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The KEK B-Factory and the Belle Detector

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Status of the KEK B-Factory (KEKB) and the detector (BELLE) is reviewed. The aim of the project is to observe CP violation effects in B meson decays and test the KM model predictions for CP violation. The project started in 1994 and the data taking is expected to begin in 1999. The design of both the accelerator and the detector are almost fixed. The goal of the luminosity is $10^{34} \text{cm}^{-2} \text{s}^{-1}$, which produces 10^8 B-meson pairs per year.

1. INTRODUCTION

The KEK B-Factory (KEKB) is a asymmetric, two-ring, e^+e^- collider. It is built in the TRISTAN tunnel and accommodate only one detector (BELLE). The design luminosity is $10^{34} \text{cm}^{-2} \text{sec}^{-1}$. The objective of the Belle experiment is perform definitive tests of the KM model prediction for CP violation in the decays of B mesons. CP violation effects are observed by measuring CP asymmetry in a B^0 decay into CP eigenstate. At asymmetric e^+e^- collider running at $\Upsilon(4S)$ the produced $\Upsilon(4S)$'s are Lorentz boosted in the beam direction. As a result the distance between two vertices of B meson and $\bar{B}$ meson can be measured using a silicon micro vertex detector. This distance measurement along with flavor identification of B and $\bar{B}$ mesons enables us to measure CP asymmetry. Since the B decay branching ratios into CP eigenstates are rather small $O(10^{-4})$ to $O(10^{-5})$, huge number of B mesons, a few times 10^7 to 1 times 10^8 B mesons depending on the values of CP angles, must be produced per year to measure CP asymmetry. Therefore such a experiment requires very high luminosity, a few times $10^{33} \text{cm}^{-2} \text{sec}^{-1}$ to 1 times $10^{34} \text{cm}^{-2} \text{sec}^{-1}$, good vertexing and good particle identification capability.

2. Accelerator

The design of the accelerator is almost fixed and reported in the design report. [1] The 3.5

GeV e^+ ring (LER) and 8 GeV e^- ring (HER) are placed side by side in the TRISTAN tunnel of about 3 km circumference. Fig. 1 shows the layout of the two rings. The two rings cross at two points, but collide at only one point. The beam energies were determined by considering the total integrated luminosity that is required to observe CP violation (see Fig.2) and other physics topics that do not require decay time measurement. The energy asymmetry has been chosen as $\beta\gamma = 0.42$. In order to obtain large luminosity we require a small vertical β function at interaction point ($\beta_y = 1 \text{cm}$), large tune shift (0.05). These values determine the necessary respective beam currents for electron and positron ($I_- = 1.1 \text{ A}$, $I_+ = 2.6 \text{ A}$) for the goal luminosity of $10^{34} \text{cm}^{-2} \text{sec}^{-1}$. Since the maximum beam current stored in a bunch is a few mA, about 5000 bunches must be stored in each beam. One of most important features of KEKB is finite angle crossing of $\pm 11 \text{mrad}$.

2.1. Injection

In order to inject electron and positron beams directly the current 2.5 GeV linac is upgraded to 8 GeV linac. The positron intensity is increased by factor 20 by changing electron energies impinging a target from 200 MeV to 2 GeV. Thanks to this higher intensity we can accumulate the necessary positron beam current within 800 sec. Thus the average luminosity is expected to be as high as 77% of the maximum luminosity.

Figure 1. Configuration of the KEKB accelerator system.

2.2. Lattice design

Strong sextupole magnets are needed to correct for large chromaticity produced by strong focussing of the beams at the interaction point (low β_y value). However, insertion of sextupole magnets caused another problem since the non-linear effects of sextupole magnets decreases the dynamic aperture. This problem can be cured by adopting the non-interleaved chromaticity correction with 2.5π phase advance.

2.3. Coupled bunch instability and RF cavity

The electromagnetic field induced by the beams in a cavity affects the successive beams and if this effects accumulate by positive feedback the beams are lost. Such an instability, called as coupled bunch instability (c.b.i.), is a serious problem for the high beam current and many bunch machine. For the B-factory with a long circumference, in addition to the c.b.i. due to the higher order modes, the c.b.i. due to the accelerating mode

Figure 2. Required integrated luminosity for observing CP violation as a function of energy asymmetry ($\beta\gamma$).

becomes serious. In order to get rid of these instabilities two different types of RF cavities have been developed at KEK. One is the ARES (Accelerating Resonantly Coupled with Energy Storage) normal conducting cavity and the other is a super conducting cavity.

The ARES is made by connecting a dumped cavity with a storage cavity via a connecting cavity. In the dumped cavity higher order modes are extracted out the cavity and absorbed by SiC absorber, but the accelerating mode is kept in the cavity by a notch filter. In order to suppress the c.b.i. due to the accelerating mode the detuning frequency Δf must be kept below the revolution frequency (100 Mz for KEKB). Δf is inversely proportional to the accelerating voltage per cavity V_c and Q value of the cavity. In case of ARES Δf is reduced by increasing the Q value by connecting the storage cavity with low energy loss. Using the ARES Δf can become as low as 20 KHz, which is much lower than 100 kHz. The test results of the 1/5 scale ARES model are encouraging.

The super conducting cavity has large beam holes through which higher order modes propagate outward and absorbed by ferite absorbers while accelerating mode is kept inside the cavity thanks to the cutoff frequency. The detuning fre-

quency for a super RF cavity can be made much lower than the normal RF cavity by raising the V_c value. We have already succeeded to achieve an accelerating voltage of 11 MV/m with a prototype cavity, which exceeds the required voltage. Although the super RF cavity is usable in the HER, it is not good enough for application in the LER.

There is another type of coupled bunch instability due to the resistive wall impedance. This problem can be solved only by using a fast feedback system. It is one of the most challenging problems of KEKB and such a scheme is under study.

2.4. Finite angle crossing

KEKB has chosen a finite angle crossing scheme of $\pm 11 \text{ mrad}$ because of the following many advantages.

- No parasitic collisions occur.
- No bending magnet for beam separation is required. As a result the background due to synchrotron light is significantly reduced and a circular beam pipe instead of a race-track one can be adopted.
- A room for superconducting solenoid magnets for compensation of the fringe field of the detector solenoid magnet.

An intensive simulation studies of the beam behavior reveal that reduction of the luminosity due to finite angle crossing can be kept small by keeping the synchrotron tune less than 0.02. If the effect of finite angle crossing on the beam lifetime is serious, crab crossing scheme must be adopted. Therefore crab cavities are also under development.

3. The BELLE Detector

3.1. Requirements for the detector

The BELLE detector has to be designed based on the following requirements.

- Angular acceptance
The angular acceptance for both charged and neutral particles is $17^\circ < \theta < 150^\circ$.

- Vertex Resolution
The resolution of measurements of the distance between two B meson vertices is less than 95 μm . It is deduced from $\sigma(\Delta t) < 0.5\tau_B$.
- Charged particle tracking
Detection of low momentum particles with $p_t > 0.05 \text{ GeV}/c$ is good.
Momentum resolution is as good as $\sigma(p)/p < 0.2\%(1 + p_t^2)^{1/2}$ (p_t in GeV/c).
- Particle identification
Particle identification capability of π , K and e is good enough for B-flavour tagging. Good π/K separation for $p < 3.5\text{--}4 \text{ GeV}/c$ is required for $B^\pm \rightarrow DK^\pm$ and $B \rightarrow \pi^+\pi^-$ detection.
- Electromagnetic calorimetry
High efficiency and good resolution, in particular, for low energy photons ($20 \text{ MeV} - 500 \text{ MeV}$), are necessary.
- K_L and muon detection
High detection efficiency and good resolution in angle measurements for K_L are needed. High detection efficiency and low fake rate are needed for muons with momentum of as low as $0.6 \text{ GeV}/c$.

3.2. Status of Belle collaboration and design of the detector

The Belle group is an international collaboration consisting of approximately 160 researchers from 40 institutions in 7 countries. After we showed the preliminary detector design at the Letter of Intent (LoI)[2] in February 1994, the design of the detector has been evolved and fixed during 1995 in the following way.

- January: Technical Design Report (TDR)[3] was submitted to LCPAC.
- March: Instead of direct counters aerogel Čerenkov counters plus TOF counters were chosen for the barrel particle ID devices.
- July: Aerogel Čerenkov counters were also chosen for the endcap particle ID device.

- September: Design of almost all the detector components is fixed.

Fig. 3 and Fig. 4 show the overall pictures of the detector. Particles from the interaction point go through the beam pipe, then Silicon Vertex Detector (SVD), Central Drift Chamber (CDC), Particle ID Device (Aerogel Čerenkov Counters), TOF, and reaches CsI calorimeter. All these components are embedded inside the 1.5 Tesla magnetic field. K_L/μ detector is placed outside the solenoid. In the next section we describe each detector component.

Figure 3. Side view of the Belle detector.

3.3. Each detector component

3.3.1. Vertex Detection

Thanks to the finite angle crossing we can place a cylindrical beryllium beam pipe at $r = 20$ - 23 mm. It consists of two cylinders of 0.5 mm thick berillium and Helium gas is filled in the 2 mm gap between the two cylinders. The silicon vertex detector (SVD) is made by double-sided silicon strip detectors with a double-metal-layer readout. The r - ϕ strips are slanted by $\pm 1^\circ$, which enable us to measure z coordinates also by using them. Pitch for r - ϕ strip is constant, but that

Figure 4. Birdseye view of the Belle detector.

for r - z strip is variable, namely larger pitch at larger z . The detector has cylindrical configuration with two super layers (total 4 layers) as seen in Fig. 5 and Fig. 6. The expected S/N ratio is larger than 20. The expected resolution of ΔZ is about $80 \mu\text{m}$, which satisfies our requirement. The radiation hardnesses of SVD and its preamplifiers are strong enough for the expected radiation dose of 10 krad/year for normal running. In the test experiment using the 3.5 GeV/c pion beam we obtained the space resolution which is close to the expected one calculated by Monte Carlo simulations as seen in Fig. 7.

3.3.2. Tracking

The structure of the central drift chamber (CDC) is shown in Fig. 8. The chamber has small square cell structure and 52 cylindrical layers organized in 13 super layers in $r=8.5$ to 90 cm. In order to minimize multiple Coulomb scattering effects and still to retain good space resolution and dE/dX , we have chosen $He/C_2H_6(50/50)$ gas mixture as chamber gas. With extensive beam and cosmic-ray tests we obtained the space resolutions of $130 \mu\text{m}$ in the $r\phi$ plane and the dE/dX resolution of 5.3% as seen in Fig. 9. The expected momentum resolution is estimated us-

Figure 5. The cross section of SVD.

ing GEANT simulation, track reconstruction program BACE and the measured space resolution. The result is shown in Fig. 10 and parametrized as $\sigma(p)/p < (0.17 \times p_t \oplus 0.19/\beta)\%$ at 90° .

The z cathode-strips are placed at the innermost layer to measure z coordinates for the fast r-z trigger. Using BACE program we can reconstruct more than 90% of CDC tracks with p_t larger than 80 MeV/c. The main charged track trigger is provided by the CDC $r - \phi$ triggers.

Figure 6. Schematic side view of SVD showing the two end rings.

Figure 7. Test beam results for the space resolution of the silicon detector. The crosses are the data points and the curve is the Monte Carlo simulation result.

3.3.3. Particle Identification

An array of scintillator time-of-flight (TOF) counters with fine mesh (FM) photomultiplier (PM) readout is capable of identifying particles below 1.2 GeV/c. Full size prototype barrel TOF/TSC counters were tested with the pion beam. They were 3 m long, 5 cm thick and 6 cm wide BC408 scintillators with attenuation lengths of 2.5 m. The time resolution obtained in our prototype tests exceeded our design goal

Figure 8. The structure of the tracking chamber.

Figure 9. The resolution of dE/dX for 3.5 GeV/c π^- beam in 1.5 T.

of 100 ps. Figure 11 shows the π^+/p separation. An array of silica aerogel Čerenkov counters (ACC) with FM-PM readout provides identification for the momentum region between 1.0 and 3.6 GeV/c. This can be accomplished by a single layer of aerogel with a refractive index varying from $n=1.01$ at forward angles to $n=1.02$ for angles $\theta = 90^\circ$ and greater. The typical size of a counter is $12 \times 12 \times 12 \text{ cm}^3$. The schematic view of a barrel ACC is shown in Fig. 12. At KEK, we have developed a new technique for producing low refractive index aerogel with excellent hydrophobic properties. The principal concern for ACC is the light yield. Recently we have succeeded to improve the light yield drastically. In Fig. 13 we show the beam test results of the light yield for $n=1.01$ aerogel. The average number of photoelectrons obtained by the October experiment for 3.5 GeV/c pions in $B=0\text{T}$ is 18-20. This number is reduced to 8-10 by the corrections for the response function effects of PM and the 1.5T magnetic field effects.

Figure 10. The momentum resolution as a function of p_t for π^- with $\theta = 90^\circ$ in 1.5 T. The open circles are the full simulation results using the measured space resolution and the curve is the analytic calculation.

3.3.4. Electromagnetic Calorimetry

Electromagnetic calorimetry is provided by a highly segmented array of CsI(Tl) crystals with silicon photodiode readout. Each crystal has a tower like shape and a dimension of $(5.5 \times 5.5 - 6.6 \times 6.6) \times 30 \text{ cm}^3$, and points almost to the interaction point (tilted by 1.9°). Each crystal is read out by two photodiodes and a preamplifier. The total number of crystals amounts to about 9000. Each half of them is produced by BINP in Russia and JCCG in China, respectively. About 1300 crystals have already been delivered to KEK from BINP. The quality of the crystals produced by BINP was proved to be acceptable according to various tests. Their energy resolution for electrons measured by the beam test is shown in Fig. 14. The quality of the JCCG crystals was also found to be acceptable except for the radiation hardness.

Figure 11. Time of flight measurements with prototype (a) barrel TOF and (b) endcap TOF counters for a 2 GeV/c π^+ /p unseparated beam over a flight path of 1.4 m.

3.3.5. K_L and Muon Detection

The detector to identify K_L mesons and muons (KLM) consists of an octagonal barrel and two endcaps. The KLM detector measures the position of the K_L meson's interaction and thereby the momentum direction. The best candidate for KLM technologies is resistive plate counter (RPC). Tests of RPC were performed using resistive electrode made by glass and gas mixture of Ar(61%), isobutane(35%) and Freon 116(4%). The results are promising. One residual worry for RPC is the longevity and *R&D* work for it is continuing.

4. Physics

A number of Monte Carlo simulation studies have been performed to test the capabilities of the reference detector for measuring CP violation effects in B decays and for determining the angles of the KM unitary triangle. The results are shown in Table.1. The expected errors in $\delta\sin 2\phi_1$, $\delta\phi_2$ ($\delta\sin 2\phi_2$) and $\delta\phi_3$ are estimated for an integrated luminosity of 100 fb^{-1} . Although penguin contributions in the channels for the ϕ_1 analyses are negligibly small, those for the ϕ_2 analyses are sizable. The result for $\pi\pi$ channel is an optimistic value since penguin contributions are neglected. The results for the $\rho\pi$ channel was obtained by a full amplitude analysis including penguin dia-

Figure 12. Schematic view of a barrel aerogel Cerenkov counter.

grams and final state rescattering. By combining all the listed channels, the errors are $\delta\sin 2\phi_1 = 0.05$, $\delta\phi_2 = 11^\circ$, and $\delta\phi_3 = 13^\circ$.

5. Schedule of the accelerator and the detector

Schedule of the accelerator and the detector is shown as follows.

- Apr 1994 Project approval
- Jan 1995 Start of dismantling of TRISTAN
- Jan 1997 Start of installation in the tunnel
- Apr 1998 Completion of linac upgrade
- Oct 1998 Completion of detector installation
- Jan 1999 Start of commissioning of the beams

6. Summary

- Basic designs of both the accelerator and the detector of the KEK B-factory are almost fixed.
- Results of *R&D* studies of the accelerator and the detector components are promising.

Table 1

Expected sensitivity for angle measurements of the KM unitary triangle with an integrated luminosity of 100 fb^{-1} .

ϕ_i	decay mode	BR(B)	$\delta \sin 2\phi_i$ or $\delta\phi_i$	comments
ϕ_1	ψK_S	5.0×10^{-4}	0.07	Penguin ≈ 0
	ψK_L	5.0×10^{-4}	0.10	Penguin ≈ 0
	ψK^{*0}	1.6×10^{-3}	0.17	Penguin ≈ 0 100% polarized K^* is assumed
ϕ_2	$\pi^+\pi^-$	1.3×10^{-5}	0.15	Assume penguin = 0
	$\rho^\pm\pi^\mp, \rho^0\pi^0$	6.0×10^{-5}	$9^\circ \sim 13^\circ$	full amplitude analysis
ϕ_3	$D^0 K_S$	5.0×10^{-5}	$\leq 25^\circ$	direct CP violation
	$D^0 K^\pm$	5.0×10^{-5}	$\leq 15^\circ$	direct CP violation

Figure 13. Improvement of the light yield of the ACC beam test.

Figure 14. Beam test results for the energy resolution of the 30 cm-long CsI(Tl) array.

- The first commissioning of the beams is expected as scheduled in early 1999.
- For the one year data taking with the final goal luminosity (100 fb^{-1}) we expect to obtain angle measurements of the KM unitarity triangle with precisions of $\delta \sin 2\phi_1 = 0.05$, $\delta\phi_2 = 11^\circ$, and $\delta\phi_3 = 13^\circ$.

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