Tile and crystal calorimeters for the KLOE$^2$ experiment

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The upgrade of the DAΦNE machine layout requires a modification of the size and position of the inner focusing quadrupoles of KLOE$^2$ thus asking for the realization of two new calorimeters covering the quadrupoles area. To improve the reconstruction of $K_L \rightarrow 2\pi^0$ events with photons hitting the quadrupoles, a tile calorimeter, QCALT, with high efficiency to low energy photons (20-300 MeV), time resolution of less than 1 ns and space resolution of few cm, is needed. We propose a tile calorimeter with a high granularity readout corresponding to about 2500 silicon photomultipliers (SiPM) of $1 \times 1 \text{mm}^2$ area. Moreover, the low polar angle regions need the realization of a dense crystal calorimeter with very high time resolution performances to extend the acceptance for multiphotons events. Best candidates for this calorimeter are LYSO crystals with APD readout or PbWO$_4$ crystals with large area SiPM readout.

1. The KLOE$^2$ proposal

In the last decade a wide experimental program has been carried out at DAΦNE$^1$, the $e^+e^-$ collider of the Frascati National Laboratories, running at a center of mass energy of 1020 MeV, the $\Phi$ resonance mass. During KLOE run, DAΦNE delivered a peak luminosity of $1.5 \times 10^{32}$ cm$^{-2}$s$^{-1}$ which granted about 1 fb$^{-1}$ per year in the last data taking period.

A new machine scheme has been recently proposed by the Frascati accelerator group aiming at increasing the luminosity of the machine up to a factor 5. This scheme has been successfully tested at DAΦNE, and these encouraging results push for a new data taking campaign for the KLOE experiment to complete its physics program and to perform a new interesting set of measurements.

The new experiment, named KLOE$^2$, expects to collect 5 fb$^{-1}$/year. We are now working to improve the performances of our detector$^2$ adding: an inner tracker, a tagger system to study $\gamma\gamma$ physics, a new small angle calorimeter and a new quadrupole calorimeter. In this paper we explain the project and the R&D for these last two items.

2. Quadrupole tile calorimeter, QCALT

In Fig[1] we show a section of the KLOE detector in which is visible the old position of the focalizing quadrupoles and the surrounding calorimeters QCAL$^3$ which have a polar angle coverage of $0.94 < |\cos \theta| < 0.99$. Each calorimeter consists of 16 azimuthal sectors composed by alternating layers of 2 mm lead and 1 mm BC408 scintillator tiles, for a total thickness of $\sim 5X_0$. The readout is done by wavelength shifter fibers (Kuraray Y11-200) and photomultipliers. The fiber arrangement allows the measurement of the longitudinal coordinate by time differences. These calorimeters are characterized by a low light response ($\sim 3$ pe/mip/tile at zero distance from the photomultiplier) due to the coupling in air, to the fiber length ($\sim 2$ m for each tile) and to the quantum efficiency of the used photomultipliers (standard bialkali with $\sim 20\%$ QE).

The project of the new QCAL consists in a dodecagonal structure, 1 m long, covering the region of the quadrupoles. The structure consists in a sampling of 5 layers of 5 mm thick scintillator plates alternated with 3.5 mm thick tungsten plates, for a total depth of 4.75 cm ($5.5X_0$). The active part of each plane is divided into twenty
tiles of $5 \times 5 \text{ cm}^2$ area with 1 mm diameter WLS fibers embedded in circular grooves. Each fiber is then optically connected to a silicon photomultiplier of 1 mm$^2$ area, SiPM, for a total of 2400 channels.

We have done some R&D studies on SiPM, fibers and tiles to choose the combination which optimizes the response of our system.

2.1. Test on MPPC

We have compared the characteristics of two different SiPM produced by Hamamatsu (multi pixel photon counter, MPPC): 100 (S10362-11-100U) and 400 pixels (S10362-11-050U), both with $1 \times 1 \text{ mm}^2$ active area. To manage the signals, the electronic service of the Frascati Laboratory (SELF) has developed a custom electronics composed by a $1 \times 2 \text{ cm}^2$ card, containing the pre-amplifier, and a multifunction NIM board. For these tests, we have set the pre-amplifier gain to 50. The NIM board supplies the voltage to the photodetector (Vbias) with a precision of 2 mV and a stability at the level of 0.03 permill. A low threshold discriminator and a fanout are also present in the board.

To determine the gain, we have prepared a setup based on a blue light LED and a polaroid filter to change light intensity. We have measured the gain and the dark rate variation as a function of the applied Vbias and the temperature of the photodetector.

The readout electronics was based on CAMAC, with a charge sensitivity of 0.25 pC/count and a time of 125 ps/count.

Our tests confirm the performances declared by Hamamatsu and show a significative variation of the detector gain as a function of the temperature. The 400 pixels shows a temperature dependence of the gain which is a factor four smaller than the 100 pixels (3% versus 12%), with a gain reduction of a factor five.

2.2. Tests on fibers

We have studied the light response of three different, $1 \text{ mm}^2$, fibers optically connected to MPPC:

- Kuraray SCSF81 (blue scintillating)
- Saint Gobain BCF92 single cladding (WLS from blue to green)
- Saint Gobain BCF92 multi cladding (WLS from blue to green)

The test is done firing the fiber with a $\text{Sr}^{90}$ source. The trigger is provided by a NE110 scintillator finger ($1 \times 5 \times 0.5 \text{ cm}^3$) connected to a bialkali photomultiplier positioned below the fiber.

As expected, a large light yield is shown for SCSF81 while the WLS fibers have a reduced response. However, the BCF92 multi cladding has a reasonable light yield as shown in Fig. 2. For this fiber we have: maximum light yield, fast response (5 ns/pe) and high attenuation length (3.5 m).

2.3. Tests on tiles

Light response and time resolution of tiles have been measured using cosmic rays. The system was prepared connecting the fiber to the MPPC and using two NE110 fingers to trigger the signal. We have prepared two different tiles:

A 3 mm thick tile with 400 pixels MPPC,
Using ADC distribution we find: 14 pe/mip for tile “A” and 26 pe/mip for tile “B” (See Fig.3). These results are comparable taking into account the thickness ratio between tiles and the photon detection efficiency of the two detectors (40% for 400 pixels and 45% for 100 pixels).

Correcting for the time dependence on pulse height, we find a preliminary time resolution of 1000 ps (750 ps) for tile “A” (“B”).

2.4. Next plans

We are now assembling two small dimension multi-tiles prototypes of the QCAL, to study signal transportation and to measure the effective radiation length. In 2009, we plan also to construct a “module 0” consisting of a complete slice of the dodecagon (1/12 of one calorimeter) with final material and electronics.

3. Crystal calorimeter with timing, CCALT

In the new design of DaΦne interaction region, the position of the quadrupoles increases the acceptance of the central calorimeter from 21° to 18°. Below this limit we can safely insert few crystals to improve the acceptance for photons coming from η and KS decays. This detector could work as veto detector for photons down to 8°. The particular region is visible in Fig.1 and is delimited between the focalizing quadrupoles and the spherical interaction region of the KLOE detector.

The proposed solution is to insert an homogeneous calorimeter based on LYSO (Lu18Y2SiO5 : Ce) crystals. The most important characteristics of these crystals are a very high light yield, a time emission, τ, of 40 ns, high density and X0 without being hygroscopic (See Tab.1). These crystals well match the request of high efficiency to low energy photons and excellent time resolution for the CCALT, which will help in fighting the high level of machine background events present in the low energy region.

The preliminary project consists in a dodecagonal barrel for each side of the interaction region, composed by LYSO crystals (2×2×13 cm3) readout using avalanche photodiodes (APD).
3.1. Preliminary tests on LYSO

We have tested one LYSO crystals from Saint Gobain ($2 \times 2 \times 15$ cm$^3$) using both cosmic rays and electrons from Frascati beam test facility (BTF). For cosmic rays test, the crystal was readout using standard bialkali photomultiplier, while in the test beam we used a $5 \times 5$ mm$^2$ avalanche photodiode provided by Hamamatsu (S8664-55).

In both cases, the crystal was simply wrapped with mylar and the photodevice coupled with optical grease and simple mechanical arrangement.

After correcting the time dependence on pulse height, we obtain, from cosmic rays, a preliminary time resolution $\sigma_T = 360$ ps, which corresponds to 12000 pe/mip ($N_{pe} = (\tau/\sigma_T)^2$). Assuming a MIP to deposit 10 MeV/cm this corresponds to 600 pe/MeV.

At the BTF, we have used electrons from 50 to 400 MeV to measure the time resolution of the crystals which is well parametrized by:

$$\sigma_T = \frac{82 \text{ ps}}{\sqrt{E(\text{GeV})}} \oplus 293 \text{ ps}$$

The constant term is probably related to the different arrival times of the showering photons along the crystal axis. From the statistical term we derive a light yield of 240 pe/MeV which is in rough agreement with the results from cosmic rays taking into account quantum and collection efficiency.

3.2. Next plans

A dedicated test beam with electrons will be held in Frascati beam test facility in the first months of 2009. The aim of the test is to characterize energy and time resolution of a $3 \times 3$ matrix of high quality crystals surrounded by an outer leakage detector done with PbWO. This test will also allow to compare the response of different kind of LYSO crystals (Saint Gobain and Scionix) and a similar crystal (LFS by Zecotek) which could be an alternative candidate (See Tab.1).

4. Conclusions

The new scheme proposed for the DaΦne machine allows a factor 5 increase in the delivered luminosity. Some R&D are in progress to add new components to the KLOE apparatus. We have presented the proposal for two low angle calorimeters. QCALT is a tile calorimeter surrounding the focalizing quadrupoles to increase the coverage of the electromagnetic calorimeter. CCALT is a LYSO calorimeter aimed to be a good veto for low angle photons. We have presented the preliminary measurement on tiles and crystals and the characterization of the photodevices used with tiles.

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| Component              | LYSO | LFS  |
|-----------------------|------|------|
| Density               | 7.1  | 7.2-7.3 |
| Attenuation length (cm)| 1.2  | 1.12 |
| Decay constant (ns)   | 41   | 35-36 |
| Max emission (nm)     | 420  | 435-438 |
| Light yield (relative NaI) | 75   | 80-85 |
| Energy resolution     | 8    | 9-12 |
| Hygroscopic           | no   | no   |
| Refractive index       | 1.81 | 1.78 |

Table 1: Comparison between LYSO and LFS characteristics