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# THE PEP-II B-FACTORY AND THE BABAR DETECTOR

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**Abstract.** I summarize the physics goals of the BABAR project. I give a brief status report on the PEP-II B-Factory progress. I then describe the requirements and chosen design for each of the BABAR detection systems. In conclusion, I give projections for the physics performance expected from the BABAR experiment.

## THE BABAR PHYSICS PROGRAM

The primary physics goal of the BABAR experiment - the PEP-II B-Factory and the BABAR Detector - is the detailed study (1) of the « natural » explanation for CP violation as provided, within the Standard Model, by the complex phase in the CKM matrix.

The experimental signature is the existence of large, predictable asymmetries in the decays of the $B^0$ meson to CP eigenstates. The particular channels in which it is hoped that BABAR will be able to measure such asymmetries include the following :

- for $\sin 2\beta$, $B^0 \to J/\Psi\ K^0_{S}$, $B^0 \to J/\Psi\ K^0_{L}$, $B^0 \to J/\Psi\ K^{*0}$,

  $B^0 \to D^+ D^-$, $B^0 \to D^{*+} D^{*-}$, etc ;

- for $\sin 2\alpha$, $B^0 \to \pi^+ \pi^-$, $B^0 \to \pi^+ \pi^- \pi^0$, $B^0 \to a_1 \pi$, etc,

where $\alpha$ and $\beta$ are two angles of the unitarity triangle (Figure 1).

However, if the CP asymmetries in question are expected to be quite large, the branching ratios to reconstructible final states are very small ( $\sim 10^{-5}$ for $J/\Psi\ K^0_S$ and for $\pi^+ \pi^-$). The consequence is that in excess of $10^7$ $B^0 \overline{B}^0$ pairs will have to be produced in order to measure the asymmetries with errors at the 10% level or better.

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To achieve these measurements, in addition to a need for a high luminosity, three ingredients will play a vital role. First, the full reconstruction of exclusive final states is needed (this leads to strong requirements on the charged particle momentum resolution, on the photon detection efficiency and energy and position resolution, and on the capabilities of particle identification). Second, the flavor (beauty or anti-beauty) of the decaying particle needs to be tagged (with electrons and muons, and with charged kaons). Finally, the proper time of the $B^0$ decay with respect to its production needs to be measured (vertex reconstruction, also to unambiguously ascertain the time order of the $B^0$, $\overline{B}^0$decay).

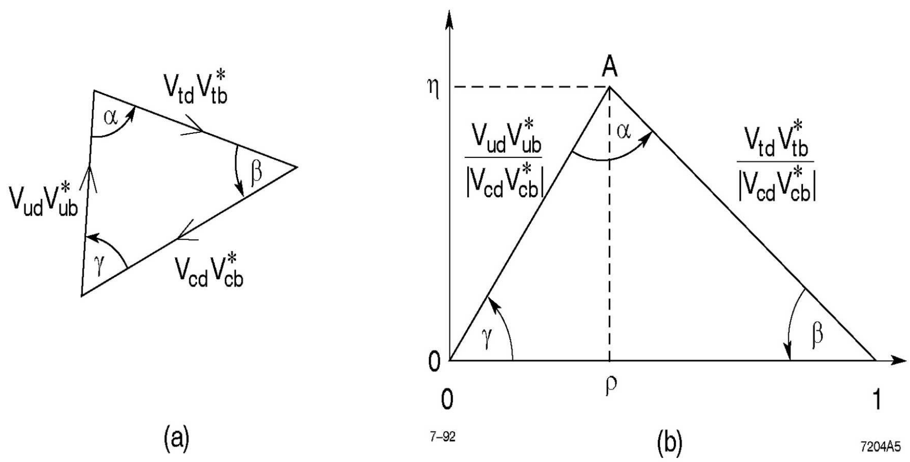


**FIGURE 1.** The Unitarity Triangle (a), rescaled (b) by choosing a phase convention such that $(V_{cd}V^*_{cb})$ is real and dividing the lengths of all sides by $|V_{cd}V^*_{cb}|$.

The PEP-II B-Factory (2) and the BABAR Detector (3) are designed and optimized to achieve the needs and goals specified above.

In addition to CP asymmetries, BABAR will be able to make also sensitive measurements of CKM elements in B decays, to search for rare B decays and to study the physics of charm and of the tau lepton, and two-photon physics.

## THE PEP-II B-FACTORY

The main challenge of an $e^+e^-$ B-factory like PEP-II is to reach the unprecedented high luminosity of $3\text{x}10^{33}$ cm$^{-2}$ s$^{-1}$, an order of magnitude or higher than any existing colliders. The luminosity for optimized $e^+e^-$ colliders has the remarkably simple form

$$L(cm^{-2}s^{-1}) \propto \frac{\Delta\nu . E(GeV) . I(Amp)}{\beta^*(cm)}.$$

Since the energy, E, is effectively fixed by the need to produce the Υ(4S) and the tune shift limit, Δν, is more or less also given, the parameters that can be pushed to achieve the maximum luminosity are the total current, I, and the beta function or focussing strength, $\beta^*$, at the interaction point.

The PEP-II B-Factory is being constructed by a collaboration of SLAC, LBL and LLNL (2) on the SLAC site. The machine is asymmetric with energies of 3.1 GeV for the positron beam (Low Energy Ring – LER) and of 9.0 GeV for the electron beam (High Energy Ring – HER). It reuses the tunnel and the magnets of the old PEP machine for the HER. The LER is new and is put in place over the HER as shown in Figure 2. Beams are stored in the two separated rings allowing PEP-II to have the very large number of 1658 bunches (about 4 ns spacing between bunches). The collisions are head-on, requiring strong dipoles to be placed very close to the interaction point. This scheme avoids the potential instabilities due to a crossing angle but, in turn, might lead to potentially high backgrounds coming from synchrotron radiation and beam debris swept into the detector. It requests also a not-too-small spacing (1.2 m) between bunches to avoid parasitic collisions. Both the HER and the LER use room temperature RF, with copper cavities and waveguides to remove the higher order modes that would otherwise coupled the bunches.

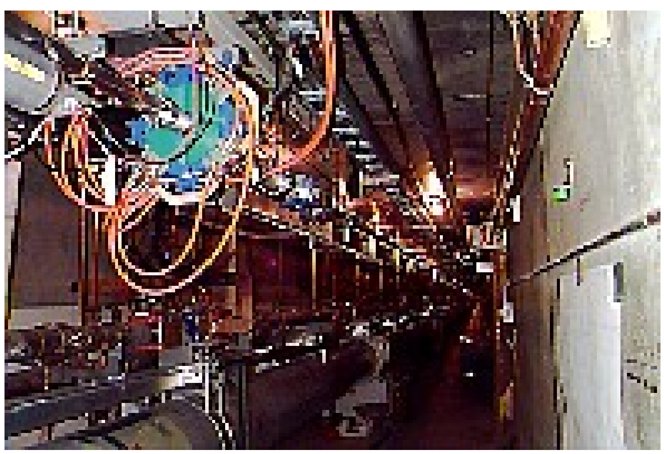

**FIGURE 2.** PEP-II B-Factory with the LER on top of the HER.

With a center of mass energy of 10.58 GeV, corresponding to a moving center of mass of $\beta\gamma = 0.56$, PEP-II provides the needed feature of asymmetric collisions to measure the time dependent CP violating asymmetries. It corresponds to an average separation of $\beta\gamma c\tau = 250$ μm between the two B vertices, which is crucial

**TABLE 1.** Main parameters of the PEP-II collider and best commissioning results (up to October 1st, 1998)

| **Machine** | | **HER** | | **LER** | |
|---|---|---|---|---|---|
| **Parameter** | **Units** | **Design** | **July 31 '98** | **Design** | **Aug. 1 '98** |
| Energy | GeV | 9.0 | 9.0 | 3.1 | 3.1 |
| Single Bunch Current | mA | 0.6 | 12.0 | 1.3 | 5.0 |
| Number of Bunches | | 1658 | 1658 | 1658 | 1658 |
| Total Beam Current | A | 0.995 | 0.75 | 2.14 | 0.053 |
| Beam Lifetime | hours | 4 | 12 @ 50mA<br>2.5 @ 725 mA | 4 | 3min@10mA |

for studying the cleanest and most promising CP violating modes. Parameters of the PEP-II B-Factory together with some achieved results are shown in Table 1. The PEP-II B-Factory has currently entered its commissioning phase. Starting in February 1999, BABAR will move onto the beam line and physics collisions will begin early May 1999.

## THE BABAR DETECTOR

In order to achieve its physics program (1), the BABAR detector needs :

- The maximum possible acceptance in the center-of-mass system. Although the forward boost of the decay products in the laboratory frame is rather a small one, optimizing the detector acceptance leads to an asymmetric detector.

- To accommodate machine components close to the interaction region (high luminosity requirement).

- Excellent vertex resolution (in particular its z-component) : the decay time difference ($t_{CP}$ - $t_{tag}$) will be measured via the difference in the z-component of decay positions of the B mesons (since they travel almost parallel to the z-axis). Also the best possible vertex resolution is needed in order to discriminate between beauty, charm and light quark vertices.

- Good momentum resolution for kinematic reconstruction and tracking over the range ~ 60 MeV/c < $p_t$ < ~ 4 GeV/c.

- To discriminate between e, μ, π, K and p over a wide kinematic range. The tagging of the flavor of B-meson decays can be done with high efficiency and purity only if electrons, muons and kaons can be well identified. In addition, $\pi$–K discrimination up to about 4 GeV/c is essential in order to discriminate between decay channels like $B^0 \to \pi^+ \pi^-$ and $B^0 \to K^{\pm} \pi^{\mp}$, $B^0 \to \rho^+ \pi^-$ and $B^0 \to K \rho$ and $B^0 \to K^* \pi$.

- To detect $\gamma$'s and $\pi^0$'s over the wide energy range ~ 20 MeV < E < ~ 5 GeV.

- To have neutral hadron identification functionality ($B^0 \to J/\Psi\ K^0_L$).

- To be able to record data at a 100 Hz trigger rate (up to about 2 kHz at the first level trigger).

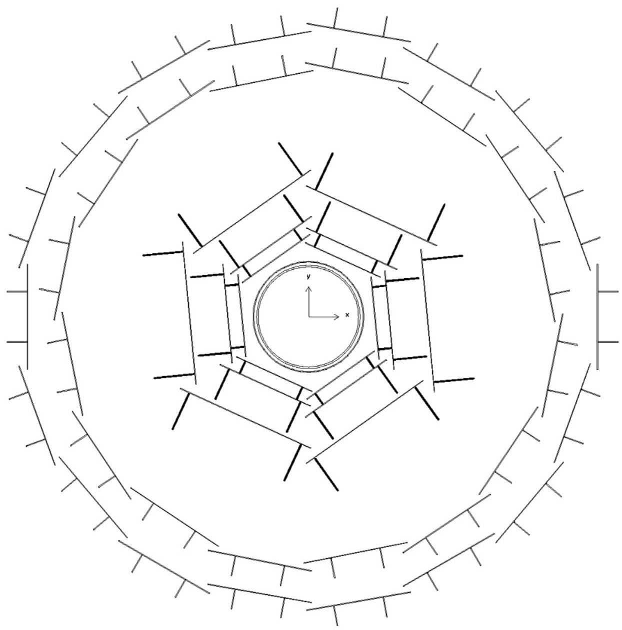

**FIGURE 3.** Layout of the BABAR silicon vertex tracker . Cross-sectional view in the plane orthogonal to the beam axis.

To provide all the above features, the major subsystems (3) of the BABAR detector are :

- A silicon vertex detector (the SVT) whom the main task is to reconstruct the decay vertices of the two primary B mesons in order to determine the time between the two decays. This determination will allow the measurement of the time dependent asymmetries. The SVT, with five concentric cylindrical layers of double-sided silicon detectors with $90^0$ stereo (see Figure 3), provides also the complete tracking information for charged particles with $p_t \leq 100$ MeV/c (which cannot reach the drift chamber). The readout pitch in the three inner layers is 50 μm in $\phi$, 100 μm in z with one floating strip. The readout electronics use a custom rad-hard IC and time-over-threshold analog readout for pulse height measurements.

- A drift chamber (the DCH) provides up to 40 measurements of space coordinate per track, ensuring high reconstruction efficiency for tracks with $p^t >$ 100 MeV/c.

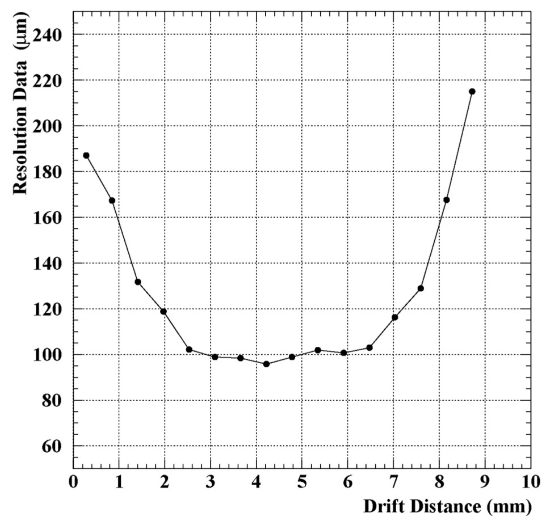


**FIGURE 4.** Spatial resolution obtained in the BABAR full-length prototype drift chamber with sense wire voltage at 1960 V.

The 7104 hexagonal drift cells (typical dimensions of 1.2x1.8 $cm^2$) are arranged in superlayers of 4 layers each (axial and stereo superlayers alternate). The chosen gas mixture, helium-isobutane (80% :20%), together with the 1.5 T magnetic field of the superconducting solenoid, provides good spatial (see Figure 4) and dE/dx resolutions (6.8% predicted resolution). Finally, the DCH provides the prompt charged trigger signals to the BABAR Level 1 Trigger system at a sampling frequency of 3.75 MHz.

- A particle identification system (the DIRC – acronym for Detection of Internally Reflected Cherenkov light) will provide excellent kaon identification up to about 4.0 GeV/c in order, in particular, to distinguish between the two-body decay modes $B^0 \rightarrow \pi^+\pi^-$ and $B^0 \rightarrow K^+ \pi^-$.

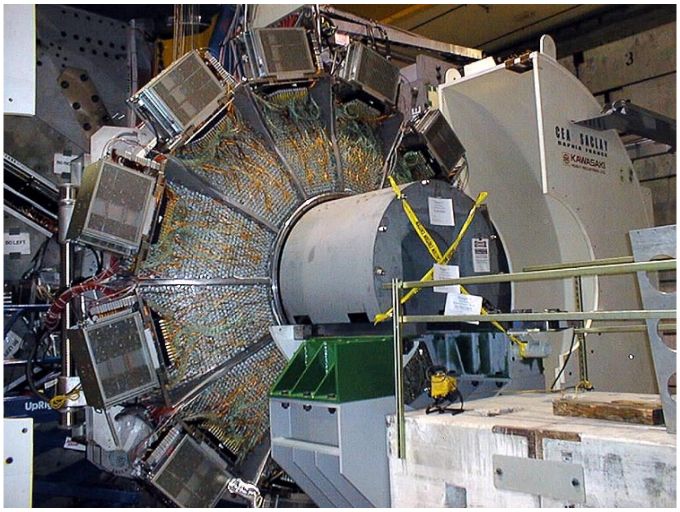

**FIGURE 5.** View of the DIRC Standoff Box – the SOB, filled with water, and of the 10,752 PMTs that cover the detection area (also the front-end electronics crates mounted on the SOB can be seen, one crate per SOB's sector to read 896 PMTs).

The DIRC concept relies on the detection of Cherenkov photons trapped in the radiator (144 long, straight bars of synthetic quartz with rectangular section, arranged in a 12-sided polygonal barrel). The Cherenkov light, through successive total internal reflections, is brought outside the BABAR tracking and magnetic volumes and is detected by a close-packed array of linear focused 2.82 cm diameter photomultiplier tubes (see Figure 5). The DIRC technique has the advantage to occupy only a small (8 cm) radial space while keeping only 14% of an $X_0$ at normal incidence. The photoelectron yield is high in the DIRC, with from 20 to 50 photoelectrons at various angles. The $\pi/K$ separation is always $>3\sigma$ within the kinematic limits for particles from B decays.

- An electromagnetic calorimeter (the EMC) based on quasi-projective CsI(Tl) crystals. It consists of a cylindrical barrel (5760 crystals) and a forward conic endcap (820 crystals) as shown in Figure 6. The EMC detects $\pi^0$'s with very high efficiency and low background for CP decays such as $B^0 \rightarrow J/\Psi K^0_S$, $K^0_S \rightarrow \pi^0\pi^0$, etc. It identifies electrons down to 500 MeV/c and supplements the information for muon and $K^0_L$ identification. Finally the EMC provides information for the neutral trigger. For photons at a polar angle of $90^0$, the energy resolution is

$$\sigma_E/E = 1\% / (E(\mathrm{GeV}))^{1/4} \oplus 1.2\%$$

and the angular resolution is

$$\sigma_{\theta,\phi} = 3\ \mathrm{mr} / (E(\mathrm{GeV}))^{1/2} \oplus 2\ \mathrm{mr}.$$

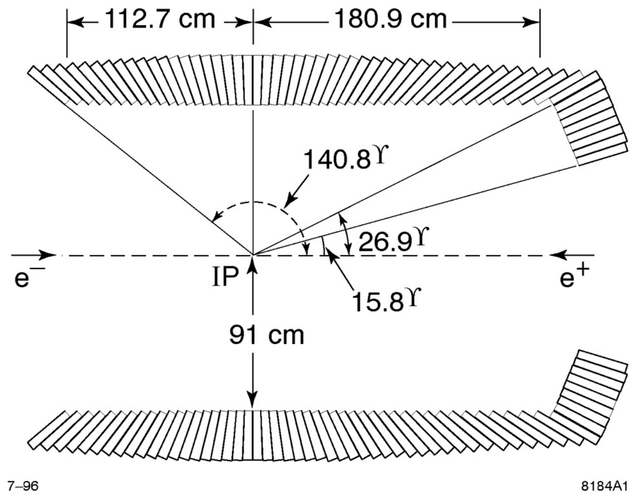


**FIGURE 6.** Side view of the BABAR electromagnetic calorimeter layout**.**

- A muon and neutral hadron identification system (The IFR – acronym for Instrumented Flux Return) uses the large iron structure needed as a magnet yoke. It consists of a central part (Figure 7) and two end caps which complete the solid angle coverage down to 300 mr in the forward direction and 400 mr in the backward direction.

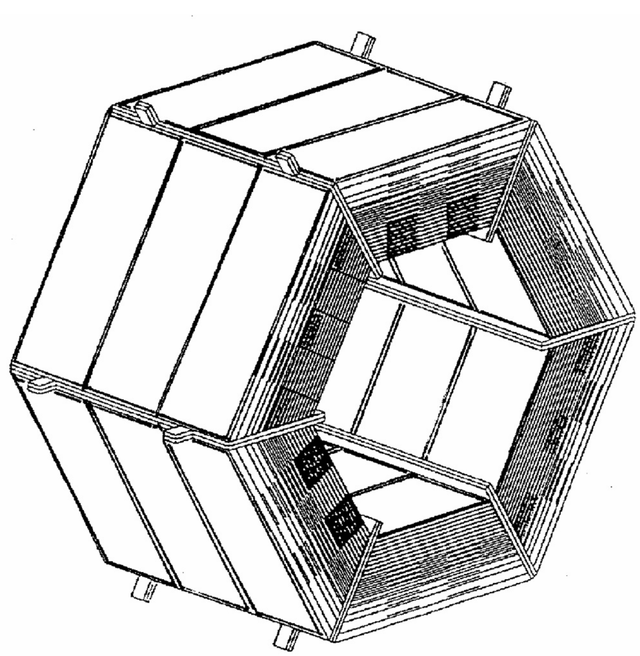

**FIGURE 7.** Layout of the BABAR IFR barrel.

A feature of the IFR system is the graded segmentation of the iron, which varies from 2 to 10 cm, increasing with the radial distance from the interaction region. The BABAR IFR uses plastic resistive plate counters filled with a gas mixture based on comparable quantities of argon and freon, plus a small amount (a few %) of isobutane. The primary goals of the IFR are to reduce the lower momentum limit for detecting muons to about 0.6 GeV/c and to detect $B^0 \rightarrow J/\Psi K^0_L$.

## CONCLUSIONS

The PEP-II B-Factory has achieved its first collisions in July 1998. From October 1998 until mid-February 1999, the commissioning of the full machine, including the final interaction region, will continue with special emphasis on the understanding of machine related backgrounds and of luminosity optimisation. The BABAR Detector (see Figure 8) has completed its installation phase. Until end of January 1999, it will be commissioned with cosmic ray data taking. Starting early February 1999, BABAR will be moved on the PEP-II beamline and the vertex detector will be installed. The first beam data are expected to be taken early May 1999.

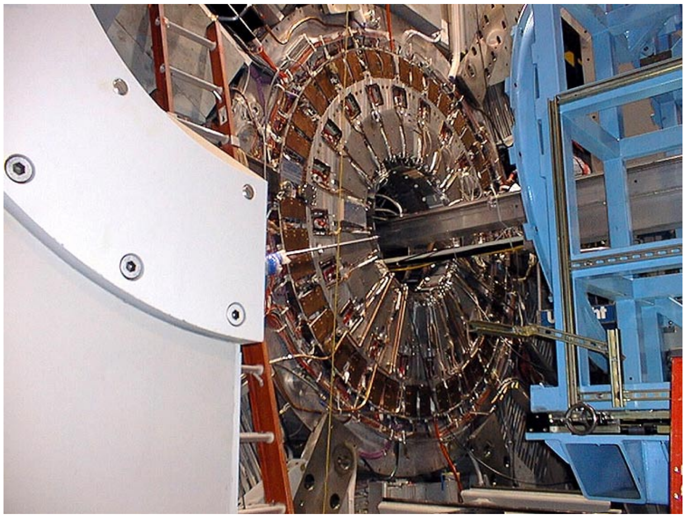

**FIGURE 8.** View of the forward part of the BABAR detector.

As an illustration of the BABAR physics sensitivity, the resolution on the β angle (see Figure 1) is given in Table 2 for some CP states. It is expected (1) that the

**TABLE 2.** Error in the measurement of sin2β (assuming sin2β = 0.7) for an integrated luminosity of 30 $fb^{-1}$

| Mode | Br. ($10^{-4}$) | Rec. eff. | $N_B/N_S$ | Error |
|---|---|---|---|---|
| $J/\Psi\ (l^+l^-)\ K^0_S(\pi^+\pi^-)$ | 4.25 | 0.60 | 0.06 | 0.12 |
| $J/\Psi\ (l^+l^-)\ K^0_S(\pi^0\pi^0)$ | 4.25 | 0.21 | 0.06 | 0.30 |
| $J/\Psi\ (l^+l^-)\ K^0_L$ | 4.25 | 0.41 | 0.59 | 0.15 |
| $J/\Psi\ (l^+l^-)\ K^{*0}(\pi^+\pi^-\pi^0)$ | 13.2 | 0.09 | 0.18 | 0.50 |
| $D^+\ D^-$ (6D modes) | 4.5 | 0.24 | 2.80 | 0.48 |
| $D^{*+}\ D^{*-}$ (4D modes) | 9.7 | 0.05 | 0.23 | 0.44 |

combined sensitivity for sin2β, for the same integrated luminosity and for all major CP modes, will likely be on the order of 0.08.

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