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Dark Matter Particle Explorer: The First Chinese Cosmic Ray and Hard γ-ray Detector in Space

CHANG Jin

(*Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing* 210008)

Abstract The Dark Matter Particle Explorer (DAMPE) mission is one of the five scientific space science missions within the framework of the Strategic Pioneer Program on Space Science of the Chinese Academy of Science (CAS) approved in 2011. The main scientific objective of DAMPE is to detect electrons and photons in the range of 5 GeV–10 TeV with unprecedented energy resolution (1.5% at 100 GeV) in order to identify possible Dark Matter (DM) signatures. It will also measure the flux of nuclei up to above 500 TeV with excellent energy resolution (40% at 800 GeV), which will bring new insights to the origin and propagation high energy cosmic rays. With its excellent photon detection capability, the DAMPE mission is well placed for new discoveries in high energy-ray astronomy as well.

Key words Dark matter particle, Cosmic ray, Electron, Gamma-ray

Classified index P 35, P 1

1 Introduction

The Dark Matter Particle Explorer (DAMPE), an upcoming satellite supported by the strategic priority science and technology projects in space science of the Chinese Academy of Sciences, is designed to address a number of scientific objectives which include, understanding the mechanisms of particle acceleration in celestial sources and the propagation of cosmic rays in the Galaxy, probing the nature of dark matter, a form of matter necessary to account for gravitational effects observed in very large scale structures such as anomalies in the rotation of galaxies and the gravitational lensing of light by galaxy clusters that cannot be accounted for by the quantity of observed matter[1], and studying the high-energy behavior of gamma-ray bursts, pulsars, Active Galaxy Nuclei and other transients. On cosmic ray study, DAMPE will provide high energy resolution spectra of electron, positron, proton, helium nuclei and other heavy ions in the energy band from 10 GeV to ~1 PeV and their anisotropy in different energy ranges, with which the nature of cosmic ray sources in the solar neighborhood can be explored. In combination with the direct and more accurate measurement of cosmic ray spectra at lower energies, the propagation and acceleration of cosmic rays can be reliably constrained. The Galactic center, dwarf galaxies as well as galaxy clusters are rich of dark matter and are ideal sites to catch the dark matter annihilation/decay γ-ray emission. Thanks to the high energy resolution, DAMPE is suitable to identify the γ-ray line signals

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E-mail: chang@pmo.ac.cn

arising from dark matter annihilation or decay. Together with the measurements of continuum γ-ray emission from the dark mater rich regions and the electron/positron pair spectrum, the physical parameters of dark matter particles, such as the rest mass, annihilation cross section or lifetime, can be reliably constrained or even evaluated. So far the physical origin of the unexpected Galactic electron/positron excesses[2−5] is still to be figured out. On gamma-ray astronomy, DAMPE will monitor steady high energy astrophysical sources such as supernova remnants, pulsars, pulsar wind nebula and variable sources such as Active Galactic Nuclei, X-ray binaries, gamma-ray bursts to explore radiation mechanisms and related physical processes. Intriguingly, the measurement of the arrival time of the high and low energy γ-rays of GRB 090510-like event[6] can also be used to limit the variation of the speed of light arising from quantum gravity effects.

2 Instrument

The DAMPE detector, as shown in Figure 1, consists of a Plastic Scintillator strip Detector (PSD) that serves as anti-coincidence detector and charge detector, a Silicon-Tungsten tracker-converter (STK) that measures the direction of incident particle, a BGO imaging calorimeter of about 31 radiation lengths that measures the energy with high energy resolution, and a Neutron Detector (NUD) that gives types of high energy particle shower.

2.1 Plastic Scintillation Array Detector (PSD)

The PSD consists of one double layer (one is for X and one for Y direction) of scintillating strip detector made of scintillating strips of 1.0 cm thick, 2.8 cm wide and 82.0 cm long. The strips are staggered by 0.8 cm in a layer, which fully covers an area of 82 cm $\times$ 82 cm. The crisscross structure of PSD will help to obtain the positions of incident particles. The position resolution of the PSD is 6 mm, while its charge resolution is 0.25 for Z from 1 to 20. With the integration of the trajectories of incident particles obtained by the STK and the BGO calorimeter, the PSD is used to identify electrons and gamma rays. Simultaneously, as the back-up of the STK, it is also used to discriminate heavy ion species by measuring the energy loss of incident particles in the PSD.

The overall design of the PSD subsystem is sketched in Figure 1. All unit modules, FEE modules and the panels of high-voltage fan-out are installed with mechanical supporter. In detail, each of the 82 unit modules in PSD has adopted the pattern of double-end readout, with double output signals on each end. The number of related high-voltage lines and electronics channels is 164 and 328, respectively. Four FEE modules are applied to readout signals, and one for 82. Four panels of high-voltage fan-out are utilized to input the overall 164 channels.

2.2 Silicon-Tungsten Tracker (STK)

The STK is made of 6 tracking double layers, and each consists of two layers of single-sided silicon strip detectors measuring the two orthogonal views perpendicular to the pointing direction of the apparatus. Three layers of Tungsten plates with thickness of 1.0 mm are inserted in front of tracking layer 2, 3 and 4 for photon conversion. The STK uses single-sided AC-coupled silicon micro-strip detectors. The sensor is 9.5 cm $\times$ 9.5 cm in size, 320 μm thick, and segmented into 768 strips with a 121 μm pitch. Only every other strip will be readout, but since analogue readout is used, the position resolution is better than 80 μm for most incident angles, thanks to the charge

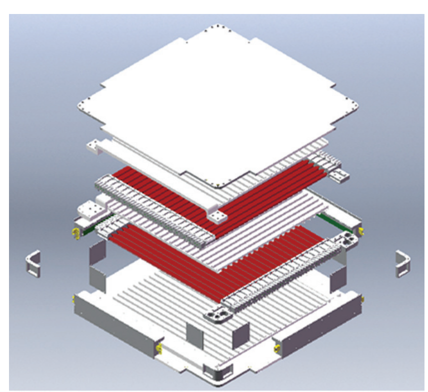

Fig. 1 Exploded view of PSD

division of floating strips. The photon angular resolution is about 0.10 at 100 GeV. Because of the analog readout, STK can also measure the charge of the incident cosmic rays. The full tracker uses 768 sensors, equivalent to a total silicon area of 7 m^2, comparable to silicon area of the AMS-02 tracker.

2.3 BGO Calorimeter (BGO)

A BGO calorimeter for the space observation of high energy cosmic-rays has been designed (Figure 2). It will be composed of 308 BGO crystal bars with a dimension of 2.5 cm × 2.5 cm × 60.0 cm. The BGO crystals form 14 layers with an area of about 60 cm × 60 cm each. The energy response to electrons and gamma-rays varies from 5 GeV to 10 TeV.

From simulation with GEANT4 code, the maximum value of deposit energy in one crystal is about 1.7 TeV for electrons of 10 TeV. For identification of EM shower from hadron shower based on shower profiles, the minimum measurable energy deposit per BGO bar down to 0.5 MIPs is required. So the dynamic readout ranges from 0.5 MIPs (about 11.5 MeV) to 1.7 TeV (about 1×10^5 MIPs) is necessary. A readout system that uses a PMT coupled with the front-end electronics circuit with VA32 chip is used. To cover the dynamic range, a multi-dynode output base is configured. The basic idea is that different energy ranges are measured by different dynodes respectively. Large signals will be readout from the earlier stage whose gain is small, while the small ones will be read from the later stage whose gain is large. As the dynamic range of electronics is about 2×10^2, the PMTs are required to provide a measuring range of 10^3, corresponding to about 35 for gain ratios of Dy8 to Dy5 and Dy5 to Dy2. The base board is shown in Figure 3. A LED calibration system was designed to test the PMT output unit (Figure 4). The outputs of the tested PMT are plotted in Figure 5. The results show that the dynamic ranges of Dy8, Dy5 and Dy2 will linearly respond to BGO energy deposits of 0.5–1.0 $\times 10^2$ MIPs, 30–3.0$\times10^3$ MIPs, and 1.0 $\times10^3$–1.0 $\times 10^5$ MIPs.

Cosmic ray test platform has been built and run

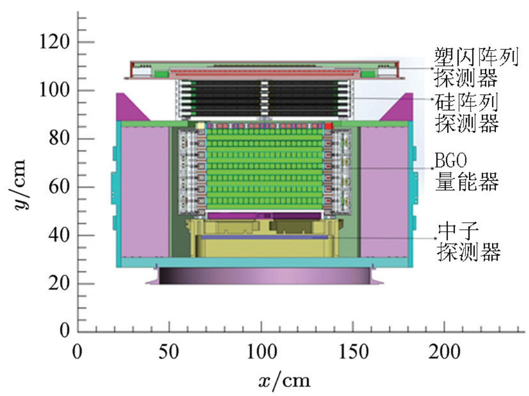

Fig. 2 Side view of the DAMPE detector

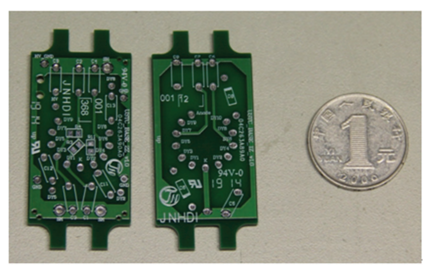

Fig. 3 PMT base board

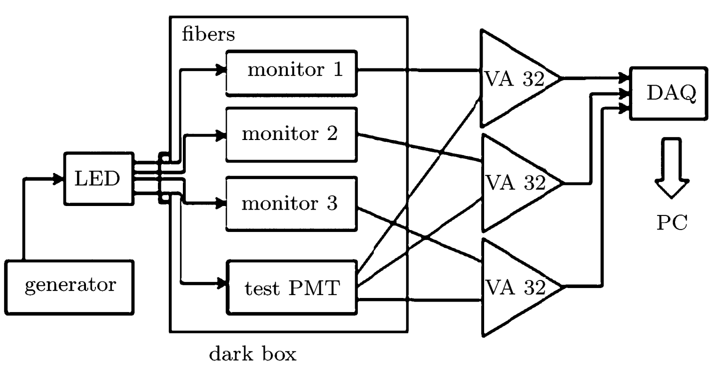

Fig. 4 LED calibration system

for MIPs-data acquisition to test each BGO crystal bar (Figure 6). The key calibration coefficients of energy deposition per ADC count for each Dy8 readout channel have been obtained. By means of this platform, a lot of reference data like calibration coefficients on ground will be obtained and updated. The trigger setting and timing for analog and logic signals were tested in the whole process for the real prototype of electro-magnetic calorimeter in Space. One typical MIPs spectrum of a BGO bar and the absorption length calibrated by MIPs are shown in Figure 7. A series of environmental tests have been done (see Figure 8).

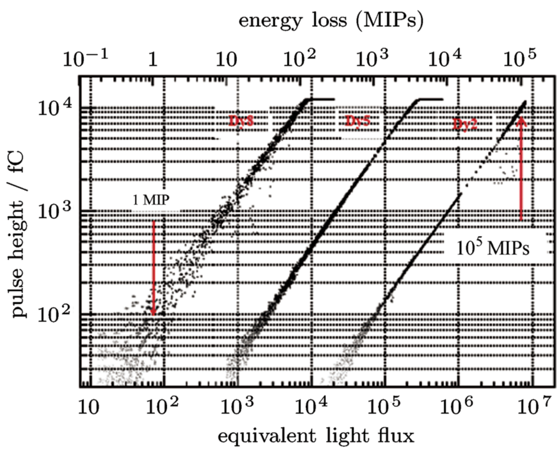

Fig. 5 Three dynodes output channel respond to light flux

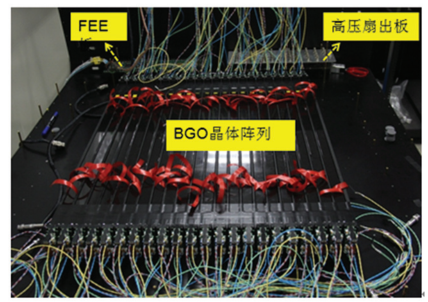

Fig. 6 Cosmic ray test platform

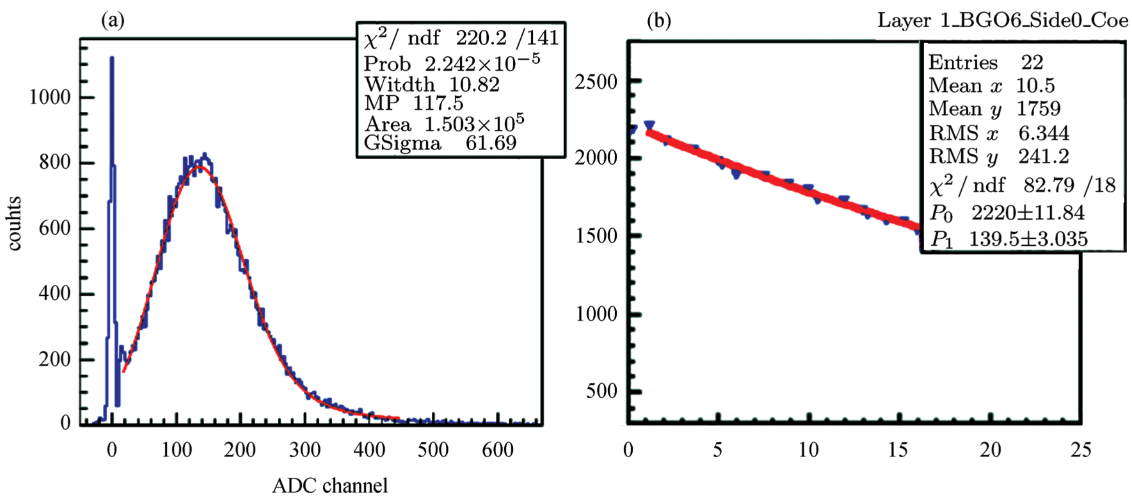

Fig. 7 BGO bar response to MIPs (a) and the absorption length of BGO bar (b)

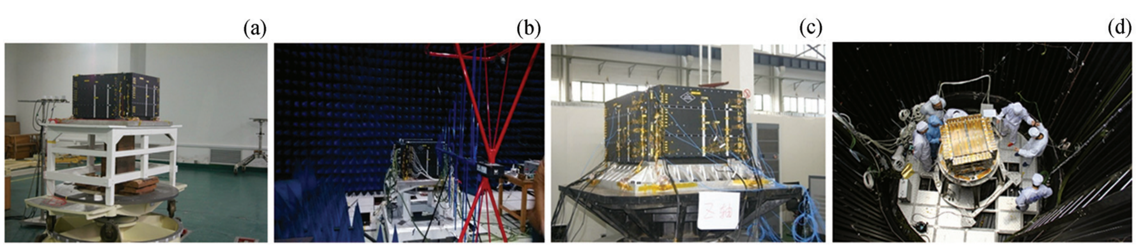

Fig. 8 Environmental test of BGO calorimeter

2.4 Neutron Detector (NUD)

The Neutron Detector (NUD) is a new detector subsystem for future DAMPE mission. It aims to complement the instrument's BGO calorimeter in identifying cosmic-ray electrons above 100 GeV. To identify electrons and gamma-rays from abundant hadronic cosmic rays is complicated. Hadron-induced showers tend to be accompanied by significantly more neutron activity than electromagnetic showers. So making use of the thermal neutron activity at late time ($> 2.5\,\mu$s) relative to the start of the shower can identify the electron from hadron. The DAMPE's NUD endeavors to measure the later thermal neutron shower activity by detecting the boron capture of these thermal neutrons in a boron-doped plastic scintillator, located underneath the BGO calorimeter.

The design of NUD is shown in Figure 9. It consists of 4 large area boron-doped plastic scintillators. The dimension of each scintillator is 30 cm $\times$ 30 cm $\times$ 1 cm.

3 Calibration of DAMPE Prototype at CERN in 2012

3.1 Instrument

The prototype detector has been built and beam tested at CERN to check the basic ideas of the detecting capabilities of the detector. The structure of the prototype and its beam test arrangement is shown in Figure 10.

Along the beamline, from left to right are, a pair of plastic scintillation detectors for outer trigger, Silicon Strip Detectors (SSD), Micromegas Detectors (MMEGAS) and the DAMPE prototype. The DAMPE prototype consists of 3 parts, *i.e.* a plastic scintillator tracker, a BGO calorimeter and a neutron detector from left to right in the plot. Two layers of plastic scintillators are installed as the tracking detector. Each layer contains X and Y dimension blocks. The signal is read out from one side of the detector through photomultiplier tubes. Each layer of the plastic scintillator tracking detector is made up of 15 blocks of plastic scintillator, which has a dimension of 2 cm $\times$ 2 cm $\times$ 100 cm. The two layers are aligned in X and Y direction alternatively. The BGO calorimeter is the main body of the prototype detector in the middle and is composed of 12 layers of BGO crystals. Each crystal has a dimension of 2.5 cm $\times$ 2.5 cm $\times$ 30.0 cm. Each layer consists of 11 crystals, covering an effective area of 30 cm $\times$ 30 cm. Alternate layers are orientated 90° to each other to provide an X and Y coordinates for tracking. BGO calorimeter is used for measurement of the shower development to determine the total energy and discriminate electrons and gamma rays from protons. One end of BGO crystal is coupled with PMT, while the other end is wrapped by reflective materials. Each PMT has 3 dynode signals (Dynode 2, 5 and 8) as output. VA32 chips are used for FEE to read out the signals.

The neutron detector is a boron-doped plastic scintillator with a dimension of 195 mm $\times$ 195 mm $\times$ 10 mm coupled to a PMT.

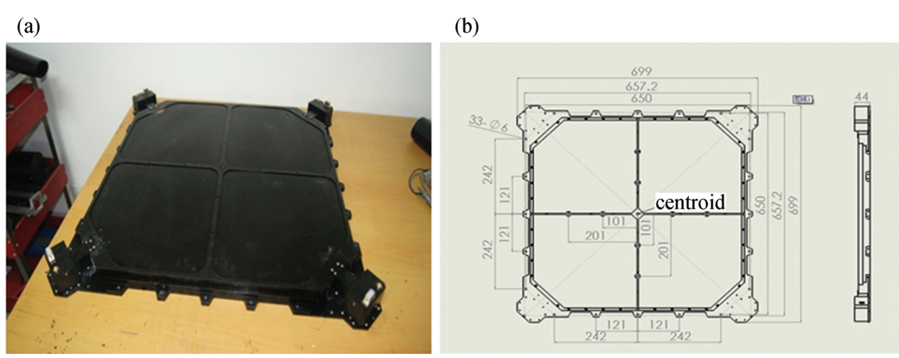

Fig. 9 The neutron detector (a) and its design (b)

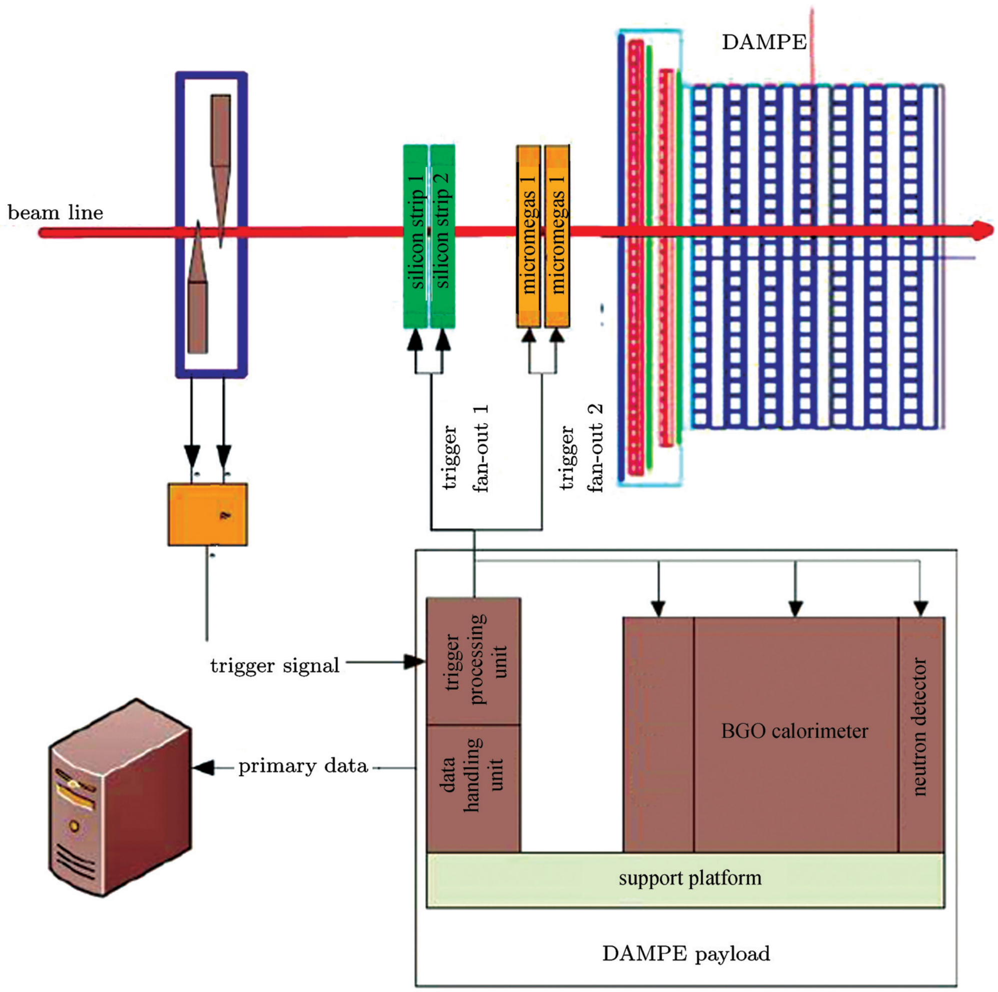

Fig. 10 Instrument along the beam

The prototype detector was installed in H4 area of CERN SPS facility. When hit by a beam particle (electron, proton or muon), the PLA at front creates a trigger signal and sends it to DAMPE trigger board. Then the trigger board fans out 3 channels of trigger signals to SSD, MMEGAS and the 3 subdetectors of DAMPE. Finally, the data handling unit of DAMPE collects and packs the data from subdetectors into a vast storage and later sends the data to a local PC. SSD and MMEGAS have their independent DAQ system.

3.2 Beamtest Results

After calibrated with cosmic muons for low energy end, the prototype was scanned with electron beam at 8 different energies, *i.e.*, 250, 200, 180, 100, 75, 50, 20 and 5 GeV respectively. Proton beams are provided with 50, 250, 280 and 300 GeV while muon beam has mono energy which is 150 GeV.

Figure 11 shows the energy resolution for the eleven electron beam energies. It can be clearly seen that for energy above 20 GeV, energy resolution is always better than 1.2% which is consistent with simulation results.

The energy linearity is shown in Figure 12.

Tracking resolution *via* center of weight is plotted in Figure 13. The center of weight is calculated layer by layer and then fitted by a straight line. The angle between the fitted line and incoming beam direction is the result, which is less than 0.5° for almost all the beam energies provided.

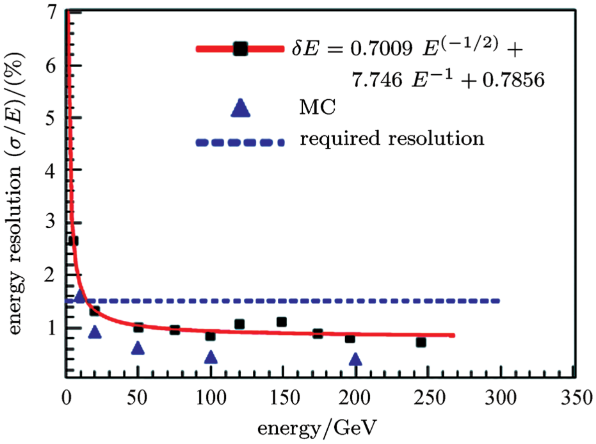

Fig. 11 Energy resolution of electron at 11 different beam energies provided in H4

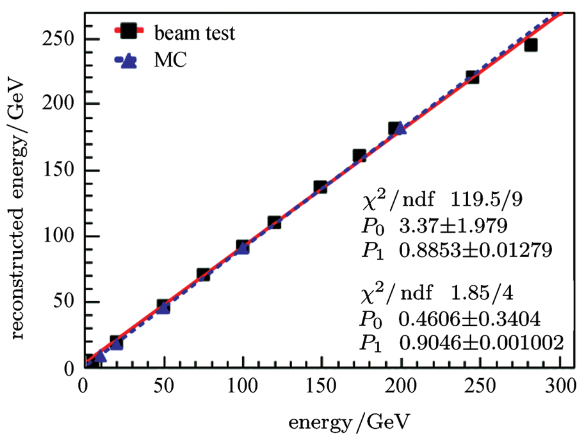

Fig. 12 Relation between beam energy and reconstructed electron energy for electrons

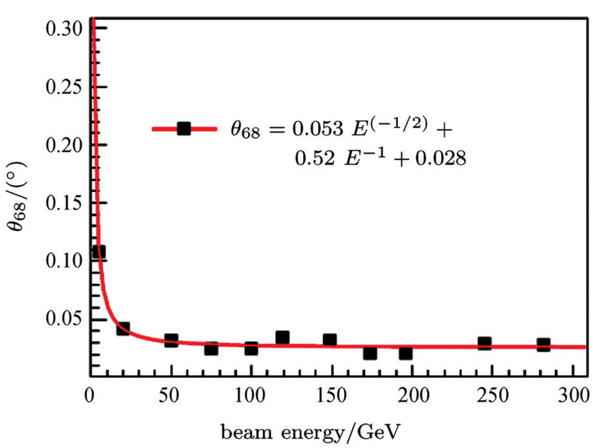

Fig. 13 Angle between the fitted straight line and the incoming beam direction

The electron (gamma) and proton separation capability is described by the so-called RMS and F-value[2]. Figure 14 and 15 are the two dimensional distribution of the relation between energy fraction and RMS^2 for BGO Layer 11 and 12 respectively. The black dots are protons and the red ones are electrons. The two components are separated clearly.

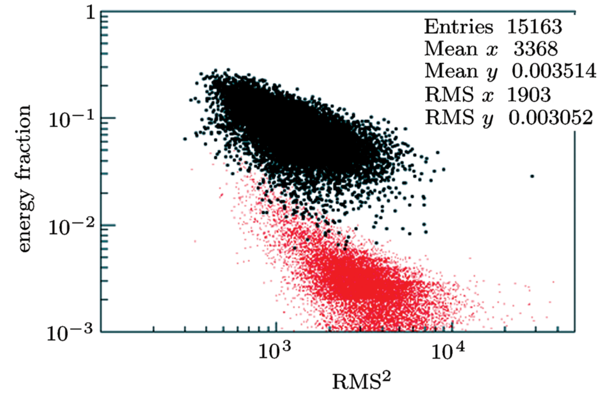

Fig. 14 Energy fraction versus RMS^2 for BGO Layer 11

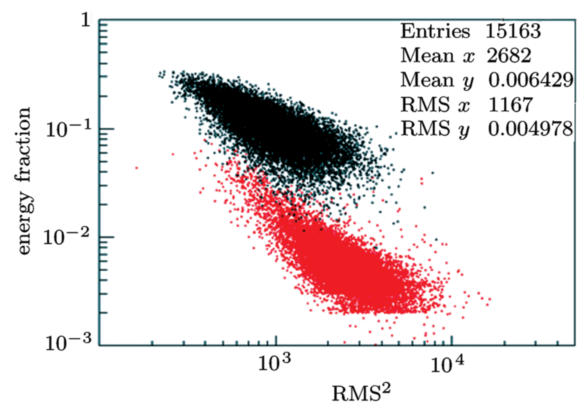

Fig. 15 Energy fraction versus RMS^2 for BGO Layer 12

Figure 16 and 17 display the F-value of BGO Layer 11 and 12 respectively. If F-value were set to be less than 19 and 14 for BGO Layer 11 and 12 respectively, the detection efficiency for electron would be 95% while the contamination of proton would be 0.0395% which is consistent with the simulation result.

The beam test results show that the design of DAMPE prototype detector for high energy cosmic electron/positron and gamma-ray measurement has a proton back-ground pollution lower than four ten-thousandth while keeping electron detection efficiency at 95%. The energy resolution is around 1% for the

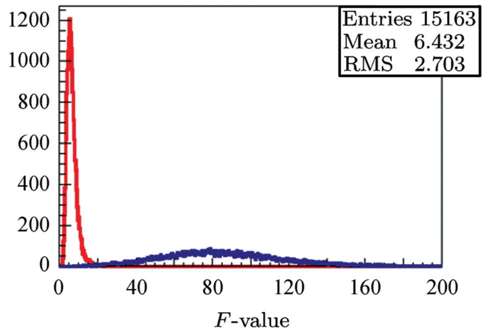

Fig. 16 F-value of BGO Layer 11

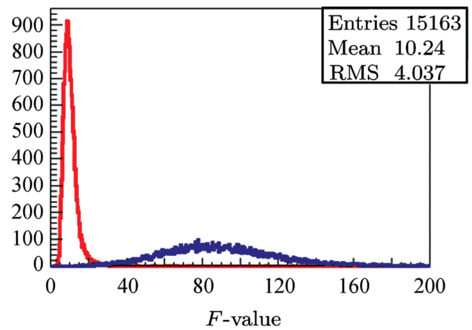

Fig. 17 F-value of BGO Layer 12

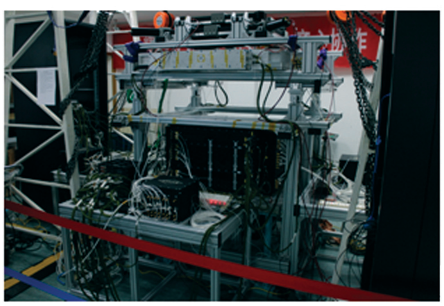

Fig. 18 DAMPE detector ground test (from top to bottom are PSD, BGO calorimeter and NUD)

interested energy range, which is consistent with simulation results. Thus the design is suitable for such a mission in principle.

4 Present Status

Three full size detectors except STK have been integrated together to form the engineering model. This model is tested with cosmic muons substantially (see Figure 18).

Fig. 19 BGO calorimeter has been installed onboard satellite

The trigger system has been calibrated using cosmic ray muons and other high energy secondaries.

After the cosmic test, all detectors are now installed on the satellite platform (see Figure 19) to be tested as a whole through mechanic and thermal vacuum environments. This model is also scheduled for beam test at CERN later on.

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