Test and Simulation of a LYSO+APD matrix with a tagged Photon Beam from 40 to 300 MeV

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Abstract. Understanding the energy resolution terms for LYSO based calorimeters with APD readout at low energy (< 500 MeV) is relevant both for the completion of the KLOE-2 experiment, at DAΦNE, and for the design of the Mu2e calorimeter. In this work, we present a dedicated comparison between experimental data, taken in 2011 at the MAMI tagged photon beam facility with a crystal matrix prototype, and a full Geant-4 simulation of this detector. The crystal prototype matrix consisted of 9 2×2 × 15 cm^3 LYSO crystals read-out by 10x10 mm^2 Hamamatsu avalanche photodiodes (APD) surrounded by 8 $PbWO_4$ crystals read-out by Bialkali photomultipliers for outer leakage recovery granting a total transverse coverage of 3 Rm. An energy resolution of ∼5.4% at 100 MeV has been achieved. A fit to the energy dependence of the resolution provides the following parametrization: $\sigma_E/\mathrm{E} = 2.1\%/\mathrm{E}^{1/4} \oplus 3.6\%$, where the sum is in quadrature. The noise term is completely negligible as expected by the reduced level of the electronic noise achieved. The constant term is still leakage dominated.

Introduction

To understand the resolution terms for LYSO based calorimetry is important for many experiments. Our interests were motivated by the need of improving the calorimeter angular coverage of the KLOE-2 experiment at DAΦNE in Frascati and to design the calorimeter system for the Mu2e experiment at Fermilab. In Frascati we are realizing the CCALT calorimeters, fig. 1, that will increase the acceptance to low energy photons of the central calorimeter from 18 to 10 degrees, covering the region where inner quadrupoles are located. This will improve the signal/background discrimination for rare K_s and η, η' rare decays. The main requirements, for the CCALT, are to get an accurate timing resolution (300-400 ps at 20 MeV) to reject the background from machine background events. The calorimeter must be compact due to space constrains and to have a very high efficiency for 20-300 MeV photons. Finally it must be able to work inside 0.5 T magnetic field. We are also designing the electromagnetic calorimeter for the Mu2e experiment, fig. 2, where instead the main requirement is to obtain an energy resolution $\leq$ 2% for 100 MeV energy electrons. Indeed the calorimeter will be used to confirm that a reconstructed track is a well measured, well identified conversion electron candidate and was not created by a spurious combination of hits in the tracker. The calorimeter must be radiation hard (80 Gy/y) and able to work inside 1 T magnetic field. In both cases a crystal calorimeter based on LYSO is an excellent choice.

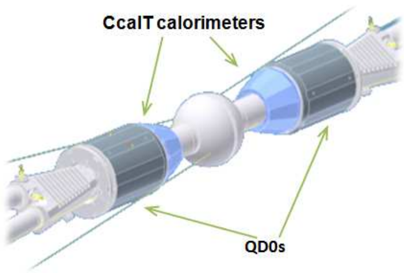

Figure 1. CCALT: a Crystal Calorimeter with Timing for the KLOE-2 upgrade.

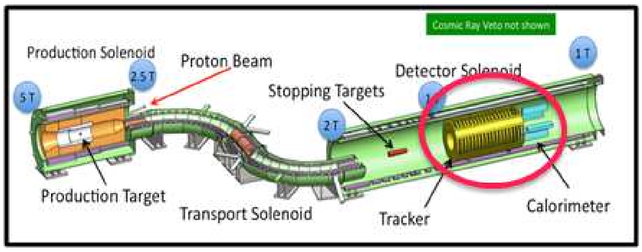

Figure 2. Overall design of the Mu2e experiment at Fermilab.

1. A LYSO Crystal Calorimeter Prototype

After a first test done in 2009 at BTF (Beam Test Facility of LNF) with a smaller size prototype [1], we have built a larger size matrix prototype to test it to a tagged photon beam. This second matrix was built In February 2011 to reach transverse dimensions corresponding to ~2.8 R_M and longitudinal dimensions corresponding to 11 ÷ 12 X_0. The prototype consists of an inner matrix of 9 LYSO crystals by SICCAS (20×20 × 150 mm^3) readout by APDs S8664 (10×10 mm^2) produced by Hamamatsu. Due to budget constraint we surrounded it with a cheaper outer matrix, for leakage recovery, composed of 8 $PbWO_4$ crystals of mixed dimensions readout by standard Hamamatsu Bialcali photo multipliers of 1 inch diameter, as shown in Figure 3.

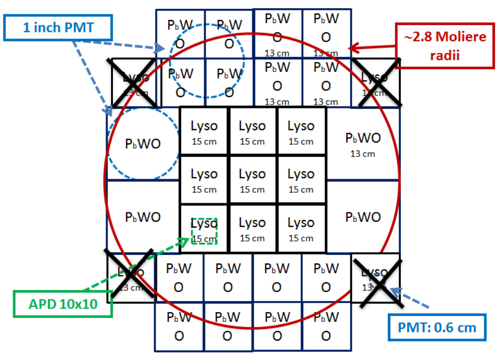

Figure 3. Layout of the improved matrix.

Each crystal was first wrapped with a 150 μm thick Tyvek sheet, which diffusely reflects the scintillation light escaping the crystal with high efficiency, and helps to increase the light collection of photosensors, in optical contact to the rear surface of the crystal by means of BICRON grease. The LYSO crystals are then wrapped with 1 mm thick black tape, to avoid cross-talk in the outer matrix which has a much higher photo sensor gain (due to the phototubes readout). The entire matrix was installed in a light shielded box, with the front layer made of Copper and the lateral and back layers made of Aluminium.

2. The MAMI accelerator facility

The MAMI (Mainz Microtron) electron beam facility produces up to a 1.5 GeV high quality ~ 100% duty factor electron beam. In the facility hall A2 the electron beam is converted to an intense beam of real photons through bremsstrahlung in a thin metal foil radiator. The scattered electrons in this process are momentum analyzed by a plastic scintillator spectrometer which provides a determination of the energy of the associated bremsstrahlung photon with a resolution of few per mil. The tagged photon beam is excellent, having Δp(FWHM) = 1 MeV and a cross section on the calorimeter front face of about 8 mm diameter. The calorimeter prototype was installed over a movable table that allowed to adjust the position of the matrix with respect to the photon beam, Fig. 4, with a precision better than 0.2 mm.

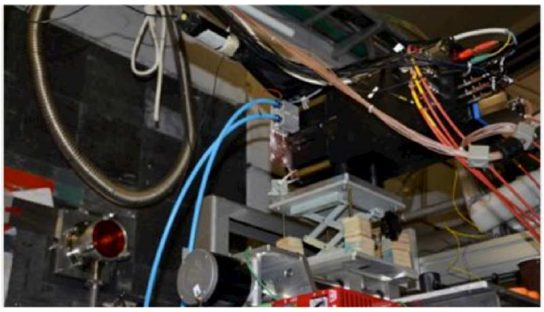

Figure 4. The calorimeter prototype is installed over a movable table in front to the photon's beam.

We have triggered using a coincidence between the OR of the discriminated signals from the inner matrix and the selected strip signal from the beam tagging system. The calorimeter analog sum discriminator (LeCroy 4419) threshold was set as low as possible ($\sim\sim$ 15 mV) and corresponded to an energy threshold of $\sim$ 10 MeV. We acquired data with a CAMAC system, reading out LeCroy ADC and TDC boards with a sensitivity of 250 fC/count and 100 ps/count, respectively. The proton beam had an average rate of 10-20 kHz. The data acquisition was writing on disk at sim 10 Hz. The temperature of the experimental hall ($\sim 24^oC$) was continuously monitored with thermo sensors attached to the electronics and preamplifiers and was stable at the level of $\pm$ 0.5 ^{o}C.

3. Data Collection

We have taken data for four days in March 2011. All of data were collected at eleven different settings of the photon-beam energy, in the range from 40 to 300 MeV. About 10k events were collected in each run. For most of the runs, the photon beam was impinging at the center of the inner crystal matrix. The same photon energy (100 MeV) was used for the position scan. Pedestal and test pulse runs were performed once every few hours during the beam time to check the system stability. Cosmic Rays (CR) were used for cross calibration of the gains. We have taken CR calibration data during the off-beam periods by means of an external trigger provided by a coincidence of a pair of scintillator counters. The average number of collected CR events per run was about 100k and was taken in about 10 hours.

We summed the charge of the 9 LYSO + APD crystals of the inner matrix and the charge of the 8 PBWO + PMT of the external matrix. The overall noise for LYSO inner matrix was of $\sim$ 3.2 counts. We use the linearity relation among energy and MIP peak to estimate the noise in MeV as follows:

$$\sigma(\mathrm{noise})_{\mathrm{tot}} = (3.2\ \mathrm{count} \times 9.6\ \mathrm{MeV/cm} \times 2\ \mathrm{cm})/120\ \mathrm{count} \approx 500\ \mathrm{keV} \quad (1)$$

Similarly, we estimated that the noise contribution of each channel is 150 keV as seen from the sigma of the pedestal distribution. Thus we observe a reasonable incoherent noise in the detector as proven by the scaling law with the number of channels,N_{ch}: $\sqrt{\mathrm{N_{ch}} * \sigma(\mathrm{noise})_{\mathrm{i}}^2} = 450\ \mathrm{keV}$. For the external matrix, the overall $PbWO_4$ + PM noise was of $\sim$ 2 counts. Thus, we get a total of 3.6 counts, 720 keV of noise for the whole calorimeter.

4. Linearity of the response

The total response of the detector is defined as:

$$Q_{TOT} = \sum_i (Q_i - P_i) \cdot 1/M_i \tag{2}$$

where Q_i and P_i are the collected charge and the pedestal of the i-th channel and M_i is the peak for a minimum ionizing particle. The energy distribution of Q_{TOT}, for different photon beam energies is shown in Figure 5. Each energy distribution has been fit with a Log Gaussian function and the peak value and the sigma has been extracted to estimate linearity and resolution.

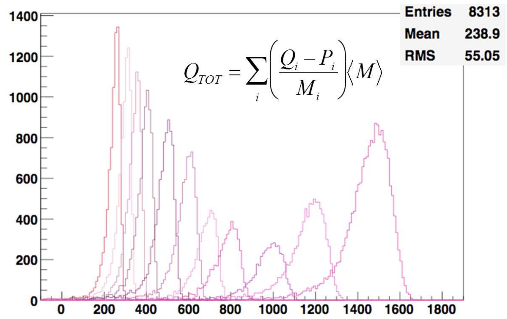

Figure 5. Distribution of Q_{tot} for the 11 selected beam energies between 40 and 300 MeV.

5. Test results and comparison with MC simulation

Test beam results have been compared with Monte Carlo studies. We ran a complete Geant-4 simulation respecting all the construction features of the matrix: dimensions, positioning, photosensors, wrapping. In Figure 6, the simulated prototype is shown. The detector has been modeled with the same geometry as the actual beam-test setup. The yellow line represents an impinging photon.

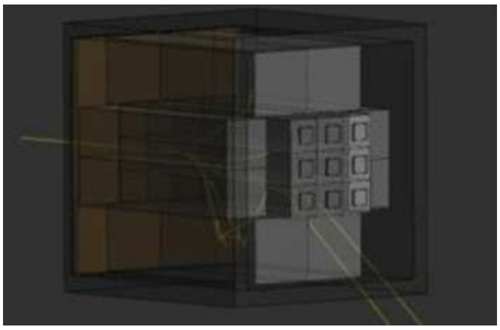

Figure 6. An event display of an 100 MeV photon (yellow line), impinging on the simulated calorimeter prototype, simulation done using Geant-4. The shower development inside the crystals is shown.

Figure 7 shows a comparison between real data and MC results, for the energy deposit of each crystal in the central row of the inner matrix. The black circles are the experimental data, the red distribution is the G4-simulation result. We are forced to add a 4% intrinsic fluctuation term to each crystal. After having inserted this correction, an excellent reproducibility of the energy distributions both in the integral and in the shower shape in the transversal direction is observed. This result has been achieved both for the inner and for the recovery matrix.
We have finally simulated and studied also the effects related to the non-linearity in response of the LYSO and to the longitudinal non-uniformity of response along the crystal. We find that the first contribution is negligible, while to explain our ad-hoc correction term we need to have a longitudinal non-uniformity of 26%. Measurement of this effect is in progress on the used crystals. After the ad-hoc correction, an excellent data-MC agreement is obtained both for the

inner and the whole matrix. In Figure 8 the superposition between data and MC is shown for the whole matrix.

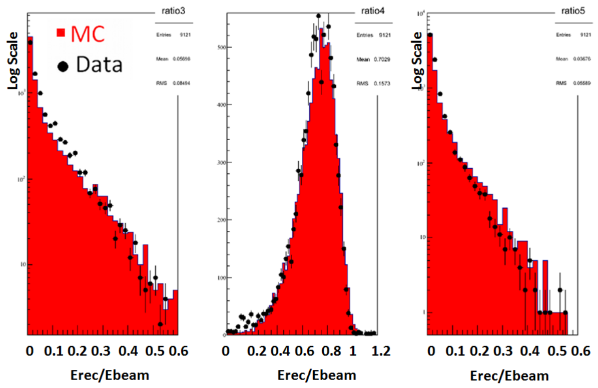

Figure 7. Comparison between real data (black circles) and MC results (red distribution), for the energy deposit in the central row of the inner matrix.

In order to evaluate the energy resolution, we have selected 11 energy values between 50 and 300 MeV. We have fit each energy distribution with a logarithmic gaussian function [2]. We used a automatic fit procedure to evaluate the systematic error of the fit. Starting from the position of the maximum in the energy distribution, we fit the histogram automatically changing the fit ranges as follows.
The fit uses as input the maximum of the histogram and its RMS as standard deviation of the gaussian; then, using an iterative procedure the left end side and the right end side of the fit range are varied by a fraction of the RMS value independently. For each energy distribution we performed several fits using about 100 different ranges. Only the fit results with χ^2/ndf between 0.5 and 2, $\Delta\sigma/\sigma_E$ and $\Delta E_{peak}/E_{peak}$ less than 0.05 are taken into account. The parameters, surviving the selection, are collected. Then we used their mean value and the RMS to evaluate the systematic error.

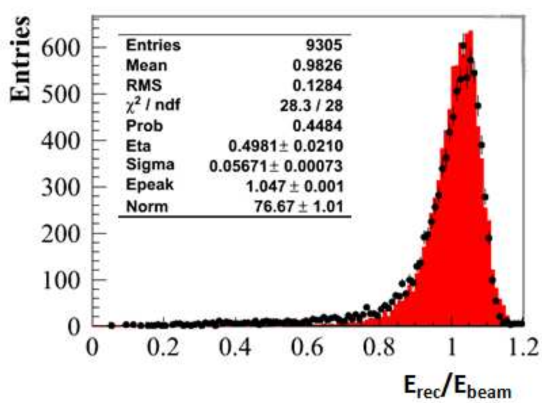

Figure 8. Data MC Comparison, sum of the whole crystals matrix. Data in black, MC in red.

In Figure 9, we show the energy dependence of the energy resolution for the whole matrix. MC is shown with and without the additional 4% spread per crystal (referred as full/ideal in the following). The dependence of the energy resolution has been fit with the standard equation:

$$\sigma_E/E = a/\sqrt[4]{E[GeV]} \oplus b/E[GeV] \oplus c \qquad (3)$$

where the sum is done in quadrature. The noise term is expected to be 0.06% and is negligible in the fit procedure. when fitting the MC distribution for the whole matrix for the ideal case we get a c term of 3.0 % and an a term of 1.4 %. Since the contribution of the photoelectron statistics is negligible the a term represents the energy dependence of the leakage fluctuation. The full simulation closely follows the data distribution. The a term increase is related to the non uniformity of the crystals.

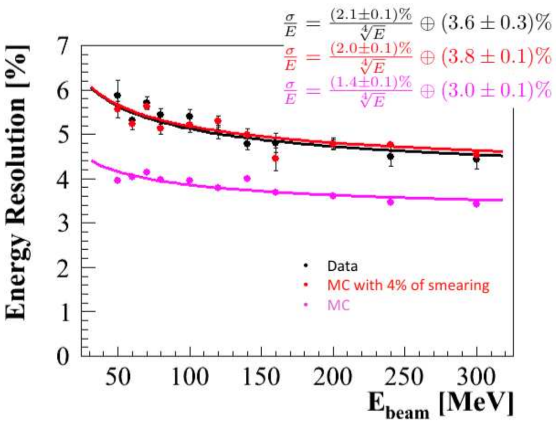

Figure 9. Dependence of the energy resolution on beam momentum, for all crystals. Black points data, red (pink) points MC with (without) the 4% correction. We get a stochastic term, a =2.1±0.1% and a constant term, c, =3.6±0.3% for data in good agreement with MC expectation. The noise term b is practically negligible.

5.1. Timing resolution
We could not determine the timing resolution at MAMI, due to the large time jitter of our trigger (1 ns). We determined it at BTF of Frascati, with a test performed on March 2009 with a smaller matrix prototype. We obtained σ_t = 250 (49) ps at 500 MeV, 291 (120) ps at 100 MeV without (with) correction for trigger jitter [3].

5.2. Position resolution results
We have also determined the position resolution with centroid method defined as $X_{pos} = \sum Q_i \cdot X_i/Q_{tot}$. We observe a position resolution of $\sim$ 3.4 mm RMS for 100 MeV photon impinging directly the calorimeter center.

6. Conclusions
A test beam study of a prototype LYSO calorimeter for KLOE-2 and Mu2e detector has been tested at a photon beam with energy from 40 to 300 MeV at MAMI. The achieved energy resolution of 5.4% is dominated by leakage and can be improved enlarging the crystals array. Results obtained at the beam test are well reproduced by the Geant-4 simulation where we have investigated the effect on the resolution related to intrinsic non-linearity in response and longitudinal non-uniformity of the crystals. We realized that the longitudinal non-uniformity is the most important contribution and we were forced to add a 4% spread to each crystal to obtain a fair data-MC agreement. To conclude the R&D for the Mu2e experiment we aim to get an energy resolution of O(2%) and we therefore need to get an energy resolution below 1% related to the longitudinal non-uniformity which has to be contained below 5 %. We are planning to build a new 5×5 LYSO Crystals (3×3×13 cm^3) matrix with more uniform crystals and better electronics to test it again at MAMI with the goal of reaching $\sigma_E/E \sim$ 2-3% at 100 MeV.

References
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