RAA 2018 Vol. **18** No. **12**, 154(6pp) doi: 10.1088/1674–4527/18/12/154
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Research in Astronomy and Astrophysics

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

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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 the High Energy Particle Package (HEPP-H) is a payload onboard *CSES* and is designed for detecting electrons (2–50 MeV) and protons (20–200 MeV) in its 500 km orbit above Earth. *CSES* was launched in February 2018. In this paper, the instrumentation and development of the HEPP-H calorimeter are described. The calibration with beam particles (electrons and protons) is discussed in detail.

Key words: telescopes — instrumentation: detectors — site testing

1 INTRODUCTION

The *China Seismo-Electromagnetic Satellite* (*CSES*), which mainly monitors electromagnetic fields, plasma parameters, high-energy particles and other physical quantities (Zhang et al. 2009), is a testing platform for exploring the precursory information on earthquakes, monitoring and forecasting the space environment, and studying Earth system science. The associated space observation technology aims at investigating seismic effects on a larger spatial and temporal scale with different observation methods that capture 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 particle bursts of high-energy particles in space are accompanied by the main shock of large earthquakes, and particle bursts occur tens of minutes to a few hours before an earthquake. Therefore, it has great significance for research on earthquake precursors and earthquake warning. 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 space. The HEPP payload was launched in February 2018.

HEPP-H is made up of an electronics box and a sensor (Fig. 1). The HEPP-H electronics box provides the power supply and data management for the sensor. A schematic diagram of the senor is shown in Figure 2. It mainly contains a front-end electronics (FEE) board, a 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 100 cm^2. It mainly provides tracking information about incident particles (Zhang et al. 2017).
(2) The calorimeter module contains five layers of scintillator with dimensions of $120 \times 120 \times 30\,\mathrm{mm}^3$. The STK and calorimeter work together to measure

the energies of charged particles passing through the DSSDs.

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

2 CALORIMETER READOUT SYSTEM

2.1 Calorimeter Design

The HEPP-H calorimeter is built on a plastic scintillator (PS) and four CsI (Tl) scintillation crystals with photomultiplier tube (PMT) readouts. The scintillators are arranged in five layers, and the dimension of each scintillator is $120 \times 120 \times 30\,\mathrm{mm}^3$. The structure of the calorimeter module is shown in Figure 3. The calorimeter module mainly measures the deposited energy of high-energy particles (electrons, protons). In order to reduce the bremsstrahlung of electrons, the first layer of the calorimeter is the PS, and the remaining four layers are CsI (Tl) crystal. Each layer of the scintillator is read out with two PMTs, and the PMT is used in R7600-300[1] produced by Hamamatsu Photonics (photocathode sensitive area is $18 \times 18\,\mathrm{mm}^2$, weighs about 30 g). A light guide is added between the scintillator and PMT to match the scintillator's end and the PMT photocathode size, which improves the collection efficiency of light. A 1 mm thick optical coupling film (silicone pad) is added between the light guide and PMT to protect the scintillator and PMT from possible collision expected during launch. A two-layer Tyvek fiber paper ($2 \times 130\,\mu\mathrm{m}$) was chosen as the reflective material for the scintillator of the calorimeter, and the reflective material is covered with a black polyimide aluminized film as a light-shielding material. Each unit structure in the calorimeter is shown in Figure 4.

2.2 Front-end Electronics Design

The signals emerging from the calorimeter are read out by the method of using discrete components. The circuits are controlled by a Microcontroller Unit (MCU) and Field–Programmable Gate Array (FPGA). The schematic diagram of the 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 a Gaussian shape with a 250 ns rise 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. 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).

The PS signal is also used for calorimeter triggering of the 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). The MCU controls the DAC to set the 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 controls the ten peak-detecting track holds to hold the calorimeter signal.

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

3 ACQUISITION BY THE CALORIMETER

3.1 Acquisition Circuit in the Calorimeter

The controller chips of the DAQ system are FPGA and MCU. FPGA chip APA300[2] was developed by ACTEL using the FLASH process, and the 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 the CsI (Tl) selects one output signal in the FEE board, and this output signal and two other outputs of peak-detecting track hold of PS are selected by a multiplexer in the DAQ board. The output of the multiplexer will be digitized by ADC. FPGA provides the timing and sequencing for ten peak-detecting

[1] *http://www.hamamatsu.com/jp/en/product/category/3100/3001/R7600U/index.html*

[2] ProASIC PLUS Flash Family FPGAS, v5.9 Actel Corporation.

[3] Atmel Rad. Tolerant 8-bit ROMless Microcontroller 80C32E, Atmel Corporation.

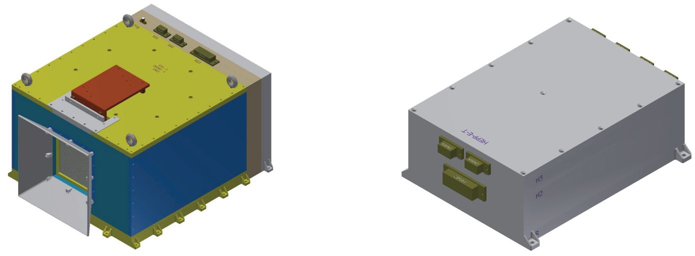

Fig. 1 The constitution of HEPP-H. *Left*: the probe of HEPP-H, *right*: the electronics box of HEPP-H.

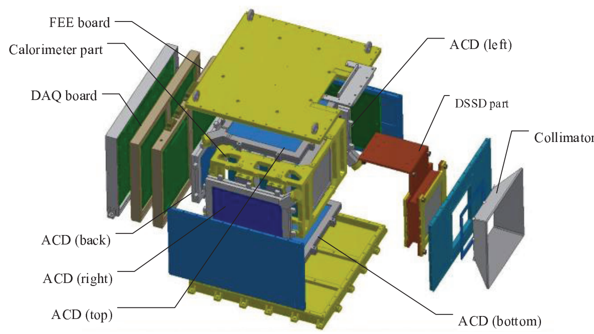

Fig. 2 Schematic diagram of HEPP-H.

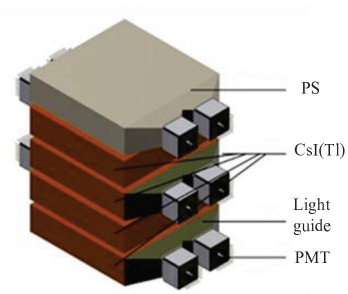

Fig. 3 HEPP-H calorimeter diagram.

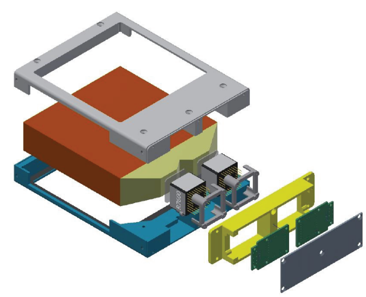

Fig. 4 Schematic diagram of HEPP-H calorimeter unit.

track holds, two multiplexers and one ADC to capture an event from the calorimeter.

The DAQ MCU is responsible for communicating with the data processing system (DPS) and setting the discriminator level. After being powered on, DAQ MCU will initialize DAC, and it can also execute instructions and data interface with the FPGA by accessing the instantiated RAM, REG and EEPROM in FPGA.

3.2 The Logic of FPGA

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

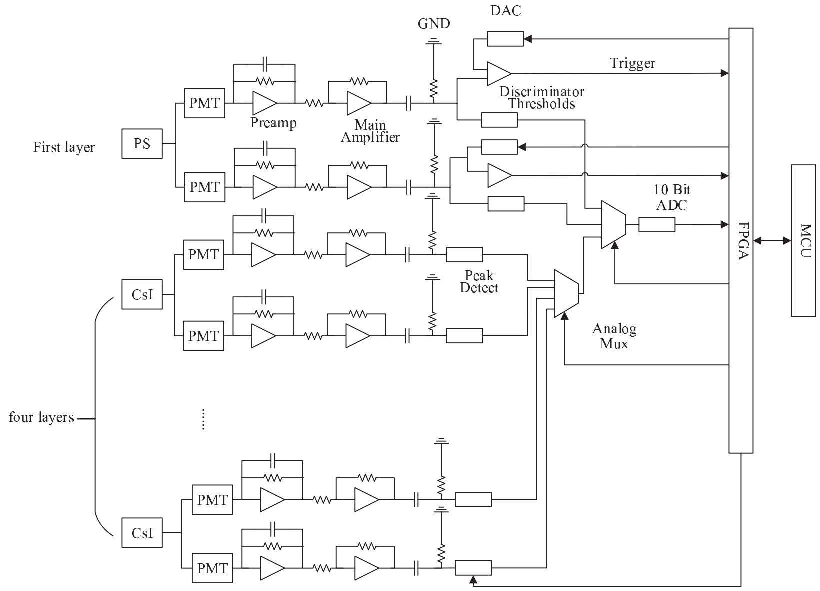

Fig. 5 The entire schematic diagram of the readout system of the calorimeter.

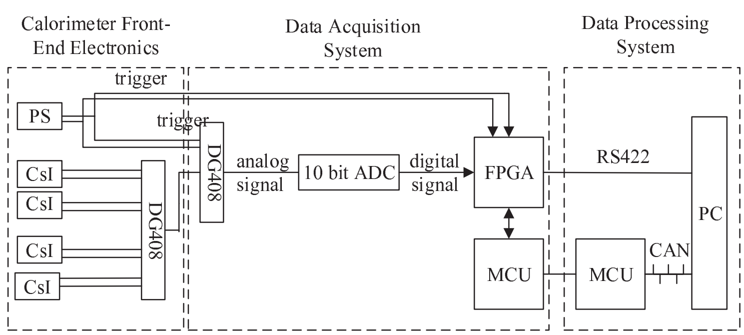

Fig. 6 Calorimeter DAQ circuit diagram.

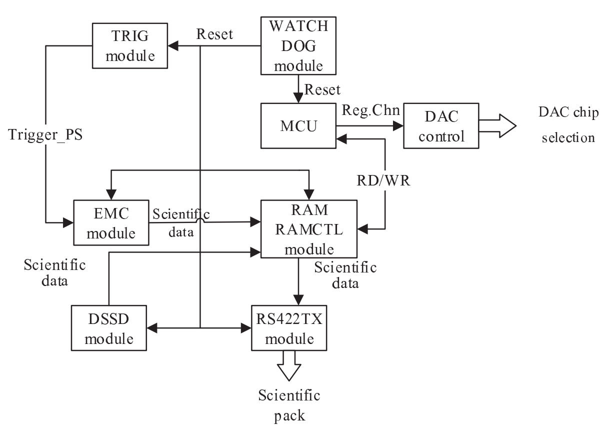

Fig. 7 Calorimeter DAQ circuit diagram.

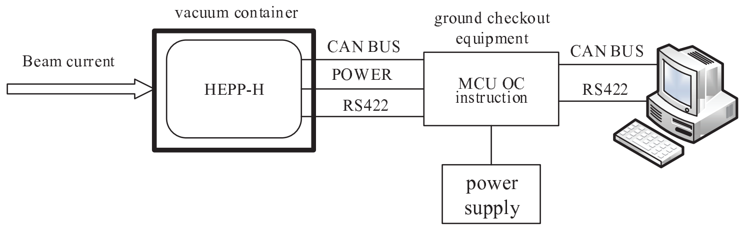

Fig. 8 HEPP-H beam test diagram.

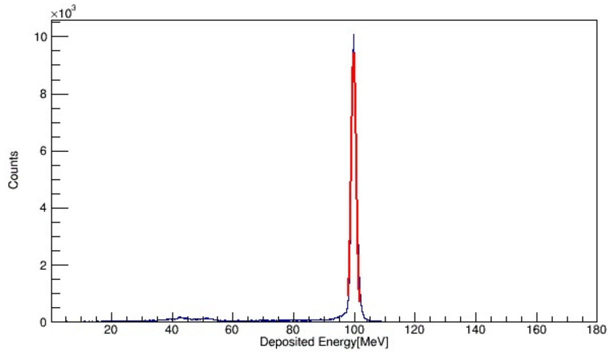

Fig. 9 100 MeV proton energy spectrum.

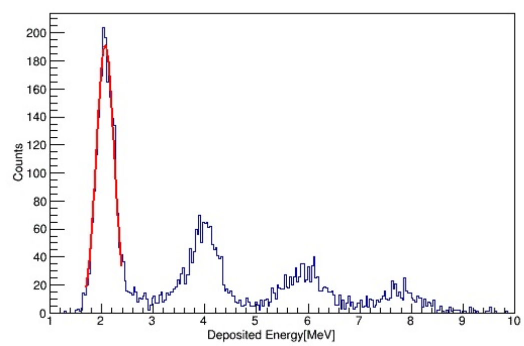

Fig. 10 2 MeV electron energy spectrum.

3.3 Processing Data System

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

4 RESULT OF BEAM TESTS

A proton beam test of HEPP-H was conducted at the Heavy Ion Research Facility in Lanzhou (HIRFL) in June 2016. The energy range of the proton beam was 15–200 MeV. In December 2016, the electron beam test was conducted at the Linear Electron Accelerator Test Beam Facility at the Institute of High Energy Physics (IHEP). The energy range of the electron beam was 1.5–40 MeV. The schematic diagram of the beam test is shown in Figure 8. In the beam tests, we connected the power supply interface, the telemetering output and the data transmission interface of the HEPP-H to the ground test equipment. The ground test equipment was connected to a personal computer and regulated power supply. The ground test equipment could control the relay power on or off by opening and closing instructions from the MCU. This system can simulate the Satellite keeping operation system that sends telemetering instructions and receives the data. At last, we stored the data in the computer.

The energy reconstruction of an 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. Energy spectra of results are shown in Figures 9 and 10. The energy points of a 100 MeV proton and a 2 MeV electron are selected here.

According to the beam test model and the structure of the calorimeter, Geant4 was 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 show comparisons of the reconstructed energy and energy resolution 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

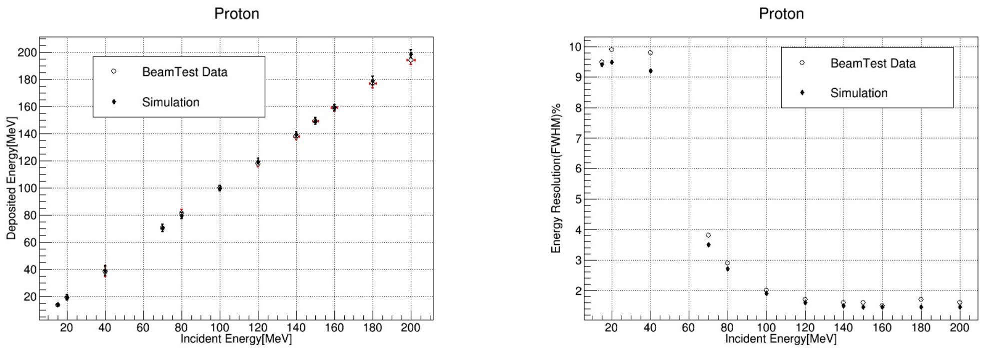

Fig. 11 The reconstructed energy (*left*) and energy resolution change (*right*) with the incident proton beam energy.

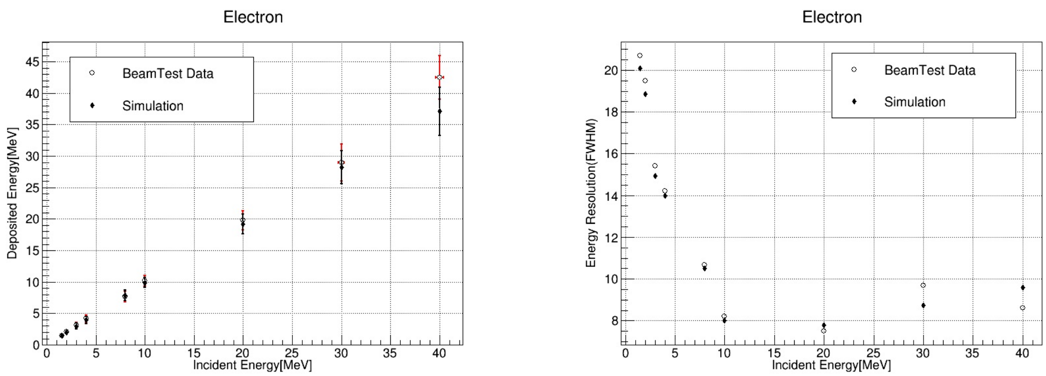

Fig. 12 The reconstructed energy (*left*) and energy resolution change (*right*) with the incident electron beam energy.

energy resolution of electrons above 9 MeV is less than 10% (full width at half maximum, FWHM). The result of the simulation corresponds to the results of the beam test in the range of error, which confirms that the calibration and reconstruction are available. When the energy of electrons is above 20 MeV, the spectrum is broadened by energy leakage because of bremsstrahlung, which leads to the deviation of energy reconstruction.

5 CONCLUSIONS

HEPP-H has been incorporated into the satellite system. It also has completed the related environmental test, beam test and so on. Judging from the results of beam tests, the energy resolution of the calorimeter of HEPP-H in the whole range of proton detection and in the region of electron energy above 9 MeV 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 an accurate measurement of the charged particle flux and energy in the radiation band.

Acknowledgements This project is supported by the National Natural Science Foundation of China (Grant Nos. 11405192 and 11775251). Thanks go 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 the Institute of Modern Physics, Chinese Academy of Sciences for their help on beam application and test setup.

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