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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 paper, brief results of the commissioning of the DR is also reported.

INTRODUCTION

SuperKEKB [1] is a double-ring asymmetric collider of 7-GeV electron ring (HER) and 4-GeV positron ring (LER) with the Belle II detector installed in the interaction region. The KEKB accelerator [2], the predecessor had been in operation from 1998 to 2010, with the then world's highest luminosity of 2.1×10^{34} $cm^{-2}s^{-1}$. To increase the luminosity by 40 times of KEKB, a new collision scheme called "Nano beam scheme" are adopted as well as two times high stored current is required. Since the stored beam has low emittance and high current, the lifetime is short, and the charge of the injection beam must also be high. We adopted an RF gun [3, 4] for generating the low-emittance electron beam. For positrons a flux concentrator [5](FC) as well as a damping ring had been adopted. The FC is a pulsed solenoid installed in right after the positron target to collect positrons generated at the target with high efficiency. The longitudinal phase distribution of the positron is huge, requiring some schemes for efficiently transporting the beam to DR as written in [6].

SuperKEKB is divided in three phases in its operation. In February 2016, we succeeded in operation of Phase 1 [7, 8] for about 5 months without Belle II detector, without collision. Completing construction of super-conducting final quadrupoles in a year and a half further, commissioning of DR and the collider with Belle II (Phase 2 [9]), in which a part of innermost detectors were unmounted, have commenced on January and March 2018 respectively. The required parameters for the positron injection beam of SuperKEKB-LER are shown in Table 1. It should be noted that these values are defined as "ultimate" parameters in each stage that should be realized in harmony with a development of collision performance.

As shown in Fig. 1, the DR, a 1.1-GeV storage ring with a circumference of about 135.5 m has been constructed at 120 m downstream the positron target of the LINAC [10]. 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 enormous energy spread from FC exceeds the energy acceptance of the DR, an energy compression system (ECS) is installed utilizing the first arc of the LTR. The damped 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 that of SuperKEKB, the resulting bunch length is too long to be accepted to the LINAC with acceleration frequency 2856 MHz (S-band). Thus a bunch compression system (BCS) in the second arc of RTL was installed. Figure 2 shows the particle distribution before and after the DR in the longitudinal phase space simulated with the parameters on Table 2. The parameters from the DR are modified from the initial design [11] to match the changes in the RF voltage from the design value of 1.4 to 1.0 MV, with the emittance accordingly changed from 89 μm to 64.3 μm. As shown in Fig. 2, since positrons from

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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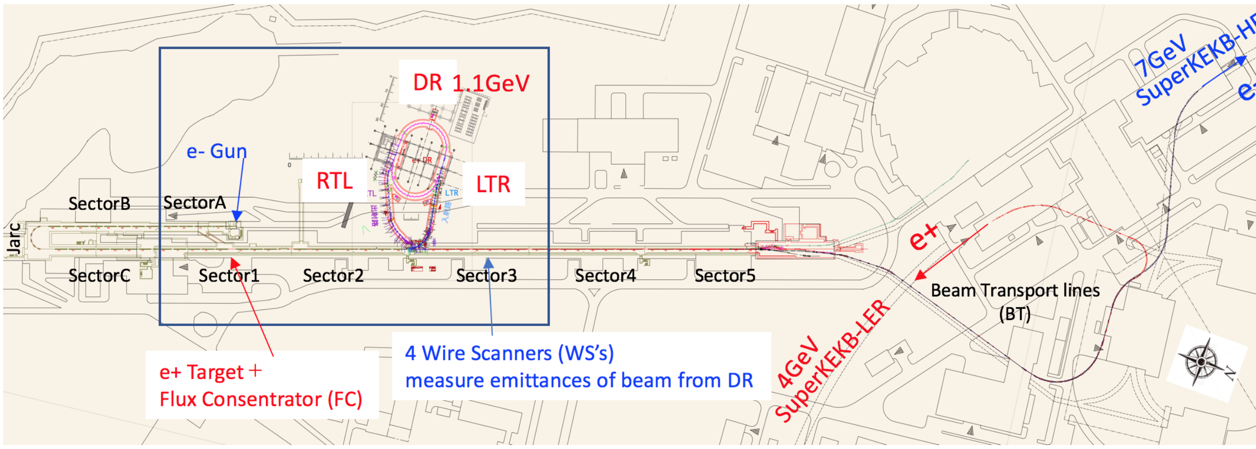

Figure 1: The LINAC consists of eight sectors from Sector A, B, C, and 1 to 5 starting from the electron sources. The electron and positron beams are accelerated up to 7 GeV and 4 GeV, respectively, and are injected into the HER and LER of SuperKEKB via each beam transport line (BT). Both of the injection/extraction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

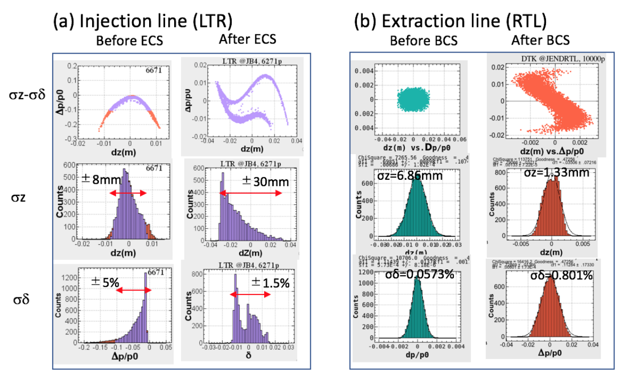

Figure 2: Simulated distributions of longitudinal phase space before and after ECS, and those of BCS.

the FC have a long energy-tail, which cannot be accepted in the DR even with ECS, we installed four collimators in the arc section of the LTR to prevent the tail particles with an energy deviation larger than 5% from passing through the LTR. The energy spread of remaining particles is compressed to ±1.5%, the DR bucket height. The bunch length of the extracted beam 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, the voltage 21.5 MV was adopted, since the simulation shows that the energy spread at the injection point to LER is optimum, owing to gymnastics in the longitudinal plane in the downstream. Because the bunch length of the beam in the BCS and ECS is not negligible with respect to the frequency of S-band, an effect of RF curvature is visible as in "After ECS/BCS" in Fig. 2. With the parameters (R_{56}, V_c) as in Table 2, the beam can be transported without notable loss.

COMMISSIONING OF LTR

LTR commissioning was started on Jan. 23rd, 2018. Initially the beam was guided by inserting a beam shutter at the end of the LTR to prevent the beam from going to the DR, and on the next day, reached the beam shutter. At that time, the FC was out of operation and the charge was 0.75 nC. The beam loss in the DR, LTR and RTL had to be strictly controlled because of the radiation limit. Figure 3 shows the beam optics of the LTR.

Tuning of LTR

Since the energy distribution is far from symmetry as shown in Fig. 2-(a), the information from beam position monitors (BPMs), which is the center of gravity of the beam, should be used with care for steering. Therefore, we first made core "Ginjo" [12] beam by using the four collimators. As shown in the upper row in Fig. 4, the highest energy could be definitely identified observing the profile monitor, and the energy peak of the beam was adjusted so as to be placed at the center of the vacuum chamber using the energy

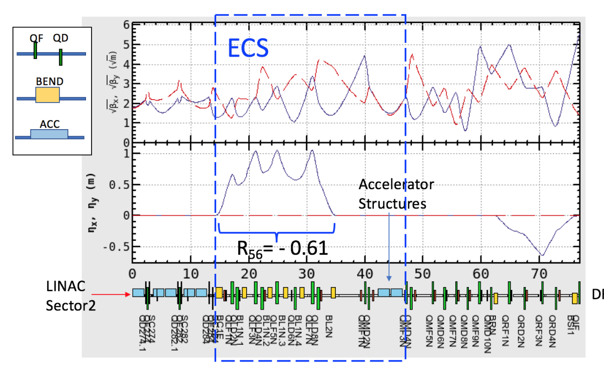

Figure 3: Beam optics of the LTR. The upper graph shows the horizontal (blue) and vertical (red) beta functions. The lower graph shows the horizontal dispersion. The horizontal axis is the distance in meter from the end of Sector 2 in the LINAC. R_{56} of the first arc of the LTR and V_c of the downstream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

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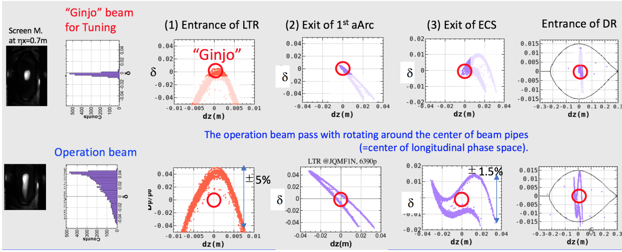

Figure 4: Distributions in the longitudinal phase space at each location. The upper row shows the distributions of the "Ginjo (core) beam" for the tuning of the LTR. The small circles are the center of the longitudinal phase space, where the "Ginjo" beam is to be positioned. The lower row shows those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

knob of Sector 2, and then collimator was adjusted so that only the peak part is left, which is called "Ginjo" beam here. The ECS RF-phase was zeroed using the "Ginjo" beam. Specifically, the zero phase is identified as the phase that the beam energy does not change even if ECS RF is off and on, which can be confirmed by observing the position change at the downstream of LTR 2nd arc that has a large horizontal dispersion.

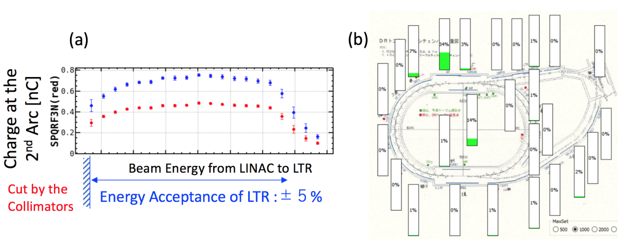

Figure 5: (a) The energy acceptance of the LTR. The horizontal axis represents the energy of the "Ginjo" beam in an arbitrary unit. (b) The green bars show the beam loss measured the beam loss monitors around the DR.

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 1st arc passes indicated by the hatching on the left side of the figure. Parameters of ECS and injection to the DR were searched only using the "Ginjo" beam, and once determined, these parameters were maintained during operation unless the machine is unexpectedly changed. After tuning process using "Ginjo" beam is completed, we returned to the ordinary beam, opened the collimators, and increased the beam energy by +5% with respect to the "Ginjo" beam. By this tuning, the beam is rotated in the longitudinal phase space around a center, where the "Ginjo" beam sits on, and in the physical space, the beam with energy spread of ±5% is placed around the center of beam pipe. Other basic beam-based measurements, such as 3-BPM measurements, local bump study, beam based alignment (BBA), and single kick response measurement, had been performed.

Effect of FC

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

On February 22nd, the FC was turned on. By setting the voltage of the FC at 5 kV, the charge passing the LTR increased to about 1.5 nC which roughly doubled that with the FC switched off. The measured emittance using four wire scanners [13], which are 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).

COMMISSIONING OF DR

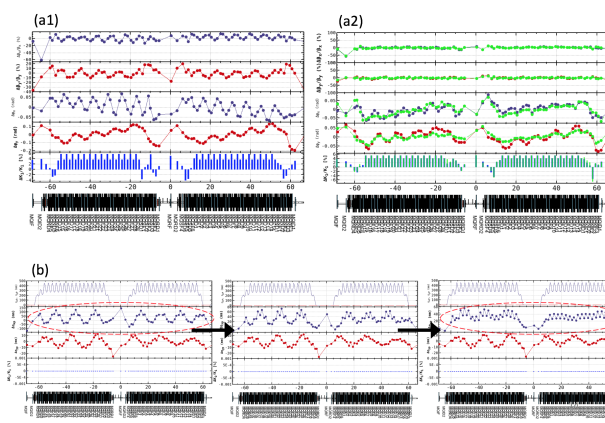

Figure 6: (a1, a2) show the measured optics before and after correction, respectively. The upper two rows represent the horizontal and vertical beta beats, and the third and fourth show the deviation of betatron phases from the design values. The green dots in (a2) show the corrected value. (b) The rows show the design horizontal dispersion, the measured difference of the horizontal and vertical dispersions from upper side. 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 includes tunings of timing for the injection septum, kickers and BPMs in the DR, orbit tuning, RF capturing, tunings of timing for the extraction septum, kickers and BPMs in the RTL, orbit tuning, BCS of the RTL, and LINAC tuning. The optics corrections of the DR were made with the results shown in Fig. 6. As shown in Fig. 6-(a2), the β-functions are somewhat improved by the correction, but phase advances

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have systematic slopes. After the β correction the dispersion corrections were made, but a pattern of horizontal dispersion remained. Further investigation is necessary.

In the first stage of operation a model parameter of fringe field was wrongly assigned. Even after the correction the fudge factors of 5% still exists in the arc quads. Calibration of bends and quads in the field measurement might be a reason.

COMMISSIONING OF RTL

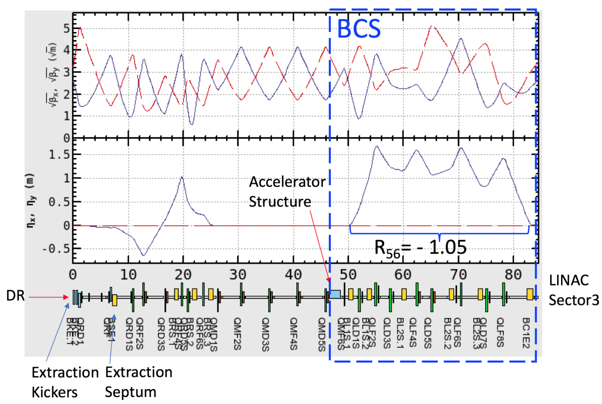

Figure 7: Beam optics of the RTL. The BCS consists of V_c of the S-band acceleration tube installed in the straight section of RTL and R_{56} of the second arc. The notations are same as Fig. 3.

Tuning of BCS from RTL to the End of LINAC

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 procedures of BCS paralleled with those of ECS; RF of BCS was set to standby first, the orbit was corrected, and the RF was turned on, finding the zero-cross phase. Since a streak camera in Sector 3 was not ready at that time, we identified a proper phase between two possibilities of 0 and π observing screen monitors where the horizontal dispersion exists. Actually however, it can also be confirmed by the fact that in the wrong phase, the beam does not pass well to Sector 5. After setting the phase of the BCS, we adjusted the RF phase of Sector 3 to 5. The energy spread at the end of LINAC was measured to be ±0.3% in full width with the screen monitor, which satisfies the requirement in Table 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, the emittance ratio of the DR is presumed to be less than 2.3%. The major issue is that the measured horizontal emittance at Sector 3 is larger than the design by a factor of 2.

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	

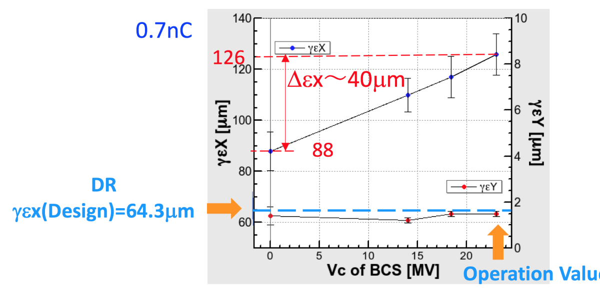

Figure 8: BCS-voltage dependence of the horizontal emittance. The blue and red dots show the measured normalized horizontal and vertical emittances. The blue dashed line shows the design emittance of the DR. The operation voltage of the BCS is 23 MV.

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

The measured emittances depend on BCS voltage as well as the bunch charge as shown in Fig. 8 and 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 larger emittances in both the horizontal and vertical planes are observed with higher bunch charge. We have checked a possibility that the emittance is caused by coherent synchrotron radiation (CSR) in the bending magnets at the arc sections of the RTL. The wake potential of the CSR is shown in Fig. 9 [15]. The resulting emittance growth by tracking simulation is shown in Table 6. The effect of the CSR on the emittance growth is negligibly small. Other possibilities are residual dispersion at the wire scanners, and the transverse wake field in Sector 3. Anyway, the measurement of the emittance in the DR is also necessary.

CONCLUSION

The commissioning of the LTR, DR, and the RTL for SuperKEKB were successfully done for a short time. No

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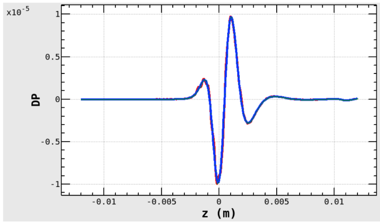

Figure 9: The wake potential of the longitudinal CSR of single-bunch effects in RTL. The vertical scale is the relative momentum change, $\Delta p/p$ for bunch charge 4 nC. The blue and red lines show the wake potential from the theoretical calculation and simulation, respectively.

Table 6: The effects of CSR on emittance

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

serious trouble occurred. The emittance of DR should be measured in the next run. An emittance growth from the DR to Sector 3 was observed. It depends on the BCS-voltage and bunch charge. More investigations should be done before Phase 3 operation.

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