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COMMISSIONING OF THE PHASE 2 AND PHASE 3 SuperKEKB / B-Factory

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Abstract

SuperKEKB is an asymmetric-energy electron-positron collider for Belle 2 experiment to search new phenomena in B-meson decays. Designed luminosity of the SuperKEKB is 40 times higher than that of KEKB. In order to accomplish the high luminosity, beam currents of the both beams are twice as large as that of the KEKB and vertical beta function at interaction point (IP) is squeezed down to bunch length by using the novel "nano-beam" collision scheme. After phase 1 commissioning without collision, final focus superconducting magnet system (QCS) and Belle 2 detector without a vertex detector were installed in interaction region (IR). Then phase 2 commissioning with beam collision to confirm the "nano-beam" scheme had been successfully completed in 2018. The vertex detector was installed in the Belle 2 detector before phase 3 commissioning. The phase 3 commissioning for the full-scale collider experiment had been started at 11 March 2019. We report the recent progress and accomplishments of the commissioning in phase 2 and 2019 spring operation of phase 3.

INTRODUCTION

The SuperKEKB is an asymmetric-energy electron-positron collider [1] constructed by 7 GeV electron high energy ring (HER) and 4 GeV positron low energy ring (LER). Its design luminosity is 8×10^{35} cm^{-2}s^{-1}, which is 40 times the performance of the previous KEKB B-factory, which had been operated for 11 years until 2010 [2]. To achieve such high intensity, the SuperKEKB is designed using a "nano-beam" scheme based on large-angle collision scheme, which was first proposed by P. Raimondi [3]. When sufficiently narrow beams are collided with a large crossing angle, longitudinal overlap of the colliding beams is shortened. As a result, the luminosity is expected to be increased by squeezing vertical beta-function at the IP (β_y^*). The "nano-beam" scheme does not require extremely short bunch length to increase the luminosity, so the bunch length comparable to that of the KEKB is allowed. The SuperKEKB is designed to achieve such high luminosity, which is 40 times higher than that of the KEKB, by doubling stored beam current and squeezing β_y^* down to 1/20 of the KEKB.

The SuperKEKB commissioning is divided by 3 stages; phase 1, phase 2 and phase 3. The phase 1 was started after the LER and the HER had been modified. The phase 1 commissioning [4] without the QCS and the Belle 2 detector was performed from February 1, 2016 to June 28, 2016. The subjects were low emittance tuning for new arc lattice, vacuum scrubbing for new vacuum vessels replace with ante-chambers, and beam background study for preparing to installation of the Belle 2 detector. The QCS and the Belle 2 detector except for the vertex detector were installed during a long shutdown between the phase 1 and the phase 2.

The phase 2 commissioning [5] was performed from March 19, 2018 to July 17, 2018 in order to confirm the "nano-beam" scheme. Prior to the main ring commissioning, beam commissioning of a positron damping ring had started on February 8, 2018. Specific luminosity as a function of bunch current product multiplied by number of bunches was improved by squeezing β_y^* down to 3 mm, which is almost half of the bunch length, in the phase 2 commissioning. After the phase 2 commissioning, the IR had been reconstructed in order to install the Belle 2 detector with the vertex detector into the IP.

First part of the following the phase 3 commissioning was performed from March 11, 2019 to July 1, 2019 with full-scale Belle 2 experiments. The major subjects of the 2019 spring operation were reestablishment of the luminosity performed in the phase 2 commissioning for further β_y^* squeezing, background study for improving the collision experiment data taking, and establishment of continuous beam injection with detector data taking to improve integral luminosity performance.

HARDWARE UPDATES

Between each commissioning states, the following hardware updates were carried out.

Between Phase 1 and Phase 2

System design of the QCS started in 2009 and construction was completed in March 2017. Figure 1 shows the layout of the superconducting magnets in two cryostats. The QCS consists of 55 superconducting magnets. The 25 magnets are assembled in QCS-L cryostats in the left side and the 30 magnets are assembles in QCS-R cryostats in the right side [6].

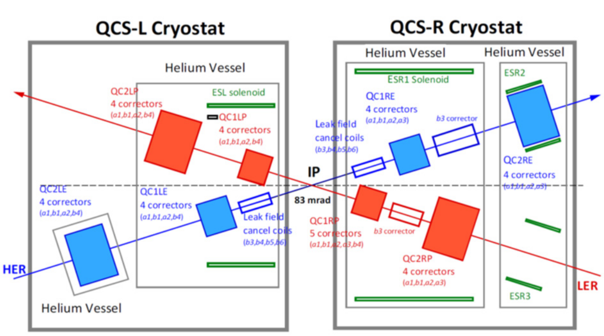

Figure 1: Layout of superconducting magnets in the QCS.

The QCS was commissioned from May to August 2017 after assembling cryostats into the Belle 2 detector without

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the vertex detector. In the QCS commissioning, the excitation to the operation currents, the magnetic field measurements and the operation stability of the system including the cryogenic system and power supplies for the magnets were confirmed. The 54 power supplies for superconducting magnets were newly manufactured. Stability on the specification of the 8 power supplies with a rated current of 2000 A for quadrupole magnets are 2 ppm / 8 hours. The rated current of the 43 power supplies for correction coils are ±70 A with stability of 5 ppm / 8 hours.

Two beam collimators, which were newly designed for SuperKEKB based on those used in PEP II at SLAC with the objective of minimizing the impedance [7], were installed in the LER for test in the phase 1. Since the predecessors worked well as expected, three new collimators were manufactured and installed for the LER and three for the HER.

Between Phase 2 and Phase 3

The Belle 2 detector with vertex detectors containing the silicon vertex detectors and the pixel detectors were installed into the IP. In order to incorporate the vertex detectors into the Belle 2 detector, accelerator devices including QCS have been disassembled and reassembled.

During the phase 2 commissioning, beam collimators, especially vertical collimators, were found to be important to protect superconducting magnets in QCS from beam-loss induced superconducting quench. The vertical collimator jaw of D01V1 collimator in the HER and D02V1 collimator in the LER were damaged by sudden unsteady main beam. These jaws were replaced. Five new collimators were installed to reduce beam back-ground signals on the detector and to protect the super-conductive magnets from the quench. D06H4 collimator in the LER was relocated to D06H1 in the LER.

Skew quadrupole corrector magnets in the IR have been improved to solve a lack of scan range of collision parameters in the IP for the luminosity tuning. The magnetic field of these corrector magnets was increased 2.23 times by adding extra winding coils. Skew quadrupole back-leg winding coils added to sextupole magnets are used for xy-coupling and dispersion correction. Almost half number of the skew quadrupole back-leg coils in the sextupole magnets installed in arc section were available in the phase 2. New power supplies for the unconnected skew quadrupole back-leg coils have been fabricated and then, all skew quadrupole back-leg coils in the sextupole magnets are available. As a result, all the magnets planned for the original design were in operation.

PHASE 2 COMMISSIONING

The phase 2 commissioning was started on March 16, 2018 with large beta-functions at the IP, which is called “detuned optics”, in order to capture beams. The horizontal beta-function at the IP (β_x^*) and β_y^* were β_x^* = 400 mm and β_y^* = 81 mm in the HER, β_x^* = 384 mm and β_y^* = 48.6 mm in the LER. The machine parameters were changed from non-collision optics to collision optics after the beta-functions at the IP were adopted to be 200 mm for β_x^* and 8 mm for β_y^*. Then, we observed the first hadronic event on 26 April 2018. The phase 2 commissioning was finished on 17 July 2018.

The beta-functions were gradually squeezed down to 100 mm for β_x^* and 3 mm for β_y^*. The history of the beta-functions for the luminosity run is shown in Table 1. The luminosity has increased even though is β_y^* smaller than the bunch length. Trial of squeezing β_y^* to 1.5 mm in the HER and 2 mm in the LER were performed in June 2018. These parameters could not be established for the luminosity run, but global optics correction was applied.

Table 1: History of the Beta-Functions

(β_x^*, β_y^*) [mm]	Established date in Phase 2		Established date in Phase 3	
	LER	**HER**	**LER**	**HER**
Detuned	3/31	3/20	3/13	3/11
(200, 8)	4/16	4/10	3/18	
(200, 6)	5/14	5/10	3/25	
(200, 4)	5/24		3/26	
(200_{LER} / 100_{HER}, 3)	6/5	6/20	3/28	4/1
(80, 2)	-		6/21	

Almost all parts of beam pipe in the LER have been replaced with new ones with ante-chambers and TiN coating before the phase 1. However, electron cloud effect (ECE) was observed in the phase 1 [8]. Vertical beam size blowing up and nonlinear behaviour of pressures were observed in the LER when the current linear density (I_d), which is the bunch current divided by the bunch spacing, exceeded 0.1. The threshold of the ECE in KEKB without solenoid coils was approximately I_d = 0.04. Installation of solenoid-like permanent magnets on bellows chambers relaxed the threshold to $I_d \sim 0.2$ in the phase 1. Then the solenoid-like permanent magnets were installed on about 86 % of the drift spaces before the phase 2 and approximately 91 % of the drift spaces were covered with them before the phase 3. The maximum I_d achieved by the phase 3 was 0.55 and the blow-up of the beam size was not observed. The design value of I_d is 0.72, where beam current is 3.6 A with 2500 bunches and the bunch spacing is 2 RF-buckets.

The superconducting magnets in the QCS made 27 times quench issues in the phase 2. When beta-functions were started squeezing down, injection beams made large beam loss around the IR due to injection errors with low beam current. The beam loss caused the most part of the quench issues before optics had been corrected and movable collimators had been adjusted. After these optimizations, several quench issues occurred when the beam currents increased larger than 500 mA. Collimator jaws were damaged with the quench issues simultaneously.

PHASE 3 COMMISSIONING

The phase 3 commissioning was started on March 11, 2019 with “detune optics”. Because the reproducibility is

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very good, the initial beam storage on the detuned optics has been achieved at March 11 for the HER and March 13 for the LER. The first season of the phase 3 in 2019 spring (phase 3-1) ended at July 1, 2019.

The maximum stored beam current in this season is 830 mA for the LER and 940 mA for the HER, respectively. The beam dose in the phase 3-1 is 500.3 Ah for the LER and 536.3 Ah for the HER, respectively. Average ring vacuum pressures normalized by a unit beam current (d*P*/d*I*) are shown in Fig. 2. The d*P*/d*I* has been smoothly decreased by vacuum scrubbing. At the end of the phase 3-1, the d*P*/d*I* for the LER is one order of magnitude higher than that for the HER. This is because most of the beam pipes in the LER had been replaced with new ones designed for suppression of the ECE before the phase 1.

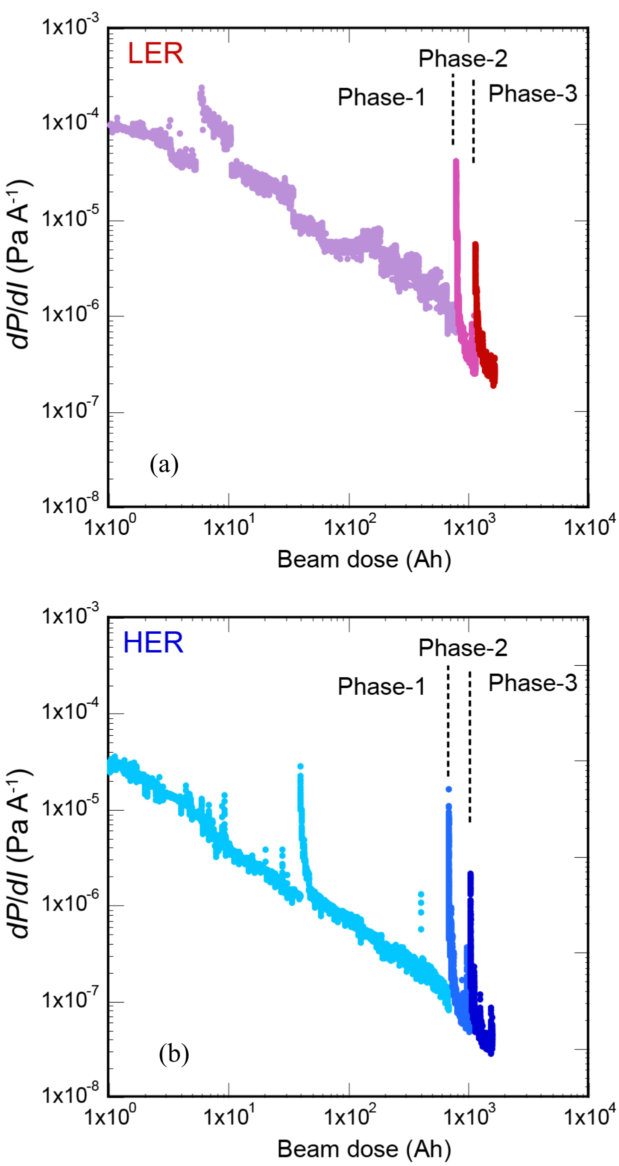

Figure 2: Average ring vacuum pressure normalized by a unit beam current for the LER(a) and for the HER(b).

The beta-functions at the IP were squeezed down via established optics in the phase 2. The history of the beta-functions at the IP is shown in Table 1. The squeezing β_y^* from the detuned optics to 3 mm collision optics is completed within 22 days without quench issues in the QCS. The additional collimators and fast abort signal from a diamond background detector in the Belle 2 detector are worked well to prevent the QCS quench owing to beam loss. The beta-functions at the IP was squeezed down to $(\beta_x^*, \beta_y^*) = (80, 2)$ on June 21, 2019. The peak luminosity with physics run was 4.39×10^{33} cm^{-2}s^{-1} at the most squeezed beta-functions. After collision tuning, the maximum peak luminosity of 1.23×10^{34} cm^{-2}s^{-1} was recorded at beam current of approximately 820 mA for the LER and 830 mA for the HER, although the Belle 2 detector could not be turned on due to high background rate from beam loss. Figure 3 shows the specific luminosity as a function of β_y^*. The specific luminosity increased in proportion to $1/\beta_y^*$, which is satisfied even for $\beta_y^* = 2$ mm.

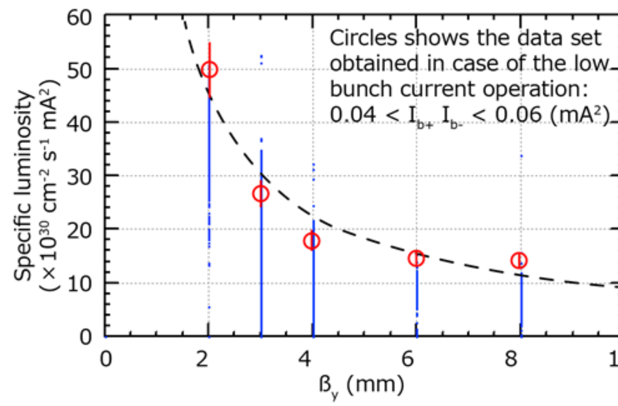

Figure 3: Specific luminosity as a function of β_y^*. Red circles show the data set obtained in case of the low bunch current operation; $0.04 < I_{b+}I_{b-} < 0.06$. Black dash line corresponds to $1/\beta_y^*$.

In order to increase integrated luminosity, continuous injection mode must be established. Due to high background rate on the Belle 2 detector during beam injection, the Belle 2 detector could turn on except during the beam injection. After the tuning of the beam injection to reduce the beam background on the Belle 2 detector, it is possible to inject the beams with the Belle 2 detector turned on. Thus, the integrated luminosity was exceeded 6 fb^{-1} at the end of the phase 3-1.

CONCLUSION

After the phase 1 commissioning, the QCS and the Belle 2 detector, without vertex detector, were installed in the IR and the phase 2 commissioning with beam collision was started. First collision and first hadronic event detected on April 26, 2018. After the phase 2 commissioning, vertex detector was installed in the Belle 2 detector and the phase 3 commissioning with full-scale collider experiment was started. The "nano-beam scheme" collision with the physics run was demonstrated down to $\beta_y^* = 2$ mm. The continuous injection for both rings is used in regular operation to increase the integrated luminosity. Although these are several issues remaining to achieve higher luminosity, we will kept trying to solve them.

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