

# CCALT: A crystal calorimeter for the KLOE-2 experiment

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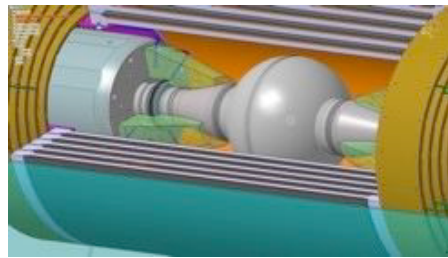
**Abstract.** The angular coverage extension of the KLOE-2 electromagnetic calorimeter, from a polar angle of  $20^\circ$  down to  $10^\circ$ , will increase the multiphoton detection capability of the experiment enhancing the search reach for rare kaon,  $\eta$  and  $\eta'$  prompt decay channels. The basic layout of the calorimeter extension consists of two small barrels of LYSO crystals readout with APD photosensors aiming to achieve a timing resolution between 300 and 500 ps for 20 MeV photons. The first test of a  $(5.5 \times 6 \times 13)$  cm<sup>3</sup> prototype for such a detector was carried out at the Beam Test Facility of Laboratori Nazionali di Frascati of INFN. We present here the results of this test.

## 1. Introduction

In the last years, a new machine layout based on the Crab-waist and a large Piwinsky angle has been proposed and tested [1] to improve the reachable luminosity at the Frascati  $\phi$ -factory, DAΦNE. The success of this test motivated the startup of a new experiment, named KLOE-2 [2]. The first running phase will start at the end of 2010 with the goal of collecting  $\sim 5 \text{ fb}^{-1}$  in one year. A second phase, for a longer data taking, will require a set of detector upgrades all concentrated around the beam-pipe. We are studying the insertion of a calorimeter between the interaction point, IP, and the first inner quadrupole (See Fig. 1) to extend the angular coverage of the main electromagnetic calorimeter. This will enhance the multiphoton detection capability of the detector for the search of rare decays of kaons,  $\eta$  and  $\eta'$  mesons.

## 2. CCALT: a Crystal Calorimeter with Time

The discussion of the previous section indicates that this calorimeter has to be very dense, with a small value of radiation length,  $X_0$ , and Moliere radius,  $R_M$ , not hygroscopic and with a large light output to improve photon detection efficiency at low energy (from 20 to 500 MeV). Moreover, the calorimeter has to be extremely fast in order to allow for prompt photon reconstruction Preliminary simulation studies indicates the need to reach a time resolution of  $300 \div 500$  ps for 20 MeV photons.



**Figure 1.** Zoomed-view of the IP region. The area available for the new calorimeter lies between the inner sphere and the closest quadrupoles.

A first detector layout consists of two concentric barrels of 24 crystals each, with transversal dimensions of  $2 \times 2 \text{ cm}^2$  and longitudinal length between 13 and 15 cm. The best crystal choice matching the requirements is provided by LYSO, which has  $X_0$  and  $R_M$  values (1.1 and 2 cm) and a scintillation emission time  $\tau_{LYSO} = 40 \text{ ns}$ .

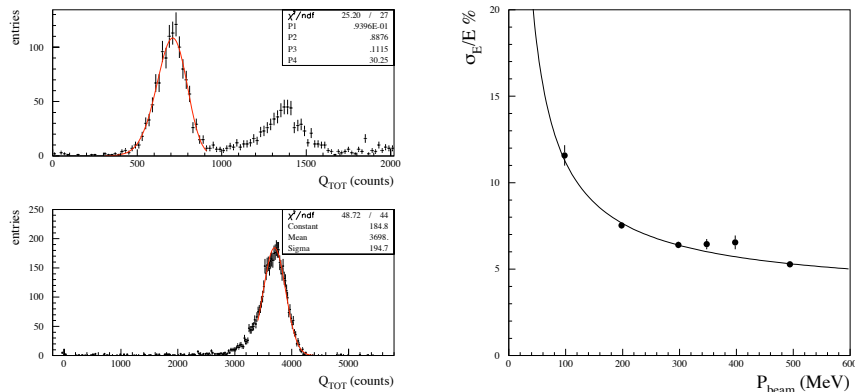
In the final location of the CCALT inside KLOE-2, the presence of an axial magnetic field of 0.52 kGauss forces the usage of silicon based photodetectors. Due to the high photon yield, the readout with APDs is a valid solution. In the following, we specifically considered only the Hamamatsu S8664-55, which has an active area of  $0.5 \times 0.5 \text{ cm}^2$ , fast timing characteristics and a quantum efficiency between 65 and 85% in the wavelength range of interest ( $390 \sim 500 \text{ nm}$ ) for the LYSO emission spectra.

In march 2009, we have built a medium size crystal matrix prototype with transversal radius larger than  $2 R_m$ , longitudinal dimensions being constrained by budget limits to be between 13 and 15 cm (corresponding to  $11 \div 12 X_0$  of longitudinal containment). The prototype consists of an inner matrix of 10 small ( $15 \times 15 \text{ mm}^2$  and  $20 \times 20 \text{ mm}^2$ ) LYSO crystals readout by APD and an outer matrix, for leakage recovery, composed by 8  $\text{PbWO}_4$  ( $20 \times 20 \text{ mm}^2$  and  $(30 \times 30 \text{ mm}^2)$ ) crystals readout by standard Hamamatsu Bialcali photomultipliers of 1,1/8" diameter. To test the quality of the crystals offered by different vendors, the inner matrix has been assembled in three rows composed by: LFS crystals from Zecotek, LYSO crystals from Saint Gobain and LYSO crystals from Scionix. The LFS from Zecotek is a Lutetium Fine Silicate crystal, with very similar properties to LYSO. Each crystal is wrapped with  $100 \mu\text{m}$  of tyvek on the lateral faces, leaving free both the front and end faces, thus allowing one to bring calibration light pulses through an external LED and a fast change of the photosensors readout. The optical connection of the photosensors with the crystals is done with optical grease. The amplifiers are based on the MAR8A+ chip from Minicircuits, with a gain factor of 25 and a bandwidth of 1 GHz.

### 3. Test results with electron beams.

We have taken data at the Beam Test Facility, BTF, of LNF for two weeks in april 2009. The BTF plant provides electron and positron beams with a momentum ranging from 50 to 500 MeV/c and can reach a single particle multiplicity. The matrix was positioned at the center of the beam axis with an area delimited by a cross of two finger BC408 scintillators of  $1 \times 0.5 \times 5 \text{ cm}^3$  dimensions,  $f1, f2$ . The scintillators were used to discriminate single electron events from higher multiplicity ones looking at the pulse height distributions as shown in Fig. 2. In most of the tests, the fingers were aligned in such a way to define a beam spot of  $1 \times 1 \text{ cm}^2$ . In front of the fingers it was also present a beam position monitor, BPM, of the BTF group, consisting of sixteen horizontal and vertical scintillator strips readout by two Multi Anode PMs.

We have triggered by using a replica of the spill signal from the Linac adjustable from remote



**Figure 2.** (Left) Distribution of  $Q_{TOT}$  for single electron events at 100 MeV (top) with a logG fit superimposed and at 500 MeV (bottom) with a gaussian fit. (Right) Dependence of the energy resolution on beam momentum.

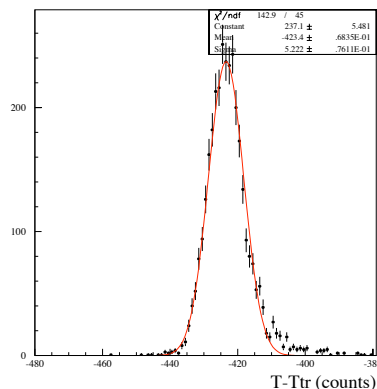
in order to correctly put the signals in time. We acquire data with the KLOE-2 daq system, VME based, reading out KLOE ADC and TDC boards with a sensitivity of 100 fC/count and 50 ps/count respectively.

Observing the response of the prototype to single electrons, we realized that the outer matrix was not properly working due to an unexpected optical cross-talk between crystals. We observe large cross-talk only on the  $PbWO_4$  of the outer matrix. We believe this to be due by a cooperation between a light leak through the tyvek and the different amplification gains between PMs and APDs. In the following, we therefore report only results related to the inner matrix which has an overall dimension of  $60 \times 55 \text{ mm}^2$  ( $\leq 1.5 R_M$ ).

By using the UV LED, we have first equalized each channel at 10% level by proper HV adjusting. We have then calibrated the calorimeter response of each channel with minimum ionizing particles, m.i.p., crossing the calorimeter horthogonally to the crystal axis. We get  $\sigma_{ped}$  of 5 counts and a m.i.p. peak,  $M_i$ , of around 100 counts for the smaller size crystals. The total response of the detector is then defined as:  $Q_{TOT} = \sum (Q_i - P_i) \times M_0/M_i$ , where  $Q_i$  and  $P_i$  are the collected charge and the pedestal of the  $i$ -th channel,  $M_0$  represents an average calibration of all channels in counts and the calibration for the larger crystals is corrected for the different size. In Fig. 2 left, we show the distribution of  $Q_{tot}$  for a beam of 100 and 500 MeV respectively after having selected single electron events with a cut on the finger scintillators. We have fit the distribution corresponding to one electron either with a simple gaussian, centered around the peak, or with a logarithmic gaussian, logG, function as follows:  $N \cdot \exp(-\frac{1}{2\sigma_0^2} \ln(1 - \frac{\eta}{\sigma_E}(E - E_{peak}))^2 - \frac{\sigma_0^2}{2})$  where  $N$  is a normalization factor,  $\eta$  represents the asymmetry,  $E_{peak}$  the most probable value of the distribution,  $\sigma_0 = \frac{2}{2.36} \sinh^{-1}(2.36\eta/2)$  and  $\sigma_E = \frac{FWHM}{2.36}$  is the resolution.

By performing a linear fit to the distribution of  $E_{peak}$  vs  $P_{beam}$ , we get a slope of  $7.5 \pm 0.1$  counts/MeV which sets the  $M_i$  value to be  $\sim 16$  MeV for a small crystal consistent with an expected energy loss of  $\sim 10$  MeV/cm. At the running voltages of 410 V, the expected APD gain varies between 300-500 from which we estimate the light yield to be between 500 and 800 p.e./MeV.

To understand the different terms of the energy dependence of the energy resolution, we are carrying on a full simulation of the prototype based on Geant-4. Studies on photoelectron



**Figure 3.** Distribution of the average timing reconstructed with the inner matrix for 500 MeV electron beam.

collection efficiency are still underway. This simulation indicates that there is a large leakage term between 5 and 4 % from 100 to 500 MeV.

In Fig. 2 right, we show the energy dependence of the energy resolution measured on data which has been fit with the following equation:  $\sigma_E/E = a \oplus b/(E/\text{GeV}) \oplus c/\sqrt{E/\text{GeV}}$ , where, accordingly to MC, we have fixed the constant term to be 5 %. We found  $b = 1.1\%$  and  $c = 1.4\%$  when using the gaussian fits to the spectra. If we repeat this procedure, for the fits with the logG function, we get  $b = 0.8\%$  and  $c = 2.4\%$ .

We have investigated the large  $b/E$  term by measuring the total detector noise with a gaussian fit to  $Q_{TOT}$  in events without any electron beam impinging. We find  $\sigma_Q = 4.2 \div 4.8$  MeV which is slightly larger than the incoherent sum of  $\sigma_{ped}$  resulting to be  $3.6 \div 3.8$  MeV showing that a not negligible coherent noise is present. However, the noise does not fully explain the large  $b$  term found. We are unable to understand the origin of this contribution. A measurements of the LYSO longitudinal response has been carried out and we found a difference below 5% scanning along the crystals.

In the attempt of understanding the single terms to the energy resolution we developed a full GEANT4 simulation of the calorimeter to check the leakage contributions and the fluctuation of the shower shape, that, convoluted with the longitudinal disuniformity of the crystal response, could give rise to a sizeable contribution to the resolution. We find an effect at th level of 1-2 %, whereas the leakage contribution is at the level of 1%.

We are now planning a new test at the MAMI tagged photon beam facility at Mainz to esclude that the observed resolution is due to the BTF beam intrinsic spread.

We have also determined the position resolution by comparing the reconstructed centroid done with the crystals with the position provided by the Beam Position Monitor of BTF; The centroids were defined as  $X_{pos} = \sum Q_i X_i / Q_{tot}$ . We observe a position resolution of  $2.8 \div 3$  mm at 500 MeV.

We have finally reconstructed the calorimeter timing after correcting it, event by event, for the arrival time of the electrons in the LINAC spill. This was done by measuring the timing with the scintillators f1,f2. The weighted energy average over all calorimeter,  $T_{clu}$ , was done after subtracting the average  $T_0$  of each cell. As shown in Fig. 3, a clean gaussian response is observed with a time resolution,  $\sigma_T$ , of  $\sim 49$  ps ( $\sim 120$  ps) at 100 MeV (500 MeV) after correcting for trigger jitter.

## References

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- [3] F. Bossi et al, for the KLOE collaboration, “Precision Kaon and Hadron Physics with KLOE”, Riv. Nuovo Cimento 031:531-623 (2009)