DESIGN STUDY OF THE SUPERKEKB INTERACTION REGION OPTICS

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Abstract

SuperKEKB is an upgrade project of KEKB e^+e^- ring collider and is aimed to open up a new luminosity frontier. The target peak luminosity is $8 \times 10^{35} \mathrm{cm}^{-2}\mathrm{s}^{-1}$. In order to achieve this target, a nano-beam scheme is adopted, in which colliding beams are squeezed to nano-scale sizes in the vertical direction at the interaction point (IP). The interaction region (IR) is an essential part of the SuperKEKB lattice design since the large chromaticity originated in the final focusing system (QCS) and strong lattice nonlinear forces make the particle motion unstable. An optics with detailed hardware specifications has been designed to optimize a performance of the beam dynamics. Design studies of IR taking into account a possible QCS imperfection are reported in this paper.

INTRODUCTION

SuperKEKB [1] is a 7 GeV electron (HER) and 4GeV positron (LER) collider based on the nano-beam scheme [2]. The design luminosity of $8 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is 40 times higher that of achieved by previous KEKB [3] collider. The key changes of machine parameters from KEKB are 2 times higher beam current (3.6 A for e^+ and 2.6 A for e^-), 1/20 times smaller vertical beta function, β_y^* (0.3 mm) and larger crossing angle of 83 mrad. In addition to squeezing the beta function, the low emittance optics is also required for the nano-beam collision. Meanwhile, instabilities which accompany beam self-field are enhanced in such a low emittance beam. Furthermore, the huge beta function and strong lattice nonlinearity in IR likely restricts the beam stability. Therefore, the lattice has been designed with considering both low emittance optics and sufficient dynamic aperture.

Although a storage ring that provides high-brightness light sources also has same issues, a design of collider ring with low emittance and sufficient dynamic aperture is much challenging subject due to difficulties of IR. A detector solenoid and strong focusing magnets in IR involve complicated beam dynamics. Therefore, IR is the most critical part in the SuperKEKB lattice design. A large number of feedback procedures between hardware and optics group have been repeated with consideration on detailed hardware specifications such as maximum field strength and available space. Overview of the lattice design and related numerical simulation study are reported in this paper.

IR DESIGN OVERVIEW

Figure 1 shows schematic of IR. The final focus system adopts 8 superconducting magnets (4 magnets per ring) [4]. All quadrupole magnets except for QC1Ps have iron or permendur yoke for preventing leakage fields to the opposite beam line. In order to compensate the leakage filed from
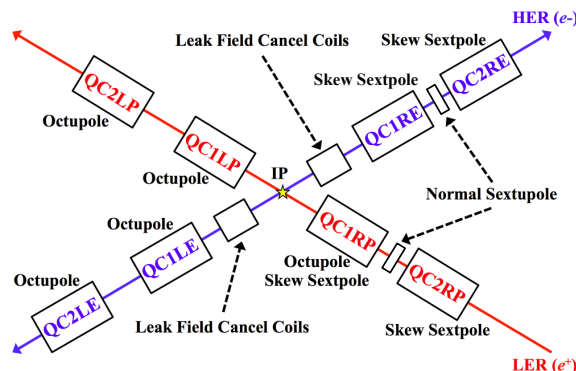

Figure 1: IR schematic view and arrangement of higher-order corrector coils. All magnets have superconducting corrector coils of a dipole, a skew dipole and a skew quadrupole.

QC1RP and QC1LP magnets, sextuple, octupole, decapole and dodecapole cancel coils are installed in the HER beam line. The dipole and quadrupole components as the leakage field are utilized in optics matching in HER.

The SuperKEKB IR has a detector solenoid of 1.5 T, and angles between the solenoid axis and two beam lines are chosen to be half of the crossing angle. This angle is determined by compromising vertical emittance that induced from the solenoid fringe field in HER and LER. In order to suppress the effect of the solenoid field on the beam optics as much as possible, compensation solenoids are installed. The field distribution is optimized so that the solenoid field integral from IP to each side of IR vanishes, $\int B_z(s)\,ds = 0$ for coupling matching, and peak of $\partial B_z/\partial s$ reduces for vertical emittance suppression.

All quadrupole magnets have superconducting corrector coils of a dipole, a skew dipole and a skew quadrupole. Horizontal or vertical offset of the quadrupole magnets from the beam line is adopted to reduce required field strength of the dipole corrector in orbit matching. Rotations of the quadrupole magnets are also introduced in LER to help the optics matching. In addition to these low order correctors, sextupole and octupole coils are installed to optimize dynamic aperture. The arrangement of sextuple and octupole coils is determined by a tolerance of QCS imperfections and fabrication schedule as described later.

DYNAMIC APERTURE

Dynamic aperture is evaluated by particle tracking simulation using accelerator modeling code SAD [5]. In our numerical model, full three-dimensional (3D) magnetic field distribution in IR is simulated by series of multipole slices of 1 cm length. The multipole fields up to 44 poles are taken into account, and their strengths are obtained from multi-

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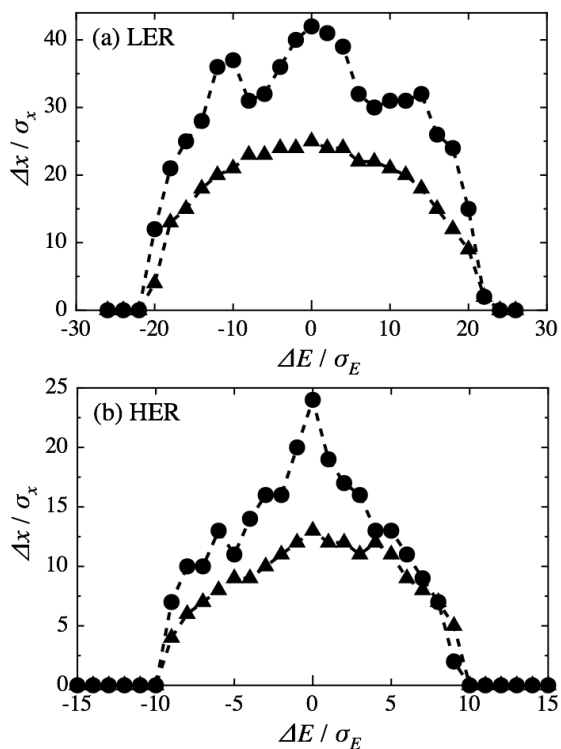**D01 Beam Optics - Lattices, Correction Schemes, Transport**

Figure 2: Dynamic aperture of (a) LER and (b) HER. Horizontal and vertical axes represent horizontal and momentum space in unit of their equilibrium values, respectively. The initial vertical amplitude of the tracking particle is chosen to be 0.27% of the initial horizontal amplitude. The initial horizontal and vertical betatron phases (ϕ_{x0}, ϕ_{y0}) are $(0,0)$ (dots) and $(\pi/2, \pi/2)$ (triangles).

pole filed expansion of 3D field data calculated by ANSYS code [6]. The dynamic aperture is evaluated through 1000-turn particle tracking simulation. In this paper, beam-beam force, synchrotron radiation and quantum excitation are not considered.

Figure 2 shows the dynamic aperture of LER and HER. The dynamics aperture is optimized by the Down-hill simplex algorithm. Available knobs are 54 sextupole pairs along the ring and octupole correctors (3/LER, 2/HER) installed in IR. The initial set of the sextupole magnets for the Downhill simplex optimization is chosen by off-momentum optics matching. The Touschek lifetimes estimated from the dynamic aperture are ~550 sec in LER and ~600 sec in HER.

Higher-order Corrector Coils

IR have octupole and sextupole corrector coils as shown in Fig. 1. The octupole corrector is utilized to manipulate the shape of the Hamiltonian torus so that a particle with large action variable can pass through the IR physical aperture. The sextupole corrector is introduced to compensate possible sextupole error field of QCS as described later.

In the design study of IR, frequency map analysis [7] is applied to reveal the resonance feature of the ring. An illus-
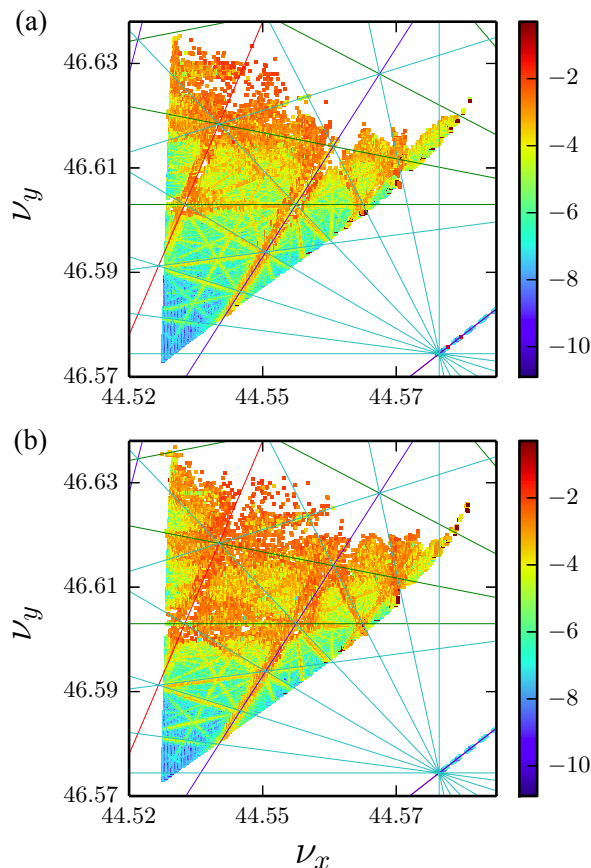

Figure 3: Footprints of LER (a) with and (b) without the QC1RP octupole corrector.

trative result is shown in Fig. 3, where the so-called footprint of LER is plotted. The color indicates the tune diffusion rate defined by $\log_{10} \sqrt{(\nu_{x1} - \nu_{x2})^2 + (\nu_{y1} - \nu_{y2})^2}$, where ν_{x1} and ν_{y1} respectively denote the horizontal and vertical tunes calculated by the tracking data of first 1000 turns, ν_{x2} and ν_{y2} are those for the following 1000 turns. The NAFF algorithm [7], which is a more accurate technique compared to the fast Fourier transform is applied in the tune calculation. The tracking simulation is done for on-momentum particle.

Figure 3(a) is the footprint with the octupole arrangement shown in Fig. 1, while the right side octupole corrector is missing in Fig. 3(b). These figures show that the tune diffusion of the particle with large amplitude is well suppressed by the corrector.

QCS Imperfection

Field measurement of the QC1P prototype shows unexpected normal and skew sextupole field, and their field strength is ~0.1% of the quadrupole field. These error fields are likely due to misalignment of the main coils of a few tens of μm. Numerical simulation campaign is conducted to investigate its effect on the dynamic aperture. Thin lens sextupoles are inserted to four quadrupole magnets, and their

magnitudes are identical in the simulation. All 16 possible combinations of signs of the sextupole field are evaluated.

Touschek lifetime of LER as a function of the amplitude of sextupole error field is shown in Fig. 4. The sextupole field reduces the dynamic aperture even though the error field is order of 0.01% of the quadrupole field, B_2. We, therefore, decide to install the sextupole and skew sextupole coils to the final focus system. The best cure for this issue is to install corrector coil to all magnets. However the design of left side of IR is already fixed and the fabrication has been started when this issue is found. Furthermore the space is limited because a lot of hardwares occupy IR. The location between QC1R and QC2R is considered to be a candidate for installation of a sextupole and a skew sextupole coil.

Touschek lifetime after optimizing the thin sextupole corrector is also shown in Fig. 4 (blue dots). The optimization is done for the worst case of the all 16 cases. The simulation results shows that degradation of the lifetime is less than 100 sec when the error field is less than 0.1% of the quadrupole field. This number is now used as the tolerance of the sextupole field of the magnets in the QCS fabrication.

Similar simulations for skew sextupole field are also carried out and found that it does not work better than what we expected from the normal sextupole case. To investigate the best location for the skew sextupole coil, the numerical simulation has been done by changing the corrector location. The simulation results for LER are summarized in Fig. 5, where the lifetime as a function of corrector location is plotted. For the simplicity, only QC1RP has error field in the simulation. The simulation result for normal sextupole case is also presented for comparison. The lifetime is strongly depends on the corrector position compared to the sextupole case. Figure 5 also implies that it is possible to compensate the left-side magnet error by the right-side corrector. Considering this numerical results we decide to

Figure 5: Touschek lifetime of LER as a function of the corrector position, where B_3/B_2 =0.02% is considered. The vertical dashed line indicates position of the sextupole error field.

install skew sextupole corrector to two final focus magnets in the right-side as summarized in Fig. 1.

SUMMARY

The IR design is an essential issue to optimize the dynamic aperture of the SuperKEKB lattice. The considerations on detailed hardware specification is very important. The octupole correctors are effectively used to enlarge the dynamic aperture. Numerical studies on the arrangement of higher-order corrector coils to cure QCS imperfections are also reported. The normal and skew sextupole corrector coils are installed to compensate possible sextupole error field, which degrades the dynamic aperture significantly.

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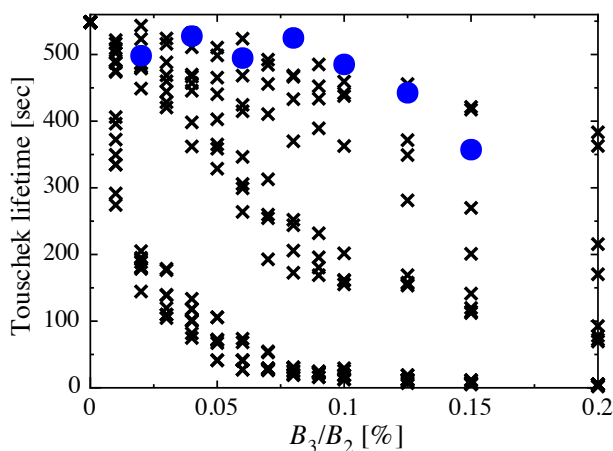[7] L. Nadolski and J. Laskar, Phys. Rev. ST Accel. Beams **6**, 114801 (2003).

Figure 4: Touschek lifetime of LER as a function of the amplitude of sextupole error field, where horizontal axis indicates the ratio of normal sextupole field B_3 to quadrupole field B_2. Touschek lifetime afte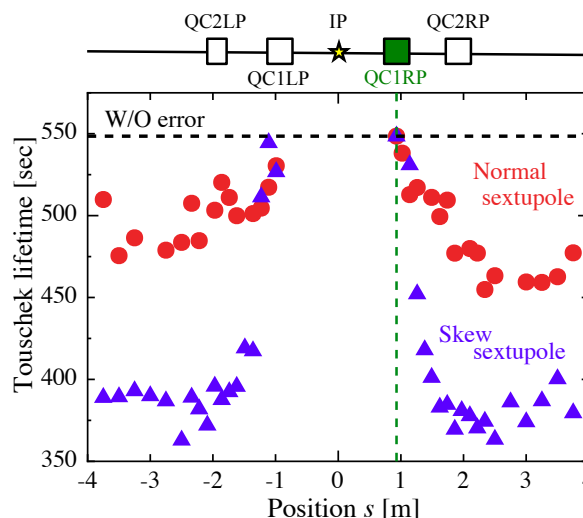r tuning the corrector coil also shown as blue dots