COMMISSIONING OF POSITRON DAMPING RING AND THE BEAM TRANSPORT FOR SuperKEKB

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Abstract

The Positron Damping Ring (DR) for SuperKEKB successfully started its operation in February 2018, and the commissioning was continued until the end of SuperKEKB Phase 2 in July without serious troubles. This paper describes achievements of the beam commissioning of injection and extraction lines (LTR and RTL) between the LINAC and DR. In the LTR commissioning, the positron beam with high emittance, wide energy spread, and high charge were transported and injected into the DR. In the RTL commissioning, special cares were necessary to preserve the low emittance. The observed emittance growth in the RTL was not a problem for Phase 2, but it should be resolved in the coming Phase 3. In this proceedings, the commissioning of the DR will be also reported.

INTRODUCTION

SuperKEKB [1] is a double-ring asymmetric collider with 7 GeV electronic ring (HER) and 4 GeV positron ring (LER) in which the Belle II detector is installed. The previous KEKB accelerator [2], which had been in operation from 1999 to 2010, recorded the world's highest luminosity at that time, 2.1×10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. In order to increase the peak luminosity by 40 times of KEKB, a beam collision called "Nano beam scheme" are adopted, and the injection beam is required to have low emittance. Since the stored beam has low emittance and high current, the lifetime is short, so that the charge of the injection beam to be supplied must also be high. We adopted an RF gun [5, 6] for generating the electron beam, and a flux concentrator [7](FC) and a damping ring for the positron beam. The FC is a pulsed solenoid installed in right after the positron target to collect positrons coming from the target with high efficiency. The resulting longitudinal phase distribution of the positron is huge, requiring some schemes for transporting the beam to DR efficiently as written in [8].

SuperKEKB is operated in Phases 1, 2, and 3 for each purpose. In February 2016, we succeeded Phase 1 [9, 10] for about 5 months without a Belle II innermost detector, without collision. After remodeling about a year and a half further, a DR commissioning from January 2018, and a collision experiment (Phase 2 [11]) from March to July were carried out without incorporating a part of the Belle-II innermost detectors. The required parameters for the positron injection beam of SuperKEKB-LER are shown in Table 1. These values gradually approaches the final values according to the collision performance such as β^* .

As shown in Fig. 1, the DR is a ring with a circumference of about 135.5 m installed about 120 m downstream the positron target of the LINAC. The positron beam is extracted from the end of sector 2 of the LINAC whose energy is 1.1 GeV, and injected into the DR. Since the beam of enormous energy spread from FC exceeds the energy acceptance of the DR, an energy compression system (ECS) is installed in the first arc of the LTR. The damped positron beam from the DR is returned to the entrance of Sector 3 of the LINAC. The acceleration frequency of the DR is about 508.9 MHz, which is same as SuperKEKB, the resulting bunch length is too long to return to the LINAC with acceleration frequency 2856 MHz (S-band). Thus the RTL has a bunch compression system (BCS) in the second arc. Fig. 2 shows the particle distribution in the longitudinal phase space simulated with the parameters on Table 2 before and after the DR. The parameters from the DR are modified from the initial design [3]. Since the RF voltage has been changed from the design value of 1.4 to 1.0 MV, the emittance is changed from 89 μm to 64.3 μm. As shown in Figure 2, since positron from the FC has a long energy tail in the LTR, the beam passing through the ECS causes beam loss in the LTR and the DR. We set up 4 collimators in the arc section of the ECS cutting the

Table 1: Required parameters of injection beam for SuperKEKB-LER Phase 2 and 3

	DR Extraction	Phase2	Phase3–
$\gamma\epsilon_x$ [μm]	64.3	< 200	< 100
$\gamma\epsilon_y$ [μm]	3.2	< 40	< 15
σ_δ [%]	0.055	0.16	0.10
Charge [nC]	1.5	1.5	4.0

Table 2: Design Parameters of the Injection and Extraction Beam for DR (* shows a full width.)

Parameters	ECSin	ECSout =DRin	BCSin =DRout	BCSout
$\gamma\varepsilon_x$ [μm]		2800	64.3	
$\gamma\varepsilon_y$ [μm]		2600	3.2	
σ_z [mm]	±8*	±30*	6.6	1.3
σ_δ [%]	±5*	±1.5*	0.055	0.8
R_{56} [m]	–0.61			–1.05
V_c [MV]	41			21.5

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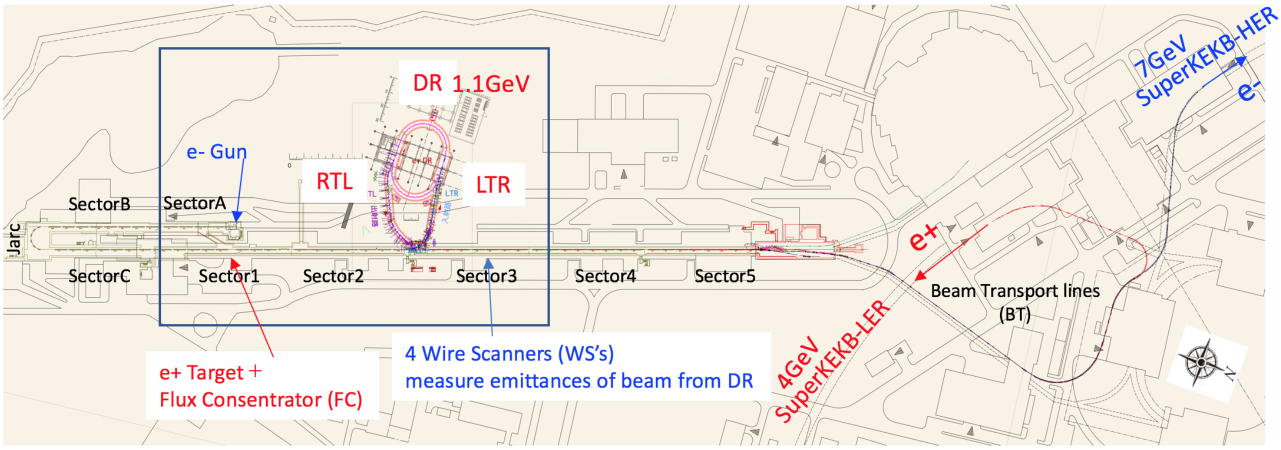

Figure 1: The LINAC consists of eight sectors from Sector A, B, C, and 1 to 5 starting from the electron sources. The electron and positron beams are accelerated up to 7 GeV and 4 GeV, respectively, and are injected into the HER and LER of SuperKEKB via each beam transport line (BT). Both of the injection/extraction lines for the DR (LTR/RTL) have two arc sections with straight sections between them.

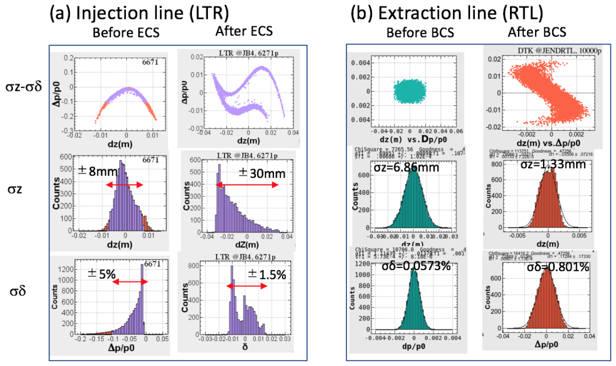

Figure 2: Simulated distributions of longitudinal phase space before and after ECS, and those of BCS.

energy tail beforehand (red part in (a) Before ECS) to make the energy spread within ±5%. In the ECS downstream it is compressed to ±1.5%, which safely enters into the DR bucket height ±1.5%. The bunch length of the beam extracted from the DR is compressed from 6.6 mm to 1.3 mm with the BCS. Although for V_c =18.4 MV, the bunch length is compressed to the minimum at the BCS exit, 21.5 MV was adopted, since the simulation shows that the energy spread at the injection point to LER is small. Because the bunch length of the beam in the BCS and ECS is longer than the frequency of S-band, the sine wave of S-band is visible as in "After ECS/BCS" in Fig. 2. By choosing the parameters (R_{56}, V_c) as in Table 2, the beam can be transported almost without loss.

COMMISSIONING OF LTR

LTR commissioning was started on Jan. 23rd, 2018. Initially the beam was guided by inserting a beam shutter in the end of the LTR not to go to the DR, and on the next day, reached the beam shutter. At that time, the FC was set to standby and the charge was 0.75 nC. The beam loss in the DR, LTR and RTL was strictly controlled because of the radiation limit. Figure 3 shows the beam optics of the LTR. Four collimators are installed in the first arc where the horizontal dispersion is large.

Tuning of LTR

Actually in order to adjust the beam with asymmetric distribution from the FC as shown in Fig. 2-(a), the information from beam position monitors (BPMs) should not be used for the steering. Therefore, we first made core "Ginjo" [12] beam by using the four collimators. As shown in the upper row in Figure 4, the energy peak of the beam was adjusted as to come to the center of the vacuum chamber using the energy knob in the sector 2, and collimated so that only the peak part is left, which is called "Ginjo" beam. The zero-crossing of the ECS acceleration phase is measured with the "Ginjo" beam. Specifically, the phase where the

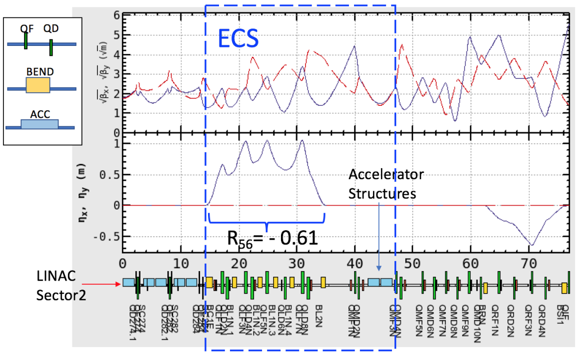

Figure 3: Beam optics of the LTR. The upper graph shows the horizontal (blue) and vertical (red) beta functions. The lower graph shows the horizontal dispersion. The horizontal axis is the distance in meter from the end of Sector 2 in the LINAC. R_{56} of the first arc of the LTR and V_c of the downstream accelerating structure constitute the ECS.

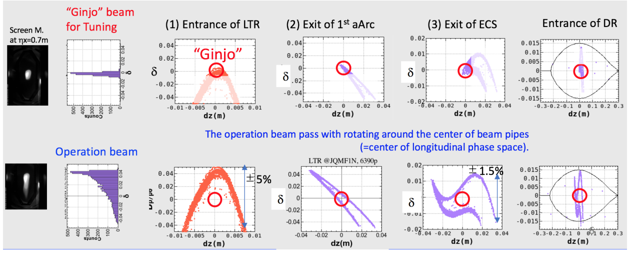

Figure 4: Distributions in the longitudinal phase space at each location. The upper row shows the distributions of the "Ginjo (core) beam" for the tuning of the LTR. The small circles are the center of the longitudinal phase space, where the "Ginjo" beam is to be positioned. The lower row shows those of the operation beam with wider spread.

beam energy does not change between on/off of the ECS acceleration is measured. It was confirmed by the displacement of the downstream LTR 2nd arc with a large horizontal dispersion.

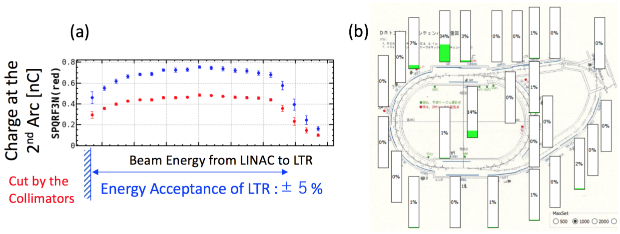

Figure 5: (a) The energy acceptance of the LTR. The horizontal axis represents the energy of the "Ginjo" beam in an arbitrary unit. (b) The green bars show the beam loss measured the beam loss monitors around the DR, which are within the allowable level.

The result of measured energy acceptance of the LTR 1st arc by using the "Ginjo" beam is shown in Fig. 5-(a). It is cut by the collimator during operation where the low energy beam of the first arc passes indicated by the dashed line on the left side of the figure. Tuning of injection to the DR is also performed only using the "Ginjo" beam, and once adjusted, the ECS and the DR injection parameters should not be tuned with the beam for operation. At the end of these tuning processes, we returned to the operation beam, opened the collimators, and increased the beam energy by +5% higher than the "Ginjo" beam. By this tuning, the operating beam rotates around the center of the phase space where the "Ginjo" beam has passed, that corresponds to the center of the vacuum chamber and the longitudinal phase space, then the beam loss is minimized. Other basic measurements, such as 3-BPM measurements, local bump study, beam based alignment (BBA), and single kick response measurement, were made.

Effect of FC

On February 22nd, the FC was turn on. By turning on the voltage of the FC at 5 kV, the charge passing the LTR increased to about 1.5 nC which roughly doubled that without the FC. The measured emittance by the four wire scanners [13] installed in the straight section of the LTR is shown in Table 3. The results are almost same as the design emittances as shown in "DRin" of Table 2, and there was no significant difference in the emittance measured on and off of FC. The beam loss measured by the beam loss monitors [14] around the DR were small enough as shown in Fig. 5-(b).

Table 3: Measured emittances by wire scanners at the straight section of LTR when the FC is stand-by and on.

	FC: Stand-by	FC: 5kV
$\gamma\epsilon_x$ [μm]	2350	2760
$\gamma\epsilon_y$ [μm]	2310	2450
Charge [nC]	0.75	1.5

COMMISSIONING OF DR

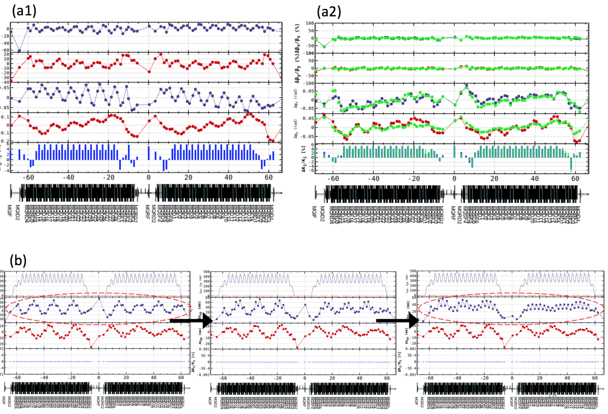

Figure 6: (a1, a2)The measured optics before and after correction, respectively. The upper two rows represent the horizontal and vertical beta beats, and the third and fourth show the deviation of betatron phases from the of the design. The green dots in (a2) show the corrected value. (b) The rows are the design horizontal dispersion, the measured difference of the horizontal and vertical dispersions. The correction was applied twice, from left to right.

The first commissioning of the DR and the beam transportation to the end of LINAC were done in three days. That was, the tuning of timing for the injection septum, kickers, and BPMs in the DR, orbit tuning, RF capturing, the tuning of timing for the extraction septum, kickers, and BPMs in the RTL, orbit tuning, BCS of the RTL tuning, and LINAC tuning. The optics corrections of the DR were done as shown in Fig. 6. As shown in Fig. 6-(a2), the β-functions are somewhat improved by the correction, but the phase advances have systematic slopes. Further after the β correction, the dispersion corrections were done two times, but a pattern reflecting the horizontal dispersion of the model gradually appears. Further investigation is necessary.

The model lattice of the DR was wrongly specified in SAD in the definition of the fringe field of dipoles at the first operation time. After corrected that, the imbalance between the correction coefficients of the quads were improved from 11% to 5%. The reason why the coefficient is still too large is under investigation. The calibration of magnetic measurements are in question. More basic measurements including the beam size, tunes, and so on should be done.

COMMISSIONING OF RTL

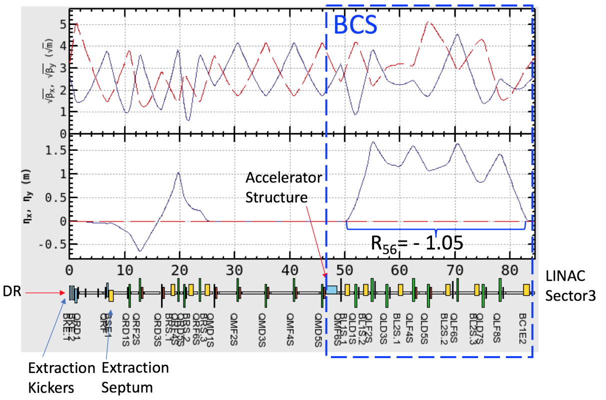

Figure 7: Beam optics of the RTL. The BCS consists of V_c of the S-band acceleration tube installed in the straight section of RTL and R_{56} of the second arc. The notations are same as Fig. 3.

On February 8th, as the beam revolved around the DR, it was extracted to the RTL at the same time, and on February 10th the beam after tuning of the BCS was transported to the beam dump at the end of the LINAC. The low emittance beam from the DR has fewer worries of beam loss unlike at the time of the LTR, but there is a difficulty in keeping the low emittance during the transportation. Since the beam distribution from the DR is clearly Gaussian, it is already "Ginjo" beam. Figure 7 shows the optics of the RTL.

Tuning of BCS from RTL to the end of LINAC

Like the ECS of the LTR, the BCS acceleration was set to standby first, the orbit was corrected, and even if the acceleration was turned on, the RF phase where the orbit does not move was set at the zero cross. Since a streak camera in Sector 3 was not ready yet at that time, we distinguished whether the RF phase is zero or π by looking at screen monitors where the horizontal dispersion exists. However, without the judgment, it can also be confirmed that in the case of the opposite phase, the beams do not pass well from Sector 3 to Sector 5. After setting the phase of the BCS, we adjusted the RF phase of the acceleration of Sector 3 to 5. The energy spread at the end of LINAC was ±0.3% in full width in the screen monitor, which satisfies the requirement from SuperKEKB-LER of Table 1.

Table 4: Measured emittances by wire scanners at Sector 3

	Measured Emittance	DR Design
$\gamma\varepsilon_x$ [μm]	126±8.2	64.3
$\gamma\varepsilon_y$ [μm]	1.5±0.1	

EMITTANCE GROWTH

The emittances of the positron beam from the DR and RTL are measured at Sector 3 in LINAC with four wire scanners as shown in Table 4. Assuming that the horizontal emittance is same as the design value of the DR and the vertical emittance of the DR is less than the measured value in Sector 3, the emittance ratio of the DR is presumed to be less than 2.3%. The question is that the measured horizontal emittance at Sector 3 is larger than the design value by a factor of 2. The measured emittances have two dependencies. One is the BCS-voltage dependence of the horizontal emittance as shown in Figure 8, another is bunch charge dependence as shown in Table 5. The measured horizontal emittance depends on the bunch length and/or energy spread. The $\gamma\varepsilon_x$ measured at Sector 3, even minimum of them, is larger than the design value of the DR. Furthermore, the emittance growth of both the horizontal and vertical emittances are observed by increasing the bunch charge. We suspected the blowup of the emittance is caused by longitudinal coherent synchrotron radiation (CSR) in the bending magnets at the arc sections of the RTL. The wake potential from the longitudinal CSR is shown in Figure 9 [15] by a numerical simulation. The values are in good agreement in the theoretical ones. The resulting emittance growth by tracking simulation is shown in Table 6. Clearly seen in the table, the effect of the longitudinal CSR effect on the emittance growth

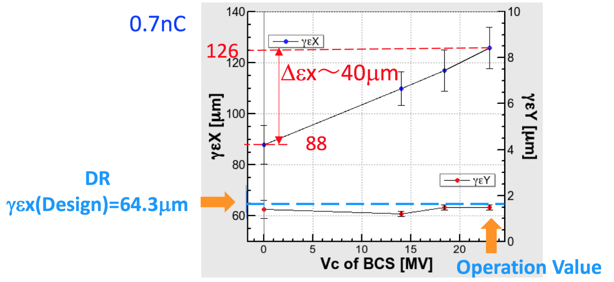

Figure 8: BCS-voltage dependence of the horizontal emittance. The blue and red dots show the measured normalized horizontal and vertical emittances. The blue dashed line shows the design emittance of the DR. The operation voltage of the BCS is 23 MV.

Table 5: Bunch charge dependence of the horizontal emittance

Charge [nC]	V$_{BCS}$ [MV]	$\gamma\varepsilon_x$ [μm]	$\gamma\varepsilon_y$ [μm]
0.7	0	88±7.6	1.4±0.4
1.5	0	104±7.4	3.7±0.5

is negligibly small. A possibility of another cause is that the residual dispersion from the arcs of the RTL makes the beam size blow-up, and the transverse wake field in Sector 3 also causes an emittance growth with the charge increase. Thus these emittance growth is still mystery. Anyway, the measurement of the emittance in the DR is also necessary.

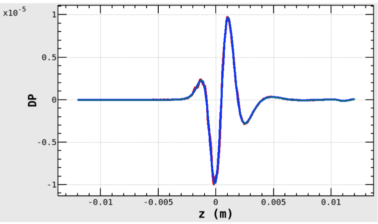

Figure 9: The wake potential of the longitudinal CSR of single-bunch effects in RTL. The blue and red lines show the wake potential from the theoretical calculation and simulation, respectively.

Table 6: The effects of CSR on emittance

V_{BCS} [MV]	Q [nC]	$\Delta\varepsilon_x/\varepsilon_x$
21.5	0.7	$3.2{\times}10^{-6}$
21.5	4.0	$3.1{\times}10^{-5}$
0	4.0	$1.1{\times}10^{-8}$

CONCLUSION

The first commissioning of the LTR, DR, and the RTL for SuperKEKB were successfully and quickly done. No serious trouble was occurred. The injection into the LER of SuperKEKB in Phase 2 has been done safely and continuously. The basic parameters of DR should be measured in the next run. An emittance growth from the DR to Sector 3 was observed. The BCS-voltage and bunch charge dependences of the horizontal emittance have been mystery. We have more serious emittance growths in the LINAC and Beam Transport line (BT) to LER [17]. More investigations should be done before SuperKEKB Phase 3 operation.

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