Chapter 2

Overview

2.1 Introduction

KEKB is an electron-positron collider with asymmetric beam energies of 3.5 GeV (positron) and 8 GeV (electron). It was operated at KEK from 1998 to 2010 and achieved the world-highest peak luminosity of 2.018 $\times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which is twice higher than the design luminosity of KEKB; 1 $\times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The Belle detector collected the integrated luminosity of more than 1 ab^{-1}. With this large amount of data, the Belle experiment accomplished various important physics outcomes including the verification of the Kobayashi-Masukawa theory as is described in the previous chapter.

SuperKEKB is the upgrade project of KEKB and aims at the peak luminosity of 8 $\times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which is 40 times higher than the achievement of KEKB and the integrated luminosity of 50 ab^{-1}. The Belle detector is also upgraded to Belle II and its physics goals are to search for New Physics (NP) in the flavour sector at the luminosity frontier as is described in the previous chapter. The configuration of SuperKEKB is shown in Fig. 2.1. The choice of machine parameters for achieving this design peak luminosity is explained in the next section.

2.2 Idea of nano beam scheme and choice of fundamental parameters

The fundamental machine parameters of SuperKEKB have been chosen based on the "nano beam scheme", which was first proposed for the Super B factory in Italy [1]. The basic idea of the nano beam scheme is to squeeze the vertical beta function at IP to extremes by minimizing the size of an overlap region of the two beams at IP,

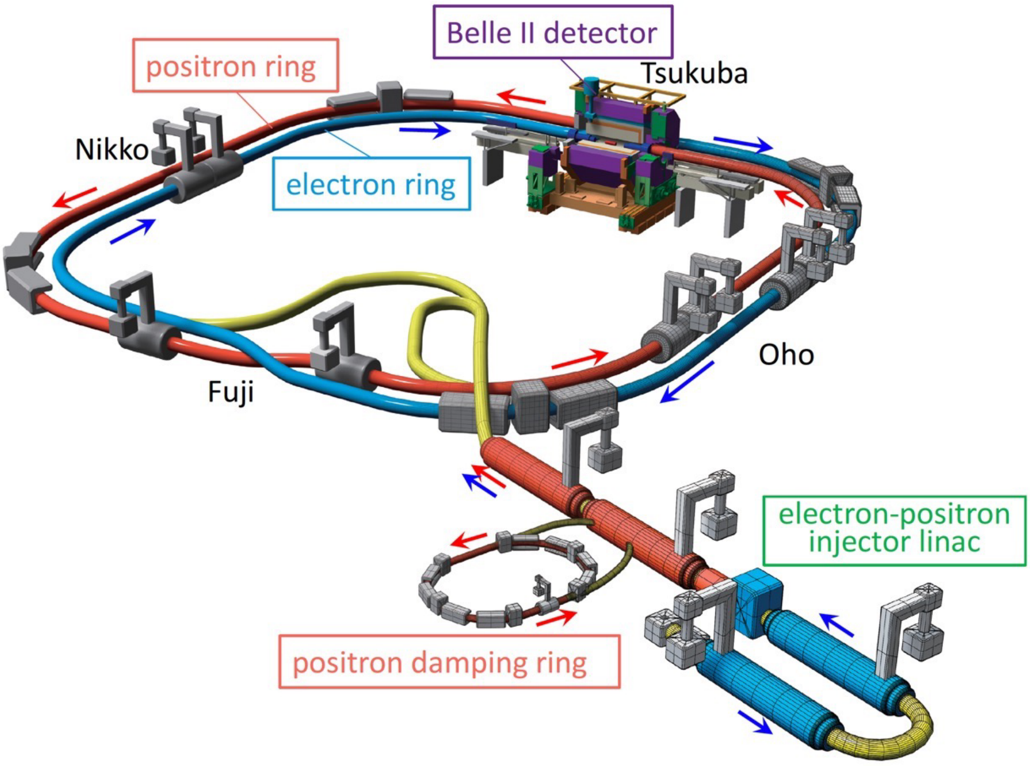

Figure 2.1: Configuration of the SuperKEKB accelerator system.

which generally limits the minimum value of the vertical beta function at IP through the "hourglass effect". Fig 2.2 shows a schematic view of the beam collision, which is a plane figure, in the nano beam scheme. The size of the overlap region is not determined by the bunch length (σ_z), which is the case of the head-on collision but by the much smaller region d, which is considered to be the effective bunch length for the nano beam scheme. The length d is determined by the half crossing angle (ϕ) and the horizontal beam size at IP (σ_x^*) with the following equation;

$$d \cong \frac{\sigma_x^*}{\phi}.$$

The hourglass condition in the nano beam scheme is expressed as

$$\beta_y^* \gtrsim d,$$

instead of that for a usual head-on collision of

$$\beta_y^* \gtrsim \sigma_z.$$

In the nano beam scheme, a relatively large horizontal crossing angle, extremely small horizontal emittances and horizontal beta functions at IP for both beams are required to shorten the length d. The ratio between σ_z and d is equal to the Piwinski angle defined as

$$\phi_{Piwinski} = \frac{\sigma_z}{\sigma_x^*}\phi.$$

The nano beam scheme is characterized by a large Piwinski angle and the angle determines to what extent β_y^* can be squeezed beyond the hourglass limit. Figure 2.3 shows the schematic view of the beam collision in the boosted frame in the horizontal direction so that the tilted two bunches (electron and positron) on the outside of the figure collide without the crossing angle. As for the luminosity and the beam-beam parameters, a collision of the two bunches on the inside of the figure, which are projected bunches of the outside bunches, gives the same values as the tilted bunches. Here, the effective horizontal beam size $\sigma_x^{effective}$ and the effective bunch length $\sigma_z^{effective}$ are defined as

$$\sigma_x^{effective} = \sigma_z \mathrm{sin}\phi,$$

and

$$\sigma_z^{effective} = \sigma_x / \mathrm{sin}\phi.$$

The luminosity is expressed as

$$L = \frac{1}{4\pi}\frac{N_p N_e}{\sigma_x^{effective}\sigma_y^*} f_{col} R_L.$$

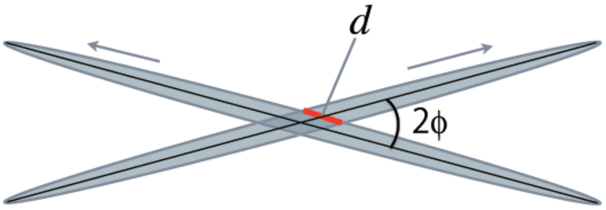

Figure 2.2: Schematic view of beam collision in nano beam scheme.

Here, N_p, N_e, σ_y^*, f_{col} and R_L are denote the number of positrons and electrons in a bunch, the vertical beam size at IP, the collision frequency and a reduction factor for the luminosity due to the crossing angle and the hourglass effect. In this formula, we assume that the horizontal and vertical beam sizes are the same for the two beams. Also in the formula of the beam-beam parameters, we have to use the effective horizontal beam size instead of the usual horizontal beam size. The parameter d is equal to the effective bunch length $\sigma_z^{effective}$ and the Piwinski angle is written as

$$\phi_{Piwinski} = \frac{\sigma_z}{\sigma_z^{effective}}.$$

The luminosity of colliders is also expressed by the following well-known formula assuming the flat beams and equal horizontal and vertical beam sizes for two beams at IP;

$$L = \frac{\gamma_\pm}{2er_e}\left(\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right).$$

Here, the suffix ± specifies the positron (+) or the electron (−). The parameters γ, e and r_e are the Lorenz factor, the elementary electric charge and the electron classical radius, respectively. These are constant or a parameter which can not be taken freely. The parameter R_{ξ_y} represents a reduction factor for the vertical beam-beam parameter, which arises from the crossing angle and the hourglass effect. The ratio of these parameters is usually not far from unity. Therefore, the luminosity is mainly determined by three fundamental parameters; *i.e.* the total beam current (I), the vertical beam-beam parameter (ξ_y) and the vertical beta function at IP (β_y^*). Choice of these three parameters, the beam energy and the luminosity is shown in Table 2.1 together with those of KEKB.

As for the vertical beam-beam parameter ξ_y, we assume almost the same values as that achieved in KEKB. The vertical beta functions at IP β_y^* for SuperKEKB are almost by a factor 20 smaller than those of the KEKB owing to the adoption of the nano beam scheme. Assuming these parameters, to achieve the luminosity goal of

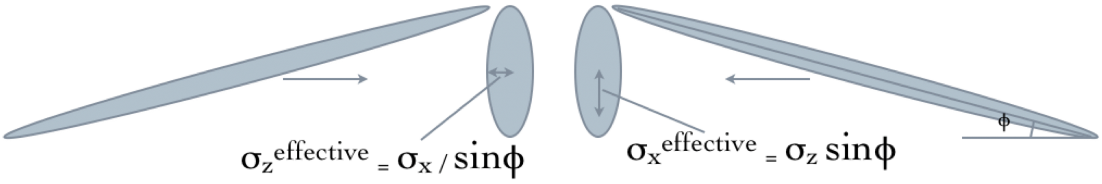

Figure 2.3: Schematic view of beam collision in nano beam scheme in a boosted frame.

Table 2.1: Fundamental parameters of SuperKEKB and KEKB.

	KEKB Achieved	SuperKEKB
Energy (GeV) (LER/HER)	3.5/8.0	4.000/7.007
ξ_y (LER/HER)	0.129/0.090	0.0881/0.0807
β_y^* (mm) (LER/HER)	5.9/5.9	0.27/0.30
I (A) (LER/HER)	1.64/1.19	3.6/2.6
Luminosity ($10^{34}\text{cm}^{-2}\text{s}^{-1}$)	2.11	80

SuperKEKB, $8 \times 10^{35}\text{cm}^{-2}\text{s}^{-1}$, we need to double the total beam currents compared with those of KEKB. The choice of the beam energy is explained below.

2.2.1 Machine parameters of SuperKEKB

Machine parameters of SuperKEKB including the three fundamental parameters are shown in Table 2.2. In the following, it is shown how these parameters are determined.

2.2.2 Emittance, crossing angle, beta functions at IP

To realize the nano beam scheme, the effective bunch length $d(= \sigma_x^*/\phi)$ should be small. Of the two parameters of σ_x^* and ϕ, smaller σ_x^* is more important than larger ϕ, since it becomes difficult to obtain the design beam-beam parameter if we decrease d only by enlarging ϕ. In the nano beam scheme, each particle in a bunch interacts with a small portion of the other colliding bunch. To obtain the design value of ξ_y, extremely small horizontal and vertical beam sizes are needed. In the optics design of SuperKEKB, we have made efforts to minimize the horizontal emittance as much as possible with a constraint that most of magnets of KEKB will be reused. The design values of the horizontal emittance shown in Table 2.2, which are by a factor 5 smaller than those of KEKB, include some enlargements due to the intra-beam scattering. Values at zero

Table 2.2: Machine Parameters of SuperKEKB.

		LER (e+)	HER (e-)	units
Beam Energy	E	4.000	7.007	GeV
Circumference	C	3016.315		m
Half Crossing Angle	ϕ	41.5		mrad
Emittance	ε_x	3.2(1.9)	4.6(4.4)	nm
Emittance ratio	$\varepsilon_y/\varepsilon_x$	0.27	0.28	%
Beta Function at IP	β_x^*/β_y^*	32 / 0.27	25 / 0.30	mm
Horizontal Beam Size	σ_x^*	10	11	μm
Vertical Beam Size	σ_y^*	48	62	nm
Betatron tune	ν_x/ν_y	44.53/46.57	45.53/43.57	
Momentum Compaction	α_c	3.20×10^{-4}	4.55×10^{-4}	
Energy Spread	σ_ε	$7.92(7.53) \times 10^{-4}$	$6.37(6.30) \times 10^{-4}$	
Beam Current	I	3.6	2.6	A
Number of Bunches/ring	n_b	2500		
Energy Loss/turn	U_0	1.76	2.43	MeV
Total Cavity Voltage	V_c	9.4	15.0	MV
Harmonic number	h	5120		
Synchrotron Tune	ν_s	-0.0245	-0.0280	
Bunch Length	σ_z	6.0(4.7)	5.0(4.9)	mm
Beam-Beam Parameter	ξ_y	0.0881	0.0807	
Luminosity	L	8×10^{35}		$\mathrm{cm}^{-2}\mathrm{s}^{-1}$

*) Values in parentheses denote parameters at zero beam currents. The vertical beam sizes include the beam-beam blowup.

beam currents are shown in the parentheses. The horizontal beta functions at IP are also very small compared with those of KEKB the typical value of which is 1.2 m. Even with the very small horizontal emittances and the horizontal beta functions at IP, rather small x-y coupling of 0.27 $\sim$ 0.28 % is needed to obtain the design values of ξ_y. The half crossing angle ϕ is 41.5 mrad and is about 4 times larger than that of KEKB. This choice of ϕ also contributes to decreasing the effective bunch length d. However, the design value of ϕ has been determined mainly considering the IR optics and magnet design and the detector background. With a large crossing angle, the final focus quadrupole magnets can be independent for the two beams which brings a great merit of much lower detector background due to the synchrotron radiation. Another merit of a larger crossing angle is that the final focus quadrupole magnets can be placed closer to the IP, which contributes to widening dynamic aperture. Dynamic aperture is one of the most serious issues of SuperKEKB in the nano beam scheme. Narrow dynamic aperture shortens the beam lifetime from the Touschek effect and the lost particles can not be compensated by the injector if the lifetime is too short. With the parameters in Table 2.2, the effective bunch length d is $\sim$ 0.24 mm and $\sim$ 0.25 mm for LER and HER, respectively. From the viewpoint of the hourglass condition, even smaller values of β_y^* are possible than those in Table 2.2. However, there exists another restriction for β_y^*, dynamic aperture. The achievable values of β_y^* in SuperKEKB are restricted more strictly by dynamic aperture than by the hourglass effect.

2.2.3 Beam energy

In SuperKEKB, the beam energies have been changed from the KEKB values of 3.5 and 8.0 GeV to 4.0 and 7.0 GeV. This change was decided from motivations of the accelerator design. In the nano beam scheme, the emittance growth from the intra-beam scattering and the short beam lifetime from the Touschek effect are very serious problems particularly in LER. The increase in the beam energy of LER from 3.5 to 4.0 GeV is very helpful to mitigate these problems. An impact of this change of the beam energy asymmetry on the physics sensitivity is discussed elsewhere in this report.

2.2.4 Beam-beam parameter

As a design value of ξ_y, we assumed the value of 0.09 which was actually achieved in KEKB. However, this value of KEKB was achieved by using the crab cavities which enable effectively a head-on collision in the crossing angle collision system. SupeKEKB will adopt a large crossing angle. Therefore, we need a careful study of the effect of the crossing angle on the achievable value of ξ_y. In the case of the crossing angle, there exists another kind of hourglass effect. A particle with a finite horizontal offset at IP collides with (the center of) the other beam at the place where the vertical beta function β_y is larger than its minimum value β_y^*. The difference of β_y from its minimum value depends on the amount of the horizontal offset. This shift of the collision point from the vertical waist position depending on the horizontal offset brings another kind of hourglass effects. This hourglass effect could possibly degrade the beam-beam performance and lower the achievable value of ξ_y. It is known that this effect can be avoided by using so-called the "crab waist" scheme [1]. The crab waist scheme shifts the vertical waist position using sextupole magnets so that the vertical waist positions of one beam are aligned along the trajectory of the other beam around IP. Beam-beam simulations have been done based on the strong-weak mode to investigate the beam-beam performance in the nano beam scheme including effectiveness of the crab waist scheme. The simulations showed that effectiveness of the crab waist scheme depends on machine parameters and with the parameters of SuperKEKB shown in Table 2.2 the luminosity improvement with the crab waist scheme is only about 10 %. The simulation also showed that the design values for ξ_y is achievable with the design parameters in Table 2.2 without the crab waist scheme. In the present design of SuperKEKB, we does not employ the crab waist scheme. However, we still consider the crab waist scheme as a backup option. A tune survey was also done in the beam-beam simulations to find the best working point. The fractional parts of the betatron tunes shown in Table 2.2 were determined by the simulation to maximize ξ_y. The optimum horizontal tune is not so near to the half integer as the case of KEKB.

2.2.5 Beam current and beam current related parameters

To achieve the target luminosity of $8 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with the design values of β_y^* and ξ_y in Table 2.2, the beam currents of 3.6 and 2.6 A are needed for LER and HER, respectively. These currents are about twice as high as those of KEKB. We have been conducting R&D's for hardware components such as the vacuum system and the RF system assuming even higher beam currents of 9.4 and 4.1A. These currents had been assumed before we adopted the nano beam scheme. Feasibility of the present design beam currents are ensured by these long-term R&D's. The number of bunches per ring (n_b) is 2500, which implies that every other RF buckets are filled with the beams. If we decrease n_b with keeping the total beam currents, which means higher bunch currents, then we can obtain the same luminosity with a larger x-y coupling. That will somewhat relax difficulty of the optics design or the x-y coupling correction in the actual beam operation. However, the higher bunch currents bring other problems such as difficulty of handling higher HOM power, single bunch instabilities like the micro-wave instability or the emittance growth due to the intra-beam scattering. With the design value of n_b in Table 2.2, it has been confirmed that these problems are tolerable. As for the bunch length σ_z, a shorter bunch is preferable, since with a longer bunch length we need to decrease the x-y coupling or increase the bunch currents to compensate lower particle densities at the beam overlap region of the two beams at IP. However, several bunch lengthening effects, the potential-well distortion, the micro-wave instability and the intra-beam scattering, prevent us from achieving a short bunch length. The calculations of σ_z considering these effects with the wakefield including the effect of CSR (Coherent Synchrotron Radiation) showed that the design values of σ_z in the Table 2.2 are attainable. The RF voltages in Table 2.2 were adjusted so that the design value for σ_z is obtained at the design bunch currents with the effects mentioned above. As for the energy spread σ_ε, we also made calculations on the effect of the micro-wave instability at the design bunch currents. Although some enlargements of σ_ε are expected, they are still tolerable.

Bibliography

[1] P. Raimondi, 2nd SuperB Workshop, Frascati, (2006).