The measurement of cosmic ray proton energy with electromagnetic calorimeter of PAMELA instrument

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***Abstract*. The method developed for proton energy measurement in energy range more than 50 GeV by the instrumentality of thin sampling calorimeter of PAMELA instrument is described. This method is based on a measurement of total deposited energy in calorimeter and usage of certain selection criteria of events. The results were obtained with a Monte Carlo simulation and then were applied to beam test data and flight information. The energy resolution of proton energy measurement remain about 45% for energies up to 10 TeV.**

***Keywords*: proton, high energy, method, calorimeter**

I. INTRODUCTION

The PAMELA is space experiment [1] for study charged particles in the cosmic radiation that has been launched on June 15 2006. The main scientific goal of experiment is precise measurement of the energy spectra of antiprotons, protons, positrons, electrons, light nuclei and their isotopes in cosmic rays in wide energy range [2]. PAMELA consist of several specialized detectors [3]: magnetic spectrometer with silicon tracking system, a time of flight system with three double planes, an anticoincidence system, a neutron detector, bottom shower scintillator detector and silicon−tungsten sampling electromagnetic calorimeter. The total depth calorimeter is 16.3 radiation lengths and 0.6 nuclear interaction length. The calorimeter composed of 44 silicon layers interleaved by 22 0.26 cm thick tungsten plates. Each silicon plane segmented in 96 strips. 22 planes are used for the X view and 22 for the Y view in order to provide topological and energetic information of the shower development inside the calorimeter [4].

Each thin calorimeter as spectrometer PAMELA electromagnetic one has ability to measure the energy of hadrons. The absorption of hadronic particles in matter, which undergo strong interaction, develops as a cascade process. The hadronic cascade is propagated through a succession of various inelastic interactions in which about half of the incoming energy is carried away by leading particles and the remaining part is absorbed in the production of secondaries. Neutral pion amount, on average, is a third of the all produced pions. The nuclear processes involved in the generation of the hadron cascade produce relativistic hadrons, nucleons from spallation and from evaporation, break-up and recoiling nuclear fragments [5]. It is generally known that energy dependence signals for hadrons are non-linear in most types of calorimeters. In thick calorimeters (e.g. about 10 nuclear length and more) hadrons have more energy more fraction of deposited energy transfer from the hadronic component to the electromagnetic one, as the number of hadronic interactions increases therefore the numbers of generated π's increases as well. Then π^0 decays into pairs of photons gives rise of electromagnetic showers [6].

However, in thin calorimeters (e. g. less than 2 nuclear length), the energy dependent signals are near linear with initial energy as mainly the first hadron interaction is contained inside. The measured energy of hadronic shower almost all is of electromagnetic fraction. Transferring energy from the hadronic component to electromagnetic component of the shower with energy increase does not exist in this case. At the same time the existence of energy-independent fluctuations in nondetectable part of energy lead up to value of energy resolution which will be worse than 20%.

So, in "thin" calorimeter primary hadrons and most of the charged pions produced in the first inelastic interaction escape the calorimeter without a second nuclear interaction. Neutral pions produced in the same interactions decay into two photons, which generate electron-positron pairs. The average energy of secondary pions is less than 10% of the initial energy. The electromagnetic shower resulting from the π^0s represents a superposition of several electromagnetic showers, with energy approximately 40 times less than the energy of the initial hadron [7]. Depending on the depth of the first inelastic interaction, these compact low energy electromagnetic showers will be fully or partially contained inside the calorimeter. Therefore measuring the signal produced by such electromagnetic shower superposition one can determine the energy of the incoming particle.

II. SELECTION OF APERTURE EVENTS

The Monte Carlo simulation's code GPAMELA [8] was used to assess the performances of the PAMELA calorimeter for high-energy protons and high-energy electrons as well as data of calibration with particle test beams at CERN. The described method shall be used to obtain proton spectrum in cosmic ray so it is necessary to select only aperture particles.

On the first step events in which primary particles downward crossed calorimeter were selected. For this events were rejected as follows:

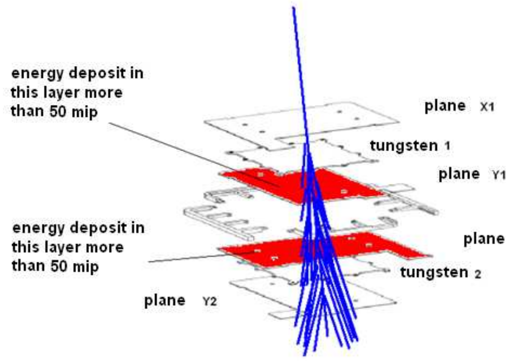

Fig. 1: The estimation method of starting point of the hadronic shower. For example in this fig shown the start of shower in first planes

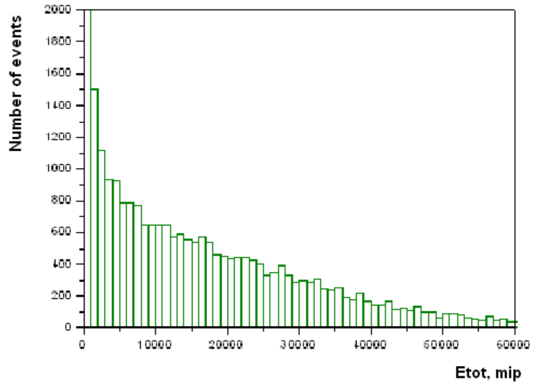

Fig. 2: Without any cut-off distribution of the total deposited energy in calorimeter initiated by a 1 TeV protons

1) Strips with maximum energy release are near side face of calorimeter by one cm at least in two nearby planes.
2) The centre of gravity of energy release in one plane is near side face of calorimeter by at least one cm from 7 till 21 layers.

As initiated shower high energy protons with energy more to 50 GeV is to be of interest, total deposited energy in calorimeter 4000 mip threshold was installed.

On the next step shower axis was reconstructed to extract particles with incident angle within aperture. The starting point of shower was identified by condition that energy deposit increases on 50 mip in any two subsequent layers for upper-half calorimeter (e.g. the maximum shower has to be inside calorimeter), as shown in fig.1. To identify the shower axis the center of gravity position within the i-th plane was used. It was defined as mean coordinate of distribution of the measured energies, E_j deposited in strips with co-ordinate x_{ij}, where:

$$\overline{x_i} = \frac{\sum\limits_j x_{ij} E_j}{\sum\limits_j E_j} \qquad (1)$$

j - number of strip in i-th plane [9]. Summation of series begins from starting shower plane. The determination of shower axis was based on method of least-squares approximation [10]. The values of angular resolution are defined as most probable value of proton energy distribution. It should be noted that value of angular resolution is considerably conditioned by independent shower energy fluctuation. Thus accuracy was obtained at about 0.1 rad. To cut the events with big mean of χ^2 (it means that axis not precisely known) the additional criterion was used.

III. Determination of the protons energy

Without any selection the total energy deposit distribution is similar to the one in fig 2 (for 1 TeV protons with in aperture incidence on the top surface of calorimeter). However, after described above cuts of events the peak on the left-side of this histogram, produced by non-interacting protons disappeared (see fig.3). This distribution can be represented by a universal curve KNO [11] at all energies.

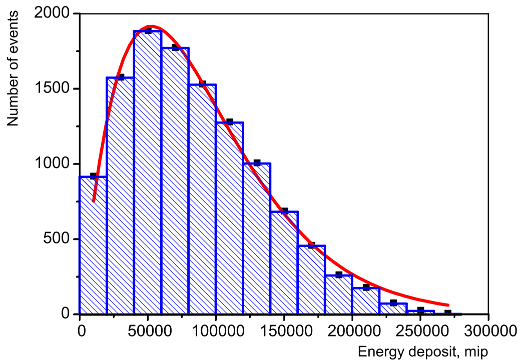

Fig. 3: Distribution of the total energy deposit for 2 TeV protons remaining after event selection (simulation result). The fitting function is KNO

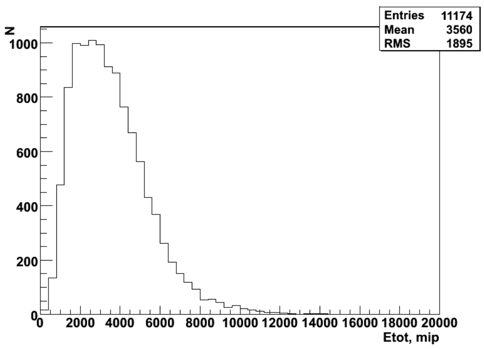

Fig. 4: Distribution of the total energy deposit for incident at 0^o 100 GeV protons remaining after event selection for the beam test data CERN 2003

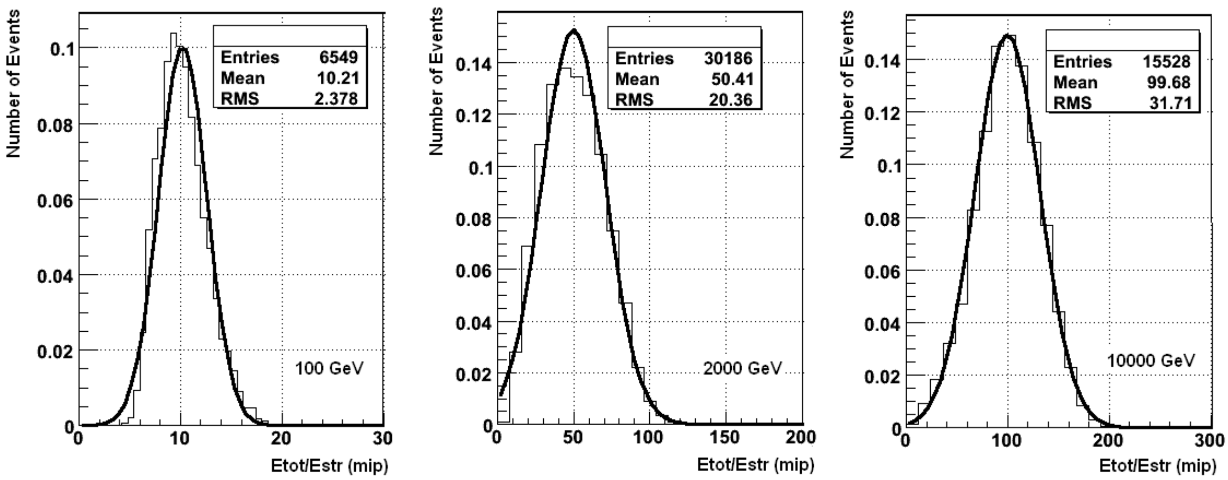

Fig. 5: Distribution of Etot/Est for 100, 2000, 10000 GeV protons remaining after event selection (simulation data)

The KNO scaling function giving the probability to get a response A, for protons with energy E is [12]:

$$P(A) = N_0(A/a)^b \exp -(A/a)^c \tag{2}$$

where N_0 is normalization factor, a, b are parameters depending on primary protons energy of, c is constant equal to 1.7.

This curve reflects the pion production multiplicity in the proton interaction with tungsten planes. It has RMS of about 45%.

Results of the KNO fit is presented on fig 3.

Described above selection cuts are applied also to the signal obtained from beam-test data and results in distribution shown in fig. 4. However, high-energy tail of this distribution can distort the spectral index and result in big errors of spectral slope after reconstruction of cosmic ray proton energy spectra. For all these reasons the using other variable than Q_{tot} is necessary. Such variable was found. The relation between total deposited energy E_{tot} and total number of hit strips E_{str} provide distribution better than the one obtain from the E_{tot}. Fig.5 shows E_{tot}/E_{str} distribution for 100, 2000 and 10000 GeV protons after on the same event selection. It is seen that there aren't any considerable tails in distribution and RMS is smaller than for previous case. From the Guassian fit to this distribution it was found that the RMS increase from 25% till 30% in energy range 100 GeV - 1 TeV, and then slowly drops. It could be seen in fig. 6. The described above selection cut efficiency for protons as function of initial energy was obtained and shown in Fig. 7. The efficiency E_{ff} has been fit over the energy range up to 10 TeV by follows function:

$$E_{ff} = \alpha E^{-\beta/E} \tag{3}$$

where α =0.33; β =37 GeV. Finally the initial energy of primary proton E (GeV) as function of mean value of E_{tot}/E_{str} (mip) was obtained. It is shown in fig 8. This

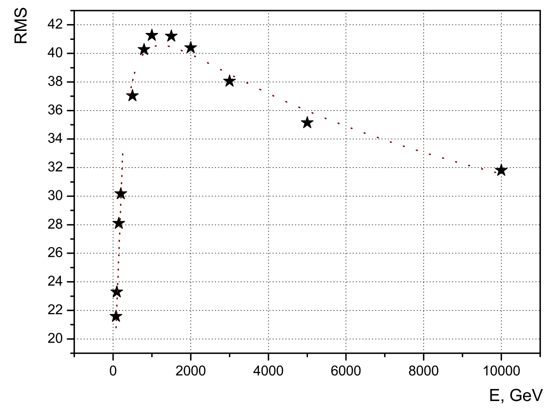

Fig. 6: The initial energy dependence of RMS

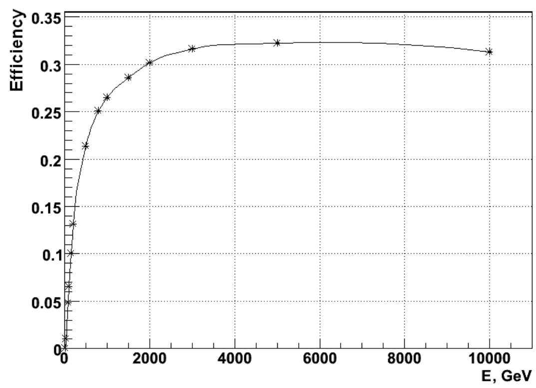

Fig. 7: Proton efficiency as function of primary energy

curve is non-linear beginning from about 3 TeV and can be fitted by 3^{th} order polynom:

$$E = a + b[\frac{E_{tot}}{E_{str}}] + c[\frac{E_{tot}}{E_{str}}]^2 + d[\frac{E_{tot}}{E_{str}}]^3 \tag{4}$$

where a=-500 GeV; b=60 GeV/mip; c=-1 GeV/mip^2 , d=0.015 GeV/mip^3.

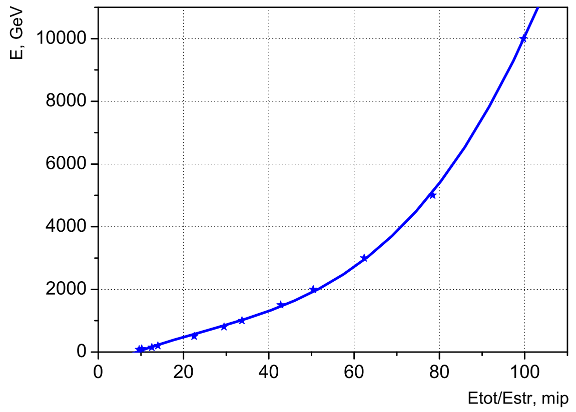

Fig. 8: The initial energy of primary proton E (GeV) as function of mean value of Etot/Estr (mip)

IV. Conclusion

The method of measurement of cosmic ray proton energy with electromagnetic calorimeter of PAMELA instrument was developed using simulation data. This method based on value of total deposit energy in calorimeter and total number of hit strips. The energy resolution in this case is about 30% that is good result because electromagnetic calorimeter of PAMELA is thin for hadron interactions. In addition, the efficiency for high-energy proton (> 1 TeV) is about 30%. It's more than enough to obtain the high-energy proton spectrum with due statistics for more than three year measurements in PAMELA experiment. Preliminary results agree in general with spectral slope index 2.75 in energy range 20-10000 GeV.

V. Acknowledgments

This work was partially supported by RFBR (grant #07-02-000922a). The authors thanks for help NtSOMZ and TsKB Progress.

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