LESSONS LEARNED FROM THE B-FACTORIES AND IMPLICATIONS FOR A HIGH-LUMINOSITY CIRCULAR e+e- HIGGS FACTORY

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Abstract

Experiences on the electron clouds, optics corrections, an orbit feedback at IP and luminosity tuning at KEKB are described. An emphasis is placed on the beam instrumentations and the beam control.

INTRODUCTION

KEKB [1] is an energy-asymmetric double-ring collider for B meson physics. KEKB consists of an 8-GeV electron ring (the high energy ring: HER), a 3.5-GeV positron ring (the low energy ring: LER) and their injector, which is a linac-complex providing the rings with both of the electron and positron beams. The construction of KEKB started in 1994, utilizing the existing tunnel of TRISTAN, a 30 GeV $\times$ 30 GeV electron-positron collider. The machine commissioning of KEKB started in December 1998. The physics experiment with the physics detector named Belle was started in June 1999. The peak luminosity surpassed the design value of 1.0 $\times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in May 2003. The maximum peak luminosity of KEKB is 2.11 $\times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which was recorded in June 2009. This value has been the world-record since then. The KEKB operation was terminated at the end of June 2010 for the works to upgrade KEKB to SuperKEKB. The commissioning of SuperKEKB is expected to start in autumn in 2015. The total integrated luminosity collected by the Belle detector was 1041 fb^{-1}. The history of KEKB is shown in Figure 1. In this report, some experiences at KEKB are described. An emphasis is places on the beam instrumentation and the beam control. Some of them may be useful in future colliders such as a high-luminosity circular e+e- Higgs factory. Achievements of KEKB and details of commissioning are described elsewhere [2] [3].

ELECTRON CLOUDS

A beam size enlargement depending on the beam current in the LER has given one of the most serious luminosity restrictions to KEKB. This type of beam-blowup was not considered in the design phase of KEKB. It turned out that the cause of the blowup is the electron clouds. Although the electron clouds are formed by the bunch train, the blowup is induced by a single bunch instability. The mechanism of this blowup has been studied theoretically by F. Zimmermann and K. Ohmi. They showed by simulations that the blowup can be explained by a fast head-tail instability caused by wake fields by the passage of the bunch particles though the electron clouds [4]. This explanation has been experimentally confirmed by observing vertical betatron sideband due to the electron clouds at KEKB LER [5]. Figure 2 shows a typical results of the sideband measurements. More detailed explanations and an experimental setup for this measurement are described in [5].

To suppress this instability, solenoid coils have been wound around approximately 95% of the drift space in the LER ring with a maximum field at the center of the beam pipe of ~60 Gauss [6]. Although the solenoids drastically improved the luminosity, performance of KEKB was still affected by the effects of electron clouds with a higher beam current of the LER than about 1.6 A. The luminosity of KEKB did not increase with a higher LER beam current than about 1.6 A. It is believed that this is due to the effects of electron clouds. For this reason, the operation beam current in LER of 1.6 A is much lower than the design beam current, 2.6 A. Another impact of the electron clouds to the beam operation at KEKB is the choice of bunch spacing. In the design, the bunch spacing is one RF bucket, which means that every RF bucket is filled with beam particles. However, in the actual operation, the bunch spacing is approximately 3 RF buckets. With shorter bunch spacing, the specific luminosity lowered. This restriction to bunch spacing is also believed to come from the effects of the electron clouds. Figure 3 shows a result of an experiment on bunch spacing carried out on March 21st 2008. For the experiment, a special filling pattern was used. In the beam filling pattern of KEKB, the same pattern should be repeated every 49 RF-buckets to be compatible with the two bunch injection. Due to the synchronization problem between the injector linac and the KEKB rings, only the two bunches in 49 RF-buckets in the rings can be injected from linac to the rings. In the filling pattern used in the experiment, 17 RF-buckets out of 49 RF-buckets were filled with the beam and the same patterns repeated 99 times. Most of bunch spacing between adjacent bunches was 3 RF-buckets but only 2 bunches out of 17 bunches in a unit of 49 RF-buckets followed the preceding bunches at a distance of 2 RF-buckets. In Fig. 3, the specific luminosity per bunch is plotted as function of bunch ID in a unit of 49 RF-buckets. Note that the specific luminosity of each bunch ID in the figure is the average of 99 bunches in the equivalent position in the units of 49 RF-buckets. The error bars in the graph show the standard deviations of the 99 bunches. As is seen in the figure, the specific luminosity after 2 RF-buckets is ~15 % lower than that of the other bunches. It is believed that this degradation in the specific luminosity comes from the effects of the electron clouds. In the case of short bunch trains, this degradation was not observed and then we can deny the possibility that the degradation in the specific luminosity after short bunch spacing is caused by the effects of the parasitic collisions.

Another instrument for the electron clouds measurement used at KEKB is an retarding field analyzer (RFA) [7]. A

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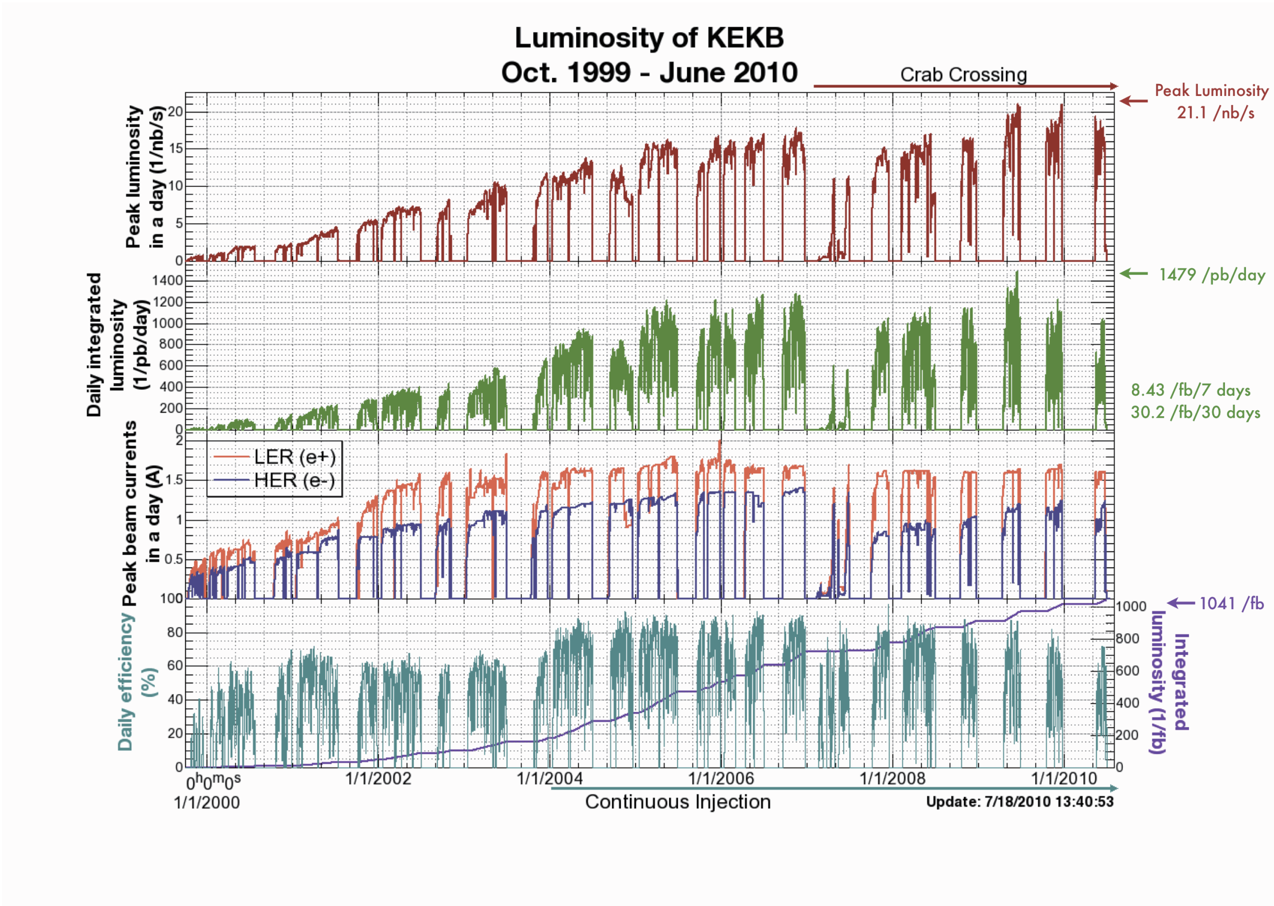

Figure 1: History of the performance of KEKB from October 1999 until June 2010. The rows represent (top to bottom) the peak luminosity in a day, the daily integrated luminosity, the peak stored currents in the LER and HER in a day, the daily efficiency, and the total integrated luminosity at Belle, respectively.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

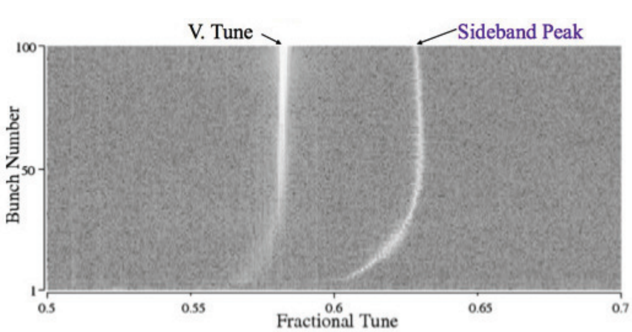

Figure 2: The horizontal axis is the fractional tune, from 0.5 on the left edge to 0.7 on the right edge. The vertical axis is the bunch number in the train, from 1 on the bottom edge to 100 on the top edge. The bunches in the train are spaced 4-rf buckets (about 8 ns) apart. There are two peaks corresponding to the vertical tune and the sideband beak.

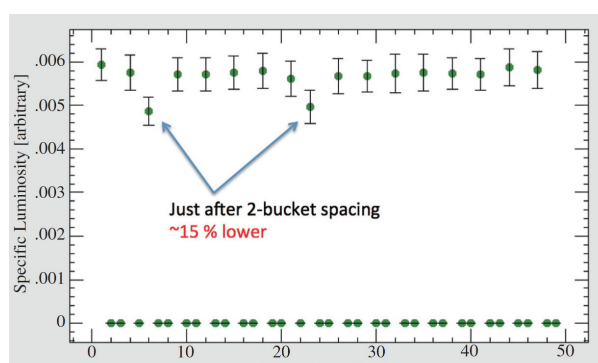

Figure 3: Specific luminosity per bunch depending on the bunch position in the unit 49 RF-buckets. Each datum is the average of 99 bunches in the equivalent position in the unit 49 RF-buckets and the error bars are the standard deviations of the 99 bunches.

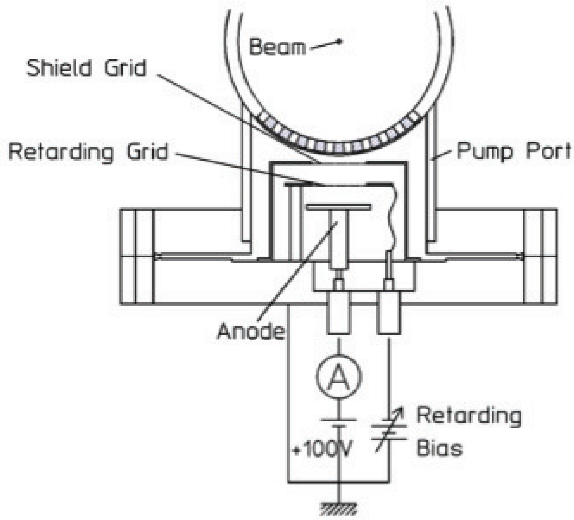

Figure 4: Conceptual drawing of the RFA monitor.

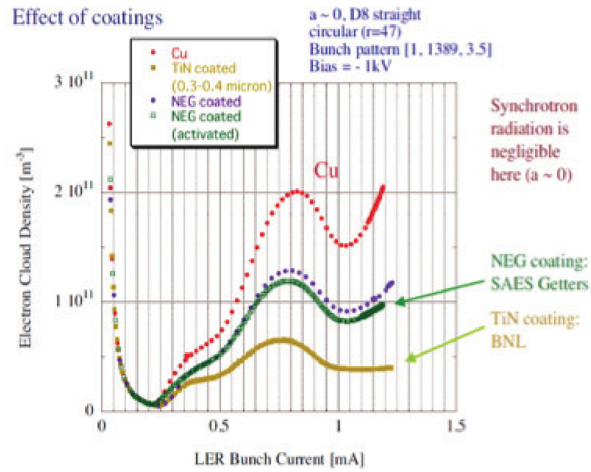

Figure 5: Typical result of the electron clouds density measurement using the RFA monitor.

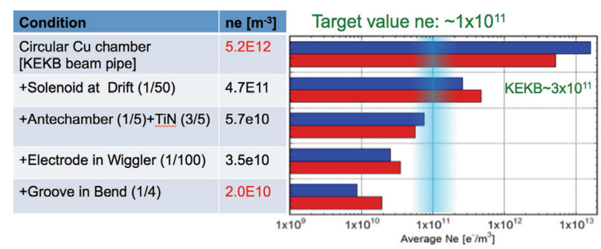

Figure 6: Effectiveness of countermeasures for suppressing the effects of the electron clouds at SuperKEKB. The data in blue and red are those from simulations and the measurements using the RFA monitor, respectively.

conceptual drawing of the monitor is shown in Fig. 4. This monitor has been used for measuring electron cloud density in KEKB LER using various materials for R&D's. A typical result of the measurements is shown in Fig. 5. In this experiment, the electron cloud density was measured in three conditions, *i.e.* a bare circular Cu chamber, the chamber with a NEG coating and with a TiN coating. The beam fill pattern was a single train, 1389 bunches and 3.5 RF-bucket spacing. The bias (retarding) voltage of RFA was set to -1 kV. As is seen in the figure, the electron clouds density is reduced by a factor 3 ~ 5 by TiN coating. In SuperKEKB we will adopt ante-chambers with the TiN coating. The chambers with other countermeasures for SuperKEKB such as electron cloud clearing electrodes for the wiggler sections and grooved chambers in bending sections are tested with the RFA monitor. Figure 6 summarizes effectiveness of countermeasures for the electron clouds [8]. The data bars in blue and red are those from simulations and the measurements using the RFA monitor, respectively. The consistency between the measurements and the simulations is not so bad. With bare circular Cu beam pipes, an expected average density of the electron clouds is $\sim 3 \times 10^{11}$electrons m^{-3}. With all of countermeasures in Fig. 6, the expected electron cloud density will be reduced down to $\sim 2 \times 10^{10}$electrons m^{-3}. This value is about 1/5 of the target density of $\sim 1 \times 10^{11}$electrons m^{-3} and seems to be well below the threshold of the instabilities due to the electron clouds.

Summary of Experiences with Electron Clouds at KEKB

The electron clouds at LER of KEKB gave serious effects on the KEKB performance. Winding solenoid coils in the drift space in the ring was effective to suppress the effects, although there remained some effects even after almost all drift spaces were covered with the solenoid fields. To analyze phenomena, bunch-by-bunch measurement systems such as the bunch-by-bunch BPM and the bunch-by-bunch luminosity monitor have been important. A RFA monitor has been used to measure electron cloud density and the data was very helpful to design the vacuum system for SuperKEKB.

BPMS AND OPTICS CORRECTIONS

BPMs

At KEKB, every quadrupole magnet is equipped with a BPM and the number of BPMs is about 450 for each ring for measuring the closed-orbit distortion (COD) [9]. In order to avoid picking up the RF leakage from the highpower RF system, the 1 GHz (twice the RF frequency) component of the beam-induced button signal is detected by a spectrum analysis method using a digital signal processor (DSP). The effective bandwidth of the signal detection is widely programmable, and it is easy to optimize the measuring time and the accuracy for the various operation modes of the accelerator. The CODs of both rings are continuously measured every 2~3 s and corrected every 20~30 s based on the BPM data to suppress any orbit drift appearing in both rings.

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A typical resolution of the COD measurement at 30 mA is a few μm.

To ensure the reliability of an orbit measurement, the center offset of each BPM relative to the quadrupole nearby was corrected by a beam-based alignment. In addition, BPMs near sextuploles have capacitive sensors to measure relative transverse position of BPMs to the sextupoles and the measured values were automatically applied as offsets to the BPM readings. Another important beam based diagnostics for BPMs is gain mapping of BPM electrodes [10]. By using beams, calibration was done to find the relative gains of all KEKB BPM heads. With this BPM gain mapping, the consistency of BPM measurement was drastically improved. Each BPM has four electrodes and the BPM consistency is defined as an rms value of four beam position data using four different sets of combinations of three electrodes. We needed to do this gain mapping for all BPMs typically every month.

At KEKB, 38 turn-by-turn BPMs were used. The monitor heads are common to the BPMs for COD measurement and the electronics were switched for turn-by-turn measurements. The turn-by-turn BPMs were not used for routine operation but for the orbit measurement before beam storage after a long shutdown and for the beam studies such as a x-y coupling measurements.

Optics Correction

The optics correction is the basis of the machine operation [12]. Typically every two weeks after a regular maintenance time, we did the optics corrections. At KEKB, the optics corrections of the x-y coupling, the dispersion and beta-beating around the each ring were done. Since there are not many turn-by-turn BPMS at KEKB, the corrections were done by measuring COD using the BPMS. A loop of corrections for the x-y coupling, the dispersion and the beat-beating took 30~60 minutes per ring to converge. Each correction took 3.5 to 7 minutes. With this method, we do not have to solve the entire problem at once by a single big matrix. Although these corrections are not independent, their cross-talks are smaller than the diagonal parts, so the iteration converged quickly. The optics corrections gave a basis of the luminosity tuning shown below.

As for the slow ground deformation, a relatively large subsidence has been observed at KEKB as shown in Fig. 7. A cumulative amount of the tunnel deformation of the South arc section amounted to 25mm. Although there are a couple of speculations as to why the South arc section continues to sink, there has not been any clear explanation determined yet. In the construction period of KEKB (1998), all magnets were aligned on a horizontal plane. The vertical positions of the magnets have been changing according to the tunnel deformation. However, almost no degradation of performance has been observed with the position shifts of the magnets owing to the optics corrections developed at KEKB and the best luminosity of KEKB was achieved with the deformed ground. A simulation confirmed that the effects of the alignment errors which are slower than the betatron wave length are small.

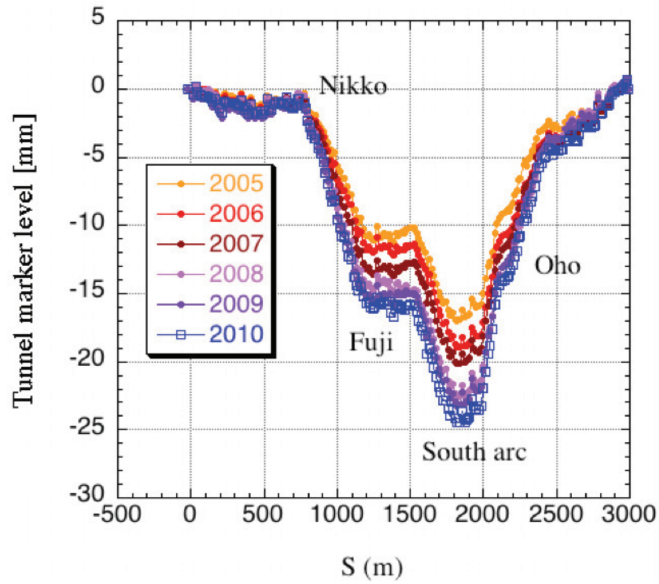

Figure 7: Tunnel level marker height with respect to that at the interaction point over years.

Day Night Difference of Luminosity

In the process of increasing the luminosity, we encountered a peculiar problem. This problem became first conspicuous in March 2003. The problem has the following features. 1) The luminosity degrades in the daytime. The difference in the luminosity between day and night is about 20 % at the worst. 2) The difference seems to depend on the temperature difference between day and night. The difference is not remarkable in winter or on a rainy day. 3) When the luminosity drops in the daytime, the HER beam blowup *is observed. Tuning on the x-y coupling parameters at IP is* somewhat effective to mitigate the luminosity drop, although its effectiveness is insufficient. A lot of efforts have been devoted in vain to solve the problem. Eventually, we found that the BPM consistency also shows the day-night difference. The consistency is defined as the standard deviation of four BPM readings by using four different combinations of BPM electrodes (choice of three electrodes out of four). Orbit corrections based on changing BPM offsets bring optics deformation and may result in the luminosity degradation. The mechanism that we found is that a part of BPM cables goes through the outside of buildings and is affected by the day-night temperature change. To solve the problem, we installed thermal insulator sheets to the BPM cables in the outside. An example of the thermal insulator sheets is shown in Fig. 8. After the installation, the day-night change of the BPM consistency error decreased by 30 or 50 % and the day-night difference in the luminosity became almost invisible.

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Figure 8: A thermal insulator sheet for BPM cables installed near the local control building (LC4).

Summary of Experiences on Optics Corrections Based on COD Measurement.

At KEKB, the optics corrections were done based on the COD measurement, since KEKB did not have many turn-by-turn BPMs. In the following, some experiences on the optics corrections are summarized.

- Global COD correction was done continuously every 20 seconds.
- Optics corrections were done every 2 weeks.
- Method of iteration of x-y coupling, dispersions and β-beating was used.
- The methods worked very well even with the large tunnel deformation based on BPM measurements.
- However, when the BPMs give the incorrect values, the luminosity tuning has a trouble such as the day-night problem which KEKB encountered.
- It seems that the BPM gain mapping and Quad-BPM tuning are very important at high luminosity machines.

COLLISION FEEDBACK

In double ring colliders such as KEKB, we have to solve some special problems which we never encountered in conventional single ring colliders. One such critical problem is how to maintain optimum beam collision conditions. For this purpose, we have developed a special system which manipulates beam orbits around the IP [13]. As is schematically shown in Fig.9, there are three possible ways to maintain optimum beam collision condition, *i.e.* a beam-beam deflection method, the luminosity dithering method and the method relying on the beam size measurement [13]. Of these algorisms, KEKB mainly used the beam-beam deflection method. As is shown in Fig.10, a set of 4 QCS BPMs (A,B,C and D) or another set of 2 OctoPos BPMs (E and F) gives sufficient information to the feedback system. In

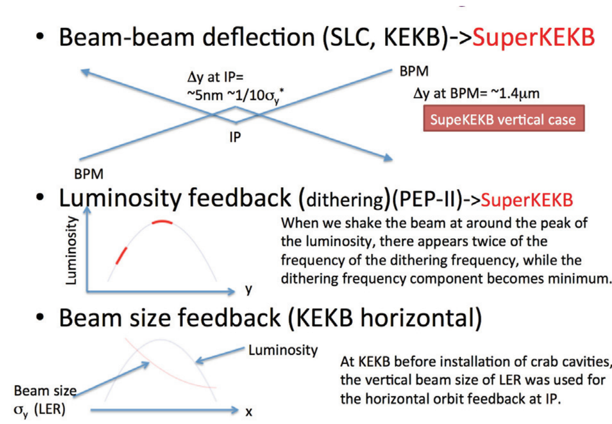

Figure 9: Three algorisms for orbit feedback at IP.

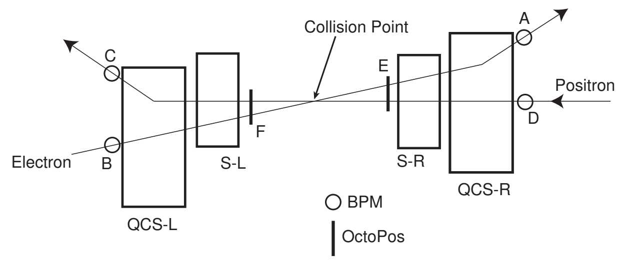

Figure 10: Schematic view of BPM configuration. Tow of six BPMs (E and F) are special BPMs called "OctoPos". The OctoPos BPMs are located closer to the IP than the other usual BPMs. They have 8 electrodes and can measure orbits of the two beams simultaneously.

actual beam operation, we usually use the set of 4 regular BPMs, since the beam current dependence in the orbit measurements is larger with the set of OctoPos BPMs than with the regular BPMs. The orbit feedback system around IP at KEKB worked by making orbit bumps so as to reduce orbit offsets at IP which are measured using the BPMs. The speed of the feedback is $\sim$ 1/4Hz. The resolution of the BPMs is $\sim 2\mu$m.

Figure 11 shows a typical behavior of the orbit feedback system. In the figure, plotted is the history of the vertical bump amplitude at the IP created by the orbit feedback system for two hours. During this period, the machine condition was very stable and the luminosity was kept almost constant owing to the orbit feedback system. The beam currents were also kept almost constant thanks to the continuous beam injection mode. The period was not special one but was chosen rather randomly on the condition that the machine status is stable. The change of the vertical offset during this period is much larger than the vertical beam size. This means that the vertical offset at the IP would largely change in a short time without the feedback. The amount of the offset change is unexpectedly large. Some part of the offset change may be created by the CCC (Continuous Closed orbit Correction) system. Therefore, the orbit feedback system is vital for KEKB.

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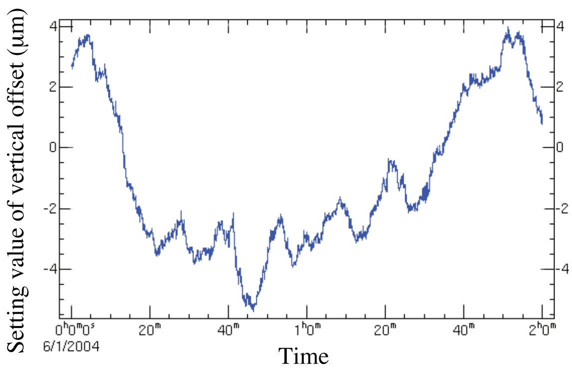

Figure 11: History of the vertical bump amplitude at the IP.

Some Experiences of IP Orbit Feedback at KEKB

In the following, some experiences with the IP orbit feedback system at KEKB are summarized.

- In double ring colliders such as KEKB, an orbit feedback system for maintaining the beam orbits around IP is vital. Without such a system, we cannot maintain the luminosity even for a short period.
- With the system based on BPM measurement, we could prevent luminosity loss due to orbit change almost completely.
- One of the problems with the system was the stability of the target values (feedback points) of the feedback.
  - To trace their changes, we frequently (typically once an 8-hour shift) had to do the target scan for optimum values.
  - The origin of the target change was thought to be mechanical movement of the BPMs or the QCS magnets.
  - We experienced that the target changes greatly after beam aborts.
  - Our observations have shown that heating of vacuum chambers brings sizable mechanical movement of the vacuum chamber and BPMs (and even of the quadrupole magnets).
  - Countermeasures for this problem was reinforcement of the cooling power of the IR vacuum chambers, displacement sensors for BPMs, introduction of continuous beam injection scheme.

LUMINOSITY TUNING

There are a number of knobs to tune up the luminosity. Only a few of them can be tuned up with independent observables besides the luminosity. Table 1 lists the tuning parameters and its observables. Tuning parameters related to the crab cavities are not listed in the table. We found that the liner optics correction is important for suppressing the beam-beam blowup. In usual beam operation, we frequently (typically every 2 weeks) made optics corrections where we corrected global beta functions, x-y coupling parameters and dispersions [6]. Sometimes, the optics corrections were done with a different set of strength of the sextupole magnets to narrow the stop-band of the resonance ($2\nu_x + \nu_s$ = integer) or ($2\nu_x + 2\nu_s$ = integer). The optics correction is the basis of the luminosity tuning. On this basis, we carry out tuning on the other parameters in Table 1. At KEKB, we found that the local x-y coupling and the vertical dispersion at IP are very important for increasing the luminosity. We have developed tuning knobs to adjust those parameters. In the conventional method of tuning at KEKB, most of these parameters (except for the parameters optimized by observing their own observables) were scanned one by one just observing the luminosity and the beam sizes. As a more efficient method of the parameter search, we introduced in autumn 2007 the downhill simplex method for twelve parameters of the x-y coupling parameters at IP and the vertical dispersions at IP and their slopes, which are very important for the luminosity tuning from the experience of the KEKB operation. 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.

For the luminosity tuning, only the luminosity monitor [14] and the beam size monitor based on the SR interferometer [11] are used and so these monitors are particularly important at KEKB. Also, the continuous injection scheme (top-up injection) made the luminosity tuning easier through more stable beam conditions [3]. With the scheme, the beam currents were almost constant and heating effects by the beams were saturated at some points. Generally speaking, a machine has a tendency that its operation becomes more stable with operation conditions unchanged. As an example in the KEKB operation, in the conventional injection scheme we used different working points during the injection and the physics run and the beam abort sometimes occurred in changing the tunes due to wrong setting of the tunes. We can avoid this problem with the continuous injection. Of course, the direct motivation of the continuous injection was to increase the integrated luminosity. Roughly speaking, the gain of the continuous injection in the integrated luminosity was about 30%. One third of it came from elimination of the loss time, while two third from keeping the maximum beam currents. We started the beam operation with the continuous injection scheme in the middle of January 2004. Since then, this scheme has been very successfully applied to the KEKB operation and has brought an enormous gain in the integrated luminosity to Belle. In Table 2, we show a comparison of luminosity performance before and after the continuous injection. For comparison, we took two shifts that were stable and gave record integrated luminosities. The beam operations of the two shifts are shown in Fig. 12 and Fig.13.

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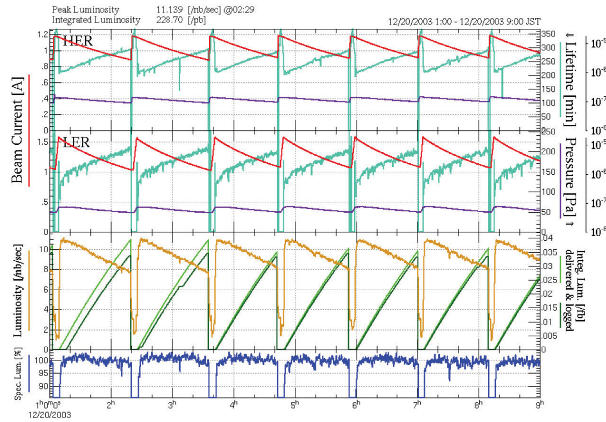

Figure 12: Beam currents and luminosity trend before continuous injection.

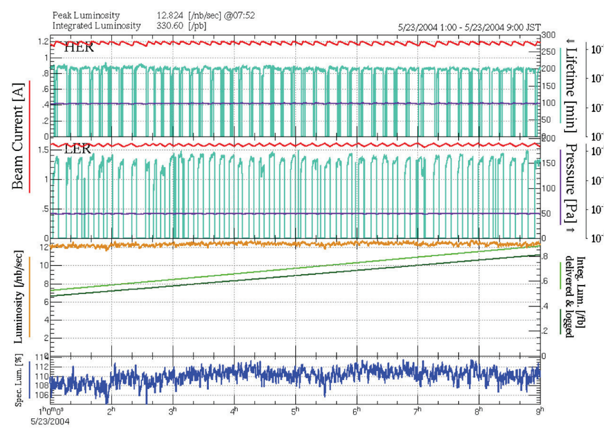

Figure 13: Beam currents and luminosity trend after continuous injection.

Some Experiences of Luminosity Tuning at KEKB

In the following, some experiences of luminosity tuning at KEKB are summarized.

- The KEKB luminosity has been increased by many and continuous parameter scans.
  - The machine operators did almost always (even in physics run) parameter scans. (scan, scan, scan...)
  - An introduction of downhill simplex method for the parameter search speeded up the parameter search. However, the achievable luminosity was not increased with this method.
- Most of the luminosity tuning used the luminosity monitors and the beam size monitor (SR interferometer) as observables. Reliability of those monitors were important.
- The continuous injection scheme (top-up injection) made the luminosity tuning easier through more stable beam conditions.

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Table 1: Tuning knobs for the luminosity and their observables. Many depend only on the beam size at the synchrotron radiation monitor (SRM), besides the luminosity.

Knob	Observalbe	frequency
Beam offset at IP (orbit feedback)	Beam-beam kick (BPMs)	~1 s
Crossing angle at IP (orbit feedback)	BPMs	~1 s
Target of orbit feedback at IP (offset)	vertical size at SRM, luminosity	~1/2 day
Target of orbit feedback at IP (angle)	vertical size at SRM, luminosity	~1/2 day
Global closed orbit	BPMs	~ 20 s
Betatron tunes	tunes of non-colliding bunches	~ 20 s
Relative RF phase	center of gravity of the vertex	~ 10 min
Global coupling, dispersion, beta-beat	orbit response to kicks, RF freq.	~ 14 days
Vertical waist position	vertical size at SRM, luminosity	~ 1/2 day
x-y coupling and dispersion at IP	vertical size at SRM, luminosity	~ 1/2 day
Chromaticity of x-y coupling at IP	vertical size at SRM, luminosity	~ 1/2 day

Table 2: Comparison of the continuous injection with the conventional injection scheme. *: due to injection and HV up/down.

Injection mode	Continuous	Conventional	
Reference shift	Dec. 20 2003 owl	May 23 2004 owl	
Integrated luminosity per shift	330.6	228.7	pb^{-1}
Peak luminosity	12.824	11.139	$nb^{-1}s^{-1}$
Loss time*	0	~13.4	%
Veto time during injection	3.5	0	ms
Increase of dead time due to Veto	~2.3	0	%
Linac repetition rate	10	50	Hz
Injection rate (e+)	~0.39	~3.1	mAs^{-1}
Injection rate (e-)	~0.71	~4.5	mAs^{-1}
Peak beam current (e+)	1600	1570	mA
Peak beam current(e-)	1200	1175	mA

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