The MU2E experiment at Fermilab

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1 Introduction

The Mu2e experiment [1] searches for the conversion of a negative muon into an electron in the Coulomb field of a nucleus and it is an example of a Charged Lepton Flavour Violation (CLFV) process. This process is strongly suppressed in the Standard Model (SM), but many scenarios of new physics predict higher production rates close to the reaches of current or near future experiments. Any conversion signal will be a compelling evidence of new physics. The Mu2e goal is to achieve a single event sensitivity of 2.5 $\times 10^{-17}$, four orders of magnitude better than the best previous experiment. The design is driven by the need to suppress potential backgrounds while producing a high intensity, low energy, muon beam to provide 10^{18} stopped muons on target. A beam pulsed structure and a veto gate allow prompt beam background to die down in the first 750 ns, after which data are acquired to look for μ-atom decays. The Mu2e beam line consists of an evacuated inner bore (to 10^{-4} Torr) of a series of superconducting solenoids: Production Solenoid (PS), Transport solenoid (TS) and Detector solenoid (DS). The LNF group, together with INFN groups of Lecce and Pisa is in charge of the design, prototyping and construction of the electromagnetic calorimeter. The INFN group of Genova has designed and built a prototype for one of the TS modules and is now working on follow up the TS construction while providing a certification of all kind of superconducting cables.

During 2015, we have reached four important steps both for the Mu2e experiment schedule and for the visibility of the INFN contribution inside the project: (1) The CD3-b has been obtained in April 2015 both for the civil construction and for the construction of the PS, DS and TS magnets. The ground-breaking ceremony for the experiment has also been held on April. (2) During summer 2015, the TS magnet prototype done by INFN Genova in collaboration with ASG Superconducting and Fermilab has been successfully tested. In October, the international bid for the construction of the whole TS magnet has been assigned to ASG superconducting recognising the relevance of the prototyping work done. (3) The CSN1 has evaluated the participation of the INFN groups to the experiment and has granted its approval for the construction of the electromagnetic calorimeter that is being designed under LNF leadership. The technology choice has been changed along the time. At CD-1, the baseline choice was LYSO, a very performing scintillating crystal emitting at 420 nm that we have intensively used also for the construction of the LET and CCALT calorimeter in KLOE-2. Due to the large increase of its cost in 2013, we have opted for other, less performing, cheaper, candidates such as BaF_2 (emitting at 220 nm) or pure CsI (emitting at 310 nm). For the calorimeter construction, an overall envelope of 2.7 (3) MEuro core has been approved by the CSN1 and INFN depending upon if CsI (BaF_2) will be selected. (4) A Technology Choice Review has been held on July to discriminate between the two scintillator options. As result of this review, a Mu2e management meeting in December 2015 has opted for the most conservative option, un-doped CsI, that satisfies requirements while presenting less risks.

The Mu2e calorimeter design is now being finalised and engineered. At the moment of writing, the detector is composed of around 1400 un-doped CsI crystals, 34x34x200 mm^3, each one readout by means of two large area, 12x18 mm^2, UV extended Silicon Photomultipliers (SIPM).

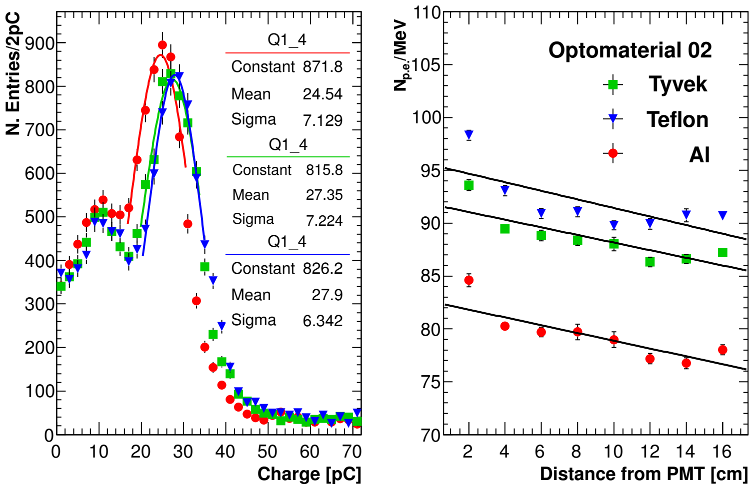

Figure 1: *Study of light yield in pC (left) and longitudinal response uniformity (right) for one Optomaterial crystal as a function of different materials used for wrapping. Results are shown for the case of air-gap optical coupling between crystal and a UV sensitive PMT. Response is to the 511 keV γ from a Na^{22} test source.*

In order to complete the above mentioned technical choice, during 2015 we have carried out a long list of R&D items, most of them under the responsibility or guide of the LNF group. In this report, we summarise the most important studies and measurements done for the characterisation of un-doped CsI crystals and SIPMs. A parallel effort has also been done to understand the BaF_2 option, but, in order to keep this report short, here we will omit the description of such a work . The R&D is logically divided in four items that are described in the following four subsections: 1) test of un-doped CsI crystals with PMT and SIPM readout; 2) construction of a 3x3 CsI matrix with SIPM readout and result at an electron test beam; 3) irradiation of crystals with neutrons and dose and 4) irradiation of SIPMs with neutrons and dose. We will conclude this report showing also the progresses achieved on the engineering design.

2 Test of CsI crystals with PMT and SIPM readout

BaF_2 and un-doped CsI crystals from different producers have been tested by the Mu2e group during 2015 in preparation for the final technology choice. While most of the BaF_2 tests have been carried out from our Caltech colleagues, LNF has taken the leadership in the test of un-doped CsI crystals. In our crystal laboratory, we have tested 2 BaF_2 crystals from INCROM, Russia, and 16 un-doped CsI crystals from SICCAS (China), Optomaterial (Italy) and ISMA (Ukraine). All of them have been tested at our crystal test station where a reference Na^{22} source was illuminating both the crystal under test (DUT) and a tag system provided by a small 3x3x6 mm^3 LYSO crystal readout with a 3x3 mm^3 MPPC. The 511 keV annihilation photon was providing our test probe. The DUT was readout by means of a UV extended PMT from EMI. Optical contact with the PMT was done either with an air-gap or via a Silicon Paste that had a very high transmittance at the mean CsI emission wavelength of 310 nm. The light yield reported in these plots have been obtained integrating the signal shape in a fix window of 200 ns around the pulse height maximum.

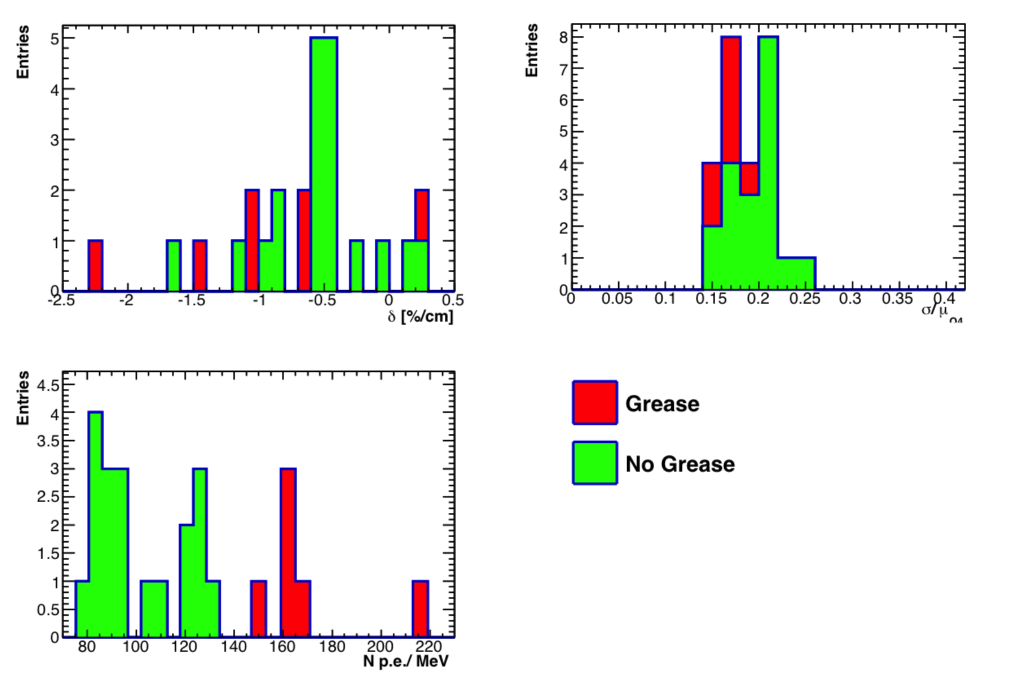

Figure 2: *Summary of the measurement performed at the crystal test station for un-doped CsI crystals: (Top-left) Distribution of the LRU slope, (top-right), distribution of the energy resolution at 511 keV, (bottom-left) distribution of the LY. Green (red) colours are for crystals measured with air-gap (silicon paste).*

This integration takes into account most of the fast emission component that has a τ of $\sim$ 30 ns. Measurements on the slow emission component in the μsec range are in progress at the moment of writing. A longer description of the measurements performed on the crystals can be found in a Mu2e note [2] and in a NIM paper [3]. In this report, we show only the basic results.

In Fig. 1, we show the effect of the wrapping. The left plot shows the charge distribution for a 511 keV photon of an Optomaterial crystal in 3 different wrapping configurations: a) 4 layers of 25 μm Teflon, b) 150 μm of Tyvek or c) simple 100 μm Aluminum. In the right plot the average of the response as a function of the source position along the crystal axis is also shown. We refer to the spread along the axis as *Longitudinal Response Uniformity* or LRU. The number used for its characterisation is the slope of a linear fit. It is clear that Teflon and Tyvek provide better light collection than aluminium, with Teflon collecting few % more light than Tyvek. LRU looks similar in all cases. Other considerations regarding the quality and the simplicity of the wrapping method pushed us for finally selecting Tyvek as the best option. In Fig. 2, we show a collection of summary plots for the 16 CsI crystals measured. In the Top-left plot, the LRU distribution is shown. The LRU slope average, for air-gap coupling, is close to 0.5%/cm i.e. a spread of $\pm$ 5% for a 20 cm long crystal, that is perfectly acceptable. A much wider spread is observed for coupling with optical grease that increases the fraction of direct light collected along the axis. In the Top-right plot, the distribution of energy resolution at 511 keV is shown. The average is 20% (16%) for the air-gap (grease) coupling. Finally in the Bottom-left plot the distribution of the light yield is shown. Consistently with the resolution measurement, the grease-coupling method

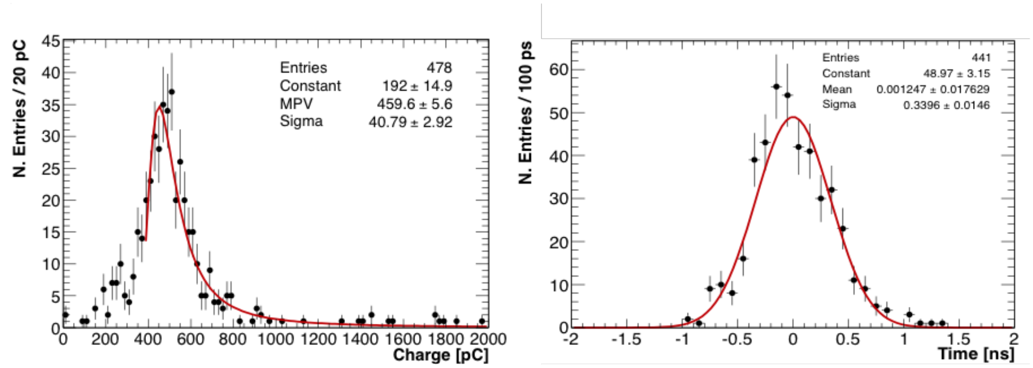

Figure 3: *Distribution of the response to minimum ionising particles selected with a cosmic ray trigger for (left) energy and (right) timing variables.*

presents 50-60% hight light yield. The light yield average stays between 80 to 130 pe/MeV for the air-gap case. Large spread among producers is observed. A tight specification on this variable will be asked for pre-production and production Quality Assurance.

A long series of test using minimum ionising particles have been also carried out by selecting cosmic rays with a pair of thin scintillating counters. In this way the DUT was tested at an equivalent energy deposition of 18-20 MeV. The crystal were readout with different generation of MPPCs to study the response and the timing. During 2015, Hamamatsu has released a first version of UV extended MPPCs with a Silicon Protection Layer (SPL) or a MicroFilm (MF) technique that have replaced the standard epoxy coverage of the silicon substrate thus increasing the particle detection efficiency (PDE) at lower wavelength. Indeed, the PDE at the wavelength of interest (310 nm) increases from 5-10% to 30-40%. We have selected an MPPC array of 16 3x3 mm^2 cells, with 50 μm pixel, corresponding to an active area of 12x12 mm^2 and TSV (Through Silicon Vias) technique. The increase in PDE has been experimentally proven by comparing the timing resolution obtained coupling, to the same CsI crystal, the UV extended and the standard MPPCs. Differences in time resolution up to a factor of 2.5 have been observed. In Fig. 3, we report the distribution of energy (left) and timing (right) response for the new UV extended MPPC. Timing resolution is consistent with 330 ps/MIP (280 ps/MIP) without (with) subtraction of the trigger jitter.

3 Test beam of a 3x3 CsI array

A 3$\times$3 array of un-doped CsI crystals (of 30x30x200 mm^2 dimension) readout by means of 12x12 mm^2 UV extended TSV SLP MPPCs have been assembled at LNF and then tested at BTF with an electron beam in the energy range from 80 to 120 MeV. A full description of the work done can be found elsewhere [4]. A light yield of $\sim$ 30 pe/MeV has been measured thus translating in a negligible noise level for the detector (50 keV/channel, 150 keV/array) and in a negligible contribution of the stochastic term at 100 MeV for the energy resolution. The large amplification of the MPPCs allows as planned for large pulse heights and fast rise time that imply a precise time resolution.

An energy resolution of $\sim$ 7% and a time resolution of 110 ps (see Fig.4.right) have been achieved for 100 MeV electrons impinging perpendicularly to the calorimeter surface. For the energy resolution, the result is still dominated by a very large beam-spread and a large energy

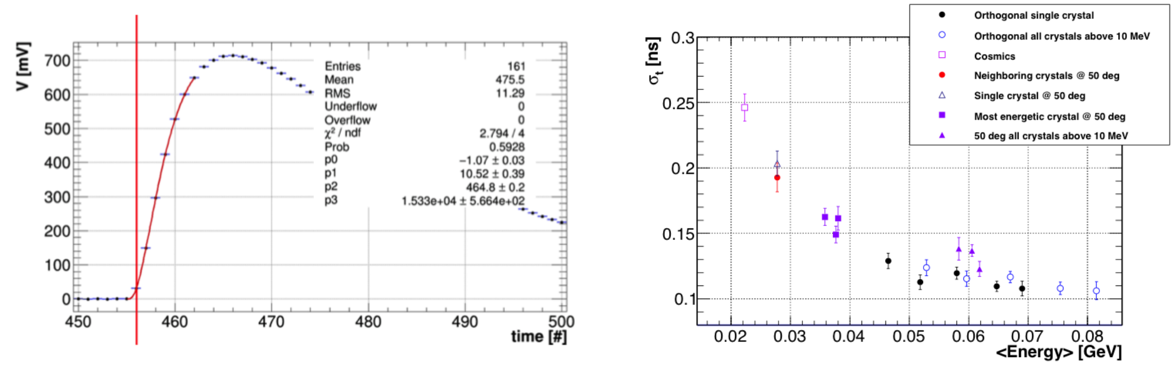

Figure 4: *Test beam results for the 3x3 CsI array readout with MPPC: (left) example of a fit to the waveform to extract the start time, (right) dependence of the timing resolution as a function of the beam energy.*

leakage. On paper, resolution up to 3-4 % are still achievable. For the timing, the excellent result found is related to to the improved reconstruction method used for the timing. Differently from what used (and published) for the LYSO case, we are now fitting only the leading edge and not the whole signal shape. This is shown in the example of the digitised signal shape for one event in Fig.4.left. The digitisation sampling used was 4 ns (250 Msps). An optimisation with respect to the Constant Fraction threshold used has also been carried out. The Geant-4 based simulation well reproduces the observed energy distribution while a simulation of the timing response is still in progress. To test a geometrical configuration more similar to the experiment one, the dependence of response and resolution has been tested also as a function of the impinging angle at 50°. The energy resolution increases up to 10.6% as expected by the simulation being dominated by energy leakage. The timing resolution increases no more than 20% from 110 to 130 ps at 100 MeV.

These test beam results have shown that the CsI+MPPC configuration well satisfies the Mu2e calorimeter requirements while granting flexibility for the possible running options. Indeed, another gain factor of two in light yield is expected by using a double MPPC readout/crystal so that the options of coupling crystal photosensor optical with air-gap as well as operating at voltages slightly below Vop are realistic ones.

4 Irradiation test of CsI

During 2015, a long irradiation campaign for crystals have been carried out in USA and Italy to understand the radiation hardness of the two kinds of crystal under test. Experiment requirements from Mu2e [5)] simulation are that the crystals in the hot areas will be exposed, in 3 years of running, to a dose of 100 krad and a fluency of 10^{12} n/cm^2, taking into account also a factor of 3 (2) of safety for dose (fluency) respectively. The dose study was mostly based in USA at Caltech while in Italy, we just confirmed the response losses for CsI crystals at Calliope (ENEA Casaccia) while instead leading the irradiation with neutrons at FNG (Frascati Neutron Generator) of ENEA Frascati. Both BaF_2 and CsI are radiation hard for the scope of Mu2e experiment, with the first crystal kind (BaF_2) loosing up to 50% of the light yield at 100 krad and then becoming rad hard up to 10 Mrad while the second crystal (CsI) loosing only 10-20% of the light at 100 krad but keep dropping response linearly at higher doses. The neutron irradiation seems to be less effective on these crystals as described in full details in [6)]. In Fig. 5, the distribution of the LRU for

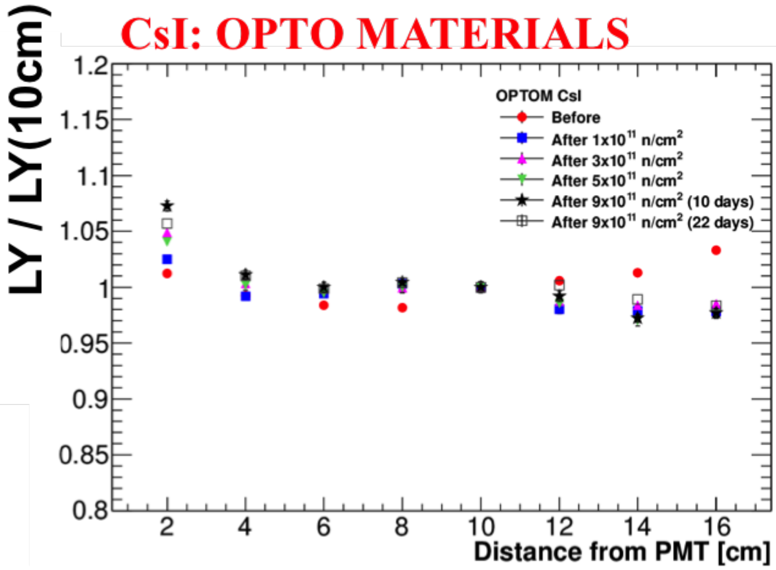

Figure 5: *Distribution of the response for an Optomaterial crystal normalised to the crystal center, and as a function of source position, before, during and after the irradiation campaign with neutrons.*

an Optomaterial crystals during, and after, the irradiation campaign with neutrons is shown. No relevant deterioration of the uniformity are observed after a period of annealing of 10-22 days is waited for. The response remained consistent with the one pre-irradiation at a level better than 10% on all points. Average light yield decreases not more than 8%.

5 Irradiation test of SIPM

Due to the large dose and high neutron flux expected in the experiment lifetime, one of the crucial parameters for the photo-sensor choice is their radiation hardness. Our simulation indicates that, in the hottest area, a fluency of 6 $\times 10^{10}$ $n_{1\mathrm{MeV}}/\mathrm{cm}^2$/year and a dose of few krad will occur. The derived safety requirement is to have photosensors working up to $3\mathrm{x}10^{11} n_{1\mathrm{MeV}}/\mathrm{cm}^2$ and 20 krad. Therefore, during 2015, we have investigated the radiation damage induced on SiPMs. Similarly to the crystal case, the irradiation campaign has been carried out at FNG and Calliope. We have irradiated and tested: (i) 16 cells array for SPL and MF Hamamatsu SIPMs (see Fig. 6.top.left) and (ii) 6x6 mm^2 UV extended SIPMs from FBK (Fig.6.top.right). We have measured both the leakage current increase and the response drop by biasing two of the sixteen cells of the Hamamatsu arrays. One cell has been used to read the dark current with a pico ammeter while the second one has been illuminated with a UV light at 350 nm. The light was provided by a UV LED by means of a two-ways optical fiber splitter. One of the two split fibers was positioned in front of the SIPM under test and the SIPM signal used for determining the gain drop. The second split fiber was used as stability monitor of the LED light and sent to a reference PMTs positioned far away from the irradiation source. The dose related damage resulted to be negligible when irradiating these sensors up to 20 krad. A leakage current increase smaller than a factor of 2 and a negligible response drop were also observed. On the other hand, the irradiation with neutron created much more problems on the photosensors. A neutron fluency of 4×10^{11} $n_{1\mathrm{MeV}}/\mathrm{cm}^2$ induced an increment

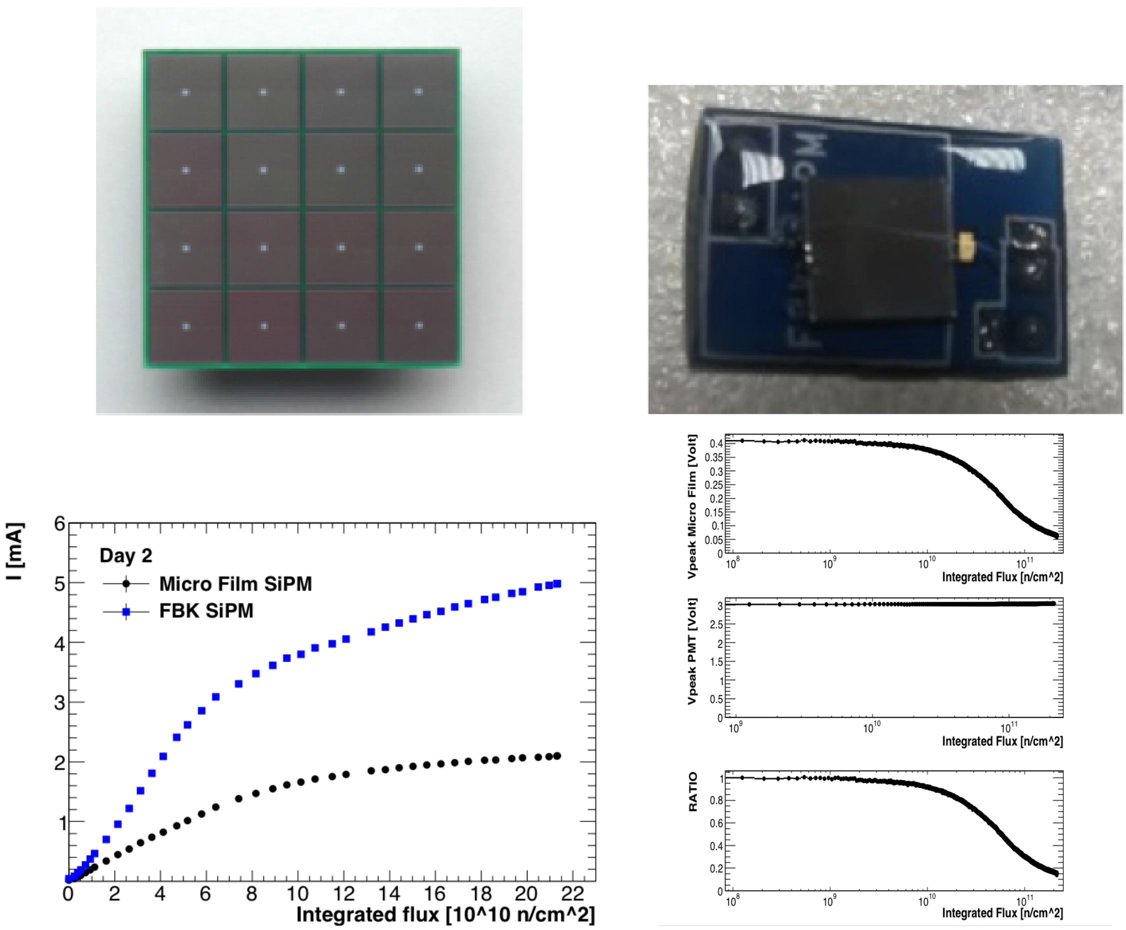

Figure 6: *Irradiation of SIPMs: (Top-left) MF MPPC array. (Top-right) FBK SIPM. (Bottom) Dependance of SIPM parameters as a function of integrated neutron flux for: (left) MF Hamamatsu and FBK SIPMs, (right) the bottom plot indicates the drop in response for the MF SIPM.*

of a factor 2 $\times 10^4$ on the leakage current (see Fig.6.bottom.left) and a factor of 8 reduction on the gain response (see Fig.6.bottom.right) on the SPL/MF SIPMs. The gain response drop has been obtained as the ratio between the SIPM and the reference PMT responses. The leakage current increase for the FBK detector is also shown in Fig.6.bottom.left. and resulted to be twice worse than that of the Hamamatsu case. Few days of annealing reduced the leakage current of a factor of 2. The leakage current expected after irradiation is at the level of several mA and cannot be tolerated for the 2800 calorimeter channels so that we have investigated the dependance of Idark and Gain from the SIPM temperature and bias. At the end, we have demonstrated that we can safely operate these devices, in the Mu2e environment, by keeping them at a temperature of 0 °C and -0.5 V of under bias.

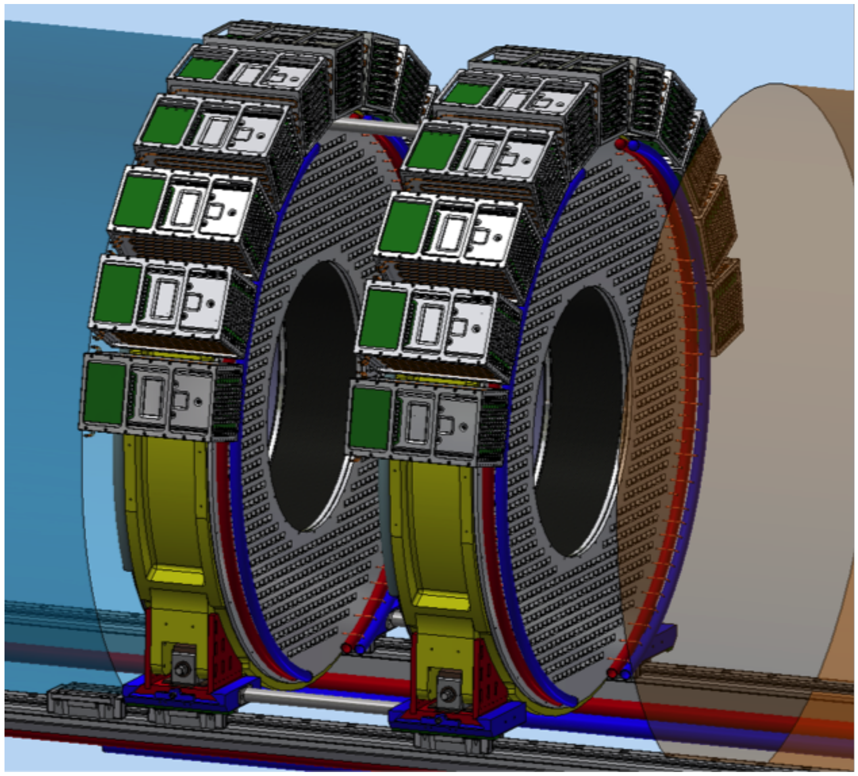

Figure 7: *Final mechanical design.*

6 Engineering of the mechanical design

In 2015, we have also consolidated the engineering design of the calorimeter mechanical structure and have almost completed its integration in the experiment. The Mu2e calorimeter consists of two disks sitting on the experiment rails system. Each disk has a donut shape. It is composed by an external aluminium structural cylinder, connected to the rails through two feet; an inner cylinder made of light composite material to reduce the amount of passive material crossed by incoming electrons; a frontal plate made of light composite material; a rear plate that has the function of housing the FrontEnd electronics and photosensor. The back plate will be connected to the cooling system to extract the heat dissipated by the FrontEnd Electronics. Around each of the outer cylinders, the digitizer system and the HV regulator boards will be arranged in 11 crates, each one containing 8 electronic boards (20 channel granularity each). In Figures 7 the final drawings of the system are shown. The biggest change with respect to the previous design is that now the rear plate has also the role of photosensor cooling system to bring the SIPM at the needed running temperature. In order to do this, we are designing a tracking independent cooling station that will provide the right calorimeter coolant circulated directly in dedicated channels created inside the rear disk. The photosensors will be coupled with air-gap to the crystals in order not to cool down also the full mass of the calorimeter at 0 °C. A full-scale mockup of the system is under way.

7 Acknowledgments

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8 List of Conference Talks/prices by LNF Authors in Year 2013

1. S.R. Soleti, "Characterization of a prototype for the electromagnetic calorimeter of the Mu2e experiment", IFAE-2015, Roma, April 2015.
2. S.Miscetti, "Design and status of the Mu2e electromagnetic calorimeter", plenary talk at Frontier detectors for frontier physics, Elba's Island, May 2015.
3. S.Giovannella, "Energy and time resolution of a LYSO matrix prototype for the Mu2e experiment", poster session at Frontier Detector for Frontier Physics, Elba's Island, May 2015.
4. R. Donghia, "Characterization and performances of pure CsI crystals for the Mu2e experiment", poster session at Frontier Detector for Frontier Physics, Elba's Island, May 2015. **Awarded Price as Best Poster for Young Students.**
5. I. Sarra, " Characterization of a 5x5 LYSO matrix calorimeter prototype", Scint 2015, Berkley, CA, June 2015.
6. S. Miscetti, " The Mu2e experiment", Seminario su invito at Universita' di Roma "La Sapienza", June 2015.
7. F. Happacher, "L'esperimento Mu2e al Fermilab", plenary talk at SIF-2015, Roma, September 2015
8. R. Donghia, "Studio di un calorimetro a cristalli di CsI puro letto con MPPC di grande area per l?esperimento Mu2e", student contribution at SIF-2015, Roma, September 2015
9. I. Sarra, "**Awarded the SIF Fellowship Ettore Pancini for young researchers**", SIF-2015, Roma, September 2015
10. S.Miscetti, " Design and status of the Mu2e experiment", Flavour changing and Conserving Processes 2015, Capri's Island, September 2015.

9 List of Note/Papers/Proceedings

1. S.R. Soleti, "Characterization of a prototype for the electromagnetic calorimeter of the Mu2e experiment", proceedings IFAE-2015, accepted on Nuovo Cim. C (to be pubblished in 2016).
2. S.R. Soleti, "Determination of energy resolution for a LYSO crystal matrix prototype for the Mu2e experiment", Mu2e DocDB 5130-v1, FERMILAB-MASTERS-2015-01
3. N.Atanov *et al.*, " Design and status of the Mu2e electromagnetic calorimeter", Nucl. Instrum. Meth. A, DOI: http://dx.doi.org/10.1016/j.nima.2015.09.074
4. M.Angelucci ıet al., " Longitudinal uniformity, time performances and irradiation test of pure CsI crystals", Nucl. Instrum. Meth. A, DOI: http://dx.doi.org/10.1016/j.nima.2015.11.042
5. N.Atanov *et al.*, "Energy and time resolution of a LYSO matrix prototype for the Mu2e experiment", Nucl. Instrum. Meth. A, DOI: http://dx.doi.org/10.1016/j.nima.2015.09.051

6. S.Miscetti on behalf of the Mu2e collaboration, “Design and status of the Mu2e experiment”, Proceedings for FCCP-2015, submitted to EPJ-C.

7. N.Atanov *et al.*, “Characterization of a 5x5 LYSO matrix calorimeter prototype”, Proceedings for Scint-2015, submitted to IEEE.

8. N.Atanov *et al.*, “Measurement of the time resolution of the Mu2e LYSO calorimeter prototype”, Nucl. Instrum. Meth. A 812 (2016) 104, DOI: http://dx.doi.org/10.1016/j.nima.2015.12.055.

9. V.Baranov *et al.*, “Determination of energy resolution for a LYSO crystal matrix prototype for the Mu2e experiment”, Mu2e-doc-5538, maggio 2015.

10. M.Cordelli ,*et al.* “Irradiation tests with ionization dose and neutrons for undoped CsI and BaF2 crystals”, Mu2e-doc-5800, luglio 2015.

11. O.Atanova *et al.* ‘Experimental test of an un-doped CsI+MPPC calorimeter prototype with electron beam in the energy range 80 to 140 MeV”, Mu2e-doc-5816, luglio 2015.

12. M.Cordelli *et al.* “Study of light yield and longitudinal uniformity of pure CsI and BaF2 crystals tested with Na22 radioactive source”, Mu2e-doc-5817, luglio 2015.

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1. The Mu2e Collaboration, “The Mu2e Technical Design Report”, Fermilab-TM-2594, arXiv:1501.05241, (2014)

2. M.Cordelli *et al.* “Study of light yield and longitudinal uniformity of pure CsI and BaF2 crystals tested with Na22 radioactive source”, Mu2e-doc-5817, luglio 2015.

3. M.Angelucci ıet al., “ Longitudinal uniformity, time performances and irradiation test of pure CsI crystals”, Nucl. Instrum. Meth. A, DOI: http://dx.doi.org/10.1016/j.nima.2015.11.042

4. O.Atanova *et al.* ‘Experimental test of an un-doped CsI+MPPC calorimeter prototype with electron beam in the energy range 80 to 140 MeV”, Mu2e-doc-5816, luglio 2015.

5. B.Echenard *et al.* “Study of the radiation dose and neutron flux on the calorimeter”, Mu2e-doc-2853, luglio 2015.

6. M.Cordelli *et al.* “Irradiation tests with ionization dose and neutrons for undoped CsI and BaF2 crystals”, Mu2e-doc-5800, luglio 2015.