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Development, construction and qualification tests of the Mu2e electromagnetic calorimeter mechanical structures

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1. The Mu2e experiment and the Calorimeter

The "muon-to-electron conversion" (Mu2e) experiment at Fermilab will search for the Charged Lepton Flavour Violating neutrino-less coherent conversion of a muon into an electron in the field of an aluminum nucleus. The observation of this process would be the unambiguous evidence of New Physics. Mu2e detectors comprise a straw-tracker, an electromagnetic calorimeter (Figure 1) [1] placed inside an evacuated vessel at 10^{-4} Torr and surrounded by a large superconducting solenoid which generates an axial magnetic field of 1 T, and an external veto for cosmic rays. The main calorimeter function is providing complementary information to the tracker to achieve a

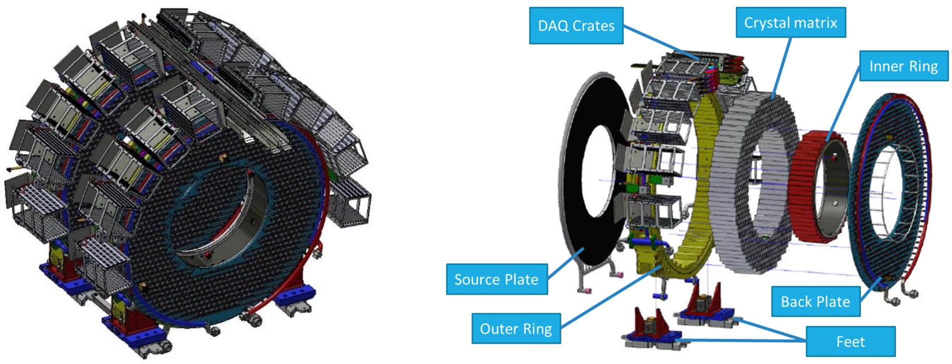

Figure 1: CAD drawings of the Mu2e electromagnetic calorimeter. Global view of the two disks (*left*). Exploded view of one disk: the Outer Ring, the Source Plate, the Crystal Matrix, the DAQ Crates, the Inner Ring, the Back Plate and the Feet are shown (*right*).

powerful μ/e separation which is crucial to extract the conversion electron signal from the expected overwhelming background. The calorimeter is also exploited in a calorimeter-seeded track finder algorithm which improves track reconstruction efficiency and makes the algorithm more robust in high detector occupancy conditions. Moreover, the calorimeter is used to implement a fast online standalone trigger independent from the tracker. These tasks translate into the following requirements for 105 MeV electrons: (a) large geometric acceptance; (b) time resolution better than 500 ps; (c) energy resolution better than 10% and (d) position resolution of the order of 1 cm.
The detector has been designed as a state-of-the-art crystal calorimeter and employs 1348 pure Cesium Iodide (CsI) crystals readout by UV-extended silicon photosensors (SiPM) and fast front-end and digitization electronics. A design consisting of two identical annular matrices (named "disks") positioned at the relative distance of 70 cm downstream the aluminum target along the muon beamline satisfies the Mu2e physics requirements.
The hostile Mu2e operational conditions, in terms of radiation levels (total expected ionizing dose of 12 krad and a neutron fluence of 5×10^{10} n/cm^2 @ 1 MeVeq (Si)/y), magnetic field intensity (1 T) and vacuum level (10^{-4} Torr) have posed tight constraints on the characteristics of scintillating materials, sensors, electronic components and the design of the detector mechanical structures and material choice.

2. The calorimeter components and qualification tests

The heart of each of each disk is the ring-shaped matrix of 674 un-doped CsI crystals (34x34x200 mm^3) which has an internal/external diameter of 650/1314 mm. Each crystal has been inspected on a CMM machine to check dimensional tolerances (±0.1mm short sides, ±0.1mm long sides), parallelism (±0.1mm) and perpendicularity (±0.1mm) between faces. Each crystal has been characterized for its optical properties and Radiation Induced Noise (RIN) [2] next. 87% of the received crystals was accepted after the QA process. Crystals have been then wrapped in Tyvek foils (150 µm thick) to improve internal light reflection, and after with black Tedlar foils (50 μm thick) horizontally and vertically to minimize optical cross-talk with their neighbor crystals in the matrix. At the moment, 1350 crystals are stored in nitrogen fluxed cabinets at Fermilab to avoid moisture damages, waiting for the assembling.
Because of the presence of various soft materials (Tyvek and Tedlar), to analyze crystal stacking and predict crystal position, some CMM measurement tests have been performed and some position model have been realized [3] (2-left).
The crystal matrix is externally supported by the Outer Ring made of Al6082 aluminum. The outer diameter and the thickness of the ring are 1460 mm and 146 mm, respectively. The Outer Ring also provides all the fastening features for the other components. It hosts the manifolds for the crate cooling system and supports the DAQ crates on the lateral surface.
The material choice and budget of the mechanical structures that can be traversed by the particles have been optimized to minimize particle energy losses. The two components placed on the particle trajectories are the Source Panel, which is the frontal cover of the each crystal matrix, and the Inner Ring, which occupies the inner bore surface. They are both made of carbon fiber planes strengthened by light aluminum structures when necessary.
The Source Plate supports 10 thin-wall (0.375" OD x 0.02" thickness) aluminum tubes symmetri-

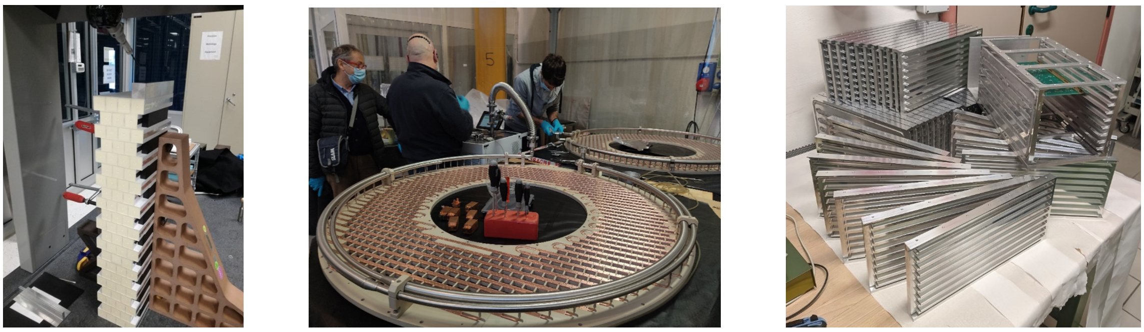

Figure 2: Crystal piling up test on a CMM (*left*). Back Plate leak test at Cinel, Vigonza (Italy) (*center*). Preparation of the create sides fotr the leak test at INFN Laboratories in Pisa, Italy (*right*).

cally arranged on each disk to flow the calibration source fluid (CF-770). It also provides the frontal enclosure for crystal protection. The Source Plate is made of a sandwich with 1.4 mm carbon fiber skins and a core of aluminum honeycomb (series 3003) 22 mm thick, 3/8” cell size, and 0.003” wall thickness. The expected energy loss is 1.2 MeV for 100 MeV electrons. Pipes have been already manufactured and leak tested and allowed to verify that the leak rate is below $3 \times 10^{-10} mbar\ l/s$ at the pressure of $10^{-3} mbar$ with a Vacuum Helium Leak test.

The Inner Ring performs a fundamental function for the support and alignment of the crystal matrix. It is made of a carbon fiber cylindrical skin with an internal diameter of 712 mm, 4.2 mm thick, an F-.220/193/50 CF fabric (0/90° texture) with cyanate ester resin; two 5083 H111 aluminum alloy reinforcement internal rings with an internal diameter of 672 mm, an outer diameter of 712 mm, 13 mm thick to increase its stiffness; three outer step ribs made of a sandwich slab with 1.4 mm carbon fiber skins (same as the cylindrical skin) and a core of aluminum honeycomb (series 3003) 22 mm thick, 3/8" cell size, and 0.003" wall thickness. The Inner Ring is connected and supported by the Back Plate and Source Plate and provides the internal vertical/horizontal reference for the crystal matrix. All the sub-components have been realized, and a dry run has been performed which allowed to verify that the sub-components are within design specifications.
The Back Plate is the rear mechanical enclosure of the calorimeter. It also supports the 674 front-end units which include the SiPMs and front-end electronic boards. Each SiPM has been qualified with a dedicated set up both for geometrical and electrical properties [4]. The SiPM and front-end electronic modules are composed of 2 SiPMs glued on a copper holder, 2 front-end boards and a copper protective cage. At this time, each assembled module is being tested for thermal and electrical properties to verity connections between the SiPM, the holder and the FEE boards. The modules are fastened directly on the Back Plate Cooling lines to optimize thermal conductivity. The Back Plate is made of two PEEK plates glued with a V-Notch joint because of PEEK sheet availability. It is 20 mm thick and host 674 hollow for SiPM modules insertion. PEEK was chosen to optimize thermal isolation of the electronics and for its good outgassing characteristics. The Back Plate integrates the cooling system of the front-end units. It embeds a network of vacuum brazed copper lines flowing fluid (3M Novec 649) at -15 C to minimize SiPM dark current and maintain an acceptable signal/noise ratio over the three years of data taking. Two AISI 316L I/O manifolds placed on the external border distribute the cooling fluid among the network of 38 parallel copper cooling lines embedded in the PEEK to maximize the temperature uniformity that is less then 1°C between the inlet and the outlet, with a head loss less than 0.6 bar. A leak test has been performed on the cooling system, with a leak rate $< 10^{-10} atm\ cc/s$ (2-center), and dimensional measured to check references and hollows positions on a CMM at INFN.
Each calorimeter disk supports 10 DAQ crates placed on its lateral surface to host 80 DAQ boards which digitize and transmit the data received from the front-end through optical fibers out of the vessel to the central DAQ system. Each crate integrates a network of cooling lines to remove the 320 W dissipated by the set of 8 DAQ boards. To reduce crate envelope and optimize the thermal system performance, the cooling lines are directly carved in the crate sides and TIG welded. All the crates are connected in parallel to minimize head losses and they are connected with S-shaped pipes to make easy assembling and to compensate pipe welding misalignment. The crate also include a cable holding system to distribute and hold FEE cables. Each crate has been pressure tested and leak tested singularly (2-right), the same will be made for the manifolds as soon they will be completed. At the moment of writing these Proceedings, the firm is sill welding all the connections. Optimal thermal contact between the electronic components and the heat sink is achieved through a machined copper plate positioned on top of the DAQ boards and placed in thermal contact with the components with vacuum proof thermal grease (Apiezon). The DAQ crate structure is completed by a set of tungsten plates which protect the electronic components from the radiation present in the experimental area at run time. Thermal simulations and experimental tests have been performed

to crosscheck the cooling system performance. Each crate has been pressure tested and leak tested singularly and the same will be done for the manifolds as soon they will be completed.

3. Conclusions

The calorimeter components construction is almost done, and most of the mechanical components have been produced and tested. The QA process has been applied to all the critical components of the calorimeter, in particular for the CsI crystals, which has been crucial to identify the out of the specification crystals, that were a not negligible amount, and they could affect negatively the calorimeter performance. Further tests have been planned during the assembling steps in order to monitor the good functionality of all the subsystems before the final installation. These tests will take place at SiDet facility at Fermilab (USA) in a dedicated cleanroom, and only after the final assembling, each disk will be moved in the detector facility, at Fermilab.

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