

KEKB Accelerator

Achievements of KEKB

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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 summarize the history of KEKB and show the achievements made there.

1. Introduction

KEKB is a two-ring, asymmetric-energy, electron–positron collider constructed at KEK with the aim of producing B mesons as in a factory. The construction of KEKB started in 1994, utilizing the existing tunnel of TRISTAN, a $30\text{ GeV} \times 30\text{ GeV}$ electron–positron collider. The machine commissioning of KEKB started in December 1998. The physics experiment with the physics detector named Belle was started in June 1999. The peak luminosity surpassed the design value of $1.0 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ in May 2003. The maximum peak luminosity of KEKB is $2.11 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, which was recorded in June 2009. This value has been the world record since then. The KEKB operation was terminated at the end of June 2010 to upgrade KEKB to SuperKEKB. The total integrated luminosity collected by the Belle detector was 1041 fb^{-1} . The history of KEKB is shown in Fig. 1.

The most important outcome of the physics experiment at KEKB/Belle is the detection of CP violation in B mesons predicted on the basis of the Kobayashi–Maskawa theory. Prof. M. Kobayashi and Prof. T. Maskawa were awarded the 2008 Nobel Prize in Physics for this theory. The Belle experiment, carried out using KEKB, contributed greatly to confirmation of the theory.

2. Features of KEKB

In this section, we describe the design of KEKB and its features.

2.1. General scheme

The design concepts of KEKB are reported in the KEKB design report [1]. Figure 2 shows the schematic layout of KEKB. In Table 1, the machine parameters of KEKB with which the record peak luminosity was achieved on 7 June 2009 are summarized. The design parameters of KEKB are also shown in the table in parentheses. This table shows some basic features of KEKB. First of all, KEKB is an energy-asymmetric collider. Although it is mostly operated on the $\Upsilon(4S)$ resonance like CESR-B, the energies of the two beams are different. This asymmetry comes from the physics motivation. The low energy ring (LER) is for the positron beam and the high energy ring (HER) is for the electron beam. This choice of charge was made considering the ion effects (the fast ions and the trapped ions) in the electron ring and the situation of the injector upgrade to realize direct injection. The second feature is a high design luminosity of $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. To realize this luminosity, we chose the following design parameters:

- Very low β_y^* : 1 cm for both beams
- Very high beam currents: 1.1 A for electrons and 2.6 A for positrons
- Relatively high beam-beam parameters: 0.052 in the vertical plane.

2.2. Energy transparency

As seen in Table 1, we assumed so-called energy transparency conditions in the design in order to balance the beam-beam effects between the two beams with different energies. We assumed that the beta functions at the IP, the beam-beam parameters, the radiation damping time, the emittances, the synchrotron tune, and the (fractional part of the) betatron tunes are the same for the two beams. To equalize the radiation damping time, wiggler magnets were installed in the LER. As a result of these, the design beam currents are inversely proportional to the beam energy.

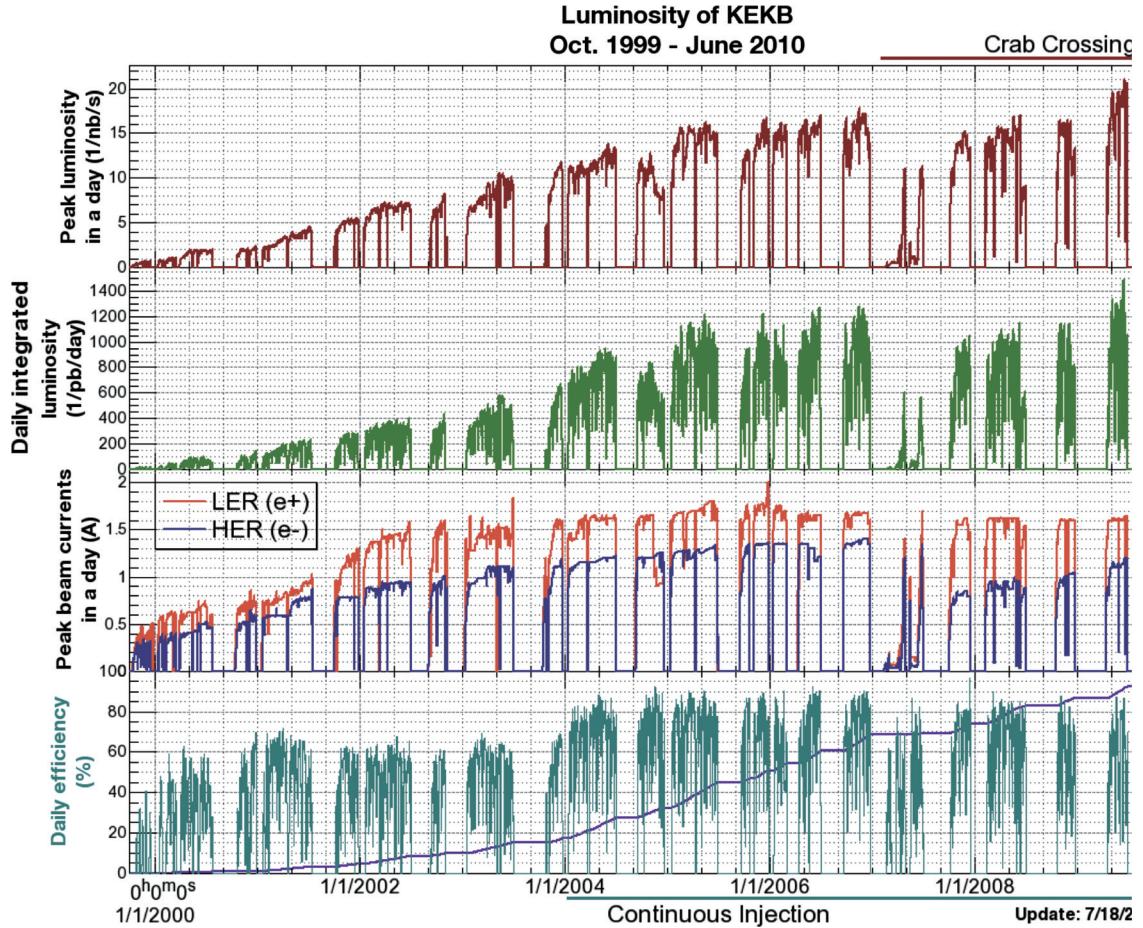


Fig. 1. History of the performance of KEKB from October 1999 to June 2010. The rows represent (from top to bottom) the peak luminosity in a day, the daily integrated luminosity, the peak stored currents in the LER and HER in a day, the daily efficiency, and the total integrated luminosity at Belle, respectively. The integrated luminosities are the numbers recorded by Belle. The daily efficiency is defined as (daily integrated luminosity)/(peak luminosity times 1 day), and was boosted in January 2004 by the continuous injection mode. The crab crossing scheme has been in use since February 2007.

2.3. IR design

We introduced a horizontal crossing angle of ± 11 mrad. There are two motivations for this. One is to avoid the harmful effects of parasitic collisions. The other is to simplify the IR design. With this scheme, no separation bending magnets for separating the two beams around the IP are needed. This contributes to avoiding possible problems with the detector beam background from synchrotron radiation emitted from the separation bending magnets. The issue of synchro–betatron coupling from the crossing angle is discussed in Sect. 2.7. As for the final focus quadrupoles, we adopted superconducting magnets. In the LER, we adopted a local chromaticity correction scheme. With this scheme, the chromaticity created by the IR quadrupoles is corrected within the straight section including the IP. With this scheme, it is expected that the ring energy acceptance is widened and the strength of the synchro–betatron resonance lines shown in Sect. 3.3.1 is weak. We also introduced compensation solenoid magnets for the purpose of compensating the detector solenoid. By using them, an integral of the solenoid field along the longitudinal direction around the IP can be set to zero. This scheme contributed to reducing the strength of the skew quadrupoles drastically.

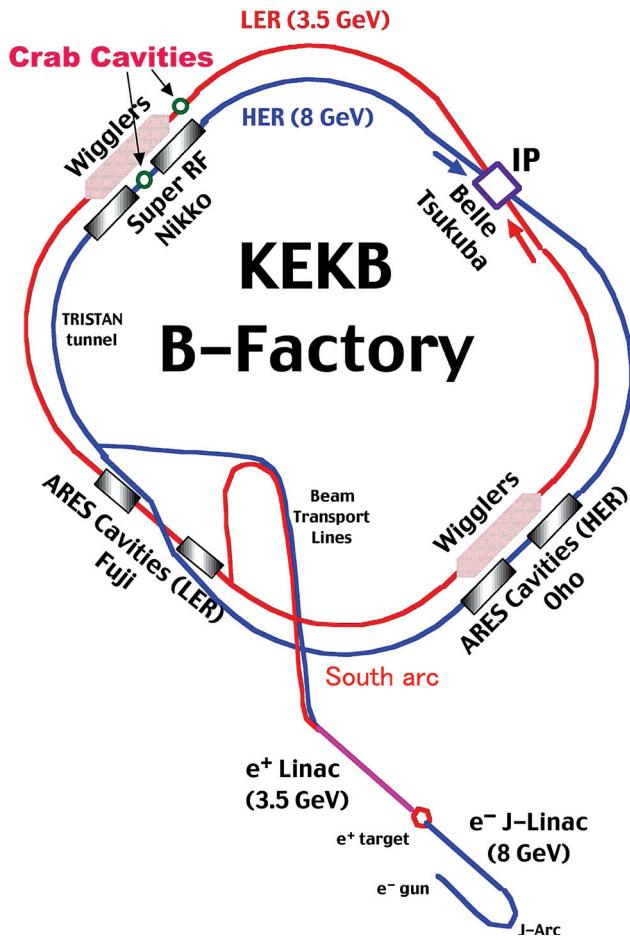


Fig. 2. Schematic layout of KEKB.

2.4. Lattice design

In modern machines like KEKB, the lattice design is much more important than in past machines. The goals of the lattice design at KEKB were to keep a sufficient dynamic aperture in both the transverse and longitudinal directions, to give a short bunch length in order to reduce the hourglass effect and to keep enough tunability in the momentum compaction factor and the emittance. To keep enough (transverse) dynamic aperture, we adopted the non-interleaved sextupole scheme. In this scheme, each pair of sextupole magnets with the same strength are connected with a $-I$ 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. A new lattice called a 2.5π cell lattice was devised. 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 2.5π cell lattice, a very flexible change in the emittance and the momentum compaction factors is realized by controlling the dispersion functions. As seen in Table 1, the design emittance and the momentum compaction are relatively small. The small value of the momentum compaction factor is favorable for obtaining the short bunch length. If needed, the momentum compaction factor and the emittance can be changed over a very wide range. For example, the momentum compaction factor can be set negative with the same absolute value as the design value.

Table 1. Machine parameters of KEKB (27 June 2009). Parameters in parentheses denote the design parameters.

	LER	HER	
Energy	3.5	8.0	GeV
Circumference	3016		m
RF frequency	508.88		MHz
Horizontal emittance	18 (18)	24 (18)	nm
Beam current	1637 (2600)	1188 (1100)	mA
Number of bunches	1585*) (\sim 4600**)		
Bunch current	1.03 (0.57)	0.75 (0.24)	mA
Bunch spacing		1.84 (0.59)	m
Total RF voltage	8.0 (5–10)	13.0 (10–20)	MV
Synchrotron tune ν_s	–0.0246 (–0.1––0.2)	–0.0209 (–0.1––0.2)	
Horizontal tune ν_x	45.506 (45.52)	44.511 (47.52)	
Vertical tune ν_y	43.561 (45.08)	41.585 (43.08)	
Beta at IP β_x^*/β_y^*	120/0.59 (33/1)	120/0.59 (33/1)	cm
Momentum compaction α	3.31 (1–2)	3.43 (1–2)	$\times 10^{-4}$
Beam-beam parameter ξ_x	0.127 (0.039)	0.102 (0.039)	
Beam-beam parameter ξ_y	0.129 (0.052)	0.090 (0.052)	
Vertical beam size at IP σ_y^*	0.94***) (1.34)	0.94***) (1.34)	μm
Beam lifetime	133@1637	200@1188	min@mA
Luminosity (Belle CsI)	2.108 (1.0)		$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
Total integrated luminosity	1041		fb^{-1}

*) with 5% bunch gap, **): with 10% bunch gap, ***): estimated value from the luminosity assuming that the horizontal beam size is equal to the calculated value.

2.5. High beam currents and beam instabilities

The design beam currents of 2.6 A and 1.1 A were unusually high values even compared with those of existing SR machines. What we considered the most severe obstacle for the high currents was a coupled bunch instability from the fundamental modes of RF cavities. To overcome this problem, we developed two different types of RF cavities. One is a cavity system called ARES. In this system, a large energy storage cavity is attached to an accelerating cavity and RF power is fed through this storage cavity. Owing to this large energy storage, the R/Q value of the system can be reduced drastically, which contributes to suppression of the instability. This ARES system is used both in the LER and the HER. The other system we developed is a superconducting RF cavity system (SCC). The high field gradient and the high Q value of the system can also suppress instability against heavy beam loading. This SCC system is used in the HER, in which we need a high RF voltage. Both the ARES and SCC systems are a single-cell cavity and have a damped structure with higher-order mode (HOM) absorbers for the purpose of suppressing the coupled bunch instability from HOMs. The other possibly harmful multibunch instabilities we considered were the fast ion instability in the HER and the electron cloud instability in the LER. To stabilize these instabilities, a transverse bunch-by-bunch feedback system was developed. A damping time of about 1 ms was expected with the system. In addition to the development of the feedback system, we chose the design value of the vacuum pressure as 10^{-9} Torr for suppression of the fast ion instability. As for the single bunch instability, we considered that the microwave instability could be the most serious. To avoid this possible problem, we planned to fill all the RF buckets with beams, except for some beam gap, which is needed to maintain a sufficient rise time for the abort kicker magnets and also to suppress the ion trapping effect. The design value of the bunch gap is 10% of the ring. With this beam filling scheme, the bunch currents of the beams are relatively small and the design emittances were chosen to fit these bunch currents. The design bunch current of the LER thus chosen is about 1/5 of the

estimated threshold intensity for the microwave instability. As for the electron cloud instability, we did not use the antechamber. We kept a backup plan to install solenoid magnets around the LER ring in case the instability could not be suppressed by the feedback. In the design, we only considered the coupling bunch instability by electron clouds.

2.6. Vacuum system

The first design issue was how to manage the power and outgassing due to synchrotron radiation. The design vacuum pressure is 10^{-9} Torr with full design currents [2]. The vacuum pump system and the chamber cooling system were designed to achieve the design vacuum pressure with the design beam currents. The second design issue was the cross section of a beam chamber. There were two choices, a simple beam pipe or one with antechambers. We adopted the simple beam pipe. The reason for this is as follows. First, the fabrication cost of a beam chamber with antechambers is expensive. Second, to guide 90% of the photons of synchrotron radiation to the antechamber, we need rather a wide gap between the beam duct and the antechamber. The design of an effective antechamber seemed not possible without reconsidering the design of the magnets. The third issues were those related to the electromagnetic interaction between the stored charge and vacuum components. Without actual experience from the high beam currents, we had to design an RF bridge of bellows, movable masks, and other components. The movable mask is a beam scraper to stop particles with a large energy deviation and/or a large orbit oscillation from hitting the beam pipes around the interaction region.

2.7. Beam-beam effects

As described in Sect. 2.3, a big challenge at KEKB was to introduce the horizontal crossing angle. In the design phase of KEKB, it was commonly believed that a finite crossing angle would not work well based on the experience at DORIS, where the synchro–betatron resonances originating at the finite crossing angle strictly limited the performance of DORIS [3]. The problem at DORIS was that the decoupling transmitter and the RF-quadrupole were needed to suppress the coupled bunch instabilities. Those devices created tune spread among bunches and some bunches always hit the satellite resonances due to synchro–betatron resonances. In the KEKB design, it was shown that the coupled-bunch instabilities originating from the RF cavities could be avoided by careful design of the RF cavities. The remaining coupled bunch instabilities were supposed to be suppressed by the bunch-by-bunch feedback and by not introducing a tune spread. In addition, a fairly low synchrotron tune ($-0.02 < \nu_s < -0.01$) was planned to be used. The low synchrotron tune also contributes to keeping enough space to avoid the synchro–betatron resonance in the betatron tune space. A large amount of tune surveys by using a strong–weak model were done for the best tune values. The simulations showed that it was possible to reach a vertical beam–beam parameter of 0.052 with the design tune values, even with the horizontal crossing angle of ± 11 mrad. We considered that a short bunch length is important to obtain a high beam–beam parameter. The design criterion for the bunch length was less than half of the IP beta function, β_y^* .

2.8. Crab crossing

The crab crossing scheme was considered in the design of KEKB from the beginning as a backup measure in case the horizontal crossing angle induced unexpectedly large harmful effects. Once, the crab cavities seemed non-urgent because ξ_y reached 0.05 at the early stage of the operation of KEKB in 2003. However, after that, an interesting beam–beam simulation result appeared [4], predicting

that head-on collision or crab crossing would provide higher $\xi_y \sim 0.15$ and the luminosity would be doubled, if combined with a horizontal tune very close to a half-integer. Later on, this simulation result was confirmed by a different simulation [5]. Thus, the development of the crab cavities has been revitalized. The original design of KEKB had two cavities for each ring on both sides of the IP so that the crab kick excited by the first cavity is absorbed by another one. To reduce the cost of introducing the crab cavity system, a single crab cavity scheme was devised. This scheme extends the region with the crab orbit until both cavities eventually merge with each other in a particular location in the ring. Then only one cavity per ring is needed. The crab cavities were installed at KEKB during the winter shutdown in fiscal year (FY) 2006 [6] and have been in use since February 2007. After this, a dedicated machine study and the physics run were done with the crab cavities.

2.9. Beam instrumentation

Fine orbit control is very important for a high luminosity machine. In KEKB, each quad is equipped with one beam position monitor (BPM), as well as a pair of horizontal and vertical steering magnets for high flexibility of orbit control. Another important instrumentation system is the interferometer-type beam-size monitor. By measuring the peak and valley ratio of the interference pattern created by synchrotron light rays passing through two thin slits, we can estimate the beam sizes in both the horizontal and vertical planes.

2.10. Injector

The electrons and positrons are directly injected from a linac-complex into each ring at full energies. This direct injection is important for shortening the injection time and gaining integrated luminosity. To realize direct injection, the linac has been upgraded from 2.5 GeV to 8 GeV by (1) combining a main 2.5 GeV electron linac and a 250 MeV linac for positron production, (2) adding new accelerating sections, and (3) by compressing RF pulses using SLED systems. As seen in Fig. 2, the two linacs were connected by an arc to make the linac-complex J-shaped. A new production target was installed at the 3.7 GeV point, and generated positrons are accelerated up to 3.5 GeV by the downstream half of the linac. For direct injection of the two beams into the KEKB rings, a new 400 m tunnel for beam-transport lines was constructed.

3. Experiences at KEKB

3.1. Lattice

The lattice design has been successful. The IP vertical beta function, β_y^* , reached the design value of 10 mm in 1999. This was the world's minimum value. The chromaticity correction scheme based on the non-interleaved sextupole scheme gave sufficient dynamic aperture even with a smaller β_y^* value than the design, as shown in Table 1. Although an even lower value of β_y^* was possible, the luminosity did not increase due to the hourglass effect. The momentum compaction factor is relatively small, consistent with the short bunch length. One of the reasons for the world's highest luminosity at KEKB is this short bunch length and the corresponding low value of β_y^* . The measured bunch length, which depends on the bunch current, is somewhat longer than was expected. One of the reasons for this is the microwave instability in the LER, as shown below. In a real machine, a model lattice cannot be realized due to machine errors such as misalignment of magnets. We found that an optics correction, which causes the machine lattice to be as close to the model as possible, is important for achieving good performance. For this purpose, we have developed correction tools [7,11]. This

kind of correction was particularly important at KEKB, since the horizontal tunes of KEKB were very close to the half-integer and the machine optics is very sensitive to machine errors with such tunes. This optics correction provided the basis for further tuning. In addition to the optics correction, we needed more fine tuning to achieve a high luminosity, as described in Sect. 3.4. Our experience is that a good condition once obtained with the optics correction and other tuning does not last very long due to orbit drifts and BPM gain drifts. The machine performance tended to degrade as time went by. Typically we needed to do the optics correction and other tuning every two weeks after standardization of the ring magnets. As for the tunability of the lattice, we tried a lattice with negative values of the momentum compaction factors, as described below. Although this lattice did not improve the luminosity, such a trial was important for the machine physics. In SuperKEKB, an extremely low emittance will be needed [8]. The lattice of SuperKEKB is basically the same as that of KEKB except for some modifications. The lattice of SuperKEKB will be tuned so that it will realize the low emittance by making use of the tunability of the 2.5π cell lattice.

3.2. High beam current operation

3.2.1. Vacuum system. The vacuum pressure had been improved gradually as a result of vacuum scrubbing with beams and reached the design pressure in the physics operation. In this sense, the basic design of the vacuum system of KEKB worked very well. However, we experienced many problems with the vacuum components, which have a strong electromagnetic interaction with the stored beam. Particularly problematic components were the bellows and the movable masks. We had rather frequent problems with the RF bridges of the bellows. We adopted a conventional design for the bellows, where the RF bridge is made of thin metal fingers touching the outside of a thin beam pipe. If the touching force is weak, discharge occurs at the touching point by a passing wall current and the finger is often broken. In addition, fingers are sometimes spot-welded at the contact point to the thin beam pipe. Then the fingers cannot slide. The bellows unit loses its flexibility. Also, through the gap between fingers, a beam-induced electromagnetic field enters into the space between the RF bridge and an outer corrugation. Such a field causes the surrounding structure to heat up, and the thin fingers became very hot because of their small heat capacity and low heat conductive cross section. This is observed in the bellows unit near high impedance sources. To cope with these problems, a robust RF bridge (comb-type bridge) was invented. This bellows has a comb-like structure on the facing end of each beam pipe, whose tooth enters the space between the teeth of the other side. Figure 3 in Ref. [2] shows a picture of the comb-type structure and its typical dimensions. The structure is backed up by electrically connecting the fingers outside the comb coupling directly (Fig. 4(a) in Ref. [2]). The design was successful. The temperature rise at the bellows reached an acceptable level. The bellows showing the problems were replaced by the comb-type bellows. In SuperKEKB, we will use this type of bellows.

As for the movable masks, we developed several versions using trial and error. The first version was a hummer-like structure whose head approaches the circulating beam. The stem moves through a hole in a beam pipe and slide contacts at the entrance of the hole electrically connect the stem and the beam pipe wall with spring action. Since the head is very close to the beam (a few mm), a strong electromagnetic field is induced. That field is trapped in the structure of this mask. The trapped field causes beam instability, and high alternative current passing the slide contact produced damage on it. The final (4th) version was a bent-pipe type. Beam collimation is realized by bending the beam pipe itself. With this structure, a local trap of the electromagnetic field is avoided. However, the impedance is still high and an induced field propagates inside the beam pipe. As a result, nearby

bellows units were heated up. To reduce the temperature of these bellows units, a pair of HOM absorbers was set to the enclose movable masks. Another issue related to the movable mask was the direct hit of the beam on it. To avoid such a hit, we developed a special beam abort system, as described in Sect. 3.6. Through these experiences, we learned the importance of avoiding local trapping of an electromagnetic field and of a robust structure, among other things. This knowledge was only obtained from actual experience in real high beam current machines. It will provide a good basis for an even higher beam current machine, SuperKEKB.

3.2.2. RF system. The HER was routinely operated with a beam current of 1.2–1.3 A, which is higher than the design beam current, in the usual physics operation. The maximum peak beam current of the LER was 2.0 A, which is about 77% of the design. Under these high beam currents, both the ARES and SCC systems worked very well. The longitudinal coupled bunch instability from the fundamental mode is suppressed by these systems, although we needed additional -1 mode and 0 mode dampers to overcome the instability completely. No beam instabilities originating from HOMs of the RF cavities have been observed at KEKB. At KEKB, the longitudinal feedback system for suppressing the coupled bunch instability was not needed. The maximum HER beam current was 1.4 A, which is much higher than the design beam current of 1.1 A. This high beam current was achieved mainly by increasing the beam load of the SCCs from ~ 250 kW to 350–400 kW. For this purpose, we carried out coupler tuning and reinforced cooling power of the HOM dampers. The LER beam current was not limited by the RF system but by the electron cloud instability, as explained below.

When we installed the crab cavities in 2007, they were considered to be utilized in the beam study. We considered the possibility that they would be removed from the rings after the beam test, in the case that they did not work well in the presence of the high beam currents. However, they worked very well even in the high beam current operation and we decided to continue using them in the usual physics operation. The crab cavities worked very well up to the end of the KEKB operation and imposed almost no beam current limitations on the operation.

In the following, the significance of the experiences of the RF operation at KEKB is summarized. First of all, it has been proven that the ARES and SCC cavities developed at KEK have excellent performance to accelerate a high intensity beam stably. The ARES cavities have been operated under a high beam load of 1–2 A for a long time and their reliability and stability as a complete RF system have been proven. The SCC cavity is the only cavity system in the world that accelerates the ampere class beam current. We established an SCC system that damps harmful higher modes (the power amounts to 16 kW) and realizes a HOM-free cavity. We also established technology to produce and maintain a coaxial-type input coupler that feeds a high RF power of 350 kW to the SCC cavity. The SCC cavity system works very stably and the trip rate of the SCC cavity is once every 3 months on average per cavity with a beam current of ~ 1 A. As a result of this, the KEKB-type SCC cavity became a promising candidate for the RF system to be adopted for middle-class ring accelerators like the SR machine. BEPC-II and the Taiwan Light Source have already adopted the KEKB-type SCC cavity system.

3.2.3. Instabilities. The beam instabilities observed at KEKB were beam-size blowup induced by electron clouds, coupled bunch instability, and microwave instability. A beam-size enlargement depending on the beam current in the LER has caused one of the most serious luminosity restrictions at KEKB. This type of beam blowup was not considered in the design phase of KEKB. It turned out

that the cause of the blowup is electron clouds. Although the electron clouds are formed by the bunch train, the blowup is induced by a single bunch instability. The mechanism of this blowup has been studied theoretically by Zimmermann and Ohmi [9]. They showed by simulations that the blowup can be explained by a fast head-tail instability caused by wake fields by the passage of the bunch particles through the electron clouds. This explanation has been experimentally confirmed by observing the vertical betatron sideband due to the electron clouds in the LER at KEKB [10]. To suppress this instability, solenoid coils have been wound around approximately 95% of the drift space in the LER with a maximum field at the center of the beam pipe of ~ 60 G [11]. Although the solenoids drastically improved the luminosity, the performance of KEKB was still affected by electron clouds with a higher LER beam current than about 1.6 A. 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 of 1.6 A in the LER is much lower than the design beam current, 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 lowered. This restriction on bunch spacing is also believed to come from the effects of the electron clouds.

The major sources of the coupled bunch instabilities at KEKB were fast ions and electron clouds. Here, the instability due to fast ions is a transient effect and has a different nature from the usual coupled bunch instability, although we categorize the instability as the coupled bunch instability. As for the fast ion instability in the HER, it is well suppressed by the transverse bunch-by-bunch feedback system in the usual vacuum conditions. Only in some bad vacuum conditions, such as after a vacuum leakage or vacuum works, does the instability limit the total beam current. The coupled bunch instability from the electron clouds can also be suppressed by the feedback system with the solenoid magnets at the maximum beam current in the LER of 2.0 A. At KEKB, the effects of trapped ions were not observed owing to the bunch gap. The bunch gap was decreased from 10% of the ring to 5% in 2008 by shortening the rise time of the abort kickers without any problems related to ions. An luminosity increase of about 5% was caused by this. Although the coupled bunch instability due to the impedance of the resistive walls was considered in the design phase, this instability has been well suppressed by the feedback system.

Bunch lengthening depending on the bunch current has been observed at KEKB. The measured bunch length is around 7 mm for both beams under operation conditions, while the natural bunch length is around 5 mm for both beams. In the design phase of KEKB, the threshold bunch current of the microwave instability in the LER was estimated to be around 2.4 mA, which was calculated by summing up all possible impedance sources. The estimated threshold bunch current was more than twice as high as the operation bunch current. Therefore, the bunch lengthening had been believed to be induced by potential-well distortion. In 2008, Cai suggested that microwave instability actually occurs in the LER [5], based on the broadband impedance model whose parameters were determined by the longitudinal profile data taken by the streak camera. This suggestion was confirmed by the Belle detector by measuring the ratio between the hadron and Bhabha events on the $\Upsilon(2S)$ resonance [5]. This resonance has a much narrower width than the $\Upsilon(4S)$ resonance, on which the B-factory machine is usually operated. The measured bunch current dependence of the hadron to Bhabha ratio was consistent with the prediction using the broadband impedance model, which suggested that the threshold bunch current for the microwave instability is around 0.5 mA and the energy spread in the LER is 20% larger than the nominal value at the operation bunch current of ~ 1.0 mA.

In the design phase, the impedance from CSR (coherent synchrotron radiation) was not counted. The microwave instability would be induced by this impedance or other missing impedance sources.

3.3. Beam-beam effects

3.3.1. Comparison with design. As is seen in Table 1, the beam current ratio in the actual operation is very different from the design determined by the energy transparency condition. The origin of this difference is charge asymmetry. The electron cloud instability, which is induced only in the positron ring, is much severer than the fast ion instability in the electron ring. Due to this, the bunch current ratio between the two rings is very different from the energy transparency condition. The KEKB experience suggests that the energy transparency condition is not very serious and the beam-beam tuning can find an optimum tuning condition at a given bunch current ratio.

No effects of the parasitic collision were observed at KEKB owing to the finite crossing angle, even in the case of the minimum bunch spacing of 0.59 m in the machine study.

The beam-beam effects depend strongly on the working points. The horizontal betatron tune in Table 1 is closer to the half-integer than the design. The KEKB luminosity tends to increase with a horizontal tune closer to the half-integer. This tendency was first found in the tune survey in the real KEKB machine and was later confirmed by a strong-strong beam-beam simulation. In the design phase, the tune survey was done using a strong-weak model. Similar tendencies were also found at PEP-II and BEPC-II. When we operated KEKB with a horizontal tune close to the half-integer, a severe obstacle was the synchro-betatron resonance of ($2\nu_x + \nu_s = \text{integer}$). This resonance line is not created or enhanced by the crossing angle and its strength did not change much with crab crossing. 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 the usual operation, we can operate the machine with the horizontal tune below the resonance line in the LER case, while we cannot lower the horizontal tune of the HER below the resonance line. The effects of the resonance line lower the luminosity directly or indirectly through beam-size blowup, beam current limitation due to poor beam lifetime, or a narrower variable range of tunes. We made lots of efforts to weaken the resonance line. These include an extensive search for better setting of the sextupole strength and the optics correction. As part of the efforts to weaken the strength of the resonance line in the HER, we tried to change the sign of α (momentum compaction factor). Since ν_s is negative with positive α , the resonance is a sum resonance ($2\nu_x + \nu_s = \text{integer}$). By changing the sign of α , 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 α in the LER, an unexpectedly large synchrotron oscillation due to the microwave instability occurred. Due to this instability, we gave up the trial of the negative α optics.

The vertical tune in the operation is also different from the design, as shown in Table 1. At the beginning of the KEKB operation, the vertical tune was near the design value. In February 2001, the vertical tunes were moved to above the half-integer based on the results of beam-beam simulations [12]. This change improved the stability of the vertical orbit at the interaction point and in the entire ring. This contributed to the stability of the beam injection. It also contributed to stabilization of the vertical dispersion and x - y coupling. While the peak luminosity was slightly increased, the average luminosity was clearly improved.

We have observed no serious effects from the synchro-betatron resonance from the horizontal crossing angle. With the crossing angle, the vertical beam-beam parameters of both beams exceeded the design value of 0.052.

The design value of the bunch length, σ_z , was set at half of β_y^* . In the design phase, it was considered that this short bunch length was needed to obtain a high beam-beam parameter. This was not based on the beam-beam simulation but on some empirical observations. Our experience at KEKB is that the luminosity is saturated at around the bunch length when we squeeze β_y^* , and a beam-beam parameter of ~ 0.05 can be obtained with the condition $\beta_y^* \cong \sigma_z$. This result is consistent with the beam-beam simulation. The condition $\beta_y^* \geq \sigma_z$ is now widely accepted as the hourglass condition and is used when a new collider is designed.

3.3.2. Tuning with crab cavities. After the installation of the crab cavities at the beginning of 2007, the peak luminosity was lower than that before the installation for a while. Since the specific luminosity was better than before the crab cavities, this was because the beam currents were lower, particularly in the HER, as is shown in Fig. 1. This beam current limitation in the HER was not due to a hardware problem with the crab cavities but was associated with a beam-beam issue. As the HER beam current increased, the LER beam lifetime became short or the beam was lost. It turned out that the cause of this short beam lifetime in the LER was the physical aperture in the horizontal direction around the crab cavities associated with dynamic beam-beam effects (dynamic beta and dynamic emittance issues) [13]. To mitigate this problem, we changed the lattice in both rings around the crab cavities by modifying the wiring of the quadrupole magnets. With this change, the peak values of the horizontal beta function around the crab cavities could be reduced while keeping the beta functions at the crab cavities at the same values. In addition, we increased the horizontal beta function at the IP. This also contributed to lowering the beta functions around the crab cavities. Owing to those countermeasures, we could increase the HER beam current. Another improvement in the crab operation was the introduction of skew-sextupole magnets in 2009. The motivation for installing these magnets was to handle the chromatic x - y coupling at the IP [14]. A 15% increase in the peak luminosity was caused by using these magnets. As a result of these efforts, the beam-beam parameter ξ_y with the crab cavities reached 0.09. Although this value is very high, it is still much lower than the prediction of $\xi_y \sim 0.15$ by the beam-beam simulation. We could not identify the reason for this discrepancy in the period of KEKB operation. This is an unsolved problem at KEKB.

3.3.3. Tuning for higher beam-beam parameter. Our experience with tuning for suppressing the beam-beam blowup to obtain a higher beam-beam parameter is that improvements in the tuning are made only step-by-step [13]. Although such tuning is done by trial and error and most parameter changes do not lead to an improvement in the luminosity, all of these efforts are needed to improve the luminosity. It makes the tuning very difficult, as we have to optimize lots of machine parameters, which are usually rather sensitive to beam-beam blowup. 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 [11]. Sometimes, the optics corrections were done with a different set of strengths of the sextupole magnets to narrow the stop-band of the resonance ($2\nu_x + \nu_s = \text{integer}$) or ($2\nu_x + 2\nu_s = \text{integer}$). The optics correction is the basis of the luminosity tuning. On this basis, many parameters were scanned one-by-one for a higher luminosity. The parameters scanned included the x - y coupling parameters at the IP, the vertical dispersion at the IP, the waist point of the IP vertical beta function, the betatron tunes, the target values of the orbit feedback system around the IP, the collision timing of the two beams, the chromatic x - y coupling at the IP, and others. The scans were

done so that the luminosity was maximized or the beam sizes measured by using the interferometer were minimized. Such tuning was done almost constantly, even during the physics experiment. Originally, the parameters were scanned one-by-one for a higher luminosity. One important question was whether we could reach the parameter set that gives the maximum luminosity with this method. To investigate this fundamental issue, in autumn 2007 we introduced a downhill simplex method for 12 parameters of the x – y coupling parameters at the IP and the vertical dispersions at the IP and their slopes. These 12 parameters can be searched for at the same time with this method. We have been using this method since then. However, even with this method, the achievable specific luminosity has not been improved, although the speed of the parameter search seems to be rather improved. In any case, the KEKB luminosity is the result of such enormous amounts of scans or searches.

3.3.4. Beam-beam simulation. In the era of TRISTAN, the ability of the beam-beam simulation to predict beam-beam phenomena quantitatively seemed to be very poor due to the limited computer power. In the design phase of KEKB, the situation was greatly improved and the beam-beam simulation played an important role, particularly in the adoption of the crossing angle. In the operation period of KEKB, the beam-beam simulation was a useful tool. The beam-beam limit without the crab cavities, $\xi_y \sim 0.052$, which was obtained by the experiment, was correctly predicted by the strong-strong beam-beam simulation. In luminosity tuning, we found that the local x – y coupling at the IP can induce vertical beam blowup. It seemed that vertical emittance dilution from the horizontal emittance could occur through beam-beam interaction with the x – y coupling. These phenomena were reproduced by the beam-beam simulation. The importance of the chromaticity of the x – y coupling at the IP was found by the beam-beam simulation. It seems that emittance dilution occurs for the off-momentum particles in this case. According to this simulation, we introduced skew-sextupole magnets in both rings, which contributed to the increase in the luminosity mentioned in Sect. 3.3.2. The introduction of the crab cavities was also determined based on the beam-beam simulation. However, there is a large discrepancy between simulation and experiment on the luminosity achievable with crab cavities. This problem remained unsolved at KEKB.

3.4. Efforts to improve beam injection

The beam injection and its scheme is important for accumulating the luminosity. In the upgrade from TRISTAN to KEKB, the linac was upgraded to realize direct injection. Although KEKB has no damping ring for the positron beam, we did not encounter serious problems without it. In the period of KEKB operation, the beam injection and its scheme were significantly improved, which contributed greatly to the integrated luminosity.

3.4.1. 2-bunch injection. At KEKB, there is no simple relationship between the acceleration frequencies of the linac and the rings, and the multibunch beams in the linac are not easily injected into the rings. Considering the synchronization between the linac and the rings, only 2 bunches separated in 49 RF buckets of the ring were able to be injected into the rings. Such 2-bunch injection for the positron beam was realized in 2002 [15]. The integrated luminosity increased after this, since the injection time was shortened. After this success, 2-bunch injection for the electron beam was also developed.

3.4.2. Continuous injection. Another example of excellent progress in the injection scheme was the realization of continuous injection [13]. Before this scheme, the beam injection was done after the

physics run, which restarted after the beam injection was completed. Therefore, the physics detector could not take data during the beam injection. In the continuous injection scheme, however, the detector can continue to take data even during the beam injection except for some veto time after the pulses from the linac are injected to the rings. To realize this scheme, some of the Belle detectors had to solve some problems in addition to careful tuning for the beam injection. The continuous injection scheme started to be used during the physics run in January 2004. The integrated luminosity was boosted by 20–30% with this scheme.

3.4.3. 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 KEKB operation, we succeeded in achieving simultaneous injection for 3 rings (the 2 KEKB rings and the PF ring) [15]. Before simultaneous injection, the beam injection to the PF ring was done once a day for about 20 min. During PF injection, KEKB had to stop continuous injection. After simultaneous injection was introduced, the PF ring also started continuous injection, called top-up injection, which could be done in parallel with the continuous injection to the KEKB rings. With simultaneous injection, the machine study of the PF ring, which demands frequent beam injections, became less interruptive to the KEKB operation. Another merit of simultaneous injection for KEKB is that the beam currents become more constant. This is preferable in the scan for luminosity tuning, and the tuning speed increased.

3.5. Influence of accelerator environment

Unlike earlier colliders like TRISTAN, we found that KEKB is much more sensitive to changes in the accelerator environment. To minimize the effects of orbit drift, we needed to correct the closed orbits of both rings continuously. The correction frequency was about 1/30 Hz. The source of orbit drift is considered to be the slow deformation of the ground. The closed orbit correction system can detect and compensate for the change of the ring circumference. The changes are brought about by earth tides or changes of atmospheric pressure, e.g. the passage of a typhoon. These circumference changes were well compensated by the orbit correction system. In addition to the continuous closed orbit correction system, we needed an orbit feedback system around the IP to maintain an optimum beam collision [16]. Our experience was that the orbit feedback system is vital and the luminosity decreases seriously in less than one minute without the feedback. The frequency of the IP orbit feedback was about 1 Hz. We also observed faster orbit vibrations such as that at a frequency of 13 Hz, originating from the vibration of the final focus quadrupole magnets. However, the amplitudes of such fast orbit vibrations were small compared with the beam sizes and their effect on the luminosity was negligible. Therefore, we did not need orbit feedback to suppress the effects of the fast vibrations that are used in SR machines. As for the slow ground deformation, a relatively large subsidence has been observed at KEKB as shown in Fig. 3. The cumulative amount of tunnel deformation in the south arc section amounted to 25 mm. Although there is some speculation as to why the south arc section continues to sink, no clear explanation has yet been determined. In the construction period of KEKB (1998), all magnets were aligned on a horizontal plane. The vertical positions of the magnets have been changing according to the tunnel deformation. However, almost no degradation of performance has been observed with the position shifts of the magnets owing to the optics corrections developed

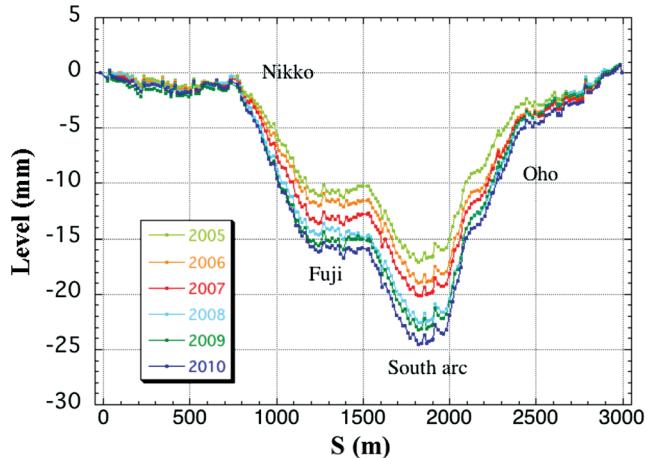


Fig. 3. Tunnel level marker height with respect to that at the interaction point over a number of years.

at KEKB and the best luminosity at KEKB was achieved with the deformed ground. A simulation confirmed that the effects of alignment errors that are slower than the betatron wavelength are small.

In the process of increasing the luminosity, we encountered a peculiar problem. This problem first became evident in March 2003. The problem has the following features. 1) The luminosity degrades in the daytime. The difference in the luminosity between day and night is about 20% at worst. 2) The difference seems to depend on the temperature difference between day and night. The difference is not remarkable in winter or on a rainy day. 3) When the luminosity drops in the daytime, HER beam blowup is observed. Tuning of the x - y coupling parameters at the IP is somewhat effective to mitigate the luminosity drop, although its effectiveness is insufficient. A lot of effort has been devoted in vain to solve the problem. Eventually, we found that the BPM consistency also shows the day–night difference. The consistency is defined as the standard deviation of four BPM readings by using four different combinations of BPM electrodes (a choice of three electrodes out of four). Orbit corrections based on the changing BPM offsets cause optics deformation and may result in the luminosity degradation. The mechanism that we found is that a section of the BPM cables goes through the outside of buildings and is affected by the day–night temperature change. To solve the problem, we installed thermal insulator sheets on the BPM cables outside. After the installation, the day–night change in the BPM consistency error decreased by 30 or 50% and the day–night difference in the luminosity became almost invisible.

The lesson that we learned from the above experiences is that we can develop effective correction methods if the status of the beams is monitored correctly, but a serious problem could be induced when the beam instrumentation system gives incorrect information. The BPM consistency is a good measure for the reliability of the position measurements. We found that the consistency slowly became worse due to the gain drift of the BPM electrodes. This was one reason for luminosity degradation as time went by. We developed a method to detect and correct the drift of the electrode gain by using beams [17]. We made this correction (BPM gain mapping) from time to time (typically every month). Another important measurement related to the BPMs is the so-called beam-based alignment of the BPMs. This measurement is taken to detect the offset of the BPMs to the quadrupole magnets nearby. To minimize the residual vertical dispersion, this measurement was important. The measurement was done typically once a year or when anything happened to a BPM, such as reconnection of cables.

3.6. Beam aborts

A beam abort system has been installed and successfully utilized at KEKB to protect the hardware components in the rings and the Belle detector from damage from the beams. Many hardware components can issue the triggers for the abort. Typical beam aborts are the beam loss monitor abort, the beam phase abort and the Belle abort. The beam phase abort was developed using the experiences of the KEKB operation. When some type of RF trip occurred, a movable mask was broken by the direct hit of the beam in the transient of the trip. Although the RF system and the beam loss monitor issued the abort, they were too late to protect the masks. Although this is a very rare case, we needed to avoid this situation. When the RF trip occurs, the beam energy changes and the beam phase also changes accordingly. The beam phase abort is issued when the monitored value of the beam phase reaches some threshold value. We found that the beam phase abort can prevent the damage to the mask after the RF trip. From a beam operation viewpoint, reducing the frequency of the beam aborts is important for the integrated luminosity. Sometimes it was not easy to identify the true reason for the abort. To identify the reason for each abort and optimize the abort system as well as improve the machine operation, a diagnostic system was developed. Fast signals, such as beam currents, accelerating voltages of the RF cavities, and beam loss monitor signals from PIN photo-diodes, are recorded and analyzed by a data logger system with a high sampling rate at the moment of each abort [17,18]. This system was very useful for analyzing the abort phenomena and reducing the abort frequency.

4. Achievements of KEKB

The KEKB luminosity surpassed $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ for the first time in the history of colliders. The maximum luminosity of KEKB, $2.11 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, was the world record. Based on all the experiences at KEKB as a luminosity frontier machine, we can now envision a machine that has a luminosity of $10^{35} - 10^{36} \text{ cm}^{-2} \text{ s}^{-1}$ [8]. Figure 4 shows a comparison of the luminosities of the world's colliders. Before the success of KEKB and PEP-II, such a high luminosity machine could not be seriously considered.

As for the tuning to suppress beam-beam blowup, as the specific luminosity increased, we observed that the luminosity became sensitive to many parameters, which was not observed in the lower luminosity situation. To increase the beam-beam parameter, we found that machine error corrections, particularly for the x - y coupling parameters at the IP and their chromaticity, are essentially important. As for the global x - y coupling, the emittance ratio ($\varepsilon_y/\varepsilon_x$) achieved was around the $\sim 1\%$ level from a measurement using the interferometer. This value is not very low compared with those achieved in SR machines. Since the beam-beam simulation predicts a higher luminosity with a smaller emittance ratio, we need to pay more attention to this issue in future machines.

In a very high luminosity machine, the beam instrumentation system, particularly the BPM system, is much more important than in past machines. The issue of the day-night difference in the luminosity is a typical example of this. In the luminosity tuning at KEKB, the beam-size monitor (interferometer) played an important role.

The instability that has been most serious at KEK is beam blowup in the vertical direction due to electron clouds. Although the blowup was drastically improved by installing solenoid coils all around the LER ring, the effects still existed at more than ~ 1.6 A. In future machines, we need more thorough countermeasures, such as installation of antechambers for the instability. The coupled bunch instabilities in the transverse direction have been well suppressed by the bunch-by-bunch feedback system. Such a system is vital in a high beam current machine. In a bad vacuum situation, the fast

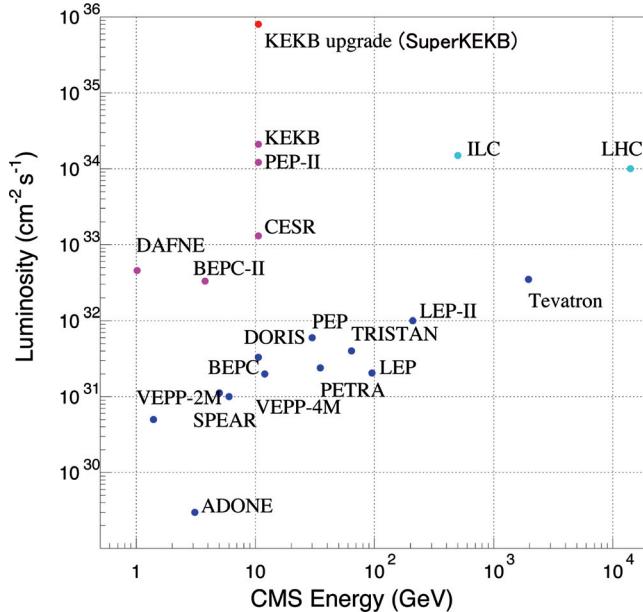


Fig. 4. Comparison of the luminosities of the world's colliders.

ion instability was serious at KEKB. In the higher beam current machines in the future, we will have to pay more attention to this instability. Also, we have to seriously consider the microwave instability from the impedance from CSR or other missing sources.

Accumulation of the very high beam currents has been a challenge at KEKB. We experienced many kinds of vacuum problems in the process of increasing the beam currents. These experiences will provide a good basis for future machines such as SuperKEKB [8], which will be operated with higher beam currents. The ARES and SCC systems have shown excellent performance for accumulating very high beam currents. They have the potential to hold more beam currents than those achieved at KEKB. In SuperKEKB they will be used with small modifications.

As for the orbit control around the IP to maintain an optimum collision condition, an orbit feedback system based on the beam-beam deflection has been developed at KEKB [16]. This system worked very well and almost no luminosity degradation due to the orbit drift around the IP was observed during the beam operation.

The total integrated luminosity finally collected by the Belle detector was 1041 fb^{-1} . For accumulation of the luminosity, machine reliability is one of the key issues. We have made a great deal of effort to achieve this. This includes taking countermeasures against the cooling water problems in the magnet system, reducing the frequency of quenches of the superconducting quadrupole magnets, countermeasures for the vacuum problems, and reducing the abort frequency. The machine control system is the basis of the machine operation and the KEKB control system based on EPICS has worked very well throughout the beam operation [19].

KEKB pioneered the development of crab cavities. The crab cavities were successfully utilized at KEKB in the physics operation. Nowadays, research and development of crab cavities are in progress in several laboratories for future uses of them. The success of the crab cavity at KEKB is significant in the sense that it encouraged these future plans. The experiences of the beam operation with the crab cavities are expected to be helpful for the future use of crab cavities in LHC.

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