PEP-II: The SLAC-based Asymmetric B Factory*

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Abstract

Construction has started for an asymmetric-energy B meson factory in the PEP tunnel at SLAC. We describe the status of the project including the physics objectives, the PEP-II accelerator complex, and the *BaBar* detector.

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1 Physics Motivation

The main goal of the asymmetric B Factory is a comprehensive study of the phenomenon of CP violation, using the rich spectrum of B meson decays. In addition, there will be an extensive program of heavy-flavor physics (b, c, and τ) and two-photon physics. (See Ref. [1, 2] and references quoted therein.)

In the Standard Model (SM), the source of CP violation is a complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix which describes the mixing of quarks. However, we have no conclusive evidence that this is the full explanation of the CP asymmetries observed sofar only in the kaon system. If the imaginary phase in the CKM matrix is the origin of this phenomenon, one expects rather large CP-violating asymmetries in B meson decays.

The unitarity of the CKM matrix leads to a relation

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0\,. \tag{1}$$

This can be represented in the complex plane by the so-called unitarity triangle, shown in Fig. 1. The SM predictions for CP asymmetries in neutral B meson decays into CP eigenstates are fully determined by the values of the three angles of the unitarity triangle, α, β, and γ. Thus, the CP-violating asymmetries depend only on weak CKM phases without hadronic uncertainties, allowing for a conclusive test of the SM scheme! The goal is to measure as many sides and angles of the triangle as possible and get an overconstraint set of measurements.

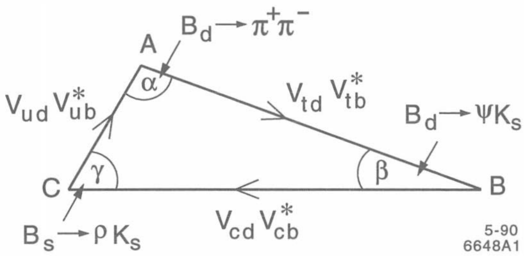

Figure 1: The unitarity triangle representing the unitarity constraint between the first and last columns of the CKM matrix for three families of quarks. Also shown are the three unitarity angles, α, β and γ, and three examples of B decay modes to measure them.

In the case of neutral B meson decays to CP eigenstates, f_{CP}, CP violation arises from the interference between the amplitude for the direct decay, $B^0 \rightarrow f_{CP}$, and the amplitude for the decay after particle-antiparticle mixing, $B^0 \rightarrow \bar{B}^0 \rightarrow f_{CP}$. Thus, B^0-$\bar{B}^0$ mixing is essential here! Because of the complex nature of some of the CKM matrix elements involved, the interference term violates CP. While the predicted CP asymmetries are large (of the order of 10%), CP-eigenstate decay branching fractions are small (typically $10^{-4} - 10^{-5}$); hence one needs a machine that produces in excess of 10^7 neutral B mesons per year.

One approach to achieve this is a high-luminosity e^+e^- collider operating on the $\Upsilon(4S)$ resonance, *i.e.*, at a center-of-mass (CM) energy of 10.58 GeV. The $\Upsilon(4S)$ production cross section is about 1 nb; hence the luminosity requirement for the machine is in excess of $3 \times 10^{33}\,\mathrm{cm}^{-1} s^{-1}$ (assuming a "Snowmass year" of $10^7\,s$). The $\Upsilon(4S)$ decays exclusively to pairs of B mesons, approximately 50% $B^0\bar{B}^0$ and 50% B^+B^-, which make up about 30% of all events at this CM energy. The two B mesons are mono-energetic in the CM system since they are not accompanied by other particles; this presents an invaluable kinematic constraint. They are produced in a coherent p-wave state which remains a $B\bar{B}$ state until such time as one of the (anti-)particles decays.

If at time t one of the two B mesons decays into a final state that tags its flavor (lepton tag, kaon tag), then the flavor of the other B in the event is unambiguously determined at this time due to the coherence. This other B will then undergo B^0-$\bar{B}^0$ oscillations until it decays at time t'. One must measure four distinct configurations depending on whether the tagging decay (f_B) or CP eigenstate decay (f_{CP}) occurs first, and whether the tag is a B^0 or $\bar{B}^0$:

$$\begin{array}{llll} n_1: & f_B(t)f_{CP}(t') & n_2: & f_{CP}(t')f_B(t) \\ \bar{n}_1: & f_{\bar{B}}(t)f_{CP}(t') & \bar{n}_2: & f_{CP}(t')f_{\bar{B}}(t) \end{array}$$

CP violation produces a $t' - t$ distribution which is different for n_1 and $\bar{n}_2$ from that of $\bar{n}_1$ and n_2. In particular, it modulates the usual decay exponentials by a sinusoidal oscillation with amplitude $\sin 2\phi$ and frequency $\sin \Delta m \Delta t$[1]; here ϕ is one of the unitarity angles α, β or γ (depending on the nature of f_{CP}), and Δm is the mass difference between the two neutral B meson mass eigenstates. It is imperative to tag the flavor of the decaying B meson, and to study the decays as a function of Δt since the modulation is an odd function of Δt! A measurement integrated over t and t' will not show a CP violating asymmetry, which can be defined as

$$A_{CP}(\Delta t) = \frac{n_1 + \bar{n}_2 - (\bar{n}_1 + n_2)}{n_1 + n_2 + \bar{n}_1 + \bar{n}_2}\,. \tag{2}$$

The ability to measure the decay distributions as a function of Δt allows for a number of important experimental cross checks: CPT requires $n_1 = \bar{n}_2$ and $\bar{n}_1 = n_2$; unitarity requires $n_1 + n_2 = \bar{n}_1 + \bar{n}_2$. Thus one can construct asymmetries which should vanish identically if the systematics of the measurement is under control (and if CPT and unitarity hold). Another important test is to measure A_{CP} in channels where the SM predicts zero asymmetry, like $B \to \phi\pi^0$, $K_S^0 \bar{K}_S^0$

A simple counting experiment, *i.e.*, integrating over Δt, yields

$$A_{CP} = \frac{\chi}{1 + \chi^2} \sin 2\phi\,, \tag{3}$$

[1] This is true if a single weak phase dominates the decay. Methods have been developed to unravel additional contributions from, *e.g.*, Penguin amplitudes.

which exhibits a direct dependence on the angle in the unitarity triangle, diluted though by a factor given by the strength of the B^0-$\bar{B}^0$ mixing, χ. A better way to extract the information is to fit the observed distributions $n_i(\Delta t)$ to the expected functional form:

$$\frac{dn(\overset{(-)}{B} \to \overset{(-)}{f})}{d\Delta t} \propto \exp(-\Gamma\Delta t)[1 \overset{(-)}{+} \sin 2\phi \sin \Delta m \Delta t]\,, \tag{4}$$

where Γ is the average decay width of the two neutral B meson mass eigenstates.

The way to do a time-ordered measurement is to boost the $\Upsilon(4S)$ as to achieve a separation of the B decay vertices which can be measured by a state-of-the-art vertex detector. At PEP-II this is realized by an asymmetric-energy storage ring with electron and positron beam energies of 9 and 3.1 GeV respectively. The resulting boost of the $\Upsilon(4S)$ is $\beta\gamma = 0.56$; the B decay length is $\beta\gamma c\tau \approx 250\,\mu$m, allowing for a measurement of the B vertex separation along the beam axis, Δz. This separation translates into the required difference in decay time, Δt, to a very good approximation.

The time-evolution measurements turn out to be very rich indeed. They are not restricted to CP self-conjugate final states; many more B decay modes are usable as long as the final state is accessible from both B^0 and $\bar{B}^0$. One can distinguish three classes of final states:

- Final states which are CP self-conjugate:
  $B_d \to J/\psi K^0_S(K^0_L)$, $\psi' K^0_S(K^0_L)$, $\chi K^0_S(K^0_L)$, $\eta_c K^0_S(K^0_L)$,
  ρK^0_S, ωK^0_S, ϕK^0_S, $D\bar{D}$, $\pi^+\pi^-$, $\pi^0\pi^0$, $\rho^0\pi^0$, $p\bar{p}$, ...
- Final states which are admixtures of different CP:
  $B_d \to \psi K^*$, $D^*\bar{D}^*$, $\rho\rho$, ...
- Final states with no intrinsic CP:
  $B_d \to D^* D$, $\rho^{\pm}\pi^{\mp}$, $a_1^{\pm}\pi^{\mp}$, ...

These final states yield many measurements of $\sin 2\beta$ and $\sin 2\alpha$. Combined with improved measurements of the sides, *i.e.*, V_{cb} and V_{ub} from exclusive semileptonic B decays, and V_{td} from B^0-$\bar{B}^0$ mixing, this will overconstrain the unitarity triangle in several different ways. The third angle, γ, can be measured in channels like $B_d \to D^0_{CP} K^{*0}$ and $B_s \to \rho K^0_S(K^0_L)$, $\omega K^0_S(K^0_L)$. This will be difficult though because of small branching fractions in the first case, and the need to run on the $\Upsilon(5S)$ resonance in the second case.

The measurement strategy will evolve as the experiment matures. Initially, CP asymmetries from a variety of channels will be combined for maximal sensitivity on the unitarity angles; see Tab. 1 for the estimated error on $\sin 2\phi$ in a number of channels. When more data are accumulated, further tests of the underlying assumptions of the SM become possible, as CP asymmetries in different channels purporting to measure the same unitarity angle are compared. If the measured asymmetries are not consistent, it will be possible to determine experimentally which SM model assumptions are violated and generate leads to physics beyond the SM.

Mode	BF (10^{-4})	Reconst. Fraction	Effcy.	Dilution Factor	Evts.	Bkgd.	$\sigma(\sin 2\phi)$
$J/\psi K^0_S$	3.85	0.124	0.51	0.52	367	0	0.13
$J/\psi K^{*0}$	12.6	0.021	0.38	0.53	150	0	0.20
D^+D^-	6.0	0.067	0.26	0.53	158	17	0.20
$D^{*+}D^{*-}$	15.0	0.105	0.12	0.52	272	30	0.16
$\pi^+\pi^-$	0.2	1.000	0.35	0.54	106	9	0.24
$\rho^\pm\pi^\mp$	0.8	1.000	0.47	0.51	567	127	0.12

Table 1: Summary of the *CP* sensitivity in selected B decay modes for a data sample of $30\,\mathrm{fb}^{-1}$ (one "Snowmass year") collected on the $\Upsilon(4S)$ resonance with the *BaBar* detector. The first set of B decay modes is used to measure $\sin 2\beta$, the second one yields $\sin 2\alpha$.

2 The PEP-II Accelerator

The PEP-II asymmetric B Factory [2] involves the upgrade of the existing PEP machine to a two-ring collider with a high-energy electron beam of 9 GeV colliding head-on with a low-energy positron beam of 3.1 GeV; see Fig. 2 for a schematic layout.

The high-energy ring (HER) is being constructed using the refurbished magnets from the existing PEP ring, together with a new copper vacuum chamber. The low-energy ring (LER) will be constructed from all-new components and placed above the HER. In a single interaction region (IR) the beams are brought into collision and separated magnetically afterwards. Both rings are located in the existing PEP tunnel, avoiding the need for any civil construction and making full use of all existing utilities The tunnel has a hexagonal geometry with a circumference of 2000 m and (six) 100 m long straight sections, which provide ample space for the detector, RF, damping wigglers, and injection. The 486 MHz RF system uses room-temperature copper cavities with added higher-order-mode damping waveguides.

The route to high luminosity in this machine is through high circulating currents, 1.5 A and 2.1 A for the HER and LER, respectively. This requires a powerful injector for fast filling and a vacuum system that can deal with the large synchrotron radiation load. To control single-bunch instabilities, high current is achieved through a large number of bunches, 1658 per ring with a bunch length of 1 cm and a bunch spacing of 1.26 m. The design philosophy has been to adopt single-bunch parameters (*e.g.*, charge, tune-shift, β-function, emittance, *etc.*) very similar to those used routinely in present-day storage rings. The challenge then is to deal with the multi-bunch effects. This requires low-impedance vacuum and RF systems, and a powerful longitudinal and transverse feedback system. The injection system will make use of the high-intensity, low-emittance beams developed for the SLC. The damped beams will be extracted at their correct energy from appropriate points along the Linac and transported down

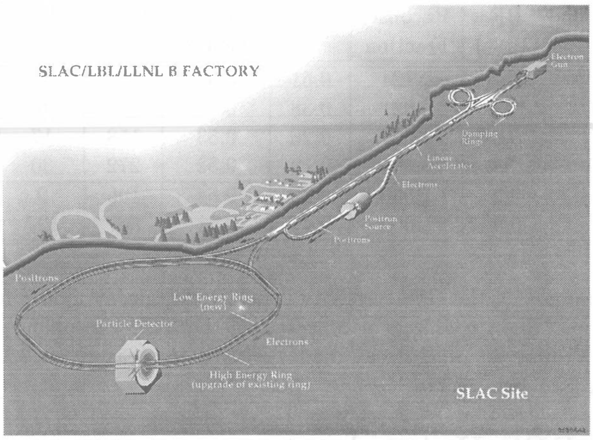

Figure 2: Schematic layout of the PEP-II accelerator complex, showing the existing injector with the Linac, damping rings and positron source, and the PEP-II storage rings with a particle detector in the interaction region.

two parallel-bypass lines inside the Linac housing to connect to existing PEP injection lines. More details on the machine design can be found in Ref. [2].

All major machine components have been prototyped and tested at other accelerators as necessary. The machine design is flexible and includes technical margin. Plausible schemes exist for increasing the luminosity, the asymmetry, and the CM energy if desirable. The project schedule calls for commissioning of the HER in Q2/1997, of the LER in Q1/1998, and of the whole machine in Q3/1998.

3 The *BaBar* Detector

While the *BaBar* detector design [1] is driven by the desire to achieve maximal sensitivity for the *CP* measurements, care has been taken not to compromise the performance for other physics. The *CP* physics requirements are:

- Observe B meson decays to a wide range of exclusive final states with high efficiency and low background;
- Tag the flavor of the other B in the event with high efficiency and accuracy;
- Measure the relative decay time of the two B mesons with high accuracy.

High efficiency for exclusive final state reconstruction requires the largest possible solid angle coverage of the detector. As a result of the boost of the CM system, which folds half of the particles into the region $\cos\theta_{lab} > 0.5$, the detector is asymmetric with increased length in the forward direction. Excellent detection efficiency for charged particles and photons over a wide dynamic range is mandatory. Background rejection is achieved by the best possible B mass resolution; this requires excellent charged particle momentum and photon energy resolution within the active volume of the detector. Hadron- as well as lepton identification over a wide range of momentum is required for both B flavor tagging and B reconstruction. Excellent 3-dimensional vertex resolution is mandatory for time-ordering of the B meson decays and helps in rejecting backgrounds from non-B events.

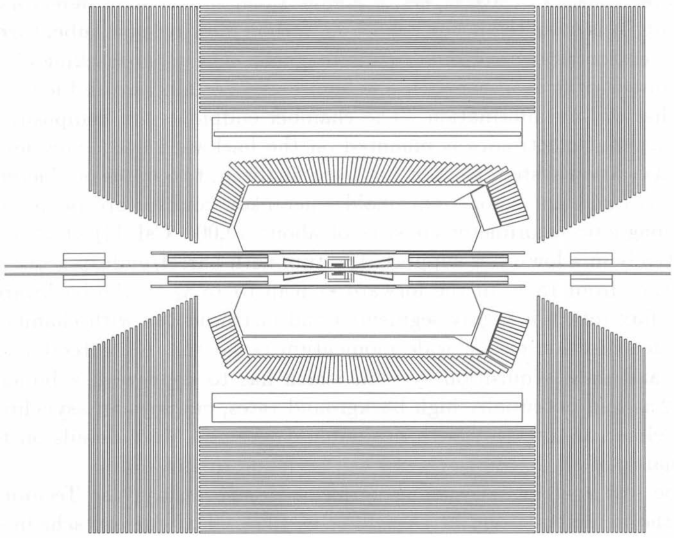

Figure 3: Cross-sectional view of the *BaBar* detector showing from the beam line outward a silicon vertex detector, tracking drift chamber, particle identification system, CsI calorimeter, superconducting coil, and instrumented flux return.

A characteristic $B\bar{B}$ event at the $\Upsilon(4S)$ has an average multiplicity of about 11 charged particles and 11 photons. Because of the boost, the particle density is increased in the forward direction and there is a correlation between particle momentum/energy and polar angle in the laboratory. The average charged particle momentum is less than 1 GeV; thus multiple Coulomb scattering must be held to a minimum in the tracking system. The average photon energy is even lower, about 0.25 GeV; thus material in front of the electromagnetic calorimeter must be minimized. All systems must also be able to deal with CP-relevant two-body B decays that produce particles with momenta up to about 5 GeV in the forward direction. This puts a heavy burden on the particle identification system. To achieve ultimate momentum- and thus B mass resolution requires a high magnetic field. However, care has to be taken not to compromise the detection efficiency for low-momentum particles.

The current *BaBar* detector design is shown in Fig. 3. It consists of a silicon vertex detector, a tracking drift chamber, a particle identification system, a CsI electromagnetic calorimeter, a 1.5 T superconducting coil, and an instrumented flux return. All detectors are designed to operate with good performance down to forward angles of 300 mrad and backward angles of about 400 mrad; coverage in the forward direction is limited by machine elements which start only 22 cm from the interaction point. The vertex detector consists of five layers of double sided silicon strip detectors with 90° stereo readout. It is mounted inside a 0.5% X_0 carbon fiber support tube, together with the first accelerator dipole and quadrupole magnets. The main tracking chamber is a 40 layer small-cell drift chamber with a helium-based gas mixture and low-mass wires; it also supplies dE/dx information. The chamber endplates are composite materials and all the readout electronics is mounted on the backward end. The design of the particle identification system has not yet been finalized; two types of Cherenkov ring-imaging devices and an Aerogel threshold Cherenkov counter are being considered. The electromagnetic calorimeter consists of about 10,000 CsI(Tl) crystals arranged fully projectively in a low-mass support structure with barrel/endcap geometry. Crystal lengths vary from 18 X_0 in the forward endcap to 15 X_0 in the backward endcap. The magnet flux return is highly segmented and instrumented with chambers to provide muon identification over a wide momentum range and K_L^0 detection capability. The trigger and data acquisition system, which has to cope with a bunch crossing period of 4.2 ns and potentially high background rates, employs an asynchronous and digitally pipelined architecture with negligible deadtime. More details on the design and performance of all detector systems can be found in Ref. [1].

Prototype test are currently being performed as necessary; the Technical Design Report for the detector is due in December of 1994. The current schedule calls for completion of the detector in Q3/1998, leaving six months for testing during the commissioning of the accelerator.

References

[1] *Letter of Intent for the Study of CP Violation and Heavy Flavor Physics at PEP-II*, SLAC-443, June 1994.

[2] *PEP-II, An Asymmetric B Factory*, SLAC-418, June 1993.