OPTICS MEASUREMENTS AND CORRECTIONS AT THE EARLY COMMISSIONING OF SuperKEKB

Y. Ohnishi*, H. Sugimoto, A. Morita, H. Koiso, K. Oide,
K. Ohmi, D. Zhou, Y. Funakoshi, KEK, Tsukuba, Japan
N. Carmignani, S. M. Liuzzo, ESRF, Grenoble, France
M. E. Biagini, M. Boscolo. S. Guiducci, INFN/LNF, Frascati, Italy

Abstract

We present experimental results of measurements and corrections for the optics at the early Phase-1 commissioning of SuperKEKB. The aim of SuperKEKB is a positron-electron collider built to achieve the target luminosity of 8x10^{35} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. We have three stages; Phase-1 is the commissioning of the machine without the final focus magnets and detector solenoid(no collision); the collision with the final focus system and the Belle II detector will be performed at Phase-2 and Phase-3. The strategy for the luminosity upgrade is a novel "nano-beam” scheme found elsewhere [1]. In order to achieve the target luminosity, the vertical emittance has to be reduced by corrections of machine error measured with an orbit response. The vertical emittance should be achieved to be less than 10 pm(~0.2 % coupling) during Phase-1 by fully utilizing correction tools of skew quadrupole-like coils wound on sextupole magnets and power supplies for each correction coil in quadrupole magnets.

OPTICS DESIGN

SuperKEKB is a double-ring collider which is an asymmetric-energy collider; 4 GeV for positrons(LER) and 7 GeV for electrons(HER) [2]. The circumference is 3 km. The lattice design consists of 4 straight sections and 4 arc sections as shown in Fig. 1. The collision point is located at one of the straight sections and RF cavities and wiggler magnets are located in the other straight sections. The final focus system and Belle-II detector with 1.5 T solenoid will be installed in Phase-2, therefore there is no interaction region at Phase-1. The purpose of Phase-1 is a vacuum scrubbing and an optics tuning without the final focus system. In particular, the small vertical emittance is necessary to accomplish the nano-beam scheme. The target value of the vertical emittance is less than 10 pm. The optics variables such as X-Y coupling, dispersion, and beta function should be well understood to achieve the small vertical emittance.

The arc lattice applies a non-interleaved sextupole correction scheme. Figure 2 shows the unit cell lattice in LER. The unit cell consists of 7 quadrupole families and 4 dipole magnets. The 4 families of quadrupoles out of 7 families are utilized to make a $-I'$ transform between two sextupoles. The transfer matrix between two identical sextupoles is $-I'$ so as to suppress a nonlinear kick induced by the sextupole while chromaticity is corrected. Consequently, a large dynamic aperture for on-momentum particles can be expected.

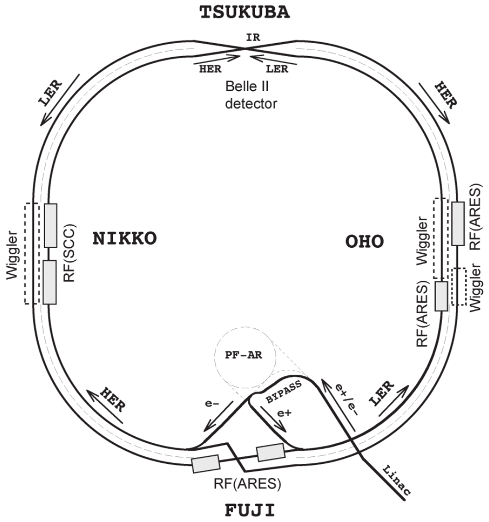

Figure 1: Layout of SuperKEKB.

The natural chromaticity is $\xi_{x0} = -62$, $\xi_{y0} = -84$ in LER and $\xi_{x0} = -81$, $\xi_{y0} = -71$ in HER. There are 50 sextupole families in the arc sections. Since the number of correctors is enough, the sextupoles can correct not only the natural chromaticity but also chromatic behavior of Twiss parameters at RF cavities. The remaining three families of quadruples are used to adjust the emittance and the momentum compaction factor, which can be varied independently in the higher emittance region. However, the momentum compaction factor is unique in the case of the smallest emittance.

The arc section makes emittance to be 4 nm in LER and 5 nm in HER. The emittance becomes 1.8 nm in LER and 4.6 nm in HER together with the wiggler sections in total. The emittance becomes 3.2 nm in the collision optics due to intrabeam scattering when the nominal bunch current and the coupling parameter are assumed. The machine parameters at Phase-1 are shown in Table 1. The optics is modeled and the response of orbit distortions is calculated by using *SAD* [3] in this paper.

OPTICS MEASUREMENTS AND CORRECTIONS

The main optical functions are X-Y coupling, dispersion, and beta function which are global variables. In the early commissioning during Phase-1, optics measurements based on a response of closed orbit are adopted. There are 438 BPMs in LER and 460 BPMs in HER for an averaged mode

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* yukiyoshi.onishi@kek.jp

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Table 1: Machine Parameters (April 2016) — Intra-beam Scattering is Not Included

Parameter	LER	HER	Unit
E	4	7	GeV
I	650	590	mA
n_b	1576	1576	
ε_x	1.8	4.6	nm
α_p	2.45×10^{-4}	4.44×10^{-4}	
σ_δ	7.72×10^{-4}	6.30×10^{-4}	
V_c	7.45	11.99	MV
U_0	1.87	2.43	MeV
τ_s	22	29	msec
σ_z	4.8	5.4	mm
ν_s	-0.0190	-0.0246	
ν_x	44.575	45.558	
ν_y	46.586	43.573	

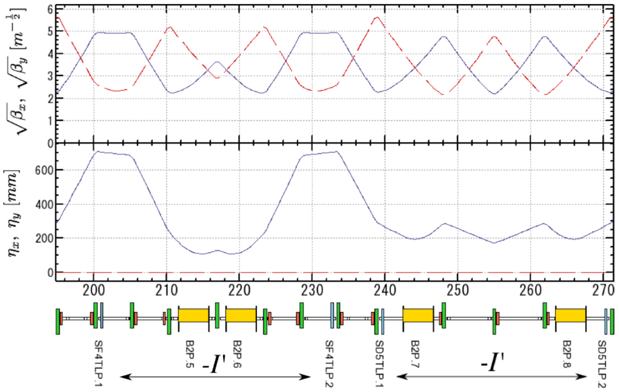

Figure 2: Arc cell in LER. The phase-advance is 2.5 π. The SF and SD indicate sextupoles.

to measure orbits. The accuracy of the BPM is within a few μm.

Skew quadrupole-like correction coils are wound on the poles in each sextupole magnet to correct X-Y coupling and vertical physical dispersion. Since a pair of sextupoles are connected by the $-I'$ transformation, the X-Y coupling and the vertical physical dispersion can be corrected independently. The same sign of the field correct only the X-Y coupling without a leakage of dispersion outside of the sextupole pairs. On the other hand, the opposite sign of the field correct only the vertical physical dispersion and vice versa. The field strength of the skew-quadrupole correction coil is 8×10^{-3} 1/m at the maximum. Although a vertical local bump orbit can also make the correction as the same way of the above method, the vertical orbit is not suitable for an ante-chamber structure where synchrotron light is considered.

In order to correct horizontal physical dispersion, the horizontal bump orbits at the focusing sextupoles are utilized. Beta functions are corrected by using fudge factors which adjust field strength of quadrupole magnets. Most of quadrupole magnets have correction coils to change the field gradient. The corrector field strength or the local bump height are obtained by solving linear equations which include residuals of measured optical functions from the model and response matrices calculated in the model lattice.

X-Y Coupling

X-Y coupling is measured by a leakage orbit in the vertical direction when the horizontal orbit is induced by six kinds of steering magnets as shown in Fig. 3. In order to correct the X-Y coupling, skew quadrupole-like field with a same sign induced by correction coils on sextupole pairs is utilized.

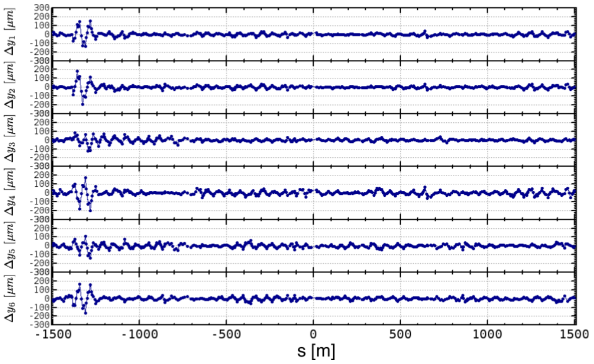

Figure 3: Leakage orbits in the vertical direction due to X-Y coupling in LER. After corrections. Kick angle of each horizontal steering is 200 μrad. Lambertson septum is located at s=-1400 m and $s = 0$ m indicates a location of IP.

Figure 4 shows a result of coupling measurement by using a closest tune approach [4] after corrections in LER.

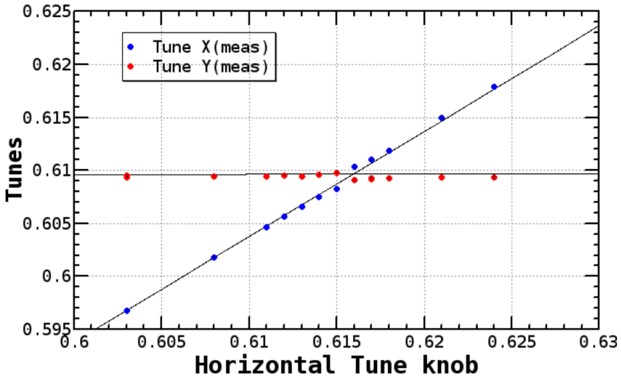

Figure 4: Coupling measurement in LER. After corrections.

The parameter of $\mid C^{-1} \mid$ is obtained to be 0.0012 from the bandwidth of the coupling resonance. The $\mid C^{-1} \mid$ parameter was 0.013 without any optics corrections.

Physical Dispersion

Horizontal and vertical dispersion are measured by a displacement from a reference orbit due to varying the RF frequency. The frequency shift is typically ±200 Hz which corresponds to ±0.16 % in LER and ±0.088 % in HER. In the case of the horizontal dispersion, not only the horizontal asymmetric bumps but also fudge factors of quadrupole magnets in the interaction region(TSUKUBA straight section

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shown in Fig. 1) are utilized as the corrector because there is no corrector in the local chromaticity correction consists of many dipole magnets(possible error source). In this paper, an iterative procedure of the horizontal dispersion and the beta correction is performed although both the dispersion and the beta function can be corrected simultaneously by solving mixed linear equations. The physical dispersion after the correction in LER is shown in Fig. 5. The rms of the residuals of the measurement from the model can be reduced to be 14.8 mm in the horizontal and 9.5 mm in the vertical direction in LER. The second order dispersion(second row) is also in good agreement with the model.

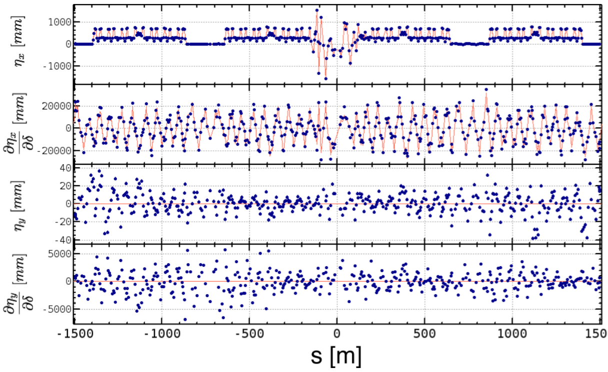

Figure 5: Physical dispersion in LER after corrections. Measurements are indicated by dots and lines are obtained from the model lattice.

Beta Function

Orbit distortions are induced by using six kinds of steering magnets in each x and y direction. The response of the orbit in the horizontal or the vertical direction is found elsewhere [5]. The beta functions and the phase advance are obtained from an iterative procedure of the least square method [6]. Once the beta-beat and the phase modulation are obtained from the above fitting procedure with measured betatron tunes, the fudge factor, in another word, the correction of the field gradient, ΔK_1 can be calculated from solving linear equations. Figure 6 shows the beta function in LER after a series of the optics corrections.

CONCLUSION

Results of optical functions after optics corrections in LER and HER are listed in Table 2. The fundamental measurements and corrections for the optics have been well performed in the early commissioning at Phase-1. Vertical emittance in LER is measured to be 20 pm obtained from a X-ray beam-size monitor [7] which is a preliminary measurement. In order to accomplish the vertical emittance less than 10 pm, it is necessary to be reduced by a factor of 2. It is expected that the dominant error comes from misalignment of the sextupole magnets and/or leakage skew quadrupole field from a Lambertson septum(s=-1400 m) to abort beams.

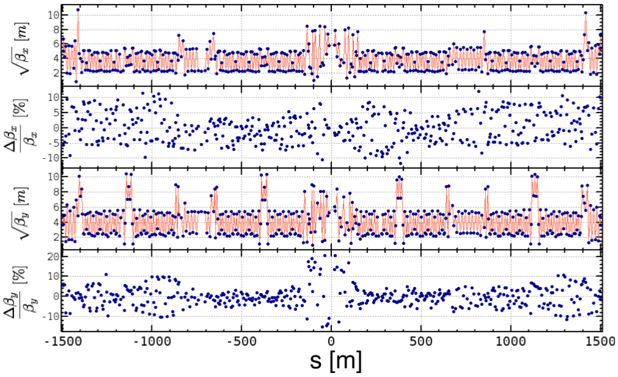

Figure 6: Beta function in LER after corrections. Measurements are indicated by dots and lines are obtained from the model lattice.

The leakage skew field can be localized between the Lambertson septum and the near arc section by using the skew quadrupole-like correctors as shown in Fig. 3. However, we have a plan to install additional correction magnets in the vicinity of the Lambertson septum to compensate the leakage field as much as possible. We will also check the alignment of the sextupoles and the quadrupoles near them.

Table 2: Results of Optics Corrections; X-Y Coupling, Dispersion, Beta Function, Tune, and Chromaticity. Discrepancy between measurement and model.

Items	**LER**	**HER**	**Unit**
average of rms(Δy_{1-6})	23.6	7.7	μm
rms($\Delta\eta_x$)	14.8	16.1	mm
rms($\Delta\eta_y$)	9.5	4.8	mm
rms($\Delta\beta_x/\beta_x$)	4.9	4.3	%
rms($\Delta\beta_y/\beta_y$)	5.3	3.7	%
$\Delta\nu_x$	0.001	0.001	2π
$\Delta\nu_y$	-0.008	0.002	2π
$\Delta\xi_x$	2.27	-1.00	
$\Delta\xi_y$	-4.27	0.22	

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