COMMISSIONING OF SuperKEKB

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Abstract

After five and half years upgrade works from KEKB to SuperKEKB, the Phase 1 commissioning of SuperKEKB was conducted from February to June in 2016. This paper describes the progress of the Phase 1 commissioning. Brief plans of the Phase 2 commissioning are also described.

INTRODUCTION

The purpose of SuperKEKB is to search a new physics beyond the standard model of the particle physics in the B meson regime. SuperKEKB consists of the injector linac, a damping ring for the positron beam and two main rings; *i.e.* the low energy ring (LER) for positrons and the high energy ring (HER) for electrons, and the physics detector named Belle II. The beam energies of LER and HER are 4GeV and 7GeV, respectively. The design beam currents of LER and HER are 3.6A and 2.6A, respectively. The design luminosity is $8 \times 10^{35}\text{cm}^{-2}\text{s}^{-1}$. Design machine parameters are shown in Table 1. More details of SuperKEKB are described elsewhere [1].

The main issues for SuperKEKB are listed below.

- IR design and dynamic aperture
- Optics corrections and low emittance tuning
- Magnet alignment strategy
- Beam-beam related issues
- Orbit control to maintain beam collision
- Beam loss and beam injection
- Effects of electron clouds
- Injector upgrade for low emittance and high intensity beams
- Detector beam background

Some of those are studied in the Phase 1 commissioning this year.

BEAM COMMISSIONING

Commissioning Strategy

The beam commissioning will proceed in three steps; *i.e* Phase 1, 2 and 3. The Phase 1 commissioning has been already done for 5 months this year. In Phase 1, the superconducting final focus doublets and other correction coils (called QCS) and the physics detector (called Belle II) were not installed and no beam collision was performed. The idea of Phase 1 is that we conduct sufficient vacuum scrubbing and other beam tuning such as beam injection before installing the Belle II detector. The commissioning of the damping ring, which is newly introduced for SuperKEKB, will start in November 2017. The Phase 2 commissioning of main rings will start in January 2018 and continue for about 5 months. In Phase 2, the QCS magnets and the main part of the Belle II detector will be installed. But the vertex detector will not be installed in Phase 2. This is based on an idea that the vertex detector, which is very sensitive to the beam background, should be installed after sufficient beam tuning with the QCS magnets. From the viewpoint of the accelerator tuning, we can make tuning on condition that hardware components are fully installed except for the beam background tuning to the vertex detector. The target luminosity in Phase 2 is $1 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$. The Phase 3 commissioning will start in autumn 2018. In this phase, the vertex chamber will be installed and we will continue beam tuning aiming at the design luminosity in parallel with the physics experiment.

Table 1: Design machine Parameters of SuperKEKB (Values in parentheses of the emittances correspond to those at zero bunch currents).

	LER	HER	Units
Beam Energy	4.000	7.007	GeV
Beam Current	3.6	2.6	A
# of Bunches	2500		
Circumference	3016.315		m
Hor. Emittance	3.2(1.9)	4.6(4.4)	nm
Ver. Emittance	8.6(2.8)	11.5(1.5)	pm
β-function at IP(H/V)	32/0.27	25/0.30	mm
Moment. compaction	3.25	4.55	$\times 10^{-4}$
Energy spread	8.08	6.37	$\times 10^{-4}$
RF voltage	9.4	15.0	MV
Hor. tune ν_x	44.53	45.53	
Ver. tune ν_y	46.57	43.57	
Synchrotron tune ν_s	-0.0247	-0.0280	
Energy loss / turn	1.87	2.43	MeV
Damping time $\tau_{x,y}/\tau_s$	43/22	58/29	ms
Bunch length	6.0	5.0	mm
Beam-beam param. H	0.0028	0.0012	
Beam-beam param. V	0.0881	0.0807	
Luminosity	8×10^{35}		/cm^2/s

Results of Phase 1 Commissioning

Missions in Phase 1 After five and half years of upgrade work from KEKB, the Phase 1 beam commissioning of SuperKEKB started on Feb. 1st this year and finished at the end of June this year. Missions of the commissioning in

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Phase 1 are startup of each hardware component, establishment of beam operation software tools, preparation of Belle II detector, an optics study and tuning without QCS and the detector solenoid magnet and other machine studies. As for preparation for installation of the Belle II detector, vacuum scrubbing is of essential importance. The Belle II group require 1 month vacuum scrubbing with the beam current of 0.5-1 A, which corresponds to the beam dose of 360-720 Ah. In addition, the study on the beam background to the detector is also important by using a test detector named Beast. As for the optics study, Phase 1 provides us with an unique opportunity to conduct a study without the detector solenoid nor QCS. The low emittance tuning is an important item.

History of beam Commissioning Figure 1 shows the history of Phase 1 commissioning. In the figure, the red, violet and cyan dots show the beam currents, averaged vacuum pressure and the beam lifetime, respectively. The commissioning started on Feb. 1st. The first week was devoted to tuning of the beam transport lines. Tuning of the beam injection to LER (positron ring) started on Feb. 8th and the beam injection succeeded on Feb. 10th. Tuning of the beam injection to HER (electron ring) started on Feb.22nd and the beam injection succeeded on Feb. 25th. The beam currents increased gradually and the maximum beam currents of LER and HER in Phase 1 were 1010 mA and 870 mA, respectively. In the latter half of June, we had to decrease the HER beam current due to a trouble of a stripline kicker of the transverse bunch-by-bunch feedback. The beam current increase proceeded at a much faster pace than KEKB. The reasons for this short rise time of the beam currents are thought to be in the following.

- The transverse bunch-by-bunch feedback system worked validly from the very beginning of the commissioning.
- Each hardware component has been upgraded based on the experiences at KEKB and worked validly.
- Software tools for the beam operation has been established based on the experiences at KEKB and worked from the beginning.
- We had less troubles compared with the case at KEKB.

We owe the quick start of SuperKEKB largely to the experiences at KEKB. The machine parameters in Phase 1 are shown in Table 2.

Table 2: Machine Parameter in Phase 1 (Horizontal emittances are values at zero bunch currents).

	LER	HER	Units
Beam Energy	4.000	7.007	GeV
Beam Current	1010	870	mA
# of Bunches	1576	1576	
Hor. Emittance	1.8	4.6	nm
Momentum compaction	2.45	4.44	$\times 10^{-4}$
Energy spread	7.7	6.3	$\times 10^{-4}$
RF voltage	7.45	11.99	MV
Hor. tune ν_x	44.53	45.53	
Ver. tune ν_y	46.57	43.57	
Synchrotron tune ν_s	-0.0190	-0.0246	
Energy loss / turn	1.87	2.43	MeV
Damping time $\tau_{x,y}/\tau_s$	44/22	58/29	ms
Bunch length	4.8	5.4	mm

Vacuum scrubbing In LER, 98 % of vacuum chambers of KEKB were replaced with new ones. In arc sections, ante-chambers with TiN coating to suppress the effects of the electron clouds and mitigate the issues of heating by the synchrotron radiation were adopted. In HER, the most of the vacuum chambers in arc sections are reused from KEKB. About 18 % of vacuum chambers in the whole ring were replaced with the new ones in HER. Vacuum scrubbing proceeded smoothly as is seen in Fig. 1. The averaged vacuum pressures of LER and HER were 4.7×10^{-7} Pa with the beam current of 1.01 A on June 17th and 5.7×10^{-8} Pa with the beam current of 0.87 A on June 22nd, respectively. The corresponding beam lifetime of those times of LER and HER were about 60 min. and 200 min. The main processes to determine the beam lifetime are the Touschek effect and the scattering from the residual gas particles. The cumulative doze of the beam currents in Phase 1 of LER and HER are 776 Ah and 662 Ah and we have met the requirement from the Belle II group. More details on the commissioning of the vacuum system are written elsewhere [2].

Issue related to high beam current operation One of the issues was the longitudinal coupled bunch instability observed in LER. The instability was first observed around 660mA. The mode number was ~-40. We needed the use of longitudinal feedback system to suppress it. At KEKB, we never needed the longitudinal feedback system. The source of the instability may be the 0 and π modes of the ARES cavities which were detuned for operational budget reduction. The ARES cavity consists of three cavities; *i.e.* an acceleration cavity, an energy storage cavity and a coupling cavity and so there are three modes near the RF frequency. The $\pi/2$ mode is used for beam acceleration. The 0 and π modes are almost symmetric with respect to the RF frequency and the contributions to the beam instability from those modes are almost canceled out. However, when the detuning frequency is large, this cancellation breaks. In HER, Sometimes, detuned cavities induced the instability due to the fundamental mode. The -1 mode damper was set up to suppress the instability.

Another problem was a nonlinear vacuum pressure rise against the beam current observed in LER. As shown in Fig. 2, the LER vacuum pressure had a nonlinear behavior and got rapidly worse with an increasing beam current. The

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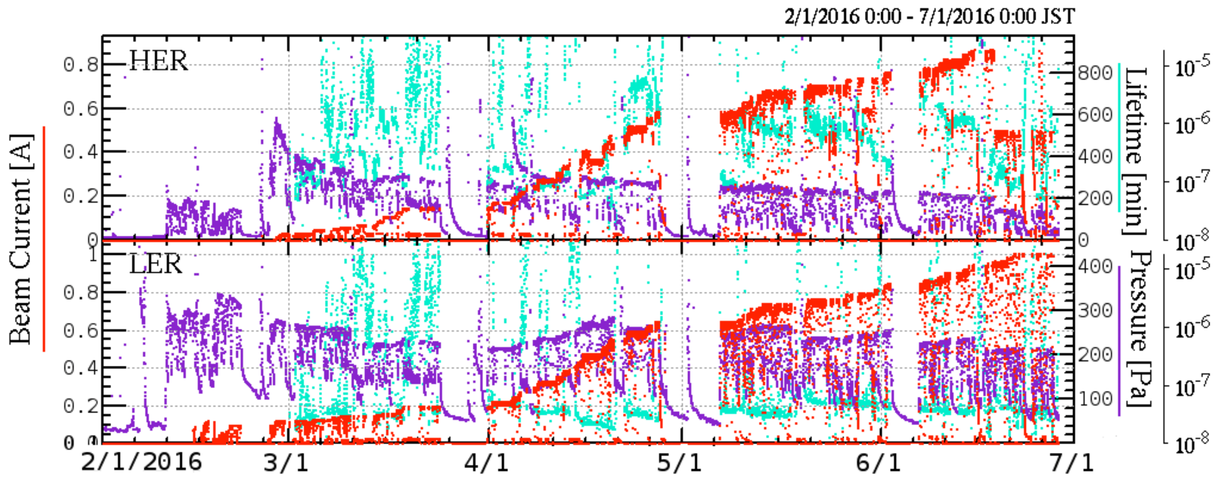

Figure 1: History of SuperKEKB operation in Phase 1.

aluminum bellows chambers were suspected of inducing this phenomenon. The other vacuum chambers in LER are applied TiN coating. But no TiN coating is applied to them. The secondary electron emission coefficient for them is high and it may induce electron multipactoring. At a test vacuum chamber without TiN coating installed in LER, the measured electron density showed a similar nonlinear behavior as function of the beam current to the vacuum pressure rise. As shown in Fig. 2, the beam current dependence of vacuum pressure at a bellows chamber became rather linear by installing a solenoid magnet or a permanent magnet which creates a solenoid-like magnetic field. The magnetic field of the solenoid magnet and the permanent magnet were ∼ 50 Gauss and ∼ 100 Gauss, respectively. During a short operation break in the beginning of June, permanent magnets were installed at all of ∼ 800 such aluminum bellows chambers. As a result, the nonlinear vacuum pressure rise was suppressed with the filling pattern for vacuum scrubbing (1576 bunches in total, 3.06 RF bucket spacing in average) up to 1 A of the beam current.

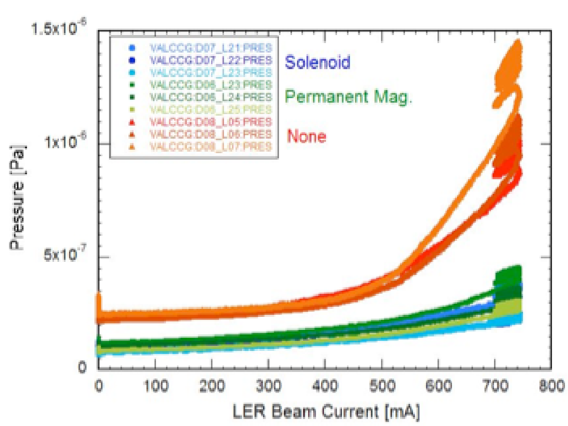

Figure 2: Nonlinear vacuum pressure against beam current in LER.

Vertical beam size blowup in LER In LER of KEKB, the electron clouds caused the vertical beam size blowup and gave a serious limit to the luminosity, although various efforts were devoted to suppress it throughout the beam operation period of KEKB. Based on the experiences at KEKB, we made more fundamental countermeasures for the problem. The vacuum chambers newly introduced are antechambers with TiN coating. In the wiggler section, the chambers have clearing electrodes. The vacuum chambers of the bending magnets have the grooved structure. In addition to those countermeasures which were already made, we plan to install solenoid magnets in the drift section which have not yet been installed in Phase 1. In Phase 1, we observed a vertical beam size blowup as shown in Fig. 3(a). In the graph, the vertical beam size with an emittance control knob is also shown. This knob can create vertical dispersions all around the ring. In the vacuum scrubbing operation, we intentionally enlarge the beam size to increase the beam lifetime mainly from the Touschek effect. In both cases, the vertical beam size started to increase at around 500 mA and showed serious blowup at higher beam currents with a filling pattern used for the vacuum scrubbing (1576 bunches in total, 3.06 RF bucket spacing in average). As is described above, permanent magnets were installed at all of ∼ 800 aluminum bellows chambers in June. By installing the permanent solenoid magnets, it was also expected that the beam size blowup is suppressed. As shown in Fig. 3(b), the blowup was almost suppressed up to 800 mA with the same filling pattern except for the slow blowup which we haven't understood yet. To study the blowup in more details, we conducted a machine study with shorter bunch spacing a part of which is shown in Fig. 3(a). The details of this study are described elsewhere [3].

Optics corrections and low emittance tuning Details of the optics correction are described elsewhere [4]. In this paper, only some highlights on the low emittance tuning in Phase 1 are described. The X-Y coupling correction and dispersion correction are important to get a low vertical

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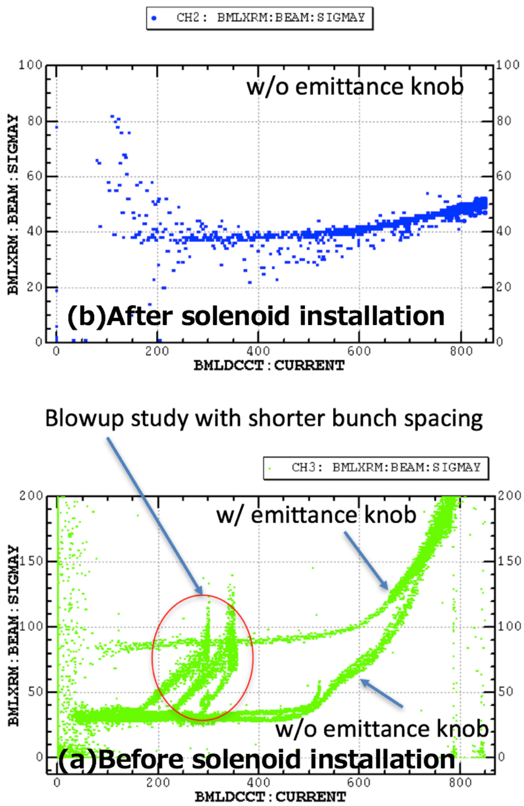

Figure 3: Vertical beam size as function of beam current in LER. (a)before solenoid installation, (b)after solenoid installation.

emittance. While the corrections in HER went well, we encountered a difficulty in the LER corrections. The obstacle of the corrections was leakage magnetic field from the Lambertson septum magnets whose main component is skew-Q.The Lambertson magnet is a part of the beam abort system. To cope with this problem, we took two measures. First, we activated skew-Q coils wound at a focusing sextupole magnet downstream of the septum magnet. Second, we installed a permanent skew-Q magnet upstream of the septum magnet. The picture and drawing of the permanent skew-Q magnet is shown in Fig. 4. With the two countermeasures, both the X-Y coupling and the vertical dispersion were improved. Figure 5 shows results of measurements of the X-Y coupling before taking the countermeasures and after them. In the measurement, vertical leakage orbits caused by 6 independent horizontal steering kicks were observed. In the graph, such 6 vertical leakage orbits are shown as function of the ring position where s=0 corresponds to the IP. The horizontal steering kicks were 200μrad and the horizontal orbit amplitude was about 2-3 mm in its peaks. As for correctors for X-Y coupling, we employ skew-Q windings on sextupole magnets. Around s = -1300m, there remains some large X-Y coupling. At the location of s = ~1400m, a Lambertson DC septum magnet is located. As a results of the two countermeasures, the residual X-Y coupling at around the Lambertson septum almost vanished. Similarly the vertical dispersion was much improved by the countermeasures. Table 3 shows the reaching point of the optics corrections in Phase 1 together with typical values of KEKB LER. The dispersions and the beta-beats in the list are r.m.s values of the deviations from the design measured at the BPMs around the rings. As seen in the table, the beta-beats are already smaller than the typical values of KEKB, although the distance of the horizontal betatron tunes from the half integer is longer than KEKB. From the measured vertical dispersion and the X-Y coupling, the vertical emittances of LER and HER are estimated as ~6.8 pm and~8.0 pm, respectively. In LER, the vertical emittance is calculated from the beam size measurement using the X-ray monitor as ~10 pm and is consistent with the optics measurement. On the other hand, the vertical emittance from a measurement by using the X-ray monitor in HER was ~200 pm and there was a large discrepancy between the estimation from the optics measurement and the measurement by using the X-ray monitor. We took this issue seriously and investigated it in detail. First, we tried the calibration of the X-ray monitor by using the emittance control knob. Second, we measured the beam size with changing the vertical beta function at the source point of the X-ray monitor. As for the calibration, the calibration constant was determined to be 1.18, which means that the measured size is larger than the true beam size by a factor 1.18. From the measurement by changing the beta function at the source point, it turned out that the measured beam size of the X-ray monitor includes a large offset. The measured value is about ~ 40μm and the offset value is more than 30μm. Here, the measured size is assumed to be the square root of the square-sum of the the true beam size and the offset value. This large offset was also supported by an independent analysis using a data on the beam size dependence of the Touschek beam lifetime. The origin of this large offset has not been understood. Even with this large offset and the calibration factor, an estimated vertical emittance in HER is about 40 pm and is still much larger than the estimation from the optics measurement. We will continue the investigation on this problem in Phase 2 commissioning.

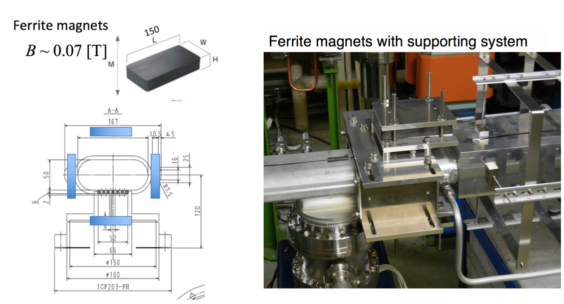

Figure 4: Picture and drawing of permanent skew-Q magnet.

Plans for Phase 2 Commissioning

In the present plan, the commissioning of the damping ring (DR) will start Nov. 20th 2017 prior to the commis-

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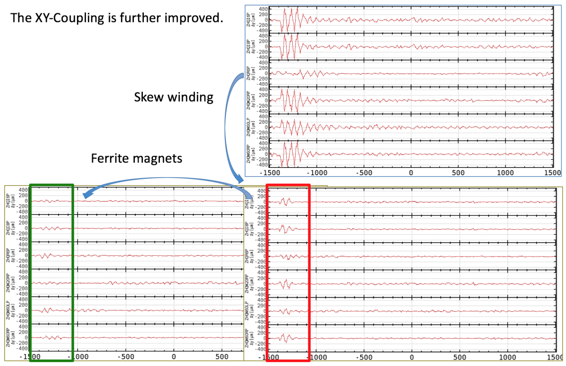

Figure 5: Improvement of X-Y coupling with two countermeasures at LER.

Table 3: Reaching point of optics corrections in Phase 1.

	LER	HER	LER KEKB	Units
X-Y coupling*)	0.9	0.6		%
$\Delta\eta_x$ r.m.s.	8	11	10	mm
$\Delta\eta_y$ r.m.s.	2	2	8	mm
$\Delta\beta_x/\beta_x$ r.m.s.	3	3	6	%
$\Delta\beta_y/\beta_y$ r.m.s.	3	3	6	%

*) Ratio of average of r.m.s values by 6 vertical leakage orbits (horizontal to vertical).

sioning of main rings. It will take about 3 months to finish the DR commissioning including vacuum scrubbing. The commissioning of HER will start in middle of January 2018 in parallel with the DR commissioning. The commissioning of LER will start in middle of February. The Phase 2 commissioning will continue for about 5 months and finish in middle of June. Important tasks in Phase 2 commissioning are in the following.

- Performance check of QCS magnets
- Squeezing IP beta functions at IP
- Belle II beam BG study and tuning
- Beam collision tuning with Nano beam scheme
- Luminosity tuning

In Phase 2, the target luminosity is $1\times10^{34}\text{cm}^{-2}\text{s}^{-1}$. This luminosity is achieved with the beam currents of 1.0 A (LER) and 0.8 A (HER), the horizontal beta functions at IP of 128 mm (LER) and 100 mm (HER), the vertical beta functions at IP of 2.16 mm (LER) and 2.4 mm (HER) and the vertical beam-beam parameters of 0.024 (LER) and 0.0257 (HER). With these parameters, a strong-weak beam-beam simulation shows that a luminosity of $2\times10^{34}\text{cm}^{-2}\text{s}^{-1}$ can be achieved. In the last 1 month, we plan to conduct the physics experiment, although there is no vertex detector. Before the physics experiment, we will operate SuperKEKB on $\Upsilon(4S)$ and we will discuss the beam energy in the physics experiment with the Belle II group.

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