A Status Report of KLOE at DAΦNE

Sergio Bertolucci
I.N.F.N - Laboratori Nazionali di Frascati
Via E. Fermi 40, 00044 Frascati, Italy
for the KLOE collaboration

1 Introduction

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

Because the vector meson ϕ decays into K^+K^- 49 % , $K_S K_L$ 34% of the times, DAΦNE can be considered a factory of neutral and charged kaons, produced in collinear pairs, with momenta of $\sim$ 110 MeV/c and in a pure quantum state ($J^{PC} = 1^{--}$). Interference effects will then appear in the decays of the $K_S K_L$ ($K\overline{K}$) pairs, allowing the measurement of all (except one) of the parameters of CP and CPT violation. The observation of one charge conjugate state of the kaon guarantees *(tags)* the existence of the other one in the opposite direction. This allows one to define a pure K_S beam *without using any regenerator*.

At the design luminosity, DAΦNE will produce, in one HEP physics year (10^7 s), 8.5×10^9 $K_S K_L$, 1.2×10^{10} K^+K^-, 2.5×10^8 η, 2.5×10^6 η', and $\sim 10^5$ a_0 and f_0.

A detector, KLOE, has been built to pursue 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 (which has not been measured so far);
- the study of radiative ϕ decays, investigating the nature of the a_0 and f_0 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 pb^{-1} of collected data, we already expect to measure $\Re(\varepsilon'/\varepsilon)$ 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 ϕ decays.

Because the double ratio (R) is related to $\Re(\varepsilon'/\varepsilon)$ by

$$R = \frac{N(K_L \to \pi^+\pi^-)/N(K_S \to \pi^+\pi^-)}{N(K_L \to \pi^0\pi^0)/N(K_S \to \pi^0\pi^0)} = 1 + 6\Re(\varepsilon'/\varepsilon)\ , \tag{1}$$

the final goal of the experiment of measuring $\Re(\varepsilon'/\varepsilon)$ 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 $K_L \to \pi^+\pi^-\pi^0$ ($K_L^{\pi\pi\pi}$) 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.

Because at these energies the decay length (λ) 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. Essentially, all the K_S decay in vacuum inside a beam pipe of radius 10 cm, which approximates an infinite decay volume for this state. But for the K_L, the difference between the boundaries of charged and neutral decay volumes 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 another source of systematics. The main backgrounds for the CP violating K_L decays are $K_L \to \pi^0\pi^0\pi^0$ (K_L^{000}) and $K_L \to \pi\mu\nu$ ($K_{\mu 3}$), 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. To reach the desired accuracy in $\Re(\varepsilon'/\varepsilon)$, we need to collect $\sim 4 \times 10^6$ $K_L \to \pi^0\pi^0$. This can be done in two HEP years (2×10^7 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 ($L_0 \sim L_{VEPP-2M} = 4 \times 10^{30}$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 μm, 2 mm, 3 cm) intersect with a half angle of $\sim$ 12 mrad to reduce parasitic interactions between ingoing and outgoing bunches. The crossing frequency is up to 368 MHz (with 120 bunches). The 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.

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

The KLOE insertion has introduced a large perturbation in the ring optics due to the large $\int Bd\ell$ of the solenoid (2.4 Tm, to be compared with a beam rigidity $B\rho \simeq 1.7$ Tm). If uncompensated, the KLOE field would rotate the beam of ~ 40 degrees at the interaction point.

Compensation has to be obtained in both rings through the careful tuning of solenoidal compensators, while the quadrupoles of the low β insertion need to be rotated to reduce transverse coupling. Only a first order pass has been made so far, which still cannot achieve either a satisfactory coupling or a good matching of the β^* on both rings.

At the moment of this conference, single bunch luminosities $L_0 \sim 2{\times}10^{29}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with 10 mA/bunch, and multi-bunch, $L \sim 2{\times}10^{30}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ with ten bunches, have been reached.

The KLOE detector has been 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 April 23, 1999.

Another few weeks were later dedicated to the study of the ϕ 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 $\sim 200\ \mathrm{nb}^{-1}$, which allowed us to tune-up the calibration and reconstruction procedures.

3 Overview of KLOE and its performances

The KLOE detector [2, 3] is a general purpose e^+e^- detector of respectable dimension ($\sim$ 7 m diameter, 6 m length), illustrated in Fig. 1. Going outward, a 0.5 mm thick cylindrical beryllium beam pipe with a spherical shape of 10 cm radius (16 λ_s) surrounds the interaction point. The inner permanent quadrupole region is instrumented by two lead-scintillator tiles calorimeters of $\sim$ 5 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, their γ detection efficiency, timing, and position resolution ($\varepsilon \geq 98\%$, $\sigma_x \sim 5$ cm, $\sigma_t \sim 1$ ns) are enough to achieve the desired rejection power.

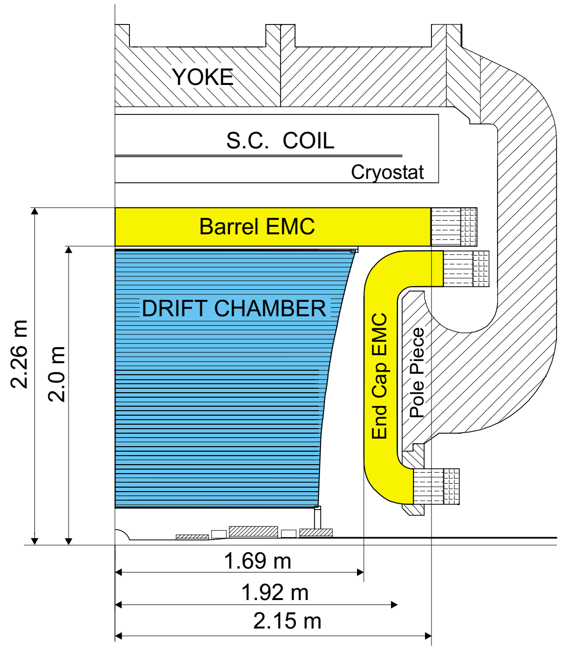

Figure 1: Schematic view of the KLOE detector

A large drift chamber (DCH) [4], of 4 m diameter and 3.5 m length, follows. This is surrounded by an electromagnetic calorimeter (EMC), which covers the solid angle almost hermetically. Everything is embedded inside the coil cryostat and a specially shaped iron yoke. The superconducting coil generates a field of 6 kG. The trigger [5] and data acquisition (DAQ) [6] systems allow one to collect a very high event rate. At the highest luminosity, we expect to have $\sim$ 2.5 KHz of ϕ, $\sim$ 50KHz of Bhabha, 2.5 KHz of cosmics, and few KHz of machine background. The 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 level trigger is based on EMC energy deposit and DCH hit multiplicity. The main task of this trigger is to reduce the event rate to the one allowed by DAQ without losing any relevant ϕ decay, while retaining some portions of Bhabhas and cosmics for calibration purposes.

The main task of the EMC is to reconstruct the K_L^{00} decay vertex and to efficiently reject the K_L^{000} background. The vertex reconstruction of the decay $K_L \to \pi^0\pi^0$ is performed by accurately measuring the arrival time at the calorimeter of all the photons [2, 3]. Using the flight direction of the $K_S \to \pi^+\pi^-$, 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. $\sigma_E/E \sim 5\%/\sqrt{E\ (\mathrm{GeV})}$;
2. $\sigma_T \simeq 70\ \mathrm{ps}/\sqrt{E\ (\mathrm{GeV})}$;
3. full efficiency for γ'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) approximates a cylindrical shell of 4 m inner diameter, 4.3 m active length, 23 cm thickness ($\sim$ 15 X_0), and consists of 24 modules. Two end-caps, consisting of 32 "C" shaped modules, hermetically close 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 PMs with a total 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 channel 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 one 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 is given by 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 the left side of Fig. 2.

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

To evaluate the time performances of the calorimeter, the quantity $\Delta t = (t_{clu1} - R_1/c) - (t_{clu2} - R_2/c)$ is measured for the two photons of $e^+e^- \to \gamma\gamma$ events, where t_{clu} is the arrival time of the particle as measured by the calorimeter cluster and R is the position of the cluster centroid. We observe $\sigma_{\Delta T} \sim 150$ ps, corresponding to $\sigma_t \sim 75\ \mathrm{ps}/\sqrt{E\ (\mathrm{GeV})}$.

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

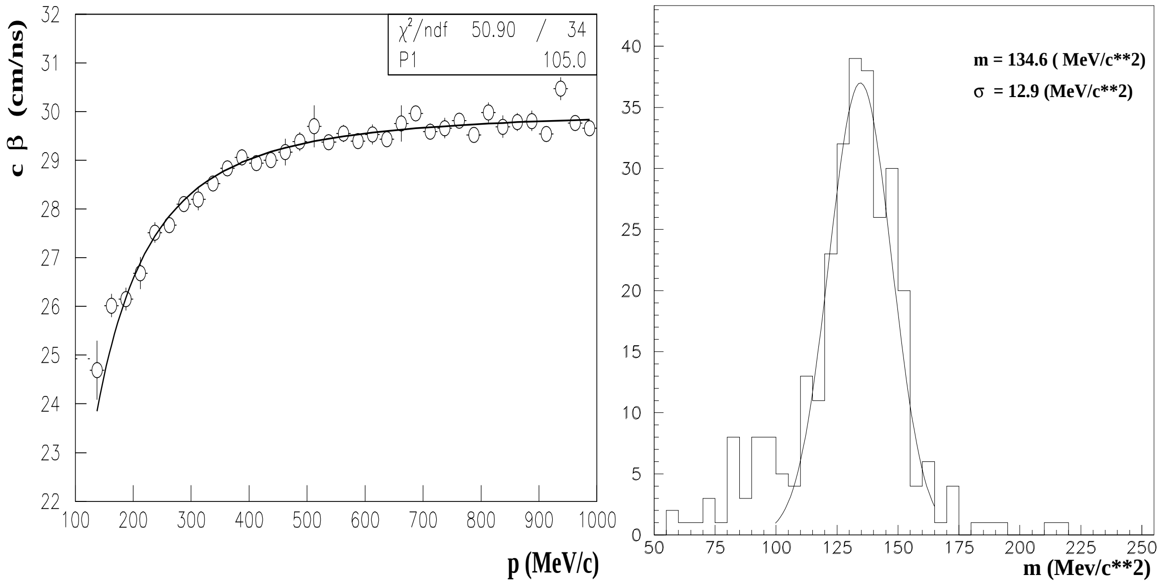

Figure 2: EMC performances left): $c\beta$ vs P(Mev/c) for cosmic ray events, the fit is described in the text; right): Invariant mass of the two γ's coming from π^0 in $\pi^+\pi^-\pi^0$ events.

sensitive volume. In order to efficiently reject the $K_{\mu 3}$ 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. Because 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 solution adopted is a cylindrical drift chamber with a supporting structure made entirely of carbon-fiber and filled with an ultra-light gas mixture (90% He-10% iC_4H_{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. To keep a constant drop, the stereo angle varies with increasing radius from ±60 mrad to ± 150 mrad. The cells are organized in 12 inner layers of smaller cells (2×2 cm^2) and 46 outer layers of bigger cells (3×3 cm^2). Good efficiency and spatial resolution, together with negligible aging effects, are obtained running at a gas gain of $\sim 10^5$. This requirement is met with 25 μm W(Au) sense wires and 80 μm 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 oper-

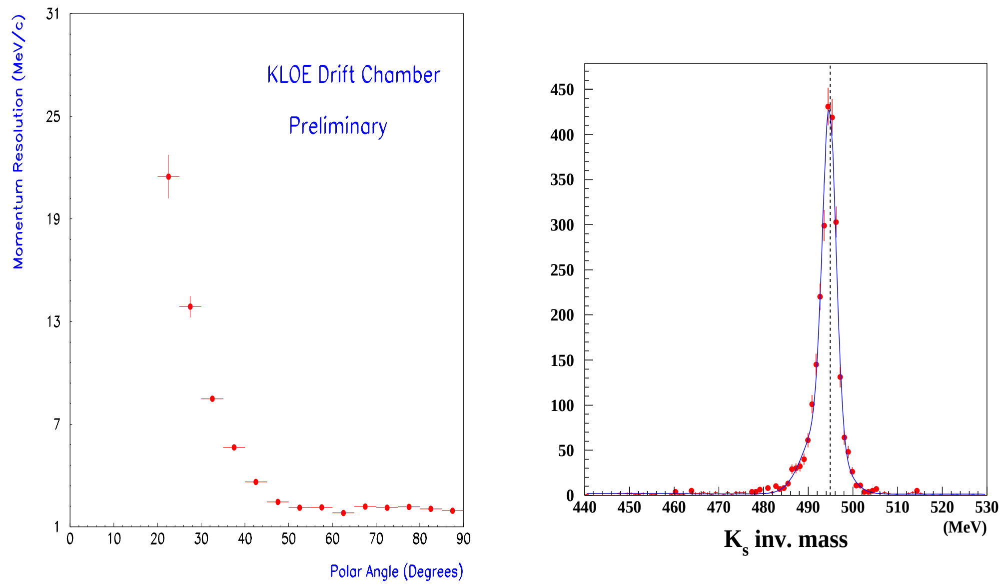

Figure 3: DCH performances: left): momentum resolution as function of θ angle for Bhabha events, right): $\pi^+\pi^-$ invariant mass for K_S decays.

ation 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 parameterized with a fifth order Chebychev polynomial. The minimization procedure stops whenever the mean of the fit residuals is below 100 μm. The behavior of the spatial resolution along the cell shows the usual dependence on primary ionization and longitudinal diffusion. The average value of the resolution is $\sim$ 150 μm. The whole chamber calibration can be performed in $\sim$ 4 hours using cosmic rays.

Using Bhabha events and $K_s \to \pi^+\pi^-$, we can then evaluate the momentum resolution and the momentum scale. As shown in the left side of Fig. 3, 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 the right side of Fig. 3. Fitting with a gaussian, we obtain $M_{K_s} \sim 496$ MeV with σ of $\sim$ 1 MeV.

4 Conclusions

KLOE has started operations on the beam. DAΦNE is presently delivering a luminosity L of $\sim 2 \times 10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. 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.

References

[1] G. Vignola, Proceedings of the 1996 European Particle Accelerator Conference.

[2] KLOE collaboration, LNF-92/019 (1992).

[3] KLOE collaboration, LNF-93/002 (1993).

[4] KLOE collaboration, LNF-94/028 (IR) (1994).

[5] KLOE collaboration, LNF-96/043 (IR) (1996).

[6] KLOE collaboration, LNF-95/014 (IR) (1995).