KEKB Accelerator

Lattice of the KEKB colliding rings

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This paper describes a few outstanding features of the beam-optical lattice of the KEKB colliding rings. A chromaticity correction scheme with non-interleaved sextupole pairs, a new cell structure with 2.5π betatron phase advances, etc. have been introduced. The lattice successfully squeezed the vertical beta functions at the interaction point, which greatly contributed to the achievement of the world’s highest luminosity.

1. Introduction

The KEKB B-Factory [1] was an energy-asymmetric double-ring collider, which consisted of an 8 GeV electron ring (high-energy ring, HER), a 3.5 GeV positron ring (low-energy ring, LER), and an injector linac. KEKB delivered the world’s highest luminosity since 2001 and achieved a record of $2.11 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$, which was more than twice the design value [2,3]. The performance of the beam-optical lattice of the KEKB colliding rings made a significant contribution to achieving the luminosity [4], as well as other innovative features of KEKB beyond the previous colliders.

As is well known, higher luminosity values in ring colliders require higher stored beam currents $I_{\pm}$, larger vertical beam–beam tune-shift parameters $\xi_{y\pm}$, and smaller vertical beta functions at the interaction point (IP) $\beta_{y\pm}^*$. Among these three key parameters ($I_{\pm}$, $\xi_{y\pm}$, and $\beta_{y\pm}^*$), $\beta_{y\pm}^*$ are directly related to the lattice design. The smallest attainable value of $\beta_{y\pm}^*$ depends on not only the design of the interaction region (IR) but also the lattice of all the rings.

Large chromaticity is inherent in a ring collider with small $\beta_{y\pm}^*$ insertion. To compensate the chromaticity, strong sextupole magnets are required in such rings, whose dynamic apertures easily shrink if special care is not taken when handling the nonlinearities of the sextupole magnets. One of the most serious issues for the lattice design is how to ensure sufficient dynamic aperture for good injection efficiency and long beam lifetime.

KEKB aimed to squeeze $\beta_{y}^*$ to 1 cm, which corresponded to a vertical beam size of $\sim 2 \text{ \mu m}$ at the IP. For this purpose, various unique features, such as a chromaticity correction scheme with non-interleaved sextupole pairs (an application for a storage ring is seen in Ref. [5]), a new cell structure with 2.5π phase advances, local chromaticity correction in the IR etc., were introduced in the lattice of the KEKB rings [1,6–8]. These features are described in this paper.

2. Machine parameters

The main machine parameters of KEKB are listed in Table 1. These parameters are related to each other in a complicated way. Their selection strategy [1] is summed up here.
Table 1. Machine parameters of KEKB, achieved and designed [1,4,18]. Both designed and achieved (22 mrad crossing angle and crab crossing) parameters are listed. The vertical beam sizes at the IP in this table were estimated from the luminosity on the assumption that they were equal in both rings and that the $\beta^*$s were not changed by the beam–beam interaction.

| Eff. crossing angle | 6/17/2009 LER | 11/15/2006 LER | Design LER | Design HER |
|---------------------|---------------|----------------|------------|------------|
| Current            | 1.64          | 1.19           | 1.65       | 1.33       |
| Bunches            | 1584          | 1389           | 5000       |            |
| Current/bunch      | 1.03          | 0.75           | 1.19       | 0.96       |
| Spacing            | mostly 1.8    | 1.8 or 2.4     | 0.6        |            |
| Horizontal emittance $\varepsilon_x$ | 18            | 24             | 18         | 24         |
| Emittance ratio $\kappa$ | 0.0083       | 0.0062         | 0.034      | 0.025      |
| $\beta^*_x$        | 120           | 120            | 59         | 56         |
| $\beta^*_y$        | 0.59          | 0.59           | 0.65       | 0.59       |
| Hor. size @IP      | 147           | 170            | 103        | 116        |
| Ver. size @IP      | 0.94          | 0.94           | 1.9        | 1.9        |
| Bunch length       | $\sim$7       | $\sim$7       | 4          |            |
| Momentum compaction| 3.3           | 3.4            | 3.3        | 3.3        |
| Energy spread      | 7.3           | 6.7            | 7.3        | 6.7        |
| Synchrotron tune $\nu_t$ | $-0.025$ | $-0.021$ | $-0.025$ | $-0.021$ |
| Betatron tune $\nu_x$ | 45.506       | 44.511         | 45.505     | 44.509     |
| Betatron tune $\nu_y$ | 43.561       | 41.585         | 43.534     | 41.565     |
| $\xi_x$            | 0.127         | 0.102          | 0.116      | 0.134      |
| $\xi_y$            | 0.129         | 0.090          | 0.101      | 0.056      |
| Luminosity         | 21.08         | 17.6           | 10         |            |

The crossing angle at the IP was one of the key choices that had to be decided at the beginning. We relied on beam–beam simulations and chose a 22 mrad horizontal crossing angle, while preparing crab crossing [9,10] as a backup.

In the design stage, at first, $\xi_y$ was assumed to be $\sim$0.05, which was nearly the maximum value achieved by any collider in the world around 1995, and $\beta^*_y$ was chosen to be 1 cm, which was also the shortest at that time. Then the total beam currents $I_{\pm}$ were determined from the target luminosity according to the formula

$$L = \frac{\gamma_{\pm}}{2er_e} \left(1 + \frac{\sigma_y^*}{\beta_y^*} \right) \left( \frac{I_{\pm} \xi_y}{\beta_y^*} \right) \left( \frac{R_L}{R_{\xi_y}} \right),$$

where the beam sizes at the IP $\sigma^*_x, \beta^*_y,$ and $\xi_y$ were assumed to be equal in both rings. The parameters $R_L$ and $R_{\xi_y}$ are correction factors for the geometrical loss due to the crossing angle at the IP and the hour-glass effect. Equations (1) and (2) are derived in Ref. [1].

After fixing the three key parameters, the other main parameters were selected from various viewpoints, such as:

- The bunch length $\sigma_z$ should be shorter than half of $\beta_y^*$ in order to keep the hour-glass effect and the synchrotron–betatron coupling caused by the beam–beam effect within a tolerable magnitude.
- The number of particles per bunches $N_{\pm}$ should be smaller than the threshold of the longitudinal single-bunch instabilities. Based on the estimation of the threshold intensity in the LER, one and two rf-bucket spacings were acceptable [11]. One rf-bucket spacing, which was the lowest bunch...
intensity, was selected as the design value. The rf-frequency had to be almost equal to that of TRISTAN (see, e.g., Ref. [12]) to recycle the existing rf components.

- The horizontal emittance $\varepsilon_x$ should be adjusted to be $\varepsilon_x \propto (N_{\pm}/\sqrt{\kappa \beta_x^*})$ according to the expression

$$\xi_y \approx \frac{r_e N_{\pm} \beta_y^*}{2\pi \gamma_\pm \sigma_y^* (\sigma_x^* + \sigma_y^*)} R_{\xi_y} \approx \frac{r_e \sqrt{\beta_y^*}}{2\pi \gamma_\pm \varepsilon_x \sqrt{\kappa \beta_x^*}} R_{\xi_y}, \quad (2)$$

where the vertical-to-horizontal emittance ratio $\kappa$ and the horizontal beta function at the IP $\beta_x^*$ are assumed to be equal in both rings. If $\kappa$ and $\beta_x^*$ are constant, $\varepsilon_x$ should be proportional to $N_{\pm}$.

- The momentum spread $\sigma_\delta$ should be near the maximum allowed by the Belle experiment [13,14] in order to make the radiation damping time as short as possible. In order to halve the damping time in the LER, wiggler magnets with the same total effective length as the main dipole magnets were installed. Thus the total length of the wiggler magnet poles reached 76 m (the total effective length was 105 m).

- The synchrotron tune $\nu_s$ should be small in order to keep a wide working area in the betatron tune space (the $\nu_x - \nu_y$ space), avoiding the effects of synchrotron–betatron resonances caused by lattice nonlinearities and the beam–beam effect. Weak–strong beam–beam simulations showed that the small $\nu_s$ ($|\nu_s| \leq 0.02$) and the short $\sigma_z$ (=4 mm) retained a sufficiently large area in the $\nu_x - \nu_y$ space to reach the design luminosity, although the crossing angle at the IP induced synchrotron–betatron resonances [1,15].

- The momentum compaction factor $\alpha_p$ is related to the bunch length, the momentum spread, and the synchrotron tune as [16]

$$\sigma_z \approx \frac{c \alpha_p \omega_s}{\omega_s} \sigma_\delta, \quad (3)$$

where $c$ is the speed of light, $\omega_s \equiv 2\pi \nu_s/T_{\text{rev}}$, and $T_{\text{rev}}$ is the revolution period. Thus $\alpha_p$ should be adjusted to the value determined by $\sigma_z$, $\sigma_\delta$, and $\nu_s$.

It was required that the lattice design should consistently realize all of these beam-optical parameters.

3. Overall structure

The HER and the LER were placed side by side horizontally in the tunnel originally constructed for TRISTAN. The horizontal separation was a natural choice and consistent to the horizontal crossing angle at the IP. Many dipole and quadrupole magnets of TRISTAN were reused in the HER. Each ring had four arcs and four 200 m long straight sections named Tsukuba, Nikko, Fuji, and Oho. The straight sections were effectively utilized as shown in Fig. 1. Sufficient numbers of rf cavities for both rings and wiggler magnets in the LER were able to be installed. Crab cavities had been installed in the Nikko section since 2007 [2,17].

4. $2.5\pi$ cell and chromaticity correction scheme

In order to achieve sufficient dynamic apertures for good injection efficiency and long beam lifetime, in particular, the Touschek lifetime in the LER, a chromaticity correction scheme with non-interleaved pairs of sextupole magnets was adopted [6]. All of the sextupole magnets were placed to
Fig. 1. Beam optical functions of the HER and the LER. The square root of the beta functions (top) and the dispersions (bottom) are shown. The blue solid (red dashed) lines show the horizontal (vertical) data. The IR was built in the Tsukuba section. Rf cavities for the HER and wiggler magnets for the LER were installed in the Nikko and Oho sections. The injection points from the injector linac for both rings and rf cavities for the LER were in the Fuji section.

make pairs in which two identical sextupole magnets were connected by a pseudo $-I$ transformer

$$
\begin{pmatrix}
-1 & 0 & 0 & 0 \\
0 & -1 & 0 & 0 \\
0 & 0 & -1 & 0 \\
0 & 0 & m_{43} & -1
\end{pmatrix}.
$$

(4)

Even if $m_{21}$ and $m_{43} \neq 0$, the transverse nonlinearities were canceled within a pair, and two free parameters were then used for further optics matching.

A special cell structure called the 2.5π cell was newly devised for KEKB in order to distribute the non-interleaved sextupole pairs densely and effectively over the rings and also to achieve the required values for the horizontal emittance and the momentum compaction factor. The sextupole
Fig. 2. 2.5π cell structure. This figure shows the HER cell. The yellow rectangles show the main dipole magnets, reusing TRISTAN magnets whose effective length was 5.9 m. In the LER, the structure was same as in the HER. The effective length of the dipole magnets was much shorter (0.9 m).

pairs neighbored each other in the betatron phase differences of ∼π/4 as shown in Fig. 2, and hence the relative phases of the sextupole magnets were effectively distributed.

The 2.5π cell has a wide range of tunability on both the horizontal emittance εₓ and the momentum compaction factor αₚ. There are 7 families of quadrupole magnets in a cell. Three free parameters remain after making the pseudo −I conditions between the sextupole magnets by using four parameters. Therefore, by adjusting the horizontal dispersion ηₓ at the dipole magnets, εₓ and αₚ are still independently tunable over a wide range, as shown in Figs. 3 and 4.

This tunability was fully utilized in the real beam operation. For example, one rf-bucket spacing was selected in the original design, as mentioned before. However, the minimum bunch spacing was actually limited to 3 rf-buckets because of serious vertical beam-size blowup due to the electron-cloud instability in the LER [2–4]. In order to store the design beam currents in smaller numbers of bunches, the bunch currents needed to be increased while avoiding damage to the hardware components. To deal with this situation, the bunch lengths of both rings were lengthened by changing αₚ as shown in Table 1. In the HER, εₓ was also adjusted larger to be balanced with the LER.

5. Optimization of sextupole fields

The KEKB colliding rings were the first to completely adopt the non-interleaved sextupole scheme [4]. Fifty-four (fifty-two) sextupole pairs were installed in the LER (HER) and each pair had an individual power supply. By using these large numbers of sextupole families, the chromaticities of many optical functions, including the betatron tunes, Twiss parameters at the IP and at some reference points in the rf sections, etc., were corrected over a finite momentum width of typically Δp/p₀ = 0.015–0.02, as shown in Fig. 5. The dependences of the optical functions on the transverse amplitude were also corrected at some finite momentum deviations [8].
Fig. 3. Tunability of the 2.5π cell for the LER (left) and HER (right). The parameter spaces on the upper sides of the envelope curves are achievable. In the case of $\varepsilon_x = 18$ nm (design), $\alpha_p$ can be tuned over the range of $-2 \times 10^{-4} \leq \alpha_p \leq 7 \times 10^{-4}$. Note that $\alpha_p$ determined in the whole ring is smaller (73% in the LER and 90% in the HER) than that estimated only in the cell. In the LER only, $\varepsilon_x$ can be changed further by adjusting $\eta_x$ in the wiggler sections. When $\eta_x \sim 0$ in the wiggler sections, $\varepsilon_x$ decreases by half.

Fig. 4. Example of parameter tuning in the 2.5π cell. In this example, the horizontal emittance of the LER was adjusted to (a) 9, (b) 18, and (c) 36 nm keeping the momentum compaction factor $\alpha_p \sim 4.5 \times 10^{-4}$. Each panel shows the square root of the beta functions (top) and the dispersions (bottom). The blue solid (red dashed) lines show the horizontal (vertical) data. The rectangles labeled B2P denote the main dipole magnets. The horizontal axis shows the orbit length in meters.

The dynamic apertures were usually estimated by particle tracking in six-dimensional phase space during 1000 turns without the effect of radiation damping (Fig. 6). These estimations were on safe side since the dynamic apertures were smaller than those estimated by tracking during one transverse damping period (4600 turns) with radiation damping.

Good sextupole solutions with large dynamic apertures were expected to bring about long beam lifetime and weaken the effect of the synchrotron–betatron resonances. However, it was difficult to judge their performance by the tracking simulation only. In real beam operation, the sextupole candidates were sometimes selected by checking the loss rate at the crossing of the synchrotron–betatron resonance $2\nu_x + \nu_s = \text{integer}$ in the LER, as shown in Fig. 7.

6. IR optics

The final-focus system consisted of two superconducting quadrupole magnets (QCSR and QCCL), six iron quadrupole magnets with special shapes, and two superconducting compensation solenoids [19]. A prominent feature was the horizontal crossing angle of 22 mrad at the IP.
Fig. 5. Example of sextupole strength optimization. Chromaticities of betatron tunes, beta functions at the IP and in the rf sections, etc. were corrected in a momentum width of typically \( \Delta p/p_0 = 0.02 \). In this example, the horizontal and vertical linear chromaticities in the LER were corrected to 1.15 and 3.88, respectively.

Fig. 6. Dynamic apertures of the LER (left) and the HER (right) with several kinds of sextupole solutions. The transverse apertures at \( \Delta p/p_0 = 0 \) did not change among the solutions thanks to the cancellation of the pseudo \(-I\) transformer.

as shown in Fig. 8. Since the crossing angle separated the beams without dipole magnets, beam background due to the synchrotron radiation was drastically reduced. This collision scheme worked well without inducing synchrotron–betatron resonances as expected in the weak–strong beam–beam simulations [1,3,4,15].

The \( x-y \) couplings produced by the Belle detector solenoid were mainly corrected by the compensation solenoids placed on the IP sides of the QCSs. The integrated solenoid fields were canceled on each side of the IP, as shown in Fig. 9. The remaining small couplings were corrected with weak skew
Fig. 7. Selection of sextupole candidates by checking the loss rate. The red and blue lines show histories of the beam current (left vertical axis) and the horizontal tune (right vertical axis), respectively. In this example, six candidates whose dynamic apertures were estimated as shown in Fig. 6 (left) were checked in the LER, then Solution D was selected. Although at least this example showed a rough dependence that larger dynamic apertures resulted in smaller loss rates, it was difficult to select D rather than F only by the dynamic apertures in Fig. 6 (left). The real performances conflicted with simulation results in many other examples.

Fig. 8. Layout of the final-focus magnets in the horizontal plane. QCSR and QCSSL are superconducting quadrupole magnets that work on both beams and are placed parallel to the Belle solenoid axis. QCSSL is shifted by 35 mm to be set on the orbit of the incoming electron beam. On the IP sides of the QCSs, superconducting solenoids (ESR and ESL) are placed to compensate the Belle solenoid field. The others are iron quadrupole magnets of special shapes with field-free spaces for the counter-rotating beams.

quadrupole magnets located in the IR. This correction scheme reduced the chromaticities of the $x$–$y$ coupling components, and thus the dynamic apertures were improved in the momentum direction. The vertical dispersions and the vertical orbits due to the crossing angle between the beam orbits and the solenoid axis were also corrected with skew quadrupole magnets and vertical dipole magnets in the IR.
Fig. 9. Compensation of the Belle solenoid, LER (left) and HER (right). Each shows the solenoid field, $\frac{1}{B_0} \frac{\partial B_y}{\partial x}$, and the beta functions, from top to bottom. The horizontal axis shows the orbit length.

Fig. 10. Local chromaticity correction in the LER. The sextupole pairs were placed in phase for the QCSs to correct the vertical chromaticities. It was possible to change $\beta^*_x$, $\beta^*_y$ only by using the quadrupole magnets in a tuning section at each end of the IR. The local chromaticity correction works effectively when the $\beta^*_x$, $\beta^*_y$ are changed, because the $\beta^*_x$, $\beta^*_y$ tuning sections are outside the local chromaticity correction section. The HER also had $\beta^*_x$, $\beta^*_y$ tuning sections.

The local chromaticity correction section was introduced only in the LER because much larger dynamic apertures were required in the LER than in the HER because the Touschek lifetime was $\propto E^3$. The chromaticities produced by the QCSs were locally corrected by the sextupole pairs installed in the IR, as shown in Fig. 10.

For precise modeling of the optics, the nonlinear Maxwellian fringe fields of magnets, the kinematic terms of field-free spaces, and overlapping of the solenoid field on the quadrupole magnets were taken into account [20]. Normal and skew nonlinear multipole fields accompanied by final-focus magnets were also taken in up to K21 and SK21 ($Kn = \frac{1}{B_0} \int \frac{\partial^{(n)}B}{\partial x^{(n)}} ds$) [21].
7. Optics correction

The real performance of the beam optics depended on how accurately machine errors were corrected. Corrections of the $x$--$y$ couplings, the dispersions, and the beta functions were indispensable in high-luminosity operation. The horizontal beta functions became much more sensitive to quadrupole errors because the horizontal betatron tunes came closer to the half-integer resonances than the design, to improve the luminosity as listed in Table 1.

Whenever the beam optics was changed or the magnets were initialized for various reasons, errors of the beam optical functions over the whole rings were measured and corrected at low beam currents ($\sim30$ mA) [22,23]. The errors were estimated by using the responses of the beam orbit to dipole kicks or rf frequency shifts. In the corrections, two types of knobs were used: fudge factors for the power supplies of the normal and skew quadrupole magnets and orbit bumps at the sextupole magnets in the horizontal and vertical planes. The horizontal and vertical bumps at the sextupole magnets caused normal and skew quadrupole fields, respectively. Moreover, the symmetric and asymmetric vertical bumps at the paired sextupole magnets connected to the pseudo $-I$ transformer adjusted the $x$--$y$ couplings and the vertical dispersions almost independently. The usual correction procedures were as follows:

- Correct the $x$--$y$ couplings with fudge factors for the skew quadrupole magnets and the symmetric vertical bumps at the sextupole magnets.
- Correct the horizontal and vertical dispersions with the horizontal and vertical asymmetric bumps at the sextupole magnets.
- Correct the beta functions with fudge factors for the quadrupole magnets and the horizontal symmetric bumps at the sextupole magnets.

In addition, during high-luminosity operation with high stored currents, the $x$--$y$ couplings and the dispersions at the IP were also adjusted by the vertical bumps at the sextupole magnets [3,22].

8. Conclusions

The lattice of the KEKB colliding rings had unique design features, such as a chromaticity correction scheme with non-interleaved sextupole pairs, a $2.5\pi$ cell structure, local chromaticity correction in the IR, etc. It successfully realized vertical beta functions at the IP even smaller than the design values, which served as an essential driving force in achieving the world’s highest luminosity. The flexibility of the KEKB lattice made it possible to adjust the main optical parameters, such as the beta functions at the IP, the emittances, the momentum compaction factors etc., for various situations, including crab crossing. The performance of the lattice was also supported by continuous efforts and developments in error corrections throughout the operating period of KEKB.

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