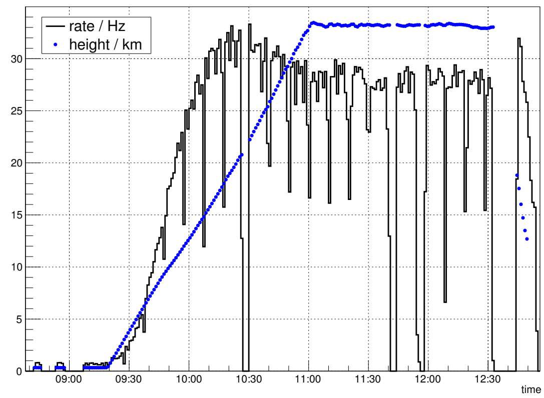

Figure 3. Trigger rate plotted together with the height of the BEXUS-11 balloon.

Fig. 4 shows the interplay of spectrometer and time-of-flight system. The reconstructed momentum is plotted versus β^{-1} for float and ground data. The data shows that during flight mostly protons are reconstructed while on ground there are mostly muons. Also in the flight data 2.1 % of the measured particles are Albedo particles which do not exist on ground.

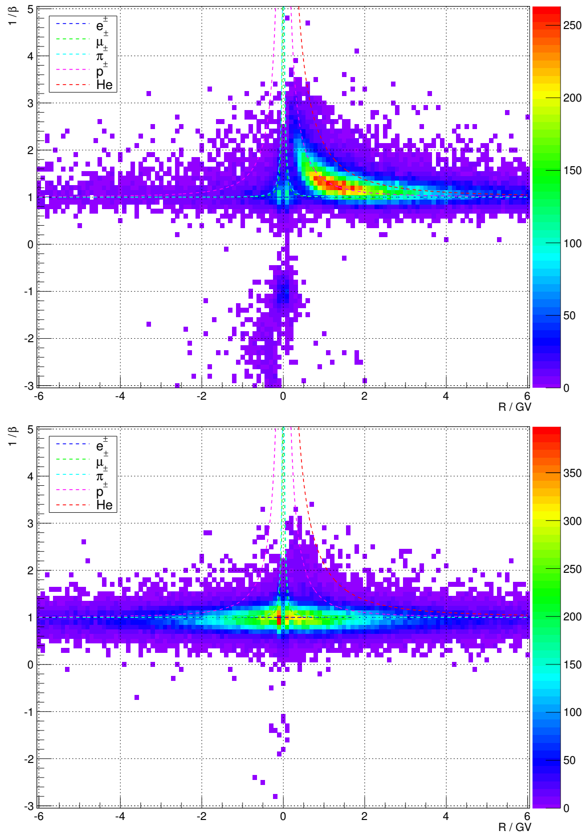

Figure 4. Correlation between reconstructed inverse velocity β^{-1} and reconstructed rigidity R during float phase (upper) and on ground (lower).

4. ANALYSIS PROCEDURE

Obtaining final results requires the calibration and a full understanding of the detector. For example the fiber tracker can measure particle tracks with a resolution better than 50 µm, i.e. much better than the mechanical mounting precision. This misalignment has to be corrected for in several iterations. The TOF system can measure time differences on the level of 300 ps. The resolution is of the order of the signal delays due to cable length variations which have to be calibrated. The TRD signal height depends on the gas density inside the proportional counters. During flight the density changed due to the temperature gradient which has to be corrected for. In order to calculate the flux of particles as a function of the momentum the detection efficiency has to be determined.

All these analysis steps are worked on intensely. The data presented here is preliminary but already show the expected behavior and is considered a success.

5. CONCLUSION

The results presented show that the PERDaix detector had a successful flight on board the BEXUS-11 balloon. The physics goal of determining the proton spectrum together with the solar modulation parameter is achievable with further analysis of the taken data. Moreover, from a technical point of view, the flight was a full success. Novel detector technologies, that is scintillation fiber with silicon photomultipliers readout, have been used in harsh stratospheric conditions. These technologies can be used for upcoming cosmic-ray experiments in the higher atmosphere or in space.

6. OUTLOOK

A testbeam was carried out in May 2011 at CERN (European Organization for Nuclear Research) near Geneva, Switzerland. The goal was to calibrate the detector with well defined particle properties. Protons, pions, muons, electrons and their corresponding anti-particles were chosen in a momentum range between $0.5 - 10$ GeV. The analysis is ongoing and will greatly help understand the detector properties.

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REFERENCES

[1] O. Adriani *et al.* [PAMELA Collaboration], An anomalous positron abundance in cosmic rays with energies $1.5 - 100$ GeV, Nature 458 (2009) 607

[2] D. Hooper *et al.*, Excesses in cosmic ray positron and electron spectra from a nearby clump of neutralino dark matter, Phys. Rev. D 79 (2009) 103513

[3] M. Cirelli *et al.*, Minimal Dark Matter predictions for galactic positrons, anti-protons, photons, Nucl. Phys. B 800 1-2 (2008) 204

[4] M. Cirelli, A. Strumi, Minimal Dark Matter predictions and the PAMELA positron excess, PoS IDM2008 (2008) 89

[5] L. Bergström *et al.*, Dark Matter Interpretation of Recent Electron and Positron Data, Phys. Rev. Lett. 103 (2009) 31103

[6] D. Hooper *et al.*, Pulsars as the sources of high energy cosmic ray positrons, JCAP 01 (2009) 25

[7] L. J. Gleeson, W. I. Axford, Solar Modulation of Galactic Cosmic Rays, ApJ 154 (1968) 1011

[8] J.A. Simpson *et al.*, The Ulysses Cosmic-Ray and Solar Particle investigation, Astron. Astrophys. Suppl. 92 (1992) 365

[9] Ulysses KET database available online at http://ulysses.physik.uni-kiel.de/kett.php

[10] J. Z. Wang *et al.*, Measurement of Cosmic-Ray Hydrogen and Helium and Their Isotopic Composition with the BESS Experiment, ApJ 564 (2002) 244

[11] Y. Shikaze *et al.*, Measurements of 0.2 to 20 GeV/n cosmic-ray proton and helium spectra from 1997 through 2002 with the BESS spectrometer, Astropart. Phys. 28 (2007) 154

[12] S. Orito *et al.*, Precision Measurement of Cosmic-Ray Antiproton Spectrum, Phys. Rev. Lett. 84(6) (2000) 1078

[13] L. Jenniches, Untersuchungen zur solaren Modulation der geladenen kosmischen Höhenstrahlung, bachelor thesis, RWTH Aachen University (2009), available online at http://www.perdaix.de

[14] Ph. von Doetinchem *et al.*, Performance of the AMS-02 Transition Radiation Detector, NIM A 558 (2006) 526

[15] B. Beischer *et al.*, A high-resolution scintillating fiber tracker with silicon photomultiplier array readout, NIM A 622 (2010) 542

[16] P. Jarron *et al.*, NINO: An Ultrafast Low-Power Front-End Amplifier Discriminator for the Time-of-Flight Detector in the ALICE Experiment, IEEE Trans. Nucl. Sci. 51 (2004) 1974

[17] J. Christiansen, HPTDC High Performance Time to Digital Converter, Manual Version 2.2 (2004)