LATTICE DESIGN OF LOW EMITTANCE AND LOW BETA FUNCTION AT COLLISION POINT FOR SuperKEKB

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Abstract

The SuperKEKB project[1] requires a positron and an electron collider with a peak luminosity of 8×10^{35} cm^{-2}s^{-1}. The luminosity is 40 times the KEKB B factory that has been operated up to 2010 for 11 years. SuperKEKB is an asymmetry-energy and double-ring collider, the beam energy of the positron (LER) is 4 GeV and the electron (HER) is 7 GeV. An extremely small beta function at the interaction point (IP) and a low emittance are necessary to achieve this target. In addition the target luminosity can be achieved with a large horizontal crossing angle between two colliding beams and a bunch length much longer than the beta function at IP. This method is called "Nano-beam scheme". We will report on the outlook of the lattice design which includes the interaction region to squeeze the beta functions.

INTRODUCTION

The luminosity is proportional to a beam current, a vertical beam-beam parameter, and an inverse of a vertical beta function at IP. First of all, the vertical beta function at IP is squeezed to be 1/20 of KEKB. Secondary, the vertical beam-beam parameter is assumed to be 0.09 at the maximum value which is similar to KEKB and comes from the experience. Finally, the beam currents increase twice in order to achieve the luminosity of 40 times of KEKB. The key point is how to make an extremely low beta function at IP since an hour-glass effect degrades the luminosity in general. In order to overcome this situation, a small beam size at IP with a large Piwinski angle is applied[2]. The advantage of the nano-beam scheme is a bunch length longer than the vertical beta function at IP can be available which can suppress an effect of a coherent synchrotron radiation (CSR). In addition the target luminosity can be achieved with relatively smaller beam currents and smaller beam-beam parameters compared with a conventional head-on collision. However, the low emittance of a few nm and the low vertical beta function of a few hundreds μm at IP are necessary. Table 1 shows the machine parameters of SuperKEKB.

LOW EMITTANCE LATTICE

There is a requirement that quadrupole magnets of KEKB are reused as much as possible and the magnet configuration is almost the same as KEKB for the arc section. In order to make the low emittance in LER, dipole magnets are replaced by the length of 4.2 m from 0.89 m. On the other hand, beta functions and dispersions are changed to make the emittance as small as possible in HER since it is impossible to make the length of dipole magnet longer than that of KEKB-HER. Wiggler magnets are also installed to each ring to make the emittance small in addition to the change of the arc cell. The lattice designs of the arc cell for LER and HER are shown in Figs. 1 and 2, respectively.

Table 1: Machine parameters. * indicates IP.

	LER	HER	Unit
E	4.000	7.007	GeV
I	3.6	2.6	A
N_b	2500		
C	3016.3149		m
ε_x	3.2	4.6	nm
ε_y	8.64	11.5	pm
β_x^*	32	25	mm
β_y^*	270	300	μm
$2\phi_x$	83		mrad
α_p	3.25×10^{-4}	4.55×10^{-4}	
σ_δ	8.08×10^{-4}	6.37×10^{-4}	
V_c	9.4	15.0	MV
σ_z	6	5	mm
ν_s	-0.0247	-0.0280	
ν_x	44.53	45.53	
ν_y	44.57	43.57	
U_0	1.87	2.43	MeV
τ_x/τ_s	43.1/21.6	58.0/29.0	msec
ξ_x	0.0028	0.0012	
ξ_y	0.0881	0.0807	
L	8×10^{35}		cm^{-2}s^{-1}

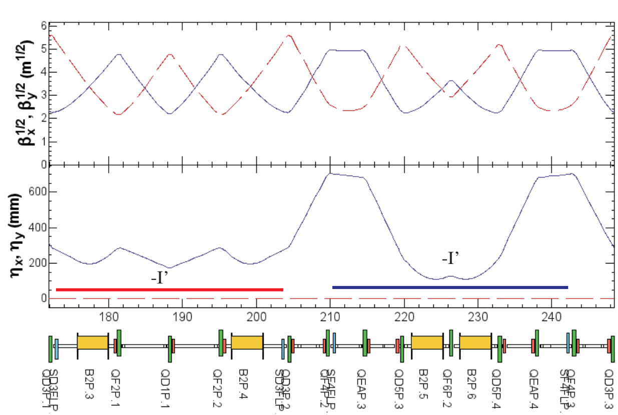

Figure 1: LER arc cell

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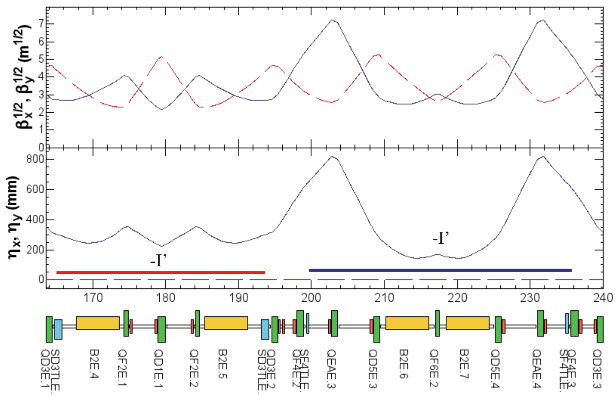

Figure 2: HER arc cell

INTERACTION REGION

The final focus (FF) is designed to achieve extremely small beta function at IP. In order to squeeze the beta functions, doublets of vertical focus quadrupole magnets (QC1s) and horizontal focus quadrupole magnets (QC2s) are utilized. Figure 3 shows the final focus magnets. Those magnets are super-conducting magnets and have correction coils of a dipole, a skew dipole, a skew quadrupole, and an octupole field. Iron yokes are attached to the QC1s and QC2s, except for QC1LP and QC1RP which are magnets of LER and the closest to IP, to shield a leakage field for the opposite beam line. Therefore, HER takes correction coils to compensate sextupole, octupole, decapole, and dodecapole leakage fields from QC1LP and QC1RP. The leakage dipole field from QC1LP and QC1RP affects the orbit in HER. The QC1s and QC2s in HER are shifted parallel to the original beam axis by 680 μm in horizontally to make strength of dipole field of QC1LE and QC1RE as small as possible. Consequently, the dipole angle becomes 1.26 mrad for the QC1 correction coils.

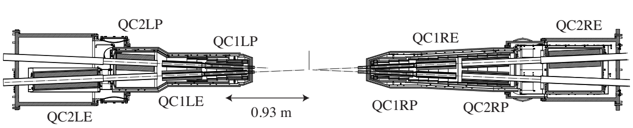

Figure 3: Final focus magnets

There is 1.5 T solenoid field for the Belle II detector in the vicinity of IP which is one of the characteristics of colliders. Compensation solenoid magnets are almost overlaid with QC1s and QC2s and utilized to fully compensate the detector solenoid for each side of IP,

$$\int_{IP} B_z(s)ds = 0. \tag{1}$$

The compensation solenoid is adjusted to make a rotation angle of QC1s and QC2s around the beam axis as small as possible. QC1s and QC2s are rotated to make a vertical dispersion and a X-Y coupling small together with an adjustment of a vertical orbit by a skew dipole filed of the correction coils in QC1s and QC2s. The rotation angle of QC1s and QC2s around the beam axis is written by

$$\theta_{QC} = \frac{1}{2B\rho}\int_{IP}^{QC} B_z(s)ds. \tag{2}$$

The fringe filed due to the horizontal angle between the axis of the solenoid field induces the vertical emittance. The vertical emittance can be expressed by

$$\varepsilon_y \propto \left(\frac{p}{\rho}\right)^2 \int H(s)ds \propto B_x^4(s) \tag{3}$$

$$B_x(s) \simeq -\frac{x}{2}B_z'(s) \simeq -\frac{s\phi}{2}B_z'(s), \tag{4}$$

where ϕ is the angle between the beam axis and the solenoid axis and s is a length along the beam axis from IP. In order to suppress the vertical emittance, the angle should be decreased and the derivative of B_z should be small. However, the horizontal crossing angle between two colliding beams is fixed to be 83 mrad. The angle is determined so as to be a similar contribution and less than 1.5 pm to the vertical emittance in LER and HER, then 41.5 mrad is chosen from the optics calculation.

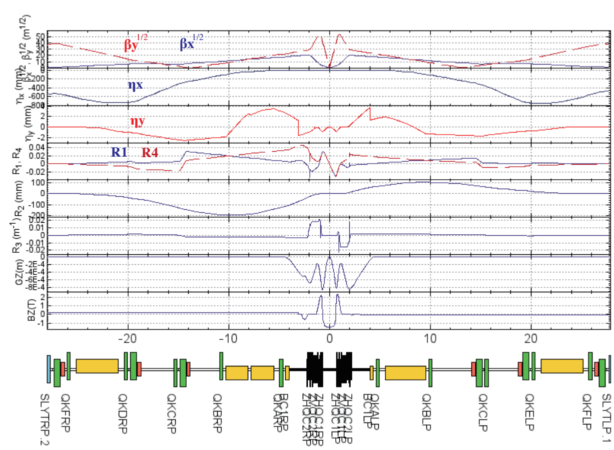

Figure 4: LER interaction region

The residual of the X-Y coupling and the vertical dispersion are corrected between the FF and a local chromaticity correction by using skew quadrupole magnets and/or skew dipole magnets. Figures 4 and 5 show the lattice design in the vicinity of IP.

DYNAMIC APERTURE

The FF is sliced by thickness of about 40 mm to make the lattice model and higher order multipole fields up to 44-poles for a normal and a skew fields are considered[3]. The natural chromaticity is ξ_{x0}/ξ_{y0}=-104/-738 for LER and ξ_{x0}/ξ_{y0}=-161/-1073 for HER. Since about 80% of the natural chromaticity in the vertical plane is induced in the FF section, a local chromaticity correction (LCC) is adopted to correct the huge chromaticity near the FF section. A larger

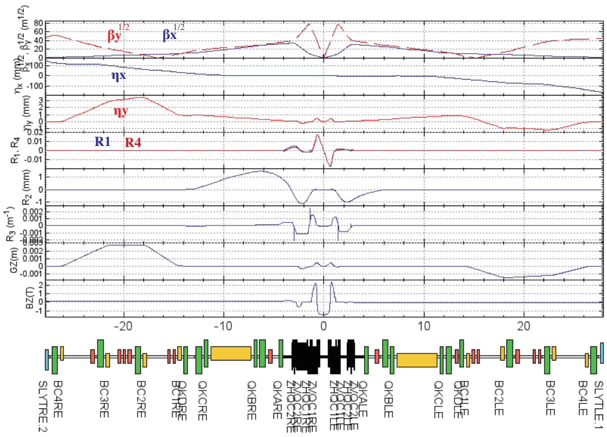

Figure 5: HER interaction region

dynamic aperture is expected by adopting LCC. Figures 6 and 7 show the local chromaticity correction. The transfer matrix between the identical two sextupole magnets is $-I'$ in order to compensate nonlinear kick due to a strong field of the sextupoles. The strong sextupoles are necessary to correct the huge chromaticity as described above. The noninterleaved chromaticity correction similar to LCC is also adopted in the arc cell shown in Figs. 1 and 2.

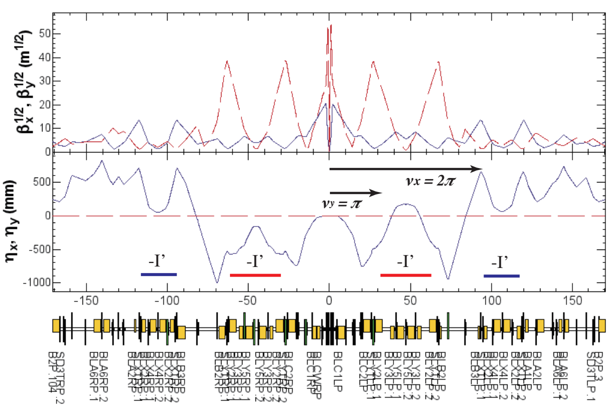

Figure 6: LER local chromaticity correction

The dynamic aperture and estimated Touschek lifetimes are shown in Figs. 8 and 9. SAD code[4] is utilized to evaluate the dynamic aperture by using a tracking simulation. The ratio of the vertical to the horizontal amplitude is fixed to be the emittance ratio. Two initial betatron phases of $(0, 0)$ and $(\pi/2, \pi/2)$ in the horizontal and the vertical plane are calculated. Touschek lifetime is defined by averaged values of two cases because the larger amplitude becomes the nonlinear region as show in the phase space plots in the figures. The larger dynamic aperture is obtained by optimizing 54 families of sextupoles, 12 families of skew sextupoles, and 4 families of octupoles in QCs. The optimization utilizes an off-momentum matching and a downhill simplex method as a function of the lifetime. The target

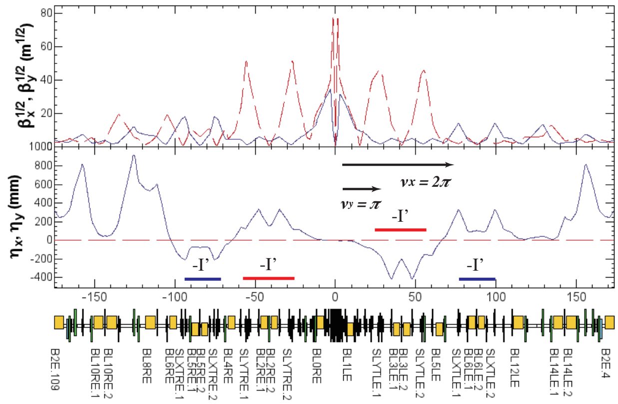

Figure 7: HER local chromaticity correction

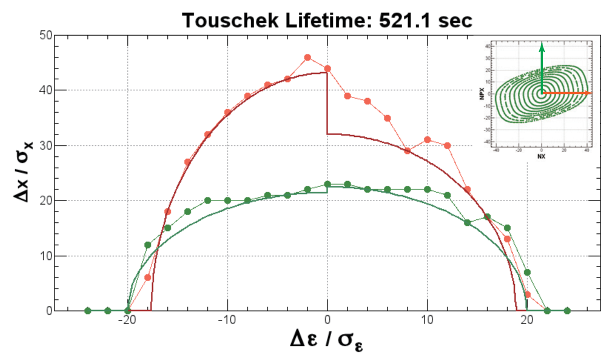

Figure 8: LER dynamic aperture and Touschek lifetime

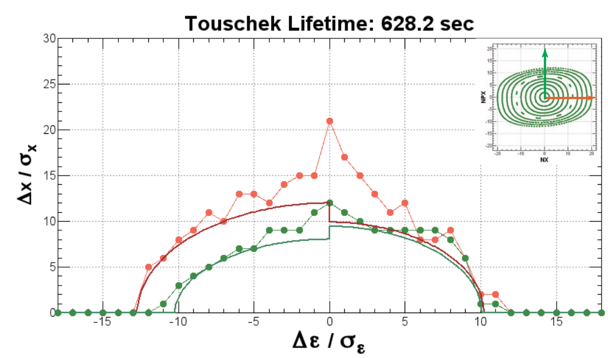

Figure 9: HER dynamic aperture and Touschek lifetime

lifetime is ∼600 sec and the requirement is almost satisfied.

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