COMPENSATION OF THE CROSSING ANGLE WITH CRAB CAVITIES AT KEKB

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Abstract

Crab cavities have been installed in the KEKB B–Factory rings to compensate the crossing angle at the collision point and thus increase luminosity. The beam operation with crab crossing has been done since February 2007. This is the first experience with such cavities in colliders or storage rings. The crab cavities have been working without serious issues. While higher specific luminosity than the geometrical gain has been achieved, further study is necessary and under way to reach the prediction of simulation.

KEKB B–FACTORY

KEKB B–Factory[1] has been operating since 1999 for the collision experiment mainly at the Υ(4S) resonance. KEKB consists of the low energy positron ring (LER) at 3.5 GeV, the high energy electron ring (HER) at 8 GeV, and the injector linac. Two beams collide at the Belle detector. The machine parameters are listed in Table 1. The highest luminosity, $1.72 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, was recorded in Nov. 2006. The peak luminosity became 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 the Continuous Injection Mode as well as acceleration of 2 bunches per an rf pulse at the linac. The electron cloud in the LER, which was much more severe than thought in the design, has been mitigated up to 1.8 A with 3.5 bucket spacing by solenoid windings for 2,200 m.

CRAB CROSSING

One of the main design features of KEKB is the horizontal crossing angle, 22 mrad, at the interaction point (IP). Although there are a lot of merits in the crossing angle scheme, the beam-beam performance may degrade. The design of KEKB predicted that the vertical beam-beam parameter ξ_y is as high as 0.05 if betatron tunes are properly chosen, and actually KEKB has already achieved $\xi_y \approx 0.055$. 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, invented by R. Palmer[3], was an idea to recover the head-on collision with the crossing angle. It has been also shown that the synchrotron-betatron coupling terms associated with the crossing angle are canceled by crab crossing[4]. The crab crossing scheme has been considered in the design of KEKB from the beginning as a backup solution for the crossing angle. Once, the crab crossing seemed non-urgent issue because KEKB achieved $xi_y \sim 0.055$ in the early stage of the operation (around the year 2000). Sooner or later an ineresting beam-beam simulation results appeared[5], predicting that the head-on or the crab crossing provides higher $\xi_y > 0.1$. Figure 1 shows the comparison of ξ_y for the head-on (crab) and crossing angle with a strong-strong beam-beam simulation. Then the development of the crab cavities has been revitalized.

Single Crab Cavity Scheme

The original design of KEKB had two cavities for each ring, both side of the IP, where 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 Fig. 2. In the case of KEKB, this scheme not only saved the cost of the cavities, but made it possible to use the existing cryogenic system at Nikko

Table 1: Machine parameters of KEKB at its best before crab crossing, comparing to the design. All luminosities are recorded values at the Belle detector[2]. The best data were recorded on Nov. 16, 2006, except for the integrated luminosities.

		Best		**Design**		
		LER	**HER**	**LER**	**HER**	
Circumference	C	3014				m
Beam Energy	E	3.5	8	3.5	8	GeV
Stored beam current	I	1.65	1.33	2.6	1.1	A
Number of bunches / ring	N_b	1389		5000		
Bunch current	I_b	1.19	0.96	0.52	0.22	mA
Bunch spacing	s_b	1.8–2.4		0.6		m
Horizontal Emittance	ε_x	18	24	18	18	nm
Horizontal β at IP	β_x^*	59	56	33	33	cm
Vertical β at IP	β_y^*	0.65	0.59	1.0	1.0	cm
Horizontal size @ IP	σ_x^*	103	116	77	77	μm
Vertical size @ IP	σ_y^*	1.9	1.9	1.9	1.9	μm
Hor. Beam-beam parameter	ξ_x	0.115	0.075	.039	.039	
Ver. Beam-beam parameter	ξ_y	0.101	0.056	.052	.052	
Bunch length	σ_z	7	6	4	4	mm
Horizontal rossing angle	θ_x	22				mrad
Luminosity	$\mathcal{L}$	17.12		10		/nb/s
$\int$Luminosity / 1, 7, 30 days		1.23, 7.82, 30.21		$\sim$ 0.6, –, –		/fb
$\int$Luminosity, total		720		100 for 3 years		/fb

Table 2: Typical parameters for the crab crossing.

Ring	LER	HER	
θ_x	22		mrad
β_x^*	80	80	cm
β_x^C	73	162	m
$\mu_x/2\pi$	0.505	0.511	
$\psi_x^C/2\pi$	$\sim$ 0.25	$\sim$ 0.25	
V_C	0.95	1.45	V
$\omega_{\rm rf}/2\pi$	509		MHz

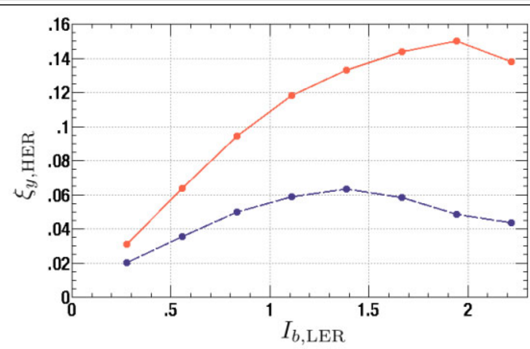

Figure 1: Enhancement of the vertical beam-beam parameter by a head-on (crab) collision (upper curve) comparing to the crossing angle of 22 mrad (lower curve), obtained by a strong-strong beam-beam simulation. Parameters are same as the present KEKB.

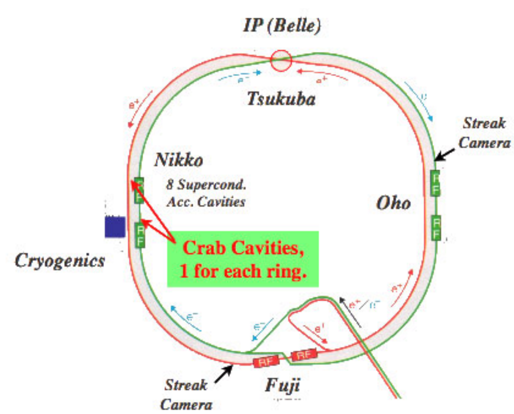

Figure 2: The layout of the crab cavities at KEKB with the LER (red) and the HER (green). Each ring has one crab cavity at the Nikko straight section where the cryogenics already exists for the accelerating cavities. Each ring is equipped with a streak camera.

for the superconducting accelerating cavities for the crab cavities.

The beam optics was modified for the crab cavities to provide necessary magnitude of the β-functions at the cavities and the proper phase between the cavities and the IP[6]. A number of quadrupoles have switched the polarity and became to have independent power supplies. The necessary horizontal kick voltage of the crab cavity V_c must satisfy

$$\frac{\theta_x}{2} = \frac{\sqrt{\beta_x^C \beta_x^*}\cos(\psi_x^C - \mu_x/2)}{2\sin(\mu_x/2)} \frac{V_C \omega_{\rm rf}}{Ec}, \qquad (1)$$

where β_x^C, ψ_x^C, μ_x, and $\omega_{\rm rf}$ are the horizontal β function and the betatron phase relative to the IP at the crab cavity, tune of the ring, and the rf frequency of the crab cavity, respectively. The actual crab cavity deflects the beam by a magnetic field, but we can define "crab kick voltage" by the effective change in the transverse momentum. The resulting parameters for the crab cavities and beam optics are shown in Table 2. The rf frequency of the crav cavity is chosen equal to the accelerating cavities.

CRAB CAVITIES

Design and Production

The crab cavity for KEKB was originally designed by K. Akai since 1991[7] and has been already included in *KEKB Design Report*. It is a superconducting cavity at 4K to use the lowest transverse mode to give the horizontal crab kick. The main components of the crab cavity is shown in Fig. 3. The cavity is horizontally squashed so as to make the frequency of the vertical kick mode higher enough than the horizontal mode that is tuned to the accelerating rf frequency, 509 MHz. As it has an accelerating mode lower than the crab mode, a coaxial beam pipe is equipped to make it propagate out. The coax is also used as the frequency tuning of the crab mode by changing the insertion depth with a tuner rod externally driven by a piezo device and a pulsed motor located in room temperature. The higher order modes are basically damped by two absorbers made of ferrite, one in the large beam pipe and the other at the end of the coax. Some parasitic modes excited around the coax was mitigated by tilting the rod in the notch filter[9]. The engineering design of the crab cavity, cryostat, and periferal devices was done by K. Hosoyama and a number of prototypes have been tested since 1994 by his group[8], and finally converged into the present one.

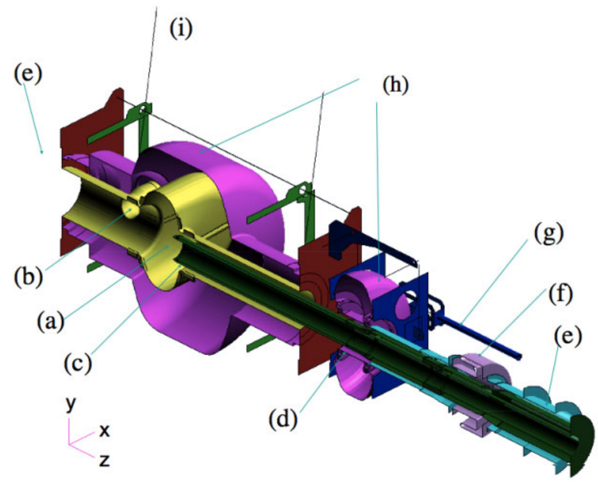

Figure 3: KEKB crab cavity consists of cavity cell (a), input coupler (b), coaxial beam pipe made of Nb (c) and its stub support (d), ferrite higher order mode (HOM) absorbers (e), notch filter (f) to reflect back the crab mode, tuning rod (g) of the coax, jacket type He vessels (h), and the support rods (i). The length in the z-direction shown in this figure is about 3 m, and the total system including the cryostat is about 6 m.

Performance

The crab cavity for the HER was first assembled and tested in June 2006. Although the volage and Q-values satisfied the requirement, the cavity frequency were out of the tunable range. The reason was that the estimation of the relative thermal contraction between the cavity and the coax was not quite adequate. After the correction of the alignment, the second test was done in October 2006, then all performance satisfied the goal. The cavity for the LER was assembled and tested in December 2006, and the result was satisfactory. Both cavities were conditioned up to 1.8 MV kick voltage, with the unloaded Q–values higher than 10^9 at the design voltage, 1.4 MV. The conditioning took less than a few days for the both cases.

As an example to show the performace of the crab cavities, Fig. 4 shows the rf phase stability achieved with the rf feedback. The requirements for the phase fluctuation was achieved for both cavities. The reason why the LER has larger fluctuation than the HER was that the movement of the coax for the LER was not smooth enough, showing some friction or backlash, whose real cause has not yet been identified. The data in Fig. 4 were taken by a data logger with a time constant of 1 second. An independent measurement with a spectrum analyzer was done to detect faster phase fluctuation. The results of the phase fluctuation were within ± 0.01 degree for frequency region higher than 2 kHz, and within ± 0.1 degree between about 20 Hz and 2 kHz for the both rings. These results indicate that the high fluctuation in the LER in Fig. 4 was in frequency region lower than 1 Hz. Both measurement of the phase fluctuation with the data logger and the spectrum analyzer were well below the requirement. The measurement by the data logger involves additional noise in phase detectors.

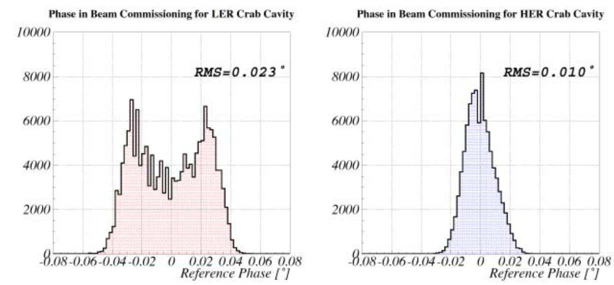

Figure 4: Phase distribution of the crab cavities for the LER (left) and the HER (right) with the rf feedback. The standard deviations of the phases are 0.023 deg and 0.010 deg for the LER and the HER, respectively.

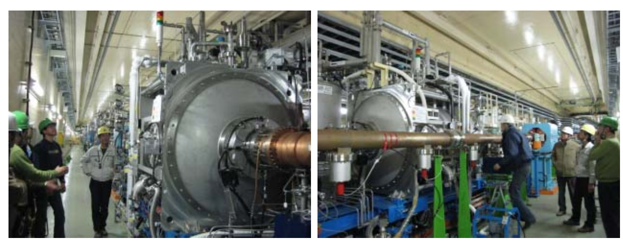

Figure 5: Crab cavities were installed in the HER (left) and the LER (right), one for each ring.

The both cavities were installed in the rings in the winter shutdown from the end of December 2006 through January 2007, as shown in Fig. 5. Further conditioning was done after the installation. These cavities have been working with beam showing enough stability. These cavities have been warmed up three times to 80K, and once to 300K to remove the absorbed gas. The warm up to 300K significantlly reduced the rate of trips for both cavities, from 2 trips/day/cavity to 1 (HER) or 1/2 (LER) trips/day/cavity.

FIRST BEAM TEST OF CRAB CROSSING

The first beam test of the crab cavities started on February 14, 2007. After beam storage without crab voltage for a few days, the crab voltage was applied one by one. The tuning were mostly done with 50 or 100 bunches per ring in collision. The highest bunch current was kept below 1.5 mA in the LER, which was limited to protect the BPM electronics, and 0.5 to 0.7 mA in the HER. The maximum luminosity with crab crossing was $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

with 1,000 mA and 540 mA in the LER and the HER, respectively, with 1091 bunches so far.

Observation of Crabbing

The very first test with the crab cavity was the observation of the kick in the horizontal orbit, changing the phase of the crab rf. It fits to a sine curve very well and the resulting kick voltages agree with estimation from the rf power in both rings within a few % errors.

Then the tilts of the bunches were observed by streak cameras located in the rings. One of the merits of the single-cavity scheme is such an observation is possible, as the tilt is everywhere in the ring. Figure 6 shows tilt of bunches. The response of the tilt to the phase of the crab cavities were right.

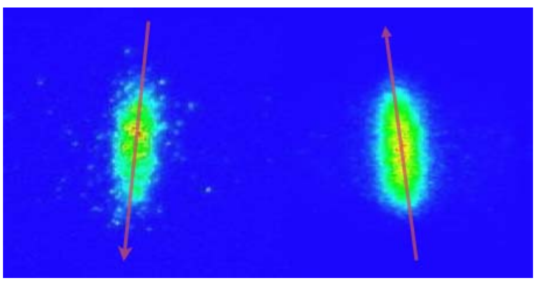

Figure 6: Images taken by streak cameras, which locate as Fig. 2, show tilt of the bunches in the LER (left) and the HER (right)[12].

Effective Head-on Collision

As a result of the crab crossing, the response of the horizontal offset between two beams were greatly changed from with the crossing angle. With the crossing angle, the behavior of the beam, especially the vertical beam size of the LER was not symmetric to the sign of the offset[10]. The vertical beam size blows up drastically when the HER beam comes inside at the IP relative to the LER. In this case the head of the LER beam collides to the HER beam with larger horizontal offset, as both beams comes from the inside to the outside at the IP. The longitudinal asymmetry of the LER bunch charge caused by the impedance, more charge at the head than the tail, is suspected as the cause of the asymmetry. Actually this asymmetry in the vertical beam size has been utilized to control the horizontal offset, as it has even better sensitivity than the horizontal beam-beam kick.

By the introduction of the crab crossing, such asymmetry disappeared or greatly reduced, since one of the sources of the asymmetry, the crossing angle, went away. Then the feedback looking at the vertical size became unusable and feedback with horizontal beam-beam kick took place. This is a clear indication of the effective head-on collision.

Specific Luminosity

Figure 7 shows the achieved specific luminosity per bunch as a function of the product of bunch currents, comparing the crab crossing and the crossing angle. The high-

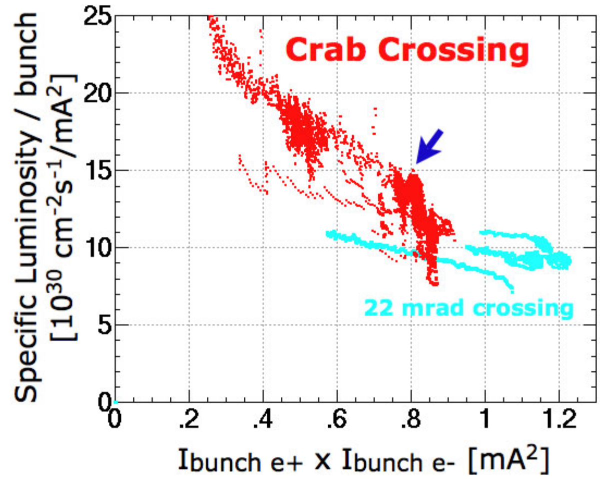

Figure 7: Specific luminosity per bunch with crab crossing (red) comparing to crossing angle (blue) as a function of the product of bunch current. The highest $\xi_y \sim 0.088$ was achieved at the arrow.

est beam-beam parameter achieved with the crab crossing was 0.088, while it was 0.055 with crossing angle. The slope for the crab crossing data roughly follows a curve with $\xi_y \approx$constant, for the current product between 0.4 to 0.8 mA^2. The curve may seem steeper below 0.4, but the reason is not known. The product of the bunch did not become higher than 0.9, as the lifetimes dropped rapidly. The gain in the specific luminosity is higher than the geometrical one ($\sim$ 15%), but it has not reached the prediction of the beam-beam simulation.

Tuning Parameters

There are a number of knobs to tune up the crab crossing. Only a few of them can be tuned up with independent observables besides the luminosity. Table 3 lists the tuning parameters and its observables.

The issue is that so many knobs are optimized only by the luminosity and the beam size. The number of such knobs is about 30. It is in question that such multidimensional optimization actually reach the optimum starting with the large unknown errors. The tuning process of these knobs are slow due to the statistical error of the luminosity monitor especially at low current. Another slowing factor is that the data must be taken with the same beam currents to minimize the current dependence for each setting of the knobs.

In many cases, the optimum setting of the knob is different for the luminosity maximum from the size minimum of the beam with the knob. Usually the size minima are pursued for a few days scanning all knobs for a few cycles, then switch to luminosity optimum. It is not clear that this kind of algorithm is adequate.

One of the peculiar knobs for the crab crossing is to control the vertical crabbing at the IP. There are conceivable sources of the vertical crabbing such as x-y coupling at the IP and at the crab cavities, tilt of the accelerating cavities. The x-y coupling knobs at the IP and at the crab cavities

Table 3: Tuning knobs for the crab crossing and their observables. Many depend only on the beam size σ_y at the synchrotron radiation monitor (SRM), besides the luminosity $\mathcal{L}$.

Knob	Observable	frequency: every
Relative beam offset IP	Beam-beam kick measured by BPMs around the IP	1 sec
Relative beam angle IP	BPMs around the IP	1 sec
Global closed orbit	All $\sim$ 450 BPMs	15 sec
Beam offset at crab cavities[11]	BPMs around the crab cavity	1 sec
Betatron tunes	tunes of non-colliding pilot bunches	$\sim$ 20 sec
Relative rf phase	center of gravity of the vertex	10 min.
Global couplig, dispersion, beta-beat	orbit response to kicks & rf frequency	$\sim$ 14 days
LER to HER crab voltage ratio	response in the hor. beam-beam kick. vs. crab rf phase	$\sim$ 7 days
Rf phase of crab cavity	hor. kick vs. crab voltage response	$\sim$ 7 days
Vertical waist position	$\mathcal{L}$ and σ_y at the SRM	$\sim$1 day
Local x-y couplings and dispersions at IP	$\mathcal{L}$ and σ_y at the SRM	$\sim$1 day each
Sextupole settings	$\mathcal{L}$ and lifetime	$\sim$ 3 days
X-y coupling parameter at the crab cavities	$\mathcal{L}$ and σ_y at the SRM	$\sim$ 3 days
Crab kick voltage	$\mathcal{L}$ and σ_y at the SRM	$\sim$ 7 days

can basically compensate such effects, but again there is no independent observable on this effect besides the luminosity and the beam sizes.

Discussions

The crab crossing has been tested at KEKB for about 4 months. The crab cavities has been working basically very well providing the necessary kick voltage stably. Although there are a lot of indications of the effective head-on collision, the specific luminosity has not reached the predicted value yet. There are a few speculation on the reason:

- Too many knobs are tuned only by the luminosity and the vertical beam size as described above.
- The horizontal tunes are close to the synchrotron-betatron resonance line $2\nu_x + \nu_z = \text{integer}$. Actually single-beam blowup of the horizontal and vertical beam sizes and drop of the beam lifetime were observed when the betatron tunes cross the resonance line.[14] The magnitude of the blowup strongly depend on the setting of the sextupoles. It is possible to estimate the blowup in the model by considering of the equilibrium horizontal emittance in the synchrotron phase space[13]. Such an optimization as well as the dynamic aperture has been tried to find out a good solution of sextupoles.
- Negative momentum compaction factors have been tried in both rings to examine the effect of the resonance above, expecting a sum and difference resonances may behave differently. It was not successful, however, a longitudinal oscillation was found in the LER caused by a single bunch microwave instability.
- There was a speculation related to the dynamic emittance effect caused by the beam-beam effect as the horizontal emittance largely increases when the horizontal tune is close to a half integer as KEKB (0.505 and 0.511). If the lattice has errors in the x–y coupling, such horizontal dynamic emittance may dilute to the vertical emittance. On the other hand, this effect can be cancelled if the local coupling at the IP is properly corrected.

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