Commissioning and Beam Operation of KEKB Crab RF System

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Abstract

Two heavily damped superconducting crab cavities were installed in KEKB, one for the low-energy positron ring (LER) and the other for the high-energy electron ring (HER). After adjusting the RF system and conditioning the cavities, beam operation started in February 2007. During the four-and-a-half-month operation until summer shut down, the crab cavities have been operating very stably to conduct crab crossing experiment. They have shown excellent performance with high stored beam currents up to 1.7 A in the LER and 1.35 A in the HER. It was also demonstrated that the crab crossing works at a high luminosity over 10^{34}/cm^{2}s that exceeds the KEKB design luminosity. Machine tuning with crab crossing will continue for achieving a big boost in luminosity, as expected from beam-beam simulations. In this paper, we present an RF system for the crab cavities, commissioning process, performance of the crab cavities with high-current beams, and beam-loading-related issues on the crabbing mode.

INTRODUCTION

KEKB, consisting of a 3.5-GeV low-energy positron ring (LER) and 8.0-GeV high-energy electron ring (HER), has been operating since 1999 for asymmetric-energy e^+e^- collision experiment. The RF system with twenty normal-conducting (nc) cavities in the LER and eight superconducting (sc) cavities and twelve nc cavities in the HER has been operating stably with beam currents up to 2 A and 1.4 A in the LER and HER, respectively. KEKB has achieved various records including the peak luminosity of 1.71×10^{34}/cm^{2}s, the daily integrated luminosity of 1231/pb, and the total integrated luminosity of 720/fb.

Beams collide at a finite angle of ±11 mrad at the interaction point (IP). Recent beam-beam simulations showed the possibility of further increasing the luminosity by adopting the crab-crossing scheme [1]. Then, it was decided to conduct the the crab-crossing experiment in KEKB. The scheme of a single crab cavity per ring is adopted instead of the original design with two crab cavities per ring located on both sides of the IP.

For the crab cavities, we had adopted the heavily damped structure proposed in 1992, which has a squashed cell and a coaxial beam pipe (coax) with a notch filter [2]. This scheme sufficiently damps any parasitic modes to avoid coupled-bunch instabilities caused by a high-current stored beam: not only higher-order modes (HOMs) but also the lower-frequency mode corresponding to the accelerating mode and the unwanted polarization of the crabbing mode.

On the basis of this design, two sc crab cavities have been developed at KEK [3]. After their fabrication, horizontal tests were performed in 2006, and the result was satisfactory. The details of these horizontal tests are reported elsewhere [4]. Then, the cavities were installed in the KEKB rings, one for each ring, in the winter shut down from the end of December 2006 through January 2007, followed by the commissioning with beams.

CRAB RF SYSTEM

Since the crabbing mode is a transverse mode, the beam loading on a crab cavity depends on the horizontal beam orbit. The required RF power P_g to maintain the crabbing voltage V_c is given by Eq. 9 of Ref. [5]. For the case of the input coupling $\beta \gg 1$, the crabbing phase $\phi_c = \pi/2$, and the loading angle $\alpha_L = 0$, the relation is simplified as follows:

$$P_g = \frac{1}{4\left(\frac{R_\perp}{Q_0}\right) Q_L} \left\{ V_c + I_b \left(\frac{R_\perp}{Q_0}\right) Q_L k \Delta x \right\}^2 , \qquad (1)$$

where Q_L is the loaded Q value; k, the wave number; Δx, the horizontal displacement of the beam orbit; and I_b, the beam current. Fig. 1 shows P_g as a function of Q_L for the case of $\Delta x = 0$ and 1 mm and $I_b = 2$ A. P_g increases at a lower Q_L, while a higher Q_L makes the system more sensitive to Δx. We have chosen $Q_L = 1{\sim}2 \times 10^5$ for a good compromise. This value is suitable for operating the system with a possible error of $\Delta x = 1$ mm, and a high-power source of $P_g = 200$ kW is sufficient for conditioning the cavity up to 2 MV. Table 1 summarizes the machine parameters for the crab crossing in KEKB.

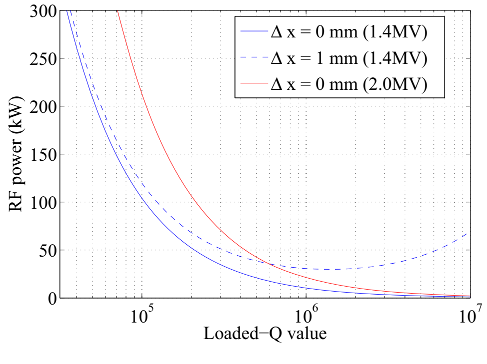

Figure 1: Dependence of RF power on the loaded Q value and a horizontal beam orbit for a beam current of 2 A.

Two new RF stations, each for one crab cavity, were constructed next to the stations for the sc accelerating cavities

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Table 1: Parameters for the crab crossing for KEKB.

	LER	**HER**	**unit**
Beam energy	3.5	8.0	GeV
Beam current	1.7	1.35	A
RF frequency	508.9		MHz
Crossing angle	±11		mrad
$\beta_{x,IP}$	80	80	cm
$\beta_{x,crab}$	80	170	m
V_{kick}	0.9	1.45	MV
Loaded-Q	2.0×10^5	1.6×10^5	
RF power for V_{kick}	23	90	kW

in the D11 building. Two reused klystrons that have been tested up to 600 kW were set. The high-power system and most of the low-level RF system are similar to those of the sc accelerating stations. Conventional amplitude and phase feedback loops are used to control the cavity field and the klystron output. The resonant frequency of the cavity is controlled by the main tuner system consisting of a motor and piezo element, which moves the coax in the longitudinal direction with respect to the cavity cell. The interlock system that protects the cavity includes a quench detector, arc sensors at the input coupler, vacuum pressure gauges, etc. Special cares are taken for the coax: (1) a sub-tuner is added to align the coax horizontally with respect to the cell in order to minimize the coupling of the crabbing mode between the cell and the coax. (2) RF signals monitored at seven pickup ports located in the coax are connected to the fast interlock system. It protects the ferrite damper at the end of the coax from abnormally large crabbing-mode power that can leak through the coax on the occasion of a discharge at the coax or the notch filter.

COMMISSIONING AND BEAM OPERATION

After the crab cavities were installed in the KEKB tunnel, the input couplers were conditioned at room temperature up to 200 kW for the HER and 150 kW for the LER [6]. The cavities were cooled down slowly at about 2 K/h, and attained a temperature of 4 K in a week. Then, the main and sub tuners and the RF control system were adjusted and the cavities were conditioned in about two weeks.

The first crabbed beam was obtained on Feb. 19, and the first collision with the crabbed beams was performed on Feb. 21. Since then, machine tuning with the crab crossing continued until the end of June. Fig. 2 shows an overview of the beam operation for four and a half months. Most of the time was devoted to low-beam-current operation with a small number of bunches in order to achieve high specific luminosity, as expected from the beam-beam simulations. Two weeks in both April and June were devoted to high-beam-current operation. Meanwhile, the crab cavities were warmed up twice to 80 K and once to room temperature in order to remove the absorbed gas on the cavity surface.

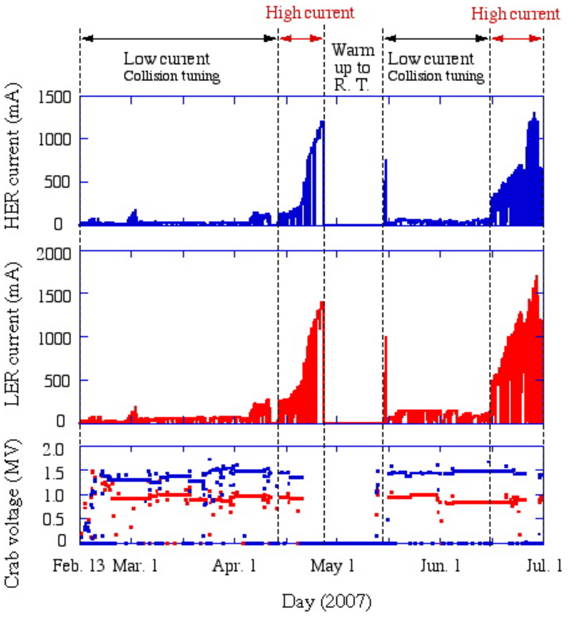

Figure 2: Overview of the beam operation for four and a half months. HER beam current (upper), LER beam current (middle), and the HER (blue) and LER (red) crab kick voltage (lower).

System Adjustment

The crabbing voltage and phase, alignment of the coax as well as beam orbit adjustment were performed in the following manner:

- The crabbing voltage was calibrated from klystron output power and the loaded Q value of the cavities, taking account of power loss in the high power system. The usual method that uses the external Q value of a pickup port could not be applied, since the coupling was changed after a vertical test.
- The field center was searched by measuring the amplitude of the crabbing mode excited by a beam when the cavity was detuned. A local bump orbit was set to adjust the beam on the cavity axis.
- The beam orbit difference between the crabbing voltage on and off was measured by changing the crabbing phase, and the phase was set to minimize the difference, so that the bunch center is not kicked by the crabbing voltage. This measurement also gives an independent calibration of the crabbing voltage, which was in good agreement with the result of the other calibration described above.
- The tilt of both beams was observed using a streak camera. The observed bunch images for the right crabbing phase, the opposite phase, and no crabbing voltage clearly showed the tilts produced by crabbing [7].

Performance of the Crab Cavities

Table 2 summarizes the achieved parameters of the crab cavities in the beam operation. Details will be described below.

Table 2: Achieved parameters during beam operation.

	LER	HER	unit
Beam current (detuned)	1700	1350	mA
Beam current (crab ON)	1300	700	mA
Number of bunches	1389	1389	
Crab voltage (max)	1.5→1.1	1.8	MV
Crab voltage (operation)	0.9	1.45	MV
Tuner phase stability	±15	±1	deg
Crab phase stability	±0.1	±0.1	deg
HOM power	11.5	12	kW
Average trip frequency	1.57	1.27	/day

High beam current The beam current was increased by increasing the number of bunches up to 1389, keeping the bunch current almost constant. The first trial of the high-current operation in April was not very successful. As the beam current was increased, the vacuum pressure in the cavity degraded, and the trip rate increased. Therefore, we suspended the trial, detuned the cavities to scrub the beam pipe chambers using a high-current beam, and then warmed up the cavities to room temperature in order to remove the condensed gas on the surface. After the second cool down, the vacuum pressure in the cavity greatly improved, as shown in Fig. 3. Another problem was the temperature rise of the inner conductor of the coax. The temperature measured at the return gas flow after cooling the inner conductor reached to 9 K. In order to reinforce the cooling power, a bypass line at the return gas flow was added, and the pressure inside the helium vessel was increased. Then, the temperature rise was suppressed up to the maximum beam currents, as shown in Fig. 4.

After these improvements, the second trial of the high-current operation was conducted successfully in June: the crab cavities performed up to 1.3 A in the LER and 0.7 A in the HER. The peak luminosity with the crab crossing reached to $1.06 \times 10^{34}/\mathrm{cm}^2\mathrm{s}$. The beam currents were not limited by the cavity performance; however, we did not increase the currents further due to several reasons: short machine time left, the breakdown of the LER piezo tuner, and beam oscillation phenomena observed at high current, which will be discussed later.

The high-beam-current operation was also conducted with the crab cavities off and detuned. The purpose of this test is to prove that the crab cavities are able to stay in the ring with the high-current beam for the physics run, in case the crab crossing would have to be given up for some reason. The beam currents required for the physics run, 1.7 A in the LER and 1.35 A in the HER, were successfully stored.

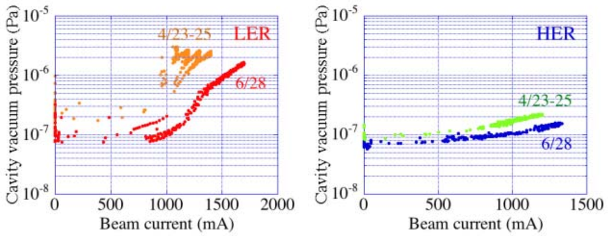

Figure 3: Vacuum pressure in the cavity before and after the warm up.

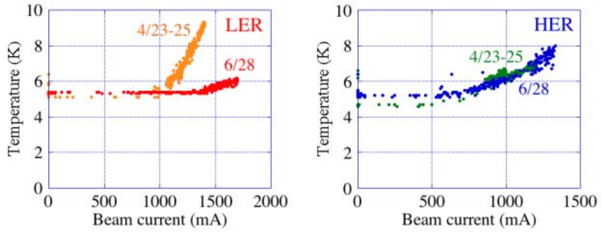

Figure 4: Temperature at the inner conductor of the coax before and after the reinforcement of the cooling power of the LER cavity.

HOM dampers The HOM power is absorbed by two ferrite dampers: one damper is located at the large beam pipe (LBP); the other, at the end of the coax. The damper at the coax also absorbs the lower-frequency-mode power. Fig. 5 shows the power absorbed by the dampers in the high-current operation. In each cavity, the power absorbed at the maximum beam current was about 10 kW by the LBP damper and 2 kW by the coaxial damper. The operation of the dampers has been satisfactory and trouble-free. The power absorbed by the HER dampers fairly agrees with the parasitic loss estimated from a loss factor for a bunch length of 6 mm. On the other hand, the power absorbed by the LER dampers is about 60% of the estimated value. In the case of LER, an additional damper made of SiC is located between two taper sections outside the LBP damper. Measurement system for the power loss at the SiC damper was implemented in the summer shut down, and it was observed in the autumn run that most of the missing power is absorbed by this damper. The discrepancy may also be attributed to a longer bunch length than 6 mm in the LER.

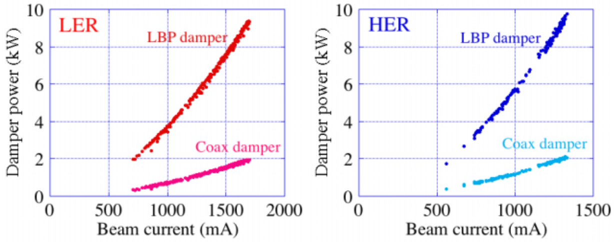

Figure 5: HOM power absorbed by the ferrite dampers at the large beam pipe (LBP) and the coax.

The spectrum of the RF signal observed at the pickup ports did not show any high-Q mode excited by the beam. The measured spectrum was compared with a calculated spectrum. In particular, the Q value of the most dangerous lower-frequency mode is sufficiently damped to about 140. The details of the HOM power and spectrum are described elsewhere [8].

Crabbing voltage The HER cavity has maintained good performance during the four-month operation. For most of the time, it was operating at the design voltage of 1.45 MV. Its voltage was sometimes raised up to 1.7 MV when the tilt angle was scanned to search for the best crabbing angle.

On the other hand, the LER cavity has degraded. A heavy quench occurred on March 17 when the operating voltage was raised from 1.0 to 1.2 MV. Conditioning of the cavity for several hours could not recover the performance above 1.0 MV; then, the operating voltage was reduced to 0.9 MV. A week later, it was warmed up to 80 K; then, it slightly recovered to 1.1 MV. However, no further improvement was achieved, even after the warmup to room temperature. Fortunately, the necessary crab kick could be maintained by increasing the beta function at the crab cavity $\beta_{x,crab}$ from 40 to 80 m.

Trips of crab cavities Most crab cavity trips are associated with a discharge and/or thermal breakdown, similar to those of sc accelerating cavities. In most cases, a trip is detected by a quench detector and/or vacuum pressure rise. In a fewer cases, an arc sensor at the input coupler or other interlocks work. When a trip occurs, the input RF power is shut off to protect the cavity, and the stored beam is aborted by the interlocks, beam loss monitors, or radiation sensors at the Belle detector.

Table 3 shows the monthly statistics of the number of beam aborts due to the crab cavity trips as well as operating days with the crabbing on. The average number of trips per day is about 1.6 for the LER cavity and 1.3 for the HER cavity. This rate is fairly low for the new sc cavities that operate with a high-current beam and for which sufficient time is not available to condition a cavity and its neighboring beam ducts. Fig. 6 shows the daily statistics of the trips. The crab cavity trips have not caused serious disturbance to the beam operation, except for two occasions when the LER cavity suffered from a higher trip rate: one occasion is in the middle of March, when the performance degraded as described above. The trip rate decreased after the operating voltage was reduced to 0.9 MV. The other occasion is in the first trial of the high-beam-current operation in the middle of April. As seen in the figure, the trip rate was greatly reduced after the cavity was warmed up to room temperature.

Frequency tuner The LER frequency tuner system has a large backlash behavior due to a mechanical problem, whose real cause has not yet been identified. When the moving direction of the piezo element and motor is changed, the resonant frequency still moves in the original direction far away until it finally changes the direction. As a result, when the tuning control feedback loop is on, the tuning phase, that is, the relative phase between the input and cavity field, fluctuates by about ±15 deg. By adjusting the loop parameters, the oscillation period was extended; however, the phase fluctuation could not be reduced. The HER tuner does not have such a problem; the tuning phase stays within about ±1 deg.

The piezo element of the LER tuner was broken twice in June, and replaced with a spare one. The HER piezo element was broken twice at the beginning of the autumn run, and the HER tuner is currently operating without the piezo element. Then, the fluctuation of the tuning phase is increased to ±3 deg. It is suspected that the breakdown is

Table 3: Number of beam aborts due to the crab cavity trips and the average trip frequency.

	Days for	Number of trips	
	crabbing on	LER	HER
Mar. 2007	30	58	43
Apr.	17	54	21
May	16	13	16
Jun.	25	12	32
Total	88	137	112
Trips/day	—	1.56	1.27

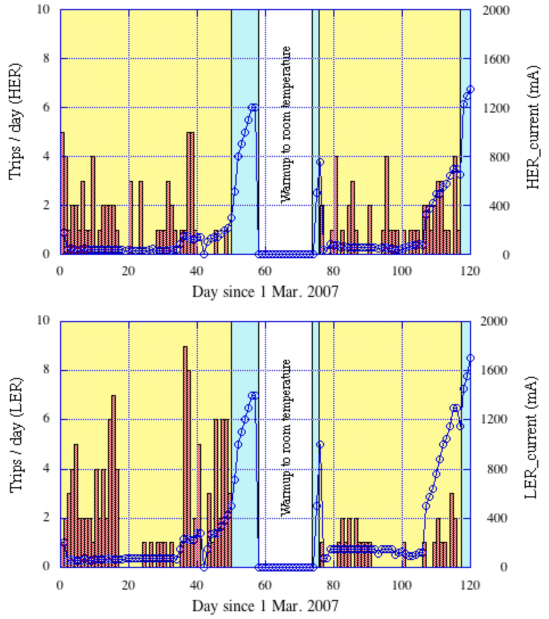

Figure 6: Number of trips per day of the HER (upper) and LER (lower) crab cavities for four-month operation. They were operated in the period marked by the yellow area, whereas they were detuned in the period marked by the blue area. Blue circles show the maximum beam current in a day.

caused by some force perpendicular to the tuning rods.

Phase stability Despite the large fluctuation of the tuning phase, the amplitude and phase of the cavity field is sufficiently stabilized by low-level feedback loops. Fig. 7 shows the spectrum of the RF signal measured at a pickup port for various frequency spans. The phase fluctuation is estimated from the sideband peak heights, assuming that they arise from phase modulation. The phase fluctuation faster than 1 kHz is less than ± 0.01 deg, and slow fluctuation from ten to several hundreds of hertz is about ± 0.1 deg. They are much less than the allowed phase error obtained from the beam-beam simulations for the crabbing beams in KEKB. An independent measurement was performed by monitoring a phase detector signal, and the result is consistent with the measured spectrum.

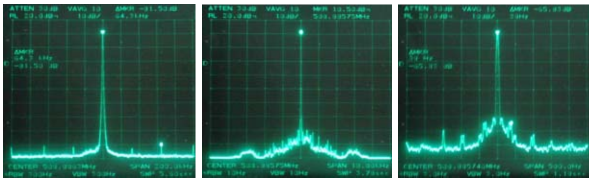

Figure 7: Spectrum around the crabbing mode measured at a pickup port of the LER crab cavity. Frequency span is 200 kHz (left), 10 kHz (center), and 500 Hz (right). Phase modulation is estimated from the sideband peaks. Beam current was between 450 and 600 mA.

Beam-Loading Issues

Beam power A horizontal displacement of the beam orbit gives rise to the beam-loading on the crabbing mode, as shown in Eq. 1. In the high-current operation, the beam-loading effect was observed. The RF power into the LER cavity on resonance decreased with an increase in the beam current. This implies that the beam orbit was on the decelerating side. This situation was corrected by shifting the beam orbit toward the accelerating side by 0.7 mm, as shown in Fig. 8 (left).

Oscillation at high-current crab collision In the high-current crab-crossing operation, we encountered a large-amplitude oscillation of beams and the crabbing field. The phase and amplitude of both crab cavities oscillated coherently at about 540 Hz, as shown in Fig. 8 (right). A horizontal beam oscillation was also observed at the same frequency. Once the oscillation occurred, it caused unstable collision of the beams, short beam life time, and luminosity degradation. It is attributed to none of the beam orbit feedback systems, since their response time constants are typically 1 to 20 sec, much slower than the oscillation.

A series of machine studies were conducted to understand the phenomenon and correct for it. The oscillation occurred only with the colliding beams of beam currents higher than about 1 A in the LER and 0.5 A in the HER. It never occurred with low-current colliding beams, nor it occurred with a single beam, even at a high beam current. It is related to some of the crab RF system parameters such as the crabbing phase, tuning phase, and loop gain of the phase and amplitude control. It is concluded that the oscillation is caused by the beam loading on crab cavities together with the beam-beam force at the IP. It was also found that the oscillation can be avoided by shifting the crabbing phase, shifting the tuning offset angle, and adjusting the loop gain appropriately. By employing these remedies, we will attempt to increase the beam current further with the crabbing on in the autumn run. More quantitative analysis to understand this phenomenon is under way.

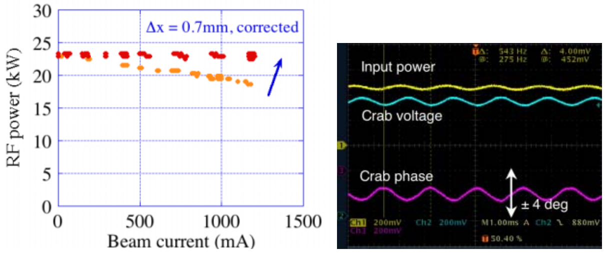

Figure 8: RF power to the LER cavity on resonance before and after correcting the beam orbit (left). The oscillation observed with the crab-crossing of high-current colliding beams (right).

SUMMARY

The RF system with the crab cavities has been constructed and commissioned. The first operation of the crab RF system with beams has been conducted successfully. The crab cavities have shown excellent performance with high-current beams up to 1.7 A in the LER and 1.35 A in the HER. After the four-month operation dedicated for the crab crossing experiment, KEKB resumed the operation in October for high-luminosity physics run. Based on the successful results during the experiment, the autumn physics run uses the crab cavities in the routine operation.

ACKNOWLEDGMENTS

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