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Characterization of a prototype for the electromagnetic calorimeter of the Mu2e experiment

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Summary. — The Mu2e experiment at Fermilab searches the neutrinoless conversion of the muon into electron in the field of an Aluminum nucleus. The observation of this process would be a proof of the Charged Lepton Flavor Violation (CLFV). In case of no observation, the upper limit will be set to $R_{\mu e} < 6 \times 10^{-17}$ @ 90% CL, improving by a factor of 4 the previous best determination. The Mu2e detector apparatus consists of a straw tubes tracker that will measure the electrons momentum, and an electromagnetic calorimeter that provides a tracking-independent measurement of the electron energy, time and position. In this paper, we describe the baseline project of the EMC and present results in terms of performances and R&D.

1. – Introduction

The Mu2e experiment [1], proposed at Fermilab, aims to search for Charged Lepton Flavor Violation (CLFV) in the neutrinoless, coherent conversion of a negative muon into an electron in the Coulomb field of an Al nucleus. The Standard Model predicted rate is $\mathcal{O}(10^{-54})$ [2]. Any observed signal would be a compelling evidence of new physics.

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The experiment is designed to reach a single event sensitivity (SES) of 2.4×10^{-17} in three years of running [1].

The conversion of a muon to electron in the field of a nucleus is a coherent process, resulting in monoenergetic electrons with an energy equal to the muon rest mass $m_\mu c^2$ minus the corrections for the nuclear recoil $C(A)$ and the binding energy of the muon $B_\mu(Z)$, which, in the case of an $^{27}_{13}$Al nucleus, is $E_e = m_\mu c^2 - B_\mu(Z) - C(A) = 104.97\,\mathrm{MeV}$.

2. – Experimental apparatus

The Mu2e apparatus is extensively documented in its Technical Design Report [1]. The layout for the muon beam line and the detector system shows a typical S-shape (fig. 1): the entire system is surrounded by the Superconducting Solenoid Magnet System.

In order to meet the experiment requirements, the calorimeter must have a timing resolution better than 500 ps, position resolution better than 1 cm to perform PID and allow pileup separation, and an energy resolution of $\mathcal{O}(5\%)$ to provide an efficient trigger. The calorimeter should be able to operate in an environment where the n, p and γ from muon capture processes and beam flash events deliver a maximum dose of $\sim 120\,\mathrm{Gy/year}$. It must also function in 1 T axial magnetic field and a 10^{-4} torr vacuum. The present design provides two disks of internal/external radius 35.1/66 cm, separated one from the other by 70 cm: this choice allows to suppress the main background of the experimental, constituted by the electrons generated by the muon decay in the orbit of the nucleus (DIOs). Indeed, electrons with an energy below E_e will pass through the hole without being detected.

The first calorimeter version developed for Mu2e consisted of two disks of lutetium-yttrium oxyorthosilicate (LYSO) crystals read out by two large-area avalanche photodiodes (APDs) per crystal [3]. This configuration provided the required characteristics of high light yield, fast response and radiation hardness: however, the increase of the lutetium price made this choice unfeasible for the project budget. Thus, present baseline design provides barium fluoride (BaF_2) readout by custom, solar-blind APDs.

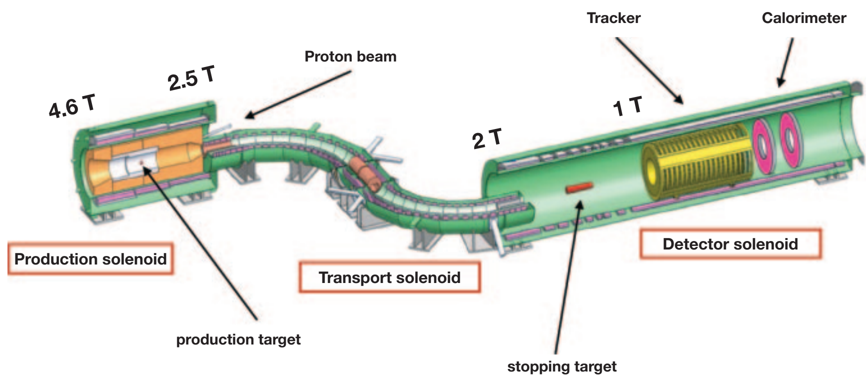

Fig. 1. – Schematic layout of the experimental apparatus: the 8 GeV proton beam enters from the right and strikes the production target placed inside the production solenoid. Back-scattered pions and muons are then captured by the Production Solenoid and transported through the Transport Solenoid to the stopping target in the Detector Solenoid. Here, the muons can be captured and decay, or emit a conversion electron, whose momentum and energy will be measured by the tracker and the calorimeter, respectively.

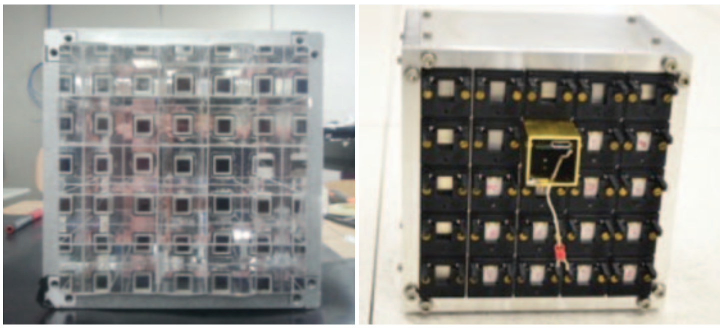

Fig. 2. – On the left (right), picture of the front (back) view of the 5×5 LYSO crystal matrix is shown. The APDs attached to the back of each crystal are visible in both views. The figure on the right shows a brass Faraday cup that is placed around each Amp-HV board.

In this paper, we report on the tests done with a LYSO-based prototype, which allowed us to test the expected performance and evaluate the front-end electronics (FEE) and read out system.

3. – LYSO matrix prototype

A LYSO matrix prototype was built in March 2014 with an overall transverse dimension corresponding to a ~ 3.6 Molière Radius (R_M) and a longitudinal dimension corresponding to ~ 11.2 radiation lengths (X_0). The prototype consisted of 25 LYSO crystals ($30 \times 30 \times 130\,\text{mm}^3$) from SICCAS (fig. 2).

Each crystal was wrapped with a $60\,\mu$m thick layer of super-reflective ESR-3M and read out by a Hamamatsu S8664-1010 APD. The APDs were optically connected to the crystals by means of Saint-Gobain BC-630 optical grease.

Energy resolution, position resolution and longitudinal uniformity of the LYSO matrix have been tested with tagged photon beams in the energy range 60–190 MeV at MAMI [4] (Mainz, Germany), while the time resolution has been measured with 80–130 MeV electron beams at BTF [5] (Frascati, Italy). Data were acquired with CAEN V1720 waveform digitizer, 250 Msps, 12 bit resolution and 0–2 V dynamic range.

Equalization of matrix channels at 10% level was obtained using minimum ionizing particles (MIPs) crossing vertically the detector. Calibration of cell response was done directly with beams (450 MeV e^- at BTF, 92.5 MeV γ at MAMI) impinging orthogonally on each cell center.

4. – Test beam results

Beam events have been selected with a cut on the waveform time distribution, corresponding to the arrival time on the calorimeter prototype. Multiple scattering events has been reduced by cutting on the distance between the energy weighted centroid and the impact point in the calorimeter, that is kept below 0.5 cm. For BTF beams, electrons can arrive at the experimental hall with multiplicities higher than 1. Peaks due to one-, two- and three-particle events are clearly visible and well separated in the energy spectra. In this analysis, single-particle events have been selected with a cut on the total charge of both scintillation counters.

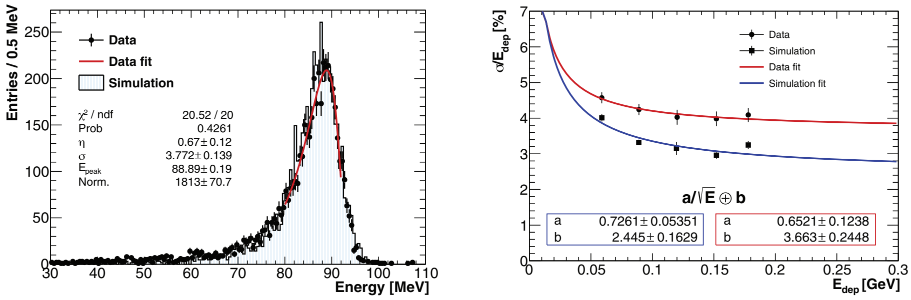

Fig. 3. – Left: Energy distribution for 92.5 MeV photons (dots) compared with GEANT4 simulation (filled histogram). MC spectrum includes an additional 2.6% Gaussian smearing. Energy resolution is obtained from a fit with a Lognormal distribution [6] (solid line). Right: energy resolution as a function of the deposited energy for data and MC.

After channel-by-channel equalization, the total calorimeter charge Q is then converted to energy E_{tot} by setting an energy scale factor (pC/MeV), comparing Q with the expected energy deposited in the entire matrix, E_{dep}, as estimated by a GEANT4 simulation. To reproduce real data, an additional constant 2.6% Gaussian smearing is needed in the simulation to account for miscalibration, non uniformity and non linearity in the response. The energy resolution has been obtained as a function of the deposited energy from a fit to the E_{tot} distribution with a lognormal function (fig. 3, left). The energy resolution as a function of the deposited energy (fig. 3, right) has then been fitted with the formula:

$$\sigma_E/E_{tot} = a/\sqrt{E_{tot}/\text{GeV}} \oplus b, \tag{1}$$

obtaining $a = (0.65 \pm 0.12)\,\%$ ($a = (0.73 \pm 0.05)\,\%$) and $b = (3.66 \pm 0.24)\,\%$ ($b = (2.45 \pm 0.16)\,\%$) for data (Monte Carlo). This parametrization then gives, at 105 MeV, an energy resolution $\sigma_E/E_{tot} = (4.17 \pm 0.44)\%$.

The position resolution has been measured from the energy weighted average of the position of the crystal hit by the electron. The standard deviation of this distribution, which provides a first measurement of the position resolution of the device, is 3.96 ± 0.03 mm (4.08 ± 0.03 mm) for the x (y) axis.

The time resolution has been measured at BTF with two methods. In the first one, it has been estimated from the standard deviation of the distribution for the Δt variable:

$$\Delta t = \frac{\sum_{i=1}^{25} t_i E_i}{\sum_{i=1}^{25} E_i} - t_{start}, \tag{2}$$

where i) t_i is the peak time of the i-th crystal obtained with a Landau fit of the waveform, ii) E_i is the energy deposited in the i-th crystal and iii) $t_{start} = (t_{f_1} + t_{f_2})/2$ provides the timing start, with t_{f_1} and t_{f_2} the peak times of the two scintillation counters obtained with a lognormal fit to the waveforms. In the second method [7], the beam is fired between two considered crystals: in this case the time resolution is quoted from the standard deviation of the $\Delta t = t_1 - t_2$ distribution, where t_1 and t_2 are the peak times of the two hit crystals. The time resolution obtained with the first method must then be jitter-subtracted to be comparable with the second method. A summary of these

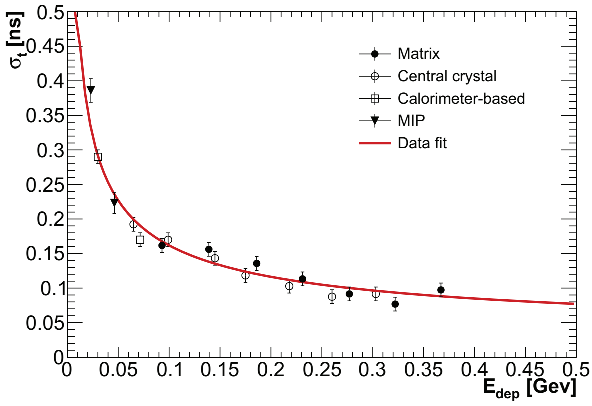

Fig. 4. – Time resolution as a function of the energy deposited in the matrix, obtained with scintillation counters (both for the central cell and the entire matrix), with calorimeter-based method and for MIPs events.

measurements is reported in fig. 4. The energy dependence has then been fitted with a stochastic term

$$\sigma_t(E) = a/\sqrt{E/\mathrm{GeV}}, \tag{3}$$

obtaining $a = (51 \pm 1)\,\mathrm{ps}$ and a time resolution of $\sigma_t = (157 \pm 3)\,\mathrm{ps}$ at 105 MeV.

Summarizing, the built prototype fully satisfies the Mu2e requirements, with an energy resolution better than 5%, a position resolution better than 1 cm and a time resolution better than 500 ps at the signal energy of 105 MeV.

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