CROSSTALK BETWEEN BEAM-BEAM INTERACTION AND LATTICE NONLINEARITIES IN THE SuperKEKB

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Abstract

Momentum-dependent lattice nonlinearities have been proven to be important for the luminosity performance in the KEKB B-factory. As an upgrade of KEKB, the SuperKEKB adopts nano-beam scheme, in which the colliding beams are squeezed to extremely small sizes at the interaction point. Consequently, the lattice nonlinearities in SuperKEKB become more stronger than in KEKB. Using two codes, SAD and BBWS, we did various simulations to study the crosstalk between beam-beam interaction and lattice nonlinearities. It is found that lattice nonlinearities can cause remarkable luminosity loss in the SuperKEKB.

INTRODUCTION

The SuperKEKB B-factory is now under construction at the same campus of KEKB, and its operation is expected to be started in 2015. The SuperKEKB adopts nano-beam scheme, which is based on extremely small beta sizes at the interaction point (IP) in combination of large Piwinski angle [1, 2]. To achieve the small beam sizes, strong superconducting quadrupoles are used in the interaction region to squeeze the beta functions at the IP. Consequently, strong lattice nonlinearities (LN) are unavoidable in the interaction region (IR) [3], demanding tough efforts of lattice design and optics optimization. It is shown that the dynamic aperture of SuperKEKB rings is fundamentally defined by the nonlinearities in IR [3].

In SuperKEKB, the beam-beam (BB) interaction is another important source to generate strong nonlinearities in particles' motions. Besides the study of these two beam dynamics issues separately, the interplay between them is also an important subject if one wants to well understand the machine performance during the beam commissioning period. In this paper, we present simulation results using two codes SAD and BBWS.

SIMULATION METHODS

For the nano-beam scheme, the two beams collide with large crossing angle and only small part of the beams overlap with each other. Therefore BB simulations are done with large number of slices, typically the order of 100, in the longitudinal direction [4]. This fact leads to requests of serious improvements in effectiveness of numerical algorithms and increase in computing power. At present, it is not feasible to use strong-strong code to do simulation investigations on the crosstalk between LN and BB interaction. Indeed, at KEK the SAD code [5] is utilized to do

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element-by-element tracking simulations, since it has included the weak-strong model for BB interaction. The total one-turn map used in the simulations can be represented by

$$M = M_{rad} \circ M_{bb} \circ M_0, \qquad (1)$$

where M_{bb} and M_{rad} are maps for the BB interaction and radiation damping/quantum excitation, respectively. And M_0 indicates the transfer map felt by a particle when it travels through normal magnetic and electromagnetic components along the ring. One can see that the LN are naturally included in M_0 when a realistic lattice is load into SAD code.

Another method for the simulations with momentum-dependent LN is discussed in Refs. [6, 7, 8, 9], where a symplectic formalism was developed to describe the perturbation maps for the chromatic aberrations. The method is much faster than the previous one since all the momentum-dependent LN are lumped to the IP. And another figure of merit of it is that chromatic aberrations in different Twiss parameters can be studied separately [7]. But one limitation of this method is that amplitude-dependent LN are neglected.

The total symplectic one-turn map used in the weak-strong BB code BBWS is constructed as

$$M = M_{rad} \circ M_{chr} \circ M_{bb} \circ M_L, \qquad (2)$$

where M_{chr} and M_L are the map for the chromatic aberrations and one-turn linear matrix at the IP, respectively. The chromatic aberrations can be calculated from fitting the Twiss parameters for off-momentum particles using SAD. Up to third order of the chromatic aberrations in Twiss parameters are considered, that is

$$f(\delta) = \sum_{i=0}^{3} f_i \delta^i \qquad (3)$$

where f indicates alpha functions $\alpha_{x,y}$, beta functions $\beta_{x,y}$, X-Y couplings $r_{1,2,3,4}$, and dispersion functions $\eta_{x,y}$ and $\eta'_{x,y}$. The parameter $\delta = (p - p_0)/p_0$ is the relative momentum deviation, and the zero-order term f_0 represents the nominal optics parameters at design beam energy. The coefficients f_i denotes strengths of chromatic aberrations in a lattice.

SIMULATION RESULTS

Machine Parameters

The main parameters used in the BB simulations for the SuperKEKB low/high energy rings (LER/HER) are summarized in Table 1. For complete and latest overview of the

machine design, see Ref. [2]. In SuperKEKB, the sources of emittance growth include intra-beam scattering, BB interaction, space charge (SC), and machine errors. It is impractical to include all the effects of these sources in tracking simulations because of lack of an effective tracking model for intra-beam scattering. For our purpose of studying BB effects with LN, we close the default radiation damping and quantum excitation implemented in SAD, but define them manually in the SAD script for tracking simulations. Thus we can set both the vertical and horizontal emittances at zero beam current to design values. Machine errors contribute to LN but is not a concern in our present studies, since it is always possible to do optics corrections to minimize its effects.

Table 1: Main Parameters of the SuperKEKB use for Beam-beam Simulations

Parameter	LER(e^+)	HER(e^-)
E (GeV)	4.0	7.007
C (m)	3016	3016
N (10^{10})	9.04	6.53
β_x^* (mm)	32	25
β_y^* (μm)	0.27	0.3
ϵ_x (nm)	3.2	4.6
ϵ_y (pm)	8.64	11.5
σ_z (mm)	6	5
σ_δ (10^{-4})	8.08	6.37
ν_x	44.53	45.53
ν_y	46.57	43.57
ν_z	0.0247	0.028

Simulated Luminosity Performance

The betatron tunes of SuperKEKB are optimized based on luminosity performance predicted by BB simulations. At present, both rings of the SuperKEKB are optimized with fractional tunes of (0.53, 0.57). As shown in Fig. 1, the scan of horizontal tunes shows that very strong synchro-betatron resonances exist in the nano-beam scheme due to large crossing angle [10]. In this tune scan, the beam currents are set to design values. The red solid and green dashed lines indicates results of using pure weak-strong BB model and SAD code, respectively. From pure weak-strong simulations, the resonances of $2\nu_x + 2\nu_s = N$ and $2\nu_x + 4\nu_s = N$ with integer number N are clearly seen. Their widths are narrower in the case of HER than in the case of LER. It implies that the high energy beam is relatively immune from BB perturbation. The LN enhance the synchro-betatron resonances by widening their widths. On the other hand, direct emittance growth and significant luminosity degradation are observed from simulations. It is also noteworthy that the resonances of $2\nu_x + 6\nu_s = N$ and $2\nu_x + 8\nu_s = N$ are also driven by the interplay of BB and LN in the case of LER. Due to existence of these synchro-betatron resonances, the horizontal tunes of SuperKEKB are hard to be more closer to half integer, as has

been achieved in KEKB. One can also see that at fractional tune of ν_x higher than .55, the luminosity with LN included degrade faster than that without LN. It seems to suggest that there is smaller area for choice of horizontal tunes at SupeKEKB than at KEKB.
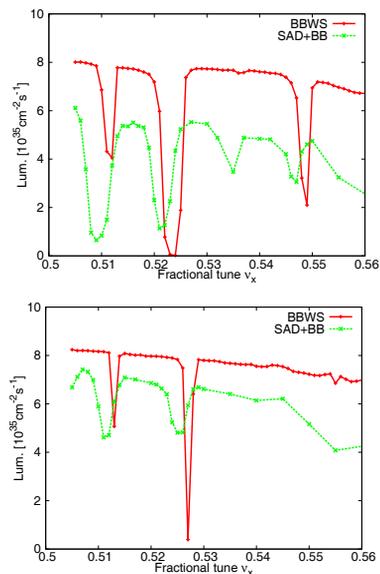

Figure 1: Total luminosity as a function of horizontal tune. Top picture is for LER, and bottom picture is for HER.

The luminosity performance as a function of bunch current products are shown in Fig. 2. In the figure, the red solid lines indicate results of using pure weak-strong model. The blue dashed lines indicates results of using pure weak-strong model plus perturbations of chromatic aberrations. The green dashed lines indicates results of using SAD code with weak-strong model. The cyan lines represent the design values of luminosity and beam current products. It is seen that significant loss of luminosity appears at high bunch currents due to interplay of BB and LN in the LER. Especially, the specific luminosity drops quickly at very low beam currents. These phenomena can not be explained by the momentum-dependent LN. The mechanism is not well understood yet. One possibility is that amplitude-dependent nonlinearities plays an important role in the LER. On the other hand, the luminosity loss due to interplay of BB and LN in the HER is not as serious as in the LER, and can be well attributed to the chromatic aberrations in the HER lattice.

Frequency Map Analysis

To further understand how LN interplay with BB interaction, frequency map analysis (FMA) is performed for three cases: bare lattice, pure BB, and BB with LN. The FMA method discussed in Ref. [11] is introduced to both SAD and BBWS codes. The initial conditions are taken over a mesh in the horizontal (x) and vertical direction (y) inside a area of $10\sigma_x \times 10\sigma_y$, and the corresponding tunes are plotted in the tune plane. The color indicates the diffusion rate of the orbit motion. Figures 3 and 4 show the FMA
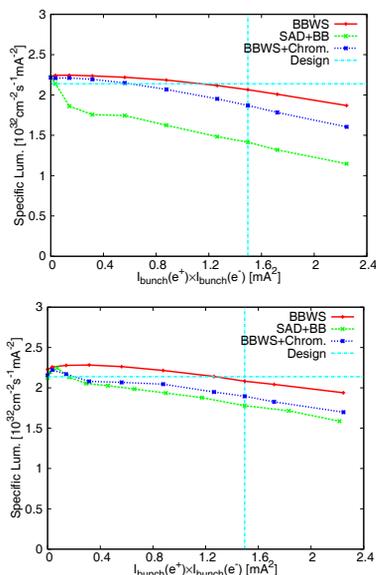
Figure 4: FMA plot for the HER in the plane of betatron tunes.

DISCUSSION

Simulations of crosstalk between LN and BB are performed for SuperKEKB. It is found that crosstalk between LN and BB may cause remarkable luminosity loss. Next step investigations include: 1) studying the impacts of crosstalk between LN and BB on beam lifetime and detector background; 2) searching for correction methods of minimizing the chromatic aberrations; 3) devising strategies in tuning knobs for future beam commissioning of SuperKEKB.

Electron cloud and SC also contribute to emittance growth in SuperKEKB, they should be added in the same studies. It is found that space charge can cause tune shift in the same order as BB does. But tune shifts in BB and SC have opposite signs. Since both SC and BB are vey nonlinear, the interplay of SC, BB and LN is another issue to be studied carefully.

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Figure 2: Specific luminosity as a function of bunch current products. Top picture is for LER, and bottom picture is for HER.

results for SuperKEKB. In each figure, the blue dots extended from the origin (.53, .57) indicate footprints for a bare lattice; the black dots indicate footprints for pure BB; the rest dots represent footprints for BB with LN. In the same figures, resonance lines up to eighth order are also plotted for reference.

From the frequency maps, the footprints in tune space with the bare lattice show strong dependence on initial amplitude. This is the results of strong amplitude-dependent LN in both rings. The pure BB causes large spread in the horizontal tunes while very small spread in the horizontal tune. The footprints are strongly deteriorated by the crosstalk between LN and BB. Particle with initial amplitudes of several sigma performs very chaotic motion with large diffusion rate. The resonances driven by BB as revealed in Ref. [11] are not clearly seen when LN are included, because the particle motions become strongly chaotic.
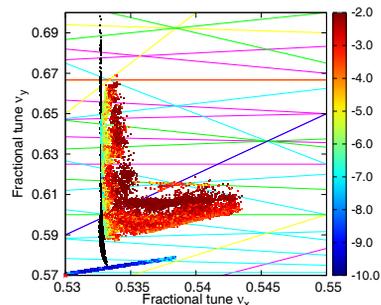

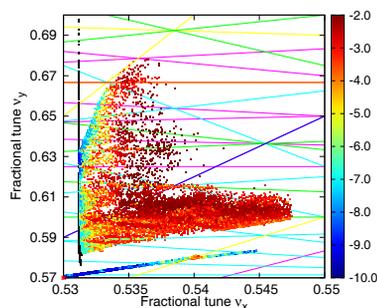Figure 3: FMA plot for the LER in the plane of betatron tunes.