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An automated QC station for the characterization of the Mu2e Calorimeter Readout Units

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The Mu2e experiment at Fermilab will search for the Standard Model forbidden conversion, within the field of a nucleus, of a negative muon into an electron. The Mu2e detector is composed of a straw tube based tracker for the precise determination of the conversion electron momentum and a calorimeter for providing particle identification and supporting track seeding.

The Mu2e crystal calorimeter is made of two annular disks filled with pure CsI crystals. Each crystal is read by two UV-extended Silicon Photomultipliers which, with two Front End Electronics boards, form a Readout Unit (ROU). To ensure consistency and reliability of the ROUs, we have designed, assembled and put in operation an automated Quality Control (QC) station to test and calibrate the $\mathcal{O}(1500)$ ROUs needed by the Mu2e calorimeter. In this paper, we present the design details of the QC Station and the results obtained on the measured parameters for a large sample of production ROUs. The achieved reproducibility on the parameter determination is also reported.

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1. The Mu2e experiment at Fermilab

The Mu2e experiment, shown in Fig. 1, is being built at Fermilab (IL) and it will search for the coherent neutrinoless conversion of muons into electrons. It will measure the ratio between the conversion events and all the capture events, defined as:

$$R_{\mu e} = \frac{\mu^- + N(A,Z) \to e^- + N(A,Z)}{\mu^- + N(A,Z) \to \nu_\mu + N(A,Z-1)}, \tag{1}$$

improving by four orders of magnitude the current limit set by SINDRUM II at 7×10^{-13} at 90% CL on a Au target [1]. A clean discovery signature is provided by the observation of mono-energetic conversion electrons with energy of 104.967 MeV. The Mu2e goal is to reach on $R_{\mu e}$: a single event sensitivity of 3×10^{-17}, a 5σ discovery of 2×10^{-16} and a 90% CL upper limit of 8×10^{-17}.

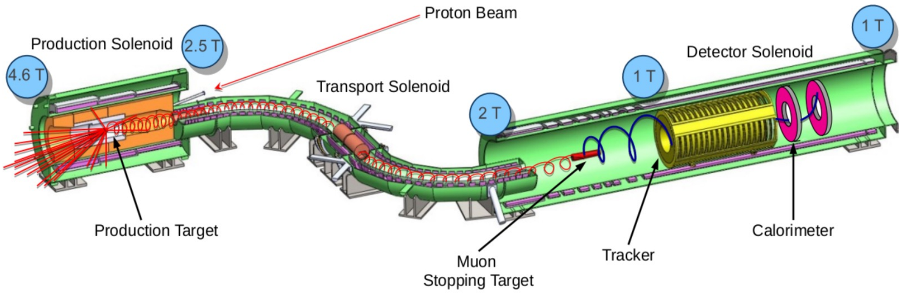

Figure 1: Schematic representation of the Mu2e experimental apparatus.

Core of the Mu2e experiment is a very large solenoidal system (see Fig. 1) composed of three large magnets. The muon beam is produced and transported in the first two sections, while in the third one is stopped on an aluminum target. The produced particles are analized by a tracker and a calorimeter system. A cosmic ray veto, surrounding the last magnet, identifies the incoming cosmic ray muons. The high momentum resolution straw tube tracker is 3 meters long and it is made of $\sim 2 \times 10^4$ straws arranged in 36 planes. Its principal task is to accurately measure the particles momentum, to reconstruct their curved trajectories and suppress the irreducible decay in orbit background.

2. The Mu2e Crystal Calorimeter

The Mu2e calorimeter complements the tracking information, performing cluster-based seeding for track finding at high occupancy. It has particle identification capabilities with a μ/e rejection factor > 200 and provides a stand-alone online trigger capability. In order to perform these tasks, the calorimeter should achieve an energy resolution < 10% and a time resolution of the order of 500 ps for 100 MeV electrons. All of this while operating in a 10^{-4} Torr vacuum, in a 1 T magnetic field and in a strong radiation environment. Indeed, in the hottest region, the calorimeter will be exposed to $\sim$ 90 krad and to an equivalent neutron fluence of $\sim 1.2 \times 10^{12}\ \mathrm{n}_{1MeV}/\mathrm{cm}^2$ [2]. The calorimeter [3] is made of two annular disks, each one filled with 674 pure CsI crystals. Each crystal is read-out by two custom made arrays of UV-extended Silicon Photomultipliers (SiPMs). Two

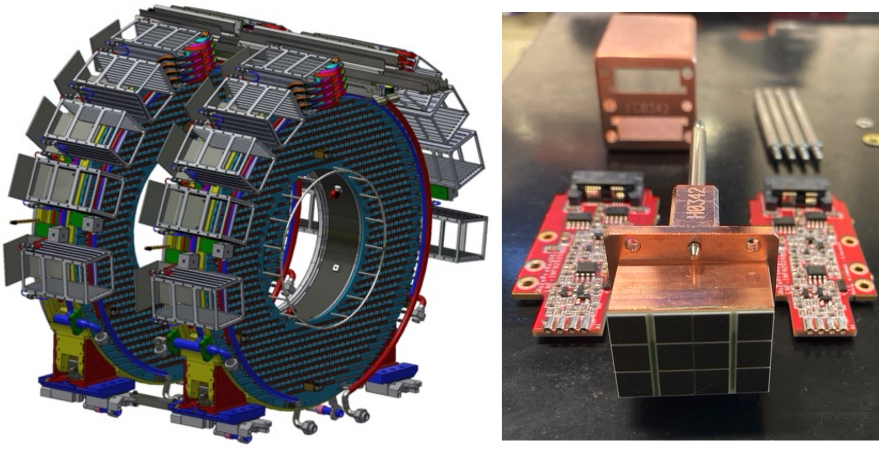

Figure 2: Left: rendering of the Mu2e calorimeter with a few ROUs screwed to the back panel. Right: picture of a calorimeter ROU disassembled. The SiPM matrices and the FEE boards can be seen.

SiPMs glued on a copper holder and two independent Front End Electronics (FEE) boards form a Readout Unit (ROU). A ROU attached to the calorimeter back panel is shown in Fig. 2 (left). The breakdown of a ROU is shown in Fig. 2 (right). As can be seen, the SiPMs are glued to a copper thermal block for cooling and mechanical support. Two FEE boards couple directly to the SiPMs via 4 pins. A guide for the fiber optic needle used for the secondary distribution layer of the laser calibration system is also shown. The Mu2e ROU provides two independent readout channels per crystal, one per SiPM, thus ensuring redundancy and a higher light collection.

3. Properties and Quality Controls of SiPMs and FEE boards

The SiPMs for the Mu2e calorimeter have been custom made by Hamamatsu. Two adjacent 2×3 SiPM matrices per ROU are employed as a way to increase redundancy and reliability of the read-out. Each cell has an effective area of $6 \times 6\,\mathrm{mm}^2$ and is made of 14400 $50\,\mu$m pixels. The photodetectors are UV-extended to match the 315 nm emission peak of pure CsI. The operational voltage (V_{op}) supplied through the FEE is $\sim$ 165 V. Strict requirements were applied as quality control for the production SiPMs. The gain at V_{op} has to be higher than 10^6 and the Photon Detection Efficiency (PDE) per cell has to be greater than 20% at 315 nm. The Mean Time To Failure (MTTF) at 0°C has to be better than 10^6 hours and when the SiPMs are irradiated up to $3 \times 10^{11}\ \mathrm{n_{1MeV\,eq.}}/\mathrm{cm}^2$ at 20°C, the leakage current must be smaller than 10 mA at V_{op}. A long set of qualification control steps have been performed on the production SiPMs [4]. More than 3000 SiPMs are now glued to their copper holders and are assembled in a ROU with the FEE boards.

The FEE boards [5] incorporate a SiPM preamplifier and a fast pulse shaper with a 25 ns rise time. The regulated high voltage supply is distributed at 200 V to the individual FEE boards, which provide the individual bias voltages to each SiPM by means of a linear regulator. The regulator employs 12-bit ADC and DAC to allow a minimum step of 50 mV (1 Least Significant Bit, i.e. LSB). The photosensors temperature is checked via a sensor located in close proximity to the SiPM holder. The FEE underwent a 6 hours burn-in test at 65°C, a stress test with 2 mA current and a linear 2-points calibration procedure of the ADC and DAC was performed. After this procedure, an accuracy of 1 LSB was achieved on the high voltage set-point. All FEE boards have undergone the QC steps and are ready to be assembled in a ROU.

4. The ROUs Quality Control Station

In order to perform a Quality Control (QC) on the assembled ROUs, a QC Station has been set up at LNF (Laboratori Nazionali di Frascati). A schematic of the station is shown in Fig 3.

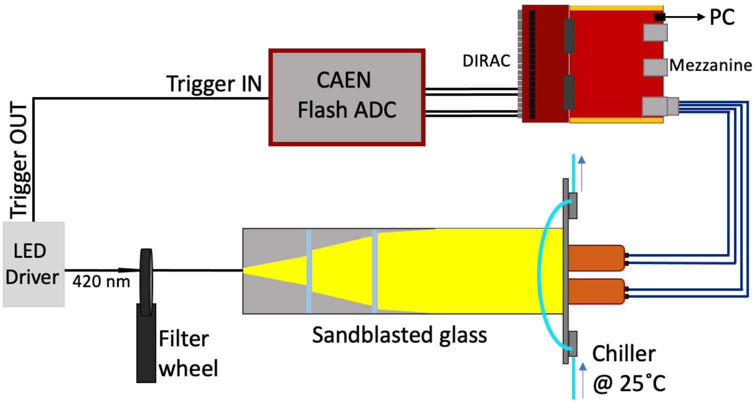

Figure 3: Scheme of the ROUs QC Station at LNF. Mezzanine and DIRAC are the boards that handle the data acquisition and digitisation.

This setup can measure two ROUs at the same time. As source, a 420 nm blue LED at 10 kHz is used. The light goes through an automatic wheel with 9 positions, each one holding a filter that acts as an attenuator to decrease the intensity of the transmitted light in a calibrated manner. The transmitted light is uniformly diffused on the SiPMs surface thanks to a box, with sanded glass, that also provides light tightness. The copper holders of the ROUs are screwed onto an aluminum plate that serves as a conductive medium for temperature stabilization at ∼ 25°C. Albeit the temperature stabilization, some residual variation of few degrees is still observed on the SiPMs, so that we also record their temperature. The data acquisition is started by the user thanks to a graphic interface which interacts with the setup via USB through Python and C++ programs. Thanks to a high parallelization level, 10^4 events per wheel position can be acquired in around one minute.

5. ROUs characterisation at the QC Station

A nine points scan in light intensity at the SiPM operational voltage is performed to allow setting a baseline for the ROU performance. The gain is extracted from the values of σ_Q/Q for the different filter wheel positions (Fig. 4). The function used for the fit is $\sigma_Q/Q = \sqrt{p_0/Q + p_1^2/Q^2 + p_2^2}$. The term p_0 is directly related to the gain via the charge of the electron: $G = p_0/q_e$ with $q_e = 1.6 \times 10^{-7}$ pC.

To keep the leakage current below the technical limit of 2.5 mA, the V_{op} of the worst irradiated SiPMs will probably need to be decreased. To study the SiPM behaviour at different V_{op} values and their gain and PDE, several HV scans were performed. The chosen analysis for the ROUs is a 7 points scan at 1 V intervals. In Fig. 5 a summary plot of the gain, charge and PDE for a ROU is

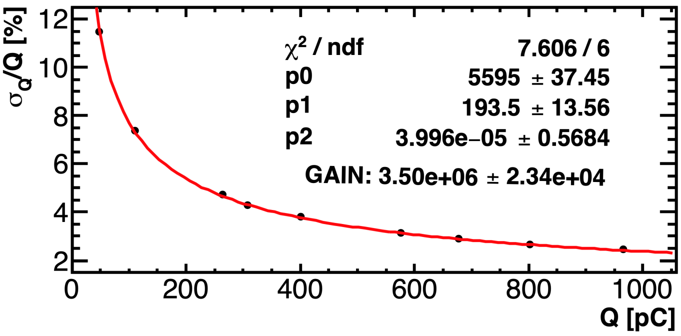

Figure 4: σ_Q/Q results for a scan in light intensity for the 9 filters at V_{op}.

also shown. The gain is fitted with an exponential, the charge with a linear function and the PDE with the Hamamatsu proposed parametrization $\mathrm{PDE(V)} = \mathrm{p_0} \cdot [1 - (\mathrm{p_1} \cdot \mathrm{V} \cdot \exp(-\mathrm{p_2}/\sqrt{\mathrm{V}})^{-2}]$ [6].

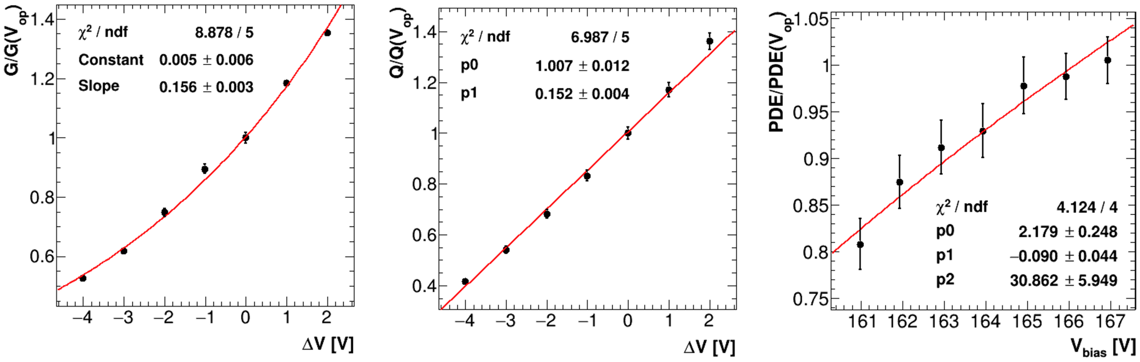

Figure 5: Example of the results of a 7 points scan for gain, collected charge and PDE. All values are normalised to the results at V_{op}. G and Q are show as a function of the overvoltage, while the PDE vs V_{bias}.

The temperature sensor on the FEE allowed to study the gain dependence on the temperature that was found to be consistent with ∼ 1.6%/°C. The gain temperature profile is shown in Fig. 6 (left). In order to present results at fixed temperature, we corrected the gain with the observed dependence. As can be seen from the Gaussian fits shown in Fig. 6 (right), the sigma of the Gaussian distribution fit gets reduced from 4% to 3% after applying the temperature correction. The average gain at V_{op} results to be $(3.541 \pm 0.003) \times 10^6$, in good agreement with Hamamatsu specifications.

6. Conclusions

To ensure the Mu2e Calorimeter requirements are met, a characterization of its ROUs has been implemented. The QC Station allows to perform a HV scan of 2 ROUs in ∼ 7 minutes. The dependence of gain, charge and PDE on the SiPM overvoltage and on temperature has been studied. The average gain value at operational voltage is 3.5×10^6, with a spread along production of ∼ 3%. Around 900 ROUs have been scanned at the moment of writing. All the Mu2e calorimeter read-out components and the ROUs as a whole meet the requirements, allowing the calorimeter assembly, scheduled to be completed by the end of 2023, to move forward.

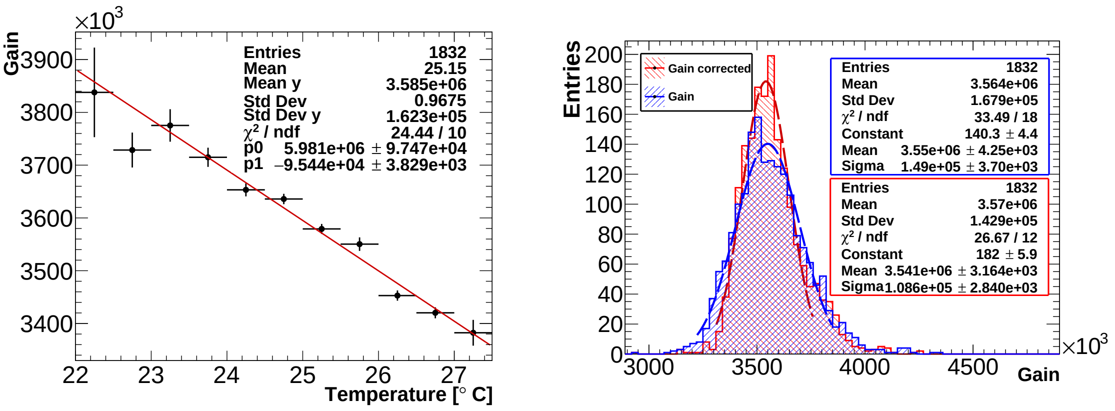

Figure 6: Left: gain temperature profile. Right: gain distribution, corrected and not corrected for the temperature variation.

7. Acknowledgements

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