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Nuclear Instruments and Methods in Physics Research A 499 (2003) 1–7

NUCLEAR  
INSTRUMENTS  
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# Overview of the KEKB accelerators

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## Abstract

An overview of the KEKB accelerators is given as an introduction of the following articles in this issue, first by summarizing the basic features of the machines, and then describing the improvements of the performance since the start of the physics experiment.

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*PACS:* 29.20.

*Keywords:* Colliding machine; Storage ring

## 1. Introduction

We have witnessed a steady improvement in the performance of KEKB from the start of the physics experiment in June 1999 to the present time. To review this improvement, we list here milestone dates of the peak luminosity: the peak luminosity of KEKB exceeded  $1.0 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$  in April 2000, reached  $2.0 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$  in July 2000, surpassed  $3.0 \times 10^{33}$  and  $4.0 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$  in March and June 2001, and finally reached  $5.47 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$  in November 2001. Along with the increase in the peak luminosity, integrated luminosity per day and per month were also increased up to  $281 \text{ pb}^{-1}/\text{day}$  and  $6120 \text{ pb}^{-1}/\text{month}$  in November 2001. This indicates that KEKB has indeed entered into a new realm of collider machines and has shown that it can work as a machine capable of producing real physics. Fig. 1 summarizes the increase in peak and integrated luminosity, stored currents in the rings and the accumulated luminosity

by Belle from the start of the physics experiment in June 1999 up to November 2001.

This steady improvement in the performance of KEKB and the achievement of unprecedented luminosity of  $5.47 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$  are the culmination of almost a 10-year effort by KEKB staff members. There still remain many things to be improved in KEKB, to first reach the design luminosity of  $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ , and then to eventually exceed it. The papers compiled here summarize our efforts made for KEKB and were written to serve as a basis of further improvements of KEKB. We sincerely hope that these papers are of some help to people working on other colliders and accelerators.

Table 1 summarizes the main design parameters of KEKB and the achieved performances.

## 2. Features of KEKB

The construction of KEKB started in 1994, utilizing the existing tunnel for TRISTAN, a

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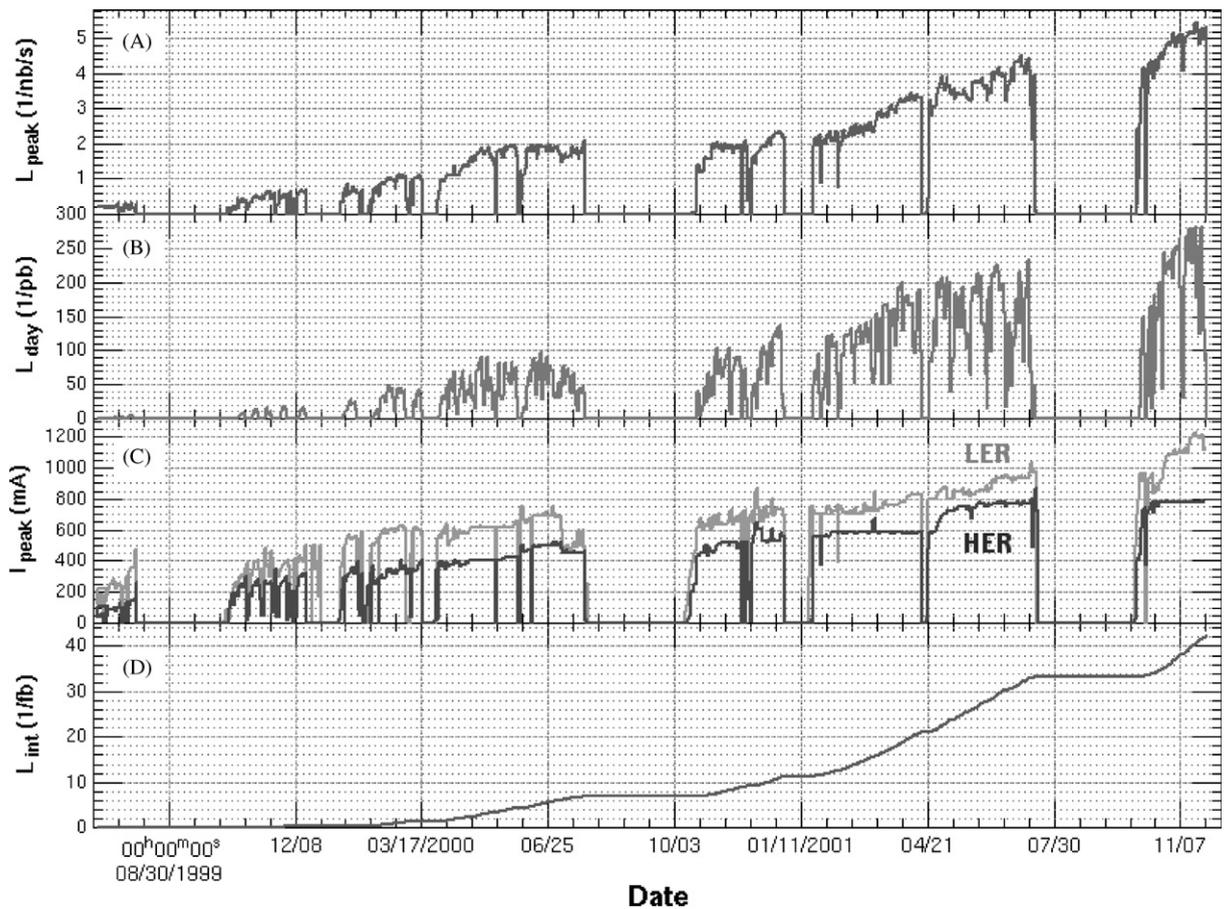


Fig. 1. History of the peak luminosity of KEKB. Also the histories of the integrated luminosity per day, peak currents of the both rings and the integrated luminosity of total runs are shown.

30 GeV  $\times$  30 GeV electron–positron collider. After 32 months of dismantling of TRISTAN, the construction of KEKB was completed in November 1998, and commissioning started in December 1998.

### 2.1. General scheme

KEKB is a two-ring, asymmetric-energy, electron–positron collider and is aimed at producing copious  $B$  and anti- $B$  mesons as in a factory. The design luminosity of KEKB is  $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ , which is more than one order of magnitude higher than the maximum luminosity ever achieved by electron–positron colliders before the advent of  $B$ -

factories. Two 3016 m long rings, an 8-GeV electron ring (HER) and a 3.5-GeV positron ring (LER) are installed side by side in a tunnel 11 m below the ground level. The cross-section of the tunnel is large enough to install the two rings side by side, since TRISTAN was originally designed as a three-ring collider. The two rings cross at one point, called the interaction point (IP), where electrons and positrons collide. The Belle detector surrounds the IP to catch particles produced by the collisions. Just opposite to the IP the two rings pass each other at different heights, and the electrons and positrons do not collide. At the IP and the cross-over point, two rings exchange their inner and outer positions; this is necessary to make

Table 1  
Machine parameters of KEKB (design and achieved)

	Design	Achieved
Luminosity ( $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ )	10	5.47
Number of rings	2	—
Number of interaction points	1	—
Circumference (m)	3,016	—
Beam energy (GeV)	$8.0(e^-)/3.5(e^+)$	$8.0(e^-)/3.5(e^+)$
Total current per beam (A)	$1.1(e^-)/2.6(e^+)$	$\sim 0.4(e^-)/\sim 0.7(e^+)$
Number of bunches	$5120 \times 0.9(10\% \text{ gap})$	$\sim 1100$
Bunch spacing (m)	0.59	2.36 (regular operation)
Crossing angle (mr)	$\pm 11$	$\pm 11$
Beam-beam tuneshift $e^- \xi_x/\xi_y$	0.039/0.052	0.061/0.035
$e^- \xi_x/\xi_y$	0.039/0.052	0.073/0.047
Beta-function at the IP $e^- \beta_x^*/\beta_y^*(\text{cm})$	33/1	0.63/0.007
$e^+ \beta_x^*/\beta_y^*(\text{cm})$	33/1	0.59/0.0065
RF frequency (MHz)	508.887	—
Type of cavities	NCC/SCC for $e^-$ ; NCC for $e^+$	—
Detector	Belle	—

NCC and SCC stand for normal conducting and superconducting cavity.

the circumferences of the rings equal. After carefully aligning the two rings, the circumferences of the rings were found to differ by less than 1 cm.

The electrons and positrons are directly injected from a linac-complex into each ring at full energies. In order to facilitate this direct injection, the linac has been upgraded from 2.5 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. The direction of the positron beam just after the positron-production target was reversed and the two linacs (the upstream half and downstream half) 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 resultant positrons are accelerated to 3.5 GeV by the downstream half part of the linac.

For TRISTAN, an 8-GeV ring, called the accumulation ring (AR), was used to accumulate and accelerate electrons and positrons, prior to injection to the TRISTAN main ring. For direct injection of the two beams into the KEKB rings (AR is now not necessary), a new 400-m tunnel for beam-transport lines was constructed; for most of the way the lines run vertically stacked. Fig. 2 shows a schematic layout of KEKB.

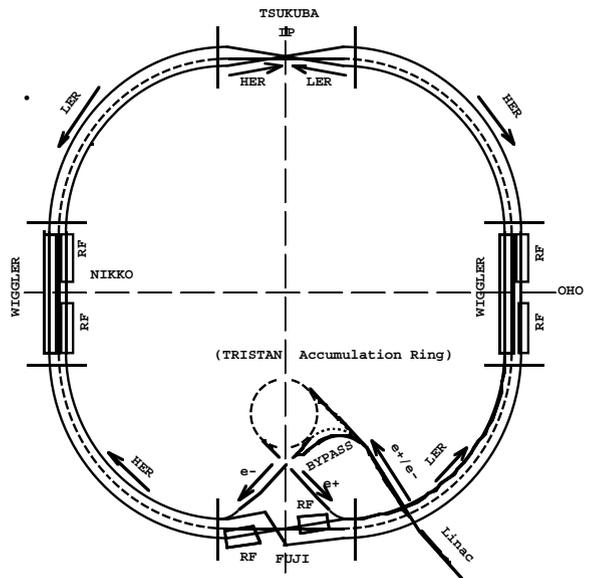


Fig. 2. Schematic of layout of KEKB.

## 2.2. Storage of high currents, vacuum chambers and cavities

In order to obtain high luminosity, the stored currents in the rings should be as high as possible, and the beam sizes at the IP should be as small as

possible. In KEKB, the design currents in the rings are 1.1 A in the HER and 2.6 A in the LER. The beam is distributed among about 5000 bunches with a bunch spacing of 59 cm. These high currents stored in the rings may excite strong coupled-bunch instabilities. The design beam size at the IP is 90  $\mu\text{m}$  in the horizontal direction and 1.9  $\mu\text{m}$  in the vertical direction. The main issue is, therefore, how to store such large currents in the rings and at the same time to maintain stable collisions between the electron and positron beams.

For both of the KEKB rings, we adopted copper vacuum chambers that can sustain a high heat load of synchrotron radiation. The HER vacuum chambers have a race-track shape, whereas those of LER have a round shape with an inner diameter of 94 mm. This large diameter is effective to lower the growth rate of coupled-bunch instabilities due to the resistive-wall impedance. Copper also has other advantages: a self-shielding capability against synchrotron light, and a relatively low photodesorption coefficient.

The beam excites the fundamental mode and higher-order modes (HOM) in a cavity. The fundamental mode is the lowest-frequency mode, and is used for acceleration, whereas HOMs are modes with higher frequencies. In a small ring, only HOMs are responsible for coupled-bunch excitation; however, in a large ring with a high stored current, the fundamental mode also becomes responsible for instability. A straightforward way to avoid coupled-bunch instabilities due to HOMs is to devise a cavity where no HOMs are excited by the beam. KEKB uses two kinds of HOM-free cavities: normal conducting cavities, called ARES, for the LER and HER, and superconducting cavities (SCC) for the HER.

ARES is an acronym of accelerator resonantly coupled with energy storage. It consists of three cells: an accelerating cell, an energy-storage cell, and a coupling cell between them. HOMs are extracted from the cavity by four wave guides attached to the accelerating cell, and are absorbed by SiC absorbers equipped at the end of the wave guides. Beam pipes attached to the cell are grooved to make those HOMs which cannot be extracted by the waveguides propagate towards the beam

pipes. The large-volume, low-loss energy-storage cell effectively increases the stored energy of the cavity system.

The superconducting cavity for KEKB has two large-bore beam pipes that are attached to both ends of the cavity cell. The diameters of the beam pipes are chosen so that the frequencies of all modes, except for the fundamental one, become higher than the cut-off frequencies of the pipes. HOMs propagate towards beam pipes and are eventually absorbed by ferrite dampers attached to the inner surfaces of the pipes.

As mentioned before, in a large ring with high stored current, such as KEKB, PEP-II, and LHC, the fundamental mode of a cavity may excite a strong longitudinal coupled-bunch instability by the following mechanism: (1) the cavity is matched to the RF source to prevent RF power from being reflected by the cavity at zero current; (2) a finite current through the cavity destroys this matching condition; (3) the cavity resonance frequency is lowered by  $\delta f$  to recover this matching. This operation is called detuning of the cavity; (4) if the detuning  $\delta f$  is larger than or comparable to the revolution frequency of the ring ( $f_{\text{rev}}$ ), the impedance peak of the cavity hits or approaches one of the oscillation modes of coupled-bunch instability located about  $n \times f_{\text{rev}}$  ( $n$  is an integer) below the RF frequency ( $f_{\text{rf}}$ ). This mode is strongly excited.

The necessary detuning frequency  $\delta f$  is inversely proportional to the stored energy of the cavity. The more energy the cavity stores, the less the cavity is affected by the beam. This is the reason why ARES has a large energy-storage cell. The stored energy of ARES is increased by an order of magnitude by the energy-storage cell, and  $\delta f$  becomes much smaller than the revolution frequency of the ring. A superconducting cavity can achieve 2–5 times the high field gradient of a normal conducting cavity. Since the stored energy of the cavity is proportional to the square of the field gradient, the superconducting cavity has a larger stored energy and is immune to beam loading.

In order to investigate the characteristics of these two new types of cavities, a high-current (up to 500 mA) test of a prototype ARES and

superconducting cavities was performed at the AR. This test operation was carried out in 1996 to fix the final design of these cavities. The performance of a prototype bunch-by-bunch feedback system was also studied in this AR high-current operation.

ARES and superconducting cavities have been working well from the time of commissioning without any serious problem. Notable are a small trip rate of superconducting cavities of once per cavity per month and a maximum power delivered to the beam of 380 kW per cavity.

### 2.3. Finite-angle crossing at IP and superconducting final-focus quads

One of the salient features of KEKB is the adoption of a finite-angle crossing at the IP, where the electron and positron bunches collide at a finite angle of  $\pm 11$  mrad. This scheme does not require any separation dipole magnets and makes the interaction region much simpler than in head-on collision scheme. Another advantage is that bunches are separated quickly after the collision, allowing a minimal bunch spacing of 59 cm.

A pair of superconducting final-focus quads are used to squeeze the beams at the IP. These quads are fully immersed within the high magnetic field of a detector solenoid of 1.5 T. These quads are one of the first superconducting quads in the world of this type, and have been stably running with only a few quenches due to beam halos under unusual conditions of the beams.

Although simulation does not show any degradation of the luminosity due to the finite-angle crossing of KEKB, we plan to use crab crossing as a fall-back option. For this purpose, superconducting crab cavities are being developed.

### 2.4. Instrumentation and controls

Beam position monitors play an important role in the beam operation in the rings. In KEKB, each quad is equipped with one beam-position monitor, as well as a pair of horizontal and vertical steering magnets for high flexibility of orbit control. Another important instrumentation system involves interferometer-type beam-size monitors.

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 horizontal and vertical planes. These monitors proved their usefulness during the commissioning, and have become one of the most powerful tools of beam tuning.

The KEKB control system is based on the EPICS environment. The KEKB control system is now the world's largest working EPICS system.

## 3. Improvements

During the summer shutdown of 2000, we made some modifications to the machine. First, in addition to the original four superconducting cavities, four superconducting cavities were added to the HER so as to increase its current limit up to 900 mA. Second, we replaced movable masks of the LER with much more robust ones. During operation before the summer shutdown of 2000, movable masks in the LER suffered from arcings, which caused a few cases of vacuum leakage. The new mask is actually a special beam chamber with almost constant cross-section. The position of this chamber can be moved horizontally or vertically and the inner surface of the chamber itself functions as a mask. This shape of mask greatly reduces the amount of HOM power generated by the beam. The replacement of the moveable masks removed the current limitation in the LER. Third, the bellows near the IP were replaced by new ones with better cooling, because of a heating problem with the old ones. The last main modification was solenoid winding over the LER vacuum chambers. Before the summer shutdown, most of the LER vacuum chambers in the arc section had been equipped with permanent-magnet quads (called C-yoke magnets). During the shutdown, we removed these permanent magnets and installed solenoids over 800 m of the LER vacuum chambers.

Operation resumed on October 10, 2000. The increase in the peak luminosity was not prominent during this autumn run; however, the integrated luminosity per day and per 7 days increased

considerably due mainly to the stable operation of KEKB.

During a short winter shutdown around the New Year Holidays, we wound another 430 m of solenoids over the LER vacuum chambers. Operation resumed in January 2001, and from that time onward, the performance of KEKB has steadily improved. In mid-February, vertical tunes of the LER and HER were changed from a value just above integer (0.08) to a value above half-integer (0.60). This new choice of the tune made the machine much more stable. Also, in mid-March, the horizontal tunes of both rings were made much closer to half-integer from 0.52 to 0.51, which helped to increase the peak luminosity. On March 22, 2001, the peak luminosity surpassed  $3.0 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ , and on July 3, 2001, it reached  $4.49 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ .

During the summer shutdown of 2001 from mid-July to the end of September, the movable masks of the HER have been replaced by the same type as the masks installed in the LER. Coverage of solenoid field over the LER vacuum chamber was increased by 500 m during this shutdown. Now, almost all of the field-free region of the LER is covered with solenoids; and the total length amounts to 1800 m.

The lattice of KEKB was designed to maximize the dynamic apertures of the rings. In the rather early stage of the commissioning, namely in March 2000, the  $\beta_y^*$  at IP was squeezed down to 7 mm from the design value of 10 mm, keeping enough dynamic apertures. This reduction of  $\beta_y^*$  contributed to the increase of the luminosity and is a manifestation of the success of the lattice design of KEKB.

#### 4. Electron cloud instability

In KEKB, the most serious instability which limits its performance is the electron cloud instability (ECI), which has been observed in the LER. Synchrotron light from the beam hits the inner wall of the vacuum chambers and produces photoelectrons. These photoelectrons are attracted by the positively charged beam to form clouds around the beam orbit. Also, electrons created by

multipacting form clouds around the beam. The clouds then excite head–tail-type oscillation within a bunch, and the beam blows up.

If we apply a solenoid field parallel to the beam axis, electrons that come out from the inner surface of the vacuum chambers are confined to close to the wall, and even though they hit the wall again the energy of the electrons is still relatively low; secondary electron emission is of no concern. Based on this consideration we wound solenoid coils over the LER vacuum chambers, as we described before.

In October 2000, after solenoids of total length of 800 m had been wound, we made a beam study for estimating the effect of the solenoid field on the beam size. Two trains of 60 bunches were stored and the beam size at the light-source point was measured by the double-slit interferometer. Fig. 3 shows the result of the experiment. In the figure, the beam sizes (after being converted to the size at the IP) with respect to the stored current are depicted under several excitation-patterns of the solenoids: (1) all solenoids excited at 5 A, (2) all solenoids excited at 3 A, (3) half of the solenoids excited at 5 A, and (4) all solenoids switched off. An excitation current of 5 A corresponds to 50 G of the solenoid field. From this figure, we can see

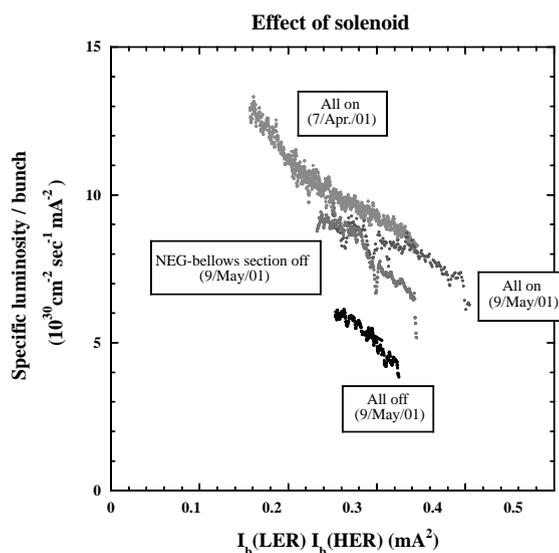


Fig. 3. Effect of the solenoid field on the beam size in LER.

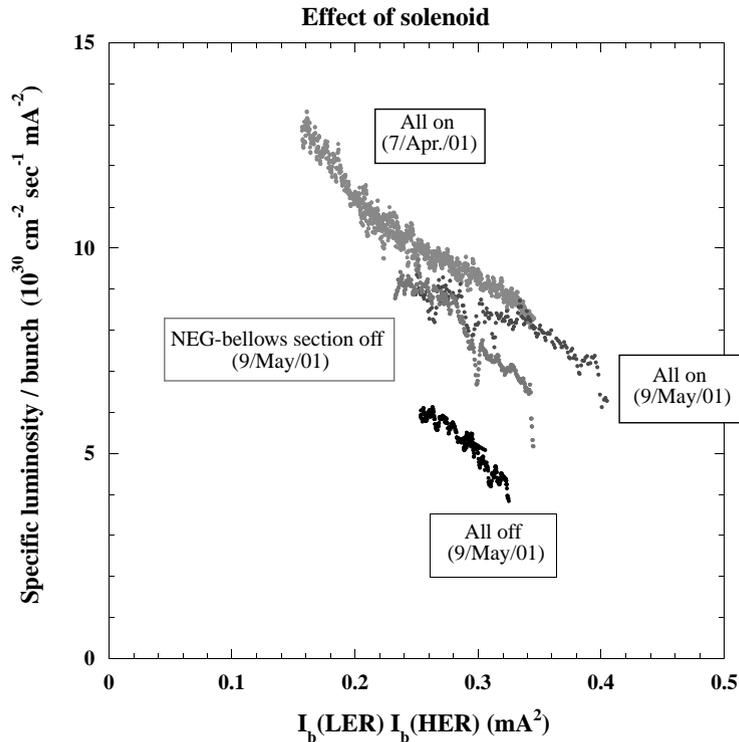


Fig. 4. Luminosity measurements performed in May 2001.

that (1) solenoids effectively suppressed the electron cloud instabilities, and increased the threshold; (2) 30 G was sufficiently strong to suppress the instability; and (3) the increase in threshold current was proportional to the length of the applied solenoids.

The effect of the solenoids on the luminosity was also measured in the collision mode. Fig. 4 shows the result of the measurement carried out in May 2001. It shows that (1) when the 430-m long solenoids (NEG-bellows section) wound in January 2001 were turned off, the luminosity decreased by 25% at high currents, and the reduction in the luminosity became small when the current decreased; (2) if all solenoids were turned off the reduction in the luminosity was much larger. It is

highly probable that the rapid improvement of the performance of KEKB observed in year 2001 has been owing to suppression of the electron clouds by the solenoid field.

## 5. Future prospects and conclusion

KEKB now has the capability to deliver  $5\text{--}6 \text{ fb}^{-1}$  per month; therefore, it is reasonably expected that by the end of 2002, Belle will have accumulated  $100 \text{ fb}^{-1}$ , and in 4–5 years, the accumulated luminosity will be up to, or higher than,  $300 \text{ fb}^{-1}$ . Recently, discussions have started about upgrading it to a super *B*-Factory with a goal luminosity of  $10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ .