Operational experience with Crab Cavities at KEKB

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

Abstract

KEKB was in operation from December 1988 to June 2010. The crab cavities were installed at KEKB in February 2007 and have worked very stably until the end of the KEKB operation. Operational experience of the crab cavities with beams is described.

KEKB B-FACTORY

KEKB B-Factory [1] was an energy asymmetric double ring e+e- collider at KEK which was in operation from December 1998 to June 2010. KEKB was mainly operated at the $\Upsilon(4S)$ resonance. KEKB was composed of the low energy positron ring (LER) operated at 3.5 GeV, the high energy electron ring (HER) at 8 GeV, and an injector linac. Two beams collided at the physics detector named "Belle". The machine parameters of KEKB with the crab cavities are listed in Table 1 together with its design parameters. The highest luminosity, $2.108 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$, was achieved in June 2009. The peak luminosity is twice as high as the design value and is the world's highest value so far.

The HER beam current exceeded the design value. However, the LER beam current is rather lower than the design. This was not due to hardware limits. The luminosity was saturated at around 1.6A and a higher beam current did not bring a higher luminosity. It is believed that this was due to the electron cloud instability. The bunch spacing is also much longer than the design to mitigate the electron cloud instability. As a result, the bunch currents were much higher than the design. The vertical beta function at the IP (β_{y}^*) was 5.9 mm and was much lower than the design value. Owing to the crab cavities, the vertical beam-beam parameter (ξ_{y}) was as high as 0.09 and was much higher than the design. Another feature of KEKB was that the horizontal tune was very close to a half integer. This also contributed to the high luminosity. The daily integrated luminosity was twice as high as the design due to the continuous injection mode as well as acceleration of 2 bunches per an rf pulse at the linac.

Figure 1 shows the history of KEKB. The crab cavities were installed at KEKB in February 2007 and have worked stably until the end of the KEKB operation. After installation of the crab cavities, the luminosity was somewhat lower than before the crab cavities. Although the specific luminosity was higher, the beam currents particularly in HER was much lower and the luminosity was lower. This was not due to a hardware limitation. As described below, this was caused by the dynamic beam-beam effects. By solving this problem, the luminosity increased. In addition to this, the skew-sextupole magnets, which were installed in winter shutdown of 2009, contributed to a higher luminosity.

Table 2: Comparison of KEKB machine parameters before and after installation of crab cavities.

	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
$\mathrm{I}_{\mathrm{beam}}$	1619	854	1662	1340	mA
$\mathrm{N}_{\mathrm{bunches}}$	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	1.092		1.232		/fb

CRAB CROSSING SCHEME

Motivation of crab cavities

One of the design features of KEKB is the horizontal crossing angle of ± 11 mrad at 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. 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 been also shown that the synchro-betatron coupling terms associated with the crossing angle in ring colliders are canceled by crab crossing [3]. The crab crossing scheme has been considered in the design of KEKB as a backup measure against possible problems with the crossing angle. The crab cavities had seemed

Table 1: Machine parameters of KEKB (June 27th 2009). Parameters in the parentheses denote the design parameters.

	LER	HER	
Energy	3.5	8.0	GeV
Circumference	3016		m
RF Frequency	508.88		MHz
Horizontal emittance	18 (18)	24 (18)	nm
Beam current	1637 (2600)	1188 (1100)	mA
Number of bunches	1585*) (∼4600 **))		
Bunch current	1.03 (0.57)	0.75 (0.24)	mA
Bunch spacing	1.84 (0.59)		m
Total RF voltage	8.0 (5 $\sim$ 10)	13.0 (10 $\sim$ 20)	MV
Synchrotoron tune ν_s	-0.0246 (-0.1 $\sim$ -0.2)	-0.0209 (-0.1 $\sim$ -0.2)	
Horizontal tune ν_x	45.506(45.52)	44.511 (47.52)	
Vertical tune ν_y	43.561 (45.08)	41.585 (43.08)	
Beta's at IP β_x^*/β_y^*	120/0.59 (33/1)	120/0.59 (33/1)	cm
Momentum compaction α	3.31 (1 $\sim$ 2)	3.43 (1 $\sim$ 2)	$\times 10^{-4}$
Beam-beam parameter ξ_x	0.127 (0.039)	0.102(0.039)	
Beam-beam parameter ξ_y	0.129 (0.052)	0.090 (0.052)	
Vertical beam size at IP σ_y^*	0.94***) (1.34)	0.94***) (1.34)	μm
Beam lifetime	133@1637	200@1188	min@mA
Luminosity (Belle CsI)	2.108 (1.0)		10^{34}cm^{-2}s^{-1}
Total integrated luminosity	1041		fb^{-1}

*): w/ 5% bunch gap, **): w/ 10% bunch gap, ***): estimated value from the luminosity assuming that the horizontal beam size is equal to the calculated value

not to be urgently necessary once because KEKB achieved $\xi_y > 0.05$ at the early stage of the operation in 2003. However, afterward interesting beam-beam simulation results appeared [4][5],[6], predicting that the head-on collision or crab crossing provides a higher value of $\xi_y \sim 0.15$, if combined with the horizontal tune very close to the half integer such as 0.508. Figure 2 shows the comparison of ξ_y for the head-on (crab crossing) and the crossing angle by a strong-strong beam-beam simulation. After this, the development of the crab cavities was revitalized and the crab cavities were finally installed at KEKB in February 2007.

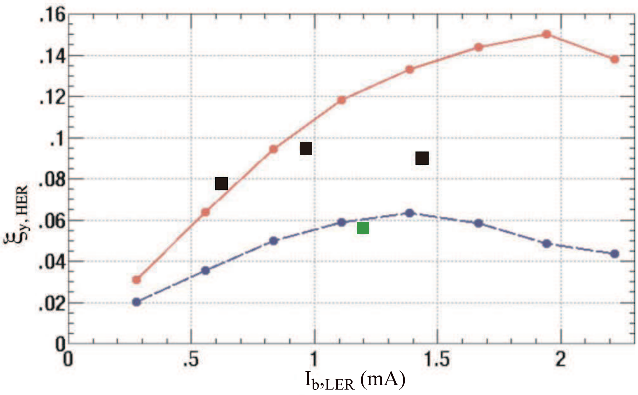

Figure 2: Predicted beam-beam parameters by the strong-strong beam-beam simulations with the crossing angle of 22 mrad (purple) and the head-on (crab crossing) (red). Some experimental data are also shown with squares. The black and green squares denote data with the crab cavities and without them, respectively.

Single crab cavity scheme

In the original design of KEKB, we planned to install two crab cavities for each ring on both sides of IP so that the crab kick excited by the first cavity is absorbed by another one. The 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 Fig. 3. This scheme not only saved the cost of the cavities, but made it possible to use the existing cryogenic system at the Nikko region which has been utilized for the superconducting accelerating cavities.

In the single crab cavity scheme, the following equation should be met for both beams to realize a head-on collision;

$$\frac{\phi_x}{2} = \frac{\sqrt{\beta_x^C \beta_x^*} \cos(\pi\nu_x - |\Delta\psi_x^C|)}{2\sin\pi\nu_x} \frac{V_c \omega_{RF}}{Ec}. \qquad (1)$$

Here, ϕ_x is the full crossing angle. β_x^C and β_x^* are the beta functions at the crab cavity and IP, respectively. $\Delta\psi_x^C$ denotes the horizontal betatron phase advance between the

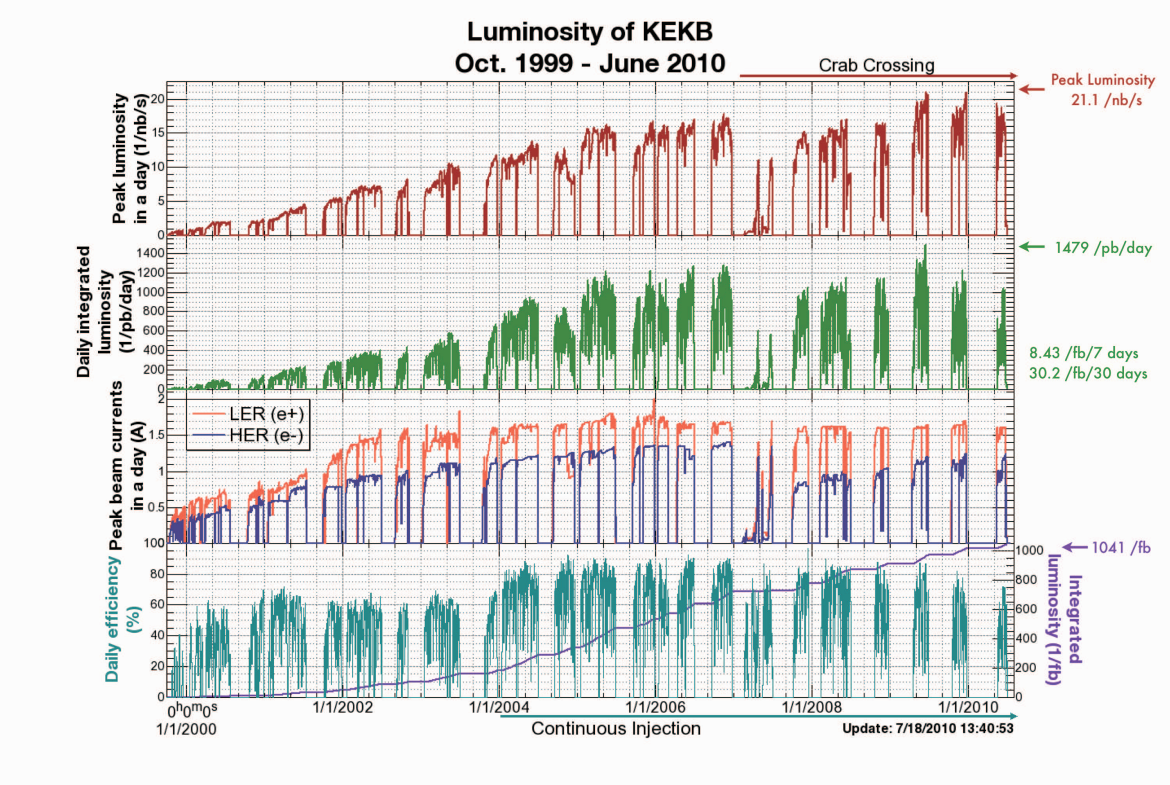

Figure 1: History of KEKB.

crab cavity and IP. ν_x is the horizontal tune. Vc and ω_{RF} are the crab voltage and the angular RF frequency, respectively. Typical values for those parameters are shown in Table 3.

Table 3: Typical parameters for crab cavities. The crossing angle, the horizontal beta functions at IP and the crab cavities, the horizontal tunes, the horizontal phase advance from the cavities to IP, the crab voltage and the RF frequency are shown.

	LER	HER	
ϕ_x	22		mrad
β_x^*	1.2	1.2	m
β_x^C	51	122	m
ν_x	45.506	44.511	
$\psi_x^C/2\pi$	0.25	0.25	
V_C	0.97	1.45	MV
f_{RF}	508.89		MHz

The beam optics was modified for the crab cavities to provide necessary magnitude of the beta functions at the cavities and the proper phase advance between the cavities and IP. A number of quadrupoles have switched the polarity and have become to have independent power supplies.

OPERATION WITH CRAB CAVITIES

Tuning method of crab cavity parameters with beams and beam tuning with crab cavities

Crab voltage Prior to the beam operation, the calibration of the crab voltage was done by using the klystron output power and the loaded Q values of the crab cavities without actual beams. The crab voltage was also calibrated by using beams. If a bunch passes by the crab cavity at the zero-cross timing of the crab RF voltage, the center of the bunch receives no dipole kick. When the crab phase shifts from this condition, the bunch receives a net dipole kick from the cavity like the case of a steering magnet. This dipole kick makes the closed orbit distortion (COD) and its size depends on the crab phase. From the CODs around the ring created by the crab cavity, the dipole kick angle can be estimated. By scanning the crab phase by more than $360°$ and fitting the kick angle estimated at each data point as function of the crab phase, the crab voltage can be determined. The crab voltage thus determined is consistent with that calibrated from the klystron power and the Q value within a few percent. From the crab phase scan and the fit, the phase shifter of the crab cavity system can also be calibrated. In the actual beam operation in the physics run mode, the crab voltages of both rings are scanned to maximize the luminosity as is shown below.

Crab phase In principle, the crab phase should be set so that the center of bunch passes by at the zero-cross tim-

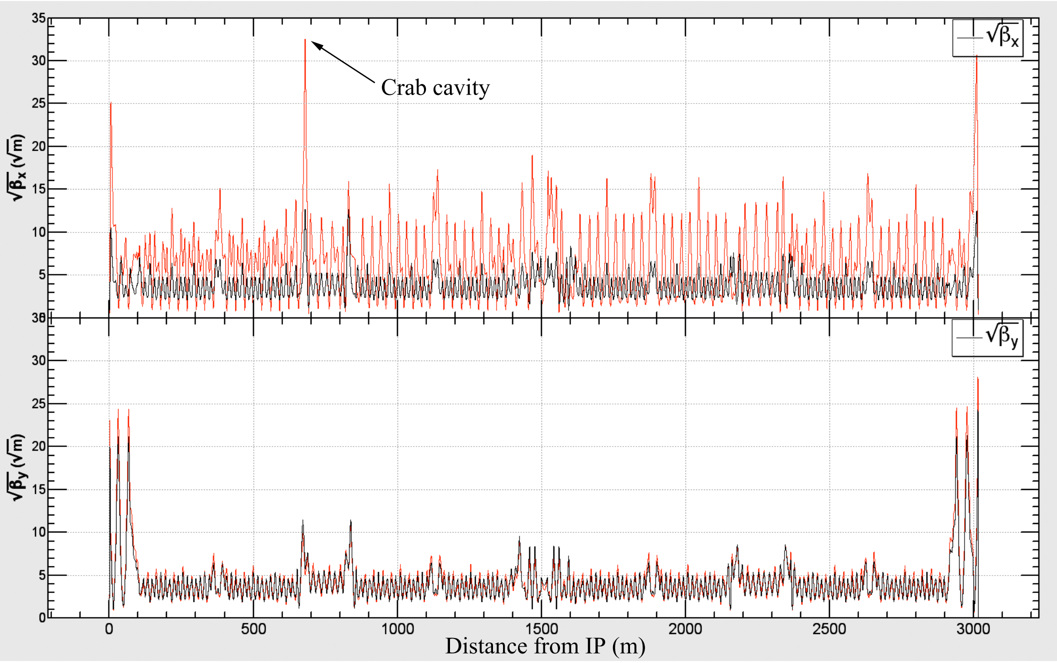

Figure 5: Beating of beta functions due to dynamic beam-beam effects in LER before we took some counter-measures for this problem with ν_x of .506 and the unperturbed beam-beam parameter (ξ_{x0}) of 0.127. The red and black lines are the beta functions with the dynamic beam-beam effect and without the effect, respectively.

ing of the crab cavity. In this condition, the bunch receives no net dipole kick. This condition can be found by scanning the crab phase as is described above. However, this method is rather time consuming and so a easier method is used in the usual operation. This method is to search the crab phase which brings no change in the COD between the crab on and off by trial and error. Although there are two zero-cross phases, we can choose the correct phase by observing the phase of the COD. In the actual physics run, in which high beam currents are needed, the crab phase is shifted by some amount (typically $10°$) to suppress the dipole oscillation observed at high-current crab collision. The COD induced by the net dipole kick by the crab cavity can be compensated by steering magnets in the ring.

Beam orbits at the crab cavities The beam loading for the crabbing mode increases linearly as function of a horizontal orbit displacement from the center of the crab cavity. If the RF power to operate the cavity is too sensitive to the beam orbit, the cavity operation under the existence of the beams could be difficult. To avoid this situation, we have chosen the loaded Q value of the cavity to be $Q_L = 1 \sim 2 \times 10^5$. With this relatively low Q value, the RF power for the operation is relatively high (typically 100 kW at 1.4MV). However, the RF power becomes less sensitive to the beam orbit (typically 20 % change for 1mm orbit change). When we condition the cavity, we need a higher power. However, with this Q value 200kW is sufficient for conditioning the cavity up to 2MV. In addition, we have developed an orbit feedback system to keep the horizontal beam orbit at the crab cavity stable [7]. This system is composed of 4 horizontal steering magnets to make an offset bump for each ring and 4 BPMs for each ring to monitor the beam orbit at the crab cavity. The design system speed is 1 Hz and the target accuracy of the orbit is within 0.1 mm. However, in the actual beam operation, we found that the beam orbit is stable enough even without the orbit feedback system. Therefore, usually we do not use the orbit feedback system. In the beginning of the beam operation with the crab cavities, we searched the field center in the cavities by measuring the amplitude of the crabbing mode excited by beams when the cavities were detuned. In this search, we found that the field center of the HER crab cavity shifted by about 7mm from the assumed center position of the crab cavity. A possible reason for this large displacement is due to a mis-alignment of the cavity. We feel that there could be such a large mis-alignment, since a precise alignment of the crab cavity to the cryostat was very difficult.

Luminosity tuning with crab cavities The luminosity tuning in general is described above. Here, we describe the method of the luminosity tuning related to the crab cavities. In the following, we mention two tuning items, *i.e.* the crab Vc(crab voltage) scan and the tuning on the x-y coupling at the crab cavities. As for the crab Vc, the calibration can be done with a single beam mentioned above. However, this is not enough for the beam collision operation, since optics errors such as those for the beta functions or the phase advance between the crab cavity and IP could

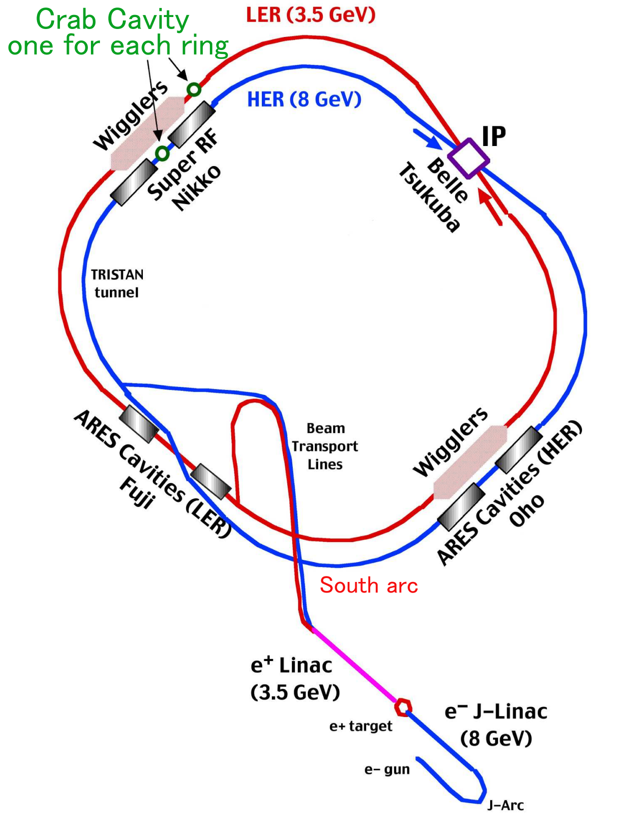

Figure 3: Layout of the KEKB rings and the crab cavities.

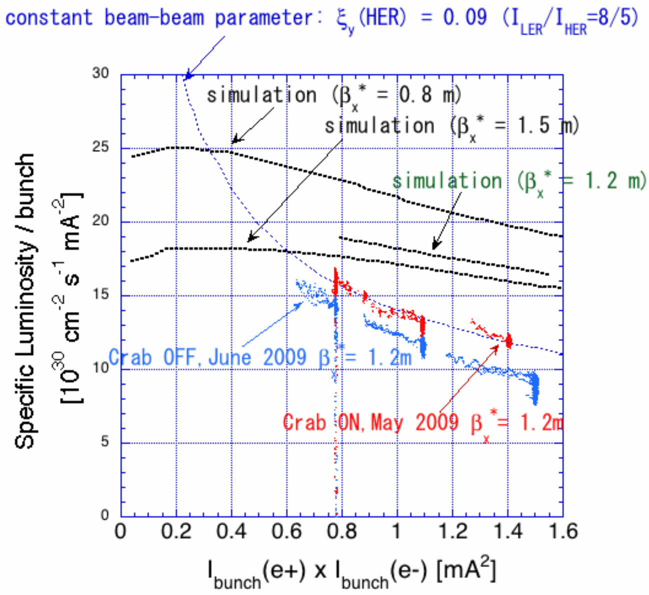

Figure 4: Comparison of specific luminosity per bunch with and without the crab cavities as function of the bunch current product of the two beams. The specific luminosity is defined as the luminosity divided by the bunch current product of the two beams and also divided by the number of bunches. Three different lines from the beam-beam simulations are also shown, corresponding to different values of the IP horizontal beta function, β_x^*. The simulations predicted that a smaller β_x^* (smaller σ_x^*) gave a higher luminosity. In the figure, also shown is a line which corresponds to a constant vertical beam-beam parameter for HER of 0.09 assuming the bunch current ratio between LER and HER is 8/5. As is seen in the figure, the data with crab cavities are aligned on this line. This means that the HER vertical beam-beam parameter, $\xi_y(\mathrm{HER})$ is saturated at around 0.09.

shift the optimum crab Vc. In the actual tuning, we first tune the balance of the crab Vc between the two rings. For this purpose, we employ a trick to change the crab phase slightly and observe the orbit offset at IP. The IP orbit feedback system [8] can detect the orbit offset at IP precisely. With changing the crab phases of both ring by some amount (typically $10 \sim 15°$), we tune the balance of the crab Vc between the two rings so that the IP orbit offset becomes the same for both rings. In this tuning, we rely on accuracy of the phase shifter of the crab cavity system. With keeping this balance (the ratio of the crab Vc), we scan the crab Vc for both rings and set the values which give the maximum luminosity. In our experience, the optimum set of the crab Vc thus found is not much different from the calibrated values with the single beam. The difference is usually within 5%.

The motivation to control the x-y coupling at the crab cavities is to handle the vertical crabbing. In principle, the crab cavity kicks the beam horizontally. However, if there is the x-y coupling at the crab cavity or the crab cavity has some rotational mis-alignment, the beam could receive the vertical crab kick. This could degrade the luminosity. The local x-y coupling is expressed by 4 parameters, $R1$, $R2$, $R3$ and $R4$ as described above. In the actual beam operation, these coupling parameters are scanned one by one to maximize the luminosity. We found that the tuning with these knobs has some effect to the luminosity and the luminosity gain with the knobs is typically 5 %. We expected that $R2$ and $R4$ may be effective to the luminosity, since these parameters are related to the vertical crab at IP. However, in reality, there is no big difference in the effectiveness to the luminosity among these four parameters.

Specific luminosity with and without crab cavities

Since the introduction of the crab cavities, we have been made efforts [9] [10] to realize the beam-beam performance predicted by the beam-beam simulation. As a result of those efforts, we accomplished a relatively high beam-beam parameter of about 0.09 as shown in Table 4. We found that the correction of the chromaticity of the x-y coupling at IP is effective to increase the luminosity [11]. This correction increased the vertical beam-beam parameter from ~ 0.08 to ~ 0.09. However, even with this improvement, the achieved beam-beam parameter ~ 0.09 is

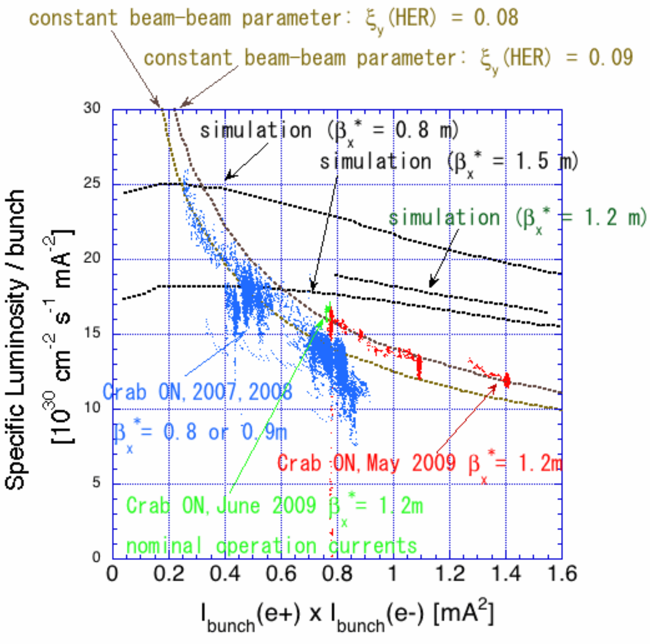

Figure 6: Specific luminosity per bunch as function of the bunch current product of the two beams with different β_x^*. Three different lines from the beam-beam simulations are also shown, corresponding to different values of the IP horizontal beta function, β_x^*. The simulations predicted that a smaller β_x^* (smaller σ_x^*) gave a higher luminosity. In the figure, also shown are lines which correspond to constant vertical beam-beam parameters for HER of 0.08 and 0.09 assuming the bunch current ratio between LER and HER is 8/5. As is seen in the figure, the data with crab cavities are aligned on those lines. This means that the HER vertical beam-beam parameter, $\xi_y(\mathrm{HER})$ was saturated at around 0.08 or 0.09. In the experiment, we found that the luminosity did not depend on the IP horizontal beta functions, β_x^* contrary to the simulation. The data with β_x^* = 0.8 or 0.9 m (blue dots) was taken before we introduced the skew-sextupole magnets. The data after the introduction of the skew-sextupoles (green and red dots) are aligned on the line corresponding to $\xi_y(\mathrm{HER})$ of 0.09. This means that the maximum beam-beam parameter increased from 0.08 to 0.09 owing to the skew-sextupoles. The change of β_x^* from 0.8 or 0.9 m to 1.2 m was done to increase the bunch currents by mitigating the physical aperture problem at the crab cavities and to compare the data with the simulations at a higher bunch current region. Even with solving the physical aperture problem, there remained a large discrepancy between the simulation and the experiment.

much lower than the predicted value ~ 0.15 by the simulation. We have not yet understood the cause of this discrepancy.

In Fig. 4, the comparison between the specific luminosity per bunch with the crab cavities on and off is shown. The specific luminosity is defined as the luminosity divided by the bunch current product of the two beams and also divided by the number of bunches. If the beam sizes are constant as function of the beam currents, the specific luminosity per bunch should be constant. As is seen in the figure, the specific luminosity is not constant. This means that the beam sizes are enlarged as function of the beam currents. In the experiment to take data in Fig. 4, the number of bunches was reduced to 99 to avoid the possible effects of the electron clouds. In the usual physics operation, the number of bunches was 1585. For this experiment, the IP horizontal beta function, β_x^* was changed from 0.8 m to 1.2 m to avoid the physical aperture problem and to increase the bunch currents as described in section 5.1.1. In the usual physics operation, the bunch current product was around 0.8 mA^2. The specific luminosity per bunch with the crab on is about 20% higher than that with the crab off. Since the geometrical loss of the luminosity due to the crossing angle is calculated as about 11%, there is definitely some gain in the luminosity by the crab cavities other than recovery of the geometrical loss. However, effectiveness of the crab cavities is much smaller than the beam-beam simulation as is seen in Fig. 4. The beam-beam parameter is strictly restricted for some unknown reasons.

Table 4: Comparison of KEKB Machine Parameters with and without crab crossing.

	June 2010 with crab		**Nov. 2006** w/o crab		
	LER	HER	LER	HER	
Energy	3.5	8.0	3.5	8.0	GeV
Circum.	3016		3016		m
I_{beam}	1637	1188	1662	1340	mA
# of bunches	1585		1387		
I_{bunch}	1.03	0.75	1.20	0.965	mA
Ave. spacing	1.8		2.1		m
Emittance	18	24	18	24	nm
β_x^*	120	120	59	56	cm
β_y^*	5.9	5.9	6.5	5.9	mm
Ver. size@IP	0.94	0.94	1.8	1.8	μm
RF Voltege	8.0	13.0	8.0	15.0	MV
ν_x	.506	.511	.505	.509	
ν_y	.561	.585	.534	.565	
ξ_x	.127	.102	.117	.071	
ξ_y	.129	.090	.108	.057	
Lifetime	133	200	110	180	min.
Luminosity	2.108×10^{34}		1.760×10^{34}		$/\mathrm{cm}^2/\mathrm{s}$
Lum/day	1.479		1.232		fb^{-1}

Efforts to increase specific luminosity with crab cavities

Performance with the crab cavities has been considered to be very important not only for KEKB but also SuperKEKB in so-called the high current scheme. Therefore, we have made every effort to understand the discrepancy between the beam-beam simulation and the experiments on the beam-beam performance with the crab cavities. Although we have not identified the cause, we summarize these efforts in the following.

Short beam lifetime related to physical aperture around crab cavities In the beam operation with the crab cavities, we encountered the situation that we can not increase the bunch current of one beam due to poor beam lifetime of the other beam. We took this issue seriously and made efforts to solve it, since this issue is possibly a cause of degradation of the beam-beam performance with the crab crossing. We could identify the process which is responsible for the lifetime decrease. The process 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, the effects are very large. In Fig. 5, the beta functions around the LER ring are depicted with and without the dynamic beam-beam effect before we solved the problem. The horizontal beta function around the crab cavity becomes very large. Here, the horizontal tune was .506 and the unperturbed horizontal beam-beam parameter was around 0.127 with the operation bunch current of HER. Without the beam-beam perturbation, the horizontal beta functions at IP and at a quadrupole magnet next to the crab cavity were 0.9 m and 161 m, respectively. With the beam-beam effect, the beta functions were calculated to be 0.138 m and 1060 m at IP and at the quadrupole magnet, respectively. To meet the crab condition, the horizontal phase advance between the crab cavity and IP was chosen at $\pi/2$ times an odd integer. With this phase advance, the horizontal beta function becomes very large around the crab cavity. Also due to the dynamic beam-beam effect, the horizontal emittance (ε_x) was enlarged from 18 nm to $\sim$52 nm. In this situation, we found that the horizontal beam size at around the crab cavity is very large (typically 7 mm) at the operation bunch currents and the physical aperture there is only around 5 σ_x. Therefore, physical aperture around the crab cavities could affect the beam lifetime seriously. The same problem is also observed at HER. However, the effect is less serious, since the horizontal tune of HER is more distant from the half integer than the case of LER.

To mitigate this problem, we have taken several counter-measures. In the original optics of LER, the horizontal beta function around the crab cavity took the local maximum value not at the crab cavity but at the quadrupole magnets closest to the crab cavity. To satisfy the crab condition, the horizontal beta function at the crab cavity should be set at the target value. If we can decrease the beta function at the quadrupole magnet keeping the beta function at the crab cavity unchanged, we can widen the physical acceptance around the crab cavity. In the summer shutdown in 2008, we changed the optics around the crab cavity by adding some power supplies for the quadrupole magnets and changing wiring of the power supplies. As a result, the horizontal beta function at the quadrupole magnets next to the crab cavity was reduced down to the same value at the crab cavity. Before this change, the horizontal beta function at the quadrupoles are about twice larger than that at the crab cavity. With this change, the beam lifetime problem was mitigated to some extent. However, when we increased the bunch currents beyond the usual operation values, the lifetime problem appeared again. To investigate the specific luminosity at higher bunch currents, we decided to increase the horizontal beta function at IP. By enlarging the IP beta function, we can lower the beta function at the crab cavity and enlarge the physical acceptance. We enlarged the β_x^* from 0.8 or 0.9 m to 1.2 m or 1.5 m. With this change, we could increase the bunch currents up to the value shown in Fig. 4 and discrepancy between the simulation and the experiment was shown more definitely. Figure 6 shows a comparison of the specific luminosity with different values of β_x^*. In the beam-beam simulations as is shown in the figure, the specific luminosity with β_x^* = 0.8 m is much higher than that with β_x^* = 1.5 m. In the experiment, however, this change of β_x^* did not make any difference in the specific luminosity. The specific luminosity with β_x^* = 0.8 m or 0.9 m in Fig. 6 is lower than that with β_x^* = 1.2 m. This is because the data with β_x^* = 0.8 m or 0.9 m was taken before the introduction of the skew-sextupole magnets. In Fig. 6, the specific luminosity with the nominal operation bunch currents is also shown (green dots) as a reference. In addition to these counter-measures for the lifetime problem, we also tried to raise the crab voltage. If this were successful, we could have lowered the horizontal beta function at the crab cavity with keeping β_x^* the same. We tried to operate the He refrigerator with lower pressure to lower the He temperature. From the data in the R&D stage, it was expected that we can operate the crab cavity stably with a higher voltage, if the He temperature was lowered. We actually succeeded to lower the He temperature from 4.4°K down to 3.85°K in April 2009. However, it turned out that the maximum crab voltage was unchanged even with this lower He temperature. Therefore, we gave up this trial.

With these counter-measures, we also expected to improve the specific luminosity by solving the lifetime problem, since we sometimes encountered a situation where we could not move some machine parameter such as a horizontal orbital offset at IP to the direction giving a higher luminosity due to poor beam lifetime. However, we found that the lifetime problem has almost nothing to do with the specific luminosity except for the high bunch current region where the lifetime problem was serious.

As for the short lifetime problem, we have developed another counter-measure of the e+/e- simultaneous injection. The injector linac is shared by 4 accelerators. Two are the KEKB rings and the other two are the PF ring and another SR ring called PF-AR. Before the simultaneous injection scheme is successfully introduced, there were 4 injection modes corresponding to the 4 rings. Switching from one mode to another took about $\sim$ 30 s or $\sim$ 3 min. The concept of the simultaneous injection is to switch the injection modes pulse-to-pulse. In the period of the KEKB operation, we succeeded in the simultaneous injection for 3 rings (the 2 KEKB rings and the PF ring) [12] [13]. With this new injection scheme, the beam operation with shorter beam lifetime became possible. However, as is mentioned above, we found that the lifetime problem has almost nothing to do with the specific luminosity, although the machine parameter scan at KEKB has become much faster with constant beam currents stored in the rings and it has become possible to find out better machine parameters much quickly than before.

Synchro-betatron resonance In the KEKB operation, we found 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. 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 weakened by choosing properly a set of sextupole magnets. KEKB adopted the non-interleaved sextupole scheme to minimize non-linearity of the sextupoles. LER and HER have 54 pairs and 52 pairs of sexupoles, respectively. With so many degrees of freedom in the number of the sextupoles, optimization of sextupole setting is not an easy task even with present computing power. Prior to the beam operation, the candidates of sextupole setting are searched by the computer simulation. Usually dynamic aperture and an anomalous emittance growth [**?**] are optimized on the synchro-betatron resonance. Usually a setting of sextupoles which gives good performance in the computer simulation 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 changed a linear optics, usually we needed to try many candidates of settings until we finally obtained 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 sextupole performance, a beam loss was observed when the horizontal tune was 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 could operate the machine with the horizontal tune below the resonance line in case of LER, while we could 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, an unexpectedly large synchrotron oscillation due to the microwave instability occurred. Due to this oscillation, we gave up the trial of the negative α optics. So far, we have no conclusion on the effect of the synchro-betatron resonance on the specific luminosity.

Machine errors The method of luminosity tuning is described in the preceding section. 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 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.

Another possibility that we can not achieve a higher luminosity with the tuning method above is the side effects of the large tuning knobs. Although machine errors can be compensated by using the tuning knobs, too large tuning knobs bring side effects and would degrade the luminosity. Therefore, if the machine errors are too large, the luminosity predicted by the simulation can not be achieved by using usual tuning knobs. We actually confirmed that large tuning knobs on the x-y coupling at IP can degrade single beam performance. The problem is how large machine errors exist at KEKB. According to the simulation, with reasonable machine errors such as mis-alignments of magnets and BPMs, the offsets of BPMs and the strength errors of the magnets, such large errors of the x-y coupling or the dispersion at IP are not created as the luminosity can not be recovered by the knobs due to their side effects. One possibility would be the error related to the detector solenoid. The Belle detector is equipped with the 1.4 T solenoid. The field is locally compensated by the compensation solenoid magnets installed near to IP so that the integral of the solenoid field is zero on both sides of IP. The remaining effects of the solenoid field are compensated by the skew-quadrupole magnets located near to IP. If the compensation is not enough (or over-compensated), there would remain a large error of the x-y coupling. Although there is no direct evidence that the compensation of the Belle solenoid is not enough, the effect of the Belle solenoid on the luminosity was doubted as for the beam energy dependence of the luminosity. KEKB was designed to operate on the $\Upsilon(4\mathrm{S})$ resonance ($E_{CM} = 10.58\mathrm{GeV}$). KEKB was also operated on $\Upsilon(1\mathrm{S})$($E_{CM} = 9.46\mathrm{GeV}$), $\Upsilon(2\mathrm{S})$($E_{CM} = 10.02\mathrm{GeV}$) and $\Upsilon(5\mathrm{S})$($E_{CM} = 10.87\mathrm{GeV}$). We found that the luminosity on $\Upsilon(5\mathrm{S})$ is almost same as that on $\Upsilon(4\mathrm{S})$. However, the luminosity on $\Upsilon(1\mathrm{S})$ and $\Upsilon(2\mathrm{S})$ is lower than that on $\Upsilon(4\mathrm{S})$ by ∼50% and ∼20%, respectively. The design beam energy of KEKB is that of $\Upsilon(4\mathrm{S})$ and the x-y coupling due to the Belle solenoid is compensated completely at this design energy. When we change the beam energy, we do not change the strength of the Belle solenoid and the compensation solenoids. Thus, the x-y coupling correction for the Belle solenoid is not complete on the resonance other than $\Upsilon(4\mathrm{S})$ and the luminosity would be affected by the remaining x-y coupling. To investigate this issue, a machine study was done on $\Upsilon(2\mathrm{S})$ in Oct. 2009 with the Belle solenoid and compensation solenoid which is tracked to the beam energy. Contrary to the initial expectation, the luminosity in this condition was even worse than the usual 2S run. We gave up this trial in about 2 days, since the Belle experiment could not use the data with the different strength of the detector solenoid. Therefore, the correlation between the detector solenoid and the luminosity was not confirmed in this experiment.

We also tried to measure the x-y coupling at IP directly by using the injection kicker magnets and the BPMs around IP. Although some data showed a very large value of the x-y coupling at IP, we have obtained no conclusive results due to poor accuracy of the measurements.

Vertical emittance in a single beam mode The beam-beam simulation showed that the attainable luminosity depends strongly 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 the value which was considered before. However, the latest values of the global x-y coupling of both beams are around 1.3 % and these values of the coupling do not explain the discrepancy on the specific luminosity between the experiment and the simulation shown in Fig. 6 where the x-y coupling in the simulation is assumed to be 1%.

Vertical crabbing motion The vertical crab at IP could degrade the luminosity. It can be 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. The x-y coupling parameters at the crab cavities give a tuning knob to adjust the vertical crab at IP. By tuning them, we can eliminate the vertical crab at IP even if it is created by other sources such as a mis-alignment of accelerating cavities. However, tuning of these parameters is not so effective to increase the luminosity as described above.

Off-momentum optics It has been shown by the beam-beam simulation that the chromaticity of the x-y coupling at IP could reduce the luminosity largely through the beam-beam interaction, if the residual chromatic coupling is large [14][15]. While even an ideal lattice has such a chromatic coupling, the alignment errors of the sextupole magnets could make a large chromatic coupling. It has been thought that this kind of chromatic couplings is one of the candidates that bring the serious luminosity degradation with crab crossing. Parallel to trials to measure such chromatic couplings directly, we introduced tuning knobs to control them. For this purpose, we installed 14 pairs of skew sextupole magnets (10 pairs for HER and 4 pairs for LER) in the beginning of 2009. The maximum strength of the magnets (bipolar) is $\mathrm{K}_2 \sim 0.1/\mathrm{m}^2$, and $\mathrm{K}_2 \sim 0.22/\mathrm{m}^2$ for HER, and LER respectively. The tuning knobs by using these magnets were introduced to the beam operation at the beginning of May 2009. The luminosity gain by these knobs is about 15 %. Even with the improvement in the luminosity by the use of the skew-sextupole magnets, there still remains a large discrepancy between the experiment and the simulation.

Fast noise Fast noises would bring a loss in the luminosity. According to the beam-beam simulation, allowable 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 ($\geq 1\mathrm{kHz}$) 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 allowable values given by the beam-beam simulation. Besides the noise from the crab cavities, any fast noise could degrade the luminosity. For example, we found a phenomenon in 2005 that the luminosity depends on the gain of the bunch-by-bunch feedback system. With a higher gain by about 6 dB, the luminosity decreased about 20 % [16]. This seems to indicate that the some noise in the feedback system degraded the luminosity. However, this phenomenon disappeared after the system adjustment including the replacement of an amplifier for the feedback system. Although we confirmed that some artificially strong noise to the crab cavities or to the feedback system can decrease the luminosity [17], there is no evidence that the achievable luminosity at KEKB was limited by some fast noise.

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

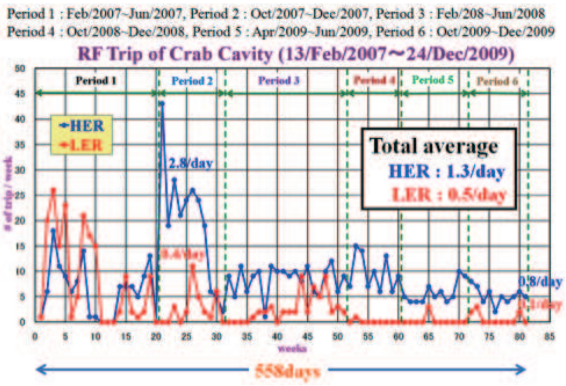

Figure 7: Trip rate of crab cavity system.

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 ~ 1.5MV to ~ 1.1MV 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.

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, M. Tawada, Y. Cai, S. Kamada, K. Oide, and J. Qiang, Phys. Rev. ST Accel. Beams **7**, 104401 (2004).

[5] K. Ohmi, M. Tawada, Y. Cai, S. Kamada, K. Oide, and J. Qiang, Phys. Rev. Lett. **92**, 214801 (2004).

[6] K. Ohmi and K. Oide, Proc. of EPAC'06, Edinburgh, Scotland, 616 (2006).

[7] M.Masuzawa, Y.Funakoshi, T.Nakamura and J.Odagiri, Proc. of EPAC'06, Edinburgh, Scotland, 613 (2006).

[8] Y. Funakoshi, M. Masuzawa, K. Oide, J. Flanagan, M. Tawada, T. Ieiri, M. Tejima, M. Tobiyama, K. Ohmi, and H. Koiso, Phys. Rev. Special Topics, Accelerator and Beams, **10**, 101001 (2007).

[9] Y. Funakoshi et al., Proc. of EPAC'08, Genoa, Italy 1893 (2008).

[10] T. Abe et al., Prog. Theor. Exp. Phys. 2013, 03A0010 (2013).

[11] T. Abe et al., Prog. Theor. Exp. Phys. 2013, 03A001 (2013).

[12] M. Akemoto et al., Prog. Theor. Exp. Phys. 2013, 03A002 (2013).

[13] N. Iida et al., Prog. Theor. Exp. Phys. 2013, 03A003 (2013).

[14] D. Zhou, K. Ohmi, Y. Seimiya, Y. Ohnishi, A. Morita, and H. Koiso, Phys. Rev. Special Topics, Accelerator and Beams, **13**, 021001 (2010).

[15] Y. Seimiya, K. Ohmi, D. Zhou, J. W. Flanagan and Y. Ohnishi, Prog. Theor. Phys., Vol. 127, No. 6, June (2012).

[16] M. Arinaga et al., Prog. Theor. Exp. Phys. 2013, 03A007 (2013).

[17] K. Ohmi, R. Tomas, Y. Funakoshi, R. Calaga, T. Ieiri, Y. Morita, K. Nakanishi, K. Oide, Y. Ohnishi, Y. Sun, M. Tobiyama and F. Zimmerman, Phys. Rev. ST Accelerator and Beams, **14**, 111003 (2011).