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BaBar - THE DETECTOR FOR THE PEP II B FACTORY AT SLAC

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ABSTRACT

BaBar refers to the detector that is being designed for the PEP II B-Factory at SLAC to perform a comprehensive study of *CP* violation in *B* meson decays. The design requirements and the principal detector components are briefly described. A summary of the expected physics performance is presented.

1. Introduction

CP violation remains one of the most compelling issues in particle physics. In the Standard Model (SM), the origin of *CP* violation is the Cabibbo-Kobayashi-Maskawa (CKM) Matrix which describes the coupling of quarks to the weak charged current. The SM predicts the existence of large, calculable asymmetries in the decays of B^0 mesons to *CP* eigenstates. The observation and systematic study of such asymmetries in *B* meson decays is the primary motivation for the construction of the *BaBar* detector[1] that is being designed for PEP II,[2] an energy-asymmetric e^+e^-storage ring that will operate at the $\Upsilon(4S)$ resonance. The $\Upsilon(4S)$ decays exclusively to $B^0\overline{B}^0$ or B^+B^-.

PEP II promises to provide luminosities of initially $3\times10^{33}cm^{-2}s^{-1}$ and ultimately $10^{34}cm^{-2}s^{-1}$ with energy asymmetric beams of 9 GeV electrons and 3.1 GeV positrons. The c.m. boost of $\beta\gamma = 0.546$ is sufficient to enable the reconstruction of the two B^0 decay vertices and the determination of the *CP* - violating parameters of the CKM matrix from the measurement of the decay time dependent rate asymmetries.

While the primary physics goal of the *BaBar* experiment is the systematic study of *CP* asymmetries, important secondary goals are the exploration of a variety of rare decays beauty and charm mesons, as well as the τ lepton, two-photon interactions, and Υ spectroscopy. The design of the detector is optimized for the *CP* studies, but also serves well for these other physics goals that become will accessible with the high luminosity of PEP II.

Studies carried out over the last several years at SLAC[7,8] and for other *B*-Factory proposals[3–6] have led to a consensus on the basic performance requirements for the detector. The critical objectives required to achieve the desired sensitivity for *CP* measurements are:

- to observe the decays of *B* mesons to a wide range of exclusive final states with high efficiency, thus requiring a detector with large and uniform acceptance;
- to observe the rare *B* decays with low background, requiring a detector of high resolution and efficiency for both charged and neutral particles over a wide range of particle momenta;

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- to tag the flavor of the second B meson in the event via the charge of a secondary lepton or kaon, requiring excellent lepton and hadron identification over a wide range of momenta; and
- to measure the relative decay times of the two B mesons so as extract the time dependent asymmetry, requiring a precision vertex detector.

2. The Detector Overview

The overall layout of the *BaBar* detector is shown in Figure 1. The detector is composed of a silicon vertex detector, a drift chamber, a particle identification system, a CsI electromagnetic calorimeter, and a magnet with an instrumented flux return. The superconducting solenoid provides a field of 1.5 T, and the magnet flux return is instrumented for muon identification and coarse hadron calorimetry. All of these detectors extend to forward angles of 300 mr and backward angles of $\sim$400 mr. The vertex detector is mounted inside a $\sim$40 cm diameter support tube, along with the first accelerator dipole and quadrupole magnets. This support tube introduces $\sim$0.5% X_0 of extra material into the fiducial volume of the detector, but it is deemed crucial for the precise and reproducible alignment of the close-in machine components.

The detector commissioning is scheduled to commence in parallel to the commissioning of PEP II in the fall of 1998. This represents an extremely tight time scale for the design, engineering, construction, and assembly of an apparatus of appreciable size and complexity.

2.1. Silicon Vertex Detector

A precision vertex detector is critical to the *BaBar* detector, since it is necessary to measure the difference in the decay time of the two B^0 mesons. It must have good spatial resolution, low multiple scattering, small segmentation, and reasonably good resistance to radiation damage. Since the vertex detector is the only tracking device inside a radius of about 22 cm, it must not only measure precisely the track position and angles near the beam, but also provide for good pattern recognition for very low momentum tracks.

A five layer system made of double-sided silicon microstrip detectors is foreseen. The inner three layers are in a barrel geometry with detectors parallel to the beam pipe. The outer two layers combine barrel detectors in the central section with wedge detectors in the forward and backward sections. The strip pitch increases with radius from $50\mu m$ in the inner to $200\mu m$ in the outer layers. Thin kapton cables will be designed to transfer the signals to the electronics which - together with the cooling - is placed outside the active volume. The signals are read into a pipeline with 100 ns time stamping. The total power of the amplifier/shaper/comparator circuit is to be kept to less than 100 mW. The total amount of material is estimated to be less than 3.5% (8%) X_0 in the center (at the ends). The possibility of increasing charged particle coverage down to 200 mr by replacing the forward section with a small TPC is also being considered.

2.2. Main Tracking Chamber

The main drift chamber is designed primarily to provide excellent momentum resolution and pattern recognition for charged particles. It also improves the angular measurement, measures dE/dx, and supplies information for the charged track trigger.

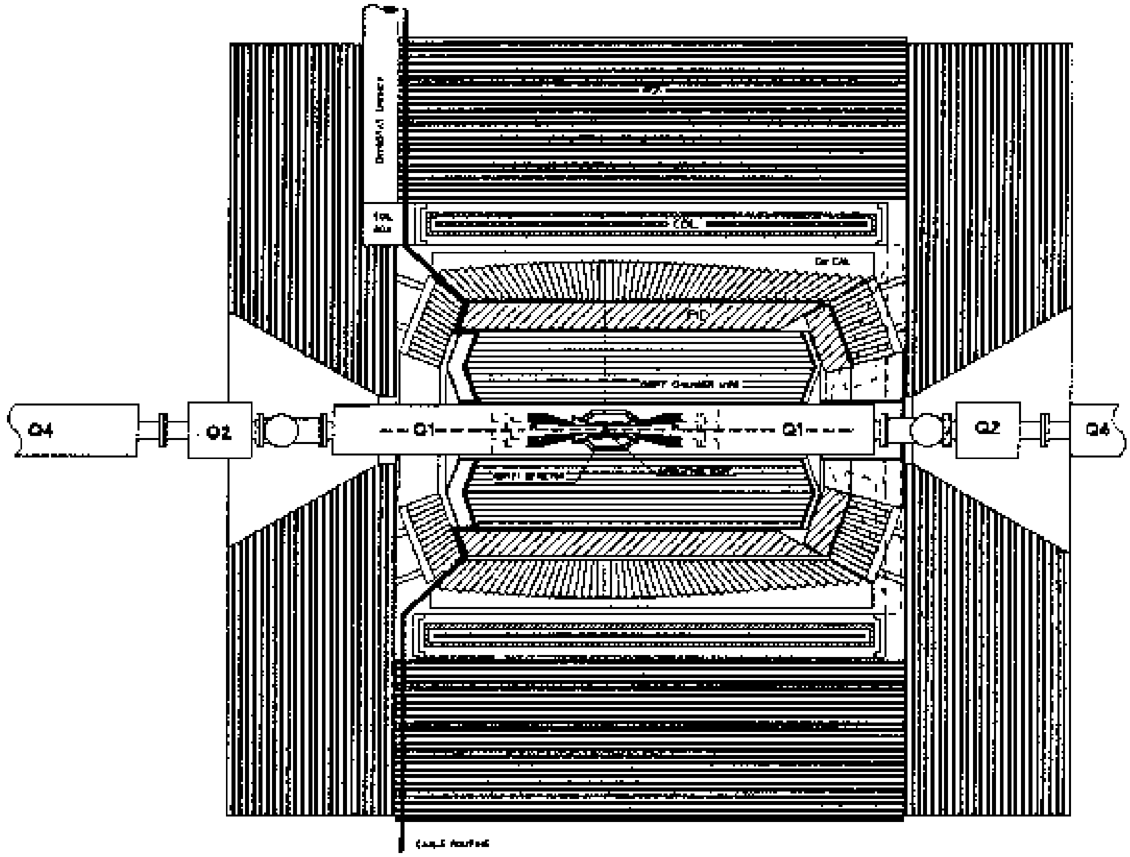

Fig. 1. Cross-sectional view of the BaBar detector, showing (from the beamline outward) the silicon vertex detector, central tracking chamber, particle identification (PID) system, CsI calorimeter, superconducting coil, and instrumented flux return (IFR). The space allowed for the PID system can accommodate any of the three possible options: an aerogel threshold counter system, or one of two ring imaging Cherenkov counters, DIRC or RICH. The overall length is 6.7 m, the diameter is 6.4 m, the drift chamber is displaced by 0.5 m in the direction of the high-energy beam.

The drift chamber extends from 22.5 cm to 80 cm in radius. Approximately 40 layers of small drift cells of either hexagonal or quadratic design are under study. Since the momenta of particles from B decay are very low, the momentum and angle measurements are dominated by multiple scattering. By using a helium-based gas mixture and low-mass wires a transverse momentum resolution of $d\sigma_{pt}/p_t = 0.003 \oplus 0.003 p_t$ should be obtainable in a solenoidal magnetic field of 1.5 T. The readout electronics will be placed on the backward end of the chamber, thus reducing the amount of material in front of the particle identification and calorimeter systems in the forward region. Composite materials are under consideration for the conical endplates and the cylindrical outer enclosure.

2.3. Identification of Hadrons

The most important task for the PID system is the identification of charged kaons for flavor tagging. Another task is the separation of pions from kaons in decays such as $B^0 \to \rho^+\pi^-$ and $K^{*+}\pi^-$. The kaon momenta extend from a 300 MeV/c to more than 4 GeV/c. The traditional tools for identifying hadrons in experiments at e^+e^- colliders are dE/dx and time of flight (TOF) measurements, which work well up to momenta of about 1.5 GeV/c. In the backward endcap region, the kaon momenta are lower and dE/dx measurements in the main tracking chamber are adequate. In the barrel and forward region, higher momenta require a dedicated particle identification device based on Cherenkov radiation.

Three promising options are presently under study that can all fit into the detector layout with only small variations. These options are:

- An Aerogel Threshold Cherenkov Counter (ATC) composed of about 2000 cells arranged in projective geometry: Each cell consists of two longitudinal segments, a 10 cm (4 cm) deep front (back) section with n=1.008 (n=1.06) resulting in a kaon threshold of 3.9 GeV/c (1.42 GeV/c). Each section is viewed by a photo-multiplier or an avalanche hybrid photo-diode that is sensitive to single photo-electrons. The proof of principal, *i.e.* a reliable yield of 10 or more photons inside a 1.5 T magnetic field, is expected in the next few weeks.

- A Ring Imaging Cherenkov Counter (RICH) covering both the barrel and the forward endcap region: Cherenkov light generated in a 1 cm thick liquid radiator with a 3 mm quartz window is detected by a CsI photo-cathode deposited on a pixel array. The proof of principal. *i.e.* the detection of more than 10 photons per particle remains difficult due to the loss of photons in the quartz window and rather low quantum efficiency of the cathodes. The operational experience with ring imaging Cherenkovs at DELPHI and SLD is also not fully convincing.

- DIRC, a novel concept for the generation and transmission of Cherenkov light: Cherenkov light is generated in 12 mm thick, 25 mm wide, 3-5 m long quartz radiators and transmitted by total reflection to the exterior of the flux return. The Cherenkov rings are detected by a densely packed array of small photo-multipliers placed at a distance of more than 100 cm from the end of the radiator. The stand-off region is to be filled with water. A proof of principal exists in terms of the number of detected photons and the angular resolution. There is a significant impact on the detector access and endcap support due to the long cylindrical array of quartz bars and the sizable stand-off volume.

For all three options there remain severe concerns about their performance in the storage ring environment, their detailed design and technical feasibility, and the amount of material in front of the calorimeter. All these issues will have to be assessed in terms of their impact on the physics capability of the detector as a whole, as well as a PID in particular. It may be necessary (though clearly less desirable) to chose different solutions in the forward endcap and barrel region.

2.4. Electromagnetic Calorimeter

The identification of leptons (electrons and muons) is of particular importance for the tagging of B decays, while photons from π^0 decays (in the energy range 20 MeV to 3 GeV) play a very significant role in the reconstruction of exclusive B and D meson decays. Thus excellent photon detection efficiency as well as energy and angular resolution are crucial. Furthermore, great care has to be taken to keep the amount of material in front of the calorimeter to a minimum.

A fully projective CsI(Tl) crystal calorimeter provides the required energy and angular resolution and retains high detection efficiency at the lowest relevant photon energies. The expected energy resolution is 2.5% at 100 MeV, and 1.5% at 1 GeV. The crystal length varies from 18 X_0 in the forward endcap to 15 X_0 in the backward endcap; the transverse crystal dimensions are typically 4.5 cm at the front face. The total calorimeter volume remains an important consideration in choosing the detector geometry; the design foresees 10,000 crystals with a volume of $\sim 8m^3$. Each crystals is to be read-out by two large PIN diodes that view a fluorescent flux concentrator that is mounted on the back surface. Efforts are underway to reduce the noise per channel to a level of 50 keV.

2.5. Muon and Neutral Hadron Detector

Muons are identified by their energy deposition in the calorimeter and their range and scattering angle in the Instrumented Flux Return (IFR). The IFR also serves as a detector of neutral hadrons (particularly K_L^0). To achieve sensitivity down to momenta of 0.5 GeV/c the flux return (60 cm of steel in total) is divided into approximately 24 layers, with Resistive Plate Chambers or Plastic Streamer Tubes as the active elements interspersed with 2.5 cm thick steel plates. Preliminary studies indicate that efficiencies for more than 90% can be achieved for muon momenta above 500 GeV/c. K_L^0 interactions can be detected with 70% efficiency above 2 GeV/c momentum.

2.6. Data Acquisition and Computing

The expected high data rates require a data acquisition system that is considerably more powerful than any currently used in e^+e^- experiments. The goal is to operate with negligible deadtime even if the backgrounds are much higher than present calculations predict. The bunch crossing period of 4.2 ns is so short that the interactions are effectively continuous. The solution is to pipeline the information and to trigger asynchronously. The design uses commercial processors and data links for pattern recognition and data flow wherever practical. The offline computing loads are also expected to be larger than in previous experiments at e^+e^- colliders, but are within the capacity of existing technology.

3. Detector Performance and Sensitivity to *CP* Asymmetries

A measure of the estimated sensitivity of the experiment is the error in the measurement of the *CP* asymmetries $\sin 2\beta$ and $\sin 2\alpha$. At present, estimates are based on a parametric Monte Carlo simulation of the *BaBar* detector. For a nominal year of operation with an integrated luminosity of 30 fb^{-1} accumulated on the $\Upsilon(4S)$ resonance, the results are summarized in Table 1. Also listed are the efficiencies and the expected numbers of tagged events for some of the typical *CP* modes.

A crucial parameter in obtaining this level of sensitivity is the effective tagging efficiency, $\epsilon_{eff} = \epsilon_{tag}(1-2w)^2$. Here ϵ_{tag} refers to the fraction of reconstructed B decays for which the flavor of the second B is tagged, and w is the fraction of those events which are incorrectly tagged. The effective tagging efficiency is estimated to be about 11% from the observation of leptons from semileptonic B decays, while the detection of charged kaons from the charm decay of the second B contributes an additional 16%.

Combining the modes shown in Table 1, the errors on the *CP* asymmetry parameters are $\delta[\sin 2\beta] = 0.09$ and $\delta[\sin 2\alpha] = 0.11$. It should be noted here, that the stated errors are statistical only. Potential penguin contributions are neglected, and for $J/\psi K^{0*}$ it is assumed that a single *CP* eigenstate dominates the decay.

These preliminary estimates indicate that the *BaBar* experiment promises a comprehensive and significant measurements of *CP* violation in the B system. It is expected

Mode	Events Reconstructed	Background	$\delta[\sin 2\phi]$
$J/\psi K_S^0$	367	0	0.13
$J/\psi K^{*0}$	150	0	0.20
D^+D^-	158	0	0.20
$D^{*+}D^{*-}$	272	30	0.16
$\pi^+\pi^-$	106	9	0.24
$\rho^\pm\pi^\mp$	567	126	0.12

Table 1. *CP* reach of the BaBar detector for some major decay modes in a data sample of 30 fb^{-1} accumulated at the $\Upsilon(4S)$ resonance.

that this experiment will operate for many years and thus will allow increasingly precise tests of the Standard Model prediction for *CP* violation.

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