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Production and Quality Assurance of the Mu2e Calorimeter Silicon Photomultipliers

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Abstract. The Mu2e calorimeter consists of 1348 undoped CsI crystals coupled to two large area UV-extended Silicon Photomultipliers (SiPMs). A modular and custom SiPM layout, a 3×2 matrix of 6×6 mm² monolithic SiPMs, has been developed to satisfy the Mu2e requirements. As well as ensuring the performances needed for the muon-to-electron conversion search, these photosensors have to guarantee a good reliability while operating maintenance-free in the Mu2e hostile environment: any failure can only be replaced during a long technical shut-down scheduled once a year. After testing prototypes from different vendors, we selected Hamamatsu and the final production of about 4000 pieces is now ongoing. A detailed Quality Assurance (QA) program is then mandatory to minimize the risk of an unexpected further degradation in the performances. The QA process for each photosensor includes a first visual inspection and the subsequent characterization of each of its monolithic cells by means of an automatized test station, able to measure the breakdown voltage, the gain and the dark current. For each production batch (~ 300 pieces), 5 devices are exposed to a neutron fluency up to $\sim 1.4 \times 10^{11}$ 1 MeV (Si) eq. n/cm²; others 15 devices are undergone an accelerated aging in order to verify the Mean Time To Failure (MTTF) of the batch. A summary of the QA and the results for the firsts 4 production batches are presented in the paper.

1. Introduction

The Mu2e Experiment [1] will search for the Charged Lepton Flavour Violation (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 Silicon Photomultipliers (SiPMs) and arranged in two disks. Its main role is to provide excellent particle identification capabilities to reject the cosmic muons background, to guarantee a fast online trigger and to help the tracker in the pattern recognition.

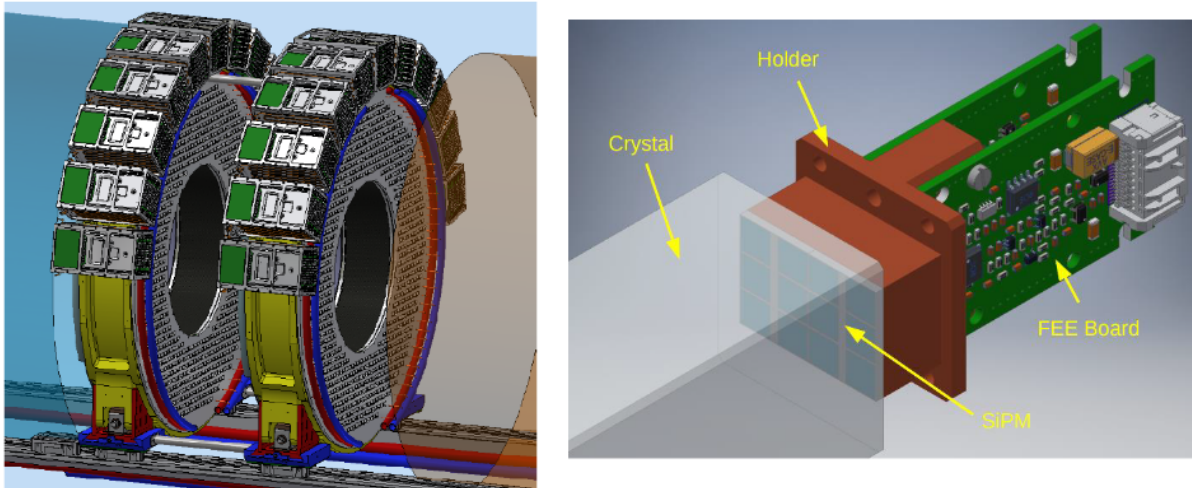


Figure 1. Left - Drawings of the two calorimeter disks. Right - Drawings of one crystal + sensors + FEE modular unit.

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, standing to the high radiation fluxes coming from the muons stopping target. Furthermore, in the inner region of the front disk, the hottest one, the Total Ionizing Dose (TID) will reach ~ 10 krad/year while the neutron fluency $\sim 2 \times 10^{11}$ n/cm²/yr. Since the detector will only be accessible only once a year, the reliability and the radiation hardness of the photosensors are one of the critical aspect for the success of the Mu2e experiment.

2. The Mu2e Custom SiPMs Array

The main scintillation component of CsI is emitted at a wavelength of 310 nm so that have been selected the new generation of UV extended SiPMs. In these sensors, the epoxy resin in the front window has been substituted by a silicon resin thus providing a Photon Detection Efficiency (PDE) greater than 20% from the blue region down to 280 nm.

Since redundancy is a good tool for reliability, each of the two sensors coupled to the same crystal has to independently satisfy the request of 20 p.e./MeV on the light collection. In this way, to lose a calorimeter channel both the sensors have to fail. To reach the requested geometrical acceptance while keeping a smaller total capacity for the sensor, a custom package has been developed. It consists of a 3×2 matrix of 6×6 mm² monolithic SiPMs (cells) with the readout organized as the parallel of 2 series of three cells. With this configuration the length of the signal significantly decreases, allowing for a better pileup discrimination: this is shown in Figure 2, where the quenching time for the series of 3 cells is compared with the one of a single cell. On the other hand, the bias voltage becomes three times the one of a single cell.

An international bid has been organized in order to take the final photosensor choice and 150 custom prototypes have been purchased from three vendors: Hamamatsu and SensL, with a pixel size of $50 \mu\text{m}$, and AdvanSid, with a pixel size of $30 \mu\text{m}$. After a deep characterization [3], Hamamatsu devices (with the model 13360-6050CS used as cell) have been selected.

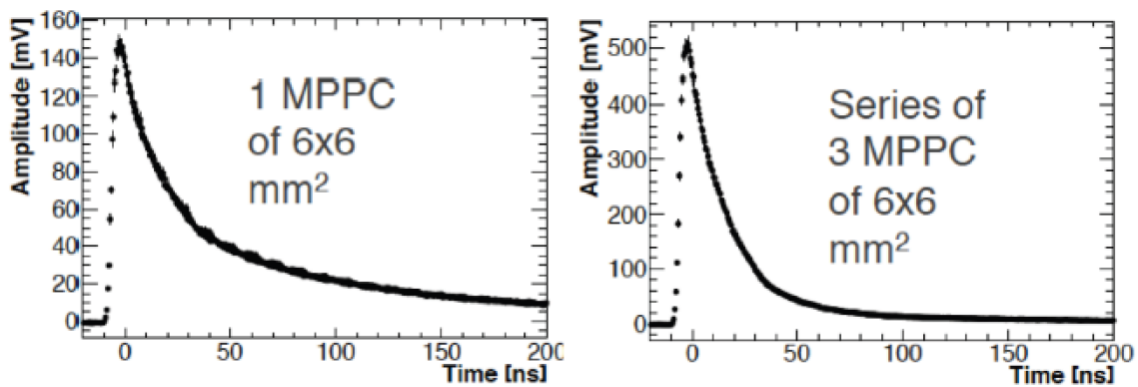


Figure 2. **Left** - Signal shapes for a single 6×6 mm² cell when illuminated with a 50 ps wide laser pulse, without preamplification and terminated on 50 Ohm. **Right** - Signal shape for the series of three cells using the same laser pulse.

3. Quality Assurance on SiPMs Production

The Quality Assurance (QA) process for the calorimeter photosensors is carried out in a dedicated soft clean room in the SiDet Fermilab department, the same in where the calorimeter disks will be assembled. The clean room, shared with the crystals QA, has controlled humidity and temperature respectively of the 40% and 20° C degrees. Starting from March 2018, we are receiving one batch of ~ 300 photosensors/month. QA is kept in phase with the production, so to check the stability of the sensors characteristics and eventually to reject batches with reduced performances.

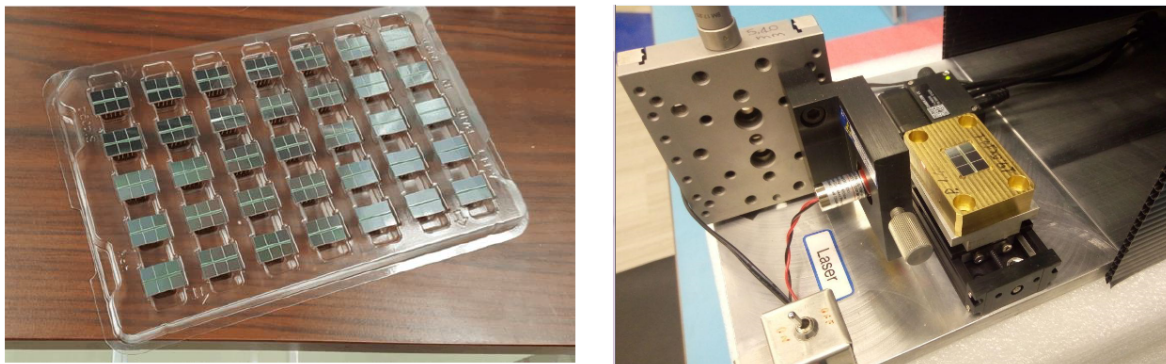


Figure 3. **Left** - Picture of a package of 35 photosensors. **Right** - Picture of the dimensional station.

QA is also requested to detect any device with operative performances under the standards and to check the accuracy of the mechanical dimensions. As first step, each sensor is subjected to a visual inspection to detect any scratch on the resin surface or mechanical damages. Then it is performed a dimensional check with a dedicated station. It consists of a mask (made with a few μm accuracy) where to plug the SiPMs and a laser. A stepper motor moves the sensor in front of the laser light and the shadow is projected on a graduated screen. With this *chinese shadow* technique it is possible to guarantee the requested tolerance of 100 μm for both the

transverse dimension and the thickness. The third step is the characterization of each sensor at the level of the single cell. Selection 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 p.e./MeV, as suggested by simulation [4]. 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 \times PDE(310nm) at $V_{op} > 0.2 \times 10^6$ for each cell;

If a sensor doesn't meet these specifications is rejected. Measurements are performed with a fully automatized test station, described in details in the next section. For each batch are also being measured the Mean Time to Failure (MTTF) and the radiation Hardness using random selected samples.

4. Measurement of SiPMs parameters

In view of the large number of measurements to perform ($\sim 24k$ single cell characterizations), a fully automatized station has been developed. It is controlled with dedicated Labview software, allowing to test at a controlled temperature 25 sensors per time without any external intervention of an operator. The range of temperatures goes from -10°C to 20° C. To avoid water vapors condensations at low temperatures, tests are carried on inside a vacuum vessel kept at a pressure of 100 mbar. A drawing of the station is shown in Figure 4.

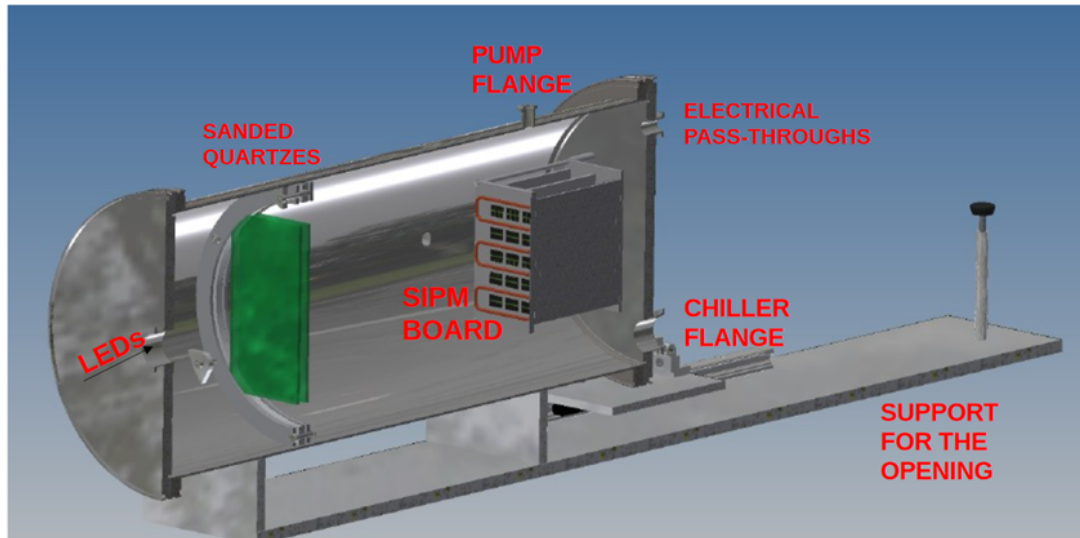


Figure 4. CAD drawings of the SiPMs QA station.

The photosensors under test are plugged on a copper plate, cooled by a chiller Julabo FL300 and posed on the top of a castle of custom PCB boards. An UV LED with the emission peaked at 310 nm and far ~ 1 m from the plate can illuminate the sensors. The light is spread by a couple of fine sanded quartzes ~ 30 cm far from the LED, powered by a dedicated board that monitor the drained current, the voltage and the temperature. The electronics is composed of a microcontroller that drives 110 relays to connect the wanted cell to a Keithley 6487, that provides the bias voltage and performs the current measurements. For each of the 150 cells on the plate it is performed an I-V scan to determine the breakdown voltage; thus, sensors are biased at

their operational voltage and the dark current and the relative $\text{Gain} \times \text{PDE}$ are measured. This is repeated for three temperatures: -10°C (backup option), 0°C (the operational temperature) and 20°C (temperature used to evaluate the technical requirements). With three points it is so possible to extrapolate the parameters in all the temperatures range. The 5 sensors posed at the corners and at the center of the board are used as reference to monitor the stability of the station, the uniformity of the light and to measure the $\text{Gain} \times \text{PDE}$.

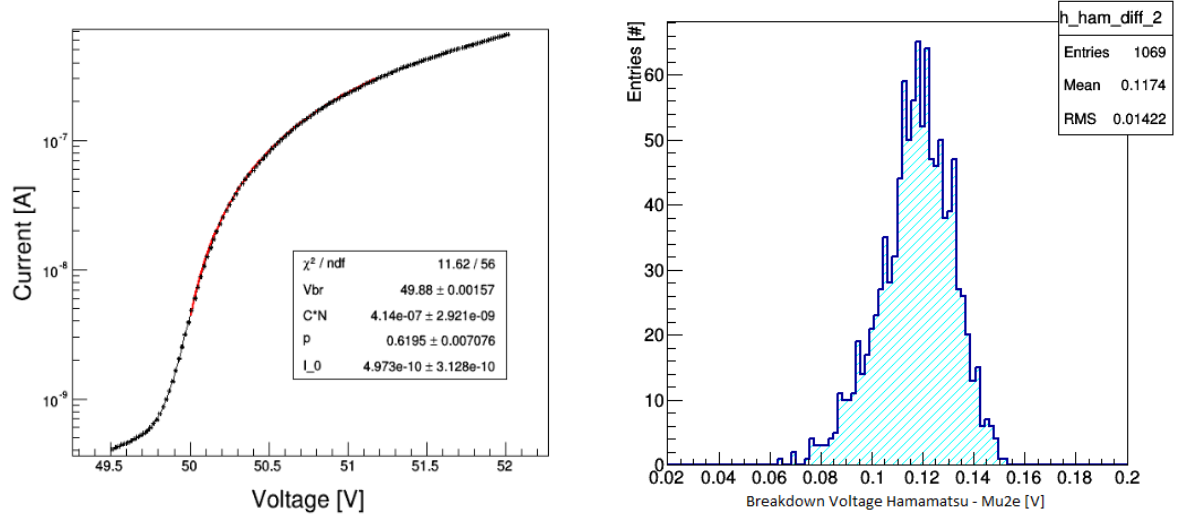


Figure 5. Left - Example of fit of the I-V curve for one cell while illuminated with a low light. **Right** - Distribution of the difference between the V_{br} quoted by the producer at 25°C and the one obtained with our techniques at 20°C .

Going down with temperature the dark current decreases of a factor ~ 2 every 10°C , reaching at -10°C the nA level around V_{br} . The I-V curve is thus performed while illuminating the sensor with a low level light, so to increase the current and to obtain a more fast and precise measurement. A first estimation of the V_{br} , dependent by the incident light, is obtained by constructing the $\text{dlog}(I)/\text{dV}$ curve and by fitting the peak position. This value is then used to initialize a second unbiased fit with:

$$I(V) = \begin{cases} I_0 + C \times (1 - e^{-p \cdot (V - V_{br})}) \times (V - V_{br}) & V > V_{br} \\ I_0 & V < V_{br} \end{cases} \quad (1)$$

where V is the bias voltage, V_{br} is the breakdown voltage, I_0 is the current before the breakdown, p is the triggering probability and C is a factor proportional to the number of the free carriers (thermal + optical). Equation 1 has been obtained starting from [5] and making a couple of assumptions to limit the number of free parameters: (i) the afterpulse and the crosstalking are negligible; (ii) we are far from the second breakdown zone. To avoid regions in where the behavior of the current while the sensor is illuminated does not follow this model, the fit is performed in an interval that starts 200 mV over V_{br} . An example of this procedure is shown in Figure 5, together with the difference between the quoted V_{br} from the producer at 25°C and our technique at 20°C .

To measure the $\text{Gain} \times \text{PDE}$, the LED is turned on and the five calibrated sensors in the corners and the center of the board are used as reference. The value is obtained by the ratio of the currents pulled by the sensor under test and the reference, while illuminating by the

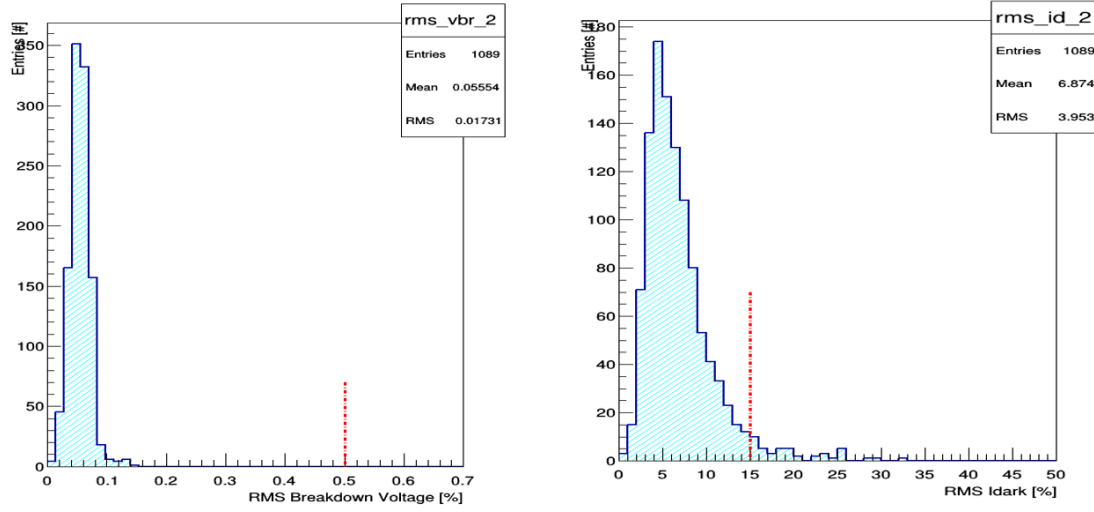


Figure 6. **Left** - Distribution of the RMS of V_{br} within each sensor. **Right** - Distribution of the RMS of the dark current within each sensor. About the 3% of the sensors resulted out of the technical specifications.

same LED light. Since the light after the diffusion is not completely uniform, an additional normalization to take into account the Gaussian light profile is applied:

$$Gain \times PDE = \frac{I}{I_{ref}} \times \frac{LightProfile(x_{ref}, y_{ref})}{LightProfile(x, y)} \times (Gain \times PDE)_{ref} \quad (2)$$

where the $LightProfile()$ function is obtained by fitting the 2D histogram of the pulled currents by the illuminated cells disposed on the copper plate with a 2D-Gaussian (see Figure 7-Left) and the $(Gain \times PDE)_{ref}$ value is obtained by a previous calibration of the closer reference sensors. The dark current is instead extracted by biasing the cell at the operational voltage and recording the current while the LED is turned off.

The RMS distributions resulting from the characterizations of the firsts 4 batches are shown in Figure 6. The uniformity of the breakdown voltage inside the sensor presents a very good behavior, while the dark current has a small tail that falls out of the specifications: Around the 3% of the production is being rejected for this reason. All the tested sensors instead widely satisfy the requirement on the $Gain \times PDE$, as shown in Figure 7-Right.

5. Radiation Hardness

Radiation damage in SiPMs mainly increases the dark current [6]. In three years of running, 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/cm². A safety factor of three has been taken into account to overcome uncertainties in the Montecarlo simulation. The damage dealt by ionizing particles is negligible with respect to the displacement damage due to neutron interactions, thus each batch of photosensors is tested only with neutrons. Figure 8 shows the behavior of the dark current at 20°C with the increase of the neutron fluence for one cell of the device: at Mu2e expected level, the dark current increases of a factor $\sim 2 \cdot 10^3$. The limit for our application is 2 mA and can be reached by using two handles: (i) cool down the SiPM at a running

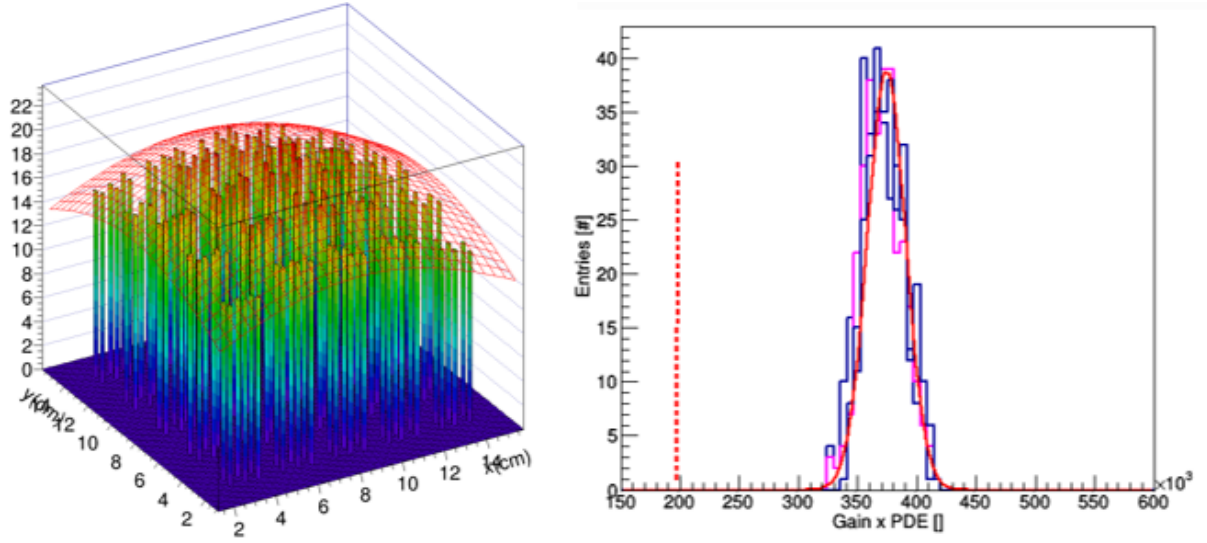


Figure 7. **Left** - Example of fit of the light profile. **Right** - Distribution of the obtained Gain \times PDE at V_{op} for each cell at 20°C (black), 0°C (blue) and -10°C (magenta). The Gaussian fit of the distribution reports a $\sigma/\mu \sim 4\%$.

temperature of 0°C and (ii) apply a reduction in operating voltages.

For each batch, 5 samples are irradiated at the EPOS facility of HZDR in Dresden up to a fluence of $\sim 8.5 \times 10^{11}$ 1 MeV (Si) eq. n/cm². This facility can provide a clean neutron flux centered at 1 MeV with negligible photon contamination. The sensors are tested unbiased and are sent back to Fermilab after the irradiation to be remeasured in the QA station. If more than 3 out of 5 irradiated SiPMs fail to meet the specifications, the entire batch will be rejected. So far, no sensors out of the specifications have been found.

6. Mean Time To Failure

The Mean Time To Failure (MTTF) needed to maintain a fully performing calorimeter (no channels lost) along the planned three years of running is of the order of $\sim 10^6$ hours/SiPM [4]. To obtain an MTTF experimental estimation for each batch of the Mu2e custom SiPMs, 15 sensors per batch are subjected to accelerated aging. These sensors are stressed by operating them at V_{op} inside a dedicated station kept at a temperature of 65° C for 18 days. It is made of an external PVC box with another internal box of aluminum. A copper support for a series of four power resistors of 0.5 Ω , responsible of heating the air, is placed inside the Aluminum box. The resistors are powered using an external control (TC-XX-PR-59 temperature controller) that ensures the internal temperature to be stable inside 0.5° C. The air temperature is recorded as well as the copper radiator temperature through PT 1000. The MTTF value is obtained using this formula:

$$MTTF = 0.5 \times N_{SiPM} \times N_{hours} \times AF \quad (3)$$

where AF is the acceleration factor. According to the Arrhenius Equation:

$$AF = e^{\frac{E_a}{k} \cdot [\frac{1}{T_{use}} - \frac{1}{T_{stress}}]} \quad (4)$$

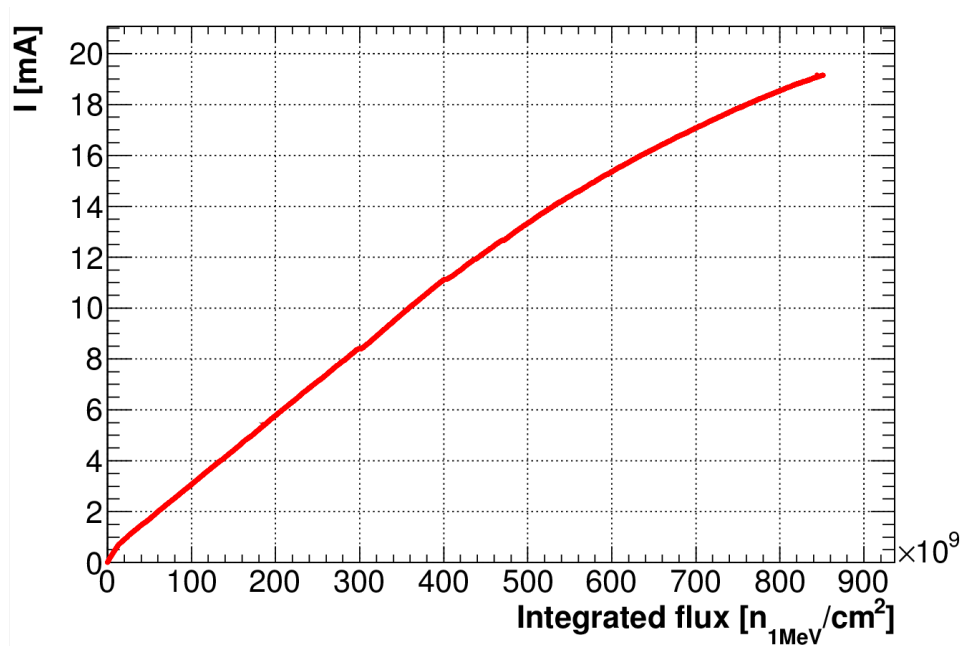


Figure 8. Dark current as a function of the integrated 1 MeV (Si) eq. neutron fluence.

In our case, $T_{stress} = 65^\circ \text{C}$ and the $T_{use} = 0^\circ \text{C}$, the acceleration factor is equal to 305. During the 432 hours of each test, the sensors were continuously monitored by registering their dark current every five minutes. Over the test of 4 batches, all SiPMs under test were still alive and perfectly working at the end of the stress period so to confirm a total MTTF value greater than 4×10^6 hours.

7. Conclusions

The production of the Mu2e calorimeter custom SiPMs is ongoing, proceeding in parallel with the QA. So far, a quarter of the photosensors has been characterized and only the 3% resulted out of the technical specifications. The overall calorimeter schedule sees the start of the first calorimeter disk assembly in 2019 and complete its construction in 2020. The qualification of all the photosensors will end in middle 2019.

Acknowledgments

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