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The Mu2e crystal and SiPM calorimeter

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ABSTRACT

The calorimeter of the Mu2e experiment is being assembled, with all production components completed and tested, apart from the digital electronics that is still underway. The mechanical structure is fully built, with a complete integration and test of all the analog sensors and electronics. We summarize construction and assembly phases, Quality Control tests, calibration procedures and first tests performed in the assembly area, as well as the installation and commissioning plans of the final disks in the Mu2e hall.

1. Introduction

The Mu2e experiment [1] is under construction at the Fermilab Muon Campus. It will search for the charged-Lepton Flavor Violating (cLFV) conversion of negative muons into electrons in the Coulomb field of an aluminum nucleus, planning to reach a single event sensitivity of about 3×10^{-17} [2], four orders of magnitude beyond the current best limit [3].

The conversion electron has a monoenergetic signature at approximately 105 MeV and is identified by a high-resolution straw tracker and an electromagnetic calorimeter (EMC), both inserted in a 1 T solenoid. The entire detector region is surrounded by a Cosmic Ray Veto to reduce the background from cosmic ray events. A High Purity Germanium Detector and a Lanthanum Bromide crystal constitute the Stopping Target Monitor (STM), providing normalization to cLFV events by detecting X rays emitted from the muon capture process in the aluminum target.

The EMC [4] should achieve $\leq 10\%$ energy resolution and 500 ps timing resolution for 100 MeV electrons while maintaining high levels of reliability in a harsh operating environment with high vacuum, 1 T B-field, and radiation exposures up to 100 krad and 10^{12} n_{1MeVeq}/cm^2. It is composed of 1348 $(34 \times 34 \times 200)$ mm^3 pure CsI crystals produced from SICCAS and Saint Gobain, arranged in two annular disks. Each crystal is read by two adjacent custom Silicon Photo-Multipliers (SiPM's). Each SiPM is connected to a Front-End Electronics (FEE) board providing amplification and shaping of the signal. Groups of 20 signals are sent to a custom digitizer module (DIRAC, DIgitizer and ReAdout Controller) where they are sampled at 200 million samples per second (Msps) and transferred to the data acquisition system. A radioactive source and a laser system allow setting the energy scale and monitoring the fast changes of response and resolution.

The calorimeter technological choice and the design of the custom electronics, cooling and mechanical systems were validated through an

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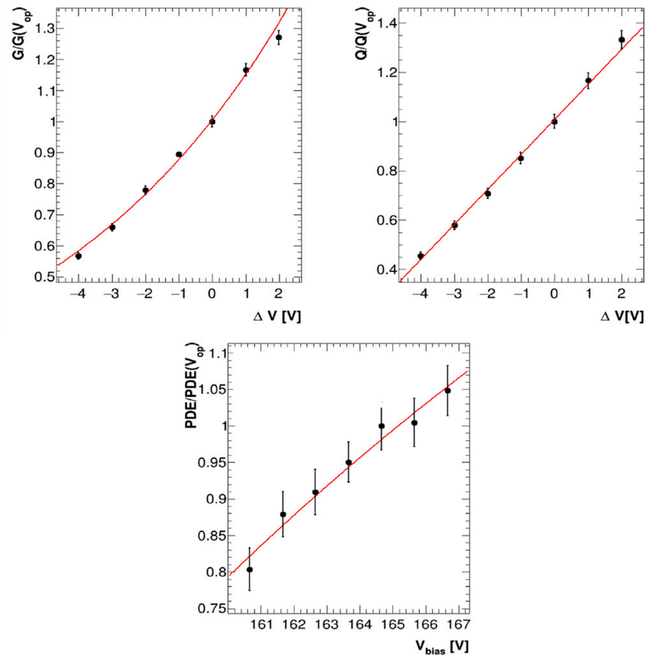

Fig. 1. Example of a ROU Quality Control results: normalized gain (top left), charge (top right) and photo-detection efficiency (bottom) as a function of the overvoltage ΔV, which is the difference between the applied bias voltage V_{bias} and the SiPM operational voltage, V_{op}.

electron beam test on a large-scale 51-crystal prototype (Module-0) [5], obtaining 7% (<150 ps) energy (time) resolution for 100 MeV electrons. Extensive test campaigns characterized and verified the performance of crystals, photo-detectors, analogue and digital electronics. This included hardware stress tests and irradiation campaigns with neutrons, protons, and photons. A series of vertical slice tests with the final electronics was carried out on the Module-0 along with implementation and validation of the relevant calibration procedures, by collecting cosmic ray data samples.

2. Quality Control of production components

The Quality Control (QC) of crystals and SiPM's was concluded in 2020, with the test of all produced components, including radiation hardness of random samples [6]. CsI and SiPM properties have been verified to be well within specifications. Irradiation tests assumed the full experiment lifetime with a large safety factor, corresponding to the requirements reported in Section 1. Crystal optical properties after irradiation tests still match Mu2e requirements. SiPM's increase of $\approx$ 2.5 in dark current can be reduced to conditions compatible with the performance limits by cooling down the sensors down to −10 °C and adjusting the bias voltages during the experimental run-time.

Recently, we have completed the QC tests of the crystal Read-Out Units (ROUs), composed by two SiPM's glued on a copper holder, along with the corresponding FEE boards inserted in a Faraday cage. An automated test station was assembled to measure in a few minutes the light yield for different HV settings and LED light intensity, thus allowing the calibration of response, gain and photo-detection efficiency, and their dependence on the bias voltage. A 4% gain variation is observed, in agreement with expectations from SiPM specifications. Fig. 1 reports the result of a seven step scan around the SiPM operational voltage for one readout channel.

Digital electronics consists of Mezzanine Boards (MZBs) for SiPM/FEE setting and readout, and DIRAC boards. Both components underwent several irradiation campaigns during the R&D phase [7]. Good radiation hardness was demonstrated for ionization dose and neutrons up to 30 krad and 10^{12} n_{1MeVeq}/cm^2, respectively. When exposing them to $\sim$ 10^{11} protons/cm^2, with a 60–200 MeV/c momentum beam, Single Event Latch-up problems were identified for specific components, requiring minor modifications in the layout. At the moment of writing, the burn-in and QC tests of the whole MZB production are completed, while tests of half of the DIRAC boards (70 units) are in progress.

A thermal vacuum test of a calorimeter crate (8 DIRAC and 8 MZB boards) has been set up to complete temperature measurements in vacuum, with more than 20 thermal sensors monitored. Modified calorimeter FEE boards provide signals from pulse injection to a DIRAC board, whose data are acquired through the Mu2e DAQ, thus performing a full Vertical Slice Test of the readout. A preliminary test at room temperature demonstrates good performance of the system, with an increase of +20 °C in the hottest points, as expected from thermal simulation.

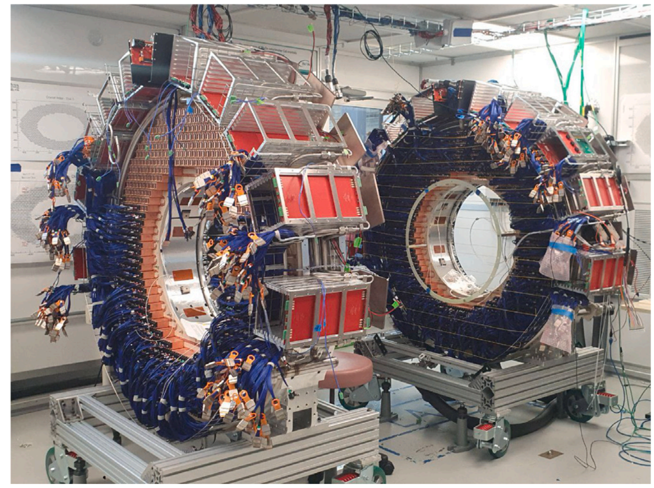

Fig. 2. Mu2e calorimeters disks being assembled at the Fermilab SiDet facility.

3. Calorimeter assembly

The calorimeter disks are being assembled at the Fermilab SiDet facility (Fig. 2). The mounting of the calorimeter mechanical parts is completed, with all crystals stacked on both disks, source calibration pipes embedded in the front carbon fiber plates, crates for digital electronics installed, and cooling lines leak tested. The assembly of Read-Out Units and power distribution is also completed, while 1/3 of the cable routing from ROUs to crates is still missing for one of the two disks. All calorimeter power supplies and half of the DAQ cables and optical fibers are already installed in the Mu2e hall.

The source calibration system consists of neutrons from a deuterium–tritium (DT) generator irradiating a fluorine rich fluid that flows in the front face of the disks when the calibration is performed. A reaction chain produces 6.13 MeV photons uniformly illuminating the calorimeter surface. A few minutes of data taking are sufficient to determine an absolute energy scale at percent level for each crystal. The DT generator was installed in the Mu2e hall in 2022, with final shielding completed in 2023 and radiation survey well within safety limits. It was successfully operated up to the nominal running condition of 120 kV.

A pulsed green laser illuminates all crystals through a distribution system based on optical fibers and integration spheres to monitor gain variation at a level of 0.5% and determine time offsets with $\sim$ 100 ps precision. Laser stability is at per cent level, and it is monitored with PIN photodiodes both at laser source and on the diffusing spheres. A preliminary test of the whole laser chain was performed in the

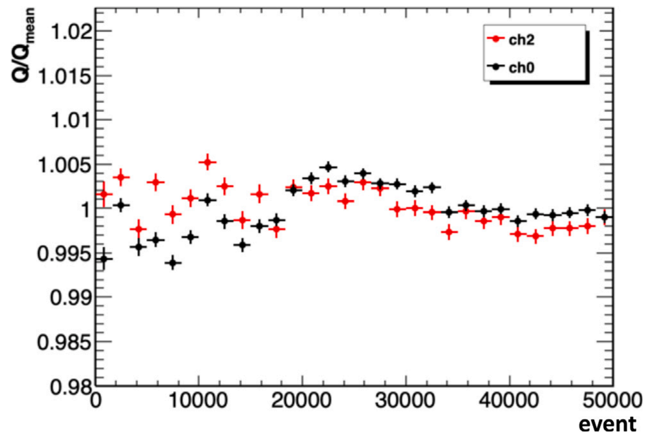

Fig. 3. Normalized charge response for two calorimeter readout channels monitored with a 15-hour laser run.

assembly room, acquiring data from 8 calorimeter channels with a commercial 250 Msps digitizer. A 15-hour long run was carried out to check pulse charge stability. Fig. 3 shows the normalized charge response for two different channels. An overall response stability of 1% is observed, consistent with the expected SiPM gain drift due to temperature fluctuations inside the clean room.

4. Calorimeter calibration and commissioning

The Mu2e calorimeter will be commissioned in the assembly room by acquiring data from half of a disk at a time. Cosmic ray (CR) events and laser runs will be used to check calorimeter functionality and perform a first calibration of the detector. All the Mu2e DAQ infrastructures (PC servers, Data Transfer Controllers, fibers) are ready for the readout of 36 DIRAC boards. The event builder reconstructs raw CR data that are filtered by the online trigger selection for cosmic ray events and then saved on disk. Laser run data will be fully transferred to disk after event building. After the test of the whole calorimeter is completed, the calorimeter will be moved into the Mu2e hall, tentatively in fall 2024.

Calibration algorithms for energy and time calibration are tuned on 10-hour equivalent simulated cosmic ray data sample. A fast, calorimeter-based trigger is developed to select clean CRs crossing the calorimeter. With this sample, the deposited energy distribution is used to extract their average response, resulting in 0.5% spread on energy calibration. Moreover, the timing of readout channels is aligned through an iterative procedure, obtaining a time calibration at 15 ps level. Additionally, we have defined a procedure to evaluate the light yield of crystals by measuring the asymmetry of the response of the two SiPM's connected to the same crystal, obtaining ∼ 20 photo-electrons/MeV.

The calorimeter calibration procedures were tested on data taken with a full Vertical Slice Test (VST) performed on Module-0, equipped with the production readout chain. The VST was used to validate readout, data reconstruction, calibration, and performance characterization at various operating conditions of temperature, SiPM bias, and vacuum. CR events were triggered with external scintillators. The two-dimensional track reconstruction and selection was performed offline, using the calorimeter hit information. Energy response was equalized on the 21 MeV peak from minimum ionizing particles. An equivalent noise of 200 keV was observed, stable in time. The stability of SiPM gain and response was tested with a two-week data taking. The observed response variation was consistent with the ±1 °C temperature stability of sensors and electronics provided by the cooling system. Timing offsets were calibrated according to a procedure developed on simulated events, reaching a timing alignment at the 15 ps level. After

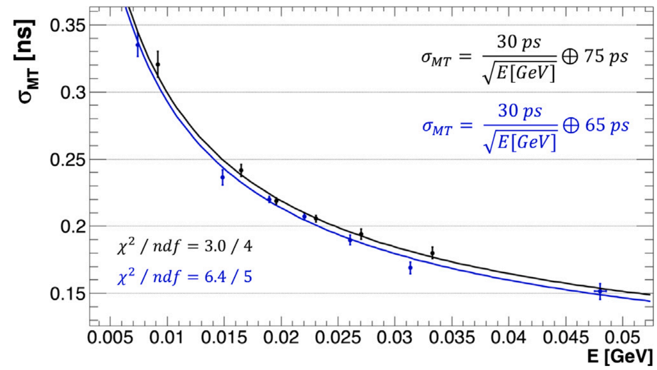

Fig. 4. Resolution of the mean time (MT) variable as a function of the deposited energy evaluated from cosmic ray events acquired with the Module-0 calorimeter prototype. Blue and black curves are results obtained for two calorimeter crystals.

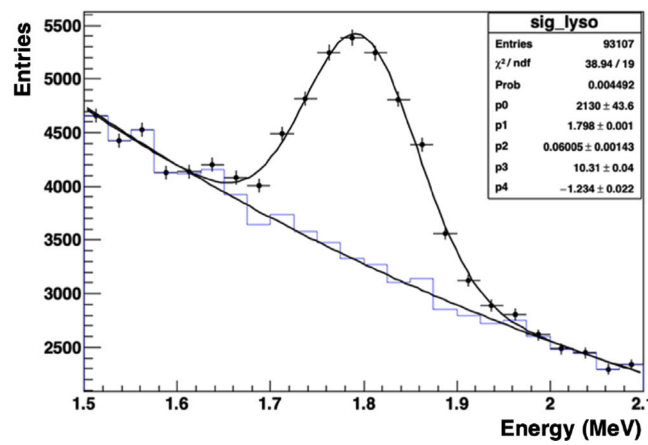

Fig. 5. Simulation of the response of a CAPRHI LYSO crystal for a high intensity Mu2e run.

applying time calibration offsets, the timing resolution was evaluated by reconstructing the cell mean time, defined as $\frac{T_0+T_1}{2}$, where $T_{0,1}$ are the times measured by the two SiPM's connected to the same crystal. A ∼ 210 ps resolution is obtained for crystals uniformly crossed by minimum ionizing particles. Fig. 4 reports the timing resolution dependence of the mean time variable as a function of the energy deposited in the crystal. Extrapolating this results obtained for CRs, a time resolution of 100 ps is obtained for 100 MeV electrons, well within Mu2e requirements.

5. The CAPHRI detector

The calorimeter is also used as an independent monitor of the muon nuclear captures, which is a well-known fraction of the muon stops used to normalize cLFV events [8]. Four crystals of the front disk in the outer region of the detector are replaced with same-size LYSO counters from SICCAS company, constituting the Calorimeter Precision Hi-Resolution Intensity Detector (CAPHRI). As for the STM, CAPHRI measures the muon capture rate (MCR) detecting the 1.8 MeV golden γ-ray line, but with a faster response.

A characterization of LYSO crystals, wrapped with 3M Enhanced Specular Reflector (ESR) foils [9] and coupled to a calorimeter ROU, was carried out using 511 keV annihilation photons from a ^{22}Na source. A light yield of approximately 2000 photoelectrons/MeV and a flat 7%–8% energy resolution for ^{22}Na photons is measured along the crystal length. The extrapolation to 1.8 MeV is done assuming a $c/\sqrt{E}$ behavior, obtaining a resolution of about 3% for muon capture events.

CAPHRI performance has been studied through a preliminary simulation of the Mu2e minimum bias background, overlayed with the expected normalization photon signal shape. Photon acceptance was evaluated through 1.8 MeV photons generated from the target. The resulting energy distribution is reported in Fig. 5. A 0.25 signal-to-background ratio is expected in the signal region, with a 3% counting error per accelerator injection cycle (1.4 s), dominated by background.

6. Conclusions

The Mu2e calorimeter demonstrated excellent energy and time resolution for 100 MeV electrons, allowing particle identification, triggering and track seeding. The production of detector components is completed, with digital electronics nearing completion. Successful vertical slice tests proved reliable operations and performance in a vacuum and at low temperature.

The assembly of the calorimeter is in an advanced stage, including source and laser calibration systems, while final integration of the detector with the trigger and DAQ is underway. Commissioning of the whole calorimeter with cosmic ray events is planned, acquiring data from 1/2 disk at a time. Calibration procedures developed on Monte Carlo events and verified on prototype, will be applied.

As a complementary monitoring system, four high-precision LYSO crystals are embedded in the calorimeter to provide an independent measurement of the muon capture rate by detecting the emitted 1.8 MeV γ-ray line.

Installation and transportation plans are progressing well, with disks transport to the Mu2e hall foreseen in fall 2024.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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