Chapter 2

Machine Parameters

2.1 Luminosity, tune shift, beam intensity

KEKB is a double-ring asymmetric e^+e^- collider at 3.5 GeV×8 GeV. Its target peak luminosity is $\mathcal{L} = 10^{34}$ cm^{-2}s^{-1}. To determine basic machine parameters, we begin with the most fundamental equations for the luminosity and vertical beam-beam tune shift:

$$\mathcal{L} = \frac{N_1 N_2 f}{4\pi\sigma_x^*\sigma_y^*} R_{\mathcal{L}}\left(\theta_x, \beta_x^*, \beta_y^*, \varepsilon_x, \varepsilon_y, \sigma_z\right) \ , \tag{2.1}$$

$$\xi_{yk} = \frac{N_{3-k} r_e \beta_{yk}^*}{2\pi\gamma_k\left(\sigma_x^* + \sigma_y^*\right)\sigma_y^*} R_{\xi y}\left(\theta_x, \beta_x^*, \varepsilon_x, \varepsilon_y, \beta_y^*, \sigma_z\right) \ . \tag{2.2}$$

Here, $N_{1,2}$ is the number of particles per bunch, and f is the bunch collision frequency. The suffix $k = 1, 2$ specifies each beam in the low energy ring (LER) and high energy ring (HER). The θ_x is the half crossing angle at the interaction point (IP). The functions $R_{\mathcal{L}}$ and $R_{\xi y}$ represent reduction factors for the luminosity and the vertical tune shift, which arise from the crossing angle and the hour-glass effect. Since there is no obvious reason for choosing unequal beam parameters, except for the number of particles per bunch, we simply set ξ_y, $\beta_{x,y}^*$, $\varepsilon_{x,y}$, and σ_z to be equal for the two beams. This implies that $N_1\gamma_1 = N_2\gamma_2$.

The possibility of a round-beam collision has been excluded. With a round beam with small β^* in two planes, so far no consistent design solutions have been found with an acceptable dynamic aperture and with a feasible two beam separation at the IP. We thus combine Equations 2.1 and 2.2, and by assuming equal beam-parameters and flat beams ($\sigma_x^* \gg \sigma_y^*$),

$$\mathcal{L} = \frac{\gamma_k I_k \xi_y}{2 e r_e \beta_y^*} \frac{R_{\mathcal{L}}}{R_{\xi y}} \ , \tag{2.3}$$

where $I_k = N_k e f$ is the current for each beam, with $k = 1, 2$. It should be pointed out that if the relation $\beta_y^* \gg \sigma_z$ holds (*i.e.* if the hour-glass effect is small), the ratio of the reduction factors above becomes close to a unity,

$$\frac{R_{\mathcal{L}}}{R_{\xi y}} \approx 1 \ . \tag{2.4}$$

This means that Equation 2.3 can be rewritten in a form that is nearly independent of the choice of the crossing angle. Thus, to a good approximation,

$$\mathcal{L} \approx \frac{\gamma_k I_k \xi_y}{2 e r_e \beta_y^*} \ . \tag{2.5}$$

Equations 2.3, 2.4 and 2.5 state that while the luminosity may be reduced due to the crossing angle, the beam-beam interaction is also reduced by approximately the same ratio. Therefore, if the dynamics of the beam-beam interaction with the crossing angle allows the same value of ξ_y as for the head-on collision, there is no loss of the luminosity for a fixed total beam current. Figure 2.1 shows the calculated reduction factors and the ratio $R_{\mathcal{L}}/R_{\xi y}$ as functions of the half crossing angle θ_x. Note that the reduction factors above simply involve geometric effects due to the crossing angle and the hour-glass effect. No effects due to the dynamics of the beam-beam interactions are included.

In the design of KEKB, we assume $\xi_y \approx 0.05$ and $\beta_y^* = 1$ cm. Then, the beam intensities required for $\mathcal{L} = 10^{34}$ cm^{-2}s^{-1} are $I = 2.6$ A for the LER and $I = 1.1$ A for the HER. Exactly how much luminosity will be actually available at KEKB can be answered only after operating the machine and after examining where the performance limitations come from. Re-optimization of operating parameters will naturally follow studies during operation. An important issue concerning the design of KEKB at this stage is to allocate some flexibility in the parameter space, so that such changes in the future can be easily accommodated. Details of some of the specific issues are discussed in subsequent chapters.

2.2 Crossing angle

Near the IP a rapid two beam separation is necessary in order to maintain optimized focusing of the LER and the HER beams without significantly increasing the chromaticity. Suppression of emerging parasitic crossing effects also calls for a good beam separation, except the designated IP.

Several beam separation schemes based on horizontal bend magnets, a finite beam crossing angle, and their mixed combinations have been examined for KEKB. For

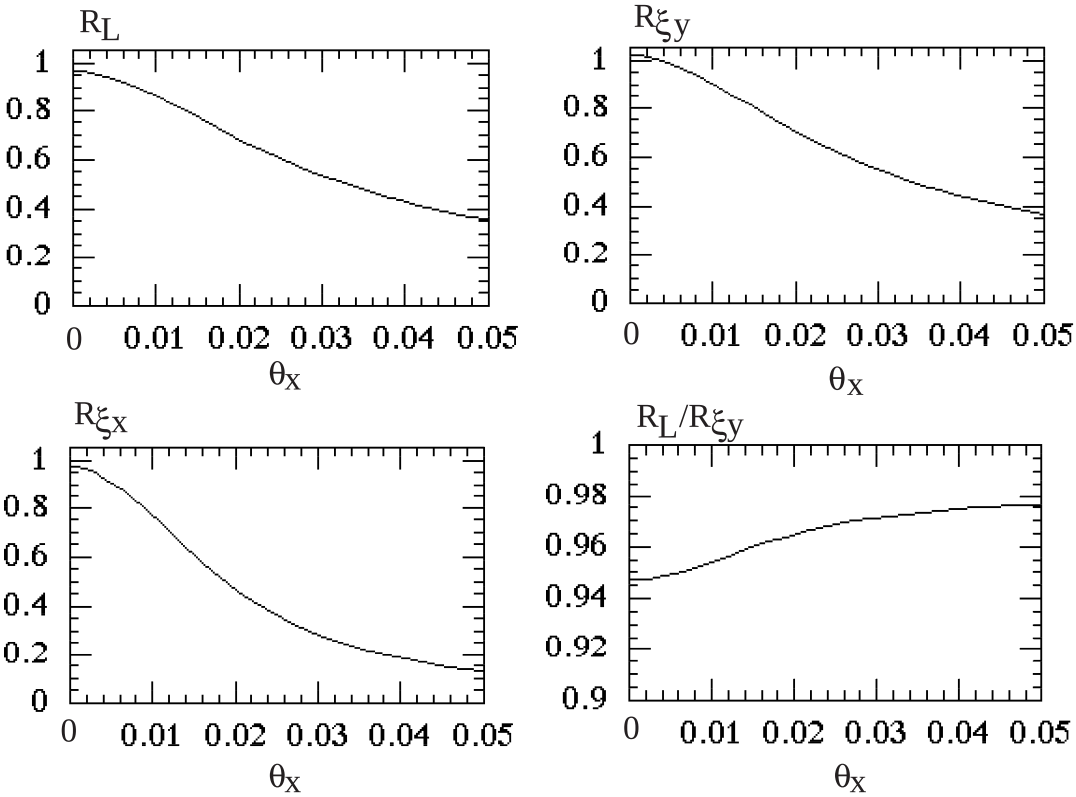

Figure 2.1: Reduction factors of the luminosity and tune shifts as functions of the half crossing angle θ_x. Other parameters are KEKB's. The ratio $R_{\mathcal{L}}/R_{\xi y}$ is always close to unity.

example, it has been found that to allow more than a $20\sigma_x$ beam separation at the first parasitic crossing point, it will be very difficult to accommodate a bunch spacing s_b below 3 m if a small or zero crossing angle at the IP ($\theta_x \leq 3$ mrad) is to be maintained. The reasons include:

- The separation bend magnets will have to be strong (> 0.6 T) compared to the standard bend magnets in the arc sections, leading to significant problems in handling synchrotron radiation in the vicinity of the IP.

- There is a severe limitation of geometrical space available for separation bends very close to the IP (*i.e.* a distance comparable to a half of the bunch spacing).

However, the situation can change significantly when a larger beam crossing angle is allowed. A brief summary of the hardware and beam-dynamics issues involved in the beam separation of varying crossing angle choices is given in Table 2.1.

Crossing angle	Hardware	Beam dynamics
0 mrad	Very compact separation bend magnets (such as permanent magnets) are necessary.	Rapid beam separation is critical for staying away from parasitic crossing effects
2 mrad	Superconducting separation bend is feasible with a reasonable field strength (< 0.7 T).	Synchro-betatron resonance OK?
5 mrad		Comfortable for parasitic crossing effects with $s_b \approx 0.6$ m.
8 mrad	Separation bend magnets are no longer necessary.	
10 mrad		Synchro-betatron resonances OK? Need to be checked.
20 mrad	Use of common quadrupole magnet for two opposing beams per side becomes painful.	Increased need for Crab-crossing.

Table 2.1: Possible choices of the crossing angle, and their implications to the hardware design and beam dynamics.

The big advantage of a moderately large crossing angle of $\theta_x \geq 10$ mrad is that although it eliminates the need for separation bend magnets, it allows final focusing with superconducting quadrupole magnets with reasonable inner aperture sizes. It also offers a flexible configuration that permits a wide range of combinations of the bunch intensity vs. bunch spacing for varying center-of-mass energies. The scheme allows us to safely stay away from potential problems due to parasitic crossing effects. The critical energy of synchrotron radiation that passes through the IP is also significantly reduced by not using separation bend magnets.

It has been estimated that with a crossing angle of $\simeq 3$ mrad or less, the maximum achievable luminosity, with its inevitably large bunch spacing ($\simeq 3$ m), is roughly 3×10^{33} cm^{-2}s^{-1}. Therefore, assuming that full-bunch operation with $s_b = 0.6$ m is eventually possible from RF and multi-bunch stability viewpoints, a scheme with a crossing angle of $\simeq 10$ mrad brings big advantages, if the beam-beam parameter can be maintained at $\xi_y \geq 0.015$. Thus, the critical question is how the beam dynamics behavior will be with finite crossing angles. To investigate this issue, we have conducted extensive simulation studies on the beam-beam interaction with finite crossing angles. The results, as detailed in later chapters, demonstrate an absence of serious degradations at many operating points.

From these considerations and from practical evaluations of the accelerator layout near the IP, we have chosen the half-crossing angle θ_x to be 11 mrad. As a fall-back position, the use of a crab-crossing scheme with superconducting cavities is also being considered. It will serve as a cure to reduce the remaining luminosity degradation, or to extend the acceptable combinations of operating parameters. It should be noted that a crossing angle 11 mrad is close to the minimum that allows us to eliminate the IP separation bend magnets. It is also nearly the maximum crossing angle that allows final focusing of both beams at the IP with common quadrupole magnets. If separate quadrupole magnets are to be used for the two beams, hardware design constraints will force us to use a crossing angle larger than 40 mrad. In that case, the field strength of the crab cavities will have to be increased four-fold, and their reliable operation can be problematic. Up to now the 11 mrad value for the half crossing angle is the most preferred one.

2.3 Bunch length

A shorter bunch length is preferred for reduced intrinsic synchrotron-betatron coupling in the beam-beam interaction. It is also preferred for reduced hour-glass and reduced crossing-angle effects. The lower limit of the bunch length is given by the single-bunch longitudinal instability, Touschek lifetime, and the required accelerating voltage. We have chosen the bunch length to be $\sigma_z \geq 4$ mm, which is close to the minimum possible value. Here, the bunch-lengthening due to a potential-well distortion needs to be taken into account. The target value of 4 mm includes this bunch-lengthening effect of 20% in the LER. As detailed in subsequent chapters, the lattice design of KEKB will allow us to tune the momentum compaction over a wide range, so that the actual bunch length can be optimized by looking at the beam behavior.

2.4 Bunch spacing

The bunch spacing is the next parameter to be determined. First, the accelerating RF frequency should be $\sim$ 508 MHz, because the RF resources at TRISTAN, which will be reused at KEKB, are based on this frequency. Therefore, the allowed bunch spacing will be an integer multiple of $\sim$ 0.59 m. Since the total beam current has been determined to be 2.6 A for the LER and 1.1 A for the HER, the number of particles per bunch is proportional to the bunch spacing. The hardest limit on the number of particles per bunch comes from the longitudinal single-bunch threshold for the LER. At KEKB, the threshold bunch intensity is about 2.5 times the bunch intensity for the minimum bunch spacing of $s_b = 0.6$ m. Therefore, either $s_b = 0.6$ m or $s_b = 1.2$ m is a possible choice.

Second, we examine the relation between the required bunch intensity and emittance. The vertical beam-beam tune shift given by Equation 2.2 can be rewritten as

$$\xi_{yk} = \frac{N_{3-k} r_e}{2\pi\gamma_k} R_{\xi y} \sqrt{\frac{\beta_y^*}{\kappa\beta_x^*}} \frac{1}{\varepsilon_x} \,, \tag{2.6}$$

where $\kappa = \varepsilon_y/\varepsilon_x$ is the ratio of the horizontal and vertical emittance. We thus obtain the relation

$$\varepsilon_x \propto \frac{N}{\sqrt{\kappa\beta_x^*}} \,. \tag{2.7}$$

Consequently, if the emittance ratio κ and β_x^* are kept constant, the required horizontal emittance is proportional to the bunch spacing, because $N \propto s_b$. Another reason for increasing the emittance, besides Equation 2.7, is the need for maintaining a sufficiently long Touschek beam lifetime for an increased bunch intensity when the bunch spacing is increased.

However, design considerations concerning the interaction region limit the practical maximum beam emittance. This is because when the beam emittance is increased for a fixed β_x^* at IP, the angular divergence there is also increased, resulting in an increased synchrotron radiation background to the detector. Although a smaller emittance coupling ratio may allow a larger emittance without increasing the angular divergence, it will be problematic to rely on delicate operating conditions of this sort.

In conclusion, at KEKB we have chosen s_b=0.6 m as the standard value. Consequently, the number of particles per bunch with $s_b = 0.6$ m is set as $N = 3.3 \times 10^{10}$ for the LER and $N = 1.4 \times 10^{10}$ for the HER.

2.5 Emittance

When the bunch spacing is chosen, and once the β_x and κ are given, the horizontal emittance is determined by Equation 2.7. As stated earlier, although a smaller β_x^* is preferred for a larger κ, there is a limit given by the angular divergence limit at IP. The horizontal beam-beam tune shift, which can be written as

$$\xi_{xk} = \frac{N_{3-k} r_e}{2\pi \gamma_k \varepsilon_x} R_{\xi x} \left(\theta_x, \beta_x^*, \beta_y^*, \varepsilon_x, \varepsilon_y, \sigma_z \right) \ , \tag{2.8}$$

also speaks for reduced horizontal emittance. The horizontal tune shift does not have to be equal to the vertical value. However, it should not be significantly larger than 0.05, which corresponds to $\varepsilon_x = 1.4 \times 10^{-8}$ m. We have chosen the horizontal emittance so that the luminosity given by the strong-weak beam-beam simulation is maximized in the allowable range. The results are $\beta_x^* = 33$ cm, $\kappa = 2.4\%$, and $\varepsilon_x = 1.8 \times 10^{-8}$. With this choice, the bunch diagonal angle at the IP σ_x^*/σ_z will be 19 mrad, nearly equal to the total beam crossing angle. The reduction ratios, luminosity, and tune shifts are summarized in Table 2.2.

The lattice design (discussed in detail in Chapter 6) will incorporate quadrupole magnet "knobs" so that it can vary the horizontal emittance in the range of $1.0 \times 10^{-8} \leq \varepsilon_x \leq 3.6 \times 10^{-8}$ m. This is to manage possible changes of the bunch spacing, angular divergence, beam intensity, and emittance ratio under actual operating conditions. For instance, full-current operation with $s_b = 1.2$ m instead of 0.6 m will be possible by using this measure.

2.6 Momentum spread and synchrotron tune

The momentum spread of the beam is set to be $\sim 0.07\%$, which is close to the upper limit value from a high energy physics experiment viewpoint, which prefers a small energy spread. From accelerator design considerations, it is hard to reduce the energy spread much below 0.07% without decreasing the radiation damping rate.

The last issue among the choice of basic parameters is the synchrotron tune ν_s, and the momentum compaction factor α_p. Since the bunch length and the momentum spread σ_δ have been determined, ν_s and α_p are not independent. They are related as

$$\sigma_z = \frac{c\alpha_p}{\omega_s}\sigma_\delta \ , \tag{2.9}$$

where $\omega_s = 2\pi\nu_s/T_0$ is the synchrotron frequency. Generally speaking, a large ν_s induces pronounced synchro-betatron resonances, due to lattice nonlinearity effects and beam-beam interactions. It also causes an anomalous emittance growth at synchro-betatron resonance lines. A small value of $\nu_s \leq 0.02$ is necessary to have a sufficiently large tune space as the possible operational parameter space.

On the other hand, a small ν_s decreases the threshold for single-bunch instabilities. Also, higher-order momentum compaction can be more harmful with a small α_p for synchrotron motions with large amplitudes.

Our choice is $\nu_s = 0.015$ for both the LER and the HER. However, the lattice design of KEKB will incorporate another set of quadrupole strength "knobs," so that it can vary the momentum compaction in the range $-1 \times 10^{-4} \leq \alpha_p \leq 4 \times 10^{-4}$, without affecting the horizontal beam emittance.

2.7 Other Issues

The particles in the LER have been chosen to be positrons, so as to reduce the effects of the ion trapping phenomenon of residual gas molecules in the vacuum chamber. In the HER (*i.e.* electron ring), 100–500 of RF buckets need to be left vacant in order to avoid ion trapping. Even if ions are not trapped, transient ions created by the bunch train may interact with the trailing bunches, and a beam break-up phenomenon may result, as has been observed in linear accelerators. Studies of these phenomena are in progress.

The radiation damping time of the LER is longer than that of the HER's by a factor of 2, if the sole source of radiation is bending due to dipole magnets in the lattice. A room will be allocated in straight sections of the LER to implement damping wiggler magnets, if it is found necessary to change the LER damping time.

The machine parameters are listed in Table 2.2.

		LER	HER	
Beam Energy	E	3.5	8.0	GeV
Luminosity	$\mathcal{L}$	1.0×10^{34}		$\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Luminosity Reduction Factor	$R_{\mathcal{L}}$	0.845		
Half crossing angle	θ_x	11		mrad
Tune shifts	ξ_x/ξ_y	0.039/0.052		
Tune shift reductions	$R_{\xi x}/R_{\xi y}$	0.737/0.885		
Beta functions	β_x^*/β_y^*	0.33/0.01		m
Beam current	I	2.6	1.1	A
Bunch spacing	s_b	0.59		m
Particles/bunch	N	3.3×10^{10}	1.4×10^{10}	
Number of bunches/ring	N_B	5000		
Emittance	$\varepsilon_x/\varepsilon_y$	$1.8 \times 10^{-8}/3.6 \times 10^{-10}$		m
Bunch length	σ_z	4		mm
Momentum spread	σ_δ	7.1×10^{-4}	6.7×10^{-4}	
Synchrotron tune	ν_s	0.01∼0.02		
Momentum compaction factor	α_p	$1 \times 10^{-4} \sim 2 \times 10^{-4}$		
Betatron tunes	ν_x/ν_y	45.52/46.08	47.52/43.08	
Circumference	C	3016.26		m
Damping time	τ_E	44.9	22.5	ms

Table 2.2: Machine Parameters of KEKB.