A SCHEME FOR HORIZONTAL-VERTICAL COUPLING CORRECTION AT SUPERKEKB

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Abstract

SuperKEKB is a 7 GeV electron and 4 GeV positron double-ring collider based on a nano-beam scheme. The target luminosity is 8x10^{35} cm^{-2} s^{-1}, which is 40 times higher than that of KEKB. One of critical parameters to achieve the design luminosity is a ratio of a vertical to a horizontal emittance ($\varepsilon_y/\varepsilon_x$). The vertical emittance is likely increase due to unexpected machine errors through horizontal-vertical (X-Y) couplings. The X-Y coupling correction, therefore, plays a key role in the actual operation. In this paper, we numerically investigate a measurement scheme for the X-Y coupling correction in the SuperKEKB lattice. The coupling information is extracted from a beam-envelope matrix obtained from turn-by-turn beam position data. We present, by using numerical simulations, the coupling after corrections decreases below 0.15 % which is the target value without a beam-beam interaction.

INTRODUCTION

The well-known expression for luminosity L of collider machines is,

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\left(\frac{R_L}{R_{\xi y}}\right) \tag{1}$$

where R_L and $R_{\xi y}$ are reduction factors for luminosity and vertical beam-beam tune-shift parameter, respectively. The strategy of target luminosity is 2 times higher beam current (I) and 20 times smaller vertical beta function at the interaction point (β_y^*). The nano-beam scheme is also employed to mitigate an hourglass effect. Since the beam-beam parameter $(\xi_{\pm y})$ is proportional to $\sqrt{\beta_y^*/\varepsilon_y}$ in case of the nano-beam scheme[1], the vertical emittance (ε_y), namely global coupling ratio should be also very small to realize the nano-beam collision. The tentative target of the coupling ratio is 0.15% in the absence of the beam-beam effect and intra-beam scatterings.

In the KEKB[2] operation, the global coupling correction is performed with closed-orbit (COD) response. A X-Y coupling is measured by observing vertical leakage orbits associated with horizontal steering kicks. The measured leakage orbits are suppressed by adjusting vertical bumps at sextupole magnets. For low beam-current operation, this scheme is expected to work well since no fundamental difficulties are found in the KEKB operation except for orbit drift. On the other hands, for high beam-current operation, it is practically impossible to employ this scheme since it inevitably distorts the COD and may lead to serious beam losses.

In order to perform the optics correction during beam collision, the optics measurement with single-pass BPMs for a pilot bunch is planned at SuperKEKB. This kind of approach is expected to be a new probe for high-current optics, and is probably necessary to achieve the target luminosity.

In this paper, we briefly describe a coupling measurement scheme, and show numerical simulation results of both coupling measurement and correction in SuperKEKB. All simulation results presented in this paper are obtained by using a simulation code, named “SAD”[3].

COUPLING MEASUREMNT

There are some ways to formulate the two-dimensional coupled motion by two independent betatron motions. The definition of the coupling parameters $R_{1\text{-}4}$ in this paper is,

$$\begin{pmatrix} u \\ p_u \\ v \\ p_v \end{pmatrix} = \begin{pmatrix} \mu & 0 & -R_4 & R_2 \\ 0 & \mu & R_3 & -R_1 \\ R_1 & R_2 & \mu & 0 \\ R_3 & R_4 & 0 & \mu \end{pmatrix} \begin{pmatrix} x \\ p_x \\ y \\ p_y \end{pmatrix} \tag{2}$$

where (x, p_x, y, p_y) is the physical coordinate and (u, p_u, v, p_v) is referred as the normal or betatron coordinate, which decouples horizontal and vertical motions into two independent betatron motions. For simplicity, we ignore longitudinal phase space coordinate.

Measurement with Beam-Envelope Matrix

Turn-by-turn data acquisition with a single-pass BPM has proven to be beam optics measurements. Total 135 single-pass BPMs per each ring will be available in SuperKEKB. We can determine all coupling parameters $R_{1\text{-}4}$ at BPMs by following procedure[4].

When one of betatron motions, for example, H-mode (v=0 and p_v=0) is excited by a kicker, $R_{1\text{-}4}$ can be calculated by sequence of turn-by-turn beam position data as,

$$\begin{pmatrix} R_1 & R_3 \\ R_2 & R_4 \end{pmatrix} = -\mu\, \Sigma^{-1} \begin{pmatrix} \langle xy \rangle & \langle xp_y \rangle \\ \langle yp_x \rangle & \langle p_x p_y \rangle \end{pmatrix} \tag{3}$$

where,

$$\Sigma = \begin{pmatrix} \langle x^2 \rangle & \langle xp_x \rangle \\ \langle xp_x \rangle & \langle p_x^2 \rangle \end{pmatrix} \tag{4}$$

Though canonical momentum $p_x(p_y)$ is not directly observed, it can be estimated by using two BPMs and the design transfer matrix between them. Though μ can be calculated by an iterative procedure, we put $\mu = 1$ in the presented analysis assuming weak coupling. Coupling parameters $R_{1\text{-}4}$ can be also measured by a similar way in the case of V-mode (u=0 and p_u=0) excitation.

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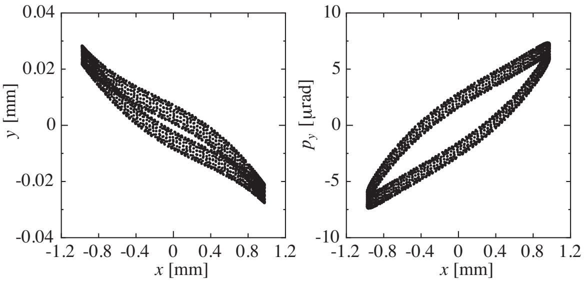

Figure 1: Phase space plots obtained from a single-pass BPM in the SuperKEKB HER lattice. BPM jitter and rotation errors are not included.

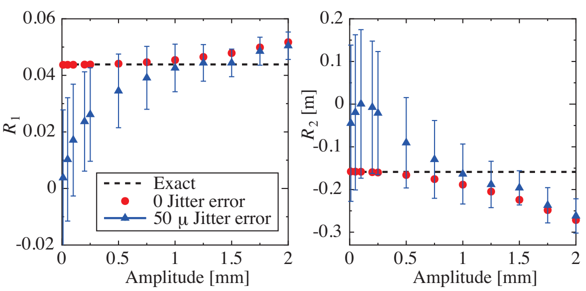

Figure 2: Measured R_1 and R_2 parameters as a function of H-mode amplitude. Triangle dots and vertical bars represent mean value and standard deviation of 100 measurements, respectively.

A simulation result of the coupling measurement in the SuperKEKB HER (e^-) lattice is shown in Fig.1, where 2^{11} turn-by-turn data recorded at a single-pass BPM is taken. In this calculation, all sextupole magnets have random vertical misalignment (100 μm in rms). A single particle with a finite H-mode amplitude is launched from the interaction point of the ring, and is then tracked through the ring during 2^{11} turns without radiation damping. The distribution has a finite width, and its shape is distorted due to nonlinear focusing forces of the lattice. The correlation between horizontal and vertical canonical variables reflects $R_{1\text{-}4}$ parameters as shown in Eq. (3). The evaluated $R_{1\text{-}4}$ parameters with the turn-by-turn data are $R_1 = 0.45$, $R_2 = -0.19$ m, $R_3 = 0.0056$ m^{-1} and $R_4 = -0.10$. The exact values calculated by beam transfer-matrix for an infinitesimal amplitude are $R_1 = 0.44$, $R_2 = -0.16$ m, $R_3 = 0.0058$ m^{-1} and $R_4 = -0.11$.

There are some discrepancies between the measured and the exact value due to a lattice nonlinearity. The effect of lattice nonlinearity on the measurement is shown in Fig. 2, where measured R_1 and R_2 are plotted as a function of oscillation amplitude of the tracked particle. The measured value depends on the amplitude of the tracked particle. The measurements without jitter error(red dots) reach the exact value as the amplitude goes zero. Also shown triangle (blue) dots are measurement results with 50 μm BPM jitter error. These results indicate that the kicker amplitude should be

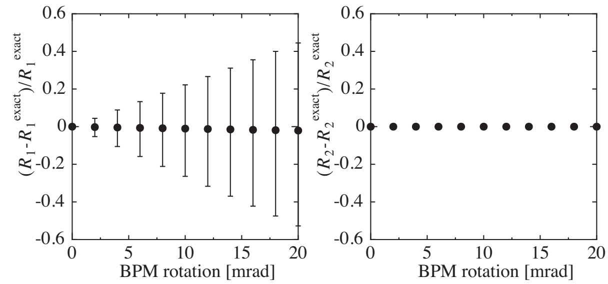

Figure 3: Measurement error of R_1 and R_2 as a function of the BPM rotation angle. Dots and vertical bars represent mean value and standard deviation of 100 measurements, respectively.

determined by considering the tradeoff between the nonlinear effect and a signal to noise ratio of the BPM.

Other error source we have to pay attention is BPM rotation error. Figure 3 shows measurement error of $R_{1\text{-}2}$ as a function of the amplitude of BPM rotation error. Measurement error of R_1 due to BPM rotation is proportional to the error amplitude in this parameter range. This behavior is similar to R_3 and R_4 parameters. On the other hand, R_2 parameter is insensitive to the rotation error. The rotation error limits the performance of the correction as shown in the Fig. 5.

GLOBAL COUPLING CORRECTION

Numerical simulations of global coupling correction with presented measurement method are carried out by the accelerator code SAD to investigate how effective this scheme is. The SuperKEKB HER lattice is assumed in the simulation. All quadrupole magnets expect for the final focusing quadrupoles are randomly rotated along the beam axis, and vertical misalignments of all sextupole magnets are also considered. All error sources are generated by Gaussian distribution, with rms 100 μrad and 100 μm, respectively. Expect for the final focusing system, these two types of misalignments are considered to be the most dominant error sources of the vertical emittance dilution, namely the coupling ratio. Global effects from the imperfection of the final focusing system will be investigated in the near future.

Since our goal of the global coupling correction is to minimize a vertical emittance, correction of vertical dispersions are also performed in the following simulations. The vertical dispersion is, in this paper, tentatively measured by observing a displacement of CODs induced by frequency changes of rf cavities.

Both a X-Y coupling and vertical-dispersion corrections are carried out by adjusting strengths of 108 skew quadrupole correctors installed in sextupole magnets. The strength of the corrector fields are determined by solving linear equations involving measured optical functions and response matrices of the design lattice.

In the simulations, 5 iterative optics corrections are performed after introducing error sources. Simulations are

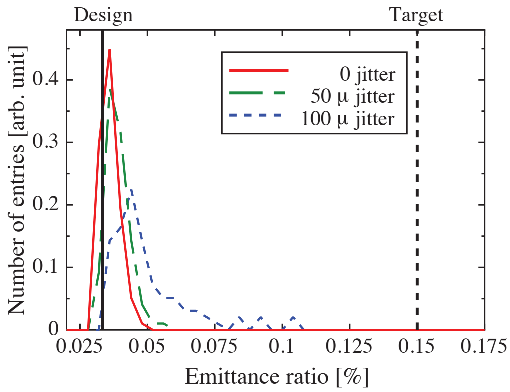

Figure 4: Coupling ratio ($\varepsilon_y/\varepsilon_x$) after optics correction with 3 different amplitudes of BPM jitter errors.

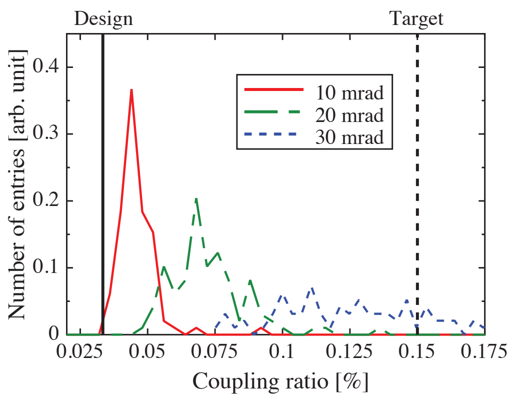

Figure 5: Coupling ratio ($\varepsilon_y/\varepsilon_x$) after optics correction with 3 rotation errors for BPMs.

carried out with 100 different seeds of random number. Figure 4 shows distribution of the coupling ratio after the optics corrections with 0, 50 and 100 μm BPM jitter errors. The coupling ratio is almost recovered to the design value. Some samples result smaller coupling ratio than the design value because of horizontal emittance dilution. As the jitter error increases, the peak shifts to the higher side, and the distribution becomes wider. Random error, such as jitter error, in general increases number of needed iterations for the target coupling ratio. Since the typical value of the jitter error assumed to be 100 μm in the KEKB, the presented scheme is feasible.

Similar results to Fig. 4 are shown in Fig. 5. The BPM rotation errors are assumed to be 10, 20, and 30 mrad, respectively. Figure 5 indicates that the tolerance of BPM rotation error in the SuperKEKB HER is ~20 mrad.

A dynamic aperture (DA) is one of fundamental quantities. The SuperKEKB lattice has a strong nonlinear force especially in the final focusing system. The DA is likely to be reduced by the lattice imperfection, such as misalignment or gradient error of magnets. Figure 6 shows DA before and after optics correction. The DA is highly degraded despite the fact that the final focusing system is perfectly aligned in the simulation. The global coupling and vertical-dispersion corrections remarkably improve DA especially at the on-momentum region.

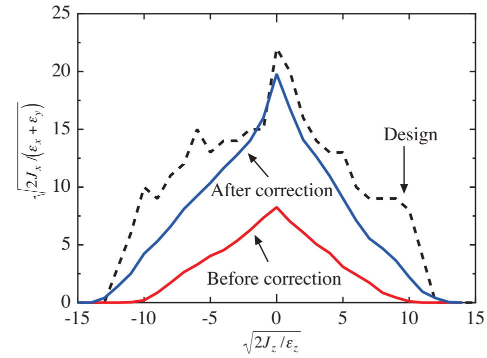

Figure 6: Dynamic aperture before and after correction, where averages of 100 results are shown. BPM jitter and rotation error assumed here are 100 mm and 10 mrad, respectively.

Though off-momentum DA is improved, the design performance is not resumed. Adjustments of sextupole fields and corrector knobs of the final focusing magnets are probably necessary for further improvement.

SUMMARY

As a new probe to the high beam current optics of SuperKEKB, an application of the coupling measurement method using a pilot bunch with single-pass BPM is considered. The presented method uses the beam-envelope matrix obtained from analysis of turn-by-turn beam position data. One of betatron motions is excited by a kicker to extract the phase space information of the pilot bunch.

Since the SuperKEKB lattice has strong nonlinear forces, the kicker amplitude should be determined by considering the tradeoff between the nonlinear effect and the signal to noise ratio of the BPM. The measurement error of $R_{1\text{-}4}$ due to BPM rotations is proportional to the error amplitude expect for R_2.

Numerical simulations of the optics correction based on the additional skew quadrupole correctors at the sextupole magnets are also performed. Simulation results indicate that the coupling ratio is recovered within the target value after 5 optics corrections with realistic BPM jitter and rotation errors.

Corrections of the global coupling and vertical dispersion improve the DA as well as the coupling ratio especially at the on-momentum region. Adjustments of another corrector are necessary to improve the off-momentum DA. More detailed study to optimize both the coupling ratio and DA is under study.

REFERENCES

[1] C. P. Raimondi, 2nd SuperB Workshop, Frascati, Italy, Mar. 16-18, 2006.
[2] "KEKB Design Report, " KEK Report 95-7.
[3] K. Oide, Nucl. Inst. Meth. A **276**, 427 (1989). http://acc-physics.kek.jp/SAD/
[4] Y.Ohnishi *et al.*, PRSTAB **12**, 091002 (2009)

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