33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013
THE ASTROPARTICLE PHYSICS CONFERENCE

Report on Development of Readout Electronics for the Prototype of DAMPE Calorimeter

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Abstract: The DArk Matter Particle Explorer (DAMPE) is being developed as a space instrument to observe high energy primary cosmic rays, especially positrons/electrons and gamma rays with an energy range from 5 GeV to 10 TeV. The DAMPE detector is intended to operate on a satellite orbit in future, and its major scientific objectives are cosmic ray, gamma ray astronomy and dark matter particles. A Bismuth Germanate(BGO) calorimeter, which composed of a stack of BGO crystals, is a critical sub-detector for measuring the energy of cosmic particles, distinguishing positrons/electrons and gamma rays from hadron background, and providing trigger information. In year 2012 a prototype model of DAMPE was accomplished, including a scaled-down BGO calorimeter and its readout electronics. After ground-based cosmic ray tests in Nanjing, China, we successfully carried out an accelerator experiment at CERN, in October, 2012, using the Super Proton Synchrotron (SPS). The development of the readout electronics and the performances during experiments is to be presented in this paper.

Keywords: Dark Matter, DAMPE, Calorimeter, BGO.

1 Introduction

Observing high energy particles in space is becoming a hot topic in the international community of physics, which is regarded as a much hopeful method for revealing the hidden nature of dark matter. Several experiments have been carried out, such as the ATIC Antarctic Baloon[1], Fermi satellite[2], PAMELA satellite[3] and AMS02[4].

DAMPE (DArk Matter Particle Explorer) is a scientific satellite proposed by Purple Mountain Observatory, CAS, University of Science and Technology of China, Institute of Modern Physics, CAS, etc. The main scientific objectives of DAMPE are cosmic ray study, gamma ray astronomy, and searching for the clue of dark matter particles by investigating the composition and energy spectra of primary cosmic rays, especially positrons, electrons and gamma rays over an energy range from 5 GeV to 10 TeV.

The calorimeter, which is composed of a stack of BGO (Bismuth Germanate) crystals, is a critical sub-detector for measuring the energy of cosmic particles, distinguishing positrons/electrons and gamma rays from hadron background, and providing trigger information. The BGO calorimeter consists of 14 layers with 22 BGO crystals in each layer. Each crystal is viewed from both sides with two PMTs (photomultiplier tubes) respectively. In order to achieve a large dynamic range, each PMT base incorporates a three dynode (2, 5, 8) pick off, which results in 616 PMTs and 1848 readout channels.

During 2012, a prototype model of DAMPE, including a scaled-down calorimeter, was developed. After one month joint-test with ground-based cosmic rays in Nanjing, a beam test was successfully carried out at CERN in October, 2012[5].

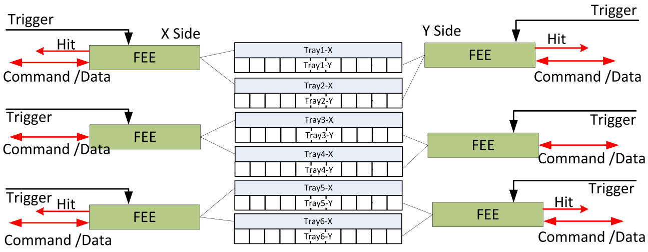

Figure 1: Architecture of the prototype calorimeter detector and readout electronics.

2 Architecture of the prototype calorimeter and readout electronics

The prototype system is assembled in August, 2012. As shown in Figure1, the prototype calorimeter is composed of 6 trays (from 1 to 6), with 2 layers in each tray, while each layer contains 11 BGO crystals. Two adjacent layers are oriented by 90 degree to provide a X-Y measure of the particle hit position. Each crystal, with the size of 2.5 cm by 2.5 cm by 30 cm, is viewed by a R5610 PMT from single side, thus 132 BGO crystals and 132 PMTs are used, with 396 readout channels in total.

The readout system consists of 6 FEE (Front End Electronics) modules, while each module takes charge of reading out two X or two Y layers from adjacent trays. The top two trays (1,2) and bottom two trays (5,6) are used for triggering, and the corresponding 4 FEEs needs to provide hit signals besides performing precise charge measurement of the PMT dynode signals. Two PDHU (Payload Data Handling Unit) crates are used for controlling the FEEs, receiving scientific data, and generating trigger.

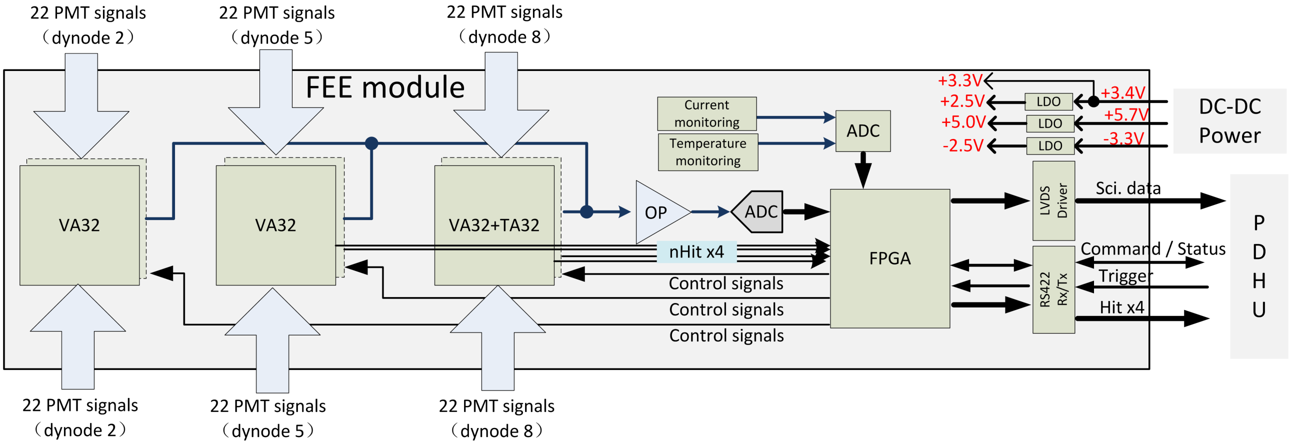

Figure 2: Block diagram of the prototype FEE module.

3 The FEE Module

The main functions of FEE module are measuring charge of PMT signals and providing hit information of the detector. Figure2 shows the block diagram of FEE prototype module. There are 2 VA32 chips and 4 VA32+TA32 chips mounted on each FEE. The VA32 and TA32 ASICs are developed by IDEAS (Norway), and the versions in the prototype FEE are VA32HDR14.2 and TA32CG.

The VA32HDR14.2 is a 32-channel low noise, low power ASIC for charge measurement, with a dynamic range from -3 pC to +13 pC. The TA32CG is a 32-channel trigger chip, which is designed to be used with a matching VA ASIC, such as VA32HDR14.2. The TA32CG chip includes a fast CR-RC shaper followed by a level-sensitive discriminator in each channel. The trigger signals from 32 channels are are or'ed together to be a common output. The analog output of six VA32 chips are wired together to a I-V conversion circuit and digitized by a 14-bit ADC (analog-to-digital converter).

In our prototype design, each TA32CG is bonded with a VA32HDR14.2 in a single ceramic package (CQFP132). Each VA32 chips handles only 11 inputs, while other channels are left unconnected on PCB. When any input channel in a layer is active, the corresponding TA32CG will generate a trigger pulse. The thresholds of 4 TA32 chips are provided independently. Thus two dual-channel DAC chips are used to generate the thresholds.

A built-in charge-injection circuit is implemented in the FEE module for charge calibration of all VA32 channels. An analog switch is used to generate step pulses and then to inject charge into VA32 chips through a capacitor. The amplitude of the calibration charge is determined by the voltage set by a 12-bit DAC (digital-to-analog converter). In order to record the ambient temperature of the electronics and detectors during long term operation, a temperature monitoring circuit using two thermal-resistors are applied. Besides, a current monitoring circuit is designed to record the total VSS (-2.5V) supply current of all VA32 and TA32 chips, which can be used to indicate SEL (single event latch-up) event after launch.

In most case of a cosmic ray event, only a few channels are "fired", which means it's not necessary to record the data of all channels. A simple compressing method is applied, which uses a high threshold and a low threshold for each channel. After digitization, the ADC data of each channel is compared with two thresholds respectively. The data less than the low threshold (means pedestal), or greater than the high threshold (means saturation) will be discarded, which can greatly reduce the amount of scientific data, and therefore lighten the load of data storage and transmission.

The control logic of ASIC chips, ADCs, DACs and calibrations circuit, and data compressing algorithm, are all implemented in a ProAsic-Plus Flash-based FPGA. All configuration data, including TA registers and compressing thresholds, are transmitted to FEE by PDHU through RS422 serial bus, and stored in FPGA block RAM. The charge measurement results of all channel are packed into a scientific data format, and send to PDHU through serial bus with LVDS signals. The monitoring information, including temperature, current and some status registers in the FPGA are packed into a remote-sensing data format, and send out to PDHU through serial bus with RS422 signals.

4 Test Results

4.1 Electronics Test

During 2012 we developed 8 FEE prototype modules, while 6 modules are installed for detector readout and the other 2 modules are spares. In order to insure the quality, we carried out strict test process for all modules, including pedestal test, signal/calibration sweep test, hit test, etc.. Figure4 illustrate the sweep test result using calibration circuit, while the calibration capacitors are 5 pF. Figure5 shows the sweep test result using a Tek AFG3251 pulse generator. The charge is injected to the FEE channel by a step pulse through a 10 pF capacitor. We can calculate the coefficient of input charge versus ADC bin from the figures, and the result is about 0.9 fC/bin. Figure6 illustrates the pedestal noise of all channel in a prototype FEE. The equivalent noise of all channels is below 3 fC in rms.

4.2 Ground-based Cosmic Ray Test

After mass production, quality test and burn-in, the FEEs are installed with prototype calorimeter, in Nanjing, in August, 2012. Other sub-detectors and PDHU, are assembled as well, for ground-based cosmic-ray joint test. Figure7 shows the pedestal distribution of three dynodes from one PMT unit, which indicates that the maximum equivalent noise (sigma) is about 4 fC and much less than the design requirement (10 fC). Figure8 shows the muon spectra from dynode 8 of a PMT. Figure9 shows good linear correla-

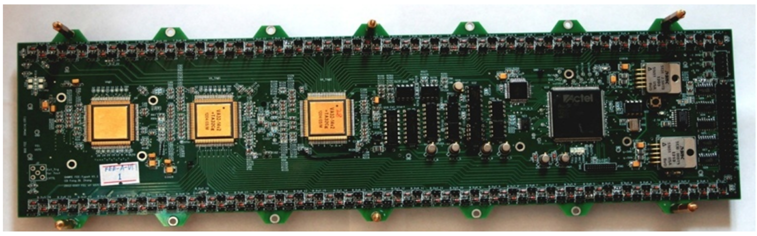

Figure 3: Picture of the prototype FEE module.

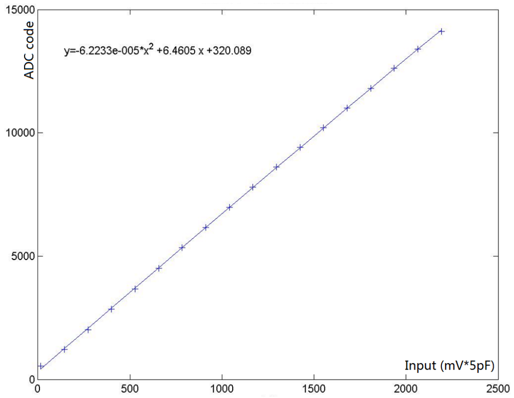

Figure 4: Test Result of calibration (Ch1, FEE-03).

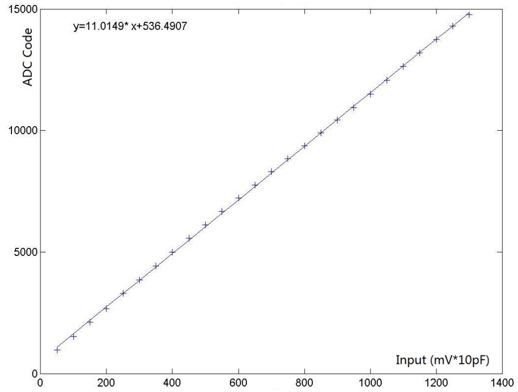

Figure 5: Sweep test with a pulse generator (Ch1, FEE-03).

tion between ADC values from dynode 5 (medium energy range) and dynode 8 (low energy range). The relative gain of the two dynodes is about 30, which matches the expectation.

4.3 Beam Test

After one month continually cosmic ray tests, the whole prototype system was transported to Prevessin, CERN, for beam test, in late September, 2012. The accelerator experiment was carried out in the first week of October, using the H4 beam of Super Proton Synchrotron (SPS). The purpose of the experiment is to evaluate the performances of detector and readout electronics. Positron/electron beams in the energy region from 5 to 290 GeV, and hadron beams from 30 to 300 GeV are used. Figure10 shows the MIPs spectra of one crystal. Figure11 shows linear correlation between dynode 5 and dynode 8 using 50 GeV electrons.

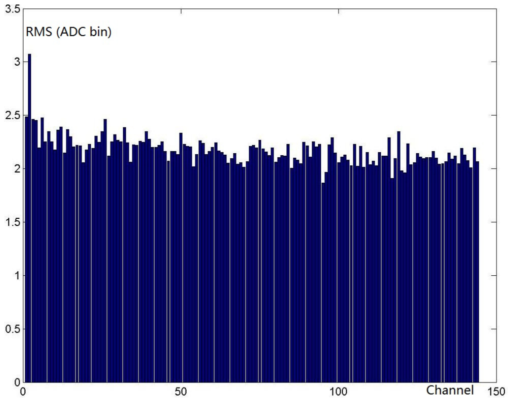

Figure 6: Pedestal rms (all channels of FEE-03).

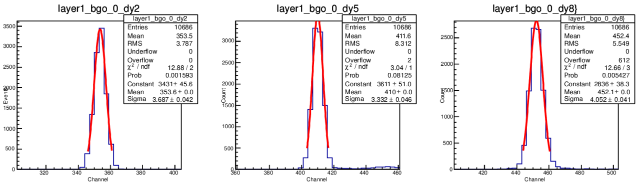

Figure 7: Pedestal distribution of three channels from a PMT unit.

These test results suggested that the performances and expectations of the electronics are well consistent. More detailed performances of the BGO calorimeter in Beam test, such as energy linearity, energy resolution and hadron discrimination, will be presented by the paper of Jian Wu in ICRC2013 proceeding, which suggests that the readout electronics meet the requirement of detectors.

5 Conclusions

The readout electronics for the prototype DAMPE calorimeter have been successfully developed. Ground-based cosmic-ray test and beam test were carried out. The test results showed that the readout system is compatible with the prototype detector, and its main features can satisfy the design requirements.

Acknowledgment: This work is supported by the Strategic Priority Research Program on Space Science, the Chinese Academy of Sciences (Grant No. XDA04040202-4).

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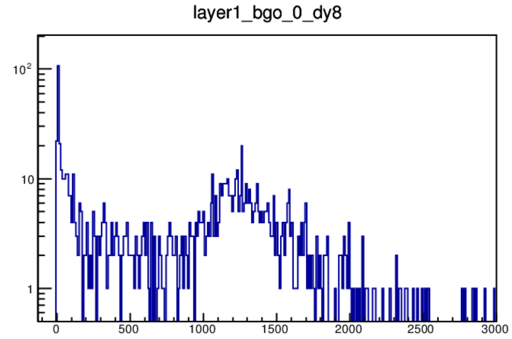

Figure 8: Spectra of a dynode 8 channel in ground-based cosmic test.

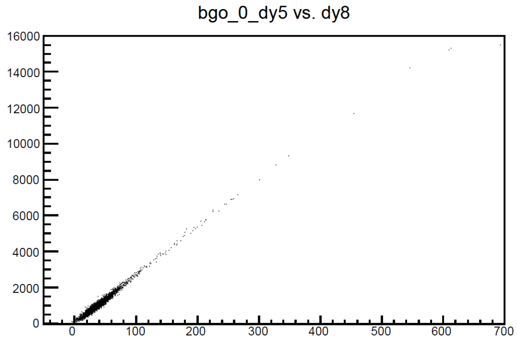

Figure 9: Correlation between dynode 5 and dynode 8 in ground-based cosmic test.

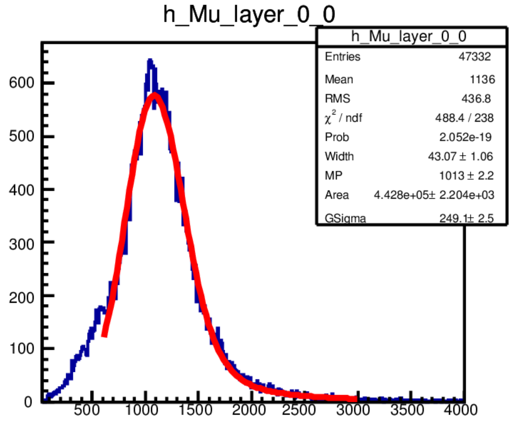

Figure 10: MIPs spectra of a crystal unit with hadron beam.

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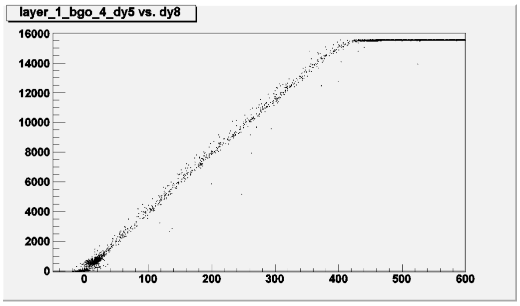

Figure 11: Correlation between dynode 5 and dynode 8 with 50 GeV electron beam.