2 Future Energy-Frontier Circular Colliders

2.1 Highlights from SuperKEKB Commissioning Phase 1 and Plan for Phase 2

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2.1.1 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 an 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 x 10^{35} $cm^{-2}s^{-1}$. More details of SuperKEKB are described elsewhere [1].

The beam commissioning of SuperKEKB will proceed in three steps; *i.e.* Phase 1, 2 and 3. The Phase 1 commissioning has been already done for 5 months in 2016. In Phase 1, the superconducting final focus doublets and other correction coils (called QCS as a whole) and Belle II were not installed and no beam collision was performed. The commissioning of the damping ring, which is newly introduced for SuperKEKB, will start in December 2017. The Phase 2 commissioning of the main rings will start in middle of February 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 machine 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 x 10^{34} cm^{-2} s^{-1}. The Phase 3 commissioning will start in autumn 2018. In this phase, the vertex detector will be installed and we will continue beam tuning aiming at the design luminosity in parallel with the physics experiment.

2.1.2 Highlights from SuperKEKB Commissioning Phase 1

2.1.2.1 *Missions of Phase 1 commissioning*

After 5 years of upgrade work from KEKB, the Phase 1 beam commissioning of SuperKEKB started on Feb. 1st 2016 and finished at the end of June 2016. Missions of the commissioning in Phase 1 were startup of each hardware component, establishment of beam operation software tools, preparation of installation 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 was of essential importance. The Belle II group required 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 was also important by using a test detector named Beast. As for the optics study, Phase 1 provided us with a unique opportunity to conduct a study without the detector solenoid nor QCS. The low emittance tuning was an important item.

2.1.2.2 *History of Phase 1 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 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. 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 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 dose 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].

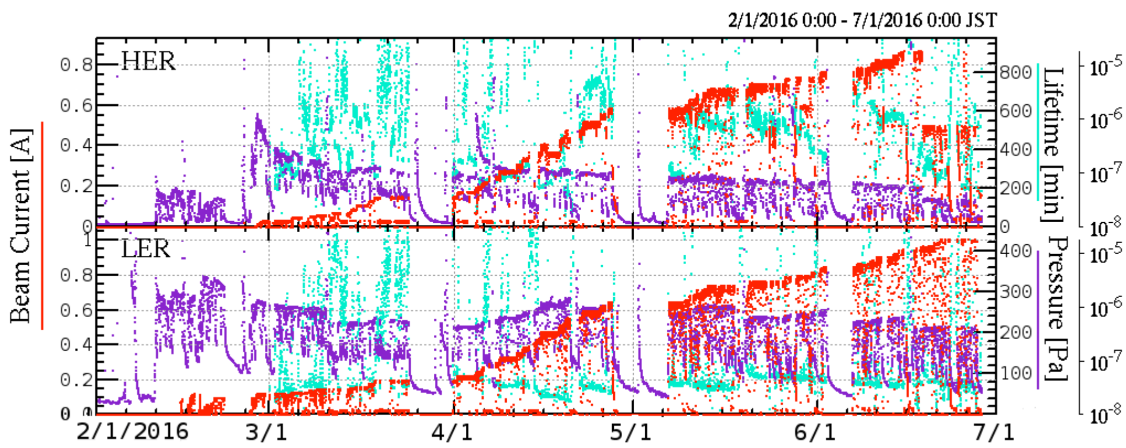

Figure 1: History of SuperKEKB operation in Phase 1.

2.1.2.3 *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 fabricated are antechambers with the 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 were not installed before in Phase 1. In Phase 1, we observed a vertical beam size blowup as shown in Fig. 2(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 and control the vertical emittance. 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). In addition to this problem, a nonlinear vacuum pressure rise against the beam current was also observed in LER. The aluminum bellows chambers were suspected of inducing those phenomena. TiN coating is applied to the other vacuum chambers in LER. But no TiN coating is applied to the bellows chamber. During a short operation break in the beginning of June, permanent solenoid-like magnets, whose typical magnetic field is ~ 100 Gauss were installed at all of ~ 800 such aluminum bellows chambers. By installing the permanent solenoid magnets, both problems were mitigated. As shown in Fig. 2(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. 2(a). The details of this study are described elsewhere [3]. It turned out that the vertical beam blowup is still serious with the shorter bunch spacing. During the period between Phase 1 and Phase 2, all of the drift space other than the bellows chambers were covered with the permanent solenoid magnets to suppress the blowup.

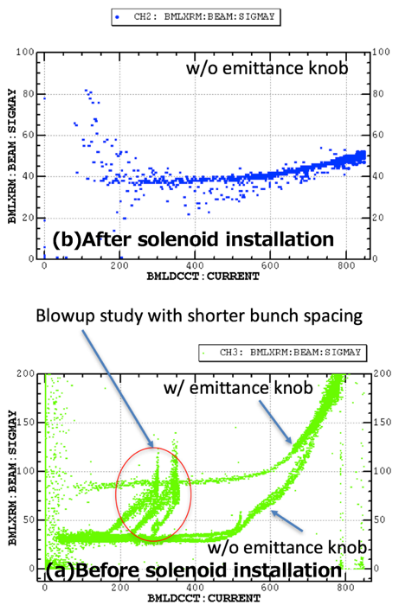

Figure 2: Vertical beam size as function of beam current in LER. (a)before solenoid installation, (b)after solenoid installation.

2.1.2.4 *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 emittance. While the corrections in HER went well, we encountered a difficulty in the LER. The obstacle of the corrections was leakage magnetic field from the Lambertson septum magnet 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. 3. With the two countermeasures, both the X-Y coupling and the residual vertical dispersion were improved. Figure 4 shows results of measurements of the X-Y coupling before taking the countermeasures and after them. In the measurement, vertical leakage orbits created by 6 independent horizontal steering kicks were observed. In the graph, such 6 vertical leakage orbits are shown as a function of the ring position where s = 0 corresponds to the interaction point (IP). The horizontal steering kicks were 200μrad and the horizontal orbit amplitude was about 2-3 mm in its peaks. As for correctors for the 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, the Lambertson DC septum magnet is located. As a result 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.

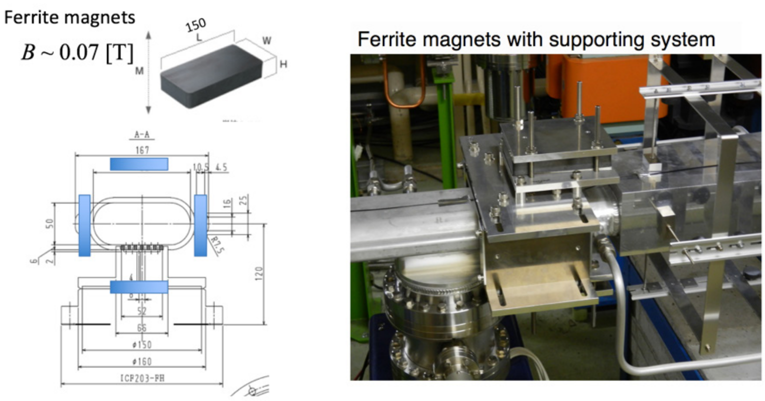

Figure 3: Picture and drawing of permanent skew-Q magnet

Table 1 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 more or less 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 op- tics 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 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.

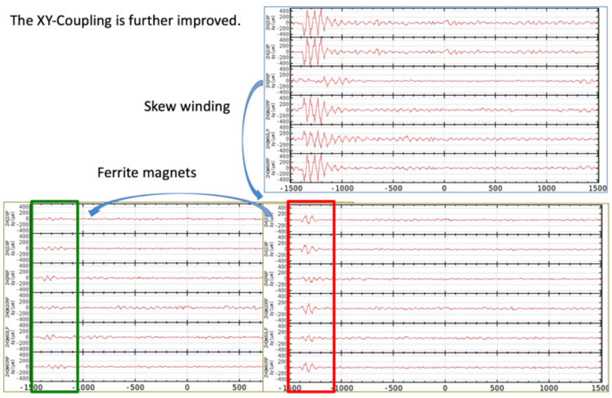

Figure 4: Improvement of X-Y coupling with two countermeasures at LER

Table 1: 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 between the average of r.m.s. values of 6 vertical leakage orbits and that for the horizontal orbits.

2.1.3 **Commissioning Plan for Phase 2**

A verification of the nano-beam scheme is one of the targets for the commissioning in Phase 2 at SuperKEKB [5]. The nano-beam scheme adopts low emittance optics with a large Piwinski angle [6]. The specific luminosity is expected to be larger than 4 x 10^{31}

$cm^{-2}s^{-1}/mA^2$ with the beam-beam parameter of about 0.05. On the other hand, a study of the beam background for the Belle II detector is very important before the installation of the pixel vertex detector (PXD) that is used in Phase 3 as the most inner detector.

The luminosity for the nano-beam scheme is described by

$$L = \frac{N_+ N_- n_b f_0}{4\pi\sigma^*_{x,eff}\sigma^*_y} R_L = \frac{N_+ N_- n_b f_0}{4\pi(\sigma_z \phi_x)\sqrt{\varepsilon_y \beta^*_y}} R_L,$$

where the N_+ and N_- are the number of particles per bunch for positrons and electrons, respectively, n_b is the number of bunches, f_0 is the revolution frequency, σ^*_x and σ^*_y are the beam size at the IP in the horizontal and vertical direction, the suffix of *eff* means an effective value, ε_y is the vertical emittance, β^*_y is the beta function at the IP, σ_z is the bunch length, ϕ_x is the half crossing angle, and R_L is the luminosity reduction factor. Then, the specific luminosity can be defined by

$$L_{sp} = \frac{L}{I_+ I_- n_b} = \frac{1}{4\pi e^2 f_0}\frac{R_L}{\sigma^*_{x,eff}\sigma^*_y} \propto \frac{\xi_{y+}}{I_- \beta^*_y},$$

where I_+ and I_- are the bunch beam currents. The beam-beam parameter in the case of the nano-beam scheme can be expressed by

$$\xi_{y+} = \frac{r_e \beta^*_y}{2\pi\gamma_+}\frac{N_-}{\sigma^*_y\left(\sigma^*_{x,eff} + \sigma^*_y\right)} R_{\xi y} \simeq \frac{r_e}{2\pi\gamma_+}\frac{N_-}{\sigma_z \phi_x}\sqrt{\frac{\beta^*_y}{\varepsilon_y}} R_{\xi y},$$

where $R_{\xi y}$ is another reduction factor. Alternatively, the luminosity formula is written by

$$L = \frac{\gamma_+}{2er_e}\left(1 + \frac{\sigma^*_y}{\sigma^*_{x,eff}}\right)\frac{n_b I_+ \xi_{y+}}{\beta^*_y}\frac{R_L}{R_{\xi y}} \propto \frac{N_+ N_-}{\sigma_z \phi_x \sqrt{\varepsilon_y \beta^*_y}}.$$

These formulae tell us that the luminosity can be large with keeping the beam-beam parameter constant when the both the vertical beta function at the IP and the vertical emittance can be small by the same ratio. The Piwinski angle implies how much we can squeeze the vertical beta function and SuperKEKB realizes the large Piwinski angle, Φ, more than 10-20, where

$$\Phi = \frac{\sigma_z}{\sigma^*_x}\tan\phi_x.$$

The hourglass effect in the nano-beam scheme determines a possible beta function at the IP. The vertical beta function at the IP can be squeezed to be

$$\beta^*_y > \frac{\sigma_z}{\Phi}.$$

In order to make a larger Piwinski angle, the small horizontal emittance is necessary, however, the horizontal beam-beam parameter is not affected in the nano-beam scheme. The machine parameters in Phase 2 are shown in Table 2.

There are several sub phases in Phase 2. We will start big beta functions at the IP, for instance, 81 mm in the vertical direction, in the first commissioning in order to find a closed orbit with the final focus system (QCS) [7]. This sub phase is called Phase 2.0. The hardware and software are checked and measurements and corrections of the beam optics with QCS are performed during Phase 2.0. The vacuum scrubbing in the vicinity of the IP will be done before the beam collision. The dithering system is also prepared and tested in this phase. Then, the beta functions are squeezed down to be 6 mm that is the same value of the bunch length, if necessary in Phase 2.1. In Phase 2.2, the vertical beta function is squeezed to be about 2 mm to test the nano-beam scheme. The first collision that means a measurement of beam-beam deflection will be performed during this phase. Once we can perform Phase 2.2 successfully, we can squeeze the beta functions at the IP adiabatically. The local chromaticity corrections should be worked and several quadrupole magnets located in the matching sections near the arc sections are used to squeeze the beta functions without any modifications both of the final focus system and the local chromaticity corrections. Further beta squeezing in the vertical direction down to 1 mm will be done in Phase 2.4. The beta squeezing to the final value of 0.3 mm in the vertical direction will be tested between Phase 2.3 and Phase 2.4. We have a plan to squeeze the vertical beta function down to about 0.1 mm to study a possibility of future linear colliders, ILC and CLIC, if possible [8].

Table 2: Machine parameters in Phase 2 and comparisons with those of KEKB and Phase 3 final parameters. The left column is values in the LER and those of the HER in the right.

Parameter LER / HER	*KEKB (2006)*	*Phase 2.2*	*Phase 2.3*	*Phase 2.4*	*Phase 3 (final)*
β_x^* [mm]	590 / 560	256 / 200	128 / 100	128 / 100	32 / 25
β_y^* [mm]	6.5 / 5.0	2.16 / 2.40	2.16 / 2.40	1.08 / 1.20	0.27 / 0.3
ε_x [nm]	18 / 24	2.1 / 4.6	2.1 / 4.6	2.1 / 4.6	3.2 / 4.6
$\varepsilon_y/\varepsilon_x$ [%]	3 / 2.5	5.0	1.4	0.7	0.27 / 0.28
σ_x^* [μm]	103 / 116	23.2 / 30.3	16.4 / 21.4	16.4 / 21.4	10.1 / 10.7
σ_y^* [nm]	1900 / 1900	476 / 743	252 / 393	126 / 197	48 / 62
σ_z [mm]	7 / 7	6 / 5	6 /5	6 / 5	6 / 5
ϕ_x [mrad]	11	41.5	41.5	41.5	41.5
Φ (Piwinski)	0.75 / 0.66	10.7 / 8.2	15.2 / 9.7	15.2 / 9.7	24.7 / 19.4
I [A] (n_b)	1.66 / 1.34 (1388)	1.0 / 0.8 (1576)	1.0 / 0.8 (1576)	1.0 / 0.8 (1576)	3.6 / 2.6 (2500)
ξ_x	0.117 / 0.070	0.005 / 0.002	0.005 / 0.002	0.005/ 0.002	0.0028 / 0.0012
ξ_x	0.105 / 0.056	0.026 / 0.026	0.048 / 0.050	0.050 / 0.050	0.0881 / 0.0807
L_{sp} [$cm^{-2}s^{-1}/mA^2$]	1.06 x 10^{31}	1.97 x 10^{31}	3.94 x 10^{31}	7.88 x 10^{31}	2.14 x 10^{32}
L [$cm^{-2}s^{-1}$]	1.71 x 10^{34}	10^{34}	2 x 10^{34}	4 x 10^{34}	8 x 10^{35}

The specific luminosity as a function of the number of bunches multiplies the bunch current products is show in Fig. 5. We will start small beam currents with small number of bunches to keep bunch currents as much as possible. The nominal bunch current is 0.64 mA in the LER and 0.51 mA in the HER. When we will reach the specific luminosity of 2 x 10^{31} $cm^{-2}s^{-1}/mA^2$, we will increase the number of bunches up to 1576 that corresponds to 3-bucket spacing similar to that of Phase 1. The total beam current of 1 A in the LER and 0.8 A in the HER achieves 10^{34} $cm^{-2}s^{-1}$ luminosity with 5 % emittance ratio. If we can improve the emittance ratio down to 1.4 %, the specific luminosity becomes approximately 4 x 10^{31} $cm^{-2}s^{-1}/mA^2$ and 2 x 10^{34} $cm^{-2}s^{-1}$ can be achieved which is almost the same luminosity of KEKB world record [9].

The dynamic aperture of the LER and HER are considered in Phase 2. In the case of Phase 2.3, Touschek lifetime is expected to be 60 min in the LER and 189 min in the HER without considering machine errors and beam-beam interactions. The machine error reduces the dynamic aperture about 10-20 % and the effect of the beam-beam interaction will be less than 10 %. Consequently, we assume the total lifetime of 40 min in the LER and 150 min in the HER during Phase 2.

Table 3 shows the requirements of linac beams during Phase 2. Since the dynamic aperture for the injected beam will be much smaller than that of Phase 1, the small emittance is necessary for the injected beam. In order to satisfy the requirements, the RF gun [10] is utilized for the electron beam and the positron beam are captured by the flux concentrator [11] and the huge emittance is reduced by using the 1.1 GeV damping ring [12] which locates an intermediate of the injector linac.

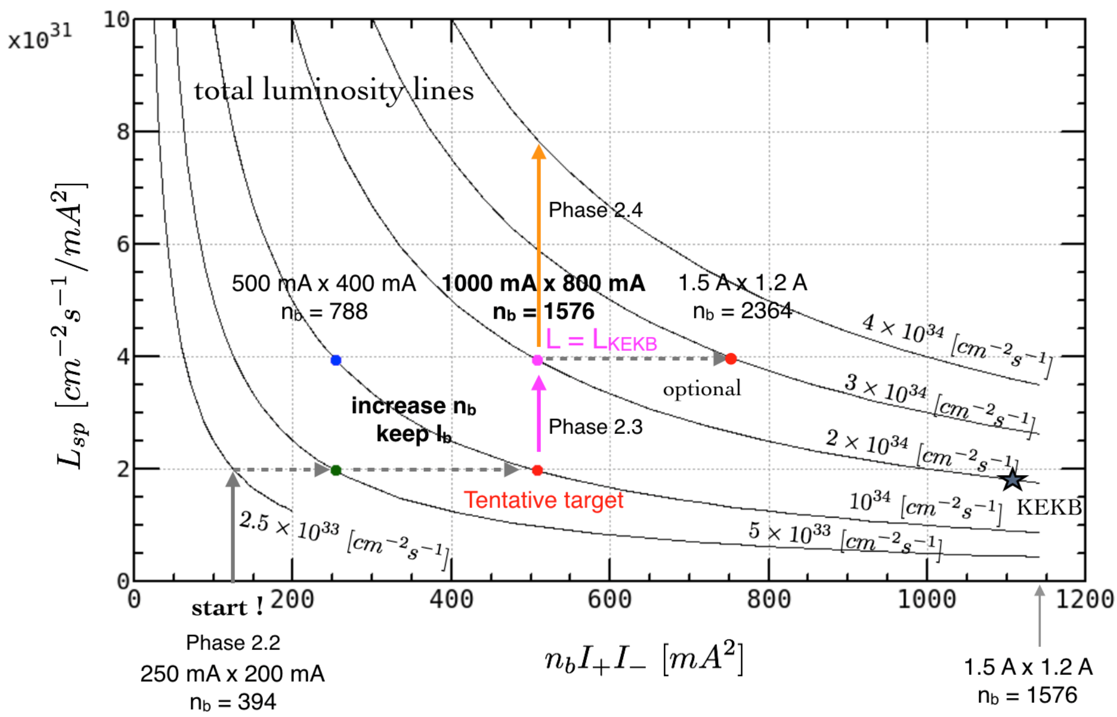

Figure 5: Travel guide for Phase 2. Specific luminosity as a function of number of bunches multiplies bunch current products. The curved line indicates total luminosity.

The commissioning of Phase 2 will be start mid of February 2018 and continue until mid of July 2018 for about five months. We expect that it will take one month at least for each sub phase. Several machine studies are planed with the physics run and the luminosity tuning. The vertical emittance is one of the most important parameters to improve the luminosity. Permanent solenoid-type magnets are installed in the LER as one of the countermeasures for the electron cloud effect during the long shutdown between Phase 1 and Phase 2. New type collimators are also installed in the both of LER and HER in the straight section near the IP to control beam backgrounds for the Belle II detector. We try to verify the nano-beam scheme and to get knowledge the beam background due to Touschek effects, beam-gas scatterings, and injection errors during Phase 2.

Table 3: Requirements for linac in Phase 2. The area of 95.4 % occupied by particles defines 2σ. The emittance is derived from the σ. The energy acceptance is defined by $3\sigma_\delta$.

Parameter	***Positron (LER)***	***Electron (HER)***	***Unit***
Beam energy	4	7	GeV
Normalized emittance, $\gamma\beta\varepsilon_x$ / $\gamma\beta\varepsilon_y$	200 / 40	150 / 150	μm
Energy spread, σ_δ	0.16	0.10	%

Bunch charge at injection point	0.5	1.0	nC

2.1.4 References

1. T. Abe et al., Technical Design Report of SuperKEKB, in preparation and to be published as a KEK report. A preliminary version is seen in https://kds.kek.jp/indico/event/15914/.
2. Y. Suetsugu, H. Hisamatsu, T. Ishibashi, K. Kanazawa, K. Shibata, M. Shirai, S. Terui, “First Commissioning of the SuperKEKB Vacuum System”, proceedings of the IPAC’ 16, Buson, Korea, TUP105 (2016).
3. H. Fukuma K. Ohmi, Y. Suetsugu, M. Tobiyama, “ELECTRON CLOUD AT SuperKEKB”, proceedings of eeFACT2016, Daresbury, UK.
4. Y. Ohnishi, Y. Funakoshi, H. Koiso, A. Morita, K. Oide, H. Sugimoto, “Optics Correction and Low Emittance Tuning at the Phase 1 commissioning of SuperKEKB”, proceedings of eeFACT2016, Daresbury, UK.
5. Y. Ohnishi et al., Prog. Theor. Exp. Phys., 2013 03A011 (2013).
6. “SuperB Conceptual Design Report”, INFN/AE-07/2, SLAC-R-856, LAL 07-15, March 2007.
7. N. Ohuchi et al., “Design of the Superconducting Magnet System for the SuperKEKB Interaction Region”, in Proceedings of NAPAC ’13, Pasadena, September 2013, WEODA1, pp. 759-961.
8. P. Thrane et al, CLIC-Note-1077, (2017).
9. T. Abe et al., Prog. Theor. Exp. Phys. 2013 03A001 (2013).
10. X. Zhou et al., “Developing an Yb/Nd Doped Hybrid Solid Laser of RF Gun for SuperKEKB Phase II Commissioning”, in Proceedings of IPAC ’17, Copenhagen, Denmark, May 2017, THPVA047, pp. 4540-4543.
11. T. Kamitani et al., “SuperKEKB Positron Source Construction Status”, in Proceedings of IPAC ’14, Dresden, Germany, MOPRI004, pp. 579-581.
12. M. Kikuchi, Nucl. Inst. Meth. A556, pp. 13-19 (2006), M. Kikuchi et al., “Design of Position Damping Ring for SuperKEKB”, in Proceedings of IPAC ’10, Kyoto, Japan, TUPEB054, pp. 1641-1643.

2.2 FCC-ee Optics Design

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