ISSUES ON IR DESIGN AT SuperKEKB

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Abstract

The design of the interaction region is one of the most important issue in SuperKEKB. The lattice design with the final focus system and the local chromaticity correction as well as the dynamic aperture under the influence of beam-beam interactions are presented.

SUMMARY OF INTERACTION REGION

The machine parameters of SuperKEKB [1] are shown in Table 1. The final focus system is designed to achieve the extremely low beta function at the IP. In order to squeeze the beta functions, doublets of a vertical focusing (QC1) and a horizontal focusing quadrupole magnet (QC2) are adopted. Figure 1 shows the layout of the final focus system. The magnet system consists of superconducting magnets to make strong focusing strength. Those magnets have an iron yoke or a permendure yoke to shield the magnetic field to the opposite beam line except for the most inner magnets QC1Ps in the LER. Cancel coils for the leakage field of sextupole, octupole, decapole, and dodecapole filed from QC1s in the LER are installed in the HER. The dipole and quadrupole leakage fields are used in the lattice design of the interaction region in the HER. The dipole, skew dipole, skew quadrupole coils are quipped with the main quadrupole magnets to adjust X-Y couplings and vertical dispersions induced by solenoid field, although the 1.5 detector solenoid field is almost corrected by compensation solenoid magnets. The octupole coils are also installed to make dynamic aperture large, especially in the transverse direction. In addition to the coils for the lattice design, skew sextupole coils to correct imperfections of the main quadrupole magnet.

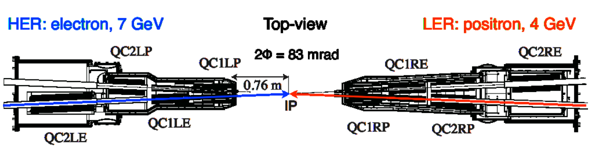

Figure 1: Top View of the Final Focus System.

The natural chromaticity is ξ_x =-105 and $\xi_y = -776$ in the LER, ξ_x =-171 and $\xi_y = -1081$ in the HER. Since approximately 80 % of the linear chromaticity in the vertical direction is induced in the final focus system, a local chromaticity correction (LCC) is adopted to correct the large chromaticity near the final focus system. There are 2 pairs for the vertical direction (Y-LCC) and another 2 pairs of sextupoles for the horizontal direction (X-LCC) in the IR. The phase advance between QC1 and the Y-LCC is π in the vertical direction and between QC2 and X-LCC is 2π in the horizontal direction for each side of the IP. Horizontal dispersions are created at the LCC by using several dipole magnets. Figures 2 and 3 show the lattice design of the LCC region.

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}		$cm^{-2}s^{-1}$

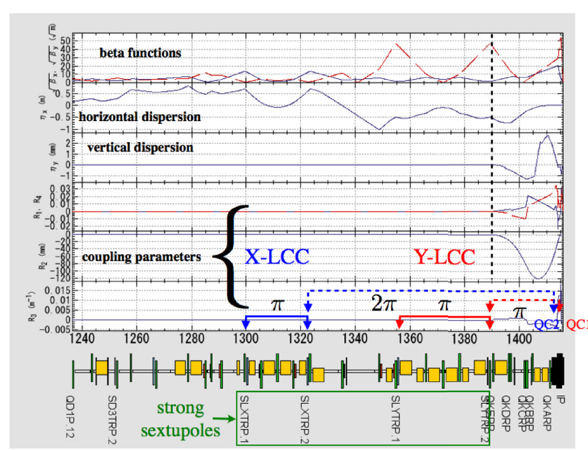

Figure 2: Local Chromaticity Correction in the LER.

NONLINEAR TERM IN FINAL FOCUS

Nonlinear effects in the final focus system decreases the dynamic aperture significantly. In addition to the nonlinear magnetic field, the drift space is not linear system as

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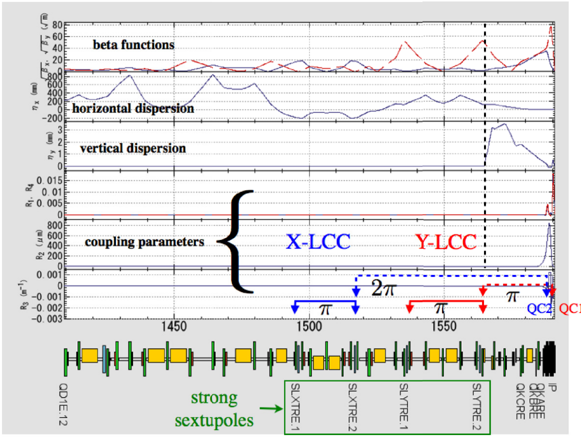

Figure 3: Local Chromaticity Correction in the HER.

shown in a Hamiltonian. Especially, when the beta function is squeezed in the vicinity of the IP and decreased with distance from the IP, the effect cannot be ignored. The aperture of the motion can be described by a simple one-dimensional Hamiltonian [2]. The Hamiltonian of the nonlinear term is expressed by

$$H_{nl} = \left(1 - \frac{2}{3}k_1 L^{*2}\right) \frac{L^*}{\beta_y^*} J_y^2 \cos^4 \psi_y, \tag{1}$$

where

$$k_1 = \frac{1}{B\rho}\frac{\partial B_y}{\partial x}. \tag{2}$$

Table 2 shows the coefficient of the Hamiltonian and related parameters for various machines. The coefficient of the nonlinear Hamiltonian can be used to evaluate the dynamic aperture in SuperKEKB. The coefficient of SuperKEKB is about 200 times larger than that of KEKB [3] and 10 times larger than that of FCC-ee.

Table 2: Coefficient of the Nonlinear Hamiltonian Term. The c indicates $H_{nl}/J_y^2 \cos^4 \psi_y$.

	β_y^* [mm]	k_1 [m^{-2}]	L^* [m]	c [μm^{-1}]
HER	0.30	-3.05	1.22	55.56
LER	0.27	-5.10	0.76	31.25
FCC-ee	1	-0.336	2	3.79
CEPC	1.2	-0.176	1.5	1.32
KEKB	5.9	-1.78	1.76	0.237
DAΦNE	8.66	-9.23	0.2	0.0033

DYNAMIC APERTURE UNDER INFLUENCE OF BEAM-BEAM EFFECT

The dynamic aperture will be reduced under the influence of beam-beam effects in the nano-beam scheme. A particle with a horizontal amplitude collides at a location different from the IP in the longitudinal direction due to the crossing angle of 83 mrad between two beam lines in the horizontal plane. The deviation along the beam axis is written by

$$\Delta z = \frac{\Delta x}{2\phi_x}, \tag{3}$$

where Δx is the horizontal amplitude and ϕ_x the half crossing angle. The beta function is written by a function of the distance from the IP:

$$\beta_y(\Delta z) = \beta_y^* + \frac{\Delta z^2}{\beta_y^*}. \tag{4}$$

Therefore, the particle with a horizontal amplitude is kicked at a large vertical beta function and the vertical amplitude will increase due to the beam-beam interactions for an initial non-zero vertical amplitude. This behavior is a kind of an hourglass effect. The vertical amplitude given by the beam-beam kick is

$$\Delta y \propto \theta_{bb,y}\sqrt{\beta_y(\Delta z)}. \tag{5}$$

The particle is lost if the vertical amplitude increases and is out of a stable region. In the case of a particle with the horizontal amplitude of $30\sigma_x$ in the LER, the deviation from the IP becomes 3.6 mm in the longitudinal direction where the vertical beta function is 48 mm. The vertical beta function becomes 180 times of the nominal beta function at the IP.

Touschek lifetime in the HER reduces about 10 % due to the beam-beam effect, however, the impact in the LER is much larger than the HER. Figure 4 (b) shows the dynamic aperture in the vertical and the horizontal plane under the influence of the beam-beam effect. The simulation of a particle tracking uses a weak-strong model. The initial momentum deviation is zero in the figure. The transverse aperture is reduced significantly compared with the dynamic aperture without the beam-beam effect (Fig. 4 (a)). The particle with the horizontal amplitude larger than $10\sigma_x$ is lost due to the vertical oscillation even though the initial amplitude is zero in the vertical direction because of the vertical amplitude is induced by nonlinearities such as X-Y coupling originate from the IR.

CRAB-WAIST SCHEME

One of the approaches to compensate the beam-beam effect for the large horizontal amplitude is "crab-waist scheme" [4]. Hamiltonian of the crab-waist term is

$$H_{cw} = \frac{\lambda}{2} x p_y^2, \tag{6}$$

where

$$\lambda = \frac{1}{\tan 2\phi_x}. \tag{7}$$

If we consider the ideal case of the crab-waist scheme, the map of the beam-beam interaction is replaced with

$$f_{BB} \to f_{cw}(+\lambda) \cdot f_{BB} \cdot f_{cw}(-\lambda), \tag{8}$$

where the map of the crab-waist is

$$f_{cw}(\lambda) : p_x \to p_x + \frac{\lambda}{2} p_y^2 \tag{9}$$

$$y \to y - \lambda x p_y. \tag{10}$$

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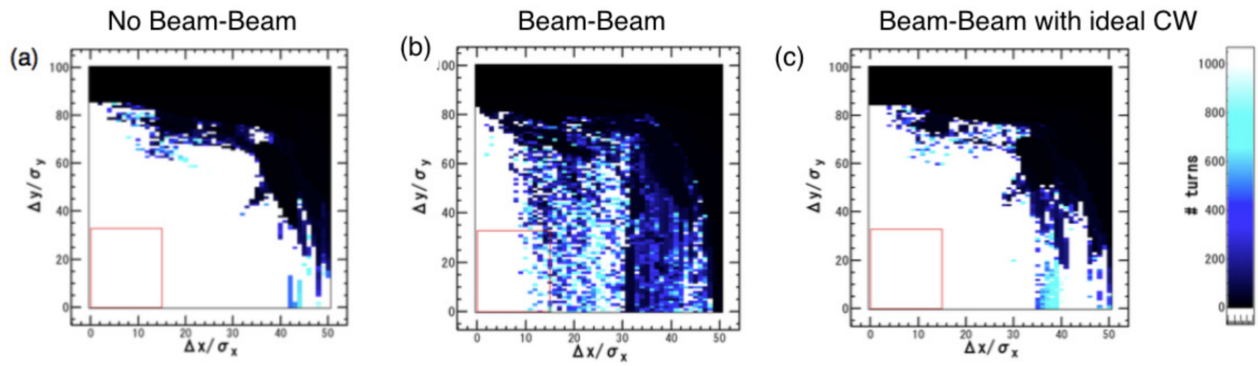

Figure 4: Dynamic Aperture. (a) No Beam-Beam, (b) Beam-Beam Interaction, (c) Crab-Waist Scheme with Beam-Beam. Red Rectangle indicates an Injection Aperture.

A feasibility of the ideal crab-waist scheme has been studied by using tracking simulations. The dynamic aperture is almost recovered by the ideal crab-waist(Fig. 4 (c)). In order to accomplish the crab-waist in the realistic lattice, two sextupole magnets are utilized. In the case of the realistic lattice, the x^3 term comes from the sextupole is added to the crab-waist term in the Hamiltonian. However, it can be ignored by choosing a large ratio of the vertical beta function to the horizontal at the sextupole magnet.

Two sextupole magnets are placed for each side of the IP and shift a waist of colliding particles having a horizontal amplitude to cancel the deviation from the waist. The betatron phase advance between a crab-waist sextupole and the IP is adjusted to be $m\pi$ in the horizontal direction and $(n + 1/2)\pi$ in the vertical direction, where m and n are arbitrary integers. The strength of the crab-waist sextupoles are

$$| K_2 |= \frac{1}{\tan 2\phi_x \beta_y^* \beta_{y,s}} \sqrt{\frac{\beta_x^*}{\beta_{x,s}}}, \quad (11)$$

where $\beta_{x,s}$ and $\beta_{y,s}$ are the horizontal and the vertical beta function at the sextupoles, respectively. The sign of K_2 is chosen so as to shift the waist at the IP properly and cancel a nonlinear kick between a pair of the crab-waist sextupoles. The lattice design for the crab-waist scheme in the LER is shown in Fig. 5. The crab-waist sextupole is assumed to be a thin lens to make the model simple in this report. The machine parameters for the crab-waist scheme in the LER are shown in Table 3.

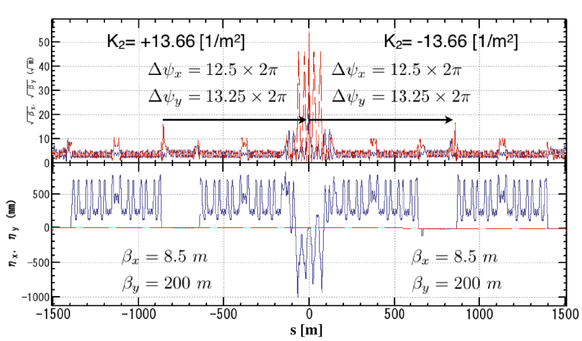

Figure 5: Lattice for the Crab-Waist Scheme in the LER for SuperKEKB.

Table 3: Parameters for the Crab-Waist Scheme in the LER.

	Symbol	LER	Unit
Horizontal beta at the IP	β_x^*	32	mm
Vertical beta at the IP	β_y^*	270	μm
Half crossing angle	ϕ_x	41.5	mrad
Horizontal beta at sextupole	$\beta_{x,s}$	8.5	m
Vertical beta at sextupole	$\beta_{y,s}$	200	m
Horizontal phase advance	$\Delta\psi_x$	25π	rad
Vertical phase advance	$\Delta\psi_y$	26.5π	rad
Nominal field of sextupole	$\mid K_2 \mid$	13.66	1/m^2

DYNAMIC APERTURE WITH CRAB-WAIST SCHEME

Figure 6 (a) shows transverse dynamic aperture in the LER as a function of K_2 for the crab-waist sextupoles. The initial momentum deviation and the vertical amplitude are zero in the simulations. The dynamic aperture decreases as increasing the strength of the sextupoles. The beam-beam effect is turned off in the simulation. The nonlinear kick due to the crab-waist sextupole can be canceled by another sextupole for the reference particle, however, it cannot be canceled for a particle with a large initial amplitude. The transfer map between two sextupoles which includes the IR with the final focus is no longer the linear map. The term of $\Delta p_y = K_2 xy$ will increase the vertical amplitude, then the particle will be lost and the dynamic aperture will be reduced. Figure 6 (b) shows the transverse dynamic aperture in the LER which is similar to Fig. 6 (a), but the beam-beam effect is turned on. The dynamic aperture is indeed recovered by the crab-waist sextupoles as increasing the field strength until the nonlinear kick from the sextupoles restricts the dynamic aperture. Therefore, it implies the difficulty comes from the cancellation of the nonlinear kick by a pair of crab-waist sextupoles for the large horizontal amplitude of a particle without the beam-beam effect.

In order to investigate the reduction of the dynamic aperture in the crab-waist scheme, a simple model for the IR lattice is considered in the LER as an ideal case. The IR model is simplified to be no solenoid field, no offset of the

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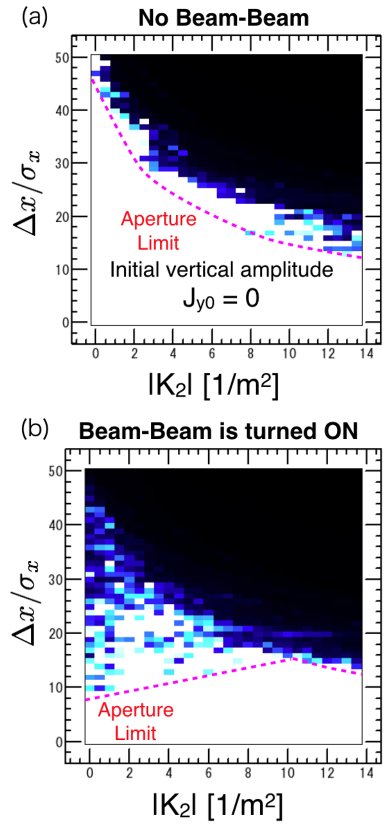

Figure 6: Dynamic Aperture in the Transverse Direction as a Function of the Strength of Crab-Waist Sextupoles for the Crab-Waist Lattice; (a) No Beam-Beam, (b) Beam-Beam interaction.

final focus quadrupole magnets, and no higher-order multipole fields from the IP (s=0) to s=4 m for each side of the IP. In addition to the simple IR, QC1 and QC2 in which nonlinear Maxwellian fringe fields are turned off are considered to study the dynamic aperture. The transverse dynamic aperture for the on-momentum particle as a function of K_2 for the crab-waist sextupoles is shown in Fig. 7. The dependence of the field strength is almost disappeared for the dynamic aperture without the beam-beam interaction(Fig. 7 (a)). On the other hand, the dynamic aperture is recovered by using the crab-waist sextupoles under the influence of the beam-beam interaction(Fig. 7 (b)). We have also studied the dynamic aperture which depends on the location of the crab-waist sextupoles. In the case of SuperKEKB, there is no dependence of the location outside of the final focus doublets. The reason is that the strength of the nonlinear effect due to the final focus doublets is very strong compared with other machines as shown in Table 3. It is also fond that the length of the crab-waist sextupole does not affect the dynamic aperture in this study. Therefore, the issue is how to linearize the lattice between two sextupoles that include the nonlinear IR in the realistic lattice.

CONCLUSIONS

We present the design of the IR at SuperKEKB and the study of the dynamic aperture. The dynamic aperture for

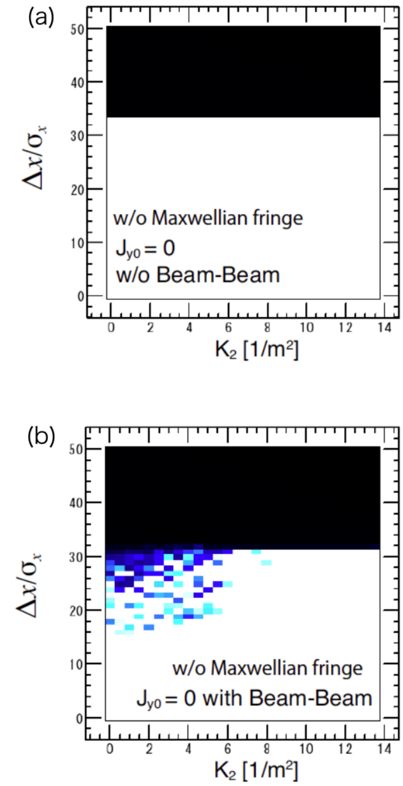

Figure 7: Dynamic Aperture in the Transverse Direction as a Function of the Strength of Crab-Waist Sextupoles for the Crab-Waist Lattice with the Simple IR; (a) No Beam-Beam, (b) Beam-Beam Interaction.

the both of the LER and the HER can be achieved to make Touschek lifetime 600 sec without machine error. However, the dynamic aperture under the influence of the beam-beam interaction will be reduced significantly in the nano-beam scheme. The beam-beam kick will be enhanced because the waist is shifted due to the $x - z$ coordinate exchange. One of the solutions to recover the dynamic aperture is the crab-waist scheme. The interference between the nonlinearity of the final focus doublets and the crab-waist sextupoles reduces the dynamic aperture. The transfer map between the IP and the crab-waist sextupole should be linear to improve the dynamic aperture in the case of SuperKEKB. The development of a cancellation technique for the nonlinearity is under study.

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