The MU2E experiment at Fermilab

C. Bloise, S. Bini, S. Ceravolo (Tech.), M. Cordelli (Ass.Senior), G. Corradi (Tech. Senior), E. Diociaiuti (AR), R. Donghia (AR), F. Fabiano (Laur.), F. Fontana (Ass.), S. Giovannella, D. Hampai, F. Happacher (Res.), M.Martini (Ass.), A. Mengucci (Tech), S. Miscetti (Res.Naz.), D. Paesani (Laur.), B. Ponzio (Tech), G. Pileggi (Tech), A. Saputi (Tech), I. Sarra (Art. 36), M. Ventura (Tech).

1 Introduction

During 2020, Mu2e has achieved many important milestones although there have been substantial delays on the overall schedule due to the COVID-19 pandemics and to the construction of the magnetic system.

The construction of the magnetic system and detectors has started in 2018 and is progressing at good pace albeit some relevant difficulties. Indeed the magnetic system still guides the "critical path" of the experiment. The Transport Solenoid coils and components are all at Fermilab and are being assembled and tested. The construction of the Detector and Production solenoids (DS and PS) at General Atomics is in progress.

Due to the delays caused by the Covid-19 pandemics and the magnetic system construction, the data taking period has been staged in two phases. A first phase at low beam intensity (with a factor of two reduction) and a gradual increase of the beam intensity in a second phase until the foreseen accelerator shut-down required to prepare the neutrino beam dedicated to the DUNE experiment (2026). An operation group has been formed to organize the transition phase between the construction of the detectors and of the magnets and start-up of the commissioning operations (with and without beam). Within the current schedule, the start of the physics run is planned for end of 2023.

2 Status of the Mu2e Magnetic system

The construction of the Transport Solenoid (TS) magnetic coils, assigned to ASG Superconducting (Genoa), has been concluded. All 52 coils have been completed and have been integrated in their modular mechanical structure. At the moment of writing, ASG has delivered to Fermilab all needed 14 modules that are being integrated in the final configuration. The cold test phase of single units is being carried out at the HAB facility. The preparation of the upstream part of TS, TSu, is almost completed, with all the modules connected . The downstream part is in advanced stage. In Fig. 1 the TSu/d bore and thermal shield are shown.

The construction of the Detector (DS) and Production Solenoid (PS) at General Atomics (GA) in the USA is also progressing. Most of the technical problems highlighted during 2019 are being solved. The three coils of the PS, which uses the thicker super-conducting cable, are being fabricated but still suffer of some issues: PS3 has to be tested at low temperature, PS2 has some issues in the thermal bridges connections and PS1 has some problems in the spicing of different coil layers. On the other side, the DS suffers of exceeding the tolerance on the roundness of the aluminum shells that have to support the different coils. In total there are 11 coils. Three of them have been winded but their shells have to be corrected before insertion. At the moment of writing, a solution has been found by using an expansion tool to recover the correct dimensions. As a conclusion, the critical path of the whole experiment is still dominated by the delivery of these two magnets and by the follow-up installation and commissioning phase. The CD-4 achievement date

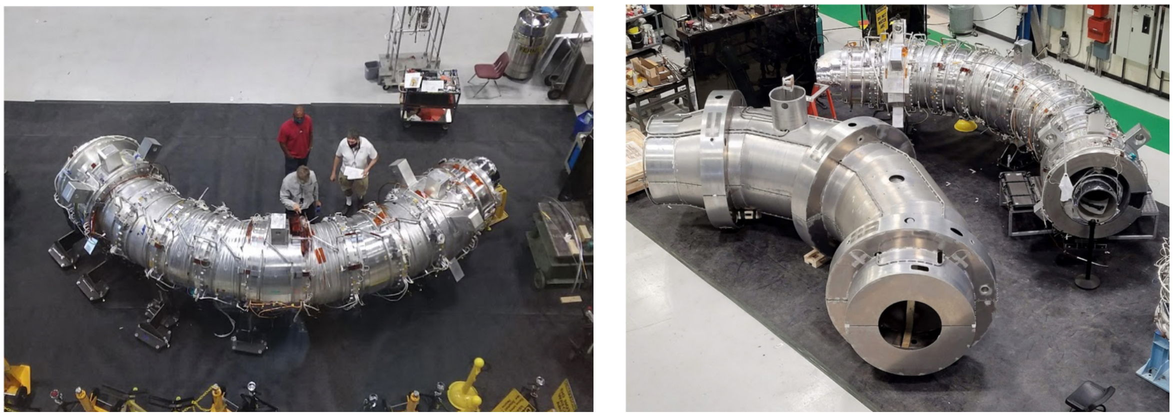

Figure 1: First half of TS, TSu, installed with insulation and aligned. The second half of the TS, TSd, will soon be completed.

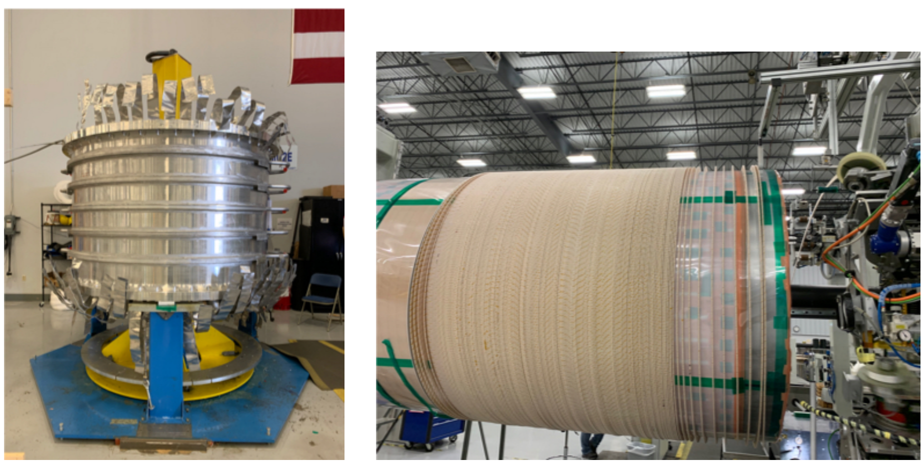

Figure 2: Production Solenoid, PS, and Detector Solenoid, DS, construction status.

(i.e. magnets and detectors completed and installed in the building) is currently estimated for the first half of 2023.

3 Tracker and cosmic ray veto status

The Mu2e tracker system consists of approximately 20'000 very thin straw tubes (5 mm in diameter, length varying within 40 and 100 cm, thickness of 15 μm) organized in 18 stations (2 planes per station, for 6 panels per plane), for a gran total of 216 panels. In 2020, the panel production has reached a stable production, solving most of the technical problems for their realization. After a stop of 6 months due to the pandemics, the tracker group succeeded to reach a panel production of 2 panels/week and conclude the realization of 40 panels. Moreover, two important milestones have been reached: (a) the construction of a first fully assembled plane and (b) the preparation of a Vertical Slice test for the full-chain readout. Assuming to improve the production pace from 2 to 4 panels/week, the panel construction should end for middle of 2022 and the overall tracker to be assembled for the end of 2022, followed up by installation in the pit in 2023.

The cosmic ray veto detector system (CRV) consists of 330 m^2 of extruded scintillation counters, each about 4 m long, where two WLS fibers are inserted to collect the scintillation light on (2×2 mm^2) Hamamatsu SiPMs, The production is organized to construct the counters at first. Then they are grouped in modules containing 4 counters. The scintillation counter construction has been completed and the module production has reached 40% of the total. The module production completion is planned by summer 2021. The CRV SiPM production is also concluded, so that the CRV group is now focalizing its efforts on the electronics production. The CRV installation in the pit will take place at the end of the magnetic system assembly phase and after the installation of the concrete shielding around the DS, that will help reducing the neutrons and irradiation to the DS.

4 Production status of the Calorimeter system

As shown in Fig. 3, the Mu2e calorimeter is composed by two annular disks containing 674 pure CsI crystals each. Each crystal is readout by 2 UV-extended Mu2e-SiPMs (a Mu2e SiPM is a custom array of 6 SiPMs cells of 6×6 mm^2 dimensions). This detector design is the result of a long and intense R&D phase, that has been led by the LNF-INFN group. At the moment of writing, the production phase of all the components is well advanced. However, again due to pandemics, it has been impossible to follow up the original schedule since many operations were moved back to Italy and we could not operate safely in US for the assembly of components. As a grand-total, we have accumulated so far around 10 months of delay in our scheduled target, that now foresees the calorimeter installed in the pit in the second half of 2022.

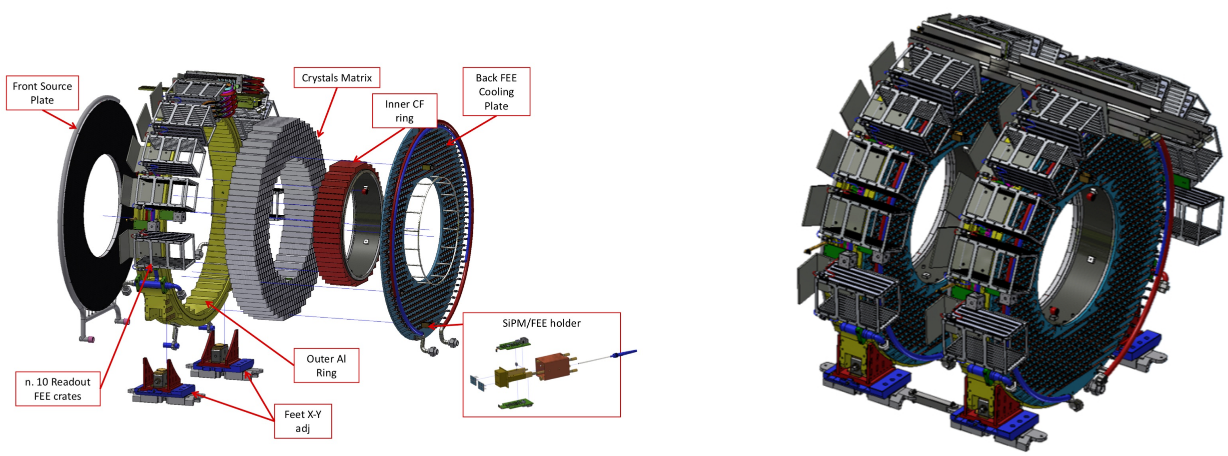

Figure 3: Exploded view of all the mechanical components and view of the two annuli on the detector train.

4.1 Crystal and SiPM production phase

The production of the basic calorimeter components (i.e. 1450 crystals and 4000 SiPMs) has started in 2018 and completed this year. While the SiPM prodution was concluded in 2019, the crystals took a little bit longer time. We had two different crystal producers, SICCAS (China) and St.Gobain (France) that were supposed to produce 50% of crystals/each. The situation was very different between the two selected producers: SICCAS produced all 725 crystals within May 2019, with only one month of delay compared to schedule, and the crystals were perfect both from an optical and dimensional point of view, complying to specifications. On the contrary, the St.Gobain crystals showed evident problems in dimensional precision. After alternating successes and failures, we retained only 400 crystals from St. Gobain, we close their contract and reassigned the production of the last 330 pieces to SICCAS, that successfully fulfilled the production during 2020.

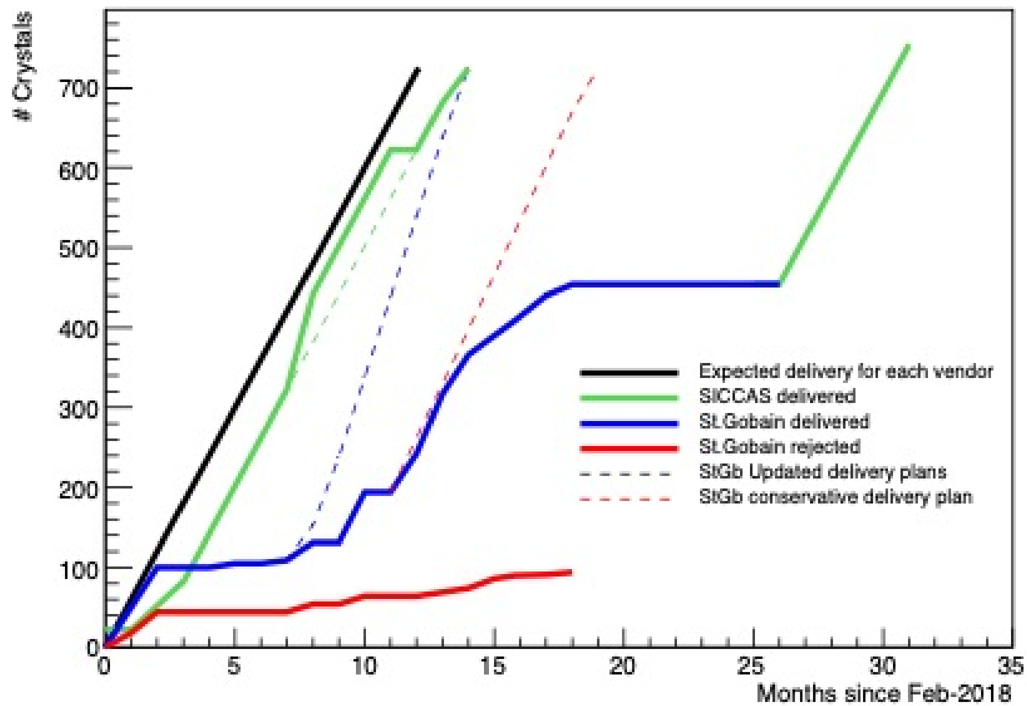

Figure 4: Crystal delivery.

Once at Fermilab, crystals were first of all subject to an optical survey, in order to check polishing and scratches on the surfaces, and to a dimensional measurement using a Dimensional Control Machine, to check the congruence of the thickness, length and shape within a tolerance of 100μm. All the crystals mechanical measurements are reported and summarized in Figure 5. All crystals have been completely characterized also for the optical parameters, as reported in Figure 4.

In 2020, we have started the gluing procedure of the SiPMs to the copper supports that were all produced at the end of 2019. Figure 8 shows the gluing of the SiPMs on the copper holder and the details of the mask for the gluing procedure. The gluing procedure was planned to be performed at Fermilab but, due to the pandemics, was moved to our laboratory at the National Laboratories of Frascati.

The last step of integration of the basic components consists on integrating also the FEE boards and testing the completed assembled unit. At the end of 2020, the first 60 FEE production chips were installed on 30 holders to verify the final gain after the gluing procedure: an automatic scan was performed using 9 progressive neutral density filters on a selector wheel: 10000 waveforms were acquired for each filter and successively integrated over a 200 ns gate.The reconstructed charge resolutions obtained in each position were used to evaluate the gain of the SiPMs+Fee. In Figure 9

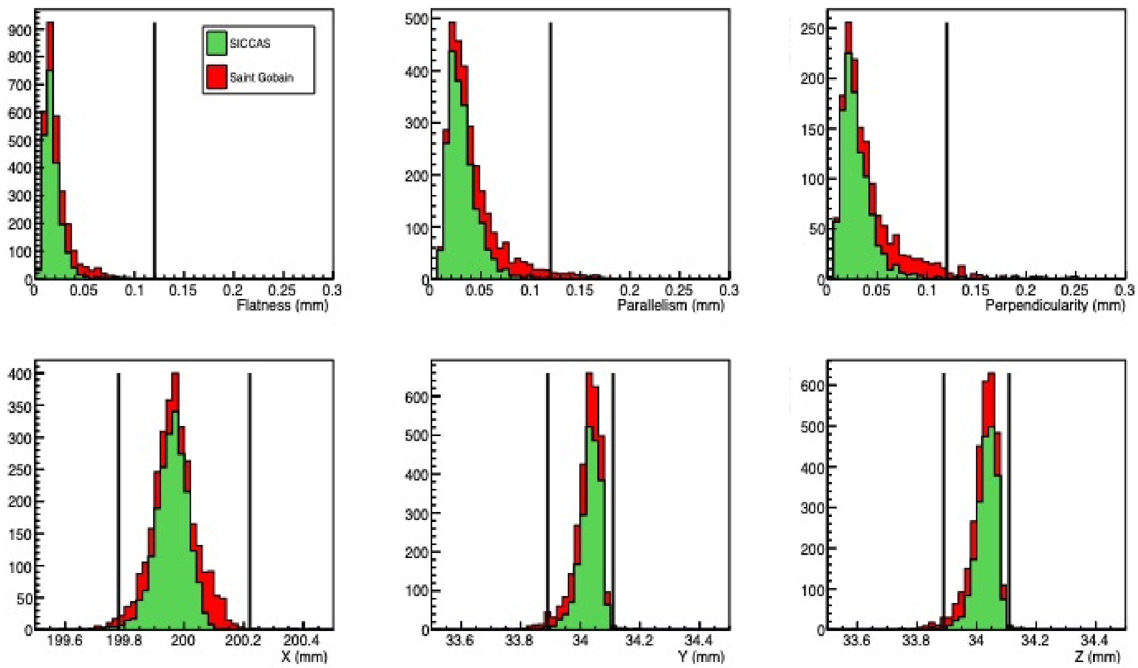

Figure 5: Crystals dimensional measurements performed with a CMM machine.

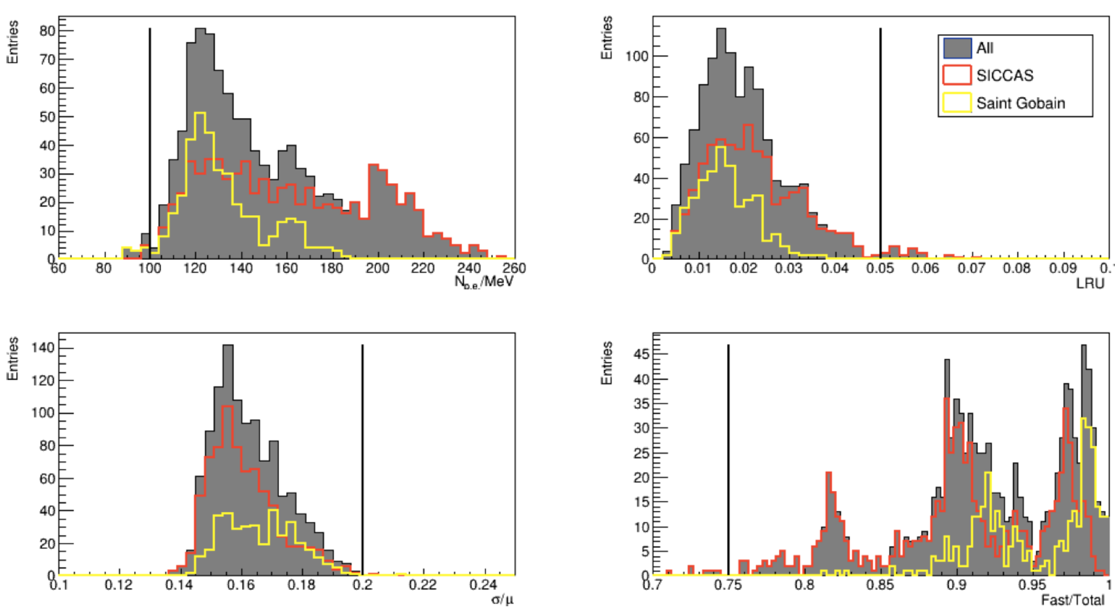

Figure 6: Crystals optical properties evaluated with 511 keV electrons form a ^{22}Na source scan on the longitudinal axis and a PMT readout.

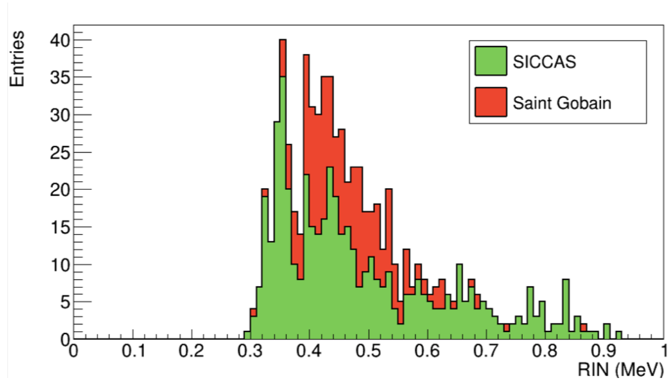

Figure 7: Crystals Radiation Induced Noise evaluated using a ^{60}Co source.

Figure 8: SiPM glued on copper holders. Gluing procedure details.

a summary of the gain obtained for each SiPMs tested is shown. The results is well in agreement with the Mu2e specifications and with the product of the expected gains.

4.2 Electronic boards production phase

During 2020, there have been a lot of progresses in the electronics design and production with the conclusion of the irradiation chain and of the design phase.

The Mu2e electronics chain is composed of two parts: the Front End Electronics (FEE) connected to the SiPM pins, and the control and digital part (MB+DIRAC) that is located in the custom crates surrounding the calorimeter support structure. The MB or mezzanine board is used to set the HV and monitor the slow control parameters of FEE in group of 20 channels. The MB also transfers the differential signals to the DIRAC (Digital Readout Card) that is the heart of the data transfer and digitalization and is connected to the TDAQ system via optical fibers. The FEE and MB components have been designed by the SEA of LNF, while the DIRAC has been designed from INFN Pisa. In the following, we discuss only the parts related to the LNF effort.

As reminded before, the FEE design was substantially modified during 2019 to make it rad-hard for total ionization doses (TID) up to 100 krad. This has been achieved by means of a long set

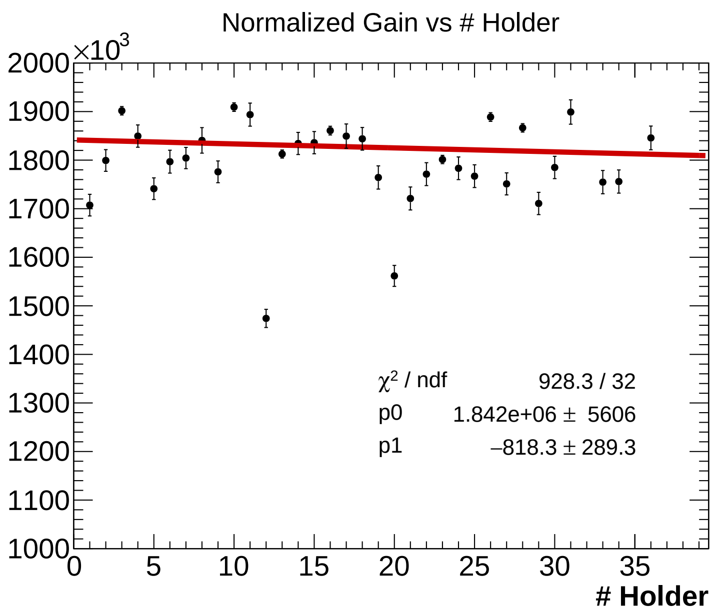

Figure 9: Summary plot for the gain test performed at LNF.

of irradiation campaigns started in June 2018 that helped on identifying the weakest components to TID. In particular, it has been needed to substitute the ADC/DAC chips located on the FEE to carry out the HV setting and the readout of HV, current and temperature. After the FEE CRR of November 2019, we have also completed the test of functionality in B-Field and further improved the radiation-hardness of the boards with some circuit improvement and with a dedicated test to the input MOSFETs. A first pre-production of 10 FEE boards, done in May 2020, has been used as pilot run for production and to certify the executive design by means of further irradiation tests in June and November 2020. Green light for production has been provided in October 2020 after having controlled the first 80 boards in a bench test and in the integration test with SiPMs in the holders described in the previous sub-section. The FEE production has started in November 2020 from the ARTEL firm. At the end of 2020, all PCB were produced without mounting the final components. End of production with components is expected for April 2021.

In the meantime, the SEA has also completed the final gerbers for the MB and produced the first 5 boards with final design that are going to be used on Module-0. These boards have also been tested for resistance to TIP at the Calliope facility in ENEA Casaccia, showing to retain a good functionality up to 30 krad. A first test in B-Field has been carried out at the end of 2020 at Fermilab. Unfortunately, the small dimension of the used dipole allowed to arrive to test the board only up to 5 kGauss. A new test will be performed in 2021, inserting the MB inside a large solenois where an axial field of 15 kGauss is available. The CRR for the MB is foreseen for May-June 2021 so that we expect production to start in summer 2021.

4.3 Construction of the mechanical components.

The completion of the Construction Readiness Review in 2019 has sanctioned the maturity of the design and the technological choices, together with the executable drawings, of all the mechanical components of the Mu2e calorimeter.

The detector is composed of two identical annuli with an Outer Radius of 1820 mm anInner

Radius of 336 mm and placed 700 mm apart along the Muon Beam line. As shown in Figure 3, each calorimeter annulus is composed of:

- an Outer monolithic stepped structural Al ring to house the parallelepiped crystals stack
- an inner Carbon Fiber and Al honeycomb mixture structural stepped ring;
- pair of feet with X-Y adjustment
- a Carbon Fiber and Al honeycomb front plate with an embedded pipes system for the flowing of a calibration radioactive fluorinert fluid;
- a PEEK back plate with apertures in correspondence of each crystal for the housing of the photosensors and their FEE electronics, with an embedded cooling circuit made of copper pipes;
- 10 digital electronic crates with a cooling serpentine connected to the main cooling pipes;
- 674 CsI crystals wrapped with Tyvek and black tedlar;
- 2 SiPM's and FEE electronics per crystal integrated in a copper holder and Faraday cage box (zoomed picture);
- a Laser calibration system.
- FEE cabling, HV/LV cabling and DAQ fibers

During 2020 we have identified and provided the manufacturing companies, that had the individual tenders assigned, with all the quoted drawings and kept interacting with them to assess and agree on the best construction techniques. At the end of 2020 most of the parts of the calorimeter were produced.

- have concluded the production of the 2 outer Al cylinders made of a monolithic Aluminum block to ensure maximum rigidity and resistance. The two component before the company delivery to INFN have been checked by INFN people with a CMM and we measured the respondence with the drawings and required tolerances.
- have concluded the construction of the FEE back plate, and also for these parts we have performed a Quality Assurance both checking the delicate geometry and leak and pressure testing the cooling circuit and the correct fitting of the SiPM holder in the plate apertures.
- have finalized all the construction details of the Carbon Fiber parts together with the company and the construction of the stepped inner cylinders has begun. The stepped margin will be a mixed sandwich of carbon fiber skins and Al honeycomb. Unfortunately the two Source plates where the source system piping will be embedded are cannot be completed because the pipes shipment from Fermilab went lost and our US colleagues had to start over their production.
- have purchased the raw material and identified the company for the construction of the calorimeter rings feet.
- have assigned the construction of the 2 crates that are housing MB+Dirac electroic boards together with the purchase of 160 copper shield that will also dissipate power from the electronics

- built all the components of the outgassing vessel

Towards the end of 2020 we shipped to FNAL a crate with several parts that were ready for delivery, i.e. one Al ring and all the outgassing equipment. Soon after some of us traveled to FNAL and started to assemble the parts in the Assembly hall at SiDet. Figures 10 show the Outer cylinder built and installed on the assembly stand in the SiDet assembly clean room at FNAL and the FEE plate being tested at the manufacturing company.

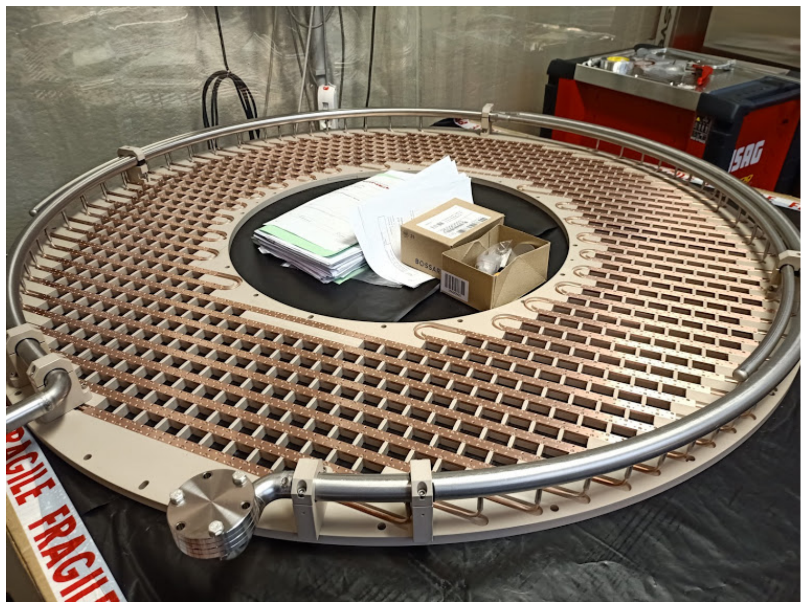

Figure 10: First Outer Cylinder installed on calorimeter assembly stand at SiDet. FEE plate.

5 Software and Data Analysis

During 2020 the Mu2e Italian group was also intensely committed to the software development, starting from TDAQ to reconstruction and analysis of the simulated data. Moreover, a major effort concerned the developing of calibration and reconstruction algorithms with full simulation and with data taken with the large size prototype of the calorimeter, dubbed Module-0.

5.1 Sensitivity Update 2020 (SU2020)

Due to the important changes in the schedule of the Mu2e data-taking phase and to the improved understanding of background sources and reconstruction, the collaboration decided to update the sensitivity evaluation for the two golden conversion processes, the $\mu^- \to e-$ (CLFV) and $\mu^- \to e+$ (CLFV+LNV).
An important goal achieved is related to the improvement of the calorimeter energy and timing resolution, obtained thanks to the intense work on our prototype and to the updated noise level estimation during the data-taking.

5.2 Montecarlo study of the IN-SITU Calibration procedures

Using a sample of 2×10^6 cosmic events (6 hours running equivalent), a trigger software algorithm was developed to better select well defined cosmic topologies useful for calibration purposes. Thanks to the fast clustering reconstruction algorithm 0.11 % of the events are selected with a mean processing time of 0.5 ms/events. The expected total rate dedicated to monitor and calibration during the data-taking is evaluated to be of ~ 20 Hz. In Figure 11 the four different topologies of calibration events with clusters of energies between 120 and 600 MeV are reported.

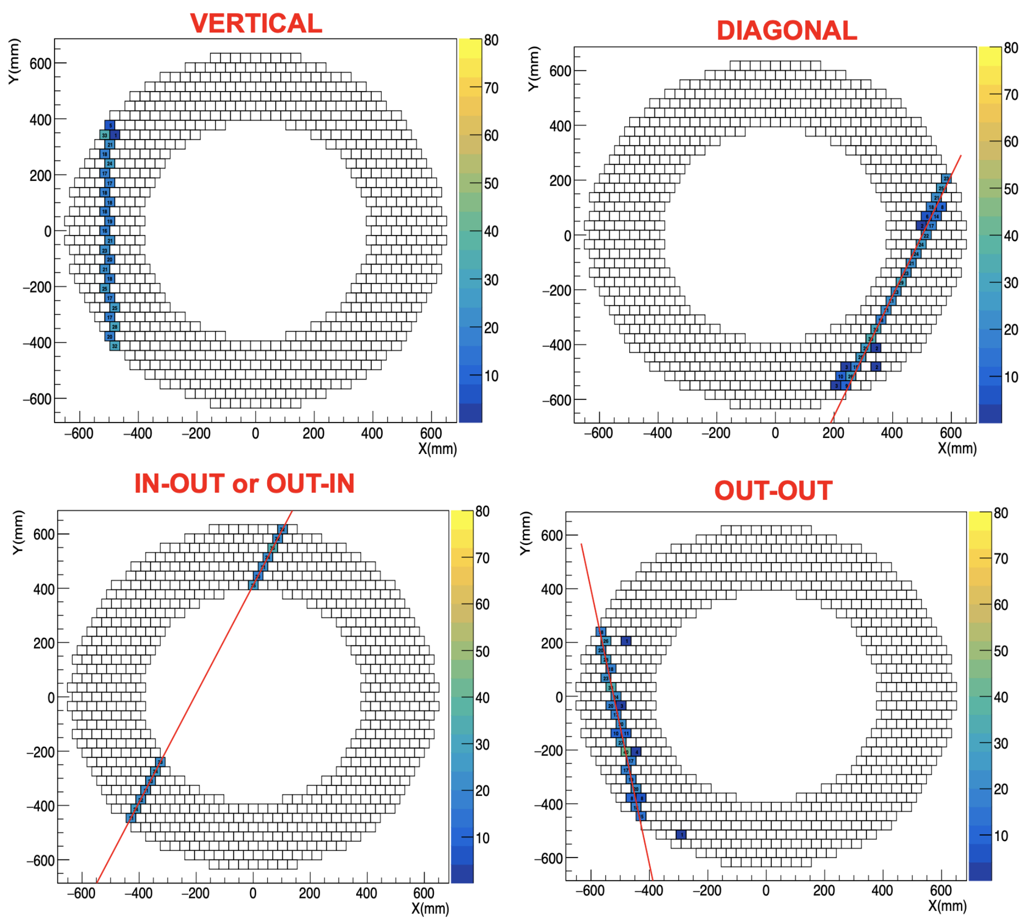

Figure 11: Four cosmic event topologies selected for monitoring and calibration purposes: Vertical (top left), Diagonal (top right),In-out (bottom left) and Out-out (bottom right).

5.3 Montecarlo study of Timing performances

The "golden" cosmic events previously selected have been used to define the timing and energy calibration of the calorimeter. In particular, for what concerns the determination of temporal offsets (T_0), an iterative procedure has been developed that allowed to obtain the timing residual with an error of ~ 10 ps after three repetitions. This calibration procedure is based on the minimization of the residuals obtained from a linear fit to the cosmic trajectories while imposing the speed of the light between the timing of the crossed cells. Moreover, from the calibrated timing difference

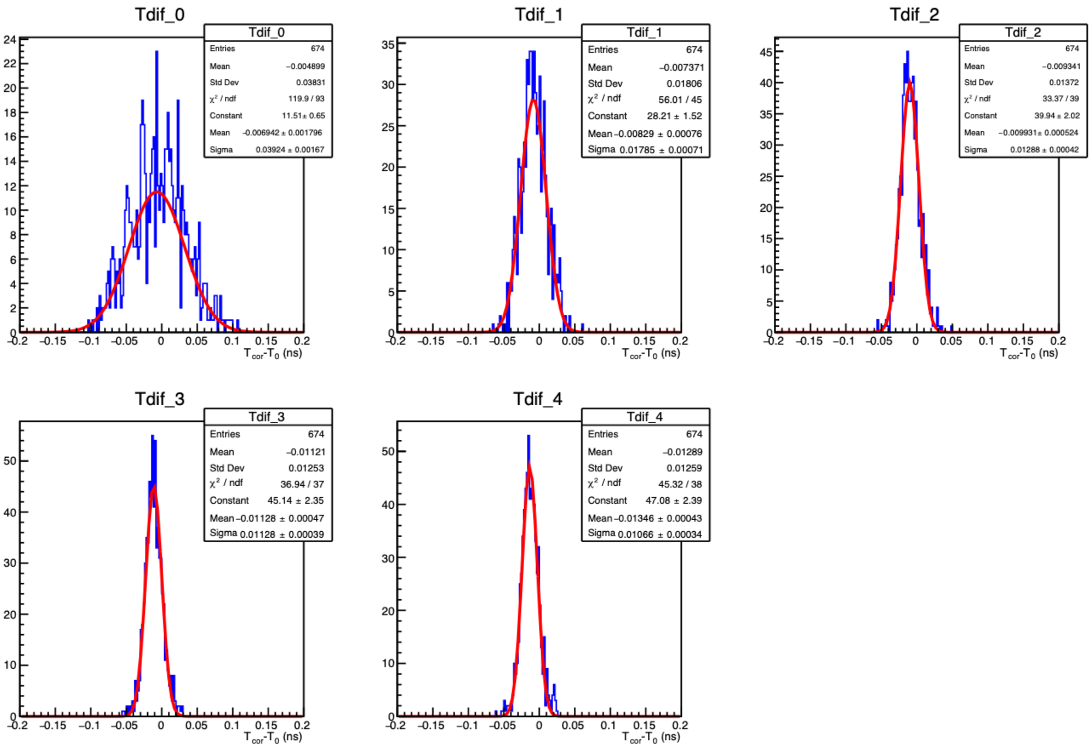

Figure 12: Timing residual of the different iterations.

it is possible to evaluate, event per event, the cosmic ray crossing angle along the crystal axis. By selecting particular configurations, we can trace back the impact position along the crystal axis and then study the energy and timing response as a function of the distance from the SiPM.

5.4 Radiative Muon Capture (RMC) studies

The RMC process can expressed as:

$$\mu^- + N(A,Z) \to \gamma\nu_\mu + N(A,Z-1) \tag{1}$$

Experimental results from previous experiments indicate the RMC endpoint (kmax) of the photon spectrum to be of $\sim$ 90 MeV. The latest evaluation of this process dates back to the end of 1990, with the results of the TRIUMF experiment based on $\sim$ 2000 events. During 2020, we determined, by simulation, the rate of this process in Mu2e and it resulted clear that in few days of data-taking we will be able to improve the knowledge of this process of a large factor (7×10^4 event/day with a dedicated trigger at few Hz rate). A precise modeling of this process is relevant for the Mu2e experiment due to the proximity of the photon spectrum endpoint (k_{max}) to the energy of the positron emitted in the $\Delta L = 2$ conversion process $\mu^- + N(A,Z) \to e^+ N(A,Z-2)$, the second important search for new physics that can be performed with the Mu2e experiment.

In Figure 13 the expected reconstructed energy spectrum surviving the dedicated analysis selection is shown after 0.38 s of data-taking. As shown, the contribution of the cosmics and machine background sources are completely negligible in the end-point region.

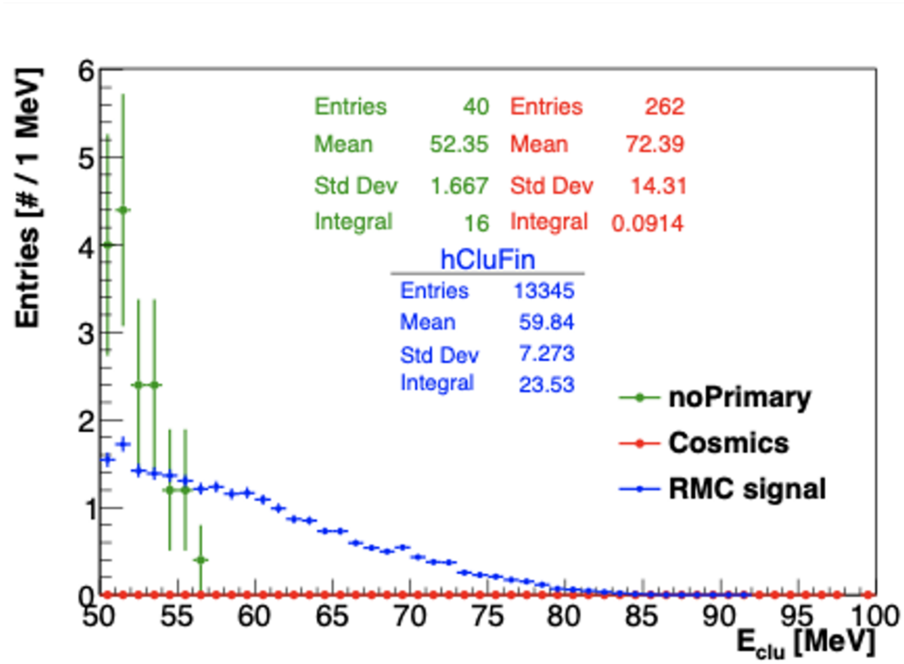

Figure 13: Energy spectrum of RMC photon (blue), CR (red) and machine background (green) after 0.38 seconds of data-taking.

5.5 Calibration studies with the Module-0

The Module-0 (built in 2017) was tested with an electron beam at BTF showing that the calorimeter design satisfies the Mu2e experimental requirements. In 2020, it allowed the LNF group to verify its response in an environment more similar to the working conditions, i.e. in vacuum between 10^{-2} and 10^{-4} Torr, at low temperatures (~ 0 °C) and with neutron irradiated sensors.

In winter 2020, several improvements were achieved on the grounding connections allowing to intensively study the achievable noise levels and thus making the Module-0 a perfect "tool" for the completion of a full-chain Vertical Slice Test (VST). Before performing the VST, we also updated the Module-0 layout to make it consistent with the latest calorimeter design changes: (i) a layer of Tedlar has been added to the crystal wrapping to prevent the optical cross-talk discovered at the test beam, (ii) the SiPMs (FEE) have been replaced with their final version and glued to the production copper holders and (iii) the FEE-MB cables and the Mezzanine Board were replaced with the production version. The updated version of the module-0 is shown in Figure 14. At the moment of writing, only 16 channels were acquired, for a total of 13 crystals, of which 3 were armed with a double readout. Indeed, due to the missing DIRAC board from PISA, we were forced to make up a dummy DIRAC board and readout the electronics signals by means of two commercial CAEN digitizers with a similar sampling (4 ns) to the final DIRAC board.

In Figure 15, the noise, evaluated as the reconstructed charge observed with a random trigger, is shown before and after the improvements previously described. The RMS of the charge distribution is reduced from the 4 pC observed in the initial configuration to 1 pC after the modifications. Moreover all non gaussian tails are removed.

To select clean minimum ionizing particles (MIPs) an external trigger based on the coincidence of the top and bottom scintillators (see the blue rectangles in Figure 14 (Left)) is used. To further improve the MiPs selection, a minimum energy deposit of 10 MeV is required in the first

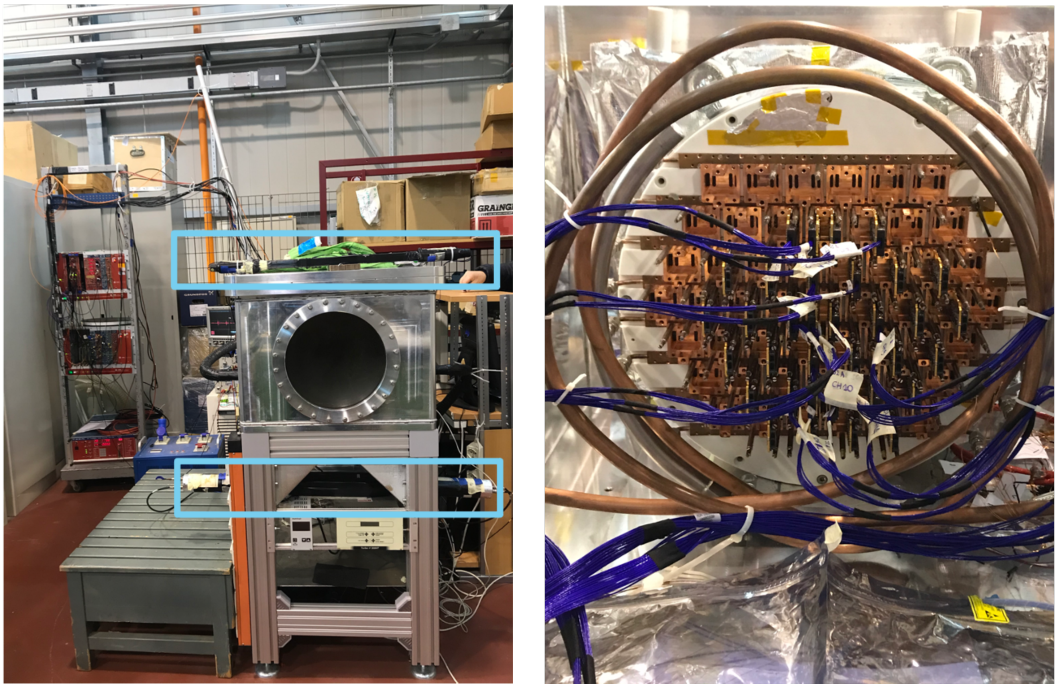

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Figure 14: Left: view of the experimental hall housing the cryostat containing the Module-0. Right: view of the Module-0 inside the cryostat.

and the last layers of the Module-0. An example of a MIP path inside the Module-0, as well as the energy distribution in one crystal, are reported in Figure 16. The energy distribution was fit with the convolution of a Landau and a Gaussian function.

In Figure 17 the timing distribution, evaluated as the difference between the timing of the two sensors coupled to the same crystal, as well as the timing resolution obtained using the time calibration procedure described in 5.3, are reported. A slight deterioration of the timing resolution with respect to test beam data is observed as due to the light loss of the Module-0 crystals related to the Tedlar wrapping.

Moreover, to further improve the trigger system, a Cosmic Ray Tagger (CRT) made of 16 $160 \times 1.5 \times 2.5$ cm^3 EJ-200 bars coupled at both end with a Mu2e-SiPM has been designed. A first rendering of this system can be seen in Figure 18. The CRT system is composed by units to be installed above and below the calorimeter disk under test, with the scintillator axes orthogonal to the crystal ones, in order to track the passage of MIPs throughout the entire calorimeter volume. This will allow also the reconstruction of the coordinate along the crystal axis.

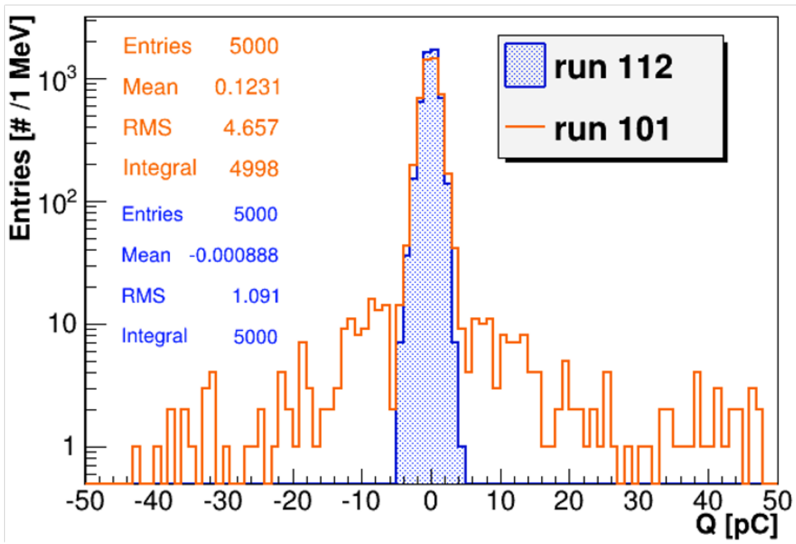

Figure 15: Noise charge distribution before (orange line) and after (blue line) the cables connection improvement

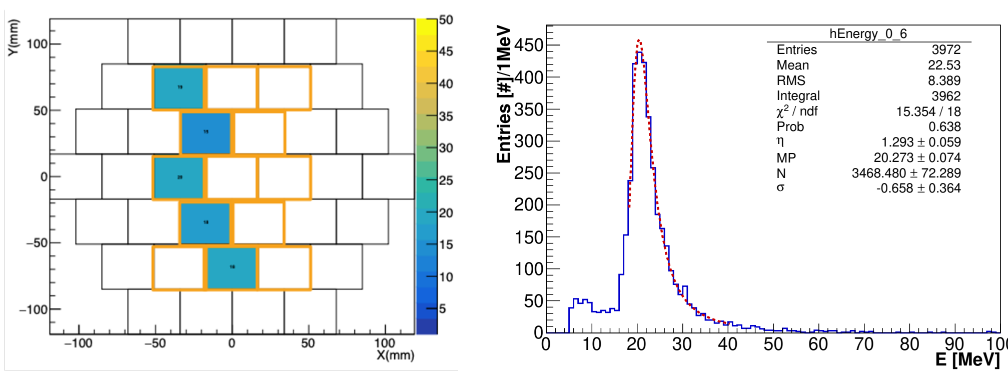

Figure 16: Left:Event display showing a vertical MIPs. Right:Energy spectrum of a MIP for a single readout channel

6 List of Conference talks by LNF authors in Year 2020

Talks:

1. R. Donghia, " Final design of the Mu2e crystal calorimeter",talk at INSTR20: Instrumentation for Colliding Beam Physics.
2. D. Paesani, "The Mu2e crystal calorimeter", talk at New Perspective 2020.
3. E. Diociaiuti, "The Mu2e experiment at Fermilab", invited talk at SIF National Congress 2020, online.
4. S. Giovannella," Final design, R& D and beginning of construction of the Mu2e crystal calorimeter, Virtual IEEE Nuclear Science Symposium and Medical Imaging Conference.

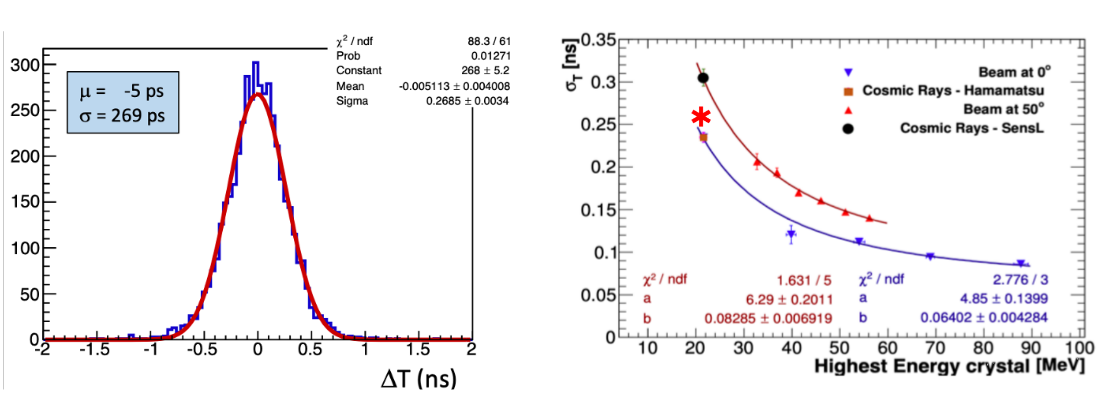

Figure 17: Left:ΔT of two adjacent SiPMs coupled to the same crystal. Right: timing resolution obtained with the Module-0 (red star) compared with the previous results at the test beam.

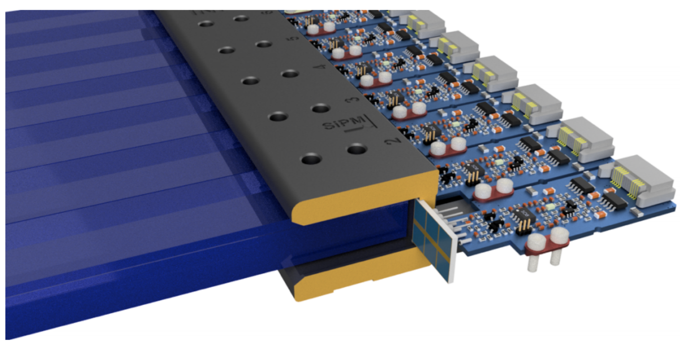

Figure 18: CAD rendering of a single module of the CRT system. The optical coupler block is shown for the readout system of single side

Publications:

1. N. Atanov, V. Baranov, C. Bloise, J. Budagov, F. Cervelli, F. Colao, M. Cordelli, M. Corradi, Y. I. Davydov and S. D. Falco, *et al.* "Construction status of the Mu2e crystal calorimeter," JINST **15**, no.09, C09035 (2020) doi:10.1088/1748-0221/15/09/C09035

2. N. Atanov, V. Baranov, J. Budagov, D. Caiulo, F. Cervelli, F. Colao, M. Cordelli, M. Corradi, Y. I. Davydov and S. D. Falco, *et al.* "The Mu2e e.m. Calorimeter: Crystals and SiPMs Production Status," IEEE Trans. Nucl. Sci. **67**, no.6, 978-982 (2020) doi:10.1109/TNS.2020.2988422

3. E. E. Pedreschi, F. Cervelli, S. Di Falco, S. Donati, L. Morescalchi, F. Raffaelli, F. Spinella, S. Ceravolo, G. Corradi and E. Diociaiuti, *et al.* "The Digitizer ReAdout Controller (DIRAC) of the Mu2e electromagnetic calorimeter at Fermilab," PoS **TWEPP2019**, 119 (2020) doi:10.22323/1.370.0119

4. S. Giovannella [Mu2e], "The Detectors of the Mu2e Experiment," JINST **15**, no.06, C06022 (2020) doi:10.1088/1748-0221/15/06/C06022 [arXiv:2002.03643 [physics.ins-det]].

5. N. Atanov, V. Baranov, C. Bloise, J. Budagov, F. Cervelli, S. Ceravolo, F. Colao, M. Cordelli, G. Corradi and Y. I. Davydov, *et al.* "Design and status of the Mu2e crystal calorimeter," Nucl. Instrum. Meth. A **958**, 162140 (2020) doi:10.1016/j.nima.2019.04.094

Theses:

1. E. Diociaiuti, "Study of the Mu2e sensitivity to $\mu^- \to e^+$ conversion process", PhD thesis at the Universitá degli Studi di Roma 2.

2. D. Paesani, "Design and characterisation of the CsI crystal calorimeter, Cosmic Ray Tagger and SiPM front-end electronics for the Mu2e experiment at Fermilab". Master Thesis at the Politecnico di Torino.