Design and performance study of the HEPP-H Calorimeter onboard the CSES satellite *

Yu-Fei Nan1, Zheng-Hua An2, Hang-Xu Li2, Xiao-Yun Zhao2, Xiang-Yang Wen2, Da-Li Zhang2, Shu-Guang Cheng1, Xin-Qiao Li2, Hui Wang2, Xiao-Hua Liang2, Feng Shi2, Yan-Bing Xu2, Xiao-Xia Yu2, Ping Wang2, Hong Lu2, Huan-Yu Wang2, Yu-Qian Ma2

1 School of Physics, Northwest University, Xi’ an 710069, China
2 Key Laboratory of Particle Astrophysics (LPA), Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China; anzh@ihep.ac.cn

Received 2017 December 27; accepted 2018 July 9

Abstract The China Seismo-Electromagnetic Satellite (CSES) will investigate iono-magnetospheric disturbance and will monitor the temporal stability of the inner Van Allen radiation belts. In particular the mission aims at confirming the existences of a temporal correlation between the occurrence of earthquakes and the observation of electromagnetic disturbances, plasma fluctuations and anomalous fluxes of high-energy particles precipitating from the inner Van Allen belt in space. The high energy detector of High Energy Particle Package (HEPP-H) is a payload of CSES and is designed for detecting electrons (2–50MeV) and proton (20–200MeV) in earth 500km orbit. CSES has been launched in the February of 2018. In this paper, the instrumentation and development of the HEPP-H calorimeter is described. The calibration with beam particles (electrons and proton) is discussed in detail.

Key words: telescopes — instrumentation: detectors — site testing

1 INTRODUCTION

The China Seismo-Electromagnetic Satellite (CSES) which mainly monitors the electromagnetic fields, plasma parameters, high-energy particles and other physical quantities (Zhang et al. 2009) is a testing platform for exploring precursory information of earthquake, monitoring and forecasting the space environment and studying the Earth System Science. The space observation technology is aimed at studying seismic effects in a larger spatial and temporal scale and different observation methods of capturing dynamic changes of particles, which has the advantages of surface observation techniques. The results (Parrot et al. 1985; Larkina et al. 1989; Aleksandrin et al. 2009; Li et al. 2010) show that the particles bursts of high-energy particles in space are accompanied by the main shock of large earthquakes. And the particles bursts occurs in tens of minutes to a few hours before the earthquake. Therefore, it has the great significance for the research of earthquake precursor and earthquake warning. The high-energy particle package (HEPP) is one of the payloads of CSES. HEPP-H is a part of HEPP. The primary objectives of HEPP-H are to measure the flux, energy spectrum and angle of incidence of highly energetic charged particles (protons and electrons) in the space. The HEPP payload has been launched in the February of 2018.

* The subject is supported by the National Natural Science Foundation of China (Fund: 11405192) and the National Natural Science Foundation of China (Fund: 11775251).
HEPP-H is made up of the electronics box and the sensor (Figure 1). The HEPP-H electronics box provides the power supply and data management for sensor. The structure explosion diagram of the sensor is shown in Figure 2. It mainly contains front-end electronics (FEE) board, data acquisition (DAQ) board and three sub-detectors.

1) The silicon-strip tracker (STK) consists of two layers of double-sided silicon strip detectors (DSSDs) which have an active area of 100cm². It mainly provides the tracking information of the incident particles (Zhang et al. 2017).

2) The calorimeter module contains 5 layers of scintillator in dimensions of $120 \times 120 \times 30$ mm$^3$. STK and calorimeter work together to measure the energies of the charged particles passing through the DSSDs.

3) The anticoincidence plastic scintillation detector (ACD) surrounds the five sides of calorimeter except the side of detection viewing field. It is designed to eliminate the influence of incident particles which traverse the spectrometer or outside the detective field (Liu 2013).

2 CALORIMETER READOUT SYSTEM

2.1 Calorimeter Design

The HEPP-H calorimeter is built on a plastic scintillator (PS) and four CsI (TI) scintillation crystals with photomultiplier tube (PMT) readouts. The scintillators are arranged in five layers, and the dimension of each scintillator is $120 \times 120 \times 30$ mm$^3$. The structure of calorimeter module is shown in Figure 3. Calorimeter module is mainly measures the deposited energy of high-energy particles (electrons, protons). In order to reduce the bremsstrahlung of electrons, the first layer of calorimeter is the plastic scintillator, and the remaining four layers are CsI (TI) crystal. Each layer of the scintillator is read out with two PMTs, and the PMT is used in R7600-300 produced by Hamamatsu Photonics (photocathode sensitive area is $18 \times 18$ mm$^2$, weighs about 30g). A light guide is added between the scintillator and PMT to match with the scintillator’s end and the PMT photocathode size, which improves the collection efficiency of light. And a 1mm thick optical coupling film (silicone pad) is added between the light guide and PMT to protect scintillator and PMT from the collision expected on launch. A two-layer Tyvek fiber

---

paper (2 × 130µm) was chosen as the reflective material for the scintillator of calorimeter, and the reflective material is covered with a black polyimide aluminized film as a light-shielding material. Each unit structure of calorimeter is shown in Figure 4.

2.2 Front-end Electronics Design

The signals emerging from calorimeter are read out by the method of using discrete components. And the circuits are controlled by Microcontroller Unit (MCU) and FieldProgrammable Gate Array (FPGA). The frame diagram of calorimeter is shown in Figure 5.

The PMT injects currents to a charge sensitive preamp which converts the charge into voltage and amplifies the voltage signal. The preamp signal is further amplified and filtered by the main amplifier into Gaussian shape with 250ns rising time. The Gaussian shape is followed by a peak-detecting track hold which can track the amplitude of the pulse and hold the peak amplitude on the holding capacitor.
Fig. 5 The whole readout system frame diagram of calorimeter

Two multiplexers on the output of the ten peak-detecting track holds select the sampling signal of each scintillator for subsequent conversion to a digital signal by the analog-to-digital converter (ADC).

PS signal is also used for calorimeter triggering of HEPP-H instrument. Therefore, the PS signal is divided into two parts after the main amplifier. One part is held by a peak-detecting track hold. The other part is identified by a discriminator. The discriminator contains a comparator, a monostable chip, and a digital-to-analog converter (DAC). MCU controls the DAC to set discriminator level, and the comparator identifies the PS signal overflow. The output signal of the comparator is shaped into a TTL pulse. When this TTL pulse triggers the FPGA, the FPGA control the ten peak-detecting track holds to hold the calorimeter single.

The readout circuits of the four CsI (Tl) crystals are similar to PS circuits. The signal of CsI is amplified by the preamp and main amplifier, and then this signal peak is held by a peak-detecting track hold. The difference from PS circuits is that CsI circuits does not have the discriminator.

3 THE ACQUISITION OF CALORIMETER

3.1 The acquisition circuit of calorimeter

The controller chips of DAQ system are FPGA and MCU. FPGA chip APA300\(^2\) was developed by ACTEL using the FLASH process. And MCU chip S80C32E\(^3\) was developed by Atmel. The DAQ system is shown in Figure 6. DG408 is a single 8-Channel analog multiplexer. Therefore, a multiplexer on the output of the eight peak-detecting track holds of CsI (Tl) selects one single in FEE board, and this single and two outputs of peak-detecting track hold of PS are selected by a multiplexer in DAQ board. The output of the multiplexer will be digitized by ADC. FPGA provide the timing and sequencing for ten peak-detecting track holds, two multiplexers and one ADC to capture the event of calorimeter.

The DAQ MCU is responsible for communicating with the processing data system and setting the discriminator level. After powered on, DAQ MCU will initialize DAC. And it also can accomplish instruction and data transfer with the FPGA by accessing the instantiated RAM, REG, and EEPROM in FPGA.

\(^2\) ProASIC PLUS Flash Family FPGAS, v5.9 Actel Corporation.

\(^3\) Atmel Rad. Tolerant 8-bit ROMless Microcontroller 80C32E, Atmel Corporation.
3.2 The logic of FPGA

FPGA is responsible for providing the timing and sequencing and receiving data from FEE. All the logic of the calorimeter readout system is accomplished by the FPGA. It mainly includes seven parts, as shown in Figure 7. After power on, all the modules will be initialized by the watchdog module. And the configuration of DAC is realized by the MCU via DAC control module. When TTL pulse triggers the FPGA, trigger module will judge the trigger. If the trigger is valid, the EMC module would begin to acquire the data of FEE. EMC module controls the ten peak-detecting track holds to stretch the peak pause. After peak-detecting track holds charging complete, EMC module will control the two multiplexers to successively output the ten holding signal. At the same time, EMC module controls the timing of ADC to digitalize the analog signals. Then the digital data from ADC will be packaged into scientific data. RAM module caches and packages the scientific data in a packet. When the packet is full, RS422 module pushes it to satellite system.

3.3 Processing Data System

S80C32E is the controller of processing data system (PDE). Its main function is to communicate with satellite system via the CAN bus. PDE MCU and DAQ MCU mainly communicate with the serial port. When the PDE MCU receives the instruction which is sent by satellite system, it will judge the type of instructions, and then respond the feedback data to the satellite system. After that the PDE MCU will repackage the instruction and send it to DAQ MCU to adjust the detectors and receive the key data. PDE MCU will store the feedback data of DAQ MCU into the array, waiting for the response of the next satellite system instructions.

4 RESULT OF BEAM TESTS

The proton beam test of HEPP-H was conducted at HIRFL (Heavy Ion Accelerator in Lanzhou) in June 2016. The energy range of proton beam: 15–200MeV. In December 2016, electron beam test was conducted at Linear Electron Accelerator Test Beam Facility at the IHEP. The energy range of electron beam: 1.5–40MeV. The connection diagram of beam test is shown in Figure 8. In the beam tests, we connected the power supply interface, the telemetering output and data transmission interface of
HEPP-H to ground checkout equipment. And the ground checkout equipment was connected to PC and the regulated power supply. The ground checkout equipment can control the relay power on or off by OC instructions of MCU. It can simulate Satellite Keeping Operation system to send the telemetering instructions and receive the data. At last, we store the data in the computer.

The energy reconstruction of the incident particle requires the addition of deposition energy in each layer of the scintillator and DSSDs. We also need to calculate the deposition energy of particles in the packaging layer and structure. Finally, we revised the results. The Energy spectrum of results are shown in Figure 9 and Figure 10. The energy points of the 100MeV proton and the 2MeV electron are selected here.

According to the beam test model and the structure of the calorimeter, Geant4 were used to simulate the incidence of particles, the deposition of energy, the light transport and the PMT response in the calorimeter of HEPP-H. Figures 11 and 12 shows comparisons of the reconstructed energy and energy resolutions change with the incident particle beam energy between the beam test data and the simulation. The energy resolution of protons is less than 10% (FWHM) in the whole energy range. The energy resolution of electrons above 9MeV is less than 10% (FWHM). The result of simulation is corresponding
Fig. 9 100MeV proton energy spectrum

Fig. 10 2MeV electron energy spectrum

Fig. 11 The reconstructed energy (left) and energy resolutions change (right) with the incident proton beam energy.

to the results of beam test in the range of error, which confirms that the calibration and reconstruction is available. When the energy of electrons is above 20MeV, spectrum is broadened by energy leakage because of the bremsstrahlung, which leads to the deviation of energy reconstruction.
CONCLUSION

HEPP-H has been delivered to satellite system. It also has completed the environmental test, beam test and so on. Judging from the results of beam tests, the energy resolution of calorimeter of HEPP-H in the whole range of proton detection and in the region of electron energy above 9MeV can be better than 10% (FWHM). Other particle resolution and pitch angle test results will be completed in the next few months. With the launch of CSES, HEPP-H will get the accurate measurement of the charged particle flux and energy in the radiation band.

Acknowledgements  Thanks to the proton beam provided by the Heavy Ion Research Facility in Lanzhou (HIRFL). The authors wish to thank Professor Wang Jian-Song and Professor Liu Jie from Institute of modern physics, Chinese Academy of Sciences on the beam application and test setup.

References

Liu, H.-Y. 2013, The design and development of the HEPP anti-coincidence detector and front-end electronics, PhD thesis, University of Chinese Academy of Sciences