Kloe Note 162

October 1996

A status report on the KLOE electromagnetic calorimeter

M. Antonelli,[c] F. Anulli,[c] G. Barbiellini,[j] S. Bertolucci,[c] C. Bini,[f] C. Bloise,[c] R. Caloi,[f] G. Cabibbo,[g] P. Campana,[c] F. Cervelli,[e] G. De Zorzi,[f] G. Di Cosimo,[f] A. Di Domenico,[f] O. Erriquez,[a] S. Di Falco,[e] A. Farilla,[a] A. Ferrari,[f] P. Franzini,[f,d] P. Gauzzi,[f] S. Giovannella,[c] E. Graziani,[h] S. W. Han,[c,b] M. Incagli,[e] W. Kim,[i] G. Lanfranchi,[f] J. Lee-Franzini,[c,i] T. Lomtadze,[e] S. Miscetti,[c,*] F. Murtas,[c] F. Scuri,[j] E. Spiriti,[h] L. Tortora,[h] G. Venanzoni,[e] S. Wölfle,[c] J. Q. Zhang.[c,b]

[a] Dipartimento di Fisica dell'Università e Sezione INFN, Bari

[b] Institute of High Energy Physics of Academica Sinica, Beijing, China

[c] Laboratori Nazionali di Frascati dell'INFN, Frascati

[d] Physics Department, Columbia University, New York

[e] Dipartimento di Fisica dell'Università e Sezione INFN, Pisa

[f] Dipartimento di Fisica dell'Università e Sezione INFN, Roma I

[g] Dipartimento di Fisica dell'Università e Sezione INFN, Roma II

[h] Istituto Superiore di Sanità and Sezione INFN, ISS, Roma

[i] Physics Department, State University of New York at Stony Brook

[j] Dipartimento di Fisica dell'Università e Sezione INFN, Trieste/Udine

Abstract

The design, the methodology and status of construction of the KLOE electromagnetic calorimeter are described in this report. 18 out of 24 *barrel* modules have been fully assembled and more than 50% of the *end-cap* modules have been

*Reporting for the EmCal group at the ICHEP 96 conference held in Warsaw-Poland

built. End of construction is foreseen for the beginning of 1997. All experimental specifications are fulfilled as shown by the nice test beam results on the final size prototype (module 0) carried on at the Paul Scherrer Institute in summer 1994. Since then the quality of fibers and photomultipliers have gone through improvements resulting in final calorimeter performances which exceed our expectations. The main calorimeter parameters of each module (light yield, attenuation length and timing resolution) are fully surveyed at the Cosmic Ray Stand which has been setup in the Frascati National Laboratories. Extrapolating these values to electromagnetic showers a time resolution of $\sim\ 55\,\mathrm{ps}/\sqrt{\mathrm{E(GeV)}}$ and a resolution of $0.9\,\mathrm{cm}/\sqrt{E(\mathrm{GeV})}$ on the coordinate along the fibers are obtained for *barrel* modules. An energy resolution of $4.7\%/\sqrt{E(\mathrm{GeV})}$ can also be quoted. Preliminary results for the calibration of the first *end-cap* module are also very satisfying. An equalization in response at a level of 2 % for all the calorimeter readout elements is in progress.

1 Introduction

The main goal of the KLOE [1] experiment at the DAΦNE ϕ-factory is to study CP violation in neutral kaons decays by measuring $\Re(\epsilon'/\epsilon)$ with an accuracy of $\mathcal{O}(10^{-4})$. To perform this measurement the electromagnetic calorimeter should detect photons coming from π^0's in order to reconstruct the vertex of the neutral decay $K_{L,S} \to \pi^0\pi^0$ and reject the $K_L \to \pi^0\pi^0\pi^0$ background. Because of the low speed of kaons ($\beta_K \sim 0.2$), vertex reconstruction can be performed independently for each photon by measuring its arrival time on the calorimeter. This method requires excellent timing performances of the calorimeter. Detector simulation studies provide the following requirements:

1. Energy resolution of $\mathcal{O}(6\%/\sqrt{E(\mathrm{GeV})})$;
2. Time resolution of $\mathcal{O}(70\,\mathrm{ps}/\sqrt{E(\mathrm{GeV})})$;
3. Determination of γ's conversion point with an accuracy of $\mathcal{O}(1\ \mathrm{cm})$;
4. High efficiency for γ's down to 20 MeV;
5. Hermeticity;
6. Fast signals for triggering purposes.

We chose a lead–scintillating fibers sampling calorimeter with very thin lead foils to exploit the excellent timing performances of fibers, providing also good energy resolution.

2 The KLOE calorimeter

The KLOE electromagnetic calorimeter [2] consists of a central part, the *barrel* and two *end-caps*. The *barrel* is organized in 24 modules, 4.3 m long and 23 cm thick, with a trapezoidal cross section arranged on a cylindrical shell of 4 m inner diameter. Fibers run parallel to the beam. Each *end-cap* consists of 32 modules of different lengths which run vertically along the chords of the circle inscribed in the *barrel*. They are 23 cm thick and are bent outwards at the two ends, becoming parallel to the *barrel*. The resulting C shape provides a hermetical coverage of the calorimeter.

Each calorimeter module is built by glueing 1 mm diameter scintillating fibers between thin grooved lead planes obtained by plastic deformation of 0.5 mm thick foils. Fibers run parallel to each other and are located at the corner of adjacent quasi–equilateral triangle with a pitch of 1.35 mm. The result is a homogeneous and compact structure with a density of $\sim$ 5 g/cm^3 and a fiber:lead:glue volume ratio of 50:40:10, which corresponds to a 15% sampling fraction for a *minimum ionizing particle (m.i.p.)*. Kuraray SCSF-81 and Pol.Hi.Tech. 0046 fibers, both emitting in the blue region, are used: measurements carried on samples of fibers show that they satisfy our requirement for light yield, scintillation decay time and attenuation length [3].

The modules are read-out at both ends, in order to reconstruct the coordinate along the fibers using time differences, with a granularity of about (4.4×4.4) cm^2. Each light guide consists of a mixing part and a Winston cone concentrator which allows an area reduction up to 4 with an efficiency in light collection of $\sim$ $80 \div 90\%$. Since the calorimeter is inside a 0.6 T magnetic field, fine mesh Hamamatsu R5946 PMs, specially designed for KLOE, are used [4].

3 Test of Module 0

At the beginning of 1994 the first full size *barrel* module has been built, equipped with the final light guides, PMs' and front-end electronics. The readout consists of 60 elements/side organized in 12 columns and 5 planes along the calorimeter depth. It was taken to the Paul Scherrer Institut, Zurich, in July to be tested with electron, muon and pion beams in a momentum range $100 \div 450$ Mev/c. The module was calibrated using *m.i.p.*s: the energy released in each cell from particles impinging perpendicularly at the calorimeter center (MIP) represents our unit of energy. In the following paragraphs results for electrons are discussed.

3.1 Energy response and resolution

The distributions of total energy, that is the calibrated sum of energy over all fired channels, are gaussian with almost no tails. The energy response is linear, independently of the incidence angle (see Fig. 1.a). The slope of 31 MIP/GeV corresponds to a sampling fraction of 13% and to a light yield of $\sim$ 1660 N_{pe}/GeV for Kuraray fibers and $\sim$ 1075 for Pol.Hi.Tech. ones. The energy resolution (Fig. 1.b) is $\sigma_E/E = 5\%/\sqrt{E(\mathrm{GeV})}$ and is fully dominated by sampling fluctuations.

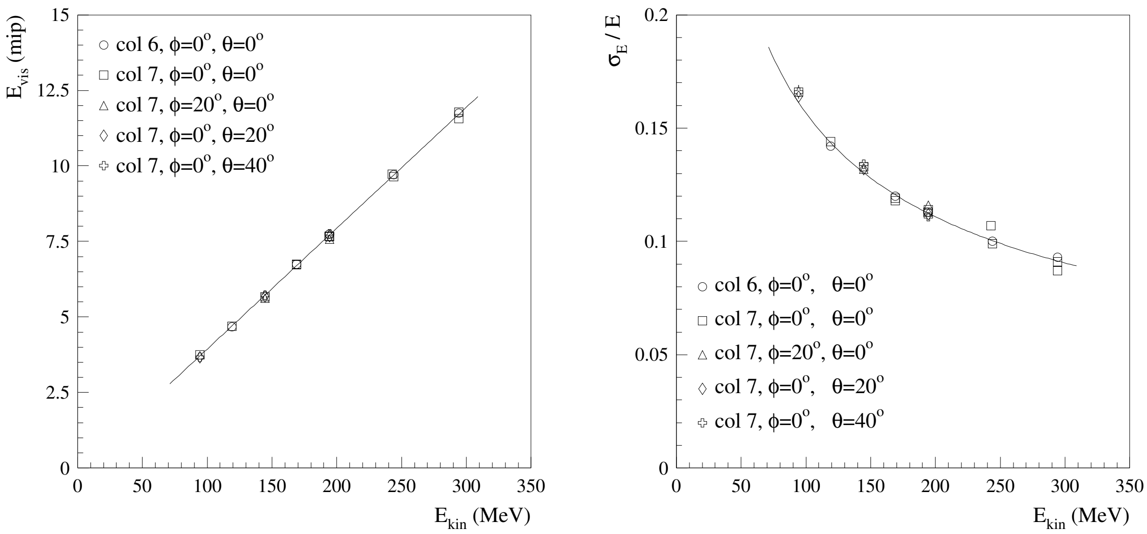

Figure 1: Energy response and resolution for electrons as function of beam momentum. Solid lines correspond to 31 MIP/GeV and $5\%/\sqrt{E(\mathrm{GeV})}$ for the energy response and energy resolution respectively.

3.2 Time resolution

The event time is defined as the mean between the times of A (T_A) and B (T_B) sides, obtained using all the cells belonging to the shower and weighted with their own energy:

$$T = \frac{1}{2} \frac{\sum_i (T_A + T_B)_i \, (E_A + E_B)_i}{\sum_i (E_A + E_B)_i}$$

A simple gaussian fit nicely reproduces the time distribution. After quadratically subtracting the jitter of the trigger ($\sim$180 ps), the time resolution (Fig. 2) can be parameterized as: $\sigma_T = 72\,\mathrm{ps}/\sqrt{E(\mathrm{GeV})}$ showing its dependence on the number of collected photoelectrons N_{pe}.

4 Methodology and status of construction

The satisfactory results of the prototypes [5] and of module 0 convinced us to freeze the design and to start the massive construction. A description of the mechanical assembly, the fiber quality control, the final module wrapping and the status of construction are reported in the following paragraphs.

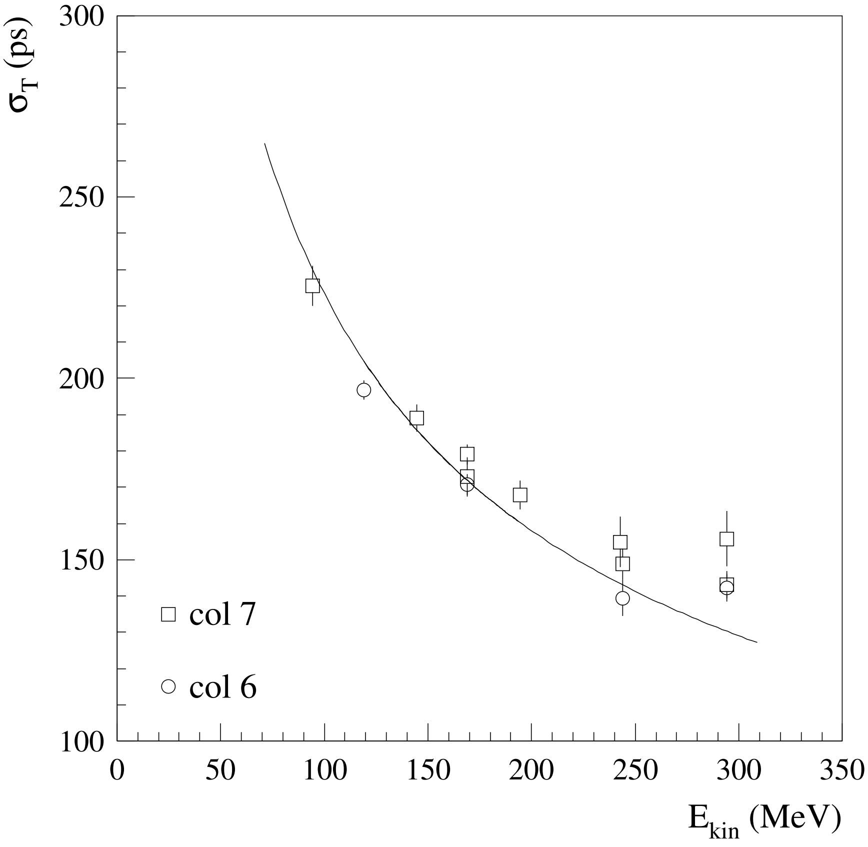

Figure 2: Time resolution for electrons as function of beam momentum. Solid line corresponds to 72 ps/$\sqrt{E(\mathrm{GeV})}$.

4.1 Mechanical assembly

After a preliminar transferring of a set of tools and our basic *know-how*, the mechanical assembly of the *barrel* modules is being carried out from Pol.Hi.Tech. industry. The procedure of construction for the *barrel* can be summarized in the following 3 steps:

1. Lead foils of 0.5 mm thickness are machined to the proper grooved shape by plastic deformation through a lead rolling machine (*lead-o-matic*). This machine consists in two grooved rollers, made of hardened steel and ground to shape by a sintered diamond tool, mounted with ball bearings on a very rigid frame and aligned with a set of micrometers. Tolerances on foil construction are kept tight in order to facilitate the assembly of the lead-fibers stack and to build an homogeneous composite. Lead foils used for the *barrel* are 450 cm long and 65 cm wide; The pitch between grooves is precise to a level of $20-30\mu$m. The grooves do not deviate by more than 0.5 mm from a straight line. The grooved lead foils thickness is required to be in within 100 μm from nominal.

2. The mechanical assembly starts by glueing the first lead foil on the 3 cm thick aluminum supporting plate. After the first layer has been set, a small amount ($\sim$130 g) of non aggressive epoxy glue (*Bicron BC600*) is distributed on the plane; a layer of fibers is then positioned in the grooves semi-manually with the help of a fibers-holder, then glue is spread again before positioning next lead foil. This procedure is repeated until a stack of 7-8 planes is formed. Before the glue starts curing, a uniform pressure of 1 Ton is applied for 2 hours on the calorimeter surface to allow a more uniform distribution of the glue. The thickness of the growing stack is surveyed during the construction in 30 specific points along the module surface.

3. The procedure of stacking is repeated until a thickness of 23 cm is reached which corresponds to $\sim$ 200 lead-fibers planes. Modules thicknesses stay inside 2 mm from nominal dimensions.

The calorimeter composite has a density of 64 fibers/cm^2; given a transverse area of around 1300 cm^2 and a 4.3 m length we need around 82000 fibers for each *barrel* module, which is $\sim$ 350 Km. Typical weight of a module is 3 Tons, with around 280 Kg of fibers and 50 Kg of glue. Speed of construction is 3 weeks/module.

A similar technique is used also for the *end-cap* modules; the only relevant difference being the treatment of the curved sections. The growing stack is assembled flat by using a special platform with removable ends, after stacking $\sim$ 15-30 layers these extensions are removed and the lead-fibers composite is laid down with a special tool along the curved aluminum support; pressure is then applied on the straight and curved sections for $\sim$ 2 hours. Since we have 64 modules of different weight and dimensions, we are building them in parallel in 3 assembly stations, (Pisa,Roma, Frascati) each one being specialized for different module sizes. Speed of construction is 2 weeks/module.

4.2 Monitoring of fibers quality

One of the most stringent requirements in our calorimeter is to maintain the excellent time resolution shown by module 0 for all the modules. In order to do this and to allow the most uniform response as possible we monitor the fibers quality we use by randomly selecting and then testing two of these fibers per batch. There are two test stations, one in Pol.Hi.Tech. and one in Frascati National Laboratories (LNF); they mainly consists of a moveable β source (Sr^{90}) which can be positioned in reference points along the fibers, the light is then collected on a PM optically air-coupled. The intensity of current is registered on each point and then fitted with a the sum of two decreasing exponentials.

Fig. 3 shows the distribution of the longest attenuation length, λ, and its corresponding current, I, for the fibers monitored in Frascati; these parameters are measured with a reproducibility of 2% and 4% respectively.

Since the timing resolution depends on the light yield proportionally to $1/\sqrt{\mathrm{N}_{pe}}$ its lower limit is given by the N_{pe} collected from the farthest point from the PM. Our

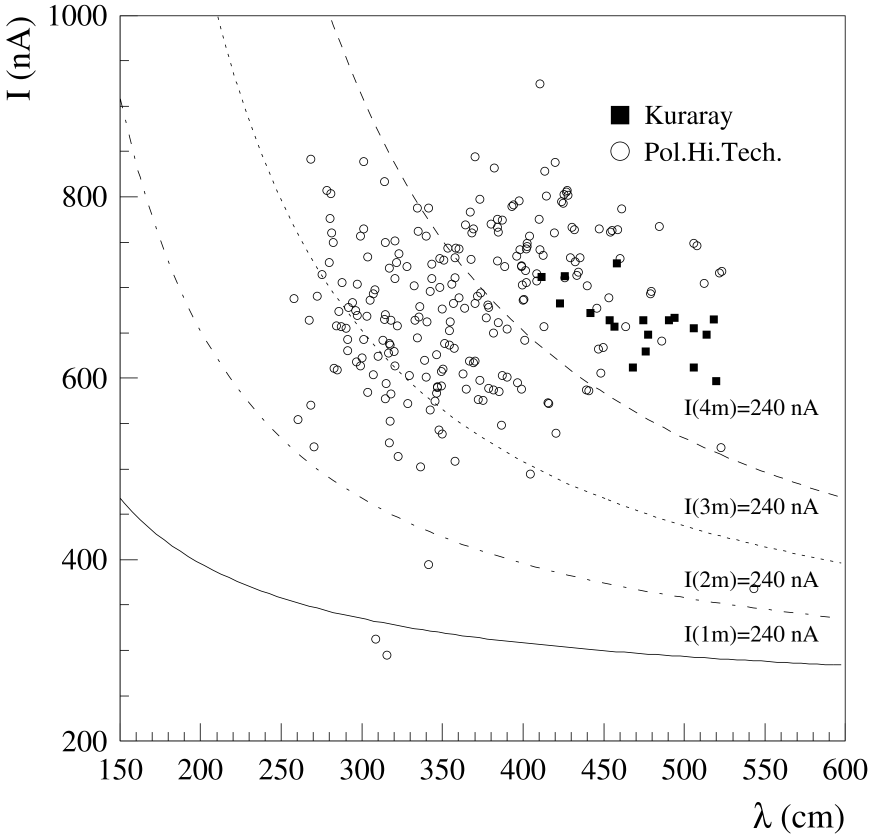

Figure 3: Current (I) and attenuation length (λ) for fibers measured at LNF.

policy is to accept all fibers giving a minimum amount of current (240 nA in our setting) when illuminated at their farthest end. The Pol.Hi.Tech. production has gone through a continuous improvement in 1994 and since 1995 it is practically equivalent to the Kuraray one. The older Pol.Hi.Tech. production, with smaller values of λ is used for the construction of short *end-cap* modules. Up to now we have accepted all received Kuraray fibers and rejected less than 1% of Pol.Hi.Tech. ones.

4.3 Modules final coverage

Once the modules are mechanically assembled they are brought to another firm for the milling and then sent back to LNF for the final assembly. Here a new set of measurements on mechanical dimensions are taken. The modules should deviate from nominal thickness not more than 2 mm along all the surface.

Modules are then wrapped with aluminium tape of 0.1 mm thickness for light tightness; only the faces are left uncovered. The lead deposition on fibers due to milling is removed by using a razor. The surface is then smoothed by distributing a small amount of optical glue on it. A preliminar mounting of light guides is tried before glueing them to check if they stay inside tolerances; corrections of the order of 0.1 mm per light guide is sometime necessary in order to glue them on the right place. A survey of the final light-guides positioning is also performed. After this is done the PMs' holder is mounted in an aluminum box.

4.4 Status of construction

At the moment we have 18 out of 24 *barrel* modules fully assembled and more than 50 % of the *end-cap* modules mechanically built. Given the speed of construction we foresee to have all calorimeter modules completely done at beginning of 1997.

5 The Cosmic Ray Test Stand

In order to test and calibrate calorimeter modules a Cosmic Rays Test Stand, consisting of a telescope exposed to cosmic *m.i.p.*s, has been set-up at the Frascati INFN Laboratories.

5.1 The experimental set-up

The calorimeter module under test is positioned between the two parts of the telescope as sketched in Fig. 4. Each part consists of: (*i*) six (60×7) cm^2 NE110 scintillator slabs; (*ii*) two planes of (310×64) cm^2 Limited Streamer Tubes (LST) with longitudinal and transverse read-out provided by 1 cm pitch aluminum strips. A 5 cm thick lead layer is inserted between the module and the bottom halves of the telescope to harden the energy spectrum of the particles. The trigger, requiring a coincidence of scintillators or LST in the top and in the bottom halves, provides 10^6 good tracks in few days of data taking.

5.2 Evaluation of calibration constants

Calibration constants have been evaluated selecting events with a single track impinging on the calorimeter surface with an angle smaller than 15° respect to the vertical direction.

To obtain the energy response and the attenuation length λ for each read-out element, the dependence of the ADC signal on z_{fit} (the z coordinate of the cell as extrapolated by the telescope) is studied. The full area covered by LST ($\sim$ 3 m) is then divided in slices of 20 cm along z and the corresponding ADC distributions, Fig. 5.a are fitted to get the peak. Fig. 5.b shows the result of this procedure for a calorimeter channel; the superimposed exponential fit gives λ and the value of the energy deposited at $z=0$ (MIP) with a reproducibility of 2% and 0.5% respectively.

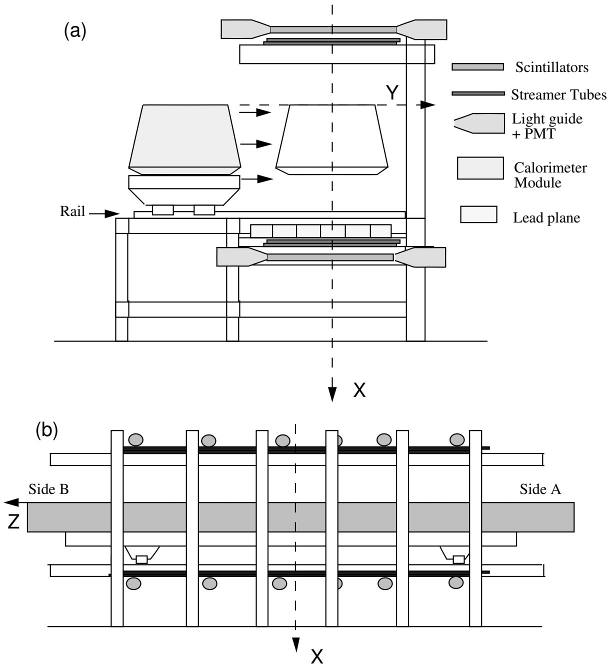

Figure 4: Front view (a) and side view (b) of the Cosmic Rays Test Stand set-up.

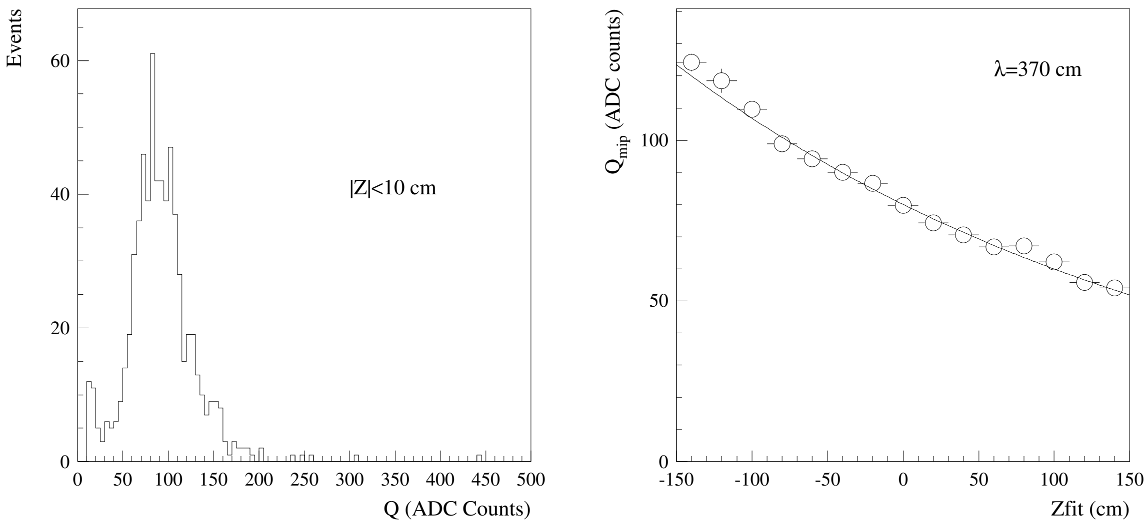

Figure 5: Example of ADC distribution for $m.i.p.$s (a), ADC vs Z_{fit} (b).

The time difference between the two sides of a calorimeter cell is linearly related to the z impact position of the particle: $\mathrm{z} = \frac{1}{2} v_f \Delta T$, where v_f is the light velocity within fibers. Fig. 6 shows the dependence of ΔT on z_{fit}. A linear fit gives v_f with a statistical uncertainty of 0.2% and the time difference between T_0's of the two sides with an uncertainty of 10 ps. Typical values for v_f are around 17 cm/ns. In order to subtract event by event the large jitter of the trigger, ΔT is also used to evaluate the

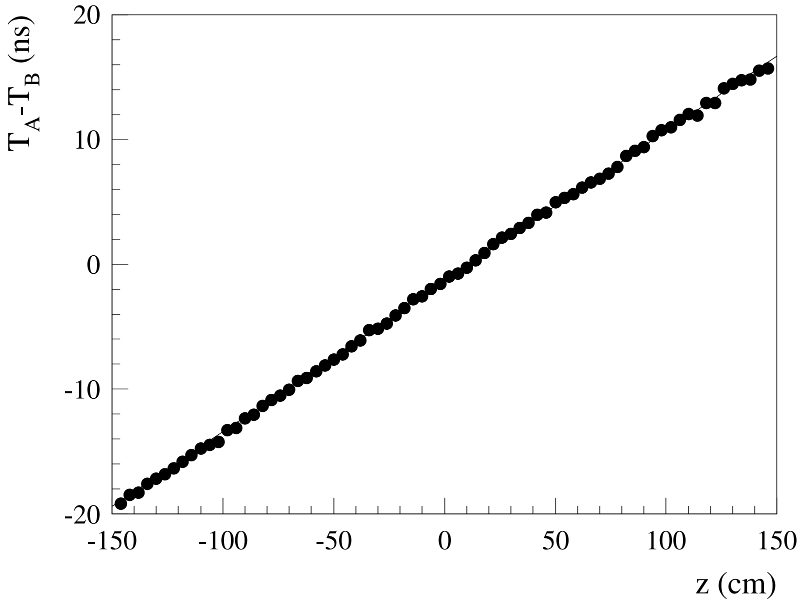

Figure 6: Time difference as function of the Z_{fit} coordinate for a calorimeter element.

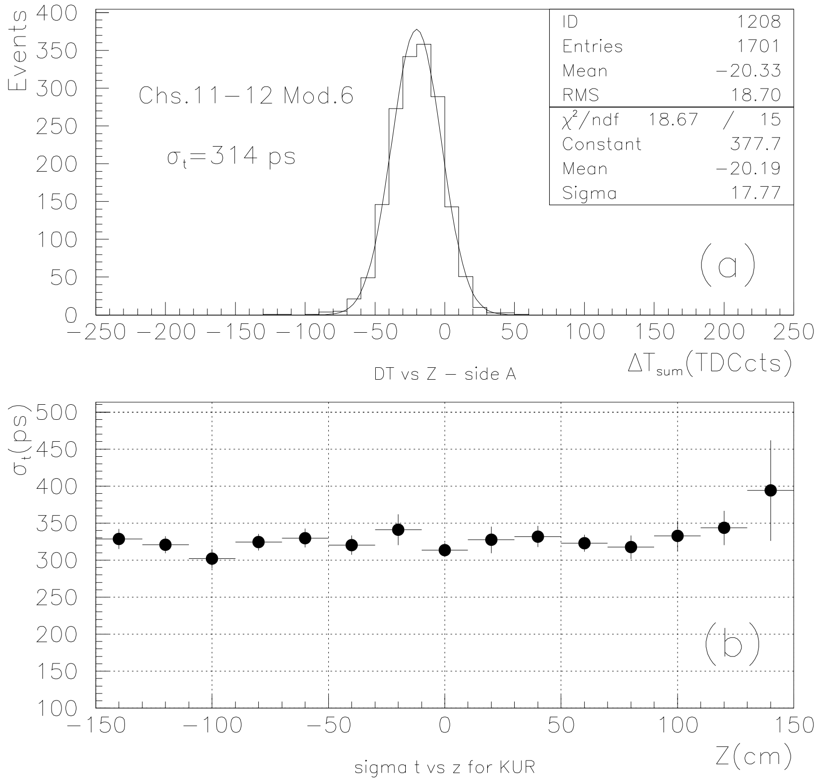

Figure 7: Example of Time resolution for Kuraray fibers.

time resolution. Assuming that at cell center the two sides have identical response: $\sigma_{T_{A,B}} \sim \sigma_{\Delta T}/2$. A complementary method consists in evaluating the difference of the mean times for two consecutive cells along the calorimeter depth. We restrict this method only to the pairs of cells build with Kuraray or Pol.Hi.Tech. fibers. Example of this new ΔT variable is shown in Fig. 7 together with its dependence on the Z coordinate. Both methods give consistent results on timing resolution in within 10 %.

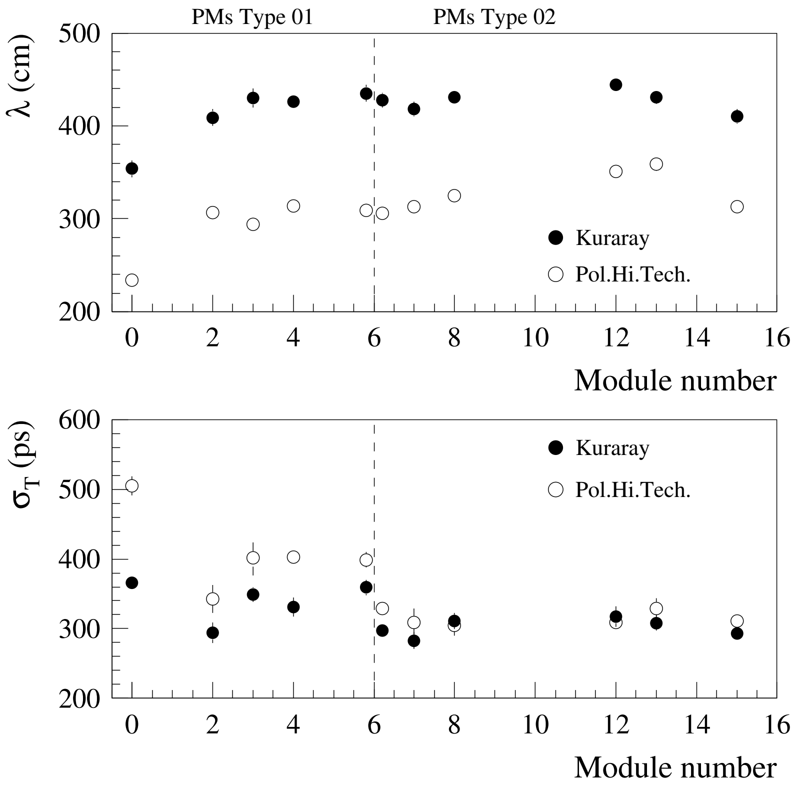

Figure 8: Average module characteristics as function of module production number.

5.3 History of modules performances

The characteristics of the built modules are summarized in Fig. 8 where the average values of λ and σ_t are shown as function of the module construction number. We averaged separately the cells built with Kuraray or Pol.Hi.Tech. fibers to investigate their differences and their changes in production along the time.

The first relevant information to be pointed out is the big improvement in performances, both in λ and σ_t between the module 0 and the first produced module. This is mostly due to a more careful handling of the fibers since we have observed a fast deterioration of their characteristics by exposing some samples to day-light [6]. It has also been shown that this damage is produced by UV light destroying the scintillating centers. In order to reduce this problem all major light sources in the assembling buildings have been covered with yellow filters; this was done during construction of module 6 as it can be observed from the flattening of the characteristics for the modules with higher production number.

Lately, an improved version of PM R5946, series 02, with higher quantum efficiency (ϵ_q) than series 01 has been produced by Hamamatsu. In order to test it, we have measured module 6 with both kind of PMs; as expected the time resolution, which behaves as $1/\sqrt{N_{pe}}$, shows a decrease of $\sim$ 15 %, corresponding to an improvement of 30 % on ϵ_q. As expected no changes are observed on the determination of λ.

We will use 1300 PMs, series 01, for the readout of the last planes of the *barrel* and the shortest *end-cap* modules. The remaining 3700 PMs, series 02, will be used elsewhere.

All tested modules from 6 to 15 have been equipped with their own final PMs. They all show excellent timing performance of $\sim$ 310-330 ps per cell; since the energy deposited by a *m.i.p.* is equivalent to a 32 MeV photon, we can extrapolate for e.m. showers a time resolution of $55\,\mathrm{ps}/\sqrt{E(\mathrm{GeV})}$ and a resolution of $0.9\,\mathrm{cm}/\sqrt{E(\mathrm{GeV})}$ on the coordinate along the fibers. From the measured light yield and the PSI test beam measurements an energy resolution of $4.7\%/\sqrt{E(\mathrm{GeV})}$ is quoted. Simple test of this extrapolation has been done on module 0 by comparing results obtained at PSI with the CRS ones; the agreement is pretty good.

In the last months, we have also extended the CRS to calibrate at the same time both *end-cap* and *barrel* modules. This extension basically consists of:

- A support platform, to insert the *end-cap* module , which is positioned $\sim$ 20 cm above the top half of the telescope;
- A scintillating fibers counter: 350 cm long, 15 cm wide, with y-z reconstruction capabilities (σ_y =5 mm, σ_z =5 cm) positioned above the *end-cap* to help reconstructing the track trajectory.

Analysis criteria similar to the ones described for the *barrel* on sect. 5.2 have been developed. Results on the first fully equipped *end-cap* module show values for λ in agreement with the *barrel* and values of σ_t of 280-300 ps/cell. This last result is even better than the one for *barrel* modules as it can be seen on Fig. 9; the difference is mostly accounted for by the shorter *end-cap* length.

5.4 Equalization

In order to select the final PMs for each module and to set a good HV working point for each PM, we are equalizing in response all calorimeter cells. An equalization below 5 % grants a sufficient accuracy for the trigger to avoid using correcting weights when performing the analog sum of cells. Furthermore, although we expect some changes of PMs gain when inserted inside the B-field of the experiment, we are confident that

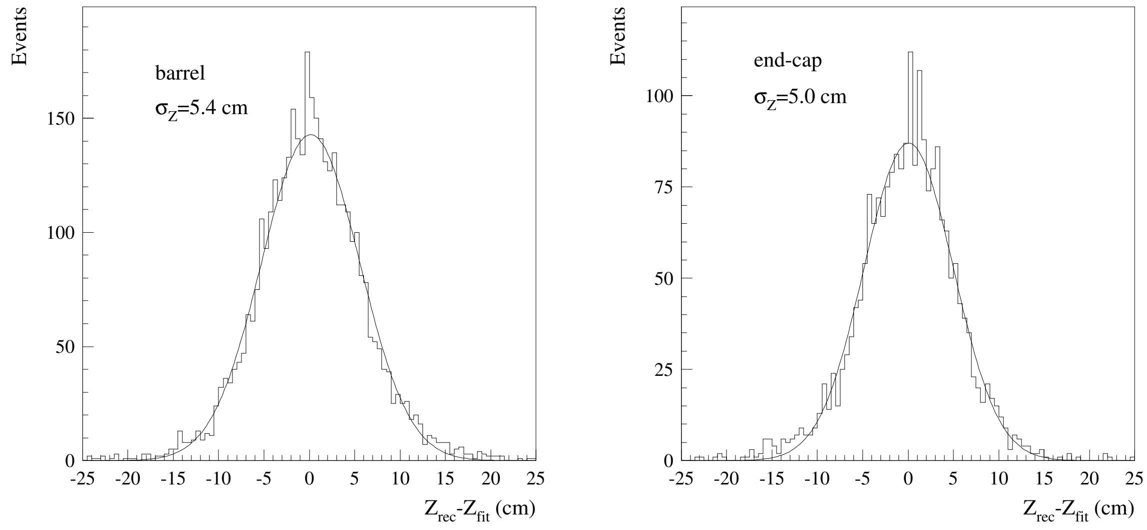

Figure 9: Z reconstructed for barrel and endcap.

these changes will be minimal (below 10 %) and mostly concentrate on the last planes of the *end-cap* modules.

The calibration point has been set by requiring an average response (Q_0) of 15 pC per side for *m.i.p.*s crossing at module center. This value has been selected in order to guarantee an efficient coverage of the ADC full range for the signals expected in the experiment.

We start setting the HV in order to get an average gain (G) of 2×10^6 using the measured PM gain curve. We then take data for two days to evaluate the MIP value with reasonable accuracy and we set again the HV to better adjust the calibration point. This procedure is usually repeated for 3 times; at the end of the third round the HV setting and the calibration constants are recorded. The level of equalization obtained is below the 2% as shown by Fig. 10.

6 Conclusions

The construction of the KLOE e.m. calorimeter is more than half a way through and the end of construction is foreseen for the beginning of 1997. All the technical choices made look appropriate to achieve the required performances.

Along construction the fibers and photomultipliers used had gone through a sensible improvement and by measuring each module at the CRS with *m.i.p.*s we can extrapolate an average improvement of $\sim$ 30 % on timing. A timing resolution of $\sim 55\,\mathrm{ps}/\sqrt{\mathrm{E(GeV)}}$ and a resolution of $0.9\,\mathrm{cm}/\sqrt{E(\mathrm{GeV})}$ on the coordinate along the fibers have been obtained in the last modules. An energy resolution of $4.7\%/\sqrt{E(\mathrm{GeV})}$ is estimated.

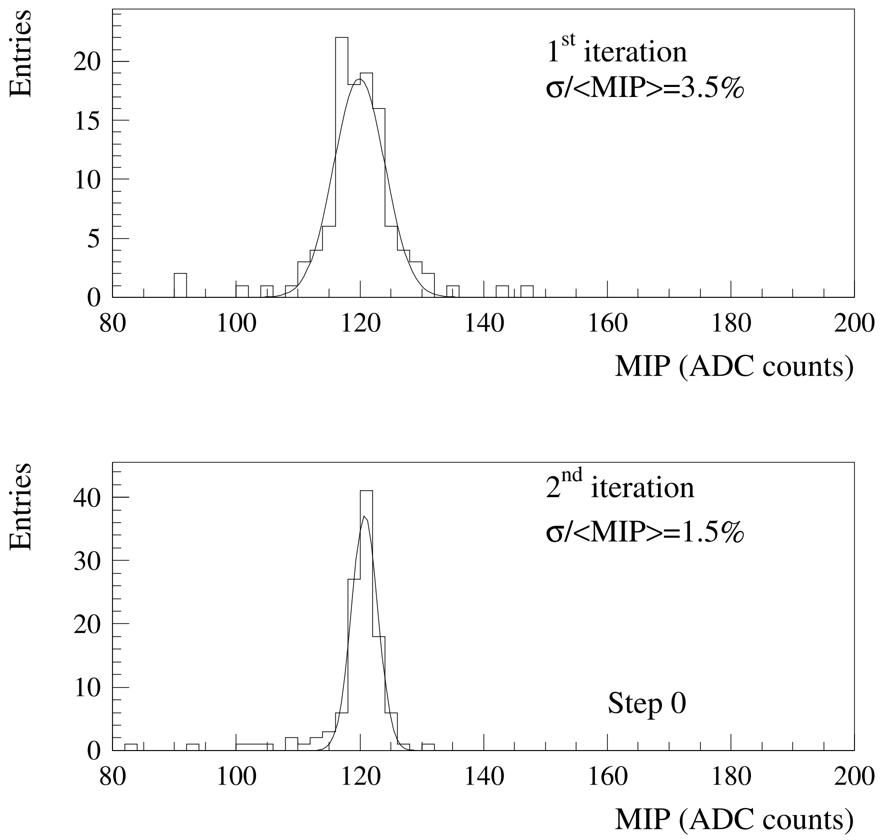

Figure 10: Example of equalization in response for the 120 PMs of a barrel module.

Results for the calibration of the first fully assembled *end-cap* module are also excellent.

An equalization in response at a level of 2 % for all the calorimeter readout elements is in progress.

Acknowledgements

We gratefully acknowledge our excellent technical stuff.

References

[1] The KLOE Collaboration, A General Purpose Detector for DAΦNE, LNF-92/019 (1992).

[2] The KLOE Collaboration, The KLOE Detector Technical Proposal, LNF-93/002 (1993).

[3] A. Antonelli et al., Nucl. Instr. and Meth. A 370 (1996) 367.

[4] A. Antonelli et al., Nucl. Instr. and Meth. A 368 (1996) 628.

[5] A. Antonelli et al., Nucl. Instr. and Meth. A 354 (1995) 352.

[6] M. Anelli et al., Damage induced by light irradiation on blue scintillating fibers, KLOE note 136 (1995).