A Status Report of KLOE at DAΦNE

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Abstract

The major goal of the KLOE experiment is to measure $\Re(\epsilon'/\epsilon)$ in the $K\bar{K}$ system with a precision of $10^{-4}$, both via the traditional double ratio method and quantum interferometry. The experiment has started taking data at DAΦNE, the $\phi$-factory built at the Frascati National Laboratory (LNF) of INFN in Italy, beginning in April 1999. In the early phase of the commissioning (before KLOE roll-in), DAΦNE has achieved multi bunch luminosities of $1 \times 10^{31}$ cm$^{-2}$ s$^{-1}$ with 13 bunches and 200 mA. Detailed studies are presently underway to compensate for the large perturbation brought in by the KLOE solenoid, which has caused a drastic decrease of the peak luminosity. Nevertheless the first collected data, corresponding to an integral luminosity of 220 nb$^{-1}$, show that KLOE is performing to the design specifications in all its hardware and software components.

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1 Introduction

The Frascati \( \phi \) factory, DAΦNE, is an \( e^+e^- \) collider optimized to operate at center of mass energy of \( M_\phi \) with very high luminosity (\( L_{\text{peak}} = 5 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1} \)).

Since the vector meson \( \phi \) decays into \( K^+K^- \) 49\% , \( K_SK_L \) 34\% of the times, DAΦNE can be considered a factory of neutral and charged kaons, produced in collinear pairs, with momenta of \( \sim 110 \text{ MeV/c} \) and in a pure quantum state (\( J^{PC} = 1^{--} \)). Interference effects will then appear in the decays of the \( K_SK_L(K\bar{K}) \) pairs, allowing the measurement of all (except one) CP and CPT violation parameters.

The observation of one charge conjugated state of the kaon guarantees the existence of the other one in the opposite direction. A pure \( K_S \) beam without using any regenerator is therefore available.

At the design luminosity, DAΦNE will produce, in one HEP physics year (\( 10^7 \) s), \( 8.5 \times 10^9 K_SK_L, 1.2 \times 10^{11} K^+K^-, 2.5 \times 10^8 \eta, 2.5 \times 10^6 \eta' \) and \( \sim 10^5 a_o \) and \( f_o \).

A detector, KLOE, has been built to exploit the following main physics goals:

- the measurement of \( CP/CPT \) parameters from interferometry and the double ratio \( R \), with a sensitivity of \( 10^{-4} \);
- the measurement of the kaon form factors, \( K_S \) rare decays and the \( K_S \) semileptonic asymmetry (not measured so far);
- the study of the radiative \( \phi \) decays, investigating the nature of the \( a_o, f_o \) mesons and providing a precise determination of the relative branching ratio between \( \phi \to \eta\gamma \) and \( \phi \to \eta'\gamma \).

With the first 100 \( \text{pb}^{-1} \) of collected data we already expect to measure \( \Re(\epsilon'/\epsilon) \) with an error of \( \sim 0.1\% \), to improve the measurement of the kaon form factors and to carry out most of the program on the radiative \( \phi \) decays.

Since the double ratio (\( R \)) is related to \( \Re(\epsilon'/\epsilon) \) by:

\[
R = \frac{N(K_L \to \pi^+\pi^-)/N(K_S \to \pi^+\pi^-)}{N(K_L \to \pi^0\pi^0)/N(K_L \to \pi^0\pi^0)} = 1 + 6\Re(\epsilon'/\epsilon) \tag{1}
\]

the final goal of the experiment of measuring \( \Re(\epsilon'/\epsilon) \) with a precision of \( 10^{-4} \), translates into a global error on \( R \) of few \( 10^{-4} \). While the production rate of the kaon pairs and the tagging efficiency for the \( K_S \) and the \( K_L \) cancel out identically in the double ratio, this is not true for the detection efficiencies, which for this reason have been kept as high as possible in the detector design stage.

In addition, KLOE is a self-calibrating experiment: the abundance of events such as \( K_L \to \pi^+\pi^-\pi^0 (K^{\pm}\pi\pi) \) or \( K^\pm \to \pi^\pm\pi^0 \) which produce in the final state both charged and neutral pions, will allow the determination of the efficiencies from the data themselves.
Since at these energies the decay length ($\lambda$) of the $K_S$ and $K_L$ is 0.6 cm and 345 cm, event counting will have to be performed in two different fiducial volumes. While essentially all the $K_S$ decay in vacuum inside a beam pipe of radius 10 cm, which approximates an infinite decay volume, the difference between the boundaries of charged and neutral decay volumes of the $K_L$ has to be known with a precision of $\sim 0.5$ mm. Again, the use of $K_L^{\pi\pi\pi}$ and $K^\pm \to \pi^{\pm}\pi^0$ events will help in surveying and correcting for this difference.

Background subtraction is finally another source of systematics. Main backgrounds for the CP violating $K_L$ decays are $K_L \to \pi^0\pi^0\pi^0 (K_L^{000})$ and $K_L \to \pi\mu\nu (K_{\mu3})$ which have signal to noise ratios of $1/240$ and $1/135$ respectively, so that rejection factors of $8(6) \times 10^{-4}$ are needed.

Statistics is the other half of the game: in order to reach the desired accuracy in $\Re(\epsilon'/\epsilon)$ we need to collect $\sim 4 \times 10^6$ $K_L \to \pi^0\pi^0$, which can be done in two HEP years ($2 \times 10^7$ s) at DAΦNE design luminosity $L_0 \sim 5 \times 10^{32}$ cm$^{-2}$s$^{-1}$.

## 2 DAΦNE and KLOE: the pilot run

In order to reach this ambitious goal, DAΦNE has been designed to operate at a conservative single bunch luminosity ($L_0 \sim L_{VEP-2M} = 4 \times 10^{30}$ cm$^{-2}$s$^{-1}$) and with a large number of bunches (up to 120). The DAΦNE complex consists of two coplanar rings, a Linac accelerating $e^+$ up to 550 MeV and $e^-$ to 800 MeV and a 510 MeV accumulator ring for fast topping-up. The two beams ($\sigma_x, \sigma_y, \sigma_z = 20$ $\mu$m, 2 mm, 3 cm) intersect with an half angle of $\sim 12$ mrad to reduce parasitic interactions between ingoing and outgoing bunches. Crossing frequency is up to 368 MHz (with 120 bunches). Typical number of particles/bunch is $\sim 10^{11}$, corresponding to $\sim 43$ mA/bunch, with a total current per beam of 5.2 A.

A coupling $\beta_y/\beta_x$ ($\sim 1\%$) with a $\beta_y = 0.045$ m, together with a rather aggressive value for the tune-shift ($\xi = 0.04$) have been chosen. Before KLOE rolled-in, a single bunch luminosity $L \sim 1.5 \times 10^{29}$ cm$^{-2}$s$^{-1}$ was achieved with 20 mA/beam and soon after $L \sim 10^{31}$ cm$^{-2}$s$^{-1}$, with 13 bunches and $\sim 200$ mA/beam, was also reached.

KLOE insertion has introduced a large perturbation in the rings optics, due to the large Bdl of the solenoid (2.4 T/m, to be compared with a beam rigidity $B\rho \sim 1.7$ T/m). If uncompensated, the KLOE field would rotate the beam of $\sim 40$ degrees at the interaction point.

Compensation has to be obtained on both rings through the careful tuning of solenoidal compensators, while the quadrupoles of the low $\beta$ insertion need to be rotated, in order to reduce transverse coupling. Only a first order pass has been made so far, which still cannot achieve neither a satisfactory coupling, nor a good matching of the $\beta^*$ on both rings.
At the moment of this conference, single bunch luminosities \( L_0 \sim 2 \times 10^{29} \text{cm}^{-2} \text{s}^{-1} \) with 10 mA/bunch and multi-bunch \( L \sim 2 \times 10^{30} \text{cm}^{-2} \text{s}^{-1} \) with ten bunches have been reached.

The KLOE detector was fully operational since July 1998 and a lot of experience on the detector calibration, data acquisition and triggering has been gained running with cosmic rays. The detector was installed in DAΦNE early in 1999 and was fully operational in March 1999. First collisions were observed and recorded on the 23rd April 1999. Another few weeks were later dedicated to the study of the \( \phi \) line shape running in single bunch mode. Once the beam energy was determined, multi-bunch operation started, for a total of 10 days of stable operation. The integrated luminosity of this pilot run was \( \sim 200 \text{nb}^{-1} \), which allowed us to tune-up the calibration and reconstruction procedures.

![Figure 1: Schematic view of the KLOE detector](image)

### 3 Overview of KLOE and its performances

The KLOE detector \[\text{[2]}\ [3]\] is a general purpose \( e^+e^- \) detector of respectable dimension (\( \sim 7 \text{m diameter, 6 m length} \)). Going outward (fig. [4]), a 0.5 mm thick cylindrical beryllium beam pipe with a spherical shape of 10 cm radius (16 \( \lambda_e \)) surrounds the interaction point. The inner permanent quadrupole region is instrumented by two lead-scintillator tiles calorimeters of \( \sim 5 \text{cm thickness} \), each organized in 16 wedges.
Their major function is to improve the rejection efficiency for $K_L^{000}$. Although their reduced shower containment results in a poor energy resolution, $\gamma$ detection efficiency, timing and position resolution ($\epsilon \geq 98\%$, $\sigma_x \sim 5$ cm, $\sigma_t \sim 1$ ns) are enough to achieve the desired rejection power.

A large drift chamber, DCH [4], of 4 m diameter and 3.5 m length, follows surrounded by an electromagnetic calorimeter, EMC, which covers almost hermetically the solid angle. Everything is embedded inside the coil cryostat and a specially shaped iron yoke. The superconducting coil generates a field of 6 kG. The trigger [3] and data acquisition, DAQ [5], systems allow to collect a very high event rate. At the highest luminosity we expect to have $\sim 2.5$ KHz of $\phi$, $\sim 50$ KHz Bhabha, 2.5 KHz cosmics and few KHz of machine background. DAQ is able to handle a data throughput well above 50 MB/sec, through two levels of data concentration via dedicated hardware processors and online event building in parallel farms. The two levels trigger is based on EMC energy deposit and DCH hit multiplicity. Its main task is to reduce the event rate to the one allowed by DAQ without losing any relevant $\phi$ decay, while retaining some portions of Bhabha and cosmics for calibration purposes.

The main task of the EMC is to reconstruct the $K_L^{000}$ decay vertex and to efficiently reject the $K_L^{000}$ background. The vertex reconstruction of the decay $K_L \rightarrow \pi^0\pi^0$ is performed by accurately measuring the arrival time to the calorimeter of all the photons [2, 3]. Using the flight direction of the $K_S \rightarrow \pi^+\pi^-$, one can easily demonstrate that a single photon is sufficient to determine the $K_L$ decay vertex. These requirements correspond to the following design specifications:

1. $\sigma_E/E \sim 5\%/\sqrt{E}$ (GeV);
2. $\sigma_T \simeq 70$ ps/$\sqrt{E}$ (GeV);
3. full efficiency for $\gamma$’s in the range 20–280 MeV; (4) hermeticity.

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. Two end-caps, consisting of 32 “C” shaped modules, close hermetically the barrel. The modules are read out on the two sides with a granularity of $\sim 4.4 \times 4.4$ cm$^2$ by fine mesh PM’s, for a total number of 4880 channels. The basic calorimeter structure consists in an alternating stack of 1 mm scintillating fiber layers glued between thin grooved lead foils. The final composite has a fiber:lead:glue volume ratio of approximately 48:42:10, a density of $\sim 5$ g/cm$^3$ and a $X_0$ of $\sim 1.6$ cm.

The EmC modules and the front-end electronics were fully installed in KLOE at the beginning of 1998. The calorimeter has been fully operational since then. After the installation, a first calibration of the calorimeter with cosmic rays has been performed, to obtain the minimum ionizing peak for each calorimeter channels with an accuracy better than 1%. The responses of all PMs is equalized to a few percent, in order not to bias the trigger response. The times measured at the two ends of a cell allow to obtain the arrival time of the particles and the coordinate along the fiber. Fitting the measured time pattern for the fired cells in high energy cosmic ray events,
the time offset of each channel is determined with a precision of \( \sim 10 \) ps. A check of this calibration consists in measuring the velocity of cosmic rays as a function of their momentum, as reconstructed by the drift chamber. A fit to the measured distribution of \( \beta = p/\sqrt{p^2 + m^2} \), leaving the mass \( m \) as the only free parameter, yields a value in good agreement with the muon mass, as shown in fig. 2-left.

The Bhabha and \( e^+e^- \rightarrow \gamma\gamma \) events allow then to set the energy and time scales. The measured energy resolution at 510 MeV is \( \sim 7.8\% \), corresponding to \( \sigma/E \approx 5.5\%/\sqrt{E(\text{GeV})} \). As a check of the energy scale calibration, we reconstructed the invariant mass of the photon pair from \( \phi \rightarrow \pi^+\pi^-\pi^0 \) events. The peak in the invariant mass distribution is within 1 MeV from the \( \pi^0 \) mass, as shown in fig. 2-right.

![Figure 2: EMC performances left): c\beta vs P(Mev/c) for cosmic ray events, the fit is described in the text; right): Invariant mass of the two \( \gamma \)'s coming from \( \pi^0 \) in \( \pi^+\pi^-\pi^0 \) events.](image)

In order to evaluate the time performances of the calorimeter, the quantity \( \Delta t = t_{\text{clu}1} - R_1/c - (t_{\text{clu}2} - R_2/c) \) is measured for the two photons of \( e^+e^- \rightarrow \gamma\gamma \) events; \( t_{\text{clu}} \) is the arrival time of the particle as measured by the calorimeter cluster, \( R \) is the position of the cluster centroid. We observe \( \sigma_{\Delta T} \sim 150 \) ps, corresponding to \( \sigma_t \sim 75 \) ps/\( \sqrt{E (\text{GeV})} \);

The DCH should provide 3-D tracking with a resolution of \( \sim 200 \) \( \mu \)m in the bending plane and a z-resolution of \( \sim 1 \) mm on the decay vertices over the whole sensitive volume. In order to efficiently reject the \( K_{\mu3} \) background, a momentum resolution of 0.5% for low momentum tracks is required; the active volume should be as transparent as possible to minimize multiple scattering. Since the \( K_L \)'s decay almost uniformly all over the whole chamber, the tracking reconstruction efficiency
should have minimal dependence on the position in the DCH. The design of the tracker is also driven by the requirement of having a light and homogeneous active volume to prevent $K_L$ regeneration and photon conversions; for the same reason low-mass walls are necessary. The adopted solution is a cylindrical drift chamber whose supporting structure is entirely made of carbon-fiber and filled with an ultra-light gas mixture (90% He-10% iC$_4$H$_{10}$). The requirement of a 3-D reconstruction and of uniform tracking forces the choice of square cells arranged in layers with alternating stereo angles. In order to keep a constant drop, the stereo angle varies with increasing radius from $\pm 60$ mrad to $\pm 150$ mrad. The cells are organized in 12 inner layers of smaller cells ($2 \times 2$ cm$^2$) and 46 outer layers of bigger cells ($3 \times 3$ cm$^2$). Good efficiency and space resolution, together with negligible ageing effects, are obtained running at a gas gain of $\sim 10^5$. This requirement is met with 25 $\mu$m W(Au) sense wires and 80 $\mu$m field Al(Ag) wires kept at $\sim 1.9$ KV. The DCH has a total of 52000 wires with a ratio 3:1 between the number of field to sense wires.

The DCH was moved inside KLOE on April 1998 and has been kept in operation for more than 1 year with a very low number of dead/hot channels/wires (below 0.1%). The calibration of the drift chamber proceeds, after subtracting the time offsets of each single wire, via an iterative procedure which minimizes the fit residuals by redefining the $s - t$ relations. In this gas mixture we do not expect to have a saturated drift velocity. The $s - t$ relations are therefore not linear and they are parametrized with a 5th order Chebychev polynomial. The minimization procedure stops whenever the mean of the fit residuals is below 100 $\mu$m. The behaviour of the

Figure 3: DCH performances: left): momentum resolution as function of $\theta$ angle for Bhabha events, right): $\pi^+\pi^-$ invariant mass for $K_S$ decays.
space resolution along the cell shows the usual dependence on primary ionization and longitudinal diffusion. The average value of the resolution is $\sim 150 \, \mu m$. The whole chamber calibration can be performed in $\sim 4$ hours, using cosmic rays.

Using Bhabha events and $K_s \rightarrow \pi^+\pi^-$, we can then evaluate the momentum resolution and the momentum scale. As shown in fig. 3-left, we obtain a momentum resolution better than 0.4% for polar angles greater than 45°. The invariant mass of the $K_S$ is also shown in fig. 3-right; fitting it with a gaussian, we obtain $M_{K_s} \sim 496$ MeV with $\sigma$ of $\sim 1$ MeV.

4 CONCLUSIONS

KLOE has started operations on the beam. DAΦNE is presently delivering a luminosity $L$ of $\sim 2 \times 10^{30} \text{cm}^{-2}\text{s}^{-1}$. Using the 200 nb$^{-1}$ of delivered luminosity so far, the detector has shown to be fully operational in all its hardware and software components, reaching or being very close already to its design specifications. KLOE is ready for real data.

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