KLOE / KLOE-2

The KLOE-LNF Collaboration


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1 Outline

During 2009 the KLOE collaboration has finalized several analyses in the field of kaon physics, low-mass scalars and pseudoscalars, and precision measurements of hadronic cross section. The collaboration was also committed to the preparatory work for data-taking in year 2010 and to the R&D activities for the detector upgrades, to be installed during the third quarter (3Q) of 2011.

On the kaon sector, the analysis of the helicity-suppressed $K^e_2$ channel has been published. It has been presented to the international conferences over the year and to the CERN community with the seminar held in May. The ratio $R_{K^{12}} = \frac{BR(K^e_2)}{BR(K^\mu_2)}$ is sensitive to couplings beyond the Standard Model (SM) \(^1\) which should enhance the BR($K^e_2$) well above SM prediction. The KLOE result \(^2\), $R_{K^{12}} = (2.493 \pm 0.025_{stat} \pm 0.019_{syst}) \times 10^{-3}$, is in agreement with SM expectation constraining lepton–flavor violating processes in minimal supersymmetric standard model (MSSM). Other published results in year 2009 include the upper limits on the BR($K_S \rightarrow \mu^+\pi^-$) and BR($\phi \rightarrow K_SK_S\gamma$), the measurement of the BR($\eta \rightarrow \pi^+\pi^-\pi^+\pi^-$) and the study of the $a_0(980)$ with the analysis of $\phi \rightarrow \eta\pi^0\gamma$. For the hadronic cross section, the results on $\pi\pi\gamma$ events with photons emitted at low polar angle ([|\cos(\theta)| > \cos(\pi/12)]) have been published \(^3\). The pion form factor in the $M_{\pi\pi}$ invariant mass range [0.592, 0.975] GeV has been determined and used in the evaluation of the hadronic contribution to the muon anomaly. The result confirms the 3–$\sigma$ discrepancy between SM expectation and the measurement of the muon ($g - 2$) by the E821 experiment at the BNL. Independent and consistent results have been obtained with the study of the off-peak data, taken at $\sqrt{s} = 1$ GeV \(^4\). The summary on hadronic cross section measurements is presented in Sect. 4. For the kaon decays, the status of the analysis of the $K^+ \rightarrow \pi^+\pi^+\pi^-$ is described in Sect. 2. For the $\eta$ decays, the first observation of the $e^+e^-e^+e^-$ mode and the study of the $\pi\pi\gamma$ channel are reported in Sect. 3.

Test and revision of the KLOE detector subsystems have been completed and the upgrade of obsolete components, including data storage and the software for data handling, has been worked on. The technical design report (TDR) of the tagger system for $\gamma\gamma$ physics at KLOE-2 has been finalized and the construction of the detector has started. A status report on the project is given.
in Sect.5. R&D activities on the calorimeters to detect photons at low polar angle (CCALT) and to instrument the zone of the DAΦNE quadrupoles in the new beam interaction region (QCALT) have progressed as described in Sect.6. The design of the cylindrical triple–GEM chamber has been finalized with the analysis of the detector response to test beam in magnetic field and the completion of the TDR as reported in Sect.7.

2 $K_L$ lifetime and $\text{BR}(K^+ \to \pi^+\pi^-\pi^+(\gamma))$

The availability at KLOE of tagged kaons enables precision measurements of absolute branching ratios (BR). The detection of one $K_L$ ($K_S$) guarantees the presence of the $K_S$ ($K_L$) with opposite momentum and the same holds for charged kaons pairs $^5$. The $K_L$ beam is tagged by the reconstruction of $K_S \to \pi^+\pi^-$ decays. The selection of $K^+$ beam is done reconstructing the 2–body decays $K^- \to \pi^-\pi^0$ and $K^- \to \mu^-\nu$, which are identified from two clear peaks in the distribution of the momentum of charged secondary tracks in the kaon rest frame.

Two independent measurements of the $K_L$ lifetime, $\tau_L$, have already been published. The first one, $\tau_L = 50.92 \pm 0.17_{\text{stat}} \pm 0.25_{\text{syst}}$ ns $^6$, has been obtained from the fit to the proper–time distribution of $\sim 8.5 \times 10^6 K_L \to 3\pi^0$ decays tagged by $K_S$ reconstruction, while the second one, $\tau_L = 50.72 \pm 0.11_{\text{stat}} \pm 0.35_{\text{syst}}$ ns $^7$, from the measurement of the dominant $K_L$ branching fractions imposing the constraint $\sum \text{BR}(K_L) = 1$ on a tagged sample of $\sim 13 \times 10^6 K_L$. Since the error on $\tau_L$ is the limiting factor on the accuracy of $V_{us}$ from the $K_L$ semileptonic decays $^8$, we are continuing the analysis of the KLOE data sample to improve both statistics and systematics on the $\tau_L$ measurement. Timing performance of the calorimeter (EMC) allows precision measurement of the flight path of the $K_L$ neutral decay products from the arrival time of photons to the calorimeter and from shower position, while $K_L$ momentum is obtained from drift chamber (DC) measurements of the charged pions from $K_S$ decay. To obtain a high and uniform neutral vertex reconstruction efficiency, at least 3 photons are required to be reconstructed.

A control sample of $K_L \to \pi^+\pi^-\pi^0$ decays has been used to study efficiency and resolution of the neutral vertex reconstruction procedure. The proper–time distribution of residual background, $\sim 1.8\%$, shows two peaks at $t^* < 8$ ns due to regeneration on the beam pipe and internal wall of the DC, and one peak at $t^* > 25$ ns due mainly to $K_L \to \pi^+\pi^-\pi^0$. The preliminary result is:

$$\tau_L = 50.56 \pm 0.14_{\text{stat}} \pm 0.21_{\text{syst}}$$ ns $= 50.56 \pm 0.25$ ns

in agreement with previous KLOE $^6,7$ measurements. The statistical error can be improved by increasing the sample by a factor of 1.5 and extending the fit region to lower values of the proper time, with a procedure to account for the $K_L$ beam losses from regeneration process. A statistical error of $\sim 0.1$ ns is expected for the final result.

The measurement of the $\text{BR}(K^+ \to \pi^+\pi^-\pi^+)$ completes the KLOE program of precise and fully inclusive kaon dominant BR’s measurements. The most recent result, $\text{BR}(K^\pm \to \pi^\pm\pi^\mp) = (5.56 \pm 0.20\%)$ $^9$, dates back to more than 30 years ago.

We use two normalization samples given by the two tagging modes, $K_{\mu2}$ and $K_{\pi2}$. The track of the tagging kaon is backward extrapolated to the interaction point and the kinematics of $\phi \to K^+K^-$ is exploited to obtain the momentum of the tagged kaon.

The three pions from kaon decay have momentum smaller than 200 MeV/c and curl up in the KLOE magnetic field increasing the probability to reconstruct broken tracks and fake vertices. If
we select kaon decays outside the DC volume, the maximum number of tracks to be reconstructed is three instead of four, and the reconstruction quality improves. We require at least two reconstructed tracks in the DC (pion candidates) and, if their backward extrapolation crosses the path of the tagged kaon before the DC inner wall (geometrical acceptance is \( \sim 26\% \)), we evaluate the missing mass of the decay. Figure 1 shows the comparison between data and MC for the missing mass spectrum. The background contribution from MC simulation is also shown.

The selection efficiency is being evaluated from MC, and corrections are applied to account for data-MC tracking differences. The measurement, still in progress, should reach a statistical relative error of a few per mil.

3 The study of \( \eta \) decays

In the \( \eta \to \pi^+\pi^-\gamma \) decay, a significant contribution from chiral box anomaly is expected \(^{10}\). The box anomaly accounts for the direct (non–resonant) coupling of three pseudoscalar mesons with the photon. The invariant mass of the pions \((m_{\pi\pi})\) is a good observable to disentangle this contribution from other possible resonant ones, e.g. from the \( \rho \)-meson. However, the momentum dependence cannot be determined from chiral theory only because the kinematic range of the \( \eta \to \pi^+\pi^-\gamma \) decay extends above the chiral limit, where the Weiss–Zumino–Witten term of the ChPT Lagrangian properly describes the direct coupling. Several theoretical approaches have been developed to treat the contributions of the anomalies to the decay \(^{11, 12, 13}\).

The \( \eta \to \pi^+\pi^-\gamma \) decay has been measured in 1970s \(^{14, 15}\). The analysis of the two data sets, 7,250 and 18,150 events respectively, shows some contradiction. Theoretical papers trying to
Figure 2: (color online). Invariant mass of two photons (left) and the cosine of the angle between \( \gamma \) and \( \gamma \eta \) calculated in the rest frame of \( \pi^0 \) (right). The experimental data (points) are fitted simultaneously in both plots with signal and dominant background contributions (the sum of all MC backgrounds is shown).

combine the two measurements have found discrepancies in data treatment and problems with obtaining consistent results \(^{16}\). Recently, the CLEO collaboration published the measurement of the ratio of branching ratios, \( \Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\eta \to \pi^+\pi^-\pi^0) = 0.175 \pm 0.007 \pm 0.006 \), which differs by more than 3–\( \sigma \) from old results. We aim at the solution of the inconsistency of experimental data with precision measurements of the branching ratio and \( m_{\pi\pi} \) invariant mass distribution.

The analysis steps include selection of samples of \( \eta \to \pi^+\pi^-\gamma \) and \( \eta \to \pi^+\pi^-\pi^0 \). The main background is the decay \( \phi \to \pi^+\pi^-\pi^0 \). In order to evaluate signal and background events, the two distributions in Fig.2 were simultaneously fitted with the two contributions. The preliminary measurement of the ratio of branching ratios, \( \Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\eta \to \pi^+\pi^-\pi^0) = 0.2014 \pm 0.0004_{\text{stat}} \), is in agreement with the old results from Refs. \(^{14},^{15}\) while significantly differs from the recent CLEO results, as compared in Tab. 1.

<table>
<thead>
<tr>
<th>PDG08 Average</th>
<th>LOPEZ (CLEO) 2007</th>
<th>THALER 1973</th>
<th>GORMLEY 1970</th>
<th>KLOE Preliminary</th>
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<tbody>
<tr>
<td>0.203 ± 0.008</td>
<td>0.175 ± 0.007 ± 0.006</td>
<td>0.209 ± 0.004</td>
<td>0.201 ± 0.006</td>
<td>0.2014 ± 0.0004</td>
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The finalization of the analysis with the control and the precise evaluation of the background sources is in progress.

Recently, KLOE has started studying the \( \eta \to e^+e^-e^+e^- \) decay. This decay, together with the \( \eta \to \mu^+\mu^-e^+e^- \), is interesting for the \( \eta \) meson form factor. Events with four electrons in the final state are selected using the time of flight to the calorimeter. Backgrounds from \( \eta \to \gamma\gamma/e^+e^-\gamma \)
with photon conversion are rejected by reconstructing the invariant mass and the distance of the candidate electron track from the beam pipe or drift chamber walls. Most of the background comes from events in the continuum, with a small contribution from \( \phi \) decays. The latter is subtracted from data using the distributions from MonteCarlo (MC) simulation. The number of events is obtained fitting the data distribution of the four–electrons invariant mass, \( M_{eeee} \), with signal and background shapes (Fig.3). From the fit we obtain \( 413 \pm 31 \) events. This is the first observation of the decay.

4 The measurement of the hadronic cross section

The published KLOE measurements\(^{17, 3}\) of the hadronic cross section for the process \( e^+e^- \rightarrow \pi^+\pi^- \) were based on initial–state–radiation (ISR) events with photon emitted at small angle, resulting in kinematical suppression of events with \( M_{\pi\pi}^2 < 0.35 \text{ GeV}^2 \). To access the two–pion threshold, a new analysis is performed requiring events with photon at large polar angles (\( 50^\circ < \theta_\gamma < 130^\circ \)), in the same angular region of the pions. The drawback of such acceptance cuts is a reduction in statistics of about a factor of five, as well as an increase of events with final–state–radiation (FSR) and from \( \phi \) radiative decays. The uncertainty on the model dependence of the \( \phi \) radiative decays to the scalars \( f_0(980) \) and \( f_0(600) \) together with \( \phi \rightarrow \rho\pi \rightarrow (\pi\gamma)\pi \) has a strong impact on the measurement\(^ {18} \). For this reason, the present analysis uses the data taken by the KLOE experiment in 2006 at a value of \( \sqrt{s} = 1 \text{ GeV} \), about \( 5 \times \Gamma(\phi) \) outside the narrow peak of the \( \phi \) resonance. This reduces the effect due to contributions from \( f_0\gamma \) and \( \rho\pi \) decays of the \( \phi \)-meson to a relative amount of 1\%. Contaminations from the processes \( \phi \rightarrow \pi^+\pi^-\pi^0 \) and \( e^+e^- \rightarrow \mu^+\mu^-\gamma \) are rejected using kinematical variables. A particle ID estimator based on calorimeter information and time–of–flight is used to efficiently suppress the high rate of radiative Bhabhas. The radiative differential cross section is then obtained subtracting the residual background events and dividing by the selection efficiencies and the integrated luminosity. The total cross section \( \sigma_{\pi\pi} \) is obtained.
Figure 4: Pion form factor $|F_\pi|^2$ obtained in the present analysis (KLOE09) compared with the previous KLOE result (left) and results from the CMD and SND experiments (right). KLOE09 data points have statistical error attached, the superimposed band gives the statistical and systematic uncertainty (added in quadrature). Errors on KLOE08, CMD2 and SND points contain the combined statistical and systematic uncertainty.

using $^{19}$):

$$s \cdot \frac{d\sigma_{\pi\pi\gamma ISR}}{dM^2_{\pi\pi}} = \sigma_{\pi\pi}(M^2_{\pi\pi}) H(M^2_{\pi\pi}, s),$$

where $H$ is the radiator function describing the photon emission in the initial state. This formula neglects FSR terms, which are however properly taken into account in the analysis. From $\sigma_{\pi\pi}$, the squared modulus of the pion form factor $|F_\pi|^2$ can be derived. Fig. 4 shows $|F_\pi|^2$ as a function of $(M^2_{\pi\pi})$ for the new KLOE measurement (KLOE09) compared with the previous KLOE publication (KLOE08) and with results from CMD-2 $^{20, 21}$ and SND $^{22}$ experiments at the Novosibirsk collider. On the $\rho$–meson peak and above, the new analysis confirms KLOE08 data being lower than the Novosibirsk results, while below the $\rho$-peak the three experiments are in agreement.

The cross section, corrected for $\alpha_{em}$ running and inclusive of FSR, is used to determine the dipion contribution to the muon anomalous magnetic moment, $\Delta a_{\mu\pi}$:

$$\Delta a_{\mu\pi}((0.1 - 0.85) \text{ GeV}^2) = (478.5 \pm 2.0_{\text{stat}} \pm 4.8_{\text{exp}} \pm 2.9_{\text{theo}}) \cdot 10^{-10}.$$

The evaluation of $\Delta a_{\mu\pi}$ in the range between 0.35 and 0.85 GeV$^2$ allows the comparison of the result obtained in this new analysis with the previously published result by KLOE $^{3}$, showing that these two independent analyses provide fully consistent contributions to the muon anomaly.
5 The tagger system for $\gamma\gamma$ physics

The term “$\gamma\gamma$ physics” (or “two–photon physics”) stands for the study of the reaction $e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-X$, where $X$ is some arbitrary final state resulting by the fusion of two photons. Since the two (on-shell) photons are in a $C = +1$ state and the value $J = 1$ is excluded, the study of these processes at the $e^+e^-$ colliders gives access to states with $J^{PC} = 0^{\pm}+, 2^{\pm}+, \text{not directly coupled to one photon (} J^{PC} = 1^{--} \text{).}$

In the low-energy region covered by the KLOE detector at DAΦNE, existing measurements \(^{23}\) are affected by large statistical and systematic uncertainties due to small detection efficiencies, large background contributions and particle identification ambiguities in the low-mass hadronic systems. KLOE-2 is the ideal place for precision measurements of low–mass hadronic systems with high statistics and well controlled systematic errors.

Many interesting channels can be investigated and both, the two-photon width of light pseudoscalar mesons, and the meson transition form factors \(^{24}\), can be obtained. Search for $\sigma$ meson, especially in the channel $\gamma\gamma \rightarrow \pi^0\pi^0$, is one of the interesting topics addressed by the $\gamma\gamma$ physics program. The precision of available data does not allow any firm conclusion on the presence of a resonance in the region from (400-500) MeV. To improve on the measurement of the $\gamma\gamma \rightarrow \pi\pi$ cross section, high statistics has to be complemented by a careful control of the systematics which cannot be obtained without strong suppression of the background events. The main source of background comes from $\phi$ decays. Studies are underway on the KLOE data sample using the off-peak data in order to evaluate the experimental capability without the background from $\phi$ decays. At KLOE-2 we aim at the analysis of the on–peak data performing background suppression thanks to the information coming from the tagging system which is designed to efficiently detect scattered electrons. Scattered electrons from $\gamma\gamma$ reaction deviate from the main DAΦNE orbit while propagating on the machine lattice. For the design of the tagging system we performed MC studies of the trajectories of the scattered electrons whose initial kinematical distribution is given by $\gamma\gamma$ generators developed for these studies. The magnetic fields in DAΦNE have been fully simulated. The results show that the constraints coming from the DAΦNE structure do not prevent KLOE-2 from obtaining a good coverage of the kinematic region of interest.

Satisfactory results have been obtained using a tagging system composed by:

- A station to detect leptons at low energy (LET), located in the region between the two quadrupoles inside KLOE (QD0 and QF1), about 1 m from the interaction region (IP). Scattered leptons on the LET detector pass through the first quadrupole, QD0 and, being off-energy, are deflected with respect to the main orbit. The energy distribution of these leptons is very broad, with tails reaching 50 MeV on one side and 450 MeV on the other. The measurement of the lepton energy requires a calorimeter, being the position of the exit point weakly correlated with the lepton momentum.

- A station for leptons with high energy (HET), located at the exit of the first bending magnet (about 11 m from the IP). The leptons propagate through the magnetic fields of the machine and are separated by the B-fields according to their momenta. The energy of the scattered particles is in the range (425-475) MeV (for a minimum distance of 50 mm between the detector and the nominal orbit). In this case a position detector allows the measurement of the lepton momentum with good precision.
When both scattered leptons are detected by HET/LET taggers, the two–photons centre–of–mass energy $W_{\gamma\gamma}$ can be measured independently from the central KLOE detector. With the realistic assumption of a 3 mm pitch for the HET, and a LET resolution of $\sigma(E)/E = 5%/\sqrt{E(\text{GeV})}$, in the case of coincidence HET $\otimes$ LET, we obtain a resolution on $W_{\gamma\gamma}$ of $\sigma = 12.8$ MeV, while in the case of coincidence LET $\otimes$ LET the resolution becomes $\sigma = 33.4$ MeV.

5.1 The Low Energy Tagger detector

Several tests have been performed at the Frascati beam test facility (BTF), in order to study different technological options and geometrical design for the LET calorimeters.

We exposed different kinds of crystals and photosensors at the BTF with electron beams from 100 to 500 MeV in order to characterize all of the scintillators and photosensors, namely two PbWO and two LYSO crystals connected to either SiPM or APD.

For the measurement of the energy and time resolutions of the system made of several crystals and to test the assembly procedure, the calibration and the operational stability of the detectors, we built two full-size LET prototypes which have been studied with electrons from the test beam and with cosmic rays.

The first prototype had a transversal radius larger than 2 Moliere radius ($R_M$), and longitudinal dimension of 13 cm. This prototype was built on April 2009 and consisted of an inner matrix with LYSO crystals readout by SiPM and an external matrix of PbWO$_4$ crystals readout by standard photomultipliers of 1.1/8” diameter.

A second prototype was built in October 2009 using the first batch of LYSO crystals purchased for the construction of the LET calorimeters. It was simpler than the first one and of the same size and shape as one of the LET calorimeters to be built for data taking at KLOE-2. It consisted of 20 crystals, 15x15x120 mm$^3$ each, packed side-by-side to obtain a 5x4 crystal matrix structure. Each crystal was readout by one Hamamatsu MPPC, 3x3 mm$^2$ active area, 14400 pixel each, coupled to custom front-end electronics realized by the LNF Electronics Service (SELF). An indirect coupling between SiPM and the front-end, i.e. via coaxial cable, was also tested with success. The front-end electronics has been custom–designed to satisfy the detector requirements in terms of power supply, stability, remote–control setting and sensing, low noise linear amplification, and to be compatible with the KLOE EMC readout chain 25). Both prototypes were tested at the BTF using a clone of the standard KLOE DAQ in order to acquire data with the same chain as in the experiment.

The first prototype was tested in May-June 2009, by exposing it to electrons of energy ranging from 150 to 500 MeV (cf. Sect.6). Linear response of LYSO+SiPM from 150 to 500 MeV was achieved. This implies that less than $10^3$ photoelectrons were collected at the maximum energy which corresponds to about 2 photoelectrons/MeV. The stochastic term was $2.8%/\sqrt{E(\text{GeV})}$, consistent with the expected yield of $\sim 2$ photoelectrons/MeV. The noise term was evaluated from the pedestals of the electronic channels, and contributes with $0.7%/E$ to the energy resolution. Some additional noise due to test beam setup brings the total noise contribution to $1.2%/E$. The constant term in the energy resolution of $\sim 4\%$ is fully dominated by the leakage, according to the shape of the prototype.

The second prototype was exposed to electrons from 100 to 450 MeV and only 14 over 20 crystals were readout. The best energy resolution and linearity were obtained with the cable–coupling of SiPMs to front-end electronics as shown in Fig. 5.1. The contributions to the energy resolution from the beam energy spread, higher than expected, and from the lateral leakage on
crystals which are not readout have been also observed. We moved the test beam across cracks among adjacent crystals, obtaining no dead-zone effect. The last test beam results validated the cable-coupling option, in agreement with previous laboratory test made with LED pulses.

In order to carefully study signals from the crystal and to extrapolate the results to the full matrix, we have simulated the first prototype with GEANT4, creating two different volumes for the inner matrix, one made of PbWO$_4$ and the other of LYSO. The external matrix was simulated with PbWO$_4$ crystals + PM. For each crystal we considered a dead space of 100 µm of mylar and activated the optical transport of photons inside the scintillating material. Photodetectors consist of a sensitive, 100% efficient area. The correct emission curve both in frequency and time has been considered for the different scintillators. An attenuation length of 100 cm has been also assumed.

The small available space for the LET makes it necessary to carefully choose the dimension of the active part of the detector in order to maximize the acceptance to $e^+/e^-$ while minimizing the shower leakage. Extensive MC simulations, made with the GEANT4 simulation package, have been used to evaluate the expected energy and time resolution with different geometric options for the final design. Simulations of LYSO crystals energy response, based on test-beam data, have allowed us to optimize the LET design and positioning. A full simulation of the LET active volume and beam trajectories was used to determine the detector response to the off-momentum particles.

As the result, each detector will consist of 20 crystals, 1.5x1.5x12 cm$^3$ each, pointing to the average direction of the off-energy particles, i.e. 11° with respect to the beam axis, centered on the horizontal plane. The crystals will be readout by one SiPM each, the signals being taken out from the detector via coaxial cables to the front-end electronics. A LED pulsing system will also be installed to monitor the gain drift of the SiPMs. Figure 6 shows the integration of the LET in the interaction region of DAΦNE.

![Figure 5: Energy response expressed in minimum-ionizing–particle unit (mip) with respect to beam energy for the LYSO crystals.](image)
5.2 The High Energy Tagger detector

The requirements for the HET detector are summarized as follows: good time resolution to disentangle each DAΦNE bunch coming with a period of $\sim 2.7$ ns; capability to acquire data at a frequency of 368 MHz in order to permit event reconstruction with the KLOE apparatus; radiation hardness in order to stand 50 mm from the beam (a closer position would interfere with the proper operation of DAΦNE) for long term data-taking; and tiny size to allow the installation by means of mechanical supports inside the vacuum chamber.

The tagger detector consists of a set of scintillators arranged in two “stairs” and is constituted of 30 EJ-228 scintillators $3 \times 6 \times 3$ mm$^3$, which provide a spatial resolution of 2 mm (corresponding to a momentum resolution of 500 keV). Two additional scintillators, $3 \times 6 \times 120$ mm$^3$, are used for the coincidence. The output light is collected by clear light guides coupled with Hamamatsu R9880U-110sel photomultipliers. To minimize the interference with the DAΦNE high-vacuum system, the detector will be installed inside a movable steel sleeve (cf. Fig.7).
During spring 2009, tests have been performed at the BTF in order to study the performance of the detector. The time of flight of electrons has been measured with a HET prototype composed by two modules only (scintillator and photomultiplier). A time resolution of $\sim 300$ ps has been obtained (cf. Fig. 8). Mechanics, flanges, box, and motors have been realized and the system will be ready in April, 2010.

The PMT efficiency will be monitored and the ageing of the photocathode will be compensate (as much as possible) by increasing high voltage (HV) supply. An automatic system, controlled via Ethernet, is being developed. The system will be structured as follows:

- a pulsed LED controlled by a linear current generator (already successfully tested);

- 32 optical fibres to bring the same light to the each PMTs;

- 32–channels CAEN VME QDC to acquire the spectrum of every single PMT;

- a VME board with a PIC microcontroller to monitor the efficiency of the PMTs and change the HV supply.

In the case of serious damage of one PMT it can be easily replaced thanks to the design of the mechanical structure. The front-end electronic board (a fast buffer, an amplifier, two voltage regulators, and a thermometer) provides an analog signal to the Data Acquisition board with embedded discriminators. This part of the electronics has been successfully tested obtaining a signal with a rise time shorter than 0.5 ns. The signals come from the HET detector, DAΦNE (fiducial) and KLOE (Trigger and ACQ logic). The acquisition logic has been implemented inside
the FPGA. A microcomputer, inside a Virtex5 FPGA, controls communication with KLOE DAQ via the VME bus. As the HET detector is placed far away from the IP, the number of beam bunches must be registered to reconstruct the related information in the KLOE-2 detector. Therefore, consecutive bunches must be separated in time and a resolution better than 1 ns is required. The time resolution can be reached with a 500 MHz clock which is under test. The complete acquisition system is planned to be ready in the 3Q of 2010.

6 The calorimeters for the detector upgrade

To improve the reconstruction of $K_L$ decays in the DC with photons hitting the DAΦNE quadrupoles, a calorimeter with high efficiency to low energy photons, (20-300) MeV, time resolution better than 1 ns, and space resolution of a few cm, is needed. To match these requirements, we have designed a tile calorimeter, QCALT, where each single tile is readout by one SiPM, for a total of 2,400 channels.

A small angle calorimeter, CCALT, will extend the angular coverage of the KLOE-2 EMC, from polar angle of 20° down to 8°, increasing the photon detection capability of the experiment and enhancing the search reach for rare $K_S$, $\eta$ and $\eta'$ decays. The calorimeter extension consists of two small barrels of LYSO crystals readout with APD photosensors aiming at a time resolution of (300–500) ps for 20 MeV photons. The first test of a (5.5 $\times$ 6 $\times$ 13) cm$^3$ prototype for such a detector was carried out in April 2009 at the BTF with an electron beam from 100 to 500 MeV. In the selected energy range, we measured a light yield of $500 \div 800$ p.e./MeV, an energy resolution which can be parametrized as $0.05 \oplus 0.01/(E/\text{GeV}) \oplus 0.015/\sqrt{E/\text{GeV}}$, a position resolution of 2.8 mm, and a time resolution of 200 $\div$ 300 ps.

6.1 The quadrupole instrumentation, QCALT

In the old IP scheme of DAΦNE, the inner focusing quadrupoles were surrounded by two calorimeters, QCAL 26), covering a polar angle down to 21°.

Figure 9: IP scheme of KLOE-2 with the QCALT calorimeter surrounding the DAΦNE quadrupoles.
The new QCALT design (Fig. 9) consists of a dodecagonal structure, 1 m long, covering the region of the new DAΦNE quadrupoles and composed by a sampling of 5 layers, 5 mm thick, of scintillator plates alternated with 3.5 mm thick tungsten plates, for a total depth of 4.75 cm (5.5 $X_0$). The active part of each plane is divided into twenty tiles of $\sim 5 \times 5 \text{ cm}^2$ 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 2,400 channels. R&D studies have been carried out on SiPM, fibers and tiles to select the components of the detector.

We compared the characteristics of two different SiPM produced by Hamamatsu (multi pixel photon counter, MPPC): 100-pixels MPPC (S10362-11-100U) and 400-pixels MPPC (S10362-11-050U), both with $1 \times 1 \text{ mm}^2$ active area. We prepared a setup based on a blue light pulsed LED, a polaroid filter to modify the light intensity and a SiPM polarization/amplification circuit based on Minicircuits MAR8-A+ amplifier. We measured the gain and the dark rate variation as a function of both, the applied $V_{\text{bias}}$, 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 sensitivity of 125 ps/count.

Our tests confirm the performance declared by Hamamatsu and show a significative variation of the detector gain as a function of the temperature (3% for 400 pixels versus 6% for 100 pixels). For the fibers, we studied the light response of two different, 1 mm$^2$, WLS from blue to green, optically connected to MPPC when hit by electrons produced by a $^{90}$Sr source: Saint Gobain BCF92 single-cladding and Saint Gobain BCF92 multi-cladding fibers. The adopted solution is Saint Gobain BCF92 multi-cladding. For this fiber we find, as expected, larger light yield than the one with single-cladding fibers ($\times 1.5$), fast emission time (5 ns/pe) and long attenuation length.

Light response and time resolution of a complete tile have been measured using cosmic rays. The system was prepared connecting fiber to MPPC and using two external NE110 scintillators fingers to trigger the signal. We have prepared different tiles (3 and 5 mm thick) readout with 100- or 400-pixels MPPC. The adopted solution is 5 mm thick BC408 tile readout by 400-pixels MPPC which gives the best results in terms of light yield versus dark rate.

For this system we obtain 32 pe/mip with a time resolution of 750 ps after correcting for the time dependence on pulse height. Controlling enviromental conditions and using LED light, we have also studied SiPM response when varying $V_{\text{bias}}$. By using the photon counting properties of the SiPM we observe an increase of the light yield when increasing $V_{\text{bias}}$. The device reach a plateau 600 mV above the operation voltage, which is consistent with a variation of the photon detection efficiency of the SiPM for the avalanche probability.

To manage the signals from many channels, the SELF has developed some custom electronics composed by a $1 \times 2 \text{ cm}^2$ chip, containing the pre-amplifier and the voltage regulator, and a multifunction NIM board. The NIM board supplies the $V_{\text{bias}}$ to the photodetector with a precision of 2 mV and a stability at the level of 0.03 per mil. A low threshold discriminator and a fanout are also present.

6.2 The Crystal Calorimeter, CCALT

In Fig. 10, we show a zoomed-view of the available region around the IP which can be used to extend the angular coverage of the main electromagnetic calorimeter, limited to a polar angle of $\geq 20^\circ$, with the addition of a new dedicated calorimeter. Assuming to be able to lower the minimum
polar angle for photon detection down to $8^\circ$, this will enhance the multiphoton detection capability of the detector for the search of rare decays of $K_S$, $\eta$ and $\eta'$ mesons.

The only available area to place a calorimeter lies between the end of the spherical beam pipe, of 10 cm radius, and the first quadrupole, positioned at 30 cm from the IP.

This calorimeter has to be very dense, with a small value of both 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 prompt photon reconstruction in an environment with a large background rate ($\sim 1 \div 5$ MHz) of secondary showers generated by off-axis $e^+, e^-$ coming from intra–bunch scattering (Touschek effect). Preliminary simulation studies indicates the need to reach a time resolution of $300 \div 500$ ps for 20 MeV photons.

A suitable solution is offered by a crystal calorimeter with good timing performance, CCALT. A first detector layout consists of two concentrical barrels of 24 crystals each, with transversal dimension of $2 \times 2$ cm$^2$ and longitudinal length from 13 to 15 cm. The best crystal choice is provided by new generation of Cerium doped Lutetium Yttrium Orthosilicate, LYSO, which has...
and $R_M$ values (1.1 and 2 cm) comparable to the ones (0.9 and 2 cm) of the Lead Tungstate, PbWO$_4$, with the advantage of a much larger light yield ($\times 300$). On the negative side, LYSO shows a scintillation emission time ($\tau_{\text{LYSO}} = 40$ ns) slower than PbWO$_4$ ($\tau_{\text{PbWO}} = 10$ ns). However, from the basic scaling law of the time resolution, $\sigma_t = \tau/\sqrt{N_{\text{pe}}}$, we expect LYSO to be a factor of four more performant than PbWO$_4$.

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 large photon yield, the readout with APDs is a valid solution since, at the lowest photon energy of 20 MeV, the collected photoelectrons will be $\sim 10,000$ which corresponds to $\sim 12$ pC assuming an average gain of 300 and an amplification stage of $\times 25$, well matching the ADC sensitivity of the KLOE calorimeter (100 fC/count). In the following, we specifically considered only the Hamamatsu S8664-55, which has an active area of $0.5 \times 0.5$ cm$^2$, fast timing characteristics and a quantum efficiency from 65 to 85 per cent in the wavelength range of interest, (390–500) nm for the LYSO emission spectra.

As reported in Sect. 5, we have built a medium–size crystal matrix prototype with transversal radius larger than $2 R_M$, longitudinal dimension being constrained by budget limits from 13 to 15 cm. The prototype consists of an inner matrix of 10 LYSO crystals readout by APD and an outer matrix, for leakage recovery, composed by eight PbWO$_4$ 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 (Fig. 11) composed (from bottom to top) as follows:

- 3 LFS crystals from Zecotek of $2 \times 2 \times 13$ cm$^3$,
- 2 LYSO St. Gobain crystals of $1.5 \times 1.5 \times 15$ cm$^3$, 1 LYSO St. Gobain + 1 LYSO Scionix crystals of $1.5 \times 1.5 \times 13$ cm$^3$
- 1 LYSO St. Gobain crystal of $2 \times 2 \times 15$ cm$^3$, 2 LYSO Scionix crystals of $2 \times 2 \times 13$ cm$^3$.

The LFS from Zecotek is a Lutetium Fine Silicate crystal, with similar properties to LYSO. Each crystal is wrapped with 100 µm of tyvek on the lateral faces, leaving free both the front and end faces, thus allowing a fast change of the photosensors readout and the calibration light pulses to be brought through an external LED. Each APD is inserted in a PVC mask with the amplifier soldered on its anode and mechanically positioned inside a stainless steel box closed by a PVC cap with only the electronic pins coming out for connection to HV and readout cables. An external holder takes the PMs in position for the readout of the outer crystals while allowing to press the boxes containing the APDs. 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.

The crystal matrix at the BTF was centered on the beam axis with an area delimited by the cross of two BC408 scintillators of $1 \times 0.5 \times 5$ cm$^3$. In most of the tests, the fingers were aligned in such a way to define a beam spot of $1 \times 1$ cm$^2$. Moreover, a beam position monitor, BPM, consisting of sixteen horizontal and vertical scintillator strips readout by two Multi Anode PMs, was placed in front of the fingers. Each strip is built by three 1 mm diameter scintillating fibers thus providing an accuracy below 1 mm on the beam localization.

By using the UV LED, we have first equalized each channel at 10% level and then calibrated the calorimeter response of each channel with minimum ionizing particles, mip, crossing
Figure 12: Distribution of $Q_{TOT}$ for single electron events at 100 MeV (top) with a logG fit and (bottom) with a gaussian fit superimposed.

the calorimeter orthogonally to the crystal axis. We get $\sigma_{ped}$ of 5 counts and a dip peak, $M_i$, of about 100 counts for the small–size crystals. The statistical precision on the peak determination is $\sim 1\%$. 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. 12, 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. A surviving fraction of events with more than 1 electron is still observed in the matrix, especially at low energies. We have fit the distribution corresponding to one electron either with a simple gaussian, centered around the peak, or with a logarithmic gaussian, logG, as follows:

$$N \cdot \exp\left(-\frac{1}{2\sigma_0^2} \ln\left(1 - \frac{\eta}{\sigma_E} (E - E_{peak})\right)^2 - \frac{\sigma_E^2}{2}\right)$$

where $N$ is a normalization factor, $\eta$ represents the asymmetry, $E_{peak}$ the most probable value of the distribution, $\sigma_0 = \frac{2}{\sqrt{E}} \sinh^{-1}\left(\frac{2.36}{\eta}\right)$ and $\sigma_E = \frac{\text{FWHM}}{\sqrt{2}}$ give the resolution.

In Fig. 13, we show the energy dependence of the energy resolution measured on data which has been fitted with:

$$\sigma_E/E = a \oplus b/(E/\text{GeV}) \oplus c/\sqrt{E/\text{GeV}},$$

where, accordingly to MC, we have fixed the constant term to 5%. We found $b = 1.1\%$ and $c = 1.4\%$ when using the gaussian fit to the spectra, and $b = 0.8\%$ and $c = 2.4\%$ with the logG function.
The innovative idea of the cylindrical triple–GEM chamber, CGEM, has been tested for the first time with a small prototype (7 cm radius and 24 cm length). The very positive results obtained opened the way for the project of a CGEM as the Inner Tracker (IT) for KLOE-2. Since then the R&D activities for the IT have been focused on: i) the construction and complete characterization of a full-scale CGEM prototype, ii) the study of the XV strip readout configuration and its operation in magnetic field and iii) the construction and characterization of a large-area GEM realized with the new single–mask photolitographic technique.

The construction, safe operation and extensive test of an almost full-size Cylindrical-GEM prototype during 2007 has demonstrated the feasibility of such a novel low-mass and dead-zone-free vertex detector. Results show the expected spatial resolution from a digital readout of 650 µm pitch strips. We have studied the XV readout configuration and operation in magnetic field. The results are reported in the following subsections, together with the progress on the large–area GEM. The simulation of the final detector by 3D Finite Element Code ANSYS has been also worked on thanks to the collaboration with L. Quintieri, to evaluate the structural response under tensile loads, i.e., strain, stress, and displacements. The model has been validated by laboratory tests on prototypes and the simulation results used to settle the tensile load to be applied on the inner tracker.

The project has been approved and the construction of the CGEM will start by 2Q of 2010 in order to be ready for the installation by 3Q of 2011.

### 7.1 XV readout and operation in magnetic field

A typical orthogonal XY readout can not be used for the inner tracker, due to its cylindrical geometry. The final IT readout will be then performed with an XV pattern of strips and pads engraved on a polyimide foil substrate, 100 µm thick (Fig. 14). The X strips with 650 µm pitch
will provide the r-φ coordinate while the pads, connected through internal vias to form V strips with 650µm pitch, will provide the z coordinate. This quite innovative readout solution was not implemented on the CGEM prototype, therefore its characteristics have been extensively studied with dedicated planar chambers. In addition, since the IT will operate inside the KLOE magnetic field, the effects on the cluster formation and electronics readout had to be studied. To address these issues a dedicated test has been done at the H4 permanent facility, setup at the CERN-SPS 150 GeV pion beam line within the RD51 collaboration. Five 10 × 10 cm² planar triple-GEM (PGEM) detectors with 650 µm pitch readout have been assembled and successfully tested: four chambers with standard XY readout and the fifth with the XV readout. The setup was 1 m long with detectors placed equidistantly with the XV chamber placed in the center. For the operation in magnetic field, the GOLIATH magnet was used, providing a field adjustable up to 1.5 T, orthogonal to the horizontal beam-plane. The coincidence of 6 scintillators (3 × 3 cm²) readout by silicon photomultipliers provided the trigger signal for the acquisition. The planar chambers were partially equipped with 22 digital readout GASTONE boards, 32 channels each, four on each XY chamber and six on the XV chamber. The working point was: Ar/CO₂ (70/30) gas mixture and operating voltages $V_{\text{fields}} = 1.5/3/3.5$ kV/cm and $V_{\text{GEM}} = 390/380/370$ V ($\sum V_G = 1140$ V, Gain = $2 \times 10^4$). The GASTONE threshold was set at 3.5 fC.

The effect of the magnetic field (B) is twofold: a displacement $\Delta x$ and a spread $\sigma_{\Delta x}$ of the charge over the readout plane. The expected values obtained from simulation studies of our chambers done with GARFIELD are $\Delta x = 600 \mu$m and $\sigma_{\Delta x} = 200 \mu$m at $B = 0.5$ T. The test beam configuration the magnetic field effect was mainly present on the X-view. The setup used to measure the displacement on the XV chamber due to the magnetic field is shown in Fig. 15. All four XY chambers are likewise oriented, with the same anode-cathode configuration, and provide the external tracking system for the XV chamber which is instead in a cathode-anode arrangement, reversed with respect to the other chambers. Since the XY chambers are subjected to the same Lorentz force, the reconstructed track will be shifted by the same offset $\Delta x$ with respect to the

![Figure 14: Scheme of the XV readout configuration.](image)
true track trajectory. The displacement in the XV chamber instead will be of the same magnitude \(dx\) but with opposite direction, due to the reversed cathode-anode arrangement. First, with zero magnetic field \((B = 0 \, \text{T})\), the setup was aligned to a few micrometer precision and then, with the magnetic field turned on, the total displacement \((D)\) between the track reconstructed by the XY telescope and the point in the XV chamber was measured: \(D = 2 \times dx\) (Fig. 15). The displacement \(dx\) was measured for 5 values of the magnetic field and found in good agreement with the value obtained from the GARFIELD simulation at \(B = 0.5 \, \text{T}\) (Fig. 16). Fig. 17 shows the resolution on the X coordinate as a function of the magnetic field, the values ranging from 200 \(\mu\text{m}\) at \(B = 0 \, \text{T}\) up to 380 \(\mu\text{m}\) at \(B = 1.35 \, \text{T}\). The resolution on the Y coordinate, measured from the crossing of X and V strips readout, is \(\sim 370 \, \mu\text{m}\) at \(B = 0 \, \text{T}\), in agreement with what expected from the digital readout of the two X and V views (Fig. 18). The performance of the front-end chip GASTONE has
been studied measuring the cluster size and reconstruction efficiency as a function of the magnetic field and operating the XV chamber with four different gain values.

Figure 17: Resolution on the X coordinate as a function of the magnetic field.

Figure 18: Resolution on the Y coordinate at $B = 0$ T.

The efficiency for the nominal KLOE magnetic field $B = 0.52$ T and voltage settings was measured to exceed 99%, slightly decreasing at higher B fields. The charge sharing, grounding and cross-talk between strips could have been in principle different for X and V views, due to the different readout geometry. Our measurements demonstrates the good behavior of both X and V readout views, which give equalized response.

7.2 Large Area GEM

To build the IT outermost layer, a GEM foil as large as $1440 \times 700 \text{ mm}^2$ is needed. This foil can be obtained splicing 3 separate $480 \times 700 \text{ mm}^2$ foils with a technique that we have developed, using an epoxy adhesive and a vacuum bag. The urge for larger GEM foils has driven a change of the
production procedure by CERN TS-DEM-PMT laboratory, switching to a single-mask etching, more suitable for large surface. The procedure has been finalized: the new GEMs have quasi-cylindrical holes and a new characterization is necessary. The GEM foils produced with the new technique will be delivered in April 2010. Meanwhile dedicated tools for the stretching, handling and assembling of such large foils have been designed, realized and tested with a dummy chamber. A 700x300 mm² planar triple-GEM will be used to check the uniformity of the new single-mask GEMs over large area. The chamber, the largest GEM detector ever operated, will be equipped with the GASTONE 64-channels final release and readout by the Off Gastone Electronic (OGE) Board 27). It will be studied with a test beam at CERN. The external tracking system will be provided by the four XY chambers used for the XV readout studies, replacing the XV chamber with the Large Area GEM.

8 Papers


9 Public notes

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10 Contributions to Conferences and Seminars


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