Status of SuperKEKB construction

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Abstract

SuperKEKB is a major upgrade of the asymmetric B-factory collider, KEKB, to provide 40 times higher luminosity than that achieved at KEKB. The design of SuperKEKB adopts the nano-beam scheme for the collision of two beams, which was originally proposed for the Italian SuperB project. The nano-beam scheme is realized with low-emittance optics, a very small β-function, and a large crossing angle at the collision point. For the low-emittance design, a substantial part of the positron ring (LER) was reconstructed. All dipole magnets in the LER were replaced with longer ones. The beam pipes in the LER were redesigned to mitigate the electron cloud problem. Around the interaction point, about 300 m of both rings were completely redesigned for the new collision scheme. The commissioning of SuperKEKB is divided into three phases. Phase 1 is used for vacuum scrubbing of new beam pipes without the Belle-II detector and the final focus magnets. The final focus magnets and Belle-II are installed in Phase 2. However, the central vertex detector (VXD) of Belle-II is not installed. Phase 2 is devoted to background studies and collision tuning. After the installation of VXD, Phase 3 starts for the new luminosity frontier. The construction of SuperKEKB for Phase 1 is nearing completion. The preparation of hardware for Phase 2 and Phase 3 is in steady progress. From various aspects, the nano-beam scheme SuperKEKB is a challenging accelerator. The tolerances for the hardware to realize nano-scale beam sizes and to keep the collision are very tight. The optics design is still being optimized to maximize the dynamic aperture. It is hard to predict how the commissioning will proceed.

Keywords: Asymmetric-energy collider, B-factory, Low emittance, High luminosity

1. Introduction

During the period from 1999 to 2010, two asymmetric-energy electron-positron colliders for B-physics, KEKB (KEK) and PEP-II (SLAC), competed on the luminosity frontier to study the physics of CP violation [1]. Their effort was rewarded with the 2008 Noble Prize in Physics for Professors Kobayashi and Maskawa, who shared the award with Professor Nambu. PEP-II was ceased operations on 7th April 2008. Two years later, KEKB was shut down on 30th June 2010, in order to be updated and reborn as SuperKEKB, which will continue the search for new physics on the luminosity frontier.

SuperKEKB aims for a 40 times higher luminosity (= 8×10^{35}cm^{-2}s^{-1}) than that recorded by KEKB [2]. The increase in luminosity is achieved by using low emittance flat beams colliding with a large crossing angle. In this collision scheme, the vertical β-function at the interaction point will be 20 times smaller than that of KEKB. The 40-fold increase in luminosity target is based on combining this with the increase of stored currents to twice those of KEKB. This new collision scheme was first proposed for SuperB in Italy by P. Raimondi [3]. We call it the "nano-beam"

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Table 1
Parameters for KEKB and SuperKEKB

	KEKB Achieved LER/HER	SuperKEKB Nano-beam scheme LER/HER	Units
Circumference	3016	3016	m
Energy	3.5/8.0	4.0/7.0	GeV
Crossing angle	22	83	mrad
Horizontal β-function at IP	1200/1200	32/25	mm
Vertical β-function at IP	5.9/5.9	0.27/0.41	mm
Emittance	18/24	3.2/2.4	nm
Emittance ratio	0.85/0.64	0.27/0.28	%
Horizontal beam size at IP	147/170	10.2/7.75	μm
Vertical beam size at IP	940	59	nm
Bunch length	6 ~7	6.0/5.0	mm
Beam-beam parameter	0.129/0.090	0.090/0.0875	
Beam current	1.64/1.19	3.60/2.62	A
Number of bunches	1585	2503	
Luminosity	2.11	80	$10^{34}cm^{-2}s^{-1}$

The LER is the positron ring and the HER is the electron ring. The IP is the interaction point.

scheme. The parameters for SuperKEKB are listed in Table 1, and compared with those achieved at KEKB.

The new low emittance lattice requires the replacement of dipole magnets in the KEKB LER with longer ones, while the dipoles of the KEKB HER can be reused since they are long enough. The HER lattice preserves the present cells in the arc. Damping wigglers are installed in both rings. In KEKB, only the LER had wigglers. In SuperKEKB, the KEKB LER wigglers are moved to the HER, and new wigglers with shorter periods are installed in the LER. The final focus is designed using an independent focusing pair for each ring. Superconducting magnets are used for the final focus system. The lattice of the local chromaticity correction section around the IP is completely redesigned for the new collision scheme. The tolerances for alignment errors in the local chromaticity correction section are very tight.

The energy of the LER is increased to 4 GeV. This gives the LER beam a longer Touschek lifetime and the mitigation of emittance growth due to intra-beam scattering. The beam pipes for the LER are all redesigned to cope with higher synchrotron radiation power, with features designed to mitigate the electron cloud problem. The beam energy of the HER is changed from 8 GeV to 7 GeV. As a result, the increase of synchrotron radiation power on beam pipes in the arc is only about 30%, despite the increase of the beam current. This makes it possible to reuse beam pipes in the arc sections of the HER. The increase in beam powers and the change of power balance between the two rings also require modification of the accelerating system. The RF cavities are rearranged according to the power balance between the rings. The number of klystrons will be increased in accordance with increasing beam power.

Additional cooling facilities are necessary for the magnets and beam pipes. The heat load on the beam pipes requires a three times higher cooling capacity than that provided by existing facilities. The heat load is relatively high in the wiggler sections. The total number of magnets is increased from about 1600 to 2000. Increase in cooling capacity is also necessary. Most new magnets are in wiggler sections. The delivery pipes for cooling water in the tunnel must be altered to conform to the new wiggler cells. This work must be completed before the installation of magnets and beam pipes.

Since the low emittance lattice of SuperKEKB has a narrower dynamic aperture than that of KEKB, the upgrade of the injector linac to provide low emittance bunches with high charge is necessary. The low emittance electron beam will be achieved with a new RF-gun. The construction of a positron damping ring (DR) is necessary to provide low emittance positron beam.

To maintain the collision of small cross-section beams, speed and precision are required in the orbit control system. Suitable feedback systems must be developed to keep a good collision condition. For the detector, it is very important to establish a reliable beam collimator system.

In the following sections, after discussing commissioning strategy, the present status of the upgrade of the accelerator will be described.

2. Commissioning strategy

The commissioning of SuperKEKB consists of three phases. The timing of each phase described below is tentative. The whole schedule is quite sensitive to the available budget.

Phase 1 (from October 2015)

The first phase is essentially a vacuum scrubbing phase. All beam pipes in the LER are new. Beam-gas background at the interaction point is expected to be high because of high pressure due to photon desorption. Collimators in the LER are not fully installed in this phase. Therefore the new detector, Belle-II, is not installed at this phase. Also the final focus superconducting magnets (QCS), the fabrication of which needs considerable time to complete, are not installed. The scrubbing requires at least a dose of one month with a beam current of 0.5 - 1 A. During this phase, the electron cloud instability in LER will be extensively studied to evaluate the adopted mitigation methods. Performance of the bunch by bunch feedback system will be checked. No beam collision is possible with the optics in this phase. However, low emittance tuning will be tried using the new arc lattice. Low emittance electron beam is expected to be delivered by the injector linac from the start of this phase. Using the last month of this phase, the commissioning of the DR is done in parallel, and then low emittance positron beam will be injected to the LER. It is expected that this phase requires 5 - 7 months to achieve the intended goals.

Phase-2 (late 2016 - early 2017)

In this phase, QCSs and Belle-II are installed at the IP and optics tuning of the nano-beam scheme starts. However, the central VXD is not installed yet, in order to avoid accidental exposure to excessive radiation. This phase is essentially a background study for the detector with a fully installed collimator system. The target of this phase is to achieve the design luminosity of KEKB (1×10^{34} cm^{-2} s^{-1}) with stored beams of 1000/800 mA (LER/HER) and a 2.2 mm vertical β-function at the IP. The increase of beam current will be done in careful steps while studying the accelerator performance. The target luminosity will be approached by utilizing improved feedback systems such as an overall orbit feedback system, a fast vertical feedback to correct the vertical position of bunches at the IP, and a dithering system to correct the horizontal position of bunches at the IP [4]. This phase will continue 4.5 - 6.5 months.

Phase-3 (from October 2017)

The real challenge starts from this phase. The VXD will be installed to complete the Belle-II detector. To realize the final machine parameters, we must overcome many difficulties in hardware control and optics design. The first important milestone in this phase is to achieve a luminosity of 1×10^{35} cm^{-2} s^{-1}.

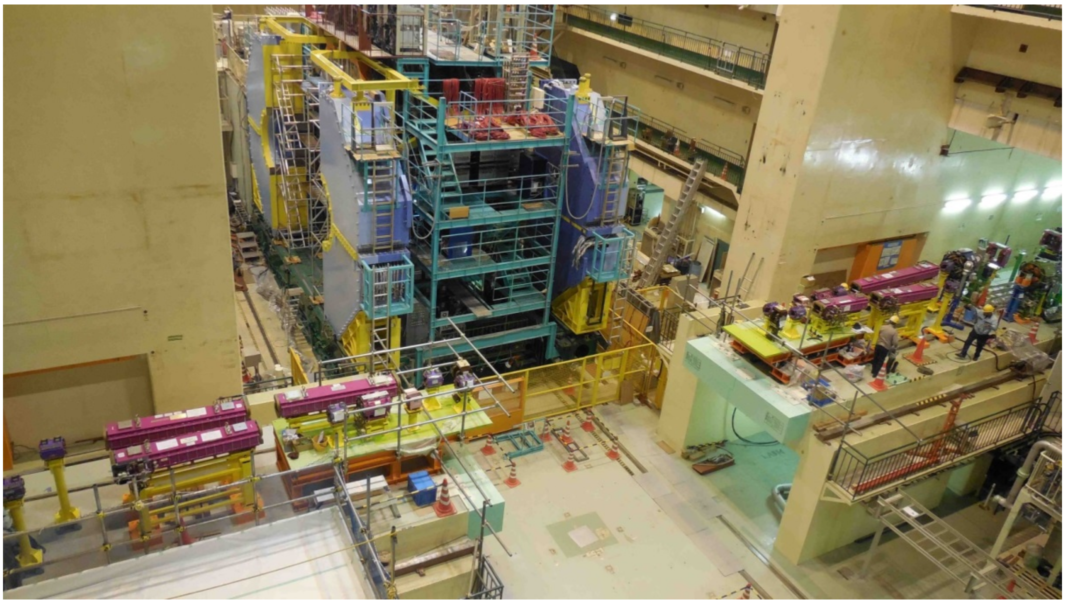


Figure 1: Scene around the IP in the Tsukuba experimental hall

3. Present status of construction

We are now in the last stage of construction leading up to Phase 1. Figure 1 shows a picture of the interaction region. The Belle-II detector is rolled out from the beam line and in the midst of upgrades. Magnets outside the final focus have been already installed along the beam line. At the gap in the accelerator floor, the base of a temporary concrete shield for Phase 1 will be constructed during October 2014. Then beam pipes will be installed.

The production of all new magnets is completed. The installation of all magnets will be complete in January 2015. The survey for alignment work is ongoing. Since all the segments of the KEKB tunnel except for experimental halls float in the ground soil without piles, heavy construction work going on above ground changes the vertical position of the segments. It is difficult to define an overall reference orbit under this condition. A first overall survey is planned from October 2014 to February 2015 when such construction is over. The fabrication of superconducting final focus magnets is in progress to be ready at the end of Phase 1. The magnets are integrated in a single cryostat at each side of IP. The collaring of all necessary magnets is over (Fig. 2). The left hand side cryostat will be delivered by March 2015. The right hand side cryostat will be delivered in July 2015. The installation of the QCSs is scheduled for soon after the Phase-1 commissioning.

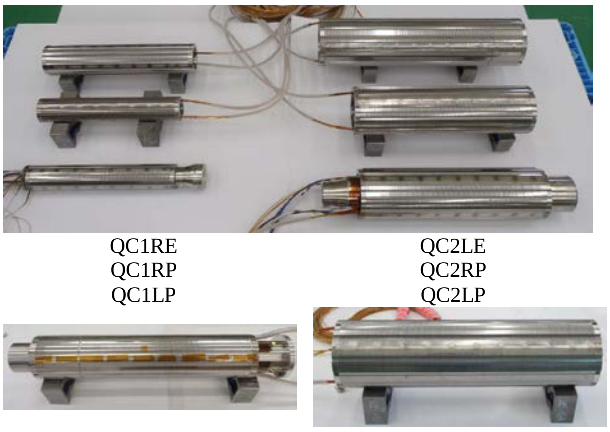


Figure 2: Final focus superconducting magnets after collaring. QC1XX and QC2XX form a focusing pair.

The production of beam pipes is nearly completed. For Phase 1, temporary beam pipes have beem prepared for the IP. The injection point of the LER will be rebuilt for low emittance positrons after Phase 1. Electron cloud mitigation in the LER is a key issue in realizing low emittance at high current. The head-tail instability caused by the electron cloud induces vertical emittance growth. Based on studies made during KEKB operation [5], a set of mitigations was selected for the LER [6]. All LER beam pipes are coated with 200 nm thick TiN. For the coating process, vertical DC magnetron sputtering apparatuses were constructed in the Oho vacuum laboratory. A beam pipe has an antechamber to trap source electrons due to synchrotron radiation. For wiggler sections, clearing electrodes are installed. Beam pipes in dipole magnets have grooved surfaces on top and bottom. Beam pipes in drift spaces are covered with solenoid coils. By using these countermeasures, an average electron density on the order of 10^{10} m^{-3} is expected for the design beam current. The threshold of the head-tail instability at the design current is estimated as ~1.6 × 10^{11} m^{-3} [7]. New beam pipes are baked at the Oho vacuum laboratory before installation. At present, except the local chromaticity correction region and the interaction region, the installation of beam pipes is almost finished.

Improvements of the cooling system are nearly complete. A large part of the cooling water pipes in the tunnel were replaced. This replacement of cooling water pipes in the tunnel was performed in the limited space between remaining accelerator components and the tunnel wall. Figure 3 shows an arc section of SuperKEKB.

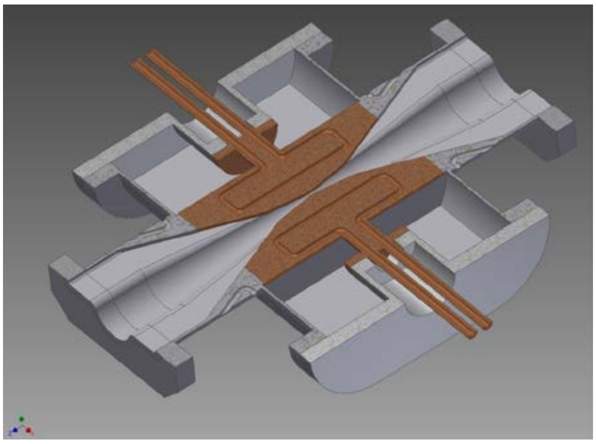
Figure 3: An arc section of SuperKEKB. The right hand side ring is HER. Left is LER. New cooling water pipes are seen along the outside tunnel wall.

The rearrangement of RF cavities is complete. Preparation work for aging in early 2015 is now on-going. The number of klystrons will be increased step-by-step after Phase 1, keeping pace with the increase of beam currents.

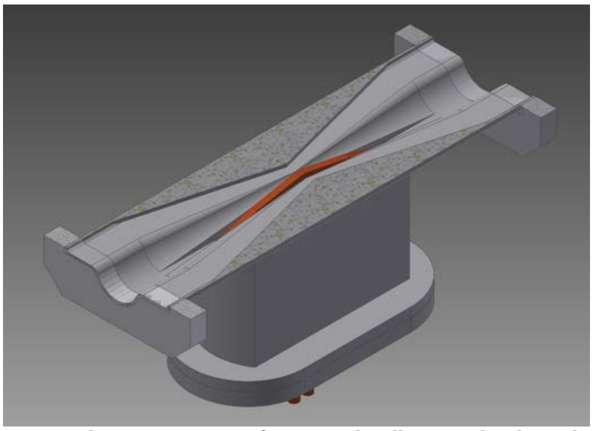
A new low emittance RF-gun and a new positron source were installed at the injection linac. Figure 4 shows the new positron source. The commissioning of these new components has just started [8][9]. The construction of the DR tunnel and the utility building is complete. The fabrication of accelerator components is on-going. The installation of the damping ring will start before March 2015.

Figure 4: New positron source. At the top is the flux concentrator. Below the concentrator, a positron target can be seen.

The preparation of a system for fast orbit control is in progress. Gated turn-by-turn detectors are being fabricated. By the time of Phase 1, 117 units will be available. The number of units will be increased to 270 for Phase 2. R&D on the IP vertical orbit feedback system is in progress. A down-converter for signal detection has been completed. A bunch-by-bunch feedback system is necessary from the start. Transverse kickers, button electrodes, power cables and power amplifiers have been installed. LER longitudinal kickers will be installed in August 2015. Visible light monitors that can endure high power synchrotron radiation will be available for Phase 1. Fabrication of the mirror, the holder and the chamber has been completed. Installation of the chambers, mirrors and holders will be finished by March 2015. X-ray monitors that are essential to measure a very small vertical beam size will also be available for Phase 1. Testing of the Large-Angle Beamstrahlung Monitor, which is expected to work as a collision geometry monitor, starts in Phase 1. At first, backgrounds without collision will be carefully studied [10]. The hardware of the dithering system consists of luminosity monitors and air-core corrector coils. The coils are going to be installed after the installation of beam pipes around IP. The final design of the luminosity monitors including necessary modification of beam pipes will complete during 2015.



Cut-away view of a horizontal collimator system.



Horizontal cut-away view of a vertical collimator chamber. The central vertical ridge is the collimator.

Figure 5: Conceptual drawings of collimators.

Beam collimators are very important components of the accelerator in Phase 2. The design is developed based on the PEP-II collimator (Fig. 5). Two horizontal collimators are in production, and will be installed before Phase 1 in the arc section of the LER. (For Phase 1, the HER collimators are of the old type). Others will be installed after Phase 1. The design optics parameters put vertical collimators in challenging position. Vertical collimators are installed to stop Coulomb-scattered beam particles before they reach the Belle-II detector. Without vertical collimators, such particles are lost at the final vertical focus magnet where the vertical β-function is very large and the aperture of the beam pipe is small. To stop these particles, vertical collimators must be placed very close to the beam. On the other hand, the collimator should not be close enough to the beam to induce transverse mode coupling instability (TMCI). According to a detailed analysis [11], to avoid the instability, the location of the vertical collimator should be in a low β-function region. Also, the number of the vertical collimators is limited to one or two. Because of the low β-function value at a collimator, a slight change of the collimator position causes a drastically large change of the envelope of the collimated beam at the final vertical focus magnet. For example, if the collimator position changes 0.1 mm, the beam loss at the final focus increases more than one order of magnitude. Studies during Phase 2 will clarify whether the situation is controllable or not.

According to recent studies of the final optics design, the beam-beam effect reduces the Touschek beam lifetime of the LER to half that of the design target. A crab-waist scheme to cure the beam-beam effect has been proposed, but no feasible crab waist lattice design has been be found at the moment [12][13].

Thus, in moving towards operation with the design parameters some difficulties are emerging. Investigations to find solutions will continue.

4. Summary

SuperKEKB aims for a luminosity of $8\times10^{35}\text{cm}^{-2}\text{s}^{-1}$ with the nano-beam collision scheme. The commissioning of SuperKEKB proceeds in three phases. Preparation for Phase 1 will be complete in early 2015. The design of the beam pipes for the LER adopts the latest available mitigation technologies against electron cloud. Their effectiveness will be studied in Phase 1. Collimators are fully equipped in Phase-2. Coulomb background is very sensitive to the apertures of the vertical collimators. The beam-beam effect degrades the Touschek lifetime of the LER to the half of the design value. A solution to this issue is now under study.

Acknowledgments

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