Nuclear Inst. and Methods in Physics Research, A 899 (2018) 94–100

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Performance of SiPMs and pre-amplifier for the wide field of view Cherenkov telescope array of LHAASO

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ARTICLE INFO

Keywords:
Silicon photomultiplier
Dynamic range
Pre-amplifier
LHAASO
WFCTA

ABSTRACT

The Wide Field of View Cherenkov Telescope Array (WFCTA), a main component of the Large High Altitude Air Shower Observatory (LHAASO), is designed for cosmic rays spectrum measurement from 30 TeV to several EeV. Silicon photomultipliers (SiPMs) have been adopted for the telescope cameras as they do not suffer any aging even with strong light exposure and thus they can be operated with moonlight. The physics of WFCTA requires a dynamic range of SiPMs to be within 10 p.e. (photoelectrons) to 32, 000 p.e. at any energy range. And the dynamic range of SiPMs is proportional to the total number of APDs and depends on the distribution of light hitting on the active area. This light distribution is affected by the use of light concentrator and also by the use of spherical mirrors of the telescope. The effect of these two factors on the Cherenkov light distribution has to be taken into account to evaluate the dynamic range and in this work they have been simulated with a ray-tracing software. The non-uniform light distribution caused by the light concentrator and the spherical mirror will be below 2% for 32, 000 p.e. at the condition if the SiPM has 360, 000 cells. The characteristics of SiPMs from three different producers – Hamamatsu, FBK, and SensL – are measured in laboratory, and the dynamic range of them has also been measured using a uniform light flux. The results of dynamic range correspond with the calculation by the function which describes the relationship between the number of fired APDs and the total number of APDs in the SiPM. The performance of the SiPMs and PMTs under long time duration light pulses up to 3 μs are compared, in order to investigate the stability of the gain of the SiPMs for the fluorescence mode.

1. Introduction

The Large High Altitude Air Shower Observatory (L-HAASO), located at Mt. Haizi (4400 m asl, 29°21′31′′N, 100°8′15′′E) in Sichuan Province, China, is a hybrid experiment designed for γ-ray astronomy and cosmic ray physics [1,2]. There are three main components in the LHAASO project: a square kilometer array (KM2A), a water Cherenkov detector array (WCDA) and a wide field of view Cherenkov telescope array (WFCTA) [3]. KM2A includes 5195 scintillator detectors, with 15 m spacing, for electromagnetic particles detection and 1171 underground water Cherenkov tanks (36 m^2 per tank), with 30 m spacing, for muon detection. WCDA has two 150 m × 150 m water pools and one 300 m × 110 m pool with the effective depth of 4 m. The total area of WCDA is about 78,000 m^2 with 3120 cells, and the size of each cell is 5 m × 5 m. WFCTA has 16 Cherenkov telescopes. Each Cherenkov telescope has a 4.7 m^2 spherical mirror, and a camera featuring an array of 32 × 32 SiPM based pixels. It has a field of view (FOV) of 16° × 16° with the pixel size of approximately 0.5° × 0.5°. The camera will be located at the focal plane which is 2870 mm away from the center of the mirror.

WFCTA is designed to measure cosmic ray spectrum. The flux of cosmic ray follows a power law $\Phi \propto E^{\gamma}$. The index γ changes from −2.7 to −3.1 at around 1 PeV and to −3.3 at around 100 PeV, the so-called "knee" region. The spectrum hardens to $\gamma \sim -2.9$ just below 10 EeV, the so-called "ankle" [4,5]. WFCTA covers the energy range from 30 TeV to several EeV, thus including both the "knee" and the "ankle" ranges. WFCTA will have two main observation modes: Cherenkov mode and fluorescence mode. The energy range covered in the Cherenkov mode is split in two regions, from 30 TeV to 10 PeV and from 1 PeV to 300 PeV. This mode requires the dynamic range of photosensors from 10 p.e. to 32,000 p.e. The fluorescence mode is used to measure the

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https://doi.org/10.1016/j.nima.2018.05.019
Received 17 December 2017; Received in revised form 6 May 2018; Accepted 9 May 2018
Available online 17 May 2018
0168-9002/

ultra-high energy cosmic rays from hundreds of PeV to a couple of EeV, The duration of fluorescence light can last from tens of nanoseconds to several microseconds. It requires a stable gain of the sensors for a time up to 3 μs.

Silicon photomultiplier (SiPM) consists of an array of independent avalanche photodiodes (APDs), so-called cells, which are operated in Geiger mode [6]. SiPM has many advantages like single photon resolution, high detection efficiency, high gain at low bias voltage, no aging due to strong light exposure and insensitivity to magnetic fields. The typical gain of SiPMs is around 10^6 while the operating voltage is less than 100 V. SiPM suffers no aging due to strong light exposure, which allows SiPM-based cameras to operate under moonlight condition. The duty cycle of SiPM-based cameras could increase from 10% up to 30% with respect to PMT-based cameras, which is very important for high energy events due to the cosmic-ray's low flux (about 1 particle per m^2 per year at 1 PeV). The First G-APD Cherenkov Telescope (FACT) has been exploring the use of the SiPM technology for Cherenkov telescopes [7]. The single mirror Small Size Telescopes (SST-1M) and dual mirror SSTs of the Cherenkov Telescope Array (CTA) project will use SiPMs [8].

The APD cells in SiPMs are operated in Geiger mode, which is a binary mode. In this mode, no matter how many photons hitting on one cell, the output will be the same. Therefore, the dynamic range of SiPM depends on the total number of cells and the uniformity of the distribution of photons hitting on the SiPM. In this paper, the SiPM candidates as well as the pre-amplifier, and the test system are described in Section 2. The results of experiments are shown in Section 3, including dynamic range and performance under long duration light pulses of SiPMs. In addition, non-linearity due to non-uniformity of the distribution is simulated, and the details are discussed in Section 4.

2. SiPM candidates, pre-amplifier and test system

2.1. SiPM candidates and pre-amplifier

SiPMs from Hamamatsu, FBK and SensL, listed more details in Table 1, have been measured. The cell size was different for the different devices, and in some cases also its definition. For both Hamamatsu and FBK, the cell size is the distance between the centers of cells, thus including APD non-photosensitive area. For SensL, instead, the cell size is defined as the side of the cell active area. So the 35 μm (20 μm) cell of a SensL devices correspond to 40 μm (25 μm) according to the definition of Hamamatsu/FBK.

An air conditioning system keeps the temperature with-in the range of 20 °C and 30 °C over the year and stable within 2° over the day. Two sensors were sitting near the SiPM to monitor the temperature and adjust the operating voltage of the SiPM to compensate the working point change due to temperature variation. The voltage is changed according to the temperature coefficients, the values of which provided by the producers are: 54 mV/°C, for Hamamatsu, 27 mV/°C for FBK and 20.5 mV/°C for SensL. And the values measured in the laboratory are used in the experiments.

Fig. 1 shows the design of pre-amplifier for LHAASO-WFCTA camera. The capacitor C_1 (1 μF) is the bypass capacitor to keep the operating voltage of the SiPM stable, especially while there is a long light pulse with a width of up to several microseconds. The resistor R_1 (250 Ω) is used to protect the SiPM from high current generated by very intense light. The resistor R_2 is used to convert the SiPM output current to voltage signal. Clearly this also affects the pulse shape as shown in Fig. 2, for different values of R_2. The value chosen is $R_2 = 3$ Ω, corresponding to a FWHM of the pulse of 50 ns, which suits the 50 MHz FADC used in the electronics [9]. The amplifier OPA846 is selected because of its high gain bandwidth and low noise. For the chosen value of $R_3 = 100$ Ω and $R_4 = 1$ kΩ, the gain of the inverting amplifier is 10.

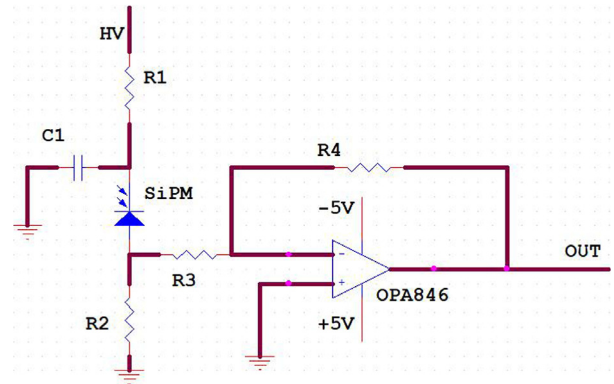

Fig. 1. The schematics of the pre-amplifier for the SiPM-based cameras of LHAASO-WFCTA.

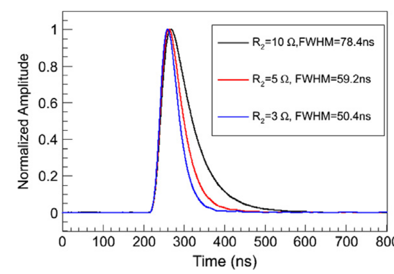

Fig. 2. The pulses for different value of R_2 under a fixed intensity of light. The amplitudes are normalized to 1.

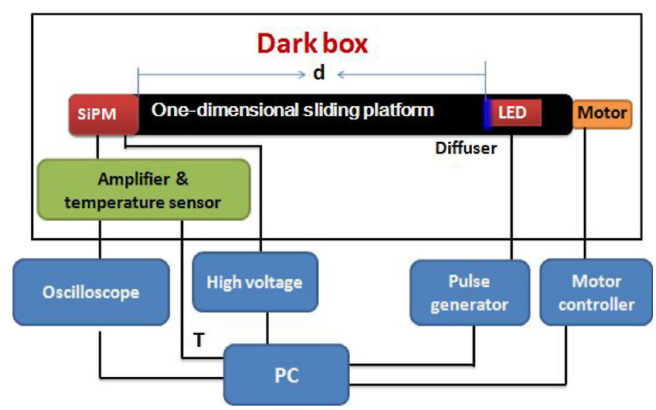

Fig. 3. The schematic diagram of the test platform.

2.2. Test system

The schematic diagram of the SiPM test system is shown in Fig. 3. The linear moving stage, the light source (LED) and the SiPM with the pre-amplifier are placed in a dark box, while the other devices are outside. An oscilloscope is used to collect the output of the pre-amplifier with the maximum sampling rate of 2.5 GHz. LED is driven with pulses of 20 ns long at a frequency of 100 Hz using a function generator. The linear moving stage is used to change the distance between the LED and the SiPM. All these devices of the system are controlled by a computer, thus, the test procedures can be completed automatically.

2.2.1. The LED driver

The maximum output voltage of the pulse generator is 5 V, which is not sufficient to get 32,000 p.e. in 20 ns. In order to make the LED brighter, we designed a high current driver for LED, as illustrated in