MEASUREMENT OF XY COUPLING USING TURN-BY-TURN BPM AT KEKB

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Abstract

We have measured xy coupling of the interaction point(I.P.) at KEKB. When a normal mode is excited by a shaker with tune frequency, the horizontal or vertical betatron oscillations can be measured by a turn-by-turn BPM in the laboratory coordinate system. A harmonic analysis has been performed to extract the xy coupling parameters at I.P. from the detected betatron oscillations.

1 IDEA AND FORMALISM

The transformation from the physical coordinate, (x, p_x, y, p_y) to the normal(xy decoupled) coordinate, (u, p_u, v, p_v) at a position is written by

$$\begin{pmatrix} u \\ p_u \\ v \\ p_v \end{pmatrix} = \mathbf{C} \begin{pmatrix} x \\ p_x \\ y \\ p_y \end{pmatrix}, \qquad (1)$$

where the 4×4 matrix **C** is defined by

$$\mathbf{C} = \begin{pmatrix} \mu I & JR^T J \\ R & \mu I \end{pmatrix}, \qquad (2)$$

and the relation between μ and R is μ^2 + det R = 1.

The submatrices are

$$I = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \quad J = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}, \qquad (3)$$

and

$$R = \begin{pmatrix} r_1 & r_2 \\ r_3 & r_4 \end{pmatrix}. \qquad (4)$$

We refer to r_1, r_2, r_3, r_4 as *xy coupling* in this paper. The coupling matrix **C** is defined at each position along an orbit. If there is no coupling, the coupling parameters, r_1, r_2, r_3, r_4 are zero. The 4×4 physical transfer matrix of the one-turn is written in a block form as

$$\mathbf{T} = \mathbf{C}^{-1} \begin{pmatrix} M_u & 0 \\ 0 & M_v \end{pmatrix} \mathbf{C}, \qquad (5)$$

where

$$M_{u,v} = \begin{pmatrix} \cos(2\pi\nu_{u,v}) + \alpha_{u,v}\sin(2\pi\nu_{u,v}) & \beta_{u,v}\sin(2\pi\nu_{u,v}) \\ -\gamma_{u,v}\sin(2\pi\nu_{u,v}) & \cos(2\pi\nu_{u,v}) - \alpha_{u,v}\sin(2\pi\nu_{u,v}) \end{pmatrix}. \qquad (6)$$

When only single mode is excited, the phase space of the beam in the physical coordinate can be obtained by

$$\begin{aligned} x &= \mu u \\ p_x &= \mu p_u \\ y &= -r_1 u - r_2 p_u \\ p_y &= -r_3 u - r_4 p_u \end{aligned} \qquad (7)$$

for H-mode($v = 0$, $p_v = 0$) or

$$\begin{aligned} x &= r_4 v - r_2 p_v \\ p_x &= -r_3 v + r_1 p_v \\ y &= \mu v \\ p_y &= \mu p_v \end{aligned} \qquad (8)$$

for V-mode($u = 0$, $p_u = 0$), respectively. The xy coupling can be extracted from the physical beam oscillations with consecutive turns applying a harmonic analysis for Eqs.(7) or (8):

$$\begin{pmatrix} r_1 & r_2 \\ r_3 & r_4 \end{pmatrix} = -\mu \begin{pmatrix} C_y^u & S_y^u \\ C_{p_y}^u & S_{p_y}^u \end{pmatrix} \begin{pmatrix} C_x^u & S_x^u \\ C_{p_x}^u & S_{p_x}^u \end{pmatrix}^{-1} \qquad (9)$$

from H-mode,

$$\begin{pmatrix} r_4 & -r_2 \\ -r_3 & r_1 \end{pmatrix} = \mu \begin{pmatrix} C_x^v & S_x^v \\ C_{p_x}^v & S_{p_x}^v \end{pmatrix} \begin{pmatrix} C_y^v & S_y^v \\ C_{p_y}^v & S_{p_y}^v \end{pmatrix}^{-1} \qquad (10)$$

from V-mode, where

$$\begin{aligned} C_w^{u,v} &= \sum_n w(n)\cos(2\pi\nu_{u,v} n) \\ S_w^{u,v} &= \sum_n w(n)\sin(2\pi\nu_{u,v} n), \end{aligned} \qquad (11)$$

n is the number of turn, $\nu_{u,v}$ is the betatron tune, and w represents x, p_x, y, or p_y.

2 MEASUREMENT OF XY COUPLING

The beam centroid position is measured by two turn-by-turn BPM which located at either side of the I.P. between a pair of super conducting quadrupole magnets(QCS). We call these turn-by-turn BPM *OctoPos*[1]. The distance between I.P and the left side of OctoPos is 478.7 mm and 699.5 mm for the right side, respectively. The OctoPos can record the beam position of 64000 consecutive turns on two orthogonal coordinates. We utilize AM/PM method for the readout electronics[2]. The AM/PM is the method

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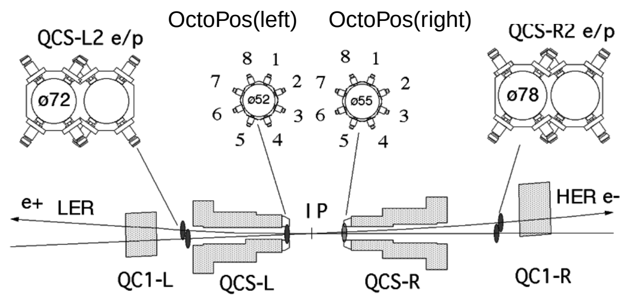

Figure 1: The schematic view of BPMs in the interaction region. Two OctoPos BPMs(left and right side of I.P) are located between the super conducting quadrupoles, in the longitudinal field of the BELLE detector.

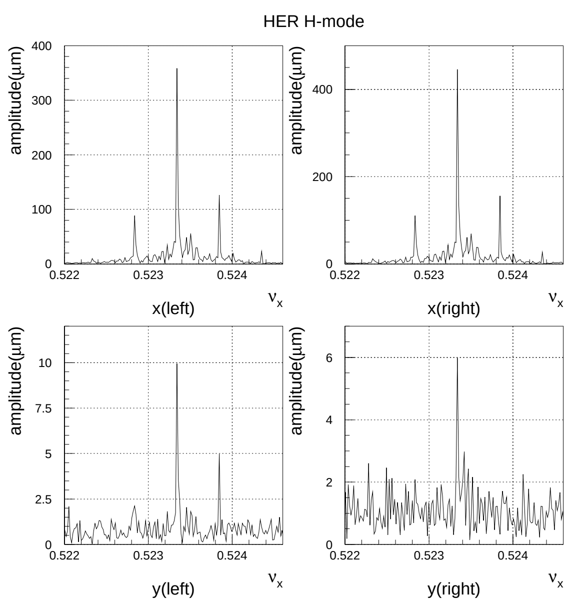

Figure 2: Typical spectrum of FFT analysis of beam oscillations at the left and right side of OctoPos in the electron ring(HER). The beam oscillations are excited by a shaker in the horizontal plane(H-mode).

converts the ratio of amplitudes to the phase. The OctoPos has eight electrodes and four electrodes(two pairs of 1 and 5, 3 and 7 as shown in Fig. 1) are used to detect the beam position with the AM/PM electronics. Since the local coordinate determined by four AM/PM electrodes has a slant of 22.5° with respect to the design physical coordinate, the raw data from the OctoPos should be rotated by 22.5° after a mapping correction. All electrodes of the OctoPos are usually used for the measurement of a closed orbit and connected to the conventional electronics as same as the other BPMs in the KEKB. The gains of the OctoPos with the conventional electronics were corrected using signals from the beam. We corrected the AM/PM data with a mapping function obtained from the response for the beam compared with the conventional electronics whose calibration has done completely. The mapping data were taken for the AM/PM and the conventional electronics using the local bump orbit simultaneously. The third polynomials are utilized for the mapping functions for both horizontal and vertical direction.

The beam was a single bunch and its current was 1.5 mA to measure the beam oscillations excited by a shaker. The shaker can excite a single normal mode, H-mode or V-mode, by changing the betatron frequency. Fig. 2 shows spectrum of FFT analysis at each OctoPos for the H-mode. The horizontal betatron tune of the electron ring(HER) was $\nu_x = 44.5233$ and the peak at the betatron frequency is clearly appeared in the x coordinate. The peak in the y direction is also found at the horizontal betatron frequency as shown in Fig. 2. This behavior is caused by the designed xy coupling due to solenoid field and the residual xy coupling due to machine error. The xy coupling, r_1, r_2 and r_4 can be extracted from the H-mode or V-mode at each OctoPos using only positions, however, r_3 can not be extracted without momentum information.

Further, we are interested in the xy coupling at I.P because it might affect the luminosity. The beam centroid positions are detected at both OctoPos using the same trigger signal for the revolution. Assumed that the transfer matrix defined by Eq.(5) of the model lattice, we can reconstruct the phase space at I.P as follows:

$$\begin{pmatrix} x \\ p_x \\ y \\ p_y \end{pmatrix}_{IP} = \begin{pmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ n_{11} & n_{12} & n_{13} & n_{14} \\ n_{31} & n_{32} & n_{33} & n_{34} \end{pmatrix} \begin{pmatrix} x_L \\ y_L \\ x_R \\ y_R \end{pmatrix},$$

where m_{ij} and n_{ij} are the ij-th element of the transfer matrices from I.P to the left-side and right-side OctoPos, (x_L, y_L) is measured beam position at the left-side OctoPos, and (x_R, y_R) at the right-side. We calculate the model lattice with *SAD*[3] which is a computer code for the accelerator design developed at KEK. Figure 3 shows spectrum of FFT analysis of beam oscillations at I.P with the resonant excitation of the H-mode. The xy coupling can be extracted by the FFT analysis at I.P using Eq.(9) for the H-mode or Eq.(10) for the V-mode. In Eqs.(9)(10), we assumed that μ is 1 approximately since the xy coupling should be small and its determinant is nearly equal to zero.

Tables 1 and 2 show the measured parameters of the xy coupling at I.P. for the electron(HER) and the positron(LER) ring, respectively. Since two OctoPos BPMs are common for both HER and LER, the same electrodes and AM/PM electronics are utilized to measure each beam. In order to confirm the repeatability of the measurement, we took ten samples of the oscillation data and present the average values of the xy couplings and r.m.s. of those fluctuations which we call statistic error. The rotation of the OctoPos is considered as the systematic error. The accuracy of the alignment of the OctoPos is estimated by $\sim 500\mu$m in the azimuthal direction and it becomes $\sim 1^\circ$ rotation angle. The systematic errors estimated from the rotation errors are also shown in Tables 1 and 2. The statistic errors look like enough small and the systematic errors are slightly larger than the statistic errors. It is found that the systematic error of r_3 is larger than those of other parameters.

We can also measure the phase advance between two OctoPos BPMs using beam oscillations. We obtained that the phase advance between two OctoPos BPMs is 100.1° for the HER and 74.5° for the LER in the x coordinate from the H-mode analysis. The accuracy is estimated by less than 0.5° in the phase measurement. We found that the discrepancy between measurements and the model lattice was 20° for the HER and 5° for the LER. The measured phase advance is good agreement with the model lattice in LER, however, the discrepancy in the HER implies large machine errors. It was figured out that the horizontal beta function was too squeezed at I.P. The turn-by-turn BPMs are useful for the diagnostics of the lattice as well as the xy coupling measurement.

We tried to measure the xy coupling using the V-mode, however, a good accuracy could not be achieved because of a finite crossing angle(22 mrad) in the horizontal plane. When there is a large offset of the beam orbit due to the large crossing angle, the distances between two electrodes become extremely asymmetry and the ratio method such as the AM/PM can not provide enough resolution if the oscillation amplitude is quite small. Therefore, We choose the H-mode to measure the xy coupling in this analysis.

Table 1: Measured xy coupling parameters at I.P in the electron ring(HER).

parameter		stat. err	syst. err
r_1	0.0004	±0.002	±0.006
r_2 (m)	-0.007	±0.001	±0.005
r_3 (1/m)	0.053	±0.001	±0.012
r_4	-0.016	±0.002	±0.007

Table 2: Measured xy coupling parameters at I.P in the positron ring(LER).

parameter		stat. err	syst. err
r_1	0.043	±0.005	±0.010
r_2 (m)	-0.010	±0.002	±0.005
r_3 (1/m)	0.041	±0.006	±0.015
r_4	-0.008	±0.002	±0.007

3 CONCLUSION

We have measured the xy coupling at I.P in the both HER and LER at KEKB. The xy coupling parameters have been derived from harmonic analysis of the beam oscillations excited with a shaker. The beam is driven at the tune frequency in one plane which can separate two normal mode. We confirmed the repeatability of the measurement was

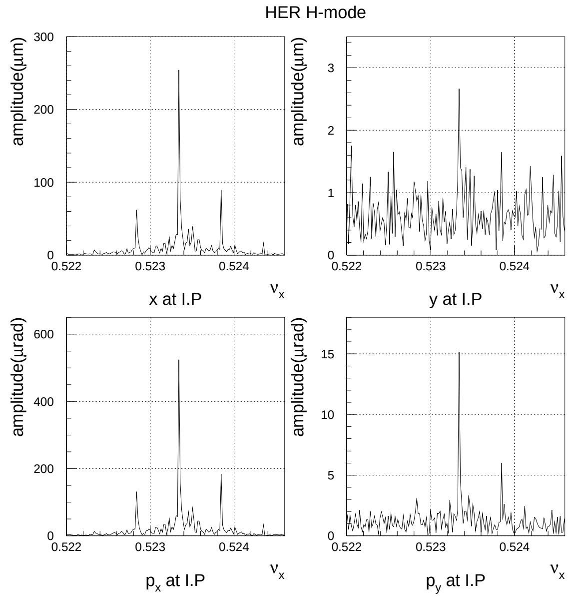

Figure 3: Typical spectrum of FFT analysis of beam oscillations at I.P in the electron ring(HER). The phase spaces are reconstructed by two OctoPos data using transfer matrices between OctoPos and I.P. The beam oscillations are excited by a shaker in the horizontal plane(H-mode).

quite good. We also estimated the systematic error as the rotation error of the monitor. However, the systematic error common to two OctoPos BPMs should be compensated when we consider the relative xy coupling of HER against the LER. The xy coupling parameters, r_2 and r_3, in the HER are found to be similar values of the LER. This is the result of the adiabatic tuning to maximize the luminosity. The xy coupling parameters, especially r_2 and r_3, are very effective for the luminosity from our experiences[4]. Some simulation result also tells us importance to reduce the xy coupling at I.P in the machine with a finite crossing angle to improve the luminosity[5]. In the near future, we have a plan to control the xy coupling at I.P using several skew quadrupole magnets based on this measurement.

4 ACKNOWLEDGEMENTS

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5 REFERENCES

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