ISBN: 978-3-95450-192-2 doi:10.18429/JACoW-IBIC2017-TU3AB1

OPTICS MEASUREMENTS AT SuperKEKB USING BEAM BASED CALIBRATION FOR BPM AND BEAM BASED EXPERIMENT

Hiroshi Sugimoto, Yukiyoshi Ohnishi, Haruyo Koiso, Akio Morita, Masaki Tejima
KEK, Tsukuba, Japan

Abstract

SuperKEKB is an electron-position collider realizes a new luminosity frontier. The target luminosity is $8\times10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The initial beam commissioning started in February 2016 and operated until June 2016. Low Emittance Tuning (LET) is an important issue in the beam commissioning. The Beam-Based Calibration (BBC) scheme for Beam-Position-Monitor (BPM) has been applied in order to establish reliable beam measurement system. In the BBC, a response model among beam position, charge and output signals of the BPM electrodes are introduced to calibrate the relative gain of each electrodes. The gains are adjusted by least squares fitting so that the model reproduces the measured BPM signals. The Beam-Based Alignment (BBA) is also performed to determine the magnetic center of each quadrupole magnet. Using the BBC, the performance of the BPM system and optics correction has been successfully improved. After the series of the optics tuning and the BPM calibration, the vertical emittance of about 10 pm is achieved in the positron ring. This paper presents what we experienced during the beam commissioning focusing on the beam optics measurement and the BBC scheme for the BPM system.

INTRODUCTION

SuperKEKB [1] is an upgrade project of KEKB [2], which has been successfully finished at 2010 after about 10 years of operation with the world luminosity record of $2.1\times10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$. SuperKEKB consists of electron (HER) and positron (LER) storage rings with an injector linac and a newly constructed positron damping ring. The target peak luminosity is $8\times10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

The design concept is based on the nano-beam scheme [3], in which colliding beams are squeezed to nano-scale sizes in the vertical direction at the interaction point (IP). The key changes of machine parameters from KEKB are 2 times higher beam current, 1/20 times smaller vertical betatron function at the IP with a larger crossing angle. Low emittance beams are essential for the nano-beam scheme as well as squeezing the betatron function.

The SuperKEKB commissioning has stared after over 5 years of the upgrade work. The initial beam commissioning started on February 1st 2016 and finished on June 28th 2016. The final focus system to collide two beams is not installed in this commissioning period. The commissioning is devoted to the vacuum scrubbing and the setup of both hardware and software. The LET is the one of the most important issue. The nominal machine parameters in this commissioning period are listed in Table 1.

Table 1: Machine Parameters as of June 2016

Parameter	HER	LER	Unit
E	7	4	GeV
I	0.87	1.01	A
N_{bunch}	1576	1576	
ε_x	4.6	1.8	nm
α_p	4.44×10^{-4}	2.45×10^{-4}	
σ_E	6.30×10^{-4}	7.52×10^{-4}	
V_c	12.61	7.65	MV
U_0	2.43	1.76	MeV
τ_s	29	23	msec
σ_z	5.3	4.6	mm
ν_s	-0.0253	-0.0192	
ν_x	45.530	44.430	
ν_y	43.570	46.570	

Calibration of the BPM system is a key issue for better control of beam orbit and optics. We employ the BBC technique to the BPM system as at KEKB [4] . In BBC, both the relative gain of the BPM electrodes and the relative offset between the BPM electrical center and the magnetic center of a quadrupole are determined using measured BPM signals. In this paper we show the idea and results of BBC together with experience on the LET in the initial beam commissioning.

BPM SYSTEM

The SuperKEKB accelerator has about 900 quadrupole magnets, and BPM is attached to each quadrupole magnets for precise orbit control. Most of the BPMs installed in the HER are based on 1 GHz narrow-band system [5] reused KEKB since most of the vacuum chambers are same as those of KEKB. On the other hand, the vacuum chambers of LER are replaced with new ones with ante-chamber structure, and the cutoff frequency is lower than 1 GHz in SuperKEKB. Therefore a newly developed narrow-band system is installed in the LER.

TheBPM 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 can be used as gated turn-by-turn BPMs. The gated turn-by-turn BPM system was very helpful in the first injection tuning at the very early stage of the beam commissioning. Although optics measurement with turn-by-turn beam position data was performed in the initial commissioning and some results are already obtained, we concentrate on the BBC and beam measurement based on closed orbit analysis in this paper.

ISBN: 978-3-95450-192-2 doi:10.18429/JACoW-IBIC2017-TU3AB1

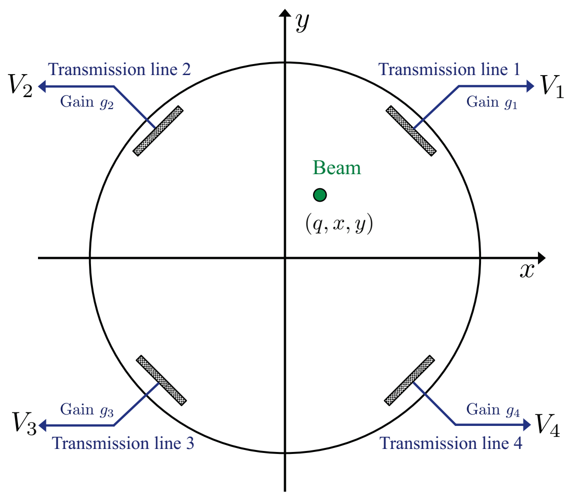

Figure 1: Schematic view of the BPM model used in BGC.

BEAM-BASED CALIBRATION

Two calibration factors are discussed here. One is calibration of relative gains of the BPM electrodes (BPM Gain Calibration, BGC) and the other is the determination of the BPM offset relative to the neighbour quadrupole magnet. In this section, we show a strategy of these calibration work and its result.

Gain Calibration

In the presented BPM system, a BPM has four button-type pickups and outputs four voltages $V_{1,2,3,4}$ induced by the beam as shown in Fig. 1. In order to eliminate dependency on beam intensity, normalized horizontal and vertical voltages (u, v) are used in the calculation of the beam position as,

$$u \equiv (V_1 - V_2 - V_3 + V_4)/\Sigma, \quad (1)$$

$$v \equiv (V_1 + V_2 - V_3 - V_4)/\Sigma, \quad (2)$$

where Σ is the sum of all four voltages. These normalized variables are transformed to horizontal and vertical beam positions (x, y) by using mapping functions as $x = F_x(u, v)$ and $y = F_y(u, v)$. The functions $F_{x,y}(u, v)$ are approximated by third order polynomial functions. The polynomial coefficients are obtained by a finite boundary element method with a two-dimensional electrostatics BPM model.

Assuming the ideal BPM with a perfectly conducting beam pipe and considering the transverse electric and magnetic field, the output voltage of i-th electrode is expressed by a single response function $F_i(x, y)$ as $V_i = qF_i(x, y)$. The voltage of each electrode is measured through a detector system after traveling through a different transmission path. Therefore the response of each electrode depends on the electrical characteristic of the transmission path and may be different from that of the ideal system.

We introduce a single calibration factor g_i to i-th electrode, called its gain, in order to describe the imbalance among the electrical characteristics of the four electrodes. The measured voltage is now re-written as $V_i = g_i qF_i(x, y)$, and

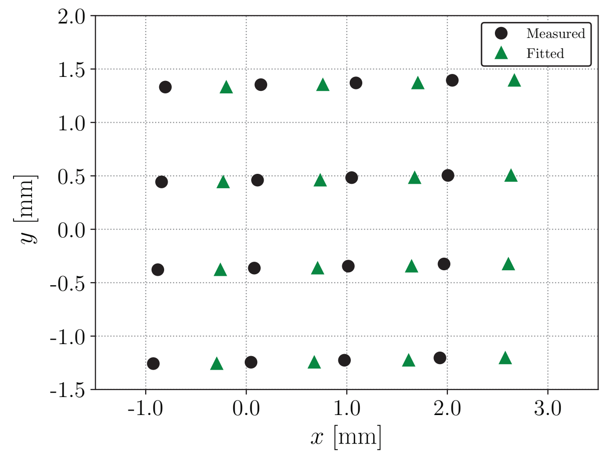

Figure 2: Example of the gain calibration. The dots represent measured beam position before the fitting, while the triangles represent beam positions obtained by the chi-square minimization.

all gains are equal to 1 for the ideal condition. Because only the relative value is essential in the calculation of beam positions as shown in Eqs. (1) and (2), we choose $g_1 = 1$ in the following.

The gain factor can be determined by a beam measurement so that the BPM model reproduces the measured BPM signals [6]. For this purpose we minimize a chi-square function,

$$\chi^2 \equiv \sum_i^4 \sum_j^m \frac{\left[V_{ij} - g_i q_j F(x_i, y_i)\right]^2}{\sigma_{ij}^2}, \quad (3)$$

where m is the number of measurements. The symbol σ represents the measurement error and is 10^{-3} in the presented system. The fitting parameters are three gain factors $g_{2,3,4}$, m sets of beam charges and positions (q_j, x_j, y_j). Therefore $3 + 3m$ parameters are determined by $4m$ measured voltages. It is expected that the unique solution can be obtained when $m > 4$ because the number of fitting variables becomes larger than that of measurement data. A sufficiently wide area of beam position data should be used to avoid degeneracy of the measurement data and failure in the chi-square minimization.

The response function $F_i(x, y)$ is approximated by a fourth order polynomial fit to numerical data obtained with the BPM model. The Levenberg-Marquardt algorithm [7, 8] is employed to minimizing χ^2. The BPM reading and gain factors at that point is used as an initial guess for the optimization algorithm.

Figure 2 illustrates experimental result obtained in the LER, where beam positions before the BGC and those obtained by the chi-square minimization are plotted. The electrode voltages are measured while changing strength of horizontal and vertical steering magnets. The chi-square χ^2 defined in Eq. (3) is converged from 4.8×10^8 to 1.3 after 17

ISBN: 978-3-95450-192-2 doi:10.18429/JACoW-IBIC2017-TU3AB1

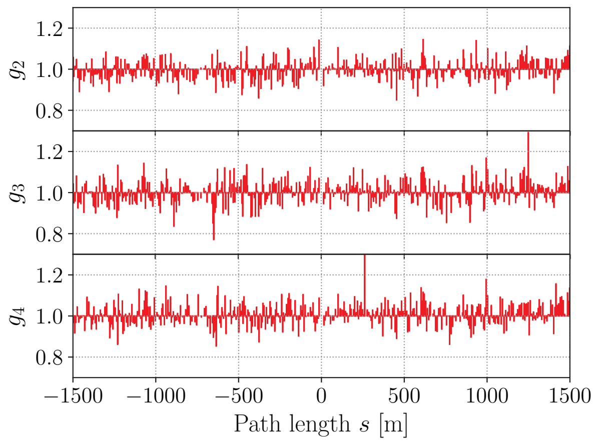

Figure 3: Gain parameters for the LER BPMs.

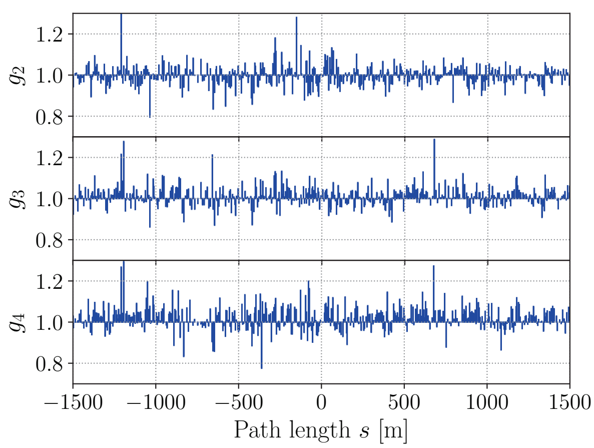

Figure 4: Gain parameters for the HER BPMs.

iterations of the minimization algorithm, and the resultant gains are $(g_2, g_3, g_4) = (0.994, 1.031, 0.987)$.

The BGC is performed for all BPMs in the both LER and HER. Two sets of horizontal and vertical steering magnets are used in the measurement considering betatron phase advance between them. The obtained gain factors are plotted along the ring in Figs. 3 and 4. The deviation from the ideal gain $\Delta g_{2,3,4} \equiv g_{2,3,4} - 1$ is about 5 % in the root-mean-square for both rings.

Beam Based Alignment

Another calibration parameter discussed in this paper is the BPM offset, that is, a misalignment between the magnetic center of a neighbour quadrupole magnet and the BPM electrical center. The BPM offset respect to the magnet causes unexpected orbit and optics distortion and may lead emittance degradation.

The offset respect to an adjoined quadrupole magnet is determined by Beam-Based-Alignment (BBA) technique [9]. We find a BPM reading which is insensitive to the field strength of the quadrupole magnet. The measurement is performed by using a semi-automated software implemented

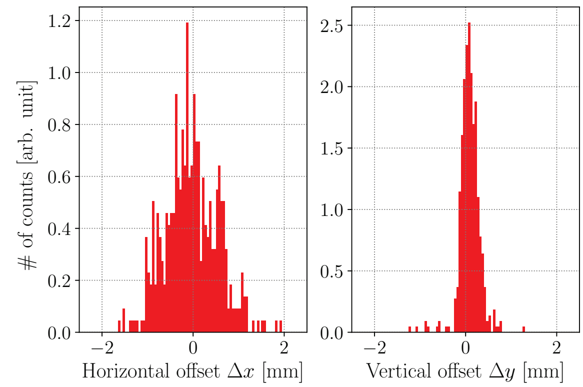

Figure 5: Offset distribution for the LER BPMs.

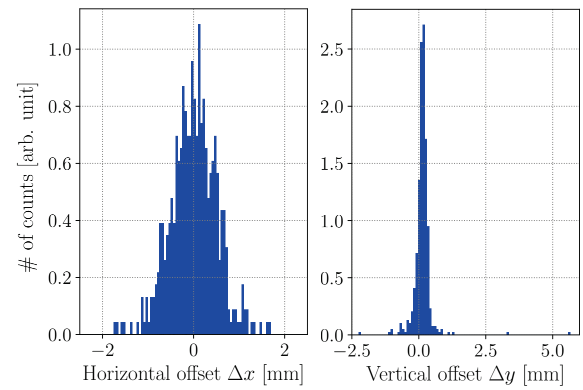

Figure 6: Offset distribution for the HER BPMs.

Table 2: Statistics of the Offset Distribution Shown in Figs. 5 and 6

Parameter [mm]	LER	HER
Δx^{min} / Δy^{min}	-1.60 / -1.22	-1.73 / -2.24
Δx^{max} / Δy^{max}	1.95 / 1.26	1.67 / 5.62
Δx^{rms} / Δy^{rms}	0.57 / 0.24	0.50 / 0.42

by the accelerator code SAD [10]. The offset information is incorporated into the BPM system.

The offset distributions are shown in Figs. 5 and 6, and their statistical information is summarized in Table 2. A few BPMs show relatively large vertical offset in the HER. In order to understand this unexpected vertical offset in the HER, some details on treatment of the offset parameters in the BPM system are described as follows.

The BBA technique finds out the BPM reading at which beam passes through the magnetic center, while the BGC redefines the electrical center of the four electrodes and changes the BPM reading. Therefore we should adjust the BPM offset parameter after BGC by considering the change of the BPM reading due to gain factor update, otherwise the BPM reading used in the orbit correction changes and unexpected orbit correction may be performed. To avoid this,

ISBN: 978-3-95450-192-2 doi:10.18429/JACoW-IBIC2017-TU3AB1

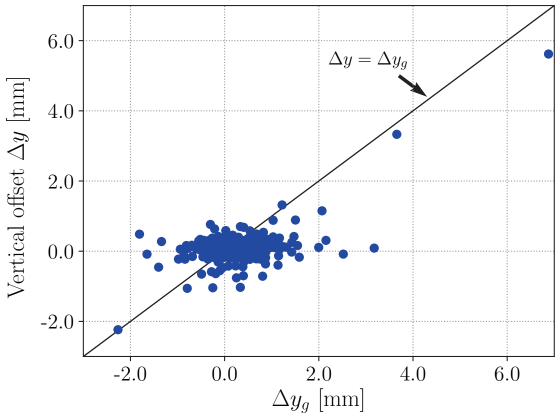

Figure 7: The vertical offset parameter Δy of the HER BPM system as shown in Fig. 6 against the offset Δy_g originated in the gain imbalance.

the offset parameter is adjusted after the BGC so that the BPM reading after the BGC is same as that before the BGC. This indicates the offset parameters shown in Figs. 5 and 6 are results from both the BGC and the BBA.

The change of horizontal and vertical BPM readings $(\Delta x_g, \Delta y_g)$ caused by a gain imbalance $\Delta g_{2,3,4}$ are given by, $\Delta x_g = A\,(\Delta g_2 + \Delta g_3 - \Delta g_4)$, $\Delta y_g = B\,(\Delta g_2 - \Delta g_3 - \Delta g_4)$ in the first order of $\Delta g_{2,3,4}$, respectively. The coefficients A and B can be evaluated by the mapping functions $F_{x,y}(u, v)$. The vertical offset parameter of the HER BPM system shown in Fig. 6 is plotted against Δy_g in Fig. 7. The extremely large offsets clearly have correlation with Δy_g, namely, the gain imbalance. The correlation indicates that the observed large offset does not mean misalignment of the mechanical center of the BPM and the magnetics center of the magnet, but a large gain imbalance among the electrodes.

OPTICS MEASUREMENT AND CORRECTION

Optics measurement and correction toward low emittance beams are iteratively carried out in parallel to the BBC during the commissioning period. The beam optics is measured by analyzing closed orbit distortions induced by horizontal dipole kicks to the beam or frequency change of rf cavities.

The important optics parameters in the LET are the vertical dispersion function and the coupling between horizontal and vertical betatron motions (xy-coupling parameter). The xy-coupling parameter is a correlation between horizontal and vertical betatron motions, thus a vertical leakage orbit induced by a horizontal dipole kick reflects xy-coupling parameters. Six kinds of vertical leakage orbits are measured by using six different steering magnets considering the betatron phase advance among them. The correction of xy-coupling is performed against these leakage orbits. Additional skew quadrupole coils are newly installed to sextupole magnets in SuperKEKB for the optics correction. The adjustment of the skew quadrupole filed is calculated with

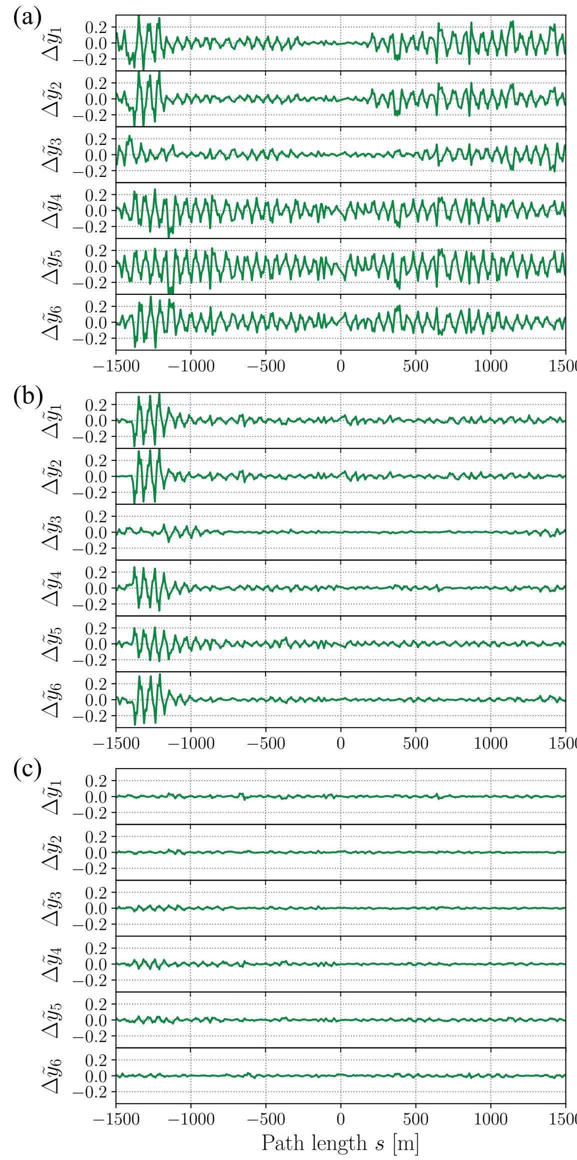

Figure 8: Measured vertical leakage orbits induced by horizontal dipole kicks in the LER ring (a) before correction, (b) after correction, (c) after two countermeasures for the leakage field of the Lambertson septum magnet. The vertical axis is normalized by root-mean-square amplitudes of the horizontal orbit.

the measured vertical leakage orbits and the model response matrix computed by SAD.

The vertical leakage orbits in the LER measured before and after the xy-coupling correction are shown in Figs. 8(a) and 8(b), respectively. After adjusting the skew quadrupole correctors, the vertical leakages are significantly suppressed. However, an uncorrectable leakage orbit was observed around $s = -1300$ m.

We find after a series of investigations that the uncorrectable xy-coupling is due to the leakage field from a Lambertson septum magnet which delivers aborted beams to

ISBN: 978-3-95450-192-2 doi:10.18429/JACoW-IBIC2017-TU3AB1

Table 3: Summary of the Optics Correction

Optics parameter	LER	HER
$\Delta y^{rms}/\Delta x^{rms}$ [10^{-3}]	9	6
$\Delta\eta_x^{rms}$ [mm]	8	11
$\Delta\eta_y^{rms}$ [mm]	2	2
$(\Delta\beta_x/\beta_x)^{rms}$ [%]	3	3
$(\Delta\beta_y/\beta_y)^{rms}$ [%]	3	3

a beam dump. Two cures are applied during the commissioning period. One is activation of skew quadrupole coils installed in the nearby sextupole magnets by using spare power supplies. Another cure is installation of permanent magnets. The specification of the permanent magnets is determined by considering the measured vertical leakage orbits shown in Fig. 8(b). We attached ferrite magnets with field strength of 0.07 T to the beam chamber near the septum magnet [11]. The xy-coupling due to the leakage field is successfully reduced by these cures as shown in Fig. 8(c). The same problem is observed in the HER, and we applied same cures to the HER. The residual of optics parameters respect to the model lattice is summarized in Table 3.

The history of vertical emittance of the LER beam during the commissioning period is plotted in Fig. 9. The vertical emittance is evaluated by vertical beam size measured by an x-ray beam size monitor [12]. The achieved lowest vertical emittance is about 10 pm. This value is consistent with that estimated by measured beam optics. On the other hand the vertical emittance of the HER beam is about 40 pm according to the beam size measurement. It is considerably larger than 10 pm expected from measured beam optics. The discrepancy in the HER is still under investigation.

One difference between the LER and the HER in beam size measurement is the vertical betatron function at the x-ray source point. The betatron function at the source point is 67 m in the LER, whereas 8 m in the HER. Therefore, required resolution in the beam size measurement is higher in the HER when the emittance is comparable in the both rings. We plan to enlarge the vertical betatron function from 8 to 28 m by installing pole changers to some quadrupole magnets, and investigate this issue more systematically in the next commissioning period.

SUMMARY

The BBC technique for the BPM system in the SuperKEKB first commissioning and the results of the LET are presented. Assuming the BPM model, the relative gains of the BPM electrodes are calibrated so that the model reproduces the measured output voltages. The BPM offset respect to the magnetic center of the neighbour quadrupole magnet is determined by finding the BPM reading which is insensitive to the quadrupole field strength.

The optics correction using the reliable BPM system is successfully worked. Though an unexpected problem due to the leakage field from the Lambertson septum magnet is revealed, it was resolved within the commissioning period.

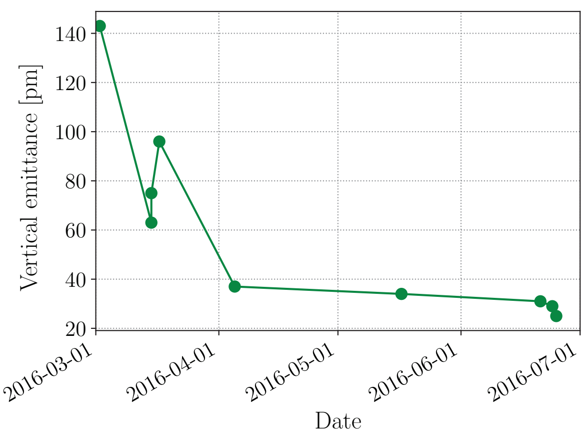

Figure 9: History of vertical emittance in LER.

The achieved vertical emittance in the LER ring is about 10 pm. The vertical emittance of the HER beam is about 40 pm according to the beam size measurement. It is considerably larger than that expected from measured beam optics. The vertical emittance in the HER is still under investigation. More detailed study is planned in the next commissioning period to fix this issue.

ACKNOWLEDGEMENT

The authors would like to thank the entire SuperKEKB accelerator group for developing the hardware system and supporting the beam measurement presented in this paper.

REFERENCES

[1] Y. Ohnishi *et al.*, *Prog. Theor. Exp. Phys.* 2013 03A011 (2013).

[2] T. Abe *et al.*, *Prog. Theor. Exp. Phys.* 2013 03A001 (2013).

[3] C. P. Raimondi, *2nd SuperB Workshop*, Frascati, Italy, Mar. 16-18, 2006.

[4] M. Tejima, in *Proc. of IBIC2015*, Melbourne, Australia, 2015 pp. 267-272.

[5] M.Arinaga *et al.*, *Prog. Theor. Exp. Phys.* 2013 03A007 (2013).

[6] K. Satoh and M. Tejima, in *Proc. of PAC1997*, Vancouver, Canada, 1997, pp. 2087-2089.

[7] D. Marquardt, *J. Soc. Indus. Appl. Math.*, Vol. 11, no 2, pp. 431-441, June 1963.

[8] H.B. Nielsen, *Technical Report*, IMM-REP-1999-05, Technical University of Denmark, 1999.

[9] M. Masuzawa *et al.*, in *Proc. of EPAC2000*, Vienna, Austria, 2000, pp. 1780-1782.

[10] K. Oide, Nucl. Inst. Meth. A 276, 427 (1989). http://acc-physics.kek.jp/SAD/

[11] N. Iida *et al.*, in *Proc. of IPAC2017*, Copenhagen, Denmark, 2017, pp. 2918–2921.

[12] E. Mulyani *et al.*, in *Proc. of IBIC2016*, Barcelona, Spain, 2016, pp. 524–527.