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# Design and test of the Mu2e undoped CsI + SiPM crystal calorimeter

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## ABSTRACT

The Mu2e experiment at Fermilab will search for the charged-lepton flavor violating neutrino-less conversion of a negative muon into an electron in the field of an aluminum nucleus. The calorimeter plays an important role in providing a fast trigger filter, excellent particle identification and a seeding for track reconstruction. Its requirements are to provide an energy (timing) resolution better than 10% (0.5 ns) and a position resolution below 1 cm, for 100 MeV electrons. The calorimeter consists of two disks, each one made of 674 un-doped CsI crystals readout by two large area arrays of $2 \times 3$ UV-extended SiPMs of $6 \times 6$ mm$^2$ dimensions. A large scale prototype (Module-0) has been constructed and tested with an electron beam in the energy range between 60 and 120 MeV at the BTF of Frascati National Laboratories. Results demonstrated that this calorimeter satisfies the Mu2e requirements.

**Contents**

## 1. Introduction

The calorimeter of the Mu2e experiment [1] is designed to achieve an energy resolution better than 10% and a time resolution below 0.5 ns, for the 104.97 MeV electrons coming from the muon to electron conversion process. After a long R&D phase [2,3], the baseline calorimeter design consists of two disks of 674 un-doped CsI crystals readout by two

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large area UV-extended Silicon Photomultipliers (SiPMs) [4]. The Front End (FEE) amplification and HV regulator chips are connected to the SiPM pins while the digization of the signals are carried out by custom boards located in nearby crates. A radioactive source systems and a laser system allow to set the energy scale and monitor the fast changes of response and resolution. Several tests have been performed on single components and on a large scale calorimeter prototype (Module-0) to confirm that the chosen design satisfies the Mu2e requirements. In the following, we summarize the qualification tests carried out during the pre-production phase to select the vendors of crystals and sensors and we then discuss the realization and test of Module-0. At the moment of writing, the production of components is also started. A summary of the methods and results obtained so far for the production can be found in [5].

## 2. Pre-production of CsI crystals and Mu2e SiPMs

During 2016, we received 72 square cross section crystals of $34 \times 34 \times 200$ mm$^3$ dimensions from three different vendors: Saint Gobain, Siccas, Amcrys. A dedicated Quality Assurance process was carried out to evaluate the crystals characteristics. The scintillation properties were evaluated with a $^{22}$Na source, which emits back-to-back 511 keV photons, by coupling the crystals in air to a UV-extended PMT [6]. The collected light yield (LY) exceeded the specifications of LY>100 photolectrons/MeV. The Longitudinal Response Uniformity (LRU), defined as the RMS of the LY measured in 8 different positions along the crystal axis, was required to be smaller than 5%. All the crystals satisfied this requirement, except four Siccas and one St.Gobain crystals. The energy resolution at 511 keV was in average of 14.5% well within the 19% requirement. Finally, the ratio (F/T) between the response to the fast (F) light emission component (at ∼ 315 nm wavelength) over the total light (T) had to be better than 75%. Most of the crystals satisfied this specification apart some of the Amcrys crystals. All crystals demonstrated a good radiation hardness up to a dose of 100 krad. St.Gobain and Siccas were chosen as vendors for the crystals production, due to Amcrys F/T measurements.

A Mu2e-SiPM is defined as the parallel of two series of three UV-extended SiPMs of $6 \times 6$ mm$^2$ dimensions for a total active area of $12 \times 18$ mm$^2$. The readout series configuration has been chosen to reduce the overall capacitance and narrow the shape of signals. In 2016, we procured 150 custom Mu2e-SiPMs from Hamamatsu, SensL and AdvanSiD companies. All these pre-production sensors have been characterized at an automatized station built to measure the operational voltage, the photon detection efficiency and the gain of all cells as well as their RMS spreads of each array [7]. Measured parameters were well within the required technical specifications ($G > 10^6$, PDE > 20%, $RMS_{Vop} < 0.5\%$). Moreover, mean time to failure (MTTF) and radiation hardness tests were performed.

From the Mu2e specifications, the SiPMs have to grant an MTTF of 1 million hours when operating at 0 °C. To accelerate this test, 15 SiPMs have been positioned and monitored in a box at 65 °C for a month. No Mu2e SiPMs breaking have been observed and an MTTF larger than $6 \times 10^5$ h for all vendors has been reached. SiPM prototypes were not damaged when exposed to a ionization dose up to 18 krad.

As neutron hardness test, a SiPM for each vendor was exposed to a total flux of up to $8.5 \times 10^{12}$ n/cm$^2$ at 1 MeV equivalent energy. The Hamamatsu SiPM maintained a dark current lower than 20 mA and better than a factor of two with respect to the other sensors. For this reason, Hamamatsu was selected as the vendor for the production phase.

## 3. Realization and test of the Module-0 prototype

A large scale prototype, called Module-0 (Fig. 1), has been built using 51 crystals and 102 Mu2e SiPMs produced and qualified during the pre-production phase. Module-0 was built trying to resemble as much as possible to the final disk. The back disk was done by Zedex insulator instead of PEEK but the cooling lines connecting the SiPM and FEE holders were realized with the final technique, thickness and shape. For the electron beam test, carried out in May 2017 at the LNF Beam Test Facility, the detector was thermally stabilized at room temperature. In a later test, it was operated under vacuum to measure the outgassing rates and then cooled down to the temperature of 0 °C inside a large vacuum chamber.

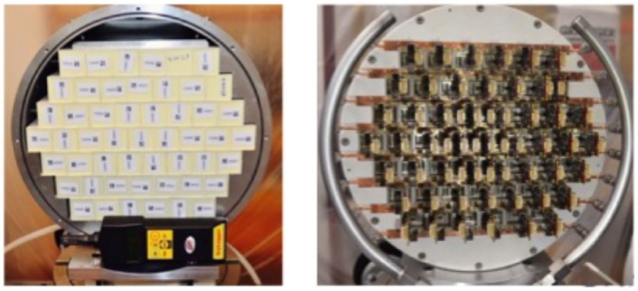

**Fig. 1.** Pictures of the Module-0 during assembly: frontal view with crystals (left) and back view with SiPM and FEE chips (right).

The SiPM signals were amplified with a first prototype of the FEE chips. On the same chip, a local HV regulator allowed to set and read back the bias voltages. A NIM prototype of the Mezzanine board allowed to perform the slow control in groups of 16 channels. Since the Mu2e custom digitizer (DIRAC) was not ready yet for the electron beam test, data were sampled and acquired by means of two 32-channels V1742 CAEN boards at 1 GHz sampling rate. Due to the limited number of available channels in the DAQ system, only the 7 central crystals were equipped and readout with two sensors and two FEE chips per crystal. For the outer crystals, one of the sensors was left without FEE and unbiased. In total 58 SiPMs were readout. The remaining 6 digitizer channels were used to collect trigger and scintillating counters' signals.

Similarly to the calorimeter disks, Module-0 is a structure of staggered crystals with a size large enough to contain most of the electromagnetic shower for an 105 MeV electron beam. Energy and time measurements were obtained using an electron beam in the energy range between 60 and 120 MeV impinging at 0 and at 50 degrees on the calorimeter surface. Two small plastic scintillating counters ($5 \times 1 \times 2$ cm$^3$), crossed at 90 degrees, were positioned on the beam axis, at few centimeters from the front face of Module-0. These beam counters provided a trigger for electrons and allowed to select single particle events. To select cosmic rays, a large plastic scintillator ($50 \times 50 \times 200$ mm$^3$), was located above the calorimeter. All scintillators were read out by photomultipliers. A calibration laser system was installed to monitor the response of the central crystal during running time. The temperature was kept stable to 20 °C by using an external chiller connected to the Module-0 cooling pipes and monitored by the temperature sensors present on each FEE chip.

We have acquired data for one week by triggering with the OR logic of different trigger signals. The beam trigger (BT) was produced by the coincidence of the discriminated signals of the two beam counters. A trigger (BTF) provided by the BTF system allowed to take beam events, without relying on our beam counters. A cosmic ray trigger (CRT) generated by the discriminated signals of the scintillation counter was used to collect cosmic rays events for calibration purposes. A synchronization signal from the Laser system (LT) allowed to acquire the laser pulses for monitoring purposes.

### *3.1. Energy resolution*

The charge collected by a SiPM from a crystal was estimated by numerical integration of the collected waveforms in a 200 ns wide time window. A single-particle selection cut has been applied during the analysis. To equalize the response of each channel of the Module-0 two calibration strategies were followed:

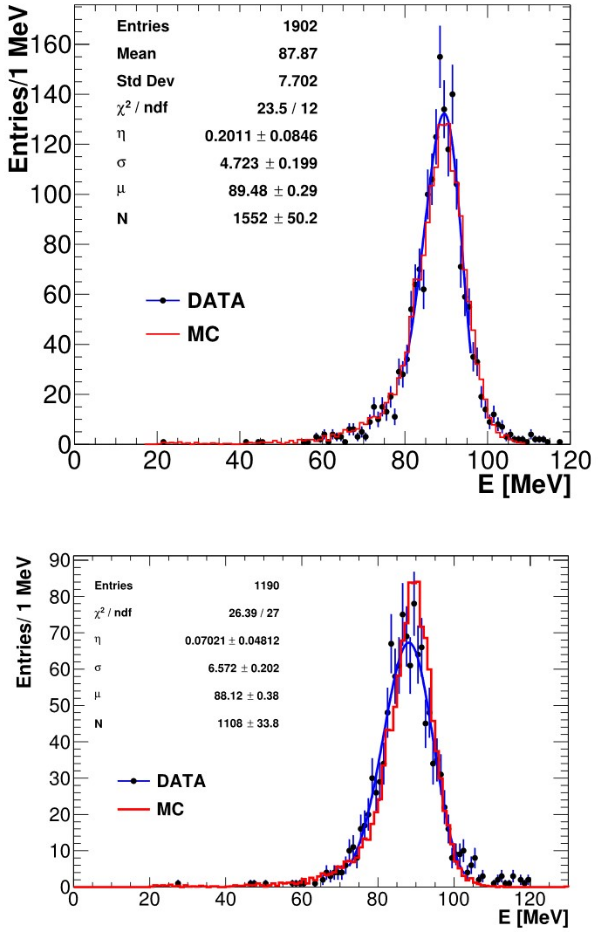

**Fig. 2.** Data — MC comparison of the energy deposited in the entire calorimeter prototype when a 100 MeV electron beam strikes at an incidence angle of 0° (top), 50° (bottom) on the Module-0 surface. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

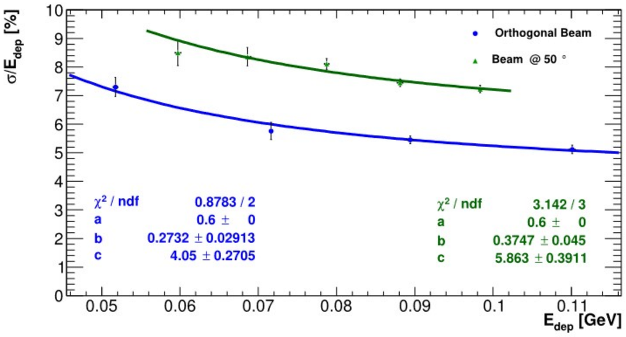

**Fig. 3.** Energy resolution as a function of the deposited energy in Module-0. Black points 0 degrees, red points 50 degrees. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

- Equalization based on the beam energy deposit of a 100 MeV beam centered on the center of the crystal under calibration. This was carried out only for the two innermost groups of crystals; for a total of 26 channels. Statistical error of each calibration was around 0.48%.
- Equalization based on the energy deposition from Minimum Ionizing Particles (MIP) selected from the CRT trigger. This was done for all calorimeter channels. Statistical error of each calibration was around 0.45%.

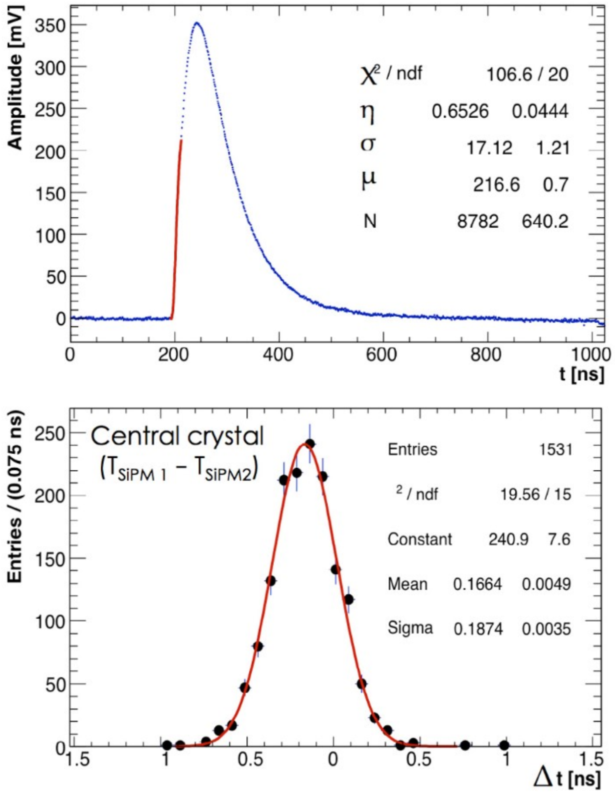

**Fig. 4.** Top: example of a Hamamatsu SiPM waveform for a beam energy of 100 MeV and sampled at 1 GHz. The red line represents the log-normal fit used to extrapolate the signal time. Bottom: Time difference between the two Hamamatsu SiPMs reading out the central crystal, when a 100 MeV beam enters perpendicularly. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The two calibration techniques were compared for the 26 common channels. The ratio of these calibration constants with respect to the central channel are well centered to 1 with an RMS of 3% providing an upper limit for the systematic error of such procedure. The peak values were obtained through a Log-Normal fit to the charge reconstructed in a single crystal.

For the final equalization, we have applied the calibration factors obtained with the CRT sample. The energy scale has been set, after the equalization, by comparing the reconstructed charge in the whole matrix ($Q_{rec}$) with the expected energy deposited in the Module-0, as evaluated by a Geant4 based Monte Carlo simulation. A good linearity in response is obtained. The energy scale factor resulted to be $E_{sc}$ = (12.07± 0.11) pC/MeV and was then applied to all reconstructed charges to obtain the calibrate energy $\mathrm{E} = Q_{rec} \times E_{sc}$. In Fig. 2 (top), the energy distribution of E for 100 MeV electron beam entering at 0° in the Module-0 is shown. Monte Carlo simulation (red line) is in well agreement with data. A similar distribution for the 100 MeV electrons impinging at 50° is shown in the bottom plot.

The energy resolution ($\sigma_E/E$) is evaluated as the ratio between the sigma and the peak of a Log-Normal fit applied to the energy distribution. An energy resolution of ∼ 5.4% (7.5%) is obtained at 100 MeV for 0 (50) degrees, in good agreement with the Mu2e requirements. The energy resolution at different beam energies is reported in Fig. 3. The dependence of the energy resolution as a function of the deposited energy $\mathrm{E}_{dep}$ for single particle events has been parametrized by the function:

$$\frac{\sigma_E}{E_{dep}} = \frac{a}{\sqrt{E_{dep}[GeV]}} \oplus \frac{b}{E[GeV]} \oplus c \qquad (1)$$

where $a$ represents the stochastic term, $b$ the noise term and b the constant term. The fit is rather insensitive to the stochastic term that

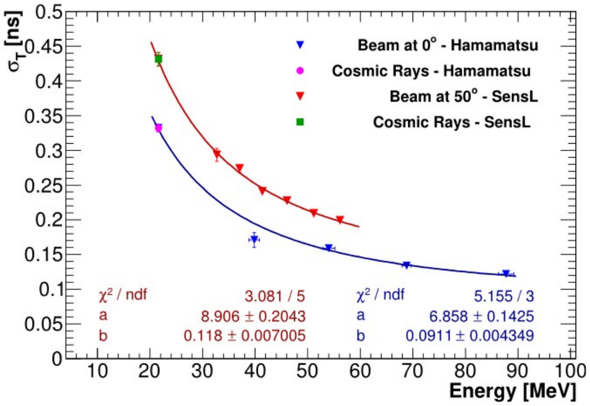

**Fig. 5.** Time resolution as a function of the deposited energy in the highest energetic crystal.

is almost negligible and it has been fixed to 0.6% as estimated by the light yield contribution of 40 pe/MeV. The deterioration of resolution at increasing incidence angles is dominated by the increase fluctuation of the leakage term.

### *3.2. Timing resolution*

After applying the same selection criteria explained above, the signal time is determined by fitting the leading edge of the waveform with an analytic function. The best accuracy was achieved by setting the signal time at a constant fraction (CF) of the pulse height. For the time evaluation, three free components have to be fixed: (i) the waveforms fit function; (ii) the fit range and (iii) the best CF value. After a study of several different functions, the best result was obtained using an asymmetric log-normal function [8]. The optimization of the resolution was then performed by varying the fit range and the constant fraction threshold over a grid and by choosing the best configuration. Fig. 4 (top) shows an example of a Hamamatsu SiPM waveform fit by a log-normal function in the optimized region.

The time difference ($\Delta T$) of the two Hamamatsu SiPMs, reading out the central crystal of Module-0, is shown in Fig. 4 (bottom) for 100 MeV electron beam at 0°. The red line represents the Gaussian fit and the time resolution for a single sensor is evaluated as $\sigma(\Delta T)/\sqrt{2}$. A single sensor resolution of ∼ 132 ps is obtained. Since in the Mu2e experiment the sampling frequency of the digitizer boards will be 200 MHz, the waveforms were offline re-sampled in 5 ns bins. A time resolution deterioration smaller than 30% is obtained, which is negligible with respect to the Mu2e calorimeter requirements Fig. 5 shows the time resolution as a function of the highest crystal energy deposit at different beam energies and for cosmic rays. Both Hamamatsu and SensL SiPMs results are reported. The dependence of the single sensor time resolution $\sigma_T$ from the deposited energy $E_{dep}$ for single particle events was parametrized by the function: $\sigma_T = a/E[GeV] \oplus b$, where $a$ is proportional to the emission time constant of the undoped CsI and $b$ represents the additional contribute due to the readout electronics.

## 4. Conclusion

The Mu2e calorimeter is a state of the art crystal calorimeter with excellent energy ($< 10\%$) and timing ($< 500$ ps) resolutions, for 100 MeV electrons. Our tests demonstrated that pure CsI + SiPMs design readout by a fast analog electronics and a digitization at 200 Msps can largely satisfy Mu2e requirement.

There are many other demanding requests to be satisfied by this detector, such as to keep the required performance in presence of 1 T axial magnetic field, under a $10^{-4}$ Torr vacuum and in a radiation harsh environment. The CsI crystals will withstand the expected dose and fluence with a small light yield loss [9]. The Mu2e SiPMs will work under neutron irradiation when cooled to 0 °C [10], thus asking for a good engineering design of the calorimeter mechanics and of its cooling system. Test on single crystals and SiPMs demonstrates the required technical specifications can be reached. The calorimeter crystals and SiPMs production phase in now ongoing and the readout electronic design is almost concluded. The schedule is to start assembly the first disk in winter 2018 and complete the calorimeter construction in 2020.

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