Performance of KEKB with Crab Cavities

Y. Funakoshi, T. Abe, K. Akai, M. Akemoto, A. Akiyama, M. Arinaga, K. Ebihara, K. Egawa, A. Enomoto, J. Flanagan, S. Fukuda, H. Fukuma, K. Furukawa, T. Furuya, K. Hara, T. Higo, S. Hiramatsu, H. Hisamatsu, H. Honma, T. Honma, K. Hosoyama, T. Ieiri, N. Iida, H. Ikeda, M. Ikeda, S. Inagaki, S. Isagawa, H. Ishii, A. Kabe, E. Kadokura, T. Kageyama, K. Kakihara, E. Kako, S. Kamada, T. Kamitani, K. Kanazawa, H. Katagiri, S. Kato, T. Kawamoto, S. Kazakov, M. Kikuchi, E. Kikutani, K. Kitagawa, H. Koiso, Y. Kojima, I. Komada, T. Kubo, K. Kudo, N. Kudo, K. Marutsuka, M. Masuzawa, S. Matsumoto, T. Matsumoto, S. Michizono, K. Mikawa, T. Mimashi, S. Mitsunobu, T. Miura, K. Mori, A. Morita, Y. Morita, H. Nakai, H. Nakajima, T. T. Nakamura, H. Nakanishi, K. Nakanishi, K. Nakao, S. Ninomiya, M. Nishiwaki, Y. Ogawa, K. Ohmi, S. Ohsawa, Y. Ohsawa,Y. Ohnishi, N. Ohuchi, K. Oide, M. Ono, T. Ozaki, K. Saito, H. Sakai, Y. Sakamoto, M. Sato, M. Satoh, K. Shibata, T. Shidara, M. Shirai, A. Shirakawa, T. Sueno, M. Suetake, Y. Suetsugu, R. Sugahara, T. Sugimura, T. Suwada, O. Tajima, S. Takano, S. Takasaki, T. Takenaka, Y. Takeuchi, M. Tawada, M. Tejima, M. Tobiyama, N. Tokuda, S. Uehara, S. Uno, Y. Yamamoto, Y. Yano, K. Yokoyama, Ma. Yoshida, Mi. Yoshida, S. Yoshimoto, K. Yoshino
KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
E. Perevedentsev, D. N. Shatilov, BINP, Novosibirsk, Russia

Abstract

20 years after they were initially proposed, in February 2007 crab cavities are for the first time installed in an operating collider, KEKB. The commissioning of KEKB with crab cavities is reported, and the performance of the collider is compared with the performance without crab cavities and with the beam-beam simulation. Operational experience of the crab cavities with beams is described.

KEKB B-FACTORY

KEKB B-Factory [1] has been operating at KEK since 1999 for the e+e- collision experiment mainly at the $\Upsilon(4\mathrm{S})$ 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. Figure 1 shows the history of KEKB. The highest luminosity, $1.72\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, 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 clouds in the LER have been mitigated up to 1.8 A with 3.5 bucket spacing by solenoid windings of 2,200 m.

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		22		mrad
$\mathrm{I_{beam}}$	1619	854	1662	1340	mA
$\mathrm{N_{bunches}}$	1584		1387		
$\mathrm{I_{bunch}}$	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	1.092		1.232		/fb

CRAB CROSSING SCHEME

One of the main design features of KEKB is the horizontal crossing angle of 22 mrad, at the interaction point (IP). Although there are many 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 was proposed in 1988 by R. Palmer[2] as an idea to recover the head-on collision with the crossing angle for linear colliders. It has

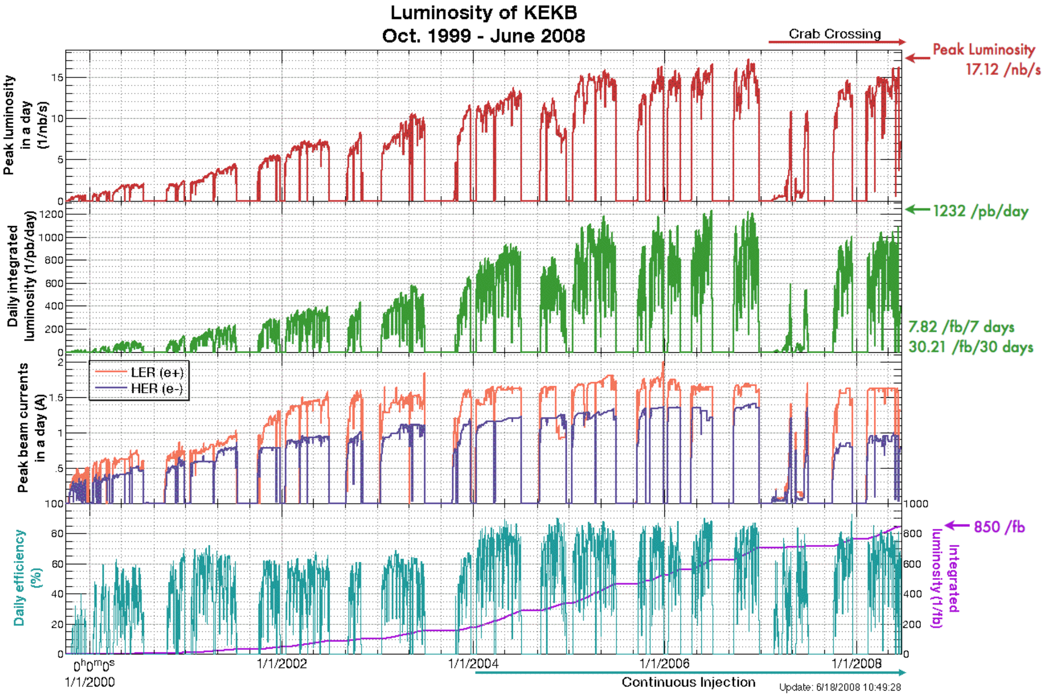

Figure 1: History of KEKB.

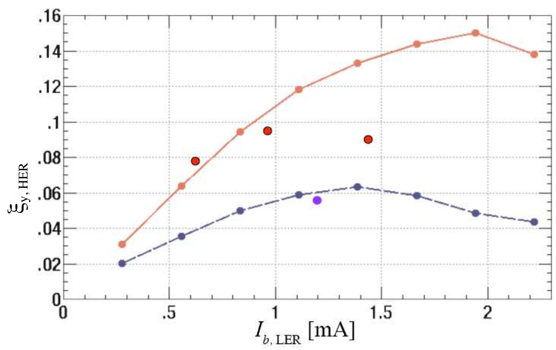

Figure 2: Predicted beam-beam parameters by the strong-strong beam-beam simulations with the crossing angle of $22\mathrm{mrad}$ (purple) and the head-on(crab crossing) (red). Some experimental data are also shown with closed circles.

been also shown that the synchro-betatron coupling terms associated with the crossing angle in ring colliders are canceled by the crab crossing[3]. The crab crossing scheme has been considered in the design of KEKB from the beginning as a backup measure against the crossing angle. Once, the crab cavities seemed non-urgent 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[4], predicting that the head-on or the crab crossing provides higher $\xi_y > 0.1$, if combined with the horizontal tune very close to the half integer. 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 sides 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. 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.

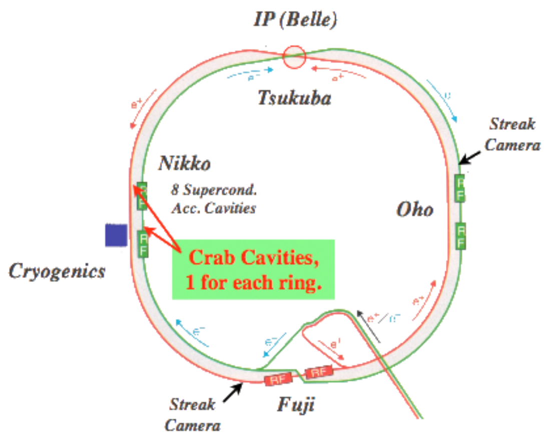

Figure 3: Layout of the crab cavities in the KEKB rings.

Table 2: Typical parameters for crab cavities. The crossing angle, the horizontal beta functions at the IP and the crab cavities, the horizontal tunes, the horizontal phase advance from the cavities to the IP, the crab voltage and the RF frequency are shown.

	LER	HER	
ϕ_{cross}	22		mrad
β_x^*	$80 \sim 90$	$80 \sim 90$	cm
β_x^C	68	130	m
ν_x	45.506	44.511	
$\psi_x^C/2\pi$	0.25	0.25	
V_C	0.83	1.37	MV
f_{RF}	508.89		MHz

MACHINE STUDY AND PHYSIC RUN WITH CRAB CAVITIES

The crab cavities were installed at KEKB during the winter shutdown in FY 2006[5]. A dedicated machine time from Feb. 13 2007 to the end of June 2007 was devoted to the commissioning of the crab cavity system and the machine study with the crab crossing.[6] In most cases, the beam study was done with relatively small beam currents typically 100mA (LER) and 50mA (HER). The crabbing motion of the beams by the crab cavities was confirmed by observing tilts of bunches with the streak camera[7]. A high beam current operation of the crab cavities was also tried for different two purposes. Firstly, we hoped to confirm that a high luminosity is actually achieved with the crab on. In the high beam current operation, the peak luminosity exceeded the design luminosity of $1\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. 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 to the situation before the crab 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 started with the crab cavity on. Since then, we have been operating KEKB with the crab cavities on. So far, the highest luminosity with the 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 HER. A comparison of machine parameters before and after the crab installation is also shown in Table 1.

Beam-beam performance with crab crossing

Figure 4 shows the specific luminosity as function of the bunch current product. In the figure, the points in thin-blue are data of the 22mrad crossing angle in the physics run. The red points denote data of the crab crossing taken in the dedicated beam study and in most cases the bunch spacing was as long as 49 RF buckets. The data in green was taken in the physics run with the crab crossing when the highest luminosity was achieved with the crab crossing. In this case, averaged bunch spacing was 3.06 RF buckets. Since

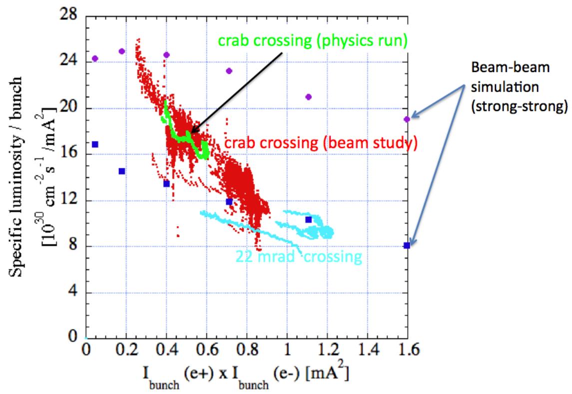

Figure 4: Beam current dependence of specific luminosity.

there is no big difference between the long and short bunch spacings, effects depending on the bunch spacing such as the electron clouds are not very important for the specific luminosity in the present operation condition. In the figure, also shown is the specific luminosity predicted by the beam-beam simulations. Both predictions with and without the 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 the 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. Another problem with the 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. As seen in the figure, the experiment value of the 22mrad crossing angle is consistent with the simulation. In case of the crab crossing, however, the experimental value is much lower than the simulation at the high bunch currents. The maximum vertical beam-beam parameter with the crab crossing exceeds 0.093. This value is very high in a usual sense, which indicates the potential superiority of the crab crossing.

POSSIBLE CAUSES OF LUMINOSITY RESTRICTION

We have not yet identified the cause of the low specific luminosity at the high bunch currents, although we have been struggling with the problem. Our efforts are discussed in more details elsewhere [8]. In this section, we briefly summarize our efforts to solve the problem.

Too many tuning parameters? 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 observables) 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 12 parameters of the x-y coupling parameters at the IP and the vertical dispersions at the IP and their slopes. These 12 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. Our method of parameter search was examined by the beam-beam simulation. The same procedures as the parameter scan or the simplex search were performed in the simulation with intentionally introduced errors for the 12 parameters. The simulation showed that we can reach the parameter set which gives a satisfactory luminosity, if the errors are in the range of our usual tuning.

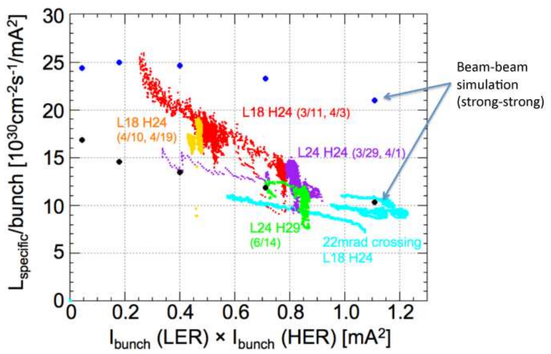

Figure 5: Beam current dependence of specific luminosity with different horizontal beta functions at the IP.

Beam lifetime issue In the luminosity tuning, we sometimes encounter the situation that we can not set parameters giving a higher luminosity due to poor beam lifetime. We have been suspecting that poor beam lifetime brings the low specific luminosity at high bunch currents. As for the process which affects beam lifetime, we recently found a 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. If this is true, we can mitigate the situation by lowering the horizontal beta function at the crab cavities, which is possible by enlarging β_{x}^* without changing the crab voltages. We performed an experiment where we enlarged β_{x}^* from 0.8m to 1.5m for both rings. The experimental result is shown in Figure 5. 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 currents 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.

Synchro-betatron resonance In the course of KEKB operation, it turned out that the synchro-betatron resonances of ($2\nu_{\mathrm{x}} + \nu_{\mathrm{s}} = \mathrm{integer}$) and ($2\nu_{\mathrm{x}} + 2\nu_{\mathrm{s}} = \mathrm{integer}$) affects the KEKB performance seriously. Nature of the resonance lines was studied in details during the machine study on the 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 resonance lines in HER are stronger than those in LER, since we do not have a local chromaticity correction in HER. In the usual operation, the horizontal tune of LER can be set below the resonance of ($2\nu_{\mathrm{x}} + \nu_{\mathrm{s}} = \mathrm{integer}$), while that of HER is just above the resonance line, although the lower tune is preferable according to the beam-beam simulation.

The strength of the resonance lines is strongly dependent on the choice of sextupole magnets. A large amount of efforts has been devoted for searching a better set of sextupole magnets [9][8] and they contributed to the increase of the luminosity. At present, there is no direct evidence that the synchro-betatron resonances are responsible for the low specific luminosity at the high bunch currents. However, we still think that they are a possible candidate.

Phase errors of crab cavity Fast noises may induce some loss in the luminosity. According to the beam-beam simulation, allowed phase error of the crab cavities for N turn correlation is $0.1 \times \sqrt{\mathrm{N}}$ degrees. On the other hand, the measured error under the presence of the beams was less them 0.01 degree for fast fluctuation ($\succeq$ 1kHz) and less than 0.1 degree for slow fluctuation (from ten to several hundreds Hz). Then, the measured phase error is much smaller than the allowed values given by the beam-beam simulation.

Other possibilities There are yet other possibilities that may degrade the specific luminosity.

- The vertical crab at the IP, which is created by some errors related to the crab kick such as a mis-alignment of the crab cavity and the local x-y coupling at the crab cavity, degrades the luminosity?
- An unexpectedly large vertical single-beam emittance degrades the luminosity?
- The cross talk between the beam-beam effects and the lattice non-linearity affects the luminosity? [10]
- Fast noises from the transverse bunch-by-bunch feedback system degrades the beam-beam performance?

These possibilities have been investigated by experiments and/or beam-beam simulations. However, we have not yet found a promising explanation for the degradation of the specific luminosity.

EXPERIENCE OF CRAB CAVITY OPERATION WITH BEAMS

The initial goal of the beam study of the crab cavities was to prove that the high beam-beam parameters predicted by the simulation is actually achieved in a real machine. This study could be done with relatively low beam currents with a fewer number of bunches. A high beam current operation of the crab cavities had the second priority, since their tolerance against the high beam currents was unknown. However, they have been working much more stably than the initial expectation and are presently being used in the usual physics run. Figure 6 shows a history of the trip rate of the crab cavities. Period 1 in the figure was a dedicated machine time for the study of the crab cavities and the crab crossing. In most of cases, the beam currents are rather low, typically 100mA (LER) and 50mA (HER). Around the 6th week, the maximum attainable kick voltage of the LER crab cavity dropped suddenly from $\sim 1.5\mathrm{MV}$ to $\sim 1.1\mathrm{MV}$ for an unknown reason. In the middle of this period, we had to warm up the system up to the room temperature to recover from frequent trips of LER carb cavities. It was also expected that the performance degradation of the LER crab cavity was recovered with the warm-up. However, the performance was not improved and this problem has not been solved since then. In the summer shutdown following Period 1, the cavities were warmed up again to the room temperature. From Period 2, the use of the crab cavities in the usual physic run started. At the beginning of this period, we were troubled with frequent trips of the HER crab cavity. This problem was solved by lowering the crab voltage, which was possible by enlarging the horizontal beta function at the crab cavity, and RF conditioning. In the winter shutdown following Period 2, the cavities were warmed up once again to the room temperature. During Period 3, the trip rate of the HER crab cavity seems to be more or less stable, while that of the LER crab has a tendency to increase slowly after the warm-up. Generally speaking, the HER crab cavity shows a higher trip rate than that of LER corresponding to the higher crab voltage as shown in Table 2. It seems that the situation of the trip rate has reached a more or less stationary state and the similar situation will continue from now on. As for causes of the trips, most of HER cases are breakdowns of superconductivity due to discharge in the cavity. On the other hand, causes of LER cavity are discharge in the coaxial coupler or at the input coupler.

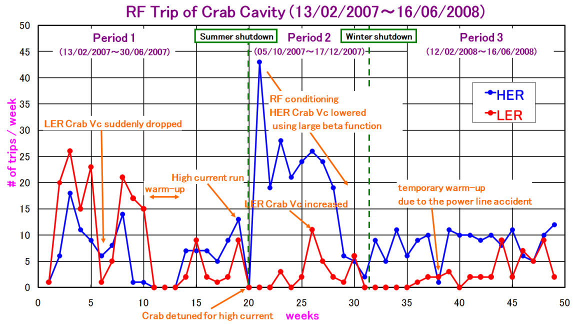

Figure 6: Trip rate of crab cavity system.

ACKNOWLEDGMENTS

The authors thank H. Sugawara, Y. Totsuka, A. Suzuki, F. Takasaki, Y. Kamiya, S.-I. Kurokawa, M. Yamauchi, and the Belle Collaboration for supporting this program, A. Hutton and the members of the KEKB Accelerator Review Committee for various suggestions for years, and R. Calaga, F. Zimmermann and M. Zobov for useful discussions.

REFERENCES

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

[2] 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.

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

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

[5] K. Hosoyama et al., SRF2007, Peking University, Beijing, China, MO405 (2007).

[6] T. Abe *et al.*, Proc. of PAC07 (2007).

[7] H. Ikeda *et al.*, Proc. of PAC07 (2007).

[8] Y. Funakoshi, Proc. Of Factories Workshop08, BINP(2008).

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

[10] K. Ohmi *et al.*, in these proceedings.