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SuperKEKB OPTICS TUNING AND ISSUES

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Abstract

SuperKEKB is an electron-positron double-ring asymmetric-energy collider at the High Energy Accelerator Research Organization (KEK) in Japan. It adopts a novel collision method named nano-beam scheme to avoid the so-called hourglass effect. In the nano-beam scheme, two beams are squeezed to extremely small sizes at the interaction point and are collided with a large crossing angle between them. Since starting the collision operation in April 2018, numerous machine tunings and beam studies have been performed to improve the machine performance. The highest peak luminosity so far is 4.65×10^{34} cm^{-2}s^{-1} reached in June 8th, 2022. This record is the world's highest instantaneous luminosity and is more than two times higher than that of the previous KEKB collider This paper presents some important topics related to beam optics tuning in the SuperKEKB operation. Major issues to be resolved to boost the machine performance are also addressed.

INTRODUCTION

SuperKEKB [1] is a 7 GeV electron (HER) and 4 GeV positron (LER) double ring collider. Beam commissioning without final focusing system (QCS) was carried out from February 2016 to June 2016 [2]. Beam commissioning with QCS was started March 2018 [3]. SuperKEKB adopts a novel collision scheme named nano-beam scheme to open up new luminosity frontier. In the nano beam scheme, two beams collide with a large horizontal crossing angle with extremely small beam sizes. The nano beam scheme realizes small betatron function at the interaction point (IP) while avoids so-called hourglass effect which limits the luminosity performance.

Luminosity L is written by beam current I, vertical beam-beam parameter ξ_y, vertical betatron function at IP β_y^* and a reduction factor R as,

$$L = \frac{\gamma_\pm}{2er_e}\frac{I_\pm \xi_{y\pm}}{\beta_y^*}R, \qquad (1)$$

where e, r_e, and $\gamma_\pm$ are elementary charge, classical electron radius and the Lorentz gamma factor, respectively. Since the beam-beam parameter ξ_y is proportional to $\sqrt{\beta_y^*/\varepsilon_y}$, the vertical emittance ε_y should be also very small as well as β_y^* to realize the nano-beam collision. Therefore the low emittance tuning is one of the important machine parameters in the SuperKEKB machine tuning.

The nominal β_y^* in the present operation is $\beta_y^* = 1$ mm while the final target of β_y^* is $\beta_y^* = 0.3$ mm. The operation with $\beta_y^* = 0.8$ mm was carried out for short-term trial. The achievable bunch currents is smaller than of $\beta_y^* = 1$ mm case due to poor injection efficiency. Improvement of the injection efficiency is a major issue in both squeezing β_y^* and increasing stored beam current.

Crab waist scheme (CW) [4, 5] is incorporated to both LER and HER in 2020 to mitigate a sort of hourglass effect in the transverse direction. CW is realized by applying different filed strength to sextupole magnets (SLY) used in the vertical local chromaticity correction (Y-LCC) as shown in Fig. 1. The vertical betatron function at SLY and field strength of SLY are quite large owing to the extremely small β_y^* and the resultant large chromaticity. Therefore beam optics is easily distorted by a tiny amount of lattice or orbit errors. Optics tuning and the machine operation should be performed with careful attention to the Y-LCC section as well as the interaction region (IR).

OPTICS TUNING

Beam Position Monitor and Corrector

Beam Position Monitor (BPM) is attached to each of quadrupole magnets for precise orbit and optics control. The BPM system is successfully used in the beam tuning with an averaging mode of 0.25 Hz. In addition to closed orbit measurement, more than 100 BPMs per ring can be used as gated turn-by-turn BPMs. The gated turn-by-turn BPMs are very helpful in the beam injection tuning. Optics measurement with turn-by-turn beam position is performed only for dedicated beam study. Usual optics tuning is based on closed orbit measurement.

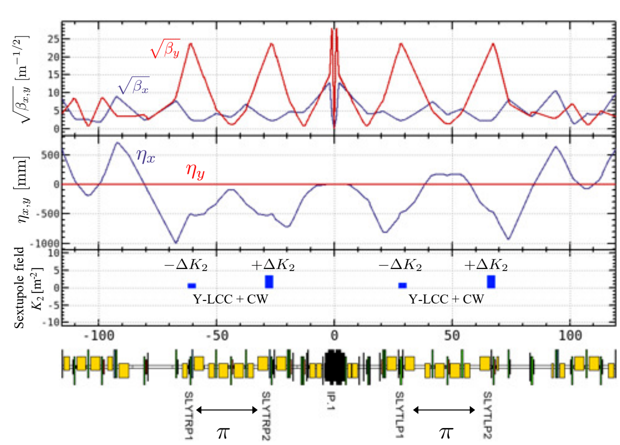

Figure 1: Betatron and dispersion functions at the Y-LCC section in LER. Two sextupoles pairs installed in both left and right sides of the interaction region. The sextupole pairs are utilized for Y-LCC and CW. Betatron phase advance between the two sextupoles is π.

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The SuperKEKB main rings have about 900 quadrupole magnets and about 200 sextupole magnets. Horizontal and vertical steering magnets are installed near the focusing and de-focusing quadrupole magnets, respectively. Almost all quadrupole magnets have independent power supply for their auxiliary coil to enable robust optics tuning. Skew quadrupole coils are installed to all sextupole magnets and utilized in optics correction and luminosity tuning.

Measurement

Beam optics at BPMs are extracted by analyzing closed orbit distortion induced by horizontal and vertical dipole kicks. Closed orbit at i-th BPM $\Delta\chi_i$ excited by j-th dipole kick $\Delta\theta_j$ is written by

$$\Delta\chi_i = \frac{\sqrt{\beta_i\beta_j}}{2\sin\pi\nu}\Delta\theta_j\cos\left(|\phi_i - \phi_j| - \pi\nu\right), \qquad (2)$$

where β, ϕ and ν are betatron function, betatron phase and betatron tune, respectively. Betatron function and its phase are determined so that Eq. (2) reproduces measured orbit distortion. Six kinds of closed orbit distortion per each direction are analyzed in the optics measurement at SuperKEKB.

Dispersion function is measured by varying the beam revolution frequency f_{rev} with Δf_{rev}. Beam orbit deviation at i-th BPM $\Delta\chi_i$ caused by the frequency change Δf_{rev} is proportional to dispersion function η_i at the BPM as

$$\Delta\chi_i = -\frac{\eta_i}{\alpha_p - \gamma^{-2}}\frac{\Delta f_{\mathrm{rev}}}{f_{\mathrm{rev}}}, \qquad (3)$$

where α_p is the momentum compaction factor of the ring. Dispersion function is calculated with measured orbit response and Eq. (3) assuming the model value for α_p. The momentum compaction factor is $\alpha_p = 3.0\times10^{-4}$ in LER and $\alpha_p = 4.5\times10^{-4}$ in HER. The amount of the relative frequency change $\Delta f_{\mathrm{rev}}/f_{\mathrm{rev}}$ is about $\pm6\times10^{-7}$, and it corresponds to 0.2 % and 0.13 % beam energy deviations in LER and HER, respectively.

The other important tuning item in SuperKEKB is coupling between horizontal and vertical betatron motions (xy-coupling). There are several parametrization techniques for betatron coupling in accelerators. Four optical functions r_{1-4} used in the SuperKEKB operation. The coupled transverse motions in four-dimensional phase space (x, p_x, y, p_y) are decomposed to two independent betatron motions as

$$\begin{pmatrix} u \\ p_u \\ v \\ p_v \end{pmatrix} = \begin{pmatrix} \mu & 0 & -r_4 & r_2 \\ 0 & \mu & r_3 & -r_1 \\ r_1 & r_2 & \mu & 0 \\ r_3 & r_4 & 0 & \mu \end{pmatrix}\begin{pmatrix} x \\ p_x \\ y \\ p_y \end{pmatrix}, \qquad (4)$$

where $\mu^2 = 1 - (r_1r_2 - r_3r_4)$. The xy-coupling parameter is a correlation between horizontal and vertical betatron motions. Therefore vertical leakage orbit induced by a horizontal dipole kick contains information of xy-coupling parameters. Although it is possible to infer the coupling parameters r_{1-4} from the leakage orbits with some model dependent assumptions, numerical simulations show that the optics correction based on vertical leakage orbit itself sufficiently reduces r_{1-4}. Therefore the vertical leakage orbit is used in the global optics correction for simplicity. Six kinds of vertical leakage orbits are used in xy-coupling correction.

Optics measurement and correction are performed with a low stored beam current (<50mA) to avoid dangerous beam loss during the measurement.

Global Optics Correction

Global optics correction is performed so that difference between measured beam optics and that of model optics is minimized. Strength of corrector magnets are obtained with measured beam optical parameters and response matrix of the model lattice. Betatron functions, dispersions and xy-coupling are in general coupled to each others. However, correction of each optical parameter is independently and iteratively performed in SuperKEKB to break down the size of problem to be solved.

An example of vertical leakage orbits in HER before and after the optics correction are shown in Fig. 2(a) and (b), respectively.

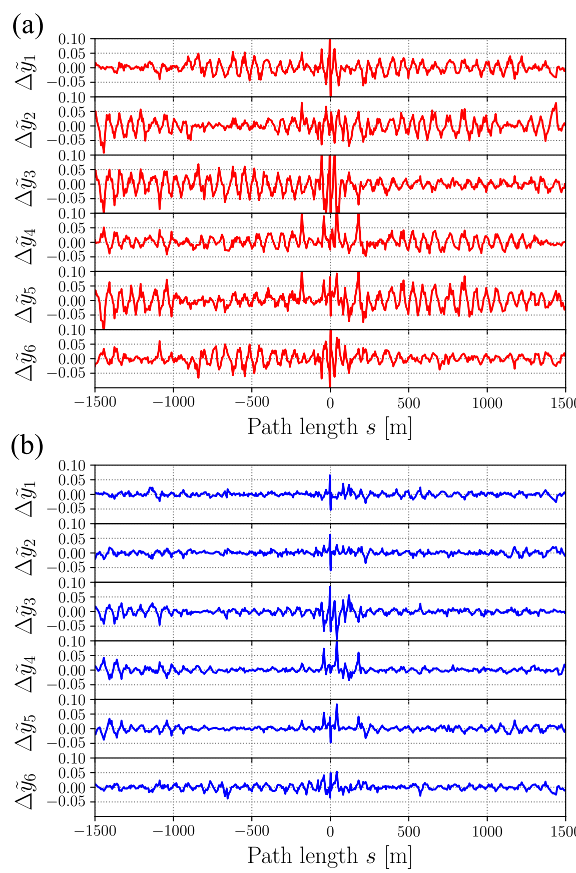

Figure 2: Measured vertical leakage orbits in HER before (a) and after (b) the optics correction. The vertical axis is normalized by root-mean-squared (RMS) amplitude of the horizontal orbits. IP is located on $s = 0$.

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spectively. The skew quadrupole corrector coils in sextupole magnets are mainly utilized. Skew quadrupole magnets near IR are also used depending on the situation.

One of essential optical parameter in the nano-beam scheme is vertical emittance. Therefore the vertical emittance is considered as the main figure of merit in the optics tuning. Each storage ring has one X-ray beam size monitor to monitor horizontal and vertical beams sizes. The vertical emittance evaluated by measured vertical beam size is used to confirm the validity of the optics correction.

Figure 3 shows time evolution of vertical emittance in HER during a series of optics correction performed on a machine maintenance day. The vertical emittance is reduced from more than 100 pm to 30 – 40 pm. Typical residual of optical parameters and vertical emittance is summarized in Table 1. The vertical emittance after the optics correction depends on daily machine condition. The urgent issue is how to keep the beam optics during physics experiment rather than the performance of optics correction itself.

Tuning of IP Parameters

Experience on SuperKEKB operation shows r_1^* and r_2^* are effective for luminosity performance. Vertical dispersion is also effective for beam size control. On the other hand r_3^* and r_4^* are not so effective for luminosity performance, but these parameters affect beam background (BG).

Several machine studies were carried out to evaluate optical parameters at IP by means of both closed orbit response and turn-by-turn beam positions. It is however difficult to determine their absolute values due to poor sensitivity of IP orbit and uncertainty in the complicated IR modeling. Therefore, the tuning of IP parameters are performed based on the observed machine performance.

One of important parameter to be optimized is xy-coupling at IP (r_{1-4}^*). Global optics correction presented in this paper does not take care IP parameters itself. Eventually a tuning knob named IPTiltKnob which can control xy-coupling and vertical dispersion at IP by using skew quadrupole coils is developed for luminosity tuning. The IPTiltKnob calculates field strength of skew quadrupoles which produces desired change of IP parameters assuming the model lattice.

Table 1: Typical Residual of Optical Parameters

Optical Parameter	**LER**	**HER**
$(\Delta\beta_x/\beta_x)^{\text{rms}}$ [%]	5	5
$(\Delta\beta_y/\beta_y)^{\text{rms}}$ [%]	5	5
$\Delta y^{\text{rms}}/\Delta x^{\text{rms}}$ [10^{-3}]	16	12
$\Delta\eta_x^{\text{rms}}$ [mm]	15	30
$\Delta\eta_y^{\text{rms}}$ [mm]	5	5
ε_y [pm]	20 ~ 40	20 ~ 40

Figure 4 shows an example of luminosity tuning using IPTiltKnob with r_2^*. IP parameters are routinely adjusted during physics experiment to keep or improve machine performance by carefully watching not only luminosity but also BG and injection efficiency.

In addition to beam optics, vertical crossing angle at IP Δp_y^* has huge impact on the luminosity performance. Figure 5 shows luminosity performance for four different values of Δp_y^* in LER. Luminosity performance was improved by about 20 % by optimizing Δp_y^*. It is also confirmed that the tuning of Δp_y^* reduces BG.

ISSUES

Optics correction is originally scheduled every two weeks on a machine maintenance day. It is also performed when the optics distortion is suspected by degradation in machine performance such as beam size, injection efficiency, BG and luminosity. Unexpected optics distortion is observed more frequently in the recent operation. Eventually, optics correction is required once every 2 or 3 days.

Beam optics of the SuperKEKB main ring are very sensitive to perturbation owing to the large betatron function at IR and SLY. Therefore the fluctuation and drifting of machine condition should be understood and minimized. Some

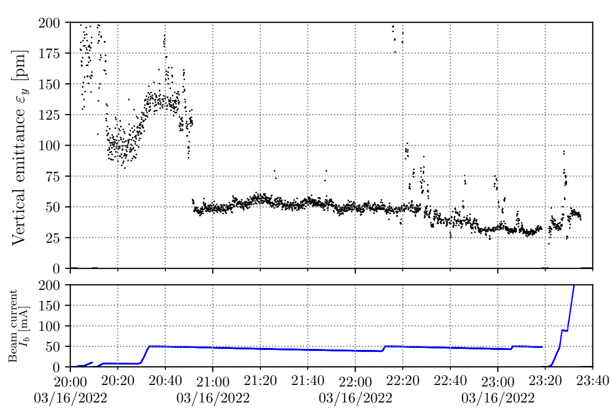

Figure 3: Time evolution of the vertical emittance together with beam current in HER during a series of optics correction.

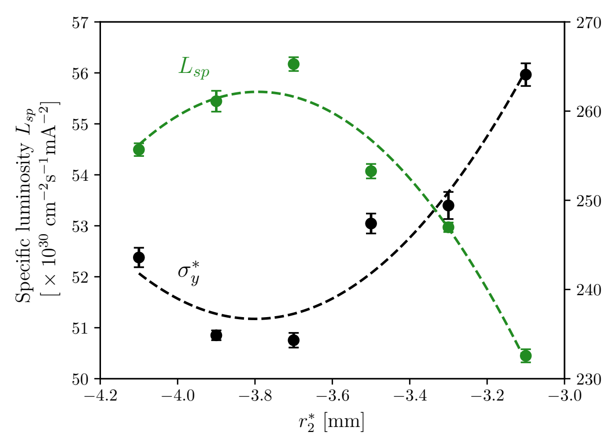

Figure 4: Specific luminosity and vertical beam size as a function of r_2^*.

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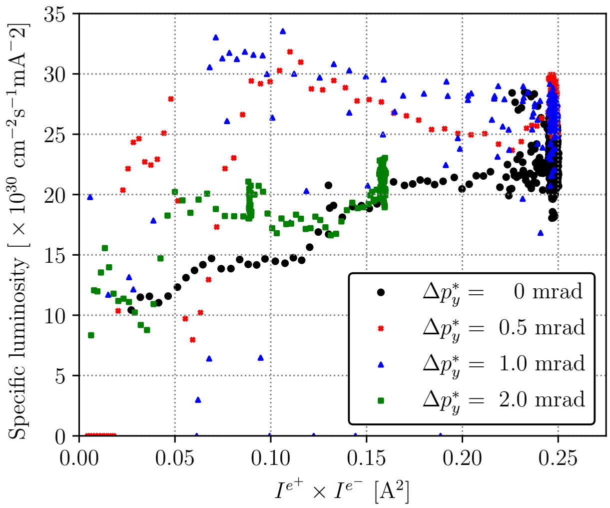

Figure 5: Specific luminosity as a function of beam current products with different four vertical crossing angle at IP.

topics related to beam optics degradation during operation are presented in this section.

Field Drifting of QCS

Unexpected vertical tune drifting was suspected in 2021 as shown Fig. 6(a), where the tune drifting is estimated by the amount of a tune feedback for the operation. The vertical beta-beating is also observed as shown in Fig. 7. It is confirmed by numerical calculation that the measured tune drifting and beta-beating are explained by QCS's quadrupole error of 10^{-2} %. It was also pointed out that the tune drifting starts just after the QCS startup. These observations and numerical calculations imply the field drifting of QCS.

Experiments on field drifting of QCS were carried out with a QCS prototype [6]. The field measurement shows drifting qudrupole field of 10^{-3}~10^{-2} % depending on ramp cycle of the magnet. Based on the measurements the ramp cycle of QCS was modified to mitigate the field drifting. Figure 6(b) shows remarkable reduction of tune drifting by the modification.

Beam Current Dependent Optics Degradation

Betatron tune is kept a constant by a tune feedback system which adjusts some quadrupole magnets in matching sections. The amount of adjustment is calculated by the model lattice. The feedback system was originally developed to compensate beam current dependent tune shift.

It is possible to estimate the beam current dependency of tune by the amount of feedback. Figure 8 shows HER horizontal and vertical tunes as a function of stored beam current I_b in various days. The amount of horizontal tune shift dose not depend on the day while that of vertical tune depends on the day. It was considered that the major source of current dependent tune shift in HER is quadrupolar components of resistive wall wake due to non-circular shape of vacuum chamber. However, Fig. 8 implies that the existence

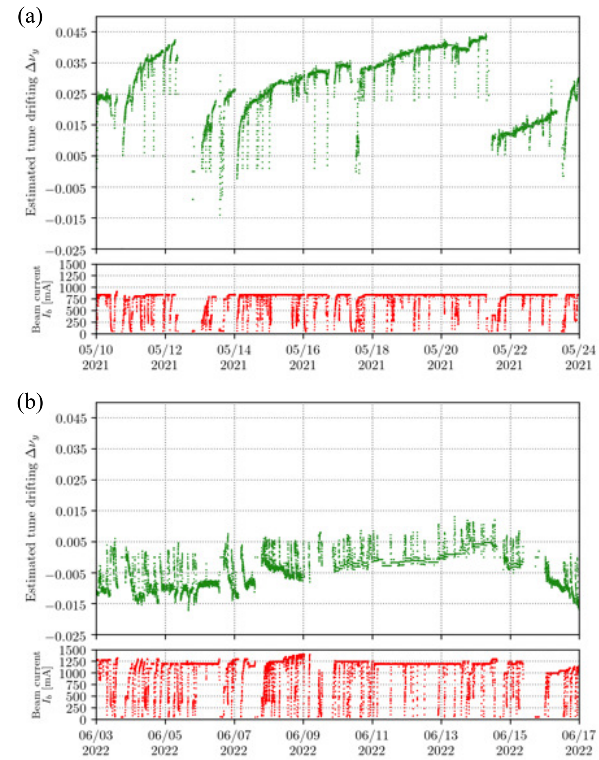

Figure 6: Vertical tune drifting in LER estimated with amount of tune feedback in 2021 (a). Tune drifting is reduced in 2022 by the modification for the ramp cycle of QCS

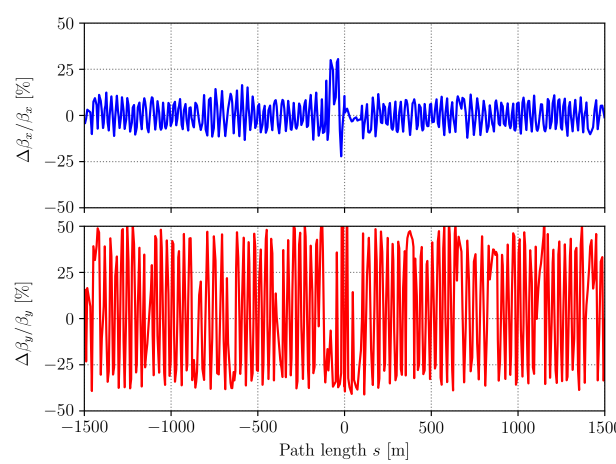

Figure 7: Measured beta-beating in LER. The measurement was performed on May 21st, 2021.

of other sources which causes a relatively large vertical tune shift and the amount of tune shift depends not only on the beam current but also on the day.

An possible source of the observed vertical tune shift is beam orbit fluctuation at strong sextupole magnets. The most crucial magnets are SLY because of the strong field strength and large betatron function β_y^s. Because the betatron phase advance between the two sextupoles is π, it is useful to consider cosine-like and sine-like orbits. The

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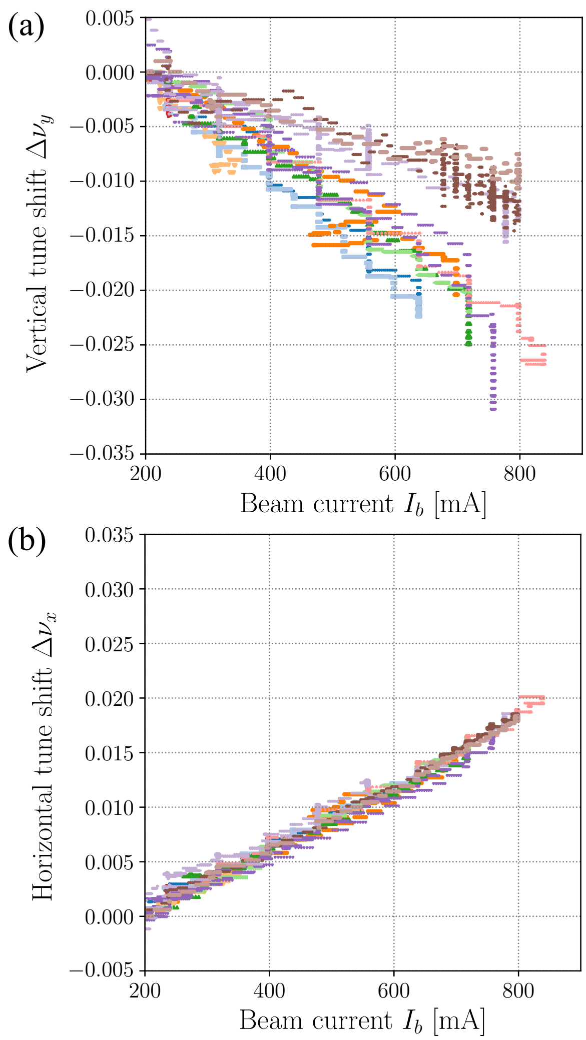

Figure 8: Horizontal (a) and vertical (a) tune shifts estimated by the amount of tune feedback as a function of stored beam current in HER. Each marker represents a measurement day.

tune shifts $\Delta\nu_{x,y}$ caused by cosine-like and sine-like orbits whose amplitude is Δx are respectively given by

$$\Delta\nu_{x,y} = \pm\frac{\beta^s_{x,y}}{4\pi}(K^1_2 + K^2_2)\Delta x, \quad (5)$$

$$\Delta\nu_{x,y} = \pm\frac{\beta^s_{x,y}}{4\pi}(K^1_2 - K^2_2)\Delta x, \quad (6)$$

where $K^{1,2}_2$ are field strengths of the two sextupole magnets. Only the cosine-like orbit causes tune shift when CW is turned off because of $K^1_2 = K^2_2$. When CW is turned on, both cosine-like and sine-like orbits cause tune shift. Assuming cosine-like orbit with $\Delta x = 10\,\mu\text{m}$ in HER for example, and inserting $\beta_y = 700$ m and $K^1_2 + K^2_2 = 16\,\text{m}^{-2}$ to Eq. (5) , the resultant vertical tune shift is $\Delta\nu_y \sim -0.009$ and comparable to the measured tune shift shown in Fig. 8.

Figure 9 shows the dependence of the beam orbits at SLYs on the stored beam current. The orbits at SLYTLE1 and SLYTLE2 move in same direction as beam current increase.

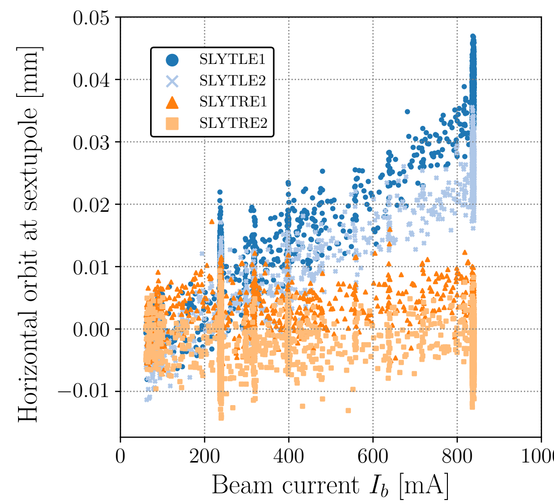

Figure 9: Horizontal beam orbits at SLYs (SLYTLE1, SLYTLE2, SLYTRE1 and SLYTRE2) and stored beam current in HER.

The vertical tune shift due to the observed beam orbit changes is evaluated by model calculations. The orbits at SLYs are imported to the model lattice as misalignments of SLYs. The betatron tune shift calculated with the misaligned SLYs as a function of stored beam current is shown in Fig. 10 together with the observed tune shifts. The measured orbit drifting causes almost no horizontal tune shift. On the other hand the measured vertical tune shift is reproduced by the orbit drifting at SLYs. It is also confirmed that the variation of the amount of vertical tune shift shown in Fig. 8 is attributed to the day to day variation of the orbit drifting.

The orbit change at SLY causes not only tune shift but also beta-beating in the whole ring. Figure 11 shows estimated vertical beta-beating as a function of stored beam current

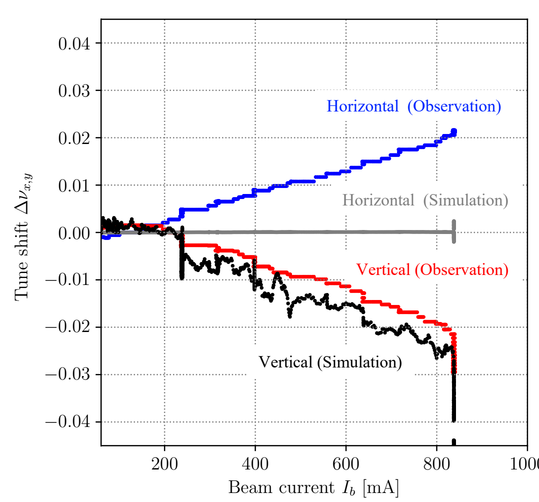

Figure 10: Current dependent tune shift estimated by orbit at SLYs together with that of observation.

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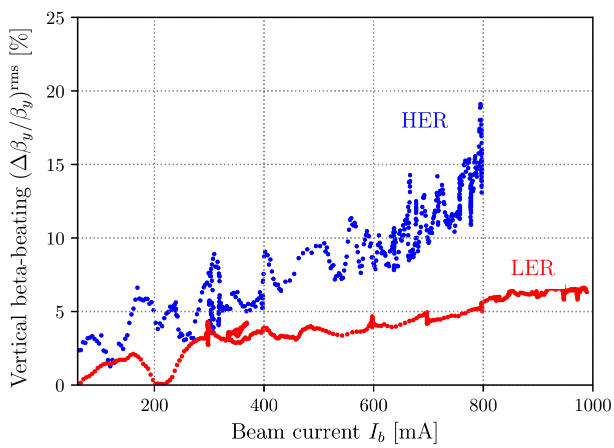

Figure 11: Estimated vertical beta-beating as a function of stored beam current, where the residual beta-beating is calculated with root-mean-squared of beta-beating at all BPMs.

for both rings. The estimated optics distortion in high beam current operation is considerably large.

The vertical betatron function at IP β_y^* is estimated in Fig. 12. It is known empirically that direction of beam orbit movement in SLYTLE1 and SLYTLE2 is somehow always same. Therefore both beams are always squeezed too much in high beam current operation. The smaller β_y^* results large vertical betatron function in QCS and makes stable machine operation more difficult because of poor injection efficiency and high BG level.

The source of beam current dependence of beam orbit is not understood yet. A possible reason is deformation of beamline due to beam pipe heating caused by synchrotron radiation from the beam. Although some experiments on the deformation is now carried out to clarify the movement of BPM and beam pipes, any scenario which explains measured orbit drifting is found so far.

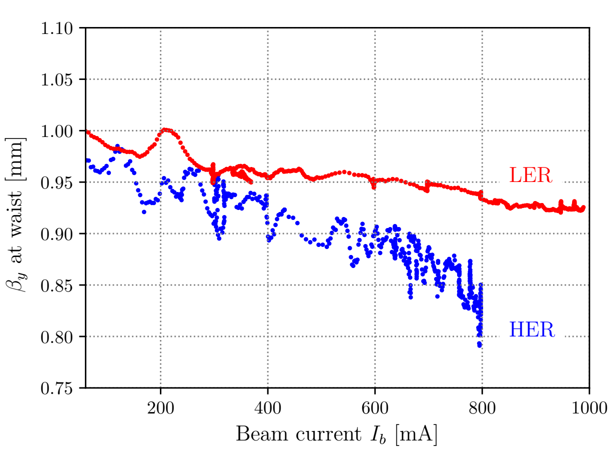

Figure 12: Estimated vertical betatron function at IP as a function of stored beam current.

Localized orbit at SLYs are applied to mitigate the optics distortion following to the above consideration. Figure 13 shows results of the beam orbit tuning at SLYs. It was confirmed that the orbit tuning improves both beam injection efficiency and BG. The localized orbit is now utilized as one of tuning knob in machine operation especially in high beam current operation.

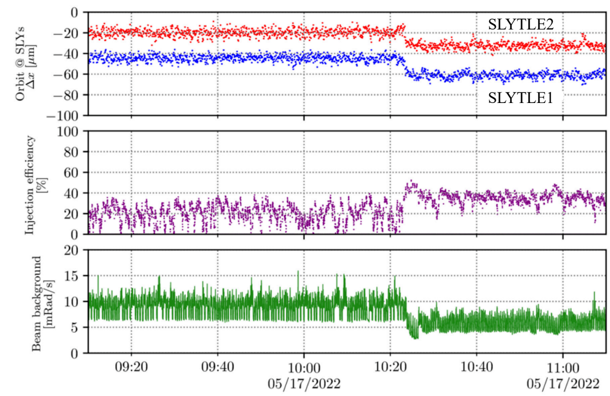

Figure 13: Tuning of orbit at SLYs with a localized orbit in HER, where time histories of orbit at SLYs, injeciton efficiency and BG are shown.

Earthquake

Japan is a country of many earthquakes. Earthquake causes beam abort in both rings in most cases. In addition, HER beam becomes unstable after earthquake in some cases. Figure 14 shows the unexpected luminosity degradation after recovery from earthquake. The vertical beam size blowup in HER can not be suppressed by tuning of IP parameters. Global optics correction is eventually necessary to recover the stable operation. Although numerical calculation implies that skew quadrupole components at SLY and/or QCS explain the observed distortion of xy-coupling, a clear reason for the skew quadrupole components is not found so far.

Stability of Beam Orbit and Optics

Although optics correction is originally scheduled every other week, more frequent optics correction is necessary in high beam current operation. Figure 15 shows time history of some machine parameters for few days. The vertical emittance gradually increases in a few days. As the results, beam injection efficiency becomes worse and BG increases. Eventually, optics correction is necessary every 2 or 3 days to resume stable operation.

A possible reason of the optics degradation is orbit changes during operation. Closed orbit in each of the SuperKEKB main rings is maintained by a slow (~0.1 Hz) orbit feedback system. The feedback system applies orbit correction with steering magnets to keep the closed orbit during machine operation. The residual of closed orbit is about 20 ~ 30 μm for both horizontal and vertical directions

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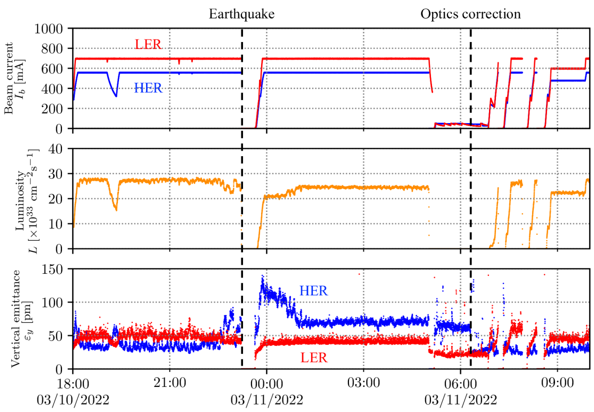

Figure 14: Machine parameters before and after an earthquake. Time histories of stored beam current, luminosity and vertical emittance are shown.

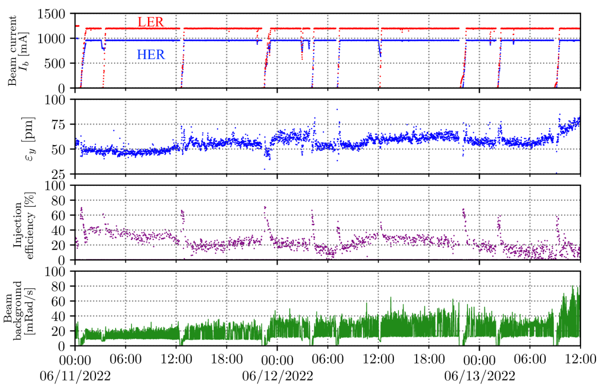

Figure 15: Degradation of machine performance within a few days in HER, where time histories of stored beam current, vertical emittance, beam injection efficiency and BG are shown.

in the RMS sense. One the other hand, numerical estimation indicates that the orbit fluctuation at strong sextupole magnets in arc cells of a few ten µm has non-negligible impact on beam optics.

Identification of error source is not trivial because tiny amount of beam orbit changes should be discussed carefully. The BPM reading used in the orbit feedback depends not only on beam orbit itself but also on various effects such as deformation of beamline, air temperature, electrical characteristics of the BPM system, etc. More systematic and precise investigation is essential to improve orbit and optics stability.

SUMMARY

Global optics tuning in SuperKEKB is based on analysis of closed orbit response. Correction of betatron function, *xy*-coupling and dispersion function are independently and iteratively applied until the residual error is converged. Correction of optical parameters at IP is performed by observing machine performance, such as beam size, luminosity, injection efficiency, BG, etc.

Field drifting of QCS was suspected by the unexpected drifting of tune feedback system in 2021. It is confirmed by field measurement with a QCS prototype magnet that the amount of field drifting depends on ramp cycle of QCS. Following to the field measurements, ramp cycle for QCS's startup was modified. The tune drifting is much reduced by the modification.

Investigation on amount of tune feedback and orbit at SLYs indicates that beam current dependence of vertical tune shift is attributed to the beam orbit change at SLYs. The orbit fluctuation at SLY causes beta-beating and makes stable operation more difficult in high beam current operation. It is demonstrated that the orbit tuning at SLYs improves both injection efficiency and BG level. The orbit at SLYs is very important parameter to be carefully monitored in the machine operation. The mechanism of the beam current dependence of the orbit is not understood yet.

Optics degradation in a few days is an urgent issue in high beam current operation. It seems that a few ten µm orbit change at strong sextupoles is not negligible according to numerical estimations. Systematic and detailed investigation on BPM reading including the BPM system itself and deformation of beamline is necessary to clarify the real beam orbit and its effects on beam optics.

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