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STATUS OF EARLY SUPERKEKB PHASE-3 COMMISSIONING

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Abstract

SuperKEKB is an asymmetric energy electron-positron collider for the Belle 2 experiment designed by using the novel "nano-beam" collision scheme. The phase-2 commissioning without the vertex detector to confirm the "nano-beam" collision had been successfully completed in 2018. After the vertex detector installation, the phase-3 commissioning for the full-scale collider experiment has been started at 11 March 2019. We report the recent progress and performance of 2019 spring operation of SuperKEKB phase-3 commissioning.

INTRODUCTION

The SuperKEKB accelerator [1] is an asymmetric-energy double-ring collider constructed by 7 GeV electron high energy ring(HER) and 4 GeV positron log energy ring(LER). Its design luminosity is $8 \times 10^{35}\ \mathrm{cm}^2 s^{-1}$ which is 40 times the performance of the previous KEKB B-factory accelerator. For achieving such high luminosity, the SuperKEKB is designed by using the "nano-beam' collision scheme, which is based on a large Piwinski angle collision scheme proposed by P. Raimondi [2]. In the "nano-beam" scheme, the hourglass effect by squeezing the vertical beta-function at the interaction point(IP) β_y^* is controlled by reducing the longitudinal overlap of the colliding beams. This overlap reduction is achieved by using the combination of the large crossing angle and the small horizontal beam size at the IP. The SuperKEKB machine parameter [3] is designed to achieve 40 times luminosity compared with the KEKB by doubling the stored beam current and squeezing β_y^* down to 1/20 of the KEKB. Considering the hourglass effect, the beam crossing angle between two rings and the horizontal beam size at the IP are designed for equalizing the longitudinal beam overlap at the IP with β_y^*.

The SuperKEKB commissioning is divided into 3 stages; phase-1, phase-2 and phase-3. The phase-1 commissioning stage [4] without the final focus system at the IP is performed from February 1, 2016 to June 28, 2016 in order to establish the low emittance operation and the vacuum scrubbing. The phase-2 commissioning stage [5] after the installation of the final focus system and the Belle 2 detector except the vertex detector is performed from March 16 1, 2018 to July 17, 2018 in order to confirm the "nano-beam" collision scheme. During the phase-2 commissioning, the specific luminosity improvement by squeezing β_y^* down to 3 mm ,which is almost half of the bunch length, is confirmed. After the phase-2 commissioning, the interaction region(IR) has been overhauled in order to install the vertex detector into the IP.

The phase-3 commissioning stage from March 11, 2019 mainly focuses on the full-scale collider experiments. The 2019 spring operation of the phase-3 commissioning until July 1, 2019 which is the first part of the following phase-3 commissioning has two big purposes. One is the reestablishment of the luminosity performance achieved in the phase-2 commissioning on the reassembled IR and further luminosity improvements. The other is the detector background study to improve the maximum acceptable beam current for the collider experiment data taking and tests the continuous injection scheme, which injects the beam during the detector data taking, to improve the integral luminosity performance.

MAJOR HARDWARE UPDATES BETWEEN PHASE-2 AND PHASE-3

Between the phase-2 and phase-3 commissioning, the following three major hardware updates for the beam commissioning were carried out.

Vertex Detector Installation

In order to install the vertex detectors containing the silicon vertex detectors and the pixel detectors into the IP, the accelerator devices in the IR have been disassembled and reassembled. After the superconducting final focus quadrupole magnets (QCSs) cryostat insertion into the Belle 2 detector, the signal cable disconnections have been found in the L-side four electrode beam position monitors(BPMs) of the final vertical focusing quadrupole magnets. These cables were damaged by the QCS cryostat insertion process, because these cable connections had been confirmed before the cryostat insertion. The affected BPMs are QC1LE for HER and QC1LP for LER, respectively. The orbit measurement accuracy of these BPMs is degraded, however, the orbit measurement is possible because three signal cables are still available against four electrodes. In order to recover the BPM cable connections, we have to detach the QCS cryostat from the Belle 2 detector and it needs many works. For avoiding schedule delay and further trouble during reassembling process, we decided to give up the BPM cable connection recovery before this spring operation. As the result of this decision, the BPM calibration by using the BPM gain mapping for the QC1LE and QC1LP has become unavailable.

Movable Beam Collimator Updates

From the phase-2 commissioning, it is turned out that the beam collimator especially vertical collimator is important to protect the final focus quadrupole superconducting magnets from the superconducting quench induced by the beam loss. During the phase-2 commissioning, the vertical beam collimator heads of D01V1 collimator for HER and D02V1

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collimator for LER were damaged by hitting with the main ring beams. The damaged D02V1 collimator was the unique vertical beam collimator for the LER during the phase-2 commissioning. These two vertical beam collimators have been recovered by the collimator head replacement during this maintenance period. Further 5 beam collimator were installed for improving the detector beam background and the QCS protection. One horizontal beam collimator D01H3 was installed for the HER. Three horizontal beam collimator D02H1, D02H2 and D03H1 and one vertical beam collimator D06V2, which is a backup vertical beam collimator for D02V1 collimator, were installed for the LER.

Optics Corrector Updates

In order to resolve the lack of the scan range of the IP xy-coupling & dispersion knob for the luminosity tuning in the phase-2 commissioning, the skew quadrupole corrector magnets have been improved. The excitation range of the skew quadrupole magnets in the IR, which contain 10 skew quadrupoles for HER and 6 skew quadrupoles for LER, have been extended 2.23 times by adding the extra winding coils. At the time of the phase-2 commissioning, almost half of the skew quadrupole back leg winding coils on the chromaticity correction sextupole magnets in the arc section were available for the xy-coupling and dispersion correction. Now, all skew quadrupole back leg winding coils on the chromaticity correction sextupole magnets are available by installing the additional auxiliary power supplies. As the result of these upgrades, the scan range of the IP xy-coupling knob is almost doubled compared with the phase-2.

2019 SPRING OPERATION OVERVIEW

SuperKEKB phase-3 commissioning is started at March 11, 2019 with the detuned optics whose IP beta-functions (β_x^*, β_y^*) are (384 mm, 48.6 mm) for LER and (400 mm, 81 mm) for HER, respectively. The phase-2 latest optics correction fudge parameters are used as the initial fudge parameters except the QCS correction parameters for both the vertical beam waist position and R2 coupling parameter at the IP for renovating the QCS correction fudge parameter management. As the reference orbit and steering data-set for the phase-3 startup, the phase-2 data-set at April 2018 operating on the detuned optics is used. The initial beam storage on the detuned optics has been achieved at March 11 for HER and March 13 for LER, respectively.

Beta Squeezing

After the initial vacuum scrubbing on the detuned optics, the IP beta-functions are step-wise squeezed down to the collision optics via the way-point optics established during the phase-2 commissioning. The way-points of the beta squeezing optics and the established date of the beam storage are summarized in Table 1, where β_x^* of the squeezed optics is 200 mm as default. Exceptionally, β_x^* of the HER $\beta_y^* = 3mm$ optics is 100 mm. The squeezing from the detuned to $\beta_y^* = 3$ mm collision optics is completed within 22 days without QCS quench. In the phase-2, it required 3 month and 27 QCS quenches. The upgraded beam collimators and the Belle 2 diamond background detector abort are worked well to prevent QCS quench due to beam loss. At the initial injection for the squeezing optics before the xy-coupling correction, we found a workaround to prevent the beam abort due to the injection beam. By reducing the beam charge of the injector linac, the beam is slowly injected into the uncorrected optics, however, the beam abort due to the injection is avoided because of the reduced beam loss rate. This workaround saves the time for tuning the initial injection after beta squeezing.

Table 1: Storage Date of Way Point Optics in Phase-2 & 3

	Phase-3 (2019)		Phase-2 (2018)	
Optics	**LER**	**HER**	**LER**	**HER**
Detuned	3/13	3/11	3/31	3/20
$\beta_y^* = 8$ mm	3/18	3/18	4/16	4/10
$\beta_y^* = 6$ mm	3/25	3/25	5/14	5/10
$\beta_y^* = 4$ mm	3/26	3/26	5/24	5/24
$\beta_y^* = 3$ mm*	3/28	4/1	6/5	6/20

Vacuum Scrubbing

The beam operation dedicated for the vacuum scrubbing had been performed on the detuned optics until March 20. The $\beta_y^* = 8$ mm optics operation dedicated for the vacuum scrubbing had been performed until March 25. The maximum stored beam current during the vacuum scrubbing operation is 350/470 mA(LER/HER) for the detuned optics and 530/540 mA(LER/HER) for $\beta_y^* = 8$ mm optics, respectively. At May 10, the beam dose reaches 129 Ah for LER and 162 Ah for HER, respectively. The vacuum pressures per the stored beam currents of two rings have been reached almost same level at the end of the phase-2 commissioning.

Operation Interruption due to Fire

At April 3 21:45 JST, the fire had been occurred in the accelerating structure assembly room of the linac building. As the result of the emergency protocol for the fire in our facility, the SuperKEKB operation had been aborted at 21:52 JST. This fire did not damage the injector linac complex directly, however, the smoke of this fire intruded into both the linac accelerator tunnel and klystron gallery. Many linac hardware devices, which are including the high voltage devices, had been polluted with the carbon soot caused by this fire. In order to scavenge the soot pollution of the linac hardware devices, the soot cleanup and replacement with the spare parts were performed. This recovery works is enough for the minimum beam operation but incomplete. Therefore the linac does not prepare enough energy margin for the breakdown of the klystron or accelerator tube at this moment. After these recovery works, the linac commissioning was started at April 22 and the beam injection for the SuperKEKB main rings was restarted at April 25. In order to reestablish the

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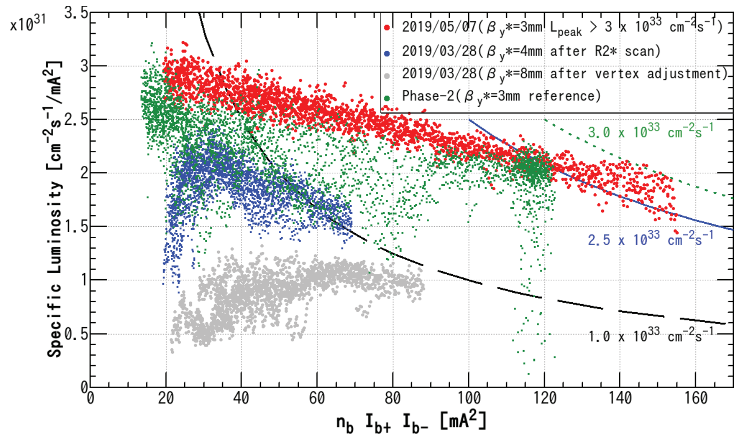

Figure 1: Specific luminosity on 789 bunch collision. The horizontal axis shows the bunch current product multiplied by the number of bunches n_b. The red, blue and gray points correspond with typical $\beta_y^* = 3$ mm, 4 mm and 8 mm collision in this spring, respectively. The green point corresponds with the typical $\beta_y^* = 3$ mm collision in the phase-2. The dotted, solid and dashed lines show the contour lines corresponding with 3.0, 2.5 and 1.0×10^{33} cm^{-2}s^{-1} luminosity, respectively.

injection for the LER collision optics, an additional β_y^* detuning and re-squeezing were performed. After the regular collision preparation containing optics correction, injection tuning and collision tuning, $\beta_y^* = 3$ mm collision operation was resumed at April 26 21:01 JST.

MACHINE PERFORMANCE

In this spring operation, the first beam-beam scan and the first physics run have been performed on $\beta_y^* = 8$ mm optics at March 20 and 25, respectively. The longitudinal vertex position was adjusted 15 mm toward to the NIKKO experimental hall based on the Belle2 detector measurement. Considering the IP vertical orbit offset for colliding and the longitudinal vertex position measurement, the relative IP orbit between two rings is consistent with the phase-2 first collision. The luminosity optimum R2* coupling knob parameter, which is most efficient IP knob found in the phase-2 commissioning, agrees with the optimum parameter in the phase-2. Therefore, the reproducibility after the IR reassembly looks fine. The regular physics run is started at April 1 on $\beta_y^* = 3$ mm optics with 789 bunches. Typical optical function errors of $\beta_y^* = 3$ mm optics measured by the global optics measurement are shown in Table 2. The peak luminosity 3.07×10^{33} cm^{-2}s^{-1} is recorded at May 7 07:07 JST with the stored beam current 345.9/334.7 mA(LER/HER). Figure 1 shows the specific luminosity as a function of the bunch current product multiplied by the number of bunches n_b. The specific luminosity of $\beta_y^* = 3$ mm optics shown as the red points reaches same performance level of the phase-2 commissioning shown as the greed points. Furthermore, the specific luminosity on the beam decaying region looks like a little bit better performance than the phase-2 one.

Table 2: Optical Function Error Measured at May 07, 2019

Item	LER	HER	Unit
$rms(\triangle\beta_x/\beta_x)$	3.104	4.479	%
$rms(\triangle\beta_y/\beta_y)$	5.094	9.006	%
$rms(\triangle y/\triangle x)$	0.014	0.008	
$rms(\triangle\eta_x)$	15.508	33.950	mm
$rms(\triangle\eta_y)$	3.801	2.278	mm

CONCLUSIONS

During 2019 spring operation of the phase 3 commissioning, the medium beam current collision operation on the $\beta_y^* = 3$ mm optics are reestablished. The reproducibility of both the relative orbit and the optical functions at the IP after the IR reassembly between the phase 2 and 3 is confirmed, however, the IR assembling procedure have to be improved to avoid the assembly errata such as the signal cable damage. The specific luminosity at the medium bunch current collision roughly reproduces the phase 2 performance. With the help of both the movable beam collimators and the Belle 2 diamond beam background detector abort, the IP vertical beta-function squeezing down to 3 mm is performed without QCS quench. The further luminosity tuning and the study for the beam backgrounds are ongoing.

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