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THE MUON AND K_L DETECTOR FOR THE BABAR EXPERIMENT: PHYSICS REQUIREMENTS, FINAL DESIGN AND START OF CONSTRUCTION

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Resistive Plate Chambers have been chosen as active elements for the μ and K_L detector in the BaBar experiment. This subsystem, now under construction, represents the most extensive use to date of the RPC technology. The design considerations are presented, together with preliminary results on the operating characteristics.

1. Introduction

The BaBar detector [1] focuses on the study of the asymmetries in neutral B meson decay, arising from CP violation. It will be installed at the PEP II e^+e^- asymmetric storage ring [2] operating at the $\Upsilon(4S)$ energy; the design luminosity of this machine is 3×10^{33} $cm^{-2}s^{-1}$ and a set of parameters already exists for an upgrade to 10^{34} $cm^{-2}s^{-1}$.

The experimental apparatus [3] consists of a Silicon Microstrips Vertex Detector, a Drift Chamber, a DIRC for particle identification, a CsI Electromagnetic Calorimeter and a Superconducting Solenoid with an Instrumented Flux Return (IFR) for muon identification and coarse hadron calorimetry [4]. Commissioning of both PEP II and BaBar is scheduled for Fall '98. The IFR is the first sub-system to be installed: the active detectors will be positioned in the iron gaps

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starting in mid '97 and completion of the installation is foreseen in December '97.

Muons are identified by range and by energy deposition topology in the IFR. The IFR also provides neutral hadron (particularly K_L) detection. To achieve μ identification down to momenta of 0.5 GeV/c, the magnet yoke is segmented in several iron layers of different thickness for a total of about 65 cm of steel. The gaps are filled with Resistive Plate Chambers (RPC) [5] whose signals are read from two planes of strips running in orthogonal directions, thus providing bi-dimensional information.

In the following we will briefly review the physics motivation and the main requirements for the IFR, with particular emphasis on the production and quality control of the RPC's. A short description of the assembly and installation procedures will also be given, together with preliminary results from R&D activities.

2. Motivations and Requirements

The primary goal of the BaBar experiment is the systematic study of the CP asymmetries in the decay of neutral B mesons into CP eigenstates.

This will provide an in depth test of the Standard Model and its underlying assumptions, and will help to clarify the origin of CP violation. The high luminosity of PEP-II will also allow significant advances in a wide range of B, charm and τ physics.

The CP asymmetry measurements require three fundamental ingredients: exclusive final state reconstruction, flavor tagging and time ordering of the decay of the two B mesons produced by the $\Upsilon(4S)$. In order to reach the necessary sensitivity, the detector must perform as well as possible in the following areas: solid angle coverage, vertex resolution (mainly along the beam axis), charged particle momentum resolution, species identification, and low energy photon detection efficiency. These considerations have motivated the detector design and the choices for each sub-detector.

Muon identification and neutral hadron detection is provided by the Instrumented Flux Return (IFR), which makes use of the large iron structure needed as the magnet return yoke. At the $\Upsilon(4S)$, muons are produced mostly in semileptonic decays, either directly from the *B* or from the cascade *D* 's. The sign of their charge determines the "*b*" or "*c*" flavor of the parent meson, thus providing a clean tagging for the CP asymmetry measurements.

Muon identification is also important in many B Physics topics, such as semileptonic decays or rare modes involving leptons. Neutral hadron detection is crucial for reducing the background in a wide variety of channels.

The main purpose of the IFR detector is an efficient and clean muon identification, to achieve the highest practical tagging efficiency [6]. Identification as *muons* or *hadrons* for particles reaching the IFR will result from the detailed analysis of the hits pattern in the active detectors [7]. To achieve a high tag efficiency it is necessary to detect low momentum μ's, to reduce hadron contamination and to correctly assign the particles identified as muons to the "*direct*" or "*cascade*" class.

Muons must have a momentum of at least 500 MeV/c (depending on the polar angle) to be detected in the IFR, and at least ~1.4 GeV/c to exit the iron. Since the momentum spectrum of the muons produced at the $\Upsilon(4S)$ extends well above 3 GeV/c, identification must be achieved over a wide momentum range.

The ability to detect K^0_L's allows the study of the CP asymmetry in the decay $B^0 \rightarrow J/\Psi\ K^0_L$, thus providing an additional measurement of the angle β of the unitarity triangle, as clean as the "golden" mode $J/\Psi\ K^0_S$ [8,9]. The momentum spectrum of the K^0_L from this decay covers the range between 1 and 3 GeV/c and is quite flat. To identify this final state it is necessary to measure the K^0_L direction with a reasonably good precision, 35 mrad or better. The hadron calorimetry is too coarse for an energy measurement.

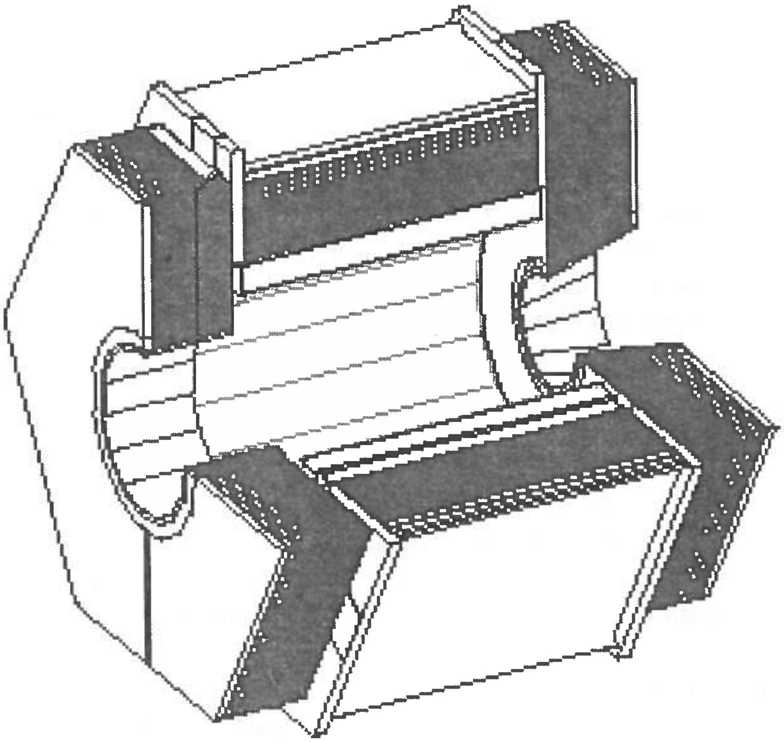

Figure 1. The IFR Detector

3. Detector design and layout

3.1. The Iron Structure

The muon and neutral hadron detector uses as absorber the flux return iron of the 1.5 T superconducting solenoid; this massive steel structure also serves as support for the inner detectors.

The design of the steel plates has taken into account both the requirements dictated by its use as hadron absorber and muon filter, and the complex mechanical problems concerning the access to the inner detectors, all subject to the space and magnetic shielding constraints imposed by the machine components.

Optimization studies, performed with detailed MonteCarlo simulations, have led to the final design of the iron structure. It has been found that a graded segmentation, with thin plates (2 cm) in the first absorption length, is the most cost effective, since thicker plates in the back of the detector do not significantly deteriorate performance, both for muon identification and K^0_L detection. The final design has 18 plates of thickness from 2 cm to 10 cm; the gap width is 3.5 cm between the inner plates, 3.2 cm elsewhere.

The IFR consists of three sections: a central Barrel, a Backward and a Forward Endcap. A view of the detector is shown in Fig. 1. The Barrel extends radially from 1820 to 3045 mm and is divided into sextants; the length of each sextant is 3750 mm, and the width varies from 1963 to 3297 mm.

The Barrel plates are welded on steel plates whose thickness (55 mm) reduces the area available for active detectors. This dead area is concentrated at the joining of the hexagonal sectors and accounts for a small loss in solid angle. The structure consists of nine plates 2 cm thick, followed by four plates 3 cm thick, three plates 5 cm thick and two plates 10 cm thick.

Each Endcap door consists of hexagonal plates, divided vertically into two halves to allow opening and access to the inner detectors. A hole in the center is required by the presence of machine components and magnetic shields; the radius is ~1m in the backward door and the hole has a conical shape in the forward direction. The gaps between plates are divided horizontally into three sections by stiffeners needed to prevent bending due to the magnetic forces and to limit stresses due to mechanical and potential seismic loads. In both Endcaps the graded iron structure consists of a sequence of nine 2 cm, four 3 cm, four 5 cm and one 10 cm plates, for a total of 60 cm. The amount of steel is adequate for satisfying the magnetic shielding requirements and represents a good compromise between cost consideration and the necessity to reduce hadron punchthrough.

3.2. The Active Detector

Particular care has been taken in the choice of the active detector. Due to the limited accessibility, high reliability is required. The area to cover is very large and is subdivided in many different shapes, so attention must be devoted also to cost and flexibility of the chosen device.

Resistive Plate Chambers (RPC) have been proven to represent a mature technique providing very high detection efficiency (>90 %) together with great simplicity of construction and low cost production and operation.

Further benefits of RPC's are fast time response (short pulse rise time), large pulse signals, excellent time resolution (of the order of 1-2 ns), good spatial resolution (few millimeters), and the possibility of large scale industrial production. Great shape flexibility allows almost complete coverage of large areas.

This choice is reinforced by the excellent results achieved in efficiency and resolution, both spatial and in time, by the L3 experiment at CERN [12-15], where it has been used for the muon forward-backward trigger. This system was built and operated by part of the group now involved in the IFR , who can take advantage of the substantial experience gained so far.

3.3. Detector Coverage

The IFR detector consists of 19 layers in the Barrel and 18 layers in each Endcap region. The total surface covered is approximately 2000 m^2.

The total number of RPC modules to be used has been substantially reduced compared to the TDR preliminary design [4]. In fact, due to the interest in RPC production from BaBar and the LHC experiments, the commercial factory which produced previous RPC systems[16] upgraded its machinery to match the maximum size available for the bakelite sheets, 1.35 x 3.20 m^2.

To take advantage of the increase in RPC size, we have redesigned the layout of the modules, reducing their number from 1464, as described in the TDR [4]), to 774 (342 for the Barrel and 432 for the Endcaps). This results in substantial savings in the RPC cost, and reductions in several areas, such as gas and H.V. distribution, monitoring, slow controls, etc.

In the Barrel the gaps have a rectangular shape, with constant length (3750 mm) and width varying from 1908 mm to 3200 mm. In order to minimize the number of RPC needed, the modules have length equal to the gap width and width equal to a third of the gap length. Each gap is therefore covered by 3 modules of the same size, with one plane of strips running across the full gap length and the other attached to each module in the orthogonal direction. The barrel system, given the sixfold symmetry, consists of 19 sets each containing 18 same-size modules.

In the Endcaps, the geometry is more complicated, due to the fact that each part is a half hexagon, with a hole in the center and divided horizontally in three parts. In each part of each gap there will be 2 RPC modules, with a total of 25 different shapes to be used. An example of Endcap geometry is shown in Fig. 2.

Studies of the granularity led us to define the strip pitch in both directions; the final design has a total of about 50,000 strips, ~22,000 in the Barrel and ~14,000 in each Endcap.. In the barrel there is the same number (96 along z, and 96 perpendicular to z) of strips in each layer, so that in the z direction all strips have the same pitch (~4 cm), while in the rϕ plane the pitch increases with the radial distance, roughly from 2 to 4 cm. This choice optimizes, at the same time, both the readout performance and the front-end electronics allocation.

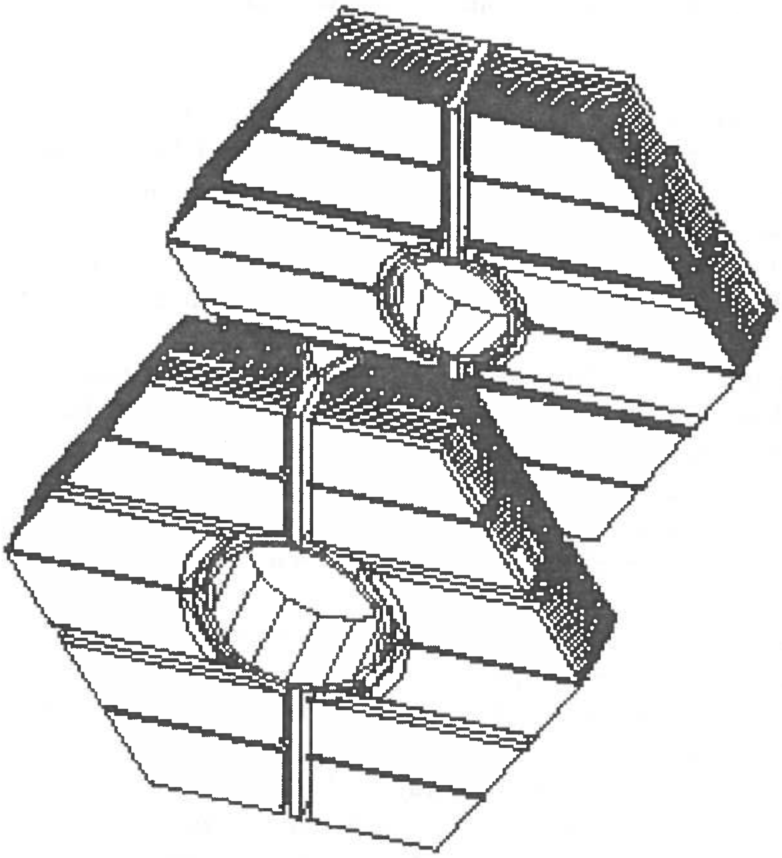

Figure 2. Three-dimensional view of the endcaps.

The excellent timing properties of the RPC's will also be exploited, reading out with TDC cards (presently under design) the ORed signal of the strips of every layer. IFR particle detection, in fact, can be much improved using time measurements: cosmics, beam halo and generic noise can be more effectively rejected, and also neutral hadron identification will gain in accuracy. This kind of measurement will be of great help to monitor data quality, both during initial commissioning and during data taking.

High voltage will be fed individually to each RPC module through series resistors (~20 MΩ); small additional series resistors will be used as fuses so malfunctioning modules can be remotely disconnected from the HV supplies. Provision will be made for measuring and recording individual currents drawn from the detectors.

4. RPC Procurement and Assembly

, Most components of the IFR detectors (the RPC's, and one side of strip planes: z-strips for Barrel RPC's and horizontal strips for Endcap ones) will be manufactured, pre-assembled and tested in Italy. The final assembly will be made at SLAC, where the detectors will be completed with the second strip plane and the final readout electronics. All RPC's are packed at the factory in boxes that will be used for the test in Frascati as well as for the trip to SLAC.

A big Bakelite procurement, of approximately 5000 m^2, is under way; the resistivity of each individual sheet (~2 m^2) is measured, and sheets beyond appropriate limits are rejected. The rejection ratio so far is of the order of 10 %. Strip layers for bidimensional readout are being produced in parallel, with an Al-stripping machine expressly designed and built: this machine provides variable-pitch strips, starting from Al foils 40 μm thick over a substrate of 200 μm thick PVC.

A dedicated test station using cosmics rays has been set up in Frascati, with the capability to process 2 boxes (24 RPC's) at a time, sandwiched between two external RPC's in coincidence to form the trigger. Each test lasts for approximately 1 day, depending on the number of requested triggers: information regarding the efficiency plateau, currents drawn and time resolution will be saved in a database for future reference, together with the resistivity of the two Bakelite sheets forming each RPC. The station so far has acceptance-tested ~200 RPC's out of a total of approximately 900 (about 400 for the barrel and 500 for both endcaps). Most of these have already been shipped to SLAC.

After the acceptance test, modules are shipped to SLAC where all good modules undergo some integrity tests, before being laid on special trays able to hold 3 Barrel RPC's (forming a Barrel chamber) or 2 Endcap RPC's (an Endcap chamber). These trays have been chosen with particular care, and will be used both for intermediate storage and as fixtures for insertion in the IFR gaps. The RPC's are joined at the seams, gas connections are then made, and the package is completed by gluing on the second strip plane (the ϕ-strips for Barrel chambers and the vertical ones for Endcap chambers).

For Barrel chambers, front-end electronics cards will be mounted on the edge of the detectors, to be finally housed inside the IFR gaps, in the spaces left free by the RPC's. For Endcap chambers, twisted pair ribbon cables will be laid from the strips to the cards, located in specially designed "mini-crates" that will be attached to the Endcap structure.

The completed detector planes on their trays will be inserted in cosmic ray towers, where detailed studies of their efficiency will again be performed, before final insertion into the iron sextants forming the Barrel, or the half-doors forming the Endcaps.

5. R&D on the Gas Mixture

Tests with different gas mixtures have been carried out at Frascati, LLNL and Naples. Behavior of the singles rate, dark current, efficiency (absolute and long range stability values), multiplicity, amplitude distribution and time resolution has been studied.

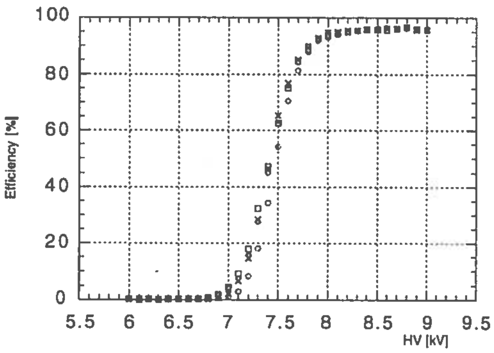

Figure 3. Efficiency plateau for typical RPC modules.

The main purpose of this investigation was to find alternatives to Freon 13B1 (atmospheric ozone layer depleting) and to reduce the amount of Isobutane in the operational mix below the flammability limit.

Without going into experimental details, the mixture under study has been compared with the standard one (Ar 58%, Isobutane 39%, and Freon 13B1 3%). Mixes based on Tetra-fluoro-methane (CF_4), Sulphur Hexafluoride (SF_6) and Tetra-fluoro-ethane ($C_2H_2F_4$, or Freon 134A) have been investigated.

As of now we believe that a non-flammable environmentally safe gas mix based on Freon 134A (Ar 48%, $C_2H_2F_4$ 48% and Isobutane 4%) offers performance at least as good as the ones of the standard mix. Figure 3 shows the efficiency plateau for a set of 12 "production" RPC's as measured in our setup.

Efficiency in excess of 97 % is reached routinely; typical spreads of the knee voltages are measured to be of the order of 150-200 V implying excellent operational characteristics for this mixture.

Conclusions and acknowledgments

The final design for the IFR detector has been completed. Construction of the full detector is in progress. Installation will begin in June 97, and the scheduled commissioning starts in November.

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