LUMINOSITY TUNING AT KEKB

Y. Funakoshi[*], KEK, Tsukuba, Japan

Abstract

KEKB achieved the world's highest luminosity. One of the key issues for the high luminosity at KEKB was a luminosity tuning which was done almost all the time even during the physics run to suppress the beam-beam blowup. In this talk, those experiences are summarized.

INTRODUCTION

KEKB [1] was an energy-asymmetric double-ring collider for B meson physics. KEKB consisted 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 × 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 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 experiences on the luminosity tuning. Some of them may be useful in future colliders such as SuperKEKB or a high-luminosity circular e+e- Higgs factory. Achievements of KEKB and details of commissioning are described elsewhere [2] [3].

MACHINE PARAMETERS RELATED TO LUMINOSITY

As is well known, the luminosity is expressed as

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm\xi_{y\pm}}{\beta_{y\pm}^*}\frac{R_L}{R_{\xi_y}}.$$

Here, γ and r_e are the Lorentz factor and the electron classical radius and the index of ± denotes the positron or electron. σ_y^* and σ_x^* are the vertical and horizontal beam sizes at the IP, respectively. I, ξ_y and β_y^* denote the total beam current, the vertical beam-beam parameter and the vertical beta function at the IP, respectively. R_L and R_{ξ_y} are the reduction factors for the luminosity and the vertical beam-beam parameter due to the hourglass effect and the crossing angle, respectively. In usual cases, the beam size ratio is much smaller than unity and the two reduction factors are not much different from unity. Therefore, the luminosity is almost determined by the three parameters; *i.e.* the beam current (I), the beam-beam parameter (ξ_y) and the vertical beta function at the IP (β_y^*). Table 1 shows machine parameters of KEKB at the time when the highest luminosity was achieved.

Table 1: Machine Parameters of KEKB

Parameters	LER	HER	Units
Energy	3.5	8.0	GeV
Circumference	3016		m
$\mathrm{I_{beam}}$	1.637	1.188	A
# of bunches	1585		
$\mathrm{I_{bunch}}$	1.03	0.75	mA
Ave. Spacing	1.8		m
Emittance	18	24	nm
β_x^*	120	120	cm
β_y^*	5.9	5.9	mm
Ver. Size@IP	0.94	0.94	μm
RF Voltege	8.0	13.0	MV
ν_x	.506	.511	
ν_y	.561	.585	
ξ_x	.127	.102	
ξ_y	.129	.090	
Lifetime	133	200	min.
Luminosity	2.108		$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Lum/day	1.479		fb^{-1}

BEAM CURRENTS AND VERTICAL BETA FUNCTIONS AT THE IP

The HER beam current of 1.188 A in Table 1 is near the hardware limit. The design beam current of HER was 1.1 A. On the other hand, the design beam current of LER was 2.6 A and there was large room to increase LER beam current from the viewpoint of the hardware limit. There are evidences that this saturation of the luminosity against the LER beam current is caused by the effects of the electron clouds [3]. Based on these experiences, we will take more fundamental countermeasures against the electron clouds effect at SuperKEKB such as adoption of antechmbers with TiN coating. As for the vertical beta function at the IP (β_y^*), the minimum values are determined by the hourglass effect. Although lower values than 5.9 mm were possible from the viewpoint of the dynamic aperture and the detector beam background, the lower β_y^* did not bring a higher luminosity.

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[*] yoshihiro.funakoshi@kek.jp

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Figure 1: History of the performance of KEKB from October 1999 to 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. The crab crossing scheme had been in use since February 2007.

SUPPRESSION OF THE BEAM-BEAM BLOWUP

In early days of KEKB, we experimentally found that a horizontal tune closer to half-integer gives a higher luminosity. This tendency is confirmed later by the beam-beam simulation. This issue was also studied theoretically later and the reason for the high luminosity with the horizontal tune close to the half-integer is explained in the context of the degree of the freedom of the dynamical system [4]. Figure 2 shows a history of the horizontal tune of KEKB.

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 2 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 [5]. 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

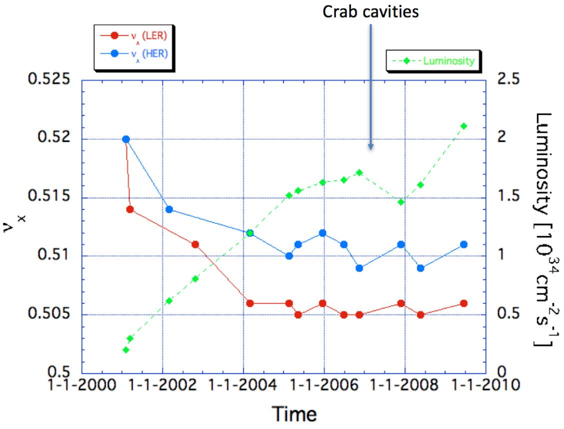

Figure 2: History of horizontal tune of LER and HER together with the luminosity.

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basis of the luminosity tuning. On this basis, we carried out tuning on the other parameters in Table 2. 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 had been using this method since then. However, even with this method an achievable specific luminosity had not been improved, although the speed of the parameter search seemed to be rather improved.

For the luminosity tuning, only the luminosity monitor [7] and the beam size monitor based on the SR interferometer [6] 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 had been very successfully applied to the KEKB operation and brought an enormous gain in the integrated luminosity to Belle. In Table 3, 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. 3 and 4.

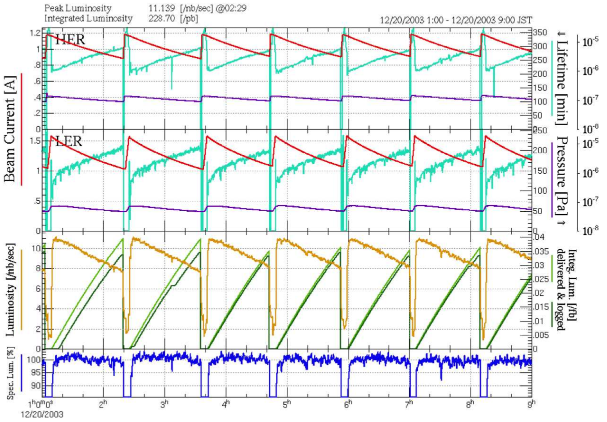

Figure 3: Beam currents and luminosity trend before continuous injection.

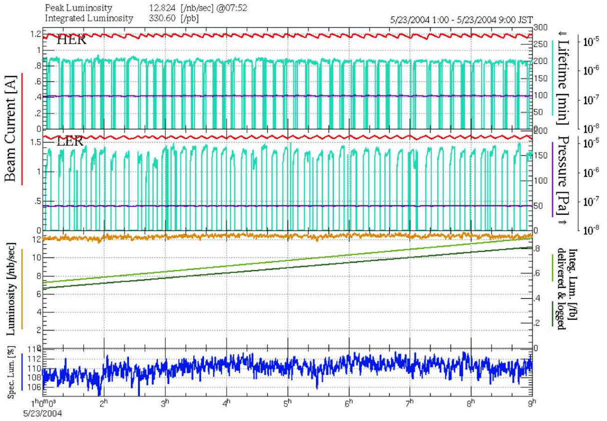

Figure 4: Beam currents and luminosity trend after continuous injection.

Some Experience of Luminosity Tuning at KEKB

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

- The KEKB luminosity had been increased by many and continuous parameter scans.
    - The machine operators performed almost always (even in physics run) parameter scans. (scan, scan, scan...). In almost all cases, scans are done in vain. But sometimes, we got an improvement in the luminosity. It was important to continue the scans.
    - 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.

Table 2: Tuning knobs for the luminosity and their observables. We relied also on the beam size at the synchrotron radiation monitor (SRM), besides the luminosity.

Knob	Observable	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 3: Comparison of the continuous injection with the conventional injection scheme.

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

* due to injection and HV up/down

OTHER EFFORTS TO INCREASE THE LUMINOSITY

Skew-sextupole Magnets

Ohmi et al. showed that the chromaticity of x-y coupling parameters at the IP could degrade the luminosity, if the residual values, which depend on machine errors, are large [8]. To control this chromaticity, skew sextupole magnets, 10 pairs for HER and 4 pairs for LER, were installed during winter shutdown 2009. It turned out that the skew sextuples are very effective to raise the luminosity at KEKB. The knobs to control the chromaticity of the x-y coupling were introduced for beam operation on May 2 2009. The gain of the luminosity by these magnets was about 15~17% [3].

Crab Cavities

20 years after they were initially proposed, in February 2007 crab cavities are for the first time installed in an operating collider, KEKB. It was expected that the beam-beam parameters (ξ_y) and the luminosity would be doubled with the crab cavities. Actually achieved luminosity gain with crab was about 30~40 % including the effect of the skew-sextupoles. The beam-beam parameter was increased from ~0.06 to ~0.09, while ~0.15 had been expected. The discrepancy between the simulation and the experiment has not been understood yet [3].

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