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Towards the construction of the Mu2e electromagnetic calorimeter at Fermilab

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Abstract. Mu2e will search for the Charge Lepton Flavor Violating (CLFV) conversion of a muon into an electron in the field of a nucleus. A clean discovery signature is provided by the mono-energetic conversion electron ($E_e = 104.96$ MeV). If no events are observed, Mu2e will set a limit on the ratio between the conversion and the nuclear capture rate below 3×10^{-17} (at 90% C.L.). In order to confirm that the observed candidate is an electron, the calorimeter resolution requirements are to provide $E_{res} < 10\%$, $T_{res} < 500$ ps for 100 MeV electrons while working in vacuum and in a high radiation environment and high magnetic field. The calorimeter is made of two annular aluminum disks, each one filled with 674 pure CsI crystals read out by SiPMs. A sophisticated mechanics and cooling system has been developed to support the crystals and cool the sensors. Radiation hard analog and fast digital electronics have been developed. In this paper the QC tests performed on the produced components and the construction status are reported, as well as the results obtained on the large size prototype with test beam data and at a cosmic ray test stand.

1. The Mu2e Experiment

The Mu2e experiment[1], under construction at Fermilab, will search for the coherent conversion of the muon into an electron in the electric field of aluminum nuclei. The aim of the experiment is to measure the ratio of the conversion rate normalized to the muon nuclear capture : $R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \to e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z)) \to \nu_\mu + N(A,Z-1)}$ at a level of $R_{\mu e} < 3 \times 10^{-17}$, improving the current best limit set by the SINDRUM-II collaboration.The conversion process has a very clear signature: a mono-energetic electron of 104.96 MeV, which is slightly below the muon rest mass. The Mu2e experiment is relies on a system of three superconducting solenoids. In the Production Solenoid, an 8 GeV proton beam hits the tungsten target producing mostly pions. Thanks to the the gradient magnetic fields, particles produced backwards are reflected towards the second solenoid, the Transport Solenoid. Thanks to the particular S shape and to the presence of collimators and absorbers in the central region, a nearly pure, low-momentum negative muon beam is obtained at the entrance of the Detector Solenoid that houses the aluminum target and the detectors, a straw-tube tracker with excellent momentum resolution (180 keV/c for 100 MeV electrons) and a crystal calorimeter [2].

2. The Calorimeter

The main role of the calorimeter[3] is to confirm the observation of a potential Conversion Electron (CE) as selected by the Mu2e tracker, providing a very high separation between electrons and muons. Moreover the calorimeter contributes to improving the tracker pattern recognition reconstruction efficiency and it can be used to implement an independent trigger based on the sum and pattern of energy deposition.

The calorimeter has to provide, for $\sim$ 100 MeV electrons, a good energy ($\sigma_E/E < 10\%$) and timing resolution ($\sigma_t < 500$ ps) and a spatial resolution of $\mathcal{O}(1$ cm). The calorimeter (Figure 1, left) is made of two annular disks filled with 674 pure CsI crystals each.The crystals are parallelepipeds with squared faces of (34×34) mm^2 and they are 200 mm long. Each crystal is coupled with two UV-extended Silicon Photo-Multipliers (SiPMs) with the corresponding Front-End Electronics boards. (Figure 1, right). The fast digital electronics is organised in boards (DIRAC) reading 20 channels each with 5 ns sampling and is located on the surrounding crates. A radioactive source and a laser system provide energy calibration with 6 MeV photons and monitoring of the gains and of the timing offsets respectively.

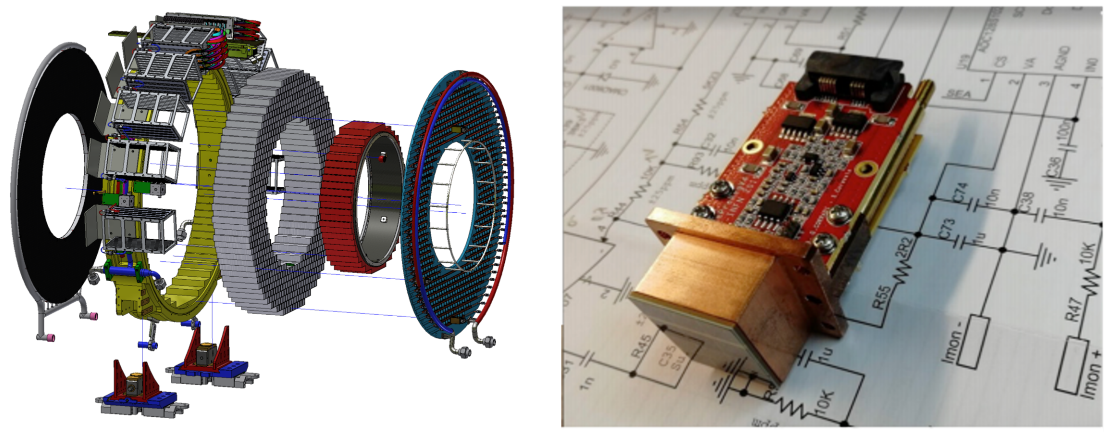

Figure 1. Left: exploded view of the Mu2e calorimeter. Right: picture of the system made of SiPMs, holders and FEE board coupled to each crystal

2.1. *Calorimeter performance with a large size prototype*

The large size calorimeter prototype, called Module-0, is made of 51 pure CsI crystals with 102 SiPMs and FEE boards. It plays a fundamental role in testing the integration and assembly procedure and was created to be similar to the final calorimeter design.

Moreover, the calorimeter performance was tested in 2017 at the Beam Test Facility [4] with an electron beam with energies ranging between 60 MeV and 120 MeV [5]. In Figure 2 the resulting energy and timing resolution, are reported.

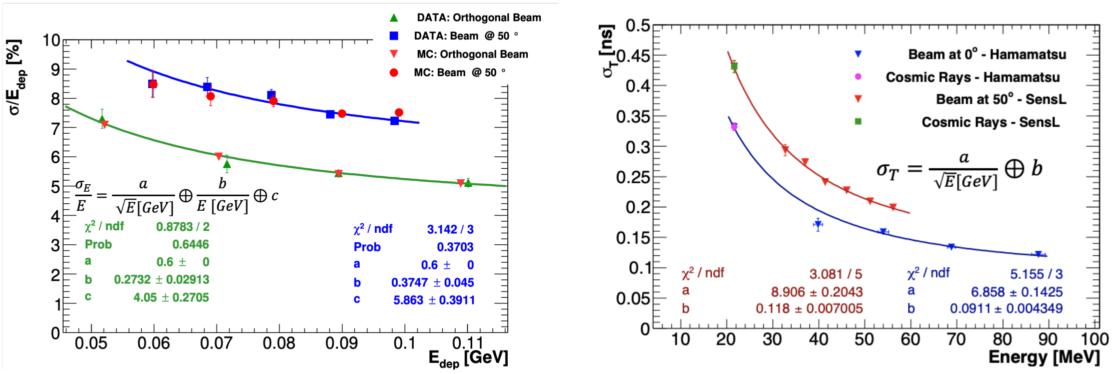

Figure 2. Left: Energy resolution as a function of the energy deposit in Module-0. Right: Time resolution as a function of the deposited energy in the highest energetic crystal

3. Calorimeter Construction Status

The production and the QC test for the crystals and SiPMs began in 2018 [6]. The CsI crystals have been produced both by Saint Gobain [7] and SICCAS [8]. The vast majority of the crystals show very good optical properties and good radiation hardness up to 100 krad. Hamamatsu [9] produced the SiPMs, which showed uniformity in operational voltages and gains, a good resistance to neutron radiation and Mean Time To Failure greater than 10^7 hours, all in agreement with technical requirements.

Several irradiation campaigns have been carried out both with neutrons at the ENEA Frascati facility Frascati Neutron Generator [10] and photons at the ENEA Casaccia facility CALLIOPE [11] to verify the resistance to radiation of the different electronics components and consequently replace them in case of failure.
At the and of 2020, 120 FEE boards have been produced for a pilot run. At the moment of this writing (May 2021) 2250 out of 3500 boards have been produced and are under test at JINR. Each board undergoes 6 hours of burn-in at 65 °C and then their linearity, gain and pulse shape are measured.

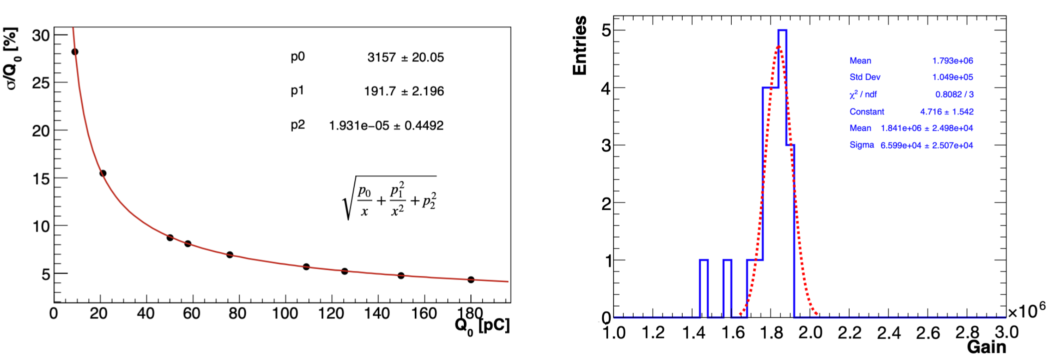

Figure 3. Left: Example of charge resolution obtained at different filter wheel position. Right: Gain of the 36 readout units made of SiPMs and FEE boards

In March 2021 the SiPM gluing procedure was relocated from FNAL to the National Laboratories of Frascati (LNF) due to the Covid-19 pandemic. Two SiPMs are glued to a cleaned and marked holder. Once the FEE boards are back at the LNF from JINR, they are assembled on the SiPM holder and the gain of the whole system is evaluated measuring the charge collected illuminating the SiPMs with a blue LED connected to a filter wheel. In May 2021 a test run done with 36 holders showed a stable gain of the system of 1.7×10^6, as reported in Figure 3.
For what concerns the status of the mechanics component production, one of the two outer cylinders is at FNAL, while the other one is at LNF over a dedicated stand for a dry run assembly of all mechanics in a clean room.

After a long phase of stability verification of Module-0 performance, a test of the full electronics chain is being carried out at LNF by measuring the response of 20 channels to Cosmic Rays (CR): the final versions of the FEE boards, the Mezzanine board (that provides SiPM biases, handles voltage readout and settings and acquires the currents and the temperature of the FEE boards) and the DIRAC board (that provides digitization at 200 Msps with 12 bit ADC for 20 channels) are used. In order to operate in conditions similar to the final calorimeter, the Module-0 is kept stable at 0°C with a chiller and at a vacuum level of $\sim 2 \times 10^{-1}$ mbar. The cooling system is connected also to the crate containing the Mezzanine and the Dirac board keeping their temperature at 5°C. In Figure 4 Left, an example of the event display is shown as well as the $\sim$ 20 MeV reconstructed energy from a MIP. In FFigure 4 Right, the distribution for the energy reconstructed by a MIP in one crystal is reported.

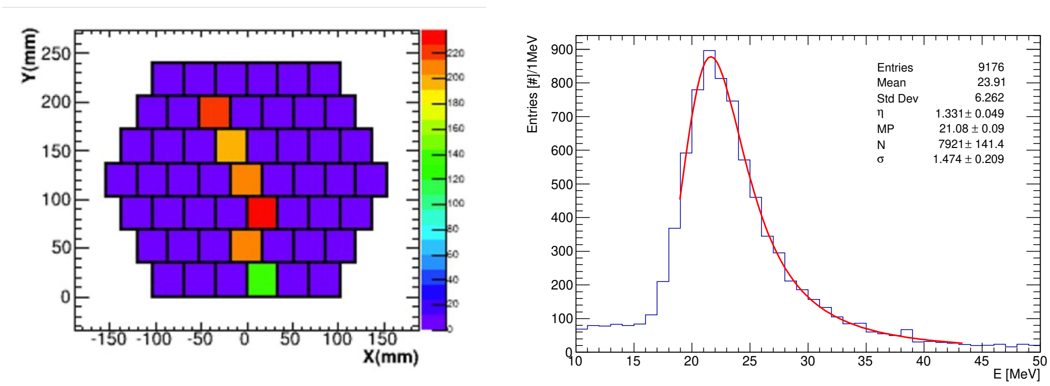

Figure 4. Left: Event display of a CR crossing the Module-0. Right: CR energy reconstructed with one crystal.

4. Conclusions

The Mu2e experiment aims to observe the CLFV process of coherent conversion of a muon into an electron in the electric field of aluminum nuclei. The electromagnetic calorimeter has a crucial role in the confirmation of a potential observation of a conversion electron made by the tracker thanks to powerful particle identification that allows for the separation of muons and electrons.
The characterization of the active components purchased for the construction of the Mu2e electromagnetic calorimeter confirmed the excellent quality of the selected producers. Detector construction is in progress and the startup of the assembly is planned for the fall of 2021. Installation at FNAL will take place in late 2022, followed by a commissioning phase in 2023.

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