Overview

1 Introduction

KEKB is an asymmetric electron-positron collider at 8×3.5 GeV, which aims to provide electron-positron collisions at a center-of-mass energy of 10.58 GeV. Its mission is to support high energy physics research programs on CP-violation and other topcis in B-meson decays. Its luminosity goal is $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. With approval by the Japanese government as a five-year project, the construction of KEKB formally began in April of 1994. The two rings of KEKB (the low-energy ring LER for positrons at 3.5 GeV, and the high-energy ring HER for electrons at 8 GeV) will be built in the existing TRISTAN tunnel, which has a circumference of 3 km. Maximum use will be made of the infrastructure of TRISTAN. Taking advantage of the large tunnel width, the two rings of KEKB will be built side by side. Since vertical bending of the beam trajectory tends to increase the vertical beam emittance, its use is minimized.

Figure 1 illustrates the layout of the two rings. KEKB has only one interaction point (IP) in the Tsukuba experimental hall, where the electron and positron beams collide at a finite angle of ±11 mrad. The BELLE detector will be installed in this interaction region. The straight section at Fuji will be used for injecting beams from the linac, and also for installing RF cavities of the LER. The RF cavities of the HER will be installed in the straight sections of Nikko and Oho. These straight sections are also reserved for wigglers for the LER. They will reduce the longitudinal damping time of the LER from 43 ms to 23 ms, i.e. the same damping time as the HER. In order to make the circumference of the two rings precisely equal, a cross-over will be built at the Fuji area. The HER and LER are located at the outer and inner sides inside the tunnel in the Tsukuba-Oho-Fuji part. The relative positions of the two rings are reversed in the Fuji-Nikko-Tsukuba part of the tunnel.

To facilitate full-energy injection into the KEKB rings, and thus to eliminate the need for accelerating high-current beams in the rings, the existing 2.5 GeV electron linac will be upgraded to 8 GeV. The upgrade program includes the following modifications to the injector configuration: combine the main linac with the positron production

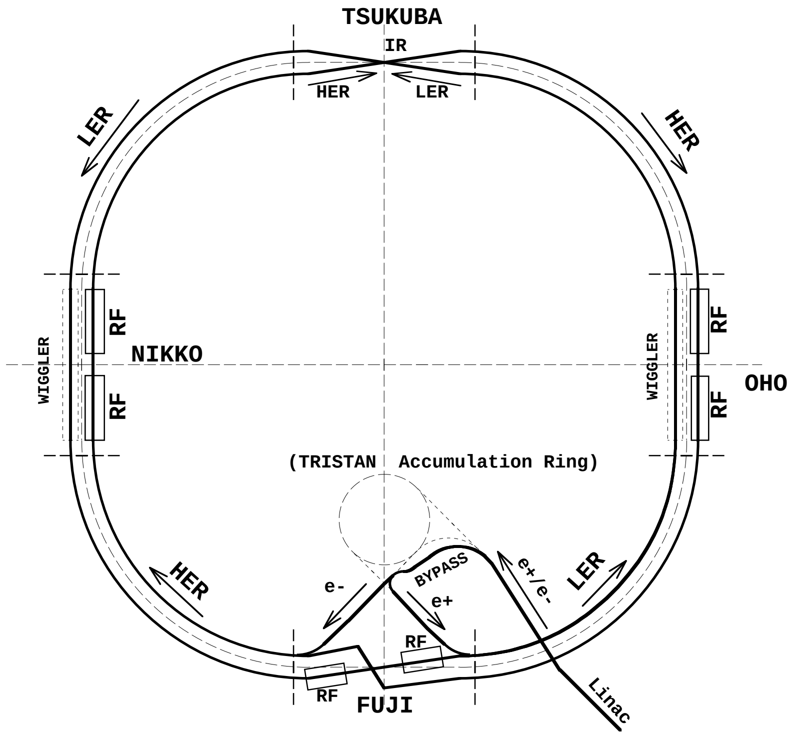

Figure 1: Configuration of the KEKB accelerator system.

linac, increase the number of accelerating structures, replace the klystrons with higher-power types, and compress the RF pulse power by using a SLED scheme. With this upgrade the energy of electrons impinging on the positron production target will be increased from 250 MeV to 4 GeV. This will increase the available positron intensity by 16. With this improvement the injection time of positrons to the LER from zero to the full current is expected to be 900 s.

A new bypass tunnel, which is 130 m long, will be excavated for building transport lines between the linac and KEKB. This new beam transport functionally separates the TRISTAN accumulation ring (AR) from KEKB. This will be an advantage to both KEKB and AR programs, since the upgrade work of either accelerator can be carried out without significantly affecting the other. The tunnel will be built in JFY 1996 and 1997.

2 Basic Design

A Beam Parameters

Table 1 summarizes the main parameters of KEKB. The HER and LER have the same circumference, beam emittance, and beta-function values at IP ($\beta*$). The large current, small $\beta*$, and finite-angle crossing of beams are salient features of KEKB.

Table 1: Main Parameters of KEKB

Ring		LER	HER	
Energy	E	3.5	8.0	GeV
Circumference	C	3016.26		m
Luminosity	$\mathcal{L}$	1×10^{34}		$cm^{-2}s^{-1}$
Crossing angle	θ_x	±11		mrad
Tune shifts	ξ_x/ξ_y	0.039/0.052		
Beta function at IP	β_x^*/β_y^*	0.33/0.01		m
Beam current	I	2.6	1.1	A
Natural bunch length	σ_z	0.4		cm
Energy spread	σ_ε	7.1×10^{-4}	6.7×10^{-4}	
Bunch spacing	s_b	0.59		m
Particles/bunch	N	3.3×10^{10}	1.4×10^{10}	
Emittance	$\varepsilon_x/\varepsilon_y$	$1.8\times10^{-8}/3.6\times10^{-10}$		m
Synchrotron tune	ν_s	$0.01\sim0.02$		
Betatron tune	ν_x/ν_y	45.52/45.08	47.52/43.08	
Momentum compaction factor	α_p	$1\times10^{-4}\sim2\times10^{-4}$		
Energy loss/turn	U_o	0.81†/1.5††	3.5	MeV
RF voltage	V_c	$5\sim10$	$10\sim20$	MV
RF frequency	f_{RF}	508.887		MHz
Harmonic number	h	5120		
Longitudinal damping time	τ_ε	43†/23††	23	ms
Total beam power	P_b	2.7†/4.5††	4.0	MW
Radiation power	P_{SR}	2.1†/4.0††	3.8	MW
HOM power	P_{HOM}	0.57	0.15	MW
Bending radius	ρ	16.3	104.5	m
Length of bending magnet	ℓ_B	0.915	5.86	m

†: without wigglers, ††: with wigglers

B Noninterleaved Chromaticity Correction and 2.5π Lattice

For efficient operation it is highly desirable to be able to inject beams into KEKB without having to modify the lattice optics from the collision time. This calls for a design which maximizes the dynamic aperture. A large dynamic aperture is also preferred for increasing the beam lifetime. For this goal, a noninterleaved sextupole chromaticity correction scheme has been adopted for the arc sections. In this scheme sextupole magnets are paired into a large number of families. Two sextupole magnets in each pair are placed π apart in both the horizontal and vertical phases. No other sextupole magnets are installed within a pair. This arrangement cancels out geometric aberrations of the sextupole magnets through a "$-I$" transformation between each member of the sextupole pair.

One unit cell of the arc lattice has a phase advance of 2.5π. It includes two pairs of sextupole magnets, SF and SD. With the introduction of an extra $\pi/2$ phase advance on the 2π structure, chromatic kicks by the lattice magnet components are very efficiently corrected, and it significantly improves the dynamic aperture.

The lattice design includes a mechanism that makes it possible to change the momentum compaction in the range from -1$\times10^{-4}$ to 4$\times10^{-4}$. By adding two quadrupole magnets in a cell the emittance is also made tunable from 50% to 200% of the nominal value. The flexibility for choosing such critical parameters will be a strong asset for optimizing the operating condition of KEKB.

In addition, a local chromaticity correction scheme will be implemented for the LER in order to correct the large vertical chromaticity that is produced by the final focus quadrupole magnets near the IP. A few dipole magnets will be introduced in the IR straight section to create a dispersion at each side of the IP. A $-I$ sextupole magnet pair will be arranged in this area for each side of the IP to correct the vertical chromaticity. In the HER, since the chromaticity correction by sextupole magnets in the arc sections can guarantee sufficient large apertures, this local correction scheme will not be applied.

C Finite-Angle Crossing of Beams

A finite-angle crossing scheme of $\pm$11 mrad has been adopted for the IP of KEKB. With this scheme, parasitic collisions will not be a concern, even when every bucket is filled by bunches. Since the need for separation bend magnets is eliminated, it allows a much less complex design of synchrotron light masks and a round vertex vacuum chamber at the IP. This choice is expected to improve the optimization of vertex detection and particle tracking devices of the experimental facility.

Superconducting final-focus quadrupole magnets will be used at KEKB for better flexibility of tuning. The use of a finite crossing angle scheme has created room for implementing superconducting compensation solenoid magnets. One superconducting solenoid and one final-focus quadrupole are contained in a single cryostat. The compensation solenoids help reduce the coupling effects due to the detector solenoid, and consequently, improve the dynamic aperture and emittance coupling.

Computer simulation work has found that the finite-angle crossing somewhat reduces usable areas in the ν_x-ν_y plane. This effect comes from synchro-betatron resonances. However, if the synchrotron tune (ν_s) is kept smaller than 0.02, a fair amount of area in the ν_x-ν_y plane will be still free from reduction of luminosity due to resonances.

D Impedance Budget and Beam Instabilities

The total inductive impedance and loss factor in the LER are estimated to be 0.014 Ω and 42.2 V/pC. They correspond to a HOM power of 570 kW. Since the HER has more RF cavities than the LER does, its total loss factor is larger, 60 V/pC. The total HOM power in the HER will be 150 kW.

According to calculations, neither bunch lengthening nor the transverse mode-coupling instability will impose a significant limitation on the stored bunch current. The design current has a factor of two margin for the threshold of the microwave instability. With the design intensity, the magnitude of bunch lengthening will be 20%.

Although a large vacuum chamber (diameter = 94 mm) is to be used in the LER, the growth time of the transverse coupled-bunch instability due to resistive wall of vacuum ducts is estimated to be 5 ms. This instability must be cured by a fast feedback system.

Recent studies indicate that two other types of transverse coupled bunch instabilities may be encountered at KEKB. One is caused by ions that are temporarily trapped around the electron beam orbit in the HER. The ions excite a vertical betatron oscillation with a typical growth time of 1 ms. It will be accompanied by a vertical emittance growth. Although this phenomenon has been neither fully understood nor observed in any storage ring, we should prepare tactical plans for the worst case. A simulation shows that instability oscillations of successive bunches have a similar phase, and hence it can be controlled by using a narrow-band feedback system. It is considered that this instability can be damped by an adequate use of the feedback system

Another is related to photoelectrons coming off synchrotron radiation onto the inner wall of the vacuum chamber. This phenomenon is expected to appear in positron storage rings, e.g. the LER. A simulation shows that the photoelectrons excite a coupled bunch oscillation with a growth time shorter than the damping time. While the photoelectrons have been recently suspected of exciting coupled bunch instabilities in

CESR and the KEK Photon Factory, the proposed conjecture is still controversial. Since the phase difference of the instability oscillations of the bunches is again predicted to be small, we will be able to suppress the photoelectron instability with a powerful narrow-band feedback system.

3 Hardware Systems

A RF System

The RF cavity for KEKB should have a structure that damps higher-order modes (HOMs) in the cavity. The growth time of coupled-bunch instabilities excited by HOMs must be comparable to or longer than the damping time. The cavity should have a sufficient amount of stored energy, so that the detuning frequency due to beam loading is brought below revolution frequency of the ring. Otherwise, a strong coupled-bunch instability will be excited by the fundamental mode of the cavity. For KEKB, two types of accelerating cavities are currently under development: a normal conducting cavity, called ARES, and a single-cell superconducting cavity.

B ARES

Extensive R&D work is under way for ARES (accelerator resonantly coupled with energy storage). It has been shown that the amount of the detuning frequency of the accelerator cell can be dramatically decreased by attaching a low-loss energy storage cell with a large volume. For practical applications at KEKB a 3-cell structure has been proposed, where an accelerating and an energy storage cells are joined via a coupling cell. The system uses a $\pi/2$ mode, which excites an almost pure TM010 mode in the accelerating cell and an almost pure TE015(013) mode in the energy storage cell. In this configuration the field excitation in the coupling cell is negligibly small. Two parasitic modes (0 and π modes) excite a field in the coupling cell. However, they can be damped relatively easily by using a coupler attached to the coupling cell.

In order to suppress HOMs in the accelerating cavity, a choke-mode structure is adopted. While the fundamental mode is confined within the accelerating volume by the choke, HOMs are extracted and absorbed by SiC absorbers. The first prototype of the choke-mode cavity has been successfully tested up to a wall loss power of 110 kW, which corresponds to a gap voltage of 0.73 MV.

C Superconducting RF Cavity

A superconducting cavity has a large stored energy because of its high field gradient. Consequently, it is less sensitive to beam-loading than standard normal-conducting cavities. The superconducting cavity for KEKB is a single-cell cavity with two large-aperture beam pipes attached to the cell. HOMs propagate toward the beam pipes, because their frequencies are above the cut-off frequencies of the pipes. The iris between the cell and the larger beam pipe prevents the fundamental mode from propagating toward the beam pipe. HOMs are absorbed by ferrite absorbers.

A full-size niobium model has been built and tested in a vertical cryostat. The maximum accelerating field of 14.4 MV/m with a Q value of 10^9 have been obtained. Another prototype cavity is under construction for beam tests at the TRISTAN AR. HOM dampers are made by using the hot isostatic pressing (HIP) method. There, ferrite powder is sintered and bonded on the vacuum pipe surface under a high temperature and high pressure environment. Two HOM damper modules built this way have been successfully tested at 508 MHz. The outgassing rate was found to be sufficiently low. No damages to the ferrite was observed. A beam test of these dampers is in preparation.

D Crab Cavity

In a case where some unexpected problems are encountered with finite-angle collisions at the interaction point (IP), a crab crossing scheme will be introduced. The beam line design around the IP includes adequate spaces for crab cavities, which can effectively restore the head-on collision condition with a finite orbit crossing angle.

The TM110 mode field of 1.4 MV at 508.9 MHz will be used to create time-dependent horizontal rotational kicks to beam bunches. Designs of the crab cavity shape and a coaxial beam pipe together with a notch filter have been developed. The required TM110 mode is trapped within the cavity, while other modes that are not required are extracted from the cavity module.

A one-third niobium model has been built for measuring the RF characteristics. The kick voltage required for KEKB has been achieved with a sufficiently high Q-value. Full scale niobium crab cavities for KEKB will be built within three years.

E Vacuum System

Copper will be used as the material for vacuum ducts for its low photo-desorption coefficient, high thermal conductivity, and capability of shielding X-ray. The maximum heat load due to synchrotron light will be 14.8 kW/m for the LER, and 5.8 kW/m for the HER.

The LER duct has a circular cross section with an inner diameter of 94 mm for reducing resistive wall instabilities. With this large duct size and dipole magnets having a short length, the use of a non-distributed pumping system is allowed for the LER. NEG cartridges will be used as the main pumps for the LER.

In the HER, since the resistive wall instabilities are not strong, a duct with a race-track shape will be used. This will minimize the gap size of the dipole magnets. However, because of the long dipole magnets to be used at the HER, a distributed pumping system with NEG strips will be used there.

F Magnets and Power Supplies

The specifications for magnets and power supplies have been nearly finalized. They are based on an optimization of the lattice design, and studies of the sensitivities of the ring performance with respect to various construction errors. Experience with TRISTAN indicates that those specifications will be satisfied by using a conventional technique.

A large number of magnets from the TRISTAN Main Ring will be recycled for the HER and LER, in as much as they do not compromise the performance of KEKB. The HER will re-use magnets from TRISTAN, except for some quadrupole magnets and defocusing sextupole magnets. For the LER new dipole and quadrupole magnets will be fabricated. This is because the LER requires quadrupole magnets with a larger bore aperture size, and short dipole magnets for obtaining a short damping time.

Some of the large power supplies from TRISTAN will be also used for cost-saving. A main issue in constructing the power supply system is that a large number of medium and small-size power supplies with good stability need to be prepared for sextupole magnets and steering correction magnets. R&D work is under way for building new power supplies to meet the specifications, while minimizing the manufacturing cost.

G Beam Instrumentation

The performance of the KEKB optics will be sensitive to various magnet errors and to the beam orbit at coupling elements, such as sextupole magnets. In order to recover the ideal optics by correcting these errors, beam-based error measurement techniques will be used. The beam position monitor (BPM) system at KEKB will be built to provide beam orbit data for these purposes. The BPM read-out at KEKB is based on a “slow system” in the sense that the beam positions averaged over many turns will be extracted. This allows the beam position data to be obtained with good stability and precision. The minimum read-out time is approximately 1 second. The signal detection is done with a narrow-band filter circuit together with a synchronous detector. The same detection system has been working at TRISTAN.

Synchrotron light monitors are being prepared for observing the beam profile and for measuring the bunch length. Weak dipole magnets will be installed as the light source. For further precise profile measurement we plan to use another system with lasers, which is now under study.

Feedback systems are being developed to damp the coupled-bunch oscillations of the beam. Since the number of bunches is large (~ 5000), and the bunch spacing is short (2 ns), the signal processing part of the system is a technological challenge. A 2-tap FIR digital filter system is being developed as the kernel of the signal processing unit. Since this filter requires only subtraction operations in the arithmetic unit (no multiplication operations are necessary), the circuit can be built with memory chips and simple CMOS logic ICs, without relying on digital signal processing (DSP) chips. This signal processing scheme is used for both the longitudinal and transverse feedback systems. Prototype units have been completed for transverse and longitudinal pick-ups that can detect bunch oscillations for the 500 MHz bunch frequency. Feedback kickers are also being developed.

H Control System

Efforts will be made to maximally utilize the existing software toolbox, libraries and the framework for efficient development of a reliable control system for KEKB.

The lowest level hardware control will be done by either CAMAC, GPIB or VME. The software to control such devices and to handle low level data manipulation will be built with the EPICS toolbox system, which has been developed by a collaboration of several high energy physics laboratories. The data acquisition and the control signal transmission are to be handled by I/O processors that operate in the framework of the EPICS system.

Fast network loops with FDDI or ethernet, wherever appropriate, will be implemented to provide a sufficient bandwidth for the data traffic. The man-machine interface layer will be built on the X-windows system which will be running on Unix workstations. A sophisticated accelerator model code will be integrated with the control system for improved efficiency in understanding the machine behavior.

4 Schedule

A three-month long beam experiment is planned for 1996 at AR. The existing RF cavities will be temporarily removed from the ring, and an ARES cavity and a single-cell superconducting cavity for KEKB will be installed for testing. The goal is to store a 500 mA electron beam at 2.5 GeV in a multi bunch mode. Transverse and longitudinal feedback systems will also be installed and tested.

The main components of the LER, such as the magnets and vacuum elements, will be fabricated in JFY 1995 and 1996, whereas those for HER will be fabricated in JFY 1996 and 1997. Operation of the TRISTAN Main Ring will be discontinued near the end of 1995. Its components will be dismantled, starting January, 1996. By the end of 1996 the TRISTAN tunnel will be ready for installing the magnets. The commissioning of KEKB is scheduled to begin within JFY 1998.

Table 2 summarizes the budget profile of the project. The total budget amounts to 354×10^8 yen. From JFY1998, the last year of construction, we expect 32×10^8 yen for operational money.

Table 2: Budget Profile of KEKB

Fiscal year	Accelerator and linac	Detector	Operational	Total
1994	14.61	5.37		19.98
1995	30.41	11.61		42.02
1996	76.53	18.63		95.16
1997	98.49	16.29		114.78
1998	73.96	8.10	32.00	114.06
Total	294.00	60.00	32.00	386.00

Unit: 10^8yen