THE KLOE LEAD-SCINTILLATING FIBER ELECTROMAGNETIC CALORIMETER FOR DETECTING LOW ENERGY PARTICLES AT DAΦNE

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The main aim of the KLOE experiment at DAΦNE, the Frascati ϕ-factory, is to study CP violation in the $K^0 - \bar{K^0}$ system. Requirements on electromagnetic shower detection, in the 20-280 MeV/c range, are very stringent. A hermetic, lead–scintillating fiber sampling calorimeter, characterized by a fiber:lead:glue volume ratio of approximately 48:42:10, has been chosen. Energy resolution of $\sigma_E/E \sim 4.7\%/\sqrt{E\ (\mathrm{GeV})}$ and time resolution of $\sigma_T \sim 55\ \mathrm{ps}/\sqrt{E\ (\mathrm{GeV})}$ are the most significant characteristics of this detector. The calorimeter is fully operational from Summer 1998. Since then, intensive calibration studies has been carried out using cosmic rays data. At present the detector is collecting data from e^+e^- interactions produced by the DAΦNE collider: the resulting performances of the e.m. calorimeter are also reported.

1 Introduction

The main goal of the KLOE [1,2,3,4,5] experiment at DAΦNE [6], the Frascati ϕ-factory, is to study CP violation in the neutral kaon system and, in particular, to measure $\Re(\epsilon'/\epsilon)$ with an accuracy $O(10^{-4})$. For this purpose the process of main interest is $\phi \to K_S K_L \to 4\pi$. The electromagnetic calorimeter (EmC) of the KLOE detector plays a crucial role in the reconstruction of the $K_{S,L} \to \pi^0\pi^0$ decay, which produces four photons with an energy ranging

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from 20 to 280 MeV, and in the rejection of the $K_L \to \pi^0\pi^0\pi^0$ background. At KLOE the vertex reconstruction of the decay $K_{S,L} \to \pi^0\pi^0 \to 4\gamma$ is performed by accurately measuring the arrival time to the calorimeter of even a single photon [1,2]. The EmC has also to provide fast signals for first level trigger and some particle identification capability to aid rejection of $K_{\mu 3}$ decays. These requirements correspond to the following design specifications for the EmC: (1) energy resolution of the order of $5\%/\sqrt{E\ (\mathrm{GeV})}$; (2) time resolution better than 70 $\mathrm{ps}/\sqrt{E\ (\mathrm{GeV})}$; (3) determination of the γ conversion point with an accuracy of $O(1\ \mathrm{cm})$; (4) full efficiency for γ's in the range 20–280 MeV; (5) hermeticity; (6) some longitudinal and transverse segmentation; (7) capability to operate inside a 0.6 T magnetic field.

2 Design, Construction and installation

The KLOE EmC is a fine sampling lead-scintillating fiber calorimeter with photomultiplier (PM) read-out. The central part (barrel) approximating a cylindrical shell of 4 m inner diameter, 4.3 m active length and 23 cm thickness ($\sim 15\ X_0$), consists of 24 modules with trapezoidal cross-section and fibers running parallel to the beam pipe. Two end-caps close hermetically the barrel. Each of them consists of 32 "C" shaped modules arranged vertically along the chords of the circle inscribed in the barrel (see Fig.1). In the end–cap modules fibers run perpendicular to the beam pipe, so that for the whole EmC, fibers are mostly transverse to the particle trajectories. The modules are read out on the two sides through plexiglas light guides optically coupled to fine mesh PM's. The read–out granularity is $\sim 4.4 \times 4.4\ \mathrm{cm}^2$. Correspondingly a module can be considered as divided into cells, each cell read out at both ends by a couple of PMs. A barrel module has 60 cells while end-cap modules have 10, 15 or 30 cells depending on their width. The total number of read–out channels is 4880. Both in the barrel and in the end–caps, PM axes are almost parallel to the magnetic field, in order to decrease the field effects on PM response, and to increase hermeticity (see Fig.1). The PM's are fine mesh type, Hamamatsu R5946, specially designed for KLOE [7].

The basic calorimeter structure consists in an alternating stack of 1 mm scintillating fiber layers glued between thin grooved lead foils, obtained by passing 0.5 mm thick lead foils through rollers of a proper shape. The grooves in the two sides of each foil are displaced half a pitch, so that fibers are located at the corners of adjacent, quasi-equilateral triangles, resulting in an optimal and uniform arrangement of the fibers in the stack. The final composite has a fiber:lead:glue volume ratio of approximately 48:42:10, a density of $\sim 5\ \mathrm{g/cm}^3$ and a radiation length X_0 of ~ 1.6 cm, is self-supporting and can be easily

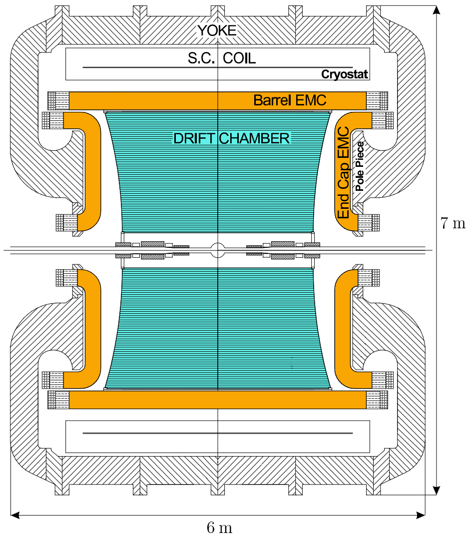

Figure 1: Schematic view of the KLOE detector

machined. The energy sampling fraction is $\sim$ 16% for a minimum ionizing particle and the efficiency for low energy photons is high due to the very small lead foil thickness ($< 0.1\ X_0$).
The module construction techniques have been reported in detail elsewhere [8]. Some EmC module prototypes were previously tested at Paul Sherrer Institute (Zurich) with e, μ, π beams of momentum ranging from 100 to 450 MeV [9]. Moreover a quality check and a first energy calibration of all the final EmC modules have been performed with cosmic rays at the Frascati Laboratory, before the installation in the experiment [10]. By extrapolating the results of the test beam and by considering that the energy release of a minimum ionizing particle crossing orthogonally one cell corresponds to the energy release of a 32 MeV photon, it is possible to derive an estimate of the final EmC performance for e.m. showers: an energy resolution $\sigma_E/E \sim 4.7\%/\sqrt{E\ (\mathrm{GeV})}$ and a time resolution $\sigma_t \sim 55\ \mathrm{ps}/\sqrt{E\ (\mathrm{GeV})}$.
The EmC modules and the front-end electronics were fully installed at the beginning of 1998. The modules, more than 4 tons weight for each barrel module and about 11 tons weight for the modules of half an end-cap, were positioned with a precision better than 1 mm.

The calorimeter has been fully operational for more than one year; $\sim$ 5000

PMs and $\sim$ 10000 ADC and TDC channels were kept in stable operation. The number of non-working channels was kept well below 0.1%.

3 Test and calibration with cosmic rays

After the installation, a fast test and calibration of the calorimeter with cosmic rays has been performed exploiting the high performance capability of the KLOE DAQ [4] and trigger [5]. The trigger consisted in requiring at least two trigger sectors fired (typical trigger rate $\sim$ 2.6 kHz), thus providing us with an unbiased sample of calibration particles along all the calorimeter volume. The DAQ system is able to record this event rate with no effort once the appropriate zero suppression is performed (typical event size of 800 Bytes for a total data throughput of 2 Mbytes/sec).
A clean sample of minimum ionizing particles crossing orthogonally five consecutive cells (a column) at the center of a module is selected by requiring an energy release greater than 32 MeV in a column, and less than the same amount of energy in the neighbouring cells. Moreover the reconstructed z coordinate along the fiber direction (see below) is required to be in the range $|z| < 30$ cm ($z = 0$ is the center of the modules). After this selection, the ADC spectrum peak (E_0) for each channel is obtained by means of a proper gaussian fit; for 1% accuracy on the peak determination, about 2000 events hitting the cell are needed. The behaviour of this peak as a function of the z coordinate, due to the attenuation of light in the fibers, can be well parametrized with a double exponential function for both sides of a cell:

$$
\begin{aligned}
E_A &= E_{0A}(R \cdot e^{-z/\lambda_1} + (1-R) \cdot e^{-z/\lambda_2}) \\
E_B &= E_{0B}(R \cdot e^{+z/\lambda_1} + (1-R) \cdot e^{+z/\lambda_2})
\end{aligned}
$$

where E_{0A}, E_{0B}, R, λ_1 and λ_2 are the free parameters of the fit.
The responses of all PMs were equalized within few percent, by adjusting the PM high voltages with an iterative procedure. The entire equalization procedure was repeated after the magnet was switched on, as the field in the PMs region slightly affects their response [7].
The times measured at the two ends of a cell are given by:

$$
\begin{aligned}
T_A &= t + T_{0A} + (L/2 + z)/v_{fib} \\
T_B &= t + T_{0B} + (L/2 - z)/v_{fib}
\end{aligned}
$$

where t is the arrival time of the particle impinging on the cell, L is the fiber length, v_{fib} is the effective light speed inside the fiber, and T_{0A}, T_{0B} are two offsets related to the delays introduced by the cable lengths. We can evaluate t and z as follows:

$$t = \frac{1}{2}[(T_A + T_B) - L/v_{fib} - T_0]$$
$$z = \frac{1}{2} \cdot v_{fib} \cdot [(T_A - T_B) - \Delta T_0]$$

where $T_0 = T_{0A} + T_{0B}$, $\Delta T_0 = T_{0A} - T_{0B}$, v_{fib} and L are constants to be determined. The L values were measured with good precision during the geometry survey of the calorimeter modules before their installation.
As cosmic rays uniformly impinge on the modules, ΔT_0 and v_{fib} can be easily determined for each cell from the measured $T_A - T_B$ distribution. The parameters ΔT_0 and v_{fib}, related to the center and to the width of the distribution, are determined by a fit with a precision of 20 ps and 0.2%, respectively.
Concerning the determination of the parameter T_0, a sample of *straight* cosmic ray events with momentum greater than 6 GeV/c is selected. The measured time pattern for each event, i.e. the measured $(T_A + T_B)$ for all the cells crossed by the cosmic muon as a function of the known distance between the cells, is fitted assuming they are crossed by a particle travelling at the speed of light. The residuals distribution for each cell is narrowed and centered to zero by an iterative procedure. At the end the T_0 for each cell is provided by the sum of the corrections applied at each step of the procedure, and are determined with a precision of 10 ps.
As cross-check of the good time calibration of the calorimeter, the time difference between the first and the last cell hit by a cosmic ray in a module is measured. Muons coming from the internal volume of the detector can be easily distinguished from those coming from outside, as shown in Fig.2-left. In this way cosmic muons can be identified (and rejected) with an efficiency of $\sim 98\%$. Another check of the time calibration consists in measuring the velocity of cosmic rays crossing the detector as a function of the momentum: the time of flight is measured with the calorimeter, while the momentum and the track length are independently measured with the KLOE drift chamber. A fit to the measured distribution with the relativistic velocity $c\beta = cp/\sqrt{p^2 + m^2}$, leaving the mass m as the only free parameter of the fit, provides a value in very good agreement with the muon mass, as shown in Fig.2-right.

4 Results with colliding beams

The KLOE detector is self-calibrating: apart from cosmic rays, the huge amount of Bhabha, $e^+e^- \to \gamma\gamma$, and kaon decay events provide fast and precise calibration signals. The general strategy for the calorimeter is to use cosmic

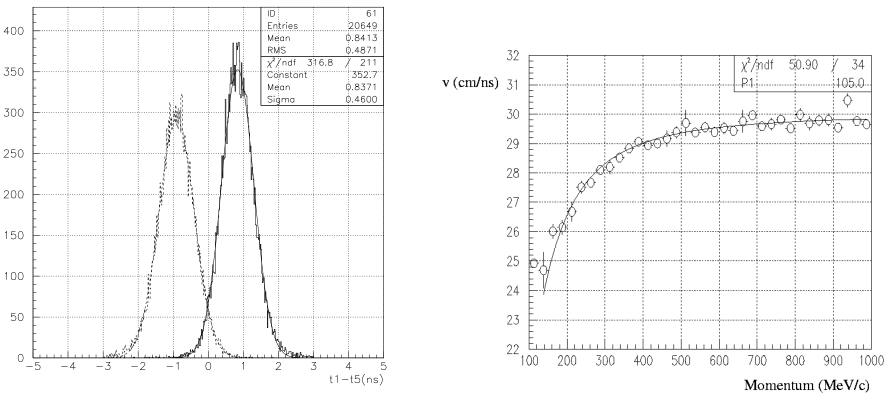

Figure 2: [Left] $t_{first} - t_{last}$ distribution for ingoing (dashed) and outgoing (solid) cosmic muons. [Right] Measured velocity as a function of momentum for cosmic rays crossing the KLOE detector. The fit with the relativistic velocity $c\beta = cp/\sqrt{p^2 + m^2}$ is superimposed.

rays for a first relative energy and time calibration in a completely stand-alone way, as described above. Then, using Bhabha and $e^+e^- \to \gamma\gamma$ events, fine corrections to the cell intercalibration are applied and the absolute energy and time scales are set.

Since April 1999 e^+e^- collisions started at DAΦNE and the first physics events were collected by KLOE. The integrated luminosity for the first period of continuous data taking was $\sim$ 200 nb^{-1} and allowed us to set-up the calibration procedure and to perform preliminary calibration corrections. More sophisticated studies will be possible at higher statistics, after the DAΦNE tuning phase.

Bhabha events are used to correct the relative energy calibration between the cells: the corrections resulted small due to the quite good cosmic ray calibration. However, since electrons and positrons from Bhabha events lose few MeV energy in crossing the beam pipe and the drift chamber walls before reaching the calorimeter, the absolute energy scale is set using $e^+e^- \to \gamma\gamma$ events. The energy resolution obtained for Bhabha electrons impinging on all barrel modules is $\sigma/E \simeq 7.8\%$, which corresponds to $\sigma/E \simeq 5.5\%/\sqrt{E(\mathrm{GeV})}$.

As a check of the calorimeter calibration we reconstructed the invariant mass of the photon pair from $\phi \to \pi^+\pi^-\pi^0$ events. The peak in the invariant mass

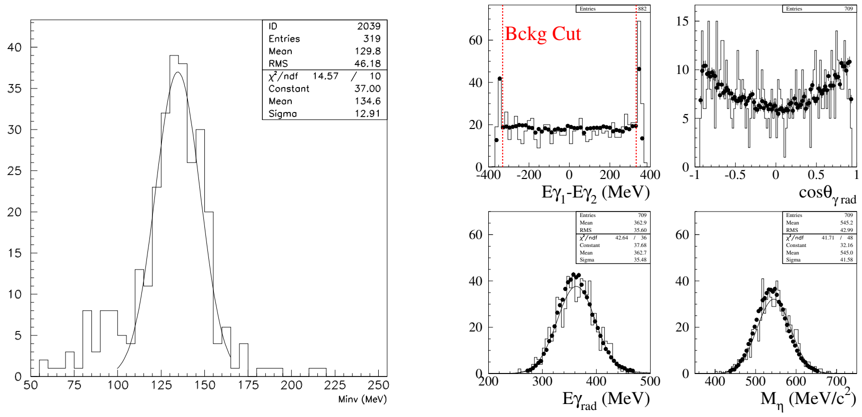

Figure 3: [Left] Reconstructed invariant mass for photon pairs from $\phi \to \pi^+\pi^-\pi^0$ events. [Right] Comparison between data (histogram) and Monte Carlo (black dots) in the case of $\phi \to \eta\gamma \to \gamma\gamma\gamma$ events. Top left: distribution of the energy difference between the photons from $\eta \to \gamma\gamma$ decays; the cuts applied to reject the background are also shown. Top right: angular distribution of the radiated photon. Bottom left: radiated photon energy distribution. Bottom right: reconstructed η invariant mass distribution.

distribution is well centered at the π^0 mass, as shown in Fig.3-left. Another good check is the reconstruction of $\phi \to \eta\gamma \to \gamma\gamma\gamma$ events [11]. The measured energy and angular distributions are in perfect agreement with the Monte Carlo estimates, as shown in Fig.3-right. The above results are compatible with a $\sim 1\%$ linearity of the energy scale. More precise tests on linearity will be performed using γ's from radiative Bhabha events.

In order to evaluate the time performances of the calorimeter, the quantity $\Delta t = t_{clus} - R_{clus}/c$ is measured for the photons of $e^+e^- \to \gamma\gamma$ events, selected for simplicity on all barrel modules; t_{clus} is the arrival time of the particle on the calorimeter, obtained by energy weighting the times measured by all the cells belonging to a shower (i.e. a *cluster* of cells); R_{clus} is the distance between the interaction point and the centroid of the cluster, so that the quantity R_{clus}/c corresponds to the time of flight of the photon. The measured Δt distribution is centered at zero, as expected. The resolution is $\sigma_{\Delta t} \simeq 138$ ps. Even though the KLOE trigger is synchronized to the machine clock, the uncertainty on the instant of e^+e^- collision due to the longitudinal beam size ($\sigma_z \sim 3$ cm) still contributes to the Δt spread with a sigma of ~ 100 ps. After subtracting this contribution we can quote a time resolution $\sigma_{\Delta t} \simeq 95$ ps, that, using an energy dependent parametrization, corresponds to $\sigma_{\Delta t} \simeq 68 \text{ ps}/\sqrt{E(\text{GeV})}$.

5 Conclusions

The KLOE calorimeter has been fully operational for more than one year. Continuous and accurate time and energy calibrations have been performed using cosmic rays. After DAΦNE e^+e^- collisions started, calibration refinements with Bhabha and $e^+e^- \to \gamma\gamma$ events have been going on. Preliminary studies on energy and time performances of the whole calorimeter show resolutions in agreement with the expected ones.

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