KEKB Status

Y. Funakoshi, T. Agho, K. Akai, K. Ebihara, K. Egawa, A. Enomoto, J. Flanagan, H. Fukuma, K. Furukawa, T. Furuya, J. Haba, S. Hiramatsu, T. Ieiri, N. Iida, H. Ikeda, T. Kageyama, S. Kamada, T. Kamitani, S. Kato, M. Kikuchi, E. Kikutani, H. Koiso, M. Masuzawa, T. Mimashi, A. Morita, T. T. Nakamura, K. Nakanishi, H. Nakayama, M. Nishiwaki, Y. Ogawa, K. Ohmi, Y. Ohnishi, N. Ohuchi, K. Oide, M. Ono, M. Shimada, M. Suetake, Y. Suetsugu, T. Sugimura, T. Suwada, M. Tawada, M. Tejima, M. Tobiyama, N. Tokuda, S. Uehara, S. Uno, N. Yamamoto, Y. Yamamoto, Y. Yano, K. Yokoyama, Ma. Yoshida, Mi. Yoshida, S. Yoshimoto, F. Zimmermann*
KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

Abstract

The KEKB status is described focusing on the beam operation with crab crossing. This report deals mainly with the beam dynamics issues with crab crossing. There is a large discrepancy between the beam-beam simulation and the experiment at the high bunch currents. We discuss causes of this discrepancy in detail.

INTRODUCTION

The crab cavities were installed at KEKB during the winter shutdown in FY 2006. A dedicated machine time from the mid. of Feb. to the end of June 2007 was devoted to the commissioning of the crab cavity system and the machine study with crab crossing. We focus on the beam dynamics issues with crab crossing in this report. Performance of the crab cavities as a hardware system is reported elsewhere [1].

KEKB B-FACTORY

KEKB B-Factory [2] has been operating at KEK since 1999 for the e+e- collision experiment mainly at the $\Upsilon(4S)$ resonance. KEKB is composed of the low energy positron ring (LER) at 3.5 GeV, the high energy electron ring (HER) at 8 GeV, and an injector linac. Two beams collide at the physics detector named "Belle". The machine parameters are listed in Table 1. The highest luminosity, $1.72 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, was achieved in Nov. 2006. The peak luminosity is higher than the design by 70 % mainly due to smaller β_{y}^{*} (6 mm vs. 10 mm), horizontal betatron tune closer to a half integer (LER:0.505 / HER:0.511 vs. 0.52), and higher stored current in the HER (1.35 A vs. 1.1 A). The daily integrated luminosity is as twice high as the design due to Continuous Injection Mode as well as acceleration of 2 bunches per an rf pulse at the linac. The electron cloud in the LER, which was much severer than was thought in the design phase, has been mitigated up to 1.8 A with 3.5 bucket spacing by solenoid windings of 2,200 m. Figure 1 shows the history of KEKB before the installation of the crab cavities.

* visiting from CERN, Switzerland

Table 1: KEKB Machine Parameters.

	May 2008		**Nov. 2006**		
	LER	HER	LER	HER	
Energy	3.5	8.0	3.5	8.0	GeV
Circum.	3016		3016		m
ϕ_{cross}	crab crossing		± 11		mrad
$\mathrm{I}_{\mathrm{beam}}$	1619	854	1662	1340	mA
$N_{bunches}$	1584		1387		
$\mathrm{I}_{\mathrm{bunch}}$	1.02	0.539	1.20	0.965	mA
ε_x	15	24	18	24	nm
β_x^*	90	90	59	56	cm
β_y^*	5.9	5.9	6.5	5.9	mm
σ_y^*	1.1	1,1	1.9	1.9	μm
V_c	8.0	13.0	8.0	15.0	MV
ν_x	.505	.509	.505	.509	
ν_y	.567	.596	.534	.565	
ν_s	-.0240	-.0204	-.0246	-.0226	
ξ_x	.099	.119	.117	.070	
ξ_y	.097	.092	.105	.056	
Lifetime	94	158	110	180	min.
Lumi.	16.10		17.12		/nb/s
Lum/day	1.232		1.232		/fb

CRAB CROSSING

One of the main design features of KEKB is the horizontal crossing angle of 22 mrad, at the interaction point (IP). Although there are a lot of merits in the crossing angle scheme, the beam-beam performance may degrade. The design of KEKB predicted that the vertical beam-beam parameter ξ_{y} is as high as 0.05 if betatron tunes are properly chosen, and actually KEKB has already achieved $\xi_{\mathrm{y}} \sim 0.056$. Thus the beam-beam issues associated with the crossing angle was not critical if ξ_{y} is lower than 0.05 or so. The crab crossing scheme, proposed by R. Palmer[3], was an idea to recover the head-on collision with the crossing angle. It has been also shown that the synchro-betatron coupling terms originating from the crossing angle are canceled by crab crossing[4]. The crab crossing scheme has been considered in the design of KEKB from the beginning as a backup measure against the crossing angle. Once, crab

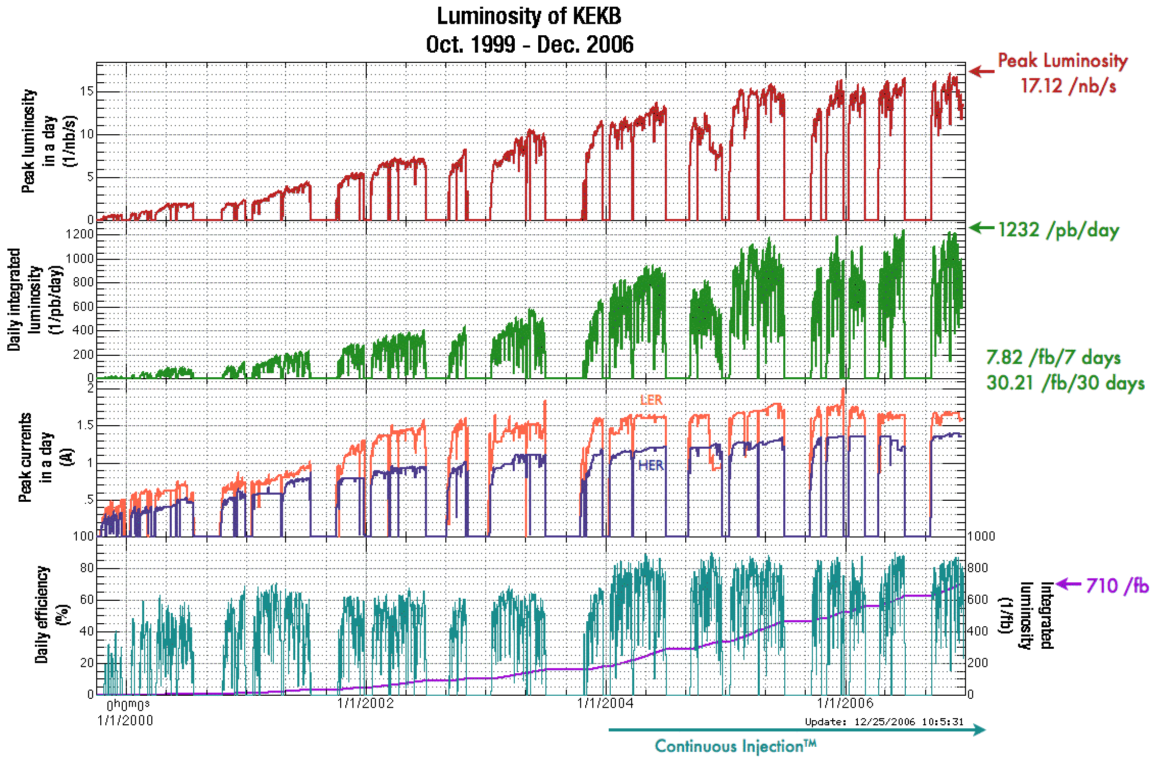

Figure 1: History of KEKB before installation of crab cavities.

crossing seemed non-urgent issue because KEKB achieved $\xi_y > 0.05$ at the early stage of the operation (in 2003). However, recently an interesting beam-beam simulation results appeared[5], predicting that the head-on or crab crossing provides higher $\xi_y > 0.1$. Figure 2 shows the comparison of ξ_y for the head-on (crab crossing) and the crossing angle with a strong-strong beam-beam simulation. Then the development of the crab cavities has been revitalized.

The original design of KEKB had two cavities for each ring, on both side of the IP, so that the crab kick excited by the first cavity is absorbed by another one. The new single crab cavity scheme extends the region with crab orbit until both cavities eventually merge to each other in a particular location in the ring. Then it needs only one cavity per ring. The layout is shown in Figure 3. In the case of KEKB, this scheme not only saved the cost of the cavities, but made it possible to use the existing cryogenic system at Nikko for the superconducting accelerating cavities also for the crab cavities. The beam optics was modified for the crab cavities to provide necessary magnitude of the beta functions at the cavities and the proper phase between the cavities and the IP. A number of quadrupoles have switched the polarity and became to have independent power supplies.

MACHINE STUDY AND PHYSICS RUN WITH CRAB CROSSING

Figure 4 shows a history of KEKB after the installation of the crab cavities. A dedicated beam study of the crab cavities and crab crossing started on 14th Feb. 2007 and

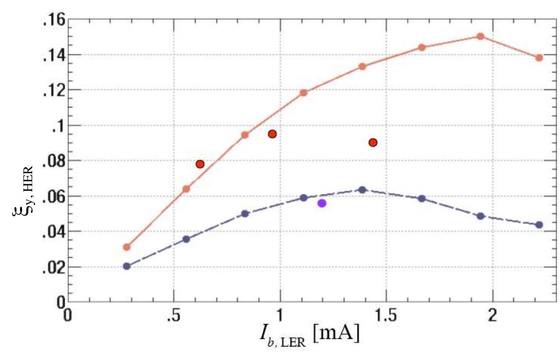

Figure 2: Predicted beam-beam parameters by the strong-strong beam-beam simulations with the crossing angle of $\pm 11\mathrm{mrad}$ (purple) and the head-on(crab crossing) (red). Some experimental data are also shown with closed circles.

finished at the end of June 2007. The beam study began with very small beam currents, since tolerance of the crab cavities against the beam power was unknown. Also conditioning of the cavities by using the beams was needed like usual accelerating cavities. A warm-up of the system up to the room temperature was needed at the end of April 2007 to recover from frequent trips. In most cases, the beam study was done with relatively small beam currents typically 100mA (LER) and 50mA (HER), since the most important purpose of the beam study is to prove that we can achieve such a high beam-beam parameter with crab crossing as the beam-beam simulation predicts. A high beam current operation of the crab cavities was also tried for different two purposes. Firstly, we hoped to confirm that a

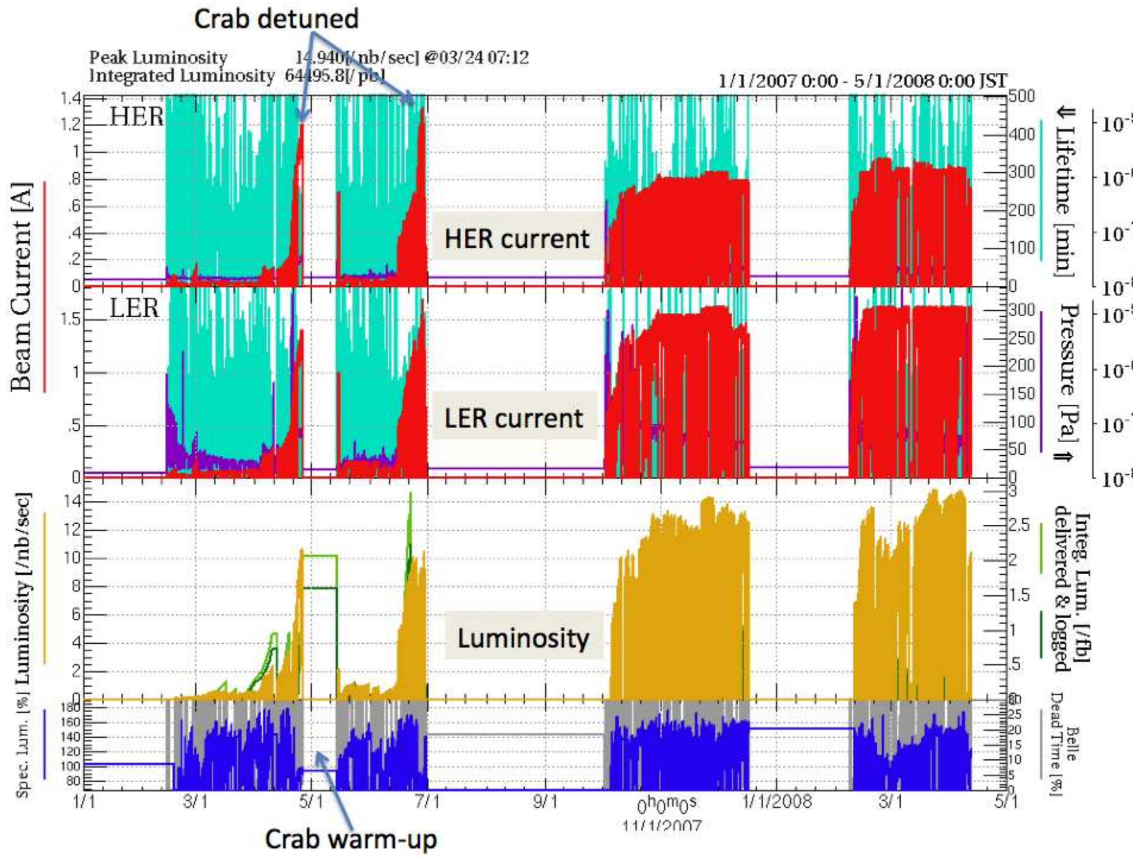

Figure 4: History of KEKB before installation of crab cavities.

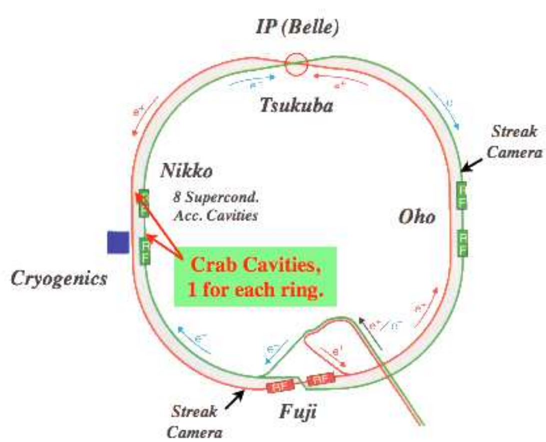

Figure 3: Layout of the crab cavities in the KEKB rings.

high luminosity is actually achieved with the crab on. In the high beam current operation, the peak luminosity exceeded $1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which is the design luminosity of KEKB. Secondary, we confirmed that the nominal beam currents before the installation of the crab cavities can be stored with the crab cavities detuned. This means that we can return the situation before carb installation by detuning them in case that the crabs are serious obstacles for the high luminosity. In the autumn run in 2007 following the beam study, the physics operation was done with the crab cavity on. Until now, we have been operating KEKB with the crab cavities on. So far, the highest luminosity with crab crossing is $1.61 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. This value is somewhat lower than before the crab installation. However, the value was achieved with much lower beam currents, particularly for the HER beam. A comparison of machine parameters before and after the crab installation is also shown in Table 1.

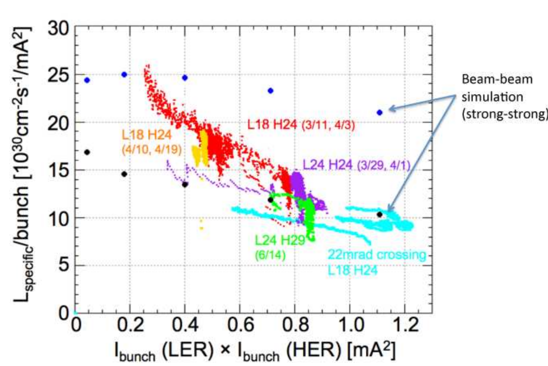

Figure 5: Beam current dependence of specific luminosity.

Beam-beam performance with crab crossing

To evaluate beam-beam performance, two parameters are used in this report, *i.e.* the specific luminosity and the beam-beam parameters. Figure 5 shows the specific luminosity as function of the bunch current product. Here, the specific luminosity is defined as the luminosity divided by a number of bunches and the bunch current product. In the figure, the points in thin-blue are data of the 22mrad crossing angle. The others are those with crab crossing. Different colors correspond to different combinations of the LER and HER horizontal emittances. In the 22mrad crossing angle operation, a combination of 18nm(LER) and 24nm(HER) was used. In the crab beam study, other combinations of 24nm(LER)/24nm(HER), 24nm(LER)/29nm(HER) were also tried in addition to the conventional combination of 18nm/24nm. The specific luminosity is inversely proportional to the beam cross section at the IP and it is constant, if the beam sizes are constant with different beam currents. In reality, however, the specific luminosity shows a very rapid decline as the bunch current product increases, indicating a rapid (vertical) beam blowup due to the beam-beam effect. In the figure, also shown is the specific luminosity predicted by the beam-beam simulation. Both predictions with and without crab crossing are shown. As seen in the figure, the experimental data are consistent with the simulation in case of the 22mrad crossing angle. On the other hand, in case of crab crossing, the experimental values are much lower than the predictions particularly at the high bunch currents, although at the low bunch currents there is a good agreement between them. This low specific luminosity at high bunch currents is a serious problem and has not been solved until now, although a large amount of efforts have been devoted to the study on this problem. We will mention these efforts in the following. Another serious problem with crab crossing is that the bunch current product is limited at around $0.85\mathrm{mA}^2$ due to decreases of beam lifetime. This problem is also serious, since the design value of the SuperKEKB is $1.53\mathrm{mA}^2$. This beam current limitation is not predicted by the beam-beam simulation.

In Figure 1, some experimental values of the vertical beam-beam parameter are shown together with the beam-beam simulation. As seen in the figure, the experiment value of the 22mrad crossing angle is consistent with the simulation. In case of crab crossing, however, the experimental value is much lower than the simulation at the high bunch currents, although there is a good agreement at the low bunch currents. The maximum vertical beam-beam parameter with crab crossing exceeds 0.093. This value is very high in a usual sense and indicates the potential superiority of crab crossing.

POSSIBLE CAUSES OF LUMINOSITY RESTRICTION

We have been struggling with the problem of the low specific luminosity at the high bunch currents. These efforts are summarized in this section.

Too wide tuning parameter space? In case of the high luminosity machine like KEKB, various kinds of machine tuning are important and without them the achievable luminosity is very low. At KEKB, most of magnets are standardized typically every two weeks. After this, the magnets are set at the values which brought good performance. This gives a basis of machine tuning. The next step is optics corrections on the global x-y coupling and the global dispersions, the beta-beatings. These corrections are very important and give a start point of the following tuning. In the routine luminosity tuning of KEKB, we make tuning on many parameters such as the orbital offsets at the IP and the crossing angles in both horizontal and vertical directions, the local x-y coupling at the IP, the horizontal and vertical dispersion at the IP and their slopes, the vertical waist points at the IP, the crab voltages, the x-y coupling parameters at the crab cavities, the betatron tunes and so on. In the conventional method of tuning at KEKB, most of these parameters (except for the parameters optimized by observing their own observable) are scanned one by one just observing the luminosity and the beam sizes. One possibility of the low specific luminosity is that we have not yet reached an optimum parameter set due to too wide parameter space. As a more efficient method of parameter search, we introduced in autumn 2007 the downhill simplex method for twelve parameters of the x-y coupling parameters at the IP and the vertical dispersions at the IP and their slopes. These twelve parameters can be searched at the same time in this method. We have been using this method since then. However, even with this method an achievable specific luminosity has not been improved, although the speed of the parameter search seems to be rather improved.

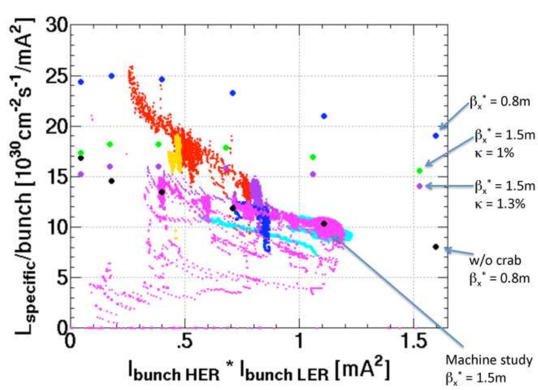

Figure 6: Beam current dependence of specific luminosity with different horizontal beta functions at the IP.

Beam lifetime issue Another possibility of the cause of the low specific luminosity is short beam lifetime. In the luminosity tuning, we sometimes encounter the situation that we can not set parameters giving a higher luminosity due to poor beam lifetime. Of these parameters, the most typical one is the horizontal beam offset at the

IP. On the other hand, we observe that the beam lifetime becomes short as the bunch currents increase. Due to this beam lifetime degradation, to what extent we can approach the optimum set of parameters for the luminosity could depend on the bunch currents. This is a possible scenario that beam lifetime limits the specific luminosity. As for the process which affects beam lifetime depending on the bunch current, there are some possibilities, *i.e.* the beam-beam tail, the degradation of dynamic aperture due to the beam-beam effect and so on. Recently, we found another process which might be responsible for the lifetime decrease. This is the dynamic beam-beam effects; *i.e.* the dynamic beta effect and the dynamic emittance effect. Since the horizontal tune of KEKB is very close to the half integer (typically .506), the effects are very large. The horizontal beta function at the IP (β_x^*) shrinks from 0.9m to 0.2m and the horizontal emittance (ε_x) is enlarged from 18nm to 55nm with ν_x of .506 and the unperturbed beam-beam parameter (ξ_{x0}) of 0.09. The change of the beta function at the IP means a large beta beat all around the ring. In this situation, we found that the horizontal beam sizes at around the crab cavity in both rings are very large (typically 7mm) at the high bunch currents and the physical aperture there is only around 5 σ_x. Therefore, there is a possibility that the physical aperture around the crab cavities affects the beam lifetime seriously. This possibility was confirmed by an orbit bump study. Then, we decided to change the optics to widen effective physical aperture around the crab cavities. For this purpose, the horizontal beta function at the IP was enlarged from 0.8m to 1.5m for both rings. As a result, the horizontal beta function at the crab cavities could be decreased, since the condition of crab crossing requires that the product of the horizontal beta functions at the IP and at the crab cavity should be preserved. With this optics, we investigated the specific luminosity. If the discrepancy of the specific luminosity between the experiment and the simulation shown in Figure 5 comes from the beam lifetime issue, this discrepancy can be decreased with the optics change. The experimental result is shown in Figure 6. The specific luminosity with $\beta_{\mathrm{x}}^* = 1.5\mathrm{m}$ is shown in the magenta color. The values of the beam-beam simulation are also plotted with two different values of the global x-y coupling. A remarkable thing with this new optics is that the maximum bunch current with this new optics is that the maximum bunch current with crab crossing was increased. It seems that the cause of this bunch current limitation is physical aperture around the crab cavities associated with the dynamic beam-beam effects. However, the tendency that the specific luminosity agrees with the simulation at the low bunch currents and disagrees at the high bunch currents still exists even with this new optics. Therefore, we can not conclude that the beam lifetime issue creates the steeper slope of the specific luminosity than the beam-beam simulation.

Other possibilities There are some other possibilities which may cause the discrepancy between the experiment and the simulation, *i.e.* the synchro-betatron resonance, the vertical crabbing motion, some unknown noise, a cross-talk of the beam-beam effects and the lattice non-linearity and so on. These effects are not implemented in the strong-strong beam-beam simulation.

In the course of KEKB operation, it turned out that the synchro-betatron resonance of ($2\nu_{\mathrm{x}} + \nu_{\mathrm{s}} = \mathrm{integer}$) or ($2\nu_{\mathrm{x}} + 2\nu_{\mathrm{s}} = \mathrm{integer}$) affects the KEKB performance seriously. Nature of the resonance lines was studied in details during the machine study on crab crossing last year. We found that the resonances affect (1) single-beam lifetime, (2) single-beam beam sizes (both in horizontal and vertical directions), (3) two-beam lifetime and (4) two-beam beam sizes (both in horizontal and vertical directions) and the effects are beam current dependent. The effects lower the luminosity directly or indirectly through the beam-size blowup, the beam current limitation due to poor beam lifetime or smaller variable range of the tunes. The strength of the resonance lines can be weaken by choosing properly a set of sextupole magnets. KEKB adopted the non-interleaved sextupole scheme to minimize non-linearily of the sextupoles. LER and HER have 54 pairs and 52 pairs of sexupoles, respectively. With so many degree of freedom in the number of the sextupoles, optimization of sextupole setting is not an easy task even with present computing power. The candidates of sextupole setting are found in computer. Usually dynamic aperture and an anomalous emittance growth [6] are optimized on the synchro-betatron resonance. Recently, in KEKB an efficient method of optimization has been developed by using Temperature Parallel Simulated Annealing (TPSA) method [7]. Usually a setting of sextupoles which gives good performance in computer does not necessarily bring good performance in the real machine and most of candidates of the sextupole setting do not give satisfactory performance. When we change a linear optics, usually we need to try many candidates of settings until we finally obtain a setting with sufficient performance. The single-beam beam size and the beam lifetime are criteria for sextupole performance. Or as an easier method of the estimation of sextuple performance, a beam loss is observed when the the horizontal tune is jumped down across the resonance line. The resonance line in HER is stronger than that in LER, since we do not have a local chromaticity correction in HER. In usual operation, we can operate the machine with the horizontal tune below the resonance line in case of LER, while we can not lower the horizontal tune of HER below the resonance line. The beam-beam simulation predicts a higher luminosity with the lower horizontal tune in HER. To weaken the strength of the resonance line in HER, we tried to change the sign of α(momentum compaction factor). Since the ν_s is negative with the positive α, the resonance is a sum resonance ($2\nu_{\mathrm{x}} + \nu_{\mathrm{s}} = \mathrm{integer}$). By changing the sign of α, we can change it to a difference resonance ($2\nu_{\mathrm{x}} - \nu_{\mathrm{s}} = \mathrm{integer}$). The trial was made in June 2007. The trial was successful and we could lower the horizontal tune below the resonance. However, when we tried the negative α in LER, unexpectedly large synchrotron oscillation due to the microwave instability occurred. Due to this oscillation, we gave up the trial of the negative α optics.

The vertical crab at the IP could degrade the luminosity. It can be created by some errors related to the crab kick such as a mis-alingnment of the crab cavity and the local x-y coupling at the crab cavity. The x-y coupling parameters at the crab cavities give a tuning knob to adjust the vertical crab at the IP. By tuning them, we can eliminate the vertical crab at the IP even if it is created by other sources such as a mis-alignment of accelerating cavities. So far, however, tuning of these parameters is not so effective to raise the luminosity.

The beam-beam simulation predicts a significant luminosity degradation if there is a fast noise to the beams. Possible noises which may induce such a loss may come from the phase error of the crab cavities themselves and the transverse bunch-by-bunch feedback system. As for the phase error of the crab cavities, the measured error was less them 0.01 degree for fast noise ($\succeq 100\mathrm{Hz}$) and 0.1 degree for slow noise ($\preceq 100\mathrm{Hz}$). The measured phase error is much smaller than the allowed values given by the beam-beam simulation. As for the feedback system, in the operation of the crossing angle of $\pm 11\mathrm{mrad}$, we once found that the luminosity decreases with a higher feedback gain. Only the LER vertical gain affects the luminosity. We found that the luminosity degrades by about 15 % with a 3 dB higher feedback gain than the usual value. Although the reason why the feedback gain affects the luminosity has not been understood yet, there is a possibility that some noise from the system affects the luminosity. In the present beam operation, we use a very low feedback gain in the LER vertical direction. Although there remains some oscillation in the single beam mode with this gain, the oscillation is damped by the Landau damping in case of the two beam operation. With an even lower gain, there is no luminosity gain.

The disagreement between the beam-beam simulation and the experiment at the high bunch current is also being investigated on the simulation side. The strong-strong beam-beam simulation, which predicted the high specific luminosity, does not include some effects. For example, the lattice non-linearity is not considered in the strong-strong simulation. Generally speaking the cross talk between the beam-beam effects and the lattice non-linearity plays some role in the beam-beam performance. To study this effect, a weak-strong simulation which includes a full lattice was done [8]. However, we found no significant degradation of the specific luminosity at the high bunch current so for.

Another possibility of a cause of the disagreement which we considered is an unexpectedly large vertical emittance. The beam-beam simulation showed that the attainable luminosity depends largely on the single beam vertical emittance. If the actual vertical emittance is much larger than the assumed value, it could create the disagreement. We carefully checked the calibration of the beam size measurement system. We found some errors in the calibration of the HER beam size measurement system and the actual vertical emittance was somewhat smaller than was considered. The latest values of the global x-y coupling of both beam are around 1.3 %. This value is within our consideration.

SUMMARY

The crab cavities which were installed at KEKB in the end of FY 2006 have been working much more stably than the initial expectation. They are presently being used in the usual physics run. It seems that the success of the development of the crab cavity is very important, since the crab cavity may have applications to other machines such as SR facilities or an upgrade of LHC. The crab cavities at KEKB, however, have not yet realized their potential capability in the sense that the specific luminosity is much lower than the prediction of the beam-beam simulation at the high bunch currents. In spite of a large amount of effort to solve this problem, we have not yet found the cause of this problem. Since the design of SuperKEB counts the luminosity gain by crab crossing, finding the cause is very important task for us.

REFERENCES

[1] K. Nakanishi *et al.*, in these proceedings.

[2] KEKB B-Factory Design Report, KEK-Report-95-7, June 1995.

[3] R. B. Palmer, SLAC PUB-4707 (1988); In Proc. DPF Summer Study Snowmass 88, Snowmass, CO, 1988, ed. S. Jensen. Singapore: World Sci. (1988), p.613.

[4] K. Oide and K. Yokoya, Phys.Rev.A40:315 (1989).

[5] K. Ohmi et al, Proc. of EPAC06, 616 (2006).

[6] K. Oide and H. Koiso, Phys.Rev. E49, 4474 (1994).

[7] A. Morita *et al.*, Proc. of PAC07 (2007).

[8] K. Ohmi, in these proceedings.