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Electron beam test of the large area Mu2e calorimeter prototype

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Abstract. The Mu2e calorimeter consists of 1348 pure CsI crystals coupled to two large area UV-extended Silicon Photomultipliers (SiPMs) organized in two separate annular disks. An intense R&D phase has been pursued to check if this configuration satisfies the Mu2e requirements. In May 2017, a dedicated test has been performed at the Beam Test Facility (BTF) in Frascati (Italy) where the large calorimeter prototype (Module-0) has been exposed to an electron beam in the energy range between 60 and 120 MeV. The prototype consists of 51 crystals, each one readout by two Mu2e SiPMs. We present results for timing and energy resolution both for electrons at normal incidence (0 °) and at a grazing impact angle (50 °) more similar to the experiment configuration. At 100 MeV, an energy resolution of 5.4% (7.4%) at normal (grazing) incidence has been achieved in good agreement with Monte Carlo expectation. In the same energy range, a time resolution of $\sim$ XX ps ($\sim$ YY ps) has been measured at normal incidence with 1 GHz (250 MHz) sampling rate. Dependence of time and energy resolutions as a function of beam energy and impinging angle are also presented.

1. Introduction

The Mu2e experiment [1, 2] at Fermilab will search for the Charged Lepton Flavor Violating process of muon to electron conversion in the field of an aluminum nucleus, improving by four orders of magnitude the world best sensitivity settled by Sindrum II experiment [?].

The Mu2e detector is composed of a tracker an electromagnetic calorimeter inside the evacuate area of the detector solenoid (DS) that provides 1 T axial field in the tracking and calorimeter region. An external veto for cosmic rays surrounds the DS. The calorimeter plays an important role in providing excellent particle identification capabilities, a fast online trigger filter while aiding the track reconstruction capabilities. The calorimeter requirements are that of providing a large acceptance for the $\sim$ 100 MeV conversion electrons (CE) and reach:

- a time resolution better than 0.5 ns, at 100 MeV;
- an energy resolution of O(10%), at 100 MeV;
- a position resolution of 1 cm.

The calorimeter consists of 1348 un-doped CsI crystals organized in two separated annular disks (see Figure 1), each crystal readout by two large area UV-extended Silicon Photomultipliers (SiPMs) (Figure 1, right)[3]. The Front End (FEE) amplification and HV regulator chips are connected to the SiPM pins while the digization of the signals is carried out by custom boards located in nearby crates. A radioactive source system [4] 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 area calorimeter prototype (Module-0) to confirm that the chosen design satisfies the Mu2e requirements. In the following, the Module-0 assembly procedure and the test results are reported.

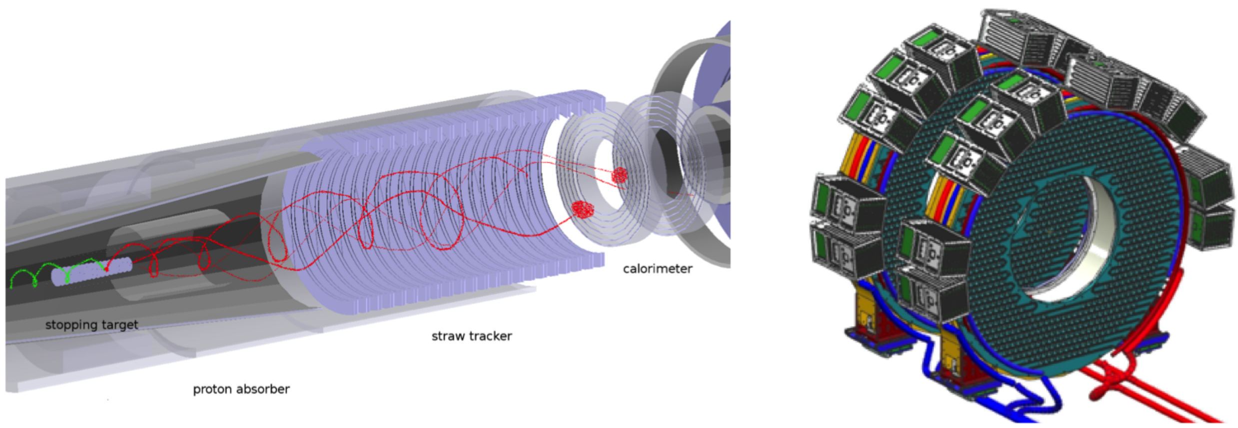

Figure 1. *(Left) Sketch of the Detector Solenoid. (Right) Engineering drawing of the Mu2e crystal calorimeter disks.*

2. Realization of the Mu2e calorimeter Module-0

A large scale calorimeter prototype, called Module-0 (Figure 2), has been built using 51 crystals and 102 Mu2e SiPMs produced and qualified during the pre-production phase [7][8]. 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 Beam Test Facility (BTF) of the Laboratori Nazionali di Frascati

(LNF), the detector was thermally stabilized at room temperature. In a later test, Module-0 was operated under vacuum to measure the outgassing rates and then cooled to low temperature inside a large vacuum chamber.

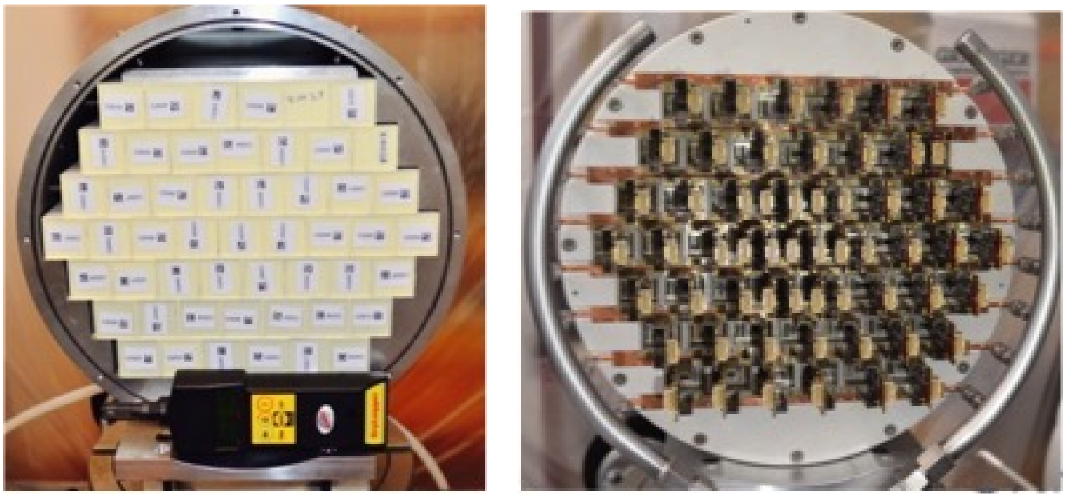

Figure 2. *Pictures of the Module-0 during assembly: frontal view with crystals (left) and back view with SiPM and FEE chips (right).*

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 central crystal and the first surrounding ring 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.

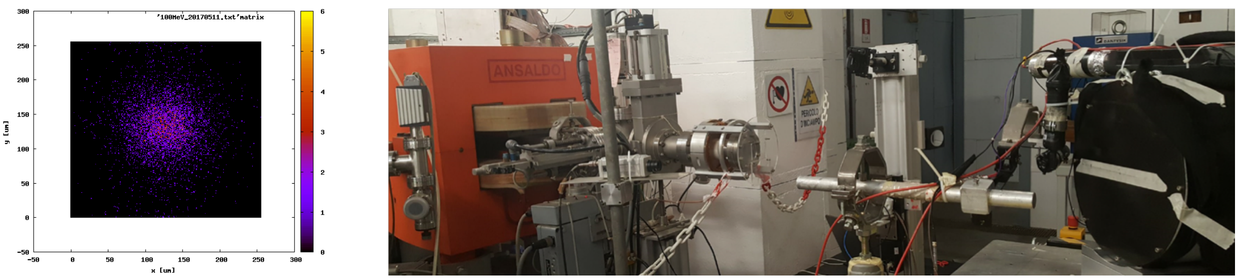

Figure 3. *Experimental setup inside the BTF hall. The Module-0 is covered with a black blanket*

The BTF uses the high current DAΦNE Linac beam to create secondary low momentum beam, sending e-(e+) with an intensity from 10^7 up to 10^{10} particle/beam and energy between 300 and 750 (550) MeV to a Cu target. A system of slits and magnets allows to deliver a secondary beam with the requested energy and intensity to the BTF hall. For Module-0 test, the system has been tuned in single-particle configuration, resulting in 0.7 particles/bunch with a bunch rate of 50 Hz. Figure 3.legt shows the trasversal beam profile, obtained thanks a MEDPIX detector placed in front on the beam. The beam energy spread is few percent at 100 MeV and the beam profile is well represented by a Gaussian shape with a σ_{xy} of $\sim$ 2-3 mm.

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 finger plastic scintillating counters ($5 \times 1 \times 2$ cm^3), crossed at 90 degrees, were positioned on the beam axis, at few centimetres 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. The temperature was kept stable to 20 °C by using an external chiller, filled with water, connected to the Module-0 cooling pipes and monitored by the temperature sensors present on each FEE chip. A calibration laser system was installed to monitor the response of the central crystal during running time. The maximum variation of the laser amplitude peak, due to changes in temperature, observed in few days of run was lower than 2.5%. A view of the entire setup is reported in Figure 3

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 synchronisation signal from the Laser system (LT) allowed to acquire the laser pulses for monitoring purposes.

2.1. Energy resolution

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

- Equalization based on the beam energy deposit of a 100 MeV beam focused on the center of the crystal under calibration. This was carried out only for the two innermost rings 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 %.

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 (Qrec) with the expected energy deposited in the Module-0, as evaluated by a Geant4 based Montecarlo simulation. A good linearity in response is obtained (see Figure5 left) The energy scale factor resulted to be $E_{sc} = (12.07 \pm 0.11)$ pC/MeV and was then applied to all reconstructed charges to obtain the calibrate energy $\mathrm{E} = \mathrm{Q_{rec}} \times \mathrm{E_{sc}}$. In Figure 4 (left), the distribution of E for 100 MeV electron beam entering at 0° in the Module-0 is

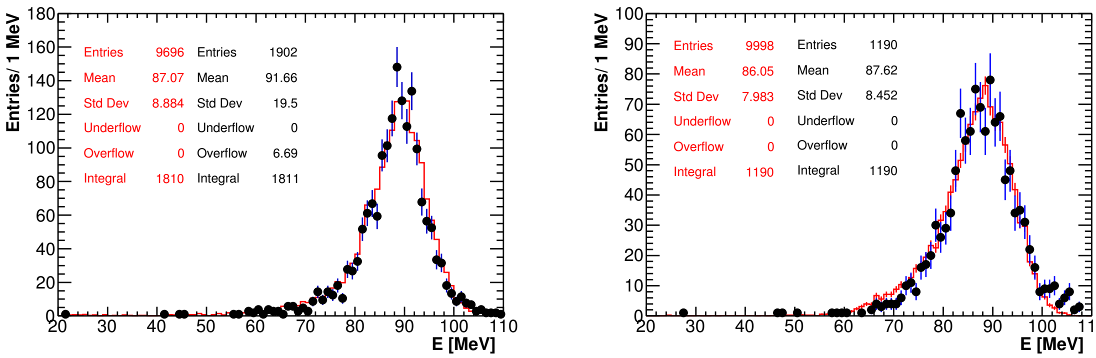

Figure 4. *Data - MC comparison of the energy deposited in the entire matrix when a 100 MeV electron beam strikes at an incidence angle of 0° (left), 50° (right) on the Module-0 surface. Black points data, red points Monte Carlo Prediction.*

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 right plot.

The energy resolution (σ_E/E) is evaluated as the ratio between the peak and the sigma of a Log-Normal fit applied to the energy distribution. An energy resolution of $\sim$ 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 Figure 5.

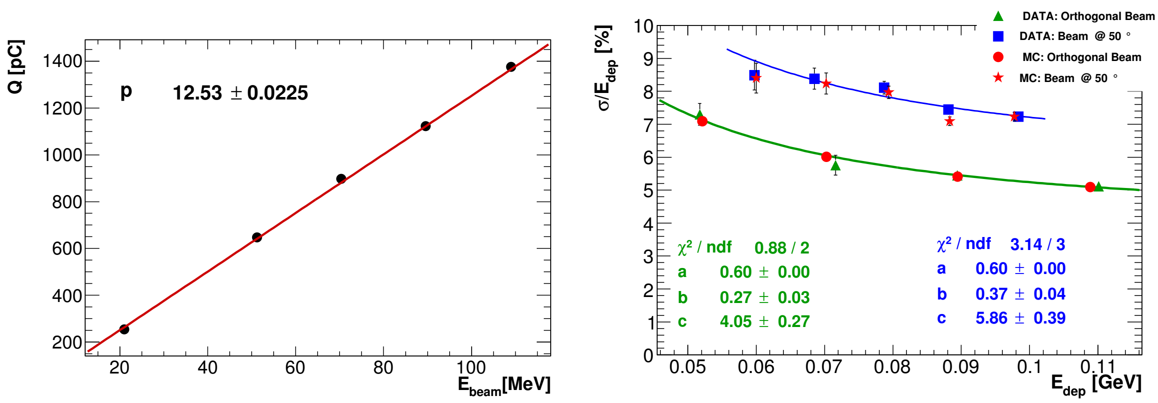

Figure 5. *Left: Linearity of the response. Right:Energy resolution as a function of the deposited energy in Module-0 on right. Green points 0 degrees, blue points 50 degrees.*

The dependance of the energy resolution as a function of the deposited energy E_{dep} for single particle events has been parametrized by the function:

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

where a represents the stochastic term, b the noise term and c the constant term. The fit is rather insensitive to the stochastic term that is almost negligible and it has been fixed to 0.6% as estimated by the light yield contribution of 20 pe/MeV. The deterioration of resolution at increasing incidence angles is dominated by the increase fluctuation of the leakage term.

2.2. 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 [9]. The optimisation 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. Figure 6 (left) shows an example of a Hamamatsu SiPM waveform fit by a log-normal function in the optimized region.

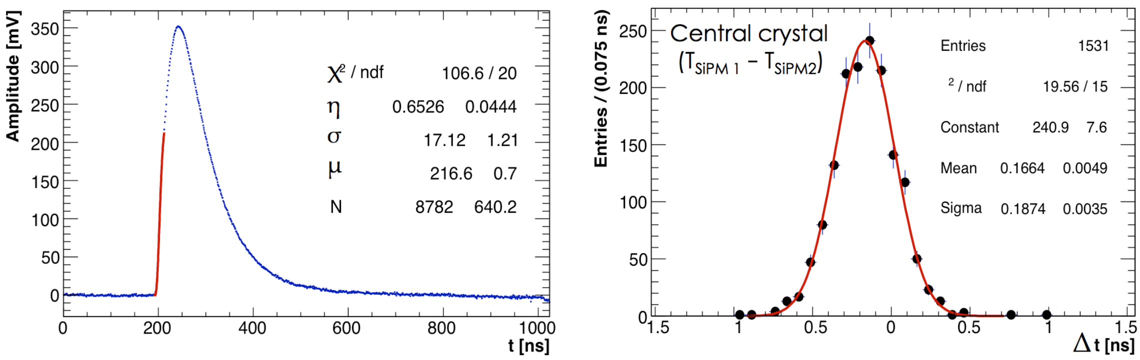

Figure 6. *Left: example of a Hamamatsu SiPM waveform for a beam energy of 100 MeV and sampled at 1 GHz. The red line represents the log-normal fit used to extrapolate the signal time. Right: Time diffeence between the two Hamamatsu SiPMs reading out the central crystal, when a 100 MeV beam enters perpendicularly.*

The time difference (ΔT) of the two Hamamatsu SiPMs, reading out the central crystal of Module-0, is shown in Figure 6 (right) 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 $\sim$ 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. Figure 7 (right) shows the time resolution as a function of the highest crystal energy at different beam energies and for cosmic rays. Both Hamamatsu and SensL SiPMs results are reported.

The dependance of the single sensor time resolution σ_T as a function of the deposited energy E_{dep} for single particle events was parametrized by the function [10]:

$$\sigma_T = \frac{a}{E[GeV]} \oplus b \qquad (2)$$

where a is proportional to the emission time constant of the undoped CsI and b represents the additional contribution due to the readout electronics.

3. 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, and a good pileup discrimination capability. There are many other demanding requests to be satisfied by this detector, such as

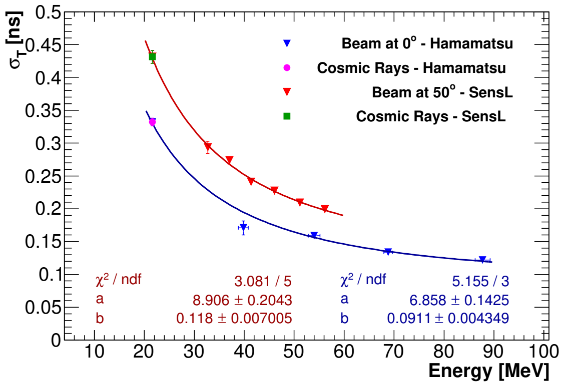

Figure 7. *Time resolution as a function of the deposited energy in the highest energetic crystal.*

to keep the required performance in presence of 1 T axial magnetic field, in an evacuated region and in a radiation harsh environment. The CsI crystals will withstand the expected dose and fluence with a small light yield loss [11]. The Mu2e SiPMs will work under neutron irradiation when cooled to 0 °C [12], thus asking for a good engineering design of the calorimeter mechanics and of its cooling system.

The realization of Module-0 provided excellent results for the integration of components and easiness of its operation. Whilst we are carrying out additional tests in vacuum and we are planning operations in a radiation harsh environment, our test at an electron beam demonstrated that pure CsI + SiPMs design assisted by a fast analog electronics and a digitisation at 200 Msps can largely satisfy Mu2e requirement. Moreover, the developed simulation and the data-Monte Carlo comparison allowed us to understand most of the issues related with the energy reconstruction.

The overall calorimeter schedule sees the start of the first calorimeter disk assembly in 2019 and complete its construction in 2020.

Aknowledgment

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