PMu2e/LNF 2023

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The Mu2e experiment aligns with a global initiative to investigate Charged Lepton Flavor Violating (CLFV) processes. The observation of such processes would serve as compelling evidence for the existence of new Physics beyond the SM. Within the muon sector, the $\mu N \rightarrow eN$ process is often regarded as the "golden channel" due to its distinct signature and substantial discovery potential. The signature of the $\mu N \rightarrow eN$ process yields a monochromatic e^- with an energy just below the rest mass of μ, specifically $E_e = m_\mu c^2 - B.E. - E_{recoil} = 104.97 MeV$, considering the combined effects of the μ-binding energy and the recoil of the nucleus [1].
The current best limit on the conversion process, evaluated as:

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \rightarrow e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \rightarrow \nu_\mu + N(A,Z-1))} < 7 \times 10^{-13} \, (90\% \text{ CL})$$

has been set by the Sindrum-II collaboration. Mu2e aims to improve it by four orders of magnitude [2].

1 The electromagnetic calorimeter

The electromagnetic calorimeter [3] (see Figure 1) is composed of two annular disks, each filled of 674 pure CsI crystals with dimensions of $34 \times 34 \times 200$ mm^3.

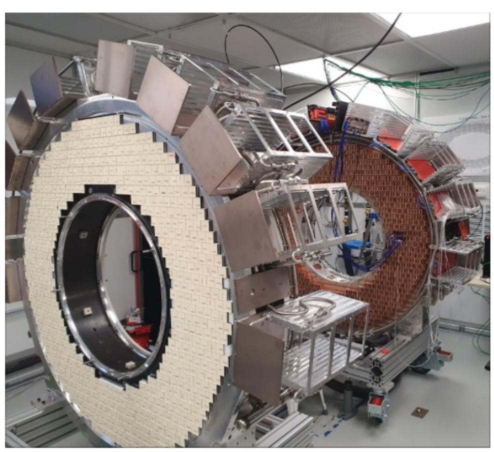

Figure 1: Status of the construction of the calorimeter disks.

The primary purpose of the calorimeter is to discriminate against cosmic ray muons that mimic the conversion electron signal: from simulation, it is expected that there will be an CE-like event produced every day, i.e. a cosmic muon converting in the Al Stopping Target at producing an electron with energy within the signal region. A particle identification ANN classifier utilizes the particle time of flight from the tracker to the calorimeter and the ratio between the calorimeter-measured energy and the tracker-measured momentum. This classifier effectively suppresses muons by a factor exceeding 100, while introducing negligible inefficiency for the electron signal. The disks, featuring an inner radius of 374 mm and an outer radius of 660 mm, are separated by 700 mm, allowing the second disk to capture electrons passing through the hole in the first one. Each crystal is coupled with two arrays of 6 SiPMs for readout. Preamplifier boards are positioned directly behind the SiPMs, while the slow control and digital electronics are housed in crates surrounding the disks.

2 Construction Status

During the 2023 period under consideration, there was a significant acceleration of activities related to the construction of the Mu2e Calorimeter. Figure 2 illustrates the breakdown of all the components comprising the calorimeter and presents a 3D model of the calorimeter. Over this period, the design transitioned into reality. All mechanical components were manufactured in Italy, and by early 2022, they were shipped to Fermilab for assembly of the Downstream Calorimeter Disk. By that time, all CsI crystals had been fully characterized in terms of geometry and optical properties, wrapped with Tyvek/Tedlar, and prepared for outgassing prior to insertion into the Disk shell, which was assembled on its stand within a Clean Room. Figure 3 depicts all the crystals and the status of the first disk at the beginning of 2022, indicating readiness for crystal insertion.

Due to the Covid Pandemic, certain activities originally planned for Fermilab were redirected to LNF-INFN, Italy. This includes the construction of the Read Out Units (ROU), involving the gluing of the SiPM on the copper holder and assembly of FEE electronics and Faraday Cages. Figure 4 displays the outcomes of this procedure, with a batch prepared for shipment to Fermilab. Each ROU underwent calibration at LNF, wherein the nominal gain of the SiPMs was set, and the I-V and gain curve behavior were characterized using a laser connected to a graded polaroid filter.

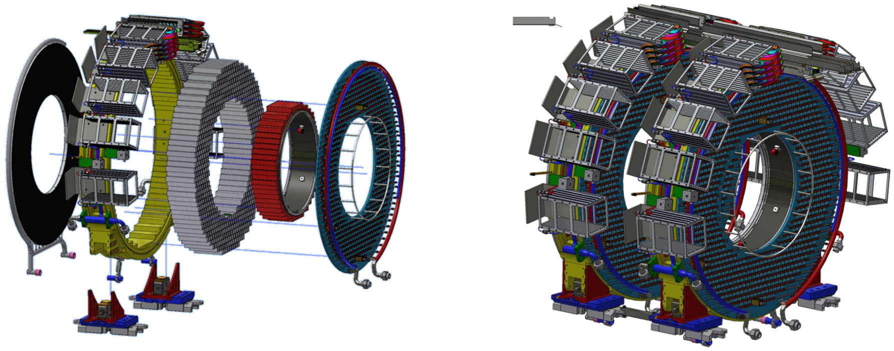

Figure 2: Breakdown of Mu2e Calorimeter components and 3D model.

During the year 2022, with all the mechanical components at hand, we completed the assembly of the Downstream Disk with crystals and enclosed the disk with the Carbon Fiber Source plate. Subsequently, in 2023, we also finished the assembly of the Upstream Disk and installed outgassed Read Out Units (ROUs) for both disks. Additionally, electronic crates hosting the Mezzanine

Figure 3: Status of CsI crystals and first disk at the beginning of 2022.

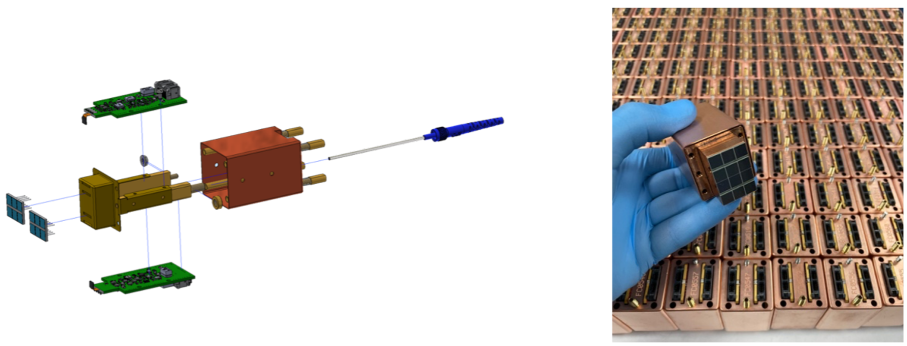

Figure 4: Result of the ROU construction procedure ready for shipment.

Boards and the Digitizers were installed and connected to the cooling circuit, which underwent leak testing. Figure 5 displays the status of the two disks by the end of 2023, when we also began installing the Front-End Electronics (FEE) cabling for the Downstream Disk.

Before "the design," it is important to mention that we undertook an enormous effort for the preparation, outgassing, and installation of all components. All ROUs and FEEs were tested at LNF and then shipped to Fermilab. A tremendous amount of work was carried out by all laboratory technicians, and currently, the assembly of FEE cables is ongoing.

The design of the Mezzanine Board (MB) was finalized in 2023 after testing prototypes for radiation hardness at several facilities: 200 MeV protons at the Warrenville Medical Proton Center (with a flux up to 10^{10} p/cm^2) and 64 MeV proton beams from the Crocker Nuclear Lab at UC Davis Cyclotron (with a flux range of 10^5 to 10^8 p/cm^2/s). These tests revealed the necessity to modify the circuit layout and include a soft reset command. Production of the Mezzanine Boards is ongoing, with half of the overall quantity (80 out of 160 pieces) expected to be at LNF in April 2024, following the preproduction of 10 units.

3 Calibration System

Each Disk is equipped with 2 Calibration systems: the laser system for SiPM gain monitoring and a source system for absolute calibration. We have set up the laser hatch for the primary light distribution to the 2 calorimeter disks, via 8 main optical fibers, and the secondary light distribution system uses 4 integrating/diffusive spheres per calorimeter to distribute the Laser light, which have been installed on the disks. 8 bundles of 200 optical fibers each will be connected to the spheres, and laser light pulses shine on the crystal face through a fiber needle inserted in

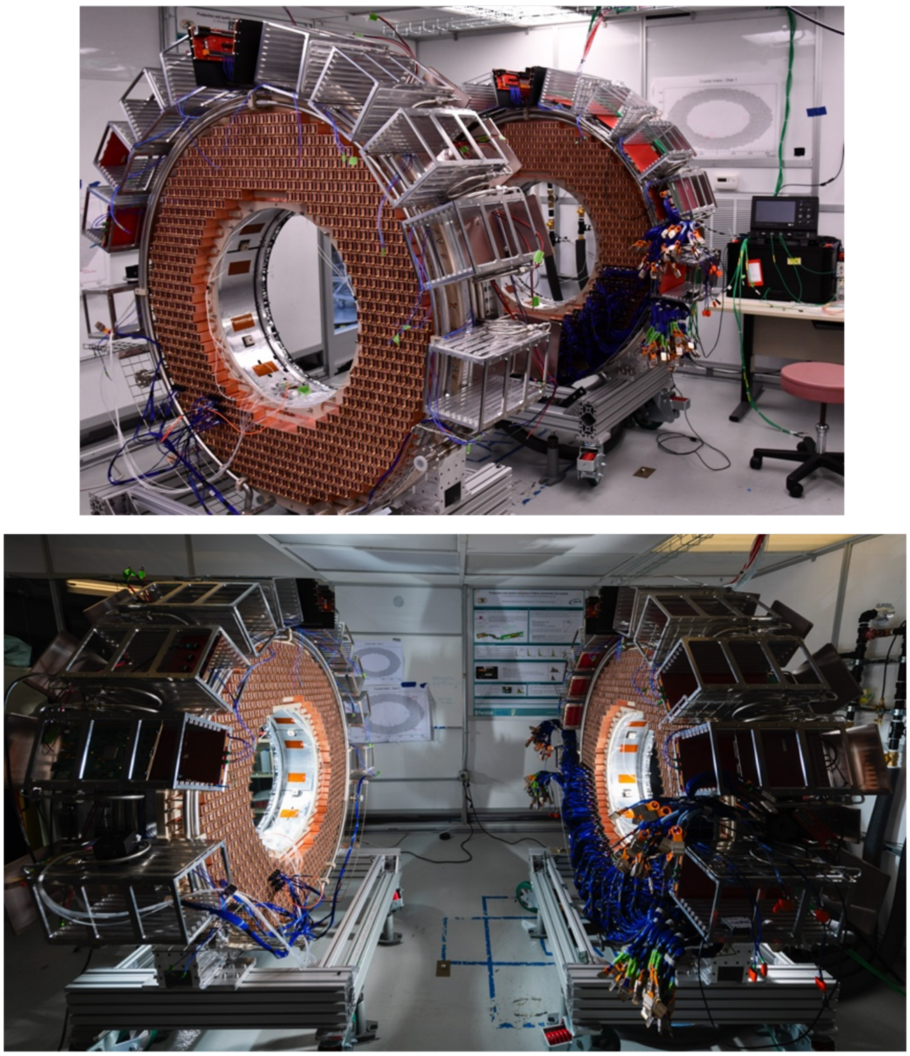

Figure 5: Status of the Downstream and Upstream Disks by the end of 2023.

the ROU. Figure 6 shows the analog signal response on the scope to the laser pulse for 4 channels being debugged during ROU installation.

The Calorimeter crystals' energy scale is calibrated with 6 MeV gamma rays produced by neutron irradiation of a Fluorinert liquid circulating in Aluminum pipes facing the crystals. In 2023, the neutrons generated by a DT generator that is already installed in the pit. All HV running tests, radiation control safety, and permissions have been obtained, the Carbon Fiber source plates with the embedded source pipes have been leak tested and are in place, and PLC and electronics installed. The absolute scale calibration will also be set offline using Cosmic Rays (CR) and looking at the minimum ionizing deposit in the crystals after selecting the CR candidate. Figure 7 shows the event topology; for each crossed crystal, we build the energy deposited distribution and fit it with a Langaus function to obtain a Most Probable Value (MPV) distribution per channel.

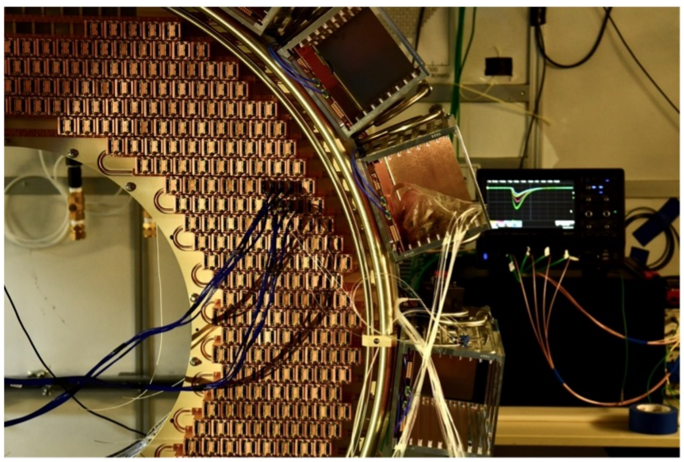

Figure 6: Analog signal response to the laser pulse for 4 channels during ROU installation.

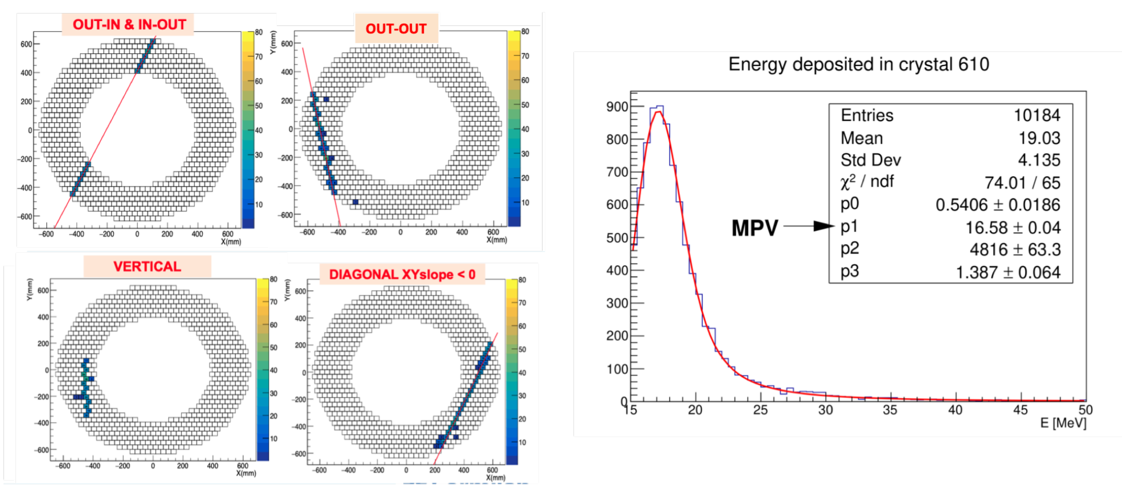

Figure 7: Event topology for CR absolute scale calibration.

4 Mu2e-II

A *Workshop on a future muon program at FNAL* (https://indico.fnal.gov/event/57834/) was held in March 2023 to pursue design studies for Mu2e-II, to organize efforts for the next generation muon facility, and to identify synergies with other R&D efforts. The workshop comprised plenary and parallel sessions discussing technical aspects and physics capabilities.
While the calorimeter has a robust rate performance at Mu2e rates but may be challenged by Mu2e-II instantaneous rates that are two to three times higher. The x10 integrated radiation dose on the calorimeter readout electronics motivates the study of appropriate rad-hard readout electronics at a level informed by the HL-LHC detector upgrades. The Mu2e-II calorimeter design has been developed based on BaF2 crystals readout with solar-blind UV sensitive SiPMs that efficiently collect the very fast UV component ($\sim$ 220 nm) of the scintillation light while suppressing the slow component near 310 nm. This alternative design would be considerably more robust against Mu2e-II rates but requires the development and commercialization of the required solid-state photo sensors, which is ongoing. The Mu2e-II calorimeter should have the same energy (<10%) and time (<500 ps) resolutions as in Mu2e, aiming to provide a standalone trigger, a track seeding, and PID as before. However, the Mu2e-II environment presents two challenges to the calorimeter system:

1. The pileup with respect to CE seems to scale linearly with beam intensity, so to keep the same level we have in Mu2e (15%) with 150 ns we need to rescale the new signal length. The signal length for Mu2e-II should be 75 ns.

2. Under the assumption that the total integrated dose (TID) from the beam flash in the calorimeter from 800 MeV protons scales as the number of stopped muons with respect to the Mu2e 8 GeV beam, a factor 10 increment is expected. The $\times 10$ increase in the integrated dose (neutron fluence) corresponds to 10 kGy (1×10^{13} n/cm^2/sec) for both crystals and sensors motivates consideration of more radiation tolerant crystals and sensors such as Barium fluoride (BaF2) crystal and Solar blind SiPMs.

The LNF Mu2e group proposed a tailored solution at the workshop, wherein LYSO crystals with a length of 8 cm are utilized in the Mu2e-II calorimeter. This approach, combined with individual 50 Ω micro-coaxial transmission lines for transporting bias voltages and SiPM signals between the SiPM board and the Mezzanine Board, offers several advantages:

- The 8 cm length of LYSO is sufficient to achieve approximately 5

- The equivalent noise energy is manageable, and there is consistent longitudinal response uniformity.

- There is no expected degradation in performance even after exposure to 10^{13} neutrons/cm^2.

- Since SiPMs already exist, no further research and development are necessary.

- The high light yield of LYSO allows for the use of SiPMs at low over-voltage, enhancing radiation resistance and reducing power dissipation.

- As long as a front-end amplifier is unnecessary, there are no issues with the radiation levels affecting electronics.

Although this backup solution seems practical, simulation studies are required to verify its rate capability in the Mu2e-II environment. Furthermore, it's worth mentioning that a research and development campaign funded by the INFN Group 1 has been initiated to validate its feasibility.

5 Thesis

- P. Fedeli, “Commissioning and calibration of the Mu2e calorimeter in extracted position”, master thesis at the Università degli Studi La Sapienza.

6 List of Conference Talks/Posters by LNF Authors in the Year 2023

1. E. Diociaiuti, Design and construction status of the Mu2e crystal calorimeter and its future upgrade, Innovative Detector Technologies and Methods (IDTM), Sep. 12-14, 2023, Lisbon Biblioteca Nacional (auditorio, room 13 in the map) Campo Grande 83, 1749-081 Lisboa.

2. F. Happacher, The Mu2e experiment and its electromagnetic calorimeter, The 3rd African Conference on Fundamental and Applied Physics (ACP2023), Sep. 25-29, 2023, Nelson Mandela University, George Campus, George, South Africa.

3. E. Diociaiuti, Status and perspectives of cLFV at Mu2e, WIFAI Second Italian Workshop on the Physics at High Intensity, Nov.8–10, 2023, Dipartimento di Architettura dell'Università Roma Tre.

7 Publications

- S. Corrodi et al., Workshop on a future muon program at FNAL, FERMILAB-CONF-23-464-PPD, CALT-TH-2023-036, Sep. 11, 2023.

- N. Atanov et al., The Mu2e Crystal and SiPM Calorimeter: Construction Status, IEEE Trans.Nucl.Sci. 70 (2023) 7, 1281-1287. DOI:10.1109/TNS.2023.3264757.

- S. Ceravolo et al., Design and qualification of the Mu2e electromagnetic calorimeter electronic system, Nucl.Instrum.Meth.A 1047 (2023) 167875. DOI:10.1016/j.nima.2022.167875.

- C. Bloise et al., Design, assembly and operation of a Cosmic Ray Tagger based on scintillators and SiPMs, Nucl.Instrum.Meth.A 1045 (2023) 167538. DOI: 10.1016/j.nima.2022.167538.

References

1. Bernstein, Robert H. et al, Charged Lepton Flavor Violation: An Experimenter's Guide, Phys. Rep.,532, 2, 27-64, 2013.

2. Bertl, W. et al, A search for µ- e conversion in muonic gold, EPJ C, 47, 337A ¸S346, 2006.

3. N. Atanov et al., “Design and status of the Mu2e calorimeter,” IEEE-TNS 65, pp. 2073-2080, 2018, ArXiV:1802.06346.