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DYNAMIC APERTURE STUDY OF SUPERKEKB WITH BEAM-BEAM EFFECT

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Abstract

The SuperKEKB accelerator has been designed to achieve 40 times higher than luminosity of KEKB B-factory. A nano-beam scheme is adopted in order to accomplish this target luminosity, however, this scheme restricts the dynamic aperture to small region due to strong nonlinearities which come from both final focus magnets and beam-beam interactions. The dynamic aperture which is shrunken by beam-beam effects is a big issue to keep enough beam lifetime for the machine operation. We report the issues on the dynamic aperture and a crab waist scheme to recover small dynamic aperture due to beam-beam effects.

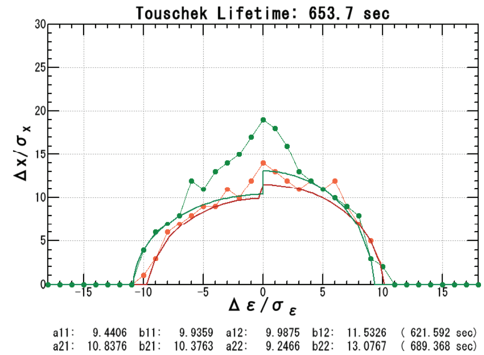
INTRODUCTION

The SuperKEKB [1] is an asymmetric-energy double-ring collider to achieve 40 times higher luminosity than that of the KEKB B-factory. 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 / 270μm(horizontal/vertical) for the low energy positron ring (LER) and 25mm / 300μm 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 nonlinearities 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 target lifetime is almost achieved without a beam-beam effect. Touschek lifetime that is degraded by the beam-beam effect has been studied.

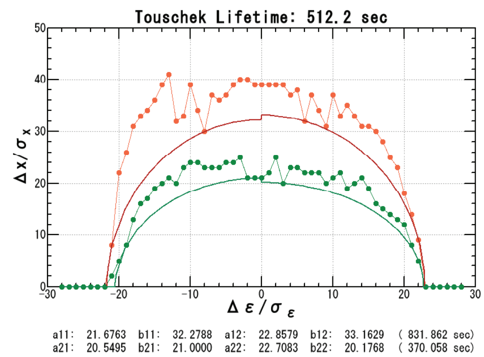
DYNAMIC APERTURE DEGRADATION BY BEAM-BEAM EFFECT

Dynamic aperture is defined by a border surface of stable region in a phase-space determined by an initial coordinates of a particle. The ratio of the initial vertical amplitude to the horizontal amplitude is fixed to be the design coupling parameter. The stable region is computed as a set of initial particles which are alive over 1000 turns calculated by a particle-tracking simulation. Touschek lifetime is estimated from a harmonic mean of lifetime of elliptic apertures obtained by fitting the border surface.

Figure 1 shows the dynamic aperture and the Touschek lifetime without beam-beam effect. Both HER and LER



(a) HER



(b) LER

Figure 1: Dynamic aperture without beam-beam. The horizontal and vertical axes show the longitudinal and transverse initial coordinates in unit of equilibrium beam size. Two different lines correspond with two different initial phases in normal mode. ($(\phi_{h\,0}, \phi_{v\,0}) = (0,0)$, $(\pi/2, \pi/2)$)

lifetime almost reach to the design target 600 seconds. On the other hand, the dynamic aperture with beam-beam effect shown in Fig. 2 is degraded.

The HER lifetime is optimized by chromaticity corrections, however, the LER lifetime is not enough recovered by not only chromaticity, chromatic X-Y couplings, and amplitude dependences but also changing a working point. Figure 3 shows the LER dynamic aperture after optimizing these corrections and changing the working point. From Touschek lifetime dependence of elliptic aperture, it is expected that this on-momentum dynamic aperture was not enough to reach lifetime in Fig. 1b, if the momentum acceptance was fully recovered.

The difference between two rings would come from the following LER aperture design concept. In order to achieve same design Touschek lifetime, the required LER dynamic aperture is larger than that of HER because of difference of beam energy. For obtaining relatively larger transverse

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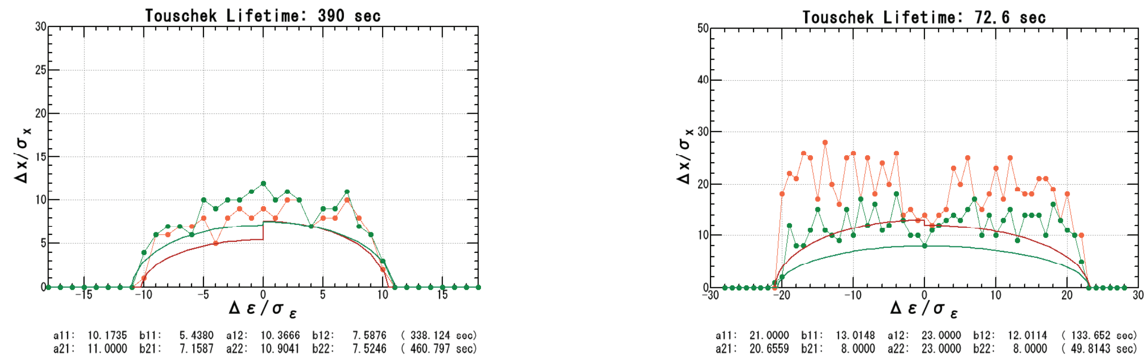

(a) HER (b) LER

Figure 2: Dynamic aperture with beam-beam.

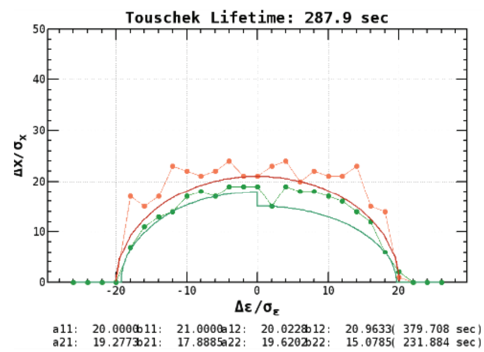

Figure 3: LER dynamic aperture with beam-beam after tune working point & chromaticity optimization

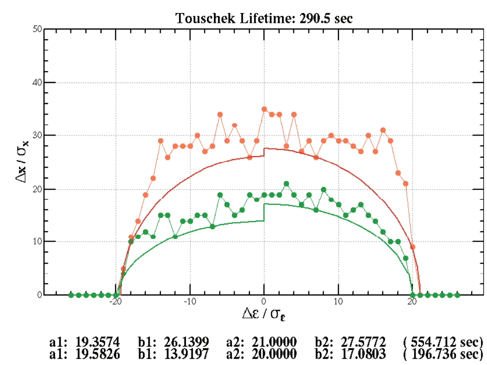

Figure 4: LER dynamic aperture with beam-beam & ideal crab waist

dynamic aperture, the octupole corrector in the final focus system is adjusted for deforming the Poincare cross section at QF-type quadrupole of final focus doublet to clear the narrowest horizontal physical aperture. Therefore, it seems like that the LER dynamic aperture is more sensitive for nonlinear beam-beam kick than that of the HER.

COMPENSATION BY CRAB WAIST

From beam-beam simulation study, the crab waist scheme [2] is proposed to compensate luminosity degradation at high current operation. The crab waist scheme adjusts the vertical beam size at the center of the opposite beam by shifting vertical waists depending with horizontal displacements. By suppressing a nonlinear term of beam-beam effect depending with crossing angle, the cure of the dynamic aperture degradation is expected. The ideal crab waist can recover the dynamic aperture with beam-beam effects, especially, for on-momentum particles as shown in Fig. 4. In this simulation, the ideal crab waist is constructed by inserting the crab waist insertion device, which is composed by a thin sextupole between two thin phase rotaters, into both entrance and exit position of the beam-beam kick. The phase rotators are adjusted to make **I**-transformation between sextupole pair to cancel sextupole nonlinearity, to act the crab waist insertion device as **I**-transformation and to tune betatron phase between the crab waist sextupole and the IP to $(0, \pi/2)$. The transfer of the crab waist sextupole insertion device is non-physical, however, the revolution map of the ideal crab waist lattice would be equivalent to the realistic crab waist lattice if the transfer between the inserted point of the crab waist insertion device and the realistic crab waist sextupole position is commutative with the linear phase rotator. Although Touschek lifetime shown in Fig. 4 is still shorter than that of Fig. 1b, its improvement is obtained by the crab waist without any other adjustment.

In the realistic lattice, the crab waist sextupoles are installed into the straight sections connected to an arc section from IR. The dynamic aperture is improved by increasing the crab waist sextupole field strength, but it is saturated before the crab waist sextupole strength reaches the theoretical optimum. The dynamic aperture is independent from beam-beam parameter after the saturation. In other words, the single beam dynamic aperture is degraded by turning on crab waist. The similar degradation was observed in a lattice study by introducing crab waist sextupoles in the KEKB B-factory. The mechanism to limit the dynamic aperture has to be studied to obtain a feasible crab waist lattice design.

CRAB WAIST STUDY ON SIMPLIFIED IR

In order to change either location of crab waist insertions or the higher order multipole field strength for study-

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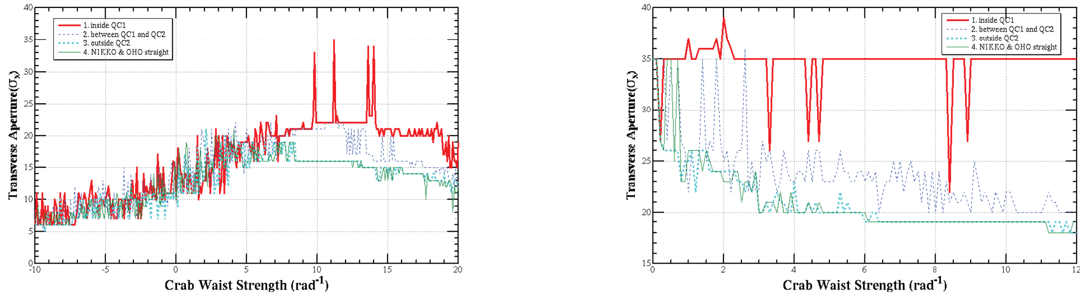

(a) with beam-beam (b) without beam-beam

Figure 5: On-momentum dynamic aperture as a function of crab waist strength in the simplified IR model with beam-beam (a) and without beam-beam (b). Four lines correspond to a location of crab waist sextupoles as follows: (1) red bold line for a location enclosing drift spaces neighbor of IP, (2) blue dashed line for a location between QD-type final focus quadrupole (QC1) and QF-type final focus quadrupole (QC2), (3) cyan dashed line for a location enclosing final focus doublets and (4) green line for the straight sections connected to arc sections from IR.

ing those dependency, it is not desired that the closed orbit passes off axis position of multipole elements in the final focus system. The simplified IR model for dependency study is constructed by removing sources of off axis orbit: the offset and rotation of the final focus quadrupole and the solenoid field. The location dependency of crab waist insertions on the simplified IR model is studied by using on-momentum dynamic aperture as an performance index instead of evaluating Touschek lifetime which needs long computational time for adjusting chromaticity correction.

The crab waist strength dependency of the on-momentum dynamic aperture is shown in Fig. 5. Figure 5a shows that the best compensation of beam-beam effect is obtained by configuration whose crab waist sextupole pair does not enclose any final focus quadrupole and the crab waist strength at the best compensation case is consistent with the theoretical optimum strength $\theta_{cross}^{-1}(\theta_{cross} = 83\text{mrad})$. The on-momentum apertures around theoretical optimum have negative correlation with the number of final focus quadrupoles enclosed within the crab waist sextupole pair. Those on-momentum apertures around theoretical optimum correlate with the single beam dynamic aperture shown in Fig. 5b. The dynamic aperture without beam-beam in Fig. 5b have negative correlation with the crab waist strength except the configuration (1).

Because the **I**-transformation between sextupoles is broken and the nonlinear kick due to sextupoles can not be canceled each other, the crab waist compensation is saturated before theoretical optimum. The largest amplitude dependence in the off-diagonal components of Jacobian between two crab waist sextupoles is M_{12} component shown in Fig. 6. The M_{12} component correlates with the on-momentum aperture at theoretical optimum of the crab waist strength. The evaluating cost of Jacobian component is inexpensive compared with that of dynamic aperture. It seems an useful index to optimize a design of IR for the crab waist scheme.

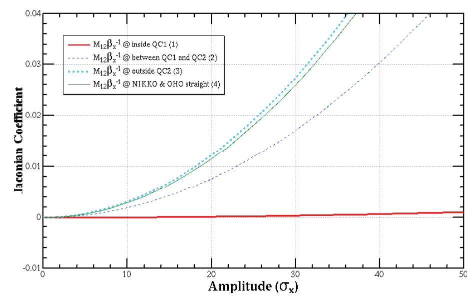

Figure 6: Amplitude dependency of M_{12} component of Jacobian between crab waist sextupoles. The horizontal and vertical axes show the transverse orbit amplitude and the normalized off diagonal component of Jacobian, respectively. The plot line notation is same as Fig. 5.

SUMMARY

The crab waist scheme restricts an on-momentum dynamic aperture, consequently, this effect prevents to achieve the design lifetime. The dynamic aperture is degraded because amplitude dependence of the transfer map between two crab waist sextupoles is broken and a sextupole nonlinear kick is not canceled. In the SuperKEKB lattice design, the main source reducing the on-momentum dynamic aperture in the crab waist scheme looks like an amplitude dependent M_{12} component of transfer map between two crab waist sextupoles. In order to apply the crab waist scheme to SuperKEKB, either IR lattice design is necessary to reduce nonlinearities in the final focus or a new scheme to compensate the amplitude dependence of the transfer map is introduced.

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