Design and status of the Mu2e crystal calorimeter

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Abstract

The Mu2e experiment at Fermilab searches for the coherent neutrino-less muon to electron conversion in the Coulomb field of an aluminium nucleus. This charged-lepton flavour violating process is characterised by a distinctive signature of a mono-energetic electron (∼ 105 MeV/c) and its observation will be a clear signature of new physics beyond the Standard Model. The Mu2e goal is to improve by four orders of magnitude the search sensitivity with respect to the previous experiments. The Mu2e detector is composed of a tracker, an electromagnetic calorimeter and an external veto for cosmic rays. The calorimeter plays an important role in providing excellent particle identification capabilities, a fast online trigger filter while aiding the track reconstruction capabilities. It consists of 1348 pure CsI crystals divided in two annular disks, each one readout by two large area Silicon Photomultipliers. A large scale prototype has been tested with an electron beam, demonstrating to largely satisfy the Mu2e requirements. At the moment of writing, the crystals and SiPMs production phase is halfway trough the completion. An overview of the characterisation tests is reported, together with a description of the final mechanical and electronical design.

Keywords: Mu2e, Calorimetry, Pure CsI crystals, SiPMs
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1. Introduction

The Mu2e experiment, aiming to search for the μ-e conversion process [1][2], consists of a straw tube tracker and a crystal calorimeter embedded inside the evacuated region of a superconducting solenoid providing a 1 T axial magnetic field in their location. The external region of the solenoid is surrounded by a cosmic ray veto detector. The calorimeter [3] helps the tracker in the identification of ∼105 MeV/c conversion electrons (CEs), building an efficient trigger, providing particle identification and improving the track reconstruction capabilities. According to Monte Carlo simulation, the calorimeter performance requirements on CEs are as follows: an energy resolution better than 10%; a time resolution below 0.5 ns and a spatial resolution better than 1 cm. The calorimeter design consists of two disks of 674 un-doped CsI crystals of $34 \times 34 \times 200$ mm^2 dimension, each readout by two custom large area UV-extended Silicon Photomultipliers (Mu2e SiPMs). Each Mu2e SiPM is an array consisting of two series of 3 monolithic 6×6 mm^2 cells connected in parallel [4]. The Front End amplification and HV regulator boards are connected to the SiPM pins while the digitization of the signals is carried out by custom boards located in nearby crates. A radioactive source and a laser system allow setting the energy scale and monitor the fast changes of response and resolution. A long R&D phase [5][6] demonstrated this design option largely satisfies the Mu2e calorimeter requirements. Updated results of a large area calorimeter prototype test beam are reported in the following sections.

2. Prototype performance

A Module-0 calorimeter prototype (Fig. 1) has been built to resemble as much as possible the final disk mechanical design.

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Its construction was used to validate the assembly procedure and evaluate the detector performance with an electron beam in the energy range of 60-120 MeV at the Beam Test Facility [7] of the INFN Laboratory in Frascati. The prototype is composed by 51 crystals and 102 Mu2e SiPMs produced and qualified during the pre-production phase [8][9].

Figure 1: Pictures of Module-0 front view during assembly : mechanical structure (top left), crystals assembly (bottom left) and final version (right).

Similarly to the calorimeter disk, Module-0 is a structure of staggered crystals with a size large enough to contain most of the electromagnetic shower for 105 MeV electrons. Energy and time measurements were obtained using the beam impinging on the calorimeter surface both at 0 and at 50 degrees, which is the expected CEs incidence angle. Data acquisition lasted one week in May 2017, by triggering both on beam and cosmic rays (CRs) data and acquiring at 1 GHz sampling rate.

2.1. Energy resolution

After selecting single-particle events, digitized waveforms are integrated in a 200 ns wide time window around the maximum amplitude, in order to evaluate the collected charge. To equalize the response of each channel, the charge deposition from CRs minimum ionizing particles is determined and then compared with the Monte Carlo (MC) expected energy deposition. The calibration statistical uncertainty for each channel is of around 0.5%. After equalization, the energy scale is set by comparing the reconstructed charge in the whole detector (Q_{rec}) with the total energy deposited by a 100 MeV electron, as evaluated by a Geant-4 based Monte Carlo simulation (MC). A good linearity in response is observed with an energy scale factor E_{sc} = (12.07 ± 0.11) pC/MeV. Such calibration is then applied to all signals to obtain the reconstructed energy, E = Q_{rec}/E_{sc}.

A log-normal fit is applied to each reconstructed energy distribution and the resolution (σ_E/E) is evaluated as the ratio between the sigma and the peak. An energy resolution of ∼ 5.3% (7.4%) is obtained at 100 MeV beam energy for 0 (50) degrees impinging angle. The energy resolution for all the test configurations is reported in Figure 2, together with MC simulation results. A very good agreement is shown. The dependence of the energy resolution as a function of the deposited energy E_{dep}

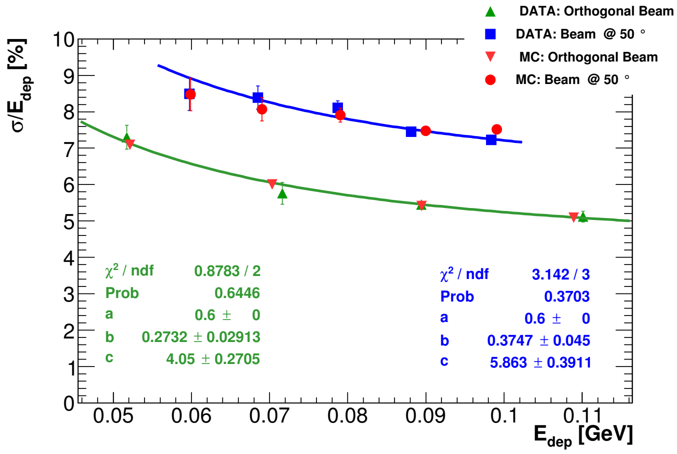

Figure 2: Energy resolution as a function of the deposited energy in Module-0. Green (blue) points are the results for the beam impinging at 0 (50) degrees. Red points are the results from MC simulation.

for single particle events has been parametrized by the function:

$$\frac{\sigma_E}{E_{dep}} = \frac{a}{\sqrt{E_{dep}[GeV]}} \oplus \frac{b}{E[GeV]} \oplus c \ , \tag{1}$$

where a represents the stochastic term, b the noise term and c the constant term. The fit resulted to be rather insensitive to the stochastic term, so that it has been fixed to 0.6%, corresponding to the measured light yield value of 30 pe/MeV [9]. The resolution deterioration at the CE average incidence angle of 50° is dominated by the increase of the leakage contribution from the Module-0 front face.

2.2. Timing Resolution

The signal time is determined by fitting the waveform leading edge with an asymmetric log-normal function and applying the constant fraction (CF) method. The fit range and CF have been varied to optimize the timing resolution. The optimized CF value found is at 5% of the amplitude peak.

The time resolution for a single sensor is evaluated as $\sigma(\Delta T)/\sqrt{2}$, where σ is extracted by applying a Gaussian fit on the time difference (ΔT) between the two readout SiPMs of the same crystal. A single sensor resolution of ∼ 130 ps is obtained for 100 MeV electron beam at 0 degree. Since the sampling frequency of the Mu2e digitizer boards is of 200 Msps, the waveforms were offline re-sampled in 5 ns bins. Figure 3 shows the time resolution as a function of the highest crystal energy deposit at different beam energies, for both 1 Gsps and 200 Msps sampling rates. A time resolution deterioration smaller than 30 % is obtained, which is negligible with respect to the Mu2e calorimeter requirements.

3. Production phase

On March 2018, we started receiving the final CsI crystals from the companies SICCAS and Saint Gobain (SG), in batches of 60 samples per month. Mechanical problems on SG crystals

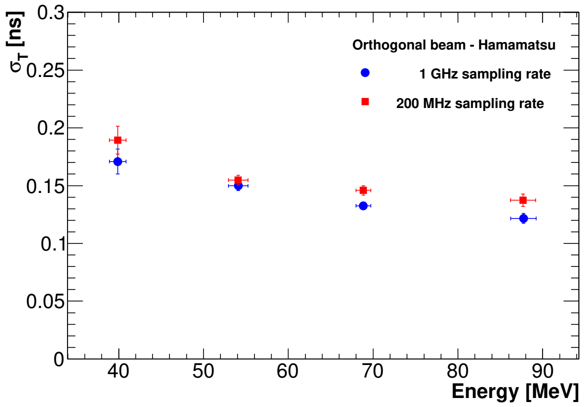

Figure 3: Time resolution as a function of the deposited energy in the highest energetic crystal, considering both the 1 GHz (blue points) and 200 MHz (red square) sampling rates.

delayed their production. At the moment of writing, 900 crystals have been already tested in dedicated automatised custom stations. The mechanical properties (lengths, perpendicularity and parallelism between faces) are evaluated using a CMM machine. Crystals outside the dimensional specification with a tolerance of 0.1 mm are rejected. The other stations are used to measure the crystal optical properties, after wrapping each of them with 150 μm Tyvek foil. A PMT readout is used. The crystals are exposed to a ^{22}Na source, which emits 511 keV photons, and the Light Yield (LY), the Longitudinal Response Uniformity (LRU) and the resolution are measured. Figure 4 shows the results on LY (left) and LRU (right) measurements. Less than 1% of the production has been rejected due to optical properties.

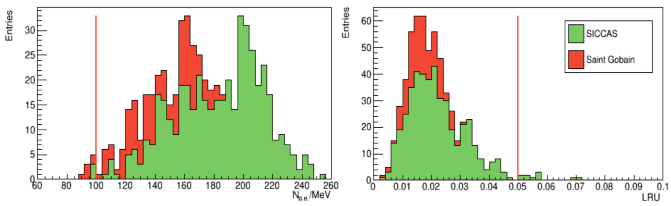

Figure 4: LY and LRU of about half of the crystal production.

In the same period, 2700 out of the 4000 Mu2e-SiPM from Hamamatsu have been characterised. For each Mu2e SiPM, the breakdown voltage, V_{br}, the dark current, I_d, and the $gain \times PDE$ are measured for all the six 6×6 mm^2 cells inside the sensor array. The spread of these measurements over the six cells is also measured and 2% of the SiPMs have been rejected due to a large RMS on the dark current (> 5%). The test is performed at three different temperatures: 0 °C, 10 °C and 20 °C. Figure 5 shows the RMS spread value of the V_{br} and I_d measurements at 20 °C, on left and right plot respectively.

The procurement proceeded with monthly batches of 280 SiPMs each. Out of each batch, we randomly select 15 units to test their Mean Time to Failure (MTTF). The Mu2e requirement is a MTTF of at least 1 million hours when operating at 0 °C. To accelerate the measurement, the sensors are tested for 18 days with a burn-in at 65 °C. No damage has been observed so far, so that the Mu2e SiPMs experimentally demonstrate an MTTF larger than 10 million hours. For each batch, additional 5 pieces are randomly chosen to carry out the neutron radiation hardness test. These sensors are exposed to a total fluence of 1.2×10^{12} neutrons/cm^2 and their leakage current is measured to control if it remains below the allowed limit of 2 mA when operating at low temperature, 0 °C, and at reduced operating voltages.

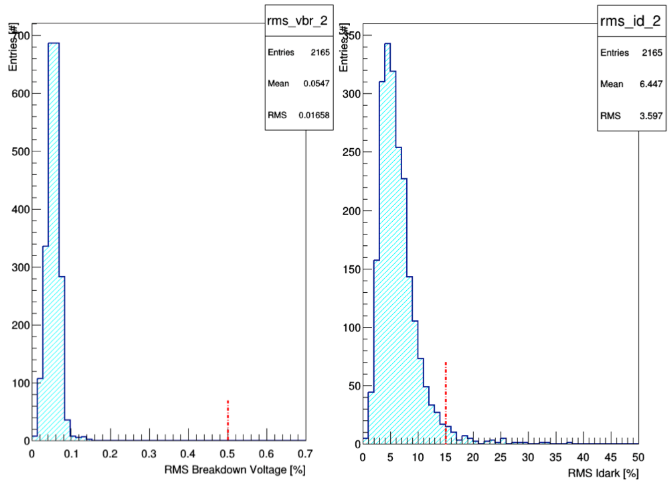

Figure 5: RMS distributions of the V_{br} and I_d measurements over the six cells of the Mu2e-SiPMs arrays.

4. Final electronics design

Each Mu2e-SiPM will be connected to its own Front End Electronic board (FEE), which provides two gain amplification stages (×3, ×6) and a linear regulation of the bias voltage. The FEE also shapes the sensor signal to obtain a 25 ns long rise time and a full signal width of 150 ns. The dynamic range is 0-2 V. The FEE board is also used to monitor the sensor temperature and current.

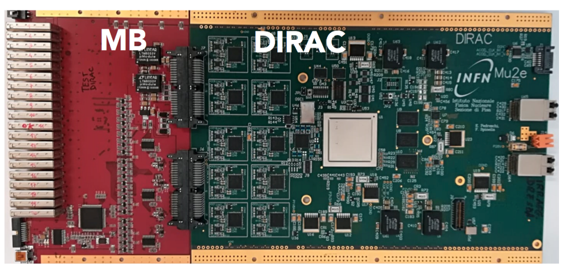

Figure 6: Picture of the electronic board used to manage and read out 20 SiPM+FEE channels.

The FEE is managed and read out by a two stages digital board (Fig. 6), for a total of 20 channels per board. The first stage, named Mezzanine Board (MB), provides setting and reading of the bias voltage as well as a reading of temperature and dark current. Moreover it receives the FEE differential signals in input that are then digitized in the second board stage at 200 Msps with a 12 bit ADC. The second stage is composed by a custom Digital Readout Controller board (DIRAC) based on a very performing FPGA (MicroSemi PolarFire). A VTRX optical link is used to readout the DIRAC board by the DAQ system.

Radiation hardness tests have been performed by exposing single boards or components both to a Total Ionization Dose (TID) or to a neutron beam. After modification of few components, the FEE boards showed to be radiation hard up to a TID of 100 krad. The digital boards demonstrated to be able to sustain a TID up to 30 krad, showing negligible deterioration. Work is in progress to optimize the selection for the DC-DC converter and to complete the test on the PolarFire FPGA. The FEE boards were exposed to few MeV neutrons up to 10^{12} $n_{1\ MeV}/cm^2$; no sign of deterioration was observed. An additional set of tests with > 20 MeV/c protons is planned to evaluate the resistance of the digital boards to single event upsets.

5. Final mechanics design

The engineering drawing of the Mu2e calorimeter is completed. Figure 7 shows an exploded view of a calorimeter disk.

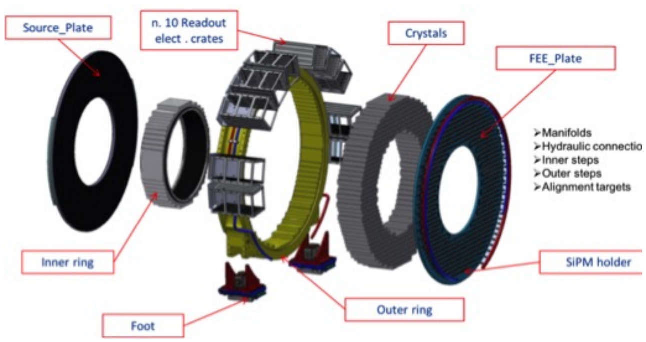

Figure 7: Exploded view of a calorimeter disk mechanich.

The main components are: the outer and the inner cylinders; the PEEK FEE plate, which is needed to insert, cool down and align the SiPMs and FEE to the corresponding crystals; the carbon fiber front face where the radioactive source pipes are integrated; the crates mounted on the external cylinder (10 per disk), where the digital electronics is located. A Finite Element Analysis has been carried out, showing a good stability of the system, with negligible stress on the supports. A full dimension calorimeter mockup has been built and filled with fake iron crystals to optimize the assembly procedure. Crystals wrapped with 150 μm Tyvek foils will be stacked from the bottom to the top inside the external aluminum cylindrical support. Finally, the calorimeter mechanical components have been inserted in the GEANT-4 simulation of the detector to control any eventual offsets in cluster reconstruction. Negligible variation in response and resolution is observed.

6. Conclusions

The Mu2e calorimeter is a state of the art crystal calorimeter with excellent energy and timing performances for 105 MeV/c electrons. A long R&D phase demonstrated that the chosen design largely satisfies the Mu2e requirements. Test beam results of the large scale calorimeter prototype show that an energy resolution of about 7% and a time resolution better than 200 ps are achievable with 100 MeV electrons impinging at 50 degrees.

The calorimeter production phase has started in March 2018 and is expected to be completed in October 2019. The readout electronic design is now concluded and the FEE boards production will start within a few months; the digital electronics production will follow soon after. The calorimeter assembly will start in November 2019 with the construction of the first disk. The calorimeter installation in the Mu2e experimental hall is planned for 2020, with a first commissioning phase done with CRs data taking.

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