COMMISSIONING OF THE PHASE-1 SuperKEKB B-FACTORY AND UPDATE ON THE OVERALL STATUS

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Abstract

The SuperKEKB B-Factory at KEK (Japan), after few years of shutdown for the construction and renovation, has finally come to the Phase-1 commissioning of the LER and HER rings, without the final focus system and the Belle II detector. Vacuum scrubbing, optics tuning, and beam related background measurements were performed in this phase. Low emittance tuning techniques have also been applied in order to set up the rings for Phase-2 with colliding beams next year. An update of the final focus system construction, as well as the status of the injection system with the new positron damping ring and high current/low emittance electron gun is also presented.

INTRODUCTION

The SuperKEKB collider [1] is an asymmetric-energy and a double-ring electron-positron collider. The energy of the electron ring is 7 GeV(HER) and the positron ring is 4 GeV(LER). The collision point is one and the circumference is 3 km. The target luminosity is 8×10^{35} cm^{-2}s^{-1}, which is 40 times as high as the predecessor KEKB collider [2]. In order to accomplish the extremely high luminosity, a nano-beam scheme [3] is adopted. A large crossing angle and a small beam spot size in the both horizontal and vertical direction are applied in the nano-beam scheme. The crossing angle between two colliding beams is 83 mrad and the horizontal beam size is approximately 10 μm. When the overlap region of two colliding beams is considered, the nano-beam scheme can exchange the coordinate x with z as:

$$\tilde{\sigma}_x^* = \sigma_z \phi_x \quad (1)$$

$$\tilde{\sigma}_z = \frac{\sigma_x^*}{\phi_x} < \beta_y^* \sim 300\,\mu\text{m}, \quad (2)$$

where the $\tilde{\sigma}_x^*$ and $\tilde{\sigma}_z$ are the effective horizontal beam size at the interaction point(IP) and the effective bunch length, respectively. Because the geometrical reduction of the luminosity depends on the effective bunch length in the nano-beam scheme, it must be smaller than the vertical beta function at the IP. The low emittance and the low beta function at the IP in the horizontal direction can realize the requirement of "hourglass condition" although the real bunch length is long. The nominal bunch length, σ_z, is 6 mm in SuperKEKB. In the case of SuperKEKB, the vertical beta function can be squeezed down to approximately 300 μm from this criterion.

The famous luminosity formula is modified by replacing with the effective values as:

$$L = \frac{N_+ N_- f}{4\pi\sigma_x^*\sigma_y^*} = \frac{N_+ N_- f}{4\pi\sigma_z\phi_x\sqrt{\varepsilon_y\beta_y^*}} \quad (3)$$

and the vertical and horizontal beam-beam parameter is expressed by

$$\xi_y \propto \frac{1}{\sigma_z\phi_x}\sqrt{\frac{\beta_y^*}{\varepsilon_y}} \quad (4)$$

$$\xi_x \propto \frac{\beta_x^*}{(\sigma_z\phi_x)^2} \sim 0.003, \quad (5)$$

where ϕ_x is the half crossing angle. Because there is an upper limit for the beam-beam parameter, both the vertical beta function at the IP and the vertical emittance must be small with keeping their ratio constant in order to achieve the higher luminosity. The horizontal beam-beam parameter is almost constant and very small in the nano-beam scheme even though the small horizontal emittance and the small horizontal beta at the IP are realized. Consequently, the dynamic beta and the dynamic emittance becomes small.

The alternative formula of the luminosity is

$$L \propto \frac{I\xi_y}{\beta_y^*}. \quad (6)$$

In order to achieve 40 times as high luminosity as the KEKB collider, the vertical beta function at the IP is

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squeezed by 1/20 and the beam currents require the double with assuming the same vertical beam-beam parameter as KEKB (ξ_y ~0.09). Table 1 shows the machine parameters of SuperKEKB.

Table 1: Machine Parameters (with Intra-Beam Scattering) for the Final Design of SuperKEKB

	LER	HER	Unit
E	4.000	7.007	GeV
I	3.6	2.6	A
n_b	2500		
C	3016.315		m
ε_x	3.2	4.6	nm
ε_y	8.64	12.9	pm
β_x^*	32	25	mm
β_y^*	270	300	µm
$2\phi_x$	83		mrad
α_p	3.19×10^{-4}	4.53×10^{-4}	
σ_δ	7.92×10^{-4}	6.37×10^{-4}	
V_{RF}	9.4	15.0	MV
σ_z	6	5	mm
ν_s	-0.0245	-0.0280	
ν_x	44.53	45.53	
ν_y	46.57	43.57	
U_0	1.76	2.43	MeV
τ_x	45.6	58.0	msec
ξ_x	0.0028	0.0012	
ξ_y	0.0881	0.0807	
L	8×10^{35}		$cm^{-2}s^{-1}$

There are three stages for the commissioning of SuperKEKB; Phase-1, Phase-2, and Phase-3. The initial commissioning was done during Phase-1 without the final focus system before Belle II roll-in. The Phase-1 commissioning was started in February 2016 and operated until the end of June 2016 for about 5 months. The commissioning for Phase-2 will start in November 2017 and will operate for 5 months with the final focus system and Belle II detector. The first collision will be performed in Phase-2, however, the vertex detector will not be installed. The physics run with the full detector in Phase-3 will start October 2018, then the luminosity will increase gradually by squeezing the beta function at the IP and increasing the beam currents toward the target luminosity.

The vertical emittance is one of the most important issues in Phase-1 as described above since the luminosity performance significantly depends on the coupling parameter in the nano-beam scheme. The beam-size blowup induced by electron cloud in the LER is also an important issue in Phase-1. The study of the electron cloud can be done and confirm mitigation techniques such as ante-chamber beam pipes with TiN coating, and so on. Before Belle II detector roll-in, the enough process of vacuum scrubbing is necessary to reduce beam related backgrounds. The Belle II group requires the beam dose of 360 - 720 Ah.

COMMISSIONING OF PHASE-1

The subjects of the Phase-1 commissioning are
- hardware check and establish a stable operation,
- vacuum scrubbing,
- orbit and optics tuning,
- beam background study,
- study of electron cloud in the positron ring(LER).

Figure 1 shows the history of 5 months commissioning in Phase-1. The total beam currents have reached 1.01 A in the LER and 0.87 A in the HER, respectively. The average vacuum pressure reached 10^{-6} Pa in the LER and 10^{-7} Pa in the HER. Table 2 shows the machine parameters for Phase-1.

The RF system in the LER consists of normal conducting cavities with a HOM dumped structure, ARES, to store large beam current stably. A hybrid system of the ARES cavities and superconducting cavities(SCC) is utilized in the HER. The number of klystrons increases and the modification of the high-power input coupler is done in order to provide large beam power. The most of the components are reused from those of KEKB [4], however, a relocation of the ARES cavities was performed. The current upgrade of the RF system makes it possible to store 70 % of the nominal beam current as shown in Table 1.

Table 2: Machine Parameters in Phase-1 (Without Intra-beam Scattering)

	LER	HER	Unit
E	4.000	7.007	GeV
I	1.01	0.87	A
n_b	1576		
ε_x	1.8	4.6	nm
α_p	2.45×10^{-4}	4.44×10^{-4}	
σ_δ	7.52×10^{-4}	6.30×10^{-4}	
V_{RF}	7.56	12.61	MV
σ_z	4.6	5.3	mm
ν_s	-0.0192	-0.0253	
ν_x	44.53	45.53	
ν_y	46.57	43.57	
U_0	1.76	2.43	MeV
τ_x	46	58	msec

Vacuum Scrubbing

The vacuum system in the LER has been newly designed in order to absorb an intense synchrotron radiation emitted from positron beams and also suppress electron cloud effects [5]. Most of the vacuum pipes, about 93 % out of the whole ring, were replaced with new pipes. Especially, ante-chambers with TiN coating were adopted in the arc section. The vacuum pipes in the arc section are made of aluminum-alloy. Most of the vacuum components were reused in the HER. The vacuum pipe of the HER was made of copper and the cross section is a race track in the arc section. Therefore, the vacuum scrubbing in the LER is necessary much more than that of the HER. Figure 2 shows an average vacuum

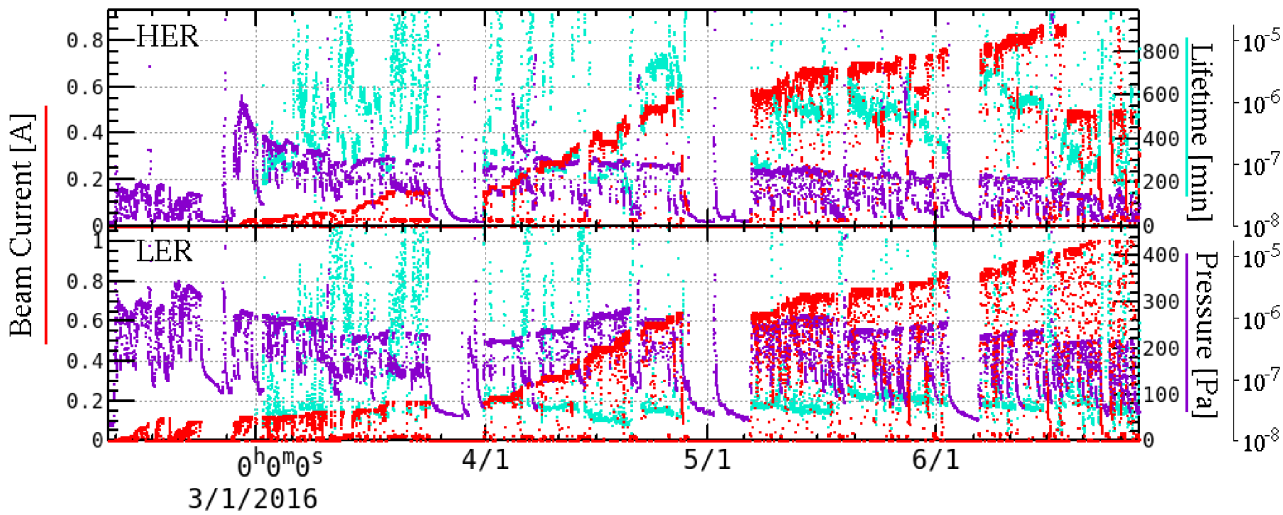

Figure 1: History of the Phase-1 commissioning. Beam current(red), lifetime(cyan), and average pressure(purple).

pressure normalized by beam currents as a function of beam dose in the LER, and that of the HER is shown in Fig. 3. An expected photon stimulated gas desorption rate, η in the arc section, is also shown in figures with assuming the linear pumping speed of 0.06 $m^3s^{-1}m^{-1}$ in the LER and 0.03 $m^3s^{-1}m^{-1}$ in the HER.

The beam dose of 780 Ah was achieved in the LER and 660 Ah in the HER during the Phase-1 commissioning. The pressure rise has reached $8{\times}10^{-7}$ PaA^{-1} in the LER and $4{\times}10^{-8}$ PaA^{-1} in the HER, respectively. The pressure rise in LER became approximately the same value as that of KEKB for the same beam dose. On the other hand, the pressure rise in the HER during the beginning of Phase-1 was smaller than that of the initial KEKB commissioning even though the vacuum pipes were exposed to the atmosphere during the upgrade work of the HER. Most of the vacuum pipes in the arc section were reused from those of KEKB. It is found that the reused surface of the vacuum pipe can keep the condition of the vacuum scrubbing at KEKB.

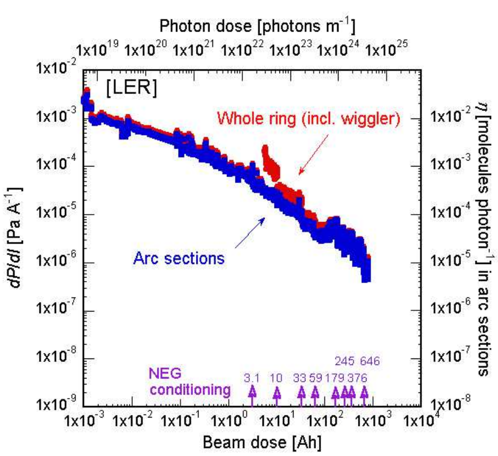

Figure 2: Pressure rise and expected photon stimulated gas desorption rate as a function of beam dose in the LER .

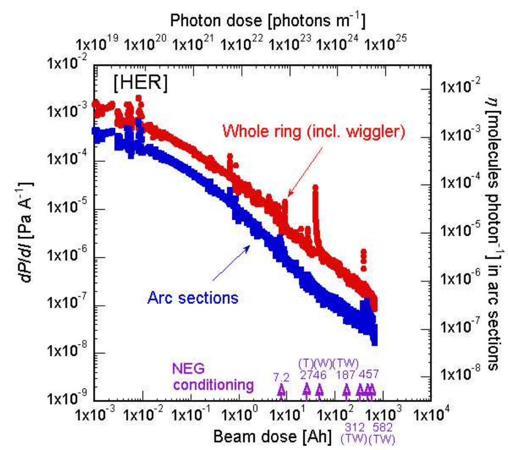

Figure 3: Pressure rise and expected photon stimulated gas desorption rate as a function of beam dose in the HER.

Optics Tuning

The lattice for Phase-1 is the same lattice as those of Phase-2 and Phase-3 except for the interaction region(IR). Since there is no final focus magnet in the vicinity of the IP, the field strengths of quadrupole magnets in the IR are adjusted so as to connect the arc lattice. The optics tuning [6] without the final focus, the solenoid field, and the local chromaticity corrections can be performed for Phase-1. The optical functions such as beta functions, dispersions, and X-Y couplings were measured and corrected in the LER and HER, respectively. The beta functions are obtained by orbit responses induced by six kinds of dipole correctors for each x and y direction. The physical dispersions are measured by orbit displacements for the rf frequency shifts between -500 Hz and +500 Hz. Note that the dispersions are physical and different from normal mode dispersions. In the case of the X-Y couplings, vertical leakage orbits from horizontal orbits induced by six kinds of horizontal dipole correctors are used to correct the X-Y couplings instead of four X-Y coupling parameters of r_1 - r_4. The number of BPMs is 438 in the LER and 460 in the HER to measure closed orbits. The

BPM gain mapping and the beam based alignment(BBA) have been performed before the optics tuning.

In order to correct the beta functions, the measured beta functions and phase-advance are compared with those calculated by the model and amount of the correction of field strength for each quadrupole magnets are estimated. Correction coils are installed for each quadrupole magnet, however, the correction was performed by families of quadrupole magnets during the Phase-1 commissioning. The arc lattice adopts non-interleaved sextupole correction scheme and two identical sextupoles are connected by $-I'$ transfer matrix. The dispersions and X-Y couplings are corrected by using this specialty. The horizontal dispersions are corrected by using asymmetric local bumps in the horizontal direction at pairs of two horizontal focusing sextupoles(SF). The horizontal offset of the sextupole generates quadrupole field, however, this quadrupole field is localized between two identical sextupoles then only horizontal dispersions can be corrected. The vertical dispersions and the X-Y couplings are corrected by using skew quadrupole-like correctors at the sextupole magnets. The opposite sign of the skew quadrupole field can correct only the vertical dispersions, on the other hand, the same sign can correct only the X-Y couplings. Because of the non-interleaved sextupole scheme, the corrections of vertical physical dispersions and X-Y couplings can be solved independently for each other.

Table 3 shows the results of optics corrections. After these optics corrections, the vertical emittance has achieved 9 pm in the LER which was measured by an X-ray beam size monitor. The vertical emittance is derived by $\varepsilon_y = \sigma_y^2/\beta_y$. In another way, the vertical emittance can be estimated by measured optical functions and magnet configurations;

$$\varepsilon_y = C_q \gamma^2 \frac{I_{5,y}}{J_x I_2}. \qquad (7)$$

The normal dispersions can be derived by X-Y coupling parameters and transfer matrix between neighboring two BPMs in the model. The vertical emittance of 8 pm in the LER is obtained by this estimation which is consistent with the X-ray measurement. On the other hand, the measured vertical beam size in the HER was 30 µm for $\beta_y = 7.6$ m, which corresponds to the vertical emittance of 120 pm. This value seems to be too large because the optics tuning is the same level between the LER and HER as shown in Table 3. A simulation assuming a misalignment of the sextupoles which reproduces the measured optical functions provides the vertical emittance of 5 – 20 pm. We consider that the calibration issues of X-ray monitor still remains. The vertical emittance is indirectly estimated to be 6 pm by using the measured optical functions in the HER.

Electron Cloud

Electron cloud is a serious issue for e^+e^- storage-ring collider. We have tried to suppress the effect by using solenoid field at KEKB with a circular vacuum pipe for many years. In SuperKEKB, ante-chambers with TiN coating are adopted in the arc section to suppress the electron cloud in the LER.

Table 3: Results of the Optics Tuning in Phase-1. X-Y coupling* refers an average value of rms(Δy)/rms(Δx) induced by six kinds of horizontal dipole correctors. Dispersions are physical variables in the table.

Items	Symbol	LER	HER
Coupling strength	$\mid C^- \mid (\times 10^{-3})$	1.2	2.0
X-Y coupling*	rms(Δy)/rms(Δx)	0.9 %	0.6 %
Hor. dispersion	rms($\Delta\eta_x$)	8 mm	11 mm
Ver. dispersion	rms($\Delta\eta_y$)	2 mm	2 mm
Hor. β function	rms($\Delta\beta_x/\beta_x$)	3 %	3 %
Ver. β function	rms($\Delta\beta_y/\beta_y$)	3 %	3 %
Hor. tune	$\Delta\nu_x$ ($\times 10^{-4}$)	2	5
Ver. tune	$\Delta\nu_y$ ($\times 10^{-4}$)	5	1

Figure 4 shows the electron current measured by the electron monitor for various vacuum chambers used at KEKB or SuperKEKB. The measured electron current indicates the electron density around the beam orbit. When the region of the lower beam current(<400 mA) is considered which dominates photoelectrons, the ante-chamber suppress photoelectrons significantly compared with the circular vacuum pipe. In the region of the high beam current(> 400 mA), the secondary electrons are dominate and it is found that the TiN coating can suppress the secondary electrons very well. The mitigation of electron cloud by using the ante-chamber with TiN coating has been confirmed in Phase-1. However, nonlinear pressure rise for the beam current and beam-size blowup were observed in Phase-1. It is found that the nonlinear pressure rise is caused by multiplication of electrons at the aluminum bellows chamber without TiN coating. The bellows chambers with a length of 0.2 m locate every 3 m in the whole ring and the number of bellows is 800. In order to suppress the multiplication of electrons, permanent magnets generating solenoid field were installed and the pressure rise was reduced significantly.

Figure 5 shows the beam-size blowup as a function of total beam current for several rf-bucket spacing with 600 bunches. It is found that the threshold of the beam-size blowup depends on the rf-bucket spacing, namely, the electron density increases as the rf-bucket spacing decreases. Even though the ante-chamber with TiN coating and solenoid magnets at the aluminum bellows were adopted, we still observed beam-size blowup above 900 mA in the case of 3 rf-bucket(6 ns separation) spacing and 1578 bunches in total. Test of nano-beam scheme will be able to be performed in Phase-2 since the beam-size blowup can be suppressed until 1 A when 4 rf-bucket spacing is adopted. We need more solenoid field at the drift spaces such as the ante-chamber to suppress the beam-size blowup when we try to achieve the design beam current with the design bunches in Phase-3.

Injector Linac

Low emittance and high intensity electron and positron beams are necessary for the injection to the LER and HER. A

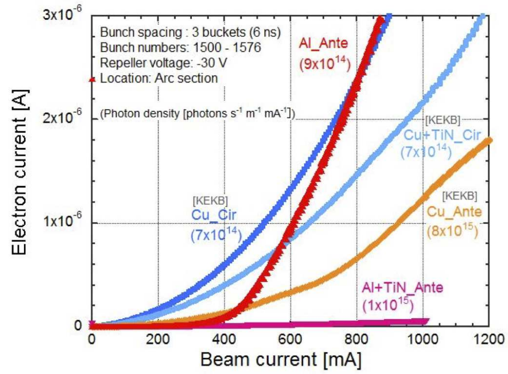

Figure 4: Electron current as a function of beam current in the LER.

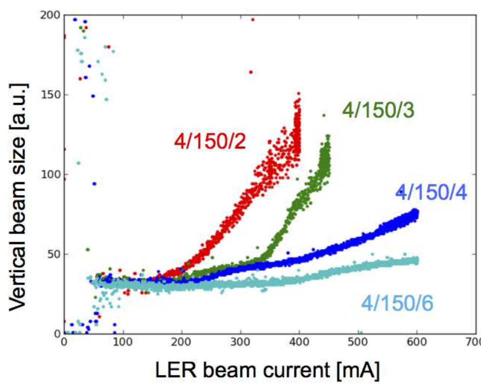

Figure 5: Beam-size blowup(vertical) in the LER.

flux concentrator and 10 large aperture S-band accelerating structures were installed to increase positron intensity for the LER. The huge emittance of the initial positron beam will be decreased by a dumping ring(DR) at 1.1 GeV. Since the DR is under construction, the positron beam is injected directly to the LER bypassing the DR during Phase-1. We operated the flux concentrator with the half of the nominal current since the head part was damaged due to large electric discharge last year. The reason of the damage comes from that the hardening process was abbreviated. The charge intensity of positron beams was 0.6 nC at the end of the linac for the 7 nC primary electrons. The modified version of the flux concentrator will be installed next year.

A photo-cathode rf gun is used to make a low emittance and high intensity electrons for the HER injection. The rf gun consists of Ir_5Ce as the cathode and a Yb doped solid state laser with a hybrid system of fiber-based amplifies and Yb:YAG thin-disk multi-pass amplifies for Phase-1. A quasi-traveling wave side-coupled cavity is adopted to accelerate an initial electron beam. The bunch length of 25 ps is compressed into 10 ps by using a chicane. We also prepared a thermionic gun to be used for primary electrons to generate positron beams and also for the injection to the HER. We stacked two pre-injectors of the rf gun and of the thermionic gun vertically to switch injection from them. The rf gun is located at the same level as the main linac, on the other hand, the thermionic gun is on the upper deck. The vertical transfer line is built to merge electron beams from the thermionic gun to the main linac. The rf gun was operated for 10 days and the condition was stable [7]. The normalized emittance of 20 - 30 µm has been achieved by the rf gun. The charge intensity was 1.7 nC measured just after the rf gun. Further modifications for the rf gun will be prepared for the injection in Phase-2 and Phase-3.

UPGRADE STATUS FOR PHASE-2

Major upgrade issue between Phase-1 and Phase-2 is a construction of the final focus system. The final focus system consists of four quadrupoles, 16 corrector coils, 4 cancel coils for the HER to compensate leakage field from the LER, and compensation solenoid for each side of the IP. These magnets are superconducting magnets and have iron or permendur yokes except for the most closest magnets to the IP in the LER. The left side of the final focus system has been installed in the IR and we have measured and adjusted an alignment of the magnets. The fabrication of the final focus system for the right side will be finished and installed within this year.

CONCLUSIONS

The vacuum scrubbing was successfully done and the low emittance tuning was performed during Phase-1. The vertical emittance of 10 pm which is the target value at this stage has been achieved in the LER. The vacuum system, the RF system, and the beam instrumentation worked without any serious trouble. The fabrication and field measurements of the final focus system and the construction of the positron damping ring will be completed next year. The first collision will be provided in the end of 2017. The SuperKEKB project keeps on going.

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