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2.3 Crab Waist Scheme for SuperKEKB

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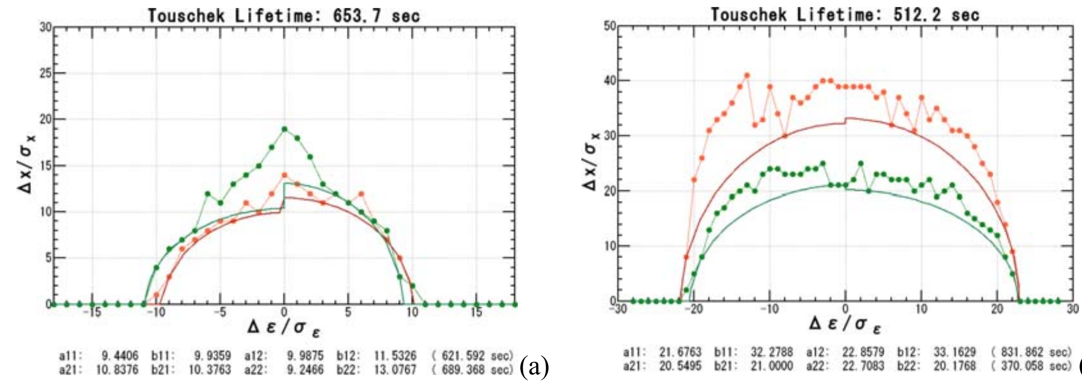
2.3.1 Introduction

The SuperKEKB [1] is an asymmetric-energy double-ring collider to achieve 40 times higher luminosity than that of the KEKB B-factory [2]. To achieve such high luminosity, the SuperKEKB interaction region (IR) is designed for large Piwinski angle collision scheme so called "nano-beam scheme". For the nano-beam scheme, the beta functions at the interaction point (IP) are designed to 32mm / 0.27mm (horizontal / vertical) for the low energy positron ring (LER) and 25mm / 0.30mm for the high energy electron ring (HER), respectively. In order to realize 1/20 times smaller beta-function at the IP than that achieved by the KEKB B-factory, the SuperKEKB IR is designed to use both super-conducting quadrupole doublets for final focus and horizontal/vertical local chromaticity correctors for compensating large natural chromaticity.

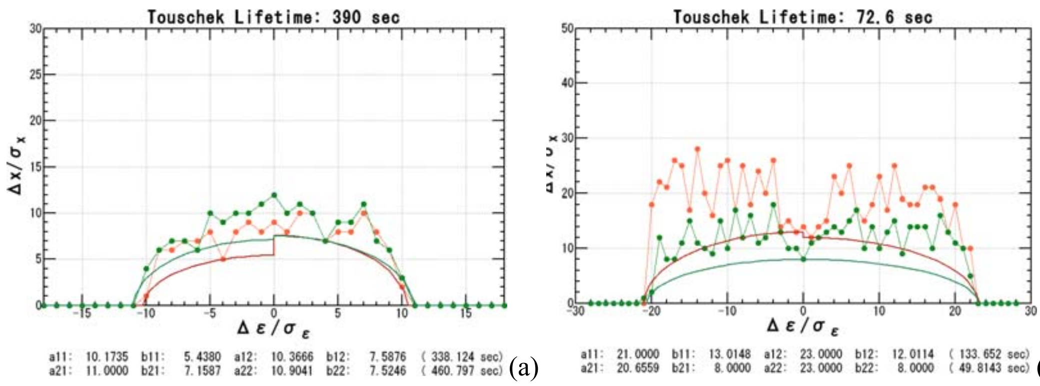
The dynamic aperture is restricted by strong nonlinearity of final focus magnets. On the other hand, Touschek lifetime required to be longer than 600 seconds without machine error in order to store design beam current. The achievement of the design target lifetime of the LER is difficult because of relatively large transverse aperture requirement 30 sigma in typical case. In order to obtain enough transverse aperture for the design target lifetime, both chromaticity corrector sextupoles and octupoles implemented on the final focus system are optimized. As the result of this optimization, the Poincare map of the LER is strongly deformed and the amplitude around QC2* quadrupole (the QF-type quadrupole of the final focus quadrupole doublets) is compressed to clear the horizontal physical aperture bottleneck.

The target lifetime is almost achieved without beam-beam effect shown in Fig.1.



(a) HER (κ=0.25%) (b) LER (κ=0.27%)

Figure 1: Dynamic aperture and Touschek lifetime of SuperKEKB nominal lattice without beam-beam effect. Horizontal and vertical axes show longitudional and transverse amplitude of initial particle, respectively. Two lines are correspond with the different initial phases.



(a) HER (κ=0.25%) (b) LER (κ=0.27%)

Figure 2: Dynamic aperture and Touschek lifetime of SuperKEKB nominal lattice with beam-beam effect.

On the other hand, the LER lifetime is remarkably degraded by beam-beam effect shown in Fig.2. The HER Touschek lifetime with beam-beam effect is recovered by optimizing chromaticity corrector sextupoles. However, the parameter set for the LER to achieve enough lifetime is not found by the sextupole and octupole parameter survey.

We report a trial result of introducing crab waist scheme [3] into the SuperKEKB lattice in this article.

2.3.2 Improvement of Dynamic Aperture with Beam-beam by Using Crab Waist

The crab waist lattice model is constructed by inserting two thin insertion devices so called crab waist unit. The crab waist unit (CWU) is constructed by a thin sextupole put between two thin linear phase rotators. These linear phase rotators are configured to satisfy following conditions.

- The beta-functions at crab waist sextupole is given as the simulation condition.
- The alpha-functions at crab waist sextupole equal 0.
- The phase advances between the IP and the crab waist sextupole are adjusted

with the proper phase for ideal crab waist.

- The map of CWU converges on the identity map in the limit when K2 of the crab waist sextupole approaches 0.

In the ideal crab waist model, the location of the CWU is configured to sandwich the beam-beam interaction element at the IP between two CWUs. Thus, the ideal crab waist does not change the dynamic aperture without beam-beam effect, because the non-linearity of the crab waist sextupole pair is perfectly canceled by these configuration condition. Figure 3 shows the significant improved dynamic aperture with beam-beam effect by applying the ideal crab waist with LER lattice. The improvement by the ideal crab waist is not perfect, however, it achieves half of design target lifetime that is achieved by optimization by using chromaticity correction sextupoles, octupoles and tune working point.

On the other hand, the dynamic aperture of the realistic crab waist model is shown in Fig.4. In this realistic lattice model, the CWUs are inserted into the feasible location, NIKKO and OHO straight sections, where are separated from TSUKUBA interaction region by arc cells.

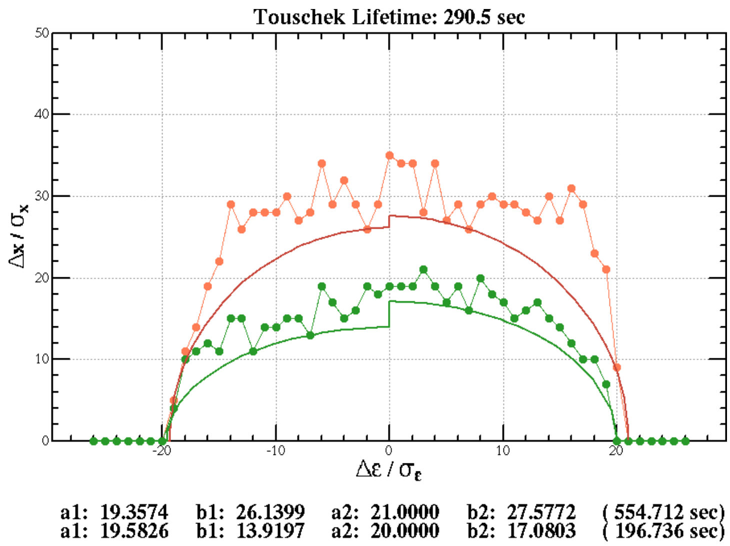


Figure 3: Dynamic aperture and Touschek lifetime of SuperKEKB LER nominal lattice with beam-beam effect and ideal crab waist.

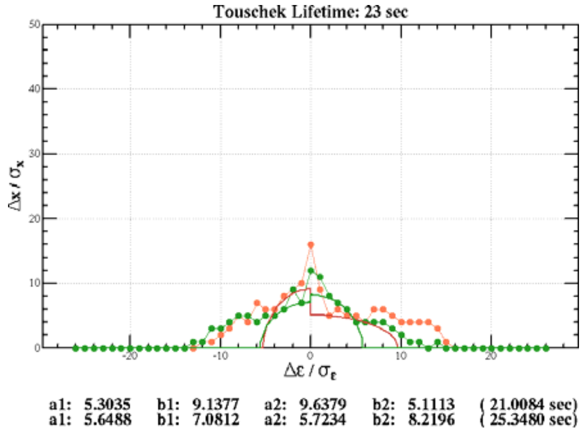


Figure 4: Dynamic aperture and Touschek lifetime of SuperKEKB LER nominal lattice with beam-beam effect and crab waist at feasible location.

In this feasible crab waist configuration, the dynamic aperture is degraded compared with the dynamic aperture without crab waist shown in Fig.2b. Under the weak limit of crab waist sextupole strength, the improvement of the dynamic aperture with beam-beam effect is observed. However, the crab waist sextupole strength dependency of the improved dynamic aperture suggests the upper bound of the aperture improvement by crab waist. In this model, the dynamic aperture without beam-beam effect is limited when K2 parameter of crab waist sextupole exceeds the threshold strength. In the nominal SuperKEKB lattice, this threshold strength of the crab waist sextupole is lower than the theoretical optimum strength and the limited LER dynamic aperture is too narrow to obtain the design target lifetime 600 seconds.

In order to apply crab waist scheme to the SuperKEKB lattice, the dynamic aperture degradation by crab waist have to be resolved.

2.3.3 Nonlinearity Blocking Crab Waist

For investigating the insert location dependency of the CWU, the IR model of the SuperKEKB LER nominal lattice, that contains the solenoid field, the tilted off-axis final focus quadrupole doublets and many higher order multipole fields, is too complex. The simplified lattice for investigation is prepared by removing the non-essential IR multipole fields. Therefore the final focus system of the simplified lattice has only the normal quadrupole doublet fields. Its optics function is re-matched to adjust the Twiss parameters at the IP with the design values.

The following figures show the on-momentum dynamic apertures of the simplified lattice with beam-beam effect and the CWUs. Five different crab waist configuration are listed as follows:

a) The CWUs are inserted into both side of beam-beam interaction element.
b) The CWUs are inserted into the inner boundary of the QD-type final focus quadrupoles QC1*. The crab waist section contains the drift space around the IP.
c) The CWUs are inserted into the inner boundary of the QF-type final focus quadrupoles QC2*. The crab waist section contains the QD-type final focus quadrupoles QC1*.
d) The CWUs are inserted between the QD-type final focus quadrupole QC2* and the suppressor bending magnet for the local chromaticity corrector section. The

crab waist section contains the final focus quadrupole doublets.

e) The CWUs are inserted into the feasible locations NIKKO & OHO straight section.

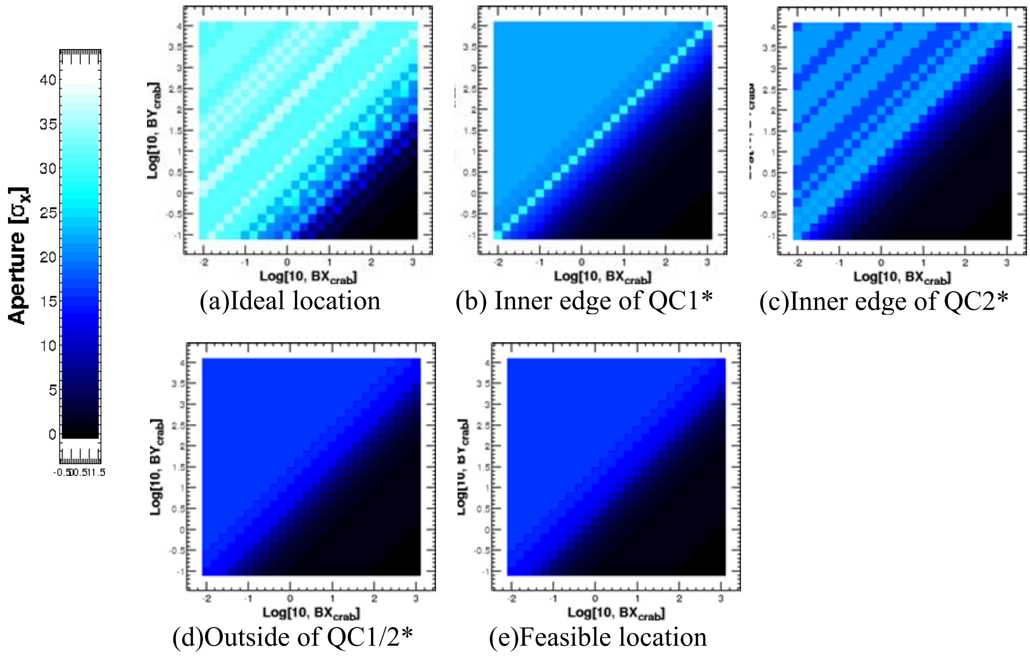


Figure 5: SuperKEK LER on-momentum dynamic aperture with beam-beam effect in different crab waist configurations. Horizontal and vertical axes show horizontal and vertical beta-function at the crab waist sextupole, respectively. The color of the cell shows the on-momentum dynamic aperture.

The on-momentum dynamic aperture of the ideal crab waist shown in Fig.5a decreases when β_y / β_x ratio approaches 0, however, the on-momentum aperture keeps wide enough for the design target lifetime when β_y / β_x ratio is large enough. This behavior and the study results removing the nonlinear term suggest that the βy / β_x ratio dependency of the on-momentum dynamic aperture is explained by breaking the cancellation between two crab waist sextupoles as the result of the interference between the side effect term of the crab waist sextupole $\Delta P_x = K2(x^2 - y^2)$ and the nonlinear term of beam-beam interaction map.

The on-momentum dynamic aperture of the crab waist containing the drift space around the IP shown in Fig. 5b has the maximum aperture 30 sigma on the line β_y / β_x = 10. The flat aperture region above β_y / β_x ratio threshold exists, however, its aperture is narrower than that of the ideal case shown in Fig.5a. In this configuration, the on-momentum dynamic aperture required for the design target lifetime could be achieved by adjusting β_y / β_x ratio at the crab waist sextupole.

In the case that the crab waist section contains the inner QD-type quadrupole of the final focus quadrupole doublet shown in Fig. 5c, the maximum aperture is reduced compared with the case shown in Fig. 5b. In this situation, the achievement of the design target lifetime is difficult, because the on-momentum dynamic aperture is narrower than 22 sigma.

From the comparison between two crab waist configurations that contain the final focus quadrupole doublet shown in Fig. 5d and Fig. 5e, the location dependency of the

CWU looks like weak in the case that the CWU is inserted into outside of the final focus quadrupole doublet.

From the comparison of the simplified crab waist lattice models, the major Touschek lifetime blocker for SuperKEKB LER lattice seems the nonlinearity of the final focus quadrupoles.

2.3.4 Summary

In the SuperKEKB lattice with the crab waist, the nonlinearity of the final focus quadrupole, which would be nonlinear Maxwellian fringe, limits the transverse aperture by breaking the sextupole nonlinearity cancellation between two crab waist sextupoles in large amplitude region. Therefore, either lattice redesigning or new nonlinearity compensation scheme for the final focus system is required in order to apply the crab waist scheme to the nominal SuperKEKB lattice.

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2.4 Beam Dynamics Issues in the SuperKEKB

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2.4.1 Introduction

Assuming 3D asymmetric Gaussian flat beams and neglecting hourglass effect, the luminosity of an electron-positron colliders is given by $\mathcal{L} = \mathcal{L}_0 R_\theta$ with

$$\mathcal{L}_0 = \frac{N_+ N_- f_c}{2\pi\sqrt{\sigma_{x+}^2+\sigma_{x-}^2}\sqrt{\sigma_{y+}^2+\sigma_{y-}^2}} \tag{1}$$

and the geometrical reduction factor

$$R_\theta = \frac{1}{\sqrt{1+\frac{\sigma_{z+}^2+\sigma_{z-}^2}{\sigma_{x+}^2+\sigma_{x-}^2}\tan^2\left(\frac{\theta}{2}\right)}}, \tag{2}$$