The KEK B-Factory Experiment

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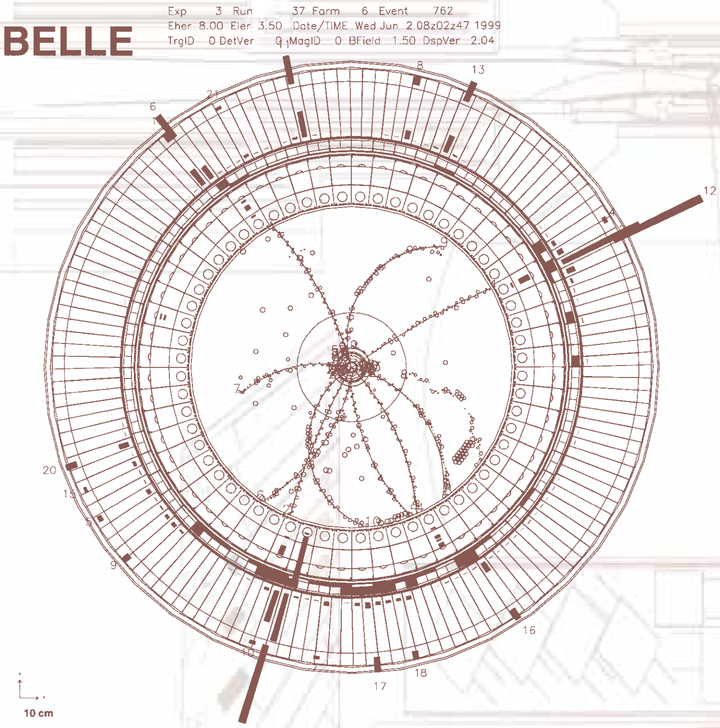
Japan's new asymmetric B factory recorded its first events on June 1. Designed to study the B-meson system, this collider may give us important clues to the differences played by matter and antimatter in the evolution of the Universe.

ON THE AFTERNOON OF JUNE 1, 1999, collision events were recorded for the first time by the BELLE detector at the KEKB collider, the new electron-positron "B factory" at the High Energy Accelerator Research Organization in Tsukuba, Japan. This facility is specifically designed to study the matter-antimatter asymmetries in decays of *B* mesons predicted by the theory proposed by Makoto Kobayashi and Toshihide Maskawa in 1972.



In many ways, the KEKB collider is similar to the PEP-II collider described by John Seeman on page 29. The KEKB collider consists of two rings of magnets; one ring stores 8 GeV electrons and the other 3.5 GeV positrons. The beams are brought into collision inside the detector, where they produce pairs of *B* mesons that move along the direction of the electron beam. This configuration is designed to measure charge-parity (CP) violations in *B* meson decays as described earlier in this issue by Robert Cahn and in the Summer 1996 *Beam Line* article by Michael Riordan and Natalie Roe.

Like PEP-II, the two magnet rings of KEKB occupy a tunnel that originally housed a higher energy electron-positron collider, in this case TRISTAN, and the high energy electron ring uses many recycled TRISTAN components. The center-of-mass energy of 10.58 GeV coincides with the mass of the $\Upsilon(4S)$ resonance, which decays into B and $\bar{B}$ meson pairs and nothing else. The different energies of the two beams cause the produced *B* mesons to travel about two tenths of a millimeter before they decay, a distance that is easily measured with modern silicon-strip detectors.

Kyoto University 1972 or 1973. Standing left to right are Makoto Kobayashi, Tsuneo Uematsu, Hideo Nakajima, Koichi Yamawaki, and Masako Bando. Seated left to right are Toshihide Maskawa and Keiichi Ito. (Courtesy Makoto Kobayashi)

The BELLE detector is also similar in many ways to PEP-II's BaBar detector. In both cases the cores of the instrument are cylindrical tracking detectors; a large array of cesium-iodide crystals situated inside a superconducting solenoidal magnet that provides a 1.5 tesla magnetic field. There are, however, some important differences in the details between the KEKB/ BELLE arrangement and that of PEP-II/ BaBar. In this article we highlight those that we consider to be the most significant.

KEKB

The most fundamental differences between the KEKB and PEP-II storage rings are the schemes used to bring the beams into collision and the techniques used to provide the radio-frequency (rf) accelerating voltages. To appreciate these differences, some awareness of the behavior of beams in storage rings is necessary.

Beam oscillations. In general, particles in a storage ring beam do not all have exactly the same energy nor move in exactly the same direction. The magnet and accelerating systems are designed to accommodate beam particles with energies and trajectories that deviate from the ideal on-energy central-orbit particle. A lattice of quadrupole focusing magnets acts as a series of lenses to deflect particles diverging from the beam back toward the ideal orbit, causing the particles to snake back and forth across the beam axis executing "betatron oscillations."

Particles circulating in the magnet rings radiate a few million electron volts of energy in synchrotron radiation during each turn. This lost energy is replaced in high voltage rf accelerating cavities. The particles in the storage rings cluster in bunches that are properly phased to "surf" on the rf accelerating voltage. The distance between bunches depends on the frequency of this voltage. In both KEKB and PEP-II the rf frequency is about 500 million hertz, and the minimum bunch-to-bunch spacing is 0.6 m. Both machines try to store as many bunches of particles as possible in order to achieve high luminosity.

The magnet systems are designed so that particles with energy above the central value take a little extra time to travel around the ring and thus tend to lag behind their on-energy neighbors. Since the particle bunches pass through the rf cavity while the voltage is decreasing, these late-arriving, higher-energy particles receive a less than average energy boost from the cavity. Likewise, particles with lower than average energy tend to lead their neighbors and arrive at the rf cavities early, where they get an above average energy boost. As a result, particles within each bunch alternate between lagging behind their neighbors and

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having higher than average energy to leading their neighbors with lower than average energies, a phenomenon called "synchrotron oscillations."

Crossing scheme. At the intersection point, where the electron and positron bunches pass through each other, the beams are focused to a very small size. Since the electron and positron beams have different energies, the two beams require magnets with different focusing strengths. The challenge to machine designers is to bring bunches from the two rings into collision inside the experimental detector and then to separate them quickly enough to get them back into their respective magnet systems before they collide with the next bunch—and to do so without producing large disturbances to the experimental detector.

In PEP-II, the beams are made to collide head-on; they are brought together and then separated by a system of "separation dipoles" made from permanent magnets that are common to both beams and located inside the detector. This scheme limits the minimum separation between bunches to 1.2 meters, twice the minimum bunch spacing.

In KEKB, the beams are made to cross at a 1.3 degree angle. Since the two beams are moving in different directions, they fly apart naturally, and no separation dipoles are necessary. In this case beam bunches can be as close together as the minimum distance of 0.6 meters.

The KEKB finite crossing angle scheme has the advantage of simplicity. With no separation dipoles, there is no bending of off-energy beam particles into the detector, resulting in more manageable backgrounds. The main disadvantage is the introduction of a possible coupling of each beam's transverse betatron modes of oscillations with the longitudinal synchrotron modes resulting in the dreaded "synchro-betatron" oscillations (see box on the next page). These were blamed for beam instabilities that limited the performance of the original two-ring configuration of the DORIS storage ring at DESY.

Using elaborate computer simulations, Kohji Hirata and Nobu Toge of KEK carefully reexamined the effects of beam-beam interactions in the case of finite-angle crossings. They concluded that the deleterious effects of a finite crossing angle would be manageable, provided that the frequency of synchrotron oscillations is a small fraction (about 1 percent) of the beam circulation frequency.

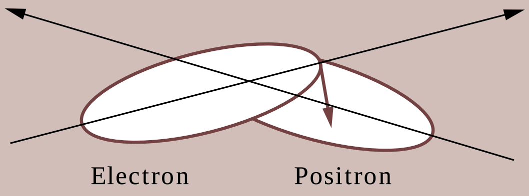
Chromatic corrections. The focusing strengths of the quadrupole magnets are set for particles that have exactly the nominal beam energy. As a result, off-energy beam particles experience non-ideal focusing, producing effects that are similar to chromatic aberrations in ordinary optical systems and for which careful compensation must be made. These corrections are provided by sextupole magnets distributed around the ring.

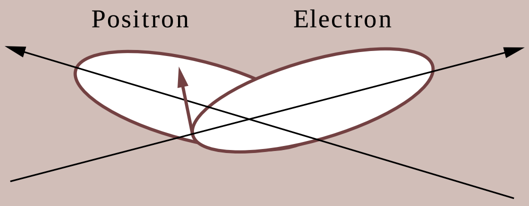
Design studies for KEKB demonstrated that standard magnet lattice arrangements, such as the one used in PEP-II, could not provide the necessary chromatic corrections while also meeting the low synchrotron frequency requirement imposed by the finite-angle crossing arrangement. Instead, KEKB uses a novel new lattice arrangement developed by KEK physicists Haruyo Koiso and Katsunobu Oide that satisfies all of the requirements. In the Koiso-Oide scheme, the chromatic corrections are provided by pairs of sextupole magnets located far apart, at positions where the optical properties of the beams are nearly mirror images of each other. The mirror imaging provides a convenient cancellation of nonlinear effects, and the scheme has the additional practical advantage of making it possible for the high energy electron ring to use recycled bending magnets from the recently dismantled TRISTAN storage ring.

Radio-frequency accelerating cavities. In order to achieve the high luminosity requirements of the *B* factory, the stored currents in each beam must be as large as a few amperes. To maintain the proper match between the klystron (which provides the rf power) and the cavity, the resonant frequency of the cavity must be shifted by an amount proportional to the current passing through the cavity. If the shift in

Crossing Angles, Synchro-Betatron Oscillations and Crab Cavities

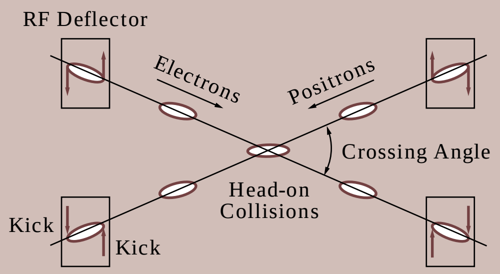
THE DISADVANTAGE of a finite angle crossing of the beam bunches is the introduction of couplings between the transverse betatron oscillation modes of beam particles with their longitudinal synchrotron oscillation modes. This establishes an additional set of possible beam-destroying resonances that must be avoided.





The coupling mechanism illustrated above shows electron and positron beam bunches when they start and finish passing through each other at an exaggerated crossing angle. The positively charged positrons in the front end of the e^+ bunch pull the negatively charged electrons in the back end of the e^- bunch sideways in one direction, while the positrons in the back end tug the electrons in the front end in the opposite direction. Changes in the front-to-back particle positions, caused by synchrotron oscillations, result in different excitations of the transverse betatron oscillations, giving rise to coupled "synchro-betatron" oscillations.

This coupling can be avoided using the "crab-cavity" trick invented by Robert Palmer of Brookhaven National Laboratory for use in high energy linear electron-positron colliders. In this scheme (shown below) rf cavities on either side of the interaction point provide transverse electric fields that rotate the beam bunches by pushing the front of the beam bunch in one direction and the rear in the opposite direction. In this way, even though the beam bunches pass by each other at an angle, the bunches go through each other head-on, and the transverse-longitudinal coupling mechanism shown above is eliminated.



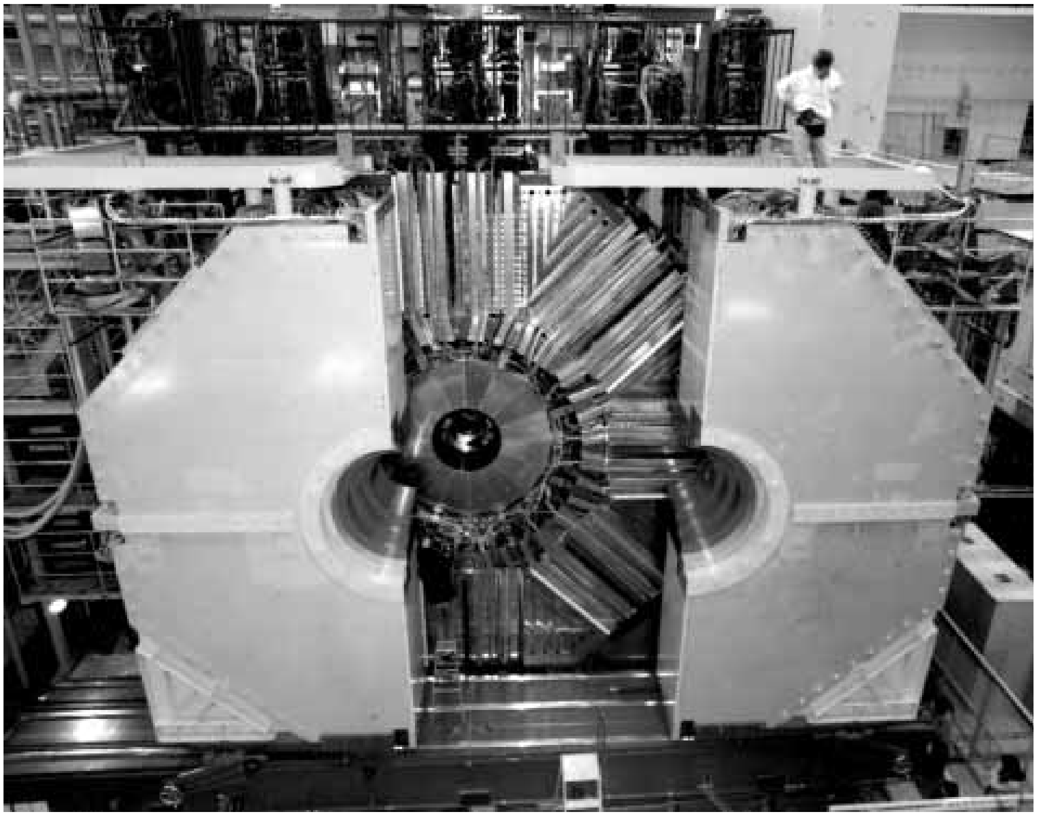
frequency exceeds the circulation frequency of the beam in the ring (100 kilohertz), beam-destroying instabilities can occur. Only large rings with large circulating currents, such as KEKB, suffer from this type of instability.

In order to reduce the effects of the beam currents on the cavity resonant frequency, KEKB uses cavity systems where the energy stored in the resonant mode is very large. The large stored energy provides sufficient inertia to reduce the effects of the beam current. Superconducting cavities naturally have lots of stored energy and these are used in the KEKB high energy ring. This is not the case for normal-conducting cavities, where heating in the cavity walls limits the amount of energy that can be stored in the cavity itself. However, it was not possible to supply all of KEKB's radio frequency requirements with superconducting rf cavities. Normal-conducting rf cavities are also needed. Tsumoru Shintake of KEK proposed a two-cell system where the accelerating cavity is closely connected to a second, very large energy-storage cavity, thereby increasing the total stored energy by about a factor of ten. This idea was improved to include a third coupling cavity.

In KEKB, all of the rf power for the low energy ring and about half of it for the high energy ring is provided by normal-conducting systems based on this three-cell scheme.

THE BELLE DETECTOR

The technical challenges presented by the *B*-factory physics program to the experimental detector are not



Eiichi Nakano from Osaka City University checks the cabling of the endcap muon chambers in the completed BELLE detector while it sits in its "rolled-out" position in the Tsukuba experimental hall at KEKB. On May 1, the detector was moved into its final location at the electron-positron interaction point, which is inside the temporary tunnel of shielding blocks seen at the right in the photograph. (Courtesy KEK)

as severe as those faced by the machine builders. This is because there are existing detectors, primarily the CLEO detector at the Cornell Electron Storage Ring, that provide useful guidance. The relative maturity of detector technologies is reflected in the fact that differences between BaBar and BELLE are not nearly as pronounced as the differences in the storage rings. Both detectors surround the beam intersection region with a 1.5 tesla magnetic field, provided by large superconducting solenoids that encompass most of the detector elements. Immediately outside of the electron-positron collision point are high resolution track detectors made of silicon that pin down the decay position of the *B* mesons. Surrounding the silicon detectors are tracking chambers that measure the trajectories of charged particles from the *B* meson decays as they travel though the magnetic field. The curvature of the trajectories is used to determine the particle momenta. Outside of the tracking chambers but still inside the coil are large arrays of cesium-iodide crystals for detecting gamma rays. The major differences between CLEO-II, BaBar, and BELLE are the techniques used to distinguish between different species of charged particles. BELLE uses arrays of plastic scintillation time-of-flight counters and aerogel Cerenkov counters.

Particle Identification. For the CP violation measurements, it is essential to distinguish charged *K* mesons from other particles, especially from the more copiously produced π mesons. The π and *K* mesons from *B* decays are quite relativistic: typical π mesons have velocities that are about 99 percent of the speed of light; the more massive K mesons are only a bit slower—their velocities are typically about 90 percent of the speed of light. Particle identification systems have to exploit these small differences in particle velocity.

One way to do this is to make a direct measurement of it. This is done in BELLE with an array of large plastic scintillation counters arranged in a barrel that surrounds the tracking system and measures the time-of-flight of particles as they cross the detector volume. Using state-of-the-art techniques, the BELLE time-of-flight system measures the particle transit times with a precision of about 100 trillionths of a second. This is good enough to distinguish π and *K* mesons up to particle energies of about 1 GeV.

At energies higher than 1 GeV, π and *K* mesons can not be reliably distinguished by the time-of-flight system; for these particles Cerenkov techniques are used. These techniques rely on the fact that when a charged particle passes through a transparent material with a speed that exceeds the speed of light in that material, it emits measurable amounts of light in the form of "Cerenkov" radiation. In BELLE, a cylindrical mosaic of nearly a thousand blocks of transparent silica aerogel with indices of refraction that range from $n = 1.01$ to 1.03 occupies the radial space between the tracking region and the barrel of time-of-flight counters. Each aerogel block is viewed by very sensitive phototubes.

Charged pions with energy above about 1 GeV have velocities that are above the Cerenkov threshold and produce light as they traverse the aerogel material. In contrast, charged kaons, which are more massive, do not have velocities above the Cerenkov threshold until they have energy in excess of 3.5 GeV, which is near the highest energy possible for particles from *B* meson decays. Kaons below this energy do not produce any light. Thus, the response of the aerogel counters can be used to distinguish high momentum pions from kaons in BELLE.

The aerogel system can be nicely tailored to the variation in particle's momentum range with polar angle that results from the asymmetric nature of the electron-positron collisions in KEKB, but it has the disadvantage of consuming a sizable volume inside the detector and interposing a considerable amount of material in front of the cesium iodide calorimeter in a complicated nonuniform pattern

KEKB AND BELLE—CURRENT STATUS

In 1994, when BELLE and the KEK *B*-factory project were started, the proposed date for the start of KEKB beam commissioning and the completion of the BELLE detector was "the middle of Japanese Fiscal Year 1998," which started in April 1998. Despite major changes from KEKB's original plans for the injection scheme, the interaction region configuration, the magnet lattice and the rf cavities, both rings were completed in November 1998 and beam was first stored in the high energy ring on December 12. Also, in spite of a number of design changes, the assembly of the entire BELLE detector was finished on December 18.

In a four-month beam commissioning run that ended in April, high current electron and positron beams (about 0.5 amperes each) were achieved with tolerable levels of background radiation at the ultimate location of the BELLE detector. These beam currents are sufficient for operation at a luminosity of about one-fifth of the ultimate design goal. The magnet lattice, chromatic corrections , and the rf systems all behaved as expected. During beam-beam collision studies, no evidence was seen for deleterious syncho-betatron oscillations.

During the KEKB commissioning run, the BELLE detector remained in the "rolled out" position, where it accumulated large samples of cosmic-ray events both with and without the magnetic field excited. These events were used to align and calibrate the detector components.

In May, the detector was moved into location at the KEKB interaction point and operations resumed. The first collision events were recorded by BELLE about a week later. This was an important proof of principle: all systems in BELLE and KEKB operated very nearly as expected. We look forward to a rich program of measurements that will elucidate the nature of CP violations and confirm or reject the Kobayashi-Maskawa theory.