EFFECTS OF LINEAR AND CHROMATIC X-Y COUPLINGS IN THE SUPERKEKB

D. Zhou*, K. Ohmi, Y. Seimiya, A. Morita, Y. Ohnishi, H. Koiso,
KEK/SOKENDAI, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

Abstract

Using a weak-strong beam-beam code, in which the symplectic maps for the linear coupling and chromatic aberrations were implemented, the luminosity degradation caused by the linear and chromatic X-Y couplings at the interaction point (IP) were evaluated for the SuperKEKB project under design. The linear and chromatic X-Y couplings were estimated through modeling the machine errors using random seeds, based on a baseline design of the SuperKEKB rings. It was found that the linear and chromatic X-Y couplings can potentially degrade the luminosity performance.

INTRODUCTION

In modern electron-positron colliders, flat beams were usually adopted at the collision point to achieve high luminosity. The transverse emittance coupling is as small as around 1%. Thus, small coupling between the vertical (Y), horizontal (X) and longitudinal (Z) motions may cause significant vertical emittance growth and subsequently resulted in unexpected loss of luminosity. In KEKB [1], the effects of linear X-Y couplings have been studied intensively [2]. As proved by beam-beam simulations, iterative tuning knobs of the X-Y couplings at IP have been effective in maintaining high luminosity. Recently, we found that the chromaticities of X-Y couplings, which characterize the X-Y-Z coupling for off-momentum particles, also plays an important role in the KEKB. Simulations revealed that the chromatic X-Y couplings can deteriorate the machine luminosity in the order of 10% with head-on colliding beams [3]. Beam commissioning with skew-sextupole tuning knobs at the KEKB has been very successful and the resulting luminosity gain was higher than 15% with crab cavities turned on [4, 5].

As an upgrade of the KEKB B-factory, the SuperKEKB has changed the design from the high-current crab-crossing scheme to the nano-beam scheme [6]. In order to achieve the extremely high luminosity of $8 \times 10^{35} cm^{-2}s^{-1}$, the transverse emittance will be reduced by a factor of around 10; meanwhile, the beta functions at IP will be strongly squeezed [7, 8] so as to maximize the luminosity and to avoid hourglass effect. Consequently, there is considerable concern over the impact of linear coupling and chromatic aberrations on the luminosity performance. In this paper, we present the simulation results obtained by introducing the optics parameters of linear and chromatic X-Y couplings into a weak-strong beam-beam code.

SYMPLECTIC MAPS

The momentum-dependent X-Y couplings are defined as

$$r_i(\delta) = r_{i0} + r_{i1}\delta \quad i = 1, 2, 3, 4 \tag{1}$$

where $\delta = (p - p_0)/p_0$ is the relative momentum deviation. The zero-order term r_{i0} is the linear X-Y coupling for on-momentum particles, and $r_{i1} = \partial r_i/\partial\delta$ is the first-order chromaticity, so called chromatic X-Y coupling. A symplectic formalism was devised and the perturbation maps for the chromatic X-Y couplings were developed in Ref. [9].

The total symplectic one-turn map used in the simulation code is constructed as

$$M = M_{rad} \circ M_{chr} \circ M_{bb} \circ M_{cw} \circ M_0 \tag{2}$$

where M_{bb}, M_{cw}, M_{chr}, and M_{rad} are maps for the beam-beam interaction, crab waist, chromatic perturbation, and radiation damping and quantum excitation, respectively. And the one-turn linear matrix at the IP is defined as

$$M_0 = R \cdot M_{lin} \cdot R^{-1} \tag{3}$$

where M_{lin} is a 6×6 block diagonalized matrix describing uncoupled betatron and synchrotron motions and R is the coupling matrix. Eqs. (2) and (3) imply that, in simulations, we can easily turn on or off the transformations for the crab waist, chromatic perturbation, or linear coupling. For detailed discussions on the derivations of these maps, see Refs. [9, 3, 10] and references therein.

In the weak-strong simulations, the tracking of the particles in a bunch have to be carried out with small step size. Typically, the longitudinal overlap area, which is equal to the vertical beta function, is sliced into 5-10 pieces. Thus the whole bunch is sliced into 100-200 pieces and the integration of single collision is performed with the same number of steps.

SIMULATIONS RESULTS

Machine Parameters

The main parameters used in the beam-beam simulations at the SuperKEKB are summarized in Table 1. For complete and latest overviews of the machine parameters, see Refs. [6, 7, 8]. The total number of bunches

* dmzhou@post.kek.jp

in each ring is 2503. Using these parameters, numerical simulations with the weak-strong code predict a luminosity of $8.7 \times 10^{35} cm^{-2}s^{-1}$ for the crab waist scheme and $7.2 \times 10^{35} cm^{-2}s^{-1}$ for the normal scheme without crab waist.

Table 1: Main parameters of the SuperKEKB use for beam-beam simulations.

Parameter	e^+	e^-
$E\,(GeV)$	4.0	7.0
C (m)	3016	3016
$N\,(10^{10})$	9.04	6.53
$\beta_x^*\,(mm)$	32	25
$\beta_y^*\,(mm)$	0.27	0.42
$\epsilon_x\,(nm)$	3.2	1.7
$\epsilon_y\,(pm)$	12.8	8.16
$\sigma_z\,(mm)$	6	5
$\sigma_\delta\,(10^{-4})$	8.34	8.34
ν_x	45.523	44.570
ν_y	43.548	41.590
ν_z	0.015	0.015

Scan of Linear X-Y Couplings

To identify the effects of each linear X-Y coupling parameter, we scanned them one by one on a large scale until significant luminosity degradation was observed. In each scan, other linear and nonlinear coupling parameters are set to be zeros. The results were summarized and shown in Fig. 1. From these figures, we can observe that the luminosity degradation is quite correlated with the blow-up of the vertical beam size. With the crab waist off, the vertical beam size is more sensitive the linear coupling than that with the crab waist on. This may indicate one of the merits of crab waist scheme.

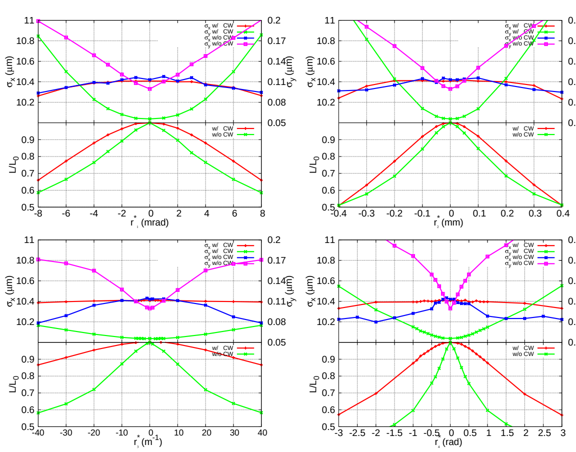

Figure 1: Beam sizes and relative luminosity as function of the linear X-Y couplings at the IP with and without crab waist.

Scan of Chromatic X-Y Couplings

In a similar way, we scanned the chromatic X-Y couplings and obtained the results depicted in Fig. 2. The linear coupling is always set to be zeros in each scan. With respect to the rate of luminosity degradation, the advantage of crab waist scheme is less remarkable than in the case of linear X-Y couplings.

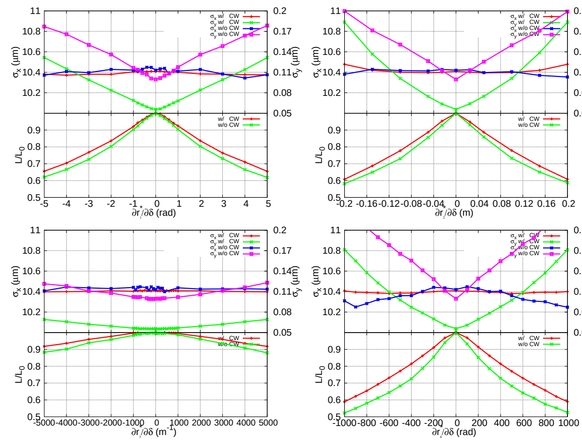

Figure 2: Beam sizes and relative luminosity as function of the chromatic X-Y couplings at the IP with and without crab waist.

Estimated Chromatic X-Y Couplings

Since no experimental data were available for the SuperKEKB, random error seeds were used to model the machine errors and estimate the amplitudes of chromatic X-Y couplings using SAD code [11]. Because the chromaticity greatly depends on the error seedings, statistics on many seeds are necessary for the estimation. In practice, 1000 seeds were applied to an ideal optics of the SuperKEKB LER. And for each seed, the transverse emittance coupling was corrected to 1%. The distributions of the chromatic X-Y couplings at the IP are presented in Fig. 3. The average values and their variations are summarized in Table 2. For more detailed analysis on the machine errors, see Ref. [8].

The average values in Table 2 are the natural chromatic X-Y couplings without machine errors. They originate from the quadrupoles and solenoids in the IR region. Obviously, the average value of r_{21} is remarkably large and will induce significant loss of luminosity (see Fig.2). This lead to the conclusion that chromatic X-Y couplings in the SuperKEKB should be corrected, as have been done in the KEKB rings [12, 3].

Tolerances for Linear and Chromatic X-Y Couplings

From the luminosity scans, we can define the tolerances for linear and chromatic X-Y couplings. Assuming a rate of 20% luminosity degradation caused by each parameter,

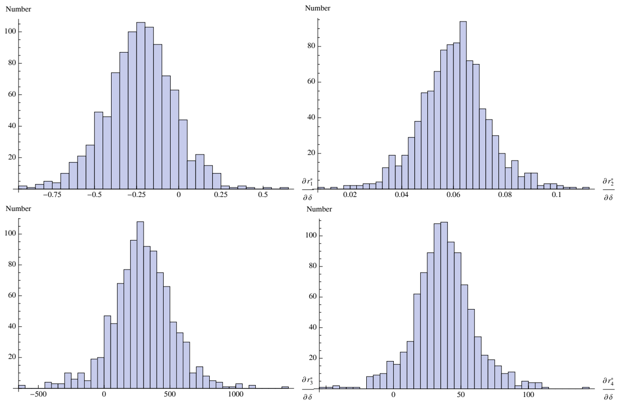

Figure 3: Distributions of the chromatic X-Y couplings with 1000 error seeds for the SuperKEKB LER.

Table 2: Average and variance of the chromatic X-Y couplings calculated from 1000 seeds of errors at the SuperKEKB LER.

Parameter	Average	Variance
$r_{11}\,(rad)$	-0.23	0.21
$r_{21}\,(m)$	0.060	0.013
$r_{31}\,(m^{-1})$	-290	230
$r_{41}\,(rad)$	37	23

we summarize the tolerances in Table 3. For practical application, these tolerances should be valuable in defining the alignment errors for the main magnets.

Table 3: Tolerances for the linear and chromatic X-Y couplings at the IP of the SuperKEKB LER, assuming a rate of 20% luminosity degradation.

Parameter	w/ crab waist	w/o crab waist
$r_1^*\,(mrad)$	± 5.3	± 3.5
$r_2^*\,(mm)$	± 0.18	± 0.13
$r_3^*\,(m^{-1})$	± 55	± 15
$r_4^*\,(rad)$	± 1.4	± 0.4
$r_{11}\,(rad)$	± 2.3	± 2.0
$r_{21}\,(m)$	± 0.09	± 0.07
$r_{31}\,(m^{-1})$	± 11000	± 9400
$r_{41}\,(rad)$	± 430	± 280

SUMMARY

The effects of the linear and chromatic X-Y couplings were investigated for the SuperKEKB, using a weak-strong beam-beam code. In the design stage, these parameters are estimated by error seeds using SAD code. With help of dedicated simulations, we defined tolerances for reference of controlling alignment errors or tuning knobs. Comparisons between these tolerances with the estimated values suggest that tight control of machine errors or reliable tuning knobs may be necessary for purpose of minimizing the luminosity degradation.

The methodology described in this paper is somewhat general and can be applied to other colliders such as SuperB [13].

The author D.Z. would like to thank M. Zobov for helpful discussions.

REFERENCES

[1] *KEKB B-factory Design Report*, KEK-Report-95-7, (1995).

[2] K. Ohmi, *Beam-Beam Effects in Crab Crossing and Crab Waist Scheme in KEKB*, Proceedings of e+e- Factories 2008.

[3] D. Zhou, et al., Phys. Rev. ST Accel. Beams 13, 021001 (2010).

[4] Y. Funakoshi, et al., *Recent Progress of KEKB*, PAC09.

[5] Y. Funakoshi, et al., *Recent Progress of KEKB*, these proceedings.

[6] H. Koiso, et al., *Design of SuperKEKB based on the Nano-beam Scheme*, these proceedings.

[7] Y. Ohnishi, et al., *Optics Design in Nano-Beam Scheme for KEKB Upgrade*, these proceedings.

[8] A. Morita, et al., *SuperKEKB LER Lattice Design and Machine Error Simulation*, these proceedings.

[9] Y. Seimiya, et al., *Symplectic Expression for Chromatic Aberrations*, to be published.

[10] K. Ohmi, et al., *Beam-Beam Effects in Crab Crossing and Crab Waist Schemes*, PAC07.

[11] http://acc-physics.kek.jp/SAD/sad.html.

[12] Y. Ohnishi et al., *Measurement of Chromatic X-Y Coupling*, Phys. Rev. ST Accel. Beams 12, 091002 (2009).

[13] *SuperB Conceptual Design Report*, INFN/AE-07/2,SLAC-R-856, LAL07-15, March 2007.