ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPGW031

ANALYSIS AND CORRECTION FOR THE EFFECT OF MULTIPOLES WITH SKEWED ERRORS ON IP BEAM DYNAMICS IN SuperKEKB

K. Hirosawa*, K. Ohmi[1], Y. Funakoshi[1], H. Koiso[1], A. Morita[1], Y. Ohnishi[1], H. Sugimoto[1], D. Zhou[1]
SOKENDAI (the Graduate University for Advanced Studies), Tsukuba, Japan
[1]also at High Energy Accelerator Research Organization (KEK), Tsukuba, Japan

Abstract

The optics aberration due to machine imperfections, such as the skew quadrupoles or the misalignment of the sextupoles, can make the beam motion coupled. In the SuperKEKB Phase-II and Phase-III commissioning, these errors were observed and caused the luminosity degradation. Machine parameters have extremely small beta functions at interaction point (IP) with large crossing angle collision, thus serious optics aberrations and complicated instabilities can be seen in every step of commissioning. In this study, x-y coupling was picked from the crowd of other issues and analyzed on the basis of the measurement in Phase-II commissionig.

INTRODUCTION

SuperKEKB is the asymmetric energy electron positron collider with the nano-beam scheme. It consists of a 7 GeV high energy ring (HER) for electrons and a 4 GeV low energy ring (LER) for positrons. The nano-beam scheme is the new collision system which is the part of crab-waist collision scheme to reach a very high peak luminosity of $8 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The point of the nano-beam scheme is to consist of low emittance, low beta (design beam size $\sigma_y^* \sim 50$nm), and large crossing angle. To realize design performance, the final focusing quadrupoles system was newly constructed in interaction region (IR) [1].

In the Phase-II commissioning of SuperKEKB, serious luminosity degradation was observed and correction and identifying of optics aberrations were required. The beam dynamics problem at interaction point (IP) was an obstacle to the luminosity improvement, thus it is necessary that analysing the detailed beam condition at IP.

The formula of luminosity with large crossing angle reflected the effective horizontal beam size ($\sigma_s << \sigma_x$) is

$$\mathscr{L} \simeq \frac{N_{\mathrm{e+}} N_{\mathrm{e-}} f N_{\mathrm{b}}}{2\pi \sin\frac{\phi}{2}\sqrt{\sigma_{s+}^2+\sigma_{s-}^2}\sqrt{\sigma_{y+}^{*2}+\sigma_{y-}^{*2}}} S_{\mathrm{L}} \quad (1)$$

$$S_{\mathrm{L}} \simeq \frac{1}{\sqrt{1+(\frac{\sigma_s}{\sigma_x}\tan\frac{\phi}{2})}} \quad (2)$$

where $N_{\mathrm{e+,e-}}$ are the particle per bunch, f is the revolution frequency, N_b is the number of bunch, ϕ is the crossing angle, σ is the beam size, σ^* is the beam size at IP, and S_L is the reduction factor for head-on collision. The most important factor is the vertical beam size, because other parameters are based on accelerator design. Thus, only vertical beam size is effective for luminosity.

The ratio between vertical and horizontal beam size is near 1:100, so vertical beam size is much sensitive when it is coupled with horizontal beam size (so-called x-y coupling). The transverse motion matrix M_4 can be decoupled by a similarity transformation

$$\mathrm{M}_4 = \mathrm{R}\mathrm{M}_{2\times2}\mathrm{R}^{-1} \quad (3)$$

where the block-diagonal 4×4 matrix $\mathrm{M}_{2\times2}$ is the well-known revolution matrix for betatron motion in x and y plane so-called Courant-Snyder matrix and the matrix R is x-y coupling matrix which is defined by [2]

$$\mathrm{R} = \begin{pmatrix} \sqrt{1-det(r)}I & -Sr^{\mathrm{t}}S \\ r & \sqrt{1-det(r)}I \end{pmatrix},\ r = \begin{pmatrix} r_1 & r_2 \\ r_3 & r_4 \end{pmatrix} \quad (4)$$

where I is Identity matrix of other 2, S is the unit symplectic matrix of order 2. From Eq. 3 and Eq. 4, the geometrical beam size with arbitrary x-y coupling is written by

$$\sigma_\beta^{*2} =< \vec{x}\vec{x}^{\mathrm{t}} >= \mathrm{RB}\begin{pmatrix} \epsilon_u & 0 & 0 & 0 \\ 0 & \epsilon_u & 0 & 0 \\ 0 & 0 & \epsilon_v & 0 \\ 0 & 0 & 0 & \epsilon_v \end{pmatrix}\mathrm{B}^{\mathrm{t}}\mathrm{R}^{\mathrm{t}} \quad (5)$$

$$\mathrm{B} = \begin{pmatrix} \sqrt{\beta_{u,v}} & 0 \\ \frac{-\alpha_{u,v}}{\sqrt{\beta_{u,v}}} & \frac{1}{\sqrt{\beta_{u,v}}} \end{pmatrix} \quad (6)$$

where $\epsilon_{u,v}$ are emittances on the normal coordinates (u, v). This relation is the transformation between the physical (coupled) coordinates (x, y) and the normal (decoupled) coordinates (u, v). As there are effective R parameters, practical beam size at IP σ_y^* (on the physical coordinates) is coupled with other beam size which is written by

$$\sigma_y^{*2} \simeq \sigma_v^{*2} + r_1\sigma_u^{*2} + r_2\sigma_{p_u}^{*2} \quad (7)$$

where $\sigma_{u,p_u,v}^*$ is the beam size on normal coordinate for convenience of representation.

These R parameters has momentum dependence, so there are difference between the case of on-momentum and off-momentum particle. The practical luminosity estimation is calculated by using Eq. 1, Eq. 7 and the beam current. The problem of the luminosity degradation of SuperKEKB Phase-II was solved by this method to find the cause.

PROBLEM OF THE LUMINOSITY IN PHASE-II COMMISSIONING

Though beam conditions such as β-waist, beam size of X-ray monitors, emittance ratio, etc. were enough optimized,

* hirosawa@post.kek.jp

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPGW031

an increase of the luminosity performance was suppressed. Especially, the geometrical specific luminosity was incongruous with the estimation value from other monitors for beam conditions. Figure 1 shows the discrepancy problem of specific luminosity. The blue dots denotes a specific luminosity ($\mathscr{L}_{\mathrm{sp}}$) measured by a fast luminosity monitor, and the red stars denotes $\mathscr{L}_{\mathrm{sp}}$ estimated by measured beam sizes of x-ray monitors.

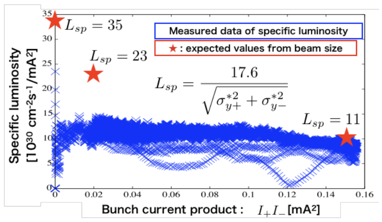

Figure 1: The measured specific luminosity (blue plot) and the estimated specific luminosity by x-ray monitor beam size (red star).

It seemed that the problem arose at only IP. The vertical beam size σ_y, which depends on vertical beta function $\beta_y(s)$, was the powerful candidate as the factor of changing luminosity in local. To research the authentic σ_y^*, current condition was inferred from measurable data.

CAUSE OF ENLARGED EFFECTIVE σ_y^*

There are several possibilities regarding the cause of enlarged vertical beam size only at IP.

- Actual and set $\beta_y^*(s)$ were mismatched
- Beam orbit at IP was distorted by unforeseen kicks
- Collision area was off to the side by local x-y coupling

The problem of mismatched beta functions was an improbable situation, because the measurement of scanning β-waist position agreed with the result of beam-beam simulations. As the similar reason, wrong collision caused by the orbit distortion was well tested in horizontal and vertical offset scan and the room phase scan. Remained x-y coupling was the questionable factor, since it is enough possible that the influence was canceled in IR.

There are two pair of magnets in IR, which are the set of “QC1” and “QC2” (in Figure 2), as the source of x-y coupling. If the QC1 set has the skewed error, the action for (p_u, p_v) at the QC1 affects the beam condition for (x, y) at IP, because the betatron phase difference between QC1 and IP is about $\pi/2$. In addition, the strength of that action is increased as the ratio of $\beta_{x,y}$ between QC1 and IP is

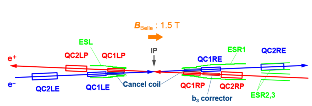

Figure 2: Schematic layout of the QCS magnets at IR of SuperKEKB. (quotation from THP065, PASJ2018)

increased. This property is consistent with the fact that the problem was not observed in early operation of phase-II. Thus we focused on the QC1 skew rotation.

From the relation of Eq. 7, the authentic σ_y^* is produced by r_1 , r_2, and horizontal beam sizes on the normal coordinates. The consequence of the existence of r_1 and r_2 is revealed as the slope with an x-y and p_x-y plane, respectively. Either cases are enough possible to interpret the luminosity degradation like a Fugure 1. On the other hand, it is difficult that r_1 coexists with r_2, because a pair of QC1 should have same field intensity to cancel the local x-y coupling inside of IR. Rewriting Eq. 3 by using the quadrupole matrix,

$$\mathrm{M}_4 = \mathrm{T}_{1\mathrm{R}}\mathrm{K}(k_{1\mathrm{R}})\mathrm{T}_{1\mathrm{R}}^{-1}\mathrm{M}_{2\times2}\mathrm{T}_{1\mathrm{L}}^{-1}\mathrm{K}(k_{1\mathrm{L}})\mathrm{T}_{1\mathrm{L}} \tag{8}$$

$$\mathrm{K}(k) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & 0 & 0 & 1 \end{pmatrix} \tag{9}$$

where $\mathrm{T}_{1\mathrm{R}}$ and $\mathrm{T}_{1\mathrm{L}}$ are transfer matrixes between QC1R and IP (upstream) and IP and QC1L (downstream), respectively. From Eq. 3 and Eq. 8, the relation in realistic SuperKEKB parameters of HER is

$$r_1 = -14.9k_{1\mathrm{L}} - 14.9k_{1\mathrm{R}} \tag{10}$$
$$r_2 = 0.716k_{1\mathrm{L}} - 0.716k_{1\mathrm{R}} \tag{11}$$
$$r_3 = 487k_{1\mathrm{L}} - 487k_{1\mathrm{R}} \tag{12}$$
$$r_4 = -1156k_{1\mathrm{L}} - 1156k_{1\mathrm{R}} \tag{13}$$

where $k_{1\mathrm{L},1\mathrm{R}}$ are matrix components of thin-lens. The pair of (r_1, r_4) and (r_2, r_3) are compresent and each pairs are incompatible in the local situation. In these pair parameters, r_3 can leak globally due to the deviation of betatron phase from $\pi/2$. Therefore, r_2 was the leading candidate as the dominant coupling factor.

CORRECTION OF THE LINEAR X-Y COUPLING

Based on the discussion in previous section, mainly r_2 parameter was tuned day by day while confirming with the luminosity. Figure 3 shows the measured specific luminosity as the function of r_2. Obviously, the specific luminosity was changed in response to the r_2 scanned. However measured data did not have remarkable improvement like a simulation, the luminosity can be decreased by other reasons.

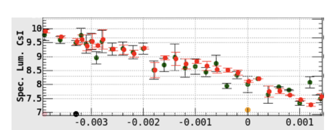

Figure 3: The measured luminosity with r_2 scan.

The result of elaborate scanning r parameters was shown in Figure 4. The major difference is the r_2 valued changed from 0mm to −7mm, and the difference of geometrical specific luminosity ($I_+I_- = 0$) is about twice. This result is consistent with the result of beam-beam simulation.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPGW031

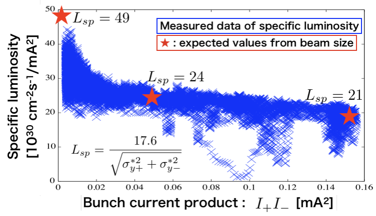

Figure 4: The specific luminosity as the function of the bunch current product in final status of Phase-II.

FURTHER PROBLEM OF THE LUMINOSITY FOR HIGH INTENSITY

In Figure 4, linear x-y coupling had been already corrected well, but on the other hand there are still issues of the beam blow up in the high current operation. The specific luminosity should keep flat even in high current, because it is independent of the beam current. Thus, as the next step, we are challenging to solve this problem in Phase-III commissioning.

There are some ways to measure x-y coupling parameters directly. Since the turn by turn data of IP includes clear information of the betatron tune on the normal coordinates, this is a strong tool to measure the x-y coupling. First, the method to calculating by using correlations of the phase space plot. An ellipse in the phase space is characterized by a correlation matrix [3]. The important relation between measured data and the correlation matrix component for the u-mode excitation is

$$< x^2 > = \mu^2 \beta_x \tag{14}$$

$$< xy > = \mu(-\beta_x r_1 + \alpha_x r_2) \tag{15}$$

$$< xp_y > = \mu(-\beta_x r_3 + \alpha_x r 4) \tag{16}$$

$$< p_x y > = \mu(\alpha_x r_1 - \gamma_x r_2) \tag{17}$$

$$< p_x p_y > = \mu(\alpha_x r_3 - \gamma_x r_4) \tag{18}$$

where <> is the average for turn by turn. However, the practical analysis is not so simple. For example, the correlation on x-y plane for the transferred data from boyh side of IP ("QC1LE" and "QC1RE") is shown in left of Figure 5. When we see the single data, the plot has good correlation and it seems that r_{i}s can be derived by correlation matrix. But the difference between these data is only pick up position. Though it should be same result, these plot are quit different distributions. Right figure shows the difference between different tuning way and set r_2 parameter which is reflected to the specific luminosity, but there are no difference. The analysis of the data by this way is still in progress. So far in SuperKEKB, the analysis by this method hasn't been going well.

In another way, the analysis on frequency domain called harmonic analysis is also useful to measure x-y coupling. By using turn by turn data, r_i parameters are calculated, and

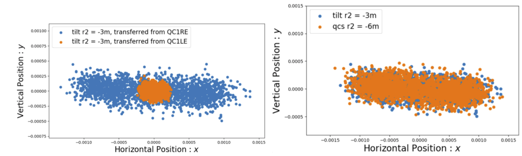

Figure 5: Left plots are comparison of turn by turn BPM signals between both side of IP transferred by using transfer matrix. Right shows correlations of the phase space plot between different x-y coupling knob tuning on x-y plane. (physical coordinates).

the formula [4] is

$$\mathrm{R} = -\mu \mathrm{C}_{(y,u)} \mathrm{C}^{-1}_{(x,u)},\ \mathrm{R}^{-1} = \mu \mathrm{C}_{(y,v)} \mathrm{C}^{-1}_{(x,v)} \tag{19}$$

$$\mathrm{C}_{(i,j)} = \begin{pmatrix} \sum_n i(n) \cos(2\pi\nu_j n) & \sum_n i(n) \sin(2\pi\nu_j n) \\ \sum_n p_i(n) \cos(2\pi\nu_j n) & \sum_n p_i(n) \sin(2\pi\nu_j n) \end{pmatrix}$$

where n is the number of turn, ν_j is the betatron tune, and i represents x or y. The turn by turn data transferred to IP is produced by both side of data and transfer matrix. When the turn by turn data of IP includes clear information of the betatron tune on the normal coordinates, this is a strong tool to measure the x-y coupling. Figure 6 shows the FFT plot of the turn by turn data. As Figure 6 shows, turn by turn data includes the betatron tune of each mode, it seems that Eq. 19 can be applied.

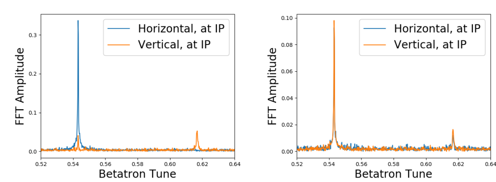

Figure 6: FFT plots of the turn by turn signal picked up at QC1LE/RE and transferred to the IP in HER. The left is the plot of x and y, the right is the plot of p_x and p_y.

Remaining x-y coupling can be chromatic terms, because linear coupling had been already optimized. The simulation result suggests that the contribution of chromatic x-y coupling can reproduce the current status like Figure 4. In phase-III commissioning, we will study about the continuation of this analysis and the chromatic x-y coupling and other factors such as the nonlinear aberration caused by skew sextupole errors [5, 6].

SUMMARY

In the SuperKEKB Phase-II commissioning, there are serious degradation of the luminosity. To correct the problem, we tuned x-y coupling parameters focusing on the r_2 component. As the result of optics tuning, the most serious issue which is the discrepancy between the measured and expected luminosity was well corrected. But the luminosity decreasing in high current operation still remain. To improve the luminosity in after Phase-III commissioning, we are analysing details of x-y coupling.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPGW031

REFERENCES

[1] Y. Ohnishi *et. al.*, "Accelerator design at SuperKEKB", *Prog. Theor. Exp. Phys.*, vol. 2013, issue 3, p. 03A0112013, 2013.

[2] Y. Seimiya *et. al.*, "Symplectic Expression for Chromatic Aberrations", *Prog. Theor. Exp. Phys.*, vol. 127, issue 6, pp. 1099–1119, 2012.

[3] K. Ohmi *et. al.*, "Optics Measurement at the Interaction Point using Nearby Position Monitors in KEKB", in *Proc. IPAC'10*, Kyoto, Japan, May 2010, paper TUPEB012, pp. 1539–1541.

[4] Y. Ohnishi *et. al.*, "Measurement of XY Coupling using Turn-by-turn BPM at KEKB", in *Proc. EPAC'00*, Vienna, Austria, Jun. 2000, paper MOP3B11, pp. 1537–1539.

[5] K. Ohmi *et. al.*, "Low emittance and luminosity tuning in SuperKEKB", in *Proc. of the 8th low emitt. ring WS*, 2019.

[6] K. Hirosawa *et. al.*, "The Influence of Higher Order Multipoles of IR Magnets on Luminosity for SuperKEKB", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 3463–3465. doi:10.18429/JACoW-IPAC2018-THPAK099