Pre-Production and Quality Assurance of the Mu2e Calorimeter Silicon Photomultipliers

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Abstract

The Mu2e electromagnetic calorimeter has to provide precise information on energy, time and position for ∼100 MeV electrons. It is composed of 1348 un-doped CsI crystals, each coupled to two large area Silicon Photomultipliers (SiPMs). A modular and custom SiPM layout consisting of a 3×2 array of 6×6 mm^2 UV-extended monolithic SiPMs has been developed to fulfill the Mu2e calorimeter requirements and a pre-production of 150 prototypes has been procured by three international firms (Hamamatsu, SensL and Advansid). A detailed quality assurance process has been carried out on this first batch of photosensors: the breakdown voltage, the gain, the quenching time, the dark current and the Photon Detection Efficiency (PDE) have been determined for each monolithic cell of each SiPMs array. One sample for each vendor has been exposed to a neutron fluency up to $\sim 8.5 \times 10^{11}$ 1 MeV (Si) eq. n/cm^2 and a linear increase of the dark current up to tens of mA has been observed. Others 5 samples for each vendor have undergone an accelerated aging in order to verify a Mean Time To Failure (MTTF) higher than $\sim 10^6$ hours.

Keywords: Calorimeter, Silicon Photomultiplier, Quality Assurance, Radiation Hardness, Mean Time To Failure

1. Introduction

The Mu2e Experiment [1] will search for the CLFV coherent conversion of muon into electron in the field of an aluminum nucleus with an unprecedented accuracy, allowing to indirectly probe energy scales up to thousands TeV. One of the most important pieces of the Mu2e detector is the electromagnetic calorimeter [2]: it consists of 1348 un-doped CsI crystals each coupled to two large area

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Silicon Photomultipliers (SiPMs) and arranged in two disks. The calorimeter is hosted in a cryostat inside a superconductive solenoid and has to operate in a 10^{-4} Torr vacuum and a 1 T magnetic field. Moreover, it also has to stand the high radiation fluxes coming from the muons stopping target: in the hottest regions, i.e. the inner crystals of the front disk, the radiation level will reach about 10 krad/year and a neutron fluence of $\sim 2\times 10^{11}$ n/cm^2/yr.

The SiPMs must have a good quantum efficiency at 310 nm for optimal coupling with the CsI scintillation emission. Since the detector will be accessible only once a year, the photosensors must have a good reliability so as not to compromise the calorimeter performances with any failure.

To fulfill the calorimeter requirements, a custom SiPM layout consisting of a 3×2 array of new generation 6×6 mm^2 UV-extended monolithic SiPMs has been designed. The readout is organized as the parallel connection of two series of three monolithic cells. The connection in series of three SiPMs allows to have a large active area with a reduced equivalent capacitance. In this way it is possible to increase the light collection and also to obtain narrowed signals useful to handle the pileup. On the other hand, the bias voltage of the series triples with respect to the one of a single SiPM.

2. Quality Assurance of SiPMs Pre-Production

The Quality Assurance (QA) process for the photosensors selection is requested to detect any device with operative performances under the standards. The QA will characterize the photosensors at the level of the single cell before the assembling in the calorimeter.

QA criteria have been fixed starting by the request to have a good uniformity between the cells of the same sensor and to have a light collection of at least 20 photo-electrons/MeV as suggested by simulation. Defining the operational voltage V_{op} as 3 V over the breakdown voltage V_{br}, the requirements at a temperature of 20° C are:

- a spread in the breakdown voltage V_{br} between the sensor cells $< 0.5\%$;
- a spread in the dark current at V_{op} between sensor cells $< 15\%$;
- a gain at V_{op} (measured in 150 ns gate) $> 10^6$ for each cell;
- a PDE at $V_{op} > 20\%$ for 315 nm;
- a quenching time < 100 ns.

In order to perform the final photosensor choice, 150 custom prototypes has been purchased from three international vendors: Hamamatsu and SensL, with a pixel size of 50μm, and AdvanSid, with a pixel size of 30μm. This first batches has been tested according to the QA procedure described below.

In view of the large number of measurement to perform, a custom semi-automatized system controlled by computer has been developed. The station keeps the temperature of the Sensor Under Test (SUT) stable at 20° C. The temperature is continuously monitored by a digital thermometer system with an accuracy of 0.3° C.

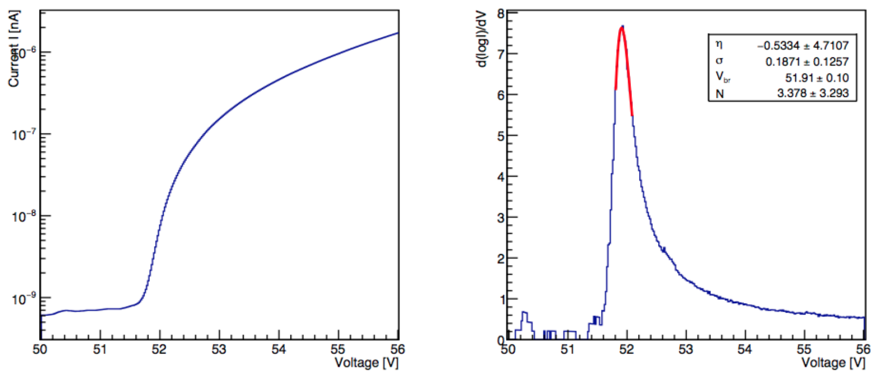

Figure 1: **Left** - Example of an I-V scan for a cell. **Right** - Logarithmic derivative of the I-V curve used to evaluate V_{br}.

First, the I-V dark curve is measured with a 50 mV step resolution. The V_{br} is then obtained by constructing the dlog(I)/dV curve and by fitting the peak position [3]. An example of this procedure is shown in Figure 1. The dark current at V_{op} is then easily extracted from the I-V dark curve.

To evaluate the gain, the SUT is illuminated with an UV LED driven by 20 ns pulses at 100 kHz frequency. The pulse amplitude is tuned to let only few photons hitting the sensor. The charge is reconstructed by integrating the first 150 ns of signal: an example of resulting charge distribution is reported in Figure 2 Left. The gain is then obtained by taking the difference between the position of the first and the second peaks in the charge distribution, corresponding respectively to 0 and 1 photons hitting the sensor. An example of the gain measurement results for Hamamatsu devices is shown in Figure 2 Right.

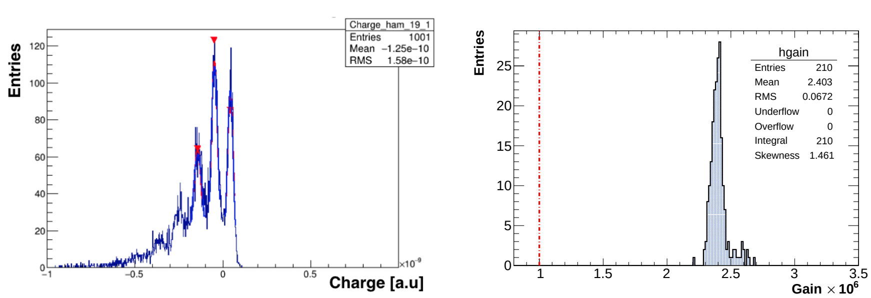

Figure 2: **Left** - Example of photo-peaks distribution for one cell. **Right** - Resulting distribution of the measured gain for the Hamamatsu devices.

The PDE is determined using a counting method that directly analyzes all the waveforms triggered in time with the LED pulse. The result is then cross-calibrated with the known PDE of a reference sensor.

The quenching time is obtained by fitting the waveform of the cells output using a superposition of two exponential functions.

3. Increase of Dark Current due to Radiation Damage

Radiation damage can create defects in silicon detectors, which mainly increase the dark current [4]. Simulation studies estimated that, in the highest irradiated regions, each photosensor will absorb a dose of 20 krad and will be exposed to a neutron fluence of $\sim 8 \times 10^{11}$ 1 MeV (Si) eq. n/cm^2 in three years of running, with a safety factor of three to take into account uncertainties in the Montecarlo simulation. Since for these fluxes the damage dealt by ionizing particles is negligible with respect to the displacement damage due to neutron interactions [5], the photosensors have been tested with the neutron generated by the EPOS facility of HZDR in Dresden. This facility can provide a clean neutron flux centered at 1 MeV with negligible photon contamination. One device/vendor has been exposed to a fluence up to $\sim$8.5 $\times$ 10^{11} 1 MeV (Si) eq. n/cm^2 over $\sim$29 hours. The dark current has been continuously measured during the irradiation. A linear increase of the dark current as a function of the fluence with a different slope between vendors has been observed (see Figure 3).

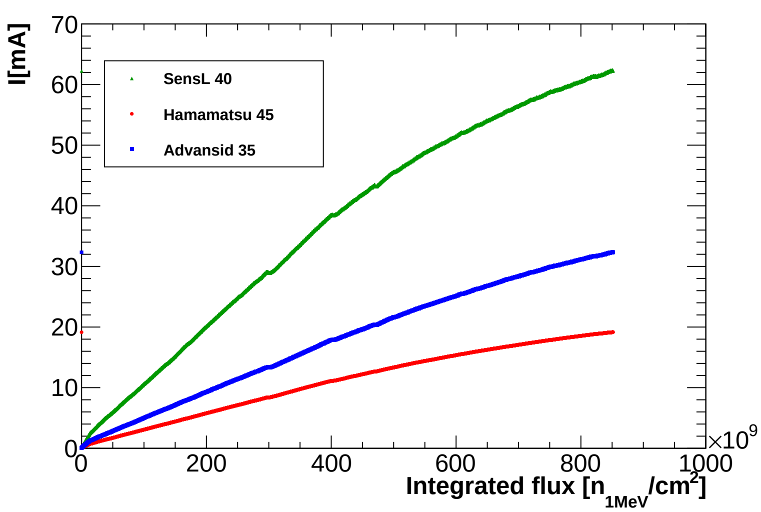

Figure 3: Dark current of a sensor cell as a function of the neutron fluence. Deviation from linear dependence at higher fluence are due to voltage drop on the cable.

After the irradiation, in order to keep the sensors draw a dark current lower than 2 mA (the maximum acceptable value from the Front-End Electronics), the solution is to cool down the operation temperature to 0° C.

4. Mean Time To Failure

Each of the two sensors coupled to the same crystal can independently satisfy the request on the light collection. In this way, to lose a calorimeter channel both the sensors have to fail. The Mean Time To Failure (MTTF) needed to maintain a fully performing calorimeter along the planned three years of running is of the order of $\sim 10^6$ hours/component. In order to obtain an MTTF experimental estimation for the Mu2e custom SiPMs, 5 sensors/vendor have been subjected to accelerated aging. These sensors have been stressed by operating them at V_{op} inside a light tight box kept at a temperature of 50° C. According to the Arrhenius Equation, this temperature corresponds to an acceleration factor of $\sim$100. During the 2500 hours of test the sensors were continuously monitored by controlling their response to a pulsed LED every 2 minutes and by registering the behavior of the dark current in time. No dead sensors have been observed for all the three vendors, confirming an MTTF value greater than 0.65×10^6 hours.

5. Conclusions

A first batch of 150 custom photosensor prototypes from three different vendors has been fully characterized and tested both for radiation hardness and reliability. These results helped to define the QA procedure to test the photosensors production: this QA process will involve more than 3000 devices, for a total of more than 18000 monolithic cells. After completing QA, the photosensors will be assembled together with the cystals in the calorimeter disks.

Acknowledgments

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References

[1] L. Bartoszek, et al., Mu2e Technical Design Report`arXiv:1501.05241`.

[2] N. Atanov, et al., The calorimeter of the Mu2e experiment at Fermilab, JINST 12 (01) (2017) C01061. `arXiv:1701.07975`, `doi:10.1088/1748-0221/12/01/C01061`.

[3] C. Xu, Study of the silicon photomultipliers and their application in positron emission tomography, Ph.D. thesis, DESY (2014).

[4] C. Leroy, P.-G. Rancoita, Particle interaction and displacement damage in silicon devices operated in radiation environments, Reports on Progress in Physics 70 (4) (2007) 493.

[5] S. Baccaro, et al., Irradiation study of uv silicon photomultipliers for the mu2e calorimeter, Journal of Instrumentation 12 (02) (2017) C02022.