PROCEEDINGS OF SCIENCE

The Mu2e crystal calorimeter

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The Mu2e experiment at Fermilab will search for the charged-lepton flavour violating conversion of negative muons into electrons in the coulomb field of an Al nucleus, planning to reach a single event sensitivity of about 3×10^{-17}, four orders of magnitude beyond the current best limit.
The conversion electron has a clear monoenergetic signature at 104.967 MeV, slightly below the muon rest mass, and will be identified by a complementary measurement carried out by a high-resolution tracker and an electromagnetic calorimeter (EMC). The calorimeter is composed of 1348 pure CsI crystals, each read by two custom UV-extended SiPMs, that are arranged in two annular disks. The EMC should achieve better than 10% energy resolution and 500 ps timing resolution for 100 MeV electrons and maintain extremely high levels of reliability and stability 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.
The calorimeter technological choice, along with the design of the custom front-end electronics, cooling and mechanical systems were validated through an electron beam test on a large-scale 51-crystals prototype (Module-0) and extensive test campaigns that characterised and verified the performance of crystals, photodetectors, analogue and digital electronics. This included hardware stress tests and irradiation campaigns with neutrons, protons, and photons.
The production and QC phases of all calorimeter components is completed apart for the digital electronics that has been revised for improving its resilience to SEU and SEL. A series of vertical slice tests with the final electronics is being carried out on the Module-0 at LNF along with the implementation and validation of the calibration procedures. The first disk has been assembled in 2022 while the second disk is under assembly at the moment of writing. Status of construction will be summarised, along with plans for commissioning and first calibration of the fully assembled disks.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August 2023
Hamburg, Germany

[*] *M*u2e Collaboration List, 2023.
[*] Speaker

PoS(EPS-HEP2023)549

1. The Mu2e experiment

The Mu2e experiment[1] aims to observe the charged-lepton flavour violating (CLFV) neutrinoless conversion of a negative muon into an electron (CE) in the field of an Aluminum nucleus:

$$\mu^- + Al \rightarrow e^- + Al \tag{1}$$

In case of no observation Mu2e aims to lower by a factor 10^4 the current 90% CL limit on the ratio between muon conversions and muon nuclear captures in Gold set by the Sindum II experiment[2]:

$$R_{\mu e} = \frac{N(\mu \rightarrow e)}{N(\text{nuclear captures})} < 7 \cdot 10^{-13} \text{ (90\% CL)} \tag{2}$$

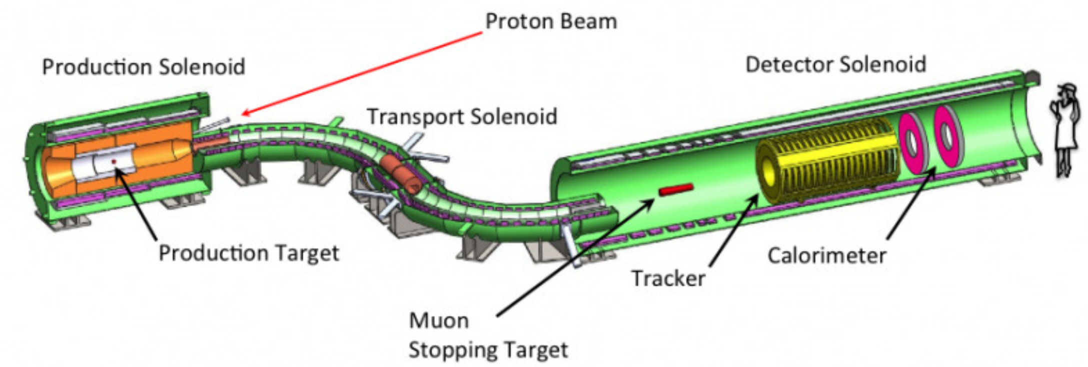

Figure 1: The Mu2e experimental apparatus.

Mu2e experimental apparatus is shown in Fig.1. It's composed of three superconducting magnets: the production solenoid hosting the tungsten production target where the 8 GeV proton beam interacts producing in particular charged pions; the S-shaped transport solenoid that thanks to a set of collimators selects the charged particles of wanted momentum and charge; the detector solenoid that hosts the Aluminum target, where muons produced by pion decays eventually stop and convert in ~ 105 MeV/c electrons, the straw tube tracker that aims to measure with high accuracy the particle momentum and the electromagnetic calorimeter. The detector solenoid and the lower half of the transport solenoid are covered by four layers of scintillators to veto the cosmic rays entering in the detectors region.

2. Mu2e calorimeter

Mu2e calorimeter has to add redundancy to the precise measurement of the conversion electron momentum performed by the tracker, helping to evaluate and reduce all possible background sources. In particular Mu2e calorimeter has to:

- have a large acceptance on conversion electrons;
- provide particle identification (e/μ separation) to improve cosmic ray rejection;

- provide information to facilitate the tracker pattern recognition;
- provide a trigger on electromagnetic particles;
- operate inside the Detector Solenoid.

A full simulation of Mu2e experiment has been used to set the calorimeter requirements. Focusing on the ~105 MeV/c conversion electrons arriving with an average impact angle of ~ 50^o Mu2e calorimeter must have:

- an energy resolution better than 10%;
- a time resolution better than 500 ns;
- a transverse position resolution better than 1 cm;
- a signal width of ~100 ns to reduce event pileup and data size;
- the capability to work in a 10^{-4} Torr vacuum and in 1 T magnetic field;
- the capability to satisfy the energy and time resolution requirements after the exposure to a total ionizing dose of 100 krad and a neutron fluence of $10^{12} n_{1MeVeq}/cm^2$.

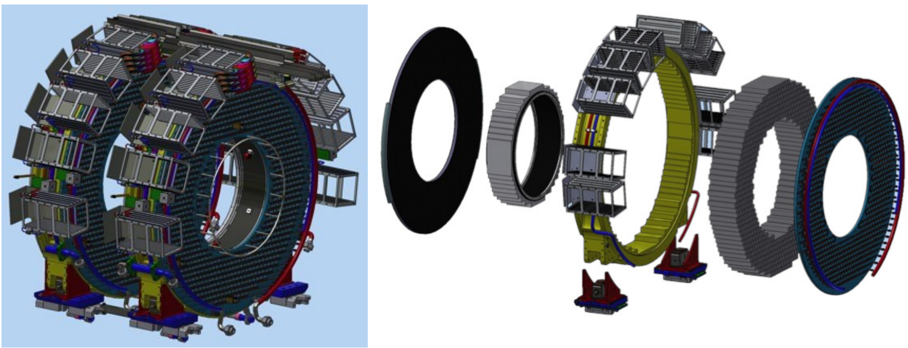

Figure 2: The double ring Mu2e calorimeter structure. On the right the exploded view of one ring. Starting from left: the front panel hosting the radioactive source pipes, the inner ring in carbon fiber, the external aluminum ring with the electronic crates, the crystals and the back panel hosting the SiPMs, the FEE boards and the cooling pipes.

The design of Mu2e calorimeter chosen to satisfy the above requirements is shown in Fig.2. The calorimeter is made of two disks (or rings) of CsI crystals. The central holes reduce radiation damage and flux of particles that can be scattered back to the tracker. The inner radius is 374 mm, the outer radius is 660 mm. The 70 cm separation between the two disks optimizes the acceptance for conversion electrons that is higher than 90%[3]. Each disk contains 674 pure CsI crystals, each read by two SiPMs. The SiPM signal is amplified in the FEE boards located just on its back. The HV regulation and the digitization boards are located in the crates placed on top of each disk. A cooling system keeps stable the temperature of the SiPMs and the boards located in the crates. The system is completed by a laser calibration system sending the same laser pulse to all the crystals and a radioactive calibration liquid that can be circulated in pipes located in front of each disk.

2.1 Crystals

The pure CsI crystals have been produced by SICCAS and Saint Gobain. Their transverse dimension is 34×34 mm^2 and their length is 200 mm, corresponding to $\sim$10 X_0. The peak emission is at 310 nm, the light yield 3.6% of the NaI(Tl) one and the decay time 26 ns. The production crystals have been selected according to mechanical tolerance, light yield (using a reference PMT), longitudinal response uniformity (LRU), fast/slow component ratio, light yield reduction after 1 kGy, light response uniformity reduction after $10^{12} n_{1MeVeq}/cm^2$, and radiation induced noise[4].

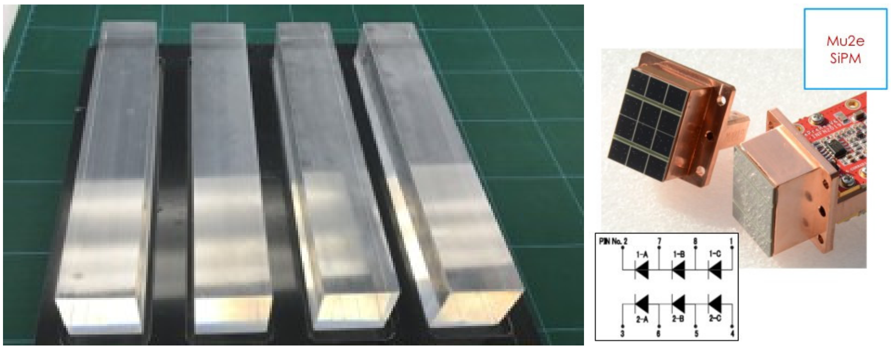

Figure 3: Pure CsI crystals and SiPMs used in Mu2e ECAL.

2.2 SiPMs

Each crystal is read through a 2 mm air gap by two 14×20 mm^2 UV extended SiPMs.Each SiPM is made of 6 individual 6×6 mm^2 50 μm pixel Hamamatsu MPPCs connected as the parallel of two series to reduce the total capacitance and power supply. The photon detection efficiency (PDE) at the CsI peak emission is $\sim$30%. The production SiPMs have been selected checking the break-down voltage and dark current spread between cells, the gain at the operating voltage, the PDE, the recovery time, the dark current after a neutron fluence of $3 \times 10^{11} n/cm^2$, and the mean time to failure[1][5].

2.3 Front End Electronics

Each SiPM is individually read by a FEE board (Fig. 4) that provides signal shaping, two possible amplifications, HV regulation and monitors SiPM voltage, current and temperature. Each readout unit, composed by 2 SiPMs and 2 FEE boards, is in thermal contact with the cooling system that keeps SiPM's temperature at -10^o C to reduce the leakage current increase due to the exposure to the intense neutron flux. All the readout units have been qualified looking at the signal raise time and fall time, the PDE, and the gain dependence on bias voltage and temperature[6].

2.4 Mu2e ECAL readout chain

FEE signals are sent in groups of 20 to a mezzanine board (MB) and a digitizer board (DIRAC) located in the crates placed on top of the disks. The MB, equipped with an ARM processor, has the

[1]The last two checks have been performed on a subsample of each production lot

PoS(EPS-HEP2023)549

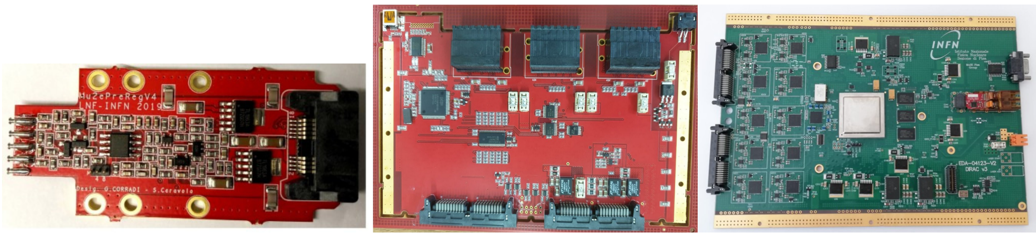

Figure 4: Mu2e ECAL electronic boards. Starting from left: the FEE, the MB and the DIRAC.

role to distribute LV and HV reference values to the FEE boards, to set and read back FEE regulated voltages and to transmit FEE differential signals to the DIRAC.

The Digitizer ReAdout Controller boar (DIRAC) is equipped with 20 TI ADS4229 12-bits ADCs, a MicroSemi Polarfire MPF300T FPGA, a TI LMK04828 jitter cleaner and a CERN VTRX optical transceiver. It samples FEE signals at 200 MHz with a synchronization better than 100 ps, suppresses the zeros, forms the digital hits and packs them in data words that are transmitted to the Data Aquisition servers.

3. Calorimeter Design validation

A calorimeter prototype with 51 crystals (Module-0), 102 SiPMs+FEE boards, a commercial digitizer and the SiPMs cooling lines has been exposed to electron beam at the Frascati Beam Test Facility in 2017. For 100 MeV electrons with a 50^o impact angle the energy resolution was 7.3% and the time resolution, using just 1 SiPM information, was 230 ps[8]. In both cases the result was well within the requirements listed in section 2.

Crystals, SiPMs and all the electronic components have been tested against ionizing and neutron radiation and the relevant components have also been tested in a 1T magnetic field. Some components failing the tests have been replaced. A protection against SEL has been added to MB and DIRAC. After these changes all the components are qualified to work in the Mu2e environment[7, 9].

4. First ECAL vertical slice test and calibration

A first vertical slice test has been performed in Frascati using 20 channels of Module-0 prototype inserted in a vacuum vessel and equipped with final crystals, SiPMs and FEE and read by 1 almost final MB and DIRAC inserted in the final crate. During 2 weeks of running the readout chain has worked as expected, ADC pedestals have remained below 200 keV and MIP peaks have been stable within 2%. Module-0 has also been used to validate the energy and time equalization that can be obtained using the cosmic rays crossing the calorimeter and the standalone ECAL trigger[10].

5. Summary and outlook

Mu2e calorimeter design has been validated and its assembly is almost complete. The calorimeter will be moved to Mu2e experimental all in 2024 where it will be integrated to the rest of Mu2e and will participate to the commissioning of the detector with cosmic rays in view of the first beam that is expected to arrive in 2026.

6. Acknowledgments

We are grateful for the vital contributions of the Fermilab staff and the technical staff of the participating institutions. This work was supported by the US Department of Energy; the Istituto Nazionale di Fisica Nucleare, Italy; the Science and Technology Facilities Council, UK; the Ministry of Education and Science, Russian Federation; the National Science Foundation, USA; the National Science Foundation, China; the Helmholtz Association, Germany; and the EU Horizon 2020 Research and Innovation Program under the Marie Sklodowska-Curie Grant Agreement Nos.734303, 822185, 858199, 101003460, and 101006726. This document was prepared by members of the Mu2e Collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359.

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