The KLOE Collaboration

KLOE
A GENERAL PURPOSE DETECTOR FOR DAΦNE

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ABSTRACT

We propose a general purpose detector, KLOE, to be used at DAΦNE the Frascati φ-factory. The detector is optimized for the study of CP violation in $K^0$ decays with the aim of achieving a statistical accuracy of $\sim 10^{-4}$ for $\Re(\epsilon'/\epsilon)$ in one year run at the DAΦNE target luminosity of $10^{33}$ cm$^{-2}$s$^{-1}$. By studying interference patterns at small time differences, we can improve by one or two orders of magnitude the accuracy in the knowledge of the 20 parameters describing the $K^0$ system from $\Delta m$ and total widths to CPT violating parameters. The detector is also well suited to perform high accuracy measurements of the $K_{\ell 3}$, $K_{\ell 4}$ form factors. Spectroscopy studies, in particular $\phi$ radiative decays, can clarify the properties of scalar states such as the $f_0$ (975) meson and improve understanding of the quark and gluon contents of $\eta$, $\eta'$. $\gamma\gamma$ physics can be explored both for neutral and charged pion final states. $K$-nucleon scattering is relevant to the strange sea contents of the nucleon.
KLOE
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1. PHYSICS WITH KLOE

1.1 INTRODUCTION

The cross section for $e^+e^- \rightarrow \phi$ at energies $W = M_\phi$ is approximately $5 \mu b$ which, for $L = 10^{33}$ cm$^{-2}$ s$^{-1}$, corresponds to a production rate of 5000 $\phi$ mesons per second. $\phi$-mesons decay with branching ratios (BR) given, together with some relevant properties, in Table 1.[1]

<table>
<thead>
<tr>
<th>Mode</th>
<th>BR %</th>
<th>$\beta_K$</th>
<th>$\gamma \beta c t$</th>
<th>$p_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+K^-$</td>
<td>49</td>
<td>0.249</td>
<td>95.4</td>
<td>127</td>
</tr>
<tr>
<td>$K_S^{-}K_L$</td>
<td>34</td>
<td>0.216</td>
<td>343.8</td>
<td>110</td>
</tr>
<tr>
<td>$\rho\pi$</td>
<td>13</td>
<td>-</td>
<td>-</td>
<td>182</td>
</tr>
<tr>
<td>$\pi^+\pi^-\pi^0$</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>462</td>
</tr>
<tr>
<td>$\eta\gamma$</td>
<td>1.3</td>
<td>-</td>
<td>-</td>
<td>362</td>
</tr>
<tr>
<td>other</td>
<td>$\sim 1$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

DAΦNE is thus a good $K^+K^-$ and $K_SK_L$ factory, a reasonable $\eta$ factory, most likely a good source of $\eta'$ mesons. In addition DAΦNE has the unique possibility of producing pure $K_S$, $K_L$, $K$ and $\bar{K}$ beams.

1.2 CP VIOLATION IN $K^0\rightarrow\pi^0\pi^0$ AND $\pi^+\pi^-$

The physics program of KLOE at DAΦNE is centered around the study of CP violation in the decays $K_L, K_S \rightarrow \pi^0\pi^0, \pi^+\pi^-$. The CP impurity of the $K_S, K_L$ states, due to second order weak $K \leftrightarrow \bar{K}$ transitions, allows for $K_L \rightarrow 2\pi$ decays[2] because of its small CP-odd component. 28 years later, we still do not know whether there is a direct, $\Delta S = 1$, CP violating amplitude, i.e., $(2\pi|K_2) \neq 0$.

Defining the usual amplitude ratios and epsilon parameters:[3]

$$\frac{\langle \pi^+\pi^- | K_L \rangle}{\langle \pi^+\pi^- | K_S \rangle} = \eta_{+-} = \epsilon + \epsilon', \quad \frac{\langle \pi^0\pi^0 | K_L \rangle}{\langle \pi^0\pi^0 | K_S \rangle} = \eta_{00} = \epsilon - 2\epsilon' \quad (1.1)$$

where $\eta$'s and $\epsilon$'s are all complex, experimental observation of $\epsilon' \neq 0$ would be proof that CP is violated in the decay amplitude. Many experiments have attempted to measure $\Re(\epsilon'/\epsilon)$ with continuously improving sensitivity. The most recent results can be summarized as: $\Re(\epsilon'/\epsilon) = (0 - 3) \times 10^{-3}$[4,5]. The standard model, in the context of the CKM quark mixing mechanism,[6] predicts[7] $\Re(\epsilon'/\epsilon) \sim 10^{-3}$, with smaller values possible, especially for $M_{\text{top}} \sim 150 \text{ GeV}$.[8] $\Re(\epsilon'/\epsilon) \equiv 0$ would be a signal of physics beyond the SM.[9] Unfortunately theory cannot at present perform accurate calculations, especially cannot exclude an accidental cancellation of the gluonic and electroweak penguin amplitudes.

1.3 $\phi \rightarrow K^0\bar{K}^0$

One of the advantages of studying $K$ mesons at DAΦNE, is that they are produced in a pure quantum state. $K^0$ (and $K^\pm$) meson are produced in collinear pairs, with a momentum of
about 110 MeV/c, thus detection of one $K$ gives the direction of the other. At $t=0$, we have:

$$|i\rangle = \frac{|K^0, p\rangle \langle K^0, -p| - |K^0, p\rangle \langle K^0, -p|}{\sqrt{2}}$$

$$= \frac{1}{\sqrt{2}} \frac{1 + |\epsilon|^2}{1 - \epsilon^2} \times (|K_s, -p\rangle \langle K_L, p| - |K_s, p\rangle \langle K_L, -p|).$$  \hspace{1cm} (1.2)

The amplitude for decay to states $f_1$ at time $t_1$ and $f_2$ at time $t_2$, with $\Delta t = t_1 - t_2$ is:

$$\langle f_1, t_1, p; f_2, t_2, -p| i \rangle = \frac{1 + |\epsilon|^2}{(1 - \epsilon^2)\sqrt{2}} \times$$

$$\langle f_1| K_S \rangle \langle f_2| K_S \rangle e^{-i\Delta M t/2} \left( \eta_1 e^{i\Delta t} - \eta_2 e^{-i\Delta t} \right).$$  \hspace{1cm} (1.3)

The decay intensity $I(f_1, f_2, \Delta t = t_1 - t_2)$ to final states $f_1$ and $f_2$ is obtained from eq. (1.3) above by integrating over all $t_1, t_2$, with $\Delta t$ constant. For $\Delta t > 0$:

$$I(f_1, f_2; \Delta t) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |A(f_1, t_1; f_2, t_2)|^2 dt_1 dt_2 =$$

$$\frac{1}{2\Gamma} |\langle f_1| K_S \rangle \langle f_2| K_S \rangle|^2 \left( |\eta_1|^2 e^{-\Gamma_L \Delta t} + |\eta_2|^2 e^{-\Gamma_S \Delta t} \right)$$

$$- 2|\eta_1||\eta_2| e^{-\Gamma \Delta t/2} \cos(\Delta m \Delta t + \phi_1 - \phi_2),$$  \hspace{1cm} (1.4)

with $\eta_i = A(K_L \rightarrow f_i)/A(K_S \rightarrow f_i) = |\eta_i| e^{i\delta_i}$, exhibiting interference terms sensitive to phase differences.

1.4 Measurements of CP and CPT Violation Parameters

Choosing $f_1 = \pi^+ \pi^-$ and $f_2 = \pi^0 \pi^0$ one can observe interference effects sensitive to $\Im(\epsilon'/\epsilon)$ in the time ordered decay distribution $I(f_1, f_2, \Delta t)$ and obtain $\Re(\epsilon'/\epsilon)$ as well from the time asymmetry.\(^{10}\) Fig. 1.1 shows a typical interference pattern and the very small effect of the experimental resolution in the the measurement of $\Delta t$ in KLOE. See section 6.
Fig. 1.1 Interference pattern without (solid line) and with finite resolution (dashed line).

If CPT is not assumed, the properties of the neutral K mesons can be described in terms of 20 parameters, all of which are measurable at DAΦNE, using the decay intensity of eq. (1.4) with appropriate choice of the final states $f_1$, $f_2$. Thus in addition to the choice indicated above, for $f_1 = f_2$ we can measure $\Gamma_S$, $\Gamma_L$ and $\Delta m$. Choosing $f_1 = \pi^+\ell^-\nu$ and $f_2 = \pi^-\ell^+\nu$ we can search for $T$ and CPT violation, including the so-called Kabir test.\textsuperscript{[11,12]} Very interesting is the case of choosing two pions for one final state and a semileptonic channel for the other, which leads to measurements of CPT violation parameters in addition to $\Delta m$, $|\eta_{\pi\pi}|$ and $\phi_{\pi\pi}$. Note that all these measurements do not require knowledge of the nature of the decaying particles, only identification of the decay channel.\textsuperscript{[13]} KLOE can improve the present knowledge of the parameters of the $K_S, K_L$ system by one or two orders of magnitude. KLOE has unique possibilities because it is self-calibrating and we have an absolute normalization of the $K_S, K_L$ fluxes. We can also use the classical method of the double ratio

$$R^\pm / R^0 = \frac{K_L \to \pi^+\pi^-}{K_S \to \pi^+\pi^-} / \frac{K_L \to \pi^0\pi^0}{K_S \to \pi^0\pi^0} = 1 + 6 \times \Re(\epsilon'/\epsilon),$$

using tagging to select pure $K_S$ and $K_L$ beams as implied in eq. (1.2). Other ways of measuring $\Re(\epsilon'/\epsilon)$ from selected final states are:\textsuperscript{[14]}

$$\frac{N(\pi^+\pi^-\pi^+\pi^-)}{N(\pi^0\pi^0\pi^0\pi^0)} \times \left( \frac{BR(K_S \to \pi^0\pi^0)}{BR(K_S \to \pi^+\pi^-)} \right)^2 = 1 + 6 \times \Re(\epsilon'/\epsilon)$$

$$\frac{N(\pi^+\pi^-\pi^+\pi^-)}{N(\pi^+\pi^-\pi^0\pi^0)} \times \frac{BR(K_S \to \pi^0\pi^0)}{BR(K_S \to \pi^+\pi^-)} = 1 + 3 \times \Re(\epsilon'/\epsilon)$$

While all the methods listed are not statistically independent, they provide very useful checks because of the very different dependence on all systematic effects. Figure 1.2 shows the statistical accuracy reachable for $\Re(\epsilon'/\epsilon)$ with the time asymmetry method and for the double ratio method vs detector dimension. For the case of $\Im(\epsilon'/\epsilon)$ the relevant parameter is the spatial
resolution for the measurement of the decay paths. In the following we propose a detector of 2 m radius and capable of a resolution in $\Delta t$ of $\sim r_2/2$ or 3 mm in space, at small distances from the interaction point. This implies that we can measure $\Re(\epsilon'/\epsilon)$ to $\sim 10^{-4}$ and $\Im(\epsilon'/\epsilon)$ to $\sim 10^{-3}$, approximately a factor 10 better than present experiments.

![Graph](image)

**Fig. 1.2** KLOE measurement accuracy as a function of fiducial volume radius.

We want to explicitly point out here that fig. 1.2 cannot be used to scale detector size vs performance in order to optimize cost vs physics. Scaling down the detector size without losing angular resolution for photons and momentum and direction accuracy for charged particles, would not reduce the number of readout channels, they would probably increase. In addition the miniaturization implied would make construction more difficult and reduce reliability. Finally some redundancy in the detector will compensate for possible lower luminosity.

### 1.5 Other Searches for CP Violation.

Observation of $K_S \to 3\pi^0$ is proof of CP violation. At present the upper limit on the BR is $3.7 \times 10^{-5}$. The amplitude ratio $\eta_{000}$ can be written as

$$
\frac{\langle \pi^0\pi^0\pi^0 | K_S \rangle}{\langle \pi^0\pi^0\pi^0 | K_L \rangle} = \eta_{000} = \epsilon + \epsilon'_{000}
$$

(1.5)

where $\epsilon'_{000}$ is the "direct" CP violating contribution. For $\epsilon'_{000} = 0$, one obtains

$$
BR(K_S \to 3\pi^0) = 2 \times 10^{-9}
$$

(1.6)

which is just observable, corresponding to $\sim 30$ events in one year. While $\epsilon'/\epsilon$ is naturally suppressed by the $\Delta I = 1/2$ rule, this is not the case for $\epsilon'_{000}/\epsilon$. However the expected suppression for $\epsilon'/\epsilon$ is only $\sim 1/20$ and it appears therefore unlikely that $\epsilon'_{000}/\epsilon > 2 \times 10^{-2}$, giving small hope for the observation of direct CP violation in $K_S \to 3\pi^0$. Still the observation for the first time of CP violation in a new channel would be of considerable interest. Evidence for direct CP violation can be obtained from the decays of charged kaons which are copiously produced.
at DAΦNE. CPT invariance requires that the total rates for \( K^\pm \to 3\pi \) be identical while CP requires equality of the partial rates for \( K^\pm \to \pi^\pm \pi^0 \pi^- \) (\( \tau^\pm \)) and for \( K^\pm \to \pi^\pm \pi^0 \pi^0 \) (\( \tau'^\pm \)). We define the fractional decay rate differences for \( \tau \) and \( \tau' \) modes as:

\[
A = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}, \quad A' = \frac{\Gamma'^+ - \Gamma'^-}{\Gamma'^+ + \Gamma'^-}.
\]

(1.7)

The present experimental information is\(^{[4]}\) \( A = (0.7 \pm 1.2) \times 10^{-3} \) and \( A' = (0 \pm 6) \times 10^{-3} \), while theoretical estimates are \( \mathcal{O}(10^{-8}) \)\(^{[15]}\). Measurements of rate differences of the order of \( 10^{-4} - 10^{-5} \) require very tight control of systematics effect. The possibility of tagging at DAΦNE, permits in fact an exact cancellation of efficiencies in this type of measurements and sensitivities of few \( \times 10^{-5} \) can be achieved.

Finally we mention the possibility of observing differences in the Dalitz plot distributions for \( K^+ \) and \( K^- \) decays in both the \( \tau \) and \( \tau' \) modes. In particular the Dalitz plot population has a slope in the odd pion energy distribution, usually characterized by a parameter \( g \), which, from CP invariance must satisfy \( g(\tau^+) = g(\tau^-) \) and \( g(\tau'^+) = g(\tau'^-) \). Present experimental limits on the asymmetry\(^{[1]}\) \( A = (g^+ - g^-)/(g^+ + g^-) \) range between few \( \times 10^{-2} \) and few \( \times 10^{-3} \) while KLOE could reach sensitivities of \( \sim 10^{-4} \)\(^{[16]}\). Predictions are \( \mathcal{O}(10^{-6}) \)\(^{[15]}\).

The examples given above do not exhaust the possibilities for searching for CP violation in \( K \) decays. For example \( K_S, K_L \to \gamma + x \) decays and \( \pi^+ \pi^- \) asymmetry in \( K_L \to \pi^+ \pi^- \pi^0 \) could also provide evidence for CP violation. Differences in radiative two pion decays of \( K^\pm \) are also proof of direct CP violation. The present experimental limit\(^{[1]}\) for \( \Delta \Gamma/2\Gamma \) is \( < 5 \times 10^{-2} \) and the theoretical prediction \( 1.6 \times 10^{-4} \). The KLOE sensitivity is \( \sim 1.4 \times 10^{-4} \). While most of the tests described are unlikely to reveal an effect, the large improvement on experimental limits possible with KLOE makes these studies very interesting and a must vis a vis the theoretical predictions.

1.6 Rare \( K \) Decays.

DAΦNE, because of eq. (1.2), is unique. By tagging one can effectively have a beam of \( K_S \), with no background, delivering up to \( 10^{10} \) kaons per year. The availability of pure \( K_S \) beams will dramatically improve knowledge of \( K_S \) branching ratios (most are not measured yet) for searches \( K_S \to \pi^0 \nu \bar{\nu}, e^+e^-\gamma, \mu^+\mu^-\gamma, \pi^0 e^+e^- \), \( \pi^0 e^+e^- \), etc., down to the \( 10^{-8} \) or better range, from statistics. Background effects have not yet been examined in detail at present, however KLOE compares favorably with some BNL set-ups. A search for \( K_S \to \pi^0 \gamma \gamma \) might yield a few detected events. Tens to hundreds of decays \( K^\pm \to \pi^\pm \gamma \gamma \) or \( K^\pm \to \pi^\pm \mu^+ \mu^- \), can also be detected. Existing limits on \( K^\pm \to \pi^0 \mu^\pm \nu \gamma, \pi^\pm \pi^\pm \mu^\mp \nu, \pi^\pm \gamma \gamma \gamma \) and \( l^\pm \nu \nu \nu \), may be substantially improved.

1.7 \( K \)-Mesons and the Chiral Lagrangian

High energy experiments have given quite convincing proofs that the strong interactions are correctly described by an exact gauge theory, QCD, based on the color \( SU(3) \) gauge group. At low energies, in the non perturbative QCD regime, it is not possible at present to obtain quantitative predictions about hadron dynamics from the exact lagrangian. The most promising attempts at present, numerical lattice simulations, are still at a rather crude level.

A possible approach to low energy problems is based on the approximate QCD invariance under the chiral transformations \( SU(3)_L \otimes SU(3)_R \)\(^{[17]}\). At lowest order, \( \mathcal{O}(m^2) \) or \( \mathcal{O}(p^2) \), the
amplitudes are determined in terms of $f_\pi$ and the quark masses. Many predictions can be obtained, such as the Weinberg relation for $\pi - \pi$ scattering lengths and the Callan-Treiman (CT) relation.

Recently several authors\cite{18} have extended these studies to the next order terms in the chiral expansion ($O(m^4)$, $O(p^4)$, $O(m^2 p^2)$). This extension introduces new parameters which must be determined experimentally. Many new amplitudes can then be predicted. In this respect, several relevant measurements can be performed at DAΦNE:\cite{19}

1.7.1 $K_{\ell 3}$

At lowest order the CT relation predicts the slope of the scalar form factor. There is at present disagreement between $K^+$ data and $K_L$ results and different experiments are mutually incompatible.\cite{1} The world averages are $\lambda_0 = 0.004 \pm 0.007$, for $K^+$ and $0.025 \pm 0.006$ for $K_L$, both in disagreement with the CT prediction, $0.017 \pm 0.004$. KLOE can measure $\lambda_0$ for $K_L$ to an accuracy of $1.4 \times 10^{-5}$. The quoted accuracy includes the effects of the measuring resolution and of cuts and ambiguities in $\pi \mu$ assignments.\cite{20} Similar accuracy are obtained for $K^{\pm}$ and for $\lambda_+$.\cite{21}

1.7.2 $K_{\ell 4}$

There is only one measurement of the relevant form factors. KLOE can improve vastly on this topic. These decays also provide a unique opportunity for the determination of the $\pi \pi$ phase shifts.

1.7.3 $K_{\ell 2,\gamma}$, $K_{\ell e^+e^-}$, $K_{\ell 3,\gamma}$

Apart from the radiative term, the amplitudes depend on the $K$ charge radius and three other parameters about which conditions are obtained from pion physics. Additional constraints and checks would follow from the processes listed.

1.7.4 $K^{\pm} \rightarrow \pi^{\pm} \gamma \gamma$

The rate for this process and the $\gamma \gamma$ distributions are uniquely predicted by the chiral lagrangian approach. Dalitz type decays of $K$ mesons and two photon production of pions are also of great interest. Both can be studied with KLOE.

1.7.5 $\gamma \gamma$ physics

The process $\gamma \gamma \rightarrow \pi^0 \pi^0$ is described by a function $\tilde{\alpha}_{\pi^0}^*(s)$, the generalized $\pi^0$ polarizability, where $\sqrt{s} = W$ is the c. m. energy.\cite{21} At threshold ($\sqrt{s} \leq 0.5$ GeV), the Crystal Ball (CB) results are consistently higher than chiral perturbation predictions. This discrepancy is reduced, within chiral perturbation, by including 2-loop effects, which give a sizeable contribution to the cross-section in this region.\cite{22} The status of the data on $\gamma \gamma$ physics is reviewed in ref. 23 and comparison with the predictions of chiral symmetry indicate that more precise measurements are needed.

The process $\gamma \gamma \rightarrow \pi^0 \pi^0$ can be studied at DAΦNE\cite{24} where an integrated $e^+e^-$ luminosity of $\sim 5 \times 10^{39}$ cm$^{-2}$ can provide measurements of $\tilde{\alpha}_{\pi^0}^*(s)$ to a few % accuracy,\cite{23} corresponding to $\sim 10^4$ observed events, almost an order of magnitude improvement over the CB results.\cite{22}

For the process $\gamma \gamma \rightarrow \pi^+\pi^-$ the cross-section is dominated by the Born term, making it harder to measure chiral perturbation corrections.\cite{25} Additional informations can however
be obtained from the angular distribution. With the quoted integrated luminosity, the same accuracy as in the \( \pi^0 \pi^0 \) case could be achieved. Backgrounds for these studies are discussed in section 6.4. Tagging appears to be necessary for the \( \pi^0 \pi^0 \) case. The possibility of tagging is under study, in collaboration with the machine group.

1.8 \( e^+e^- \) Annihilations into Hadrons from Threshold to 1.5 GeV

Precise measurements of \( \sigma(e^+e^- \rightarrow \text{hadrons}) \) up to energies of \( \sim 1.5 \) GeV are necessary for the calculation of the muon anomaly \( a_\mu \).\(^{[26]}\) The hadronic contributions to \( a_\mu \) due to vacuum polarization and light by light scattering result in the largest uncertainty in \( a_\mu \). The estimate, based on poorly known cross section for hadronic \( e^+e^- \) annihilation from the \( 2\pi \) threshold up to \( \sim 1 \) GeV gives:\(^{[26]}\) \( a_{\mu \text{had}} = 702 (19) \times 10^{-10} \) making it impossible to observe the weak interaction contribution which, to one loop, is\(^{[27]}\) \( a_{\mu \text{weak}} = 19.5 (0.1) \times 10^{-10} \).

The required accuracy for the measurements,\(^{[28]}\) of \( \sigma(e^+e^- \rightarrow \text{hadrons}) \) is \( \sim 0.5\% \), readily accessible to KLOE. Recently however doubts have been raised on the validity of the approach used to evaluate the light by light scattering contributions due to quark or hadron loops,\(^{[19,29]}\) which contribute \( 20 \times 10^{-10} \) to \( a_\mu \).

We recall that an accurate determination of the \( K \) form factor at the \( \phi \) mass will allow measurements of the interference of the \( \phi \) meson with the \( \rho \), \( \omega \) mesons and possibly with higher \( s\bar{s} \) excitations. Finally spectroscopic studies up to 1.5 GeV are still of interest. For example searching for the mysterious 1.1 GeV resonance.\(^{[30]}\)

1.9 Radiative \( \phi \) Decays

Precise measurements of the \( \eta - \eta' \) mixing has important bearing on quark models and QCD, in particular on the question whether there is a gluonic component in the \( \eta \) and in the \( \eta' \) wave functions. In this regard measurements of the radiative \( \phi \) decays to \( \eta \) and to \( \eta' \), which are feasible with great sensitivity with KLOE, can lead to a really decisive test, when combined with the information coming from other sources such as e.g. the analogous \( J/\Psi \) decays and the two-photon decays of \( \eta \) and \( \eta' \). To complete the determination of the \( \eta' \) parameters we need measurements of the rare transition \( \phi \rightarrow \eta' \gamma \). There is some room for a non vanishing gluonic component in the \( \eta' \). To give an idea of the expected order of magnitude of the branching ratio, for no gluonium in the \( \eta' \) and a mixing angle of \( -20^\circ \) we expect \( BR(\phi \rightarrow \eta' \gamma) \sim 1.2 \times 10^{-4} \). A Monte Carlo study\(^{[31]}\) shows that KLOE can reach \( BR \)’s of \( \sim 10^{-5} \). This is another interesting piece of physics for KLOE in the context of quark models and QCD.

Finally a study of the radiative decay \( \phi \rightarrow f_0(975) \gamma \) as well as of the \( f_0 \) decays might clarify the properties of this unique \( 0^{++} \) state. KLOE can detect this decay for \( BR > 10^{-7} \) and study the \( f_0(975) \) decays for \( BR > 10^{-6} \).\(^{[31]}\) The present experimental limit is \( 10^{-3} \).

1.10 Rare \( \eta \) and \( \pi^0 \) Decays

Since the \( \eta \) meson is isoscalar and non strange, its decay modes provide information complementary to those of the \( \pi^0 \), which is isovector, and of the \( K \) meson which is strange. At the present time, the non leading decay modes of the \( \eta \) are badly known. With a branching ratio of 1.28% for \( \phi \rightarrow \eta \gamma \), one expects the production of \( 6 \times 10^8 \) \( \eta \)'s in the length of time necessary to
achieve an accuracy of $10^{-4}$ in the measurement of $\Re(\epsilon'/\epsilon)$. This will allow measurements of the BR of many rare decay modes of the $\eta$ with about two orders of magnitude higher statistics than in previous experiments. Through the decays $\phi \rightarrow \rho\pi$ and $\phi \rightarrow \pi^+\pi^-\pi^0$, ten times more $\pi^0$s than $\eta$'s will be produced at DAΦNE. An abbreviated list of interesting measurements is given below. For a detailed discussion see A. Baldissieri et al.[32]

1.10.1 Electromagnetic Decay Modes

These decays give the transition form factor $F(q_1^2,q_2^2)$ for $q_2^2=0$ and $q_1^2 \neq 0$. The best measured decay is $\eta \rightarrow \mu^+\mu^-$, (BR = 5.1 ± 0.8 \times 10^{-6} at Saclay). The accuracy of all electromagnetic decays, including Dalitz and double Dalitz, could be considerably improved with the KLOE detector.

1.10.2 C and CP Tests

The decays $\eta \rightarrow \ell^+\ell^-\pi^0$ test C and CP conservation in electromagnetic processes down to the level of $10^{-8} - 10^{-9}$ where one can expect a contribution from two-photon exchange.[33] This is the level reachable at DAΦNE. Current experimental limits are two or three orders of magnitude higher. Current upper limit on the C-violating process $\eta \rightarrow 3\gamma$ (BR < 5 \times 10^{-4}) will be considerably improved.

1.10.3 Lepton Number Violation

A preliminary upper limit of $10^{-4}$ has been set on the BR of the lepton number violating process $\eta \rightarrow \mu^+\epsilon^-$, at Saclay. Up to four orders of magnitude will be gained at DAΦNE.

1.11 The Strange Sea in the Nucleon

A study of KN interactions listed below, at low energies, will shed light on the strange sea quark content in the nucleon.[34] Strange sea quark pairs seem to contribute to the static properties of the nucleon, to its mass, spin and magnetic moment. At present the low energy KN data base is extremely poor or even not existing. At DAΦNE the complex $K^\pm N$ scattering amplitudes at energies below $T_K = 14$ MeV can be studied for the first time by measuring elastic $K^\pm p$ scattering (including Coulomb-nuclear interference to determine the real part of the scattering amplitude), charge exchange $K^- p \rightarrow \bar{K}^0 n$, regeneration $K_L \rightarrow K_S$ (containing information on $K^\pm n$ scattering), elastic $K^\pm d$ scattering (also containing information on $K^\pm n$ scattering).
2. MEASURING $\epsilon'/\epsilon$ AT DAFNE

In the following we assume:

$$\int \mathcal{L} dt = \frac{1}{3} \gamma \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \sim 10^4 \text{ pb}^{-1}$$

for the luminosity of DAFNE, although $1/10$ as much is a very worthwhile beginning, and assume a 1 year run with a goal of measuring $\mathbb{R} (\epsilon'/\epsilon)$ to an absolute accuracy of $10^{-4}$. Choosing the example of the so called double ratio:

$$\mathcal{R}^\pm /\mathcal{R}^0 = \frac{N_L^\pm /N_S^\pm}{N_L^0/N_S^0} = 1 + 6\mathbb{R} \left( \frac{\epsilon'}{\epsilon} \right),$$

the statistical error on $\epsilon'/\epsilon$ can be expressed in terms of the number $N_L^0$ of observed $K_L \rightarrow \pi^0 \pi^0$ decays as:

$$\delta \left( \frac{\epsilon'}{\epsilon} \right) = \frac{1}{6} \frac{1}{\sqrt{(2/3)N_L^0}},$$

which means that $4.2 \times 10^7$ decays must be observed to achieve the desired statistical accuracy. Choosing a fiducial decay volume for $K_L$ decays of 150 cm gives:

$$N_L^0 = (5 \mu b) \times (10^{10} \mu b^{-1}) \times (2/3) \times (0.34) \times (10^{-3}) \times (1 - e^{-150/350}) = 3.9 \times 10^6$$

2.1 TAGGING

According to equation (1.2), when a $K_S$ ($K_L$) is observed a $K_L$ ($K_S$) is produced and propagates in the opposite direction allowing tagging of $K_L$ and $K_S$ beams, with absolute normalization.

The appearance of a “V” at a distance $20 < l < 180$ cm from the interaction point signals the presence of a $K_L$ decay into the modes $\pi^+ \pi^- \pi^0$, $\pi \mu \nu$, $\pi e \nu$ with essentially no background ($< 10^{-6}$) and therefore is a perfect $K_S$ tag. The efficiency is $\sim 28\%$. Using also $K_L \rightarrow \pi^0 \pi^0 \pi^0$ decays the efficiency is $\sim 35\%$.

A $K_L$ tag is provided by the observation of $\pi^+ \pi^-$ decays of $K_S$'s with path length $l_K < 2$ cm. The efficiency is about $2/3$. Contamination from $K_L$ decays and other $\phi$ decays can be kept well under control, the irreducible background, due to $K_L \rightarrow \pi^+ \pi^-$ is $\sim 6 \times 10^{-3} \times 2 \times 10^{-3}$, quite negligible.

Obviously the $K_L, K_S$ tag is independent of the decay of the $K_L, K_S$ themselves and therefore the tag efficiency drops out identically from $\mathcal{R}^\pm /\mathcal{R}^0$. The small $K_S K_S + K_L K_L$ admixture due to $\phi \rightarrow f_0(975) \gamma$, $f_0(975) \rightarrow K_S K_S + K_L K_L$ is negligible.$^{[35]}$

2.2 DETERMINATION OF EFFICIENCIES

Measuring $\mathcal{R}^\pm /\mathcal{R}^0$ requires measuring the $BR$'s for $K_L$, $K_S$ decays to $\pi^+ \pi^-$ and $\pi^0 \pi^0$, which we denote by $B_{L,S}^{\pm,0}$. We denote by $\phi$ the efficiencies involved in the various steps: tagging, detection, reconstruction and so on. In addition the smearing of the flight path due to finite
resolution is denoted by the smearing function \( g(l-l') \). The observed counts \( N_{L,S}^{\pm,0} \) in the fiducial volume (FV) are given by:

\[
N_{L,S}^{\pm,0} = N_{KK} \times g_{LS}(\text{tag}) \times BR_{L,S}^{\pm,0} \\
\times \int_{FV} \int g(l-l') \exp(-l/l_{L,S}) \times [\theta \cdot \theta \cdot \theta \cdot \theta]_{L,S}^{\pm,0} \, dl \, dl'
\]

\[
= \cdots \langle \theta \theta \theta \rangle \int_{FV} \int g(l-l') \exp(-l/l_{L,S}) \, dl \, dl'
\]

The four properly weighted efficiencies

\[
\langle \theta \theta \theta \rangle \equiv e_{L,S}^{\pm,0}
\]

are different, do not cancel, must be kept under control and measured. They are the driving forces for the design of the detector. We indicate an approach to the measurement of \( g_{L,S}^{0} \), which is by far the hardest efficiency to keep under control. To rely on Monte Carlo calculations at the required level of accuracy is not very satisfactory. However we note that we have at our disposal a sample of \( \sim 5 \times 10^9 \pi^0 \)'s of known energy, origin and direction, essentially uniformly distributed inside the 150 cm decay volume, which can be used to measure the efficiency for \( K_L \rightarrow \pi^0 \pi^0 \) to the required accuracy. These pions come from \( K^\pm \rightarrow \pi^\pm \pi^0 \) decays. Again a charged \( K \) decay tags the presence of a \( K \) of opposite charge and direction. Measurement of the charged decay pion from the tagged \( K \) uniquely determines the \( \pi^0 \) coordinates.

### 2.3 Resolution Effects

The finite vertex resolution smears the exponential distribution and therefore affects the estimate of the event losses. The resolution for the \( \pi^0 \pi^0 \) mode is in general poorer. For the case of \( K_S \rightarrow \pi^0 \pi^0 \), a vertex resolution of \( \sim 1 \) cm and a fiducial volume of 6 cm radius result in a loss of events \( N(l > 6 \text{ cm}) \sim 10^{-4} \), which is however measurable to a part in a thousand. The problem is much less severe for \( K_L \) since \( \sigma(\text{vertex}) \ll l_L \). What is important in the end is the relative position of the boundaries of the fiducial volumes for charged and neutral decays. A 1 cm error on one edge of the fiducial volume reflects in an error on \( \mathcal{R}^\pm/\mathcal{R}^0 \) of:

\[
\delta \sim 1 - e^{-1/350} \sim 1/350 \sim 3 \times 10^{-3}
\]

Using the \( K^\pm \rightarrow \pi^\pm \pi^0 \) events discussed previously we can however establish the boundary to:

\[
\frac{\sigma_{\nu}}{\sqrt{N}} = \frac{1 \text{ cm}}{\sqrt{3 \times 10^7 \text{ ev/cm}}} = 2 \times 10^{-4} \text{ cm}
\]

The relative accuracy of the integration over the fiducial volumes is therefore:

\[
1 - e^{-2 \times 10^{-4}/350} \sim 2 \times 10^{-4}/350 \sim 5 \times 10^{-7}
\]
A conceptual design of a detector able to fulfill the requirements we have indicated in the previous chapter, should be matched to the characteristics of the events to reconstruct. The decay modes we must recognize are:

\[ K_S \rightarrow \pi^0\pi^0 \quad K_S \rightarrow \pi^+\pi^- \quad K_L \rightarrow \pi^0\pi^0 \quad K_L \rightarrow \pi^+\pi^- \]

\[ K_L \rightarrow \pi^+\pi^- \quad K_L \rightarrow \pi^0\pi^0 \quad K_L \rightarrow \pi^-\mu + \nu \quad K_L \rightarrow \pi^-e + \nu \]

as well as \( \phi \) decays of interest to spectroscopy, \( K_{\ell 4} \) and so on.

The experimental apparatus must be able to track charged particles of momenta between 50 and 250 MeV/c. It must also detect with very high efficiency \( \gamma \)'s with energy as low as 20 MeV, measure their energies with a resolution \( \delta E_\gamma / E_\gamma \sim 15\% \) at 100 MeV and provide the space coordinates of the photon conversion point.

The general features of the detector are similar to those of a standard general purpose collider's apparatus: a cylindrical structure surrounding the beam pipe consisting of a tracking device capable of some particle identification, an electromagnetic calorimeter with exceptional timing ability, also providing some particle identification and a solenoidal magnet, in order of increasing radius, as shown in Fig. 3.1. The overall dimensions are quite respectable: \(~6\) m diameter, 6 m length. Charged particle detection is a relatively straightforward problem. An axial drift chamber with a helium-based gas mixture in a magnetic field, 0.6 Tesla, appears to be a satisfactory solution.
3.1 Beam Pipe

The radius of the beam pipe is chosen to be 8 cm. This allows us to define a fiducial region for $K_S$ decays without complication from regeneration. The beam pipe wall is made of 1mm thick beryllium, or some equivalent low mass, low $Z$ material to minimize multiple scattering, energy loss and regeneration. Although the last point is not important, see section 3.4.
3.2 CALORIMETRY

Reconstruction of the $\pi^0\pi^0$ decay mode of a 110 MeV/c momentum $K$, the determination of its decay point and the efficient rejection of the three $\pi^0$ decays make the e.m. calorimeter, EmC, a most demanding element of the detector. In particular the calorimeter must provide a good measurement in three dimensions of the photon conversion point. This last requirement excludes the possibility of using scintillating crystals. Calorimeters with liquified noble gas and short drift promise good energy resolution and space point resolution. Their response is however degraded by calorimeter walls to the point of becoming inferior to scintillating crystals.

We propose to use a lead–scintillator sampling calorimeter using very thin lead layers, 0.5 mm and scintillating fibers. Such device has acceptable resolution and good efficiency (> 99%) for photon energies down to 20 MeV. In addition the use of fibers gives extremely good temporal resolution. Measurement of the time of arrival of a photon gives the flight path of the $K^0$ to an accuracy $\delta l = \beta_K c \delta t \sim 6 \times 10^{-3}$ cm $\times \delta t$(ps). For a 510 MeV $K^0$, that is for four photons with $\sum E_\gamma = 510$ MeV and a sampling fraction of $\sim 12\%$, one expects a timing resolution of about 100 ps and a flight path resolution of 0.6 cm. In a realistic simulation a resolution of 8 mm is obtained. It is worth noting that time measurements for a single photon allow the determination of the flight path, up to a two–fold ambiguity. This implies that observation of only three photons still allows an overconstrained determination of both the $K^0$ mass and the flight path, using timing information to supplement geometrical and energy measurements:

Finally, among all proposed solutions, the structure discussed above is relatively simple to build, does not require a disproportionate number of read-out channels, does not have thick walls in front and lends itself most easily to the construction of a truly hermetic calorimeter.

3.3 TRACKING

The reconstruction of the CP violating decay $K_L\rightarrow\pi^+\pi^-$, the rejection of the $K_{L3}$ background, the determination to good accuracy, $\sim 10$ mr, of the $K_S$ flight direction and of the decay vertices, $\sim 3$ mm, are the main tasks of the tracking system. Material thicknesses must be kept as low as possible to minimize multiple scattering and regeneration effects and not affect the performance of the EmC. We chose a drift chamber over a time projection chamber which would suffer at the high event rates of DAFNE, especially Bhabha's at $10^\circ < \theta < 20^\circ$. The uniform distribution of the $K_L$ decay vertices requires a symmetric cell structure.

We are considering hexagonal or square cells, with an active area per cell of $\sim 4$ cm$^2$, so that the total number of wires and read-out channels is $\sim 40,000$ and $10,000$ respectively. The gas mixture is Helium with the usual addition $< 20\%$ of hydrocarbons, to control the multiple scattering and regeneration problems mentioned before. The use of a high helium content gas mixture allows counting the primary ionization clusters in order to measure the specific ionization of particles. We expect an improvement in resolution of about a factor 2 over more traditional methods, like the truncated mean of the total collected charge signals, for the same track length. This measurement would add rejection power against the $K\mu3$ background.

The chamber is cylindrical, with dimensions approximately 2 m radius and 4 m length and the 10000 sense wires are arranged in 50 layers. The radiation length of the gas is $\sim 1800$ m. The performance of the KLOE tracking device, is: $\sigma_{z,\phi}=200\mu$m and $\sigma_z=4$mm.
The mechanics of the chamber is complicated by the fact that the low $\beta$ insertion insertion quadrupoles are supported by the chamber structure. These magnets also have implications on our particle acceptance.

### 3.4 Background

The rejection of three pion decays relies on good solid angle coverage and efficiency for $\gamma$'s down to 20 MeV energy. Kinematic fitting, with good tracking, and energy measurements in the calorimeter appear to be able to reject $K_{\mu3}$ events to the required level. The remaining decays are easily distinguished. Finally we must consider $K_L\rightarrow K_S$ regeneration in the decay volume for $K_L$. Both coherent and diffractive contributions are quite negligible, if helium is used, rather than argon, as gas in the main tracker. It should also be noted that in the type of measurement discussed, regeneration cannot produce a non-zero $e^+$ signal if $e^'=0$ and that regeneration in the chamber can in fact be directly measured. Regeneration in the beam pipe and chamber entry wall is $\sim 2\%$. This problem is effectively solved by rejecting $K$ decays within the first 5 cm ($\sim 9$ $K_S$ lifetimes) of any wall.

### 3.5 Trigger

Triggering at DAΦNE will be an entirely new experience. At full luminosity, the $\phi$-event rate is $\sim 5$ kHz while the machine produced background can be estimated, scaling from other machines to be a few % of this value; all events can thus in principle be passed to the digitizing electronics (FEE) and data acquisition system (DAQ). The calorimeter can provide an adequate trigger for most events of interest. Special events might require tracking in the first inner layers of the chamber. Bhabha scattering at angles $10^\circ < \theta < 20^\circ$ and cosmic ray events must be recognized and rejected or prescaled not to overload FEE and DAQ. Both class of events are important for detector calibration. Calorimeter information and simple logic can effectively reject/scale these events.

### 3.6 Data Acquisition

$\phi$ decays and calibration events represent, at full DAΦNE $\mathcal{L}$, a very large load for the data acquisition system. At 10,000 events per second, each event consisting of 6 to 12 kBytes, we estimate that 10,000 MIPS equivalent computing power will be necessary to digest the data. The universal approach appears to be farms of the new powerful $\mu$-processors. We are at present looking at the $\alpha$-VAX product of DEC, capable of 120 MIPS, but we will not commit ourselves to any solution for the next couple of years. We must mention two more points. We intend to write to tape all raw data, and we need to perform Monte Carlo simulations at the $10^8$ or greater event level. The data produced in one year at full $\mathcal{L}$ is $\sim 10^{15}$ Bytes, to be stored at a bandwidth of 120 MBytes/s. The new 19 mm tape technology seems capable of such task. Concerning the Monte Carlo and the inevitable necessity of running production more than once we plan on two 10,000 MIPS farms.

### 3.7 Magnet

We have opted for a warm rather than superconducting solenoid. Since the KLOE detector terminates at the inner solenoid face we have no constraints on the thickness of the coil. Following
a suggestion of H. Desportes of Saclay, the coil is made of aluminum and is 66 cm thick. This results in very low operating power, \(\sim 1\) MW, and operating costs approximately equal to those of a superconducting solenoid. In addition the coil can be built more rapidly, is cheaper and will have less maintenance problems.
4. ELECTROMAGNETIC CALORIMETER

4.1 INTRODUCTION

The electromagnetic calorimeter (EmC) has to cope with four main tasks.

1. Determine the coordinates of 110 MeV/c $K^0 \rightarrow \pi^0 \pi^0$ decays, with an accuracy of a few mm.
2. Have a high discriminating power between $K_L \rightarrow \pi^0 \pi^0$ and $K_L \rightarrow \pi^0 \pi^0 \pi^0$ decays.
3. Provide a first level trigger to the detector.
4. Do all of the above, keeping the contribution to the systematic error on $\mathcal{R} (\epsilon'/\epsilon)$ below $5 \times 10^{-5}$. As discussed in section 3.1, we propose to build a sampling EmC, using very thin (0.5 mm) Pb grooved plates and scintillating fibers,\cite{36} with a high granularity read-out. Fibers have been chosen for their superior timing properties,\cite{37,38} and because they are convenient for building homogeneous structures with an (almost) arbitrary granularity. Simulation studies and measurements on prototypes\cite{38,39-42} show that this technique can achieve:
   1. full efficiency for photons down to $E_\gamma \sim 20$ MeV,
   2. good energy resolution: $\sigma (E) / E \approx 5\% / \sqrt{E}$,
   3. determination of the $\gamma$ conversion point with an accuracy $\approx 1$ cm, necessary to reconstruct the $\pi^0$ decay point from the photon showers,
   4. excellent timing performances (our goal is 300 ps for a 20 MeV incident $\gamma$\cite{40}),
   5. hermeticity.

Finally, the resulting EmC is compact ($X_0 \approx 1.6$ cm), relatively easy to build and requires a reasonable number of channels.

4.2 EM C DESCRIPTION

The EmC consists of three components: the central calorimeter, the endcap calorimeter and the plug calorimeter. Each component has the same basic structure, obtained by gluing layers of 0.5 mm thick grooved Pb (+6% Sb) plates, encapsulating 1 mm diameter scintillating fibers, laid 1.35 mm apart. The relative lead : fiber : glue ratio is 35 : 50 : 15, resulting in a sampling fraction of $\sim 12\%$ and $X_0 \approx 1.6$ cm. Grooved lead plates of a few meter length have been successfully fabricated at LNF, with a prototype rolling machine, a more rugged version of which is being presently built to process wider plates.

Detailed studies have been also carried out to characterize fiber performances (attenuation length $\lambda$, number of photoelectrons (p.e.), scintillator decay time $\tau_s$). Fibers with $\lambda \approx 300$ cm, $\tau_s \approx 2.5$ nsec and 5.5 p.e./mm for a traversing mip, are commercially available and meet the specs set by the EmC design goals. Nevertheless we are actively continuing interaction and cooperation with major producers, in the quest of better performing fibers.

4.2.1. The Central EmC

The central EmC covers the polar region $\Delta \theta = \pm 45^\circ$. It consists of 24 equal modules, forming a roman arch with inner radius $\sim 2$ m. Each module is 4.5 m long and has a minimum thickness of 15 $X_0$. The fibers run parallel to the beam (fig 4.1). At both ends, the light from the fibers belonging to trapezoidal adjacent elements, is collected by photomultipliers,
PM. The read-out granularity is on average $3.4 \times 3.4 \text{ cm}^2$, for the first 5 read-out layers, and becomes $6.4 \times 6.4 \text{ cm}^2$ in the back. Light is funneled to the PM's through a plexiglass Winston concentrator,\textsuperscript{[43]} which, owing to the smaller refraction index, allows a reduction in area of a factor 2, with no appreciable loss of light. Every module has 196 PM's, 180 1 1/8 in diameter, 16 2 in dia., for a total of 4704 for the whole central EmC.

![Fig. 4.1 EmC Structure.](image)

Fig. 4.2 Detail of mounting fixture of a central EmC module.

While photon conversion point is measured in the transverse plane with a precision at least equal to the read out granularity $x1/\sqrt{12}$, the coordinate along the beam can be determined
(although with a lower precision) by time difference at the two ends. We are presently studying the possibility of interleaving, between the first four layers, scintillator tiles, of dimensions = 3.6 cm × module width. Wave length shifter (WLS) loaded fibers are embedded in the tiles and read-out through clear spliced fibers by a multi-anode PM. Each module has an outside steel skin, 1 mm thick, which is used for the location of the supports needed in the assembly of the arch. (fig 4.2).

4.2.2. The Endcap EmC

The endcap calorimeters are built by four half disks of 1.95 m radius, with the fibers running in parallel half circles (fig 4.3). The composition of the structure is identical to the barrel, but it is rotated by 90°. However, since the fibers are laid at the vertices of equilateral rectangles, one expects the endcap calorimeter to perform very similarly to the central calorimeter. This is indeed confirmed by the simulation and the preliminary results on the prototype modules. Fibers are read on both sides along a diameter, with a similar granularity as in the barrel. In this hypothesis each endcap calorimeter module has 534 PM’s, 480 1 1/8 in and 54 2 in, for a total of 2136. Here, the granularity will determine the precision in the r, z coordinate, whereas the φ coordinate can be determined by time difference of the two corresponding PM’s. As for the case of the central calorimeter, the insertion of radial tiles of proper dimensions will improve the third coordinate resolution, and add an important redundancy. The endcap calorimeter modules will be mounted permanently on the end plates of the iron return yoke.

![Fig. 4.3 Structure of the End caps and the End plugs.](image)

4.2.3 The Plug EmC

The plug EmC are needed to shadow the area of the endcaps along all the diameter, which is used to locate the light concentrators and the PM’s. The width of this area is to our best present guess ~ 40 cm, and will hopefully be further reduced in size. Optimization of the plug shape is still underway, and a possible solution is presented here for completeness. In this option, the plug is built by 4 identical modules, 15 X₀deep, 180 cm long, and 60 cm wide. The modules have the same construction as the barrel, but fibers are read out at one end only, near the center. Third coordinate through tiles is implemented, to regain the ability to determine a space point.
In this configuration ~400 PM's are needed to instrument with the usual granularity all the four modules. Endplugs could be attached to the endcaps, or be mounted on the barrel. With this arrangement 2 holes, each 40 × 40 cm² in surface would remain uninstrumented at the center of the two endplates of the detector. This surface is contained in the projected shadow of the low beta quadrupoles, and will therefore be un consequential for the particles coming from the proximity of the interaction region. It will nonetheless affect the hermeticity of the calorimeter for particles originating from K⁻μ⁻decays, which are almost uniformly distributed over all the detector volume. It may therefore be helpful to implement a veto counter, similar to the one envisaged to surround the quads, in order to tag with good efficiency escaping γ's.

4.2.4 Phototube Choice

At the time the LOI was submitted, two options were still on the table for the PM's: the conventional high gain linear focussed type (G ~2×10⁶), which operate essentially at zero field and the proxif focus mesh type, with a gain (at 0.6 T) of about 2×10⁴. In the mean time, new proxif focus p.m's with a gain (at 0.6 T) in excess of 10⁸ (Fig. 4.4 a and b)) and with excellent timing performances, (T.T.S. ≈300 ps), have been made available, strongly biasing the choice in their favor. Their adoption will allow a great simplification (and a correspondent reduction of dimension and cost) of the magnet return yoke, where a recess with a small residual field would have been needed in order to operate the conventional PM's.

Fig. 4.4 Gain of a mesh PM (a) as function of dip angle, and (b) of field strength.

4.3 EMC Simulation

The GEANT version 3.14 was used to simulate the shower secondaries, to track them through the detector elements and to evaluate the fraction of energy sampled by the scintillating fibers. For charged secondaries full simulation of their interactions including multiple scattering, bremsstrahlung, annihilation, and ionization are taken into account. To simulate en-
ergy loss straggling, delta rays are explicitly generated instead of evaluating them from Landau distribution. The energy cut-off for all these phenomena is set to 10 keV. Dedicated simulations with different energy cuts have been done to evaluate the drawbacks of the 10 keV limit cut for such high granularity sampling devices. These studies have shown that, while the sampling fraction is somewhat dependent upon this cut, sampled energy distribution shape and its resolution reach asymptotic stability well above 10 keV cut. In order to compare simulation and the experimental results, both the effects of the fiber attenuation length and the photoelectron statistic are incorporated, based on measured values.

4.4 TEST RESULTS

Two 10×10×23 cm³ prototype modules of the electromagnetic calorimeter were built and tested on a tagged photon beam (LADON) in the energy range between 20 to 80 MeV[39,42] and on the T7 beam at CERN with electrons and muons from 250 MeV to 1.0 GeV[44,45]

![Diagram](image)

**Fig. 4.5 Sketch of CERN test set up.**

4.4.1 Energy Resolution

Data were taken with beam perpendicular to the fibers and the lead plates (side-on configuration), stacking the two modules for a total of 12.5 $X_0$. Measurements were also done in the head-on configuration (beam almost parallel to fibers), in order to evaluate effects due to larger incidence angles. At LADON the light was collected with a single PM for each module. The 100 cm² exit face was coupled to a 9 cm² photocathode through a non adiabatic guide. The area loss was a factor 9. While at LADON we tested energy resolution and linearity, the CERN test was mainly dedicated to the time performances. The module exit faces were subdivided in nine 3.3×3.3 cm² cells, equipped with Winston cones and Philips XP1910 PM's, on one end while the other end still kept the previously described single guide. (fig. 4.5)

The experimental resolution obtained from the tests at Ladon both in side-on and head-on
configurations are reported in (Fig. 4.6) and compared with the results obtained from simulation.\[^{[46]}\] The solid and dashed lines are drawn to guide the eye and correspond to a resolution of $4.7\%/\sqrt{E/1\text{ GeV}}$ and $5.7\%/\sqrt{E/1\text{ GeV}}$ respectively. The agreement of the simulation with the data is very good, the main characteristic of the detected energy distributions are well reproduced over all the investigated energy range in both side-on and head-on configuration making us confident in using it, for further detailed studies of the detector response.

Fig. 4.6 Energy resolution of the prototypes.

![Energy resolution curve](image)

Fig. 4.7 Time resolution as a function of the energy.

We can conclude that energy resolutions $\leq 5\%/\sqrt{E/1\text{ GeV}}$ can be achieved by the proposed
KLOE electromagnetic calorimeter, even at the lower end of the energy range of interest, well satisfying the needed value.

The CERN tests on energy resolution yielded slightly worse values, 6.5%/√E/1GeV, which we ascribe to the poor quality of the T7 beam, used beyond his default minimum energy value, in presence of a significant pion contamination of the electron beam and with a non negligible amount of material along the beam line (estimated in 0.3X₀).

4.4.2 Time resolution

Data at CERN have also been used for studying the timing performances of the EmC prototypes, using muons with energies bigger than 1 GeV and electrons at 250, 500, 1000 MeV. Due to time constraint, the 18 3.3×3.3 cm² elements of the EmC (see Fig 4.5), have been read-out by 3/4 in Philips XP1910 PM's, with an area ratio of ~7, resulting in a light loss of a factor ~3.5. Muons yielded 510 psec σ₁ time resolution in a single 3.3×3.3cm² cell, consistent with ~40 photoelectrons being produced. The average of hit cells, $T_{AVE} = \sum_{i=1}^{n} T_i/n$, scales as $\sqrt{n}$, indicating good uniformity of the prototype. For n=6, we obtain a σ₁ of 210 psec. The time resolution for electrons was obtained by a study of the distribution of the energy weighted average:

$$T_w = \frac{\sum_{i=1}^{n} (T_i' \times E_i)}{\sum_{i=1}^{n} E_i}$$

where $T'_i$ is the time of the i-th cell, after slewing correction and T₀ removal. Fig. 4.7 shows the distribution of σ₁ as a function of the energy. It can be parametrized as $\sigma_1 = 87 ps/\sqrt{E/1GeV}$. Points at 28 and 166 MeV, taken from muon data (1 GeV electron corresponds to ~6 m.i.p.), fall on the same curve. The projected time resolution at 20 Mev is ~550 psec, which we expect to push to ~300 psec, through better light collection, the use of fibers with higher light output which are now available and faster PM's.

4.5 EmC Calibration and Monitoring

The main items concerning the calibration and the monitoring of the KLOE Electromagnetic Calorimeter can be listed as follows:

1. energy response;
2. photon detection efficiency;
3. timing accuracy;
4. trigger performances.

It is worthwhile noticing that, while energy resolution of detected photons ranges between 20 and 30%, then requiring a control of systematic effects not particularly sophisticated (as much as 5% can be enough), on the other hand the control of time measurement accuracy, which is a critical parameter in order to achieve a good spatial resolution in determining the $K_\mu^0$ decay vertex, appears more delicate. Large part of the effort in understanding systematics will be done in this direction.

4.5.1 Energy response of the calorimeter

The calibration of the energy response of the calorimeter has the main purpose to evaluate the conversion factor between the number of photoelectrons seen at each photocathode (or
equivalent, the pulse amplitude at the ADC) and the energy of the photon. This number is expected to be function of the distance between the impact point and the photocathode, due to the non negligible attenuation length of scintillating fibers. In addition it is foreseeable that each PM (and its related readout chain) will have its own energy calibration factor, envisaging the preparation of a look-up table of correction numbers $C_{ij}$ where the index $i$ runs on readout channel number and $j$ refers to the subdivision of each fiber bundle in longitudinal elements whose granularity is of the order of few centimeters. To accomplish this job, it is foreseen to have two different kinds of calibration:

i) before calorimeter assembly, each module will be exposed to cosmic rays, in order to equalize the gain among the various channels and to evaluate systematics coming from the several elements of the readout (fiber inhomogeneity, optical coupling, PM, amplifier, shaper, cabling, etc...). More sophisticated studies (like the study of low energy photon detection efficiency), can be performed at a test facility on the DAoNE Linac.

ii) when the apparatus is mounted, since the gains will change with the magnetic field, calibration has to be redone, using physics channels.

The most natural channel which can be used to monitor the gain are the Bhabha events, which are large enough to ensure a complete and detailed mapping of the response of the modules (i.e. the evaluation of the $C_{ij}$ coefficients). The expected rates for these events are (at $L = 2.5 \times 10^{32} cm^{-2}s^{-1}$): $\sim 50$ Hz of pairs in a region of $\pm 5^0$ around $\theta = 90^0$ (central barrel), $\sim 300$ Hz around $\theta = 45^0$ (overlap region), $\sim 2200$ Hz at $\theta = 25^0$ (end cap). In the worst case, less than 1 hour of data taking is enough to have a detailed survey of the response.

In order to have a better understanding of the calorimetric behaviour we envisage to use also the $e^+e^- \rightarrow \mu^+\mu^-$ channel with 500 MeV muon passing through the calorimeter with limited multiple scattering, allowing to test also the outer layers of the calorimeter (a rate of 20 pairs/sec is expected). In addition to this, a large number of passing through cosmic rays can be used (even if the sample can be contaminated from electromagnetic activity associated to the muon).

Another useful signal is $\phi \rightarrow \pi^+\pi^-\pi^0$ (some 170 Hz) with two clean on source tracks and two photons to use for calibration and, in particular, for efficiency and trigger studies.

At the moment, we do not envisage to use any external pulsed light source, while we are considering the possibility to inject known charges into the analogic readout electronics. Of course, only experience on the first real size modules will tell.

4.5.2 Time response

As already mentioned, the determination of the arrival time of photons is crucial for a good spatial reconstruction of the $K_L^0$ decay vertex. Willing to achieve a $\sigma_t \sim 100$ ps, the systematic error has to be kept at the level of 50 ps. To this respect it is foreseen to have a detailed setting up of each channel of each module before assembly, in order to study the propagation time along fibers plus the delay introduced by the readout. An important quantity to determine is the $t_1 + t_2$ time of the two PMs, a constant characterizing the channel which is independent from the localization of the point where the particle has hit the calorimeter.

During the data taking it is possible to determine the delay times of each readout element making use of the sum and difference of $t_1, t_2$, together with the use of the tridimensional information coming from the central chamber for charged tracks that hit the calorimeter at a certain
location. A look-up table can be built containing the relevant numbers in order to obtain, on line, the corrected time values (referred to beam crossing master clock). To this aim, every track correctly reconstructed by the central chamber can be used, allowing a very fast monitoring of the delay constants. However it must be noticed that, also in this case, the external layers of the calorimeter must be calibrated with passing through particles, mainly cosmics or muon pairs.

A detailed study of timing measurement accuracy will be performed on the calorimeter modules before the assembly, exposing them to cosmics, in conjunction with the energy calibration.
5. CHARGED PARTICLES TRACKING

5.1 INTRODUCTION

CP experiments at DAΦNE require a large decay volume which at the same time must also be an efficient and precise tracker and help in particle identification. In addition to the detection of the $K^0_S, K^0_L \rightarrow \pi^+\pi^-$ decays and the accurate determination of the decay vertex position, KLOE relies on the tracking device for the rejection of decays such as $K^0_L \rightarrow \pi\mu\nu$, at the level of 50,000 to 1. Accurate momentum measurements are also important in spectroscopy study, the study of form factors in $K$ semileptonic decays. Particularly demanding of the tracking device is the fact that the momenta of interest are very low, requiring control of multiple scattering, and that material thickness must be kept at a minimum both to reduce regeneration and not to affect adversely the performance of the EmC which surrounds the chamber. While some of the requirements would suggest the adoption of a time projection chamber, we have chosen a drift chamber to track charged particles in KLOE since a TPC would suffer from severe pile-up problems from the high rate of Bhabha events, $\sim 50$ kHz in the angular region $10^\circ < \theta < 20^\circ$.[47]

In the following we discuss geometry requirements, spatial and momentum resolution, particle identification capabilities, cell and general layout of the chamber and the prototyping and R&D tests needed.

5.2 REQUIRED PERFORMANCES

5.2.1 Geometry requirements

The tracking device is located immediately outside the beam pipe; it covers a cylindrical region with inner and outer radii of 10–25 and 200 cm respectively and 400 cm long, with its axis parallel to the beam direction and to the solenoidal magnetic field in which is immersed, see fig. 5.1. The chamber defines the useful $K^0_L$ decay volume for which, as discussed in the introduction, we have chosen a radius of 1.5 m, in order to detect a sizeable fraction of the $K^0_L$ decays. By adding 50 cm to the decay volume in order to continue tracking particles produced at the boundary of the fiducial volume, we end up with a device having a radial extent of 2 m. This figure is a crucial parameter for the overall size of the experimental apparatus: it determines not only the $K^0_L$ decay products detection efficiency but also the size of the calorimeter, coil and flux return iron. We believe that cost and technological limitation restrict the outer radius of the chamber to this value.

The tracking chamber should yield many position measurements per track, even for particles generated at the boundary of the $K^0_L$ fiducial decay volume in order to obtain uniform detection efficiency and resolution. A large number of measurements is beneficial not only to obtain precise measurements of the charged tracks relevant parameters ($p_t$, $\phi$, $\theta$, $z_0$, $r_0$) but also to detect $\pi \rightarrow \mu$ or $K \rightarrow \mu$ decays in flight.

As a final remark it is worth noticing that the drift chamber should be built with as little material as possible in order to reduce multiple scattering effects in the measurement of charged particles, to prevent spoiling of the spatial and energy resolutions for $\gamma$'s to be detected in the electromagnetic calorimeter and to keep systematics in $K^0_S$ regeneration effects at a level such that the associated systematic error in the $\epsilon'/\epsilon$ measurement is below $\sim 5 \times 10^{-5}$. 
5.2.2 Momentum resolution and choice of magnetic field

Detailed Monte Carlo calculations, see chapter 6 later, have shown that a combination of kinematic cuts and kinematic fitting reduce the semileptonic background to the CP violating $K_L^0 \rightarrow \pi^+\pi^-$ channel by large values while retaining good efficiency for decays of interest. The required values for background rejection and good events acceptance can be achieved by a central tracker in a solenoidal magnetic field with the following characteristics:

- spatial resolution in the transverse plane $\sigma(r\phi) = 200 \, \mu m$
- spatial resolution along the $z$ axis $\sigma(z) = 4 \, mm$
- radiation length $X_0 = 1400 \, m$
- number of layers $\geq 40$ of which $\sim 25$ at a stereo angle of $\sim 50$ mrad

The value of the prescribed $X_0$ imposes the use of a device with a helium based gas mixture. If one were to use argon based mixtures, the multiple scattering contribution to the momentum resolution would increase by a factor of $\sim 4$. The strength of the magnetic field has been fixed at 6 kG in order to optimize the rejection of semileptonic $K_L^0$ decay. With this choice of the field, the transverse momentum for spiraling, for tracks originating at the $e^+e^-$ collision point, is 180 MeV/c. The value for the magnetic field strength indicates that particle identification, if any, should be performed within the gas volume. Fig. 5.2 shows the expected momentum resolution and its breakdown into different components.
5.2.3 Particle identification

While rejection of unwanted charged $K_L^0$ decays can be achieved by kinematics alone, redundancy is always very valuable. The rejection of $K_{\mu3}$ decay can be improved with positive $\pi/\mu$ identification. In the relevant momentum range, 200 to 250 MeV/c, the energy losses for $\pi$ and $\mu$ differ by 12% to 8%. A $\geq 2\sigma$ separation over the momentum range of interest can be reached if specific ionization measurements can be performed with a resolution of 4%. Such resolution in specific ionization cannot be achieved for the available track lengths with traditional techniques. The low value of ionization density in helium, and the slow electrons' drift velocities, typical of high helium content gas mixtures have prompted the idea of measuring energy losses in the drift chamber exploiting the \textit{cluster counting technique}\cite{48,49}. This technique may improve the resolution in the specific ionization measurement by more than a factor of 2, with respect to traditional methods, allowing $\pi/\mu$ discrimination at the required level. A test beam run has been scheduled at PSI, in order to investigate in detail the experimental possibilities and limitations of the method in the relevant momentum range.

5.3 Gas Choice

As discussed in the previous chapter, all the chamber performances like spatial resolution, angular resolution, and hence transverse and total momentum resolution would be limited, in the momentum range relevant for KLOE, by multiple scattering effects, if one were to choose
a gas mixture based on argon. A helium based gas mixture reduces multiple scattering effects, by at least a factor of \( \sim 4 \), and minimizes as well regeneration effects which \( K^0 \) would undergo in the decay volume. Because of the high ionization potential of helium the number of primary ionization clusters per unit length is small.

By counting individual clusters and recording their arrival time at the sense wires we can improve the determination of the impact parameter of the track with respect to the wire. We can also in this way make precision measurements of the specific ionization energy loss of the charged particles, significantly improving the ratio of good events over background. Monte Carlo simulations show that, given the average population of about 1.6 electrons per cluster, (measured value for helium)\(^{[50]}\) and the appropriate value of the longitudinal diffusion of electrons in this gas, one could perform a measurement of \( dE/dx \) with an uncertainty of \( \sim 3\% \) over a track length of 1 meter, provided that roughly 12 ionization clusters/cm are created in the gas and that the digitizing electronic has a dead time not larger than 3 nsec.

Under the same assumptions, for a cell of 1.5-2 cm half-width, the uncertainty on the arrival time of the first cluster is, on the average, 12 nsec which translates, with a typical drift velocity of 1.2-1.3 cm/\( \mu \)sec, into a resolution for the track impact parameter well below the goal value of 200 \( \mu \)m. The possibility of using high helium content mixtures has been experimentally demonstrated.\(^{[48]}\) A 95% helium 5% isoC\(_4\)H\(_{10}\) (with an \( X_0 \) of 2100 m) has been tested and has been shown to be electrostatically stable and efficient for minimum ionizing particles. The tests, however, have shown that the average number of ionization clusters in this gas is of the order of 8 per cm and, at this level the \( dE/dx \) measurement would be \( \sim 4.5\% \).

A way to increase the number of primary cluster per unit length, soon to be experimentally investigated, would be to use a lighter hydrocarbon, like methane, in bigger proportion. A mixture like 80% Helium 20% CH\(_4\) has the same radiation length as the one mentioned before (\( \sim 2000 \) m) and therefore the same multiple scattering characteristics; furthermore the average atomic weight is similar, implying the same \( K^0 \) regeneration effects. This gas mixture should however have a few more ionization clusters per unit length so that one may improve both the spatial and the specific ionization resolutions. The better quenching characteristics of isobutane is compensated by the bigger quantity of the quenching agent.

Another interesting characteristic of high helium content mixture is the low, unsaturated behaviour of the drift velocity, see fig. 5.3. Such an occurrence represents a big advantage because it is equivalent to a magnification of the space scale for a fixed time resolution. Moreover a low drift velocity minimizes the effect of drift distortion in magnetic field: the Lorentz angle at 6 kG is limited to a few degrees at the appropriate value of electric field, \( E \geq 0.2 \) kV/cm.

5.4 CELL DESIGN

The spatial pattern of the CP violating \( K^0 \) charged decay products at the \( \phi \) energy has the following properties: most probable opening angle of 150\(^0\) and the decay vertex distribution is almost uniform over the chamber dimensions. With such geometrical characteristics there is no advantage in choosing a chamber with multiwire or even a jet-like cell structure. Out of the many alternatives which single wire drift cells offer, we concentrate for the KLOE tracking system on two choices: hexagonal cells and square cells.
5.4.1 Hexagonal cells

This design has the field wires at the vertices of almost regular hexagons of 2 cm sides (the hexagons are only slightly irregular to fill uniformly the chamber volume) with the sense wires located at the centers, fig. 5.4. Different layers of cells, proceeding from the interaction region out, radially are arranged in superlayers either axial or at a (small) stereo angle with respect to the $z$ axis. Because the stereo wires are closer to the axis at the center of the chamber, the radial distance between superlayers needs to be such that the variation in the gains of the outer and inner wires of each superlayer is kept below the 20% level. A possible lay-out of the various superlayers is the following sequence:

```
AA UV AUV AUV AUV A
```

where the first two axial superlayers consist of 2 layers, the first UV doublet consists of superlayers with 3 layers each and the remaining superlayers consist of four layers each. With appropriate clearances (always $<2$ cm, provided that the mechanical tensions are such that the electrostatic stability is reached for the wires) it would be possible to fit 50 measurements in 1.75 m radial distance, 30 of which would be stereo at $\pm 50$ mrad. The first sense wire layers would be at 16 cm, the last field wire layer would be at 192 cm. In order to keep the sense wire gains uniform to within 20%, layers of guard wires at intermediate voltages will electrostatically isolate the different superlayers from each other. Extensive electrostatic simulations have shown that the sense wires total charge is uniform throughout the entire structure of the chamber at the level of 0.5%. The total number of wires for this configuration is 38,805: 9,775 sense wires.
24,172 field wires and 4,858 guard wires. The high voltage is chosen to have gains on the sense wires of the order of, but not in excess of $10^5$.

![Sector plot of detector](image)

**Fig. 5.4.** Layout of a chamber sector for the hexagonal cell geometry

5.4.2 Square cells

A possible alternative would be the use of an almost square cell with a layer structure similar to the ARGUS chamber\footnote{31}, as shown in fig. 5.5.

The cell dimensions are 1.805 cm half width and 1.725 cm half height. The interesting feature of this design is that there are no axial layers, so that it is possible to fill up the entire gas volume continuously without the gaps which are needed to separate axial and stereo layers.

The first layer would start at a radius of 14.36 cm, the sense wires at $r = 16.08$ cm, and would accommodate 28 cells. Every successive layer will have 6 more cells than the previous one. The last layer (the 52th) is at $r = 193.76$ cm and has 340 cells.

In this case the stereo angles do not have, in principle, upper bounds; the value, however, has to increase moving out radially. If one chooses to design with a constant drop at the center of the chamber of half a centimeter then the stereo angle ranges from $\pm 14$ mrad at 14 cm to $\pm 70$ mrad at 190 cm.

The total number of sense wires is 9,740 with 32,054 field wires. In order to equalize the gains of the innermost and outermost sense wires, two layers of guard wires are needed at $r=12$ cm and $r=197$ cm at the appropriate voltage; this will add 752 guard wires wires to the number mentioned above for a grand total of 40,392. Preliminary tests\footnote{48} have shown that 100 $\mu$m diameter sense wires work fine, even though it is better to use smaller diameter wires in order
to reduce the average drift field over the cell and, as a consequence, the drift velocity, relaxing, somehow, in this way the requirements on the digitizing electronics. Concerning the cathode wire, the usual condition $E_{\text{cath}} \leq 25 \text{ kV/cm}$ is fulfilled with 100 $\mu$m wires.

![Vector plot of $\beta x, \beta y$](image)

Fig. 5.5. Layout of a chamber sector for the square geometry

The two configurations described are essentially equivalent from the point of view of performances: the advantages of the hexagonal cell structure are its field uniformity, which translates into a simpler time to space relation, a better collection efficiency at the cell boundary, and finally a higher symmetry which better matches the topology of the $K^0_L$ decays.

The square cell geometry, however, does make a more efficient usage of the radial space since no gap is needed between axial and stereo layers and this, to some extent, compensates for the better collection efficiency characteristics of the hex cell design. Extensive MC simulations and prototype tests are in progress to quantify the qualitative points mentioned above. The complete absence of axial layers in the square cells layout would imply a pattern recognition and track reconstruction software different from the standard one that makes use of axial layers.

A last point, if the I.P. design is such that the full length of the chamber (4 m) is not free from machine components at $r \leq 25$ cm, two choices are open: either have the chamber inner wall at $25$ cm or design a chamber with a small step in the inner wall. The increase of the crossing angle in the DAΦNE design, implies that the free space along the beam line at $r \leq 25$ is limited to $\sim 140$ cm.

### 5.5 Mechanical Design

Until a final choice of the general superlayer structure is done, we work out a hypothesis based on the very reasonable assumptions of about 10000 sense wires (made of 50 $\mu$m thickness
gold plated tungsten, unless a smaller diameter is needed for HV stability) and 33000 field and guard wires (made of 200 \( \mu \)m CuBe). In order to equalize the gravitational sag for both sense and field/guard wires, one would need to string them at tensions of \( \sim 100 \) g and \( \sim 700 \) g respectively. Under these conditions, the end plates would have to sustain a force of about 25 tons. If one wants to limit mechanical deformations to acceptable values, e.g. \( \lesssim 1 \) mm, a 20 mm thick flat aluminum plate would be required on each side. Such thicknesses can be considerably reduced if the end plates were shaped like a truncated cone. A conical plate with an aperture angle of 60° would need to be only 3 mm thick. Thicknesses below this value would introduce complicated patterns of stress forces on the plates because of the large number of holes to be drilled to accurately position the wire feedthroughs. As far as the inner and outer cylindrical skins are concerned, since the internal gas pressure will be kept only slightly above (of the order of a few mbar) the normal value, their only purpose is to keep the gas from escaping the chamber, provided that the 25 tons of wire tension are unloaded to an external support structure. Nylon coated aluminum panels might prove a suitable solution if some care is taken at the junction of overlapping panels. A substantial reduction of the total tension and of the endplates thickness could be achieved using for instance, aluminum field and guard wires, resulting in a reduction of the total pull on the endplates of \( \sim 4 \), although the wire sag in this case is about 400 \( \mu \)m. Another very promising approach would be the use of carbon or kevlar fibers as wires: this materials with moderate pulls, given their extremely low density (1.76 gr/cm\(^3\) and 1.42 gr/cm\(^3\)) would have an extremely small sag (\( \lesssim 180 \mu \)m @ 75% of the yield strength). Electrostatic forces are being calculated: we anticipate that they will not create any insoluble problem, given the high degree of symmetry of the cells under consideration.

5.6 Gas System and Monitoring

5.6.1. Gas system

The KLOE chamber will be operated with a gas mixture based on helium with the advantages discussed. This mixture also has reduced sensitivity to synchrotron radiation which results in less background, reduced wire aging, and simpler track finding. These advantages are paid with a non-saturated drift velocity, strongly dependent on the pressure and the stability of the gas mixture. As a consequence, a sophisticated gas control system is required. The mixture uniformity inside the whole chamber volume is also checked with several gas outlets, each of them connected via a fan-in, to the gas analyzing system described below.

The concept is based on experiences from the Crystal Barrel Detector, the OPAL drift chamber, and the L3 Time Expansion Chamber. The gas volume of the KLOE detector (50 m\(^3\)) is in fact comparable to that of the OPAL chamber (30 m\(^3\)). The large volume makes a single pass gas system not appropriate, requiring instead a closed loop system, complex purification and control instrumentations. The gas system has to provide a two or three component gas mixture and keep its composition constant during operation. It must also remove gases with large electron attachment, like oxygen and water, to a level of few ppm. Temperature and pressure are monitored continuously for off-line correction of the chamber calibration. The gas will be circulated by means of a compressor over a filter (Oxisorb) and analyzed with regard to the appropriate mixture. The circulation should enable the exchange of the whole gas volume

32
once a day, this implies a pumping capacity of 2 m³/h.

The control of gas quality requires sophisticated instrumentation: mass flow meters, calibrated thermal conductivity detectors for measuring He and hydrocarbons content, trace oxygen analyzer, barocell sensor to record absolute pressure, temperature sensors and readout ADC’s. In addition we plan to have a small chamber in which gas from the KLOE chamber is circulated, allowing quick monitoring of the gas behaviour.

5.6.2. Other monitorings

The high voltage system supplies the resistor chains for the field shaping wires, as well as the anode wires. Common power supplies can be easily accessed by a remote control system and so be continuously monitored. Since the high voltage resistor chains and the preamplifiers are attached to the end plates of the chamber, their temperature has to be controlled by means of temperature sensors, distributed in the chamber and over the end plates. The three magnetic field components could be also measured and monitored by means of magnetoresistors. These objects are economical, stable in time and (since they are sensitive to B²) need only to be calibrated for one polarity of the field.

The electronics crates have to be monitored against big changes in temperature and power failure. Moreover we plan to calibrate Flash ADC’s by switching, under program control, their input to a test signal. All these tasks will be performed by the monitoring system, with multitask, multiuser and stand alone capabilities, and also possibility to communicate with the main online computer. Cosmic ray muons will be used for offline calibration and control.

5.7 R&D Needed Prior to Construction

As far as the tracking chamber is concerned, a long program of R&D is needed before a final design can be made. Test beam measurements will be performed at PSI, Zurich, to measure the π/μ separation in the momentum range 100-300 MeV/c, which covers the entire range of interest for the physics of KLOE, by the method of cluster counting. It is imperative, at this point not to be limited by the performances of the experimental equipment but to push for the ultimate values of resolution in order to understand where the intrinsic physics limitations of the method lie. The main purpose of this test is the measurement of the number of primary ionization clusters per unit length along the particle trajectories as a function of the particle velocity, which is the main parameter, together with the drift velocity, for specific ionization measurements. In parallel to this, one needs to have a dedicated test stand for the accurate measurement of drift velocity and of diffusion in many different gas mixtures and for different concentrations of quenching gas in helium.

Further subject of R&D is the study of mechanical structure of the chamber. To this purpose, a prototype 1:1 in length and 1:16 in azimuth is being designed and will be ready as soon as all decisions regarding gas, cell size and the superlayer structure have been made. Besides checking the structural properties of the chamber, this prototype will also answer questions like proper choice of wire material, wire sagging, wire stability, and so on.
6. DETECTOR SIMULATION AND BACKGROUND REJECTION

6.1 Detector simulation

The detector performance in terms of efficiencies, resolutions and background rejection capability has been extensively simulated in the past nine months. Some of this work involved fast generators and simplified detector geometry. At the same time we have developed a general Monte Carlo program, Geant, for the KLOE detector based on Geant.\textsuperscript{[52]} Geant has been used extensively for more realistic simulation, often with limited statistics because of the lack of adequate computer power.

The kinematics part of the program handles \( \phi \) decays into \( K^+K^- \), \( K^0_S K^0_L \), \( \pi^+\pi^-\pi^0 \) and the decays of neutral and charged kaons. Radiative corrections and the machine energy spread are included. Generators for other processes like: \( \phi \) radiative decays, Bhabha scattering, \( \gamma\gamma \) interactions are incorporated by users into the program libraries. The detector geometry is as realistic as possible at this stage. The shape and size of the beam pipe (1 mm Be) and quadrupoles for the low \( \beta \)-insertion which are located inside the drift chamber are included. For the chamber we assume wall thicknesses of 0.02 (0.05) radiation length, \( X_0 \), for inner (outer) wall and 0.07 \( X_0 \) for the endcap wall. The default \( X_0 \) of the gas mixture (helium plus hydrocarbons and wires) is 1400 m. The default value of the magnetic field is 6 kG. The central EmC is segmented in \( \phi \) as 24 modules, with realistic cracks between modules. The endcap EmC is as described in section 4.2.2. The granularity of the EmC is described by 218 planes of 0.4 mm of Pb and 0.7 mm of scintillator, equivalent to the calorimeter structure. All dimensions and media properties can be changed by data cards.

Decays, multiple scattering, e.m. showers and hadronic interactions are simulated by Geant. This includes \( K^0_S \rightarrow K^0_L \) regeneration. We are in the process of correcting some of the parameters in Geisha which appear to be incorrect at the low kaon energies. We do not smear hits of tracks in the chamber, nor of photons or charged particles in the EmC. Smearing at the analysis stage allows us to change the resolution functions without having to generate new events. For each hit on a sensitive layer of the detector the current values of \( r, p \), time of arrival and particle type are stored. Full shower development in the EmC can be turned off to speed up the execution. All output banks are in Zebra format and can be read by special routines developed inside the collaboration.\textsuperscript{[53]} A \( \phi \rightarrow K^0_S K^0_L \rightarrow \pi^+\pi^- \), \( \pi^0\pi^0 \) event uses on average, without full shower development, 4 sec of VAX8650 CPU and the average event size is 12 blocks. The graphic version of Geant is also implemented. Fig. 6.1 shows the display of a \( \phi \rightarrow K^0_S L, K^0_L \rightarrow \pi^+\pi^- \) and \( K^0_S \rightarrow \pi^0\pi^0 \) event. The \( K^0_S \) decayed into \( \pi^0\pi^0 \) inside the beam pipe, each \( \pi^0 \) sending one \( \gamma \) into the central barrel EmC (showers No.7 and No.8) and one \( \gamma \) into an end cap EmC (showers No.6 and No.9). The \( \pi^+ \) (track 2) from the \( K^0_L \) decays to a muon (track 15) which decays into an electron in the end plug (track 16). The \( \pi^- \) (track 3) undergoes an inelastic scattering in the end plug, the scattered \( \pi^- \) (track 11) decays into a muon (track 13) in the chamber, which then decays into an electron (track 14) at the end of the chamber, one sees it streaking across the chamber, see figure 6.1 (bottom).
Fig. 6.1 Geant4 front (top) and side (bottom) display of a $\phi \rightarrow K_{S,L} \rightarrow \pi^+ \pi^- \pi^0 \pi^0$ event.

6.2 EVENT RECONSTRUCTION AND EFFICIENCIES

In the following we assume as fiducial volume for $K_L^0$ decays a sphere of 150 cm radius. $\sim 35\%$ of the $K_L^0$'s decay in this volume. For $K_L^0$ studies we often exclude decays within a cylinder of 15 cm radius around the beam axis to avoid $K_S^0$ events from regeneration in the various walls.
6.2.1 Charged Tracks

Tracking in KLOE is non trivial because (i) tracks can begin at any point in the chamber volume, (ii) many tracks spiral in the chamber, $\sim 20\%$ for $K_L^0$ at 6 kG, and (iii) low energy pions undergo $\pi \rightarrow \mu$ decays. Our present tracking program is not yet optimized for all these effects, leading in general to slightly pessimistic estimates of efficiencies and accuracies.

Using a chamber accuracy of $\sigma_{r,\phi} = 200 \mu$m and $\sigma_z = 20\sigma_{r,\phi}$, we have studied the experimental resolution as function of the magnetic field $B$, from 2 to 8 kG.\cite{footnote1} For $K_L^0 \rightarrow \pi^+\pi^-$ the resolution for the invariant $\pi^+\pi^-$ mass $M$ and the total energy $E$ are shown in fig. 6.2. The resolutions improve with increasing $B$ but flatten out at high values. Reconstruction losses, due to spiraling tracks, increase with $B$ as shown in fig. 6.3 both for $K_S^0$ and $K_L^0 \rightarrow \pi^+\pi^-$ decays. A 6 kG field appears therefore to be a reasonable choice giving $\sigma_M = 0.71$ MeV and $\sigma_E = 0.73$ MeV and a momentum resolution $\sigma(p_T)/p_T = 0.3/0.6\%$ (without/with tails). These values are averaged over all $K_L^0$ decay points. The total reconstruction losses are: 14\% (short tracks) + 14\% ($r > 15$ cm) for $K_L^0$ decays and $\sim 7\%$ (short tracks) for $K_S^0$, (short tracks being those crossing less than 8 out of 40 planes). The resolution for the $K_L^0 \rightarrow \pi^+\pi^-$ decay vertex is\cite{footnote2} $\sigma_x = \sigma_y = 0.3$ mm, $\sigma_z = 2.4$ mm, after constraining the two helices to pass through a common point. For $K_S^0 \rightarrow \pi^+\pi^-$ we find $\sigma_x = 1.1$ mm, $\sigma_y = 1.0$ mm, $\sigma_z = 2.1$ mm (at 6 kG), after a constrained fit of the whole event (see below).

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig62.pdf}
\caption{$\sigma_E, M$ vs B.}
\end{figure}
Fig. 6.3 $K^0$ reconstruction losses vs $B$.

6.2.2 Photons

In evaluating the performances of the EmC we assume 100% detection efficiency down to photon energy of 20 MeV, an energy resolution of $\sigma_E/E = 5%/\sqrt{E/1 \text{ GeV}}$; a temporal resolution of $\sigma_t = 300 \times \sqrt{E/20 \text{ MeV}}$ ps. The spatial resolution for the photon apex is $\sigma_{r,\phi,\text{central}} = \sigma_{r,\text{endcap}} = 3.5/\sqrt{12} = 1$ cm from the read out granularity and $\sigma_{t,\text{central}} = \sigma_{r,\phi,\text{endcap}} = 5$ cm, from time differences. The time information is crucial to the reconstruction of the $\pi^0 \pi^0$ decay vertex. In fact, if the $K_L^0$ line of flight is known from the reconstruction of the $K_L^0 \rightarrow \pi^+ \pi^-$ in the other hemisphere, the $\pi^0 \pi^0$ vertex can be obtained for each photon from the time measurement.

The radial resolution (along $K_L^0$ line of flight $r$) worsens with the distance $r$ and we find $\sigma_r(K_L^0 \rightarrow \pi^0 \pi^0$ vertex) $= 4.4 - 8$ mm for $r=10 - 150$ cm. The resolution on the plane transverse to $r$ is dominated by the error (10-20 mrad) on the angle of the $K_L^0$ line of flight determined from the $K_S^0 \rightarrow \pi^+ \pi^-$ vertex. The $K_L^0$ vertex can be reconstructed also for events with only 3 photons detected. The spatial resolution is then about 20% worse. The vertex resolution for $K_S^0 \rightarrow \pi^0 \pi^0$ decays is $\sigma_x = 4.4$ mm, $\sigma_y = 3.7$ mm, $\sigma_z = 3.0$ cm. The resolution for the invariant four photon mass $M$ from $K^0 \rightarrow \pi^0 \pi^0 \rightarrow 4\gamma$ is found to be $\sigma_M = 3.4$ MeV for $\sigma_M/E = 5%/\sqrt{E/1 \text{ GeV}}$, using the pion mass and beam energy constraints. The resolution for $M$ is approximately linear in the EmC energy resolution but quite insensitive to the spatial and temporal resolutions of the calorimeter.

A figure of merit of the KLOE electromagnetic calorimeter is its hermeticity. Photon losses must be minimized to reject $K_L^0 \rightarrow \pi^0 \pi^0 \pi^0$ decays which can simulate $K_L^0 \rightarrow \pi^0 \pi^0$ if two photons are lost. For $K_S^0 \rightarrow \pi^0 \pi^0$ events photons are lost in forward/backward regions where $\theta < 8.5^\circ$ and in the central calorimeter cracks. Photons from $K_L^0$ decays are also absorbed on the quadrupoles. In the following we will present results with and without the assumption that the quadrupoles are covered with devices which can detect photons above some minimum energy, but with no
other information. The efficiency for detecting all four photons from \( \pi^0\pi^0 \) decays is 88%. The fraction of \( K_L^0 \rightarrow \pi^0\pi^0\pi^0 \) events with only 4 gamma detected is \( 10^{-2} \) and is reduced to \( 3.4 \times 10^{-3} \) with instrumented quads.\(^{58} \)

### 6.2.3 Global Constrained Fit

For a given final state, typically \( \phi \rightarrow K_S^0 K_L^0 \rightarrow \pi^0\pi^0\pi^+\pi^- \), one can improve the above results by simultaneously fitting all the measured quantities, imposing all the kinematical constraints. The measured quantities are momenta of charged particles, photon energies, impact points and times of arrival of photons and the e\(^+\)e\(^-\) interaction point. The global fit improves background rejection and the spatial resolution on the neutral vertex.\(^{58,57} \) For \( K_L^0 \rightarrow \pi^0\pi^0 \) we find \( \sigma_x = 6.0 \) mm, \( \sigma_y = 5.5 \) mm, \( \sigma_z = 6.6 \) mm and \( \sigma_r = 4.6 \) mm to be compared with \( \sigma_r = 6 \) mm given above. For \( K_S^0 \) we find \( \sigma_x = 3.5 \) mm, \( \sigma_y = 2.5 \) mm, \( \sigma_z = 9.4 \) mm and \( \sigma_r = 4.1 \) mm. The resolution on the charged vertex is also slightly improved.

### 6.3 Background Rejection

The main source of background in CP experiments are the non CP violating decays of \( K_L^0 \): \( \pi^0\pi^0\pi^+\pi^- \), \( \pi^+\pi^-\pi^0 \), \( K_{\mu3} \) and \( K_{\mu3} \) which are \( \sim 100 \) times more abundant. The true signal \( N_S \) is in general obtained by subtracting a background \( N_B \) from the detected events \( N_D \). If \( N_B \) is known with an error \( \delta N_B \) the corresponding error on \( \Re(\epsilon'/\epsilon) \), for a double ratio measurement, due to background subtraction is \( \delta_{bckg} = 1/6(\delta N_B/N_S) \). The \( \delta_{bckg} \) should be smaller than the statistical error \( \sim 10^{-4} \). For \( \delta_{bckg} < 0.5 \times 10^{-4} \) we have the condition \( \delta N_B/N_S < 3 \times 10^{-4} \). Defining the rejection \( \Re \) as the ratio of detection efficiencies \( \epsilon \), \( \Re = \epsilon(K_L^0 \rightarrow \text{signal})/\epsilon(K_L^0 \rightarrow \text{bckg}) \), the background to signal ratio is given by \( N_B/N_S = R_B/\Re \) where \( R_B \) is the ratio of the relevant branching ratios. We thus obtain the condition:

\[
\Re > \frac{R_B}{3 \times 10^{-4} \times \frac{\delta N_B}{N_B}}
\]

Poor rejection (small \( \Re \)) requires that the background and signal distributions be well understood. As mentioned in a previous chapter we intend to use data to achieve the knowledge, although our simulation results indicate that we can achieve the required rejections with quite modest understanding of background and signal shapes. In addition, of course, Monte Carlo simulation will help confirm our analysis. Good rejection is in general obtained at the cost of signal loss. By the same considerations above, a 10% signal loss must be known to better than \( 3 \times 10^{-3} \). Again, we intend to use real data to understand the signal shape as well as using Monte Carlo simulation.

#### 6.3.1 Rejection of \( K_L^0 \rightarrow \pi^0\pi^0\pi^0 \)

The \( K_L^0 \rightarrow \pi^0\pi^0\pi^0 \) contamination is obtained by estimating two factors. The first is the probability to loose 2 of the 6 final photons, the second is the probability that the remaining 4 \( \gamma \)'s simulate a \( K_L^0 \rightarrow \pi^0\pi^0 \) decay. We discussed in section 6.2.2 the first factor. We first apply a cut on the total energy of the four photons. The surviving events are fitted imposing the two \( \pi^0 \) masses and energy conservation constraint, using the \( K_L^0 \) direction from the reconstruction of the \( K_S^0 \rightarrow \pi^+\pi^- \) decay in the chamber. Good events are selected by a cut on \( \chi^2 \) and on the \( \pi^0\pi^0 \) invariant mass. For an EmC resolution of 5%, the rejection factor is 330,000 if photons
hitting the quadrupoles are detected, 100,000 otherwise. For 20% worse EmC resolution and active quads, the rejection is \( \approx 100,000 \).\(^{58}\)

6.3.2 Rejection of \( K_{L}^{0} \rightarrow \pi^{+} \pi^{-} \pi^{0} \)

Rejection of \( K_{L}^{0} \rightarrow \pi^{+} \pi^{-} \pi^{0} \) is considerably better than \( K_{L}^{0} \rightarrow \pi^{0} \pi^{0} \pi^{0} \). The probability of losing two out of two photons is 15 times smaller than for the two out of 6\( \gamma \) case. Together with the better momentum measurements for charged particles we estimate \( \mathcal{R} \gg 100,000 \).

6.3.3 \( K_{\mu 3} \) Rejection

Charged tracks from \( K_{L}^{0} \rightarrow \pi \mu \nu \) are generated in the chamber with 6 kG taking into account multiple scattering and pion decay. The wire hits are fitted to reconstruct the track momenta. Rather than fitting all events we first apply some kinematical cuts. We compute the visible energy \( E^{\pm} \) and the invariant mass \( M^{\pm} \) of the two particles, assuming they are pions. For \( K_{L}^{0} \rightarrow \pi^{+} \pi^{-} \) decays we define a narrow ellipse in the \( E^{\pm}, M^{\pm} \) plane containing 90% of the signal and reducing the background by 1:2000. Additional rejection is obtained by a constrained fit to the full event. The EmC energy resolution used is 6%/\( \sqrt{E} \), for the other parameters we use the values given previously. After the fit a cut on \( \chi^{2} \) retains 66% of the signal and only 3.2% of the \( K_{\mu 3} \) background. The overall rejection factor is then 50,000. Additional discrimination against \( K_{\mu 3} \) decays is provided by time of flight measurements of the charged particles in the calorimeter and by specific ionization measurements in the chamber.

6.3.4 Rejection of \( K_{e3} \)

The \( K_{e3} \) background can be treated as above. Simple estimates give \( \mathcal{R} \gg 100,000 \), mostly because \( m_{e} \ll m_{\mu} \). Additional help in distinguishing pions and electrons comes from the energy deposition pattern in the EmC.

In table 6.1 we show the values of \( \mathcal{R} \) corresponding to \( \delta N_B/N_B = 10\% \) and the expected \( \mathcal{R} \) for KLOE.

<table>
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<tr>
<th>Decay</th>
<th>( R_B )</th>
<th>( \mathcal{R} ) required</th>
<th>( \mathcal{R} ) expected</th>
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<tr>
<td>( K_{L}^{0} \rightarrow \pi^{0} \pi^{0} \pi^{0} )</td>
<td>238</td>
<td>79,000</td>
<td>330,000</td>
</tr>
<tr>
<td>( K_{L}^{0} \rightarrow \pi^{+} \pi^{-} \pi^{0} )</td>
<td>61</td>
<td>20,000</td>
<td>( \gg 100,000 )</td>
</tr>
<tr>
<td>( K_{\mu 3} )</td>
<td>133</td>
<td>44,000</td>
<td>( \gg 50,000 )</td>
</tr>
<tr>
<td>( K_{e3} )</td>
<td>191</td>
<td>64,000</td>
<td>( \gg 100,000 )</td>
</tr>
</tbody>
</table>

6.4 Backgrounds for \( \gamma \gamma \) Physics

For the process \( e^{+}e^{-} \rightarrow e^{+}e^{-} \pi^{0} \pi^{0} \) at the \( \phi \) peak the main background comes from the process \( e^{+}e^{-} \rightarrow \phi \rightarrow K_{L}^{0}K_{S}^{0} \rightarrow K_{L}^{0} \) (undetected)\( \pi^{0} \pi^{0} \)

which completely overwhelms the process \( e^{+}e^{-} \rightarrow e^{+}e^{-} \pi^{0} \pi^{0} \). KLOE is unable to do this measurement at the \( \phi \) peak without detecting the forward electrons ("tagging"). The background off peak, including that from \( e^{+}e^{-} \rightarrow \omega \pi^{0} \), is negligible.\(^{58}\)

From a preliminary study, the insertion of a tagging detector at zero degrees appears possible.\(^{59}\) It was pointed out at the Frascati workshop that tagging at DA\( \Phi \)NE should not
reduce too much the $\gamma \gamma$ luminosity. Use of tag insertion would allow measurements of azimuthal correlations. This has never been done and could be used to test theoretical models.\cite{60}

For $e^+e^- \rightarrow e^+e^- \pi^+\pi^-$ the main background is $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ with a cross section ~20× bigger. Muons and pions of these energies, ~100 MeV/c, can be distinguished by specific ionization and time of flight measurements. Work is in progress to obtain quantitative results.

6.5 SENSITIVITY AND BACKGROUNDS FOR SPECTROSCOPY

We have studied the experimental problems associated with measuring $\phi$ radiative decays by choosing two typical and interesting ones: $\phi \rightarrow f_0\gamma$ and $\phi \rightarrow \eta'\gamma$. For $\phi \rightarrow f_0\gamma$, where the $f_0$ decays to two neutral pions, the background comes only from other $\phi$ decay channels. We find that in a run of integrated $\mathcal{L}\sim10^{39}$ cm$^{-2}$, the accuracy with which we can determine the BR is 4%, in the worst case of the signal BR being $1.0 \times 10^{-6}$ (the smallest theoretically expected BR), the total background yield corresponding to BR of $1.0 \times 10^{-3}$ (experimental upper limit).\cite{61} For the case where the $f_0$ decays to a pair of charged pions, additional continuum backgrounds and interference effects lower the accuracy to 24% when the signal BR is $1.0 \times 10^{-6}$ for the case of complete destructive interference and the background from the direct decay $\phi \rightarrow \pi^+\pi^-\gamma$ has a BR (experimental limit) of $7.0 \times 10^{-3}$.\cite{62} We find the measurement of the BR of the as yet unobserved $\phi \rightarrow \eta'\gamma$ decay easy, a $6\sigma$ signal can be observed for a BR of $1.0 \times 10^{-6}$, the theoretical expectation being $\sim1 \times 10^{-4}$.

6.6 BACKGROUNDS FOR RARE $\eta$ DECAYS

A very preliminary analysis of the background has been carried out for the $\eta \rightarrow \mu\mu\pi^0$ and $\eta \rightarrow \mu\mu\gamma$ modes.\cite{32}

6.6.1 Background from $\phi$ decays

For $\eta \rightarrow \mu\mu\pi^0$ one can ask for two charged particles and 3$\gamma$'s. The main background from $\phi$ decays involves 2 or 3 $\pi^0$'s, so that in general a $\gamma$ has to be lost from the acceptance. After selecting events with the right number of charged particles and $\gamma$'s and using the tagging, a global rejection factor of $10^8$ is needed. One can confidently count on the available constraints to achieve this rejection, taking into account that the lost $\gamma$ has most frequently taken a great amount of energy. In the case of $\eta \rightarrow \mu\mu\gamma$, the main background comes from $\phi \rightarrow K^+K^-$ followed by $K^\pm \rightarrow \mu^\pm\nu$ and $K^\mp \rightarrow \pi^\mp\pi^0$. After tagging the background/signal ratio is only 200; the kinematical cuts will easily reduce the background to an acceptable value.

6.6.2 Background coming from leading $\eta$ decays

The background for $\eta \rightarrow \mu\mu\pi^0$ is $\eta \rightarrow \pi^+\pi^-\pi^0$, with possible decay of the pions. Monte Carlo calculations for a detector at Saclay have shown that a rejection factor of a few $10^8$ should be achievable. These calculations will be resumed for the KLOE detector, but one can expect only favorable conclusion in view of the projected performance of this detector. Continuum background is lower.
7. FRONT END ELECTRONICS AND TRIGGER

7.1 Trigger

All $\phi$ decay events are of interest for physics and for determining the detector response. In addition we must ensure that all the information from the detector remains available at the analysis stage and that no biases are introduced at the level of $1 \times 10^{-4}$. We must therefore pass all information from the detector to the data acquisition (DAQ) system and store them on tape. The KLOE DAQ will perform the complete production task. Data filtering at any level, even removing a single isolated hit, without possibility of recovery of the lost information, might be something we will regret later. Rejection of apparently irrelevant information can be done only if the original data has been archived. We place in this way a burden on the DAQ system, which must have enough computing power to perform the necessary analysis.

$\phi$ production, at full machine $L$, has a rate of 5 kHz. In addition there are QED processes, dominated by Bhabha scattering. All these events, including $\mu$ pairs and $2\gamma$ are essential for the detector calibration. However, the Bhabha rate at small angle is $\sim 50$ kHz and would overload the DAQ system. Bhabha's must therefore be recognized and prescaled. We also expect a $\sim 10$ kHz rate from cosmic rays, fractions of which must be rejected as early as possible. We have just begun Monte Carlo simulations of all these points and will continue these studies before finalizing our choice.

We have preliminary estimates of the machine induced backgrounds and find them negligible. Off orbit energetic electrons contribute a rate of few $\times 100$ Hz and can therefore be passed along together with good events. Synchrotron radiation background at DA$\Phi$NE is essentially absent because of:

1. the machine configuration,
2. the extremely low critical energy, $<100$ eV
3. the use of helium in the KLOE chamber. Studies of these problems will continue in collaboration with the machine group.

We feel that a trigger based on calorimeter signals could satisfy all our requirements. A simple track finder, using chamber informations might complement the trigger. Calorimeters are ideal for providing a robust trigger, not easily confused by soft radiation. In fact the EmC is fully efficient for detecting minimum ionizing particles and has fast response. We also have simple schemes for the Bhabha trigger: using simple analog sums and combinatorial logic to scale down the small angle Bhabha's, with a response time of $\mathcal{O}(50 \text{ ns})$. The exceptional timing qualities of the EmC should also be of great help in providing a cosmic ray veto.

7.2 Calorimeter Signal Processing

Given the stringent requirements in time and energy resolution of the EmC, the front end electronics, FEE, must have excellent performance, in particular with respect to noise and bandwidth. All calorimeter electronics is on the high performance side of good contemporary electronics and does not rely on next generation devices, nor on just out ones. Special attention needs to be devoted to the overall system. To control external noise, preamps must be mounted directly on the phototubes (PM) bases, together with the voltage dividers, requiring low power
design to reduce the problems connected with cooling circuitry buried in enclosed places. The large number of preamps, ∼10,000, located in inaccessible places will require additional special care in their design to insure high mean time to failure, MTTF. The proposed FEE scheme is shown in figure 7.1. The PM choice is dictated by the ability to operate in magnetic field and by low electron transit time spread, <0.7 ns, necessary to obtain a superior calorimeter time resolution. The total gain (PM plus preamp) required to obtain reasonable signals (50 mV for 20 Mev photons) is around 5×10^6. We will use grounded cathode connection for the PM (positive high voltage) in order to remove possible sources of additional noise. The consequent capacitive coupling of the PM to the preamp is possible because of the low rate and the very short signals.

![Diagram of calorimeter front end electronics](image)

**Fig. 7.1** Calorimeter front end electronics.

We will also limit the divider current to 100 μA to reduce power dissipation. Nevertheless, given the high number of channels, cooling has to be provided, ensuring also that possible gas leaks from the chamber will not expose the PM's to helium.

Each PM signal has to be split three ways to provide the following functions:
1. amplitude measurements via ADC, to provide energy deposit information,
2. time measurements through a few channel multi-hit TDC after a constant fraction discriminator,
3. trigger generation after analog sum of signals from adjacent channels (i.e. local calorimeter neighborhoods).

The maximum photon energy at DAΦNE is equal to the beam energy, 750 MeV at the
maximum design energy. If this is the full scale of a 12 bit ADC, the least count would correspond to 0.18 MeV, assuring adequate precision for the detection of minimum ionizing particles which give a signal equivalent to 20 MeV γ 's and for the proper clustering of em showers. Because of the spread of the arrival time of particles to the calorimeter, we are considering the use of 10 MHz flash ADC, with 5 word deep registers. Semigaussian shaping of the signals, with a width of ~300 ns, will allow us to avoid having to delay the signals with respect to the trigger, and will not degrade the information.

Time measurements require a sensitivity of <50 ps/count in order not to degrade the expected timing resolution. The required TDC range is determined by the spread of the arrival times of the signals on the PMs. We have estimated this range to be ~200 ns. We need therefore 12 bits TDC's with moderate, 2-5, multi hit capability.

This part of the electronics will reside in a VME environment. The use of vertical interconnects, for example VICbus, will allow very simple data concentration prior to entering the fast switches of event builders for trasmission to a microprocessor farm.

7.3 Chamber Signal Processing

Our approach to the development of the chamber wire signal processing is guided on a rate vs θ in the chamber as shown in fig.7.2, which is dominated by Bhabha scattering. From the data in fig. 7.2 we obtain the rate per wire of fig. 7.3, which we note is very low.

7.3.1 Signal Processing

The chamber electronics is pushing at the frontiers of today's almost-there technology. Cluster counting is an ambitious project and poses problems requiring elaborate solutions. We are still at a stage of very preliminary investigation, following possible alternatives in parallel. In order to measure track coordinates and measure dE/dx by cluster counting we must detect and count peaks in the wire signals and measure their arrival time. Three different methods are being investigated.

1. Slope Detector. A circuit able to detect any change in positive slope of the input signal is under test. Mutilhits TDC with adequate time resolution but short pipelines are then necessary. The number of hits together with the relative delays are obtained in real time. Thresholds in slope can be made tuneable.

2. Flash ADC's. The latest FADC's allow sampling rate up to 500 MHz. This method gives a full reconstruction of the signal and also allows changes in the cluster definition at any time. Disposing of the output of such devices, at 500 MHz, for 10,000 channels, could be a very serious problem.

3. Analog Memory. It is also possible to sample the input signal at high frequency into an analog shift register. Upon receiving a stop signal, sampling is halted and the data shifted out at lower speed into more conventional FADC's. This approach is in fact identical to the previous one, avoiding the problems of working at high bandwidth at the digitizer output.

Data concentration and transfer to the event builder will also be in a VME environment.
Fig. 7.2 Total Bhabha rate versus chamber layer.

Fig. 7.3 Bhabha rate per cell versus chamber layer.

A scheme for data reduction, by self triggering on the wire signal, is shown in figure 7.4.

Fig. 7.4 Self triggered flash encoder.
8. THE DATA ACQUISITION SYSTEM

We propose to complement the KLOE detector with enough computing power to be able to digest in real time the enormous amount of data which will be collected at DAFNE. At full \( \mathcal{L} \) we expect an event rate of 10,000 events per second, which even for a very modest event size, 10,000 bytes represent a detector output rate of 100 Mbytes per second or \( 10^{15} \) bytes/year. A first study of the feasibility of writing to tape such massive quantity of data was presented at the Frascati Workshop in 1991.\(^{65}\) The possibility was also discussed of developing microprocessor farms capable of delivering the necessary computing power, rated at the level 10,000 MIPS. Chips capable of more than 120 MIPS exist today. A farm employing them appears to be a possible and economical solution. KLOE in this area relies on the ALSAT Group\(^{66}\) who is studying these problems and has chosen KLOE as a test bench for their first project.

Briefly the proposed solution consists of fast communication channels which can communicate through intelligent switches, transmitting data from the FEE to processor farms and to tapes. The process is reversible and the farm can process data from tape. We envisage two farms, to be shared between the tasks of on line processing, Monte Carlo and second pass production. A block diagram of the system is shown in fig. 8.1.

![Block diagram of the KLOE DAQ.](image)

Fig. 8.1 Block diagram of the KLOE DAQ.
9. CONSTRUCTION SCHEDULE AND COST

9.1 Construction Schedule

The time for the completion of the KLOE detector is set by the fact that DAΦNE will have circulating beams some time in 1995. It is optimistic but not unthinkable to have KLOE ready to roll in on January 1, 1996. We outline in the following our plans for achieving this. One of the longest lead times is the construction of the central calorimeter. Fortunately this item is perhaps the most advanced in our whole venture. We are at present constructing a two m long module, to make final, realistic tests on performance at PSI, Zürich, in June '92. At the same time we are developing tooling for the preparation of the grooved lead plates. We will be ready to begin construction of the first full size module of the central calorimeter in the fall of 1992. By the end of 1992 we want to transfer our tooling and experience to commercial firms for the construction of the 24 central EmC nodules. Construction of the endcap EmC's and the plug EmC's, should begin by mid '93. The tracking chamber still requires better understanding of many of its parameters as well as the design of its mechanical structure. Its construction can however be safely delayed to the second half of 1993 and wire stringing should be completed by the end of 1995.

The magnet construction should begin as soon as possible to have the magnet available in the assembly hall for

1. field measurements,
2. central EmC assembly,
3. chamber insertion.

Since the magnet size depends on the dimensioning of all the detector components inside it, we have begun a realistic effort to optimize all dimensions, study internal and external cabling and detector motion in order to be able to begin the bidding procedure in July 1992. It is expected that two years will be necessary for the construction of the magnet components and 3-6 months for its assembly in the assembly hall, on the moving platform. Electronics, controls and services are a less serious problem, since they can proceed in in parallel with the major construction jobs. Likewise, it is wise to delay as much as possible, within safe limits, construction of the microprocessor farms, to take advantage of the most advanced and economical solutions which will become available in this rapidly changing field. For the major mentioned items, the division of efforts is indicated in table 9.1.

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### Table 9.2 KLOE Cost Estimate, MAR 92, in '92 MLit.

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<td>ea</td>
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<td>2.3</td>
<td>TOT. MAGNET</td>
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<tr>
<td>2.4</td>
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<tr>
<td>2.4.1</td>
<td>Cal. Elect.</td>
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<td>2.4.2</td>
<td>Chamber Elect.</td>
<td>ch</td>
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<tr>
<td>2.4.3</td>
<td>Trigger</td>
<td>ea</td>
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<td>2.4.4</td>
<td>Controls+HV dist.</td>
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<tr>
<td>2.4</td>
<td>TOT. ELECTRONICS</td>
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<tr>
<td>2.5</td>
<td>DAQ/PROD. FARM</td>
<td></td>
</tr>
<tr>
<td>2.5.1</td>
<td>Processor Farm</td>
<td>MIP</td>
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<td>2.5.2</td>
<td>SWTC, Comm. Contr.</td>
<td>ea</td>
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<td>2.5.3</td>
<td>Tape Drives</td>
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<td>2.5.4</td>
<td>Tape robotics</td>
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<td>Disks</td>
<td>Gby</td>
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<td>2.5</td>
<td>TOT. DAQ-FARM</td>
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<tr>
<td>2.6</td>
<td>OTHER</td>
<td></td>
</tr>
<tr>
<td>2.6.1</td>
<td>Detect. motion</td>
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<td>2.6.2</td>
<td>Cables, cabling</td>
<td>ea</td>
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<tr>
<td>2.6.3</td>
<td>Cntrm, rcks,pw,cl</td>
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<td>2.6</td>
<td>TOTAL OTHERS</td>
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<td>2</td>
<td>TOTAL</td>
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<tr>
<td>2.7</td>
<td>SPARES &amp; CONT 10%</td>
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<tr>
<td>2</td>
<td>TOTAL DETECTOR</td>
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We have done our best to estimate the detector cost, based on actual cost of items, estimates from industries and scaling from various projects with which we are well familiar, such as DØ and CDF at Fermilab, CUSB at CESR, the LEP detectors and so on. On this basis we arrive to the costs listed in table 9.2.

9.3 Funding profile

In order to build the detector by end '95, the funding profile required for the major items is estimated as shown in table 9.3.

<table>
<thead>
<tr>
<th>Year</th>
<th>Magnet</th>
<th>Central EmC</th>
<th>End EmC</th>
<th>Chamber</th>
<th>FEE</th>
<th>DAQ</th>
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<tr>
<td>'92</td>
<td>0.44</td>
<td>0.44</td>
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<tr>
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<td>3.74</td>
<td>5.28</td>
<td>1.28</td>
<td>1.19</td>
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<tr>
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<td>2.38</td>
<td>7.20</td>
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<tr>
<td>'95</td>
<td>0.94</td>
<td>1.59</td>
<td>2.55</td>
<td>2.32</td>
<td>5.77</td>
<td>2.20</td>
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<tr>
<td>'96</td>
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<td></td>
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<td>0.88</td>
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<tr>
<td>'97</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>0.44</td>
</tr>
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</table>
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66. The ALSAT (Alta Luminosità Sistemi Acquisizione e Trattamento [Dati]) group is composed of: S. Bertolucci, LNF; L. Cerrito, Roma II; A. Farilla, Bari; M. L. Ferrer, LNF; G. Mancarella, Lecce; G. Mandrioli, Bologna; A. Marini, LNF; P. Matteuzzi, Bologna; E. Pace, LNF; M. Pistoni, LNF; F. Ronga, LNF; F. Ruggieri, Bari; C. Stanescu, ISS; A. Surdo, Lecce; E. Valente, Roma.