ACCELERATOR DESIGN OF THE KEK B-FACTORY

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Abstract

The B-factory is now planned as the third phase of TRISTAN. The design study is being advanced by the accelerator task force. This report describes the temporal design and some problems in the B-factory.

Introduction

The B-factory, an asymmetric electron-positron two-ring collider, is now planned as the third phase of TRISTAN. After the present high-energy experiment at 29 GeV, we will install two rings of the B-factory in the TRISTAN tunnel. The present main ring will be converted to a synchrotron radiation factory. Then TRISTAN has three rings in its tunnel.

The accelerator task force was organized to design the B-factory, and has been working for two years[1]. More efforts are, however, still needed before we can say proudly we have "the KEK B-factory design". This report describes the temporal design and some problems related to the B-factory.

Design parameters

From requirements of the physics experiment we first set the luminosity goal to $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, and energy of the two rings to 3.5 and 8.0 GeV. Taking account of the ion trapping effect we fill the low-energy ring(LER) with positrons, and the high-energy ring(HER) with electrons. The important accelerator parameters at the design goal are shown in Table 1. These parameters were determined by guidelines[1] in which the goal should be realized with the least current and with reasonable beam-beam parameters consistent with existing machines. The beam-beam effect in an asymmetric collider is unknown because no such colliders ever exist. We can, however, choose beam parameters such that the beam-beam effect becomes almost symmetric with each other as in a symmetric collider, following an energy transparent principle. To minimize the accelerating voltage every RF bucket is filled with beam. In order to avoid peripheral crossing effects the two beams need to collide with a finite angle. If the beam-beam effect due to the finite crossing angle is large, we will need a crab crossing scheme invented during linear collider design studies[2].

At present we plan to reach the design goal in two steps. In the first step a head-on colliding scheme is to be used. The reason is that only the head-on collision has been applied in existing machines, and that the feasibility of the crab crossing with a special cavity is unknown. The important objective of the present design study is to prove the feasibility of the first step, which will provide us the minimum luminosity for studying the CP violation. We understand that the feasibility of the second step can not be shown by desk works or R&D's but only by beam studies carried out with the B-factory itself in the first step. In designing components which can not be easily reformed, for example, the lattice in the arc and vacuum chambers, we have to make them compatible with both steps.

Table 1. Design parameters of the B-factory

		HER	LER
Energy(GeV)	E	8.0	3.5
Circumference(m)	L	3018	
Luminosity($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	$\mathcal{L}$	$1 \times 10^{34}(2 \times 10^{33})$	
Number of bunches	N_B	5120(1024)	
Tune shift	ξ_x/ξ_y	0.05/0.05	
Beta function(m)	β_x^*/β_y^*	1.0/0.01	
Current(A)	I	1.1(0.22)	2.6(0.52)
Bunch length(cm)	σ_z	0.5	
Bunch spacing(m)	S_B	0.6(3.0)	
Emittance(nm)	ϵ_x/ϵ_y	19/0.19	
Energy spread	σ_E/E	7.2×10^{-4}	7.7×10^{-4}
Energy loss/turn(MeV)	U_0	4.2	0.95
Momentum compaction	α	1.0×10^{-3}	9.3×10^{-4}
RF voltage(MV)	V_c	48	22
RF frequency(MHz)	f_{RF}	508	
Synchrotron tune	ν_s	0.070	0.069
Bending radius(m)	ρ	91	15

( ): for the first step

Lattice design

The TRISTAN tunnel has a four-fold symmetry and four long straight sections. At present we plan only one interaction point in one of the four sections. The opposite side of the colliding insertion is used for beam injections, and wigglers if controlling emittance or damping time is required. The other two long straight sections are devoted to accelerating cavities. Figure 1. shows an overview of the linear optics of the half ring. All optics calculations are done with a computer code, SAD, developed in KEK.

The most important problem in the lattice design is chromaticity corrections because of the very small β_y^*. Strong sextupole magnets, which compensate for large chromaticities generated at insertion quadrupoles, tend to narrow the dynamic aperture, both in the transverse and momentum directions, with their nonlinearities. The sextupoles are so strong that transverse dynamic aperture sufficient for beam injection, 1.2×10^{-5} m, can be obtained only with a non-interlaced sextupole correction method. The conventional interlaced sextupole correction method does not promise such wide transverse dynamic aperture. The non-interlaced method is, however, not effective to widen momentum aperture, which may restrict the beam lifetime. The Touschek lifetime depends strongly on the momentum aperture as well as the beam energy. Therefore, when the bunch volume is small as in the present design, the Touschek lifetime becomes marginal in the low-energy ring in particular. It is a critical problem to find a comfortable sextupole configuration, which promises sufficient dynamic aperture both in the transverse and momentum directions.

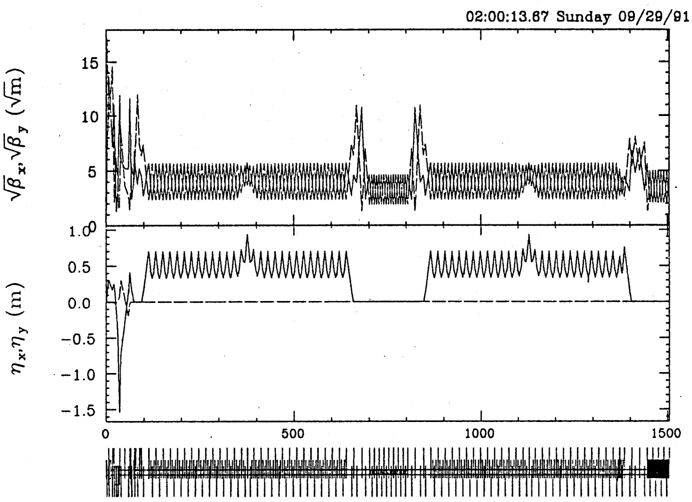

Figure 1: An overview of the linear optics for a half of LER. The horizontal scale starts at the interaction point, goes through the injection and wiggler straight section, and ends at the middle of the RF section.

We are discussing a withdraw from this critical problem. We can relax the requirement on the transverse dynamic aperture by preparing two optics, a colliding optics and an injection optics. At every beginning and end of the beam injection the optics is switched from one to another. Then we expect that the conventional interlaced sextupole correction can be applied to the B-factory. The requirement on the dynamic aperture of the colliding optics in either ring is that the transverse aperture is 5×10^{-6} m, roughly 100 times of the beam emittance, and that the momentum aperture is more than 1%. The dynamic aperture is also related to the particle loss due to the collision at the interaction point[3]. The cross section of the bremsstrahlung of the beam collision is 2.6×10^{-25}cm^2 for both rings. Those for the Bhabha scattering are 1.1×10^{-26}cm^2 and 4.0×10^{-28}cm^2 for LER and HER, respectively, and are much smaller compared with the bremsstrahlung effect. Then beam lifetimes due to the collision are 17 and 7.4 hours for LER and HER. For a given luminosity they are almost constant, slightly dependent on the momentum aperture, and hence can be considered as lifetime scales in both rings. It is reasonable to choose the Touschek lifetime as the same as, or longer than, this lifetime scale in the lattice design.

Another problem is related to the colliding insertion. The detector has a strong solenoid field, 1 T and 4 m long, which induces an x-y coupling. When a small emittance ratio is required as in the present design, the x-y coupling should be perfectly corrected using with skew quadrupoles. The computer code, SAD, deals with matching linear optics and correcting x-y coupling at the same time.

Insertion design

While in the design goal a finite crossing angle scheme is to be used, a head-on colliding scheme is used in the first step of the B-factory. We have focused on the first step in the insertion design. In designing the insertion we have to take account of the background noise, synchrotron radiations and spent electrons, to the most sensitive part of the detector beam tube. We also give attention to solenoid field deformation due to accelerator components, while keeping the detector acceptance, especially in the forward direction, as large as possible.

Figure 2. shows the layout of the insertion of the head-on collision. The two beams are separated from each other by permanent bend magnets. The first defocussing quadrupole(QCD) is common for both LER and HER, and is produced by superconducting coils. In the same cryostat of the quadrupole we add a superconducting solenoid coil, which cancels out the detector solenoid field partly along the beam orbit. To minimize the synchrotron radiation noise produced at the first quadrupole the axis of the quadrupole is adjusted to the incoming beam orbit on either side of the interaction point. Therefore the optics is no longer symmetric with respect to the colliding point. The focussing of the high-energy beam is done with a half quadrupole(QC3H) as well as the superconducting quadrupole. Further beam separation is done with septum magnets(SEPH and SEPL) inserted along the outgoing beam orbit on either side.

If a small angle crossing scheme, in which the first quadrupole is common for both beams, is chosen in the design goal, the present head-on colliding design can be converted with a slight reform by removing permanent separation bends.

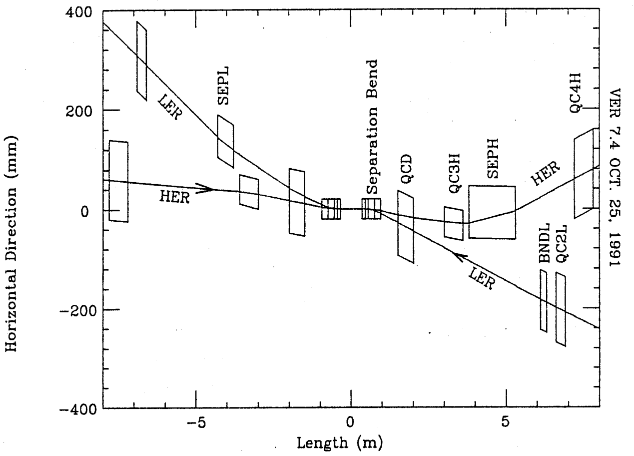

Figure 2: A layout of the insertion design for the first step.

RF cavity

The B-factory needs a large amount of stored current with many bunches, the number of which is more than 1000. It is expected that the maximum stored current is limited by coupled bunch instabilities, which are excited dominantly by resonant impedance of accelerating cavities. In order to decrease the impedance of higher order modes an idea of damped cavities was proposed[4,5] and is now under study with a full-size model. In a damped cavity the higher order resonant field is extracted outside through an antenna-like disc structure and hence its quality factor can be decreased by a large factor.

The fact that the beam loading to the cavity is extremely heavy and the revolution frequency of the ring is small leads another type of longitudinal coupled bunch instability. As the beam current increases the resonant frequency of the acceleration mode is moved by tuners to minimize the reflection power from the cavity. Under this optimum operation the frequency shift becomes several times of the revolution frequency in the B-factory. The fundamental mode then induces too strong coupled bunch instability, which can not be damped by conventional feedback damper methods.

How to cure this mechanism is now under study. One method is to keep the fundamental frequency constant if we can operate the cavity with large reflection power. This case requires a cavity with very low shunt impedance and a large amount of RF power. Another is to adopt a superconducting damped cavity. Even under the optimum power operation the frequency shift of the fundamental mode of the superconducting cavity becomes sufficiently small due to its very high Q value.

We have not yet determined the cavity type for the B-factory. Cavity parameters are closely related to the B-factory design. They depend on how to cure the coupled bunch instability, the expected performance of damper systems, the input power per cavity and so on. The input power itself depends on whether we need wigglers or not. In this meaning the B-factory design determines the cavity type and vice versa.

Vacuum

The design pressure of the vacuum system is set to 10^{-7} Pa, which is determined by the required beam lifetime and the ion trapping effect. The pumping capacity is estimated with an outgas rate which is obtained after some amount of synchrotron radiation bombardment. Therefore, although the pressure in the initial operation is not sufficiently low, the above pressure goal is expected to be realized after a short term operation, within less than one year. The pumping system can be constructed with conventional pumps, ion pumps, distributed ion pumps and NEG's.

The chamber design is another vacuum issue. The vacuum chamber is heated up by the strong synchrotron radiation in the B-factory. The beam ducts are to be made of aluminum alloy or copper, depending on the radiation density at each duct. If the power density is larger than 10 kW/m, near wiggler magnets, only copper chamber is allowed. The copper chamber is also a efficient X-ray shield compared with aluminum alloy. In Japan, however, production of copper chamber have not tried in a large scale. Aiming at utilization of copper chamber we are developing fabrication technique.

Injection

The injection rate necessary for the B-factory is determined by the beam loss rate. The lifetime is restricted by bremsstrahlung and Bhabha scattering, both related to beam collisions at the interaction point, and the Touschek effect. The number of particles lost by the beam collision during the experiment is almost the same in both rings, and its loss rate is 2.7×10^9 particles/s in the design goal. If we assume the Touschek lifetime is the same as that due to the collision, the loss rate would be doubled.

In order to keep high average luminosity the injection period should be very short compared with the experiment period. This is possible only when the injection rate, particularly of positron beam, is much larger than the total loss rate. The present positron injection system is not satisfactory for the B-factory. We plan to upgrade the positron injection by increasing the positron production rate and replacing the present accumulation ring with a rapid-cycle synchrotron. In order to increase the positron production rate the production target is moved, by which the conversion energy is multiplied by a factor of 8. At the same time the linac pulse length is increased from present 2 ns to 10 ns. With these linac upgrades the number of positrons per pulse would be, at least 8×10^8, ten times of the present value.

Positrons generated at the target is then accelerated, by the rest part of the linac, up to 0.6 GeV. The positron beam is transferred to a 0.6 GeV cooler ring, where the bunch length, the momentum spread and the emittance are reduced by radiation damping. The cooled positron bunch is then injected into the rapid-cycle synchrotron, accelerated to 3.5 GeV and transferred to the low-energy ring. The repetition rate of the linac and the synchrotron is 50 Hz. The injection rate is 4×10^{10} particles/s, exceeding the loss rate by a large factor.

The electron injection can be done without a cooler ring. The linac directly injects the electron beam into the rapid-cycle synchrotron. The synchrotron then accelerates the electron beam to 8 GeV and transfers to the high-energy ring at the same 50 Hz. We expect the electron injection rate is larger than that of positrons.

The most important reform of the injection system is the replacement of the present AR with the rapid-cycle synchrotron. The synchrotron has two acceleration modes, one for positron beam and the other for electron beam. The ring is to be switched between the two modes within several minutes. In the stationary operation we refill particles lost during the experiment in both rings, for example, every half an hour. Even with these injectors, however, we admit that the full injection time in the design goal is 1.5 hours, still long and boring. We are forced to realize a huge amount of particles required in the B-factory.

Reference

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