Study of radiation hardness of un-doped CsI crystals and Silicon Photomultipliers for the Mu2e calorimeter

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Abstract

The Mu2e calorimeter is composed by 1400 un-doped CsI crystals coupled to large area UV extended Silicon Photomultipliers (SIPMs) arranged in two annular disks. This calorimeter has to provide precise information on energy, timing and position resolution. It should also be fast enough to handle the high rate background and it must operate and survive in a high radiation environment. Simulation studies estimated that, in the hottest regions, each crystal will absorb a dose of 300 Gy and will be exposed to a neutron fluency of 6×10^{11} n/cm^2 in 3 years of running.

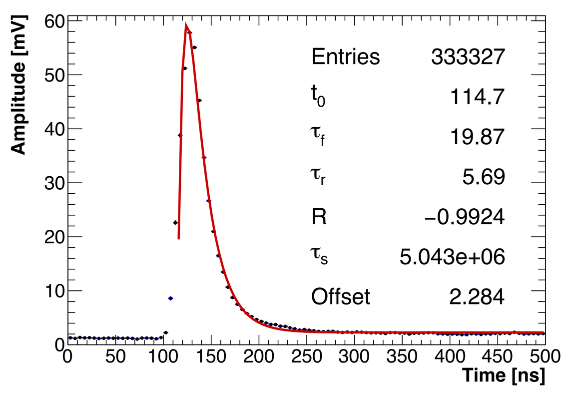
Test of un-doped CsI crystals irradiated up to 900 Gy and to a neutron fluency up to 9×10^{11} n/cm^2 have been performed at CALLIOPE and FNG ENEA facilities in Italy. We present our study on the variation of light yield (LY) and longitudinal response uniformity (LRU) of these crystals after irradiation. The ionization dose does not modify LRU while a 20% reduction in LY is observed at 900 Gy. Similarly, the neutron flux causes an acceptable LY deterioration (< 15%).

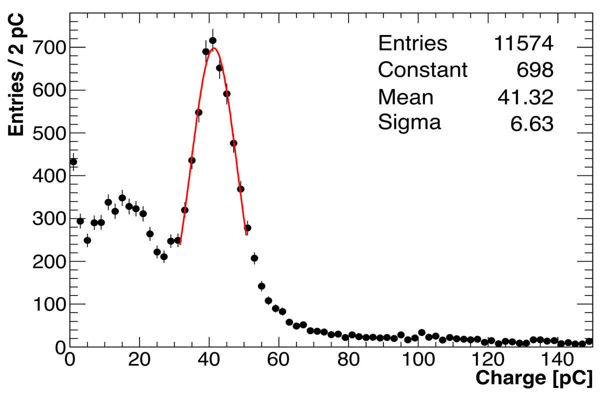
A neutron irradiation test on different types of SIPMs (two different array models from Hamamatsu and one from FBK) have also been carried out by measuring the variation of the leakage current and the charge response to an ultraviolet led. We concluded that, in the experiment, we will need to cool down the SIPMs to 0 °C reduce the leakage current to an acceptable level.

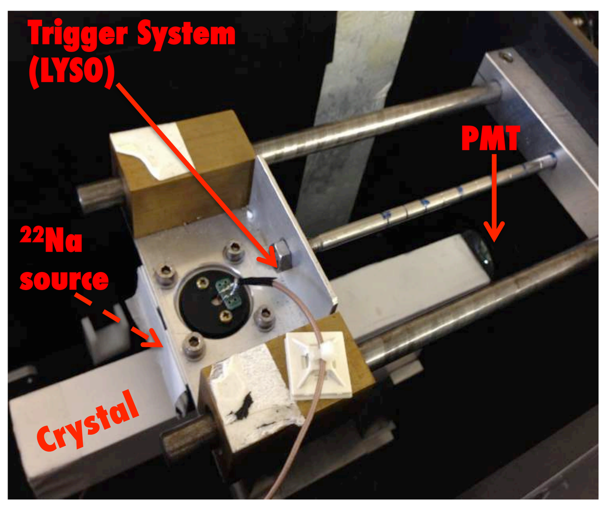
Pure CsI crystal – Radiation hardness

The damage on the crystals has been evaluated by measuring the light yield (LY, number of photoelectrons produced per MeV) before and after irradiation:

- Longitudinal scan with ^{22}Na source and PMT readout
- Peak due to the 511 keV photon clearly visible
- Peak (μ_Q) extracted with a gaussian function





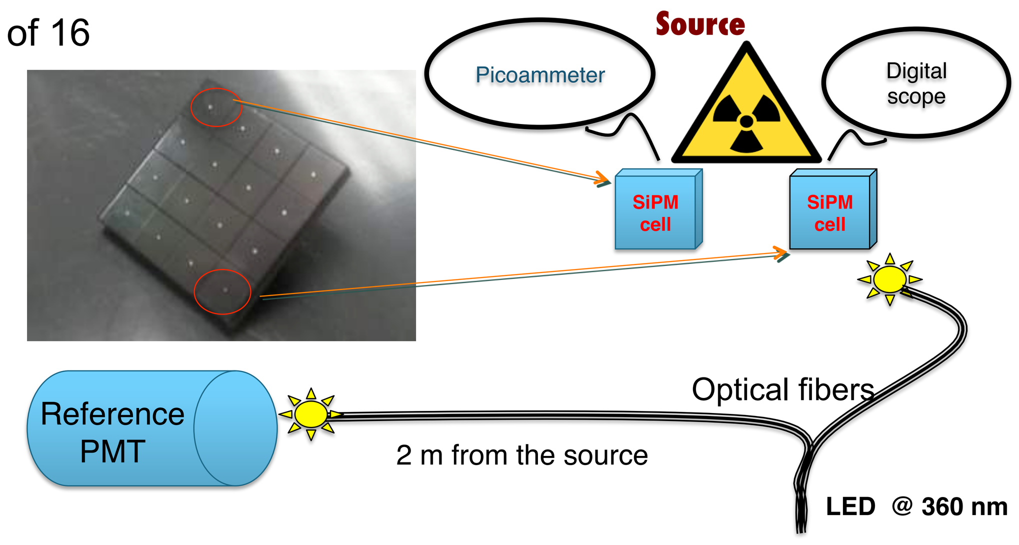


$$N_{p.e.}/MeV = \frac{Q}{Q_e \cdot G_{PMT} E_\gamma} = \frac{\mu_Q [pC]}{1.6 \times 10^{-7} [pC] \cdot 3.8 \cdot 0.511 MeV}$$

SiPM irradiation tests

- For the Hamamatsu, the SIPM is an array of 16 3 x 3 mm^2 cells. Out of these cells :
  - 1 cell is used for leakage current
  - 1 cell is used for response to a fixed UV LED pulse
  - PMT used as reference for the light input

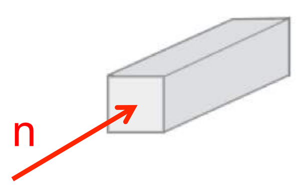
SiPMs tested	Dimension (mm^2)	V op (V)
SPL SiPM	12 x 12	53.9
Micro Film SiPM	12 x 12	53.95
FBK SiPM	6 x 6 (Monolithic)	32.5

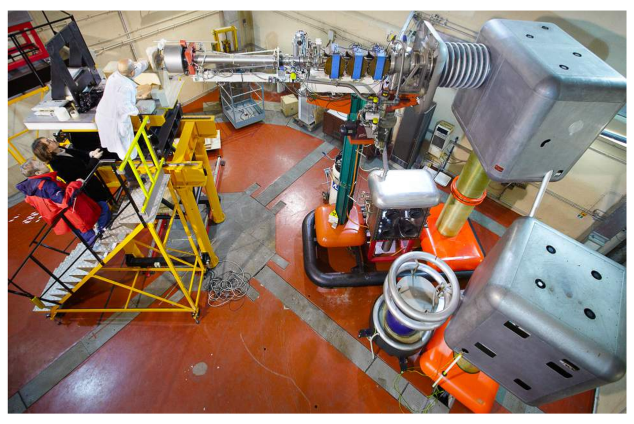


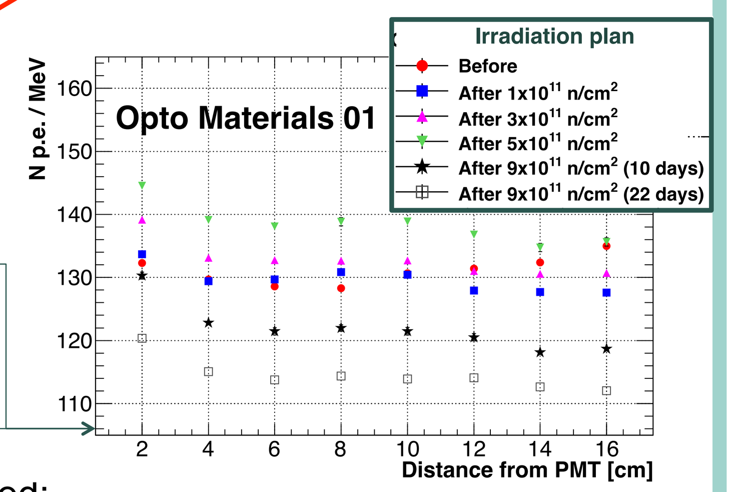
For the monolithic FBK we have measured only the leakage current

Test @ Frascati Neutron Generator Facility (FNG, ENEA)

- Four 3 x 3 x 20 cm^3 crystals, from different vendors, tested
- Total flux ~ 9×10^{11} n/cm^2 (delivered in 4 days)
- Neutrons impinging on one of the two small square faces





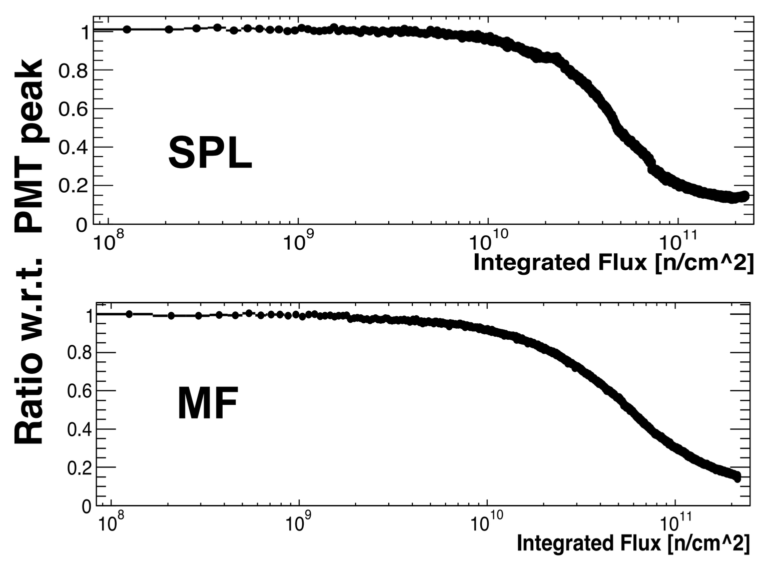


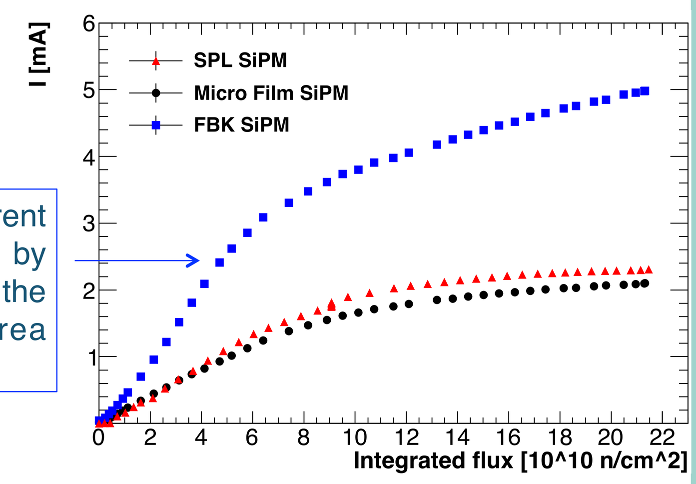
Example of LY of an Opto Materials CsI crystal measured during the irradiation plan

Forr all the 4 crystals tested:

- Activation effect is clearly visible
- The total dose caused a negligible deterioration of the LY (after 22 days of annealing)
- Longitudinal response uniformity (LRU) remains stable

- SiPM irradiated with 14 MeV neutrons up to 2.2×10^{11} n/cm^2 (fluence equivalent to 2.2 times the experiment lifetime)
- Total flux delivered in less than 4 hours





For FBK, the current has been corrected by a factor of 4, due to the different active area w.r.t. Hamamatsu

The signal peak decreased from:

- ~ 250 mV to 30 mV for SPL
- ~ 400 mV to 50 mV for MF

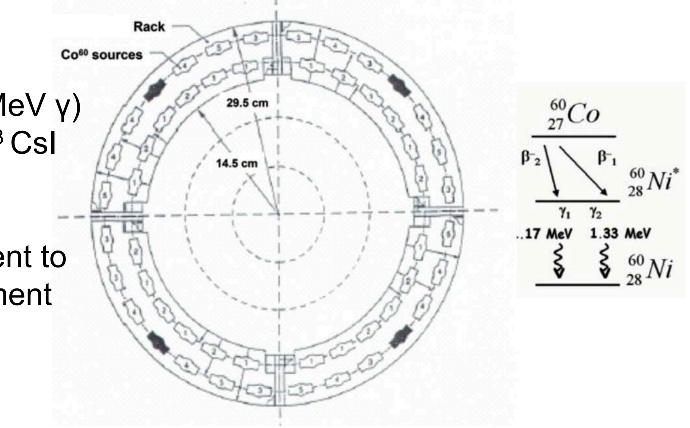
The current increased from

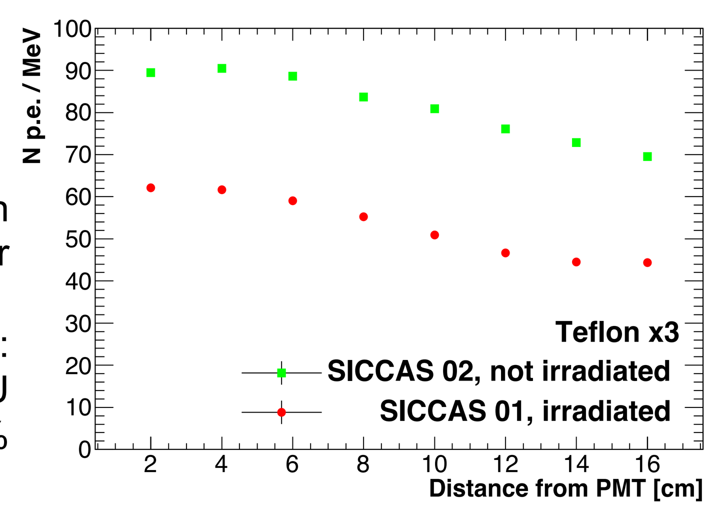
- 16 uA up to 2 mA (MF)
- 100 uA up to 2.2 mA (SPL)
- 86/4 uA up to 19/4 ~5 mA (FBK)

Drop on leakage current and gain dominated by temperature increment during irradiation

Test @ CALLIOPE - Gamma Irradiation Facility (Casaccia, ENEA)

- Calliope Source: ^{60}Co (1.25 MeV γ)
- Two SICCAS 3 x 3 x 20 cm^3 CsI crystals tested
- Total dose: 90 krad (equivalent to two times times the experiment lifetime)





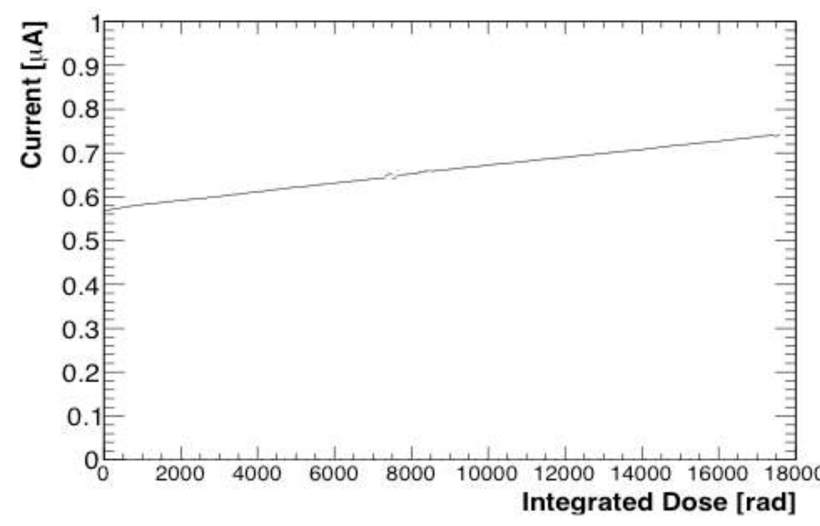
Transmittance and LY measured before and after irradiation

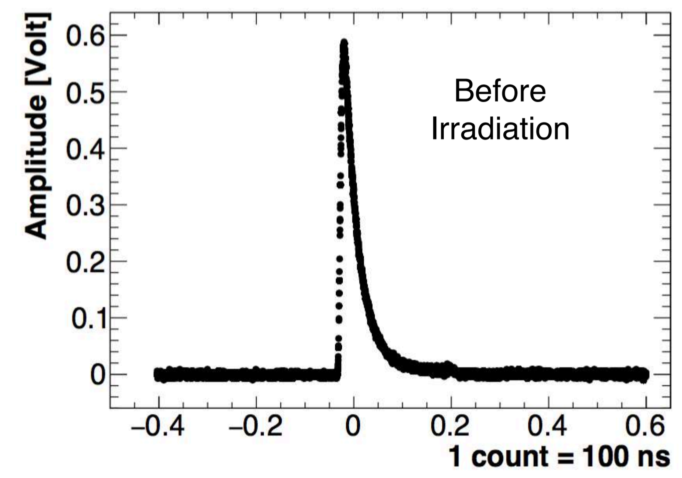
- No wrapping and readout (PMT) coupling in air

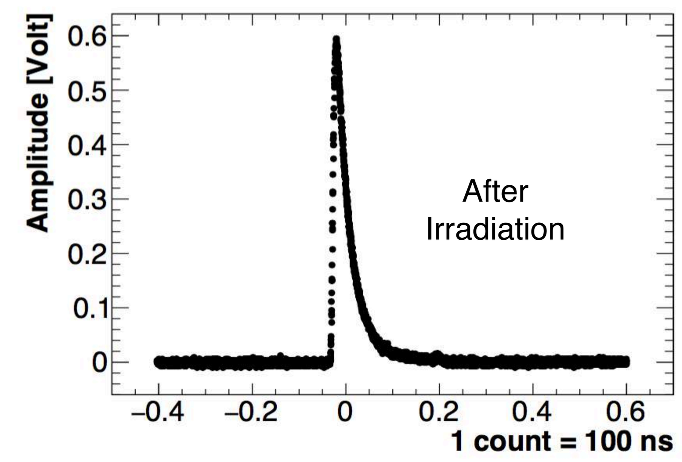
After irradiation:

- Stable LRU
- LY decrease of a about 30%

- SPL 3 X 3 mm^2 SiPM tested
- Photosensor irradiated with an high intensity ^{60}Co source up to 20 krad (200 Gy)

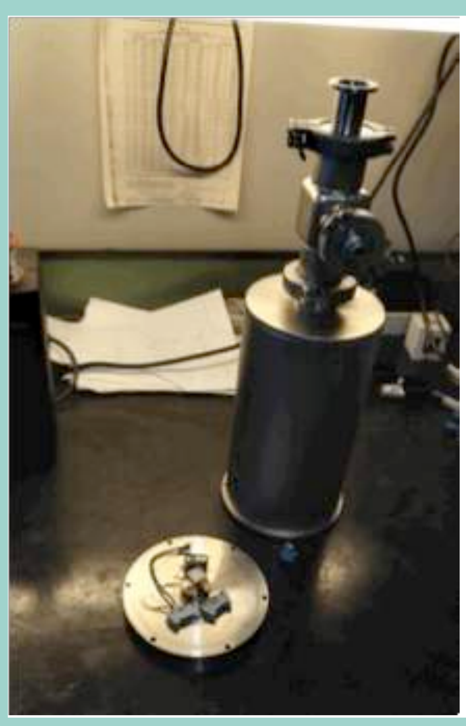






Negligible effect on the response and on the leakage current due to the dose

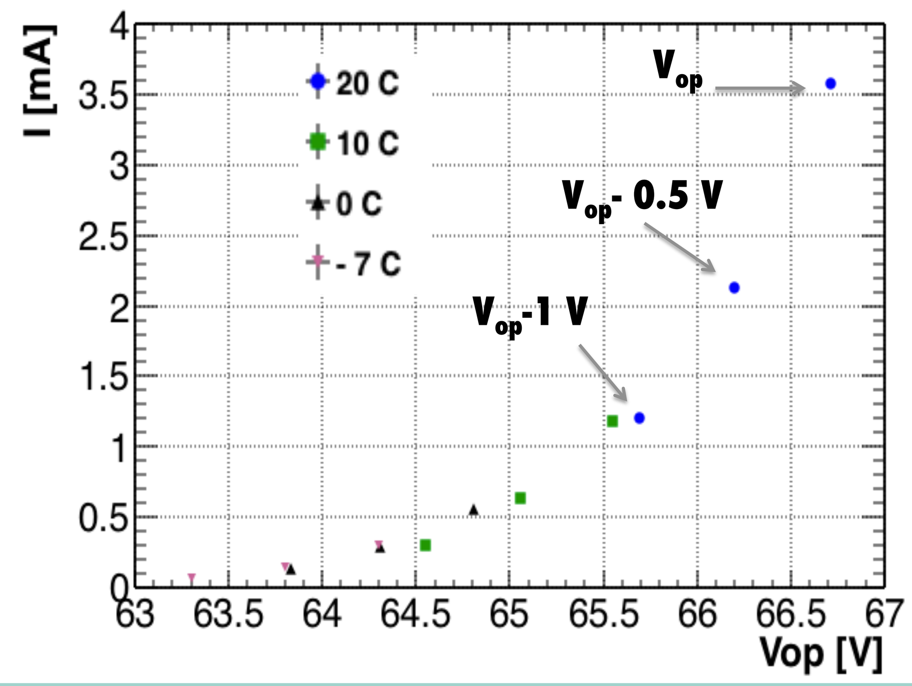
Test under vacuum and temperature dependences



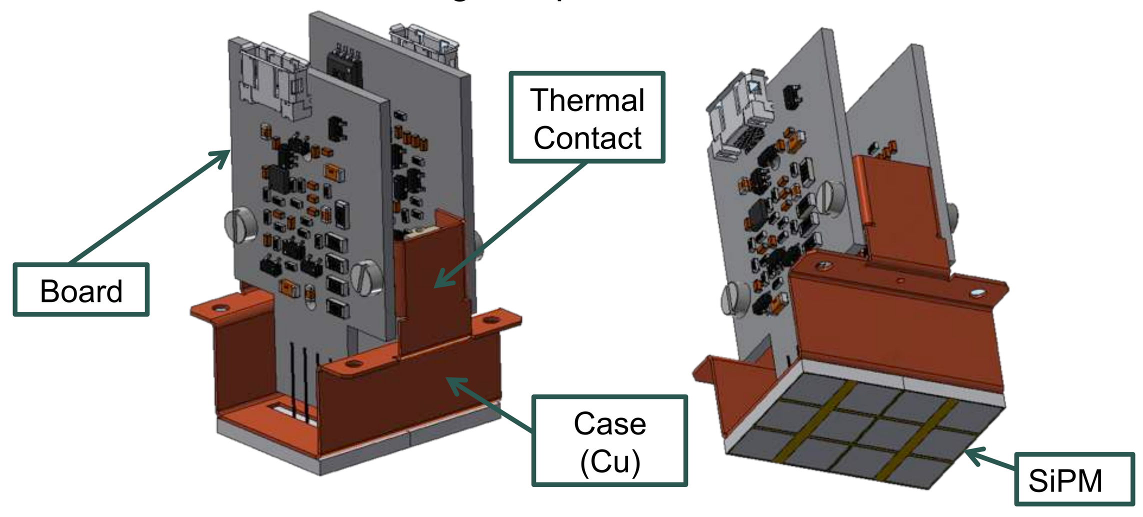
- Leakage current of the SiPMs measured changing the temperature at three different V_{bias} values (V_{op}, V_{op}-0.5 V, V_{op}-1 Volt)
- Measurement performed n vacuum (@ 10^{-4} Torr) with micro TEC Peltier and PT100 temperature sensor
- The data are related to a single (6x6 mm^2) cell.

Results

- Leakage current reduction of a factor > 8 operating at 0ºC
- We can take advantage of an additional factor of 2 if needed by lowering of 0.5 V the V_{bias} with respect to V_{op} (@ 0ºC)



Changes due to neutron flux and dose are still acceptable for the running condition in the experiment, when cooling down the SIPM to a running temperature of ~ 0 ◦C



Conclusion

The determination of the LY and LRU changes for un-doped CsI crystals after irradiation with a large ionization dose and neutron fluency provides an important benchmark for the Mu2e calorimeter, where a high radiation environment is foreseen. Our tests show that doses up to 200 Gy do not modify LY and LRU for a (3 × 3 × 18) cm^3 unwrapped CsI crystals from SICCAS coupled in air to an UV-extended PMT. After a total dose of 900 Gy, a 20% reduction in LY is obtained. Crystals from many vendors have also been irradiated with a neutron flux of 9×10^{11} n/cm^2, corresponding to about 2 times the total flux expected for the hottest calorimeter regions in three years of running. At the end of the irradiation test, an acceptable deterioration for the LY has been observed and the LRU is maintained well below 10% .

We have also tested the radiation damage of the Hamamatsu SPL and Micro Film SiPMs, as well as FBK SiPMs, with neutrons and photons by measuring their change in response and leakage current. The total neutron flux (2.2×10^{11}) causes a decreasement of the signal peak (and gain) and the increasement of the leakage current. A dose up to 200 Gy causes a negligible effect. Changes are still acceptable for the running condition in the experiment when cooling down the SiPM to a running temperature of ~ 0 ◦C.

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