The Mu2e Calorimeter Photosensors

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Abstract: A "custom" modular SiPM layout has been chosen to enlarge the active sensor area and maximize the number of collected photoelectrons from the crystal. To well match the wavelength of the emitted light produced by the CsI crystals the SiPMs have to be extended in the UV region. A configuration in series has been chosen to overcome the issues related to the parallel connection which might affect the energy and time measurements, as due to the very large capacitance that may result in an increased noise, signal rise time and width. The design, production and tests on these SiPMs will be shown.

Keywords: Photosensors, SiPM, Calorimeter.

1 Introduction

The Mu2e experiment at FNAL [1] aims to measure the charged-lepton flavor violating neutrinoless conversion of a negative muon into an electron. The conversion results in a monochromatic electron with an energy slightly below the muon rest mass (104.97 MeV). The calorimeter should confirm that the candidates reconstructed by the extremely precise tracker system are indeed conversion electrons while performing a powerful μ/e particle identification. The baseline version of the calorimeter [2] is composed by two disks of inner filled by 1348 pure CsI crystals of 20 cm length. Each crystal is readout by two large area custom SiPMs.

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A "custom" modular SiPM layout has been chosen to enlarge the active sensor area and maximize the number of collected photoelectrons from the crystal. The choice is to use two arrays of 2x3 monolithic 6x6 mm^2 UV extended SiPMs. This SiPM dimension granted an area collection efficiency of ~ 19% per sensor. With a PDE > 25% at the wavelength of the pure CsI crystal (~315 nm) [3], we collected 18 p.e./MeV with a single photosensor when coupled with an air-gap to the crystal. This possibility of not using grease or glue is a great advantage when working in vacuum since reduces the problems related to outgassing. A second SiPM, with its own independent electronics chain, is used to read out a crystal to ensure redundancy.

A configuration in series has been chosen to overcome the issues related to the parallel connection which might affect the energy and time measurements, as due to the very large capacitance that may result in an increased noise, signal rise time and width. Differently from the parallel configuration, where the signal becomes wider, the pulse shape of a series of SiPMs results narrower than that of a single SiPM due to the reduction of the total sensor capacitance. The reduction of the overall width helps improving the pileup discrimination capability. The rise time of the series remains as good as the one of a single SiPM thus not changing the time resolution performances with respect to the parallel configuration.

The design of the Mu2e custom SiPMs is reported in Fig. 1; it is organized as the parallel of 2 series of 3 6x6 mm2 monolithic UV extended SiPMs. A common bias voltage point is provided for all SiPMs.

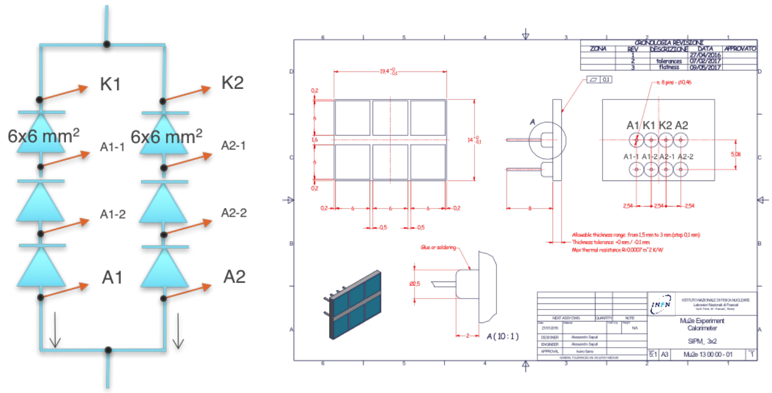

Fig. 1. Mu2e SiPM technical drawing.

2.1 Procurement Plans and pre-production

These specifications were used for an international competitive bid done by INFN to make a first pre-production while also ranking the technical capability of each producer. At the first step of the tender, three producers were selected: Hamamatsu photonics (Japan), SensL (Ireland) and Advansid (Italy). Each of this firm has been invited to produce 50 prototypes following the design shown above and the strict set of specifications:

- the value of the breakdown voltage, Vbr, and the corresponding operation voltage, Vop, that is defined as +3 V over the breakdown voltage;
- a spread on Vop of < 1 V among the different devices in the delivered batch;
- a relative spread in Vop between the sensor cells < 0.5%;
- a relative spread in the dark current, Id, at Vop between the sensor cells < 15%;
- a gain at Vop > 106 for each cell. Inside each array, the gain uniformity (RMS/mean) will be evaluated. The uniformity has to be < 10%;
- a PDE in excess of 20% at 315 nm at Vop;

- a total thermal resistance for the device below 7 x 10^{-4} m^2 K/W.

A Quality Assurance program is under way at our test station in Pisa. In Fig. 2 the results for the distribution of Vop, Id and the gain for one vendor are shown. Measurements showed good quality for the pre-production. A calibrated reference sensor has been used to obtain the relative Photon Detection Efficiency (PDE), that resulted to be in excess of 20% at 315 nm at Vop for all the vendors.

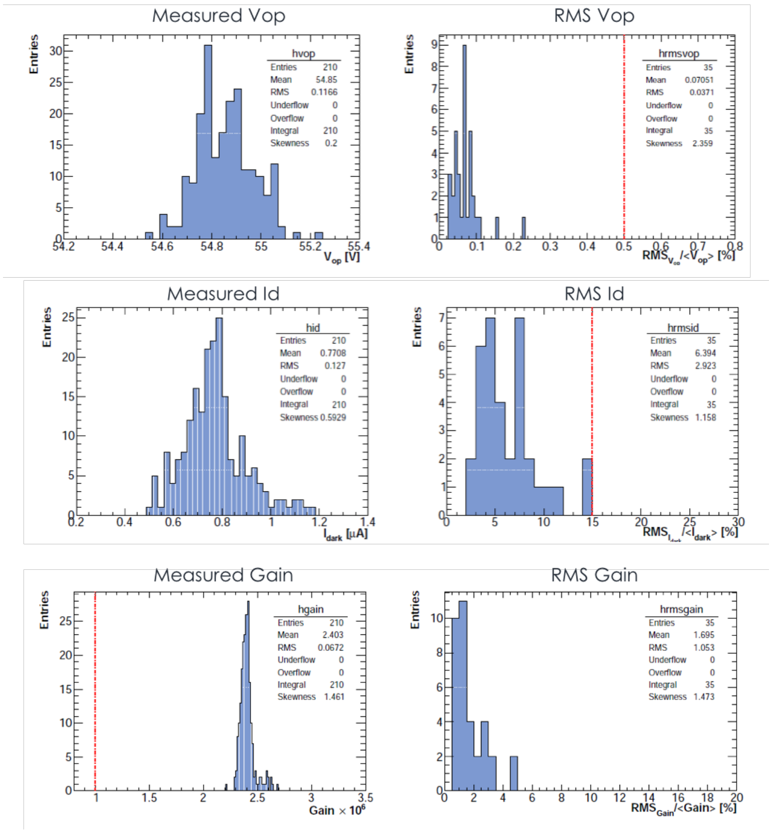

Fig. 2. Left: distribution of Vop, Id and the gain for one vendor. Right: spread between the 6 SiPMs in each array.

Since the SiPMs we are used are custom, we have developed our own control station to evaluate the MTTF of our sensors. The test has been done at LNF (Italy) and involved 15 pre-production SiPMs from (5 pieces for each vendor). The stress-test is performed by keeping the SiPMs in a light tight box at 50°C for around three months. The dark current is measured once a day by a picoammeter and the response to an UV led (360 nm) is acquired every two minutes. Not dead channels occurred, reaching an MTTF value of 0.6x10^6 hours. This value has been evaluated as follows: MTTF> 0.5 N_{hours} x AF x N_{SiPM}, where N_{hours} = 2190, N_{SiPM} = 5 and the Acceleration Factor (AF) estimated by the Arrhenius equation, with $T_{\_use}$=273 K and $T_{\_stress}$ = 323 K is 100.

The Mu2e calorimeter must operate and survive in a high radiation environment. Simulation studies estimated that the sensors have to withstand an equivalent neutron fluency, at 1 MeV energy, of ~ $1.5\text{x}10^{12}$ n/cm^2 and a Total Ionizing Dose (TID) of 50 krad of photons. These values assume 5 years of running and a factor of 3 safeties and are calculated in the hottest irradiated region, i.e. in the innermost ring of the first disk. A first irradiation campaigns was carried out in 2015, where different models of SiPMs have been tested with different protection covers: two from Hamamatsu, and one from FBK. More details on these tests can be found in ref. [4]. In this paper, we show only the measurements done with 1 MeV neutrons at HZDR, Dresden in 2017. Here, the EPOS (Elbe Positron Source) facility provides 1 MeV neutron from electron beam interacting with a tungsten target. Three SiPMs (1 per vendor) have been tested at the same time, positioned at 90 cm far away from the neutron source. The integrated fluence in 29 hours of run has been $8.5\text{x}10^{11}$ n_{1MeV}/cm^2.We acquired continuously the leakage current of one single 6x6 mm^2 for each of the three tested arrays. The temperature of the SiPMs has been kept stable at 20°C using a Peltier cell, directly connected to the SiPMs' holder, and monitored with a PT100 resistance. The heat from the hottest Peltier's side has been removed with a water Chiller. The leakage currents and the temperature have been acquired with an Agilent 34972A LXI Data Acquisition/Data Logger Switch Unit every 10 s. In Fig. 5 the experimental setup and the increase of the leakage current for the 3 samples is show.

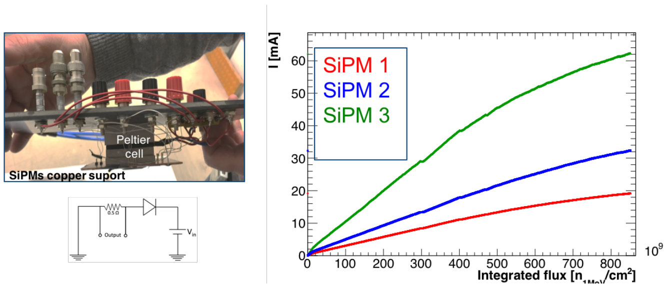

Fig. 5. Top left: mechanical structure used in the radiation test. The Peltier cell is directly connected to the SiPMs holder. Bottom left: equivalent scheme of the readout for the single 6x6 mm^2 SiPM. Right: leakage currents as a function of the fluence for the SiPMs of the three vendors.

3 Conclusions

Three different firms have delivered pre-production SiPM arrays conforming with the Mu2e final SiPM with thermal package a dimension of 2x3 array of 6x6 mm^2 cells: the Hamamatsu, the Advansid and the SensL. Measurements showed good quality for the pre-production for all the vendors. The Mu2e SiPMs well match the requirements as photosensor for the Mu2e calorimeter:

1. they keep the proportionality of the response since at 100 MeV less than10-15% of the total pixels will be fired;
2. a high collection of photoelectrons;

3. provide an excellent time resolution.

The SiPM radiation hardness to neutrons and ionization dose has been also investigated. Keeping the device at low temperature will help to mitigate the damage.

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References

1. L. Bartoszek et al.: Mu2e Technical Design Report, arXiv:1501.05241 (2015).
2. N. Atanov et al.: The calorimeter of the Mu2e experiment at Fermilab, Journal of Instrumentation 12(1), C01061 (2017).
3. N. Yahlali et al.: Imaging with SiPMs in noble-gas detectors, arXiv:1210.4746 (2012).
4. M. Angelucci et al.: Longitudinal uniformity, time performances and irradiation test of pure CsI crystals, Nuclear Instruments and Methods in Physics Research A 824, 684-685 (2016).