KEKB Accelerator Physics Report

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Abstract

1 INTRODUCTION

The KEKB B-Factory is an electron-positron double ring collider aiming at the study of B meson physics with a design luminosity of $1 \times 10^{34}/\mathrm{cm}^2/\mathrm{sec}$. The high design luminosity comes from the requirements of B meson physics which studies very rare processes. Therefore, the luminosity is a parameter of overriding importance at B factory machines. Another significant feature of the KEKB which distinguishes it from conventional electron-positron colliders is that it is an energy asymmetric collider. This feature is also required by the physics motivations. The requirement of energy asymmetry inevitably leads us to a double ring collider. From the standpoint of machine design, this double ring feature enables a “high current-multibunch” approach like synchrotron light sources, which is vital to get to a higher luminosity.

Here, we summarize the features of the B factories.

- High current multibunch collider
- Energy asymmetric collider
- Double ring collider

In this report, we try to show how these features restrict the machine performance (luminosity in this case) in the case of the KEKB. Of these features, the first one has been giving the most severe restriction to the KEKB. The history of the KEKB has an aspect of tough struggles with various hardware troubles originated from the high beam currents [1]. Another severe restriction comes from the beam instabilities originated from the high beam currents. Of the instabilities, the vertical beam blowup observed at the LER (Low Energy Ring) has been the most important in the KEKB. As is described in this report, the source of the blowup is believed to be the electron clouds which are formed by the photoelectrons and the secondary electrons. As is described later in this report, the specific luminosity of the KEKB decreases with decreasing the bunch spacing. Although we have not yet understood the true mechanism of this phenomenon, this should also have some connection to the high current multibunch feature.

The machine design of the KEKB was done with also considering the second and third features. One of the difficulties in the design phase was an IR design. To simplify the IR design and avoid deleterious effects of the parasitic crossing, the KEKB introduced a relatively large (horizontal) crossing angle of $\pm 11\mathrm{mrad}$. So far, we have not yet encountered any harmful effects induced by the crossing angle except for some geometrical loss of the luminosity. Table 1 summarizes the main design parameters of the KEKB. To realize the high design peak luminosity, the design beta functions at the IP were chosen as shown in Table 1. As shown later, the present values of the vertical beta functions are even smaller than the design value. The introduction of the finite crossing angle seems to contribute to realize the small values of the vertical beta functions at the IP.

There are the other two issues related to the second and third features. Although these are not dealt in this reports, these are not unimportant. The first issue is difficulty of optimizing machine parameters of the two beams for the beam-beam effect. Since we can choose the machine parameters of the two beams independently, it is not easy to optimize their combinations. At the design phase of the KEKB, the energy transparency conditions were proposed. However, the present machine parameters of the KEKB heavily break these conditions. This break is also brought by the feature of the high beam currents as is shown later.

The second issue is difficulty of machine tuning. Since the two rings are almost independent, we need careful tuning of the geometrical relationships between the two beams such as a beam orbit offset at the IP, a crossing angle, beam tilt at the IP, collision timing, waist points and others. Although the present KEKB can manage to keep these parameters under control, we need frequent tunings of these parameters to keep the luminosity high [2][3].

In addition to these features, the KEKB has another notable feature that horizontal tunes are very close to the half integer resonance. It turned out that these tunes bring a higher peak luminosity, as is described in this report.

	LER	HER
Luminosity	$1 \times 10^{34}/\mathrm{cm}^2/\mathrm{sec}$	
Beam energy	3.5GeV	8.0GeV
Beam currents	2.6A	1.1A
Beta functions at IP (H/V)	0.33m/10mm	
Beam-beam parameters (H/V)	0.039/0.052	
Horizontal crossing angle	$\pm 11\mathrm{mrad}$	

Table 1: Main design parameters of the KEKB

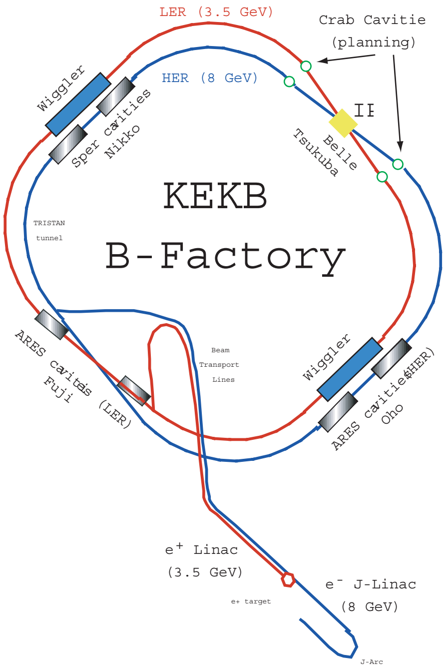

Figure 1: A schematic view of the KEKB.

2 OVERVIEW OF MACHINE COMPONENTS

Fig. 3 shows a schematic view of the KEKB. The KEKB is composed of an injector linac and two rings. The two rings were constructed in the existing TRISTAN tunnel and have the same circumference of about 3016m. Positrons of 3.5GeV are stored in the low energy ring (LER). For beam acceleration, we use specially developed damped cavities named “ARES” in the LER. The high energy ring (HER) stores 8 GeV electrons. In the HER, superconducting damped cavities are also used in addition to the ARES cavities. In the LER, wiggler magnets are also used to equalize the radiation damping time to that of the HER. As is already mentioned, the two rings cross horizontally at the IP with a half crossing angle of 11mrad. To recover the luminosity loss due to this crossing angle, installation of crab cavities is planned. However, a budget problem prevents us from installation of the crab cavities in the immediate future.

3 PRESENT PERFORMANCE

Fig. 3 shows a history of the KEKB luminosity. The top row shows a history of a peak luminosity. As is seen in the figure, the improvement of this year is remarkable. The second row shows a history of a daily integrated luminosity. The third row shows a history of peak beam currents of a day. The bottom row shows a history of an accumulated luminosity by the Belle detector. Table 1 summarizes record values of the luminosity as of May 26 2002.

Total integrated luminosity	79.8 /fb
Peak luminosity	$7.25 \times 10^{33} \mathrm{cm}^2/\mathrm{sec}$
Integrated luminosity / shift	139.9 /pb
Daily integrated luminosity	387.0 /pb
Integrated luminosity / 7 days	2524 /pb
Monthly integrated luminosity	8.01 /fb

Table 2: Record values of the luminosity as of May 26 2002.

4 MACHINE PARAMETERS AND FEATURES OF THE MACHINE

Table 4 shows a parameter list of the KEKB at the record peak luminosity. This table tells some characteristic features of the KEKB.

The present KEKB is filled with beams at every 4th RF bucket. In the design[4], the number of bunches was assumed to be around 5000 which means that every RF bucket is filled with particles (except for some abort gap). In the present KEKB, the specific luminosity is decreased when the number of bunches is increased from the every 4th RF bucket case by reducing bunch spacing. Although we tried longer bunch spacing, 4 RF bucket spacing (∼8nsec) is the best choice at the present KEKB. The other parameters are chosen under this restriction of bunch spacing.

It is notable that the bunch currents of the present KEKB are much higher compared with the design values particularly in the HER. This is also a consequence of the bunch spacing restriction. To compensate this unusually high bunch current to some extent, the horizontal emittance of the HER is enlarged compared with the design. On the other hand, the LER bunch current is not so high as the HER. Until very recent operations , the luminosity did not increase with higher LER beam current than some threshold current. It is believed that this luminosity saturation with the LER beam current arose from the beam blowup due to the electron cloud. In this situation, the LER beam current was limited by the electron cloud instability in the sense that the luminosity did not increase with a higher LER beam current. However, as a result of cumulative installations of the solenoid winding in the LER, the single beam blowup from the electron cloud is not visible with the present maximum beam current. The scrubbing effect of the chamber wall possibly contributed to suppress the blowup. The present beam current limitation comes from the heating problem in the IR region.

The horizontal and vertical beta functions at the IP has been determined by a trial and error method. The vertical beta functions are much lower than the design values.

Another feature of the KEKB is that the working points are very close to the half integer resonance as is seen in the table. These horizontal tunes make the horizontal emittance large and the horizonal beta functions small to a large

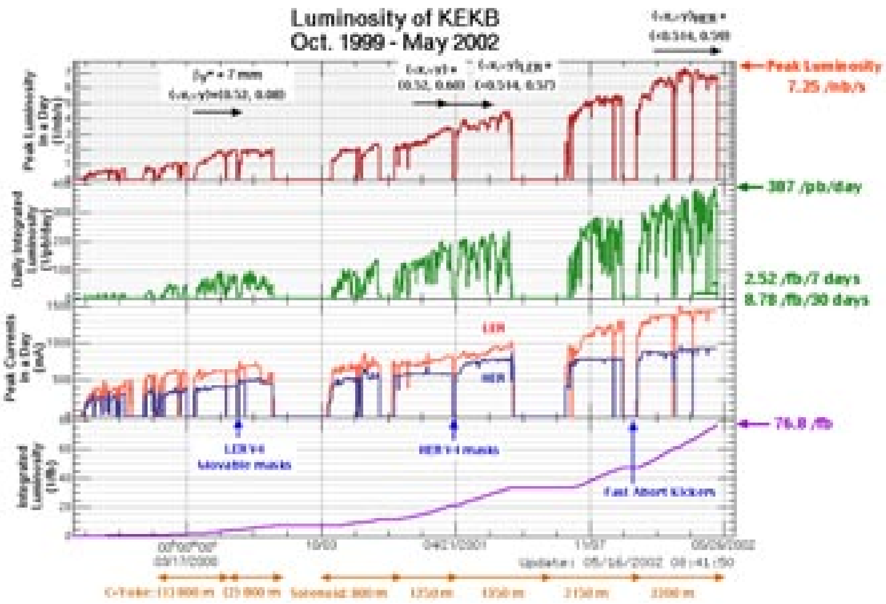

Figure 2: History of the KEKB luminosity.

extent. This large emittance compensates the large bunch currents and contributes to stabilize the beams against the beam-beam effect. As is seen in the table, both of the horizontal and vertical tunes of the both rings are located above the half integer resonance, while the vertical tunes are above the integer resonance in the design. In the early days of the KEKB, the vertical tunes were above the integer resonance. In February 2001, the vertical tunes moved to above the half integer based on results of new beam-beam simulations. This change of the tunes brought some increase of the luminosity.

5 LUMINOSITY RESTRICTIONS

5.1 *Electron cloud instability*

A beam size enlargement depending on the beam current in the LER has given one of the most serious luminosity restrictions to the KEKB. The source of the blowup is believed to be the electron cloud which is formed by photoelectrons and secondary electrons. Here, we summarize basic characteristics of the blowup [7].

- LER single beam (beam size) blowup
- Observed only in the vertical direction
- Observed only in the multibunch case
- No dipole oscillation with a high chromaticity
- The blowup has a threshold current which is determined by the charge density (bunch current / bunch spacing).
- Almost no tune dependence
- The vertical tune increases along the train and almost saturates at about 20th bunch.

	LER	HER
ε_x (nm)	18 (18)	24 (18)
β_x^*/β_y^* (m)	0.59/0.0062 (0.33/0.010)	0.63/0.007 (0.33/0.010)
bunch current (mA)	1393 (2600)	869 (1100)
# of bunches	1154 (5000)	
bunch current (mA)	1.14 (0.52)	0.71 (0.22)
bunch spacing (nsec)	8 (2)	
bunch length (mm@MV)	5.3@6.6 (calculation)	5.5@12.0 (calculation)
ξ_x/ξ_y	0.078/0.049 (0.039/0.052)	0.074/0.043 (0.039/0.052)
ν_x/ν_y	45.513/43.566 (45.52/44.08)	44.514/41.580 (44.52/42.08)
Lifetime (min@mA)	98@1393	276@869
Luminosity ($/\mathrm{cm}^2/\mathrm{sec}$)	7.25×10^{33} (1.0×10^{34})	

Table 3: Present performance compared with the design. (Values in parentheses are the design values.)

The mechanism of this blowup has been studied theoretically. F. Zimmermann and K. Ohmi showed by simulations that the blowup can be explained by a single bunch head-tail instability induced by an electron cloud [8]. Photoelectrons and secondary electrons form the electron cloud. A single-bunch like nature of the instability has been confirmed in a test bunch experiment. Fig. 4 shows a result of the test

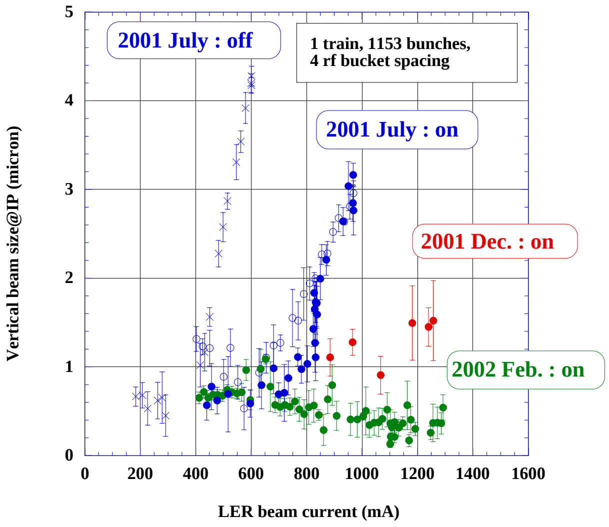

Figure 3: Current dependence of LER vertical beam size.

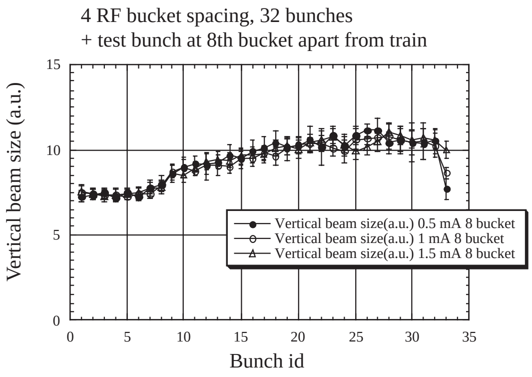

Figure 4: Test bunch experiment on the LER single beam blowup.

bunch experiment. In this experiment, a test bunch is located at the distance of 8 RF buckets from the tail of a bunch train. The train was made of 32 bunches with 4 RF bucket spacing. The bunch currents of the bunches in the train were between 0.8mA and 1mA. The vertical beam size of each bunch was measured by using a gated camera. As is shown in the figure, the vertical beam size of the test bunch changes depending on its bunch current. From this experiment, we concluded that the blowup is a single bunch effect. So far no direct observations of the head-tail motion in a bunch by using a streak camera has been succeeded.

To suppress this instability, solenoid coils have been wound around the LER ring. Works for solenoid winding were done several times, namely September 2000, January 2001, April 2001 September 2001 and January 2002. In those works, 800 m, 450m, 100m, 800m and 50m of the ring were covered with solenoid coils, respectively. A typical length of the solenoid coils is about 50cm, although there is some variety in length. A typical field strength is around 50 Gauss at the center of each solenoid when excited with a current of 5 A.

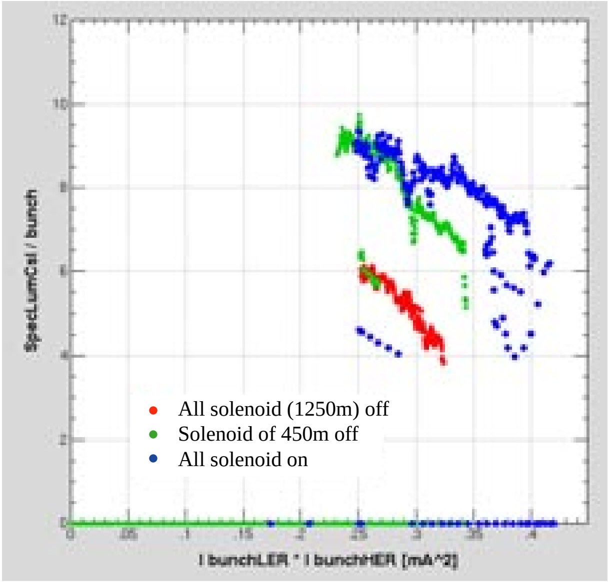

Figure 5: Effect of solenoid.

Fig. 3 shows current dependence of the LER vertical beam size in the single beam cases. In July 2001, both cases with solenoid magnets on and off are shown. The effectiveness of the solenoid magnets are clearly seen in the plot. In the measurement in February 2002, there is no blowup as a result of cumulative installations of the solenoid winding in the LER. The scrubbing effect of the chamber wall possibly contributed to suppress the blowup. The present beam current limitation comes from the heating problem in the IR region.

Effectiveness of the solenoids on the luminosity was also tested in March 2001. The result is shown in Fig. 5. The horizontal axis is a bunch current product of the tow beams. The vertical axis is a specific luminosity which is defined as a luminosity divided by a number of bunches and by the bunch current product in the unit of $10^{30}/\mathrm{cm}^2/\mathrm{sec}/\mathrm{mA}^2$. This specific luminosity is a function of beam sizes and should be constant when there is no beam blowup. In Fig. 2, there are three lines which correspond to cases with all of solenoid magnets on, with all solenoid magnets off and with the solenoids of 450m wound in January 2001 turned off. As is seen in the figure, the specific luminosity drops drastically when all solenoid magnets are turned off. The figure also shows that the solenoids wound in January 2001 is effective to increase the luminosity.

5.2 *Beam-beam effects*

Since the beam-beam effects observed in the KEKB are described in another report [5], we just give a summary of the effects here.

The beam-beam parameters calculated from the luminosity are listed in Table 1. In the calculation, we assumed that the vertical beam sizes of the two beams are equal, since we use so-called “iSize feedback” system [11]. This system aims at maximizing the luminosity by controlling the vertical emittance of the stronger beam (usually HER). It is also assumed that there is no beam-beam blowup in the horizontal direction, since we do not observe serious beam size blowup in the horizontal direction. The"hourglass" effect from a finite bunch length and degradation of the beam-beam parameters due to a finite crossing angle are also considered. As for the bunch length, 7mm is assumed. As for a comparison with the design values, the vertical beam-beam parameter of the HER is somewhat low. At present, the LER beam current is limited by the heating problem of IR radiation masks. During the summer shutdown in 2002, the cooling power of the masks will be reinforced. With higher LER beam current, the vertical beam-beam parameter of the HER is expected to be increased.

One of the notable features at the KEKB is a strong current dependence of the specific luminosity. In Fig. 6, a current dependence of the specific luminosity (per bunch) is shown in the case of 24 RF bucket spacing together with a result of the beam-beam simulation by using a strong-strong simulation code[6]. If the beam sizes are constant, this value should be constant. Therefore, the strong current dependence indicates that the beam sizes change depending on the beam currents. Although a quantitative agreement between the simulation and the experiment is not so good, the simulation reproduces the tendency of the beam current dependence of the specific luminosity. Fig. 6 also shows that the specific luminosity does not become constant even at a very low beam current and this is also supported by the simulation. Even with this notable feature, the vertical beam-beam parameter of the HER seems to increase with a higher LER beam current. In the usual operation of the KEKB, bunch spacing is 4 RF buckets. The current dependence of the specific luminosity with 4 bucket spacing is almost the same as that with 24 RF bucket spacing.

Another feature of the KEKB parameters is that the working points are close to the half integer resonance as is shown in Table 3. Particularly the horizontal tunes are very near to the resonance. In this situation, of importance is an effect that the beta function and the emittance are affected by the beam-beam force (dynamic-beta and dynamic-emittance). As a result of these changes, the horizontal beam size at the IP decreases to a some extent and the horizontal beam-beam parameter decreases [5]. In the KEKB, there is a tendency that the closer horizontal tune to the half integer resonance brings a higher luminosity. This tendency seems to be explained by the dynamic beta and dynamic emittance effects. These effects also explain why we can reach extremely high beam-beam parameters in the usual sense in the horizontal direction shown in Table 3.

In the design, the vertical tune is above the integer resonance. At present, both the horizontal and vertical tunes are above the half integer resonance. This change was done in February 2001 based on the beam-beam simulation [5] and actually brought some increase of the luminosity as is shown in Fig. 2. This change also brought more stable beam operation through less orbit drift in the vertical direction.

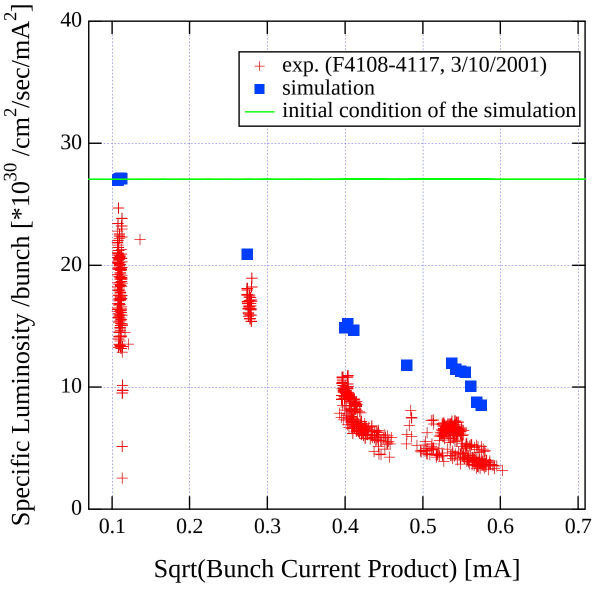

Figure 6: A comparison of the measured specific luminosity with 24 bucket bunch spacing to that from the the beam-beam simulation using a strong-strong code.

5.3 *Bunch spacing problem*

This problem is also described in another report [5]. Here, we briefly discuss the problem. Fig. 7 and 8 shows a current dependence of specific luminosity per bunch with 3 and 4 bucket spacing. The data of the Fig. 7 and 8 were taken in July and November 2001. As is seen in Fig. 7, the difference between the 3 bucket and 4 bucket spacing cases is large. If the specific luminosity is determined by the beam-beam effect alone, the curves of 3 and 4 bucket spacing cases should be the same. The difference indicates that other blowup mechanisms other than the beam-beam effect play a part. Since the beam blowup is usually observed in the vertical direction of the LER beam, the electron cloud instability is the first candidate for this mechanism. However, even blow the threshold beam current of this instability, the specific luminosity with 3 bucket spacing is much lower than that with 4 bucket spacing. Therefore, we can not attribute this difference to the electron cloud instability alone. We might have to consider a synergistic effect of the beam-beam effect and the electron cloud instability. Recently, E. A. Perevedentsev et al. and K. Ohmi independently proposed a model in which a coherent beam-beam instability of the head-tail type could be induced by the beam-beam effect combined with some ring impedance [9] [10]. This model might be applicable to the present case by considering the electron cloud as the impedance source. After addition of solenoid coils during the summer shutdown in 2001, the situation changed. As is seen in Fig. 8, the specific luminosity with 3 bucket spacing is much improved, although the improvement in that with 4 bucket spacing is small.

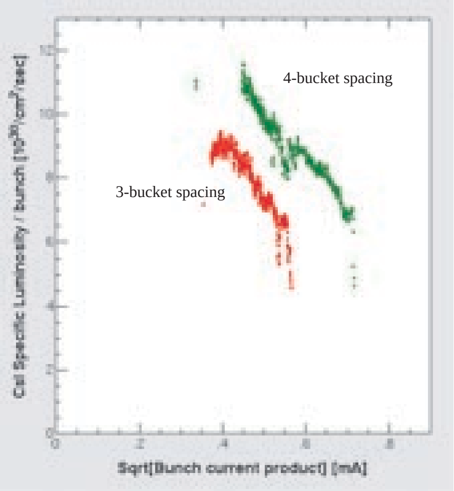

Figure 7: A specific luminosity as function of a square root of the bunch current product. The data was taken on July 11 and 12 in 2001 (before the summer shutdown). The green and red dots denote the data with 4 bucket spacing and 3 bucket spacing, respectively.

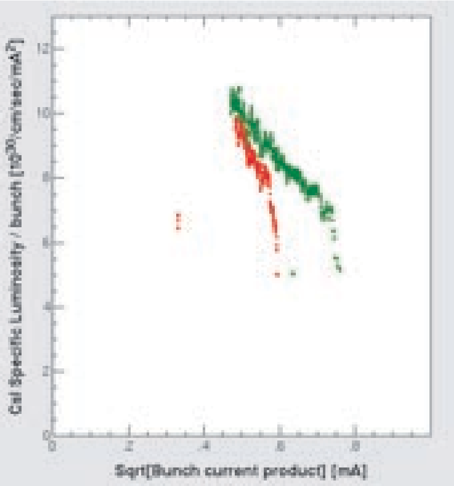

Figure 8: A specific luminosity as function of a square root of the bunch current product. The data was taken on Nov. 9 and 10 in 2001 (after the summer shutdown).

Even now, there still remains some difference of the specific luminosity depending on the bunch spacing. This problem should be solved when we increase the beam current from now on.

5.4 *Beam current limitations*

In the history of the KEKB, the beam currents have been limited from many reasons which include the detector beam background. Among those, the most serious limitation has come from tolerance of several hardware components to a high beam current. We have solved those hardware problems mainly by replacing hardware components in question with the new ones with which the problems were fixed. In the history of the KEKB, movable masks for the purpose of eliminating beam tails and suppressing the detector beam background have given the most serious limitations to the beam current. We solved this problem by replacing the old version of the masks with the new version. In the old version of the masks, some trapped modes existed and they need HOM dampers. Acceptable power limit of the HOM dampers restricted the beam currents. In the new version, a masking function is realized by deforming the vacuum chamber itself. Since there is no trapped mode, they need no HOM dampers.

At present the total beam currents are limited by the heating of radiation masks near the IP. During the summer shutdown in 2002, we will reinforce the cooling power of the masks.

5.5 *Beta functions at the IP and optics correction*

As shown in Table 3, the vertical beta functions at the IP are much smaller than the design value. To achieve these small values, simplification of the IR design by introducing the finite crossing angle seems to be effective. The local chromaticity correction scheme of the LER and the non-interleaved sextupole scheme of the both rings [4] also seem to contribute to realize the small beta functions at the IP.

Since the KEKB uses the unusual tunes which are very close to the half-integer resonance as shown in Table 3, optics corrections are important to narrow the stop bands of the resonances. In addition to the global beta corrections, global x-y coupling corrections, global dispersion corrections and continuous close orbit corrections (CCC) are done in the KEKB[12]. The global x-y coupling and global dispersion corrections are important in the sense that decreasing the zero-current emittance contributes to the increase of the luminosity. The horizontal beta functions at the IP are larger than the design to avoid higher detector beam background. However, this small zero-current emittance prevent the degradation of the luminosity due to larger horizontal beta functions. An injection efficiency is also improved by these corrections. In the global dispersion correction process, the vertical dispersion at the IP is also corrected. We found that this is very important to raise the luminosity. Since the x-y coupling and dispersion corrections are done by making orbit bumps at pairs of sextupoles, it is very important to keep the close orbits the same. CCC is always running during the operation with the repetition time of 20 or 30 seconds. For the closed orbit correction, it is important to remove offsets of BPMs. Offset measurements for all BPMs were done by using beams[13]. The measurements were done basically by detecting changes of closed orbits when changing strength of quadruple magnets beside BPMs.

There remains some room to squeeze the vertical beta functions at the IP further. However, the bunch length at high currents is around 7 or 8 mm and is comparable to the vertical beta functions. Therefore, squeezing the vertical beta function further does not bring much gain in the luminosity. We have a plan to raise the RF voltage to shorten the bunch length. It is expected to increase the luminosity to some extent with shorter bunch length.

6 SUMMARY AND SUPPLEMENT

B factories are characterized by the following features. 1) high current and multibunch collider, 2) energy asymmetric collider and 3) double ring collider.

Of these features, the first one has been giving the strictest limitations to the machine performance. First of all, the electron cloud instability in the positron ring has given a very severe restrictions to the machine performance through the vertical beam blowup. We learned that the solenoid winding around the ring is very effective to suppress the blowup. As a result of cumulative installations of solenoid windings in the LER, the single beam blowup is not visible with the present maximum beam current of around 1400mA. There is some possibility that the blowup will be an issue with a higher beam current in future.

The present beam current limitation comes from the heating problem of radiation masks near the IP. This problem will be solved in the coming summer shutdown. In the history of the KEKB, several hardware problems have given limitations to the maximum beam currents. The experiences have taught us that the increase of the maximum storable beam current can be done only step by step. The present LER beam current is still only a half of the design value.

In the KEKB, the specific luminosity decreases with shorter bunch spacing. This phenomenon can not be explained by the beam-beam effect nor the LER single beam blowup. The solenoid windings were effective to mitigate this problem. Although the mechanism of this phenomenon has not been understood, a synergistic effect of the beam-beam effect and the electron cloud instability is a candidate of the mechanism.

The coupled bunch instability originated from HOM's of the RF cavities is suppressed so far by the damped structure of the cavities. The instability from the fundamental mode is also suppressed by the ARES structure and the RF feedback system for the ARES cavities. The Superconducting RF cavity system has been also proved to be applicable for storing stably a large beam current of about 1A. The other coupled bunch instabilities such as the fast ion instability are also effectively damped by the bunch-by-bunch feedback system.

The second and third feature brought difficulty of an IR design. In the case of the KEKB, introduction of a horizontal crossing angle of $\pm 11\mathrm{mrad}$ simplified the IR design and realized small values of vertical beta functions at the IP. So far no harmful effects originated from the crossing angle is observed exept for some geometrical loss of the luminosity.

The second feature brings another problem that optimizing parameters of the two ring for the beam-beam effects is difficult. In the design phase, energy transparency conditions were proposed. However, the present KEKB parameters break these conditions heavily. This break comes from the electron cloud instability and the beam current limitations from hardware problems. In the KEKB, the parameters are determined empirically based on the balance of the two beams and the maximum luminosity.

The third feature brings anther problem that the machine tuning on the geometrical relations of the two beams is much more complicated than conventional single ring colliders. Although the present KEKB can manage to keep these parameters under control, we need frequent tunings of these parameters to keep a good luminosity condition.

Yet anther feature of the KEKB parameters is that the horizontal tunes are very close to the half integer resonance. It turned out that this feature is very important to keep the luminosity high. To realize the horizontal tunes very close to the resonance, the optics correction is very important. Since orbit drifts at the sextupole magnets can easily deform the optics, we need frequent optics correction. In a usual condition, we do the optics correction every 2 weeks.

7 FUTURE PLANS

In near future, we will try to shorten the bunch length by increasing the RF voltage. We expect that the luminosity would increase with shorter bunch length. In the coming summer shutdown, cooling power of the IR radiations masks will be reinforced. After the reinforcement, we expect that the beam current can be increased up to 1.8 or 2A for the LER, although we do not know what will limit the beam currents after that. With higher beam current, maybe we will be able to increase the luminosity with 4 bucket spacing. Needless to say, with a shorter bunch and higher bunch currents, the HOM heating may possibly be an issue. In the case that the bunch current is limited for this reason or others, we may have to consider to increase the number of bunches and reduce the bunch current. However, we have to solve the bunch spacing problem if we go for this course. Our situation is not so simple and we have to choose a right set of machine parameters. We think that we need a trial and error method for this purpose. Anyway, our next target is achievement of the design luminosity of $1\times10^{34}/\mathrm{cm}^2/\mathrm{sec}$.

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