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Readout system for ground-based tests of BGO calorimeter of DAMPE satellite

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Abstract A readout system for ground-based tests of the bismuth germanium oxide (BGO) calorimeter of the Dark Matter Particle Explorer satellite is described in this paper. The system mainly consists of a data acquisition board with a field-programmable gate array to implement the control logic, and a graphical user interface software based on LabWindows/CVI. The system has been successfully applied in a series of ground-based environmental experiments and almost all the performance tests throughout the entire manufacturing processes. These contribute significantly to the development of the BGO calorimeter before being submitted for satellite-level integration.

Keywords DAMPE · BGO calorimeter · Readout system

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1 Introduction

The Dark Matter Particle Explorer (DAMPE) satellite, nicknamed "Wukong" in Chinese, is a scientific satellite with the objectives of studying galactic cosmic rays, observing astronomical gamma rays, and searching for the dark matter indirectly by precisely measuring the energy spectra of e^-/e^+ and γ-rays in space [1–6]. It was launched into a 500-km-altitude sun-synchronous near-earth orbit on December 17, 2015, from the Jiuquan Satellite Launch Center of China. The satellite is capable of observing the e^-/e^+ and γ-rays with the widest energy range (5 GeV–10 TeV) and the best energy resolution (less than 1.5% at 800 GeV) among the dark matter searching programs so far.

As the kernel part of the DAMPE, the weight of BGO calorimeter is over one ton, with functions of precisely measuring the energy of cosmic rays, distinguishing interesting particles from background hadrons, and providing trigger information for the DAMPE payload. It consists of 308 bismuth germanium oxide (BGO) crystal bars, 616 photomultiplier tubes (PMTs), and 16 front-end electronics boards (FEEs) [7, 8]. All the BGO crystal bars are stacked in 14 layers with 22 bars each layer. Every two adjacent layers are oriented perpendicularly to provide an *X*–*Y* position of the particle hit. A pair of PMTs is mounted at both ends of each crystal bar, with three dynode signals output for each PMT [9, 10]. Thus, a total of 1848 channels allow us to achieve a large dynamic range, and the signals are received by 16 FEEs assembled around four sides of the BGO calorimeter.

From 2013 to 2015, a qualification model and a flight model (a copy of qualification model, except for the final phase prepared for launching) for the BGO calorimeter were developed. According to the strict aerospace quality control regulations, the design concepts and performances of the calorimeter should be evaluated sufficiently before launching in the manufacturing processes and ground-based environmental tests, such as vibration tests, electromagnetic compatibility tests, thermal vacuum tests, temperature cycling tests, and burn-in tests. The detailed evaluation procedure for each model took nearly half a year, which strongly demanded a ground-based facility to make the task achievable. Therefore, a readout system with stable, automated and easy-to-use features was designed, which will be described in this paper.

Figure 1 shows cosmic ray test of the flight model for the BGO calorimeter which was carried out in the Purple Mountain Observatory, Nanjing. The ground-based readout system consists of a DAQ board, DC–DC power supply modules, HV power supply modules, and a custom graphical user interface (GUI) software based on LabWindows/CVI.

2 Design of the readout system

2.1 DAQ board

As shown in Fig. 2, the DAQ board, sized at 40 cm × 36 cm, features a field-programmable gate array (FPGA) and 24 custom interfaces, with some ancillary components essential to support them. It talks to FEEs directly via the 24 custom interfaces including 16 FEE interfaces on the top and bottom edges and 8 Hit interfaces on the left and right edges. Communication signals (scientific data, trigger, and command monitoring) between FEEs and the DAQ board are integrated in the FEE interfaces. Thirty-two "Hit" signals, which are generated by the BGO FEEs when corresponding layers are fired, are connected to the FPGA trigger module via the Hit interfaces to

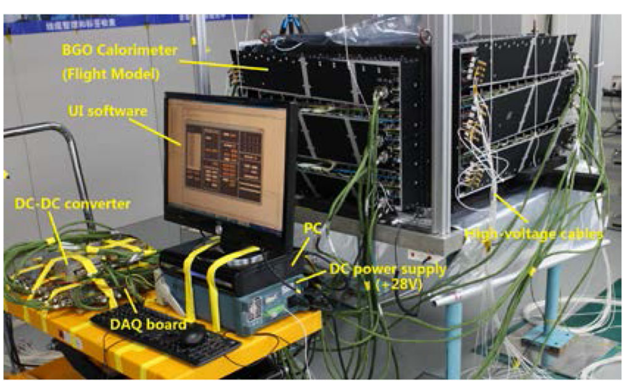

Fig. 1 (Color online) The setup for cosmic ray test of the flight model for the BGO calorimeter. The HV modules power the PMTs and DC–DC modules power the FEEs and DAQ board

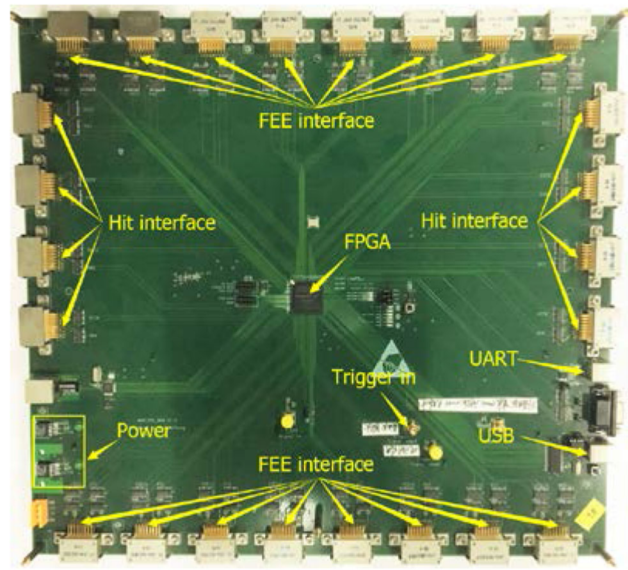

Fig. 2 (Color online) Photograph of the DAQ board

generate a trigger signal by the coincidence logic. Thus, different events of incident particles can be extracted by different coincidences of hit signals. With a USB2.0 interface chip (CY68013A, from Cypress Corp.) controlled by the FPGA, data transfer from the DAQ board to a host computer is achieved. With the trigger rate of less than 100 Hz during ground-based tests and the data package size of approximately 4 k bytes for each event, the maximum data rate for the BGO calorimeter is about 3.2 Mbps, which is far less than the USB 2.0 bandwidth. A USB-to-serial bridge controller (FT230XS, from FTDI Corp.) is employed for setting configuration parameters from the host computer to FEEs and sending BGO FEE status data to the host computer. The trigger, control, and communication logics are implemented in a single Altera FPGA device, EP3C40F484.

Figure 3 shows the block diagram of the interconnection between the FEEs and the DAQ board. Each of the interface signals has two channels for redundancy, with "A" channel as the main signal while "B" channel as the backup.

The DAQ has three trigger modes for different acquisition conditions. The BGO trigger mode, used in cosmic ray test, is triggered by specific coincidence logic of hit signals, which can be configured by the GUI software. The Inner trigger mode, used in FEE calibration test, is generated by FPGA logic itself. The External trigger mode, derived from an external logic pulse, is useful for board-level tests of BGO FEEs and debugging tests for BGO calorimeter.

Coupled with a 20-MHz clock signal, the scientific data are transmitted from FEEs to DAQ board via a user-defined serial protocol. After being locally synchronized and de-

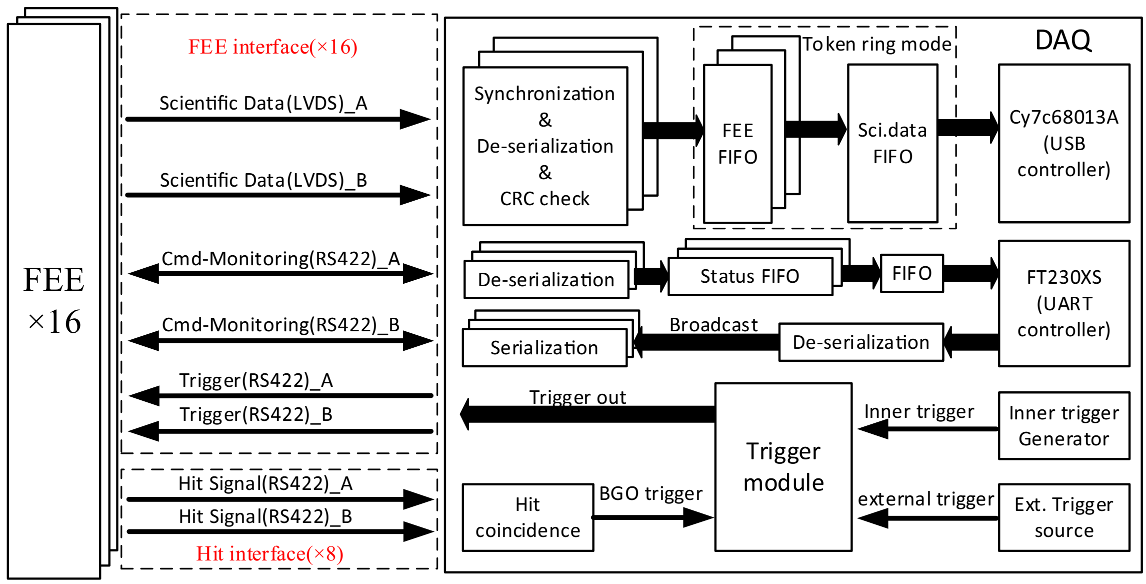

Fig. 3 Block diagram of the interconnection between BGO FEEs and the DAQ board

serialized, the data are checked by cyclic redundancy check (CRC) detection logic in case of transmission errors. In order to readout all the 16 FEEs after each trigger, the readout logic in the FPGA is designed with the daisy chain concept. Using a "token" signal, the data packages of all the FEEs are written to the USB interface chip one by one, while each FEE channel can be individually configured to stand-by mode for flexibility.

Each BGO FEE has three kinds of monitoring data: the positive (+2.5 V) and negative (−2.5 V) supply currents of the front-end chips (VA160/VATA160, from IDEAS Corp.) [11–13], the values of temperature sensors, and the status registers of the FPGA logic. After the calorimeter being assembled in the satellite, the temperature information and FPGA status are checked every 16 s, while the current information is checked every second. In ground tests, the DAQ board, which is remotely controlled by the GUI software via a UART port, checks the monitoring data periodically. In this case, the host broadcasts commands with a specific identity to all FEEs through the UART port; however, only the FEE which matches the identity will respond back to the host.

2.2 User Interface software

The custom user interface software is designed with LabWindows/CVI virtual instrument development platform and software test automation technology [14, 15]. The graphical interface, including control buttons, message display windows, and configuration text boxes, and the hierarchy structure of the software as well are shown in Fig. 4. Applications talk to the DAQ board or other instruments with NI-VISA library and CVI serial port control library. Besides design considerations for long-term ground-level cosmic ray test, more features are integrated to make the software suitable for various applications, for instance, PMT or BGO FEE performance [16] tests. It provides a guarantee for the smooth progress of the development and construction of the BGO calorimeter before launching.

2.3 Performance tests

The performance tests of the calorimeter include pedestal test, FEE calibration test [17], and ground-level cosmic ray tests. All the tests are carried out frequently, so the readout system should be automated and easy-to-use.

The calorimeter contains 2016 channels, of which 1848 are signal channels, while the others are floating as spare ones. The pedestal test is carried out under the "Inner trigger" mode which is periodically generated at about 100 Hz by the DAQ board. The statistic features of the pedestal for each channel (usually obeying an ordinary Gaussian distribution) can be used as the first diagnosis index throughout the ground-based tests before launching.

The FEE calibration is conducted by remotely controlling a DAC-based calibration circuits under the "Inner trigger" mode. The circuits are designed on each FEE, with a function of generating calibration pulses with programmable charges. The calibration goes automatically. As a result, gain differences among all channels and the drifts over temperature can be conveniently evaluated.

The ground-level cosmic rays, in most cases composed of muons of several GeV, are used to calibrate the

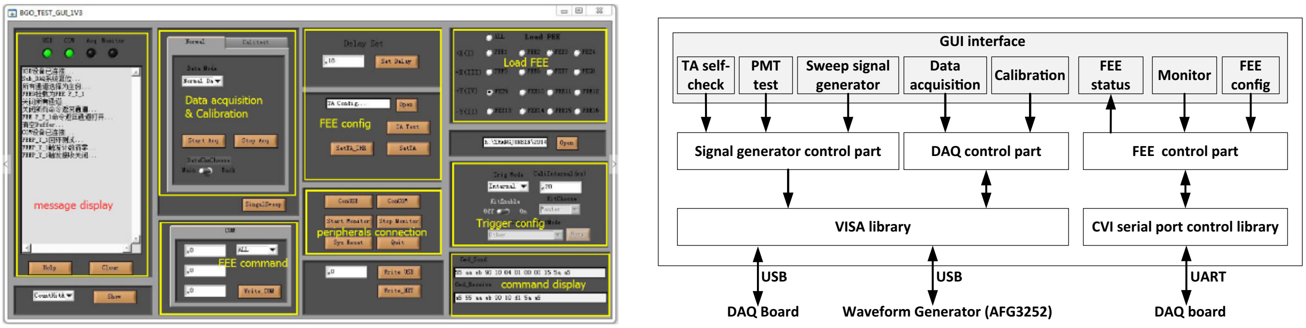

Fig. 4 (Color online) The GUI interface (*left*) and its software hierarchy (*right*)

minimum ionization particle (MIP) response of each BGO bar, which is a fundamental parameter for the energy reconstruction of the calorimeter. The ground-level cosmic ray tests are carried out under the "BGO trigger" mode. After pedestal subtraction and gain correction, MIP calibration [18, 19] can be done directly. Light yield of a BGO crystal depends on temperature significantly, and during the cosmic ray tests, the temperature effect of each BGO is investigated in the temperature cycling test and thermal vacuum test [20, 21], so as to evaluate the temperature coefficients.

3 Environmental

3.1 Description of the experiments

A series of environmental tests were carried out for the qualification and flight models. For instance, thermal vacuum test was used to verify performance of the calorimeter in a simulated vacuum and thermal environment similar to space. The BGO calorimeter, sized at 0.9 m $\times$ 0.9 m $\times$ 0.5 m, was installed in a heating cage, with a supporting structure of proper thermal insulation design. The Φ5-m vacuum tank, with an inner wall LNF (liquid nitrogen freezing) system, named as "space environmental simulator," is evacuated to 10^{-3} Pa (Fig. 5, left). The calorimeter temperature could be adjusted from -15 to $+30$ °C by the heating cage (on the outer surface of shielding panels) for multiple cycles, while the temperature range was from -25 to $+40$ °C for the qualification model.

The readout system for thermal vacuum test of the flight model is shown schematically in the right of Fig. 5, which is similar to the setup for other environmental experiments. As the kernel part of the readout system, the DAQ board receives all the hit signals with RS422 level from the BGO calorimeter and then processes them with coincidence logic and generates a trigger signal, to indicate a cosmic ray particle (a muon in most cases at ground level) penetrating several layers of BGO bars. When a trigger is received, the FEEs digitize the signals in all the channels and send the data packages to the DAQ board via low voltage differential signal (LVDS) level based on a user-defined serial protocol.

The DAQ board also broadcasts commands to FEEs and receives status information from FEEs as well. All the signals between the DAQ board and the BGO calorimeter are transmitted by twisted cables (for RS422 signal) or shielded twisted cables (for LVDS signal), which have a total length of nearly 20 meters from the control room to the vacuum tank, and go through sealed connectors in a vacuum flange.

The readout system worked stably during the 15 days of uninterrupted operation in a thermal vacuum test.

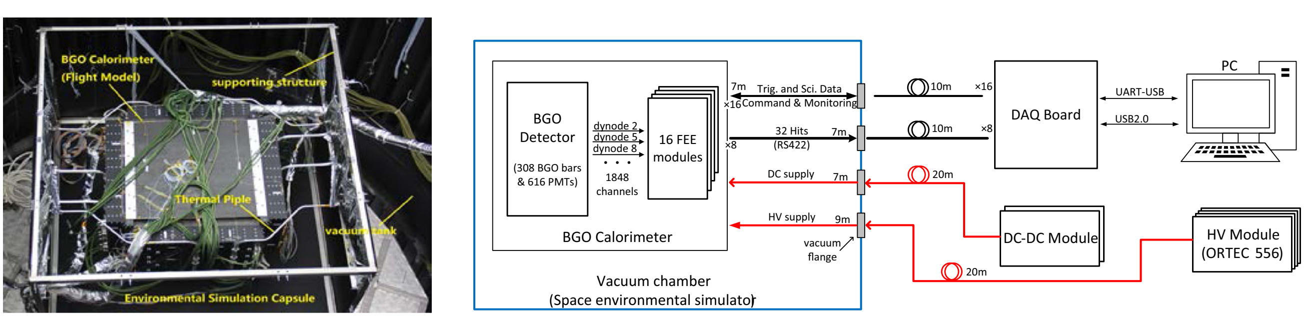

Fig. 5 (Color online) The flight model in a vacuum chamber (*left*) and schematics of the readout system (*right*), for the thermal vacuum test

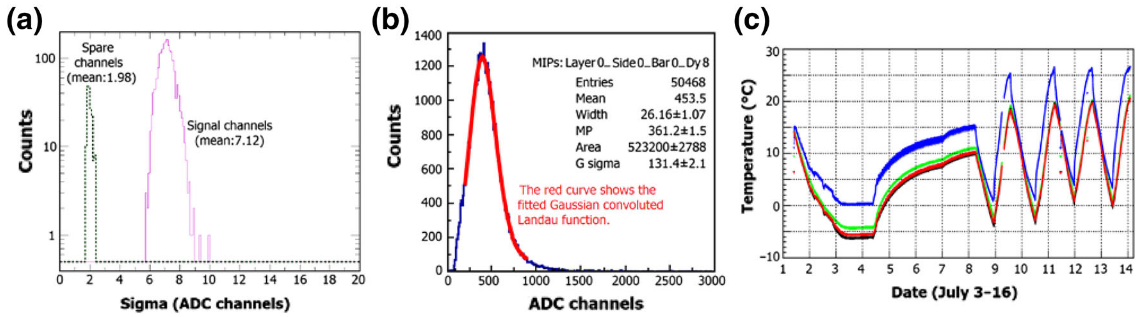

Fig. 6 (Color online) Width distribution **a** of the pedestal noises for all the FEEs channels; typical energy spectrum **b** for ground-level cosmic rays of a channel; and temperature variations at four monitoring points inside the calorimeter **c** in the thermal vacuum test (the discontinuities were caused by manual re-power operation due to experimental requirements)

3.2 Results

It took nearly half a year to accomplish the assembly and ground-based tests for both the qualification model and the flight model of the BGO calorimeter, respectively. A series of experiments were conducted, each lasted for days or weeks.

Figure 6a depicts the histogram of the pedestal noises of all the FEE channels of the flight model with the width of the Gaussian function for per channel, in which the X-axis is the pedestal noise (in RMS), and one ADC bin is 1 fC. Obviously, the spare ones with lower input capacitance have a lower noise level (approximately 2 fC).

When ground-level cosmic rays pass through the calorimeter, the energy deposit in a BGO crystal bar is digitized and MIP energy from an obtained energy spectrum is determined. Figure 6b shows a typical energy spectrum from one end of a crystal bar. The results demonstrate that the maximum equivalent noise charge for all the FEE signal channels is approximately 10 fC in RMS, which is much less than the charge of the MIP signal and meets the requirements.

In the long-term experiments, the temperature and current information of the calorimeter was real-timely monitored and recorded. Figure 6c shows temperature data from four thermal sensors inside the calorimeter in a 2-week thermal vacuum test of the flight model. The left parts of the curves depict the thermal balance process, while the right parts stand for the vacuum thermal cycling process. The experiment lasted for nearly 2 weeks, ruptured by several discontinuities due to manual re-power operation planned by the experimental program.

4 Conclusion

A readout system for ground-based tests of the DAMPE BGO calorimeter, with data acquisition, control, and monitoring functions, has been successfully realized to meet the development and production requirements of the qualification model and the flight model. With the benefits of its stable, automated, and easy-to-use features, the system has played an indispensable role in ensuring the production quality of BGO calorimeter and reducing the risk to accumulate delay on the schedule. The BGO calorimeter has been stably operating in orbit for more than 1 year. As of the end of April 2017, all the 308 detector units and 1848 electronics channels work stably, and the in-orbit performances are consistent with the ground-based test results before launching.

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