The machine commissioning of KEKB started in December 1998 and its operation was terminated at the end of June 2010 to upgrade KEKB to SuperKEKB. In this paper, we describe the commissioning procedure of KEKB from 2002 to 2010.

1. Introduction

KEKB [1] is an energy-asymmetric double-ring collider for B meson physics. Its operation started in December 1998 and finished at the end of June 2010. During these ten-and-a-half years, KEKB achieved the world’s highest luminosity in both the peak and integrated luminosities. KEKB consists of an 8 GeV electron ring (the high energy ring; HER), a 3.5 GeV positron ring (the low energy ring; LER) and their injector, which is a linac-complex providing the rings with both electron and positron beams. The issues with the beam commissioning in the first four years have been described in a previous paper [2]. In this paper, we describe the subsequent history of the beam commissioning. Emphasis is placed on how we have increased the luminosity and what issues remain unsolved.

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Fig. 1. Effects of solenoid coils on the luminosity. The specific luminosity per bunch is shown as a function of the product of the bunch currents in some cases where the conditions for the solenoid excitation are different.

2. Luminosity improvement

Figure 1 in Ref. [3] shows the history of KEKB performance from 1999 to 2010. In Table 1, the machine parameters of KEKB are summarized. In the table, two sets of parameters are shown. One is the parameter set shown in the previous paper [2] and the other is that corresponding to the best luminosity of KEKB. As for the peak luminosity, the maximum value was recorded on 17 June 2009. The total integrated luminosity is the final value collected by the Belle detector. A comparison of the machine parameters with the design values is shown elsewhere [3]. As is seen in Table 1, the most important progress is that made in the vertical beam–beam parameters. This means that the vertical beam sizes have been greatly reduced. The major sources of vertical beam size blowup were electron clouds [2] and beam–beam effects. In this paper, we describe the methods for suppressing the beam blowup due to these effects. Another source of luminosity improvements is the increase of the beam currents. In the process of increasing the beam currents, we experienced various kinds of hardware problems due to the high beam currents. We have increased the beam currents slowly by improving the relevant hardware components and/or by strengthening the cooling power for components with heating problems [3,4]. The HER beam current exceeded the design value of 1.1 A. For this high beam current, we needed to reinforce the RF system in the HER [5]. The vertical beta functions at the interaction point (IP) ($\beta^*_y$) got somewhat smaller. However, these changes did not contribute much to the increase of the luminosity, since the bunch length for the operation bunch currents is around 7 mm for both beams and the hourglass effect hindered a higher luminosity with smaller values of $\beta^*_y$. Another important source of the luminosity increase was the introduction of crab cavities. Crab cavities were installed at KEKB during the winter shutdown in fiscal year (FY) 2006 [5] and have been in use since February 2007. In this paper, we describe the beam operation with the crab cavities. The use of skew-sextupole magnets [3] also caused an increase in the luminosity, as described below. The beam injection and its scheme is important for accumulating the luminosity. In this paper, we
Table 1. Machine parameters of KEKB. Two sets of parameters are shown. One is the set of parameter given in a previous paper [2] and the other is the set that corresponds to the best luminosity at KEKB.

|                           | up to 31 May 2010 | up to 31 Oct. 2001 |
|---------------------------|-------------------|--------------------|
|                           | LER               | HER                |
|                           | LER               | HER                |
| Circumference             | 3016              | 3016               | m                   |
| RF frequency              | 508.89            | 508.89             | MHz                 |
| Harmonic number           | 5120              | 5120               |                     |
| Horizontal emittance      | 18                | 24                 | nm                  |
| Vertical emittance        | 1188              | 1072               | mA                  |
| Number of bunches         | 1637              | 1072               |                     |
| Bunch current             | 1585              | 761                | mA                  |
| Bunch spacing             | 1.03              | 0.93               |                     |
| Bunch spacing             | 1.84              | 0.66               |                     |
| Total RF voltage          | 8.0               | 6.5                | MV                  |
| Synchrotron tune $v_x$    | -0.0246           | -0.0209            |                     |
| Horizontal tune $v_x$     | 45.506            | 44.511             |                     |
| Vertical tune $v_y$       | 43.561            | 41.585             |                     |
| Beta values at IP $\beta_x/\beta_y$ | 120/0.59       | 59/0.65            | cm                  |
| Momentum compaction $\alpha$ | 3.31             | 3.41               | $3.38 \times 10^{-4}$ |
| Beam–beam parameter $\xi$ | 0.127            | 0.073              |                     |
| Beam–beam parameter $\xi_y$ | 0.129            | 0.047              |                     |
| Beam lifetime             | 133@1637          | 101@1072           | min@mA             |
| Luminosity (Belle CsI)    | $2.108 \times 10^{34}$ | $0.517 \times 10^{34}$ | cm$^{-2}$s$^{-1}$ |
| Total integrated luminosity| 1041             | 42                 | fb$^{-1}$           |

describe the continuous injection scheme, which contributed greatly to the integrated luminosity at KEKB.

3. Effects of electron clouds

In the history of KEKB, vertical beam size blowup due to electron clouds has been a very severe obstacle to obtaining a higher luminosity. The nature of the blowup has been studied theoretically and experimentally [7,8]. In the beam operation, the effects of electron clouds were drastically suppressed by the installation of solenoid coils all around the LER ring [2]. The effects of the solenoid coils were clearly observed in 2001, as shown in Fig. 1. In the figure, the specific luminosity per bunch is depicted as a function of the product of the bunch currents of the two beams. Here, the specific luminosity per bunch is defined as the total luminosity/(the number of bunches × the product of the bunch currents). As seen in the figure, when we switched off all the solenoids, the specific luminosity became almost half of that with the solenoids.

Figure 2 shows the history of the length of the region where the solenoids coils are installed. The solenoid coils were installed on several occasions and about 95% of the drift space of the LER ring was covered with the solenoid field $B_z > 20$ G. Although the solenoids drastically improved the luminosity, we found that performance of KEKB was still affected by electron clouds when an LER beam current higher than about 1.6 A was used. The luminosity of KEKB did not increase with an LER beam current higher than about 1.6 A. It is believed that this is due to the effects of electron clouds. For this reason, the operation beam current in the LER of 1.6 A is much lower than the design beam current of 2.6 A. Another impact of the electron clouds on the beam operation at KEKB is the choice of bunch spacing. In the design, the bunch spacing is one RF-bucket, which means that every RF-bucket is filled with beam particles. However, in the actual operation, the bunch spacing is approximately 3 RF-buckets. With shorter bunch spacing, the specific luminosity was reduced. This restriction on bunch spacing is also believed to come from the effects of the electron clouds.
Fig. 2. Installation history of solenoid coils in the LER ring.

Fig. 3. Specific luminosity per bunch depending on the bunch position in the unit 49 RF-buckets. Each datum is the average of 99 bunches in the equivalent position in the unit 49 RF-buckets and the error bars are the standard deviations of the 99 bunches.

Figure 3 shows the result of an experiment on bunch spacing carried out on 21 March 2008. For the experiment, a special filling pattern was used. In the beam filling pattern of KEKB, the same pattern should be repeated every 49 RF-buckets to be compatible with two-bunch injection. Due to the synchronization problem between the injector linac and the KEKB rings, only the two bunches in 49 RF-buckets in the rings can be injected from the linac to the rings. In the filling pattern used in the experiment, 17 RF-buckets out of 49 RF-buckets were filled with the beam and the same patterns repeated 99 times. Most of the bunch spacing between adjacent bunches was 3 RF-buckets but only 2 bunches out of 17 bunches in a unit of 49 RF-buckets followed the preceding bunches at a distance of 2 RF-buckets. In Fig. 3, the specific luminosity per bunch is plotted as a function of bunch ID in a unit of 49 RF-buckets. Note that the specific luminosity of each bunch ID in the figure is the average of 99 bunches in the equivalent position in the units of 49 RF-buckets. The error bars in the graph
Table 2. Tuning knobs for the luminosity and their observables. Many depend only on the beam size at the synchrotron radiation monitor (SRM), besides the luminosity.

| Knob                                      | Observable                  | Frequency       |
|-------------------------------------------|-----------------------------|-----------------|
| Beam offset at IP (orbit feedback)        | Beam–beam kick (BPMs)      | ~1 s            |
| Crossing angle at IP (orbit feedback)     | BPMs                        | ~1 s            |
| Target of orbit feedback at IP (offset)   | vertical size at SRM, luminosity | ~1/2 day       |
| Target of orbit feedback at IP (angle)    | vertical size at SRM, luminosity | ~1/2 day       |
| Global closed orbit                       | BPMs                        | ~20 s           |
| Betatron tunes                            | tunes of non-colliding bunches | ~20 s           |
| Relative RF phase                        | center of gravity of the vertex | ~10 min        |
| Global coupling, dispersion, beta-beat    | orbit response to kicks, RF freq. | ~14 days       |
| Vertical waist position                   | vertical size at SRM, luminosity | ~1/2 day       |
| $x$–$y$ coupling and dispersion at IP     | vertical size at SRM, luminosity | ~1/2 day       |
| Chromaticity of $x$–$y$ coupling at IP    | vertical size at SRM, luminosity | ~1/2 day       |

show the standard deviations of the 99 bunches. As is seen in the figure, the specific luminosity after 2 RF-buckets is ~15% lower than that of the other bunches. It is believed that this degradation in the specific luminosity comes from the effects of the electron clouds. In the case of short bunch trains, this degradation was not observed; thus, we can disprove the possibility that the degradation in the specific luminosity after short bunch spacing is caused by the effects of parasitic collisions.

4. Methods of luminosity tuning

There are a number of knobs for tuning the luminosity. Only a few of them can be tuned up with independent observables besides the luminosity. Table 2 lists the tuning parameters and their observables. Tuning parameters related to the crab cavities are not listed in the table. We found that the linear optics correction is important for suppressing the beam–beam blowup. In the usual beam operation, we frequently (typically every 2 weeks) made optics corrections where we corrected global beta functions, $x$–$y$ coupling parameters, and dispersions [2]. Sometimes, the optics corrections were done with a different set of sextupole magnet strengths to narrow the stop-band of the resonance ($2v_x + v_y$ = integer) or ($2v_x + 2v_y$ = integer). The optics correction is the basis of the luminosity tuning. On this basis, we carried out tuning on the other parameters in Table 2. At KEKB, we found that the local $x$–$y$ coupling and the vertical dispersion at the IP are very important for increasing the luminosity. We have developed tuning knobs to adjust these parameters. In the following, we describe these knobs. The parameters are changed by changing the beam orbits. Figures 4 and 5 show examples of the orbit form for changing the parameters. In the case of the LER (Fig. 4), 8 orbit bumps are made to control the $x$–$y$ coupling and the vertical dispersion parameters. Each bump is created at a pair of (defocusing) sextupole (SD) magnets. At KEKB, we use the non-interleaved sextupole scheme. Each bump is almost localized at the pair of SD magnets. Since a tail of the bump is slightly extended to the position of SF magnets next to the SD magnets, their effects are counted correctly in the calculation. The paired SD magnets are connected with pseudo $-I$ transformers ($-I'$). In this situation, if we make a symmetric bump at the paired sextupole magnets, the vertical dispersion is localized between them and the $x$–$y$ coupling is leaked around the ring. On the other hand, in the case of an asymmetric bump, the $x$–$y$ coupling is localized and the dispersion is leaked. In a real operation, 8 symmetric and/or asymmetric bumps are created to meet the condition that the $x$–$y$ coupling and the vertical dispersion are localized in the bump section and $R_1$, $R_2$, $R_3$, $R_4$, $\eta_y$ (the vertical dispersion) at the IP and $\eta'_y$ (the slope of the vertical dispersion) at the IP are equal to target
Tuning knobs to adjust the local \(x\)–\(y\) coupling parameters and the vertical dispersion and its slope at the IP in the LER. In the graph, the \(x\)–\(y\) coupling is expressed as “Tilt”. The parameters are changed by changing the vertical orbit at sextupole magnets near the IP. In the figure, the defocusing sextupole magnets (SDs) and the sextupoles in the local correction section (SLs) are shown. Although the vertical orbit at the SDs and SLs is changed by making orbit bumps at those locations, that at the focusing sextupole magnets (SFs) as shown in Fig. 6 is slightly changed. All these effects of the changes of the vertical orbit at the sextupole magnets are taken into the calculation. From top to bottom, the graphs show the vertical beta function, the vertical dispersion, and the vertical beam orbit near the IP. In machine tuning, operators set the target values of those parameters as seen in the figure, click the “Calculate” button, and then click the “Set Bump” button.

values. Here, \(R_1\), \(R_2\), \(R_3\), and \(R_4\) are local coupling parameters as defined below. The local transverse coordinates \((x, p_x, y, p_y)\) are connected to the normal (decoupled) coordinates \((u, p_u, v, p_v)\) with a matrix \(T(s)\) as

\[
\begin{pmatrix}
    u \\
    p_u \\
    v \\
    p_v
\end{pmatrix} = T(s) \begin{pmatrix}
    x \\
    p_x \\
    y \\
    p_y
\end{pmatrix}.
\]

Here, \(T(s)\) is expressed by using a coupling matrix \(R\) as

\[
T(s) = \begin{pmatrix}
\mu I & SR'S \\
R & \mu I
\end{pmatrix} = \begin{pmatrix}
\mu & 0 & -R_4 & R_2 \\
0 & \mu & R_3 & -R_1 \\
R_1 & R_2 & \mu & 0 \\
R_3 & R_4 & 0 & \mu
\end{pmatrix}.
\]
Fig. 5. Tuning knobs to adjust the local $x$–$y$ coupling parameters and the vertical dispersion and its slope at the IP in the HER. In the graph, the $x$–$y$ coupling is expressed as “Tilt”. The parameters are changed by changing the vertical orbit at sextupole magnets near the IP. In the figure, the defocusing sextupole magnets (SDs) are shown.

and

$$S = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}, \quad \mu^2 + \text{det} R = 1.$$

The locations of the sextupole magnets are shown in Figs. 4 and 5 together with typical shapes of the orbit bumps and some other optical parameters. As is seen in Fig. 4, the bump section is around $\pm 350$ m of the IP (about 700 m in total) in the LER. In the figures, the center is the IP. KEKB has a 200 m straight section around the IP. In the case of the LER, a local chromaticity correction scheme is installed in this straight section. Four SL magnets shown in Fig. 4 are sextupole magnets for the local correction. (We also use the non-interleaved sextupole scheme for the local correction.) We also make bumps at the paired sextupole magnets for the local correction. The HER case is almost the same except that we have no local chromaticity correction for the HER and so the length of the bump section is somewhat longer compared with the LER case. We need a larger number of sextupole magnets in the arc section in the HER where we cannot use the sextupole magnets in the local chromaticity correction section as part of the knob. We have enough free parameters (16 parameters for the height of the symmetric and asymmetric bumps) and so, in principle, it is possible to adjust the coupling and dispersion parameters independently. As for the orbit itself, we can set the bumps with sufficient accuracy, since the continuous closed orbit correction (CCC) system corrects the orbit if there is any deviation from the target orbit. However, machine errors may degrade the parameter
Fig. 6. The arc lattice of the LER. The lattice elements and the optics functions ($\beta_x, \beta_y, \eta_x$) are depicted as functions of the position in the ring (the distance from the IP). The yellow and green rectangles show the main dipole and quadrupole magnets. The red rectangles represent the dipole correctors. We adopted a 2.5\pi cell lattice. In this scheme, five 90-degree FODO cells are combined to make a unit cell. The number of bending magnets is decreased from ten to four. With this 2.5\pi cell lattice, a very flexible change in the emittance and the momentum compaction factors is realized by controlling the dispersion functions. As for the sextupoles, we adopted the non-interleaved sextupole scheme. In this scheme, each pair of sextupole magnets with the same strength is connected with the $-I^\prime$ transformer. This means that the nonlinearity of the sextupole magnets is canceled out within each pair of sextupoles for on-momentum particles. For wider longitudinal dynamic apertures, all of the sextupole pairs are separated and are independently excited. In the figure, SFs and SDs show the focusing and defocusing sextupole magnets. The HER arc lattice is similar to that of the LER.

independence due to the difference between real optics and a model. Even if the independence is not very good, however, we think that we can find an optimum set of parameters in the parameter space by using this knob. A magnified view of the arc lattice of the LER is shown in Fig. 6. KEKB adopted a unique “2.5\pi cell” lattice [9].

In Table 2, some parameters have their own observables. The other parameters, however, are tuned by observing only the luminosity and the vertical beam sizes. The standard tuning method at KEKB for those parameters was to scan the parameters one by one so that the luminosity is maximized, although we took the smaller vertical beam sizes in some cases. Tuning with this method seemed very inefficient and even laborious. However, the KEKB experience is that only such toil led to high luminosity. We continued such tuning almost constantly, even during the physics operation. In the
process of tuning with the crab cavities, we developed a tuning method in which 12 parameters are searched at the same time, as is described in the next section.

5. Operation with crab cavities

5.1. Motivation for installing crab cavities

One of the design features of KEKB is the horizontal crossing angle of \( \pm 11 \text{ mrad} \) at the IP. Although there are many merits of the crossing angle scheme, the beam–beam performance may degrade. The design of KEKB predicted that the vertical beam–beam parameter \( \xi_y \) could be as high as 0.05, if betatron tunes are properly chosen. The crab crossing scheme was proposed in 1988 by R. Palmer [10] as an idea to recover the head-on collision with the crossing angle for linear colliders. It has also been shown that the synchro–betatron coupling terms associated with the crossing angle in ring colliders are canceled by crab crossing [11]. As discussed in Ref. [3], the development of the crab cavities at KEKB has been encouraged by beam-beam simulations [12–14], which predicted a very high beam-beam parameter of \( \xi_y \sim 0.15 \). Figure 7 shows a comparison between \( \xi_y \) for the head-on collision (crab crossing) and the crossing angle by a strong–strong beam–beam simulation. After a long R&D period, the crab cavities were finally installed at KEKB in February 2007.

5.2. Single crab cavity scheme

As explained in Ref. [3], we have developed the single crab cavity scheme. The layout is shown in Fig. 2 in Ref. [3]. This scheme not only saved the cost of the cavities, but made it possible to use the existing cryogenic system in the Nikko region, which has been utilized for the superconducting accelerating cavities.

In the single crab cavity scheme, the following equation should be met for both beams to realize a head-on collision:

\[
\frac{\phi_x}{2} = \frac{\sqrt{\beta_x^* \beta_x}}{2 \sin \pi v_x} \left( \pi v_x - \left| \Delta \psi_x^* \right| \right) \frac{V_c \omega_{RF}}{E_c}.
\]
Table 3. Typical parameters for the crab cavities. The crossing angle, the horizontal beta functions at the IP and the crab cavities, the horizontal tunes, the horizontal phase advance from the cavities to the IP, the crab voltage, and the RF frequency are shown.

|                  | LER | HER |
|------------------|-----|-----|
| $\phi_x$        | 22  mrad |     |
| $\beta_x^*$     | 1.2 m | 1.2 m |
| $\beta_x^C$     | 51 m | 122 m |
| $\nu_x$         | 45.506 | 44.511 |
| $\psi_x^C/2\pi$ | 0.25 | 0.25 |
| $V_c$           | 0.97 MV | 1.45 MV |
| $f_{RF}$        | 508.89 MHz |     |

Here, $\phi_x$ is the full crossing angle. $\beta_x^C$ and $\beta_x^*$ are the beta functions at the crab cavity and the IP, respectively. $\Delta\psi_x^C$ denotes the horizontal betatron phase advance between the crab cavity and the IP. $\nu_x$ is the horizontal tune. $V_c$ and $\omega_{RF}$ are the crab voltage and the angular RF frequency ($= 2\pi f_{RF}$), respectively. Typical values for these parameters are shown in Table 3.

The beam optics was modified for the crab cavities to provide the necessary magnitude of the beta functions at the cavities and the proper phase advance between the cavities and the IP. A number of quadrupoles have switched polarity and have started to have independent power supplies.

5.3. Tuning method of crab cavity parameters with beams and beam tuning with crab cavities

5.3.1. Crab voltage. Prior to the beam operation, calibration of the crab voltage was done by using the klystron output power and the loaded Q values of the crab cavities without actual beams. The crab voltage was also calibrated by using beams. If a bunch passes by the crab cavity at the zero-cross timing of the crab RF voltage, the center of the bunch receives no dipole kick. When the crab phase shifts from this condition, the bunch receives a net dipole kick from the cavity, like the case of a steering magnet. This dipole kick causes a closed orbit distortion (COD), the size of which depends on the crab phase. From the CODs around the ring created by the crab cavity, the dipole kick angle can be estimated. By scanning the crab phase by more than $360^\circ$ and fitting the kick angle estimated at each data point as a function of the crab phase, the crab voltage can be determined. The crab voltage thus determined is consistent with that calibrated from the klystron power and the Q value within a few percent. From the crab phase scan and the fit, the phase shifter of the crab cavity system can also be calibrated. In the actual beam operation in the physics run mode, the crab voltages of both rings are scanned to maximize the luminosity, as is shown below.

5.3.2. Crab phase. In principle, the crab phase should be set so that the center of the bunch passes by at the zero-cross timing of the crab cavity. In this condition, the bunch receives no net dipole kick. This condition can be found by scanning the crab phase as described above. However, this method is rather time-consuming and so an easier method is used in the usual operation. This method is to search for a crab phase that causes no change in the COD between the crab on and off by trial and error. Although there are two zero-cross phases, we can choose the correct phase by observing the phase of the COD. In the actual physics run, in which high beam currents are needed, the crab phase is shifted by some amount (typically $10^\circ$) to suppress the dipole oscillation observed at high-current crab collision. The COD induced by the net dipole kick by the crab cavity can be compensated by steering magnets in the ring.
5.3.3. **Beam orbits at the crab cavities.** The beam loading for the crabbing mode increases linearly as a function of a horizontal orbit displacement from the center of the crab cavity. If the RF power to operate the cavity is too sensitive to the beam orbit, cavity operation under the existence of the beams could be difficult. To avoid this situation, we have chosen the loaded $Q$ value of the cavity to be $Q_L = (1 - 2) \times 10^5$. With this relatively low $Q$ value, the RF power for the operation is relatively high (typically 100 kW at 1.4 MV). However, the RF power becomes less sensitive to the beam orbit (typically 20% change for 1 mm orbit change). When we condition the cavity, we need a higher power. However, with this $Q$ value, 200 kW is sufficient for conditioning the cavity up to 2 MV. In addition, we have developed an orbit feedback system to keep the horizontal beam orbit at the crab cavity stable [16]. This system is composed of 4 horizontal steering magnets to make an offset bump for each ring and 4 beam position monitors (BPMs) for each ring to monitor the beam orbit at the crab cavity. The design system speed is 1 Hz and the target accuracy of the orbit is within 0.1 mm. However, in the actual beam operation, we found that the beam orbit is stable enough even without the orbit feedback system. Therefore, usually we do not use the orbit feedback system. At the beginning of the beam operation with the crab cavities, we searched the field center in the cavities by measuring the amplitude of the crabbing mode excited by beams when the cavities were detuned. In this search, we found that the field center of the HER crab cavity shifted about 7 mm from the assumed center position of the crab cavity. One possible reason for this large displacement could be misalignment of the cavity. We feel that there could be such a large misalignment, since precise alignment of the crab cavity to the cryostat was very difficult.

5.3.4. **Luminosity tuning with crab cavities.** The luminosity tuning in general is described above. Here, we describe the method of the luminosity tuning related to the crab cavities. In the following, we mention two tuning items, i.e. the crab $V_c$ (crab voltage) scan and the tuning on the $x$–$y$ coupling at the crab cavities. Regarding the crab $V_c$, the calibration can be done with a single beam mentioned above. However, this is not sufficient for the beam collision operation, since optics errors such as those for the beta functions or the phase advance between the crab cavity and the IP could shift the optimum crab $V_c$. In the actual tuning, we first tune the balance of the crab $V_c$ between the two rings. For this purpose, we employ a trick to change the crab phase slightly and observe the orbit offset at the IP. The IP orbit feedback system [17] can detect the orbit offset at the IP precisely. While changing the crab phases of both rings by some amount (typically 10–15°), we tune the balance of the crab $V_c$ between the two rings so that the IP orbit offset becomes the same for both rings. In this tuning, we rely on the accuracy of the phase shifter of the crab cavity system. While keeping this balance (the ratio of the crab $V_c$), we scan the crab $V_c$ for both rings and set the values that give the maximum luminosity. In our experience, the optimum set of the crab $V_c$ thus found is not much different from the calibrated values with the single beam. The difference is usually within 5%.

The motivation to control the $x$–$y$ coupling at the crab cavities is to handle the vertical crabbing. In principle, the crab cavity kicks the beam horizontally. However, if there is $x$–$y$ coupling at the crab cavity or if the crab cavity has some rotational misalignment, the beam could receive a vertical crab kick. This could degrade the luminosity. The local $x$–$y$ coupling is expressed by 4 parameters, $R1$, $R2$, $R3$, and $R4$, as described above. In the actual beam operation, these coupling parameters are scanned one by one to maximize the luminosity. We found that the tuning with these knobs has some effect on the luminosity, and the luminosity gain with the knobs is typically 5%. We expected that $R2$ and $R4$ might affect the luminosity, since these parameters are related to the vertical crab at
Table 4. Comparison of KEKB machine parameters with and without crab crossing.

|                | June 2010 with crab | Nov. 2006 w/o crab |
|----------------|---------------------|--------------------|
|                | LER      | HER     | LER      | HER     |
| Energy (GeV)   | 3.5      | 8.0     | 3.5      | 8.0     |
| Circumference (m) | 3016 | 1188   | 3016 | 1340 |
| $I_{\text{beam}}$ (mA) | 1637 | 1585 | 1662 | 1387 |
| # of bunches   | 1.03     | 0.75    | 1.20     | 0.965   |
| Av. spacing (m) | 1.8     | 2.1     |          |         |
| Emittance (nm) | 18      | 24      | 18       | 24      |
| $\beta^*_x$ (cm) | 120   | 120   | 59      | 56     |
| $\beta^*_y$ (mm) | 5.9   | 5.9 | 6.5      | 5.9    |
| Ver. size @ IP (µm) | 0.94 | 0.94 | 1.8 | 1.8 |
| RF voltage (MV) | 8.0      | 13.0    | 8.0      | 15.0    |
| $\nu_x$ | 0.506     | 0.511   | 0.505    | 0.509   |
| $\nu_y$ | 0.561     | 0.585   | 0.534    | 0.565   |
| $\xi_x$ | 0.127     | 0.102   | 0.117    | 0.071   |
| $\xi_y$ | 0.129     | 0.090   | 0.108    | 0.057   |
| Lifetime (min.) | 133     | 200     | 110     | 180     |
| Luminosity ($10^{34}$ cm$^{-2}$ s$^{-1}$) | 2.108 | 1.760   |          |         |
| Lum/day (fb$^{-1}$) | 1.479 | 1.232   |          |         |

the IP. However, in reality, there is no big difference in the effect on the luminosity between these four parameters.

5.4. Specific luminosity with and without crab cavities

Since the introduction of the crab cavities, we have made efforts [18] to realize the beam–beam performance predicted by the beam–beam simulation. As a result of these efforts, we accomplished a relatively high beam–beam parameter of about 0.09, as shown in Table 4. We found that the correction of the chromaticity of the $x$–$y$ coupling at the IP is effective for increasing the luminosity [3]. This correction increased the vertical beam–beam parameter from $\sim 0.08$ to $\sim 0.09$. However, even with this improvement, the beam–beam parameter achieved, $\sim 0.09$, is much lower than the value predicted by the simulation, $\sim 0.15$. We do not yet understand the cause of this discrepancy.

In Fig. 8, a comparison between the specific luminosity per bunch with the crab cavities on and off is shown. The specific luminosity is defined as the luminosity divided by the bunch current product of the two beams and also divided by the number of bunches. If the beam sizes are constant as a function of the beam currents, the specific luminosity per bunch should be constant. As is seen in the figure, the specific luminosity is not constant. This means that the beam sizes are enlarged as a function of the beam currents. In the experiment taking the data shown in Fig. 8, the number of bunches was reduced to 99 to avoid possible electron cloud effects. In the usual physics operation, the number of bunches was 1585. For this experiment, the IP horizontal beta function, $\beta^*_x$, was changed from 0.8 m to 1.2 m to avoid the physical aperture problem and to increase the bunch currents as described in Sect. 5.1.1. In the usual physics operation, the bunch current product was around 0.8 mA$^2$. The specific luminosity per bunch with the crab on is about 20% higher than that with the crab off. Since the geometrical loss of the luminosity due to the crossing angle is calculated as about 11%, there is definitely some gain in the luminosity by the crab cavities other than recovery of the geometrical loss. However, the effectiveness of the crab cavities is much smaller than the beam–beam simulation, as is seen in Fig. 8. The beam–beam parameter is strictly restricted for some unknown reason.
Specific luminosity per bunch

\[ \frac{L}{\text{bunch current product of the two beams}} \]

Fig. 8. Comparison of the specific luminosity per bunch with and without crab cavities as a function of the bunch current product of the two beams. The specific luminosity is defined as the luminosity divided by the bunch current product of the two beams and also divided by the number of bunches. Three different lines from the beam–beam simulations are also shown, corresponding to different values of the IP horizontal beta function, \( \beta_x^* \). The simulations predicted that a smaller \( \beta_x^* \) (smaller \( \sigma_x^* \)) would give a higher luminosity. Also shown in the figure is a line corresponding to a constant vertical beam–beam parameter of 0.09 for the HER, assuming the bunch current ratio between the LER and the HER is 8/5. As seen in the figure, the data with crab cavities are aligned on this line. This means that the HER vertical beam–beam parameter, \( \xi_y \), is saturated at around 0.09.

5.5. Efforts to increase the specific luminosity with crab cavities

The performance with the crab cavities has been considered very important, not only for KEKB but also SuperKEKB in the so-called high current scheme. Therefore, we have made every effort to understand the discrepancy between the beam–beam simulation and the experiments on the beam–beam performance with the crab cavities. Although we have not identified the cause, we summarize these efforts in the following.

5.5.1. Short beam lifetime related to physical aperture around crab cavities. In the beam operation with the crab cavities, we encountered the situation that we cannot increase the bunch current of one beam due to the poor beam lifetime of the other beam. We took this issue seriously and made efforts to solve it, since this issue is possibly a cause of degradation of the beam–beam performance with the crab crossing. We could identify the process responsible for the lifetime decrease. The process is the dynamic beam–beam effects, i.e., the dynamic beta effect and the dynamic emittance effect. Since the horizontal tune of KEKB is very close to the half-integer, the effects are very large. In Fig. 9, the beta functions around the LER ring are depicted with and without the dynamic beam–beam effect before we solved the problem. The horizontal beta function around the crab cavity becomes very large. Here, the horizontal tune was 0.506 and the unperturbed horizontal beam–beam parameter was around 0.127 with the operation bunch current of the HER. Without the beam–beam perturbation, the horizontal beta functions at the IP and at a quadrupole magnet next to the crab cavity were 0.9 m and 161 m, respectively. With the beam–beam effect, the beta functions were calculated to be 0.138 m and 1060 m at the IP and at the quadrupole magnet, respectively. To meet the crab condition, the horizontal phase advance between the crab cavity and the IP was chosen at \( \pi/2 \) times
Fig. 9. Beating of beta functions due to dynamic beam–beam effects in the LER before we took some counter-measures against this problem with a $\nu_x$ value of 0.506 and an unperturbed beam–beam parameter ($\xi_{x0}$) of 0.127. The red and black lines are the beta functions with and without the dynamic beam–beam effect, respectively.

an odd integer. With this phase advance, the horizontal beta function becomes very large around the crab cavity. Also due to the dynamic beam–beam effect, the horizontal emittance ($\varepsilon_x$) was enlarged from 18 nm to $\sim$52 nm. In this situation, we found that the horizontal beam size around the crab cavity is very large (typically 7 mm) at the operation bunch currents and the physical aperture there is only around $5 \sigma_x$. Therefore, the physical aperture around the crab cavities could seriously affect the beam lifetime. The same problem is also observed at the HER. However, the effect is less serious, since the horizontal tune of the HER is more distant from the half-integer than in the LER case.

To mitigate this problem, we have taken several counter-measures. In the original optics of the LER, the horizontal beta function around the crab cavity took the local maximum value not at the crab cavity but at the quadrupole magnets closest to the crab cavity. To satisfy the crab condition, the horizontal beta function at the crab cavity should be set at the target value. If we can decrease the beta function at the quadrupole magnet keeping the beta function at the crab cavity unchanged, we can widen the physical acceptance around the crab cavity. In the summer shutdown in 2008, we changed the optics around the crab cavity by adding some power supplies for the quadrupole magnets and changing the wiring of the power supplies. As a result, the horizontal beta function at the quadrupole magnets next to the crab cavity was reduced to the same value at the crab cavity. Before this change, the horizontal beta function at the quadrupoles was about twice as large as that at the crab cavity. With this change, the beam lifetime problem was mitigated to some extent. However, when we increased the bunch currents beyond the usual operation values, the lifetime problem appeared again. To investigate the specific luminosity at higher bunch currents, we decided to increase the horizontal beta function at the IP. By enlarging the IP beta function, we can lower the beta function at the crab cavity and enlarge the physical acceptance. We enlarged $\beta^*_x$ from 0.8 or 0.9 m to 1.2 m or
Fig. 10. Specific luminosity per bunch as a function of the bunch current product of two beams with different $\beta^*_x$. The specific luminosity is defined as the luminosity divided by the bunch current product of the two beams and also divided by the number of bunches. Three different lines from the beam–beam simulations are also shown, corresponding to different values of the IP horizontal beta function, $\beta^*_x$. The simulations predicted that a smaller $\beta^*_x$ (smaller $\sigma^*_x$) would give a higher luminosity. Also shown in the figure are lines corresponding to constant horizontal beam–beam parameters of 0.08 and 0.09 for the HER, assuming that the bunch current ratio between the LER and the HER is 8/5. As seen in the figure, the data with crab cavities are aligned on these lines. This means that the HER vertical beam–beam parameter, $\xi_y$(HER), was saturated at around 0.08 or 0.09. In the experiment, we found that the luminosity did not depend on the IP horizontal beta functions, $\beta^*_x$, in contrast to the simulation. The data with $\beta^*_x = 0.8$ or 0.9 m (blue dots) were taken before we introduced the skew-sextupole magnets. The data after the introduction of the skew-sextupoles (green and red dots) are aligned on the line corresponding to a $\xi_y$(HER) of 0.09. This means that the maximum beam–beam parameter increased from 0.08 to 0.09 owing to the skew-sextupoles. The change of $\beta^*_x$ from 0.8 or 0.9 m to 1.2 m was done to increase the bunch currents by mitigating the physical aperture problem at the crab cavities and to compare the data with the simulations at a higher bunch current region. Even with solving the physical aperture problem, there remained a large discrepancy between the simulation and the experiment.

With this change, we could increase the bunch currents up to the value shown in Fig. 8 and the discrepancy between the simulation and the experiment was shown more definitely. Figure 10 shows a comparison of the specific luminosity with different values of $\beta^*_x$. In the beam–beam simulations, as shown in the figure, the specific luminosity with $\beta^*_x = 0.8$ m is much higher than that with $\beta^*_x = 1.5$ m. In the experiment, however, this change of $\beta^*_x$ did not make any difference to the specific luminosity. The specific luminosity with $\beta^*_x = 0.8$ m or 0.9 m in Fig. 10 is lower than that with $\beta^*_x = 1.2$ m. This is because the data with $\beta^*_x = 0.8$ m or 0.9 m were taken before the introduction of the skew-sextupole magnets. In Fig. 10, the specific luminosity with the nominal operation bunch currents is also shown (green dots) as a reference. In addition to these counter-measures for the lifetime problem, we also tried to raise the crab voltage. If this had been successful, we could have lowered the horizontal beta function at the crab cavity while keeping $\beta^*_x$ the same. We tried to operate the He refrigerator at lower pressure to lower the He temperature. From the data from the R&D stage, it was expected that we could operate the crab cavity stably with a higher voltage, if the He temperature was lowered. We actually succeeded in lowering the He temperature from 4.4 K
down to 3.85 K in April 2009. However, it turned out that the maximum crab voltage was unchanged even with this lower He temperature. Therefore, we gave up this trial.

With these counter-measures, we also expected to improve the specific luminosity by solving the lifetime problem, since we sometimes encountered a situation where we could not move some machine parameter such as the horizontal orbital offset at the IP to the direction giving a higher luminosity due to poor beam lifetime. However, we found that the lifetime problem has almost nothing to do with the specific luminosity, except for the high bunch current region where the lifetime problem was serious.

As for the short lifetime problem, we have developed another counter-measure of $e^+/e^-$ simultaneous injection. The injector linac is shared by 4 accelerators. Two are the KEKB rings and the other two are the PF ring and another SR ring called PF-AR. Before the simultaneous injection scheme was successfully introduced, there were 4 injection modes corresponding to the 4 rings. Switching from one mode to another took about 30 s or 3 min. The concept of simultaneous injection is to switch the injection modes pulse-to-pulse. In the period of the KEKB operation, we succeeded in applying simultaneous injection in 3 rings (the 2 KEKB rings and the PF ring) [6]. With this new injection scheme, beam operation with a shorter beam lifetime became possible. However, as mentioned above, we found that the lifetime problem has almost nothing to do with the specific luminosity, although the machine parameter scan at KEKB has become much faster with constant beam currents stored in the rings and it has become possible to find better machine parameters much more quickly than before.

5.5.2. Synchro–betatron resonance. In KEKB operation, we found that a synchro–betatron resonance of $(2\nu_x + \nu_s = \text{integer})$ or $(2\nu_x + 2\nu_s = \text{integer})$ seriously affects the KEKB performance. The nature of the resonance lines was studied in detail during the machine study on crab crossing. We found that the resonances affect (1) single-beam lifetimes, (2) single-beam beam sizes (both in the horizontal and vertical directions), (3) two-beam lifetimes, and (4) two-beam beam sizes (both in the horizontal and vertical directions), and the effects are beam-current-dependent. The effects lower the luminosity directly or indirectly through beam-size blowup, beam current limitation due to poor beam lifetime, or a smaller variable range of the tunes. The strength of the resonance lines can be weakened by choosing properly a set of sextupole magnets. KEKB adopted the non-interleaved sextupole scheme to minimize the nonlinearity of the sextupoles. The LER and HER have 54 pairs and 52 pairs of sextupoles, respectively. With so many degrees of freedom in the number of sextupoles, optimization of sextupole setting is not an easy task even with the present computing power. Prior to the beam operation, the sextupole setting candidates are searched by computer simulation. Usually the dynamic aperture and an anomalous emittance growth [19] are optimized on the synchro–betatron resonance. Usually, a sextupole setting that gives good performance in the computer simulation does not necessarily give good performance in the real machine; most of the sextupole setting candidates do not give satisfactory performance. When we changed the linear optics, we usually needed to try many setting candidates until we finally obtained a setting with sufficient performance. The single-beam beam size and the beam lifetime are criteria for sextupole performance. Alternatively, as an easier method of the estimation of sextupole performance, beam loss was observed when the horizontal tune was jumped down across the resonance line. The resonance line in the HER is stronger than that in the LER, since we do not have a local chromaticity correction in the HER. In usual operation, we could operate the machine with the horizontal tune below the resonance line in case of the LER, while we could not lower the horizontal tune of the HER below the resonance line. The beam–beam
simulation predicts a higher luminosity with a lower horizontal tune in the HER. To weaken the strength of the resonance line in the HER, we tried to change the sign of $\alpha$ (momentum compaction factor). Since $\nu_s$ is negative with positive $\alpha$, the resonance is a sum resonance ($2\nu_x + \nu_s = \text{integer}$). By changing the sign of $\alpha$, we can change it to a difference resonance ($2\nu_x - \nu_s = \text{integer}$). A trial was done in June 2007. The trial was successful and we were able to lower the horizontal tune below the resonance. However, when we tried the negative $\alpha$ in the LER, an unexpectedly large synchrotron oscillation due to the microwave instability occurred. Due to this oscillation, we gave up the negative $\alpha$ optics trial. So far, we have formed no conclusion on the effect of the synchro–betatron resonance on the specific luminosity.

5.5.3. Machine errors. The method of luminosity tuning is described in the preceding section. In the conventional method of tuning at KEKB, most of these parameters (except for the parameters optimized by observing their own observables) are scanned one by one just observing the luminosity and the beam sizes. One possibility for the low specific luminosity is that we have not yet reached an optimum parameter set due to too wide a parameter space. As a more efficient method for the parameter search, in autumn 2007 we introduced the downhill simplex method for twelve parameters of the $x$–$y$ coupling parameters at the IP and the vertical dispersions at the IP and their slopes, which are very important for the luminosity tuning, from the experience of the KEKB operation. These twelve parameters can be searched at the same time with this method. We have been using this method since then. However, even with this method an achievable specific luminosity has not been improved, although the speed of the parameter search seems to be rather improved.

Another possibility for our inability to achieve a higher luminosity with the tuning method above is the side effects of the large tuning knobs. Although machine errors can be compensated by using the tuning knobs, tuning knobs that are too large cause side effects and would degrade the luminosity. Therefore, if the machine errors are too large, the luminosity predicted by the simulation cannot be achieved by using the usual tuning knobs. We actually confirmed that large tuning knobs on the $x$–$y$ coupling at the IP can degrade the single beam performance. The problem is how large machine errors exist at KEKB. According to the simulation, with reasonable machine errors such as misalignments of magnets and BPMs, offsets of BPMs, and strength errors in the magnets, such large errors in the $x$–$y$ coupling or the dispersion at the IP are not created, as the luminosity cannot be recovered by the knobs due to their side effects. One possibility could be the error related to the detector solenoid. The Belle detector is equipped with a 1.4 T solenoid. The field is locally compensated by the compensation solenoid magnets installed near the IP so that the integral of the solenoid field is zero on both sides of the IP. The remaining effects of the solenoid field are compensated by the skew-quadrupole magnets located near the IP. If the compensation is insufficient (or over-compensated), a large error in the $x$–$y$ coupling would remain. Although there is no direct evidence that the compensation of the Belle solenoid is insufficient, the effect of the Belle solenoid on the luminosity was doubted, as for the beam energy dependence of the luminosity. KEKB was designed to operate on the $\Upsilon(4S)$ resonance ($E_{CM} = 10.58$ GeV). KEKB was also operated on $\Upsilon(1S)$ ($E_{CM} = 9.46$ GeV), $\Upsilon(2S)$ ($E_{CM} = 10.02$ GeV), and $\Upsilon(5S)$ ($E_{CM} = 10.87$ GeV). We found that the luminosity on $\Upsilon(5S)$ is almost the same as that on $\Upsilon(4S)$. However, the luminosity on $\Upsilon(1S)$ and $\Upsilon(2S)$ is lower than that on $\Upsilon(4S)$ by $\sim 50\%$ and $\sim 20\%$, respectively. The design beam energy of KEKB is that of $\Upsilon(4S)$, and the $x$–$y$ coupling due to the Belle solenoid is compensated completely at this design energy. When we change the beam energy, we do not change the strength of the Belle solenoid and the compensation
Thus, the $x$–$y$ coupling correction for the Belle solenoid is not complete on a resonance other than $\Upsilon(4S)$ and the luminosity would be affected by the remaining $x$–$y$ coupling. To investigate this issue, a machine study was done on $\Upsilon(2S)$ in October 2009 with the Belle solenoid and compensation solenoid, which is tracked to the beam energy. In contrast to the initial expectation, the luminosity in this condition was even worse than the usual $2S$ run. We gave up this trial in about 2 days, since the Belle experiment could not use the data with the different detector solenoid strength. Therefore, the correlation between the detector solenoid and the luminosity was not confirmed in this experiment.

We also tried to measure the $x$–$y$ coupling at the IP directly by using the injection kicker magnets and the BPMs around the IP. Although some data showed a very large value of the $x$–$y$ coupling at the IP, we have obtained no conclusive results due to the poor accuracy of the measurements.

5.5.4. Vertical emittance in a single beam mode. The beam–beam simulation showed that the attainable luminosity depends strongly on the single beam vertical emittance. If the actual vertical emittance is much larger than the assumed value, it could create a disagreement. We carefully checked the calibration of the beam size measurement system. We found some errors in the calibration of the HER beam size measurement system and the actual vertical emittance was somewhat smaller than the value that was considered previously. However, the latest values of the global $x$–$y$ coupling of both beams are around 1.3% and these coupling values do not explain the discrepancy in the specific luminosity between experiment and simulation shown in Fig. 10, where the $x$–$y$ coupling in the simulation is assumed to be 1%.

5.5.5. Vertical crabbing motion. The vertical crab at the IP could degrade the luminosity. It can be created by some errors related to the crab kick, such as misalignment of the crab cavity and the local $x$–$y$ coupling at the crab cavity. The $x$–$y$ coupling parameters at the crab cavities give a tuning knob to adjust the vertical crab at the IP. By tuning them, we can eliminate the vertical crab at the IP, even if it is created by other sources such as misalignment of accelerating cavities. However, tuning of these parameters is not so effective for increasing the luminosity as described above.

5.5.6. Off-momentum optics. It has been shown by beam–beam simulation that the chromaticity of the $x$–$y$ coupling at the IP could reduce the luminosity largely through the beam–beam interaction, if the residual chromatic coupling is large [20,21]. While even an ideal lattice has such a chromatic coupling, the alignment errors of the sextupole magnets could cause a large chromatic coupling. It has been thought that this kind of chromatic coupling is one of the candidates causing the serious luminosity degradation with crab crossing. Parallel to trials measuring such chromatic couplings directly, we introduced tuning knobs to control them. For this purpose, we installed 14 pairs of skew-sextupole magnets (10 pairs for the HER and 4 pairs for the LER) in the beginning of 2009. The maximum strength of the magnets (bipolar) is $K_2 \sim 0.1/m^2$, and $K_2 \sim 0.22/m^2$ for the HER and LER respectively. The tuning knobs using these magnets were introduced to the beam operation at the beginning of May 2009. The luminosity gain using these knobs is about 15%. Even with the improvement in the luminosity by the use of the skew-sextupole magnets, there still remains a large discrepancy between the experiment and the simulation.

5.5.7. Fast noise. Fast noise would cause a loss in the luminosity. According to the beam–beam simulation, the allowable phase error of the crab cavities for an $N$ turn correlation is $0.1 \times \sqrt{N}$ degrees. On the other hand, the measured error in the presence of the beams was less than $\pm 0.01$
degree for fast fluctuation (≥1 kHz) and less than ±0.1 degree for slow fluctuation (from ten to several hundred Hz). Then, the measured phase error is much smaller than the allowable values given by the beam–beam simulation. Besides the noise from the crab cavities, any fast noise could degrade the luminosity. For example, in 2005, we found a phenomenon that the luminosity depends on the gain of the bunch-by-bunch feedback system. With a gain higher by about 6 dB, the luminosity decreased about 20% [15]. This seems to indicate that some noise in the feedback system degraded the luminosity. However, this phenomenon disappeared after a system adjustment, including the replacement of an amplifier for the feedback system. Although we confirmed that some artificially strong noise to the crab cavities or to the feedback system can decrease the luminosity [22], there is no evidence that the achievable luminosity at KEKB was limited by some fast noise.

6. Continuous injection scheme

The beam injection and its scheme is important for gaining integrated luminosity. In the upgrade from TRISTAN to KEKB, the linac was upgraded to enable direct injection. In the period of the KEKB operation, the beam injection and its scheme were much improved, which contributed greatly to the integrated luminosity. The improvements include 2-bunch injection [6], continuous injection, and simultaneous injection [6]. In this section, we describe the method and the results of the continuous injection scheme.

6.1. Motivation

Before we introduced the continuous injection scheme, beam injection was done after the physics run, which restarted after the previous beam injection was completed. Therefore, the physics detector could not take data during the beam injection. The idea of the continuous injection scheme is that the detector continues to take data during the beam injection. With this scheme we can expect a much higher accumulation rate of the luminosity, since we can avoid the time loss due to the beam injection and always keep the maximum luminosity.

6.2. Efforts to realize continuous injection

On the Belle detector side, the influence of the continuous injection scheme was carefully checked. The beam background was not so high, except for 2 ms just after injection. Belle could turn on the detector’s high voltage during the injection and could take data using the simple veto method for 2 ms. During the continuous injection, the CDC current draw became higher by 10% or less, as compared with that in normal running without the beam injection. Several test runs were performed and two problems were found, initially. The first problem was related to a preamplifier of the TOF (time of flight) scintillation counter. No serious problems with the preamplifier during normal physics runs had been observed for a few years. However, unexpected huge pulses entered the preamplifier at the injection in the test runs. A baseline stabilization part in the preamplifier did not work correctly for the huge pulse. All preamplifiers were replaced with new ones, which were modified to avoid such a problem. The second problem was that the data acquisition system frequently stopped. The data sizes for all sub-detectors were checked as a function of time after the injection. The events with larger data size were recorded more frequently after the veto window. The veto time was increased to 3.5 ms from 2 ms. After that, the rate of system stopping decreased dramatically. On the accelerator side, we made efforts to decrease the beam background during continuous injection. Tunings useful in decreasing the beam background during continuous injection involved narrowing the energy spread.
Fig. 11. Beam currents and luminosity trend before continuous injection.

of the positron beam from the linac by adjusting the ECS parameters, the beam orbit tuning of the injecting beams, and the setting of the movable masks.

6.3. Results of continuous injection

We started the beam operation with the continuous injection scheme in the middle of January 2004. Since then, this scheme has been very successfully applied to the KEKB operation and has brought an enormous gain in the integrated luminosity to Belle. In Table 5, we show a comparison of luminosity performance before and after continuous injection. For comparison, we took two shifts that were stable and gave record integrated luminosities. The beam operations of the two shifts are shown in Figs. 11 and 12. Between the two shifts, we have achieved some improvement in the peak luminosity, as is shown in Table 5. The improvement in the integrated luminosity contains both contributions from continuous injection and the increase of the peak luminosity. By removing the contribution from the peak luminosity, we found that the gain in the integrated luminosity of the continuous injection is about 26%. In the removal of the contribution from the improvement in the peak luminosity, we made a simple scaling calculation. However, observing more precisely the luminosity trend, we noticed that we needed a further correction. The main reasons for the improvement in the peak luminosity were the increase of the beam currents and the improvements in the specific luminosity by squeezing the beta functions at the IP and the change in the working points. However, we noticed that continuous injection itself contributed to the increase in the peak luminosity. As seen in Fig. 13, in the case of the conventional injection scheme, the maximum peak luminosity was not obtained with the maximum beam currents of a fill. On the other hand, in the case of continuous injection, the maximum peak luminosity was obtained almost at the maximum beam currents. This
Fig. 12. Beam currents and luminosity trend after continuous injection.

Fig. 13. Comparison of luminosity trend (before and after introducing continuous injection). The blue and red dots denote data taken before introducing continuous injection (on 20 December 2003) and after continuous injection (on 23 May 2004), respectively.

difference indicates that we have to change the beam tuning conditions according to the beam currents, i.e. we can tune the machine at the maximum beam currents with continuous injection, while, in the conventional injection scheme, the machine condition changes before optimizing the machine conditions to the maximum beam currents. We found that the mechanical positions of the BPMs move depending on the beam currents. The beam orbit corrections are frequently done relying on the BPMs and the changes of the orbits at the sextupole magnets result in distortions of the linear optics. This might be the reason why we have to change the machine tuning conditions depending on
Table 5. Comparison of the continuous and conventional injection schemes. *: due to injection and high voltage up/down.

| Injection mode               | Continuous                  | Conventional                 |
|------------------------------|-----------------------------|------------------------------|
| Reference shift              | 20 Dec. 2003 owl             | 23 May 2004 owl              |
| Integrated luminosity per shift | 330.6                      | 228.7                       |
| Peak luminosity              | 12.824                      | 11.139                      |
| Loss time*                   | 0                           | ~13.4                       |
| Veto time during injection   | 3.5                         | 0 ms                        |
| Increase of dead time due to veto | ~2.3                     | 0                           |
| Linac repetition rate         | 10                          | 50 Hz                       |
| Injection rate (e^+)         | ~0.39                       | ~3.1                        |
| Injection rate (e^-)         | ~0.71                       | ~4.5                        |
| Peak beam current (e^+)      | 1600                        | 1570 mA                     |
| Peak beam current (e^-)      | 1200                        | 1175 mA                     |

the beam currents. The maximum luminosity with the conventional injection scheme was obtained with lower beam currents than the peak ones by 3% (HER) and 4% (LER). In the case of continuous injection, the amounts of beam current reduction were 0% (HER) and 1% (LER). This means that continuous injection caused increases in the beam currents effectively by about 3%. Since the luminosity is roughly proportional to the beam currents in the present region of the beam currents, this (effective) increase of the beam currents causes an increase in the luminosity of about 3%. If we count this effect, the gain in the integrated luminosity of the continuous injection scheme amounts to about 30%. Also shown in Table 5, the loss time with the conventional injection scheme was about 13.4% of the whole operation time. With continuous injection, we could decrease this loss almost to zero. The injection veto caused an increase of dead time of 3.5% (at 10 Hz injection). Since the beam injection time with continuous injection was about 66% of the whole operation time, the net increase of the detector dead time due to the veto was about 2.3%. Therefore, the gain coming from eliminating the loss time was about 11%. Roughly speaking, the gain of the continuous injection in the integrated luminosity was about 30%. One-third of it came from elimination of the loss time, while two-thirds came from keeping the maximum beam currents. The continuous injection scheme has another merit that it caused more stable beam operation. Generally speaking, machines have the tendency that their operation becomes more stable with unchanged operation conditions. As an example in KEKB operation, in the conventional injection scheme we used different working points during the injection and the physics run, as mentioned above, and beam abort sometimes occurred when changing the tunes due to incorrect settings. We can avoid this problem with continuous injection. Although it is not easy to estimate how much gain in the luminosity has been caused by this merit of continuous injection, we feel that this gain was not very small. Table 5 shows beam injection rates with the two injection schemes. As is expected, the injection efficiency with continuous injection is worse than that with conventional injection by about 40% (e^+) and 20% (e^-). The degradation of the injection rates comes mainly from the narrower setting of the movable masks. The reason for much poorer injection efficiency in the positron injection may be that the positron beam from the linac has a larger emittance and a larger energy spread.

7. Discussion

As described in the previous section, one of the challenges at KEKB was the very high beam–beam parameter (ξ_y ∼ 0.15). In the history of colliders, no machines had achieved such a high beam–beam parameter. We devoted a great deal of effort to realizing this high beam–beam parameter. In parallel
to continuing the efforts to increase the specific luminosity at KEKB, we continued to study using the beam–beam simulation. We checked the validity of the beam–beam simulation code itself by comparing two different codes. In the KEKB operation, we relied on the beam–beam simulations done by K. Ohmi and the introduction of the crab cavities was decided based on these simulations [12–14]. We confirmed that a different beam–beam simulation code from that by K. Ohmi gives the same high beam–beam parameter with a horizontal tune close to the half-integer [23].

In the beam–beam simulation, only the linear lattice and the beam–beam interaction are included. Other effects, such as machine errors, lattice nonlinearity, or off-momentum optics, have been investigated by adding them intentionally to the simulation code. The simulation showed that the residual $x$–$y$ coupling at the IP due to machine errors would degrade the luminosity. However, as is described in the previous section, the amount of $x$–$y$ coupling at the IP that explains the discrepancy between the luminosity by the simulation and that achieved in KEKB is rather large compared with that expected with reasonable machine errors. As for the nonlinearity of the lattice, the IR nonlinearity is dominant over the other lattice nonlinearities in high luminosity colliders with very small IP beta functions. The IR nonlinearity was implemented in the beam–beam simulation. However, the luminosity degradation due to the IR nonlinearity was negligible. The harmful effect of the chromaticity of the $x$–$y$ coupling at the IP was shown by the simulation as described in the previous section. By correcting these values using the skew-sextupole magnets, the luminosity increased by about 15%. The introduction of the skew-sextupole magnets was motivated by the beam–beam simulation. An attempt to measure the chromaticity of the $x$–$y$ coupling at the IP was made [24]. The results of the measurements showed that the chromaticity of the $x$–$y$ coupling seemed to be well corrected by the skew-sextupole magnets. Although the accuracy of the measurements of the $x$–$y$ coupling parameters is not good concerning their absolute values, their momentum dependence seemed to be measured with enough accuracy. Another attempt was to implement the longitudinal wakefield into the beam–beam simulation [23]. The longitudinal particle distributions of both beams at KEKB greatly deviated from a Gaussian distribution due to the potential well distortion and the microwave instability in the LER. However, such simulations showed that the wakefield does not have a big effect on the luminosity performance.

The beam–beam simulations mentioned above are based on the strong–strong model. To study the effects of the nonlinearity of the entire lattice, a weak–strong beam–beam simulation was done using the SAD lattice [25]. The luminosity was consistent with the strong–strong simulation. We found that the linear IP coupling correction is essentially important even in the simulations considering the nonlinear lattice, as shown in Fig. 1 in Ref. [25]. Therefore, the lattice nonlinearity seems not to be important for luminosity performance. Another thing that we tried was to implement the crab cavities explicitly into the beam–beam simulation. Note that the simulations mentioned so far do not consider crab crossing explicitly but the head-on collision was used as crab crossing. Figure 2 in Ref. [25] shows the results of the strong–weak beam–beam simulation with the SAD lattice including a single crab cavity. The luminosity degraded by about 25% compared with the case of head-on collision without the crab cavity, even with the IP coupling correction. In KEKB, a single crab cavity per ring was used and each bunch circulates around the ring with horizontal tilting. The tilt motion may pick up the nonlinear force along the ring (M. Zobov, private communications). Then, we carried out a beam–beam simulation where two crab cavities are located on both sides of the IP and the crabbing motion is localized near the IP. We found that the luminosity was the same as that in the single cavity case. We have not yet understood the mechanism of the luminosity degradation, although effects of the chromatic phases between the crab cavities and the IP are suspected. The effects of the crabbing
motion explain some part of the discrepancy between the achievable luminosity in the strong–strong beam–beam simulation and that in the experiment. However, there still remains a big discrepancy.

8. Conclusion

After the beam commissioning of the first four years, which has been described in a previous paper [2], the KEKB performance improved drastically and KEKB recorded the world’s highest luminosity in both the peak and integrated values. The suppression of the effects of electron clouds by the solenoid windings in the LER was essentially important. However, at a higher LER beam current than about 1.6 A, the KEKB luminosity was still affected by the effects of electron clouds even with the solenoid windings.

The luminosity tuning done by using the tuning knobs for the $x$–$y$ coupling parameters and the dispersions at the IP and others was also very important for increasing the luminosity, although the tuning was a very time-consuming task. Of course, the increase in the beam currents was also important for the luminosity [3].

The crab cavities worked very well until the end of the KEKB operation and imposed almost no beam current limitation on the operation. We found that the specific luminosity with the crab cavities is about 20% higher than that without the crab cavities. This improvement in the luminosity is larger than the recovery of the geometrical loss in the luminosity due to a crossing angle of about 11%. The beam–beam parameter, $\xi_y$, with the crab cavities reached 0.09. Although this value is very high, it is still much lower than the prediction of $\xi_y \sim 0.15$ from the beam–beam simulation. Although the effects of the crabbing motion explain some of the discrepancy, there still remains a big discrepancy. We could not identify the reason for this discrepancy during the period of KEKB operation. This is an unsolved problem at KEKB.

As for the efficiency in accumulating the luminosity, the realization of the continuous injection scheme has been very important at KEKB. The gain of this scheme to the integrated luminosity was about 30%.

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