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COMMISSIONING OF THE KEKB B–FACTORY

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Abstract

The commissioning of the KEKB B–Factory storage rings started on Dec. 1, 1998. The two rings both achieved a stored current of over 0.5 A after operating for four months. The two beams were successfully collided several times. The commissioning stopped on Apr. 19, taking a 5-week break to install the Belle detector.

1 BRIEF HISTORY OF THE COMMISSIONING

The KEKB B–Factory[1] consists of two storage rings, the LER (3.5 GeV, e^+) and the HER (8 GeV, e^-), and the injector Linac/beam-transport (BT) system. The Linac was upgraded from the injector for TRISTAN, and was commissioned starting in June 1997, including part of the BT line. The injector complex was ready before the start of commissioning of the rings.[2]

Figure 1 shows the growth of the stored currents in the two rings through the period of commissioning. The first storage of the HER and LER were on Dec. 13 and Jan. 14, respectively. The initial rise of the intensity was quite good in both rings. This figure also shows several breaks, the scheduled one (for new-year holidays) and the unscheduled shutdowns. The total length of breaks were more than one month. So far both rings have achieved stored currents more than 0.5 A, which corresponds to 20% (50%) of the design goal of the LER (HER). The maximum current of the HER is limited by the rf power available from the number of cavities currently installed. On the other hand, LER's maximum current seems to be limited by the vertical beam blow-up due to a muti-bunch instability, as shown later.

Two major unscheduled shutdowns were experienced during this period. One was an accident related to a false fire alarm at the end of January, which had nothing to do with the beam operation. Another break at the end of February was the melt-down of a vacuum chamber in the HER near the interaction point (IP) due to synchrotron radiation. The synchrotron radiation produced in the outgoing superconducting quadrupole (QCS) hit the chamber as a result of radiation background tuning with a large-angle bump orbit. The chamber was replaced in 3 weeks with a new heat-resistant design.

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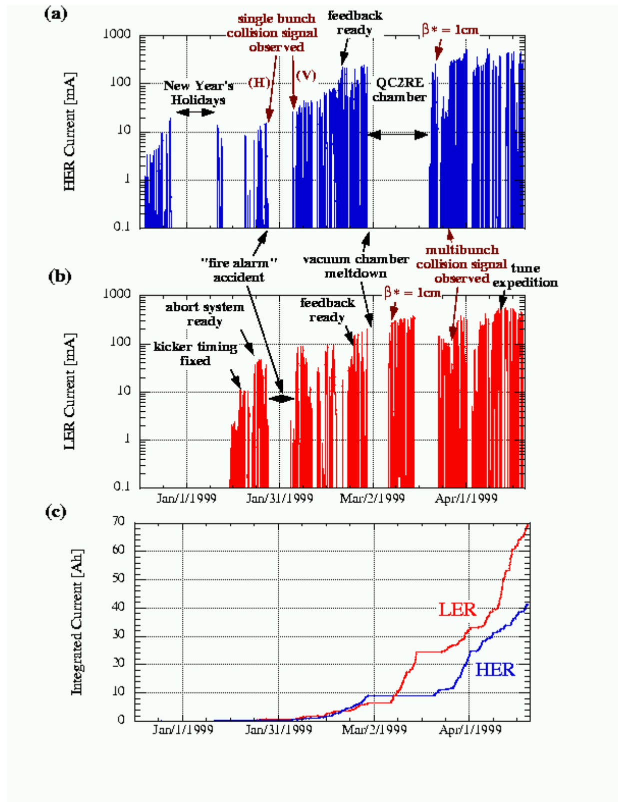

Figure 1: The stored beam currents, in log scale, during the commissioning are shown in HER (a) and LER (b). Several significant events are also shown. The integrated beam current is shown in (c).

Table 1: e^+ Linac/Beam Transport

Item	Design	Achieved	
Energy	3.5	4	GeV
Charge@e^+ target	10	10	nC
Charge@end of Linac	0.64	0.6	nC
Charge@end of BT	0.64	0.4	nC
Repetition	50	50	Hz
Emittance	0.25	0.4	μm

2 PERFORMANCE

Tables 1–4 list the main machine parameters achieved during this period, in comparison with the design values.

Table 2: LER

Item	Design	Achieved	
Energy	3.5	3.5	GeV
Beam current	2.6	0.54	A
Bunch current	0.52	2.3	mA
Bunches	5000	1024	
β_x^*/β_y^*	33/1	100/1.0	cm
ν_x/ν_y	45.35/44.41	45.27/44.18	
Rf voltage	8	4.8	MV
ν_z@4 MV	0.0118	0.0110	
Injection efficiency	100	80	%
Lifetime@0 A	14	>8	hour

Table 4: HER

Item	Design	Achieved	
Energy	8	8	GeV
Beam current	1.1	0.51	A
Bunch current	0.22	4	mA
Bunches	5000	800	
β_x^*/β_y^*	33/1	100/1.1	cm
ν_x/ν_y	44.53/42.20	44.65/42.1	
Rf voltage	20	9	MV
ν_z@8 MV	0.0119	0.0114	
σ_z@0 mA	5.6	5.6	mm
Injection efficiency	100	80	%
Lifetime@0 A	45	>8	hour

Table 3: e^- Linac/Beam Transport

Item	Design	Achieved	
Energy	8	8.5	GeV
Charge@end of Linac	1.2	1.2	nC
Charge@end of BT	1.2	1	nC
Repetition	50	50	Hz
Emittance	<0.1	0.06	μm

2.1 *Lattice*

The commissioning started with a $\beta_y^* = 2$ cm lattice, and later switched to $\beta_y^* = 1$ cm at the time shown in Fig. 1. No degradation in injection efficiency, maximum current, or lifetime was observed in either ring with the $\beta_y^* = 1$ cm optics. As for β_x^*, only 100 cm has been tried so far for either ring.

The ring lattices have been understood for the basic parameters such as tunes, β-functions, dispersions, etc.[3] The betatron tunes have been searched to optimize the injection efficiency, maximum current, beam profile, and the noise in the pilot detector at the IP, BEAST. So far the two rings have been operated at different betatron tunes, since they have been optimized independently. They will be adjusted if necessary for the beam-beam effect. Those tunes are also different from the design tunes which were optimized by beam-beam simulation. The simulation suggests a point, $(0.52, 0.08)$, which is very close to the integer or half-integer resonances. It has, however, been difficult to access such a location with the current size of the betatron stop bands ($\sim$ 0.05).

One of the discrepancies in the lattice between the model and the measurements is the differences of the betatron tunes as shown in Tables 2 and 4. They are bigger in the LER, and the calibration of the superconducting quadrupoles at the IP, which are common to both LER and HER, relative to the iron quadrupoles is under investigation. The super- and normal conducting magnetic measurements were done independently.[4] An analysis using single kicks of the corrector dipoles all around the ring was done.[5] It shows a mismatch of the β-functions in both rings of 20–50%, while the measured β^*s are sufficiently close to the model. It is speculated that the mismatch of the betas should bring an error in chromaticities, which currently differ from the model by a factor of 2–5. The higher order chromaticity is also somewhat different from that of the model.

Though such differences are seen, the measured transverse dynamic aperture is at least larger than the physical aperture. The longitudinal acceptance of the LER is about $\pm$1.5% which is smaller than the model ($\pm$2.5%). This can be a source of injection background in the LER, which is a few times higher than that in the HER.

The x-y couplings of the rings are roughly corrected by vertical bump orbits at strong sextupoles, looking at the effect of a single kick in one plane on the orbit in the other plane.

So far no problem has been seen related to the alignment of the rings. The circumferences of the rings are different from the design by about 5 mm, and their relative difference was only 0.3 mm. The offset of HER's circumference was corrected by choosing the rf frequency (including the Linac), then the LER's was adjusted to the HER's using chicanes. In the initial stage of commissioning, a turn-by-turn beam position/phase monitor (TBTM) played an important role in detecting the path length via phase oscillation.

2.2 *Orbit Fluctuation*

One of the biggest issues, unanticipated at the design stage, is fluctuations of the closed orbit. Two kinds of fluctuation, both in the vertical direction, have been observed so far. The first one is a slow drift. The vertical closed orbits of the rings drift randomly by typically 1 mm/hour at the IP quads, or 0.2 mm/hour in the arc section. The drifts in the two rings are highly correlated and the magnitudes are roughly equal. Orbit analysis locates the source at the quadrupoles at the IP, but it was hard to distinguish whether one or all of them are responsible. Also, a correlation with the ambient temperature around the IP is observed (fig. 2). The amount of drift translates into an offset at the IP of 5 μm/hour, whereas the design beam size is 1.4 μm. The

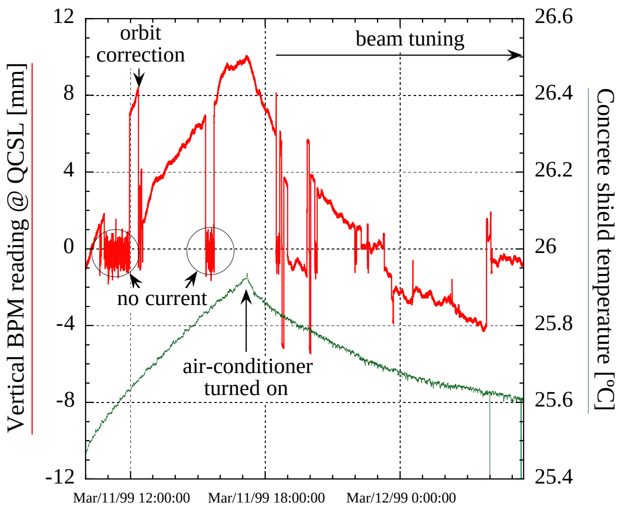

Figure 2: The change of orbit (upper trace) and the temperature of the concrete shield structure (lower) at the IP. These data were taken on Mar. 11 for about 20 hours, after switching off the air-conditioner in Tsukuba hall around the IP. The air-conditioner was turned on in the middle. Though orbit correction was applied several times during this period, a clear correlation between the orbit and the tempereture is seen.

drift is also large enough to increase the background and degrade the injection efficiency. To cure the drift a continuous closed-orbit correction system has been applied to both rings to maintain the orbit at the beam-position monitors(BPMs), and has been so far found effective.

The second kind of orbit fluctuation is a vertical vibration of the orbit at about 14 Hz. The amplitude of the vibration is about 100 μm_{pp} in the arc, and continues with constant amplitude for hours or days. Sometimes it stops for hours and then restarts. Both rings have similar vibrations, but they are not synchronized and their frequencies are slightly different. Orbit analysis points to a source around the IP, but it has not yet been identified. This vibration can make the two beams miss each other vertically by a few sigma. A collision feedback responding rapidly enough will be necessary.

2.3 *High Intensity*

The LER is equipped with 12 ARES copper cavities, and the HER 6 ARES and 4 superconducting cavities. So far the number of rf cavities installed in the rings is enough to store about half of the design intensity. The HER has already reached this limit. Both rf systems have been working quite well and the down time due to rf has been quite small.

At the initial stage of commissioning, the baking of the vacuum chamber is the most important task in any electron-positron storage ring. Figure 3 shows how the photo-desorption coefficient has improved as the integrated current has increased. These curves basically fit the expectation very well, so the baking of the chambers has been successful so far.

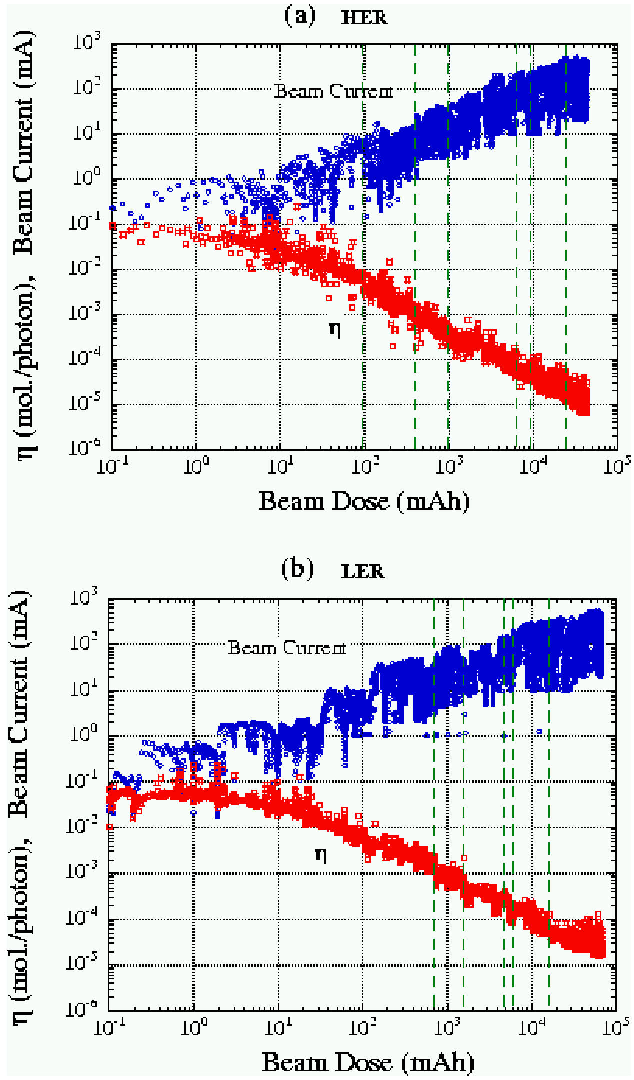

Figure 3: The photo-desorption coefficient (lower trace) and the beam current (upper trace) versus the integrated beam current for HER (a) and LER (b). The vertical dashed lines indicate the timings of the conditioning of the NEG strip modules.

The beam lifetime is so far determined by the vacuum pressure. The lifetime extrapolated to zero current is longer than 8 hours. It matches the design numbers shown in Table 2 and 4 to within the accuracy of the extrapolation. The lifetime of the LER is decreased at high current when the vertical masks are closed. This is due to a blow-up of the vertical size caused by a mutibunch instability, described below.

An abrupt decay of the lifetime has been observed in the HER below 200 mA. A possible explanation is dust-trapping. Spikes in the background have also been reported by the BEAST, which are correlated to the presumed dust events. An interesting phenomenon noticed in the BEAST was a "micro-dust event" which looks similar to a larger dust event but is too small to be evidenced in the lifetime. These dust events decrease at higher current.

2.4 Instabilities

Single bunch currents can be stored much at higher than the design value with sufficient margin. No disastrous instability or bunch-lengthening has been seen.

The LER and HER have been operated in multi-bunch mode mostly with 10 ns bunch spacing. Both rings have a bunch gap of about 10% for the rise of the abort kicker. Usually the HER has 4–7 more gaps (i.e., bunch-trains) for clearing ions.

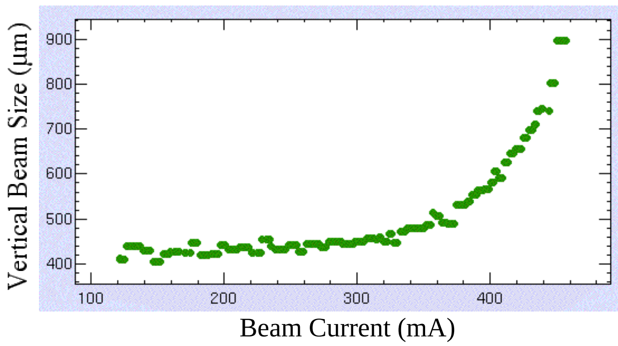

Figure 4: The vertical beam size of the LER measured by the synchrotron radiation interferometer as a function of the beam current. The bunch-by-bunch feedback was turned off.

Several multi-bunch instabilities have been observed in both rings, but none of them has an identified source yet. The LER sees an excitation of longitudinal oscillation, with its strength depending on the *betatron* tunes. With a particular choice of betatron tunes, the LER accumulated 440 mA without bunch-by-bunch transverse feedback.[6] At bad tunes, the oscillation starts at about 10 mA, but at the best tune, only at 350 mA or higher. At bad tunes, vertical oscillation was observed simultaneously, so the bunch-by-bunch feedback was effective in such cases. The threshold depends on the vertical closed orbit, vertical dispersion, and vertical chromaticity. It is unknown what the relation is between the longitudinal and the vertical instabilities.

An important phenomenon in the LER is a blow-up of the vertical beam size at $I \geq 350$ mA (Fig. 4), observed by the synchrotron light monitor,[7] using both direct imaging and interferometry. The observed vertical size, translated to emittance assuming the design β_y, reaches $\varepsilon_y/\varepsilon_x \gtrsim 1$ at $I = 500$ mA. Though the beam size increases as the current, no vertical oscillation was seen. Among suspected sources of the blow-up are vertical dispersion and synchrotron oscillations, but these are not yet confirmed. This vertical blow-up eventually limits the stored current by hitting the vertical masks in the arc. No pure-transverse instability has been seen in LER up to 500 mA.

In the HER, there is a strong vertical instability over 100 mA. The bunch-by-bunch feedback is very effective for this instability. Without the feedback, usually the tails of the bunch-trains are lost. Dependences on the tunes, orbit, synchrotron motion, bunch fill pattern, etc., are under investigation.

2.5 Injection

The injector linac has already achieved its design performance, at least for the short term.[2] There remain a number of issues related to long-term stability and repeatability. A difficult problem is switching the same linac between four modes (KEKB e^-, KEKB e^+, PF, PF-AR) which need different settings of rf, magnets, and even different guns. Further improvement in the injector is necessary.

3 COLLISION

Table 5: Parameters of the multi-bunch collision in Mar. 1999. Beam sizes are obtained from the beam-beam scan in Fig. 5, assuming equal sizes for both beams.

	LER	HER	
Current	65	13	mA
Bunches	200	200	
σ_x/σ_y	197/4.0		μm
Lifetime	200	40	min.
Estimated luminosity	1.7×10^{31}		$\mathrm{cm^{-2}s^{-1}}$

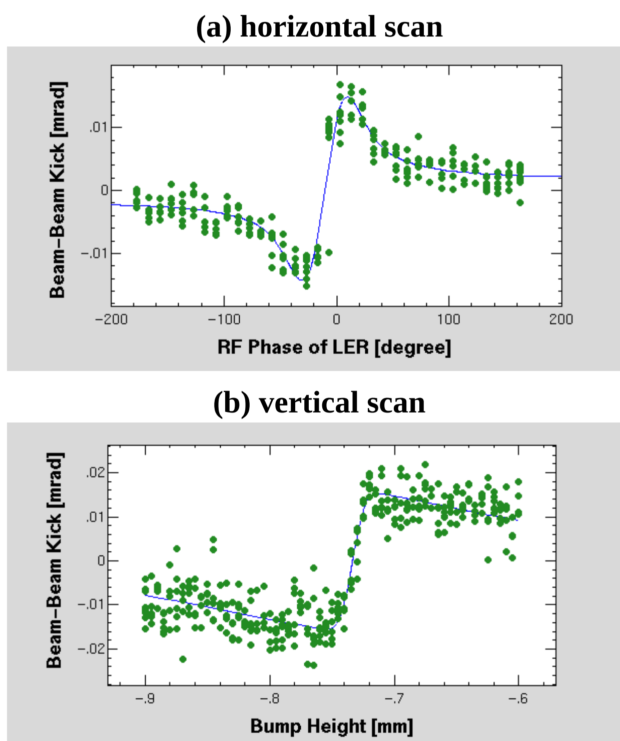

Figure 5: The beam-beam deflection in (a) horizontal and (b) vertical planes, during the multi-bunch collision in Mar. 1999. Lines are fitted curves for Gaussian bunches.

Collision of the two beams has been tried three times,[8] once per month since February. In February the first collision was done with single bunches, and horizontal and vertical beam-beam deflections were clearly observed. The horizontal deflection was detected by changing the RF phase of the LER, looking at BPM readings of the HER. Due to the finite crossing angle at the IP, the change in RF phase shifts the longitudinal collision point and the horizontal separation of the two beams. The measured horizontal offset between the beams is cancelled by use of horizontal dipole correctors. The vertical deflection was measured by scanning a vertical bump orbit in one ring, looking at the BPM signals of the other ring. It was interesting that there was a vertical offset between the two beam of 0.73 mm at the IP.

In March, a multi-bunch collision was tried with the parameters shown in Table 5. The resultant deflection curves are shown in Fig. 5. There was also a successful single-bunch collision, and the vertical offset remained the same after 50 days from the previous single-bunch collision. There was also a correlation between the beam-beam deflection and Bhabha events in the BEAST detectors. Unfortunately the orbit drift was not cured then, so it was hard to obtain a real luminosity for substantial duration.

In April there was a third trial of the collision to establish conditions with high current. This time, the orbit vibration in the LER at about 14 Hz strongly disturbed the vertical deflection signal. The vibration had disappeared fortuitously during the collisions in February and March. Also the lifetime of the LER was shortened during the vertical scan when the two beams became closer than about 30 μm. It is not known whether this loss of lifetime is related to the vibration or not. Another suspected cause of the loss of lifetime is the blowup of the vertical beam size at high current.

Optimization of the collision conditions such as tunes, orbits, beam sizes, etc. will be necessary after the roll-in of Belle.

4 DETECTOR BACKGROUND

The beam background at a detector is always a serious problem for a good and clean experiment. In an experiment with a high current collider like KEKB, it is one of the biggest concerns in two respects: radiation damage of the detector material; and high occupancy of the detector signal due to beam background.

To monitor the beam back ground during commissioning, the BEAST detector was installed around the IP chamber. It consists of 24 PIN diodes, 53 propotional counters, 10 CsI counters, 72 BGO counters and other dosimeters such as MOSFETs. Background optimization has been made by tuning the masks in the arc and at the IP, injection orbit and phase, matching wih the transport line, and so on. By a series of optimizations, the background at injection, which was the dominant source of background at the early stage of commissioning, is now comparable with the background due to stored current. The background during storage mode is almost decided by the vacuum level inside the beam pipe and, therefore, has been gradually improved.

For the HER beam, the background measured now is nearly propotional to the beam current and not quadratic. This implies that background reduction due to vacuum improvement is reaching its limit. By energy spectral measurement of background, SR can be excluded as the dominant source of the current background. The dependence of dose on radial distance from beam indicates a somewhat uniformly distributed background component, which may be generated away from the IP. One candidate source is a hot spot down stream of the IP where several beam loss monitors exhibit large activity. Further investigations are necessary to identify and extinguish it. The LER on the other hand still exhibits a quadratic dependence of background on beam current and, therofere, the background is decreasing along with vacuum improvement. Together with the fine tuning of several parameters mentioned above, LER background in storage mode has also been reduced much and is better than the one in HER.

Although the current level of background is still higher than expected at the design stage of the BELLE detector, it becomes just possible to operate the BELLE detector in this background environment with a reasonable life time due to radiation damage. Further improvement is expected by the installation of additional arc masks for both the LER and the HER and reinforcement of shielding in front of the detector.

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