Beam-beam effects observed at the KEKB

Y. Funakoshi for the KEKB commissioning group
KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801,Japan

Abstract

Beam-beam effects observed at the KEKB are reviewed. We discuss the beam-beam performance, a bunch spacing problem, dynamic beta and emittance effects and a luminosity instability related to a horizontal orbit offset at the IP.

1 INTRODUCTION

This report summarizes recent observations on the beam-beam effects at the KEKB. Since some tuning techniques such as the beam-beam scan, an waist scan, an IP orbit feedback system etc. were dealt with in other reports[1][2], they are omitted from this report.

The beam-beam performance is closely related to choice of other machine parameters. Before describing the beam-beam performance, we briefly review the basic parameters of the KEKB. Table 1 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[3], 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. The 5 RF bucket spacing pattern is inhibited at the KEKB, since this pattern induces a heating problem of the IP chamber. Although we onece tried 6 bucket spacing, we could not get higher specific luminosity than with 4 bucket spacing. Therefore, 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 (high energy ring). 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 a 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 solenoid windings 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 also possibly contributed to suppress the blowup. The present beam current limitation comes from a heating problem in the IR region.

The horizontal and vertical beta functions at the IP have been determined empirically based on maximum luminosity. The vertical beta functions are much lower than the design values.

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

2 SPECIFIC LUMINOSITY AND BEAM-BEAM PARAMETERS

To assess beam-beam performance, a common way is to record the specific luminosity and the beam-beam parameters. In the following, these parameters are discussed. One thing that one should note here is that these parameters do not necessarily describe only beam-beam performance. They could be affected by other beam blowup mechanisms such as the electron cloud instability.

In Fig. 1,2,3 and 4, the specific luminosity per bunch is shown as function of a square root of a bunch current product and an LER total beam current. The specific luminosity (per bunch) is defined by a peak luminosity divided by a number of bunches and also divided by a bunch current product of the two beams. The specific luminosity should be constant, if the beam sizes do not change.

The slopes in the figures mean that the sizes continuously shrink as the beam currents decrease in the course of the fills. The figures show comparisons of the specific luminosity with 3 RF bucket spacing to that with 4 RF bucket spacing. The data in Fig. 1 and 2 was taken before the summer shutdown in 2001 and that in Fig. 3 and 4 was after the shutdown. During the shutdown, additional solenoid coils

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

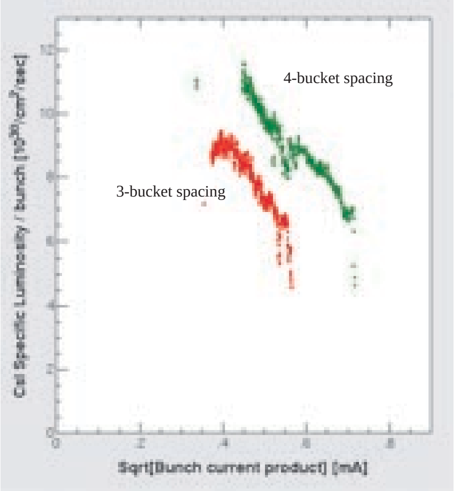

Figure 1: A specific luminosity as function of a square root of the bunch current product. The data was taken on July 11 and 12 in 2001 (before the summer shutdown). The green and red dots denote the data with 4 bucket spacing and 3 bucket spacing, respectively.

of about 800m in total were installed in LER. In Fig. 1, the specific luminosity with 3 bucket spacing is much lower than that with 4 bucket spacing. If the beam blowup is induced purely by the beam-beam effect, the two curves in this graph should overlap. Therefore, the different behavior of the two curves indicates that a beam blowup mechanism other than the beam-beam effect plays a part in the

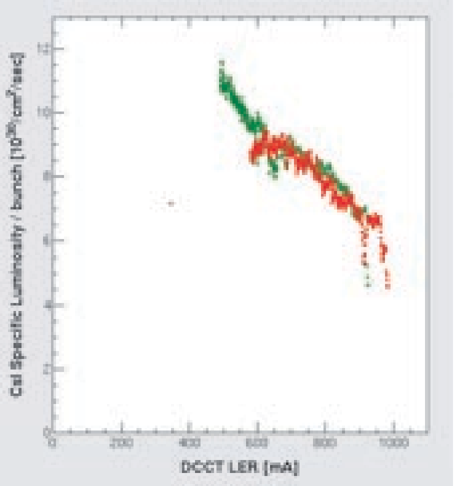

Figure 2: A specific luminosity as function of the LER total beam current. The data is the same as that of Fig. 1.

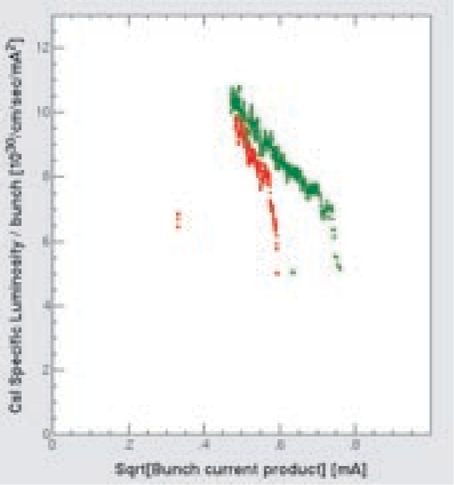

Figure 3: A specific luminosity as function of a square root of the bunch current product. The data was taken on Nov. 9 and 10 in 2001 (after the summer shutdown).

blowup. 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 below 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 [5] [6]. 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. 3 and 4, the specific lu-

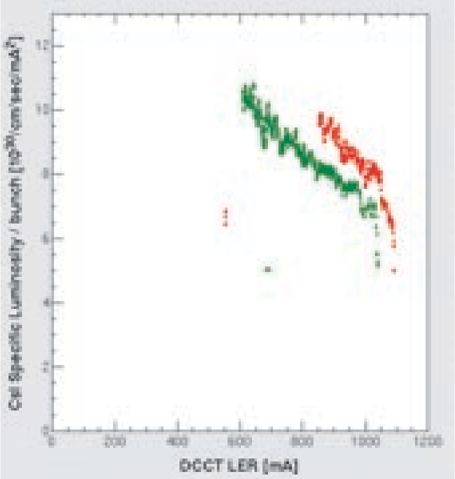

Figure 4: A specific luminosity as function of the LER total beam current. The data is the same as that of Fig. 3.

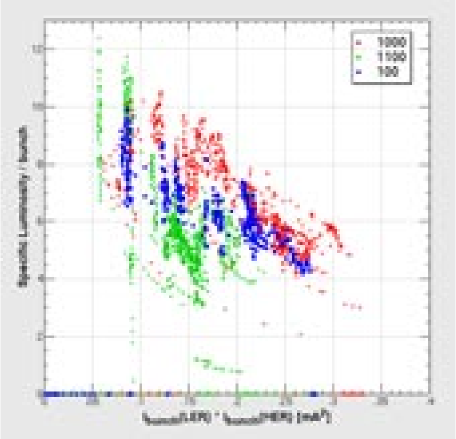

Figure 5: A comparison of specific luminosities with three different fill patterns. The data was taken on November 29 2000. The horizontal axis is a bunch current product of the two beams. The vertical axis is the same as Fig. 1 $\sim$ 4.

minosity with 3 bucket spacing is much improved, although the improvement with 4 bucket spacing is small.

Another possible explanation of the luminosity degradation with shorter bunch spacing is harmful effects of the parasitic collision. Since the KEKB has a relatively large horizontal crossing angle of $\pm 11\mathrm{mrad}$, its effects have been believed to be small. However, to examine its effects experimentally, we made an experiment with missing partner bunches in December 2000. In the experiment, we compared three types of fill patterns.

- (1000) pattern; usual 4 bucket spacing
- (100) pattern; 3 bucket spacing
- (1100) pattern

Here, ”1” means that this RF bucket is filled with a beam and ”0” means a vacant RF bucket. These patternsn are repeated all around the ring (except for some beam gap). The (1100) pattern means that we added one more bunch next to a bunch of the usual (1000) pattern. Therefore, the number of bunches was doubled. We observed that the specific luminosity with the (1100) pattern is much lower than that with the usual (1000) pattern. In Fig. 5, a comparison of the specific luminosity with the three fill patterns is shown. To investigate the effect of the parasitic collision, we tried two pattern i) (1000-LER)-(1100-HER) and ii) (1100-LER)-(1000-HER). As is seen in Fig. 6, we did not see any degradation of specific luminosity, with the fill pattern i). With the fill pattern ii), we observed some degradation. However, this degradation can be explained by the effect of the electron cloud. To confirm this explanation, we conducted another measurement. In this measurement, we tried a fill pattern of (110000000000000000000000)-HER (011000000000000000000000)-LER. Due to the long gap of 23 buckets, the effect of the electron cloud was almost

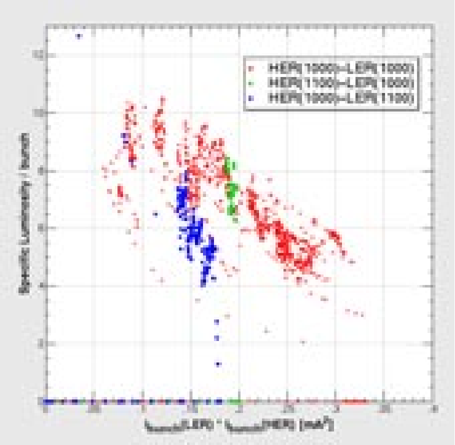

Figure 6: A comparison of the specific luminosity of the fill patterns with missing partner bunches to that of the usual 4 bucket spacing pattern.

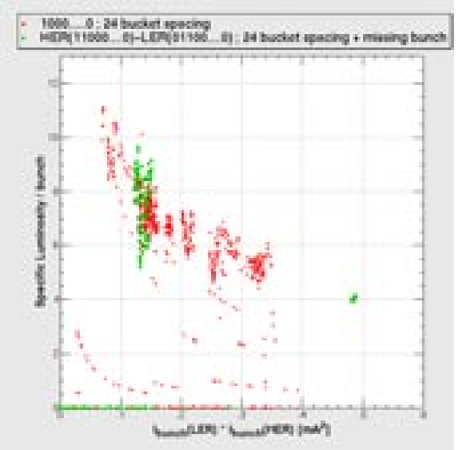

Figure 7: A comparison of specific luminosity of the pattern with missing partner bunches to that of the 24 bucket spacing case.

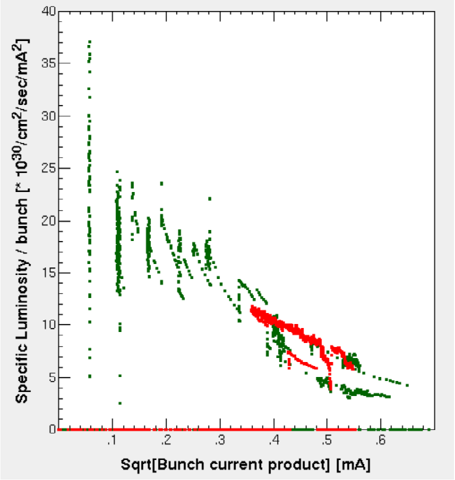

Figure 8: A current dependence of the specific luminosity with different bunch spacing of 4 bucket (red) and 24 bucket (green). The specific luminosity in this figure is somewhat lower than that in Fig. 1 and 2. This is because these data sets are a bit old and there was some luminosity improvement after these data sets had been taken. These two data sets were taken in the same day (March 10 2001).

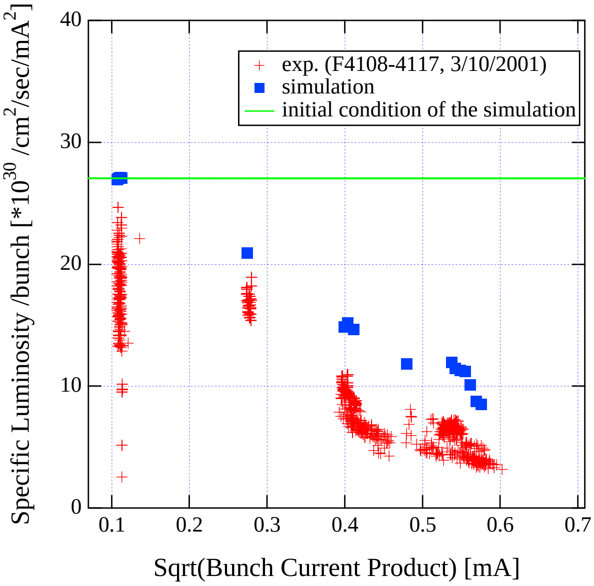

Figure 9: A comparison of the measured specific luminosity with 24 bucket bunch spacing to that from the the beam-beam simulation using a strong-strong code.

negligible. We compared the specific luminosity with this pattern to that with usual 24 bucket spacing. As is shown in Fig. 7, the specific luminosity with this pattern is almost the same as that with the 24 bucket spacing pattern. From these observations, we concluded that the parasitic collision gives no effect on the specific luminosity.

A more fundamental question is that the origin of the steep slopes of the curves in Fig. 1, 2, 3 and 4. Since the continuous beam blowup during the fill seems quite unusual compared with conventional colliders, the origin of these beam size enlargements has been controversial. There has been some doubt that the beam blowup comes not from the beam-beam effect but from the electron cloud instability. This doubt seemed to be supported by an observation that the beam blowup is mainly observed in the vertical direction of the LER. To distinguish these two effects, an experiment with longer bunch spacing of 24 RF buckets was done. With this bunch spacing, the effects of the electron cloud should be much smaller. In this experiment, we observed the luminosity with beam currents lower than in usual physics operations. The result is shown in Fig. 8. As shown in the figure, the specific luminosity with 24 bucket spacing is almost the same as that with 4 bucket spacing. This result indicates that the beam blowup in the beam current region of the usual physics run is originated not from the electron cloud instability but from the beam-beam effect. This explanation is also supported by a beam-beam simulation. In Fig. 9, a result of the beam-beam simulation by using a strong-strong simulation code[4] is also shown. 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. 9 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. As for the reason of the strong current dependence of the specific luminosity, we suspected that it may come from the crossing angle. However, even when we temporarily turned off the crossing angle in the simulation, the current dependent was still there. After that we suspected that the horizontal tune close to the half integer resonance may bring the strong current dependence. However, the simulation result did not change very much with tunes which are off from the resonance. Therefore, we have not yet understood the origin of the strong current dependence of the specific luminosity.

There still remains one more question. The above conclusion is that the main mechanism of the beam blowup with 4 bucket spacing is the beam-beam effect. On the other hand, with 3 bucket spacing, another mechanism (or the synergistic effect) plays some role. These two conclusions seem somewhat contradictory. This question is still controversial.

The beam-beam parameters are commonly used as an index of beam-beam performance. The beam-beam parameters at the record peak luminosity are also shown in Table 1. The horizontal beam-beam parameters are calculated with the design emittance, since no serious horizontal blowup is observed. As is described below, due to the large dynamic emittance effect, the actual horizontal tune shifts are much smaller than the beam-beam parameters in the table. The vertical beam-beam parameters are calculated from the measured luminosity on the assumption that the vertical beam sizes of the two beams are equal. We believe that this assumption is more or less valid, since we rely on the beam size feedback system [7] for maximizing the luminosity in the usual operation. 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. The vertical beam-beam parameter of the HER is somewhat lower than the design. With higher LER beam current, it is maybe possible that the vertical beam-beam parameter reaches the design value of 0.05.

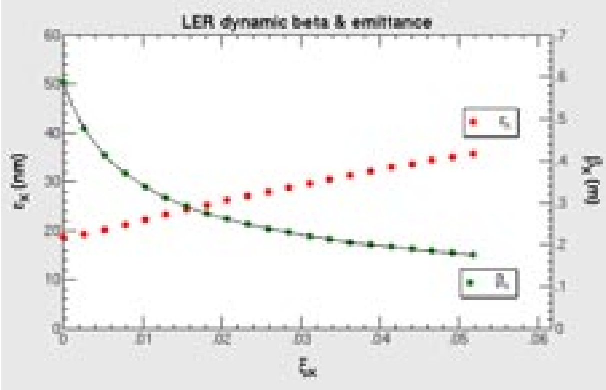

Figure 10: The dynamic beta and emittance as function of the beam-beam parameter calculated using the SAD code. The fractional part of the betatron tune is 0.51.

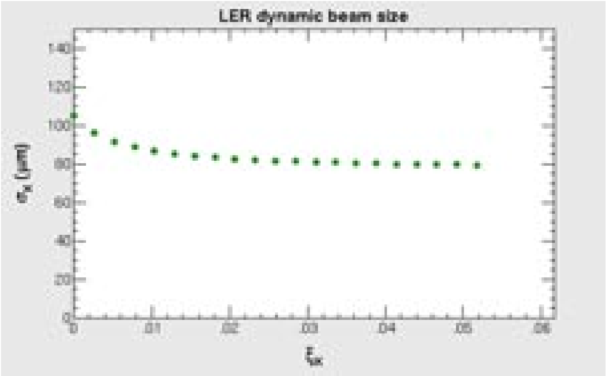

Figure 11: The size change as function of the beam-beam parameter using the beta function and emittance in Fig. 10.

3 DYNAMIC BETA AND EMITTANCE EFFECT

3.1 Analytic calculations

It is commonly known that the calculation of the dynamic beta effect is done by using a simple one-turn transfer matrix. For the sake of completeness of the description and convenience of the reference, the method is summarized in the following.

Assuming $\alpha = 0$, a two-dimensional one-turn transfer matrix without the beam-beam kick is expressed as

$$\mathrm{M}_0 = \begin{pmatrix} cos\mu_0 & \beta sin\mu_0 \\ -\gamma sin\mu_0 & cos\mu_0 \end{pmatrix}.$$

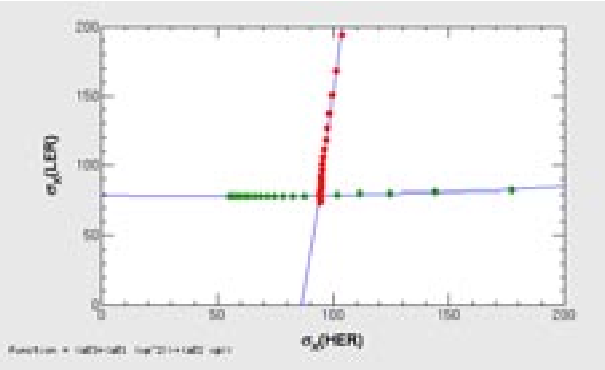

Figure 12: A beam size of one beam as function of that of the other beam. The crossing point gives consistent beam sizes from the dynamic beta and emittance effect.

A half of the beam-beam kick in the thin lense approximation is given by

$$\mathrm{B} = \begin{pmatrix} 1 & 0 \\ -\frac{1}{2f} & 1 \end{pmatrix}.$$

Here, f is the focal length of the beam-beam kick. Then, a one-turn transfer matrix including the beam-beam kick is given by

$$\begin{pmatrix} cos(\mu_0+\Delta\mu) & \beta sin(\mu_0+\Delta\mu) \\ -\gamma sin(\mu_0+\Delta\mu) & (\mu_0+\Delta\mu) \end{pmatrix} = \mathrm{BM_0B}.$$

From this equation, the following formula are obtained,

$$cos(\mu_0+\Delta\mu) = cos\mu_0 - \frac{\beta_0}{2f} sin\mu_0$$

and

$$\frac{\beta}{\beta_0} = \frac{sin\mu_0}{sin(\mu_0+\Delta\mu)}.$$

Since the beam-beam parameter is expressed as

$$\xi = \frac{\beta_0}{4\pi f},$$

the dynamic beta function is obtained with these formula as function of the beam-beam parameters.

3.2 Calculations by using SAD code

The dynamic beta effect can be calculated analytically. When the beta function is changed seriously due to this effect, however, the emittance is also changed. To predict the beam size, we need to know both of these two. For the calculation of the emittance including the beam-beam effects, the SAD code was used, although there is an analytical method which gives approximate values of the emittance. Fig. 10 shows a calculated beta function and a emittance as function of the horizontal beam-beam parameter. Also shown in Fig. 10 is an analytic calculation of the dynamic beta effect (solid line). These calculations still use

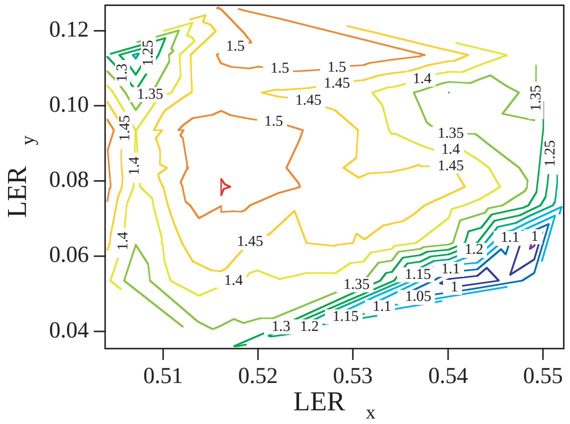

Figure 13: Results of tune surveys by using a strong-strong tracking program. The luminosity in the figure is that of a pair of bunches in unit of $10^{30}/\mathrm{cm}^2/\mathrm{sec}$. In the tracking, an effect of a finite bunch length was taken into account by slicing the bunches in the longitudinal direction. The number of slices was 5. The tunes of the HER were kept constant at (ν_x,ν_y) = (.5250,.1350). The scan range of the LER vertical tune was above the integer resonance.

the thin lense approximation and does not include an effect of the finite bunch length nor the crossing angle. In principle, it is possible to include these effects in the calculation. These calculations will be done in near future.

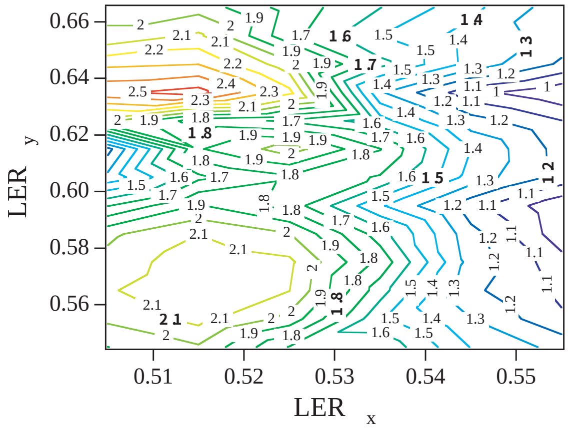

Figure 14: Results of the tune survey. The machine parameters are the same as Fig. 13 except that the HER tune is set at (ν_x,ν_y) = (.5136,.6344) and that the scan range of the LER vertical tune was above the half integer resonance. A luminosity peak near the third integer resonance of the vertical tune is seen. Although we tried this tune region, we could not obtain higher luminosity than the present working point. It turned out that this luminosity peak in the simulation can easily disappear with small errors such as a 0.1 mrad vertical crossing angle.

As is seen in Fig. 10, while the beta function at the IP shrinks drastically due to the beam-beam kick, the emittance increases to a large extent. Therefore, the beam size at the IP does not change very much as is shown in Fig. 11. In an actual situation of the machine, both beams are affected by the other beam. If the beam size of one beam is given, the focusing force by this beam is fixed and the size of the other beam is settled, and vice versa. Therefore, stable beam sizes are obtained by solving these two equations with two unknown parameters (two beam sizes). A solution of these two equations was obtained numerically by using the SAD code as is shown in Fig. 12. In Fig. 12, the two equations are depicted by the two lines and the solution is shown as their crossing point. Parameters which was determined by this calculation are summarized in Table 2. Since the horizontal tune is very close to the half integer resonance, the dynamic beta and emittance effect is very large.

	w/o beam-beam	w/ beam-beam
σ_x(LER)	103μm	79μm
σ_x(HER)	123μm	94μm
β_x^*(LER)	0.59m	0.10m
β_x^*(HER)	0.63m	0.21m

Table 2: Beam sizes and beta functions at the IP with and without the dynamic beta and emittance effect.

3.3 *Beam-beam tune shift*

The emittance with the beam-beam force is enlarged. If this effect is taken into account, the (horizontal) beam-beam tune shifts drastically decrease. In Table 3, the beam-beam tune shifts in which the emittance enlargement is included are shown together with those without considering the effects. As is expected, the horizontal beam-beam tune shifts decrease very much. This decrease seems to explain why the unusually high (horizontal) beam-beam parameters are attainable in the KEKB.

	w/o beam-beam	w/ beam-beam
ξ_x/ξ_y (LER)	0.069/0.053	0.017/0.052
ξ_x/ξ_y (HER)	0.048/0.030	0.018/0.029

Table 3: Comparison of beam-beam tune shifts with and without the dynamic beta and emittance effect.

4 TUNE SURVEY

It is commonly known that the beam-beam performance is strongly dependent on choice of working points. The KEKB is not an exception. Since the design phase of the KEKB, an enormous amount of efforts have been devoted to searches for better working points in both simulations and searches in the real machine. In the design phase, a large scale of simulations with a strong-strong code were not realistic due to restriction of computing power. The design tunes were determined by using a strong-weak simula-

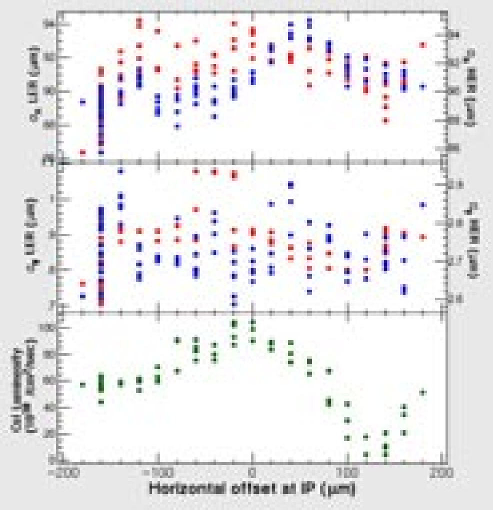

Figure 15: A horizontal offset scan with low beam currents in the backward direction (from plus to minus). The experiment was done on March 9 2001. The LER and HER beam currents were about 57 and 72 mA, respectively. The number of bunches was 1153. With these low beam currents, accuracy of the beam size measurement is not so good. The red and blue dots show horizontal or vertical beam sizes of the LER and the HER, respectively.

tion code[3]. Although there was no significant difference between just above the integer resonance and just above the half integer resonance as for the vertical tune, the vertical tune just above the integer was chosen for the design tune for the purpose of avoiding effects of the x-y coupling. Recent quickly developing computing power has enabled us to make a tune survey with a strong-strong code, although the survey is still a time-consuming task even today. Recent beam-beam simulations by using the strong-strong code predicted that the vertical tune just above the half integer gives higher luminosity than that above the integer[8]. A comparison of the simulated luminosity with these two tune regions is shown in Fig. 13 and 14. As seen in the figure, the tune above the half integer gives a higher luminosity. Guided by this prediction, we changed the vertical tunes of both rings from just above the integer to just above the half integer in February 2001. This change in tunes has brought not only some increase of the luminosity but also more stability of the machine operation through more stable beam orbits. The tunes shown in Table 1 were obtained by a trial and error method in a long-term machine operation.

5 LUMINOSITY INSTABILITY

The luminosity of the KEKB is very sensitive to the horizontal offset at the IP. To keep the luminosity high, machine operators have to tune the offset very carefully during the operation.

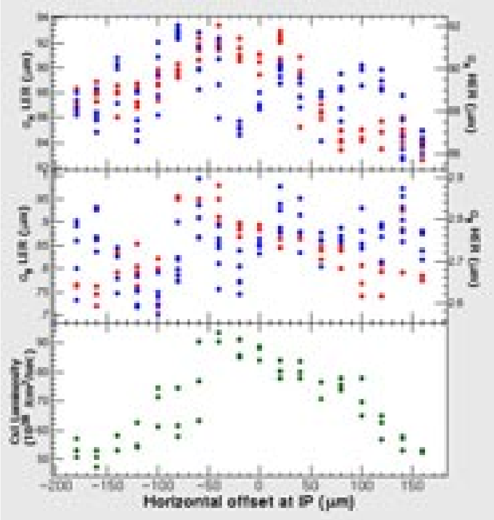

Figure 16: A horizontal offset scan with the low beam currents in the forward direction.

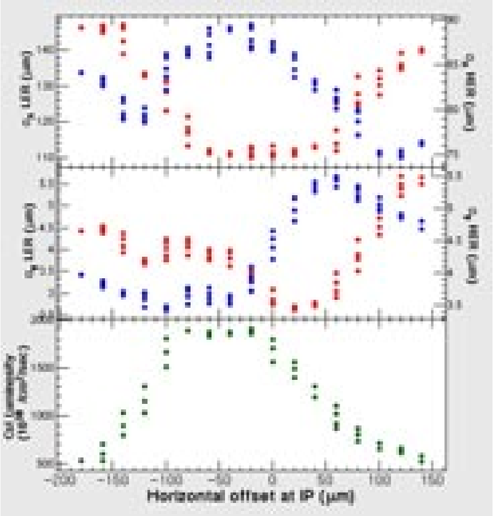

Figure 17: A horizontal offset scan with high beam currents in the forward direction. The LER and HER beam currents were about 700 and 580 mA, respectively. The number of bunches was 1153.

There are some notable observations on the behavior of the beams to the horizontal offset.

- A zero offset usually does not give the maximum luminosity and an intentional offset can increase the luminosity. At some optimum value of the offset, the luminosity becomes maximum.
- When the offset exceeds some limit, the luminosity drops drastically. At this drop, the LER (horizontal or vertical) blowup is observed.
- The optimum value of the horizontal offset depends on the beam current.
- The luminosity shows some hysteresis behavior for the change of the horizontal offset.

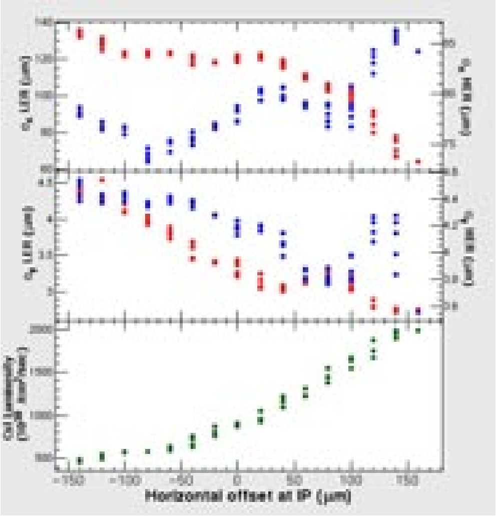

Figure 18: A horizontal offset scan with the high beam currents in the backward direction.

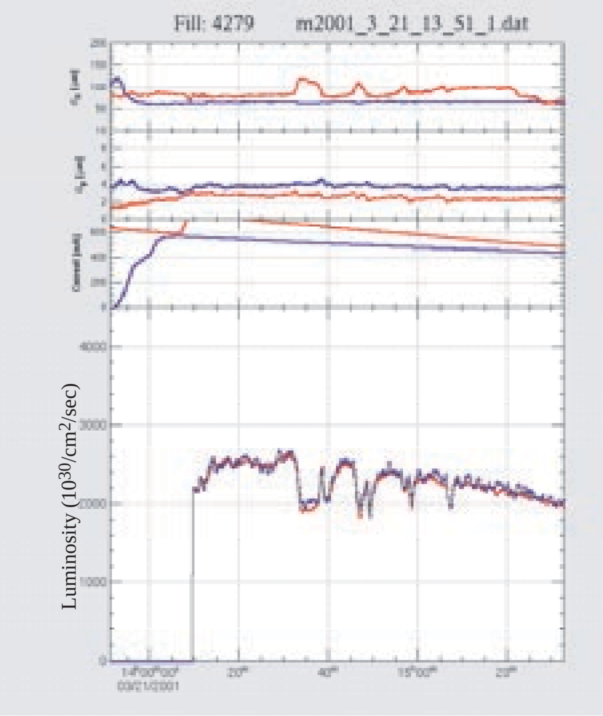

Figure 19: An example of an unstable fill. In the KEKB, there are two different types of luminosity monitors. The red and blue lines show the beam sizes or the beam currents of the LER and the HER, respectively.

To demonstrate these features, a result of an experiment is shown in Fig. 15,16,17 and 18. As is seen in the figures, the luminosity shows a peak at around zero offset with low beam currents (Fig. 15 and 16). With high beam currents, however, some intentional offset value gives a luminosity peak and an optimum value of the offset depends on the direction of the scan (Fig. 17 and 18). At the peak luminosity, the vertical beam sizes of the two beams are small, while the HER horizontal beam size becomes large in these scans.

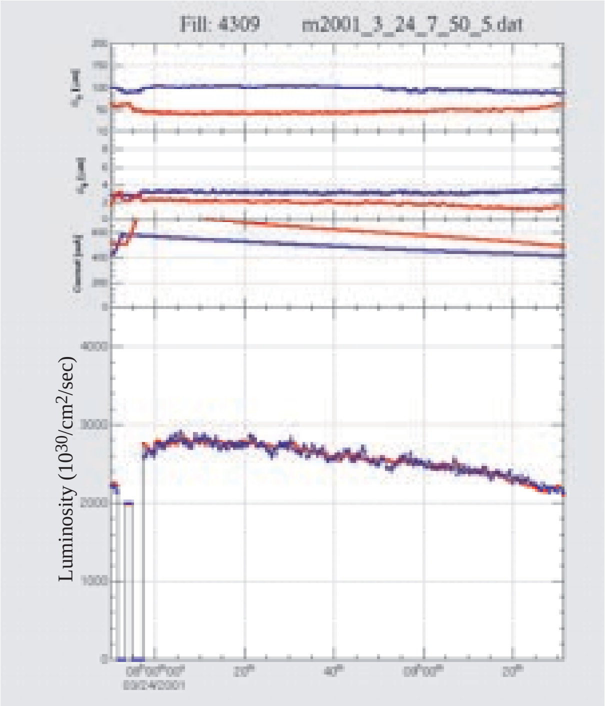

Figure 20: An example of a good fill.

In the usual operation, KEKB operators tune the horizontal offset very carefully to maximize luminosity. When the choice of the offset value is incorrect, the luminosity drops as is seen in Fig. 19. When the luminosity drops, the horizontal (and/or vertical) beam blowup of the LER is observed. The fill shown in Fig. 19 was on March 21 2001 and somewhat old. In the present KEKB, the horizontal beam size is relatively stable and the vertical blowup is seen on the occasion of the luminosity instability. When the choice of the offset is correct, no luminosity instability is seen during a fill as is shown in Fig. 20.

The origin of this luminosity instability and the sensitiveness of the luminosity to the horizontal offset has not been understood yet. Recently, F. Zimmermann found different solutions for the beam sizes concerning the dynamic beta and emittance [9]. This might have some connection to the present observations.

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