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Development of a Data Acquisition System for Cosmic Ray Tracking Using SiPM-Based Scintillating Fiber Detectors

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Abstract-The study developed a data acquisition (DAQ) system for cosmic ray tracking, using silicon photomultipliers (SiPMs) and scintillating fibers. The system employs a multi-layer, cross-aligned scintillating fiber detector structure, where the end faces of each fiber are coupled with multi-pixel photon counters (MPPCs), enabling the construction of thousands of readout channels. By measuring the amplitude of the analog signals and dark-count rates of the MPPCs, the threshold is determined. The analog signals are converted into Transistor-Transistor Logic (TTL) signals using a discriminator based on Time-Over-Threshold (TOT) method. The width of TTL signals is recorded by the Time-to-digital convertor (TDC) on the front-end board (FEE). For each single-layer detector, the FEE logs timestamps, positions, and energy of hits. These data are then transmitted to the DAQ board, where a coincidence window is opened to capture incoming events. Upon detecting a valid event, the DAQ board re-encodes the data and uploads it to a host computer. Three-dimensional reconstruction of cosmic ray trajectories was successfully achieved by analyzing spatiotemporal correlations, verifying feasibility, low-cost and high-density readout capability. The design provides a scalable hardware architecture and real-time data processing solution for large-scale particle detection system. Relevant performance tests and physical experimental results will be detailed in the conference presentation.

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1. Introduction

Cosmic ray muons are generated when high-energy cosmic rays interact with atoms to produce extensive air showers in the upper atmosphere of Earth. Tracking cosmic ray muons plays a central role in fundamental physics and applied sciences, such as cosmic ray and high-energy astrophysics, detector calibration, background modeling, and muon radiography, due to their strong penetrating ability. Since the 1950s [1], radiography has entered a period of rapid development.

Muon tracking involves reconstruction the trajectory of muons as they pass through a series of detection layers. Various types of detector have been developed and optimized over the decades including gaseous detector, scintillator-based tracking, resistive plate chambers (RPCs) silicon detectors and water Cherenkov and liquid scintillator detectors. Gaseous detector including multi-wire proportional chambers (MWPCs), drift chambers, and time projection chambers (TPCs), offer high spatial resolution and have been extensively used in accelerator-based experiments. Scintillator-based tracking utilizes plastic scintillator bars or tiles read out by photomultiplier tubes (PMTs) or silicon photomultipliers (SiPMs), widely used in ground-based arrays due to robustness and cost-effectiveness. RPCs provide fast timing and decent position resolution, widely adopted in large-scale muon arrays such as LHAASO. Silicon detectors such as microstrip or pixel detectors, offer the highest spatial resolution (tens of microns), but are costly and mainly used in precision experiments [2]. WMPCs reconstruct muon tracks via light emission and timing information, applicable for large-volume underground or surface detectors [3].

A scintillating fiber detector is used in high-energy physics experiments due to its flexible scalability and excellent performance. The fibers are easy to machine into various lengths and shapes, making them a suitable candidate for large-area tracker detectors. The scintillating fiber detector array is employed in the LHCb experiment and has yielded micron-scale results [4].

In this paper, a compact and sensitive scintillating fiber detector is proposed. A data acquisition system (DAQ) and front-end electronics (FEEs) record the energy signals from the detectors. The FEE consists of resistors, capacitors, amplifiers, and comparators. It is used to amplify the small signals from the muons and convert analog signals into digital signals (Transistor-Transistor Logic, TTL). The DAQ system includes eight front-end boards (FEBs) and a data acquisition board. All of the FEBs and the data acquisition board are field-programmable gate arrays (FPGAs). As of now, the fiber detector system is operational and can distinguish the positions of various scintillators.

2. Scintillating Fiber Detector

2.1Detector

To reconstruct the sensitive position and track of cosmic ray muons, the paper proposes an eight-layer scintillating fiber detector, as shown in Fig. 1. The entire detector is placed vertically. Each detector consists of a row and column of multi-layer fibers and three MPPCs. An MPPC is composed of 64 SiPMs. The size of the row fiber is 1 mm × 20 mm, and the size of the column fiber is 1 mm × 40 mm. Fig. 2 shows how the faces of three fibers are coupled to a single pixel of the SiPM, which has a size of 3 mm × 3 mm. The two adjacent fibers are held together with glue.

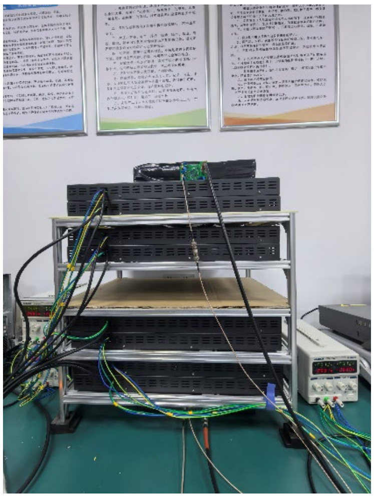


Fig.1 The Scintillating fiber detector

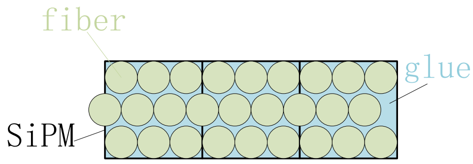


Fig.2 The scheme of coupling

The x-axis of the detector has 128-pixel SiPMs, and the y-axis has 64-pixel SiPMs. Theoretically, the detector can achieve a position resolution of 1 mm. To test the functionality of the electronics and the DAQ system, the paper uses two sizes of up-down plastic scintillators to trigger the entire detector's signals.

2.2Front-end Electronics

The SiPMs have many characteristics, such as small size, high gain, low operating voltage, high dark counts, temperature sensitivity, excellent time resolution, photon sensitivity, and low magnetic field effects. Among these, dark counts and temperature effects are the main sources of thermal noise. To recognize the true signal, the signal from the SiPM must be amplified and extracted above the noise. The comparator threshold is set to six photons, which helps reduce the false trigger rate. Fig. 3 shows the design scheme of the FEE for one channel.

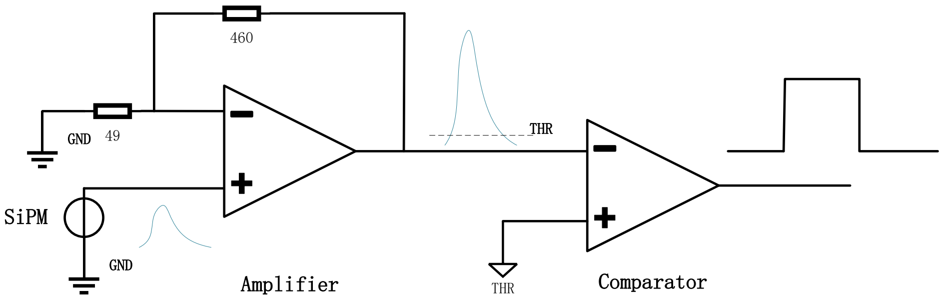


Fig.3 The scheme of FEE

Since the FPGA only receives and identifies signals above zero voltage, the anode of the SiPM is chosen to be amplified by the amplifier with a factor of ten. The output signal from the amplifier is then discriminated by the comparator. When the signal exceeds the threshold, a TTL signal will be output.

The AD4807-4 amplifiers are used to amplify the four-channel input signals. A total of 16 amplifiers are integrated onto a single board. The MPPC boards are connected to the amplifier board using an 80-pin flexible flat cable (FFC).

2.3Data Acquisition

A layer detector has 192-channel readout electronics. However, none of the available FPGAs have enough input/output interfaces to receive signals from the detector all at once. A two-stage scheme is proposed. A Cyclone V FPGA is used in the first stage to receive the 192-channel signals from each layer detector. A TR-4 FPGA is used in the second stage to perform the data acquisition role in the system. The program scheme of the DAQ system is shown in Fig. 4.

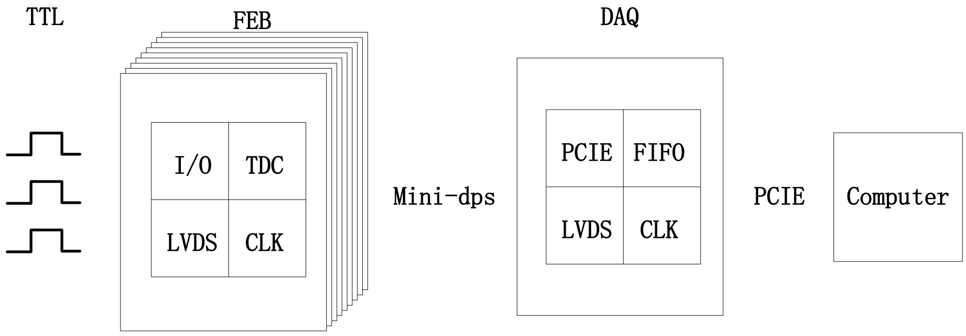


Fig.4 The scheme of DAQ

Each FEB has 256 I/O channels, of which 192 channels are used to receive energy signals from the detector. The sampling clock of the FEB operates at 240 MHz. Each channel works independently. When the first signal arrives, the corresponding channel detects the signal and uses a TDC to record the waveform width. Meanwhile, a waiting window of 160 ns is opened to confirm the signal from the event. Once all the x-axis and y-axis signals are recorded, a valid signal for the layer is raised. To ensure the stability of space and transmission, mini-DP cables and low-voltage differential signals (LVDS) are used. Since the trigger width is set shorter than the energy signal, the DAQ board detects the trigger signal first. An 800 ns layer window is opened to wait for the layer signals. When the window closes and the layer counter is greater than four, the validity of the DAQ system is raised. Otherwise, the reset signal is set high. The clock of the FEB is different from the DAQ clock. The First In First Out (FIFO) model is used to handle cross-clock domain signals. The timing diagram is shown in Fig. 5.

Once all the signals are prepared, the computer issues a command to transmit the data.

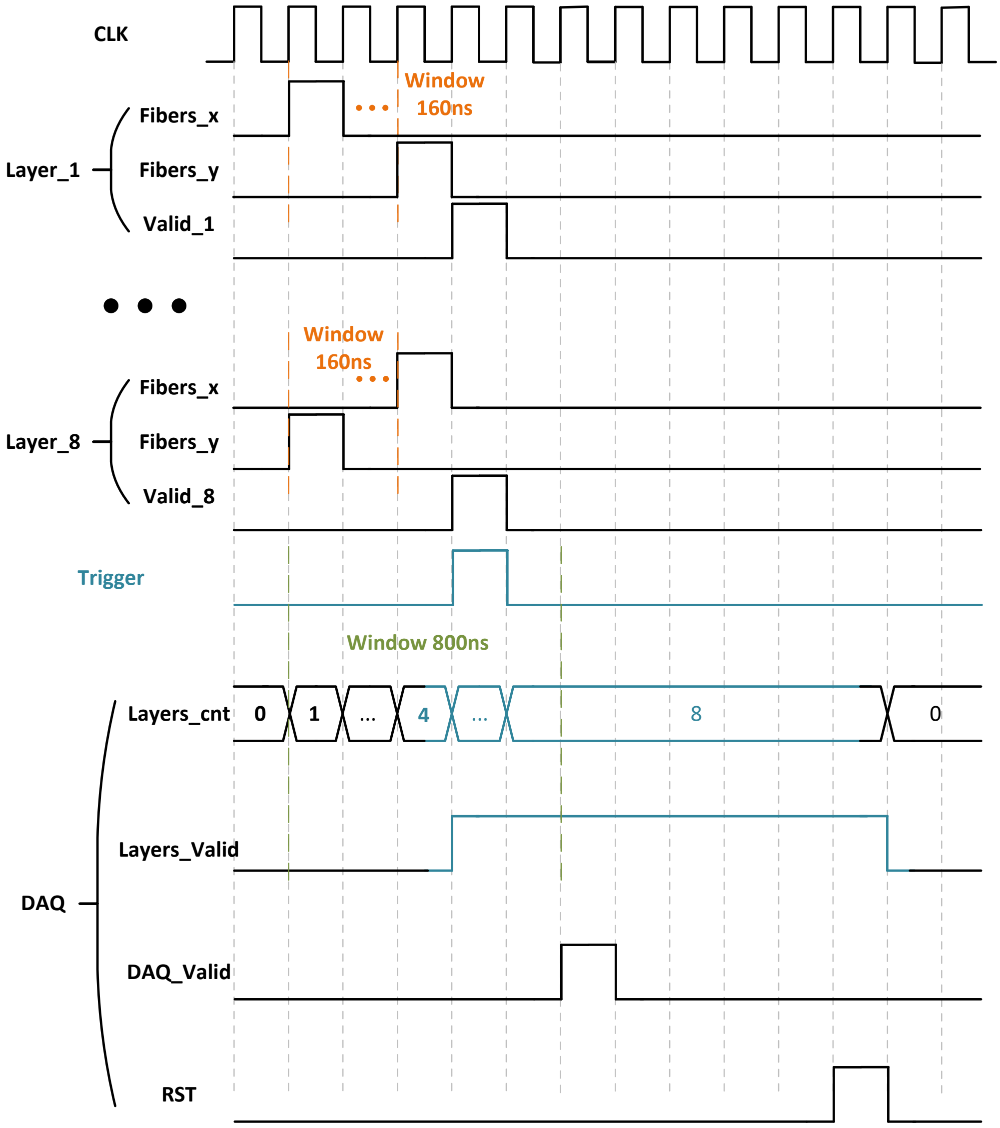


Fig.5 Sequence chart

3. Scintillating Fiber Detector

The manuscript tests two sizes of scintillators for the trigger. The smaller scintillator has dimensions of 100 mm × 100 mm, and the larger scintillator has dimensions of 200 mm × 300 mm. The results of the detector is shown in Fig. 6 and Fig. 7.

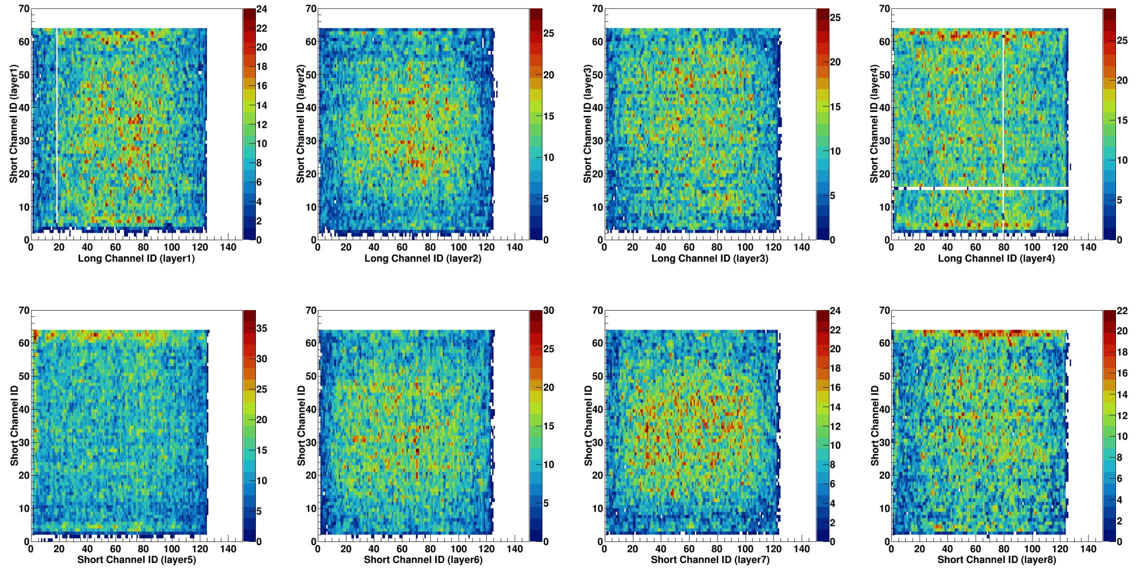
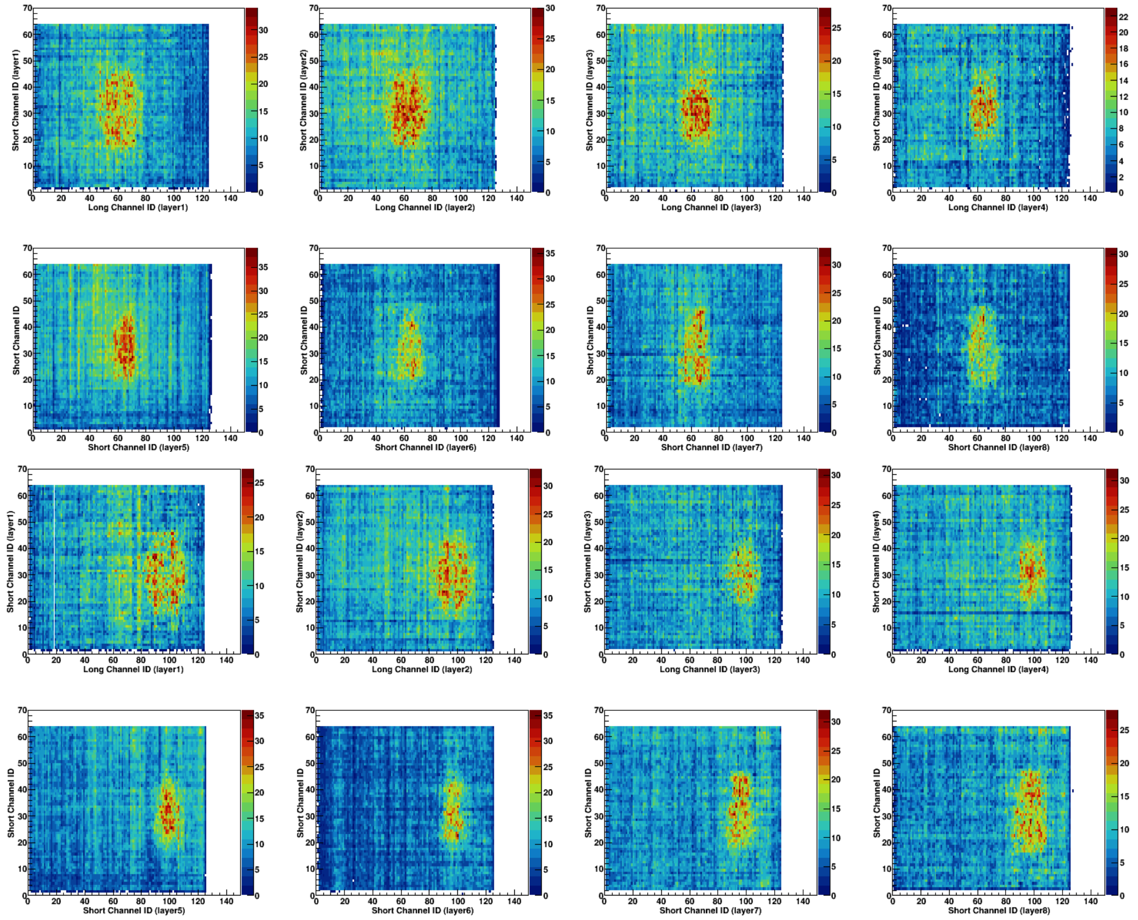


Fig.6 The results of 200mm x 300mm scintillator



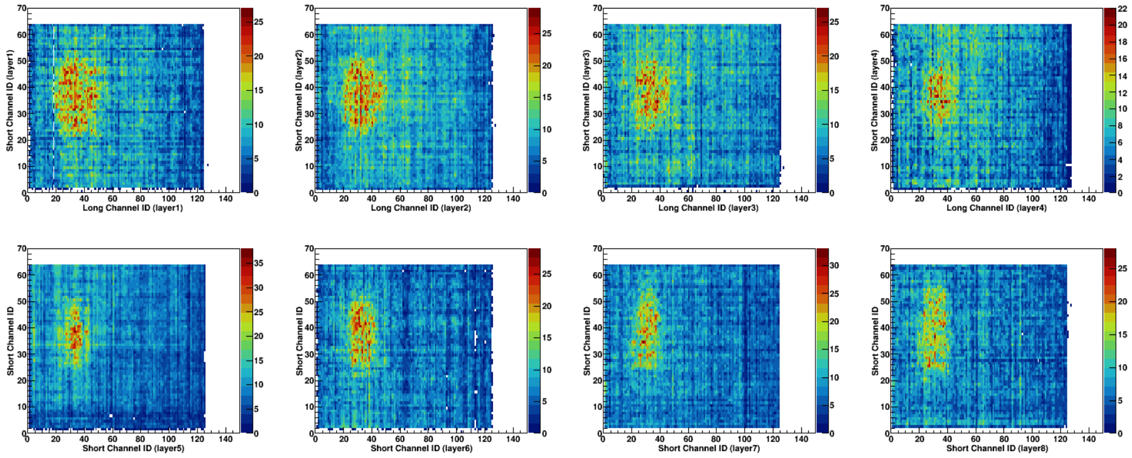


Fig.7 The results of 100mm x 100mm scintillator

Acknowledge

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