International Conference on Technology and Instrumentation in Particle Physics IOP Publishing
Journal of Physics: Conference Series **2374** (2022) 012123 doi:10.1088/1742-6596/2374/1/012123

Performance of the SiPMs operated at low temperature for the JUNO - TAO detector

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Abstract. We report on the performance of commercial SiPM-based photo-detector Multi-Pixel Photon Counter (MPPC) S13360-6075CS by Hamamatsu Photonics from room temperature down to -50 °C at INFN - Sezione di Roma Tre. The work presented here is focused on the realization of 10 m^2 SiPM surface for the Taishan Antineutrino Observatory (TAO) near detector in the framework of the Jiangmen Underground Neutrino Observatory (JUNO) neutrino experiment.

1. Introduction

Silicon Photo-Multipliers (SiPMs) are recently widely used in several applications. SiPMs working at low temperature, in particular, are the most interest application for the newly large particle detector for neutrinos and dark matter experiments.
The Taishan Antineutrino Observatory (TAO) [1] near detector of the Jiangmen Underground Neutrino Observatory (JUNO) neutrino experiment [2] is a ton-level high energy resolution liquid scintillator (LS) Gadolinium-based detector. It will be located at a distance of about 30 m from one of the 4.6 GW core of the Taishan Nuclear Power Plant (NPP), China. The main goal of TAO will be the measurement of the reactor anti-neutrino spectrum via the Inverse Beta Decay (IBD) to detect the anti-neutrino generated in the core of the NPP. In order to achieve its goal, the TAO experiment will be equipped with about 10 m^2 surface of SiPM arrays (5×5 cm^2 each), for a total of $\sim$ 95% coverage excluding fill factor, working at -50 °C to lower the dark noise at least by a factor of three. In this conditions the expected dark counts rate is about 100 Hz/mm^2 with a Photo Detection Efficiency (PDE) better than 50%.

The work presented here, performed at INFN - Sezione di Roma Tre, is focused on the performance of a commercial single analog output SiPM-based photo-detector Multi-Pixel Photon Counter (MPPC) S13360-6075CS made by the Hamamatsu Photonics [3] company, in the temperature range -50 °C, +20 °C.

2. Experimental apparatus

The experimental apparatus used for the study of the performance of the SiPMs is sketched in fig. 1. It is mainly based on a climatic chamber inside of which there is a mock up testing setup that can host up to 15 SiPM single cells or matrices of SiPMs (tiles) coupled with their own Front-end Electronic Boards (FEBs), an UV laser with a wavelength of 404 nm, that can be

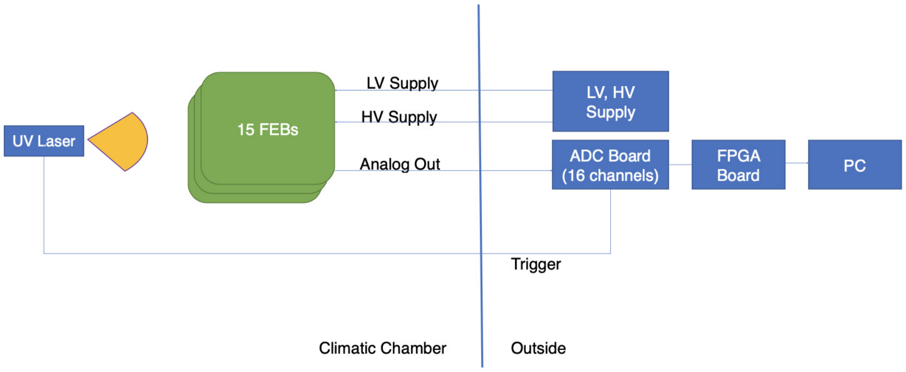

Figure 1. Block diagram of the experimental setup used for the measurements reported here, details about the single components are detailed in the text.

used to emulate scintillation light from LS, two power supplies for biasing either the Operational Amplifiers (LV, OP-AMPs) and the SiPMs (HV), and the acquisition system. The latter is mainly based on a commercial AD9083 ADC from Analog Devices company [4]. It has 16 readout channels, up to 2 GHz bandwidth and it is coupled with a commercial controller board, from Analog Devices too, that allows the connection with a personal computer. The ADC is capable to run in trigger-less mode by acquiring waveforms (WFs) 250 μs long. They are then stored and analyzed by means of the ROOT analysis package.

In standard conditions, the FEBs were supplied with ± 2 V and the SiPMs with about 54 V (about 51 V for the breakdown voltage plus about 3 V of over-voltage) at room temperature. In order to determine the breakdown voltage, finally, a Keythley 6487 source meter was used for the current-voltage (I-V) measurements.

3. I-V curves

The silicon photomultipliers under test here work in the so-called Geiger mode avalanche breakdown. This means that, in this kind of detectors high gain and very low noise, during the avalanche multiplication, offers the possibility to detect single photons. On the other hand, however, this implies also that afterpulsing and cross-talk processes distort the shape of the output signals arising an excess of noise. However, in order to have an estimation of the voltage at which the main avalanche occurs (V_{BD}), a measure of I-V distribution at different temperatures was necessary.

Following the procedure described in [5], a way to infer information about the V_{BD} from the analysis of the I-V curves is to perform a quadratic fit of the parabolic growth of the curve. The vertex of the parabola is located at the requested breakdown voltage. Fig. 2 shows the curves of of the 4 single Hamamatsu cells S13360-6075CS (from upper left clockwise, SiPM 1, SiPM 2, SiPM 3, SiPM 4 respectively) took at room temperature ($\sim 20^\circ$C). A total of five measurements were taken per each sample (blue points), while for the final analysis only the average (red points) was taken into account. Furthermore, the linear part of the data is due to surface leakage current that is determined by the carriers generated both in the bulk as well as in the surface depleted region around the junction [5]. In order to consider only the second component, the surface current, extrapolated from a linear fit (green line), has been subtracted from the device current. Depending on the working temperature, this kind of behavior is maintained up to about 55–56 V, then the current starts increasing at a much higher rate finally reaching (at about 56 V) a resistance-limited value and the device starts to saturate. The V_{BD} at room temperature is, finally, (51.6±0.1) V, and its variation as a function of the temperature is (59±5) mV. These are in very good agreement with the data sheets provided by Hamamatsu Photonics [3].

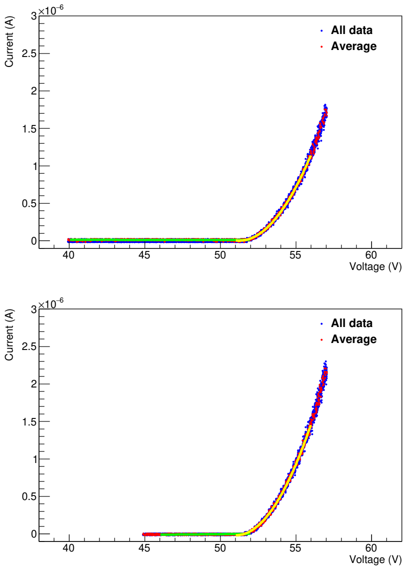

Figure 2. I-V curves taken at room temperature (∼ 20°C) during the characterization campaign of the 4 single Hamamatsu cells S13360-6075CS (from upper left clockwise). The green and yellow lines represents the linear and the parabolic fits used to extract the value of the breakdown voltage of the devices, respectively. Here all the taken measurements (blue points) are displayed together with their average (red points), details in the text.

4. Noise characterization

Several mechanisms can contribute to noise in SiPMs. The main one is the so-called Dark Count Rate (DCR). It comes from the generation of electrons even in absence of hitting photons. Those electrons are able to produce avalanches and the resulting signal is almost identical to the one produced by a "real" photon. DCR decreases with decreasing temperature but it also increases with the increasing over-voltage bias, so it is crucial to have a good estimation of V_{ov} at low temperature in order to have the least possible DCR. Other sources of noise in SiPMs are the correlated noises, and they are mainly optical cross-talks and afterpulsing. While the former are generated by photons that are produced during an avalanche that can in turn trigger an avalanche in a near cell (Single Photon Avalanche Diodes, SPAD), the latter generates when, during an avalanche, electrons are trapped by impurities in the silicon lattice of SPAD and then released generating another avalanche. Since afterpulses generate in the same cell of a primary event, it is possible to distinguish them by the identification of the time delay and the amplitude of the pulse. They also increase as the over-voltage bias increases.

4.1. Dark Counts Rate and Cross-talks probability

The DCR, in units of Hz/mm^2, can be trivially calculated by looking at the first peak (the so-called pedestal) in fig. 3. It reports an example of the so-called the Single Electron Response (SER),where every peak is given by one or multiple photoelectrons. In this kind of spectrum, furthermore, the distance between two adjacent peaks is constant and it can be, also, used for the calculation of the gain, that corresponds to the charge released by a single SPAD.
Basically the DCR rate is the number of detected pulses over the total number of triggered events per unit area and unit time collected in dark condition, i.e. without any illumination source. Measurements on the Hamamatsu samples studied in this work report about 30 kHz/mm^2 of DCR at room temperature and 60 Hz/mm^2 at -50°C.

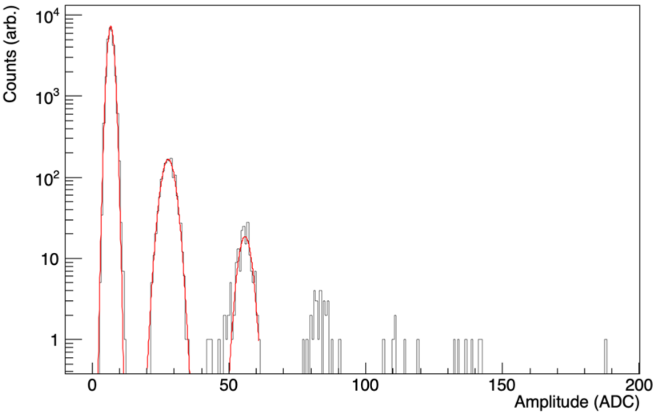

Figure 3. Amplitude spectrum of the filtered waveform taken at -50 °C and $V_{\text{bias}} = 50.7$ V (+3 V of over-voltage).

Cross-talk probability, on the other hand, can be extracted directly from the frequency distribution of trigger pulse amplitude obtained by the SER spectrum, and is calculated as the probability that one pixel triggers at least one avalanche in a neighbor one. The trigger sample is selected by using a 1 ns time window, which ensures that the contribution of afterpulsing is negligible. Indeed, within 1 ns immediately following an avalanche, the pixel over-voltage is close to zero. Hence, if a charge carrier happens to enter or be released within the depleted region 1 ns or less after the first avalanche, it will not generate an avalanche.

Direct cross-talk (DiCT) probability are measured to be about 12% at -50°C and it account for internal and external cross-talk contributions. As expected DiCTs increase almost linearly with the bias voltage since more carriers are able to trigger an avalanche in a SPAD.

5. Conclusions

The TAO experiment aims to measure the reactor anti-neutrino energy spectrum with an energy resolution better than $2.0\%/\sqrt{E[\mathrm{MeV}]}$ corresponding to about 4500 collected photons. In order to achieve its goal, the TAO detector will be equipped with about 4000 SiPMs arranged in tiles (5×5 cm^2 each), for a total of $\sim$ 95% coverage excluding fill factor, working at -50 °C. Moreover, Photon Detection Efficiency (PDE) is required to be $\geq$ 50%, dark count rate (DCR) $\leq$ 100 Hz/mm^2 at -50° C, and cross-talk probability should be less than 10%. In the case of commercial Hamamatsu Photonics S13330-6075CS single-cell SiPMs reported here, DRC is about 60 Hz/mm^2 at the working temperature of TAO (-50° C) and cross-talk probability is about 12%, accounting for internal and external cross-talk contributions. Preliminary results show that this kind of devices can fulfill the requirements of the experiment.

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